Advanced Quantitative Economics with Python

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## Contents

### I  Tools and Techniques  
1. Orthogonal Projections and Their Applications  
2. Continuous State Markov Chains  
3. Reverse Engineering a la Muth  
4. Discrete State Dynamic Programming  

### II  LQ Control  
5. Information and Consumption Smoothing  
6. Consumption Smoothing with Complete and Incomplete Markets  
7. Tax Smoothing with Complete and Incomplete Markets  
8. Robustness  
9. Markov Jump Linear Quadratic Dynamic Programming  
10. How to Pay for a War: Part 1  
11. How to Pay for a War: Part 2  
12. How to Pay for a War: Part 3  
13. Optimal Taxation in an LQ Economy  

### III  Multiple Agent Models  
14. Robust Markov Perfect Equilibrium
15 Default Risk and Income Fluctuations 275
16 Globalization and Cycles 295
17 Coase’s Theory of the Firm 313

IV Dynamic Linear Economies 327
18 Recursive Models of Dynamic Linear Economies 329
19 Growth in Dynamic Linear Economies 365
20 Lucas Asset Pricing Using DLE 377
21 IRFs in Hall Models 385
22 Permanent Income Model using the DLE Class 393
23 Rosen Schooling Model 399
24 Cattle Cycles 405
25 Shock Non Invertibility 413

V Classic Linear Models 421
26 Von Neumann Growth Model (and a Generalization) 423

VI Time Series Models 441
27 Covariance Stationary Processes 443
28 Estimation of Spectra 465
29 Additive and Multiplicative Functionals 481
30 Classical Control with Linear Algebra 505
31 Classical Prediction and Filtering With Linear Algebra 527

VII Asset Pricing and Finance 549
32 Asset Pricing II: The Lucas Asset Pricing Model 551
CONTENTS

33 Two Modifications of Mean-Variance Portfolio Theory 561
34 Irrelevance of Capital Structures with Complete Markets 585
35 Equilibrium Capital Structures with Incomplete Markets 605

VIII Dynamic Programming Squared 645
36 Stackelberg Plans 647
37 Ramsey Plans, Time Inconsistency, Sustainable Plans 673
38 Optimal Taxation with State-Contingent Debt 699
39 Optimal Taxation without State-Contingent Debt 731
40 Fluctuating Interest Rates Deliver Fiscal Insurance 761
41 Fiscal Risk and Government Debt 789
42 Competitive Equilibria of a Model of Chang 817
43 Credible Government Policies in a Model of Chang 853
Part I

Tools and Techniques
Chapter 1

Orthogonal Projections and Their Applications

1.1 Contents

- Overview 1.2
- Key Definitions 1.3
- The Orthogonal Projection Theorem 1.4
- Orthonormal Basis 1.5
- Projection Using Matrix Algebra 1.6
- Least Squares Regression 1.7
- Orthogonalization and Decomposition 1.8
- Exercises 1.9
- Solutions 1.10

1.2 Overview

Orthogonal projection is a cornerstone of vector space methods, with many diverse applications.

These include, but are not limited to,

- Least squares projection, also known as linear regression
- Conditional expectations for multivariate normal (Gaussian) distributions
- Gram–Schmidt orthogonalization
- QR decomposition
- Orthogonal polynomials
- etc

In this lecture, we focus on

- key ideas
- least squares regression

We’ll require the following imports:

```
In [1]: import numpy as np
   from scipy.linalg import qr
```
1.2.1 Further Reading

For background and foundational concepts, see our lecture on linear algebra.

For more proofs and greater theoretical detail, see A Primer in Econometric Theory.

For a complete set of proofs in a general setting, see, for example, [52].

For an advanced treatment of projection in the context of least squares prediction, see this book chapter.

1.3 Key Definitions

Assume $x, z \in \mathbb{R}^n$.

Define $\langle x, z \rangle = \sum_i x_i z_i$.

Recall $\|x\|^2 = \langle x, x \rangle$.

The law of cosines states that $\langle x, z \rangle = \|x\| \|z\| \cos(\theta)$ where $\theta$ is the angle between the vectors $x$ and $z$.

When $\langle x, z \rangle = 0$, then $\cos(\theta) = 0$ and $x$ and $z$ are said to be orthogonal and we write $x \perp z$.

For a linear subspace $S \subset \mathbb{R}^n$, we call $x \in \mathbb{R}^n$ orthogonal to $S$ if $x \perp z$ for all $z \in S$, and write $x \perp S$. 
The **orthogonal complement** of linear subspace $S \subset \mathbb{R}^n$ is the set $S^\perp := \{x \in \mathbb{R}^n : x \perp S\}$.

$S^\perp$ is a linear subspace of $\mathbb{R}^n$
- To see this, fix $x, y \in S^\perp$ and $\alpha, \beta \in \mathbb{R}$.
- Observe that if $z \in S$, then
\[ \langle \alpha x + \beta y, z \rangle = \alpha \langle x, z \rangle + \beta \langle y, z \rangle = \alpha \times 0 + \beta \times 0 = 0 \]

- Hence \( \alpha x + \beta y \in S^\perp \), as was to be shown

A set of vectors \( \{x_1, \ldots, x_k\} \subset \mathbb{R}^n \) is called an **orthogonal set** if \( x_i \perp x_j \) whenever \( i \neq j \).

If \( \{x_1, \ldots, x_k\} \) is an orthogonal set, then the **Pythagorean Law** states that

\[
\|x_1 + \cdots + x_k\|^2 = \|x_1\|^2 + \cdots + \|x_k\|^2
\]

For example, when \( k = 2 \), \( x_1 \perp x_2 \) implies

\[
\|x_1 + x_2\|^2 = \langle x_1 + x_2, x_1 + x_2 \rangle = \langle x_1, x_1 \rangle + 2\langle x_2, x_1 \rangle + \langle x_2, x_2 \rangle = \|x_1\|^2 + \|x_2\|^2
\]

### 1.3.1 Linear Independence vs Orthogonality

If \( X \subset \mathbb{R}^n \) is an orthogonal set and \( 0 \notin X \), then \( X \) is linearly independent.

Proving this is a nice exercise.

While the converse is not true, a kind of partial converse holds, as we’ll see below.

### 1.4 The Orthogonal Projection Theorem

What vector within a linear subspace of \( \mathbb{R}^n \) best approximates a given vector in \( \mathbb{R}^n \)?

The next theorem provides an answer to this question.

**Theorem** (OPT) Given \( y \in \mathbb{R}^n \) and linear subspace \( S \subset \mathbb{R}^n \), there exists a unique solution to the minimization problem

\[
\hat{y} := \arg\min_{z \in S} \|y - z\|
\]

The minimizer \( \hat{y} \) is the unique vector in \( \mathbb{R}^n \) that satisfies

- \( \hat{y} \in S \)
- \( y - \hat{y} \perp S \)

The vector \( \hat{y} \) is called the **orthogonal projection** of \( y \) onto \( S \).

The next figure provides some intuition...
1.4.1 Proof of Sufficiency

We’ll omit the full proof.

But we will prove sufficiency of the asserted conditions.

To this end, let \( y \in \mathbb{R}^n \) and let \( S \) be a linear subspace of \( \mathbb{R}^n \).

Let \( \hat{y} \) be a vector in \( \mathbb{R}^n \) such that \( \hat{y} \in S \) and \( y - \hat{y} \perp S \).

Let \( z \) be any other point in \( S \) and use the fact that \( S \) is a linear subspace to deduce

\[
\|y - z\|^2 = \|(y - \hat{y}) + (\hat{y} - z)\|^2 = \|y - \hat{y}\|^2 + \|\hat{y} - z\|^2
\]

Hence \( \|y - z\| \geq \|y - \hat{y}\| \), which completes the proof.

1.4.2 Orthogonal Projection as a Mapping

For a linear space \( Y \) and a fixed linear subspace \( S \), we have a functional relationship

\[
y \in Y \mapsto \text{its orthogonal projection } \hat{y} \in S
\]

By the OPT, this is a well-defined mapping or operator from \( \mathbb{R}^n \) to \( \mathbb{R}^n \).

In what follows we denote this operator by a matrix \( P \)

- \( Py \) represents the projection \( \hat{y} \).
- This is sometimes expressed as \( \hat{E}_S y = Py \), where \( \hat{E} \) denotes a wide-sense expectations operator and the subscript \( S \) indicates that we are projecting \( y \) onto the linear subspace \( S \).
The operator $P$ is called the **orthogonal projection mapping onto** $S$.

It is immediate from the OPT that for any $y \in \mathbb{R}^n$

1. $Py \in S$ and
2. $y - Py \perp S$

From this, we can deduce additional useful properties, such as

1. $\|y\|^2 = \|Py\|^2 + \|y - Py\|^2$ and
2. $\|Py\| \leq \|y\|

For example, to prove 1, observe that $y = Py + y - Py$ and apply the Pythagorean law.

**Orthogonal Complement**

Let $S \subset \mathbb{R}^n$.

The **orthogonal complement** of $S$ is the linear subspace $S^\perp$ that satisfies $x_1 \perp x_2$ for every $x_1 \in S$ and $x_2 \in S^\perp$.

Let $Y$ be a linear space with linear subspace $S$ and its orthogonal complement $S^\perp$.

We write

$$Y = S \oplus S^\perp$$

to indicate that for every $y \in Y$ there is unique $x_1 \in S$ and a unique $x_2 \in S^\perp$ such that $y = x_1 + x_2$. 
Moreover, \( x_1 = \hat{E}_S y \) and \( x_2 = y - \hat{E}_S y \).

This amounts to another version of the OPT:

**Theorem.** If \( S \) is a linear subspace of \( \mathbb{R}^n \), \( \hat{E}_S y = Py \) and \( \hat{E}_S . y = My \), then

\[
P y \perp My \quad \text{and} \quad y = Py + My \quad \text{for all } y \in \mathbb{R}^n
\]

The next figure illustrates

\[1.5 \text{ Orthonormal Basis}\]

An orthogonal set of vectors \( O \subset \mathbb{R}^n \) is called an **orthonormal set** if \( \|u\| = 1 \) for all \( u \in O \).

Let \( S \) be a linear subspace of \( \mathbb{R}^n \) and let \( O \subset S \).

If \( O \) is orthonormal and \( \text{span } O = S \), then \( O \) is called an **orthonormal basis** of \( S \).

\( O \) is necessarily a basis of \( S \) (being independent by orthogonality and the fact that no element is the zero vector).

One example of an orthonormal set is the canonical basis \( \{e_1, \ldots, e_n\} \) that forms an orthonormal basis of \( \mathbb{R}^n \), where \( e_i \) is the \( i \)th unit vector.

If \( \{u_1, \ldots, u_k\} \) is an orthonormal basis of linear subspace \( S \), then

\[
x = \sum_{i=1}^{k} \langle x, u_i \rangle u_i \quad \text{for all} \quad x \in S
\]

To see this, observe that since \( x \in \text{span}\{u_1, \ldots, u_k\} \), we can find scalars \( \alpha_1, \ldots, \alpha_k \) that verify
\[ x = \sum_{j=1}^{k} \alpha_j u_j \]  

(1)

Taking the inner product with respect to \( u_i \) gives

\[ \langle x, u_i \rangle = \sum_{j=1}^{k} \alpha_j \langle u_j, u_i \rangle = \alpha_i \]

Combining this result with (1) verifies the claim.

1.5.1 Projection onto an Orthonormal Basis

When the subspace onto which are projecting is orthonormal, computing the projection simplifies:

**Theorem** If \( \{u_1, \ldots, u_k\} \) is an orthonormal basis for \( S \), then

\[ P y = \sum_{i=1}^{k} \langle y, u_i \rangle u_i, \quad \forall \ y \in \mathbb{R}^n \]  

(2)

Proof: Fix \( y \in \mathbb{R}^n \) and let \( Py \) be defined as in (2).

Clearly, \( Py \in S \).

We claim that \( y - Py \perp S \) also holds.

It suffices to show that \( y - Py \perp \) any basis vector \( u_i \) (why?).

This is true because

\[ \langle y - \sum_{i=1}^{k} \langle y, u_i \rangle u_i, u_j \rangle = \langle y, u_j \rangle - \sum_{i=1}^{k} \langle y, u_i \rangle \langle u_i, u_j \rangle = 0 \]

1.6 Projection Using Matrix Algebra

Let \( S \) be a linear subspace of \( \mathbb{R}^n \) and let \( y \in \mathbb{R}^n \).

We want to compute the matrix \( P \) that verifies

\[ \hat{E}_S y = Py \]

Evidently \( Py \) is a linear function from \( y \in \mathbb{R}^n \) to \( Py \in \mathbb{R}^n \).

This reference is useful https://en.wikipedia.org/wiki/Linear_map#Matrices.

**Theorem.** Let the columns of \( n \times k \) matrix \( X \) form a basis of \( S \). Then

\[ P = X(X'X)^{-1}X' \]

Proof: Given arbitrary \( y \in \mathbb{R}^n \) and \( P = X(X'X)^{-1}X' \), our claim is that
1.6. PROJECTION USING MATRIX ALGEBRA

1. $Py \in S$, and
2. $y - Py \perp S$

Claim 1 is true because

$$Py = X(X'X)^{-1}X'y = Xa$$

when

$$a := (X'X)^{-1}X'y$$

An expression of the form $Xa$ is precisely a linear combination of the columns of $X$, and hence an element of $S$.

Claim 2 is equivalent to the statement

$$y - X(X'X)^{-1}X'y \perp Xb$$

for all $b \in \mathbb{R}^K$

This is true: If $b \in \mathbb{R}^K$, then

$$(Xb)'[y - X(X'X)^{-1}X'y] = b'[X'y - X'y] = 0$$

The proof is now complete.

1.6.1 Starting with the Basis

It is common in applications to start with $n \times k$ matrix $X$ with linearly independent columns and let

$$S := \text{span} X := \text{span} \{\text{col}_1 X, \ldots, \text{col}_k X\}$$

Then the columns of $X$ form a basis of $S$.

From the preceding theorem, $P = X(X'X)^{-1}X'y$ projects $y$ onto $S$.

In this context, $P$ is often called the projection matrix

- The matrix $M = I - P$ satisfies $My = \hat{E}_S y$ and is sometimes called the annihilator matrix.

1.6.2 The Orthonormal Case

Suppose that $U$ is $n \times k$ with orthonormal columns.

Let $u_i := \text{col} U_i$ for each $i$, let $S := \text{span} U$ and let $y \in \mathbb{R}^n$.

We know that the projection of $y$ onto $S$ is

$$Py = U(U'U)^{-1}U'y$$

Since $U$ has orthonormal columns, we have $U'U = I$.

Hence
\[ Py = UU'y = \sum_{i=1}^{k} \langle u_i, y \rangle u_i \]

We have recovered our earlier result about projecting onto the span of an orthonormal basis.

### 1.6.3 Application: Overdetermined Systems of Equations

Let \( y \in \mathbb{R}^n \) and let \( X \) is \( n \times k \) with linearly independent columns. Given \( X \) and \( y \), we seek \( b \in \mathbb{R}^k \) satisfying the system of linear equations \( Xb = y \).

If \( n > k \) (more equations than unknowns), then \( b \) is said to be **overdetermined**.

Intuitively, we may not be able to find a \( b \) that satisfies all \( n \) equations.

The best approach here is to

- Accept that an exact solution may not exist.
- Look instead for an approximate solution.

By approximate solution, we mean a \( b \in \mathbb{R}^k \) such that \( Xb \) is as close to \( y \) as possible.

The next theorem shows that the solution is well defined and unique.

The proof uses the OPT.

**Theorem** The unique minimizer of \( \| y - Xb \| \) over \( b \in \mathbb{R}^k \) is

\[ \hat{b} := (X'X)^{-1}X'y \]

**Proof:** Note that

\[ X\hat{b} = X(X'X)^{-1}X'y = Py \]

Since \( Py \) is the orthogonal projection onto \( \text{span}(X) \) we have

\[ \| y - Py \| \leq \| y - z \| \text{ for any } z \in \text{span}(X) \]

Because \( Xb \in \text{span}(X) \)

\[ \| y - X\hat{b} \| \leq \| y - Xb \| \text{ for any } b \in \mathbb{R}^k \]

This is what we aimed to show.

### 1.7 Least Squares Regression

Let’s apply the theory of orthogonal projection to least squares regression.

This approach provides insights about many geometric properties of linear regression.

We treat only some examples.
1.7. LEAST SQUARES REGRESSION

1.7.1 Squared Risk Measures

Given pairs \((x, y) \in \mathbb{R}^K \times \mathbb{R}\), consider choosing \(f : \mathbb{R}^K \to \mathbb{R}\) to minimize the risk

\[
R(f) := \mathbb{E}[(y - f(x))^2]
\]

If probabilities and hence \(\mathbb{E}\) are unknown, we cannot solve this problem directly. However, if a sample is available, we can estimate the risk with the empirical risk:

\[
\min_{f \in \mathcal{F}} \frac{1}{N} \sum_{n=1}^{N} (y_n - f(x_n))^2
\]

Minimizing this expression is called empirical risk minimization. The set \(\mathcal{F}\) is sometimes called the hypothesis space.

The theory of statistical learning tells us that to prevent overfitting we should take the set \(\mathcal{F}\) to be relatively simple.

If we let \(\mathcal{F}\) be the class of linear functions \(1/N\), the problem is

\[
\min_{b \in \mathbb{R}^K} \sum_{n=1}^{N} (y_n - b'x_n)^2
\]

This is the sample linear least squares problem.

1.7.2 Solution

Define the matrices

\[
y := \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{pmatrix}, \quad x_n := \begin{pmatrix} x_{n1} \\ x_{n2} \\ \vdots \\ x_{nK} \end{pmatrix} = \text{\text{:math:`n`-th obs on all regressors}}
\]

and

\[
X := \begin{pmatrix} x'_1 \\ x'_2 \\ \vdots \\ x'_N \end{pmatrix} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1K} \\ x_{21} & x_{22} & \cdots & x_{2K} \\ \vdots & \vdots & & \vdots \\ x_{N1} & x_{N2} & \cdots & x_{NK} \end{pmatrix}
\]

We assume throughout that \(N > K\) and \(X\) is full column rank.

If you work through the algebra, you will be able to verify that \(\|y - Xb\|^2 = \sum_{n=1}^{N} (y_n - b'x_n)^2\).

Since monotone transforms don’t affect minimizers, we have

\[
\arg\min_{b \in \mathbb{R}^K} \sum_{n=1}^{N} (y_n - b'x_n)^2 = \arg\min_{b \in \mathbb{R}^K} \|y - Xb\|
\]
By our results about overdetermined linear systems of equations, the solution is

\[ \hat{\beta} := (X'X)^{-1}X'y \]

Let \( P \) and \( M \) be the projection and annihilator associated with \( X \):

\[ P := X(X'X)^{-1}X' \quad \text{and} \quad M := I - P \]

The vector of fitted values is

\[ \hat{y} := X\hat{\beta} = Py \]

The vector of residuals is

\[ \hat{u} := y - \hat{y} = y - Py = My \]

Here are some more standard definitions:

- The total sum of squares is \( \|y\|^2 \).
- The sum of squared residuals is \( \| \hat{u} \|^2 \).
- The explained sum of squares is \( \| \hat{y} \|^2 \).

\[ \text{TSS} = \text{ESS} + \text{SSR} \]

We can prove this easily using the OPT.

From the OPT we have \( y = \hat{y} + \hat{u} \) and \( \hat{u} \perp \hat{y} \).

Applying the Pythagorean law completes the proof.

### 1.8 Orthogonalization and Decomposition

Let’s return to the connection between linear independence and orthogonality touched on above.

A result of much interest is a famous algorithm for constructing orthonormal sets from linearly independent sets.

The next section gives details.

#### 1.8.1 Gram-Schmidt Orthogonalization

**Theorem** For each linearly independent set \( \{x_1, \ldots, x_k\} \subset \mathbb{R}^n \), there exists an orthonormal set \( \{u_1, \ldots, u_k\} \) with

\[ \text{span}\{x_1, \ldots, x_i\} = \text{span}\{u_1, \ldots, u_i\} \quad \text{for} \quad i = 1, \ldots, k \]

The Gram-Schmidt orthogonalization procedure constructs an orthogonal set \( \{u_1, u_2, \ldots, u_n\} \).

One description of this procedure is as follows:
1.8. ORTHOGONALIZATION AND DECOMPOSITION

- For \( i = 1, \ldots, k \), form \( S_i := \text{span}\{x_1, \ldots, x_i\} \) and \( S_i^{\perp} \)
- Set \( v_1 = x_1 \)
- For \( i \geq 2 \) set \( v_i := \hat{E}_{S_{i-1}} x_i \) and \( u_i := v_i / \|v_i\| \)

The sequence \( u_1, \ldots, u_k \) has the stated properties.

A Gram-Schmidt orthogonalization construction is a key idea behind the Kalman filter described in *A First Look at the Kalman filter*.

In some exercises below, you are asked to implement this algorithm and test it using projection.

1.8.2 QR Decomposition

The following result uses the preceding algorithm to produce a useful decomposition.

**Theorem** If \( X \) is \( n \times k \) with linearly independent columns, then there exists a factorization \( X = QR \) where

- \( R \) is \( k \times k \), upper triangular, and nonsingular
- \( Q \) is \( n \times k \) with orthonormal columns

**Proof sketch:** Let

- \( x_j := \text{col}_j(X) \)
- \( \{u_1, \ldots, u_k\} \) be orthonormal with the same span as \( \{x_1, \ldots, x_k\} \) (to be constructed using Gram–Schmidt)
- \( Q \) be formed from cols \( u_i \)

Since \( x_j \in \text{span}\{u_1, \ldots, u_j\} \), we have

\[
x_j = \sum_{i=1}^{j} \langle u_i, x_j \rangle u_i \quad \text{for } j = 1, \ldots, k
\]

Some rearranging gives \( X = QR \).

1.8.3 Linear Regression via QR Decomposition

For matrices \( X \) and \( y \) that overdetermine \( \beta \) in the linear equation system \( y = X\beta \), we found the least squares approximator \( \hat{\beta} = (X'X)^{-1} X'y \).

Using the QR decomposition \( X = QR \) gives

\[
\hat{\beta} = (R'Q'R)^{-1} R'Q'y = (R'R)^{-1} R'Q'y = R^{-1}(R')^{-1} R'Q'y = R^{-1}Q'y
\]

Numerical routines would in this case use the alternative form \( R\hat{\beta} = Q'y \) and back substitution.
1.9 Exercises

1.9.1 Exercise 1

Show that, for any linear subspace $S \subset \mathbb{R}^n$, $S \cap S^\perp = \{0\}$.

1.9.2 Exercise 2

Let $P = X(X'X)^{-1}X'$ and let $M = I - P$. Show that $P$ and $M$ are both idempotent and symmetric. Can you give any intuition as to why they should be idempotent?

1.9.3 Exercise 3

Using Gram-Schmidt orthogonalization, produce a linear projection of $y$ onto the column space of $X$ and verify this using the projection matrix $P := X(X'X)^{-1}X'$ and also using QR decomposition, where:

\[
y := \begin{pmatrix} 1 \\ 3 \\ -3 \end{pmatrix},
\]

and

\[
X := \begin{pmatrix} 1 & 0 \\ 0 & -6 \\ 2 & 2 \end{pmatrix}
\]

1.10 Solutions

1.10.1 Exercise 1

If $x \in S$ and $x \in S^\perp$, then we have in particular that $\langle x, x \rangle = 0$, ut then $x = 0$.

1.10.2 Exercise 2

Symmetry and idempotence of $M$ and $P$ can be established using standard rules for matrix algebra. The intuition behind idempotence of $M$ and $P$ is that both are orthogonal projections. After a point is projected into a given subspace, applying the projection again makes no difference. (A point inside the subspace is not shifted by orthogonal projection onto that space because it is already the closest point in the subspace to itself.)

1.10.3 Exercise 3

Here’s a function that computes the orthonormal vectors using the GS algorithm given in the lecture
1.10. SOLUTIONS

In [2]: def gram_schmidt(X):
   
   """
   Implements Gram-Schmidt orthogonalization.
   
   Parameters
   ----------
   X : an n x k array with linearly independent columns
   
   Returns
   -------
   U : an n x k array with orthonormal columns
   """
   
   # Set up
   n, k = X.shape
   U = np.empty((n, k))
   I = np.eye(n)

   # The first col of U is just the normalized first col of X
   v1 = X[:,0]
   U[:, 0] = v1 / np.sqrt(np.sum(v1 * v1))

   for i in range(1, k):
      # Set up
      b = X[:, i]  # The vector we're going to project
      Z = X[:, 0:i]  # First i-1 columns of X

      # Project onto the orthogonal complement of the col span of Z
      M = I - Z @ np.linalg.inv(Z.T @ Z) @ Z.T
      u = M @ b

      # Normalize
      U[:, i] = u / np.sqrt(np.sum(u * u))

   return U

Here are the arrays we'll work with

In [3]: y = [1, 3, -3]

X = [[1, 0],
     [0, -6],
     [2, 2]]

X, y = [np.asarray(z) for z in (X, y)]

First, let's try projection of y onto the column space of X using the ordinary matrix expression:

In [4]: Py1 = X @ np.linalg.inv(X.T @ X) @ X.T @ y

Py1

Out[4]: array([-0.56521739, 3.26086957, -2.2173913])

Now let's do the same using an orthonormal basis created from our gram_schmidt function
In [5]: U = gram_schmidt(X)
   
   Out[5]: array([[ 0.4472136 , -0.13187609],
              [ 0. , -0.98907071],
              [ 0.89442719, 0.06593805]])

In [6]: Py2 = U @ U.T @ y
   
   Out[6]: array([-0.56521739, 3.26086957, -2.2173913 ])

This is the same answer. So far so good. Finally, let’s try the same thing but with the basis obtained via QR decomposition:

In [7]: Q, R = qr(X, mode='economic')
   
   Out[7]: array([[-0.4472136 , -0.13187609],
              [-0. , -0.98907071],
              [-0.89442719, 0.06593805]])

In [8]: Py3 = Q @ Q.T @ y
   
   Out[8]: array([-0.56521739, 3.26086957, -2.2173913 ])

Again, we obtain the same answer.
Chapter 2

Continuous State Markov Chains

2.1 Contents

• Overview 2.2
• The Density Case 2.3
• Beyond Densities 2.4
• Stability 2.5
• Exercises 2.6
• Solutions 2.7
• Appendix 2.8

In addition to what’s in Anaconda, this lecture will need the following libraries:

```python
In [1]: !pip install --upgrade quantecon
```

2.2 Overview

In a previous lecture, we learned about finite Markov chains, a relatively elementary class of stochastic dynamic models.

The present lecture extends this analysis to continuous (i.e., uncountable) state Markov chains.

Most stochastic dynamic models studied by economists either fit directly into this class or can be represented as continuous state Markov chains after minor modifications.

In this lecture, our focus will be on continuous Markov models that

• evolve in discrete-time
• are often nonlinear

The fact that we accommodate nonlinear models here is significant, because linear stochastic models have their own highly developed toolset, as we’ll see later on.

The question that interests us most is: Given a particular stochastic dynamic model, how will the state of the system evolve over time?

In particular,

• What happens to the distribution of the state variables?
• Is there anything we can say about the “average behavior” of these variables?
• Is there a notion of “steady state” or “long-run equilibrium” that’s applicable to the model?
  – If so, how can we compute it?

Answering these questions will lead us to revisit many of the topics that occupied us in the finite state case, such as simulation, distribution dynamics, stability, ergodicity, etc.

**Note**

For some people, the term “Markov chain” always refers to a process with a finite or discrete state space. We follow the mainstream mathematical literature (e.g., [46]) in using the term to refer to any discrete time Markov process.

Let’s begin with some imports:

```python
In [2]: import numpy as np
   import matplotlib.pyplot as plt
   %matplotlib inline
   from scipy.stats import lognorm, beta
   from quantecon import LAE
   from scipy.stats import norm, gaussian_kde
```

### 2.3 The Density Case

You are probably aware that some distributions can be represented by densities and some cannot.

(For example, distributions on the real numbers \(\mathbb{R}\) that put positive probability on individual points have no density representation)

We are going to start our analysis by looking at Markov chains where the one-step transition probabilities have density representations.

The benefit is that the density case offers a very direct parallel to the finite case in terms of notation and intuition.

Once we’ve built some intuition we’ll cover the general case.

#### 2.3.1 Definitions and Basic Properties

In our lecture on finite Markov chains, we studied discrete-time Markov chains that evolve on a finite state space \(S\).

In this setting, the dynamics of the model are described by a stochastic matrix — a nonnegative square matrix \(P = P[i,j]\) such that each row \(P[i, :]\) sums to one.

The interpretation of \(P\) is that \(P[i,j]\) represents the probability of transitioning from state \(i\) to state \(j\) in one unit of time.

In symbols,

\[
P\{X_{t+1} = j \mid X_t = i\} = P[i,j]
\]

Equivalently,
• $P$ can be thought of as a family of distributions $P[i, \cdot]$, one for each $i \in S$
• $P[i, \cdot]$ is the distribution of $X_{t+1}$ given $X_t = i$
(As you probably recall, when using NumPy arrays, $P[i, \cdot]$ is expressed as $P[i, :]$)

In this section, we’ll allow $S$ to be a subset of $\mathbb{R}$, such as

• $\mathbb{R}$ itself
• the positive reals $(0, \infty)$
• a bounded interval $(a, b)$

The family of discrete distributions $P[i, \cdot]$ will be replaced by a family of densities $p(x, \cdot)$, one for each $x \in S$.

Analogous to the finite state case, $p(x, \cdot)$ is to be understood as the distribution (density) of $X_{t+1}$ given $X_t = x$.

More formally, a **stochastic kernel on $S$** is a function $p : S \times S \to \mathbb{R}$ with the property that

1. $p(x, y) \geq 0$ for all $x, y \in S$
2. $\int p(x, y)dy = 1$ for all $x \in S$

(Integrals are over the whole space unless otherwise specified)

For example, let $S = \mathbb{R}$ and consider the particular stochastic kernel $p_w$ defined by

$$p_w(x, y) := \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{(y - x)^2}{2} \right\}$$  \hspace{1cm} (1)

What kind of model does $p_w$ represent?

The answer is, the (normally distributed) random walk

$$X_{t+1} = X_t + \xi_{t+1} \quad \text{where} \quad \{\xi_t\} \overset{\IID}{\sim} N(0, 1)$$  \hspace{1cm} (2)

To see this, let’s find the stochastic kernel $p$ corresponding to (2).

Recall that $p(x, \cdot)$ represents the distribution of $X_{t+1}$ given $X_t = x$.

Letting $X_t = x$ in (2) and considering the distribution of $X_{t+1}$, we see that $p(x, \cdot) = N(x, 1)$.

In other words, $p$ is exactly $p_w$, as defined in (1).

### 2.3.2 Connection to Stochastic Difference Equations

In the previous section, we made the connection between stochastic difference equation (2) and stochastic kernel (1).

In economics and time-series analysis we meet stochastic difference equations of all different shapes and sizes.

It will be useful for us if we have some systematic methods for converting stochastic difference equations into stochastic kernels.

To this end, consider the generic (scalar) stochastic difference equation given by
Here we assume that

- \( \{\xi_t\} \overset{\text{iid}}{\sim} \phi \), where \( \phi \) is a given density on \( \mathbb{R} \)
- \( \mu \) and \( \sigma \) are given functions on \( S \), with \( \sigma(x) > 0 \) for all \( x \)

**Example 1:** The random walk (2) is a special case of (3), with \( \mu(x) = x \) and \( \sigma(x) = 1 \).

**Example 2:** Consider the ARCH model

\[
X_{t+1} = a X_t + \sigma_t \xi_{t+1}, \quad \sigma_t^2 = \beta + \gamma X_t^2, \quad \beta, \gamma > 0
\]

Alternatively, we can write the model as

\[
X_{t+1} = a X_t + (\beta + \gamma X_t^2)^{1/2} \xi_{t+1}
\]

This is a special case of (3) with \( \mu(x) = ax \) and \( \sigma(x) = (\beta + \gamma x^2)^{1/2} \).

**Example 3:** With stochastic production and a constant savings rate, the one-sector neoclassical growth model leads to a law of motion for capital per worker such as

\[
k_{t+1} = s A_{t+1} f(k_t) + (1 - \delta) k_t
\]

Here

- \( s \) is the rate of savings
- \( A_{t+1} \) is a production shock
  - The \( t + 1 \) subscript indicates that \( A_{t+1} \) is not visible at time \( t \)
- \( \delta \) is a depreciation rate
- \( f: \mathbb{R}_+ \rightarrow \mathbb{R}_+ \) is a production function satisfying \( f(k) > 0 \) whenever \( k > 0 \)

(The fixed savings rate can be rationalized as the optimal policy for a particular set of technologies and preferences (see [43], section 3.1.2), although we omit the details here).

Equation (5) is a special case of (3) with \( \mu(x) = (1 - \delta)x \) and \( \sigma(x) = sf(x) \).

Now let’s obtain the stochastic kernel corresponding to the generic model (3).

To find it, note first that if \( U \) is a random variable with density \( f_U \), and \( V = a + bU \) for some constants \( a, b \) with \( b > 0 \), then the density of \( V \) is given by

\[
f_V(v) = \frac{1}{b} f_U \left( \frac{v - a}{b} \right)
\]

(The proof is below. For a multidimensional version see EDTC, theorem 8.1.3).

Taking (6) as given for the moment, we can obtain the stochastic kernel \( p \) for (3) by recalling that \( p(x, \cdot) \) is the conditional density of \( X_{t+1} \) given \( X_t = x \).

In the present case, this is equivalent to stating that \( p(x, \cdot) \) is the density of \( Y := \mu(x) + \sigma(x) \xi_{t+1} \) when \( \xi_{t+1} \sim \phi \).

Hence, by (6),
2.3. THE DENSITY CASE

\[ p(x, y) = \frac{1}{\sigma(x)} \phi \left( \frac{y - \mu(x)}{\sigma(x)} \right) \]  \hspace{1cm} (7)

For example, the growth model in (5) has stochastic kernel

\[ p(x, y) = \frac{1}{sf(x)} \phi \left( \frac{y - (1 - \delta)x}{sf(x)} \right) \]  \hspace{1cm} (8)

where \( \phi \) is the density of \( A_{t+1} \).

(Regarding the state space \( S \) for this model, a natural choice is \( (0, \infty) \) — in which case \( \sigma(x) = sf(x) \) is strictly positive for all \( s \) as required)

2.3.3 Distribution Dynamics

In this section of our lecture on finite Markov chains, we asked the following question: If

1. \( \{X_t\} \) is a Markov chain with stochastic matrix \( P \)
2. the distribution of \( X_t \) is known to be \( \psi_t \)

then what is the distribution of \( X_{t+1} \)?

Letting \( \psi_{t+1} \) denote the distribution of \( X_{t+1} \), the answer we gave was that

\[ \psi_{t+1}[j] = \sum_{i \in S} P[i, j] \psi_t[i] \]

This intuitive equality states that the probability of being at \( j \) tomorrow is the probability of visiting \( i \) today and then going on to \( j \), summed over all possible \( i \).

In the density case, we just replace the sum with an integral and probability mass functions with densities, yielding

\[ \psi_{t+1}(y) = \int p(x, y) \psi_t(x) \, dx, \quad \forall y \in S \]  \hspace{1cm} (9)

It is convenient to think of this updating process in terms of an operator.

(An operator is just a function, but the term is usually reserved for a function that sends functions into functions)

Let \( \mathcal{D} \) be the set of all densities on \( S \), and let \( P \) be the operator from \( \mathcal{D} \) to itself that takes density \( \psi \) and sends it into new density \( \psi P \), where the latter is defined by

\[ (\psi P)(y) = \int p(x, y) \psi(x) \, dx \]  \hspace{1cm} (10)

This operator is usually called the Markov operator corresponding to \( p \)

**Note**

Unlike most operators, we write \( P \) to the right of its argument, instead of to the left (i.e., \( \psi P \) instead of \( P \psi \)). This is a common convention, with the intention being to maintain the parallel with the finite case — see here
With this notation, we can write (9) more succinctly as $\psi_{t+1}(y) = (\psi_t P)(y)$ for all $y$, or, dropping the $y$ and letting $\equiv$ indicate equality of functions,

$$\psi_{t+1} = \psi_t P$$ (11)

Equation (11) tells us that if we specify a distribution for $\psi_0$, then the entire sequence of future distributions can be obtained by iterating with $P$.

It’s interesting to note that (11) is a deterministic difference equation.

Thus, by converting a stochastic difference equation such as (3) into a stochastic kernel $p$ and hence an operator $P$, we convert a stochastic difference equation into a deterministic one (albeit in a much higher dimensional space).

### Note

Some people might be aware that discrete Markov chains are in fact a special case of the continuous Markov chains we have just described. The reason is that probability mass functions are densities with respect to the counting measure.

#### 2.3.4 Computation

To learn about the dynamics of a given process, it’s useful to compute and study the sequences of densities generated by the model.

One way to do this is to try to implement the iteration described by (10) and (11) using numerical integration.

However, to produce $\psi P$ from $\psi$ via (10), you would need to integrate at every $y$, and there is a continuum of such $y$.

Another possibility is to discretize the model, but this introduces errors of unknown size.

A nicer alternative in the present setting is to combine simulation with an elegant estimator called the look-ahead estimator.

Let’s go over the ideas with reference to the growth model discussed above, the dynamics of which we repeat here for convenience:

$$k_{t+1} = s A_{t+1} f(k_t) + (1 - \delta)k_t$$ (12)

Our aim is to compute the sequence $\{\psi_t\}$ associated with this model and fixed initial condition $\psi_0$.

To approximate $\psi_t$ by simulation, recall that, by definition, $\psi_t$ is the density of $k_t$ given $k_0 \sim \psi_0$.

If we wish to generate observations of this random variable, all we need to do is

1. draw $k_0$ from the specified initial condition $\psi_0$
2. draw the shocks $A_1, \ldots, A_t$ from their specified density $\phi$
3. compute $k_t$ iteratively via (12)
2.3. **THE DENSITY CASE**

If we repeat this \( n \) times, we get \( n \) independent observations \( k_t^1, \ldots, k_t^n \).

With these draws in hand, the next step is to generate some kind of representation of their distribution \( \psi_t \).

A naive approach would be to use a histogram, or perhaps a smoothed histogram using SciPy’s `gaussian_kde` function.

However, in the present setting, there is a much better way to do this, based on the look-ahead estimator.

With this estimator, to construct an estimate of \( \psi_t \), we actually generate \( n \) observations of \( k_{t-1} \), rather than \( k_t \).

Now we take these \( n \) observations \( k_{t-1}^1, \ldots, k_{t-1}^n \) and form the estimate

\[
\psi_t^n(y) = \frac{1}{n} \sum_{i=1}^{n} p(k_{t-1}^i, y)
\]

where \( p \) is the growth model stochastic kernel in (8).

What is the justification for this slightly surprising estimator?

The idea is that, by the strong law of large numbers,

\[
\frac{1}{n} \sum_{i=1}^{n} p(k_{t-1}^i, y) \to \mathbb{E}p(k_{t-1}^i, y) = \int p(x, y) \psi_{t-1}(x) \, dx = \psi_t(y)
\]

with probability one as \( n \to \infty \).

Here the first equality is by the definition of \( \psi_{t-1} \), and the second is by (9).

We have just shown that our estimator \( \psi_t^n(y) \) in (13) converges almost surely to \( \psi_t(y) \), which is just what we want to compute.

In fact, much stronger convergence results are true (see, for example, this paper).

### 2.3.5 Implementation

A class called `LAE` for estimating densities by this technique can be found in `lae.py`.

Given our use of the `__call__` method, an instance of `LAE` acts as a callable object, which is essentially a function that can store its own data (see this discussion).

This function returns the right-hand side of (13) using

- the data and stochastic kernel that it stores as its instance data
- the value \( y \) as its argument

The function is vectorized, in the sense that if \( \psi \) is such an instance and \( y \) is an array, then the call \( \psi(y) \) acts elementwise.

(This is the reason that we reshaped \( X \) and \( y \) inside the class — to make vectorization work)

Because the implementation is fully vectorized, it is about as efficient as it would be in C or Fortran.
2.3.6 Example

The following code is an example of usage for the stochastic growth model described above.

```
In [3]: # == Define parameters == #
s = 0.2
δ = 0.1
a_σ = 0.4  # A = exp(B) where B ~ N(0, a_σ)
α = 0.4  # We set f(k) = k**α
ψ_0 = beta(5, 5, scale=0.5)  # Initial distribution
ϕ = lognorm(a_σ)

def p(x, y):
    """Stochastic kernel for the growth model with Cobb-Douglas production.
    Both x and y must be strictly positive.
    """
    d = s * x**α
    return ϕ.pdf((y - (1 - δ) * x) / d) / d

n = 10000  # Number of observations at each date t
T = 30  # Compute density of k_t at 1,...,T+1

# == Generate matrix s.t. t-th column is n observations of k_t == #
k = np.empty((n, T))
A = ϕ.rvs((n, T))
k[:, 0] = ψ_0.rvs(n)  # Draw first column from initial distribution
for t in range(T-1):
    k[:, t+1] = s * A[:, t] * k[:, t]**α + (1 - δ) * k[:, t]

# == Generate T instances of LAE using this data, one for each date t == #
laes = [LAE(p, k[:, t]) for t in range(T)]

# == Plot == #
fig, ax = plt.subplots()
ygrid = np.linspace(0.01, 4.0, 200)
greys = [str(g) for g in np.linspace(0.0, 0.8, T)]
greys.reverse()
for ψ, g in zip(laes, greys):
    ax.plot(ygrid, ψ(ygrid), color=g, lw=2, alpha=0.6)
ax.set_xlabel('capital')
ax.set_title(f'Density of $k_1$ (lighter) to $k_T$ (darker) for $T={T}$')
plt.show()
```
2.4. BEYOND DENSITIES

The figure shows part of the density sequence \( \{\psi_t\} \), with each density computed via the look-ahead estimator.

Notice that the sequence of densities shown in the figure seems to be converging — more on this in just a moment.

Another quick comment is that each of these distributions could be interpreted as a cross-sectional distribution (recall this discussion).

2.4 Beyond Densities

Up until now, we have focused exclusively on continuous state Markov chains where all conditional distributions \( p(x, \cdot) \) are densities.

As discussed above, not all distributions can be represented as densities.

If the conditional distribution of \( X_{t+1} \) given \( X_t = x \) cannot be represented as a density for some \( x \in S \), then we need a slightly different theory.

The ultimate option is to switch from densities to probability measures, but not all readers will be familiar with measure theory.

We can, however, construct a fairly general theory using distribution functions.

2.4.1 Example and Definitions

To illustrate the issues, recall that Hopenhayn and Rogerson [35] study a model of firm dynamics where individual firm productivity follows the exogenous process.
\[ X_{t+1} = a + \rho X_t + \xi_{t+1}, \quad \text{where} \quad \{\xi_t\} \overset{\text{IID}}{\sim} N(0, \sigma^2) \]

As is, this fits into the density case we treated above.

However, the authors wanted this process to take values in \([0, 1]\), so they added boundaries at the endpoints 0 and 1.

One way to write this is

\[ X_{t+1} = h(a + \rho X_t + \xi_{t+1}) \quad \text{where} \quad h(x) := x 1\{0 \leq x \leq 1\} + 1\{x > 1\} \]

If you think about it, you will see that for any given \(x \in [0, 1]\), the conditional distribution of \(X_{t+1}\) given \(X_t = x\) puts positive probability mass on 0 and 1.

Hence it cannot be represented as a density.

What we can do instead is use cumulative distribution functions (cdfs).

To this end, set

\[ G(x, y) := \mathbb{P}\{h(a + \rho x + \xi_{t+1}) \leq y\} \quad (0 \leq x, y \leq 1) \]

This family of cdfs \(G(x, \cdot)\) plays a role analogous to the stochastic kernel in the density case.

The distribution dynamics in (9) are then replaced by

\[ F_{t+1}(y) = \int G(x, y)F_t(dx) \quad (14) \]

Here \(F_t\) and \(F_{t+1}\) are cdfs representing the distribution of the current state and next period state.

The intuition behind (14) is essentially the same as for (9).

### 2.4.2 Computation

If you wish to compute these cdfs, you cannot use the look-ahead estimator as before.

Indeed, you should not use any density estimator, since the objects you are estimating/computing are not densities.

One good option is simulation as before, combined with the empirical distribution function.

### 2.5 Stability

In our lecture on finite Markov chains, we also studied stationarity, stability and ergodicity.

Here we will cover the same topics for the continuous case.

We will, however, treat only the density case (as in this section), where the stochastic kernel is a family of densities.

The general case is relatively similar — references are given below.
2.5. STABILITY

2.5.1 Theoretical Results

Analogous to the finite case, given a stochastic kernel \( p \) and corresponding Markov operator as defined in (10), a density \( \psi^* \) on \( S \) is called stationary for \( P \) if it is a fixed point of the operator \( P \).

In other words,

\[
\psi^*(y) = \int p(x,y)\psi^*(x)\,dx, \quad \forall y \in S
\]  

(15)

As with the finite case, if \( \psi^* \) is stationary for \( P \), and the distribution of \( X_0 \) is \( \psi^* \), then, in view of (11), \( X_t \) will have this same distribution for all \( t \).

Hence \( \psi^* \) is the stochastic equivalent of a steady state.

In the finite case, we learned that at least one stationary distribution exists, although there may be many.

When the state space is infinite, the situation is more complicated.

Even existence can fail very easily.

For example, the random walk model has no stationary density (see, e.g., EDTC, p. 210).

However, there are well-known conditions under which a stationary density \( \psi^* \) exists.

With additional conditions, we can also get a unique stationary density \((\psi \in \mathcal{D} \text{ and } \psi = \psi P \implies \psi = \psi^*)\), and also global convergence in the sense that

\[
\forall \psi \in \mathcal{D}, \quad \psi P^t \to \psi^* \quad \text{as} \quad t \to \infty
\]  

(16)

This combination of existence, uniqueness and global convergence in the sense of (16) is often referred to as global stability.

Under very similar conditions, we get ergodicity, which means that

\[
\frac{1}{n} \sum_{t=1}^{n} h(X_t) \to \int h(x)\psi^*(x)\,dx \quad \text{as} \quad n \to \infty
\]  

(17)

for any (measurable) function \( h: S \to \mathbb{R} \) such that the right-hand side is finite.

Note that the convergence in (17) does not depend on the distribution (or value) of \( X_0 \).

This is actually very important for simulation — it means we can learn about \( \psi^* \) (i.e., approximate the right-hand side of (17) via the left-hand side) without requiring any special knowledge about what to do with \( X_0 \).

So what are these conditions we require to get global stability and ergodicity?

In essence, it must be the case that

1. Probability mass does not drift off to the “edges” of the state space.
2. Sufficient “mixing” obtains.

For one such set of conditions see theorem 8.2.14 of EDTC.

In addition
• [61] contains a classic (but slightly outdated) treatment of these topics.
• From the mathematical literature, [41] and [46] give outstanding in-depth treatments.
• Section 8.1.2 of EDTC provides detailed intuition, and section 8.3 gives additional references.
• EDTC, section 11.3.4 provides a specific treatment for the growth model we considered in this lecture.

2.5.2 An Example of Stability

As stated above, the growth model treated here is stable under mild conditions on the primitives.

• See EDTC, section 11.3.4 for more details.

We can see this stability in action — in particular, the convergence in (16) — by simulating the path of densities from various initial conditions.

Here is such a figure.

All sequences are converging towards the same limit, regardless of their initial condition.

The details regarding initial conditions and so on are given in this exercise, where you are asked to replicate the figure.

2.5.3 Computing Stationary Densities

In the preceding figure, each sequence of densities is converging towards the unique stationary density $\psi^*$.

Even from this figure, we can get a fair idea what $\psi^*$ looks like, and where its mass is located.
However, there is a much more direct way to estimate the stationary density, and it involves
only a slight modification of the look-ahead estimator.

Let’s say that we have a model of the form (3) that is stable and ergodic.
Let $p$ be the corresponding stochastic kernel, as given in (7).
To approximate the stationary density $\psi^*$, we can simply generate a long time-series
$X_0, X_1, \ldots, X_n$ and estimate $\psi^*$ via

$$\psi^*_n(y) = \frac{1}{n} \sum_{t=1}^{n} p(X_t, y)$$  (18)

This is essentially the same as the look-ahead estimator (13), except that now the observa-
tions we generate are a single time-series, rather than a cross-section.
The justification for (18) is that, with probability one as $n \to \infty$,

$$\frac{1}{n} \sum_{t=1}^{n} p(X_t, y) \to \int p(x, y) \psi^*(x) \, dx = \psi^*(y)$$

where the convergence is by (17) and the equality on the right is by (15).
The right-hand side is exactly what we want to compute.
On top of this asymptotic result, it turns out that the rate of convergence for the look-ahead
estimator is very good.
The first exercise helps illustrate this point.

2.6 Exercises

2.6.1 Exercise 1

Consider the simple threshold autoregressive model

$$X_{t+1} = \theta |X_t| + (1 - \theta^2)^{1/2} \xi_{t+1} \quad \text{where} \quad \{\xi_t\} \stackrel{\text{iid}}{\sim} N(0, 1)$$  (19)

This is one of those rare nonlinear stochastic models where an analytical expression for the
stationary density is available.
In particular, provided that $|\theta| < 1$, there is a unique stationary density $\psi^*$ given by

$$\psi^*(y) = 2 \phi(y) \Phi \left[ \frac{\theta y}{(1 - \theta^2)^{1/2}} \right]$$  (20)

Here $\phi$ is the standard normal density and $\Phi$ is the standard normal cdf.
As an exercise, compute the look-ahead estimate of $\psi^*$, as defined in (18), and compare it
with $\psi^*$ in (20) to see whether they are indeed close for large $n$.
In doing so, set $\theta = 0.8$ and $n = 500$.
The next figure shows the result of such a computation.
The additional density (black line) is a nonparametric kernel density estimate, added to the solution for illustration.

(You can try to replicate it before looking at the solution if you want to)

As you can see, the look-ahead estimator is a much tighter fit than the kernel density estimator.

If you repeat the simulation you will see that this is consistently the case.

2.6.2 Exercise 2

Replicate the figure on global convergence shown above.

The densities come from the stochastic growth model treated at the start of the lecture.

Begin with the code found above.

Use the same parameters.

For the four initial distributions, use the shifted beta distributions

\[ \psi_\theta = \text{beta}(5, 5, \text{scale}=0.5, \text{loc}=i*2) \]

2.6.3 Exercise 3

A common way to compare distributions visually is with boxplots.

To illustrate, let’s generate three artificial data sets and compare them with a boxplot.

The three data sets we will use are:

\[ \{X_1, \ldots, X_n\} \sim LN(0, 1), \quad \{Y_1, \ldots, Y_n\} \sim N(2, 1), \quad \text{and} \quad \{Z_1, \ldots, Z_n\} \sim N(4, 1), \]
Here is the code and figure:

In [4]: n = 500
x = np.random.randn(n)  # N(0, 1)
x = np.exp(x)  # Map x to lognormal
y = np.random.randn(n) + 2.0  # N(2, 1)
z = np.random.randn(n) + 4.0  # N(4, 1)

fig, ax = plt.subplots(figsize=(10, 6.6))
ax.boxplot([x, y, z])
ax.set_xticks((1, 2, 3))
ax.set_ylim(-2, 14)
ax.set_xticklabels(('\$X\$', '\$Y\$', '\$Z\$'), fontsize=16)
plt.show()

Each data set is represented by a box, where the top and bottom of the box are the third and first quartiles of the data, and the red line in the center is the median.

The boxes give some indication as to

- the location of probability mass for each sample
- whether the distribution is right-skewed (as is the lognormal distribution), etc

Now let's put these ideas to use in a simulation.

Consider the threshold autoregressive model in (19).

We know that the distribution of $X_t$ will converge to (20) whenever $|\theta| < 1$.

Let's observe this convergence from different initial conditions using boxplots.

In particular, the exercise is to generate J boxplot figures, one for each initial condition $X_0$ in

```
initial_conditions = np.linspace(8, 0, J)
```
For each \( X_0 \) in this set,

1. Generate \( k \) time-series of length \( n \), each starting at \( X_0 \) and obeying (19).

2. Create a boxplot representing \( n \) distributions, where the \( t \)-th distribution shows the \( k \) observations of \( X_t \).

Use \( \theta = 0.9, n = 20, k = 5000, J = 8 \)

### 2.7 Solutions

#### 2.7.1 Exercise 1

Look-ahead estimation of a TAR stationary density, where the TAR model is

\[
X_{t+1} = \theta |X_t| + (1 - \theta^2)^{1/2} \xi_{t+1}
\]

and \( \xi_t \sim N(0, 1) \).

Try running at \( n = 10, 100, 1000, 10000 \) to get an idea of the speed of convergence

```python
In [5]: φ = norm()
n = 500
θ = 0.8

# == Frequently used constants == #
d = np.sqrt(1 - θ**2)
δ = θ / d

def ψ_star(y):
    "True stationary density of the TAR Model"
    return 2 * norm.pdf(y) * norm.cdf(δ * y)

def p(x, y):
    "Stochastic kernel for the TAR model."
    return φ.pdf((y - θ * np.abs(x)) / d) / d

Z = φ.rvs(n)
X = np.empty(n)
for t in range(n-1):
    X[t+1] = θ * np.abs(X[t]) + d * Z[t]
ψ_est = LAE(p, X)
k_est = gaussian_kde(X)

fig, ax = plt.subplots(figsize=(10, 7))
ys = np.linspace(-3, 3, 200)
ax.plot(ys, ψ_star(ys), 'b-', lw=2, alpha=0.6, label='true')
ax.plot(ys, ψ_est(ys), 'g-', lw=2, alpha=0.6, label='look-ahead estimate')
ax.plot(ys, k_est(ys), 'k-', lw=2, alpha=0.6, label='kernel based estimate')
ax.legend(loc='upper left')
plt.show()
```
2.7. SOLUTIONS

2.7.2 Exercise 2

Here's one program that does the job

In [6]: # == Define parameters == #
   s = 0.2
   \delta = 0.1
   a_\sigma = 0.4  \quad \# A = \exp(B) where B \sim N(0, a_\sigma)
   \alpha = 0.4  \quad \# f(k) = k^{**}a

   \phi = \text{lognorm}(a_\sigma)

   \textbf{def} \ p(x, y):
   \hspace{1em} "Stochastic kernel, vectorized in x. Both x and y must be positive."
   \hspace{1em} d = s \times x^{**}a
   \hspace{1em} \text{return} \ \phi.pdf((y - (1 - \delta) \times x) / d) / d

   n = 10000  \quad \# Number of observations at each date t
   T = 40     \quad \# Compute density of k_t at 1,...,T

   fig, axes = plt.subplots(2, 2, figsize=(11, 8))
   axes = axes.flatten()
   xmax = 6.5

   \textbf{for} i \ \textbf{in} \ \text{range}(4):
   \hspace{1em} ax = axes[i]
   \hspace{1em} ax.set_xlim(0, xmax)
   \hspace{1em} \phi_0 = \text{beta}(5, 5, scale=0.5, loc=i*2)  \quad \# Initial distribution
# == Generate matrix s.t. t-th column is n observations of k_t == #
k = np.empty((n, T))
A = Φ_rvs((n, T))
k[:, 0] = ψ_0.rvs(n)
for t in range(T-1):
    k[:, t+1] = s * A[:,t] * k[:, t]**α + (1 - δ) * k[:, t]
# == Generate T instances of lae using this data, one for each t == #
laes = [LAE(p, k[:, t]) for t in range(T)]
ygrid = np.linspace(0.01, xmax, 150)
greys = [str(g) for g in np.linspace(0.0, 0.8, T)]
greys.reverse()
for ψ, g in zip(laes, greys):
    ax.plot(ygrid, ψ(ygrid), color=g, lw=2, alpha=0.6)
ax.set_xlabel('capital')
plt.show()

2.7.3 Exercise 3

Here’s a possible solution.

Note the way we use vectorized code to simulate the k time series for one boxplot all at once.

In [7]: n = 20
   k = 5000
   J = 6
\[
\theta = 0.9 \\
d = \text{np.sqrt}(1 - \theta^2) \\
\delta = \theta / d \\
\]

```python
fig, axes = plt.subplots(J, 1, figsize=(10, 4*J))
initial_conditions = np.linspace(8, 0, J)
X = np.empty((k, n))
for j in range(J):
    axes[j].set_ylim(-4, 8)
    axes[j].set_title(f'time series from t = {initial_conditions[j]}')
Z = np.random.randn(k, n)
X[:, 0] = initial_conditions[j]
for t in range(1, n):
    X[:, t] = \theta * \text{np.abs}(X[:, t-1]) + d * Z[:, t]
axes[j].boxplot(X)
plt.show()
```
2.8 Appendix

Here’s the proof of (6).

Let $F_U$ and $F_V$ be the cumulative distributions of $U$ and $V$ respectively.

By the definition of $V$, we have $F_V(v) = \mathbb{P}\{a + bU \leq v\} = \mathbb{P}\{U \leq (v - a)/b\}$.

In other words, $F_V(v) = F_U((v - a)/b)$.

Differentiating with respect to $v$ yields (6).
Chapter 3

Reverse Engineering a la Muth

3.1 Contents

- Friedman (1956) and Muth (1960) 3.2

In addition to what’s in Anaconda, this lecture uses the quantecon library.

In [1]: !pip install --upgrade quantecon

We’ll also need the following imports:

In [2]: import matplotlib.pyplot as plt
%matplotlib inline
import numpy as np
import scipy.linalg as la
from quantecon import Kalman
from quantecon import LinearStateSpace
from scipy.stats import norm
np.set_printoptions(linewidth=120, precision=4, suppress=True)

This lecture uses the Kalman filter to reformulate John F. Muth’s first paper [48] about rational expectations.

Muth used classical prediction methods to reverse engineer a stochastic process that renders optimal Milton Friedman’s [21] “adaptive expectations” scheme.

3.2 Friedman (1956) and Muth (1960)

Milton Friedman [21] (1956) posited that consumer’s forecast their future disposable income with the adaptive expectations scheme

\[ y_{t+i, t}^* = K \sum_{j=0}^{\infty} (1 - K)^j y_{t-j} \]  

where \( K \in (0, 1) \) and \( y_{t+i, t}^* \) is a forecast of future \( y \) over horizon \( i \).
Milton Friedman justified the **exponential smoothing** forecasting scheme (1) informally, noting that it seemed a plausible way to use past income to forecast future income.

In his first paper about rational expectations, John F. Muth [48] reverse-engineered a univariate stochastic process \{y_t\}_{t=-\infty}^{\infty} for which Milton Friedman’s adaptive expectations scheme gives linear least forecasts of \(y_{t+j}\) for any horizon \(i\).

Muth sought a setting and a sense in which Friedman’s forecasting scheme is optimal.

That is, Muth asked for what optimal forecasting **question** is Milton Friedman’s adaptive expectation scheme the **answer**.

Muth (1960) used classical prediction methods based on lag-operators and \(z\)-transforms to find the answer to his question.

Please see lectures Classical Control with Linear Algebra and Classical Filtering and Prediction with Linear Algebra for an introduction to the classical tools that Muth used.

Rather than using those classical tools, in this lecture we apply the Kalman filter to express the heart of Muth’s analysis concisely.

The lecture First Look at Kalman Filter describes the Kalman filter.

We’ll use limiting versions of the Kalman filter corresponding to what are called **stationary values** in that lecture.

### 3.2.1 A Process for Which Adaptive Expectations are Optimal

Suppose that an observable \(y_t\) is the sum of an unobserved random walk \(x_t\) and an IID shock \(\epsilon_{2,t}\):

\[
\begin{align*}
    x_{t+1} &= x_t + \sigma_x \epsilon_{1,t+1} \\
    y_t &= x_t + \sigma_y \epsilon_{2,t}
\end{align*}
\]

where

\[
\begin{bmatrix} \epsilon_{1,t+1} \\ \epsilon_{2,t} \end{bmatrix} \sim \mathcal{N}(0, I)
\]

is an IID process.

**Note:** A property of the state-space representation (2) is that in general neither \(\epsilon_{1,t}\) nor \(\epsilon_{2,t}\) is in the space spanned by square-summable linear combinations of \(y_t, y_{t-1}, \ldots\).

In general \(\begin{bmatrix} \epsilon_{1,t} \\ \epsilon_{2,t} \end{bmatrix}\) has more information about future \(y_{t+j}\)’s than is contained in \(y_t, y_{t-1}, \ldots\).

We can use the asymptotic or stationary values of the Kalman gain and the one-step-ahead conditional state covariance matrix to compute a time-invariant **innovations representation**

\[
\begin{align*}
    \hat{x}_{t+1} &= \hat{x}_t + K a_t \\
    y_t &= \hat{x}_t + a_t
\end{align*}
\]

where \(\hat{x}_t = E[x_t|y_{t-1}, y_{t-2}, \ldots]\) and \(a_t = y_t - E[y_t|y_{t-1}, y_{t-2}, \ldots]\).

**Note:** A key property about an **innovations representation** is that \(a_t\) is in the space spanned by square summable linear combinations of \(y_t, y_{t-1}, \ldots\).
For more ramifications of this property, see the lectures Shock Non-Invertibility and Recursive Models of Dynamic Linear Economies.

Later we’ll stack these state-space systems (2) and (3) to display some classic findings of Muth.

But first, let’s create an instance of the state-space system (2) then apply the quantecon Kalman class, then uses it to construct the associated “innovations representation”

In [3]: # Make some parameter choices
# sigx/sigy are state noise std err and measurement noise std err
μ_0, σ_x, σ_y = 10, 1, 5

# Create a LinearStateSpace object
A, C, G, H = 1, σ_x, 1, σ_y
ss = LinearStateSpace(A, C, G, H, mu_0=μ_0)

# Set prior and initialize the Kalman type
x_hat_0, Σ_0 = 10, 1
kmuth = Kalman(ss, x_hat_0, Σ_0)

# Computes stationary values which we need for the innovation
# representation
S1, K1 = kmuth.stationary_values()

# Form innovation representation state-space
Ak, Ck, Gk, Hk = A, K1, G, 1
ssk = LinearStateSpace(Ak, Ck, Gk, Hk, mu_0=x_hat_0)

### 3.2.2 Some Useful State-Space Math

Now we want to map the time-invariant innovations representation (3) and the original state-space system (2) into a convenient form for deducing the impulse responses from the original shocks to the $x_t$ and $\hat{x}_t$.

Putting both of these representations into a single state-space system is yet another application of the insight that “finding the state is an art”.

We’ll define a state vector and appropriate state-space matrices that allow us to represent both systems in one fell swoop.

Note that

$$ a_t = x_t + σ_y ε_{2,t} - \hat{x}_t $$

so that

$$ \hat{x}_{t+1} = \hat{x}_t + K(x_t + σ_y ε_{2,t} - \hat{x}_t) $$
$$ = (1 - K)\hat{x}_t + Kx_t + Kσ_y ε_{2,t} $$

The stacked system
is a state-space system that tells us how the shocks \( \begin{bmatrix} \epsilon_{1,t+1} \\ \epsilon_{2,t+1} \end{bmatrix} \) affect states \( \hat{x}_{t+1}, x_t \), the observable \( y_t \), and the innovation \( a_t \).

With this tool at our disposal, let’s form the composite system and simulate it

In [4]:

```python
# Create grand state-space for y_t, a_t as observed vars -- Use
# stacking trick above
Af = np.array([[1, 0, 0], [K, 1 - K, K * \sigma_y], [0, 0, 0]])
Cf = np.array([[\sigma_x, 0], [0, \sigma_y], [0, 1]])
Gf = np.array([[1, 0], [1, -1], [-1, \sigma_y]])

# Create the state-space
ssf = LinearStateSpace(Af, Cf, Gf, mu_0=\mu_f)

# Draw observations of y from the state-space model
N = 50
xf, yf = ssf.simulate(N)

print(f"Kalman gain = \{K1\}"
print(f"Conditional variance = \{S1\}"

Kalman gain = [[0.181]]
Conditional variance = [[5.5249]]
```

Now that we have simulated our joint system, we have \( x_t, \hat{x}_t, \) and \( y_t \).

We can now investigate how these variables are related by plotting some key objects.

### 3.2.3 Estimates of Unobservables

First, let’s plot the hidden state \( x_t \) and the filtered version \( \hat{x}_t \) that is linear-least squares projection of \( x_t \) on the history \( y_{t-1}, y_{t-2}, \ldots \)
3.2. FRIEDMAN (1956) AND MUTH (1960)

Note how $x_t$ and $\hat{x}_t$ differ.

For Friedman, $\hat{x}_t$ and not $x_t$ is the consumer’s idea about her/his permanent income.

3.2.4 Relation between Unobservable and Observable

Now let’s plot $x_t$ and $y_t$.

Recall that $y_t$ is just $x_t$ plus white noise

```
ax.plot(xf[1, :], label="Filtered $x_t$")
ax.legend()
ax.set_xlabel("Time")
ax.set_title(r"$x$ vs $\hat{x}$")
plt.show()
```

```
In [6]: fig, ax = plt.subplots()
ax.plot(yf[0, :], label="y")
ax.plot(xf[0, :], label="x")
ax.legend()
ax.set_title(r"$x$ and $y$")
ax.set_xlabel("Time")
plt.show()
```
We see above that $y$ seems to look like white noise around the values of $x$.

### 3.2.5 Innovations

Recall that we wrote down the innovation representation that depended on $a_t$. We now plot the innovations $\{a_t\}$:

```python
In [7]: fig, ax = plt.subplots()
    ax.plot(yf[1, :], label="a")
    ax.legend()
    ax.set_title(r"Innovation $a_t$")
    ax.set_xlabel("Time")
    plt.show()
```
3.2. FRIEDMAN (1956) AND MUTH (1960)

3.2.6 MA and AR Representations

Now we shall extract from the Kalman instance `kmuth` coefficients of

- a fundamental moving average representation that represents $y_t$ as a one-sided moving sum of current and past $a_t$s that are square summable linear combinations of $y_t, y_{t-1}, ...$.
- a univariate autoregression representation that depicts the coefficients in a linear least square projection of $y_t$ on the semi-infinite history $y_{t-1}, y_{t-2}, ...$

Then we'll plot each of them

```
In [8]: # Kalman Methods for MA and VAR
coefs_ma = kmuth.stationary_coefficients(5, "ma")
coefs_var = kmuth.stationary_coefficients(5, "var")

# Coefficients come in a list of arrays, but we # want to plot them and so need to stack into an array
coefs_ma_array = np.vstack(coefs_ma)
coefs_var_array = np.vstack(coefs_var)

fig, ax = plt.subplots(2)
ax[0].plot(coefs_ma_array, label="MA")
ax[0].legend()
ax[1].plot(coefs_var_array, label="VAR")
ax[1].legend()

plt.show()
```
The **moving average** coefficients in the top panel show tell-tale signs of \( y_t \) being a process whose first difference is a first-order autoregression.

The **autoregressive coefficients** decline geometrically with decay rate \((1 - K)\).

These are exactly the target outcomes that Muth (1960) aimed to reverse engineer

```python
In [9]: print(f'decay parameter 1 - K1 = {1 - K1}')
```

```
decay parameter 1 - K1 = [[0.819]]
```
Chapter 4

Discrete State Dynamic Programming

4.1 Contents

• Overview 4.2
• Discrete DPs 4.3
• Solving Discrete DPs 4.4
• Example: A Growth Model 4.5
• Exercises 4.6
• Solutions 4.7
• Appendix: Algorithms 4.8

In addition to what’s in Anaconda, this lecture will need the following libraries:

```
In [1]: !pip install --upgrade quantecon
```

4.2 Overview

In this lecture we discuss a family of dynamic programming problems with the following features:

1. a discrete state space and discrete choices (actions)
2. an infinite horizon
3. discounted rewards
4. Markov state transitions

We call such problems discrete dynamic programs or discrete DPs.

Discrete DPs are the workhorses in much of modern quantitative economics, including

• monetary economics
• search and labor economics
• household savings and consumption theory
• investment theory
When a given model is not inherently discrete, it is common to replace it with a discretized version in order to use discrete DP techniques.

This lecture covers

- the theory of dynamic programming in a discrete setting, plus examples and applications
- a powerful set of routines for solving discrete DPs from the QuantEcon code library

Let’s start with some imports:

```python
In [2]: import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
import quantecon as qe
import scipy.sparse as sparse
from quantecon import compute_fixed_point
from quantecon.markov import DiscreteDP
```

### 4.2.1 How to Read this Lecture

We use dynamic programming many applied lectures, such as

- The shortest path lecture
- The McCall search model lecture

The objective of this lecture is to provide a more systematic and theoretical treatment, including algorithms and implementation while focusing on the discrete case.

### 4.2.2 Code

Among other things, it offers

- a flexible, well-designed interface
- multiple solution methods, including value function and policy function iteration
- high-speed operations via carefully optimized JIT-compiled functions
- the ability to scale to large problems by minimizing vectorized operators and allowing operations on sparse matrices

JIT compilation relies on Numba, which should work seamlessly if you are using Anaconda as suggested.

### 4.2.3 References

For background reading on dynamic programming and additional applications, see, for example,

- [43]
- [34], section 3.5
- [50]
- [61]
- [55]
4.3. **DISCRETE DPs**

Loosely speaking, a discrete DP is a maximization problem with an objective function of the form

\[
\mathbb{E} \sum_{t=0}^{\infty} \beta^t r(s_t, a_t)
\]

where

- \(s_t\) is the state variable
- \(a_t\) is the action
- \(\beta\) is a discount factor
- \(r(s_t, a_t)\) is interpreted as a current reward when the state is \(s_t\) and the action chosen is \(a_t\)

Each pair \((s_t, a_t)\) pins down transition probabilities \(Q(s_t, a_t, s_{t+1})\) for the next period state \(s_{t+1}\).

Thus, actions influence not only current rewards but also the future time path of the state.

The essence of dynamic programming problems is to trade off current rewards vs favorable positioning of the future state (modulo randomness).

**Examples:**

- consuming today vs saving and accumulating assets
- accepting a job offer today vs seeking a better one in the future
- exercising an option now vs waiting

### 4.3.1 **Policies**

The most fruitful way to think about solutions to discrete DP problems is to compare policies.

In general, a policy is a randomized map from past actions and states to current action.

In the setting formalized below, it suffices to consider so-called *stationary Markov policies*, which consider only the current state.

In particular, a stationary Markov policy is a map \(\sigma\) from states to actions

- \(a_t = \sigma(s_t)\) indicates that \(a_t\) is the action to be taken in state \(s_t\)

It is known that, for any arbitrary policy, there exists a stationary Markov policy that dominates it at least weakly.

- See section 5.5 of [50] for discussion and proofs.

In what follows, stationary Markov policies are referred to simply as policies.

The aim is to find an optimal policy, in the sense of one that maximizes (1).

Let’s now step through these ideas more carefully.
4.3.2 Formal Definition

Formally, a discrete dynamic program consists of the following components:

1. A finite set of states \( S = \{0, \ldots, n - 1\} \).

2. A finite set of feasible actions \( A(s) \) for each state \( s \in S \), and a corresponding set of feasible state-action pairs.

\[
SA := \{ (s, a) \mid s \in S, a \in A(s) \}
\]

1. A reward function \( r : SA \to \mathbb{R} \).

2. A transition probability function \( Q : SA \to \Delta(S) \), where \( \Delta(S) \) is the set of probability distributions over \( S \).

2. A discount factor \( \beta \in [0, 1) \).

We also use the notation \( A := \bigcup_{s \in S} A(s) = \{0, \ldots, m - 1\} \) and call this set the action space.

A policy is a function \( \sigma : S \to A \).

A policy is called feasible if it satisfies \( \sigma(s) \in A(s) \) for all \( s \in S \).

Denote the set of all feasible policies by \( \Sigma \).

If a decision-maker uses a policy \( \sigma \in \Sigma \), then

- the current reward at time \( t \) is \( r(s_t, \sigma(s_t)) \)
- the probability that \( s_{t+1} = s' \) is \( Q(s_t, \sigma(s_t), s') \)

For each \( \sigma \in \Sigma \), define

- \( r_{\sigma} \) by \( r_{\sigma}(s) := r(s, \sigma(s)) \)
- \( Q_{\sigma} \) by \( Q_{\sigma}(s, s') := Q(s, \sigma(s), s') \)

Notice that \( Q_{\sigma} \) is a stochastic matrix on \( S \).

It gives transition probabilities of the controlled chain when we follow policy \( \sigma \).

If we think of \( r_{\sigma} \) as a column vector, then so is \( Q_{\sigma}^{t} r_{\sigma} \), and the \( s \)-th row of the latter has the interpretation

\[
(Q_{\sigma}^{t} r_{\sigma})(s) = \mathbb{E}[r(s_t, \sigma(s_t)) \mid s_0 = s] \quad \text{when} \quad \{s_t\} \sim Q_{\sigma} \tag{2}
\]

Comments

- \( \{s_t\} \sim Q_{\sigma} \) means that the state is generated by stochastic matrix \( Q_{\sigma} \).
- See this discussion on computing expectations of Markov chains for an explanation of the expression in (2).

Notice that we’re not really distinguishing between functions from \( S \) to \( \mathbb{R} \) and vectors in \( \mathbb{R}^n \).

This is natural because they are in one to one correspondence.
4.3.3 Value and Optimality

Let \( v_\sigma(s) \) denote the discounted sum of expected reward flows from policy \( \sigma \) when the initial state is \( s \).

To calculate this quantity we pass the expectation through the sum in (1) and use (2) to get

\[
v_\sigma(s) = \sum_{t=0}^{\infty} \beta^t (Q_\sigma r_\sigma)(s) \quad (s \in S)
\]

This function is called the policy value function for the policy \( \sigma \).

The optimal value function, or simply value function, is the function \( v^* : S \to \mathbb{R} \) defined by

\[
v^*(s) = \max_{\sigma \in \Sigma} v_\sigma(s) \quad (s \in S)
\]

(We can use \( \max \) rather than \( \sup \) here because the domain is a finite set)

A policy \( \sigma \in \Sigma \) is called optimal if \( v_\sigma(s) = v^*(s) \) for all \( s \in S \).

Given any \( w : S \to \mathbb{R} \), a policy \( \sigma \in \Sigma \) is called \( w \)-greedy if

\[
\sigma(s) \in \arg\max_{a \in A(s)} \left\{ r(s, a) + \beta \sum_{s' \in S} w(s') Q(s, a, s') \right\} \quad (s \in S)
\]

As discussed in detail below, optimal policies are precisely those that are \( v^* \)-greedy.

4.3.4 Two Operators

It is useful to define the following operators:

- The Bellman operator \( T : \mathbb{R}^S \to \mathbb{R}^S \) is defined by

\[
(Tv)(s) = \max_{a \in A(s)} \left\{ r(s, a) + \beta \sum_{s' \in S} v(s') Q(s, a, s') \right\} \quad (s \in S)
\]

- For any policy function \( \sigma \in \Sigma \), the operator \( T_\sigma : \mathbb{R}^S \to \mathbb{R}^S \) is defined by

\[
(T_\sigma v)(s) = r(s, \sigma(s)) + \beta \sum_{s' \in S} v(s') Q(s, \sigma(s), s') \quad (s \in S)
\]

This can be written more succinctly in operator notation as

\[
T_\sigma v = r_\sigma + \beta Q_\sigma v
\]

The two operators are both monotone

- \( v \leq w \) implies \( Tv \leq Tw \) pointwise on \( S \), and similarly for \( T_\sigma \)

They are also contraction mappings with modulus \( \beta \)

- \( \|Tv - Tw\| \leq \beta \|v - w\| \) and similarly for \( T_\sigma \), where \( \| \cdot \| \) is the max norm
For any policy \( \sigma \), its value \( v_\sigma \) is the unique fixed point of \( T_\sigma \).
For proofs of these results and those in the next section, see, for example, EDTC, chapter 10.

4.3.5 The Bellman Equation and the Principle of Optimality

The main principle of the theory of dynamic programming is that
- the optimal value function \( v^* \) is a unique solution to the Bellman equation

\[
v(s) = \max_{a \in A(s)} \left\{ r(s, a) + \beta \sum_{s' \in S} v(s') Q(s, a, s') \right\} \quad (s \in S)
\]

or in other words, \( v^* \) is the unique fixed point of \( T \), and
- \( \sigma^* \) is an optimal policy function if and only if it is \( v^* \)-greedy

By the definition of greedy policies given above, this means that

\[
\sigma^*(s) \in \arg\max_{a \in A(s)} \left\{ r(s, a) + \beta \sum_{s' \in S} v^*(s') Q(s, \sigma(s), s') \right\} \quad (s \in S)
\]

4.4 Solving Discrete DPs

Now that the theory has been set out, let’s turn to solution methods.
The code for solving discrete DPs is available in ddp.py from the QuantEcon.py code library.
It implements the three most important solution methods for discrete dynamic programs, namely
- value function iteration
- policy function iteration
- modified policy function iteration

Let’s briefly review these algorithms and their implementation.

4.4.1 Value Function Iteration

Perhaps the most familiar method for solving all manner of dynamic programs is value function iteration.
This algorithm uses the fact that the Bellman operator \( T \) is a contraction mapping with fixed point \( v^* \).
Hence, iterative application of \( T \) to any initial function \( v^0 : S \to \mathbb{R} \) converges to \( v^* \).
The details of the algorithm can be found in the appendix.

4.4.2 Policy Function Iteration

This routine, also known as Howard’s policy improvement algorithm, exploits more closely the particular structure of a discrete DP problem.
4.5. **EXAMPLE: A GROWTH MODEL**

Each iteration consists of

1. A policy evaluation step that computes the value $v_\sigma$ of a policy $\sigma$ by solving the linear equation $v = T_\sigma v$.

2. A policy improvement step that computes a $v_\sigma$-greedy policy.

In the current setting, policy iteration computes an exact optimal policy in finitely many iterations.

- See theorem 10.2.6 of EDTC for a proof.

The details of the algorithm can be found in the appendix.

4.4.3 **Modified Policy Function Iteration**

Modified policy iteration replaces the policy evaluation step in policy iteration with “partial policy evaluation”.

The latter computes an approximation to the value of a policy $\sigma$ by iterating $T_\sigma$ for a specified number of times.

This approach can be useful when the state space is very large and the linear system in the policy evaluation step of policy iteration is correspondingly difficult to solve.

The details of the algorithm can be found in the appendix.

4.5 **Example: A Growth Model**

Let’s consider a simple consumption-saving model.

A single household either consumes or stores its own output of a single consumption good.

The household starts each period with current stock $s$.

Next, the household chooses a quantity $a$ to store and consumes $c = s - a$.

- Storage is limited by a global upper bound $M$.
- Flow utility is $u(c) = c^\alpha$.

Output is drawn from a discrete uniform distribution on $\{0, \ldots, B\}$.

The next period stock is therefore

$$s' = a + U \quad \text{where} \quad U \sim U[0, \ldots, B]$$

The discount factor is $\beta \in [0, 1)$.

4.5.1 **Discrete DP Representation**

We want to represent this model in the format of a discrete dynamic program.

To this end, we take

- the state variable to be the stock $s$
CHAPTER 4. DISCRETE STATE DYNAMIC PROGRAMMING

- the state space to be $S = \{0, \ldots, M + B\}$
  - hence $n = M + B + 1$
- the action to be the storage quantity $a$
- the set of feasible actions at $s$ to be $A(s) = \{0, \ldots, \min\{s, M\}\}$
  - hence $A = \{0, \ldots, M\}$ and $m = M + 1$
- the reward function to be $r(s, a) = u(s - a)$
- the transition probabilities to be

$$Q(s, a, s') := \begin{cases} \frac{1}{B+1} & \text{if } a \leq s' \leq a + B \\ 0 & \text{otherwise} \end{cases}$$

(3)

4.5.2 Defining a DiscreteDP Instance

This information will be used to create an instance of DiscreteDP by passing the following information

1. An $n \times m$ reward array $R$.
2. An $n \times m \times n$ transition probability array $Q$.
3. A discount factor $\beta$.

For $R$ we set $R[s, a] = u(s - a)$ if $a \leq s$ and $-\infty$ otherwise.

For $Q$ we follow the rule in (3).

Note:
- The feasibility constraint is embedded into $R$ by setting $R[s, a] = -\infty$ for $a \notin A(s)$.
- Probability distributions for $(s, a)$ with $a \notin A(s)$ can be arbitrary.

The following code sets up these objects for us

In [3]:
class SimpleOG:

    def _init_(self, B=10, M=5, $\alpha$=0.5, $\beta$=0.9):
        
        Set up $R$, $Q$ and $\beta$, the three elements that define an instance of the DiscreteDP class.

        
        self.B, self.M, self.$\alpha$, self.$\beta$ = B, M, $\alpha$, $\beta$
        self.n = B + M + 1
        self.m = M + 1

        self.R = np.empty((self.n, self.m))
        self.Q = np.zeros((self.n, self.m, self.n))

        self.populate_Q()
        self.populate_R()

    def $u$(self, c):
        return c**self.$\alpha$

    def populate_R(self):
"""
Populate the R matrix, with R[s, a] = -np.inf for infeasible
state-action pairs.
"""
for s in range(self.n):
    for a in range(self.m):
        self.R[s, a] = self.u(s - a) if a <= s else -np.inf

def populate_Q(self):
    """
    Populate the Q matrix by setting
    Q[s, a, s'] = 1 / (1 + B) if a <= s' <= a + B
    and zero otherwise.
    """
    for a in range(self.m):
        self.Q[:, a, a:(a + self.B + 1)] = 1.0 / (self.B + 1)

Let’s run this code and create an instance of SimpleOG.

In [4]: g = SimpleOG()  # Use default parameters

Instances of DiscreteDP are created using the signature DiscreteDP(R, Q, \(\beta\)).
Let’s create an instance using the objects stored in g

In [5]: ddp = qe.markov.DiscreteDP(g.R, g.Q, g.\(\beta\))

Now that we have an instance ddp of DiscreteDP we can solve it as follows

In [6]: results = ddp.solve(method='policy_iteration')

Let’s see what we’ve got here

In [7]: dir(results)

Out[7]: ['max_iter', 'mc', 'method', 'num_iter', 'sigma', 'v']

(In IPython version 4.0 and above you can also type results. and hit the tab key)
The most important attributes are v, the value function, and \(\sigma\), the optimal policy

In [8]: results.v

               22.3845048 , 22.57807736, 22.76109127, 22.94376708, 23.11533996,
               23.27761762])

In [9]: results.sigma
Out[9]: array([0, 0, 0, 0, 1, 1, 1, 2, 2, 3, 3, 4, 5, 5, 5, 5])

Since we’ve used policy iteration, these results will be exact unless we hit the iteration bound \( \text{max\_iter} \).

Let’s make sure this didn’t happen

In [10]: results.max_iter

Out[10]: 250

In [11]: results.num_iter

Out[11]: 3

Another interesting object is \( \text{results.mc} \), which is the controlled chain defined by \( Q_{\sigma^*} \), where \( \sigma^* \) is the optimal policy.

In other words, it gives the dynamics of the state when the agent follows the optimal policy.

Since this object is an instance of MarkovChain from QuantEcon.py (see this lecture for more discussion), we can easily simulate it, compute its stationary distribution and so on.

In [12]: results.mc.stationary_distributions

Out[12]: array([[0.01732187, 0.04121063, 0.05773956, 0.07426848, 0.08095823, 0.09090909, 0.09090909, 0.09090909, 0.09090909, 0.09090909, 0.07358722, 0.04969846, 0.03316953, 0.01664061, 0.00995086]])

Here’s the same information in a bar graph

[Bar graph image]

What happens if the agent is more patient?

In [13]: ddp = qe.markov.DiscreteDP(g.R, g.Q, 0.99)  # Increase \( \beta \) to 0.99
results = ddp.solve(method='policy_iteration')
results.mc.stationary_distributions
4.5. EXAMPLE: A GROWTH MODEL

Out[13]: array([[0.00546913, 0.02321342, 0.03147788, 0.04800681, 0.05627127,
                0.09090909, 0.09090909, 0.09090909, 0.09090909, 0.09090909,
                0.09090909, 0.08543996, 0.06769567, 0.05943121, 0.04290228,
                0.03463782]])

If we look at the bar graph we can see the rightward shift in probability mass

4.5.3 State-Action Pair Formulation

The DiscreteDP class in fact, provides a second interface to set up an instance.

One of the advantages of this alternative set up is that it permits the use of a sparse matrix for Q.

(An example of using sparse matrices is given in the exercises below)

The call signature of the second formulation is DiscreteDP(R, Q, β, s_indices, a_indices) where

- s_indices and a_indices are arrays of equal length L enumerating all feasible state-action pairs
- R is an array of length L giving corresponding rewards
- Q is an L x n transition probability array

Here’s how we could set up these objects for the preceding example

In [14]: B, M, α, β = 10, 5, 0.5, 0.9
n = B + M + 1
m = M + 1

def u(c):
    return c**α

s_indices = []
a_indices = []
Q = []
R = []
\[ b = \frac{1.0}{(B + 1)} \]

```python
for s in range(n):
    for a in range(min(M, s) + 1):  # All feasible a at this s
        s_indices.append(s)
        a_indices.append(a)
        q = np.zeros(n)
        q[a:(a + B + 1)] = b  # b on these values, otherwise 0
        Q.append(q)
        R.append(u(s - a))
```

\[ ddp = qe.markov.DiscreteDP(R, Q, \beta, s_indices, a_indices) \]

For larger problems, you might need to write this code more efficiently by vectorizing or using Numba.

### 4.6 Exercises

In the stochastic optimal growth lecture from our introductory lecture series, we solve a benchmark model that has an analytical solution.

The exercise is to replicate this solution using `DiscreteDP`.

### 4.7 Solutions

#### 4.7.1 Setup

Details of the model can be found in the lecture on optimal growth.

We let \( f(k) = k^\alpha \) with \( \alpha = 0.65 \), \( u(c) = \log c \), and \( \beta = 0.95 \)

```python
In [15]: α = 0.65
    f = lambda k: k**α
    u = np.log
    β = 0.95
```

Here we want to solve a finite state version of the continuous state model above.

We discretize the state space into a grid of size \( \text{grid size}=500 \), from \( 10^{-6} \) to \( \text{grid max}=2 \)

```python
In [16]: grid_max = 2
    grid_size = 500
    grid = np.linspace(1e-6, grid_max, grid_size)
```

We choose the action to be the amount of capital to save for the next period (the state is the capital stock at the beginning of the period).

Thus the state indices and the action indices are both \( 0, ..., \text{grid size}-1 \).

Action (indexed by) \( a \) is feasible at state (indexed by) \( s \) if and only if \( \text{grid}[a] < f(\text{grid}[s]) \) (zero consumption is not allowed because of the log utility).

Thus the Bellman equation is:
\[ v(k) = \max_{0 \leq k' \leq f(k)} \ u(f(k) - k') + \beta v(k'), \]

where \( k' \) is the capital stock in the next period.

The transition probability array \( Q \) will be highly sparse (in fact it is degenerate as the model is deterministic), so we formulate the problem with state-action pairs, to represent \( Q \) in scipy sparse matrix format.

We first construct indices for state-action pairs:

\begin{verbatim}
In [17]: # Consumption matrix, with nonpositive consumption included
C = f(grid).reshape(grid_size, 1) - grid.reshape(1, grid_size)

# State-action indices
s_indices, a_indices = np.where(C > 0)

# Number of state-action pairs
L = len(s_indices)

print(L)
print(s_indices)
print(a_indices)

118841
[ 0 1 1 ... 499 499 499]
[ 0 0 1 ... 389 390 391]
\end{verbatim}

Reward vector \( R \) (of length \( L \)):

\begin{verbatim}
In [18]: R = u(C[s_indices, a_indices])

(Degenerate) transition probability matrix \( Q \) (of shape \((L, grid_size)\)), where we choose the scipy.sparse.lil_matrix format, while any format will do (internally it will be converted to the csr format):

\begin{verbatim}
In [19]: Q = sparse.lil_matrix((L, grid_size))
Q[np.arange(L), a_indices] = 1

(If you are familiar with the data structure of scipy.sparse.csr_matrix, the following is the most efficient way to create the \( Q \) matrix in the current case)

In [20]: # data = np.ones(L)
   # indptr = np.arange(L+1)
   # Q = sparse.csr_matrix((data, a_indices, indptr), shape=(L, grid_size))
\end{verbatim}

Discrete growth model:

\begin{verbatim}
In [21]: ddp = DiscreteDP(R, Q, \beta, s_indices, a_indices)
\end{verbatim}

Notes

Here we intensively vectorized the operations on arrays to simplify the code.

As noted, however, vectorization is memory consumptive, and it can be prohibitively so for grids with large size.
4.7.2 Solving the Model

Solve the dynamic optimization problem:

In[22]: res = ddp.solve(method='policy_iteration')
   v, σ, num_iter = res.v, res.sigma, res.num_iter
   num_iter

Out[22]: 10

Note that σ contains the indices of the optimal capital stocks to save for the next period. The following translates σ to the corresponding consumption vector.

In[23]: # Optimal consumption in the discrete version
   c = f(grid) - grid[σ]

   # Exact solution of the continuous version
   ab = α * β
   c1 = (np.log(1 - ab) + np.log(ab) * ab / (1 - ab)) / (1 - β)
   c2 = α / (1 - ab)

   def v_star(k):
       return c1 + c2 * np.log(k)

   def c_star(k):
       return (1 - ab) * k**α

Let us compare the solution of the discrete model with that of the original continuous model

In[24]: fig, ax = plt.subplots(1, 2, figsize=(14, 4))
   ax[0].set_ylim(-40, -32)
   ax[0].set_xlim(grid[0], grid[-1])
   ax[1].set_xlim(grid[0], grid[-1])

   lb0 = 'discrete value function'
   ax[0].plot(grid, v, lw=2, alpha=0.6, label=lb0)
   ax[0].legend(loc='upper left')

   lb0 = 'continuous value function'
   ax[0].plot(grid, v_star(grid), 'k-', lw=1.5, alpha=0.8, label=lb0)
   ax[0].legend(loc='upper left')

   lb1 = 'discrete optimal consumption'
   ax[1].plot(grid, c, 'b-', lw=2, alpha=0.6, label=lb1)
   ax[1].legend(loc='upper left')

   lb1 = 'continuous optimal consumption'
   ax[1].plot(grid, c_star(grid), 'k-', lw=1.5, alpha=0.8, label=lb1)
   ax[1].legend(loc='upper left')
   plt.show()
The outcomes appear very close to those of the continuous version. Except for the “boundary” point, the value functions are very close:

\[
\text{In [25]: } \text{np.abs}(v - v_{\text{star}}(\text{grid})).\text{max()}
\]
\[
\text{Out[25]: } 121.49819147053378
\]
\[
\text{In [26]: } \text{np.abs}(v - v_{\text{star}}(\text{grid})[1:]).\text{max()}
\]
\[
\text{Out[26]: } 0.012681735127500815
\]

The optimal consumption functions are close as well:

\[
\text{In [27]: } \text{np.abs}(c - c_{\text{star}}(\text{grid})).\text{max()}
\]
\[
\text{Out[27]: } 0.003826523100010082
\]

In fact, the optimal consumption obtained in the discrete version is not really monotone, but the decrements are quite small:

\[
\text{In [28]: } \text{diff} = \text{np.diff}(c)
\]
\[
\text{(diff >= 0).all()}
\]
\[
\text{Out[28]: False}
\]
\[
\text{In [29]: } \text{dec_ind} = \text{np.where}(\text{diff < 0})[0]
\]
\[
\text{len(dec_ind)}
\]
\[
\text{Out[29]: 174}
\]
\[
\text{In [30]: } \text{np.abs}([\text{diff}[\text{dec_ind}]).\text{max()}
\]
\[
\text{Out[30]: } 0.001961853339766839
\]

The value function is monotone:

\[
\text{In [31]: } (\text{np.diff}(v) > 0).\text{all()}
\]
\[
\text{Out[31]: True}
\]
4.7.3 Comparison of the Solution Methods

Let us solve the problem with the other two methods.

**Value Iteration**

```python
In [32]: ddp.epsilon = 1e-4
ddp.max_iter = 500
res1 = ddp.solve(method='value_iteration')
res1.num_iter
Out[32]: 294
```

```python
In [33]: np.array_equal(σ, res1.sigma)
Out[33]: True
```

**Modified Policy Iteration**

```python
In [34]: res2 = ddp.solve(method='modified_policy iteration')
res2.num_iter
Out[34]: 16
```

```python
In [35]: np.array_equal(σ, res2.sigma)
Out[35]: True
```

**Speed Comparison**

```python
In [36]: %timeit ddp.solve(method='value iteration')
%timeit ddp.solve(method='policy iteration')
%timeit ddp.solve(method='modified_policy iteration')
```

```
321 ms ± 15.2 ms per loop (mean ± std. dev. of 7 runs, 1 loop each)
29.6 ms ± 922 µs per loop (mean ± std. dev. of 7 runs, 10 loops each)
33.6 ms ± 1.32 ms per loop (mean ± std. dev. of 7 runs, 10 loops each)
```

As is often the case, policy iteration and modified policy iteration are much faster than value iteration.

4.7.4 Replication of the Figures

Using DiscreteDP we replicate the figures shown in the lecture.
Convergence of Value Iteration

Let us first visualize the convergence of the value iteration algorithm as in the lecture, where we use \texttt{ddp.bellman_operator} implemented as a method of \texttt{DiscreteDP}

```python
In [37]: w = 5 * np.log(grid) - 25  # Initial condition
n = 35
fig, ax = plt.subplots(figsize=(8,5))
ax.set_ylim(-40, -20)
ax.set_xlim(np.min(grid), np.max(grid))
lb = 'initial condition'
ax.plot(grid, w, color=plt.cm.jet(0), lw=2, alpha=0.6, label=lb)
for i in range(n):
    w = ddp.bellman_operator(w)
    ax.plot(grid, w, color=plt.cm.jet(i / n), lw=2, alpha=0.6)
lb = 'true value function'
ax.plot(grid, v_star(grid), 'k-', lw=2, alpha=0.8, label=lb)
ax.legend(loc='upper left')
plt.show()
```

We next plot the consumption policies along with the value iteration

```python
In [38]: w = 5 * u(grid) - 25  # Initial condition
fig, ax = plt.subplots(3, 1, figsize=(8, 10))
true_c = c_star(grid)

for i, n in enumerate((2, 4, 6)):
    ax[i].set_ylim(0, 1)
    ax[i].set_xlim(0, 2)
    ax[i].set_yticks((0, 1))
    ax[i].set_xticks((0, 2))
```
\[ w = 5 \times u(\text{grid}) - 25 \quad \# \text{Initial condition} \]

\[
\text{compute\_fixed\_point}(\text{ddp.bellman\_operator}, w, \text{max\_iter}=n, \text{print\_skip}=1)
\]

\[ \sigma = \text{ddp.compute\_greedy}(w) \quad \# \text{Policy indices} \]

\[
c\_\text{policy} = \text{f}(\text{grid}) - \text{grid}[\sigma]
\]

\[
\text{ax[i].plot(\text{grid}, c\_\text{policy}, 'b-', lw=2, alpha=0.8,}
\]

\[
\text{label='approximate optimal consumption policy'})}
\]

\[
\text{ax[i].plot(\text{grid}, true\_c, 'k-', lw=2, alpha=0.8,}
\]

\[
\text{label='true optimal consumption policy'})}
\]

\[
\text{ax[i].legend(loc='upper left')}
\]

\[
\text{ax[i].set\_title(f'\{n\} value function iterations')}
\]

\[
\text{plt.show()}
\]

\[
\begin{array}{ccc}
\text{Iteration} & \text{Distance} & \text{Elapsed (seconds)} \\
\hline
1 & 5.518e+00 & 2.501e-03 \\
2 & 4.070e+00 & 3.968e-03 \\
\end{array}
\]

\[
\begin{array}{ccc}
\text{Iteration} & \text{Distance} & \text{Elapsed (seconds)} \\
\hline
1 & 5.518e+00 & 1.716e-03 \\
2 & 4.070e+00 & 3.167e-03 \\
3 & 3.866e+00 & 4.531e-03 \\
4 & 3.673e+00 & 5.867e-03 \\
\end{array}
\]

\[
\begin{array}{ccc}
\text{Iteration} & \text{Distance} & \text{Elapsed (seconds)} \\
\hline
1 & 5.518e+00 & 1.680e-03 \\
2 & 4.070e+00 & 3.088e-03 \\
3 & 3.866e+00 & 4.445e-03 \\
4 & 3.673e+00 & 5.821e-03 \\
5 & 3.489e+00 & 7.191e-03 \\
6 & 3.315e+00 & 8.521e-03 \\
\end{array}
\]
Dynamics of the Capital Stock

Finally, let us work on Exercise 2, where we plot the trajectories of the capital stock for three different discount factors, 0.9, 0.94, and 0.98, with initial condition \( k_0 = 0.1 \).

In [39]: discount_factors = (0.9, 0.94, 0.98)
k_init = 0.1

    # Search for the index corresponding to k_init
k_init_ind = np.searchsorted(grid, k_init)
sample_size = 25

fig, ax = plt.subplots(figsize=(8,5))
ax.set_xlabel("time")
ax.set_ylabel("capital")
ax.set_ylim(0.10, 0.30)

# Create a new instance, not to modify the one used above
ddp0 = DiscreteDP(R, Q, β, s_indices, a_indices)

for beta in discount_factors:
    ddp0.beta = beta
    res0 = ddp0.solve()
    k_path_ind = res0.mc.simulate(init=k_init_ind, ts_length=sample_size)
    k_path = grid[k_path_ind]
    ax.plot(k_path, 'o-', lw=2, alpha=0.75, label=f'$\beta = {beta}$')

ax.legend(loc='lower right')
plt.show()

4.8 Appendix: Algorithms

This appendix covers the details of the solution algorithms implemented for DiscreteDP.

We will make use of the following notions of approximate optimality:

- For $\varepsilon > 0$, $v$ is called an $\varepsilon$-approximation of $v^*$ if $\|v - v^*\| < \varepsilon$.
- A policy $\sigma \in \Sigma$ is called $\varepsilon$-optimal if $v_\sigma$ is an $\varepsilon$-approximation of $v^*$. 
4.8. APPENDIX: ALGORITHMS

4.8.1 Value Iteration

The DiscreteDP value iteration method implements value function iteration as follows

1. Choose any \( v^0 \in \mathbb{R}^n \), and specify \( \varepsilon > 0 \); set \( i = 0 \).
2. Compute \( v^{i+1} = T v^i \).
3. If \( \|v^{i+1} - v^i\| < \left[ \frac{(1 - \beta)/(2\beta)}{\varepsilon} \right] \), then go to step 4; otherwise, set \( i = i + 1 \) and go to step 2.
4. Compute a \( v^{i+1} \)-greedy policy \( \sigma \), and return \( v^{i+1} \) and \( \sigma \).

Given \( \varepsilon > 0 \), the value iteration algorithm

- terminates in a finite number of iterations
- returns an \( \varepsilon/2 \)-approximation of the optimal value function and an \( \varepsilon \)-optimal policy function (unless \texttt{iter_max} is reached)

(While not explicit, in the actual implementation each algorithm is terminated if the number of iterations reaches \texttt{iter_max})

4.8.2 Policy Iteration

The DiscreteDP policy iteration method runs as follows

1. Choose any \( v^0 \in \mathbb{R}^n \) and compute a \( v^0 \)-greedy policy \( \sigma^0 \); set \( i = 0 \).
2. Compute the value \( v_\sigma \), by solving the equation \( v = T_\sigma v \).
3. Compute a \( v_\sigma \)-greedy policy \( \sigma^{i+1} \); let \( \sigma^{i+1} = \sigma^i \) if possible.
4. If \( \sigma^{i+1} = \sigma^i \), then return \( v_\sigma \) and \( \sigma^{i+1} \); otherwise, set \( i = i + 1 \) and go to step 2.

The policy iteration algorithm terminates in a finite number of iterations.
It returns an optimal value function and an optimal policy function (unless \texttt{iter_max} is reached).

4.8.3 Modified Policy Iteration

The DiscreteDP modified policy iteration method runs as follows:

1. Choose any \( v^0 \in \mathbb{R}^n \), and specify \( \varepsilon > 0 \) and \( k \geq 0 \); set \( i = 0 \).
2. Compute a \( v^i \)-greedy policy \( \sigma^{i+1} \); let \( \sigma^{i+1} = \sigma^i \) if possible (for \( i \geq 1 \)).
3. Compute \( u = T v^i \; (= T_{\sigma^{i+1}} v^i) \). If \( \text{span}(u - v^i) < \left[ \frac{(1 - \beta)/\beta}{\varepsilon} \right] \), then go to step 5; otherwise go to step 4.
   - Span is defined by \( \text{span}(z) = \max(z) - \min(z) \).
4. Compute \( v^{i+1} = (T_{\sigma^{i+1}})^k u \; (= (T_{\sigma^{i+1}})^{k+1} v^i) \); set \( i = i + 1 \) and go to step 2.
2. Return $v = u + \left[\frac{\beta}{1 - \beta}\right] \left[\left(\min(u - v^i) + \max(u - v^d)\right)/2\right]$ and $\sigma_{i+1}$.

Given $\varepsilon > 0$, provided that $v^0$ is such that $Tv^0 \geq v^0$, the modified policy iteration algorithm terminates in a finite number of iterations.

It returns an $\varepsilon/2$-approximation of the optimal value function and an $\varepsilon$-optimal policy function (unless $\text{iter\_max}$ is reached).

See also the documentation for DiscreteDP.
Part II

LQ Control
Chapter 5

Information and Consumption Smoothing

5.1 Contents

- Overview 5.2
- Two Representations of the Same Nonfinancial Income Process ??
- State Space Representations 5.4

In addition to what’s in Anaconda, this lecture employs the following libraries:

In [1]: !pip install --upgrade quantecon

5.2 Overview

This lecture studies two consumers who have exactly the same nonfinancial income process and who both conform to the linear-quadratic permanent income of consumption smoothing model described in the quantecon lecture.

The two consumers have different information about future nonfinancial incomes.

One consumer each period receives news in the form of a shock that simultaneously affects both today’s nonfinancial income and the present value of future nonfinancial incomes in a particular way.

The other, less well informed, consumer each period receives a shock that equals the part of today’s nonfinancial income that could not be forecast from all past values of nonfinancial income.

Even though they receive exactly the same nonfinancial incomes each period, our two consumers behave differently because they have different information about their future nonfinancial incomes.

The second consumer receives less information about future nonfinancial incomes in a sense that we shall make precise below.

This difference in their information sets manifests itself in their responding differently to what they regard as time $t$ information shocks.

Thus, while they receive exactly the same histories of nonfinancial income, our two consumers
receive different shocks or news about their future nonfinancial incomes.

We compare behaviors of our two consumers as a way to learn about

- operating characteristics of the linear-quadratic permanent income model
- how the Kalman filter introduced in this lecture and/or the theory of optimal forecasting introduced in this lecture embody lessons that can be applied to the news and noise literature
- various ways of representing and computing optimal decision rules in the linear-quadratic permanent income model
- a Ricardian equivalence outcome describing effects on optimal consumption of a tax cut at time \( t \) accompanied by a foreseen permanent increases in taxes that is just sufficient to cover the interest payments used to service the risk-free government bonds that are issued to finance the tax cut
- a simple application of alternative ways to factor a covariance generating function along lines described in this lecture

This lecture can be regarded as an introduction to some of the invertibility issues that take center stage in the analysis of fiscal foresight by Eric Leeper, Todd Walker, and Susan Yang [? ].

### 5.3 Two Representations of the Same Nonfinancial Income Process

Where \( \beta \in (0, 1) \), we study consequences of endowing a consumer with one of the two alternative representations for the change in the consumer’s nonfinancial income \( y_{t+1} - y_t \).

The first representation, which we shall refer to as the original representation, is

\[
y_{t+1} - y_t = \epsilon_{t+1} - \beta^{-1}\epsilon_t
\]

where \( \{\epsilon_t\} \) is an i.i.d. normally distributed scalar process with means of zero and contemporaneous variances \( \sigma_{\epsilon}^2 \).

This representation of the process is used by a consumer who at time \( t \) knows both \( y_t \) and the original shock \( \epsilon_t \) and can use both of them to forecast future \( y_{t+j} \)’s.

Furthermore, as we’ll see below, representation (1) has the peculiar property that a positive shock \( \epsilon_{t+1} \) leaves the discounted present value of the consumer’s financial income at time \( t + 1 \) unaltered.

The second representation of the same \( \{y_t\} \) process is

\[
y_{t+1} - y_t = a_{t+1} - \beta a_t
\]

where \( \{a_t\} \) is another i.i.d. normally distributed scalar process, with means of zero and now variances \( \sigma_{a}^2 \).

The two i.i.d. shock variances are related by

\[
\sigma_{a}^2 = \beta^{-2}\sigma_{\epsilon}^2 > \sigma_{\epsilon}^2
\]
so that the variance of the innovation exceeds the variance of the original shock by a multiplicative factor $\beta^{-2}$.

The second representation is the **innovations representation** from Kalman filtering theory. To see how this works, note that equating representations (1) and (2) for $y_{t+1} - y_t$ implies $\epsilon_{t+1} - \beta^{-1}\epsilon_t = a_{t+1} - \beta a_t$, which in turn implies

$$a_{t+1} = \beta a_t + \epsilon_{t+1} - \beta^{-1}\epsilon_t.$$ 

Solving this difference equation backwards for $a_{t+1}$ gives, after a few lines of algebra,

$$a_{t+1} = \epsilon_{t+1} + (\beta - \beta^{-1}) \sum_{j=0}^{\infty} \beta^j \epsilon_{t-j} \quad (3)$$

which we can also write as

$$a_{t+1} = \sum_{j=0}^{\infty} h_j \epsilon_{t+1-j} \equiv h(L) \epsilon_{t+1}$$

where $L$ is the one-period lag operator, $h(L) = \sum_{j=0}^{\infty} h_j L^j$, $I$ is the identity operator, and

$$h(L) = \frac{I - \beta^{-1}L}{I - \beta L}.$$

Let $g_j = \mathbb{E}_t z_{t-j}$ be the $j$th autocovariance of the $\{y_t - y_{t-1}\}$ process.

Using calculations in the *quantecon lecture*, where $z \in C$ is a complex variable, the covariance generating function $g(z) = \sum_{j=\infty}^{-\infty} g_j z^j$ of the $\{(y_t - y_{t-1})\}$ process equals

$$g(z) = \sigma^2 \epsilon h(z) h(z^{-1}) = \beta^{-2} \sigma^2 > \sigma^2,$$

which confirms that $\{a_t\}$ is a **serially uncorrelated** process with variance

$$\sigma^2_a = \beta^{-1} \sigma^2.$$ 

To verify these claims, just notice that $g(z) = \beta^{-2} \sigma^2$ implies that the coefficient $g_0 = \beta^{-2} \sigma^2$ and that $g_j = 0$ for $j \neq 0$.

Alternatively, if you are uncomfortable with covariance generating functions, note that we can directly calculate $\sigma^2_a$ from formula (3) according to

$$\sigma^2_a = \sigma^2 + [1 + (\beta - \beta^{-1})^2 \sum_{j=0}^{\infty} \beta^{2j}] = \beta^{-1} \sigma^2.$$ 

### 5.3.1 Application of Kalman filter

We can also obtain representation (2) from representation (1) by using the **Kalman filter**.
Thus, from equations associated with the Kalman filter, it can be verified that the steady-state Kalman gain $K = \beta^2$ and the steady state conditional covariance $\Sigma = E[(\epsilon_t - \hat{\epsilon}_t)^2|y_{t-1}, y_{t-2}, \ldots] = (1 - \beta^2)\sigma^2_{\epsilon}$.

In a little more detail, let $z_t = y_t - y_{t-1}$ and form the state-space representation

\[
\begin{align*}
\epsilon_{t+1} &= 0\epsilon_t + \epsilon_{t+1} \\
z_{t+1} &= -\beta^{-1}\epsilon_t + \epsilon_{t+1}
\end{align*}
\]

and assume that $\sigma_{\epsilon} = 1$ for convenience.

Compute the steady-state Kalman filter for this system and let $K$ be the steady-state gain and $a_{t+1}$ the one-step ahead innovation.

The innovations representation is

\[
\begin{align*}
\hat{\epsilon}_{t+1} &= 0\epsilon_t + Ka_{t+1} \\
z_{t+1} &= -\beta a_t + a_{t+1}
\end{align*}
\]

By applying formulas for the steady-state Kalman filter, by hand we computed that $K = \beta^2$, $\sigma^2_a = \beta^{-2}\sigma^2_{\epsilon} = \beta^{-2}$, and $\Sigma = (1 - \beta^2)\sigma^2_{\epsilon}$.

We can also obtain these formulas via the classical filtering theory described in this lecture.

### 5.3.2 News Shocks and Less Informative Shocks

Representation (1) is cast in terms of a news shock $\epsilon_{t+1}$ that represents a shock to non-financial income coming from taxes, transfers, and other random sources of income changes known to a well-informed person having all sorts of information about the income process.

Representation (2) for the same income process is driven by shocks $a_t$ that contain less information than the news shock $\epsilon_t$.

Representation (2) is called the innovations representation for the $\{y_t - y_{t-1}\}$ process.

It is cast in terms of what time series statisticians call the innovation or fundamental shock that emerges from applying the theory of optimally predicting nonfinancial income based solely on the information contained solely in past levels of growth in nonfinancial income.

**Fundamental for the $y_t$ process** means that the shock $a_t$ can be expressed as a square-summable linear combination of $y_t, y_{t-1}, \ldots$.

The shock $\epsilon_t$ is not fundamental and has more information about the future of the $\{y_t - y_{t-1}\}$ process than is contained in $a_t$.

Representation (3) reveals the important fact that the original shock $\epsilon_t$ contains more information about future $y$’s than is contained in the semi-infinite history $y^t = [y_t, y_{t-1}, \ldots]$ of current and past $y$’s.

Staring at representation (3) for $a_{t+1}$ shows that it consists both of new news $\epsilon_{t+1}$ as well as a long moving average $(\beta - \beta^{-1})\sum_{j=0}^{\infty}\beta^j\epsilon_{t-j}$ of old news.

The better informed representation (1) asserts that a shock $\epsilon_t$ results in an impulse response to non-financial income of $\epsilon_t$ times the sequence
5.3. TWO REPRESENTATIONS OF THE SAME NONFINANCIAL INCOME PROCESS

\[ 1, 1 - \beta^{-1}, 1 - \beta^{-1}, \ldots \]

so that a shock that increases nonfinancial income \( y_t \) by \( \epsilon_t \) at time \( t \) is followed by an increase in future \( y \) of \( \epsilon_t \) times \( 1 - \beta^{-1} < 0 \) in all subsequent periods.

Because \( 1 - \beta^{-1} < 0 \), this means that a positive shock of \( \epsilon_t \) today raises income at time \( t \) by \( \epsilon_t \) and then decreases all future incomes by \( (\beta^{-1} - 1)\epsilon_t \).

This pattern precisely describes the following mental experiment:

- The consumer receives a government transfer of \( \epsilon_t \) at time \( t \).
- The government finances the transfer by issuing a one-period bond on which it pays a gross one-period risk-free interest rate equal to \( \beta^{-1} \).
- In each future period, the government rolls over the one-period bond and so continues to borrow \( \epsilon_t \) forever.
- The government imposes a lump-sum tax on the consumer in order to pay just the current interest on the original bond and its successors created by the roll-over operation.
- In all future periods \( t + 1, t + 2, \ldots \), the government levies a lump-sum tax on the consumer of \( \beta^{-1} - 1 \) that is just enough to pay the interest on the bond.

The present value of the impulse response or moving average coefficients equals \( d_\epsilon(L) = \frac{0}{1 - \beta} = 0 \), a fact that we’ll see again below.

Representation (2), i.e., the innovation representation, asserts that a shock \( a_t \) results in an impulse response to nonfinancial income of \( a_t \) times

\[ 1, 1 - \beta, 1 - \beta, \ldots \]

so that a shock that increases income \( y_t \) by \( a_t \) at time \( t \) can be expected to be followed by an increase in \( y_{t+j} \) of \( a_t \) times \( 1 - \beta > 0 \) in all future periods \( j = 1, 2, \ldots \).

The present value of the impulse response or moving average coefficients for representation (2) is \( d_a(\beta) = \frac{1 - \beta^2}{1 - \beta} = (1 + \beta) \), another fact that will be important below.

5.3.3 Representation of \( \epsilon_t \) in Terms of Future \( y \)'s

Notice that representation (1), namely, \( y_{t+1} - y_t = -\beta^{-1}\epsilon_t + \epsilon_{t+1} \) implies the linear difference equation

\[ \epsilon_t = \beta \epsilon_{t+1} - \beta(y_{t+1} - y_t). \]

Solving forward we eventually obtain

\[ \epsilon_t = \beta(y_t - (1 - \beta) \sum_{j=0}^{\infty} \beta^j y_{t+j+1}) \]

This equation shows that \( \epsilon_t \) equals \( \beta \) times the one-step-backwards error in optimally backcasting \( y_t \) based on the future \( y_t^t \equiv y_{t+1}, y_{t+2}, \ldots \) via the optimal backcasting formula

\[ E[y_t | y_t^t] = (1 - \beta) \sum_{j=0}^{\infty} \beta^j y_{t+j+1} \]
Thus, $\epsilon_t$ contains **exact** information about an important linear combination of **future** nonfinancial income.

### 5.3.4 Representation in Terms of $a_t$ Shocks

Next notice that representation (2), namely, $y_{t+1} - y_t = -\beta a_t + a_{t+1}$ implies the linear difference equation

$$a_{t+1} = \beta a_t + (y_{t+1} - y_t)$$

Solving this equation backward establishes that the one-step-prediction error $a_{t+1}$ is

$$a_{t+1} = y_{t+1} - (1 - \beta) \sum_{j=0}^{\infty} \beta^j y_{t-j}$$

and where the information set is $y^t = [y_t, y_{t-1}, \ldots]$, the one step-ahead optimal prediction is

$$E[y_{t+1}|y^t] = (1 - \beta) \sum_{j=0}^{\infty} \beta^j y_{t-j}$$

### 5.3.5 Permanent Income Consumption-Smoothing Model

When we computed optimal consumption-saving policies for the two representations using formulas obtained with the difference equation approach described in the *quantecon* lecture, we obtain:

- for a consumer having the information assumed in the news representation (1):
  
  $$c_{t+1} - c_t = 0$$
  $$b_{t+1} - b_t = -\beta^{-1} \epsilon_t$$

- for a consumer having the more limited information associated with the innovations representation (2):
  
  $$c_{t+1} - c_t = (1 - \beta^2) a_{t+1}$$
  $$b_{t+1} - b_t = -\beta a_t$$

These formulas agree with outcomes from the Python programs to be reported below using state-space representations and dynamic programming.

Evidently the two consumers behave differently though they receive exactly the same histories of nonfinancial income.

The consumer with information associated with representation (1) responds to each shock $\epsilon_{t+1}$ by leaving his consumption unaltered and **saving** all of $a_{t+1}$ in anticipation of the permanently increased taxes that he will bear to pay for the addition $a_{t+1}$ to his time $t + 1$ nonfinancial income.
5.4. STATE SPACE REPRESENTATIONS

The consumer with information associated with representation (2) responds to a shock $a_{t+1}$ by increasing his consumption by what he perceives to be the permanent part of the increase in consumption and by increasing his saving by what he perceives to be the temporary part.

We can regard the first consumer as someone whose behavior sharply illustrates the behavior assumed in a classic Ricardian equivalence experiment.

5.4 State Space Representations

We can cast our two representations in terms of the following two state space systems

$$
\begin{bmatrix}
y_{t+1} \\
ce_{t+1}
\end{bmatrix} = 
\begin{bmatrix}
1 & -\beta^{-1} \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
y_t \\
ce_t
\end{bmatrix} +
\begin{bmatrix}
\sigma_e \\
\sigma_e
\end{bmatrix}
\{v_t\}
$$

and

$$
\begin{bmatrix}
y_{t+1} \\
a_{t+1}
\end{bmatrix} = 
\begin{bmatrix}
1 & -\beta \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
y_t \\
a_t
\end{bmatrix} +
\begin{bmatrix}
\sigma_a \\
\sigma_a
\end{bmatrix}
\{u_t\}
$$

where $\{v_t\}$ and $\{u_t\}$ are both i.i.d. sequences of univariate standardized normal random variables.

These two alternative income processes are ready to be used in the framework presented in the section “Comparison with the Difference Equation Approach” in the quantecon lecture.

All the code that we shall use below is presented in that lecture.

5.4.1 Computations

We shall use Python to form both of the above two state-space representations, using the following parameter values $\sigma_e = 1, \sigma_a = \beta^{-1}\sigma_e = \beta^{-1}$ where $\beta$ is the same value as the discount factor in the household’s problem in the LQ savings problem in the lecture.

For these two representations, we use the code in the lecture to

- compute optimal decision rules for $c_t, b_t$ for the two types of consumers associated with our two representations of nonfinancial income
- use the value function objects $P, d$ returned by the code to compute optimal values for the two representations when evaluated at the following initial conditions $x_0 =

$$
\begin{bmatrix}
10 \\
0
\end{bmatrix}
$$

for each representation.
• create instances of the `LinearStateSpace` class for the two representations of the \{y_t\} process and use them to obtain impulse response functions of \(c_t\) and \(b_t\) to the respective shocks \(\epsilon_t\) and \(a_t\) for the two representations.

• run simulations of \{y_t, c_t, b_t\} of length \(T\) under both of the representations (later I’ll give some more details about how we’ll run some special versions of these).

We want to solve the LQ problem:

\[
\min \sum_{t=0}^{\infty} \beta^t (c_t - \gamma)^2
\]

subject to the sequence of constraints

\[
c_t + b_t = \frac{1}{1 + r} b_{t+1} + y_t, \quad t \geq 0
\]

where \(y_t\) follows one of the representations defined above.

Define the control as \(u_t \equiv c_t - \gamma\).

(For simplicity we can assume \(\gamma = 0\) below because \(\gamma\) has no effect on the impulse response functions that interest us.)

The state transition equations under our two representations for the nonfinancial income process \{y_t\} can be written as

\[
\begin{bmatrix}
  y_{t+1} \\
  \epsilon_{t+1} \\
  b_{t+1}
\end{bmatrix} =
\begin{bmatrix}
  1 & -\beta^{-1} & 0 \\
  0 & 0 & 0 \\
  -(1 + r) & 0 & 1 + r
\end{bmatrix}
\begin{bmatrix}
  y_t \\
  \epsilon_t \\
  b_t
\end{bmatrix} +
\begin{bmatrix}
  0 \\
  0 \\
  1 + r
\end{bmatrix}
\begin{bmatrix}
  c_t \\
  \sigma \epsilon
\end{bmatrix} +
\begin{bmatrix}
  \sigma \epsilon \\
  \sigma \epsilon
\end{bmatrix} \nu_{t+1},
\]

\(\equiv A_1\)

\(\equiv B_1\)

\(\equiv C_1\)

and

\[
\begin{bmatrix}
  y_{t+1} \\
  a_{t+1} \\
  b_{t+1}
\end{bmatrix} =
\begin{bmatrix}
  1 & -\beta & 0 \\
  0 & 0 & 0 \\
  -(1 + r) & 0 & 1 + r
\end{bmatrix}
\begin{bmatrix}
  y_t \\
  a_t \\
  b_t
\end{bmatrix} +
\begin{bmatrix}
  0 \\
  0 \\
  1 + r
\end{bmatrix}
\begin{bmatrix}
  c_t \\
  \sigma a
\end{bmatrix} +
\begin{bmatrix}
  \sigma a \\
  \sigma a
\end{bmatrix} u_{t+1}.
\]

As usual, we start by importing packages.

In [2]:
\>
import numpy as np
import quantecon as qe
import matplotlib.pyplot as plt
%matplotlib inline

In [3]:
# Set parameters
\>
\> \beta, \sigma \epsilon = 0.95, 1
\> \sigma a = \sigma \epsilon / \beta
\>
\> R = 1 / \beta

# Payoff matrices are the same for two representations
RLQ = np.array([[0, 0, 0],
                 [0, 0, 0],
                 [0, 0, 0],
                 [0, 0, 0],
                 [0, 0, 0]]);
5.4. **STATE SPACE REPRESENTATIONS**

```python
[0, 0, 1e-12]) # put penalty on debt
QLQ = np.array([[1.])

In [4]: # Original representation state transition matrices
ALQ1 = np.array([[1, -R, 0],
[0, 0, 0],
[-R, 0, R]])
BLQ1 = np.array([[0, 0, R]])
CLQ1 = np.array([[σe, σe, 0]]).T

# Construct and solve the LQ problem
LQ1 = qe.LQ(QLQ, RLQ, ALQ1, BLQ1, C=CLQ1, beta=β)
P1, F1, d1 = LQ1.stationary_values()

In [5]: # The optimal decision rule for c
-F1

Out[5]: array([[ 1. , -1. , -0.05]])

Evidently optimal consumption and debt decision rules for the consumer having news representation (1) are

\[
c^*_t = y_t - \epsilon_t - (1 - \beta) b_t, \]
\[
b^*_{t+1} = \beta^{-1} c^*_t + \beta^{-1} b_t - \beta^{-1} y_t = \beta^{-1} y_t - \beta^{-1} \epsilon_t - (\beta^{-1} - 1) b_t + \beta^{-1} b_t - \beta^{-1} y_t = b_t - \beta^{-1} \epsilon_t.
\]

In [6]: # Innovations representation
ALQ2 = np.array([[1, -β, 0],
[0, 0, 0],
[-R, 0, R]])
BLQ2 = np.array([[0, 0, R]])
CLQ2 = np.array([[σa, σa, 0]]).T

LQ2 = qe.LQ(QLQ, RLQ, ALQ2, BLQ2, C=CLQ2, beta=β)
P2, F2, d2 = LQ2.stationary_values()

In [7]: -F2

Out[7]: array([[ 1. , -0.9025, -0.05 ]])

For a consumer having access only to the information associated with the innovations representation (2), the optimal decision rules are

\[
c^*_t = y_t - \beta^2 a_t - (1 - \beta) b_t, \]
\[
b^*_{t+1} = \beta^{-1} c^*_t + \beta^{-1} b_t - \beta^{-1} y_t = \beta^{-1} y_t - \beta a_t - (\beta^{-1} - 1) b_t + \beta^{-1} b_t - \beta^{-1} y_t = b_t - \beta a_t.
\]

Now we construct two Linear State Space models that emerge from using optimal policies \(u_t = -Fx_t\) for the control variable.
Take the original representation case as an example,

\[
\begin{bmatrix}
  y_{t+1} \\
  \epsilon_{t+1} \\
  b_{t+1}
\end{bmatrix} = (A_1 - B_1 F_1) \begin{bmatrix}
  y_t \\
  \epsilon_t \\
  b_t
\end{bmatrix} + C_1 \nu_{t+1}
\]

\[
\begin{bmatrix}
  c_t \\
  b_t
\end{bmatrix} = \begin{bmatrix}
  -F_1 \\
  S_b
\end{bmatrix} \begin{bmatrix}
  y_t \\
  \epsilon_t \\
  b_t
\end{bmatrix}
\]

To have the Linear State Space model of the innovations representation case, we can simply replace the corresponding matrices.

In [8]: # Construct two Linear State Space models
Sb = np.array([0, 0, 1])

ABF1 = ALQ1 - BLQ1 @ F1
G1 = np.vstack([-F1, Sb])
LSS1 = qe.LinearStateSpace(ABF1, CLQ1, G1)

ABF2 = ALQ2 - BLQ2 @ F2
G2 = np.vstack([-F2, Sb])
LSS2 = qe.LinearStateSpace(ABF2, CLQ2, G2)

In the following we compute the impulse response functions of \(c_t\) and \(b_t\).

In [9]: J = 5 # Number of coefficients that we want
x_res1, y_res1 = LSS1.impulse_response(j=J)
b_res1 = np.array([x_res1[i][2, 0] for i in range(J)])
c_res1 = np.array([y_res1[i][0, 0] for i in range(J)])

x_res2, y_res2 = LSS2.impulse_response(j=J)
b_res2 = np.array([x_res2[i][2, 0] for i in range(J)])
c_res2 = np.array([y_res2[i][0, 0] for i in range(J)])

In [10]: c_res1 / \(\sigma_\epsilon\), b_res1 / \(\sigma_\epsilon\)

Out[10]: (array([1.99997796e-11, 1.89473992e-11, 1.78947621e-11, 1.68421319e-11, 1.57894947e-11]), array([ 0. , -1.05263158, -1.05263158, -1.05263158, -1.05263158]))

In [11]: plt.title("original representation")
plt.plot(range(J), c_res1 / \(\sigma_\epsilon\), label="c impulse response function")
plt.plot(range(J), b_res1 / \(\sigma_\epsilon\), label="b impulse response function")
plt.legend()

Out[11]: <matplotlib.legend.Legend at 0x7f924bbf3ef0>
The above two impulse response functions show that when the consumer has the information assumed in the original representation, his response to receiving a positive shock of $\epsilon_t$ is to leave his consumption unchanged and to save the entire amount of his extra income and then forever roll over the extra bonds that he holds.

To see this notice, that starting from next period on, his debt permanently decreases by $\beta^{-1}$

In [12]: c_res2 / σa, b_res2 / σa

Out[12]:
(array([0.0975, 0.0975, 0.0975, 0.0975, 0.0975]),
 array([ 0. , -0.95, -0.95, -0.95, -0.95]))

In [13]: plt.title("innovations representation")
plt.plot(range(J), c_res2 / σa, label="c impulse response function")
plt.plot(range(J), b_res2 / σa, label="b impulse response function")
plt.plot([0, J-1], [0, 0], '--', color='k')
plt.legend()

Out[13]: <matplotlib.legend.Legend at 0x7f924bb32f98>
The above impulse responses show that when the consumer has only the information that is assumed to be available under the innovations representation for \( \{ y_t - y_{t-1} \} \), he responds to a positive \( a_t \) by permanently increasing his consumption. He accomplishes this by consuming a fraction \((1 - \beta^2)\) of the increment \( a_t \) to his nonfinancial income and saving the rest in order to lower \( b_{t+1} \) to finance the permanent increment in his consumption.

The preceding computations confirm what we had derived earlier using paper and pencil. Now let’s simulate some paths of consumption and debt for our two types of consumers while always presenting both types with the same \( \{ y_t \} \) path, constructed as described below.

```
In [14]: # Set time length for simulation
    T = 100

In [15]: x1, y1 = LSS1.simulate(ts_length=T)
    plt.plot(range(T), y1[0, :], label="c")
    plt.plot(range(T), x1[2, :], label="b")
    plt.plot(range(T), x1[0, :], label="y")
    plt.title("original representation")
    plt.legend()
```

```
Out[15]: <matplotlib.legend.Legend at 0x7f924bab3cc0>
```
In [16]: x2, y2 = LSS2.simulate(ts_length=T)
plt.plot(range(T), y2[0, :], label="c")
plt.plot(range(T), x2[2, :], label="b")
plt.plot(range(T), x2[0, :], label="y")
plt.title("innovations representation")
plt.legend()

Out[16]: <matplotlib.legend.Legend at 0x7f924b6cd828>
5.4.2 Simulating the Income Process and Two Associated Shock Processes

We now describe how we form a single \( \{y_t\}_{t=0}^T \) realization that we will use to simulate the two different decision rules associated with our two types of consumer.

We accomplish this in the following steps.

1. We form a \( \{y_t, \epsilon_t\} \) realization by drawing a long simulation of \( \{\epsilon_t\}_{t=0}^T \) where \( T \) is a big integer, \( \epsilon_t = \sigma v_t \), \( v_t \) is a standard normal scalar, \( y_0 = 100 \), and

\[
y_{t+1} - y_t = -\beta^{-1}\epsilon_t + \epsilon_{t+1}.
\]

1. We take the same \( \{y_t\} \) realization generated in step 1 and form an innovation process \( \{a_t\} \) from the formulas

\[
a_0 = 0
\]

\[
a_t = \sum_{j=0}^{t-1} \beta^j (y_{t-j} - y_{t-j-1}) + \beta^t a_0, \quad t \geq 1
\]

1. We throw away the first \( S \) observations and form the sample \( \{y_t, \epsilon_t, a_t\}_{S+1}^T \) as the realization that we'll use in the following steps.

2. We use the step 3 realization to evaluate and simulate the decision rules for \( c_t, b_t \) that Python has computed for us above.

The above steps implement the experiment of comparing decisions made by two consumers having identical incomes at each date but at each date having different information about their future incomes.

5.4.3 Calculating Innovations in Another Way

Here we use formula (3) above to compute \( a_{t+1} \) as a function of the history \( \epsilon_{t+1}, \epsilon_t, \epsilon_{t-1}, \ldots \)

Thus, we compute

\[
a_{t+1} = \beta a_t + \epsilon_{t+1} - \beta^{-1}\epsilon_t
\]

\[
= \beta (\beta a_{t-1} + \epsilon_t - \beta^{-1}\epsilon_{t-1}) + \epsilon_{t+1} - \beta^{-1}\epsilon_t
\]

\[
= \beta^2 a_{t-1} + \beta (\epsilon_t - \beta^{-1}\epsilon_{t-1}) + \epsilon_{t+1} - \beta^{-1}\epsilon_t
\]

\[
= \ldots
\]

\[
= \beta^{t+1}a_0 + \sum_{j=0}^{t} \beta^j (\epsilon_{t+1-j} - \beta^{-1}\epsilon_{t-j})
\]

\[
= \beta^{t+1}a_0 + \epsilon_{t+1} + (\beta - \beta^{-1}) \sum_{j=0}^{t-1} \beta^j \epsilon_{t-j} - \beta^{t-1}\epsilon_0.
\]

We can verify that we recover the same \( \{a_t\} \) sequence computed earlier.
5.4.4 Another Invertibility Issue

This quantecon lecture contains another example of a shock-invertibility issue that is endemic to the LQ permanent income or consumption smoothing model.

The technical issue discussed there is ultimately the source of the shock-invertibility issues discussed by Eric Leeper, Todd Walker, and Susan Yang in their analysis of fiscal foresight.
Chapter 6

Consumption Smoothing with Complete and Incomplete Markets

6.1 Contents

- Overview 6.2
- Background 6.3
- Linear State Space Version of Complete Markets Model 6.4
- Model 1 (Complete Markets) 6.5
- Model 2 (One-Period Risk-Free Debt Only) 6.6

In addition to what’s in Anaconda, this lecture uses the library:

\texttt{In [1]: !pip install --upgrade quantecon}

6.2 Overview

This lecture describes two types of consumption-smoothing models.

- one is in the \textbf{complete markets} tradition of Kenneth Arrow \url{https://en.wikipedia.org/wiki/Kenneth_Arrow}
- the other is in the \textbf{incomplete markets} tradition of Hall [24]

\textit{Complete markets} allow a consumer to buy or sell claims contingent on all possible states of the world.

\textit{Incomplete markets} allow a consumer to buy or sell only a limited set of securities, often only a single risk-free security.

Hall [24] worked in an incomplete markets tradition by assuming that the only asset that can be traded is a risk-free one period bond.

Hall assumed an exogenous stochastic process of nonfinancial income and an exogenous and time-invariant gross interest rate on one period risk-free debt that equals $\beta^{-1}$, where $\beta \in (0,1)$ is also a consumer’s intertemporal discount factor.

This is equivalent to saying that it costs $\beta^{-1}$ of time $t$ consumption to buy one unit of consumption at time $t+1$ for sure.

So $\beta^{-1}$ is the price of a one-period risk-free claim to consumption next period.
We maintain Hall’s assumption about the interest rate when we describe an incomplete markets version of our model.

In addition, we extend Hall’s assumption about the risk-free interest rate to its appropriate counterpart when we create another model in which there are markets in a complete array of one-period Arrow state-contingent securities.

We’ll consider two closely related but distinct alternative assumptions about the consumer’s exogenous nonfinancial income process:

- that it is generated by a finite \( N \) state Markov chain (setting \( N = 2 \) most of the time in this lecture)
- that it is described by a linear state space model with a continuous state vector in \( \mathbb{R}^n \) driven by a Gaussian vector IID shock process

We’ll spend most of this lecture studying the finite-state Markov specification, but will begin by studying the linear state space specification because it is so closely linked to earlier lectures.

Let’s start with some imports:

```
In [2]: import numpy as np
import quantecon as qe
import matplotlib.pyplot as plt
%matplotlib inline
import scipy.linalg as la
```

### 6.2.1 Relationship to Other Lectures

This lecture can be viewed as a followup to Optimal Savings II: LQ Techniques

This lecture is also a prologomenon to a lecture on tax-smoothing Tax Smoothing with Complete and Incomplete Markets

### 6.3 Background

Outcomes in consumption-smoothing models emerge from two sources:

- a consumer who wants to maximize an intertemporal objective function that expresses its preference for paths of consumption that are smooth in the sense of varying as little as possible both across time and across realized Markov states
- opportunities that allow the consumer to transform an erratic nonfinancial income process into a smoother consumption process by purchasing or selling one or more financial securities

In the **complete markets version**, each period the consumer can buy or sell a complete set of one-period ahead state-contingent securities whose payoffs depend on next period’s realization of the Markov state.

- In the two-state Markov chain case, two such securities are traded each period.
- In an \( N \) state Markov state version, \( N \) such securities are traded each period.
- In a continuous state Markov state version, a continuum of such securities are traded each period.
These state-contingent securities are commonly called Arrow securities, after Kenneth Arrow
https://en.wikipedia.org/wiki/Kenneth_Arrow
In the incomplete markets version, the consumer can buy and sell only one security each period, a risk-free one-period bond with gross one-period return $\beta^{-1}$.

6.4 Linear State Space Version of Complete Markets Model

We’ll study a complete markets model adapted to a setting with a continuous Markov state like that in the first lecture on the permanent income model.

In that model

- a consumer can trade only a single risk-free one-period bond bearing gross one-period risk-free interest rate equal to $\beta^{-1}$.
- a consumer’s exogenous nonfinancial income is governed by a linear state space model driven by Gaussian shocks, the kind of model studied in an earlier lecture about linear state space models.

Let’s write down a complete markets counterpart of that model.

Suppose that nonfinancial income is governed by the state space system

$$
x_{t+1} = Ax_t + Cw_{t+1} \\
y_t = S_yx_t
$$

where $x_t$ is an $n \times 1$ vector and $w_{t+1} \sim N(0, I)$ is IID over time.

We want a natural counterpart of the Hall assumption that the one-period risk-free gross interest rate is $\beta^{-1}$.

We make the good guess that prices of one-period ahead Arrow securities are described by the pricing kernel

$$
q_{t+1}(x_{t+1} \mid x_t) = \beta\phi(x_{t+1} \mid Ax_t, CC')
$$

where $\phi(\cdot \mid \mu, \Sigma)$ is a multivariate Gaussian distribution with mean vector $\mu$ and covariance matrix $\Sigma$.

With the pricing kernel $q_{t+1}(x_{t+1} \mid x_t)$ in hand, we can price claims to consumption at time $t+1$ consumption that pay off when $x_{t+1} \in S$ at time $t+1$:

$$
\int_S q_{t+1}(x_{t+1} \mid x_t)dx_{t+1}
$$

where $S$ is a subset of $\mathbb{R}^n$.

The price $\int_S q_{t+1}(x_{t+1} \mid x_t)dx_{t+1}$ of such a claim depends on state $x_t$ because the prices of the $x_{t+1}$-contingent securities depend on $x_t$ through the pricing kernel $q(x_{t+1} \mid x_t)$.

Let $b(x_{t+1})$ be a vector of state-contingent debt due at $t+1$ as a function of the $t+1$ state $x_{t+1}$.

Using the pricing kernel assumed in (1), the value at $t$ of $b(x_{t+1})$ is evidently
\[ \beta \int b(x_{t+1}) \phi(x_{t+1} | Ax_t, CC') dx_{t+1} = \beta \mathbb{E}_t b_{t+1} \]

In our complete markets setting, the consumer faces a sequence of budget constraints

\[ c_t + b_t = y_t + \beta \mathbb{E}_t b_{t+1}, \quad t \geq 0 \]

Please note that

\[ E_t b_{t+1} = \int \phi_{t+1}(x_{t+1} | Ax_t, CC') b_{t+1}(x_{t+1}) dx_{t+1} \]

which verifies that \( E_t b_{t+1} \) is the value of time \( t + 1 \) state-contingent claims on time \( t + 1 \) consumption issued by the consumer at time \( t \).

We can solve the time \( t \) budget constraint forward to obtain

\[ b_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j (y_{t+j} - c_{t+j}) \]

The consumer cares about the expected value of

\[ \sum_{t=0}^{\infty} \beta^t u(c_t), \quad 0 < \beta < 1 \]

In the incomplete markets version of the model, we assumed that \( u(c_t) = -(c_t - \gamma)^2 \), so that the above utility functional became

\[ -\sum_{t=0}^{\infty} \beta^t (c_t - \gamma)^2, \quad 0 < \beta < 1 \]

But in the complete markets version, it is tractable to assume a more general utility function that satisfies \( u' > 0 \) and \( u'' < 0 \).

The first-order conditions for the consumer’s problem with complete markets and our assumption about Arrow securities prices are

\[ u'(c_{t+1}) = u'(c_t) \quad \text{for all} \ t \geq 0 \]

which implies \( c_t = \bar{c} \) for some \( \bar{c} \).

So it follows that

\[ b_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j (y_{t+j} - \bar{c}) \]

or

\[ b_t = S_y (I - \beta A)^{-1} x_t - \frac{1}{1 - \beta} \bar{c} \quad (2) \]
where $\tilde{c}$ satisfies

$$
\tilde{b}_0 = S_y(A - \beta A)^{-1}x_0 - \frac{1}{1 - \beta}\tilde{c}
$$

(3)

where $\tilde{b}_0$ is an initial level of the consumer’s debt due at time $t = 0$, specified as a parameter of the problem.

Thus, in the complete markets version of the consumption-smoothing model, $c_t = \tilde{c}, \forall t \geq 0$ is determined by (3) and the consumer’s debt is the fixed function of the state $x_t$ described by (2).

Please recall that in the LQ permanent income model studied in the permanent income model, the state is $x_t, b_t$, where $b_t$ is a complicated function of past state vectors $x_{t-j}$.

Notice that in contrast to that incomplete markets model, at time $t$ the state vector is $x_t$ alone in our complete markets model.

Here’s an example that shows how in this setting the availability of insurance against fluctuating nonfinancial income allows the consumer completely to smooth consumption across time and across states of the world

In [3]: `def complete_ss(β, b0, x0, A, C, S_y, T=12):
    """
    Computes the path of consumption and debt for the previously described complete markets model where exogenous income follows a linear state space
    """
    # Create a linear state space for simulation purposes
    # This adds "b" as a state to the linear state space system
    # so that setting the seed places shocks in same place for
    # both the complete and incomplete markets economy
    # Atilde = np.vstack([np.hstack([A, np.zeros((A.shape[0], 1))]),
    # np.zeros((1, A.shape[1] + 1))])
    # Ctilde = np.vstack([C, np.zeros((1, 1))])
    # S_ytilde = np.hstack([S_y, np.zeros((1, 1))])
    lss = qe.LinearStateSpace(A, C, S_y, mu_0=x0)
    # Add extra state to initial condition
    # xθ = np.hstack([xθ, np.zeros(1)])
    # Compute the $(I - \beta * A)^{-1}$
    rm = la.inv(np.eye(A.shape[0]) - β * A)
    # Constant level of consumption
    cbar = (1 - β) * (S_y @ rm @ xθ - b0)
    c_hist = np.ones(T) * cbar
    # Debt
    x_hist, y_hist = lss.simulate(T)
    b_hist = np.squeeze(S_y @ rm @ x_hist - cbar / (1 - β))
    return c_hist, b_hist, np.squeeze(y_hist), x_hist`
# Define parameters
N_simul = 80
α, ρ1, ρ2 = 10.0, 0.9, 0.0
σ = 1.0

A = np.array([[1., 0., 0.],
               [α, ρ1, ρ2],
               [0., 1., 0.]])
C = np.array([[0.], [σ], [0.]])
S_y = np.array([[1., 0., 0.]])
β, b0 = 0.95, -10.0
x0 = np.array([1.0, α / (1 - ρ1), α / (1 - ρ2)])

# Do simulation for complete markets
s = np.random.randint(0, 10000)
np.random.seed(s)  # Seeds get set the same for both economies
out = complete_ss(β, b0, x0, A, C, S_y, 80)
c_hist_com, b_hist_com, y_hist_com, x_hist_com = out

fig, ax = plt.subplots(1, 2, figsize=(15, 5))

# Consumption plots
ax[0].set_title('Consumption and income')
ax[0].plot(np.arange(N_simul), c_hist_com, label='consumption')
ax[0].plot(np.arange(N_simul), y_hist_com, label='income', alpha=.6,
           linestyle='--')
ax[0].legend()
ax[0].set_xlabel('Periods')
ax[0].set_ylim([80, 120])

# Debt plots
ax[1].set_title('Debt and income')
ax[1].plot(np.arange(N_simul), b_hist_com, label='debt')
ax[1].plot(np.arange(N_simul), y_hist_com, label='Income', alpha=.6,
           linestyle='--')
ax[1].legend()
ax[1].axhline(0, color='k')
ax[1].set_xlabel('Periods')

plt.show()
6.4. LINEAR STATE SPACE VERSION OF COMPLETE MARKETS MODEL

6.4.1 Interpretation of Graph

In the above graph, please note that:

- nonfinancial income fluctuates in a stationary manner.
- consumption is completely constant.
- the consumer’s debt fluctuates in a stationary manner; in fact, in this case, because nonfinancial income is a first-order autoregressive process, the consumer’s debt is an exact affine function (meaning linear plus a constant) of the consumer’s nonfinancial income.

6.4.2 Incomplete Markets Version

The incomplete markets version of the model with nonfinancial income being governed by a linear state space system is described in permanent income model.

In that incomplete markets setting, consumption follows a random walk and the consumer’s debt follows a process with a unit root.

6.4.3 Finite State Markov Income Process

We now turn to a finite-state Markov version of the model in which the consumer’s nonfinancial income is an exact function of a Markov state that takes one of \(N\) values.

We’ll start with a setting in which in each version of our consumption-smoothing model, nonfinancial income is governed by a two-state Markov chain (it’s easy to generalize this to an \(N\) state Markov chain).

In particular, the state \(s_t \in \{1, 2\}\) follows a Markov chain with transition probability matrix

\[
P_{ij} = \mathbb{P} \{ s_{t+1} = j \mid s_t = i \}
\]

where \(\mathbb{P}\) means conditional probability

Nonfinancial income \(\{y_t\}\) obeys

\[
y_t = \begin{cases} 
\bar{y}_1 & \text{if } s_t = 1 \\
\bar{y}_2 & \text{if } s_t = 2 
\end{cases}
\]

A consumer wishes to maximize

\[
\mathbb{E} \left[ \sum_{t=0}^{\infty} \beta^t u(c_t) \right] \quad \text{where } u(c_t) = -(c_t - \gamma)^2 \quad \text{and} \quad 0 < \beta < 1
\]

Here \(\gamma > 0\) is a bliss level of consumption

6.4.4 Market Structure

Our complete and incomplete markets models differ in how thoroughly the market structure allows a consumer to transfer resources across time and Markov states, there being more transfer opportunities in the complete markets setting than in the incomplete markets setting.
Watch how these differences in opportunities affect

- how smooth consumption is across time and Markov states
- how the consumer chooses to make his levels of indebtedness behave over time and across Markov states

### 6.5 Model 1 (Complete Markets)

At each date $t \geq 0$, the consumer trades a full array of one-period ahead Arrow securities.

We assume that prices of these securities are exogenous to the consumer. 

*Exogenous* means that they are unaffected by the consumer’s decisions.

In Markov state $s_t$ at time $t$, one unit of consumption in state $s_{t+1}$ at time $t + 1$ costs $q(s_{t+1} \mid s_t)$ units of the time $t$ consumption good.

The prices $q(s_{t+1} \mid s_t)$ are given and can be organized into a matrix $Q$ with $Q_{ij} = q(j \mid i)$

At time $t = 0$, the consumer starts with an inherited level of debt due at time 0 of $b_0$ units of time 0 consumption goods.

The consumer’s budget constraint at $t \geq 0$ in Markov state $s_t$ is

$$c_t + b_t \leq y(s_t) + \sum_j q(j \mid s_t) b_{t+1}(j \mid s_t)$$

where $b_t$ is the consumer’s one-period debt that falls due at time $t$ and $b_{t+1}(j \mid s_t)$ are the consumer’s time $t$ sales of the time $t + 1$ consumption good in Markov state $j$.

Thus

- $q(j \mid s_t) b_{t+1}(j \mid s_t)$ is a source of time $t$ financial income for the consumer in Markov state $s_t$
- $b_t \equiv b_t(j \mid s_{t-1})$ is a source of time $t$ expenditures for the consumer when $s_t = j$

**Remark:** We are ignoring an important technicality here, namely, that the consumer’s choice of $b_{t+1}(j \mid s_t)$ must respect so-called *natural debt limits* that assure that it is feasible for the consumer to repay debts due even if he consumers zero forevermore. We shall discuss such debt limits in another lecture.

A natural analog of Hall’s assumption that the one-period risk-free gross interest rate is $\beta^{-1}$ is

$$q(j \mid i) = \beta P_{ij}$$

To understand how this is a natural analogue, observe that in state $i$ it costs $\sum_j q(j \mid i)$ to purchase one unit of consumption next period for sure, i.e., meaning no matter what Markov state $j$ occurs at $t + 1$.

Hence the **implied price** of a risk-free claim on one unit of consumption next period is

$$\sum_j q(j \mid i) = \sum_j \beta P_{ij} = \beta$$
6.5. MODEL 1 (COMPLETE MARKETS)

This confirms the sense in which (6) is a natural counterpart to Hall’s assumption that the risk-free one-period gross interest rate is \( R = \beta^{-1} \).

It is timely please to recall that the gross one-period risk-free interest rate is the reciprocal of the price at time \( t \) of a risk-free claim on one unit of consumption tomorrow.

First-order necessary conditions for maximizing the consumer’s expected utility subject to the sequence of budget constraints (5) are

\[
\beta u'(c_{t+1}) P\{s_{t+1} \mid s_t\} = q(s_{t+1} \mid s_t)
\]

for all \( s_t, s_{t+1} \) or, under our assumption (6) about Arrow security prices,

\[
c_{t+1} = c_t
\]

Thus, our consumer sets \( c_t = \tilde{c} \) for all \( t \geq 0 \) for some value \( \tilde{c} \) that it is our job now to determine along with values for \( b_{t+1}(j \mid s_t = i) \) for \( i = 1, 2 \) and \( j = 1, 2 \).

We’ll use a guess and verify method to determine these objects

**Guess:** We’ll make the plausible guess that

\[
b_{t+1}(s_{t+1} = j \mid s_t = i) = b(j), \quad i = 1, 2; \quad j = 1, 2
\]

so that the amount borrowed today depends only on tomorrow’s Markov state. (Why is this a plausible guess?)

To determine \( \tilde{c} \), we shall deduce implications of the consumer’s budget constraints in each Markov state today and our guess (8) about the consumer’s debt level choices.

For \( t \geq 1 \), these imply

\[
\begin{align*}
\tilde{c} + b(1) &= y(1) + q(1 \mid 1)b(1) + q(2 \mid 1)b(2) \\
\tilde{c} + b(2) &= y(2) + q(1 \mid 2)b(1) + q(2 \mid 2)b(2)
\end{align*}
\]

or

\[
\begin{bmatrix}
b(1) \\
b(2)
\end{bmatrix} + \begin{bmatrix}
\tilde{c} \\
\tilde{c}
\end{bmatrix} = \begin{bmatrix}
y(1) \\
y(2)
\end{bmatrix} + \beta \begin{bmatrix}
P_{11} & P_{12} \\
P_{21} & P_{22}
\end{bmatrix} \begin{bmatrix}
b(1) \\
b(2)
\end{bmatrix}
\]

These are 2 equations in the 3 unknowns \( \tilde{c}, b(1), b(2) \).

To get a third equation, we assume that at time \( t = 0 \), \( b_0 \) is the debt due; and we assume that at time \( t = 0 \), the Markov state \( s_0 = 1 \)

(We could instead have assumed that at time \( t = 0 \) the Markov state \( s_0 = 2 \), which would affect our answer as we shall see)

Since we have assumed that \( s_0 = 1 \), the budget constraint at time \( t = 0 \) is

\[
\tilde{c} + b_0 = y(1) + q(1 \mid 1)b(1) + q(2 \mid 1)b(2)
\]

where \( b_0 \) is the (exogenous) debt the consumer is assumed to bring into period 0
If we substitute (10) into the first equation of (9) and rearrange, we discover that

\[ b(1) = b_0 \]  

(11)

We can then use the second equation of (9) to deduce the restriction

\[ y(1) - y(2) + [q(1 | 1) - q(1 | 2) - 1]b_0 + [q(2 | 1) + 1 - q(2 | 2)]b(2) = 0, \]  

(12)

an equation that we can solve for the unknown \( b(2) \).

Knowing \( b(1) \) and \( b(2) \), we can solve equation (10) for the constant level of consumption \( \bar{c} \).

6.5.1 Key Outcomes

The preceding calculations indicate that in the complete markets version of our model, we obtain the following striking results:

- The consumer chooses to make consumption perfectly constant across time and across Markov states.
- State-contingent debt purchases \( b_{t+1}(s_{t+1} = j | s_t = i) \) depend only on \( j \).
- If the initial Markov state is \( s_0 = j \) and initial consumer debt is \( b_0 \), then debt in Markov state \( j \) satisfied \( b(j) = b_0 \).

To summarize what we have achieved up to now, we have computed the constant level of consumption \( \bar{c} \) and indicated how that level depends on the underlying specifications of preferences, Arrow securities prices, the stochastic process of exogenous nonfinancial income, and the initial debt level \( b_0 \):

- The consumer’s debt neither accumulates, nor decumulates, nor drifts – instead, the debt level each period is an exact function of the Markov state, so in the two-state Markov case, it switches between two values.
- We have verified guess (8).
- When the state \( s_t \) returns to the initial state \( s_0 \), debt returns to the initial debt level.
- Debt levels in all other states depend on virtually all remaining parameters of the model.

6.5.2 Code

Here’s some code that, among other things, contains a function called consumption_complete().

This function computes \( \{b(i)\}_{i=1}^N, \bar{c} \) as outcomes given a set of parameters for the general case with \( N \) Markov states under the assumption of complete markets.

In [4]:

```python
class ConsumptionProblem:
    # The data for a consumption problem, including some default values.
    def __init__(self, 
        β=.96, 
        y=[2, 1.5], 
        b0=3,
```
\[
P = \begin{bmatrix}
0.8 & 0.2 \\
0.4 & 0.6
\end{bmatrix}, \\
\text{init} = 0
\]

Parameters
----------

\(\beta\) : discount factor \\
y : list containing the two income levels \\
b0 : debt in period 0 (= initial state debt level) \\
P : 2x2 transition matrix \\
init : index of initial state s0

```
def simulate(self, N_simul=80, random_state=1):
    Parameters
    ----------
    N_simul : number of periods for simulation
    random_state : random state for simulating Markov chain
    
    # For the simulation define a quantecon MC class
    mc = qe.MarkovChain(self.P)
    s_path = mc.simulate(N_simul, init=self.init,  
    random_state=random_state)
    return s_path
```

def consumption_complete(cp):
    Parameters
    ----------
    cp : instance of ConsumptionProblem

    Returns
    -------

    c_bar : constant consumption
    b : optimal debt in each state
    associated with the price system

    \[Q = \beta \cdot P\]

    \(\beta, P, y, b0, \text{init} = cp.\beta, cp.P, cp.y, cp.b0, cp.init\)  
    # Unpack
    Q = \beta \cdot P  
    # assumed price system
# construct matrices of augmented equation system
n = P.shape[0] + 1

y_aug = np.empty((n, 1))
y_aug[0, 0] = y[init] - b0
y_aug[1:, 0] = y

Q_aug = np.zeros((n, n))
Q_aug[0, 1:] = Q[init, :]
Q_aug[1:, 1:] = Q

A = np.zeros((n, n))
A[:, 0] = 1
A[1:, 1:] = np.eye(n-1)

x = np.linalg.inv(A - Q_aug) @ y_aug

c_bar = x[0, 0]
b = x[1:, 0]

return c_bar, b

def consumption_incomplete(cp, s_path):
    
    Computes endogenous values for the incomplete market case.

    Parameters
    ----------
    cp : instance of ConsumptionProblem
    s_path : the path of states
    
    β, P, y, b0 = cp.β, cp.P, cp.y, cp.b0  # Unpack

    N_simul = len(s_path)

    # Useful variables
    n = len(y)
y.shape = (n, 1)
v = np.linalg.inv(np.eye(n) - β * P) @ y

    # Store consumption and debt path
    b_path, c_path = np.ones(N_simul+1), np.ones(N_simul)
b_path[0] = b0

    # Optimal decisions from (12) and (13)
    db = ((1 - β) * v - y) / β

    for i, s in enumerate(s_path):
        c_path[i] = (1 - β) * (v - b_path[i] * np.ones((n, 1)))[s, 0]
        b_path[i+1] = b_path[i] + db[s, 0]

    return c_path, b_path[:,-1], y[s_path]

Let's test by checking that ċ and b₂ satisfy the budget constraint

In [5]: cp = ConsumptionProblem()
Below, we’ll take the outcomes produced by this code – in particular the implied consumption and debt paths – and compare them with outcomes from an incomplete markets model in the spirit of Hall [24]

6.6 Model 2 (One-Period Risk-Free Debt Only)

This is a version of the original model of Hall (1978) in which the consumer’s ability to substitute intertemporally is constrained by his ability to buy or sell only one security, a risk-free one-period bond bearing a constant gross interest rate that equals $\beta^{-1}$.

Given an initial debt $b_0$ at time 0, the consumer faces a sequence of budget constraints

$$c_t + b_t = y_t + \beta b_{t+1}, \quad t \geq 0$$

where $\beta$ is the price at time $t$ of a risk-free claim on one unit of time consumption at time $t + 1$.

First-order conditions for the consumer’s problem are

$$\sum_j u'(c_{t+1,j})P_{ij} = u'(c_{t,i})$$

For our assumed quadratic utility function this implies

$$\sum_j c_{t+1,j}P_{ij} = c_{t,i}$$

which for our finite-state Markov setting is Hall’s (1978) conclusion that consumption follows a random walk.

As we saw in our first lecture on the permanent income model, this leads to

$$b_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} - (1 - \beta)^{-1} c_t$$

and

$$c_t = (1 - \beta) \left[ \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} - b_t \right]$$

Equation (15) expresses $c_t$ as a net interest rate factor $(1 - \beta)$ times the sum of the expected present value of nonfinancial income $\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j}$ and financial wealth $-b_t$.

Substituting (15) into the one-period budget constraint and rearranging leads to
\[ b_{t+1} - b_t = \beta^{-1} \left[ (1 - \beta) \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} - y_t \right] \]  

(16)

Now let’s calculate the key term \( \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} \) in our finite Markov chain setting.

Define the expected discounted present value of non-financial income

\[ v_t := \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j y_{t+j} \]

which in the spirit of dynamic programming we can write as a Bellman equation

\[ v_t := y_t + \beta \mathbb{E}_t v_{t+1} \]

In our two-state Markov chain setting, \( v_t = v(1) \) when \( s_t = 1 \) and \( v_t = v(2) \) when \( s_t = 2 \).

Therefore, we can write our Bellman equation as

\[ v(1) = y(1) + \beta P_{11} v(1) + \beta P_{12} v(2) \]
\[ v(2) = y(2) + \beta P_{21} v(1) + \beta P_{22} v(2) \]

or

\[ \vec{v} = \vec{y} + \beta P \vec{v} \]

where \( \vec{v} = \begin{bmatrix} v(1) \\ v(2) \end{bmatrix} \) and \( \vec{y} = \begin{bmatrix} y(1) \\ y(2) \end{bmatrix} \).

We can also write the last expression as

\[ \vec{v} = (I - \beta P)^{-1} \vec{y} \]

In our finite Markov chain setting, from expression (15), consumption at date \( t \) when debt is \( b_t \) and the Markov state today is \( s_t = i \) is evidently

\[ c(b_t, i) = (1 - \beta) \left( [(I - \beta P)^{-1} \vec{y}]_i - b_t \right) \]  

(17)

and the increment to debt is

\[ b_{t+1} - b_t = \beta^{-1}[(1 - \beta)v(i) - y(i)] \]  

(18)

6.6.1 Summary of Outcomes

In contrast to outcomes in the complete markets model, in the incomplete markets model

- consumption drifts over time as a random walk; the level of consumption at time \( t \) depends on the level of debt that the consumer brings into the period as well as the expected discounted present value of nonfinancial income at \( t \).
• the consumer’s debt drifts upward over time in response to low realizations of nonfinancial income and drifts downward over time in response to high realizations of nonfinancial income.
• the drift over time in the consumer’s debt and the dependence of current consumption on today’s debt level account for the drift over time in consumption.

6.6.2 The Incomplete Markets Model

The code above also contains a function called consumption_incomplete() that uses (17) and (18) to
• simulate paths of $y_t, c_t, b_{t+1}$
• plot these against values of $\bar{c}, b(s_1), b(s_2)$ found in a corresponding complete markets economy

Let’s try this, using the same parameters in both complete and incomplete markets economies

In [6]:
    cp = ConsumptionProblem()
    s_path = cp.simulate()
    N_simul = len(s_path)
    c_bar, debt_complete = consumption_complete(cp)
    c_path, debt_path, y_path = consumption_incomplete(cp, s_path)
    fig, ax = plt.subplots(1, 2, figsize=(15, 5))
    ax[0].set_title('Consumption paths')
    ax[0].plot(np.arange(N_simul), c_path, label='incomplete market')
    ax[0].plot(np.arange(N_simul), c_bar * np.ones(N_simul),
               label='complete market')
    ax[0].plot(np.arange(N_simul), y_path, label='income', alpha=.6, ls='--')
    ax[0].legend()
    ax[0].set_xlabel('Periods')
    ax[1].set_title('Debt paths')
    ax[1].plot(np.arange(N_simul), debt_path, label='incomplete market')
    ax[1].plot(np.arange(N_simul), debt_complete[s_path],
               label='complete market')
    ax[1].plot(np.arange(N_simul), y_path, label='income', alpha=.6, ls='--')
    ax[1].legend()
    ax[1].axhline(0, color='k', ls='--')
    ax[1].set_xlabel('Periods')
    plt.show()
In the graph on the left, for the same sample path of nonfinancial income $y_t$, notice that

- consumption is constant when there are complete markets, but takes a random walk in the incomplete markets version of the model.
- the consumer’s debt oscillates between two values that are functions of the Markov state in the complete markets model, while the consumer’s debt drifts in a “unit root” fashion in the incomplete markets economy.

### 6.6.3 A sequel

In tax smoothing with complete and incomplete markets, we reinterpret the mathematics and Python code presented in this lecture in order to construct tax-smoothing models in the incomplete markets tradition of Barro [7] as well as in the complete markets tradition of Lucas and Stokey [45].
Chapter 7

Tax Smoothing with Complete and Incomplete Markets

7.1 Contents

- Overview 7.2
- Tax Smoothing with Complete Markets 7.3
- Returns on State-Contingent Debt 7.4
- More Finite Markov Chain Tax-Smoothing Examples 7.5

In addition to what’s in Anaconda, this lecture uses the library:

In [1]: !pip install --upgrade quantecon

7.2 Overview

This lecture describes tax-smoothing models that are counterparts to consumption-smoothing models in Consumption Smoothing with Complete and Incomplete Markets.

- one is in the complete markets tradition of Lucas and Stokey [45].
- the other is in the incomplete markets tradition of Barro [7].

Complete markets allow a government to buy or sell claims contingent on all possible Markov states.

Incomplete markets allow a government to buy or sell only a limited set of securities, often only a single risk-free security.

Barro [7] worked in an incomplete markets tradition by assuming that the only asset that can be traded is a risk-free one period bond.

In his consumption-smoothing model, Hall [24] had assumed an exogenous stochastic process of nonfinancial income and an exogenous gross interest rate on one period risk-free debt that equals $\beta^{-1}$, where $\beta \in (0, 1)$ is also a consumer’s intertemporal discount factor.

Barro [7] made an analogous assumption about the risk-free interest rate in a tax-smoothing model that turns out to have the same mathematical structure as Hall’s consumption-smoothing model.

To get Barro’s model from Hall’s, all we have to do is to rename variables.
We maintain Hall’s and Barro’s assumption about the interest rate when we describe an incomplete markets version of our model.

In addition, we extend their assumption about the interest rate to an appropriate counterpart to create a “complete markets” model in the style of Lucas and Stokey [45].

### 7.2.1 Isomorphism between Consumption and Tax Smoothing

For each version of a consumption-smoothing model, a tax-smoothing counterpart can be obtained simply by relabeling:

- consumption as tax collections
- a consumer’s one-period utility function as a government’s one-period loss function from collecting taxes that impose deadweight welfare losses
- a consumer’s nonfinancial income as a government’s purchases
- a consumer’s debt as a government’s assets

Thus, we can convert the consumption-smoothing models in lecture Consumption Smoothing with Complete and Incomplete Markets into tax-smoothing models by setting $c_t = T_t$, $y_t = G_t$, and $-b_t = a_t$, where $T_t$ is total tax collections, $\{G_t\}$ is an exogenous government expenditures process, and $a_t$ is the government’s holdings of one-period risk-free bonds coming maturing at the due at the beginning of time $t$.

For elaborations on this theme, please see Optimal Savings II: LQ Techniques and later parts of this lecture.

We’ll spend most of this lecture studying acquire finite-state Markov specification, but will also treat the linear state space specification.

### Link to History

For those who love history, President Thomas Jefferson’s Secretary of Treasury Albert Gallatin (1807) [23] seems to have prescribed policies that come from Barro’s model [7]

Let’s start with some standard imports:

```python
In [2]:
import numpy as np
import quantecon asqe
import matplotlib.pyplot as plt
%matplotlib inline
import scipy.linalg as la
```

To exploit the isomorphism between consumption-smoothing and tax-smoothing models, we simply use code from Consumption Smoothing with Complete and Incomplete Markets

### 7.2.2 Code

Among other things, this code contains a function called consumption_complete().

This function computes $\{b(i)\}_{i=1}^N, \bar{c}$ as outcomes given a set of parameters for the general case with $N$ Markov states under the assumption of complete markets

```python
In [3]:
class ConsumptionProblem:
```
The data for a consumption problem, including some default values.

```python
def __init__(self, 
    beta=.96, 
    y=[2, 1.5], 
    b0=3, 
    P=[[[.8, .2], 
        [.4, .6]], 
    init=0):
    
    Parameters
    ----------
    beta : discount factor
    y : list containing the two income levels
    b0 : debt in period 0 (= initial state debt level)
    P : 2x2 transition matrix
    init : index of initial state s0

    
    self.beta = beta
    self.y = np.asarray(y)
    self.b0 = b0
    self.P = np.asarray(P)
    self.init = init

def simulate(self, N_simul=80, random_state=1):
    
    Parameters
    ----------

    N_simul : number of periods for simulation
    random_state : random state for simulating Markov chain

    
    # For the simulation define a quantecon MC class
    mc = qe.MarkovChain(self.P)
    s_path = mc.simulate(N_simul, init=self.init, 
        random_state=random_state)

    return s_path

def consumption_complete(cp):
    
    Computes endogenous values for the complete market case.

    Parameters
    ----------

    cp : instance of ConsumptionProblem

    Returns
    -------

    c_bar : constant consumption
    b : optimal debt in each state associated with the price system
```
""" Q = β * P
β, P, y, b0, init = cp.β, cp.P, cp.y, cp.b0, cp.init  # Unpack
Q = β * P  # assumed price system

# construct matrices of augmented equation system
n = P.shape[0] + 1
y_aug = np.empty((n, 1))
y_aug[0, 0] = y[init] - b0
y_aug[1:, 0] = y
Q_aug = np.zeros((n, n))
Q_aug[0, 1:] = Q[init, :]
Q_aug[1:, 1:] = Q
A = np.zeros((n, n))
A[:, 0] = 1
A[1:, 1:] = np.eye(n-1)
x = np.linalg.inv(A - Q_aug) @ y_aug

c_bar = x[0, 0]
b = x[1:, 0]
return c_bar, b


def consumption_incomplete(cp, s_path):
    """
    Computes endogenous values for the incomplete market case.

    Parameters
    ----------
    cp : instance of ConsumptionProblem
    s_path : the path of states
    """
    β, P, y, b0 = cp.β, cp.P, cp.y, cp.b0  # Unpack

    N_simul = len(s_path)

    # Useful variables
    n = len(y)
y.shape = (n, 1)
v = np.linalg.inv(np.eye(n) - β * P) @ y

    # Store consumption and debt path
    b_path, c_path = np.ones(N_simul+1), np.ones(N_simul)
b_path[0] = b0

    # Optimal decisions from (12) and (13)
    db = ((1 - β) * v - y) / β

    for i, s in enumerate(s_path):
        c_path[i] = (1 - β) * (v - b_path[i] * np.ones((n, 1)))[s, 0]
7.2. OVERVIEW

\[ b_{path}[i + 1] = b_{path}[i] + db[s, 0] \]

\textbf{return} \( c_{path}, b_{path}[:-1], y[s_{path}] \)

7.2.3 Revisiting the consumption-smoothing model

The code above also contains a function called\texttt{consumption_incomplete()} that uses (17) and (18) to

- simulate paths of \( y_t, c_t, b_{t+1} \)
- plot these against values of \( \bar{c}, b(s_1), b(s_2) \) found in a corresponding complete markets economy

Let’s try this, using the same parameters in both complete and incomplete markets economies

In [4]:
\begin{verbatim}
    cp = ConsumptionProblem()
    s_path = cp.simulate()
    N_simul = len(s_path)

    c_bar, debt_complete = consumption_complete(cp)

    c_path, debt_path, y_path = consumption_incomplete(cp, s_path)

    fig, ax = plt.subplots(1, 2, figsize=(15, 5))

    ax[0].set_title('Consumption paths')
    ax[0].plot(np.arange(N_simul), c_path, label='incomplete market')
    ax[0].plot(np.arange(N_simul), c_bar * np.ones(N_simul), label='complete market')
    ax[0].plot(np.arange(N_simul), y_path, label='income', alpha=.6, ls='--')
    ax[0].legend()

    ax[0].set_xlabel('Periods')

    ax[1].set_title('Debt paths')
    ax[1].plot(np.arange(N_simul), debt_path, label='incomplete market')
    ax[1].plot(np.arange(N_simul), debt_complete[s_path], label='complete market')
    ax[1].plot(np.arange(N_simul), y_path, label='income', alpha=.6, ls='--')
    ax[1].legend()
    ax[1].axhline(0, color='k', ls='--')

    ax[1].set_xlabel('Periods')

    plt.show()
\end{verbatim}
In the graph on the left, for the same sample path of nonfinancial income $y_t$, notice that

- consumption is constant when there are complete markets.
- consumption takes a random walk in the incomplete markets version of the model.
- the consumer’s debt oscillates between two values that are functions of the Markov state in the complete markets model.
- the consumer’s debt drifts because it contains a unit root in the incomplete markets economy.

**Relabeling variables to create tax-smoothing models**

As indicated above, we relabel variables to acquire tax-smoothing interpretations of the complete markets and incomplete markets consumption-smoothing models.

```
In [5]: fig, ax = plt.subplots(1, 2, figsize=(15, 5))

ax[0].set_title('Tax collection paths')
ax[0].plot(np.arange(N_simul), c_path, label='incomplete market')
ax[0].plot(np.arange(N_simul), c_bar * np.ones(N_simul), label='complete market')
ax[0].plot(np.arange(N_simul), y_path, label='govt expenditures', alpha=.6, ls='--')
ax[0].legend()
ax[0].set_xlabel('Periods')
ax[0].set_ylim([1.4, 2.1])

ax[1].set_title('Government assets paths')
ax[1].plot(np.arange(N_simul), debt_path, label='incomplete market')
ax[1].plot(np.arange(N_simul), debt_complete[s_path], label='complete market')
ax[1].plot(np.arange(N_simul), y_path, label='govt expenditures', ls='--')
ax[1].legend()
ax[1].axhline(0, color='k', ls='--')
ax[1].set_xlabel('Periods')

plt.show()
```
7.3 Tax Smoothing with Complete Markets

It is instructive to focus on a simple tax-smoothing example with complete markets.

This example illustrates how, in a complete markets model like that of Lucas and Stokey [45], the government purchases insurance from the private sector. Payouts from the insurance it had purchased allows the government to avoid raising taxes when emergencies make government expenditures surge.

We assume that government expenditures take one of two values $G_1 < G_2$, where Markov state 1 means “peace” and Markov state 2 means “war”.

The government budget constraint in Markov state $i$ is

$$T_i + b_i = G_i + \sum_j Q_{ij} b_j$$

where

$$Q_{ij} = \beta P_{ij}$$

is the price today of one unit of goods in Markov state $j$ tomorrow when the Markov state is $i$ today.

$b_i$ is the government’s level of assets when it arrives in Markov state $i$.

That is, $b_i$ equals one-period state-contingent claims owed to the government that fall due at time $t$ when the Markov state is $i$.

Thus, if $b_i < 0$, it means the government is owed $b_i$ or owes $-b_i$ when the economy arrives in Markov state $i$ at time $t$.

In our examples below, this happens when in a previous war-time period the government has sold an Arrow securities paying off $-b_i$ in peacetime Markov state $i$.

It can be enlightening to express the government’s budget constraint in Markov state $i$ as
\[ T_i = G_i + \left( \sum_j Q_{ij} b_j - b_i \right) \]

in which the term \( \sum_j Q_{ij} b_j - b_i \) equals the net amount that the government spends to purchase one-period Arrow securities that will pay off next period in Markov states \( j = 1, \ldots, N \) after it has received payments \( b_i \) this period.

### 7.4 Returns on State-Contingent Debt

Notice that \( \sum_{j'=1}^{N} Q_{ij'} b(j') \) is the amount that the government spends in Markov state \( i \) at time \( t \) to purchase one-period state-contingent claims that will pay off in Markov state \( j' \) at time \( t+1 \).

Then the *ex post* one-period gross return on the portfolio of government assets held from state \( i \) at time \( t \) to state \( j \) at time \( t+1 \) is

\[ R(j|i) = \frac{b(j)}{\sum_{j'=1}^{N} Q_{ij'} b(j')} \]

The cumulative return earned from putting 1 unit of time \( t \) goods into the government portfolio of state-contingent securities at time \( t \) and then rolling over the proceeds into the government portfolio each period thereafter is

\[ R^T(s_{t+T}, s_{t+T-1}, \ldots, s_t) \equiv R(s_{t+1}|s_t)R(s_{t+2}|s_{t+1}) \cdots R(s_{t+T}|s_{t+T-1}) \]

Here is some code that computes one-period and cumulative returns on the government portfolio in the finite-state Markov version of our complete markets model.

**Convention:** In this code, when \( P_{ij} = 0 \), we arbitrarily set \( R(j|i) \) to be 0.

```python
In [6]: def ex_post_gross_return(b, cp):
    ""
    calculate the ex post one-period gross return on the portfolio
    of government assets, given b and Q.
    ""
    Q = cp.\beta * cp.P
    values = Q @ b
    n = len(b)
    R = np.zeros((n, n))
    for i in range(n):
        ind = cp.P[i, :) != 0
        R[i, ind] = b[ind] / values[i]
    return R

def cumulative_return(s_path, R):
    ""
    compute cumulative return from holding 1 unit market portfolio
    """
of government bonds, given some simulated state path.

```python
T = len(s_path)

RT_path = np.empty(T)
RT_path[0] = 1
RT_path[1:] = np.cumprod([R[s_path[t], s_path[t+1]] for t in range(T-1)])
```

```python
return RT_path
```

### 7.4.1 An Example of Tax Smoothing

We’ll study a tax-smoothing model with two Markov states.

In Markov state 1, there is peace and government expenditures are low.

In Markov state 2, there is war and government expenditures are high.

We’ll compute optimal policies in both complete and incomplete markets settings.

Then we’ll feed in a particular assumed path of Markov states and study outcomes.

- We’ll assume that the initial Markov state is state 1, which means we start from a state of peace.
- The government then experiences 3 time periods of war and come back to peace again.
- The history of Markov states is therefore \{peace, war, war, war, peace\}.

In addition, as indicated above, to simplify our example, we’ll set the government’s initial asset level to 1, so that \(b_1 = 1\).

Here’s code that initializes government assets to be unity in an initial peace time Markov state.

```
In [7]: # Parameters
β = .96

# change notation y to g in the tax-smoothing example

g = [1, 2]
b0 = 1

P = np.array([[.8, .2],
               [.4, .6]])

cp = ConsumptionProblem(β, g, b0, P)

Q = β * P

# change notation c_bar to T_bar in the tax-smoothing example

T_bar, b = consumption_complete(cp)

R = ex_post_gross_return(b, cp)
s_path = [0, 1, 1, 1, 0]

RT_path = cumulative_return(s_path, R)

print(f"P \n {P}")
print(f"Q \n {Q}")

print(f"Govt expenditures in peace and war = {g}")
print(f"Constant tax collections = \{T_bar\}")
print(f"Govt debts in two states = \{-b\}")
```
Now let's check the government's budget constraint in peace and war. Our assumptions imply that the government always purchases 0 units of the Arrow peace security.

print(msg)

AS1 = Q[0, :] @ b
# spending on Arrow security
# since the spending on Arrow peace security is not 0 anymore after we change b0 to 1
print(f"Spending on Arrow security in peace = {AS1}")
AS2 = Q[1, :] @ b
print(f"Spending on Arrow security in war = {AS2}")

# tax collections minus debt levels
print("Government tax collections minus debt levels in peace and war")
TB1 = T_bar + b[0]
print(f"T+b in peace = {TB1}")
TB2 = T_bar + b[1]
print(f"T+b in war = {TB2}")

# Total government spending in peace and war
G1 = g[0] + AS1
G2 = g[1] + AS2
print(f"Peace = {G1}")
print(f"War = {G2}")

# Let's see ex-post and ex-ante returns on Arrow securities

Π = np.reciprocal(Q)
exret = Π
print(f"Ex-post returns to purchase of Arrow securities = \n{exret}")
exant = Π * P
print(f"Ex-ante returns to purchase of Arrow securities \n{exant}")

# The Ex-post one-period gross return on the portfolio of government assets
print(R)

# The cumulative return earned from holding 1 unit market portfolio of government bonds
print(RT_path[-1])

P
[[0.8 0.2]
[0.4 0.6]]
Q
[[0.768 0.192]
[0.384 0.576]]
Govt expenditures in peace and war = [1, 2]
Constant tax collections = 1.2716883116883118
7.4. RETURNS ON STATE-CONTINGENT DEBT

Govt debts in two states = [-1. -2.62337662]

Now let's check the government's budget constraint in peace and war. Our assumptions imply that the government always purchases 0 units of the Arrow peace security.

Spending on Arrow security in peace = 1.2716883116883118
Spending on Arrow security in war = 1.895064935064935

Government tax collections minus debt levels in peace and war
T+b in peace = 2.2716883116883118
T+b in war = 3.895064935064935

Total government spending in peace and war
Peace = 2.2716883116883118
War = 3.895064935064935

Let's see ex-post and ex-ante returns on Arrow securities
Ex-post returns to purchase of Arrow securities =
[[1.30208333 5.20833333]
 [2.60416667 1.73611111]]
Ex-ante returns to purchase of Arrow securities
[[1.04166667 1.04166667]
 [1.04166667 1.04166667]]

The Ex-post one-period gross return on the portfolio of government assets
[[0.78635621 2.0629085 ]
 [0.5276664  1.38432018]]

The cumulative return earned from holding 1 unit market portfolio of government bonds
2.0860704239993675

7.4.2 Explanation

In this example, the government always purchase 1 units of the Arrow security that pays off in peace time (Markov state 1).

And it purchases a higher amount of the security that pays off in war time (Markov state 2).

Thus, this is an example in which

- during peacetime, the government purchases insurance against the possibility that war breaks out next period
- during wartime, the government purchases insurance against the possibility that war continues another period
- so long as peace continues, the ex post return on insurance against war is low
- when war breaks out or continues, the ex post return on insurance against war is high
- given the history of states that we assumed, the value of one unit of the portfolio of government assets eventually doubles in the end because of high returns during wartime.

We recommend plugging the quantities computed above into the government budget constraints in the two Markov states and staring.

Exercise: try changing the Markov transition matrix so that

\[
P = \begin{bmatrix}
1 & 0 \\
0.2 & 0.8
\end{bmatrix}
\]
Also, start the system in Markov state 2 (war) with initial government assets $-10$, so that the
government starts the war in debt and $b_2 = -10$.

7.5 More Finite Markov Chain Tax-Smoothing Examples

To interpret some episodes in the fiscal history of the United States, we find it interesting to
study a few more examples.

We compute examples in an $N$ state Markov setting under both complete and incomplete
markets.

These examples differ in how Markov states are jumping between peace and war.

To wrap procedures for solving models, relabeling graphs so that we record government debt
rather than government assets, and displaying results, we construct a Python class.

```python
In [8]: class TaxSmoothingExample:
    
        """
        construct a tax-smoothing example, by relabeling consumption problem
        """
    
        def __init__(self, g, P, b0, states, β=.96,
                      init=0, s_path=None, N_simul=80, random_state=1):

            self.states = states  # state names

            # if the path of states is not specified
            if s_path is None:
                self.cp = ConsumptionProblem(β, g, b0, P, init=init)
                self.s_path = self.cp.simulate(N_simul=N_simul,β
                      random_state=random_state)

            # if the path of states is specified
            else:
                self.cp = ConsumptionProblem(β, g, b0, P, init=s_path[0])
                self.s_path = s_path

            # solve for complete market case
            self.T_bar, self.b = consumption_complete(self.cp)
            self.debt_value = -(β * P @ self.b).T

            # solve for incomplete market case
            self.T_path, self.asset_path, self.g_path = 
                consumption_incomplete(self.cp, self.s_path)

            # calculate returns on state-contingent debt
            self.R = ex_post_gross_return(self.b, self.cp)
            self.RT_path = cumulative_return(self.s_path, self.R)

        def display(self):

            # plot graphs
            N = len(self.T_path)
            plt.figure()
            plt.title('Tax collection paths')
            plt.plot(np.arange(N), self.T_path, label='incomplete market')
```

116CHAPTER 7. TAX SMOOTHING WITH COMPLETE AND INCOMPLETE MARKETS
7.5. MORE FINITE MARKOV CHAIN TAX-SMoothing EXAMPLES

```python
plt.plot(np.arange(N), self.T_bar * np.ones(N), label='complete market')
plt.plot(np.arange(N), self.g_path, label='govt expenditures', alpha=.6, ls='--')
plt.legend()
plt.xlabel('Periods')
plt.show()

plt.title('Government debt paths')
plt.plot(np.arange(N), -self.asset_path, label='incomplete market')
plt.plot(np.arange(N), -self.b[self.s_path], label='complete market')
plt.plot(np.arange(N), self.g_path, label='govt expenditures', ls='--')
plt.legend()
plt.xlabel('Periods')
plt.show()

fig, ax = plt.subplots()
ax.set_title('Cumulative return path (complete markets)')
line1 = ax.plot(np.arange(N), self.RT_path)[0]
c1 = line1.get_color()
ax.set_xlabel('Periods')
ax.set_ylabel('Cumulative return', color=c1)

ax_ = ax.twinx()
ax_.set_lines.prop_cycler = ax_.get_lines.prop_cycler
line2 = ax_.plot(np.arange(N), self.g_path, ls='--')[0]
c2 = line2.get_color()
ax_.set_ylabel('Government expenditures', color=c2)

plt.show()

# plot detailed information
Q = self.cp.\beta * self.cp.P

print(f"P
{self.cp.P}")
print(f"Q
{Q}")
print(f"Govt expenditures in '{', '.join(self.states)} = {self.cp.y.flatten()}")
print(f"Constant tax collections = {self.T_bar}")
print(f"Govt debt in {len(self.states)} states = {-self.b}")

print("")
print(f"Government tax collections minus debt levels in '{', '.join(self.states)}")
for i in range(len(self.states)):
    TB = self.T_bar + self.b[i]
    print(f" T+b in {self.states[i]} = {TB}\n")

print("")
print(f"Total government spending in '{', '.join(self.states)}")
```
for i in range(len(self.states)):
    G = self.cp.y[i, 0] + Q[i, :] @ self.b
    print(f" {self.states[i]} = {G}"
print"
print"Let's see ex-post and ex-ante returns on Arrow securities \n"
print(f"Ex-post returns to purchase of Arrow securities:"
for i in range(len(self.states)):
    for j in range(len(self.states)):
        if Q[i, j] != 0.:
            print(f" π({self.states[j]}|{self.states[i]}) = {1/
-Q[i, j]}"
print"
exant = 1 / self.cp.β
print(f"Ex-ante returns to purchase of Arrow securities = {exant}")
print"
print"The Ex-post one-period gross return on the portfolio of-government assets"
print(self.R)
print"
print"The cumulative return earned from holding 1 unit market-portfolio of-government bonds"
print(self.RT_path[-1])

7.5.1 Parameters

In [9]: γ = .1
    λ = .1
    φ = .1
    θ = .1
    ψ = .1
    g_L = .5
    g_M = .8
    g_H = 1.2
    β = .96

7.5.2 Example 1

This example is designed to produce some stylized versions of tax, debt, and deficit paths followed by the United States during and after the Civil War and also during and after World War I.

We set the Markov chain to have three states

\[
P = \begin{bmatrix}
1 - \lambda & \lambda & 0 \\
0 & 1 - \phi & \phi \\
0 & 0 & 1
\end{bmatrix}
\]

where the government expenditure vector \( g = [g_L \ g_M \ g_H] \) where \( g_L < g_M < g_H \).
We set $b_0 = 1$ and assume that the initial Markov state is state 1 so that the system starts off in peace.

These parameters have government expenditure beginning at a low level, surging during the war, then decreasing after the war to a level that exceeds its prewar level.

(This type of pattern occurred in the US Civil War and World War I experiences.)

In [10]:
```python
g_ex1 = [g_L, g_H, g_M]
P_ex1 = np.array([[1-λ, λ, 0],
                  [0, 1-ϕ, ϕ],
                  [0, 0, 1]])
b0_ex1 = 1
states_ex1 = ['peace', 'war', 'postwar']
```

In [11]:
```python
ts_ex1 = TaxSmoothingExample(g_ex1, P_ex1, b0_ex1, states_ex1,
                      random_state=1)
ts_ex1.display()
```
CHAPTER 7. TAX SMOOTHING WITH COMPLETE AND INCOMPLETE MARKETS

Government debt paths

Cumulative return path (complete markets)

\[ P = \begin{bmatrix} 0.9 & 0.1 & 0. \\ 0. & 0.9 & 0.1 \\ 0. & 0. & 1. \end{bmatrix} \]

\[ Q = \begin{bmatrix} 0 \end{bmatrix} \]
Govt expenditures in peace, war, postwar = [0.5 1.2 0.8]
Constant tax collections = 0.7548096885813149
Govt debt in 3 states = [-1. -4.07093426 -1.12975779]

Government tax collections minus debt levels in peace, war, postwar
T+b in peace = 1.754809688581315
T+b in war = 4.825743944636679
T+b in postwar = 1.8845674740484437

Total government spending in peace, war, postwar
peace = 1.754809688581315
war = 4.825743944636679
postwar = 1.8845674740484437

Let's see ex-post and ex-ante returns on Arrow securities

Ex-post returns to purchase of Arrow securities:
\[ \pi(\text{peace}|\text{peace}) = 1.1574074074074074 \]
\[ \pi(\text{war}|\text{peace}) = 10.41666666666666 \]
\[ \pi(\text{war}|\text{war}) = 1.1574074074074074 \]
\[ \pi(\text{postwar}|\text{war}) = 10.41666666666666 \]
\[ \pi(\text{postwar}|\text{postwar}) = 1.0416666666666667 \]

Ex-ante returns to purchase of Arrow securities = 1.0416666666666667

The Ex-post one-period gross return on the portfolio of government assets
[[0.7999336 3.24426428 0. ]
[0. 1.2278992 0.31159337]
[0. 0. 1.0416667]]

The cumulative return earned from holding 1 unit market portfolio of government bonds
0.17908622141460384

In [12]: # The following shows the use of the wrapper class when a specific state path is given

s_path = [0, 0, 1, 1, 2]
ts_s_path = TaxSmoothingExample(g_ex1, P_ex1, b0_ex1, states_ex1, s_path=s_path)
ts_s_path.display()
7.5. **MORE FINITE MARKOV CHAIN TAX-SMOOTHING EXAMPLES**

\[ P \]
\[
\begin{bmatrix}
0.9 & 0.1 & 0. \\
0. & 0.9 & 0.1 \\
0. & 0. & 1. \\
\end{bmatrix}
\]

\[ Q \]
\[
\begin{bmatrix}
0.864 & 0.096 & 0. \\
0. & 0.864 & 0.096 \\
0. & 0. & 0.96 \\
\end{bmatrix}
\]

Govt expenditures in peace, war, postwar = \([0.5 \ 1.2 \ 0.8]\)

Constant tax collections = 0.7548096885813149

Govt debt in 3 states = \([-1. \ -4.07093426 \ -1.12975779]\)

Government tax collections minus debt levels in peace, war, postwar
- \(T+b\) in peace = 1.754809688581315
- \(T+b\) in war = 4.825743944636679
- \(T+b\) in postwar = 1.8845674740484437

Total government spending in peace, war, postwar
- peace = 1.754809688581315
- war = 4.825743944636679
- postwar = 1.8845674740484437

Let’s see ex-post and ex-ante returns on Arrow securities

Ex-post returns to purchase of Arrow securities:
- \(\pi(peace|peace) = 1.1574074074074074\)
- \(\pi(war|peace) = 10.416666666666666\)
- \(\pi(war|war) = 1.1574074074074074\)
- \(\pi(postwar|war) = 10.416666666666666\)
- \(\pi(postwar|postwar) = 1.0416666666666667\)

Ex-ante returns to purchase of Arrow securities = 1.0416666666666667

The Ex-post one-period gross return on the portfolio of government assets
\[
\begin{bmatrix}
0.7969336 & 3.24426428 & 0. \\
\end{bmatrix}
\]
CHAPTER 7. TAX SMOOTHING WITH COMPLETE AND INCOMPLETE MARKETS

The cumulative return earned from holding 1 unit market portfolio of government bonds

7.5.3 Example 2

This example captures a peace followed by a war, eventually followed by a permanent peace. Here we set

\[
P = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 - \gamma & \gamma \\
\phi & 0 & 1 - \phi
\end{bmatrix}
\]

where the government expenditure vector \( g = [g_L, g_L, g_H] \) and where \( g_L < g_H \).

We assume \( b_0 = 1 \) and that the initial Markov state is state 2 so that the system starts off in a temporary peace.

In [13]:

\[
g_{\text{ex2}} = [g_L, g_L, g_H] \\
P_{\text{ex2}} = \text{np.array([}[1, 0, 0], \\
[0, 1 - \gamma, \gamma], \\
[\phi, 0, 1 - \phi]])
\]

\[b_{0_{\text{ex2}}} = 1\]

\[\text{states}_{\text{ex2}} = [\text{'peace'}, \text{'temporary peace'}, \text{'war'}]\]

In [14]:

\[\text{ts}_{\text{ex2}} = \text{TaxSmoothingExample}(g_{\text{ex2}}, P_{\text{ex2}}, b_{0_{\text{ex2}}}, \text{states}_{\text{ex2}}, \text{init}=1, \text{random_state}=1)\]

\[\text{ts}_{\text{ex2}}.\text{display()}\]
7.5. MORE FINITE MARKOV CHAIN TAX-SMOOTHING EXAMPLES

\[
\begin{bmatrix}
1 & 0 & 0
\end{bmatrix}
\]
Govt expenditures in peace, temporary peace, war = \([0.5 \ 0.5 \ 1.2]\)
Constant tax collections = 0.6053287197231834
Govt debt in 3 states = \([-2.63321799 \ -1. \ -2.51384083]\)

Government tax collections minus debt levels in peace, temporary peace, war
\(T+b\) in peace = -2.027889273356399
\(T+b\) in temporary peace = 1.6053287197231834
\(T+b\) in war = 3.1191695501730106

Total government spending in peace, temporary peace, war
peace = -2.027889273356399
temporary peace = 1.6053287197231834
war = 3.119169550173011

Let's see ex-post and ex-ante returns on Arrow securities

Ex-post returns to purchase of Arrow securities:
\(\pi(\text{peace}|\text{peace}) = 1.0416666666666667\)
\(\pi(\text{temporary peace}|\text{temporary peace}) = 1.1574074074074074\)
\(\pi(\text{war}|\text{temporary peace}) = 10.416666666666666\)
\(\pi(\text{peace}|\text{war}) = 10.416666666666666\)
\(\pi(\text{war}|\text{war}) = 1.1574074074074074\)

Ex-ante returns to purchase of Arrow securities = 1.0416666666666667

The Ex-post one-period gross return on the portfolio of government assets
\[
\begin{bmatrix}
1.04166667 & 0. & 0. \\
0. & 0.90470824 & 2.27429251 \\
-1.37206116 & 0. & 1.30985865
\end{bmatrix}
\]

The cumulative return earned from holding 1 unit market portfolio of government bonds
-9.3689917325942

### 7.5.4 Example 3

This example features a situation in which one of the states is a war state with no hope of peace next period, while another state is a war state with a positive probability of peace next period.

The Markov chain is:

\[
P = \begin{bmatrix}
1 - \lambda & \lambda & 0 & 0 \\
0 & 1 - \phi & \phi & 0 \\
0 & 0 & 1 - \psi & \psi \\
\theta & 0 & 0 & 1 - \theta
\end{bmatrix}
\]

with government expenditure levels for the four states being \([g_L \ g_L \ g_H \ g_H]\) where \(g_L < g_H\).

We start with \(b_0 = 1\) and \(s_0 = 1\).

In [15]: g_ex3 = [g_L, g_L, g_H, g_H]
In [16]: ts_ex3 = TaxSmoothingExample(g_ex3, P_ex3, b0_ex3, states_ex3, random_state=1)
    ts_ex3.display()
7.5. MORE FINITE MARKOV CHAIN TAX-SMOOTHING EXAMPLES

\[ Q = \begin{bmatrix}
0.864 & 0.096 & 0 & 0 \\
0.096 & 0.864 & 0.096 & 0 \\
0 & 0.096 & 0.864 & 0.096 \\
0.096 & 0. & 0. & 0.864
\end{bmatrix} \]

Govt expenditures in peace1, peace2, war1, war2 = [0.5 0.5 1.2 1.2]

Constant tax collections = \(0.6927944572748268\)

Govt debt in 4 states = [-1. -3.42494226 -6.86027714 -4.43533487]

Government tax collections minus debt levels in peace1, peace2, war1, war2

\[ T+b \text{ in peace1} = 1.6927944572748268 \]
\[ T+b \text{ in peace2} = 4.117736720554273 \]
\[ T+b \text{ in war1} = 7.5530971593533488 \]
\[ T+b \text{ in war2} = 5.1281293302540405 \]

Total government spending in peace1, peace2, war1, war2

\[ \text{peace1} = 1.6927944572748268 \]
\[ \text{peace2} = 4.117736720554273 \]
\[ \text{war1} = 7.5530971593533488 \]
\[ \text{war2} = 5.1281293302540405 \]

Let's see ex-post and ex-ante returns on Arrow securities

Ex-post returns to purchase of Arrow securities:

\[ \pi(\text{peace1}|\text{peace1}) = 1.1574074074074074 \]
\[ \pi(\text{peace2}|\text{peace1}) = 10.416666666666666 \]
\[ \pi(\text{peace2}|\text{peace2}) = 1.1574074074074074 \]
\[ \pi(\text{war1}|\text{peace2}) = 10.416666666666666 \]
\[ \pi(\text{war1}|\text{war1}) = 1.1574074074074074 \]
\[ \pi(\text{war2}|\text{war1}) = 10.416666666666666 \]
\[ \pi(\text{peace1}|\text{war2}) = 10.416666666666666 \]
\[ \pi(\text{war2}|\text{war2}) = 1.1574074074074074 \]

Ex-ante returns to purchase of Arrow securities = 1.0416666666666667

The Ex-post one-period gross return on the portfolio of government assets

\[ \begin{bmatrix}
0.83836741 & 2.87135998 & 0 & 0 \\
0 & 0.94670854 & 1.89628977 & 0 \\
0 & 0 & 1.07983627 & 0.69814023 \\
0.2545741 & 0 & 0 & 1.1291214
\end{bmatrix} \]

The cumulative return earned from holding 1 unit market portfolio of government bonds 0.02371440178864223

7.5.5 Example 4

Here the Markov chain is:

\[ P = \begin{bmatrix}
1 - \lambda & \lambda & 0 & 0 & 0 \\
0 & 1 - \phi & \phi & 0 & 0 \\
0 & 0 & 1 - \psi & \psi & 0 \\
0 & 0 & 0 & 1 - \theta & \theta \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \]

with government expenditure levels for the five states being \([g_L \ g_L \ g_H \ g_H \ g_L]\) where \(g_L < g_H\).

We assume that \(b_0 = 1\) and \(s_0 = 1\).
In [17]:
g_ex4 = [g_L, g_L, g_H, g_H, g_L]
P_ex4 = np.array([[1-\lambda, \lambda, 0, 0, 0],
                 [0, 1-\phi, \phi, 0, 0],
                 [0, 0, 1-\psi, \psi, 0],
                 [0, 0, 0, 1-\theta, \theta],
                 [0, 0, 0, 0, 1]])
b0_ex4 = 1
states_ex4 = ['peace1', 'peace2', 'war1', 'war2', 'permanent peace']

In [18]:
ts_ex4 = TaxSmoothingExample(g_ex4, P_ex4, b0_ex4, states_ex4, random_state=1)
ts_ex4.display()
7.5. MORE FINITE MARKOV CHAIN TAX-SMOOTHING EXAMPLES

\[
P = \begin{bmatrix}
0.9 & 0.1 & 0. & 0. & 0. \\
0. & 0.9 & 0.1 & 0. & 0. \\
0. & 0. & 0.9 & 0.1 & 0. \\
0. & 0. & 0. & 0.9 & 0.1 \\
0. & 0. & 0. & 0. & 0.1 \\
\end{bmatrix}
\]
[0. 0. 0. 0. 1. ]

\[
\begin{bmatrix}
0.864 & 0.096 & 0. & 0. & 0. \\
0. & 0.864 & 0.096 & 0. & 0. \\
0. & 0. & 0.864 & 0.096 & 0. \\
0. & 0. & 0. & 0.864 & 0.096 \\
0. & 0. & 0. & 0. & 0.96
\end{bmatrix}
\]

Govt expenditures in peace1, peace2, war1, war2, permanent peace = [0.5 0.5 1.2 1.2 0.5]

Constant tax collections = 0.6349979047185738

Govt debt in 5 states = [-1. -2.82289484 -5.4053292 -1.77211121 3.37494762]

Government tax collections minus debt levels in peace1, peace2, war1, war2, permanent peace

\[T+b\] in peace1 = 1.6349979047185736

\[T+b\] in peace2 = 3.457892745537051

\[T+b\] in war1 = 6.040327103363229

\[T+b\] in war2 = 2.407109110283644

\[T+b\] in permanent peace = -2.739949713245767

Total government spending in peace1, peace2, war1, war2, permanent peace

\[\pi\] (peace1|peace1) = 1.1574074074074074

\[\pi\] (peace2|peace1) = 10.416666666666666

\[\pi\] (peace2|peace2) = 1.1574074074074074

\[\pi\] (war1|peace2) = 10.416666666666666

\[\pi\] (war1|war1) = 1.1574074074074074

\[\pi\] (war2|war1) = 10.416666666666666

\[\pi\] (permanent peace|war2) = 10.416666666666666

\[\pi\] (permanent peace|permanent peace) = 1.0416666666666667

Ex-ante returns to purchase of Arrow securities = 1.0416666666666667

The Ex-post one-period gross return on the portfolio of government assets

\[
\begin{bmatrix}
0.8810589 & 2.48713661 & 0. & 0. & 0. \\
0. & 0.95436011 & 1.82742569 & 0. & 0. \\
0. & 0. & 1.11672808 & 0.36611394 & 0. \\
0. & 0. & 0. & 1.46806216 & -2.79589276 \\
0. & 0. & 0. & 0. & 1.04166667
\end{bmatrix}
\]

The cumulative return earned from holding 1 unit market portfolio of government bonds = -11.132109773063592

7.5.6 Example 5

The example captures a case when the system follows a deterministic path from peace to war, and back to peace again.

Since there is no randomness, the outcomes in complete markets setting should be the same as in incomplete markets setting.
The Markov chain is:

\[
P = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

with government expenditure levels for the seven states being
\([g_L \ g_L \ g_H \ g_H \ g_H \ g_H \ g_L] \) where \(g_L < g_H\). Assume \(b_0 = 1\) and \(s_0 = 1\).

In [19]:

```python
\texttt{g\_ex5 = [g\_L, g\_L, g\_H, g\_H, g\_H, g\_H, g\_L]}
\texttt{P\_ex5 = np.array([[0, 1, 0, 0, 0, 0, 0],}
\texttt{[0, 0, 1, 0, 0, 0, 0],}
\texttt{[0, 0, 0, 1, 0, 0, 0],}
\texttt{[0, 0, 0, 0, 1, 0, 0],}
\texttt{[0, 0, 0, 0, 0, 1, 0],}
\texttt{[0, 0, 0, 0, 0, 0, 1],}
\texttt{[0, 0, 0, 0, 0, 0, 1]])}
\texttt{b0\_ex5 = 1}
\texttt{states\_ex5 = ['peace1', 'peace2', 'war1', 'war2', 'war3', 'permanent\_peace']}
```

In [20]:

```python
\texttt{ts\_ex5 = TaxSmoothingExample(g\_ex5, P\_ex5, b0\_ex5, states\_ex5, N\_simul=7,}
\texttt{random\_state=1)}
\texttt{ts\_ex5.display()}
```
CHAPTER 7. TAX SMOOTHING WITH COMPLETE AND INCOMPLETE MARKETS

\[
P = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}
\]
7.5. MORE FINITE MARKOV CHAIN TAX-SMOOTHING EXAMPLES

\[
Q = \begin{bmatrix}
0 & 0.96 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.96 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.96 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.96 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.96 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.96 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.96 \\
\end{bmatrix}
\]

Govt expenditures in peace1, peace2, war1, war2, war3, permanent peace = [0.5 0.5 1.2 1.2 1.2 0.5]
Constant tax collections = 0.5571895472128002
Govt debt in 6 states = [-1. -1.10123911 -1.20669652 -0.58738132 0.05773868 0.72973868 1.42973868]

Government tax collections minus debt levels in peace1, peace2, war1, war2, war3, permanent peace

\[
T+b \text{ in peace1} = 1.5571895472128001 \\
T+b \text{ in peace2} = 1.6584286588928006 \\
T+b \text{ in war1} = 1.7638860668928005 \\
T+b \text{ in war2} = 1.1445708668928007 \\
T+b \text{ in war3} = 0.4994508668928011 \\
T+b \text{ in permanent peace} = -0.1725491331071991
\]

Total government spending in peace1, peace2, war1, war2, war3, permanent peace

peace1 = 1.5571895472128003 \\
peace2 = 1.6584286588928003 \\
war1 = 1.7638860668928005 \\
war2 = 1.1445708668928007 \\
war3 = 0.4994508668928006 \\
permanent peace = -0.17254913310719933

Let's see ex-post and ex-ante returns on Arrow securities

Ex-post returns to purchase of Arrow securities:

\[
\pi(\text{peace2}|\text{peace1}) = 1.0416666666666667 \\
\pi(\text{war1}|\text{peace2}) = 1.0416666666666667 \\
\pi(\text{war2}|\text{war1}) = 1.0416666666666667 \\
\pi(\text{war3}|\text{war2}) = 1.0416666666666667 \\
\pi(\text{permanent peace}|\text{war3}) = 1.0416666666666667
\]

Ex-ante returns to purchase of Arrow securities = 1.0416666666666667

The Ex-post one-period gross return on the portfolio of government assets

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 1.04166667 \\
0 & 0 & 0 & 0 & 0 & 0. \\
0 & 0 & 0 & 0 & 0 & 1.04166667 \\
0 & 0 & 0 & 0 & 0 & 0. \\
0 & 0 & 0 & 0 & 0 & 0. \\
0 & 0 & 0 & 0 & 0 & 0. \\
0 & 0 & 0 & 0 & 0 & 0. \\
\end{bmatrix}
\]

The cumulative return earned from holding 1 unit market portfolio of government bonds
7.5.7 Continuous-State Gaussian Model

To construct a tax-smoothing version of the complete markets consumption-smoothing model with a continuous state space that we presented in the lecture consumption smoothing with complete and incomplete markets, we simply relabel variables.

Thus, a government faces a sequence of budget constraints

$$T_t + b_t = g_t + \beta \mathbb{E}_t b_{t+1}, \quad t \geq 0$$

where $T_t$ is tax revenues, $b_t$ are receipts at $t$ from contingent claims that the government had purchased at time $t - 1$, and

$$\beta \mathbb{E}_t b_{t+1} \equiv \int q_{t+1}(x_{t+1}|x_t)b_{t+1}(x_{t+1})dx_{t+1}$$

is the value of time $t+1$ state-contingent claims purchased by the government at time $t$.

As above with the consumption-smoothing model, we can solve the time $t$ budget constraint forward to obtain

$$b_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j (g_{t+j} - T_{t+j})$$

which can be rearranged to become

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j g_{t+j} = b_t + \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j T_{t+j}$$

which states that the present value of government purchases equals the value of government assets at $t$ plus the present value of tax receipts.

With these relabelings, examples presented in consumption smoothing with complete and incomplete markets can be interpreted as tax-smoothing models.

**Returns:** In the continuous state version of our incomplete markets model, the ex post one-period gross rate of return on the government portfolio equals

$$R(x_{t+1}|x_t) = \frac{b(x_{t+1})}{\beta \mathbb{E} b(x_{t+1})|x_t}$$

**Related Lectures**

Throughout this lecture, we have taken one-period interest rates and Arrow security prices as exogenous objects determined outside the model and specified them in ways designed to align our models closely with the consumption smoothing model of Barro [7].
Other lectures make these objects endogenous and describe how a government optimally manipulates prices of government debt, albeit indirectly via effects distorting taxes have on equilibrium prices and allocations.

In optimal taxation in an LQ economy and recursive optimal taxation, we study complete-markets models in which the government recognizes that it can manipulate Arrow securities prices.

Linear-quadratic versions of the Lucas-Stokey tax-smoothing model are described in Optimal Taxation in an LQ Economy.

That lecture is a warm-up for the non-linear-quadratic model of tax smoothing described in Optimal Taxation with State-Contingent Debt.

In both Optimal Taxation in an LQ Economy and Optimal Taxation with State-Contingent Debt, the government recognizes that its decisions affect prices.

In optimal taxation with incomplete markets, we study an incomplete-markets model in which the government also manipulates prices of government debt.
Chapter 8

Robustness

8.1 Contents

- Overview 8.2
- The Model 8.3
- Constructing More Robust Policies 8.4
- Robustness as Outcome of a Two-Person Zero-Sum Game 8.5
- The Stochastic Case 8.6
- Implementation 8.7
- Application 8.8
- Appendix 8.9

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

8.2 Overview

This lecture modifies a Bellman equation to express a decision-maker’s doubts about transition dynamics.

His specification doubts make the decision-maker want a robust decision rule.

Robust means insensitive to misspecification of transition dynamics.

The decision-maker has a single approximating model.

He calls it approximating to acknowledge that he doesn’t completely trust it.

He fears that outcomes will actually be determined by another model that he cannot describe explicitly.

All that he knows is that the actual data-generating model is in some (uncountable) set of models that surrounds his approximating model.

He quantifies the discrepancy between his approximating model and the genuine data-generating model by using a quantity called entropy.

(We’ll explain what entropy means below)

He wants a decision rule that will work well enough no matter which of those other models
actually governs outcomes.

This is what it means for his decision rule to be “robust to misspecification of an approximating model”.

This may sound like too much to ask for, but ... a secret weapon is available to design robust decision rules.

The secret weapon is max-min control theory.

A value-maximizing decision-maker enlists the aid of an (imaginary) value-minimizing model chooser to construct bounds on the value attained by a given decision rule under different models of the transition dynamics.

The original decision-maker uses those bounds to construct a decision rule with an assured performance level, no matter which model actually governs outcomes.

**Note**

In reading this lecture, please don’t think that our decision-maker is paranoid when he conducts a worst-case analysis. By designing a rule that works well against a worst-case, his intention is to construct a rule that will work well across a set of models.

Let’s start with some imports:

```python
In [2]: import pandas as pd
import numpy as np
from scipy.linalg import eig
import matplotlib.pyplot as plt
%matplotlib inline
import quantecon as qe
```

### 8.2.1 Sets of Models Imply Sets Of Values

Our “robust” decision-maker wants to know how well a given rule will work when he does not know a single transition law ....

... he wants to know sets of values that will be attained by a given decision rule $F$ under a set of transition laws.

Ultimately, he wants to design a decision rule $F$ that shapes these sets of values in ways that he prefers.

With this in mind, consider the following graph, which relates to a particular decision problem to be explained below
The figure shows a value-entropy correspondence for a particular decision rule $F$.

The shaded set is the graph of the correspondence, which maps entropy to a set of values associated with a set of models that surround the decision-maker’s approximating model.

Here

- *Value* refers to a sum of discounted rewards obtained by applying the decision rule $F$ when the state starts at some fixed initial state $x_0$.
- *Entropy* is a non-negative number that measures the size of a set of models surrounding the decision-maker’s approximating model.
  - Entropy is zero when the set includes only the approximating model, indicating that the decision-maker completely trusts the approximating model.
  - Entropy is bigger, and the set of surrounding models is bigger, the less the decision-maker trusts the approximating model.

The shaded region indicates that for all models having entropy less than or equal to the number on the horizontal axis, the value obtained will be somewhere within the indicated set of values.

Now let’s compare sets of values associated with two different decision rules, $F_r$ and $F_b$.

In the next figure,

- The red set shows the value-entropy correspondence for decision rule $F_r$.
- The blue set shows the value-entropy correspondence for decision rule $F_b$. 
The blue correspondence is skinnier than the red correspondence.

This conveys the sense in which the decision rule $F_b$ is more robust than the decision rule $F_r$

- more robust means that the set of values is less sensitive to increasing misspecification as measured by entropy

Notice that the less robust rule $F_r$ promises higher values for small misspecifications (small entropy).

(But it is more fragile in the sense that it is more sensitive to perturbations of the approximating model)

Below we’ll explain in detail how to construct these sets of values for a given $F$, but for now....

Here is a hint about the secret weapons we’ll use to construct these sets

- We’ll use some min problems to construct the lower bounds
- We’ll use some max problems to construct the upper bounds

We will also describe how to choose $F$ to shape the sets of values.

This will involve crafting a skinnier set at the cost of a lower level (at least for low values of entropy).

### 8.2.2 Inspiring Video

If you want to understand more about why one serious quantitative researcher is interested in this approach, we recommend Lars Peter Hansen’s Nobel lecture.
8.3. THE MODEL

8.2.3 Other References

Our discussion in this lecture is based on

- [28]
- [26]

8.3 The Model

For simplicity, we present ideas in the context of a class of problems with linear transition laws and quadratic objective functions.

To fit in with our earlier lecture on LQ control, we will treat loss minimization rather than value maximization.

To begin, recall the infinite horizon LQ problem, where an agent chooses a sequence of controls \( \{u_t\} \) to minimize

\[
\sum_{t=0}^{\infty} \beta^t \{x_t'Rx_t + u_t'Qu_t\}
\]

subject to the linear law of motion

\[
x_{t+1} = Ax_t + Bu_t + Cw_{t+1}, \quad t = 0, 1, 2, \ldots
\]

As before,

- \( x_t \) is \( n \times 1 \), \( A \) is \( n \times n \)
- \( u_t \) is \( k \times 1 \), \( B \) is \( n \times k \)
- \( w_t \) is \( j \times 1 \), \( C \) is \( n \times j \)
- \( R \) is \( n \times n \) and \( Q \) is \( k \times k \)

Here \( x_t \) is the state, \( u_t \) is the control, and \( w_t \) is a shock vector.

For now, we take \( \{w_t\} := \{w_t\}_{t=1}^{\infty} \) to be deterministic — a single fixed sequence.

We also allow for model uncertainty on the part of the agent solving this optimization problem.

In particular, the agent takes \( w_t = 0 \) for all \( t \geq 0 \) as a benchmark model but admits the possibility that this model might be wrong.

As a consequence, she also considers a set of alternative models expressed in terms of sequences \( \{w_t\} \) that are “close” to the zero sequence.

She seeks a policy that will do well enough for a set of alternative models whose members are pinned down by sequences \( \{w_t\} \).

Soon we’ll quantify the quality of a model specification in terms of the maximal size of the expression \( \sum_{t=0}^{\infty} \beta^{t+1}w_{t+1}'w_{t+1} \).
8.4 Constructing More Robust Policies

If our agent takes \( \{w_t\} \) as a given deterministic sequence, then, drawing on intuition from earlier lectures on dynamic programming, we can anticipate Bellman equations such as

\[
J_{t-1}(x) = \min_u \{x'R + u'Q + \beta J_t(Ax + Bu + Cw_t)\}
\]

(Here \( J \) depends on \( t \) because the sequence \( \{w_t\} \) is not recursive)

Our tool for studying robustness is to construct a rule that works well even if an adverse sequence \( \{w_t\} \) occurs.

In our framework, “adverse” means “loss increasing”.

As we’ll see, this will eventually lead us to construct the Bellman equation

\[
J(x) = \min_u \max_w \{x'R + u'Q + \beta [J(Ax + Bu + Cw) - \theta w'w]\}
\]

Notice that we’ve added the penalty term \(-\theta w'w\).

Since \( w'w = \|w\|^2 \), this term becomes influential when \( w \) moves away from the origin.

The penalty parameter \( \theta \) controls how much we penalize the maximizing agent for “harming” the minimizing agent.

By raising \( \theta \) more and more, we more and more limit the ability of maximizing agent to distort outcomes relative to the approximating model.

So bigger \( \theta \) is implicitly associated with smaller distortion sequences \( \{w_t\} \).

8.4.1 Analyzing the Bellman Equation

So what does \( J \) in (3) look like?

As with the ordinary LQ control model, \( J \) takes the form \( J(x) = x'Px \) for some symmetric positive definite matrix \( P \).

One of our main tasks will be to analyze and compute the matrix \( P \).

Related tasks will be to study associated feedback rules for \( u_t \) and \( w_{t+1} \).

First, using matrix calculus, you will be able to verify that

\[
\max_w \{(Ax + Bu + Cw)'P(Ax + Bu + Cw) - \theta w'w\} = (Ax + Bu)'\mathcal{D}(P)(Ax + Bu)
\]

where

\[
\mathcal{D}(P) := P + PC(\theta I - C'PC)^{-1}C'P
\]

and \( I \) is a \( j \times j \) identity matrix. Substituting this expression for the maximum into (3) yields

\[
x'Px = \min_u \{x'R + u'Q + \beta (Ax + Bu)'\mathcal{D}(P)(Ax + Bu)\}
\]
Using similar mathematics, the solution to this minimization problem is \( u = -Fx \) where 
\[
F := (Q + \beta B'D(P)B)^{-1}\beta B'D(P)A.
\]
Substituting this minimizer back into (6) and working through the algebra gives \( x'Px = x'B(D(P))x \) for all \( x \), or, equivalently,
\[
P = B(D(P))
\]
where \( D \) is the operator defined in (5) and
\[
B(P) := R - \beta^2 A'PB(Q + \beta B'PB)^{-1}B'PA + \beta A'PA
\]
The operator \( B \) is the standard (i.e., non-robust) LQ Bellman operator, and \( P = B(P) \) is the standard matrix Riccati equation coming from the Bellman equation — see this discussion.

Under some regularity conditions (see [26]), the operator \( B \circ D \) has a unique positive definite fixed point, which we denote below by \( \hat{P} \).

A robust policy, indexed by \( \theta \), is \( u = -\hat{F}x \) where
\[
\hat{F} := (Q + \beta B'D(\hat{P})B)^{-1}\beta B'D(\hat{P})A
\]
We also define
\[
\hat{K} := (\theta I - C'\hat{P}C)^{-1}C'\hat{P}(A - B\hat{F})
\]
The interpretation of \( \hat{K} \) is that \( w_{t+1} = \hat{K}x_t \) on the worst-case path of \( \{x_t\} \), in the sense that this vector is the maximizer of (4) evaluated at the fixed rule \( u = -\hat{F}x \).

Note that \( \hat{P}, \hat{F}, \hat{K} \) are all determined by the primitives and \( \theta \).

Note also that if \( \theta \) is very large, then \( D \) is approximately equal to the identity mapping.

Hence, when \( \theta \) is large, \( \hat{P} \) and \( \hat{F} \) are approximately equal to their standard LQ values.

Furthermore, when \( \theta \) is large, \( \hat{K} \) is approximately equal to zero.

Conversely, smaller \( \theta \) is associated with greater fear of model misspecification and greater concern for robustness.

8.5 Robustness as Outcome of a Two-Person Zero-Sum Game

What we have done above can be interpreted in terms of a two-person zero-sum game in which \( \hat{F}, \hat{K} \) are Nash equilibrium objects.

Agent 1 is our original agent, who seeks to minimize loss in the LQ program while admitting the possibility of misspecification.

Agent 2 is an imaginary malevolent player.

Agent 2’s malevolence helps the original agent to compute bounds on his value function across a set of models.

We begin with agent 2’s problem.
8.5.1 Agent 2’s Problem

Agent 2

1. knows a fixed policy $F$ specifying the behavior of agent 1, in the sense that $u_t = -Fx_t$ for all $t$

2. responds by choosing a shock sequence $\{w_t\}$ from a set of paths sufficiently close to the benchmark sequence $\{0, 0, 0, \ldots\}$

A natural way to say “sufficiently close to the zero sequence” is to restrict the summed inner product $\sum_{t=1}^{\infty} w'_t w_t$ to be small.

However, to obtain a time-invariant recursive formulation, it turns out to be convenient to restrict a discounted inner product

$$\sum_{t=1}^{\infty} \beta^t w'_t w_t \leq \eta \quad (9)$$

Now let $F$ be a fixed policy, and let $J_F(x_0, w)$ be the present-value cost of that policy given sequence $w := \{w_t\}$ and initial condition $x_0 \in \mathbb{R}^n$.

Substituting $-Fx_t$ for $u_t$ in (1), this value can be written as

$$J_F(x_0, w) := \sum_{t=0}^{\infty} \beta^t x'_t (R + F'QF)x_t \quad (10)$$

where

$$x_{t+1} = (A - BF)x_t + Cw_{t+1} \quad (11)$$

and the initial condition $x_0$ is as specified in the left side of (10).

Agent 2 chooses $w$ to maximize agent 1’s loss $J_F(x_0, w)$ subject to (9).

Using a Lagrangian formulation, we can express this problem as

$$\max_w \sum_{t=0}^{\infty} \beta^t \{x'_t(R + F'QF)x_t - \beta \theta (w'_{t+1} w_{t+1} - \eta)\}$$

where $\{x_t\}$ satisfied (11) and $\theta$ is a Lagrange multiplier on constraint (9).

For the moment, let’s take $\theta$ as fixed, allowing us to drop the constant $\beta \theta \eta$ term in the objective function, and hence write the problem as

$$\max_w \sum_{t=0}^{\infty} \beta^t \{x'_t(R + F'QF)x_t - \beta w'_{t+1} w_{t+1}\}$$

or, equivalently,

$$\min_w \sum_{t=0}^{\infty} \beta^t \{-x'_t(R + F'QF)x_t + \beta w'_{t+1} w_{t+1}\} \quad (12)$$
subject to (11).

What’s striking about this optimization problem is that it is once again an LQ discounted
dynamic programming problem, with \( w = \{w_t\} \) as the sequence of controls.

The expression for the optimal policy can be found by applying the usual LQ formula (see
here).

We denote it by \( K(F, \theta) \), with the interpretation \( w_{t+1} = K(F, \theta)x_t \).

The remaining step for agent 2’s problem is to set \( \theta \) to enforce the constraint (9), which can
be done by choosing \( \theta = \theta_\eta \) such that

\[
\beta \sum_{t=0}^\infty \beta^t x_t'K(F, \theta_\eta)'K(F, \theta_\eta)x_t = \eta \tag{13}
\]

Here \( x_t \) is given by (11) — which in this case becomes \( x_{t+1} = (A - BF + CK(F, \theta))x_t \).

8.5.2 Using Agent 2’s Problem to Construct Bounds on the Value Sets

The Lower Bound

Define the minimized object on the right side of problem (12) as \( R_\theta(x_0, F) \).

Because “minimizers minimize” we have

\[
R_\theta(x_0, F) \leq \sum_{t=0}^\infty \beta^t \{-x_t'(R + F'QF)x_t\} + \beta \theta \sum_{t=0}^\infty \beta^t w_{t+1}'w_{t+1},
\]

where \( x_{t+1} = (A - BF + CK(F, \theta))x_t \) and \( x_0 \) is a given initial condition.

This inequality in turn implies the inequality

\[
R_\theta(x_0, F) - \theta \, \text{ent} \leq \sum_{t=0}^\infty \beta^t \{-x_t'(R + F'QF)x_t\} \tag{14}
\]

where

\[
\text{ent} := \beta \sum_{t=0}^\infty \beta^t w_{t+1}'w_{t+1}
\]

The left side of inequality (14) is a straight line with slope \(-\theta\).

Technically, it is a “separating hyperplane”.

At a particular value of entropy, the line is tangent to the lower bound of values as a function
of entropy.

In particular, the lower bound on the left side of (14) is attained when

\[
\text{ent} = \beta \sum_{t=0}^\infty \beta^t x_t'K(F, \theta)'K(F, \theta)x_t \tag{15}
\]
To construct the lower bound on the set of values associated with all perturbations $w$ satisfying the entropy constraint (9) at a given entropy level, we proceed as follows:

- For a given $\theta$, solve the minimization problem (12).
- Compute the minimizer $R_{\theta}(x_0, F)$ and the associated entropy using (15).
- Compute the lower bound on the value function $R_{\theta}(x_0, F) - \theta \text{ent}$ and plot it against ent.
- Repeat the preceding three steps for a range of values of $\theta$ to trace out the lower bound.

**Note**

This procedure sweeps out a set of separating hyperplanes indexed by different values for the Lagrange multiplier $\theta$.

**The Upper Bound**

To construct an upper bound we use a very similar procedure. We simply replace the minimization problem (12) with the maximization problem

$$V_{\tilde{\theta}}(x_0, F) = \max_w \sum_{t=0}^{\infty} \beta^t \left\{ -x_t' (R + F'QF)x_t - \beta \tilde{\theta} w_{t+1}'w_{t+1} \right\}$$ (16)

where now $\tilde{\theta} > 0$ penalizes the choice of $w$ with larger entropy.

(Notice that $\tilde{\theta} = -\theta$ in problem (12))

Because “maximizers maximize” we have

$$V_{\tilde{\theta}}(x_0, F) \geq \sum_{t=0}^{\infty} \beta^t \left\{ -x_t'(R + F'QF)x_t \right\} - \beta \tilde{\theta} \sum_{t=0}^{\infty} \beta^t w_{t+1}'w_{t+1}$$

which in turn implies the inequality

$$V_{\tilde{\theta}}(x_0, F) + \tilde{\theta} \text{ent} \geq \sum_{t=0}^{\infty} \beta^t \left\{ -x_t'(R + F'QF)x_t \right\}$$ (17)

where

$$\text{ent} \equiv \beta \sum_{t=0}^{\infty} \beta^t w_{t+1}'w_{t+1}$$

The left side of inequality (17) is a straight line with slope $\tilde{\theta}$.

The upper bound on the left side of (17) is attained when

$$\text{ent} = \beta \sum_{t=0}^{\infty} \beta^t x_t'K(F, \tilde{\theta})'K(F, \tilde{\theta})x_t$$ (18)

To construct the upper bound on the set of values associated all perturbations $w$ with a given entropy we proceed much as we did for the lower bound.
8.5. ROBUSTNESS AS OUTCOME OF A TWO-PERSON ZERO-SUM GAME

- For a given $\tilde{\theta}$, solve the maximization problem (16).
- Compute the maximizer $V_{\tilde{\theta}}(x_0, F)$ and the associated entropy using (18).
- Compute the upper bound on the value function $V_{\tilde{\theta}}(x_0, F) + \tilde{\theta}$ and plot it against ent.
- Repeat the preceding three steps for a range of values of $\tilde{\theta}$ to trace out the upper bound.

Reshaping the Set of Values

Now in the interest of reshaping these sets of values by choosing $F$, we turn to agent 1’s problem.

8.5.3 Agent 1’s Problem

Now we turn to agent 1, who solves

$$\min_{\{u_t\}} \sum_{t=0}^{\infty} \beta^t \{x'_t Rx_t + u'_t Qu_t - \beta \theta w'_{t+1} w_{t+1}\} \quad (19)$$

where $\{w_{t+1}\}$ satisfies $w_{t+1} = K x_t$.

In other words, agent 1 minimizes

$$\sum_{t=0}^{\infty} \beta^t \{x'_t (R - \beta \theta K' K) x_t + u'_t Qu_t\} \quad (20)$$

subject to

$$x_{t+1} = (A + CK)x_t + Bu_t \quad (21)$$

Once again, the expression for the optimal policy can be found here — we denote it by $\tilde{F}$.

8.5.4 Nash Equilibrium

Clearly, the $\tilde{F}$ we have obtained depends on $K$, which, in agent 2’s problem, depended on an initial policy $F$.

Holding all other parameters fixed, we can represent this relationship as a mapping $\Phi$, where

$$\tilde{F} = \Phi(K(F, \theta))$$

The map $F \mapsto \Phi(K(F, \theta))$ corresponds to a situation in which

1. agent 1 uses an arbitrary initial policy $F$
2. agent 2 best responds to agent 1 by choosing $K(F, \theta)$
3. agent 1 best responds to agent 2 by choosing $\tilde{F} = \Phi(K(F, \theta))$
As you may have already guessed, the robust policy $\hat{F}$ defined in (7) is a fixed point of the mapping $\Phi$.

In particular, for any given $\theta$,

1. $K(\hat{F}, \theta) = \hat{K}$, where $\hat{K}$ is as given in (8)
2. $\Phi(\hat{K}) = \hat{F}$

A sketch of the proof is given in the appendix.

8.6 The Stochastic Case

Now we turn to the stochastic case, where the sequence $\{w_t\}$ is treated as an IID sequence of random vectors.

In this setting, we suppose that our agent is uncertain about the conditional probability distribution of $w_{t+1}$.

The agent takes the standard normal distribution $N(0, I)$ as the baseline conditional distribution, while admitting the possibility that other “nearby” distributions prevail.

These alternative conditional distributions of $w_{t+1}$ might depend nonlinearly on the history $x_s, s \leq t$.

To implement this idea, we need a notion of what it means for one distribution to be near another one.

Here we adopt a very useful measure of closeness for distributions known as the relative entropy, or Kullback-Leibler divergence.

For densities $p, q$, the Kullback-Leibler divergence of $q$ from $p$ is defined as

$$D_{KL}(p, q) := \int \ln \left( \frac{p(x)}{q(x)} \right) p(x) \, dx$$

Using this notation, we replace (3) with the stochastic analog

$$J(x) = \min_{u} \max_{\psi \in \mathcal{P}} \left\{ x'Rx + u'Qu + \beta \left[ \int J(Ax + Bu + Cw) \psi(dw) - \theta D_{KL}(\psi, \phi) \right] \right\}$$

Here $\mathcal{P}$ represents the set of all densities on $\mathbb{R}^n$ and $\phi$ is the benchmark distribution $N(0, I)$.

The distribution $\phi$ is chosen as the least desirable conditional distribution in terms of next period outcomes, while taking into account the penalty term $\theta D_{KL}(\psi, \phi)$.

This penalty term plays a role analogous to the one played by the deterministic penalty $\theta w'w$ in (3), since it discourages large deviations from the benchmark.

8.6.1 Solving the Model

The maximization problem in (22) appears highly nontrivial — after all, we are maximizing over an infinite dimensional space consisting of the entire set of densities.
8.6. **THE STOCHASTIC CASE**

However, it turns out that the solution is tractable, and in fact also falls within the class of normal distributions.

First, we note that $J$ has the form $J(x) = x'Px + d$ for some positive definite matrix $P$ and constant real number $d$.

Moreover, it turns out that if $(I - \theta^{-1}C'PC)^{-1}$ is nonsingular, then

$$
\max_{\psi \in \mathcal{P}} \left\{ \int (Ax + Bu + Cw)'P(Ax + Bu + Cw) \psi(dw) - \theta D_{KL}(\psi, \phi) \right\} = (Ax + Bu)'D(P)(Ax + Bu) + \kappa(\theta, P)
$$

where

$$
\kappa(\theta, P) := \theta \ln[\det(I - \theta^{-1}C'PC)^{-1}]
$$

and the maximizer is the Gaussian distribution

$$
\psi = N((\theta I - C'PC)^{-1}C'P(Ax + Bu), (I - \theta^{-1}C'PC)^{-1})
$$

Substituting the expression for the maximum into Bellman equation (22) and using $J(x) = x'Px + d$ gives

$$
x'Px + d = \min_u \{x'Rx + u'Qu + \beta (Ax + Bu)'D(P)(Ax + Bu) + \beta [d + \kappa(\theta, P)]\}
$$

(25)

Since constant terms do not affect minimizers, the solution is the same as (6), leading to

$$
x'Px + d = x'\mathcal{B}(D(P))x + \beta [d + \kappa(\theta, P)]
$$

To solve this Bellman equation, we take $\hat{P}$ to be the positive definite fixed point of $\mathcal{B} \circ \mathcal{D}$.

In addition, we take $\hat{d}$ as the real number solving $d = \beta [d + \kappa(\theta, P)]$, which is

$$
\hat{d} := \frac{\beta}{1 - \beta} \kappa(\theta, P)
$$

(26)

The robust policy in this stochastic case is the minimizer in (25), which is once again $u = -\hat{F}x$ for $\hat{F}$ given by (7).

Substituting the robust policy into (24) we obtain the worst-case shock distribution:

$$
w_{t+1} \sim N(\hat{K}x_t, (I - \theta^{-1}C'\hat{P}C)^{-1})
$$

where $\hat{K}$ is given by (8).

Note that the mean of the worst-case shock distribution is equal to the same worst-case $w_{t+1}$ as in the earlier deterministic setting.

### 8.6.2 Computing Other Quantities

Before turning to implementation, we briefly outline how to compute several other quantities of interest.
Worst-Case Value of a Policy

One thing we will be interested in doing is holding a policy fixed and computing the discounted loss associated with that policy.

So let $F$ be a given policy and let $J_F(x)$ be the associated loss, which, by analogy with (22), satisfies

$$J_F(x) = \max_{\psi \in \mathcal{P}} \left\{ x'(R + F'QF)x + \beta \left[ \int J_F((A - BF)x + Cw) \psi(dw) - \theta D_{KL}(\psi, \phi) \right] \right\}$$

Writing $J_F(x) = x'P_Fx + d_F$ and applying the same argument used to derive (23) we get

$$x'P_Fx + d_F = x'(R + F'QF)x + \beta \left[ x'(A - BF)'D(P_F)(A - BF)x + d_F + \kappa(\theta, P_F) \right]$$

To solve this we take $P_F$ to be the fixed point

$$P_F = R + F'QF + \beta(A - BF)'D(P_F)(A - BF)$$

and

$$d_F := \frac{\beta}{1 - \beta} \kappa(\theta, P_F) = \frac{\beta}{1 - \beta} \theta \ln[\det(I - \theta^{-1}C'P_F C)^{-1}] \quad (27)$$

If you skip ahead to the appendix, you will be able to verify that $-P_F$ is the solution to the Bellman equation in agent 2’s problem discussed above — we use this in our computations.

### 8.7 Implementation

The `QuantEcon.py` package provides a class called `RBLQ` for implementation of robust LQ optimal control.

The code can be found on GitHub.

Here is a brief description of the methods of the class

- `d_operator()` and `b_operator()` implement $D$ and $B$ respectively
- `robust_rule()` and `robust_rule_simple()` both solve for the triple $\hat{F}, \hat{K}, \hat{P}$, as described in equations (7) – (8) and the surrounding discussion
  - `robust_rule()` is more efficient
  - `robust_rule_simple()` is more transparent and easier to follow
- `K_to_F()` and `F_to_K()` solve the decision problems of agent 1 and agent 2 respectively
- `compute_deterministic_entropy()` computes the left-hand side of (13)
- `evaluate_F()` computes the loss and entropy associated with a given policy — see this discussion

### 8.8 Application

Let us consider a monopolist similar to this one, but now facing model uncertainty.
The inverse demand function is

\[ p_t = a_0 - a_1 y_t + d_t. \]

where

\[ d_{t+1} = \rho d_t + \sigma_d w_{t+1}, \quad \{w_t\} \overset{IID}{\sim} N(0, 1) \]

and all parameters are strictly positive.

The period return function for the monopolist is

\[ r_t = p_t y_t - \gamma \frac{(y_{t+1} - y_t)^2}{2} - cy_t \]

Its objective is to maximize expected discounted profits, or, equivalently, to minimize

\[ \mathbb{E} \sum_{t=0}^{\infty} \beta^t (-r_t). \]

To form a linear regulator problem, we take the state and control to be

\[ x_t = \begin{bmatrix} 1 \\ y_t \\ d_t \end{bmatrix} \quad \text{and} \quad u_t = y_{t+1} - y_t \]

Setting \( b := (a_0 - c)/2 \) we define

\[ R = -\begin{bmatrix} 0 & b & 0 \\ b & -a_1 & 1/2 \\ 0 & 1/2 & 0 \end{bmatrix} \quad \text{and} \quad Q = \gamma/2 \]

For the transition matrices, we set

\[ A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \rho \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 \\ 0 \\ \sigma_d \end{bmatrix} \]

Our aim is to compute the value-entropy correspondences shown above.

The parameters are

\[ a_0 = 100, a_1 = 0.5, \rho = 0.9, \sigma_d = 0.05, \beta = 0.95, c = 2, \gamma = 50.0 \]

The standard normal distribution for \( w_t \) is understood as the agent’s baseline, with uncertainty parameterized by \( \theta \).

We compute value-entropy correspondences for two policies

1. The no concern for robustness policy \( F_0 \), which is the ordinary LQ loss minimizer.

2. A “moderate” concern for robustness policy \( F_\theta \), with \( \theta = 0.02 \).

The code for producing the graph shown above, with blue being for the robust policy, is as follows
In [3]: # Model parameters

\[
\begin{align*}
    a_0 &= 100 \\
    a_1 &= 0.5 \\
    \rho &= 0.9 \\
    \sigma_d &= 0.05 \\
    \beta &= 0.95 \\
    c &= 2 \\
    \gamma &= 50.0 \\
    \theta &= 0.002 \\
    ac &= (a_0 - c) / 2.0
\end{align*}
\]

# Define LQ matrices

\[
R = \text{np.array}([\begin{array}{ccc}
0. & ac & 0. \\
ac & -a_1 & 0.5 \\
0. & 0.5 & 0.
\end{array}])
\]

\[
R = -R \quad \# \text{For minimization}
\]

\[
Q = \gamma / 2
\]

\[
A = \text{np.array}([\begin{array}{ccc}
1. & 0. & 0. \\
0. & 1. & 0. \\
0. & 0. & \rho
\end{array}])
\]

\[
B = \text{np.array}([\begin{array}{c}
0. \\
1. \\
0.
\end{array}])
\]

\[
C = \text{np.array}([\begin{array}{c}
0. \\
0. \\
\sigma_d
\end{array}])
\]

# Functions

def evaluate_policy(\theta, F):
    
    """
    Given \theta (scalar, dtype=float) and policy F (array_like), returns the value associated with that policy under the worst case path for \{w_t\}, as well as the entropy level.
    """

    rlq = qe.robustlq.RBLQ(Q, R, A, B, C, \beta, \theta)
    K_F, P_F, d_F, O_F, o_F = rlq.evaluate_F(F)
    x0 = np.array([\begin{array}{c}
1. \\
0. \\
0.
\end{array}])
    value = -x0.T @ P_F @ x0 - d_F
    entropy = x0.T @ O_F @ x0 + o_F
    return list(map(float, (value, entropy)))

def value_and_entropy(ema, F, bw, grid_size=1000):
    
    """
    Compute the value function and entropy levels for a \theta path increasing until it reaches the specified target entropy value.
    """
**Parameters**

- `emax`: scalar
  The target entropy value

- `F`: array_like
  The policy function to be evaluated

- `bw`: str
  A string specifying whether the implied shock path follows best or worst assumptions. The only acceptable values are 'best' and 'worst'.

**Returns**

- `df`: pd.DataFrame
  A pandas DataFrame containing the value function and entropy values up to the `emax` parameter. The columns are 'value' and 'entropy'.

```python
if bw == 'worst':
    θs = 1 / np.linspace(1e-8, 1000, grid_size)
else:
    θs = -1 / np.linspace(1e-8, 1000, grid_size)

df = pd.DataFrame(index=θs, columns=('value', 'entropy'))
for θ in θs:
    df.loc[θ] = evaluate_policy(θ, F)
    if df.loc[θ, 'entropy'] >= emax:
        break

df = df.dropna(how='any')
return df
```

# Compute the optimal rule
optimal_lq = qe.lqcontrol.LQ(Q, R, A, B, C, beta=β)
Po, Fo, do = optimal_lq.stationary_values()

# Compute a robust rule given θ
baseline_robust = qe.robstlq.RBLQ(Q, R, A, B, C, β, θ)
Fb, Kb, Pb = baseline_robust.robust_rule()

# Check the positive definiteness of worst-case covariance matrix to ensure that θ exceeds the breakdown point
test_matrix = np.identity(Pb.shape[0]) - (C.T @ Pb @ C) / θ
eigenvals, eigenvcs = eig(test_matrix)
assert (eigenvals >= θ).all(), 'θ below breakdown point.'
emax = 1.6e6

optimal_best_case = value_and_entropy(emax, Fo, 'best')
robust_best_case = value_and_entropy(emax, Fb, 'best')
optimal_worst_case = value_and_entropy(emax, Fo, 'worst')
robust_worst_case = value_and_entropy(emax, Fb, 'worst')

fig, ax = plt.subplots()
ax.set_xlim(0, emax)
ax.set_ylabel("Value")
ax.set_xlabel("Entropy")
ax.grid()

for axis in 'x', 'y':
    plt.ticklabel_format(style='sci', axis=axis, scilimits=(0, 0))

plot_args = {'lw': 2, 'alpha': 0.7}
colors = 'r', 'b'
df_pairs = ((optimal_best_case, optimal_worst_case),
            (robust_best_case, robust_worst_case))

class Curve:
    def __init__(self, x, y):
        self.x, self.y = x, y
    def __call__(self, z):
        return np.interp(z, self.x, self.y)

for c, df_pair in zip(colors, df_pairs):
    curves = []
    for df in df_pair:
        # Plot curves
        x, y = df['entropy'], df['value']
        x, y = (np.asarray(a, dtype='float') for a in (x, y))
        egrid = np.linspace(0, emax, 100)
        curve = Curve(x, y)
        print(ax.plot(egrid, curve(egrid), color=c, **plot_args))
        curves.append(curve)

    # Color fill between curves
    ax.fill_between(egrid, curves[0](egrid), curves[1](egrid),
                    color=c, alpha=0.1)

plt.show()
Here’s another such figure, with $\theta = 0.002$ instead of 0.02

Can you explain the different shape of the value-entropy correspondence for the robust policy?
We sketch the proof only of the first claim in this section, which is that, for any given $\theta$, $K(\hat{F}, \theta) = \hat{K}$, where $\hat{K}$ is as given in (8).

This is the content of the next lemma.

**Lemma.** If $\hat{P}$ is the fixed point of the map $\mathcal{B} \circ \mathcal{D}$ and $\hat{F}$ is the robust policy as given in (7), then

$$K(\hat{F}, \theta) = (\theta I - C' \hat{P} C)^{-1} C' \hat{P} (A - B \hat{F})$$

(28)

**Proof:** As a first step, observe that when $F = \hat{F}$, the Bellman equation associated with the LQ problem (11) – (12) is

$$\hat{P} = -R - \hat{F}'Q\hat{F} - \beta^2 (A - B \hat{F})' \hat{P} C (\beta \theta I + \beta C' \hat{P} C)^{-1} C' \hat{P} (A - B \hat{F}) + \beta (A - B \hat{F})' \hat{P} (A - B \hat{F})$$

(29)

(revisit this discussion if you don’t know where (29) comes from) and the optimal policy is

$$w_{t+1} = -\beta (\beta \theta I + \beta C' \hat{P} C)^{-1} C' \hat{P} (A - B \hat{F}) x_t$$

Suppose for a moment that $-\hat{P}$ solves the Bellman equation (29).

In this case, the policy becomes

$$w_{t+1} = (\theta I - C' \hat{P} C)^{-1} C' \hat{P} (A - B \hat{F}) x_t$$

which is exactly the claim in (28).

Hence it remains only to show that $-\hat{P}$ solves (29), or, in other words,

$$\hat{P} = R + \hat{F}'Q\hat{F} + \beta (A - B \hat{F})' \hat{P} C (\theta I - C' \hat{P} C)^{-1} C' \hat{P} (A - B \hat{F}) + \beta (A - B \hat{F})' \hat{P} (A - B \hat{F})$$

Using the definition of $\mathcal{D}$, we can rewrite the right-hand side more simply as

$$R + \hat{F}'Q\hat{F} + \beta (A - B \hat{F})' \mathcal{D}(\hat{P})(A - B \hat{F})$$

Although it involves a substantial amount of algebra, it can be shown that the latter is just $\hat{P}$.

(Hint: Use the fact that $\hat{P} = \mathcal{B}(\mathcal{D}(\hat{P}))$)
Chapter 9

Markov Jump Linear Quadratic Dynamic Programming

9.1 Contents

- Overview 9.2
- Review of useful LQ dynamic programming formulas 9.3
- Linked Ricatti equations for Markov LQ dynamic programming 9.4
- Applications 9.5
- Example 1 9.6
- Example 2 9.7
- More examples 9.8

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

9.2 Overview

This lecture describes Markov jump linear quadratic dynamic programming, an extension of the method described in the first LQ control lecture.

Markov jump linear quadratic dynamic programming is described and analyzed in [20] and the references cited there.

The method has been applied to problems in macroeconomics and monetary economics by [65] and [64].

The periodic models of seasonality described in chapter 14 of [31] are a special case of Markov jump linear quadratic problems.

Markov jump linear quadratic dynamic programming combines advantages of

- the computational simplicity of linear quadratic dynamic programming, with
- the ability of finite state Markov chains to represent interesting patterns of random variation.

The idea is to replace the constant matrices that define a linear quadratic dynamic programming problem with $N$ sets of matrices that are fixed functions of the state of an $N$
The state of the Markov chain together with the continuous $n \times 1$ state vector $x_t$ form the state of the system.

For the class of infinite horizon problems being studied in this lecture, we obtain $N$ interrelated matrix Riccati equations that determine $N$ optimal value functions and $N$ linear decision rules.

One of these value functions and one of these decision rules apply in each of the $N$ Markov states.

That is, when the Markov state is in state $j$, the value function and the decision rule for state $j$ prevails.

### 9.3 Review of useful LQ dynamic programming formulas

To begin, it is handy to have the following reminder in mind.

A **linear quadratic dynamic programming problem** consists of a scalar discount factor $eta \in (0, 1)$, an $n \times 1$ state vector $x_t$, an initial condition for $x_0$, a $k \times 1$ control vector $u_t$, a $p \times 1$ random shock vector $w_{t+1}$ and the following two triples of matrices:

- A triple of matrices $(R, Q, W)$ defining a loss function
  
  \[ r(x_t, u_t) = x_t'Rx_t + u_t'Qu_t + 2u_t'Wx_t \]

- A triple of matrices $(A, B, C)$ defining a state-transition law
  
  \[ x_{t+1} = Ax_t + Bu_t + Cw_{t+1} \]

The problem is

\[ -x_0'Px_0 - \rho = \min \left\{ u_t \right\}_{t=0}^{\infty} E \sum_{t=0}^{\infty} \beta^t r(x_t, u_t) \]

subject to the transition law for the state.

The optimal decision rule has the form

\[ u_t = -Fx_t \]

and the optimal value function is of the form

\[ -(x_t'Px_t + \rho) \]

where $P$ solves the algebraic matrix Riccati equation

\[ P = R + \beta A'PA - (\beta B'PA + W)'(Q + \beta BPB)^{-1}(\beta BPB + W) \]

and the constant $\rho$ satisfies
\begin{align*}
\rho &= \beta (\rho + \text{trace}(PCC')) \\
\text{and the matrix } F \text{ in the decision rule for } u_t \text{ satisfies} \\
F &= (Q + \beta B'PB)^{-1}(\beta(B'PA) + W)
\end{align*}

With the preceding formulas in mind, we are ready to approach Markov Jump linear quadratic dynamic programming.

### 9.4 Linked Ricatti equations for Markov LQ dynamic programming

The key idea is to make the matrices \(A, B, C, R, Q, W\) fixed functions of a finite state \(s\) that is governed by an \(N\) state Markov chain.

This makes decision rules depend on the Markov state, and so fluctuate through time in limited ways.

In particular, we use the following extension of a discrete-time linear quadratic dynamic programming problem.

We let \(s_t \in [1, 2, \ldots, N]\) be a time \(t\) realization of an \(N\)-state Markov chain with transition matrix \(\Pi\) having typical element \(\Pi_{ij}\).

Here \(i\) denotes today and \(j\) denotes tomorrow and

\[\Pi_{ij} = \text{Prob}(s_{t+1} = j|s_t = i)\]

We’ll switch between labeling today’s state as \(s_t\) and \(i\) and between labeling tomorrow’s state as \(s_{t+1}\) or \(j\).

The decision-maker solves the minimization problem:

\[
\min_{\{u_t\}} E \sum_{t=0}^{\infty} \beta^t r(x_t, s_t, u_t)
\]

with

\[r(x_t, s_t, u_t) = -(x_t'R_s x_t + u_t'Q_s u_t + 2u_t'W_s x_t)\]

subject to linear laws of motion with matrices \((A, B, C)\) each possibly dependent on the Markov-state-\(s_t\):

\[x_{t+1} = A_{s_t} x_t + B_{s_t} u_t + C_{s_t} w_{t+1}\]

where \(\{w_{t+1}\}\) is an i.i.d. stochastic process with \(w_{t+1} \sim N(0, I)\).

The optimal decision rule for this problem has the form

\[u_t = -F_{s_t} x_t\]
and the optimal value functions are of the form

\[- (x_t' P_{s_t} x_t + \rho_{s_t})\]

or equivalently

\[-x_t' P_i x_t - \rho_i\]

The optimal value functions \(-x'_P x - \rho_i\) for \(i = 1, \ldots, n\) satisfy the \(N\) interrelated Bellman equations

\[-x'_P x - \rho_i = \max_u -\left[ x'R_i x + u'Q_i u + 2u'W_i x - \beta \sum_j \Pi_{ij} E((A_i x + B_i u + C_i w)'P_j (A_i x + B_i u + C_i w)x + \rho_j) \right]\]

The matrices \(P_{s_t} = P_i\) and the scalars \(\rho_{s_t} = \rho_i, i = 1, \ldots, n\) satisfy the following stacked system of algebraic matrix Riccati equations:

\[P_i = R_i + \beta \sum_j A'_i P_j A_i \Pi_{ij} - \sum_j \Pi_{ij}[(\beta B'_i P_j A_i + W_i)'(Q + \beta B'_i P_j B_i)^{-1}(\beta B'_i P_j A_i + W_i)]\]

\[\rho_i = \beta \sum_j \Pi_{ij}(\rho_j + \text{trace}(P_j C_i C'_i))\]

and the \(F_i\) in the optimal decision rules are

\[F_i = (Q_i + \beta \sum_j \Pi_{ij} B'_j P_j B_i)^{-1}(\beta \sum_j \Pi_{ij} (B'_j P_j A_i) + W_i)\]

9.5 Applications

We now describe some Python code and a few examples that put the code to work.

To begin, we import these Python modules

```python
In [2]: import numpy as np
import quantecon as qe
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

%matplotlib inline
```

```python
In [3]: # Set discount factor
β = 0.95
```
9.6 Example 1

This example is a version of a classic problem of optimally adjusting a variable \( k_t \) to a target level in the face of costly adjustment. This provides a model of gradual adjustment.

Given \( k_0 \), the objective function is

\[
\max_{\{k_t\}_{t=1}^\infty} E_0 \sum_{t=0}^\infty \beta^t r(s_t, k_t)
\]

where the one-period payoff function is

\[
r(s_t, k_t) = f_{1,s_t} k_t - f_{2,s_t} k_t^2 - d_{s_t} (k_{t+1} - k_t)^2,
\]

\( E_0 \) is a mathematical expectation conditioned on time 0 information \( x_0, s_0 \) and the transition law for continuous state variable \( k_t \) is

\[
k_{t+1} - k_t = u_t
\]

We can think of \( k_t \) as the decision-maker’s capital and \( u_t \) as costs of adjusting the level of capital.

We assume that \( f_1(s_t) > 0 \), \( f_2(s_t) > 0 \), and \( d(s_t) > 0 \).

Denote the state transition matrix for Markov state \( s_t \in \{1, 2\} \) as \( \Pi \):

\[
\Pr(s_{t+1} = j \mid s_t = i) = \Pi_{ij}
\]

Let \( x_t = \begin{bmatrix} k_t \\ 1 \end{bmatrix} \)

We can represent the one-period payoff function \( r(s_t, k_t) \) and the state-transition law as

\[
r(s_t, k_t) = f_{1,s_t} k_t - f_{2,s_t} k_t^2 - d_{s_t} (k_{t+1} - k_t)^2
\]

\[
x_{t+1} = \begin{bmatrix} k_{t+1} \\ 1 \end{bmatrix} = A(s_t) x_t + B(s_t) u_t
\]

In [4]: def construct_arrays1(f1_vals=[1., 1.],
f2_vals=[1., 1.],
d_vals=[1., 1.]):
    ""
    Construct matrices that map the problem described in example 1 into a Markov jump linear quadratic dynamic programming problem""
# Number of Markov states
m = len(f1_vals)

# Number of state and control variables
n, k = 2, 1

# Construct sets of matrices for each state
As = [np.eye(n) for i in range(m)]
Bs = [np.array([[i, 0]]).T for i in range(m)]

Rs = np.zeros((m, n, n))
Qs = np.zeros((m, k, k))

for i in range(m):
    Rs[i, 0, 0] = f2_vals[i]
    Rs[i, 1, 0] = -f1_vals[i] / 2
    Rs[i, 0, 1] = -f1_vals[i] / 2
    Qs[i, 0, 0] = d_vals[i]

Cs, Ns = None, None

# Compute the optimal k level of the payoff function in each state
k_star = np.empty(m)
for i in range(m):
    k_star[i] = f1_vals[i] / (2 * f2_vals[i])

return Qs, Rs, Ns, As, Bs, Cs, k_star

The continuous part of the state $x_t$ consists of two variables, namely, $k_t$ and a constant term.

In [5]: state_vec1 = ["k", "constant term"]

We start with a Markov transition matrix that makes the Markov state be strictly periodic:

$$
\Pi_1 = \begin{bmatrix}
0 & 1 \\
1 & 0
\end{bmatrix},
$$

We set $f_{1,s_t}$ and $f_{2,s_t}$ to be independent of the Markov state $s_t$

$$f_{1,1} = f_{1,2} = 1,$$

$$f_{2,1} = f_{2,2} = 1$$

In contrast to $f_{1,s_t}$ and $f_{2,s_t}$, we make the adjustment cost $d_{s_t}$ vary across Markov states $s_t$. We set the adjustment cost to be lower in Markov state 2

$$d_1 = 1, d_2 = 0.5$$

The following code forms a Markov switching LQ problem and computes the optimal value functions and optimal decision rules for each Markov state.
9.6. EXAMPLE 1

In [6]: # Construct Markov transition matrix
   \[ \Pi_1 = \text{np.array}([[0., 1.],
                  [1., 0.]]) \]

In [7]: # Construct matrices
   \[ Qs, Rs, Ns, As, Bs, Cs, k\_star = \text{construct\_arrays1}(d\_vals=[1., 0.5]) \]

In [8]: # Construct a Markov Jump LQ problem
   \[ \text{ex1\_a = qe.LQMarkov}(\Pi_1, Qs, Rs, As, Bs, Cs, Ns=Ns, beta=\beta) \]
   \# Solve for optimal value functions and decision rules
   \[ \text{ex1\_a.stationary\_values}(); \]

   Let’s look at the value function matrices and the decision rules for each Markov state

In [9]: # P(s)
   \[ \text{ex1\_a.Ps} \]

Out[9]: array([[ 1.56626026, -0.78313013],
              [-0.78313013, -4.60843493]],
             [[ 1.37424214, -0.68712107],
              [-0.68712107, -4.65643947]])

In [10]: # d(s) = 0, since there is no randomness
   \[ \text{ex1\_a.ds} \]

Out[10]: array([0., 0.])

In [11]: # F(s)
   \[ \text{ex1\_a.Fs} \]

Out[11]: array([[ 0.56626026, -0.28313013],
               [ 0.74848427, -0.37424214]],
              [[ 0.74848427, -0.37424214]])

Now we’ll plot the decision rules and see if they make sense

In [12]: # Plot the optimal decision rules
   \[ \text{k\_grid = np.linspace(0., 1., 100)} \]
   \# Optimal choice in state s1
   \[ u1\_star = - \text{ex1\_a.Fs}[0, 0, 1] - \text{ex1\_a.Fs}[0, 0, 0] \times \text{k\_grid} \]
   \# Optimal choice in state s2
   \[ u2\_star = - \text{ex1\_a.Fs}[1, 0, 1] - \text{ex1\_a.Fs}[1, 0, 0] \times \text{k\_grid} \]

   fig, ax = plt.subplots()
   ax.plot(k\_grid, k\_grid + u1\_star, label="$\overline{s}_1$ (high)"")
   ax.plot(k\_grid, k\_grid + u2\_star, label="$\overline{s}_2$ (low)"")

   \# The optimal k*
   ax.scatter([0.5, 0.5], [0.5, 0.5], marker="*")
   ax.plot([k\_star[0], k\_star[0]], [0., 1.0], ‘--’)

   \# 45 degree line
The above graph plots $k_{t+1} = k_t + u_t = k_t - F x_t$ as an affine (i.e., linear in $k_t$ plus a constant) function of $k_t$ for both Markov states $s_t$.

It also plots the 45 degree line.

Notice that the two $s_t$-dependent closed loop functions that determine $k_{t+1}$ as functions of $k_t$ share the same rest point (also called a fixed point) at $k_t = 0.5$.

Evidently, the optimal decision rule in Markov state 2, in which the adjustment cost is lower, makes $k_{t+1}$ a flatter function of $k_t$ in Markov state 2.

This happens because when $k_t$ is not at its fixed point, $|u_{t,2}| > |u_{t,1}|$, so that the decision-maker adjusts toward the fixed point faster when the Markov state $s_t$ takes a value that makes it cheaper.

In [13]: # Compute time series
T = 20
x0 = np.array([[0., 1.]]).T
x_path = ex1_a.compute_sequence(x0, ts_length=T)[0]

fig, ax = plt.subplots()
ax.plot(range(T), x_path[0, :-1])
ax.set_xlabel("$t\$")
ax.set_ylabel("$k_t\$")
ax.set_title("Optimal path of $k_t$")
plt.show()
Now we’ll depart from the preceding transition matrix that made the Markov state be strictly periodic.

We’ll begin with symmetric transition matrices of the form

$$\Pi_2 = \begin{bmatrix} 1 - \lambda & \lambda \\ \lambda & 1 - \lambda \end{bmatrix}.$$ 

In [14]: \(\lambda = 0.8 \# \text{high } \lambda\)

\(\Pi_2 = \text{np.array}(\begin{bmatrix} [1-\lambda, \lambda], \\
[\lambda, 1-\lambda] \end{bmatrix})\)

\(\text{ex1_b} = \text{qe.LQMarkov(}\Pi_2, \text{Qs, Rs, As, Bs, Cs=Cs, Ns=Ns, beta=β})\)
\(\text{ex1_b.stationary_values()};\)
\(\text{ex1_b.Fs}\)

Out[14]: \([[[ 0.57291724, -0.28645862]],
[ 0.74434525, -0.37217263]])\)

In [15]: \(\lambda = 0.2 \# \text{low } \lambda\)

\(\Pi_2 = \text{np.array}(\begin{bmatrix} [1-\lambda, \lambda], \\
[\lambda, 1-\lambda] \end{bmatrix})\)

\(\text{ex1_b} = \text{qe.LQMarkov(}\Pi_2, \text{Qs, Rs, As, Bs, Cs=Cs, Ns=Ns, beta=β})\)
\(\text{ex1_b.stationary_values()};\)
\(\text{ex1_b.Fs}\)

Out[15]: \([[[ 0.59533259, -0.2976663 ]],
[ 0.72818728, -0.36409364]])\)
We can plot optimal decision rules associated with different $\lambda$ values.

In [16]:
\[
\begin{align*}
\lambda_{\text{vals}} &= \text{np.linspace}(0., 1., 10) \\
F1 &= \text{np.empty}((\lambda_{\text{vals}}.\text{size}, 2)) \\
F2 &= \text{np.empty}((\lambda_{\text{vals}}.\text{size}, 2)) \\
\text{for } i, \lambda \text{ in enumerate}(\lambda_{\text{vals}}): \\
\Pi2 &= \text{np.array}([[1-\lambda, \lambda], \\
\lambda, 1-\lambda]]) \\
ex1_b &= \text{qe.LQMarkov}(\Pi2, Qs, Rs, As, Bs, Cs=Cs, Ns=Ns, beta=\beta) \\
ex1_b.\text{stationary_values}(); \\
F1[i, :] &= ex1_b.\text{Fs}[0, 0, :] \\
F2[i, :] &= ex1_b.\text{Fs}[1, 0, :] 
\end{align*}
\]

In [17]:
\[
\begin{align*}
\text{for } i, \text{state_var in enumerate(state_vec1):} \\
\text{fig, ax = plt.subplots()} \\
ax.\text{plot}(\lambda_{\text{vals}}, F1[:, i], label="$\overline{s}_1$", color="b") \\
ax.\text{plot}(\lambda_{\text{vals}}, F2[:, i], label="$\overline{s}_2$", color="r") \\
ax.\text{set_xlabel}("$\lambda$") \\
ax.\text{set_ylabel}("$F_{s_t}$") \\
ax.\text{set_title}(f"Coefficient on \{\text{state_var}\}") \\
ax.\text{legend}() \\
\text{plt.show()} 
\end{align*}
\]
Notice how the decision rules’ constants and slopes behave as functions of $\lambda$.

Evidently, as the Markov chain becomes more nearly periodic (i.e., as $\lambda \to 1$), the dynamic program adjusts capital faster in the low adjustment cost Markov state to take advantage of what is only temporarily a more favorable time to invest.

Now let’s study situations in which the Markov transition matrix $\Pi$ is asymmetric

$$\Pi_3 = \begin{bmatrix} 1 - \lambda & \lambda \\ \delta & 1 - \delta \end{bmatrix}.$$ 

We can plot optimal decision rules for different $\lambda$ and $\delta$ values.

```python
In [18]: lambda_vals = np.linspace(0., 1., 10)
    delta_vals = np.linspace(0., 1., 10)

    lambda_grid = np.empty((lambda_vals.size, delta_vals.size))
    delta_grid = np.empty((lambda_vals.size, delta_vals.size))
```
F1_grid = np.empty((λ_vals.size, δ_vals.size, len(state_vec1)))
F2_grid = np.empty((λ_vals.size, δ_vals.size, len(state_vec1)))

for i, λ in enumerate(λ_vals):
    λ_grid[i, :] = λ
    δ_grid[i, :] = δ_vals
for j, δ in enumerate(δ_vals):
    Π3 = np.array([[1-λ, λ],
                   [δ, 1-δ]])
    ex1_b = qe.LQMarkov(Π3, Qs, Rs, As, Bs, Cs=Cs, Ns=Ns, beta=β)
    ex1_b.stationary_values();
    F1_grid[i, j, :] = ex1_b.Fs[0, 0, :]
    F2_grid[i, j, :] = ex1_b.Fs[1, 0, :]

In [20]: for i, state_var in enumerate(state_vec1):
    fig = plt.figure()
    ax = fig.add_subplot(111, projection='3d')
    # high adjustment cost, blue surface
    ax.plot_surface(λ_grid, δ_grid, F1_grid[:, :, i], color="b")
    # low adjustment cost, red surface
    ax.plot_surface(λ_grid, δ_grid, F2_grid[:, :, i], color="r")
    ax.set_xlabel("$\lambda$")
    ax.set_ylabel("$\delta$")
    ax.set_zlabel("$F_{s_t}$")
    ax.set_title(f"coefficient on {state_var}")
    plt.show()
The following code defines a wrapper function that computes optimal decision rules for cases with different Markov transition matrices.

```python
In [21]: def run(construct_func, vals_dict, state_vec):
    """
    A Wrapper function that repeats the computation above for different cases
    """
    Qs, Rs, Ns, As, Bs, Cs, k_star = construct_func(**vals_dict)

    # Symmetric II
    # Notice that pure periodic transition is a special case when \( \lambda = 1 \)
    print("symmetric II case:
    \lambda_vals = np.linspace(0., 1., 10)
    F1 = np.empty((\lambda_vals.size, len(state_vec)))
    F2 = np.empty((\lambda_vals.size, len(state_vec)))

    for i, \lambda in enumerate(\lambda_vals):
        II2 = np.array([[1-\lambda, \lambda],
                        [\lambda, 1-\lambda]])

        mplq = qe.LQMarkov(II2, Qs, Rs, As, Bs, Cs=Cs, Ns=Ns, beta=beta)
        mplq.stationary_values();
        F1[i, :] = mplq.Fs[0, 0, :]
        F2[i, :] = mplq.Fs[1, 0, :]

    for i, state_var in enumerate(state_vec):
        fig = plt.figure()
        ax = fig.add_subplot(111)
        ax.plot(\lambda_vals, F1[i, :], label="\overline{s}_1", color="b")
        ax.plot(\lambda_vals, F2[i, :], label="\overline{s}_2", color="r")

        ax.set_xlabel("\lambda")
        ax.set_ylabel("F(\overline{s}_t)")
```
ax.set_title(f"coefficient on {state_var}")
ax.legend()
plt.show()

# Plot optimal k*_{s_t} and k that optimal policies are targeting
# only for example 1
if state_vec == ["k", "constant term"]:
    fig = plt.figure()
    ax = fig.add_subplot(111)
    for i in range(2):
        F = [F1, F2][i]
        c = ["b", "r"][i]
        ax.plot([0, 1], [k_star[i], k_star[i]], "--",
                color=c, label="$k^\lambda(s_{-1})+\lambda(s_{i})$"
        )
        ax.plot(lambda vals, -F[:, 1] / F[:, 0], color=c,
                label="$k^\lambda(s_{-1})+\lambda(s_{i})$"
        )
    ax.set_xlabel("$\lambda$"
    ax.set_ylabel("$\lambda$"
    ax.set_title("Optimal k levels and k targets")
    ax.text(0.5, min(k_star)+(max(k_star)-min(k_star))/20,
            "$\lambda=0.5$"
    )
    ax.legend(bbox_to_anchor=(1., 1.))
    plt.show()

# Asymmetric II
print("asymmetric II case:
")
λ_vals = np.linspace(0., 1., 10)

λ_grid = np.empty((λ_vals.size, δ vals.size))
δ_grid = np.empty((λ_vals.size, δ vals.size))
F1_grid = np.empty((λ_vals.size, δ vals.size, len(state_vec)))
F2_grid = np.empty((λ_vals.size, δ vals.size, len(state_vec)))

for i, λ in enumerate(λ_vals):
    λ_grid[i, :] = λ
    δ_grid[i, :] = δ_vals
for j, δ in enumerate(δ_vals):
    Pi3 = np.array([[1-λ, λ],
                    [δ, 1-δ]])
    mplq = qe.LQMarkov(Pi3, Qs, Rs, As, Bs, Cs=Cs, Ns=Ns, beta=β)
    mplq.stationary_values();
    F1 grid[i, j, :] = mplq.Fs[0, 0, :]
    F2 grid[i, j, :] = mplq.Fs[1, 0, :]

for i, state_var in enumerate(state_vec):
    fig = plt.figure()
    ax = fig.add_subplot(111, projection='3d')
    ax.plot_surface(λ_grid, δ_grid, F1_grid[:, :, i], color="b"
    ax.plot_surface(λ_grid, δ_grid, F2_grid[:, :, i], color="r"
    ax.set_xlabel("$\lambda$"
    ax.set_ylabel("$\delta$"
    ax.set_zlabel("$F(s_{-1})$"
    ax.set_title(f"coefficient on {state_var}"
To illustrate the code with another example, we shall set \( f_{2,s_t} \) and \( d_{s_t} \) as constant functions and

\[
f_{1,1} = 0.5, f_{1,2} = 1
\]

Thus, the sole role of the Markov jump state \( s_t \) is to identify times in which capital is very productive and other times in which it is less productive.

The example below reveals much about the structure of the optimum problem and optimal policies.

Only \( f_{1,s_t} \) varies with \( s_t \).

So there are different \( s_t \)-dependent optimal static \( k \) level in different states \( k^*_s = \frac{f_{1,s_t}}{2f_{2,s_t}} \), values of \( k \) that maximize one-period payoff functions in each state.

We denote a target \( k \) level as \( k^{target}_{s_t} \), the fixed point of the optimal policies in each state, given the value of \( \lambda \).

We call \( k^{target}_{s_t} \) a “target” because in each Markov state \( s_t \), optimal policies are contraction mappings and will push \( k_t \) towards a fixed point \( k^{target}_{s_t} \).

When \( \lambda \to 0 \), each Markov state becomes close to absorbing state and consequently \( k^{target}_{s_t} \to k^*_s \).

But when \( \lambda \to 1 \), the Markov transition matrix becomes more nearly periodic, so the optimum decision rules target more at the optimal \( k \) level in the other state in order to enjoy higher expected payoff in the next period.

The switch happens at \( \lambda = 0.5 \) when both states are equally likely to be reached.

Below we plot an additional figure that shows optimal \( k \) levels in the two states Markov jump state and also how the targeted \( k \) levels change as \( \lambda \) changes.
asymmetric Π case:
Set $f_{1,s}$ and $d_s$ as constant functions and

$$f_{2,1} = 0.5, f_{2,2} = 1$$

In [23]: run(construct_arrays1, {"f2_vals":[0.5, 1.], state_vec1})

symmetric Π case:
9.6. **EXAMPLE 1**

Asymmetric case:

![Graph 1: Coefficient on constant term](image1)

![Graph 2: Optimal k levels and k targets](image2)
9.7 Example 2

We now add to the example 1 setup another state variable $w_t$ that follows the evolution law

$$w_{t+1} = \alpha_0(s_t) + \rho(s_t)w_t + \sigma(s_t)\epsilon_{t+1}, \quad \epsilon_{t+1} \sim N(0, 1)$$

We think of $w_t$ as a rental rate or tax rate that the decision maker pays each period for $k_t$.

To capture this idea, we add to the decision-maker’s one-period payoff function the product of $w_t$ and $k_t$.
\[ r(s_t, k_t, w_t) = f_1(s_t, k_t) - f_2(s_t, k_t^2) - d(s_t)(k_{t+1} - k_t)^2 - w_t k_t, \]

We now let the continuous part of the state at time \( t \) be \( x_t = \begin{bmatrix} k_t \\ w_t \end{bmatrix} \) and continue to set the control \( u_t = k_{t+1} - k_t \).

We can write the one-period payoff function \( r(s_t, k_t, w_t) \) and the state-transition law as

\[
\begin{align*}
r(s_t, k_t, w_t) &= f_1(s_t) k_t - f_2(s_t) k_t^2 - d(s_t)(k_{t+1} - k_t)^2 - w_t k_t \\
&= -\begin{pmatrix} x_t' & -f_1(s_t) \alpha(s_t) \rho(s_t) \end{pmatrix} \begin{pmatrix} f_2(s_t) & - \frac{f_1(s_t)}{2} & \frac{1}{2} \\ -\frac{f_1(s_t)}{2} & 0 & 0 \\ \frac{1}{2} & 0 & 0 \end{pmatrix} \begin{pmatrix} x_t & +d(s_t)u_t^2 \\ \equiv R(s_t) \\ \equiv Q(s_t) \end{pmatrix}
\end{align*}
\]

and

\[
x_{t+1} = \begin{bmatrix} k_{t+1} \\ 1 \\ w_{t+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & \alpha_0(s_t) & \rho(s_t) \end{bmatrix} x_t + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u_t + \begin{bmatrix} 0 \\ 0 \\ \sigma(s_t) \end{bmatrix} \epsilon_{t+1} \equiv A(s_t) + B(s_t) + C(s_t) \epsilon_{t+1}
\]

\[\text{In [24]: def construct_arrays2(f1_vals=[1. , 1.], f2_vals=[1. , 1.], d_vals=[1. , 1.], \alpha_0_vals=[1. , 1.], \rho_vals=[0.9, 0.9], \sigma_vals=[1. , 1.]):}
\]

""
Construct matrices that maps the problem described in example 2 into a Markov jump linear quadratic dynamic programming problem.
""

\[\text{m = len(f1_vals)}
\]\[\text{n, k, j = 3, 1, 1}
\]

\[\text{Rs = np.zeros((m, n, n))}
\]\[\text{Qs = np.zeros((m, k, k))}
\]\[\text{As = np.zeros((m, n, n))}
\]\[\text{Bs = np.zeros((m, n, k))}
\]\[\text{Cs = np.zeros((m, n, j))}
\]

\[\text{for i in range(m):}
\]\[\text{Rs[i, 0, 0] = f2_vals[i]}
\]\[\text{Rs[i, 1, 0] = - f1_vals[i] / 2}
\]\[\text{Rs[i, 0, 1] = - f1_vals[i] / 2}
\]\[\text{Rs[i, 0, 2] = 1/2}
\]\[\text{Rs[i, 2, 0] = 1/2}
\]\[\text{Qs[i, 0, 0] = d_vals[i]}
\]\[\text{As[i, 0, 0] = 1}
As[i, 1, 1] = 1
As[i, 2, 1] = α_vals[i]
As[i, 2, 2] = ρ_vals[i]

Bs[i, :, :] = np.array([[1, 0, 0]]).T
Cs[i, :, :] = np.array([[0, 0, σ_vals[i]]]).T

Ns = None
k_star = None

return Qs, Rs, Ns, As, Bs, Cs, k_star

In [25]: state_vec2 = ['k', 'constant term', 'w']

Only \(d_s\) depends on \(s_t\).

In [26]: run(construct_arrays2, {'d_vals': [1., 0.5]}, state_vec2)

symmetric \(\Pi\) case:
asymmetric II case:
Only $f_{1,s_t}$ depends on $s_t$.

In [27]: run(construct_arrays2, {"f1_vals": [0.5, 1]}, state_vec2)

symmetric II case:
asymmetric Π case:
9.7. EXAMPLE 2
Only $f_{2,s_t}$ depends on $s_t$.

In [28]: run(construct_arrays2, {"f2_vals":[0.5, 1]}, state_vec2)

symmetric II case:
asymmetric Π case:
CHAPTER 9.  MARKOV JUMP LINEAR QUADRATIC DYNAMIC PROGRAMMING
Only $\alpha_0(s_t)$ depends on $s_t$.

In [29]: run(construct_arrays2, {"\alpha0_vals": [0.5, 1]}, state_vec2)

symmetric II case:
asymmetric II case:
9.7. EXAMPLE 2

coefficient on k

coefficient on constant term
Only $\rho_{s_t}$ depends on $s_t$.

In [30]: run(construct_arrays2, {"$\varphi$ _vals": [0.5, 0.9]}, state_vec2)

    symmetric $\Pi$ case:
asymmetric II case:
Only $\sigma_s$, depends on $s_t$.

In [31]: run(construct_arrays2, {"\sigma_vals":[0.5, 1.], state_vec2)

    symmetric II case:
asymmetric II case:
9.8 More examples

The following lectures describe how Markov jump linear quadratic dynamic programming can be used to extend the [7] model of optimal tax-smoothing and government debt in several interesting directions:

1. How to Pay for a War: Part 1
2. How to Pay for a War: Part 2
3. How to Pay for a War: Part 3
Chapter 10

How to Pay for a War: Part 1

10.1 Contents

- Reader’s Guide 10.2
- Public Finance Questions 10.3
- Barro (1979) Model 10.4
- Python Class to Solve Markov Jump Linear Quadratic Control Problems 10.5
- Barro Model with a Time-varying Interest Rate 10.6

In addition to what’s in Anaconda, this lecture will deploy quantecon:

```
In [1]: !pip install --upgrade quantecon
```

10.2 Reader’s Guide

Let’s start with some standard imports:

```
In [2]: import quantecon as qe
   : import numpy as np
   : import matplotlib.pyplot as plt
   : %matplotlib inline
```

This lecture uses the method of Markov jump linear quadratic dynamic programming that is described in lecture Markov Jump LQ dynamic programming to extend the [7] model of optimal tax-smoothing and government debt in a particular direction.

This lecture has two sequels that offer further extensions of the Barro model

1. How to Pay for a War: Part 2
2. How to Pay for a War: Part 3

The extensions are modified versions of his 1979 model later suggested by Barro (1999 [8], 2003 [9]).

Barro’s original 1979 [7] model is about a government that borrows and lends in order to minimize an intertemporal measure of distortions caused by taxes.

Technical tractability induced Barro [7] to assume that

199
• the government trades only one-period risk-free debt, and
• the one-period risk-free interest rate is constant

By using Markov jump linear quadratic dynamic programming we can allow interest rates to move over time in empirically interesting ways.

Also, by expanding the dimension of the state, we can add a maturity composition decision to the government’s problem.

It is by doing these two things that we extend Barro’s 1979 model along lines he suggested in Barro (1999, 2003).

Barro (1979) assumed
• that a government faces an exogenous sequence of expenditures that it must finance by a tax collection sequence whose expected present value equals the initial debt it owes plus the expected present value of those expenditures.
• that the government wants to minimize the following measure of tax distortions: 
  \[ E_0 \sum_{t=0}^{\infty} \beta^t T_t^2, \]
  where \( T_t \) are total tax collections and \( E_0 \) is a mathematical expectation conditioned on time 0 information.
• that the government trades only one asset, a risk-free one-period bond.
• that the gross interest rate on the one-period bond is constant and equal to \( \beta^{-1} \), the reciprocal of the factor \( \beta \) at which the government discounts future tax distortions.

Barro’s model can be mapped into a discounted linear quadratic dynamic programming problem.

Partly inspired by Barro (1999) and Barro (2003), our generalizations of Barro’s (1979) model assume
• that the government borrows or saves in the form of risk-free bonds of maturities \( 1, 2, \ldots, H \).
• that interest rates on those bonds are time-varying and in particular, governed by a jointly stationary stochastic process.

Our generalizations are designed to fit within a generalization of an ordinary linear quadratic dynamic programming problem in which matrices that define the quadratic objective function and the state transition function are time-varying and stochastic.

This generalization, known as a Markov jump linear quadratic dynamic program, combines

• the computational simplicity of linear quadratic dynamic programming, and
• the ability of finite state Markov chains to represent interesting patterns of random variation.

We want the stochastic time variation in the matrices defining the dynamic programming problem to represent variation over time in
• interest rates
• default rates
• roll over risks

As described in Markov Jump LQ dynamic programming, the idea underlying Markov jump linear quadratic dynamic programming is to replace the constant matrices defining a linear quadratic dynamic programming problem with matrices that are fixed functions of an \( N \) state Markov chain.

For infinite horizon problems, this leads to \( N \) interrelated matrix Riccati equations that pin
down $N$ value functions and $N$ linear decision rules, applying to the $N$ Markov states.

10.3 Public Finance Questions

Barro’s 1979 [7] model is designed to answer questions such as

- Should a government finance an exogenous surge in government expenditures by raising taxes or borrowing?
- How does the answer to that first question depend on the exogenous stochastic process for government expenditures, for example, on whether the surge in government expenditures can be expected to be temporary or permanent?

Barro’s 1999 [8] and 2003 [9] models are designed to answer more fine-grained questions such as

- What determines whether a government wants to issue short-term or long-term debt?
- How do roll-over risks affect that decision?
- How does the government’s long-short portfolio management decision depend on features of the exogenous stochastic process for government expenditures?

Thus, both the simple and the more fine-grained versions of Barro’s models are ways of precisely formulating the classic issue of How to pay for a war.

This lecture describes:

- An application of Markov jump LQ dynamic programming to a model in which a government faces exogenous time-varying interest rates for issuing one-period risk-free debt.

A sequel to this lecture describes applies Markov LQ control to settings in which a government issues risk-free debt of different maturities.

10.4 Barro (1979) Model

We begin by solving a version of the Barro (1979) [7] model by mapping it into the original LQ framework.

As mentioned in this lecture, the Barro model is mathematically isomorphic with the LQ permanent income model.

Let $T_t$ denote tax collections, $\beta$ a discount factor, $b_{t,t+1}$ time $t + 1$ goods that the government promises to pay at $t$, $G_t$ government purchases, $p_{t,t+1}$ the number of time $t$ goods received per time $t + 1$ goods promised.

Evidently, $p_{t,t+1}$ is inversely related to appropriate corresponding gross interest rates on government debt.

In the spirit of Barro (1979) [7], the stochastic process of government expenditures is exogenous.

The government’s problem is to choose a plan for taxation and borrowing $\{b_{t+1}, T_t\}_{t=0}^\infty$ to minimize

$$E_0 \sum_{t=0}^\infty \beta^t T_t^2$$
subject to the constraints

\[ T_t + p_{t,t+1} b_{t,t+1} = G_t + b_{t-1,t} \]

\[ G_t = U_2 z_t \]

\[ z_{t+1} = A_{22} z_t + C_2 w_{t+1} \]

where \( w_{t+1} \sim N(0, I) \)

The variables \( T_t, b_{t,t+1} \) are control variables chosen at \( t \), while \( b_{t-1,t} \) is an endogenous state variable inherited from the past at time \( t \) and \( p_{t,t+1} \) is an exogenous state variable at time \( t \).

To begin, we assume that \( p_{t,t+1} \) is constant (and equal to \( \beta \))

- later we will extend the model to allow \( p_{t,t+1} \) to vary over time

To map into the LQ framework, we use \( x_t = \begin{bmatrix} b_{t-1,t} \\ z_t \end{bmatrix} \) as the state vector, and \( u_t = b_{t,t+1} \) as the control variable.

Therefore, the \((A, B, C)\) matrices are defined by the state-transition law:

\[ x_{t+1} = \begin{bmatrix} 0 & 0 \\ 0 & A_{22} \end{bmatrix} x_t + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u_t + \begin{bmatrix} 0 \\ C_2 \end{bmatrix} w_{t+1} \]

To find the appropriate \((R, Q, W)\) matrices, we note that \( G_t \) and \( b_{t-1,t} \) can be written as appropriately defined functions of the current state:

\[ G_t = S_G x_t , \quad b_{t-1,t} = S_1 x_t \]

If we define \( M_t = -p_{t,t+1} \), and let \( S = S_G + S_1 \), then we can write taxation as a function of the states and control using the government’s budget constraint:

\[ T_t = S x_t + M_t u_t \]

It follows that the \((R, Q, W)\) matrices are implicitly defined by:

\[ T_t^2 = x_t' S' S x_t + u_t' M_t' M_t u_t + 2 u_t' M_t' S x_t \]

If we assume that \( p_{t,t+1} = \beta \), then \( M_t \equiv M = -\beta \).

In this case, none of the LQ matrices are time varying, and we can use the original LQ framework.

We will implement this constant interest-rate version first, assuming that \( G_t \) follows an AR(1) process:

\[ G_{t+1} = \bar{G} + \rho G_t + \sigma w_{t+1} \]

To do this, we set \( z_t = \begin{bmatrix} 1 \\ G_t \end{bmatrix} \), and consequently:
\[ A_{22} = \begin{bmatrix} 1 & 0 \\ \bar{G} & \rho \end{bmatrix} \, , \, C_2 = \begin{bmatrix} 0 \\ \sigma \end{bmatrix} \]

In [3]: # Model parameters
\( \beta, \bar{G}, \bar{\rho}, \sigma = 0.95, 5, 0.8, 1 \)

# Basic model matrices
\[
A_{22} = \text{np.array([[1, 0],}
[\bar{G}, \bar{\rho}]],)
\]
\[
C_2 = \text{np.array([[0],}
[\sigma]])
\]
\[
U_g = \text{np.array([[0, 1]])}
\]

# LQ framework matrices
\[
A_t = \text{np.zeros((1, 3))}
\]
\[
A_b = \text{np.hstack((np.zeros((2, 1)), A_{22}))}
\]
\[
A = \text{np.vstack((A_t, A_b))}
\]
\[
B[0, 0] = 1
\]
\[
C = \text{np.vstack((np.zeros((1, 1)), C_2))}
\]
\[
S_g = \text{np.hstack((np.zeros((1, 1)), U_g))}
\]
\[
S_1[0, 0] = 1
\]
\[
S = S_1 + S_g
\]
\[
M = \text{np.array([[\beta]])}
\]
\[
R = S.T @ S
\]
\[
Q = M.T @ M
\]
\[
W = M.T @ S
\]

# Small penalty on the debt required to implement the no-Ponzi scheme
\[
R[0, 0] = R[0, 0] + 1e-9
\]

We can now create an instance of LQ:

In [4]: LQBarro = qe.LQ(Q, R, A, B, C=C, N=W, beta=\beta)
P, F, d = LQBarro.stationary_values()
x0 = np.array([[100, 1, 25]])

We can see the isomorphism by noting that consumption is a martingale in the permanent income model and that taxation is a martingale in Barro’s model.

We can check this using the \( F \) matrix of the LQ model.

Because \( u_t = -Fx_t \), we have

\[
T_t = Sx_t + Mu_t = (S - MF)x_t
\]

and
\[ T_{t+1} = (S - MF)x_{t+1} = (S - MF)(Ax_t + Bu_t + Cw_{t+1}) = (S - MF)((A - BF)x_t + Cw_{t+1}) \]

Therefore, the mathematical expectation of \( T_{t+1} \) conditional on time \( t \) information is

\[ E_t T_{t+1} = (S - MF)(A - BF)x_t \]

Consequently, taxation is a martingale \( (E_t T_{t+1} = T_t) \) if

\[ (S - MF)(A - BF) = (S - MF) \]

which holds in this case:

\[
\begin{align*}
\text{In [5]:} & \quad S - M @ F, (S - M @ F) @ (A - B @ F) \\
\text{Out[5]:} & \quad \text{array([[ 0.05000002, 19.79166502, 0.2083334 ]]), array([[ 0.05000002, 19.79166504, 0.2083334 ]]))}
\end{align*}
\]

This explains the fanning out of the conditional empirical distribution of taxation across time, computing by simulation the Barro model a large number of times:

\[
\begin{align*}
\text{In [6]:} & \quad T = 500 \\
& \quad \text{for } i \text{ in range(250):} \\
& \quad \quad x, u, w = \text{LQBarro.compute_sequence}(x0, ts_length=T) \\
& \quad \quad plt.plot(list(range(T+1)), ((S @ F) @ x)[0, :]) \\
& \quad \quad plt.xlabel('Time') \\
& \quad \quad plt.ylabel('Taxation') \\
& \quad \quad plt.show()
\end{align*}
\]
10.5. PYTHON CLASS TO SOLVE MARKOV JUMP LINEAR QUADRATIC CONTROL PROBLEMS

We can see a similar, but a smoother pattern, if we plot government debt over time.

In [7]: T = 500
   for i in range(250):
       x, u, w = LQBarro.compute_sequence(x0, ts_length=T)
       plt.plot(list(range(T+1)), x[0, :])
   plt.xlabel('Time')
   plt.ylabel('Govt Debt')
   plt.show()

![Graph showing government debt over time](image)

10.5 Python Class to Solve Markov Jump Linear Quadratic Control Problems

To implement the extension to the Barro model in which $p_{t,t+1}$ varies over time, we must allow the $M$ matrix to be time-varying.

Our $Q$ and $W$ matrices must also vary over time.

We can solve such a model using the LQMarkov class that solves Markov jump linear quadratic control problems as described above.

The code for the class can be viewed here.

The class takes lists of matrices that corresponds to $N$ Markov states.

The value and policy functions are then found by iterating on a coupled system of matrix Riccati difference equations.

Optimal $P_s, F_s, d_s$ are stored as attributes.

The class also contains a “method” for simulating the model.
10.6 Barro Model with a Time-varying Interest Rate

We can use the above class to implement a version of the Barro model with a time-varying interest rate. The simplest way to extend the model is to allow the interest rate to take two possible values. We set:

\[ p_{1,t+1} = \beta + 0.02 = 0.97 \]

\[ p_{2,t+1} = \beta - 0.017 = 0.933 \]

Thus, the first Markov state has a low interest rate, and the second Markov state has a high interest rate.

We also need to specify a transition matrix for the Markov state.

We use:

\[
\Pi = \begin{bmatrix} 0.8 & 0.2 \\ 0.2 & 0.8 \end{bmatrix}
\]

(so each Markov state is persistent, and there is an equal chance of moving from one state to the other)

The choice of parameters means that the unconditional expectation of \( p_{t,t+1} \) is 0.9515, higher than \( \beta (= 0.95) \).

If we were to set \( p_{t,t+1} = 0.9515 \) in the version of the model with a constant interest rate, government debt would explode.

In [8]: # Create list of matrices that corresponds to each Markov state
   \[
   \Pi = \text{np.array}([[0.8, 0.2], \\
   [0.2, 0.8]])
   \]

   As = [A, A]
   Bs = [B, B]
   Cs = [C, C]
   Rs = [R, R]

   M1 = np.array([[\( -\beta - 0.02 \)]])
   M2 = np.array([[\( -\beta + 0.017 \)]])

   Q1 = M1.T @ M1
   Q2 = M2.T @ M2
   Qs = [Q1, Q2]
   W1 = M1.T @ S
   W2 = M2.T @ S
   Ws = [W1, W2]

   # create Markov Jump LQ DP problem instance
   lqm = qe.LQMarkov(II, Qs, Rs, As, Bs, Cs=Cs, Ns=Ws, beta=β)
   lqm.stationary_values();

The decision rules are now dependent on the Markov state:
Simulating a large number of such economies over time reveals interesting dynamics. Debt tends to stay low and stable but recurrently surges.

In [11]: `T = 2000`  
   `x0 = np.array([[1000, 1, 25]])`  
   `for i in range(250):`  
      `x, u, w, s = lqm.compute_sequence(x0, ts_length=T)`  
      `plt.plot(list(range(T+1)), x[0, :])`  
   `plt.xlabel('Time')`  
   `plt.ylabel('Govt Debt')`  
   `plt.show()`
Chapter 11

How to Pay for a War: Part 2

11.1 Contents

- An Application of Markov Jump Linear Quadratic Dynamic Programming 11.2
- Two example specifications 11.3
- One- and Two-period Bonds but No Restructuring ??
- Mapping into an LQ Markov Jump Problem 11.5
- Penalty on Different Issuance Across Maturities 11.6
- A Model with Restructuring 11.7
- Restructuring as a Markov Jump Linear Quadratic Control Problem 11.8

In addition to what’s in Anaconda, this lecture deploys the quantecon library:

```
In [1]: !pip install --upgrade quantecon
```

11.2 An Application of Markov Jump Linear Quadratic Dynamic Programming

This is a sequel to an earlier lecture.

We use a method introduced in lecture Markov Jump LQ dynamic programming to implement suggestions by Barro (1999 [8], 2003 [9]) for extending his classic 1979 model of tax smoothing.

Barro’s 1979 [7] model is about a government that borrows and lends in order to help it minimize an intertemporal measure of distortions caused by taxes.


Our generalizations of his 1979 [7] model will also look like souped-up consumption-smoothing models.

Wanting tractability induced Barro in 1979 [7] to assume that

- the government trades only one-period risk-free debt, and
- the one-period risk-free interest rate is constant

In our earlier lecture, we relaxed the second of these assumptions but not the first.

In particular, we used Markov jump linear quadratic dynamic programming to allow the ex-
ogenous interest rate to vary over time.

In this lecture, we add a maturity composition decision to the government’s problem by expanding the dimension of the state.

We assume
- that the government borrows or saves in the form of risk-free bonds of maturities 1, 2, ..., \( H \).
- that interest rates on those bonds are time-varying and in particular are governed by a jointly stationary stochastic process.

Let’s start with some standard imports:

In [2]:
import quantecon as qe
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline

11.3 Two example specifications

We’ll describe two possible specifications

- In one, each period the government issues zero-coupon bonds of one- and two-period maturities and redeems them only when they mature – in this version, the maturity structure of government debt at each date is partly inherited from the past.
- In the second, the government redesigns the maturity structure of the debt each period.

11.4 One- and Two-period Bonds but No Restructuring

Let \( T_t \) denote tax collections, \( \beta \) a discount factor, \( b_{t,t+1} \) time \( t + 1 \) goods that the government promises to pay at time \( t \), \( b_{t,t+2} \) time \( t + 2 \) goods that the government promises to pay at time \( t \), \( G_t \) government purchases, \( p_{t,t+1} \) the number of time \( t \) goods received per time \( t + 1 \) goods promised, and \( p_{t,t+2} \) the number of time \( t \) goods received per time \( t + 2 \) goods promised.

Evidently, \( p_{t,t+1}, p_{t,t+2} \) are inversely related to appropriate corresponding gross interest rates on government debt.

In the spirit of Barro (1979) [7], government expenditures are governed by an exogenous stochastic process.

Given initial conditions \( b_{-2,0}, b_{-1,0}, z_0, i_0 \), where \( i_0 \) is the initial Markov state, the government chooses a contingency plan for \( \{ b_{t,t+1}, b_{t,t+2}, T_t \}_{t=0}^{\infty} \) to maximize.

\[
-E_0 \sum_{t=0}^{\infty} \beta^t \left[ T_t^2 + c_1 (b_{t,t+1} - b_{t,t+2})^2 \right]
\]

subject to the constraints
11.5 Mapping into an LQ Markov Jump Problem

First, define

\[ \hat{b}_t = b_{t-1,t} + b_{t-2,t}, \]

which is debt due at time \( t \).

Then define the endogenous part of the state:

\[ \tilde{b}_t = \begin{bmatrix} \hat{b}_t \\ b_{t-1,t+1} \end{bmatrix} \]

and the complete state

\[ x_t = \begin{bmatrix} \tilde{b}_t \\ z_t \end{bmatrix} \]

and the control vector

\[ u_t = \begin{bmatrix} b_{t,t+1} \\ b_{t,t+2} \end{bmatrix} \]

Here \( w_{t+1} \sim N(0, I) \) and \( \Pi_{ij} \) is the probability that the Markov state moves from state \( i \) to state \( j \) in one period.

The variables \( T_t, b_{t,t+1}, b_{t,t+2} \) are control variables chosen at \( t \), while the variables \( b_{t-1,t}, b_{t-2,t} \) are endogenous state variables inherited from the past at time \( t \) and \( p_{t,t+1}, p_{t,t+2} \) are exogenous state variables at time \( t \).

The parameter \( c_1 \) imposes a penalty on the government’s issuing different quantities of one and two-period debt.

This penalty deters the government from taking large “long-short” positions in debt of different maturities. An example below will show this in action.

As well as extending the model to allow for a maturity decision for government debt, we can also in principle allow the matrices \( U_{g,s_t}, A_{22,s_t}, C_{2,s_t} \) to depend on the Markov state \( s_t \).

Below, we will often adopt the convention that for matrices appearing in a linear state space, \( A_t \equiv A_{s_t}, C_t \equiv C_{s_t} \) and so on, so that dependence on \( t \) is always intermediated through the Markov state \( s_t \).
The endogenous part of state vector follows the law of motion:

\[
\begin{bmatrix}
\hat{b}_{t+1} \\
\hat{b}_{t+2}
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\hat{b}_t \\
\hat{b}_{t-1,t+1}
\end{bmatrix} +
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
b_{t+1} \\
b_{t+2}
\end{bmatrix}
\]

or

\[
\hat{b}_{t+1} = A_1\hat{b}_t + B_1u_t
\]

Define the following functions of the state

\[G_t = S_{G,t}x_t, \quad \hat{b}_t = S_1x_t\]

and

\[M_t = \begin{bmatrix}
-p_{t,t+1} & -p_{t,t+2}
\end{bmatrix}\]

where \(p_{t,t+1}\) is the discount on one period loans in the discrete Markov state at time \(t\) and \(p_{t,t+2}\) is the discount on two-period loans in the discrete Markov state.

Define

\[S_t = S_{G,t} + S_1\]

Note that in discrete Markov state \(i\)

\[T_t = M_tu_t + S_t x_t\]

It follows that

\[T_t^2 = x_t^r S_t^r S_t x_t + u_t^r M_t^r M_t u_t + 2u_t^r M_t^r S_t x_t\]

or

\[T_t^2 = x_t^r R_t x_t + u_t^r Q_t u_t + 2u_t^r W_t x_t\]

where

\[R_t = S_t^r S_t, \quad Q_t = M_t^r M_t, \quad W_t = M_t^r S_t\]

Because the payoff function also includes the penalty parameter on issuing debt of different maturities, we have:

\[T_t^2 + c_1(b_{t,t+1} - b_{t,t+2})^2 = x_t^r R_t x_t + u_t^r Q_t u_t + 2u_t^r W_t x_t + c_1 u_t^r Q^c u_t\]

where \(Q^c = \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\). Therefore, the overall \(Q\) matrix for the Markov jump LQ problem is:
\[ Q_i^t = Q_t + c_i Q \]

The law of motion of the state in all discrete Markov states \( i \) is

\[ x_{t+1} = A_t x_t + B u_t + C_t w_{t+1} \]

where

\[
A_t = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22,t} \end{bmatrix}, \quad B = \begin{bmatrix} B_1 \\ 0 \end{bmatrix}, \quad C_t = \begin{bmatrix} 0 \\ C_{2,t} \end{bmatrix}
\]

Thus, in this problem all the matrices apart from \( B \) may depend on the Markov state at time \( t \).

As shown in the previous lecture, the \texttt{LQMarkov} class can solve Markov jump LQ problems when provided with the \( A, B, C, R, Q, W \) matrices for each Markov state.

The function below maps the primitive matrices and parameters from the above two-period model into the matrices that the \texttt{LQMarkov} class requires:

```
In [3]: def LQ_markov_mapping(A22, C2, Ug, p1, p2, c1=0):
    
    """
    Function which takes A22, C2, Ug, p_{t, t+1}, p_{t, t+2} and penalty parameter c1, and returns the required matrices for the LQMarkov model: A, B, C, R, Q, W.
    This version uses the condensed version of the endogenous state.
    """
    
    # Make sure all matrices can be treated as 2D arrays
    A22 = np.atleast_2d(A22)
    C2 = np.atleast_2d(C2)
    Ug = np.atleast_2d(Ug)
    p1 = np.atleast_2d(p1)
    p2 = np.atleast_2d(p2)

    # Find the number of states (z) and shocks (w)
    nz, nw = C2.shape

    # Create A11, B1, S1, S2, Sg, S matrices
    A11 = np.zeros((2, 2))
    A11[0, 1] = 1
    B1 = np.eye(2)
    S1 = np.hstack((np.eye(1), np.zeros((1, nz+1))))
    Sg = np.hstack((np.zeros((1, 2)), Ug))
    S = S1 + Sg

    # Create M matrix
    M = np.hstack((-p1, -p2))

    # Create A, B, C matrices
    A_T = np.hstack((A11, np.zeros((2, nz))))
    A_B = np.hstack((np.zeros((nz, 2)), A22))
```
A = np.vstack((A_T, A_B))
B = np.vstack((B1, np.zeros((nz, 2))))
C = np.vstack((np.zeros((2, nw)), C2))

# Create Q^c matrix
Qc = np.array([[[1, -1], [-1, 1]]])

# Create R, Q, W matrices
R = S.T @ S
Q = M.T @ M + c1 * Qc
W = M.T @ S

return A, B, C, R, Q, W

With the above function, we can proceed to solve the model in two steps:

1. Use LQ_markov_mapping to map \(U_g, t, A_{22}, t, C_2, t, p_{t, t+1}, p_{t, t+2}\) into the \(A, B, C, R, Q, W\) matrices for each of the \(n\) Markov states.

2. Use the LQMarkov class to solve the resulting \(n\)-state Markov jump LQ problem.

### 11.6 Penalty on Different Issuance Across Maturities

To implement a simple example of the two-period model, we assume that \(G_t\) follows an AR(1) process:

\[
G_{t+1} = \bar{G} + \rho G_t + \sigma w_{t+1}
\]

To do this, we set \(z_t = \begin{bmatrix} 1 \\ G_t \end{bmatrix}\), and consequently:

\[
A_{22} = \begin{bmatrix} 1 & 0 \\ \bar{G} & \rho \end{bmatrix}, \quad C_2 = \begin{bmatrix} 0 \\ \sigma \end{bmatrix}, \quad U_g = \begin{bmatrix} 0 & 1 \end{bmatrix}
\]

Therefore, in this example, \(A_{22}, C_2\) and \(U_g\) are not time-varying.

We will assume that there are two Markov states, one with a flatter yield curve, and one with a steeper yield curve. In state 1, prices are:

\[
p^1_{t, t+1} = \beta, \quad p^1_{t, t+2} = \beta^2 - 0.02
\]

and in state 2, prices are:

\[
p^2_{t, t+1} = \beta, \quad p^2_{t, t+2} = \beta^2 + 0.02
\]

We first solve the model with no penalty parameter on different issuance across maturities, i.e. \(c_1 = 0\).

We also need to specify a transition matrix for the Markov state, we use:
Thus, each Markov state is persistent, and there is an equal chance of moving from one to the other.

In [4]:  # Model parameters
    β, Gbar, ρ, σ, c1 = 0.95, 5, 0.8, 1, 0
    p1, p2, p3, p4 = β, β**2 - 0.02, β, β**2 + 0.02

    # Basic model matrices
    A22 = np.array([[1, 0], [Gbar, ρ]])
    C_2 = np.array([[0], [σ]])
    Ug = np.array([[0, 1]])

    A1, B1, C1, R1, Q1, W1 = LQ_markov_mapping(A22, C_2, Ug, p1, p2, c1)
    A2, B2, C2, R2, Q2, W2 = LQ_markov_mapping(A22, C_2, Ug, p3, p4, c1)

    # Small penalties on debt required to implement no-Ponzi scheme
    R1[0, 0] = R1[0, 0] + 1e-9
    R2[0, 0] = R2[0, 0] + 1e-9

    # Construct lists of matrices correspond to each state
    As = [A1, A2]
    Bs = [B1, B2]
    Cs = [C1, C2]
    Rs = [R1, R2]
    Qs = [Q1, Q2]
    Ws = [W1, W2]

    Π = np.array([[0.9, 0.1], [0.1, 0.9]])

    # Construct and solve the model using the LQMarkov class
    lqm = qe.LQMarkov(Π, Qs, Rs, As, Bs, Cs=Cs, Ns=Ws, beta=β)
    lqm.stationary_values()

    # Simulate the model
    x0 = np.array([[100, 50, 1, 10]])
    x, u, w, t = lqm.compute_sequence(x0, ts_length=300)

    # Plot of one and two-period debt issuance
    fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
    ax1.plot(u[0, :])
    ax1.set_title('One-period debt issuance')
    ax1.set_xlabel('Time')
    ax2.plot(u[1, :])
    ax2.set_title('Two-period debt issuance')
    ax2.set_xlabel('Time')
    plt.show()
The above simulations show that when no penalty is imposed on different issuances across maturities, the government has an incentive to take large “long-short” positions in debt of different maturities.

To prevent such an outcome, we now set $c_1 = 0.01$.

This penalty is enough to ensure that the government issues positive quantities of both one and two-period debt:

In [5]: # Put small penalty on different issuance across maturities
   
   c1 = 0.01

   A1, B1, C1, R1, Q1, W1 = LQ_markov_mapping(A22, C_2, Ug, p1, p2, c1)
   A2, B2, C2, R2, Q2, W2 = LQ_markov_mapping(A22, C_2, Ug, p3, p4, c1)

   # Small penalties on debt required to implement no-Ponzi scheme
   R1[0, 0] = R1[0, 0] + 1e-9
   R2[0, 0] = R2[0, 0] + 1e-9

   # Construct lists of matrices
   As = [A1, A2]
   Bs = [B1, B2]
   Cs = [C1, C2]
   Rs = [R1, R2]
   Qs = [Q1, Q2]
   Ws = [W1, W2]

   # Construct and solve the model using the LQMarkov class
   lqm2 = qe.LQMarkov(II, Qs, Rs, As, Bs, Cs=Cs, Ns=Ws, beta=β)
   lqm2.stationary_values()

   # Simulate the model
   x, u, w, t = lqm2.compute_sequence(x0, ts_length=300)

   # Plot of one and two-period debt issuance
   fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
   ax1.plot(u[0, :])
   ax1.set_title('One-period debt issuance')
   ax1.set_xlabel('Time')
   ax2.plot(u[1, :])
   ax2.set_title('Two-period debt issuance')
   ax2.set_xlabel('Time')
   plt.show()
11.7 A Model with Restructuring

This model alters two features of the previous model:

1. The maximum horizon of government debt is now extended to a general $H$ periods.
2. The government is able to redesign the maturity structure of debt every period.

We impose a cost on adjusting issuance of each maturity by amending the payoff function to become:

$$T_t^2 + \sum_{j=0}^{H-1} c_2(b_{t+j}^{t-1} - b_{t+j+1}^t)^2$$

The government’s budget constraint is now:

$$T_t + \sum_{j=1}^H p_{t,t+j}b_{t+j}^t = b_{t-1}^{t-1} + \sum_{j=1}^{H-1} p_{t,t+j}b_{t+j}^{t-1} + G_t$$

To map this into the Markov Jump LQ framework, we define state and control variables. Let:

$$\bar{b}_t = \begin{bmatrix} b_{t-1}^{t-1} \\ b_{t+1}^{t-1} \\ \vdots \\ b_{t+H-1}^{t-1} \\ b_{t+1}^t \\ \vdots \\ b_{t+H}^t \end{bmatrix}, \quad u_t = \begin{bmatrix} b_{t+1}^t \\ b_{t+2}^t \\ \vdots \\ b_{t+H}^t \end{bmatrix}$$

Thus, $\bar{b}_t$ is the endogenous state (debt issued last period) and $u_t$ is the control (debt issued today).

As before, we will also have the exogenous state $z_t$, which determines government spending. Therefore, the full state is:
We also define a vector \( p_t \) that contains the time \( t \) price of goods in period \( t + j \):

\[
\begin{bmatrix}
p_{t,t+1} \\
p_{t,t+2} \\
\vdots \\
p_{t,t+H-1}
\end{bmatrix}
\]

Finally, we define three useful matrices \( S_s, S_x, \tilde{S}_x \):

\[
\begin{bmatrix}
p_{t,t+1} \\
p_{t,t+2} \\
\vdots \\
p_{t,t+H-1}
\end{bmatrix}
= S_s p_t \quad \text{where} \quad S_s =
\begin{bmatrix}
1 & 0 & 0 & \cdots & 0 \\
0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & 1
\end{bmatrix}
\]

\[
\begin{bmatrix}
b_{t+1} \\
b_{t+2} \\
\vdots \\
b_{t+H-1}
\end{bmatrix}
= S_x \tilde{b}_t \quad \text{where} \quad S_x =
\begin{bmatrix}
0 & 1 & 0 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & 1
\end{bmatrix}
\]

\[
b_t = \tilde{S}_x \tilde{b}_t \quad \text{where} \quad \tilde{S}_x =
\begin{bmatrix}
1 & 0 & 0 & \cdots & 0
\end{bmatrix}
\]

In terms of dimensions, the first two matrices defined above are \((H - 1) \times H\).

The last is \(1 \times H\)

We can now write the government’s budget constraint in matrix notation. Rearranging the government budget constraint gives:

\[
T_t = b_t^{t-1} + \sum_{j=1}^{H-1} p_{t+j} b_{t+j-1} + G_t - \sum_{j=1}^{H-1} p_{t+j} b_{t+j}
\]

or

\[
T_t = \tilde{S}_x \tilde{b}_t + (S_s p_t) \cdot (S_x \tilde{b}_t) + U_g z_t - p_t \cdot u_t
\]

If we want to write this in terms of the full state, we have:

\[
T_t = [(\tilde{S}_x + p_t S_s S_x) \quad U_g] x_t - p_t' u_t
\]

To simplify the notation, let \( S_t = [(\tilde{S}_x + p_t S_s S_x) \quad U_g] \).

Then

\[
T_t = S_t x_t - p_t' u_t
\]

Therefore
where
\[ R_t = S_t' S_t, \quad Q_t = p_t p_t', \quad W_t = -p_t S_t \]
where to economize on notation we adopt the convention that for the linear state matrices
\[ R_t \equiv R_{st}, Q_t \equiv W_{st} \text{ and so on}. \]
We’ll continue to use this convention also for the linear state matrices \( A, B, W \) and so on below.

Because the payoff function also includes the penalty parameter for rescheduling, we have:
\[
T^2_t + H^{-1} \sum_{j=0}^{H-1} c_2 (b_{t+j}^t - b_{t+j+1}^t)^2 = T^2_t + c_2 (\bar{b}_t - u_t)'(\bar{b}_t - u_t)
\]
Because the complete state is \( x_t \) and not \( \bar{b}_t \), we rewrite this as:
\[
T^2_t + c_2 (S_c x_t - u_t)'(S_c x_t - u_t)
\]
where \( S_c = \begin{bmatrix} I & 0 \end{bmatrix} \)
Multiplying this out gives:
\[
T^2_t + c_2 x_t' S_c' S_c x_t - 2c_2 u_t' S_c x_t + c_2 u_t' u_t
\]
Therefore, with the cost term, we must amend our \( R, Q, W \) matrices as follows:
\[
R_c^t = R_t + c_2 S_c' S_c
\]
\[
Q_c^t = Q_t + c_2 I
\]
\[
W_c^t = W_t - c_2 S_c
\]
To finish mapping into the Markov jump LQ setup, we need to construct the law of motion for the full state.
This is simpler than in the previous setup, as we now have \( \bar{b}_{t+1} = u_t \).
Therefore:
\[
x_{t+1} = \begin{bmatrix} \bar{b}_{t+1} \\ x_{t+1} \end{bmatrix} = A_t x_t + B u_t + C_t w_{t+1}
\]
where
\[
A_t = \begin{bmatrix} 0 & 0 \\ 0 & A_{22,t} \end{bmatrix}, \quad B = \begin{bmatrix} I \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 \\ C_{2,t} \end{bmatrix}
\]
This completes the mapping into a Markov jump LQ problem.

11.8 Restructuring as a Markov Jump Linear Quadratic Control Problem

As with the previous model, we can use a function to map the primitives of the model with restructuring into the matrices that the LQMarkov class requires:

```python
In [6]: def LQ_markov_mapping_restruct(A22, C2, Ug, T, p_t, c=0):
    
    """
    Function which takes A22, C2, T, p_t, c and returns the required matrices for the LQMarkov model: A, B, C, R, Q, W
    Note, p_t should be a T by 1 matrix
    c is the rescheduling cost (a scalar)
    This version uses the condensed version of the endogenous state
    """

    # Make sure all matrices can be treated as 2D arrays
    A22 = np.atleast_2d(A22)
    C2 = np.atleast_2d(C2)
    Ug = np.atleast_2d(Ug)
    p_t = np.atleast_2d(p_t)

    # Find the number of states (z) and shocks (w)
    nz, nw = C2.shape

    # Create Sx, tSx, Ss, S_t matrices (tSx stands for \tilde S_x)
    Ss = np.hstack((np.eye(T-1), np.zeros((T-1, 1))))
    Sx = np.hstack((np.zeros((T-1, 1)), np.eye(T-1)))
    tSx = np.zeros((1, T))
    tSx[0, 0] = 1
    S_t = np.hstack((tSx + p_t.T @ Ss.T @ Sx, Ug))

    # Create A, B, C matrices
    A_T = np.hstack((np.zeros((T, T)), np.zeros((T, nz))))
    A_B = np.hstack((np.zeros((nz, T)), A22))
    A = np.vstack((A_T, A_B))
    B = np.vstack((np.eye(T), np.zeros((nz, T))))
    C = np.vstack((np.zeros((T, nw)), C2))

    # Create cost matrix Sc
    Sc = np.hstack((np.eye(T), np.zeros((T, nz))))

    # Create R_t, Q_t, W_t matrices
    R_c = S_t.T @ S_t + c * Sc.T @ Sc
    Q_c = p_t @ p_t.T + c * np.eye(T)
    W_c = -p_t @ S_t - c * Sc

    return A, B, C, R_c, Q_c, W_c
```
11.8. RESTRUCTURING AS A MARKOV JUMP LINEAR QUADRATIC CONTROL PROBLEM

11.8.1 Example with Restructuring

As an example of the model with restructuring, consider this model where $H = 3$.

We will assume that there are two Markov states, one with a flatter yield curve, and one with a steeper yield curve.

In state 1, prices are:

\[ p_{t,t+1}^1 = 0.9695, \quad p_{t,t+2}^1 = 0.902, \quad p_{t,t+3}^1 = 0.8369 \]

and in state 2, prices are:

\[ p_{t,t+1}^2 = 0.9295, \quad p_{t,t+2}^2 = 0.902, \quad p_{t,t+3}^2 = 0.8769 \]

We will assume the same transition matrix and $G_t$ process as above.

```
In [7]: # New model parameters
    H = 3
    p1 = np.array([[0.9695], [0.902], [0.8369]])
    p2 = np.array([[0.9295], [0.902], [0.8769]])
    Pi = np.array([[0.9, 0.1], [0.1, 0.9]])

    # Put penalty on different issuance across maturities
    c2 = 0.5
    A1, B1, C1, R1, Q1, W1 = LQ_markov_mapping_restruct(A22, C_2, Ug, H, p1, c2)
    A2, B2, C2, R2, Q2, W2 = LQ_markov_mapping_restruct(A22, C_2, Ug, H, p2, c2)

    # Small penalties on debt required to implement no-Ponzi scheme
    R1[0, 0] = R1[0, 0] + 1e-9
    R1[1, 0] = R1[1, 0] + 1e-9
    R1[2, 0] = R1[2, 0] + 1e-9
    R2[0, 0] = R2[0, 0] + 1e-9
    R2[1, 0] = R2[1, 0] + 1e-9
    R2[2, 0] = R2[2, 0] + 1e-9

    # Construct lists of matrices
    As = [A1, A2]
    Bs = [B1, B2]
    Cs = [C1, C2]
    Rs = [R1, R2]
    Qs = [Q1, Q2]
    Ws = [W1, W2]

    # Construct and solve the model using the LQMarkov class
    lqm3 = qe.LQMarkov(Pi, Qs, Rs, As, Bs, Cs=Cs, Ns=Ws, beta=β)
    lqm3.stationary_values()

    x0 = np.array([[5000, 5000, 5000, 1, 10]])
    x, u, w, t = lqm3.compute_sequence(x0, ts_length=300)

In [8]: # Plots of different maturities debt issuance
    fig, (ax1, ax2, ax3, ax4) = plt.subplots(1, 4, figsize=(16, 4))
    ax1.plot(u[:, :])
```
In [9]: # Plot share of debt issuance that is short-term

fig, ax = plt.subplots()
ax.plot((u[0, :] / (u[0, :] + u[1, :] + u[2, :])))
ax.set_title('One-period debt issuance share')
ax.set_xlabel('Time')
plt.show()
Chapter 12

How to Pay for a War: Part 3

12.1 Contents

- Another Application of Markov Jump Linear Quadratic Dynamic Programming 12.2
- Roll-Over Risk 12.3
- A Dead End 12.4
- Better Representation of Roll-Over Risk 12.5

In addition to what’s in Anaconda, this lecture deploys the quantecon library:

```
In [1]: !pip install --upgrade quantecon
```

12.2 Another Application of Markov Jump Linear Quadratic Dynamic Programming

This is another sequel to an earlier lecture.

We again use a method introduced in lecture Markov Jump LQ dynamic programming to implement some ideas Barro (1999 [8], 2003 [9]) that extend his classic 1979 [7] model of tax smoothing.

Barro’s 1979 [7] model is about a government that borrows and lends in order to help it minimize an intertemporal measure of distortions caused by taxes.


Our generalizations of his 1979 model will also look like souped-up consumption-smoothing models.

In this lecture, we describe a tax-smoothing problem of a government that faces roll-over risk.

Let’s start with some standard imports:

```
In [2]: import quantecon as qe
   : import numpy as np
   : import matplotlib.pyplot as plt
   : %matplotlib inline
```
12.3 Roll-Over Risk

Let $T_t$ denote tax collections, $\beta$ a discount factor, $b_{t,t+1}$ time $t+1$ goods that the government promises to pay at $t$, $G_t$ government purchases, $p_{t+1}^t$ the number of time $t$ goods received per time $t+1$ goods promised.

The stochastic process of government expenditures is exogenous.

The government’s problem is to choose a plan for borrowing and tax collections $\{b_{t+1}, T_t\}_{t=0}^{\infty}$ to minimize

$$E_0 \sum_{t=0}^{\infty} \beta^t T_t^2$$

subject to the constraints

$$T_t + p_{t+1}^t b_{t,t+1} = G_t + b_{t-1,t}$$

$$G_t = U_{g,t} z_t$$

$$z_{t+1} = A_{22,t} z_t + C_{2,t} w_{t+1}$$

where $w_{t+1} \sim N(0, I)$. The variables $T_t, b_{t,t+1}$ are control variables chosen at $t$, while $b_{t-1,t}$ is an endogenous state variable inherited from the past at time $t$ and $p_{t+1}^t$ is an exogenous state variable at time $t$.

This is the same set-up as used in this lecture.

We will consider a situation in which the government faces “roll-over risk”.

Specifically, we shut down the government’s ability to borrow in one of the Markov states.

12.4 A Dead End

A first thought for how to implement this might be to allow $p_{t+1}^t$ to vary over time with:

$$p_{t+1}^t = \beta$$

in Markov state 1 and

$$p_{t+1}^t = 0$$

in Markov state 2.

Consequently, in the second Markov state, the government is unable to borrow, and the budget constraint becomes $T_t = G_t + b_{t-1,t}$.

However, if this is the only adjustment we make in our linear-quadratic model, the government will not set $b_{t,t+1} = 0$, which is the outcome we want to express roll-over risk in period $t$. 

Instead, the government would have an incentive to set $b_{t,t+1}$ to a large negative number in state 2 – it would accumulate large amounts of assets to bring into period $t + 1$ because that is cheap (Our Riccati equations will discover this for us!).

Thus, we must represent “roll-over risk” some other way.

12.5 Better Representation of Roll-Over Risk

To force the government to set $b_{t,t+1} = 0$, we can instead extend the model to have four Markov states:

1. Good today, good yesterday
2. Good today, bad yesterday
3. Bad today, good yesterday
4. Bad today, bad yesterday

where good is a state in which effectively the government can issue debt and bad is a state in which effectively the government can’t issue debt.

We’ll explain what effectively means shortly.

We now set

$$p_{t+1} = \beta$$

in all states.

In addition – and this is important because it defines what we mean by effectively – we put a large penalty on the $b_{t-1,t}$ element of the state vector in states 2 and 4.

This will prevent the government from wishing to issue any debt in states 3 or 4 because it would experience a large penalty from doing so in the next period.

The transition matrix for this formulation is:

$$\Pi = \begin{bmatrix} 0.95 & 0 & 0.05 & 0 \\ 0.95 & 0 & 0.05 & 0 \\ 0 & 0.9 & 0 & 0.1 \\ 0 & 0.9 & 0 & 0.1 \end{bmatrix}$$

This transition matrix ensures that the Markov state cannot move, for example, from state 3 to state 1.

Because state 3 is “bad today”, the next period cannot have “good yesterday”. 

In [3]: # Model parameters
$\beta$, Gbar, $\rho$, $\sigma = 0.95, 5, 0.8, 1$

# Basic model matrices
A22 = np.array([[1, 0], [Gbar, $\rho$]])
C2 = np.array([[0], [$\sigma$]])
Ug = np.array([[0, 1]])

# LQ framework matrices
A_t = np.zeros((1, 3))
A_b = np.hstack((np.zeros((2, 1)), A22))
A = np.vstack((A_t, A_b))

B = np.zeros((3, 1))
B[0, 0] = 1

C = np.vstack((np.zeros((1, 1)), C2))

Sg = np.hstack((np.zeros((1, 1)), Ug))
S1 = np.zeros((1, 3))
S1[0, 0] = 1
S = S1 + Sg

R = S.T @ S

# Large penalty on debt in R2 to prevent borrowing in a bad state
R1 = np.copy(R)
R2 = np.copy(R)
R1[0, 0] = R[0, 0] + 1e-9
R2[0, 0] = R[0, 0] + 1e12

M = np.array([[β]])
Q = M.T @ M
W = M.T @ S

II = np.array([[0.95, 0, 0.05, 0],
               [0.95, 0, 0.05, 0],
               [0, 0.9, 0, 0.1],
               [0, 0.9, 0, 0.1]])

# Construct lists of matrices that correspond to each state
As = [A, A, A, A]
Bs = [B, B, B, B]
Cs = [C, C, C, C]
Rs = [R1, R2, R1, R2]
Qs = [Q, Q, Q, Q]
Ws = [W, W, W, W]

lqm = qe.LQMarkov(II, Qs, Rs, As, Cs=Cs, Ns=Ws, beta=β)
lqm.stationary_values();

This model is simulated below, using the same process for \( G_t \) as in this lecture.

When \( p_{t+1} = \beta \) government debt fluctuates around zero.

The spikes in the series for taxation show periods when the government is unable to access financial markets: positive spikes occur when debt is positive, and the government must raise taxes in the current period.

Negative spikes occur when the government has positive asset holdings.

An inability to use financial markets in the next period means that the government uses those assets to lower taxation today.

In [4]: x0 = np.array([[0, 1, 25]])
12.5. BETTER REPRESENTATION OF ROLL-OVER RISK

\[ T = 300 \]
\[ x, u, w, \text{state} = \text{lqm}.\text{compute_sequence}(x0, \text{ts_length}=T) \]

# Calculate taxation each period from the budget constraint and the Markov state
```
tax = np.zeros([T, 1])
for i in range(T):
tax[i, :] = S @ x[:, i] + M @ u[:, i]
```

# Plot of debt issuance and taxation
```
fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(16, 4))
ax1.plot(x[0, :])
ax1.set_title('One-period debt issuance')
ax1.set_xlabel('Time')
ax2.plot(tax)
ax2.set_title('Taxation')
ax2.set_xlabel('Time')
plt.show()
```

We can adjust the model so that, rather than having debt fluctuate around zero, the government is a debtor in every period we allow it to borrow.

To accomplish this, we simply raise \( p_{t+1} \) to \( \beta + 0.02 = 0.97 \).

In [5]: \( M = \text{np.array}([[\beta - 0.02]]) \)

\[
Q = M.T @ M
W = M.T @ S
\]

# Construct lists of matrices
```
As = [A, A, A, A]
Bs = [B, B, B, B]
Cs = [C, C, C, C]
Rs = [R1, R2, R1, R2]
Qs = [Q, Q, Q, Q]
Ws = [W, W, W, W]
```

lqm2 = qe.LQMarkov(II, Qs, Rs, As, Bs, Cs=Cs, Ns=Ws, beta=\( \beta \))
x, u, w, state = lqm2.compute_sequence(x0, ts_length=T)

# Calculate taxation each period from the budget constraint and the Markov state
```
tax = np.zeros([T, 1])
for i in range(T):
```
\[ \text{tax}[i, :] = S \odot x[:, i] + M \odot u[:, i] \]

# Plot of debt issuance and taxation
fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(16, 4))
ax1.plot(x[0, :])
ax1.set_title('One-period debt issuance')
ax1.set_xlabel('Time')
ax2.plot(tax)
ax2.set_title('Taxation')
ax2.set_xlabel('Time')
plt.show()

With a lower interest rate, the government has an incentive to increase debt over time. However, with “roll-over risk”, debt is recurrently reset to zero and taxes spike up. Consequently, the government is wary of letting debt get too high, due to the high costs of a “sudden stop”.
Chapter 13

Optimal Taxation in an LQ Economy

13.1 Contents

- Overview 13.2
- The Ramsey Problem 13.3
- Implementation 13.4
- Examples 13.5
- Exercises 13.6
- Solutions 13.7

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

13.2 Overview

In this lecture, we study optimal fiscal policy in a linear quadratic setting.

We modify a model of Robert Lucas and Nancy Stokey [45] so that convenient formulas for solving linear-quadratic models can be applied.

The economy consists of a representative household and a benevolent government.

The government finances an exogenous stream of government purchases with state-contingent loans and a linear tax on labor income.

A linear tax is sometimes called a flat-rate tax.

The household maximizes utility by choosing paths for consumption and labor, taking prices and the government’s tax rate and borrowing plans as given.

Maximum attainable utility for the household depends on the government’s tax and borrowing plans.

The Ramsey problem [51] is to choose tax and borrowing plans that maximize the household’s welfare, taking the household’s optimizing behavior as given.

There is a large number of competitive equilibria indexed by different government fiscal poli-
cies.

The Ramsey planner chooses the best competitive equilibrium.

We want to study the dynamics of tax rates, tax revenues, government debt under a Ramsey plan.

Because the Lucas and Stokey model features state-contingent government debt, the government debt dynamics differ substantially from those in a model of Robert Barro [7].

The treatment given here closely follows this manuscript, prepared by Thomas J. Sargent and Francois R. Velde.

We cover only the key features of the problem in this lecture, leaving you to refer to that source for additional results and intuition.

We’ll need the following imports:

```python
In [2]:
import sys
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
from numpy import sqrt, eye, zeros, cumsum
from numpy.random import randn
import scipy.linalg
from collections import namedtuple
from quantecon import nullspace, mc_sample_path, var_quadratic_sum
```

### 13.2.1 Model Features

- Linear quadratic (LQ) model
- Representative household
- Stochastic dynamic programming over an infinite horizon
- Distortionary taxation

### 13.3 The Ramsey Problem

We begin by outlining the key assumptions regarding technology, households and the government sector.

#### 13.3.1 Technology

Labor can be converted one-for-one into a single, non-storable consumption good.

In the usual spirit of the LQ model, the amount of labor supplied in each period is unrestricted.

This is unrealistic, but helpful when it comes to solving the model.

Realistic labor supply can be induced by suitable parameter values.
13.3. THE RAMSEY PROBLEM

13.3.2 Households

Consider a representative household who chooses a path \( \{\ell_t, c_t\} \) for labor and consumption to maximize

\[
-\mathbb{E} \frac{1}{2} \sum_{t=0}^{\infty} \beta^t [(c_t - b_t)^2 + \ell_t^2]
\]

subject to the budget constraint

\[
\mathbb{E} \sum_{t=0}^{\infty} \beta^t p_0^0 [d_t + (1 - \tau_t) \ell_t + s_t - c_t] = 0
\]

Here

- \( \beta \) is a discount factor in \((0, 1)\).
- \( p_0^0 \) is a scaled Arrow-Debreu price at time 0 of history contingent goods at time \( t + j \).
- \( b_t \) is a stochastic preference parameter.
- \( d_t \) is an endowment process.
- \( \tau_t \) is a flat tax rate on labor income.
- \( s_t \) is a promised time-\( t \) coupon payment on debt issued by the government.

The scaled Arrow-Debreu price \( p_0^0 \) is related to the unscaled Arrow-Debreu price as follows.

If we let \( \pi_t^0(x^t) \) denote the probability (density) of a history \( x^t = [x_t, x_{t-1}, \ldots, x_0] \) of the state \( x^t \), then the Arrow-Debreu time 0 price of a claim on one unit of consumption at date \( t \), history \( x^t \) would be

\[
\frac{\beta^t p_0^0}{\pi_t^0(x^t)}
\]

Thus, our scaled Arrow-Debreu price is the ordinary Arrow-Debreu price multiplied by the discount factor \( \beta^t \) and divided by an appropriate probability.

The budget constraint (2) requires that the present value of consumption be restricted to equal the present value of endowments, labor income and coupon payments on bond holdings.

13.3.3 Government

The government imposes a linear tax on labor income, fully committing to a stochastic path of tax rates at time zero.

The government also issues state-contingent debt.

Given government tax and borrowing plans, we can construct a competitive equilibrium with distorting government taxes.

Among all such competitive equilibria, the Ramsey plan is the one that maximizes the welfare of the representative consumer.
13.3.4 Exogenous Variables

Endowments, government expenditure, the preference shock process $b_t$, and promised coupon payments on initial government debt $s_t$ are all exogenous, and given by

- $d_t = S_d x_t$
- $g_t = S_g x_t$
- $b_t = S_b x_t$
- $s_t = S_s x_t$

The matrices $S_d, S_g, S_b, S_s$ are primitives and $\{x_t\}$ is an exogenous stochastic process taking values in $\mathbb{R}^k$.

We consider two specifications for $\{x_t\}$.

1. Discrete case: $\{x_t\}$ is a discrete state Markov chain with transition matrix $P$.
2. VAR case: $\{x_t\}$ obeys $x_{t+1} = Ax_t + Cw_{t+1}$ where $\{w_t\}$ is independent zero-mean Gaussian with identify covariance matrix.

13.3.5 Feasibility

The period-by-period feasibility restriction for this economy is

$$c_t + g_t = d_t + \ell_t\quad(3)$$

A labor-consumption process $\{\ell_t, c_t\}$ is called feasible if (3) holds for all $t$.

13.3.6 Government Budget Constraint

Where $p^0_t$ is again a scaled Arrow-Debreu price, the time zero government budget constraint is

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t p^0_t (s_t + g_t - \tau_t \ell_t) = 0\quad(4)$$

13.3.7 Equilibrium

An equilibrium is a feasible allocation $\{\ell_t, c_t\}$, a sequence of prices $\{p^0_t\}$, and a tax system $\{\tau_t\}$ such that

1. The allocation $\{\ell_t, c_t\}$ is optimal for the household given $\{p^0_t\}$ and $\{\tau_t\}$.
2. The government’s budget constraint (4) is satisfied.

The Ramsey problem is to choose the equilibrium $\{\ell_t, c_t, \tau_t, p^0_t\}$ that maximizes the household’s welfare.

If $\{\ell_t, c_t, \tau_t, p^0_t\}$ solves the Ramsey problem, then $\{\tau_t\}$ is called the Ramsey plan.

The solution procedure we adopt is
1. Use the first-order conditions from the household problem to pin down prices and allocations given \( \{\tau_t\} \).

2. Use these expressions to rewrite the government budget constraint (4) in terms of exogenous variables and allocations.

3. Maximize the household’s objective function (1) subject to the constraint constructed in step 2 and the feasibility constraint (3).

The solution to this maximization problem pins down all quantities of interest.

**13.3.8 Solution**

Step one is to obtain the first-conditions for the household’s problem, taking taxes and prices as given.

Letting \( \mu \) be the Lagrange multiplier on (2), the first-order conditions are 

\[
p^0_t = \frac{c_t - b_t}{\mu} \quad \text{and} \quad \ell_t = (c_t - b_t)(1 - \tau_t).
\]

Rearranging and normalizing at \( \mu = b_0 - c_0 \), we can write these conditions as

\[
p^0_t = \frac{b_t - c_t}{b_0 - c_0} \quad \text{and} \quad \tau_t = 1 - \frac{\ell_t}{b_t - c_t} \tag{5}
\]

Substituting (5) into the government’s budget constraint (4) yields

\[
\mathbb{E} \sum_{t=0}^{\infty} \beta^t [(b_t - c_t)(s_t + g_t - \ell_t) + \ell_t^2] = 0 \tag{6}
\]

The Ramsey problem now amounts to maximizing (1) subject to (6) and (3).

The associated Lagrangian is

\[
\mathcal{L} = \mathbb{E} \sum_{t=0}^{\infty} \beta^t \left\{ \frac{1}{2} [(c_t - b_t)^2 + \ell_t^2] + \lambda [(b_t - c_t)(\ell_t - s_t - g_t) - \ell_t^2] + \mu_t [d_t + \ell_t - c_t - g_t] \right\} \tag{7}
\]

The first-order conditions associated with \( c_t \) and \( \ell_t \) are

\[
-(c_t - b_t) + \lambda [-\ell_t + (g_t + s_t)] = \mu_t
\]

and

\[
\ell_t - \lambda [(b_t - c_t) - 2\ell_t] = \mu_t
\]

Combining these last two equalities with (3) and working through the algebra, one can show that

\[
\ell_t = \tilde{\ell}_t - \nu m_t \quad \text{and} \quad c_t = \tilde{c}_t - \nu m_t \tag{8}
\]
• \( \nu := \lambda/(1 + 2\lambda) \)
• \( \bar{\ell}_t := (b_t - d_t + g_t)/2 \)
• \( \bar{c}_t := (b_t + d_t - g_t)/2 \)
• \( m_t := (b_t - d_t - s_t)/2 \)

Apart from \( \nu \), all of these quantities are expressed in terms of exogenous variables.

To solve for \( \nu \), we can use the government’s budget constraint again.

The term inside the brackets in (6) is \((b_t - c_t)(s_t + g_t) - (b_t - c_t)\bar{\ell}_t + \bar{\ell}_t^2 \).

Using (8), the definitions above and the fact that \( \bar{\ell} = b - \bar{c} \), this term can be rewritten as

\[
(b_t - \bar{c}_t)(g_t + s_t) + 2m_t^2(\nu^2 - \nu)
\]

Reinserting into (6), we get

\[
\mathbb{E} \left\{ \sum_{t=0}^{\infty} \beta^t (b_t - \bar{c}_t)(g_t + s_t) \right\} + (\nu^2 - \nu)\mathbb{E} \left\{ \sum_{t=0}^{\infty} \beta^t 2m_t^2 \right\} = 0 \tag{9}
\]

Although it might not be clear yet, we are nearly there because:

• The two expectations terms in (9) can be solved for in terms of model primitives.
• This in turn allows us to solve for the Lagrange multiplier \( \nu \).
• With \( \nu \) in hand, we can go back and solve for the allocations via (8).
• Once we have the allocations, prices and the tax system can be derived from (5).

### 13.3.9 Computing the Quadratic Term

Let’s consider how to obtain the term \( \nu \) in (9).

If we can compute the two expected geometric sums

\[
b_0 := \mathbb{E} \left\{ \sum_{t=0}^{\infty} \beta^t (b_t - \bar{c}_t)(g_t + s_t) \right\} \quad \text{and} \quad a_0 := \mathbb{E} \left\{ \sum_{t=0}^{\infty} \beta^t 2m_t^2 \right\} \tag{10}
\]

then the problem reduces to solving

\[
b_0 + a_0(\nu^2 - \nu) = 0
\]

for \( \nu \).

Provided that \( 4b_0 < a_0 \), there is a unique solution \( \nu \in (0, 1/2) \), and a unique corresponding \( \lambda > 0 \).

Let’s work out how to compute mathematical expectations in (10).

For the first one, the random variable \((b_t - \bar{c}_t)(g_t + s_t)\) inside the summation can be expressed as

\[
\frac{1}{2} x_t'(S_b - S_d + S_g)'(S_g + S_s)x_t
\]

For the second expectation in (10), the random variable \(2m_t^2\) can be written as
13.3. THE RAMSEY PROBLEM

\[ \frac{1}{2} x'_t (S_b - S_d - S_s)' (S_b - S_d - S_s) x_t \]

It follows that both objects of interest are special cases of the expression

\[ q(x_0) = \mathbb{E} \sum_{t=0}^{\infty} \beta^t x'_t H x_t \]  \hspace{1cm} (11)

where \( H \) is a matrix conformable to \( x_t \) and \( x'_t \) is the transpose of column vector \( x_t \).

Suppose first that \( \{x_t\} \) is the Gaussian VAR described above.

In this case, the formula for computing \( q(x_0) \) is known to be \( q(x_0) = x'_0 Q x_0 + v \), where

- \( Q \) is the solution to \( Q = H + \beta A' QA \), and
- \( v = \text{trace} (C' QC) \beta / (1 - \beta) \)

The first equation is known as a discrete Lyapunov equation and can be solved using this function.

13.3.10 Finite State Markov Case

Next, suppose that \( \{x_t\} \) is the discrete Markov process described above.

Suppose further that each \( x_t \) takes values in the state space \( \{x^1, \ldots, x^N\} \subset \mathbb{R}^k \).

Let \( h : \mathbb{R}^k \to \mathbb{R} \) be a given function, and suppose that we wish to evaluate

\[ q(x_0) = \mathbb{E} \sum_{t=0}^{\infty} \beta^t h(x_t) \quad \text{given} \quad x_0 = x^j \]

For example, in the discussion above, \( h(x_t) = x'_t H x_t \).

It is legitimate to pass the expectation through the sum, leading to

\[ q(x_0) = \sum_{t=0}^{\infty} \beta^t (P^t h)[j] \]  \hspace{1cm} (12)

Here

- \( P^t \) is the \( t \)-th power of the transition matrix \( P \).
- \( h \) is, with some abuse of notation, the vector \( (h(x^1), \ldots, h(x^N)) \).
- \( (P^t h)[j] \) indicates the \( j \)-th element of \( P^t h \).

It can be shown that (12) is in fact equal to the \( j \)-th element of the vector \( (I - \beta P)^{-1} h \).

This last fact is applied in the calculations below.

13.3.11 Other Variables

We are interested in tracking several other variables besides the ones described above.

To prepare the way for this, we define
as the scaled Arrow-Debreu time $t$ price of a history contingent claim on one unit of consumption at time $t + j$.

These are prices that would prevail at time $t$ if markets were reopened at time $t$.

These prices are constituents of the present value of government obligations outstanding at time $t$, which can be expressed as

$$ B_t := \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j p^t_{t+j}(\tau_{t+j} \ell_{t+j} - g_{t+j}) $$

(13)

Using our expression for prices and the Ramsey plan, we can also write $B_t$ as

$$ B_t = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{(b_{t+j} - c_{t+j})(\ell_{t+j} - g_{t+j}) - \ell^2_{t+j}}{b_t - c_t} $$

This version is more convenient for computation.

Using the equation

$$ p^t_{t+j} = p^t_{t+1}p^{t+1}_{t+j} $$

it is possible to verify that (13) implies that

$$ B_t = (\tau_t \ell_t - g_t) + \mathbb{E}_t \sum_{j=1}^{\infty} p^t_{t+j}(\tau_{t+j} \ell_{t+j} - g_{t+j}) $$

and

$$ B_t = (\tau_t \ell_t - g_t) + \beta \mathbb{E}_t p^t_{t+1} B_{t+1} $$

(14)

Define

$$ R_t^{-1} := \mathbb{E}_t/\beta^j p^t_{t+1} $$

(15)

$R_t$ is the gross 1-period risk-free rate for loans between $t$ and $t + 1$.

13.3.12 A Martingale

We now want to study the following two objects, namely,

$$ \pi_{t+1} := B_{t+1} - R_t[B_t - (\tau_t \ell_t - g_t)] $$

and the cumulation of $\pi_t$.
13.4. IMPLEMENTATION

\[ \Pi_t := \sum_{s=0}^{t} \pi_t \]

The term \( \pi_{t+1} \) is the difference between two quantities:

- \( B_{t+1} \), the value of government debt at the start of period \( t + 1 \).
- \( R_t[B_t + g_t - \tau_t] \), which is what the government would have owed at the beginning of period \( t + 1 \) if it had simply borrowed at the one-period risk-free rate rather than selling state-contingent securities.

Thus, \( \pi_{t+1} \) is the excess payout on the actual portfolio of state-contingent government debt relative to an alternative portfolio sufficient to finance \( B_t + g_t - \tau_t \ell_t \) and consisting entirely of risk-free one-period bonds.

Use expressions (14) and (15) to obtain

\[ \pi_{t+1} = B_{t+1} - \frac{1}{\beta E_t p_{t+1}^t} [\beta E_t p_{t+1}^t B_{t+1}] \]

or

\[ \pi_{t+1} = B_{t+1} - \tilde{E}_t B_{t+1} \] (16)

where \( \tilde{E}_t \) is the conditional mathematical expectation taken with respect to a one-step transition density that has been formed by multiplying the original transition density with the likelihood ratio

\[ m_{t+1}^t = \frac{p_{t+1}^t}{E_t p_{t+1}^t} \]

It follows from equation (16) that

\[ \tilde{E}_t \pi_{t+1} = \tilde{E}_t B_{t+1} - \tilde{E}_t B_{t+1} = 0 \]

which asserts that \( \{\pi_{t+1}\} \) is a martingale difference sequence under the distorted probability measure, and that \( \{\Pi_t\} \) is a martingale under the distorted probability measure.

In the tax-smoothing model of Robert Barro [7], government debt is a random walk.

In the current model, government debt \( \{B_t\} \) is not a random walk, but the excess payoff \( \{\Pi_t\} \) on it is.

13.4 Implementation

The following code provides functions for

1. Solving for the Ramsey plan given a specification of the economy.
2. Simulating the dynamics of the major variables.
CHAPTER 13. OPTIMAL TAXATION IN AN LQ ECONOMY

Description and clarifications are given below

In [3]: # Set up a namedtuple to store data on the model economy
   Economy = namedtuple('economy',
   ('β',   # Discount factor
    'Sg',  # Govt spending selector matrix
    'Sd',  # Exogenous endowment selector matrix
    'Sb',  # Utility parameter selector matrix
    'Ss',  # Coupon payments selector matrix
    'discrete',  # Discrete or continuous -- boolean
    'proc'))  # Stochastic process parameters

   # Set up a namedtuple to store return values for compute_paths()
   Path = namedtuple('path',
   ('g',   # Govt spending
    'd',  # Endowment
    'b',  # Utility shift parameter
    's',  # Coupon payment on existing debt
    'c',  # Consumption
    'l',  # Labor
    'p',  # Price
    'τ',  # Tax rate
    'rvn',  # Revenue
    'B',  # Govt debt
    'R',  # Risk-free gross return
    'π',  # One-period risk-free interest rate
    'Π',  # Cumulative rate of return, adjusted
    'ξ')  # Adjustment factor for Π

def compute_paths(T, econ):
   """
   Compute simulated time paths for exogenous and endogenous variables.
   
   Parameters
   ===========
   T: int
      Length of the simulation

   econ: a namedtuple of type 'Economy', containing
      β - Discount factor
      Sg - Govt spending selector matrix
      Sd - Exogenous endowment selector matrix
      Sb - Utility parameter selector matrix
      Ss - Coupon payments selector matrix
      discrete - Discrete exogenous process (True or False)
      proc - Stochastic process parameters

   Returns
   =======
   path: a namedtuple of type 'Path', containing
      g - Govt spending
      d - Endowment
      b - Utility shift parameter
      s - Coupon payment on existing debt
      c - Consumption
      l - Labor
      p - Price"""
\[\begin{align*}
\tau & \quad \text{- Tax rate} \\
\text{rvn} & \quad \text{- Revenue} \\
B & \quad \text{- Govt debt} \\
\bar{R} & \quad \text{- Risk-free gross return} \\
\pi & \quad \text{- One-period risk-free interest rate} \\
\Pi & \quad \text{- Cumulative rate of return, adjusted} \\
\xi & \quad \text{- Adjustment factor for } \Pi
\end{align*}\]

The corresponding values are flat numpy ndarrays.

```
# Simplify names
β, Sg, Sd, Sb, Ss = econ.β, econ.Sg, econ.Sd, econ.Sb, econ.Ss

if econ.discrete:
P, x_vals = econ.proc
else:
A, C = econ.proc

# Simulate the exogenous process x
if econ.discrete:
    state = mc_sample_path(P, init=0, sample_size=T)
x = x_vals[:, state]
else:
    # Generate an initial condition x0 satisfying x0 = A x0
    nx, nx = A.shape
    x0 = nullspace((eye(nx) - A))
x0 = -x0 if (x0[nx-1] < 0) else x0
    x0 = x0 / x0[nx-1]

    # Generate a time series x of length T starting from x0
    nx, nw = C.shape
    x = zeros((nx, T))
w = randn(nw, T)
    x[:, 0] = x0.T
    for t in range(1, T):
x[:, t] = A @ x[:, t-1] + C @ w[:, t]

# Compute exogenous variable sequences
g, d, b, s = ((S @ x).flatten() for S in (Sg, Sd, Sb, Ss))

# Solve for Lagrange multiplier in the govt budget constraint
# In fact we solve for \( \nu = \lambda / (1 + 2*\lambda) \). Here \( \nu \) is the
# solution to a quadratic equation \( a(\nu^2 - \nu) + b = 0 \) where
# \( a \) and \( b \) are expected discounted sums of quadratic forms of the state.
Sm = Sb - Sd - Ss

# Compute a and b
if econ.discrete:
    ns = P.shape[0]
    F = scipy.linalg.inv(eye(ns) - β * P)
a0 = 0.5 * (F @ (x_vals.T @ Sm.T)**2)[0]
    H = ((Sb - Sd + Sg) @ x_vals) * ((Sg - Ss) @ x_vals)
b0 = 0.5 * (F @ H.T)[0]
a0, b0 = float(a0), float(b0)
else:
    H = Sm.T @ Sm
    a0 = 0.5 * var_quadratic_sum(A, C, H, β, x0)
```
\[
H = (S_b - S_d + S_g).T @ (S_g + S_s)
\]
\[
b0 = 0.5 * \text{var_quadratic_sum}(A, C, H, \beta, x0)
\]

# Test that \( \nu \) has a real solution before assigning

```
warning_msg = "Warning: you probably set government spending too low. Elect a Republican Congress and start over."
```

```
disc = a0**2 - 4 * a0 * b0
if disc >= 0:
    \( \nu = 0.5 * (a0 - \sqrt{\text{disc}}) / a0 \)
else:
    print("There is no Ramsey equilibrium for these parameters."")
    print(warning_msg.format('high', 'Republican'))
    sys.exit(0)
```

# Test that the Lagrange multiplier has the right sign

```
if \( \nu * (0.5 - \nu) < 0: \)
    print("Negative multiplier on the government budget constraint."")
    print(warning_msg.format('low', 'Democratic'))
    sys.exit(0)
```

# Solve for the allocation given \( \nu \) and \( x \)

```
Sc = 0.5 * (S_b + S_d - S_g - \nu * S_m)
S_l = 0.5 * (S_b - S_d + S_g - \nu * S_m)
c = (Sc @ x).flatten()
l = (S_l @ x).flatten()
p = ((S_b - Sc) @ x).flatten()  # Price without normalization
\( \tau = 1 - l / (b - c) \)
rvn = l * \( \tau \)
```

# Compute remaining variables

```
econ.discrete:
    H = ((S_b - Sc) @ x_vals) * ((S_l - S_g) @ x_vals) - (S_l @ x_vals)**2
    temp = (F @ H.T).flatten()
    B = temp[state] / p
    H = (P[state, :] @ x_vals.T @ (S_b - Sc).T).flatten()
    R = p / (\( \beta \) * H)
    temp = ((P[state, :] @ x_vals.T @ (S_b - Sc).T)).flatten()
    \( \xi = p[1:] / \text{temp[:T-1]} \)
else:
    H = S_l.T @ S_l - (S_b - Sc).T @ (S_l - S_g)
    L = np.empty(T)
    for t in range(T):
        L[t] = var_quadratic_sum(A, C, H, \beta, x[:, t])
        B = L / p
        Rinv = (\( \beta \) * ((S_b - Sc) @ A @ x)).flatten() / p
        R = 1 / Rinv
        AF1 = (S_b - Sc) @ x[:, 1:]
        AF2 = (S_b - Sc) @ A @ x[:, :T-1]
        \( \xi = AF1 / AF2 \)
        \( \xi = \xi . \text{flatt}
```


```
\[ \pi = B[1:] - R[:T-1] * B[:T-1] - \text{rvn[:T-1]} + g[:T-1] \]
\[ \Pi = \text{cumsum}(\pi * \xi) \]
```

# Prepare return values

```
path = Path(g=g, d=d, b=b, s=s, c=c, l=l, p=p,
```
\[ \tau = \tau, \ r_vn = r_vn, \ B = B, \ R = R, \ \pi = \pi, \ \Pi = \Pi, \ \xi = \xi \]

```python
return path

def gen_fig_1(path):
    ""
    The parameter is the path namedtuple returned by compute_paths(). See
    the docstring of that function for details.
    ""

    T = len(path.c)

    # Prepare axes
    num_rows, num_cols = 2, 2
    fig, axes = plt.subplots(num_rows, num_cols, figsize=(14, 10))
    plt.subplots_adjust(hspace=0.4)
    for i in range(num_rows):
        for j in range(num_cols):
            axes[i, j].grid()
            axes[i, j].set_xlabel('Time')
        bbox = (0., 1.02, 1., .102)
        legend_args = {'bbox_to_anchor': bbox, 'loc': 3, 'mode': 'expand'}
        p_args = {'lw': 2, 'alpha': 0.7}

    # Plot consumption, govt expenditure and revenue
    ax = axes[0, 0]
    ax.plot(path.rvn, label=r'\tau_t \ell_t', **p_args)
    ax.plot(path.g, label='$g_t$', **p_args)
    ax.plot(path.c, label='$c_t$', **p_args)
    ax.legend(ncol=3, **legend_args)

    # Plot govt expenditure and debt
    ax = axes[0, 1]
    list(range(1, T+1)), path.rvn, label=r'\tau_t \ell_t',
    ax.plot(list(range(1, T+1)), path.g, label='$g_t$', **p_args)
    ax.plot(list(range(1, T)), path.B[1:T], label='$B_{t+1}$', **p_args)
    ax.legend(ncol=3, **legend_args)

    # Plot risk-free return
    ax = axes[1, 0]
    list(range(1, T+1)), path.R - 1, label='$R_t - 1$', **p_args)
    ax.legend(ncol=1, **legend_args)

    # Plot revenue, expenditure and risk free rate
    ax = axes[1, 1]
    list(range(1, T+1)), path.rvn, label=r'\tau_t \ell_t',
    ax.plot(list(range(1, T+1)), path.g, label='$g_t$', **p_args)
    axes[1, 1].plot(list(range(1, T)), path.pi, label=r'$\pi_{t+1}$',
    ax.legend(ncol=3, **legend_args)

    plt.show()

def gen_fig_2(path):
```

CHAPTER 13. OPTIMAL TAXATION IN AN LQ ECONOMY

The parameter is the path namedtuple returned by compute_paths(). See the docstring of that function for details.

\[ T = \text{len}(\text{path}.c) \]

# Prepare axes
num_rows, num_cols = 2, 1
fig, axes = plt.subplots(num_rows, num_cols, figsize=(10, 10))
plt.subplots_adjust(hspace=0.5)
bbox = (0., 1.02, 1., 0.102)
bbox = (0., 1.02, 1., 0.102)
legend_args = {'bbox_to_anchor': bbox, 'loc': 3, 'mode': 'expand'}
p_args = {'lw': 2, 'alpha': 0.7}

# Plot adjustment factor
ax = axes[0]
ax.plot(list(range(2, T+1)), path.\(\xi\), label=r'\(\xi_t\)', **p_args)
ax.grid()
ax.set_xlabel('Time')
ax.legend(ncol=1, **legend_args)

# Plot adjusted cumulative return
ax = axes[1]
ax.plot(list(range(2, T+1)), path.\(\Pi\), label=r'\(\Pi_t\)', **p_args)
ax.grid()
ax.set_xlabel('Time')
ax.legend(ncol=1, **legend_args)

plt.show()

13.4.1 Comments on the Code

The function \texttt{var_quadratic_sum} imported from \texttt{quadsums} is for computing the value of (11) when the exogenous process \(\{x_t\}\) is of the VAR type described above.

Below the definition of the function, you will see definitions of two \texttt{namedtuple} objects, \texttt{Economy} and \texttt{Path}.

The first is used to collect all the parameters and primitives of a given LQ economy, while the second collects output of the computations.

In Python, a \texttt{namedtuple} is a popular data type from the \texttt{collections} module of the standard library that replicates the functionality of a tuple, but also allows you to assign a name to each tuple element.

These elements can then be references via dotted attribute notation — see for example the use of \texttt{path} in the functions \texttt{gen_fig_1()} and \texttt{gen_fig_2()}.

The benefits of using \texttt{namedtuples}:

- Keeps content organized by meaning.
- Helps reduce the number of global variables.

Other than that, our code is long but relatively straightforward.
13.5 Examples

Let’s look at two examples of usage.

13.5.1 The Continuous Case

Our first example adopts the VAR specification described above. Regarding the primitives, we set

- $\beta = 1/1.05$
- $b_t = 2.135$ and $s_t = d_t = 0$ for all $t$

Government spending evolves according to

$$g_{t+1} - \mu_g = \rho (g_t - \mu_g) + C_g w_{g,t+1}$$

with $\rho = 0.7$, $\mu_g = 0.35$ and $C_g = \mu_g \sqrt{1 - \rho^2}/10$.

Here’s the code

```
In [4]: # == Parameters == #
      \beta = 1 / 1.05
      \rho, mg = .7, .35
      A = eye(2)
      A[0, :] = \rho, mg * (1-\rho)
      C = np.zeros((2, 1))
      C[0, 0] = np.sqrt(1 - \rho**2) * mg / 10
      Sg = np.array((1, 0)).reshape(1, 2)
      Sd = np.array((0, 0)).reshape(1, 2)
      Sb = np.array((0, 2.135)).reshape(1, 2)
      Ss = np.array((0, 0)).reshape(1, 2)
      economy = Economy(\beta=\beta, Sg=Sg, Sd=Sd, Sb=Sb, Ss=Ss,
                       discrete=False, proc=(A, C))

      T = 50
      path = compute_paths(T, economy)
      gen_fig_1(path)
```
The legends on the figures indicate the variables being tracked. Most obvious from the figure is tax smoothing in the sense that tax revenue is much less variable than government expenditure.
13.5. EXAMPLES

See the original manuscript for comments and interpretation.

13.5.2 The Discrete Case

Our second example adopts a discrete Markov specification for the exogenous process.

In [6]: # == Parameters == #
\[ \beta = \frac{1}{1.05} \]
\[ P = \text{np.array}([[[0.8, 0.2, 0.0],
                        [0.0, 0.5, 0.5],
                        [0.0, 0.0, 1.0]]]) \]

# Possible states of the world
# Each column is a state of the world. The rows are [g d b s 1]
\[ x_{\text{vals}} = \text{np.array}([[[0.5, 0.5, 0.25],
                        [0.0, 0.0, 0.0],
                        [2.2, 2.2, 2.2],
                        [0.0, 0.0, 0.0],
                        [1.0, 1.0, 1.0]]) \]
CHAPTER 13. OPTIMAL TAXATION IN AN LQ ECONOMY

\[ S_g = \text{np.array((1, 0, 0, 0, 0)).reshape(1, 5)} \]
\[ S_d = \text{np.array((0, 1, 0, 0, 0)).reshape(1, 5)} \]
\[ S_b = \text{np.array((0, 0, 1, 0, 0)).reshape(1, 5)} \]
\[ S_s = \text{np.array((0, 0, 0, 1, 0)).reshape(1, 5)} \]

\[
\text{economy} = \text{Economy(}\beta=\beta, S_g=S_g, S_d=S_d, S_b=S_b, S_s=S_s, \\
\text{discrete=True, proc=(P, x_vals))}
\]

\[ T = 15 \]
\[ \text{path} = \text{compute_paths(T, economy)} \]
\[ \text{gen_fig_1(path)} \]

The call \text{gen_fig_2(path)} generates

In [7]: \text{gen_fig_2(path)}
13.6 Exercises

13.6.1 Exercise 1

Modify the VAR example given above, setting

\[ g_{t+1} - \mu_g = \rho (g_{t-3} - \mu_g) + C_g w_{g,t+1} \]

with \( \rho = 0.95 \) and \( C_g = 0.7 \sqrt{1 - \rho^2} \).

Produce the corresponding figures.
13.7 Solutions

13.7.1 Exercise 1

In [8]: # == Parameters == #
β = 1 / 1.05
ρ, mg = .95, .35
A = np.array([[0, 0, 0, ρ, mg*(1-ρ)],
               [1, 0, 0, 0, 0],
               [0, 1, 0, 0, 0],
               [0, 0, 1, 0, 0],
               [0, 0, 0, 1, 0]])
C = np.zeros((5, 1))
C[0, 0] = np.sqrt(1 - ρ**2) * mg / 8
Sg = np.array((1, 0, 0, 0, 0)).reshape(1, 5)
Sd = np.array((0, 0, 0, 0, 0)).reshape(1, 5)
# Chosen st. (Sc + Sg) * x0 = 1
Sb = np.array((0, 0, 0, 2.135)).reshape(1, 5)
Ss = np.array((0, 0, 0, 0)).reshape(1, 5)
economy = Economy(β=β, Sg=Sg, Sd=Sd, Sb=Sb,
                    Ss=Ss, discrete=False, proc=(A, C))

T = 50
path = compute_paths(T, economy)

gen_fig_1(path)
In [9]: gen_fig_2(path)
Part III

Multiple Agent Models
Chapter 14

Robust Markov Perfect Equilibrium

14.1 Contents

- Overview 14.2
- Linear Markov Perfect Equilibria with Robust Agents 14.3
- Application 14.4

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

14.2 Overview

This lecture describes a Markov perfect equilibrium with robust agents.

We focus on special settings with

- two players
- quadratic payoff functions
- linear transition rules for the state vector

These specifications simplify calculations and allow us to give a simple example that illustrates basic forces.

This lecture is based on ideas described in chapter 15 of [26] and in Markov perfect equilibrium and Robustness.

Let’s start with some standard imports:

In [2]: import numpy as np
import quantecon as qe
from scipy.linalg import solve
import matplotlib.pyplot as plt
%matplotlib inline

14.2.1 Basic Setup

Decisions of two agents affect the motion of a state vector that appears as an argument of payoff functions of both agents.
As described in Markov perfect equilibrium, when decision-makers have no concerns about the robustness of their decision rules to misspecifications of the state dynamics, a Markov perfect equilibrium can be computed via backward recursion on two sets of equations:

- a pair of Bellman equations, one for each agent.
- a pair of equations that express linear decision rules for each agent as functions of that agent’s continuation value function as well as parameters of preferences and state transition matrices.

This lecture shows how a similar equilibrium concept and similar computational procedures apply when we impute concerns about robustness to both decision-makers.

A Markov perfect equilibrium with robust agents will be characterized by

- a pair of Bellman equations, one for each agent.
- a pair of equations that express linear decision rules for each agent as functions of that agent’s continuation value function as well as parameters of preferences and state transition matrices.
- a pair of equations that express linear decision rules for worst-case shocks for each agent as functions of that agent’s continuation value function as well as parameters of preferences and state transition matrices.

Below, we’ll construct a robust firms version of the classic duopoly model with adjustment costs analyzed in Markov perfect equilibrium.

### 14.3 Linear Markov Perfect Equilibria with Robust Agents

As we saw in Markov perfect equilibrium, the study of Markov perfect equilibria in dynamic games with two players leads us to an interrelated pair of Bellman equations.

In linear quadratic dynamic games, these “stacked Bellman equations” become “stacked Riccati equations” with a tractable mathematical structure.

#### 14.3.1 Modified Coupled Linear Regulator Problems

We consider a general linear quadratic regulator game with two players, each of whom fears model misspecifications.

We often call the players agents.

The agents share a common baseline model for the transition dynamics of the state vector

- this is a counterpart of a ‘rational expectations’ assumption of shared beliefs

But now one or more agents doubt that the baseline model is correctly specified.

The agents express the possibility that their baseline specification is incorrect by adding a contribution \( Cv_{it} \) to the time \( t \) transition law for the state

- \( C \) is the usual volatility matrix that appears in stochastic versions of optimal linear regulator problems.
- \( v_{it} \) is a possibly history-dependent vector of distortions to the dynamics of the state that agent \( i \) uses to represent misspecification of the original model.

For convenience, we’ll start with a finite horizon formulation, where \( t_0 \) is the initial date and \( t_1 \) is the common terminal date.
Player $i$ takes a sequence $\{u_{-it}\}$ as given and chooses a sequence $\{u_{it}\}$ to minimize and $\{v_{it}\}$ to maximize

$$
\sum_{t=t_0}^{t_1-1} \beta^{t-t_0} \{x'_t R_i x_t + u'_t Q_i u_{it} + u'_{-it} S_i u_{-it} + 2x'_t W_i u_{it} + 2u'_{-it} M_i u_{it} - \theta_i v'_t v_{it}\}
$$

while thinking that the state evolves according to

$$
x_{t+1} = Ax_t + B_1 u_{1t} + B_2 u_{2t} + C v_{it}
$$

Here

- $x_t$ is an $n \times 1$ state vector, $u_{it}$ is a $k_i \times 1$ vector of controls for player $i$, and
- $v_{it}$ is an $h \times 1$ vector of distortions to the state dynamics that concern player $i$
- $R_i$ is $n \times n$
- $S_i$ is $k_{-i} \times k_{-i}$
- $Q_i$ is $k_i \times k_i$
- $W_i$ is $n \times k_i$
- $M_i$ is $k_{-i} \times k_i$
- $A$ is $n \times n$
- $B_i$ is $n \times k_i$
- $C$ is $n \times h$
- $\theta_i \in [\theta_i, +\infty]$ is a scalar multiplier parameter of player $i$

If $\theta_i = +\infty$, player $i$ completely trusts the baseline model.

If $\theta_i < \infty$, player $i$ suspects that some other unspecified model actually governs the transition dynamics.

The term $\theta_i v'_t v_{it}$ is a time $t$ contribution to an entropy penalty that an (imaginary) loss-maximizing agent inside agent $i$’s mind charges for distorting the law of motion in a way that harms agent $i$.

- the imaginary loss-maximizing agent helps the loss-minimizing agent by helping him construct bounds on the behavior of his decision rule over a large set of alternative models of state transition dynamics.

### 14.3.2 Computing Equilibrium

We formulate a linear robust Markov perfect equilibrium as follows.

Player $i$ employs linear decision rules $u_{it} = -F_i x_t$, where $F_i$ is a $k_i \times n$ matrix.

Player $i$’s malevolent alter ego employs decision rules $v_{it} = K_i x_t$ where $K_i$ is an $h \times n$ matrix.

A robust Markov perfect equilibrium is a pair of sequences $\{F_{1t}, F_{2t}\}$ and a pair of sequences $\{K_{1t}, K_{2t}\}$ over $t = t_0, \ldots, t_1 - 1$ that satisfy

- $\{F_{1t}, K_{1t}\}$ solves player 1’s robust decision problem, taking $\{F_{2t}\}$ as given, and
- $\{F_{2t}, K_{2t}\}$ solves player 2’s robust decision problem, taking $\{F_{1t}\}$ as given.

If we substitute $u_{2t} = -F_{2t} x_t$ into (1) and (2), then player 1’s problem becomes minimization-maximization of
\[
\sum_{t=t_0}^{t_1-1} \beta^{t-t_0} \{ x_t' \Pi t x_t + u_t' Q_1 u_t + 2 u_t' \Gamma_1 x_t - \theta_1 v'_t v_{1t} \} \tag{3}
\]

subject to
\[
x_{t+1} = \Lambda_1 x_t + B_1 u_t + C v_{1t} \tag{4}
\]

where

- \( \Lambda_{it} := A - B_{-1} Q_{-1} \)
- \( \Pi_{it} := R_i + F_{-it} P_{-it} S_i \)
- \( \Gamma_{it} := W_i' - M_i' Z_{-it} \)

This is an LQ robust dynamic programming problem of the type studied in the Robustness lecture, which can be solved by working backward.

Maximization with respect to distortion \( v_{1t} \) leads to the following version of the \( D \) operator from the Robustness lecture, namely
\[
D_1(P) := P + PC(\theta_1 I - C' PC)^{-1} C' P \tag{5}
\]

The matrix \( F_{it} \) in the policy rule \( u_{1t} = -F_{1t} x_t \) that solves agent 1’s problem satisfies
\[
F_{1t} = (Q_1 + \beta B_1' D_1(P_{1t+1}) B_1)^{-1} (\beta B_1' D_1(P_{1t+1}) A_1 + \Gamma_{1t}) \tag{6}
\]

where \( P_{1t} \) solves the matrix Riccati difference equation
\[
P_{1t} = \Pi_{1t} - (\beta B_1' D_1(P_{1t+1}) A_{1t} + \Gamma_{1t})' (Q_1 + \beta B_1' D_1(P_{1t+1}) B_1)^{-1} (\beta B_1' D_1(P_{1t+1}) A_{1t} + \Gamma_{1t}) + \beta A_{1t}' D_1(P_{1t+1}) A_{1t} \tag{7}
\]

Similarly, the policy that solves player 2’s problem is
\[
F_{2t} = (Q_2 + \beta B_2' D_2(P_{2t+1}) B_2)^{-1} (\beta B_2' D_2(P_{2t+1}) A_{2t} + \Gamma_{2t}) \tag{8}
\]

where \( P_{2t} \) solves
\[
P_{2t} = \Pi_{2t} - (\beta B_2' D_2(P_{2t+1}) A_{2t} + \Gamma_{2t})' (Q_2 + \beta B_2' D_2(P_{2t+1}) B_2)^{-1} (\beta B_2' D_2(P_{2t+1}) A_{2t} + \Gamma_{2t}) + \beta A_{2t}' D_2(P_{2t+1}) A_{2t} \tag{9}
\]

Here in all cases \( t = t_0, \ldots, t_1 - 1 \) and the terminal conditions are \( P_{it_1} = 0 \).

The solution procedure is to use equations (6), (7), (8), and (9), and “work backwards” from time \( t_1 - 1 \).

Since we’re working backwards, \( P_{1t+1} \) and \( P_{2t+1} \) are taken as given at each stage.

Moreover, since

- some terms on the right-hand side of (6) contain \( F_{2t} \)
- some terms on the right-hand side of (8) contain \( F_{1t} \)

we need to solve these \( k_1 + k_2 \) equations simultaneously.
14.3.3 Key Insight

As in Markov perfect equilibrium, a key insight here is that equations (6) and (8) are linear in $F_{1t}$ and $F_{2t}$.

After these equations have been solved, we can take $F_{it}$ and solve for $P_{it}$ in (7) and (9).

Notice how $j$’s control law $F_{jt}$ is a function of $\{F_{is}, s \geq t, i \neq j\}$.

Thus, agent $i$’s choice of $\{F_{it}; t = t_0, \ldots, t_1 - 1\}$ influences agent $j$’s choice of control laws.

However, in the Markov perfect equilibrium of this game, each agent is assumed to ignore the influence that his choice exerts on the other agent’s choice.

After these equations have been solved, we can also deduce associated sequences of worst-case shocks.

14.3.4 Worst-case Shocks

For agent $i$ the maximizing or worst-case shock $v_{it}$ is

$$v_{it} = K_{it}x_t$$

where

$$K_{it} = \theta_i^{-1}(I - \theta_i^{-1}C'P_{i,t+1}C)^{-1}C'P_{i,t+1}(A - B_1F_{it} - B_2F_{2t})$$

14.3.5 Infinite Horizon

We often want to compute the solutions of such games for infinite horizons, in the hope that the decision rules $F_{it}$ settle down to be time-invariant as $t_1 \to +\infty$.

In practice, we usually fix $t_1$ and compute the equilibrium of an infinite horizon game by driving $t_0 \to -\infty$.

This is the approach we adopt in the next section.

14.3.6 Implementation

We use the function nnash_robust to compute a Markov perfect equilibrium of the infinite horizon linear quadratic dynamic game with robust planers in the manner described above.

14.4 Application

14.4.1 A Duopoly Model

Without concerns for robustness, the model is identical to the duopoly model from the Markov perfect equilibrium lecture.

To begin, we briefly review the structure of that model.
Two firms are the only producers of a good the demand for which is governed by a linear inverse demand function

\[ p = a_0 - a_1 (q_1 + q_2) \]  

Here \( p = p_t \) is the price of the good, \( q_i = q_{it} \) is the output of firm \( i = 1, 2 \) at time \( t \) and \( a_0 > 0, a_1 > 0 \).

In (10) and what follows,

- the time subscript is suppressed when possible to simplify notation
- \( \hat{x} \) denotes a next period value of variable \( x \)

Each firm recognizes that its output affects total output and therefore the market price. The one-period payoff function of firm \( i \) is price times quantity minus adjustment costs:

\[ \pi_i = pq_i - \gamma (\hat{q}_i - q_i)^2, \quad \gamma > 0, \]  

Substituting the inverse demand curve (10) into (11) lets us express the one-period payoff as

\[ \pi_i(q_i, q_{-i}, \hat{q}_i) = a_0q_i - a_1q_i^2 - a_1q_iq_{-i} - \gamma(\hat{q}_i - q_i)^2, \]  

where \( q_{-i} \) denotes the output of the firm other than \( i \).

The objective of the firm is to maximize \( \sum_{t=0}^{\infty} \beta^t \pi_{it} \).

Firm \( i \) chooses a decision rule that sets next period quantity \( \hat{q}_i \) as a function \( f_i \) of the current state \( (q_i, q_{-i}) \).

This completes our review of the duopoly model without concerns for robustness.

Now we activate robustness concerns of both firms.

To map a robust version of the duopoly model into coupled robust linear-quadratic dynamic programming problems, we again define the state and controls as

\[ x_t := \begin{bmatrix} 1 \\ q_{1t} \\ q_{2t} \end{bmatrix} \quad \text{and} \quad u_{it} := q_{i,t+1} - q_{it}, \quad i = 1, 2 \]

If we write

\[ x_t' R_i x_t + u_{it}' Q_i u_{it} \]

where \( Q_1 = Q_2 = \gamma \),

\[ R_1 := \begin{bmatrix} 0 & -\frac{a_0}{2} & 0 \\ -\frac{a_0}{2} & a_1 & \frac{a_1}{2} \\ 0 & \frac{a_1}{2} & 0 \end{bmatrix} \quad \text{and} \quad R_2 := \begin{bmatrix} 0 & 0 & -\frac{a_0}{2} \\ 0 & 0 & \frac{a_1}{2} \\ -\frac{a_0}{2} & \frac{a_1}{2} & a_1 \end{bmatrix} \]

then we recover the one-period payoffs (11) for the two firms in the duopoly model.

The law of motion for the state \( x_t \) is \( x_{t+1} = Ax_t + B_1 u_{1t} + B_2 u_{2t} \) where
A robust decision rule of firm $i$ will take the form $u_t = -F_i x_t$, inducing the following closed-loop system for the evolution of $x$ in the Markov perfect equilibrium:

$$x_{t+1} = (A - B_1 F_1 - B_2 F_2) x_t$$ (13)

### 14.4.2 Parameters and Solution

Consider the duopoly model with parameter values of:

- $a_0 = 10$
- $a_1 = 2$
- $\beta = 0.96$
- $\gamma = 12$

From these, we computed the infinite horizon MPE without robustness using the code

In [3]: import numpy as np
import quantecon as qe

# Parameters
a0 = 10.0
a1 = 2.0
beta = 0.96
gamma = 12.0

# In LQ form
A = np.eye(3)
B1 = np.array([[0.], [1.], [0.]])
B2 = np.array([[0.], [0.], [1.]])

R1 = [[ 0., -a0 / 2, 0.],
[ -a0 / 2, a1, a1 / 2.],
[ 0, a1 / 2., 0.]]

R2 = [[ 0., 0., -a0 / 2],
[ 0., 0., a1 / 2.],
[ -a0 / 2, a1 / 2., a1]]

Q1 = Q2 = gamma
S1 = S2 = W1 = W2 = M1 = M2 = 0.0

# Solve using QE's nnash function
F1, F2, P1, P2 = qe.nnash(A, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2, beta=beta)

# Display policies
print("Computed policies for firm 1 and firm 2:

print(F"F1 = \{F1}")
MARKOV PERFECT EQUILIBRIUM

Markov Perfect Equilibrium with Robustness

We add robustness concerns to the Markov Perfect Equilibrium model by extending the function `qe.nnash` into a robustness version by adding the maximization operator $\mathcal{D}(P)$ into the backward induction.

The MPE with robustness function is `nnash_robust`.

The function’s code is as follows

```python
In [4]: def nnash_robust(A, C, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2, 
                  \theta_1, \theta_2, beta=1.0, tol=1e-8, max_iter=1000):
    
    """
    Compute the limit of a Nash linear quadratic dynamic game with robustness concern.

    In this problem, player i minimizes
    .. math::
    \sum_{t=0}^{\infty} \left\{ x_t' r_i x_t + 2 x_t' w_i u_{\{it\}} + u_{\{it\}}' q_i u_{\{it\}} + u_{\{jt\}}' s_i u_{\{jt\}} + 2 u_{\{jt\}}' m_i u_{\{it\}} \right\}
    subject to the law of motion
    .. math::
    x_{\{it+1\}} = A x_t + b_1 u_{\{it\}} + b_2 u_{\{it+1\}} + C w_{\{it+1\}}
    and a perceived control law :math:`u_j(t) = - f_j x_t` for the other player.

    The player i also concerns about the model misspecification, and maximizes
    .. math::
    \sum_{t=0}^{\infty} \left\{ \beta^{t+1} \theta_i w_{\{it+1\}}'w_{\{it+1\}} \right\}
    The solution computed in this routine is the :math:`f_i` and :math:`P_i` of the associated double optimal linear regulator problem.

    Parameters
    ----------
    A : scalar(float) or array_like(float)
```
Corresponds to the MPE equations, should be of size \((n, n)\)

\( C \) : scalar(float) or array_like(float)
   As above, size \((n, c)\), \(c\) is the size of \(w\)

\( B1 \) : scalar(float) or array_like(float)
   As above, size \((n, k_1)\)

\( B2 \) : scalar(float) or array_like(float)
   As above, size \((n, k_2)\)

\( R1 \) : scalar(float) or array_like(float)
   As above, size \((n, n)\)

\( R2 \) : scalar(float) or array_like(float)
   As above, size \((n, n)\)

\( Q1 \) : scalar(float) or array_like(float)
   As above, size \((k_1, k_1)\)

\( Q2 \) : scalar(float) or array_like(float)
   As above, size \((k_2, k_2)\)

\( S1 \) : scalar(float) or array_like(float)
   As above, size \((k_1, k_1)\)

\( S2 \) : scalar(float) or array_like(float)
   As above, size \((k_2, k_2)\)

\( W1 \) : scalar(float) or array_like(float)
   As above, size \((n, k_1)\)

\( W2 \) : scalar(float) or array_like(float)
   As above, size \((n, k_2)\)

\( M1 \) : scalar(float) or array_like(float)
   As above, size \((k_2, k_1)\)

\( M2 \) : scalar(float) or array_like(float)
   As above, size \((k_1, k_2)\)

\( \theta_1 \) : scalar(float)
   Robustness parameter of player 1

\( \theta_2 \) : scalar(float)
   Robustness parameter of player 2

\( beta \) : scalar(float), optional(default=1.0)
   Discount factor

\( tol \) : scalar(float), optional(default=1e-8)
   This is the tolerance level for convergence

\( max_iter \) : scalar(int), optional(default=1000)
   This is the maximum number of iterations allowed

Returns
-------

\( F1 \) : array_like, dtype=float, shape\(=(k_1, n)\)
   Feedback law for agent 1

\( F2 \) : array_like, dtype=float, shape\(=(k_2, n)\)
   Feedback law for agent 2

\( P1 \) : array_like, dtype=float, shape\(=(n, n)\)
   The steady-state solution to the associated discrete matrix Riccati equation for agent 1

\( P2 \) : array_like, dtype=float, shape\(=(n, n)\)
   The steady-state solution to the associated discrete matrix Riccati equation for agent 2

# Unload parameters and make sure everything is a matrix
params = A, C, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2
params = map(np.assmatrix, params)
A, C, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2 = params
# Multiply A, B1, B2 by sqrt(β) to enforce discounting
A, B1, B2 = [np.sqrt(β) * x for x in (A, B1, B2)]

# Initial values
n = A.shape[0]
k_1 = B1.shape[1]
k_2 = B2.shape[1]

v1 = np.eye(k_1)
v2 = np.eye(k_2)
P1 = np.eye(n) * 1e-5
P2 = np.eye(n) * 1e-5
F1 = np.random.randn(k_1, n)
F2 = np.random.randn(k_2, n)

for it in range(max_iter):
    # Update
    F10 = F1
    F20 = F2

    I = np.eye(C.shape[1])

    # D1(P1)
    # Note: INV1 may not be solved if the matrix is singular
    INV1 = solve(θ1 * I - C.T @ P1 @ C, I)
    D1P1 = P1 + P1 @ C @ INV1 @ C.T @ P1

    # D2(P2)
    # Note: INV2 may not be solved if the matrix is singular
    INV2 = solve(θ2 * I - C.T @ P2 @ C, I)
    D2P2 = P2 + P2 @ C @ INV2 @ C.T @ P2

    G2 = solve(Q2 + B2.T @ D2P2 @ B2, v2)
    G1 = solve(Q1 + B1.T @ D1P1 @ B1, v1)
    H2 = G2 @ B2.T @ D2P2
    H1 = G1 @ B1.T @ D1P1

    # Break up the computation of F1, F2
    F1_left = v1 - (H1 @ B2 + G1 @ M1.T) @ (H2 @ B1 + G2 @ M2.T)
    F1_right = H1 @ A + G1 @ W1.T -
                (H1 @ B2 + G1 @ M1.T) @ (H2 @ A + G2 @ W2.T)
    F1 = solve(F1_left, F1_right)
    F2 = H2 @ A + G2 @ W2.T - (H2 @ B1 + G2 @ M2.T) @ F1

    Λ1 = A - B2 @ F2
    Λ2 = A - B1 @ F1
    Π1 = R1 + F2.T @ S1 @ F2
    Π2 = R2 + F1.T @ S2 @ F1
    Ι1 = W1.T - M1.T @ F2
    Ι2 = W2.T - M2.T @ F1

    # Compute P1 and P2
    P1 = Π1 - (B1.T @ D1P1 @ Α1 + Ι1).T @ F1 + Α1.T @ D1P1 @ Α1
    P2 = Π2 - (B2.T @ D2P2 @ Α2 + Ι2).T @ F2 + Α2.T @ D2P2 @ Α2
dd = np.max(np.abs(F10 - F1)) + np.max(np.abs(F20 - F2))

if dd < tol:  # success!
    break
else:
    raise ValueError(f'No convergence: Iteration limit of {maxiter} reached in nnash')

return F1, F2, P1, P2

14.4.3 Some Details

Firm $i$ wants to minimize

$$
\sum_{t=t_0}^{t_1-1} \beta^{t-t_0} \{ x_t' R_i x_t + u_i' Q_i u_t + u_i' S_i u_{i-1} + 2 x_t' W_i u_t \}
$$

where

$$
x_t := \begin{bmatrix} 1 \\ q_{1t} \\ q_{2t} \end{bmatrix} \quad \text{and} \quad u_t := q_{i,t+1} - q_{it}, \quad i = 1, 2
$$

and

$$
R_1 := \begin{bmatrix} 0 & -a_0/2 & 0 \\ -a_0/2 & a_1 & a_0/2 \\ 0 & a_0/2 & 0 \end{bmatrix}, \quad R_2 := \begin{bmatrix} 0 & 0 & -a_1/2 \\ 0 & 0 & a_1/2 \\ -a_1/2 & a_1/2 & a_1 \end{bmatrix}, \quad Q_1 = Q_2 = \gamma, \quad S_1 = S_2 = 0, \quad W_1 = W_2 = 0, \quad M_1 = M_2 = 0
$$

The parameters of the duopoly model are:

- $a_0 = 10$
- $a_1 = 2$
- $\beta = 0.96$
- $\gamma = 12$

In [5]:  # Parameters
  a0 = 10.0
  a1 = 2.0
  beta = 0.96
  gamma = 12.0

  # In LQ form
  A = np.eye(3)
  B1 = np.array([[0.0, 0.0, 0.0]])
  B2 = np.array([[1.0, 0.0, 0.0]])
  R1 = [[0.0, -a0 / 2, 0.0],
        [0.0, 0.0, 0.0],
        [0.0, 0.0, 0.0]]
\[
\begin{bmatrix}
-a_0 / 2. & a_1, & a_1 / 2. \\
0, & a_1 / 2. & 0.
\end{bmatrix}
\]

\[
R_2 = \begin{bmatrix}
0., & 0., & -a_0 / 2 \\
0., & 0., & a_1 / 2, \\
-a_0 / 2, & a_1 / 2, & a_1
\end{bmatrix}
\]

\[Q_1 = Q_2 = \gamma \]
\[S_1 = S_2 = W_1 = W_2 = M_1 = M_2 = 0.0\]

Consistency Check

We first conduct a comparison test to check if `nnash_robust` agrees with `qe.nnash` in the non-robustness case in which each \( \theta_i \approx +\infty \)

In [6]: # Solve using QE's nnash function

\[
F_1, F_2, P_1, P_2 = \text{qe.nnash}(A, B_1, B_2, R_1, R_2, Q_1, \\
Q_2, S_1, S_2, W_1, W_2, M_1, \\
M_2, \text{beta}=eta)
\]

# Solve using nnash_robust

\[
F_{1r}, F_{2r}, P_{1r}, P_{2r} = \text{nnash}_\text{robust}(A, \text{np.zeros((3, 1))), B_1, B_2, R_1, R_2, Q_1, \\
Q_2, S_1, S_2, W_1, W_2, M_1, M_2, 1e-10, \\
1e-10, \text{beta}=eta)
\]

print('F1 and F1r should be the same: ', np.allclose(F1, F1r))
print('F2 and F2r should be the same: ', np.allclose(F1, F1r))
print('P1 and P1r should be the same: ', np.allclose(P1, P1r))
print('P2 and P2r should be the same: ', np.allclose(P1, P1r))

F1 and F1r should be the same: True
F2 and F2r should be the same: True
P1 and P1r should be the same: True
P2 and P2r should be the same: True

We can see that the results are consistent across the two functions.

Comparative Dynamics under Baseline Transition Dynamics

We want to compare the dynamics of price and output under the baseline MPE model with those under the baseline model under the robust decision rules within the robust MPE.

This means that we simulate the state dynamics under the MPE equilibrium closed-loop transition matrix

\[
A^o = A - B_1 F_1 - B_2 F_2
\]

where \( F_1 \) and \( F_2 \) are the firms’ robust decision rules within the robust markov_perfect equilibrium

- by simulating under the baseline model transition dynamics and the robust MPE rules we are in assuming that at the end of the day firms’ concerns about misspecification of the baseline model do not materialize.
14.4. APPLICATION

- a short way of saying this is that misspecification fears are all ‘just in the minds’ of the firms.
- simulating under the baseline model is a common practice in the literature.
- note that some assumption about the model that actually governs the data has to be made in order to create a simulation.
- later we will describe the (erroneous) beliefs of the two firms that justify their robust decisions as best responses to transition laws that are distorted relative to the baseline model.

After simulating $x_t$ under the baseline transition dynamics and robust decision rules $F_i, i = 1, 2$, we extract and plot industry output $q_t = q_{1t} + q_{2t}$ and price $p_t = a_0 - a_1 q_t$.

Here we set the robustness and volatility matrix parameters as follows:

- $\theta_1 = 0.02$
- $\theta_2 = 0.04$
- $C = \begin{pmatrix} 0 & 0.01 \\ 0.01 & 0.01 \end{pmatrix}$

Because we have set $\theta_1 < \theta_2 < +\infty$ we know that

- both firms fear that the baseline specification of the state transition dynamics are incorrect.
- firm 1 fears misspecification more than firm 2.

In [7]: # Robustness parameters and matrix
C = np.asmatrix([[0], [0.01], [0.01]])
θ1 = 0.02
θ2 = 0.04
n = 20

# Solve using nash_robust
F1r, F2r, P1r, P2r = nnash_robust(A, C, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2, θ1, θ2, beta=β)

# MPE output and price
AF = A - B1 @ F1 - B2 @ F2
x = np.empty((3, n))
x[:, 0] = 1, 1, 1
for t in range(n - 1):
    x[:, t+1] = AF @ x[:, t]
q1 = x[1, :]
q2 = x[2, :]
q = q1 + q2  # Total output, MPE
p = a0 - a1 * q  # Price, MPE

# RMPE output and price
AO = A - B1 @ F1r - B2 @ F2r
xr = np.empty((3, n))
xr[:, 0] = 1, 1, 1
for t in range(n - 1):
    xr[:, t+1] = AO @ xr[:, t]
 qr1 = xr[1, :]
 qr2 = xr[2, :]
 qr = qr1 + qr2  # Total output, RMPE
 pr = a0 - a1 * qr  # Price, RMPE

 # RMPE heterogeneous beliefs output and price
 I = np.eye(C.shape[1])
 INV1 = solve(θ1 * I - C.T @ P1 @ C, I)
 K1 = P1 @ C @ INV1 @ C.T @ P1 @ AO
 AOCK1 = AO + C.T @ INV1 @ C.T @ P1 @ AO

 INV2 = solve(θ2 * I - C.T @ P2 @ C, I)
 K2 = P2 @ C @ INV2 @ C.T @ P2 @ AO
 AOCK2 = AO + C.T @ INV2 @ C.T @ P2 @ AO

 xrp1 = np.empty((3, n))
 xrp2 = np.empty((3, n))
 xrp1[:, 0] = 1, 1, 1
 xrp2[:, 0] = 1, 1, 1
 for t in range(n - 1):
     xrp1[:, t + 1] = AOCK1 @ xrp1[:, t]
     xrp2[:, t + 1] = AOCK2 @ xrp2[:, t]

 qrp11 = xrp1[1, :]
 qrp12 = xrp1[2, :]
 qrp21 = xrp2[1, :]
 qrp22 = xrp2[2, :]
 qrp1 = qrp11 + qrp12  # Total output, RMPE from player 1's belief
 qrp2 = qrp21 + qrp22  # Total output, RMPE from player 2's belief
 prp1 = a0 - a1 * qrp1  # Price, RMPE from player 1's belief
 prp2 = a0 - a1 * qrp2  # Price, RMPE from player 2's belief

The following code prepares graphs that compare market-wide output \( q_{1t} + q_{2t} \) and the price of the good \( p_t \) under equilibrium decision rules \( F_i, i = 1, 2 \) from an ordinary Markov perfect equilibrium and the decision rules under a Markov perfect equilibrium with robust firms with multiplier parameters \( \theta_i, i = 1, 2 \) set as described above.

Both industry output and price are under the transition dynamics associated with the baseline model; only the decision rules \( F_i \) differ across the two equilibrium objects presented.

In [8]: fig, axes = plt.subplots(2, 1, figsize=(9, 9))

ax = axes[0]
ax.plot(q, 'g-', lw=2, alpha=0.75, label='MPE output')
ax.plot(qr, 'm-', lw=2, alpha=0.75, label='RMPE output')
ax.set(ylabel="output", xlabel="time", ylim=(2, 4))
ax.legend(loc='upper left', frameon=0)

ax = axes[1]
ax.plot(p, 'g-', lw=2, alpha=0.75, label='MPE price')
ax.plot(pr, 'm-', lw=2, alpha=0.75, label='RMPE price')
ax.set(ylabel="price", xlabel="time")
ax.legend(loc='upper right', frameon=0)
plt.show()
Under the dynamics associated with the baseline model, the price path is higher with the Markov perfect equilibrium robust decision rules than it is with decision rules for the ordinary Markov perfect equilibrium.

So is the industry output path.

To dig a little beneath the forces driving these outcomes, we want to plot $q_{1t}$ and $q_{2t}$ in the Markov perfect equilibrium with robust firms and to compare them with corresponding objects in the Markov perfect equilibrium without robust firms.

**In [9]:** fig, axes = plt.subplots(2, 1, figsize=(9, 9))

ax = axes[0]
ax.plot(q1, 'g-', lw=2, alpha=0.75, label='firm 1 MPE output')
ax.plot(qr1, 'b-', lw=2, alpha=0.75, label='firm 1 RMPE output')
ax.set(ylabel="output", xlabel="time", ylim=(1, 2))
ax.legend(loc='upper left', frameon=0)

ax = axes[1]
ax.plot(q2, 'g-', lw=2, alpha=0.75, label='firm 2 MPE output')
ax.plot(qr2, 'r-', lw=2, alpha=0.75, label='firm 2 RMPE output')
ax.set(ylabel="output", xlabel="time", ylim=(1, 2))
Evidently, firm 1’s output path is substantially lower when firms are robust firms while firm 2’s output path is virtually the same as it would be in an ordinary Markov perfect equilibrium with no robust firms.

Recall that we have set $\theta_1 = .02$ and $\theta_2 = .04$, so that firm 1 fears misspecification of the baseline model substantially more than does firm 2

- but also please notice that firm 2’s behavior in the Markov perfect equilibrium with robust firms responds to the decision rule $F_1x_t$ employed by firm 1.
- thus it is something of a coincidence that its output is almost the same in the two equilibria.

Larger concerns about misspecification induce firm 1 to be more cautious than firm 2 in predicting market price and the output of the other firm.

To explore this, we study next how ex-post the two firms’ beliefs about state dynamics differ in the Markov perfect equilibrium with robust firms.

(by ex-post we mean after extremization of each firm’s intertemporal objective)
Heterogeneous Beliefs

As before, let $A^o = A - B_1 F_1 - B_2 F_2$, where in a robust MPE, $F_i$ is a robust decision rule for firm $i$.

Worst-case forecasts of $x_t$ starting from $t = 0$ differ between the two firms.

This means that worst-case forecasts of industry output $q_{1t} + q_{2t}$ and price $p_t$ also differ between the two firms.

To find these worst-case beliefs, we compute the following three “closed-loop” transition matrices

- $A^o$
- $A^o + CK_1$
- $A^o + CK_2$

We call the first transition law, namely, $A^o$, the baseline transition under firms’ robust decision rules.

We call the second and third worst-case transitions under robust decision rules for firms 1 and 2.

From $\{x_t\}$ paths generated by each of these transition laws, we pull off the associated price and total output sequences.

The following code plots them

```python
In [10]: print('Baseline Robust transition matrix AO is: \n', np.round(AO, 3))
print('Player 1\'s worst-case transition matrix AOCK1 is: \n', \nnp.round(AOCK1, 3))
print('Player 2\'s worst-case transition matrix AOCK2 is: \n', \np.round(AOCK2, 3))

Baseline Robust transition matrix AO is:
[[ 1. 0. 0. ]
 [ 0.666 0.682 -0.074]
 [ 0.671 -0.071 0.694]]
Player 1\'s worst-case transition matrix AOCK1 is:
[[ 0.998 0.002 0. ]
 [ 0.664 0.685 -0.074]
 [ 0.669 -0.069 0.694]]
Player 2\'s worst-case transition matrix AOCK2 is:
[[ 0.999 0. 0.001]
 [ 0.665 0.683 -0.073]
 [ 0.67 -0.071 0.695]]
```

```python
In [11]: # == Plot == #
fig, axes = plt.subplots(2, 1, figsize=(9, 9))
ax = axes[0]
ax.plot(qrp1, 'b--', lw=2, alpha=0.75,
        label='RMPE worst-case belief output player 1')
ax.plot(qrp2, 'r:', lw=2, alpha=0.75,
        label='RMPE worst-case belief output player 2')
ax.plot(qr, 'm-', lw=2, alpha=0.75, label='RMPE output')
ax.set(ylabell="output", xlabell="time", ylim=(2, 4))
ax.legend(loc='upper left', frameon=0)
```
We see from the above graph that under robustness concerns, player 1 and player 2 have heterogeneous beliefs about total output and the goods price even though they share the same baseline model and information

- firm 1 thinks that total output will be higher and price lower than does firm 2
- this leads firm 1 to produce less than firm 2

These beliefs justify (or rationalize) the Markov perfect equilibrium robust decision rules. This means that the robust rules are the unique optimal rules (or best responses) to the indicated worst-case transition dynamics.
([26] discuss how this property of robust decision rules is connected to the concept of admissibility in Bayesian statistical decision theory)
Chapter 15

Default Risk and Income Fluctuations

15.1 Contents

• Overview 15.2
• Structure 15.3
• Equilibrium 15.4
• Computation 15.5
• Results 15.6
• Exercises 15.7
• Solutions 15.8

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

15.2 Overview

This lecture computes versions of Arellano’s [4] model of sovereign default.

The model describes interactions among default risk, output, and an equilibrium interest rate that includes a premium for endogenous default risk.

The decision maker is a government of a small open economy that borrows from risk-neutral foreign creditors.

The foreign lenders must be compensated for default risk.

The government borrows and lends abroad in order to smooth the consumption of its citizens.

The government repays its debt only if it wants to, but declining to pay has adverse consequences.

The interest rate on government debt adjusts in response to the state-dependent default probability chosen by government.

The model yields outcomes that help interpret sovereign default experiences, including

• countercyclical interest rates on sovereign debt
• countercyclical trade balances
• high volatility of consumption relative to output

Notably, long recessions caused by bad draws in the income process increase the government’s incentive to default.

This can lead to

• spikes in interest rates
• temporary losses of access to international credit markets
• large drops in output, consumption, and welfare
• large capital outflows during recessions

Such dynamics are consistent with experiences of many countries.

Let’s start with some imports:

In [2]:
```python
import matplotlib.pyplot as plt
import numpy as np
import quantecon as qe
import random
from numba import jit, jitclass, int64, float64
%
```

15.3 Structure

In this section we describe the main features of the model.

15.3.1 Output, Consumption and Debt

A small open economy is endowed with an exogenous stochastically fluctuating potential output stream \( \{ y_t \} \).

Potential output is realized only in periods in which the government honors its sovereign debt.

The output good can be traded or consumed.

The sequence \( \{ y_t \} \) is described by a Markov process with stochastic density kernel \( p(y, y') \).

Households within the country are identical and rank stochastic consumption streams according to

\[
\mathbb{E} \sum_{t=0}^\infty \beta^t u(c_t) \tag{1}
\]

Here

• \( 0 < \beta < 1 \) is a time discount factor
• \( u \) is an increasing and strictly concave utility function

Consumption sequences enjoyed by households are affected by the government’s decision to borrow or lend internationally.
The government is benevolent in the sense that its aim is to maximize (1).

The government is the only domestic actor with access to foreign credit. Because household are averse to consumption fluctuations, the government will try to smooth consumption by borrowing from (and lending to) foreign creditors.

### 15.3.2 Asset Markets

The only credit instrument available to the government is a one-period bond traded in international credit markets. The bond market has the following features:

- The bond matures in one period and is not state contingent.
- A purchase of a bond with face value $B'$ is a claim to $B'$ units of the consumption good next period.
- To purchase $B'$ next period costs $qB'$ now, or, what is equivalent.
- For selling $-B'$ units of next period goods the seller earns $-qB'$ of today’s goods.
  - If $B' < 0$, then $-qB'$ units of the good are received in the current period, for a promise to repay $-B'$ units next period.
  - There is an equilibrium price function $q(B', y)$ that makes $q$ depend on both $B'$ and $y$.

Earnings on the government portfolio are distributed (or, if negative, taxed) lump sum to households. When the government is not excluded from financial markets, the one-period national budget constraint is

$$c = y + B - q(B', y)B'$$

Here and below, a prime denotes a next period value or a claim maturing next period. To rule out Ponzi schemes, we also require that $B \geq -Z$ in every period.

- $Z$ is chosen to be sufficiently large that the constraint never binds in equilibrium.

### 15.3.3 Financial Markets

Foreign creditors:

- are risk neutral
- know the domestic output stochastic process $\{y_t\}$ and observe $y_t, y_{t-1}, \ldots$, at time $t$
- can borrow or lend without limit in an international credit market at a constant international interest rate $r$
- receive full payment if the government chooses to pay
- receive zero if the government defaults on its one-period debt due

When a government is expected to default next period with probability $\delta$, the expected value of a promise to pay one unit of consumption next period is $1 - \delta$.

Therefore, the discounted expected value of a promise to pay $B$ next period is

$$q = \frac{1 - \delta}{1 + r}$$
Next we turn to how the government in effect chooses the default probability $\delta$.

### 15.3.4 Government’s Decisions

At each point in time $t$, the government chooses between

1. defaulting
2. meeting its current obligations and purchasing or selling an optimal quantity of one-period sovereign debt

Defaulting means declining to repay all of its current obligations.

If the government defaults in the current period, then consumption equals current output. But a sovereign default has two consequences:

1. Output immediately falls from $y$ to $h(y)$, where $0 \leq h(y) \leq y$.
   - It returns to $y$ only after the country regains access to international credit markets.
2. The country loses access to foreign credit markets.

### 15.3.5 Reentering International Credit Market

While in a state of default, the economy regains access to foreign credit in each subsequent period with probability $\theta$.

### 15.4 Equilibrium

Informally, an equilibrium is a sequence of interest rates on its sovereign debt, a stochastic sequence of government default decisions and an implied flow of household consumption such that

1. Consumption and assets satisfy the national budget constraint.
2. The government maximizes household utility taking into account
   - the resource constraint
   - the effect of its choices on the price of bonds
   - consequences of defaulting now for future net output and future borrowing and lending opportunities
3. The interest rate on the government’s debt includes a risk-premium sufficient to make foreign creditors expect on average to earn the constant risk-free international interest rate.

To express these ideas more precisely, consider first the choices of the government, which
1. enters a period with initial assets $B$, or what is the same thing, initial debt to be repaid now of $-B$

2. observes current output $y$, and

3. chooses either

4. to default, or

5. to pay $-B$ and set next period’s debt due to $-B’$

In a recursive formulation,

- state variables for the government comprise the pair $(B, y)$
- $v(B, y)$ is the optimum value of the government’s problem when at the beginning of a period it faces the choice of whether to honor or default
- $v_c(B, y)$ is the value of choosing to pay obligations falling due
- $v_d(y)$ is the value of choosing to default

$v_d(y)$ does not depend on $B$ because, when access to credit is eventually regained, net foreign assets equal 0.

Expressed recursively, the value of defaulting is

$$v_d(y) = u(h(y)) + \beta \int \{\theta v(0, y’) + (1 - \theta)v_d(y’}\} p(y, y’)dy’$$

The value of paying is

$$v_c(B, y) = \max_{B’ \geq -Z} \left\{u(y - q(B’, y)B’ + B) + \beta \int v(B’, y’)p(y, y’)dy’ \right\}$$

The three value functions are linked by

$$v(B, y) = \max\{v_c(B, y), v_d(y)\}$$

The government chooses to default when

$$v_c(B, y) < v_d(y)$$

and hence given $B’$ the probability of default next period is

$$\delta(B’, y) := \int 1\{v_c(B’, y’) < v_d(y’)\} p(y, y’)dy’ \quad (4)$$

Given zero profits for foreign creditors in equilibrium, we can combine (3) and (4) to pin down the bond price function:

$$q(B’, y) = \frac{1 - \delta(B’, y)}{1 + r} \quad (5)$$
15.4.1 Definition of Equilibrium

An equilibrium is

- a pricing function \( q(B', y) \),
- a triple of value functions \( (v_c(B, y), v_d(y), v(B, y)) \),
- a decision rule telling the government when to default and when to pay as a function of the state \( (B, y) \), and
- an asset accumulation rule that, conditional on choosing not to default, maps \( (B, y) \) into \( B' \)

such that

- The three Bellman equations for \( (v_c(B, y), v_d(y), v(B, y)) \) are satisfied
- Given the price function \( q(B', y) \), the default decision rule and the asset accumulation decision rule attain the optimal value function \( v(B, y) \), and
- The price function \( q(B', y) \) satisfies equation (5)

15.5 Computation

Let’s now compute an equilibrium of Arellano’s model.

The equilibrium objects are the value function \( v(B, y) \), the associated default decision rule, and the pricing function \( q(B', y) \).

We’ll use our code to replicate Arellano’s results.

After that we’ll perform some additional simulations.

We use a slightly modified version of the algorithm recommended by Arellano.

- The appendix to [4] recommends value function iteration until convergence, updating the price, and then repeating.
- Instead, we update the bond price at every value function iteration step.

The second approach is faster and the two different procedures deliver very similar results.

Here is a more detailed description of our algorithm:

1. Guess a value function \( v(B, y) \) and price function \( q(B', y) \).

2. At each pair \( (B, y) \),
   - update the value of defaulting \( v_d(y) \).
   - update the value of continuing \( v_c(B, y) \).

1. Update the value function \( v(B, y) \), the default rule, the implied ex ante default probability, and the price function.

2. Check for convergence. If converged, stop – if not, go to step 2.

We use simple discretization on a grid of asset holdings and income levels.

The output process is discretized using Tauchen’s quadrature method.

As we have in other places, we will accelerate our code using Numba.
We start by defining the data structure that will help us compile the class (for more information on why we do this, see the lecture on numba.)

In [3]: # Define the data information for the jitclass
    arellano_data = [
        ('B', float64[:]), ('P', float64[:, :]), ('y', float64[:]),
        ('β', float64), ('γ', float64), ('r', float64),
        ('ρ', float64), ('η', float64), ('θ', float64),
        ('def_y', float64[:])
    ]

    # Define utility function
    @jit(nopython=True)
    def u(c, γ):
        return c**((1-γ)/(1-γ))

We then define our jitclass that will store various parameters and contain the code that can apply the Bellman operators and determine the savings policy given prices and value functions.

In [4]: @jitclass(arellano_data)
    class Arellano_Economy:
        
        """
        Arellano 2008 deals with a small open economy whose government
        invests in foreign assets in order to smooth the consumption of
        domestic households. Domestic households receive a stochastic
        path of income.
        """

        Parameters
        ----------
        B : vector(float64)
            A grid for bond holdings
        P : matrix(float64)
            The transition matrix for a country’s output
        y : vector(float64)
            The possible output states
        β : float
            Time discounting parameter
        γ : float
            Risk-aversion parameter
        r : float
            int lending rate
        ρ : float
            Persistence in the income process
        η : float
            Standard deviation of the income process
        θ : float
            Probability of re-entering financial markets in each period
        """

        def __init__(
            self, B, P, y,
            β=0.953, γ=2.0, r=0.017,
            ρ=0.945, η=0.025, θ=0.282
        ):
# Save parameters

```
self.β, self.γ, self.r, = β, γ, r
self.ρ, self.η, self.θ = ρ, η, θ
```

# Compute the mean output

```
self.def_y = np.minimum(0.969 * np.mean(y), y)
```

def bellman_default(self, iy, EVd, EV):

```
"""
The RHS of the Bellman equation when the country is in a defaulted state on their debt
"""

# Unpack certain parameters for simplification
β, γ, θ = self.β, self.γ, self.θ

# Compute continuation value
zero_ind = len(self.B) // 2
cont_value = θ * EV[iy, zero_ind] + (1 - θ) * EVd[iy]
```

```
return u(self.def_y[iy], γ) + β*cont_value
```

def bellman_nondefault(self, iy, iB, q, EV, iB_tp1_star=-1):

```
"""
The RHS of the Bellman equation when the country is not in a defaulted state on their debt
"""

# Unpack certain parameters for simplification
β, γ, θ = self.β, self.γ, self.θ
B, y = self.B, self.y

# Compute the RHS of Bellman equation
if iB_tp1_star < 0:
    iB_tp1_star = self.compute_savings_policy(iy, iB, q, EV)
c = max(y[iy] - q[iy, iB_tp1_star]*B[iB_tp1_star] + B[iB], 1e-14)
```

```
return u(c, γ) + β*EV[iy, iB_tp1_star]
```

def compute_savings_policy(self, iy, iB, q, EV):

```
"""
Finds the debt/savings that maximizes the value function for a particular state given prices and a value function
"""

# Unpack certain parameters for simplification
β, γ, θ = self.β, self.γ, self.θ
B, y = self.B, self.y

# Compute the RHS of Bellman equation
current_max = -1e14
iB_tp1_star = 0
for iB_tp1, B_tp1 in enumerate(B):
    c = max(y[iy] - q[iy, iB_tp1_star]*B[iB_tp1_star] + B[iB], 1e-14)
m = u(c, γ) + β*EV[iy, iB_tp1]
    if m > current_max:
        iB_tp1_star = iB_tp1
        current_max = m
```
15.5. COMPUTATION

```
return iB_tp1_star

We can now write a function that will use this class to compute the solution to our model

In [5]: @jit(nopython=True)
def solve(model, tol=1e-8, maxiter=10_000):
    """
    Given an Arellano_Economy type, this function computes the optimal
    policy and value functions
    """
    # Unpack certain parameters for simplification
    β, γ, r, θ = model.β, model.γ, model.r, model.θ
    B = np.ascontiguousarray(model.B)
    P, y = np.ascontiguousarray(model.P), np.ascontiguousarray(model.y)
    nB, ny = B.size, y.size
    # Allocate space
    iBstar = np.zeros((ny, nB), int64)
    default_prob = np.zeros((ny, nB))
    default_states = np.zeros((ny, nB))
    q = np.ones((ny, nB)) * 0.95
    Vd = np.zeros(ny)
    Vc, V, Vupd = np.zeros((ny, nB)), np.zeros((ny, nB)), np.zeros((ny, nB))
    it = 0
dist = 10.0
    while (it < maxiter) and (dist > tol):
        # Compute expectations used for this iteration
        EV = P@V
        EVd = P@Vd
        for iy in range(ny):
            # Update value function for default state
            Vd[iy] = model.bellman_default(iy, EVd, EV)
            for iB in range(nB):
                # Update value function for non-default state
                iBstar[iy, iB] = model.compute_savings_policy(iy, iB, q, EV)
                Vc[iy, iB] = model.bellman_nondefault(iy, iB, q, EV)
        # Once value functions are updated, can combine them to get
        # the full value function
        Vd_compat = np.reshape(np.repeat(Vd, nB), (ny, nB))
        Vupd[:, :] = np.maximum(Vc, Vd_compat)
        # Can also compute default states and update prices
        default_states[:, :] = 1.0 * (Vd_compat > Vc)
        default_prob[:, :] = P @ default_states
        q[:, :] = (1 - default_prob) / (1 + r)
        # Check tolerance etc...
        dist = np.max(np.abs(Vupd - V))
        V[:, :] = Vupd[:, :]
        it += 1
    return V, Vc, Vd, iBstar, default_prob, default_states, q
```
and, finally, we write a function that will allow us to simulate the economy once we have the policy functions

```python
In [6]: def simulate(model, T, default_states, iBstar, q, y_init=None, B_init=None):
    
    """
    Simulates the Arellano 2008 model of sovereign debt
    
    Parameters
    ----------
    model: Arellano_Economy
        An instance of the Arellano model with the corresponding parameters
    T: integer
        The number of periods that the model should be simulated
    default_states: array(float64, 2)
        A matrix of 0s and 1s that denotes whether the country was in default on their debt in that period (default = 1)
    iBstar: array(float64, 2)
        A matrix which specifies the debt/savings level that a country holds during a given state
    q: array(float64, 2)
        A matrix that specifies the price at which a country can borrow/save for a given state
    y_init: integer
        Specifies which state the income process should start in
    B_init: integer
        Specifies which state the debt/savings state should start
    Returns
    -------
    y_sim: array(float64, 1)
        A simulation of the country's income
    B_sim: array(float64, 1)
        A simulation of the country's debt/savings
    q_sim: array(float64, 1)
        A simulation of the price required to have an extra unit of consumption in the following period
    default_sim: array(bool, 1)
        A simulation of whether the country was in default or not
    """
    # Find index i such that Bgrid[i] is approximately 0
    zero_B_index = np.searchsorted(model.B, 0.0)

    # Set initial conditions
    in_default = False
    max_y_default = 0.969 * np.mean(model.y)
    if y_init == None:
        y_init = np.searchsorted(model.y, model.y.mean())
    if B_init == None:
        B_init = zero_B_index

    # Create Markov chain and simulate income process
    mc = qe.MarkovChain(model.P, model.y)
    y_sim_indices = mc.simulate_indices(T+1, init=y_init)

    # Allocate memory for remaining outputs
    Bi = B_init
    B_sim = np.empty(T)
```

"""Simulates the Arellano 2008 model of sovereign debt"""
15.6 Results

Let's start by trying to replicate the results obtained in [4].

In what follows, all results are computed using Arellano’s parameter values. The values can be seen in the `__init__` method of the `Arellano_Economy` shown above.

- For example, \( r = 0.017 \) matches the average quarterly rate on a 5 year US treasury over the period 1983–2001.

Details on how to compute the figures are reported as solutions to the exercises.

The first figure shows the bond price schedule and replicates Figure 3 of Arellano, where \( y_L \) and \( Y_H \) are particular below average and above average values of output \( y \).
286

CHAPTER 15. DEFAULT RISK AND INCOME FLUCTUATIONS

\[ y_L \] is 5% below the mean of the \( y \) grid values
\[ y_H \] is 5% above the mean of the \( y \) grid values

The grid used to compute this figure was relatively coarse \((n_y, n_B = 21, 251)\) in order to match Arrelano’s findings.

Here’s the same relationships computed on a finer grid \((n_y, n_B = 51, 551)\)

In either case, the figure shows that
• Higher levels of debt (larger \( -B' \)) induce larger discounts on the face value, which correspond to higher interest rates.
• Lower income also causes more discounting, as foreign creditors anticipate greater likelihood of default.

The next figure plots value functions and replicates the right hand panel of Figure 4 of [4].

We can use the results of the computation to study the default probability \( \delta(B', y) \) defined in (4).

The next plot shows these default probabilities over \((B', y)\) as a heat map.

As anticipated, the probability that the government chooses to default in the following period increases with indebtedness and falls with income.

Next let’s run a time series simulation of \( \{y_t\}, \{B_t\} \) and \( q(B_{t+1}, y_t) \).
The grey vertical bars correspond to periods when the economy is excluded from financial markets because of a past default.

One notable feature of the simulated data is the nonlinear response of interest rates. Periods of relative stability are followed by sharp spikes in the discount rate on government debt.

### 15.7 Exercises

#### 15.7.1 Exercise 1

To the extent that you can, replicate the figures shown above

- Use the parameter values listed as defaults in the `__init__` method of the `Arellano_Economy`.
- The time series will of course vary depending on the shock draws.
15.8 Solutions

Compute the value function, policy and equilibrium prices

In [7]: β, γ, r = 0.953, 2.0, 0.017
    ρ, η, θ = 0.945, 0.025, 0.282
    ny = 21
    nB = 251
    Bgrid = np.linspace(-0.45, 0.45, nB)
    mc = qe.markov.tauchen(ρ, η, θ, 3, ny)
    ygrid, P = np.exp(mc.state_values), mc.P
    ae = Arellano_Economy(
        Bgrid, P, ygrid, β=β, γ=γ, r=r, ρ=ρ, η=η, θ=θ
    )

In [8]: V, Vc, Vd, iBstar, default_prob, default_states, q = solve(ae)

Compute the bond price schedule as seen in figure 3 of Arellano (2008)

In [9]: # Create "Y High" and "Y Low" values as 5% devs from mean
    high, low = np.mean(ae.y) * 1.05, np.mean(ae.y) * .95
    iy_high, iy_low = (np.searchsorted(ae.y, x) for x in (high, low))
    fig, ax = plt.subplots(figsize=(10, 6.5))
    ax.set_title("Bond price schedule $q(y, B')$")
    # Extract a suitable plot grid
    x = []
    q_low = []
    q_high = []
    for i in range(nB):
        b = ae.B[i]
        if -0.35 <= b <= 0: # To match fig 3 of Arellano
            x.append(b)
            q_low.append(q[iy_low, i])
            q_high.append(q[iy_high, i])
    ax.plot(x, q_high, label="$y_H$", lw=2, alpha=0.7)
    ax.plot(x, q_low, label="$y_L$", lw=2, alpha=0.7)
    ax.set_xlabel("$B'$")
    ax.legend(loc='upper left', frameon=False)
    plt.show()
Draw a plot of the value functions

In [10]: # Create "Y High" and "Y Low" values as 5% devs from mean
    high, low = np.mean(ae.y) * 1.05, np.mean(ae.y) * .95
    iy_high, iy_low = (np.searchsorted(ae.y, x) for x in (high, low))

    fig, ax = plt.subplots(figsize=(10, 6.5))
    ax.set_title("Value Functions")
    ax.plot(ae.B, V[iy_high], label="$y_{HS}$", lw=2, alpha=0.7)
    ax.plot(ae.B, V[iy_low], label="$y_{LS}$", lw=2, alpha=0.7)
    ax.legend(loc='upper left')
    ax.set(xlabel="$B$", ylabel="$V(y, B)$")
    ax.set_xlim(ae.B.min(), ae.B.max())
    plt.show()
Draw a heat map for default probability

In [11]: xx, yy = ae.B, ae.y
    zz = default_prob

# Create figure
fig, ax = plt.subplots(figsize=(10, 6.5))
hm = ax.pcolormesh(xx, yy, zz)
cax = fig.add_axes([.92, .1, .02, .8])
fig.colorbar(hm, cax=cax)
ax.axis([xx.min(), 0.05, yy.min(), yy.max()])
ax.set(xlabel='$B$', ylabel='$y$', title='Probability of Default')
plt.show()
Plot a time series of major variables simulated from the model

In [12]: T = 250

```
np.random.seed(42)
y_vec, B_vec, q_vec, default_vec = simulate(ae, T, default_states, \n\begin{equation}
\omega_1B_{\star}, q)
```

# Pick up default start and end dates
start_end_pairs = []
i = 0
while i < len(default_vec):
    if default_vec[i] == 0:
        i += 1
    else:
        # If we get to here we're in default
        start_default = i
        while i < len(default_vec) and default_vec[i] == 1:
            i += 1
        end_default = i - 1
        start_end_pairs.append((start_default, end_default))

plot_series = (y_vec, B_vec, q_vec)
titles = 'output', 'foreign assets', 'bond price'

fig, axes = plt.subplots(len(plot_series), 1, figsize=(10, 12))
fig.subplots_adjust(hspace=0.3)

for ax, series, title in zip(axes, plot_series, titles):
    # Determine suitable y limits
    s_max, s_min = max(series), min(series)
    s_range = s_max - s_min
    y_max = s_max + s_range * 0.1
    y_min = s_min - s_range * 0.1

```
ax.set_ylim(y_min, y_max)
for pair in start_end_pairs:
    ax.fill_between(pair, (y_min, y_min), (y_max, y_min),
                    color='k', alpha=0.3)
ax.grid()
ax.plot(range(T), series, lw=2, alpha=0.7)
ax.set(title=title, xlabel="time")
plt.show()
Chapter 16

Globalization and Cycles

16.1 Contents

- Overview 16.2
- Key Ideas 16.3
- Model 16.4
- Simulation 16.5
- Exercises 16.6
- Solutions 16.7

16.2 Overview

In this lecture, we review the paper Globalization and Synchronization of Innovation Cycles by Kiminori Matsuyama, Laura Gardini and Iryna Sushko.

This model helps us understand several interesting stylized facts about the world economy.

One of these is synchronized business cycles across different countries.

Most existing models that generate synchronized business cycles do so by assumption, since they tie output in each country to a common shock.

They also fail to explain certain features of the data, such as the fact that the degree of synchronization tends to increase with trade ties.

By contrast, in the model we consider in this lecture, synchronization is both endogenous and increasing with the extent of trade integration.

In particular, as trade costs fall and international competition increases, innovation incentives become aligned and countries synchronize their innovation cycles.

Let’s start with some imports:

```
In [1]: import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
import seaborn as sns
from numba import jit, vectorize
from ipywidgets import interact
```
16.2.1 Background

The model builds on work by Judd [36], Deneckner and Judd [18] and Helpman and Krugman [33] by developing a two-country model with trade and innovation.

On the technical side, the paper introduces the concept of coupled oscillators to economic modeling.

As we will see, coupled oscillators arise endogenously within the model.

Below we review the model and replicate some of the results on synchronization of innovation across countries.

16.3 Key Ideas

It is helpful to begin with an overview of the mechanism.

16.3.1 Innovation Cycles

As discussed above, two countries produce and trade with each other.

In each country, firms innovate, producing new varieties of goods and, in doing so, receiving temporary monopoly power.

Imitators follow and, after one period of monopoly, what had previously been new varieties now enter competitive production.

Firms have incentives to innovate and produce new goods when the mass of varieties of goods currently in production is relatively low.

In addition, there are strategic complementarities in the timing of innovation.

Firms have incentives to innovate in the same period, so as to avoid competing with substitutes that are competitively produced.

This leads to temporal clustering in innovations in each country.

After a burst of innovation, the mass of goods currently in production increases.

However, goods also become obsolete, so that not all survive from period to period.

This mechanism generates a cycle, where the mass of varieties increases through simultaneous innovation and then falls through obsolescence.

16.3.2 Synchronization

In the absence of trade, the timing of innovation cycles in each country is decoupled.

This will be the case when trade costs are prohibitively high.

If trade costs fall, then goods produced in each country penetrate each other’s markets.

As illustrated below, this leads to synchronization of business cycles across the two countries.
16.4 Model

Let’s write down the model more formally.
(The treatment is relatively terse since full details can be found in the original paper)

Time is discrete with $t = 0, 1, \ldots$.

There are two countries indexed by $j$ or $k$.

In each country, a representative household inelastically supplies $L_j$ units of labor at wage rate $w_{j,t}$.

Without loss of generality, it is assumed that $L_1 \geq L_2$.

Households consume a single nontradeable final good which is produced competitively.

Its production involves combining two types of tradeable intermediate inputs via

$$Y_{k,t} = C_{k,t} = \left( \frac{X^0_{k,t}}{1 - \alpha} \right)^{1-\alpha} \left( \frac{X_{k,t}}{\alpha} \right)^{\alpha}$$

Here $X^0_{k,t}$ is a homogeneous input which can be produced from labor using a linear, one-for-one technology.

It is freely tradeable, competitively supplied, and homogeneous across countries.

By choosing the price of this good as numeraire and assuming both countries find it optimal to always produce the homogeneous good, we can set $w_{1,t} = w_{2,t} = 1$.

The good $X_{k,t}$ is a composite, built from many differentiated goods via

$$X^{1-\frac{1}{\sigma}}_{k,t} = \int_{\Omega_t} \left[ x_{k,t}(\nu) \right]^{1-\frac{1}{\sigma}} d\nu$$

Here $x_{k,t}(\nu)$ is the total amount of a differentiated good $\nu \in \Omega_t$ that is produced.

The parameter $\sigma > 1$ is the direct partial elasticity of substitution between a pair of varieties and $\Omega_t$ is the set of varieties available in period $t$.

We can split the varieties into those which are supplied competitively and those supplied monopolistically; that is, $\Omega_t = \Omega^c_t + \Omega^m_t$.

16.4.1 Prices

Demand for differentiated inputs is

$$x_{k,t}(\nu) = \left( \frac{p_{k,t}(\nu)}{P_{k,t}} \right)^{-\sigma} \frac{\alpha L_k}{P_{k,t}}$$

Here

- $p_{k,t}(\nu)$ is the price of the variety $\nu$ and
- $P_{k,t}$ is the price index for differentiated inputs in $k$, defined by

$$\left[ P_{k,t} \right]^{1-\sigma} = \int_{\Omega_t} \left[ p_{k,t}(\nu) \right]^{1-\sigma} d\nu$$
The price of a variety also depends on the origin, \( j \), and destination, \( k \), of the goods because shipping varieties between countries incurs an iceberg trade cost \( \tau_{j,k} \).

Thus the effective price in country \( k \) of a variety \( \nu \) produced in country \( j \) becomes \( p_{k,t}(\nu) = \tau_{j,k} p_{j,t}(\nu) \).

Using these expressions, we can derive the total demand for each variety, which is

\[
D_{j,t}(\nu) = \sum_k \tau_{j,k} x_{k,t}(\nu) = \alpha A_{j,t}(p_{j,t}(\nu))^{-\sigma}
\]

where

\[
A_{j,t} := \sum_k \frac{\rho_{j,k} L_k}{(P_{k,t})^{1-\sigma}} \quad \text{and} \quad \rho_{j,k} = (\tau_{j,k})^{-\sigma} \leq 1
\]

It is assumed that \( \tau_{1,1} = \tau_{2,2} = 1 \) and \( \tau_{1,2} = \tau_{2,1} = \tau \) for some \( \tau > 1 \), so that

\[
\rho_{1,2} = \rho_{2,1} = \rho := \tau^{1-\sigma} < 1
\]

The value \( \rho \in [0, 1) \) is a proxy for the degree of globalization.

Producing one unit of each differentiated variety requires \( \psi \) units of labor, so the marginal cost is equal to \( \psi \) for \( \nu \in \Omega_{j,t} \).

Additionally, all competitive varieties will have the same price (because of equal marginal cost), which means that, for all \( \nu \in \Omega^c \),

\[
p_{j,t}(\nu) = p_{j,t}^c := \psi \quad \text{and} \quad D_{j,t} = y_{j,t}^c := \alpha A_{j,t}(p_{j,t}^c)^{-\sigma}
\]

Monopolists will have the same marked-up price, so, for all \( \nu \in \Omega^m \),

\[
p_{j,t}(\nu) = p_{j,t}^m := \frac{\psi}{1 - \frac{1}{\sigma}} \quad \text{and} \quad D_{j,t} = y_{j,t}^m := \alpha A_{j,t}(p_{j,t}^m)^{-\sigma}
\]

Define

\[
\theta := \frac{p_{j,t}^c y_{j,t}^c}{p_{j,t}^m y_{j,t}^m} = \left(1 - \frac{1}{\sigma}\right)^{1-\sigma}
\]

Using the preceding definitions and some algebra, the price indices can now be rewritten as

\[
\left(\frac{P_{k,t}}{\psi}\right)^{1-\sigma} = M_{k,t} + \rho M_{j,t} \quad \text{where} \quad M_{j,t} := N_{j,t}^c + \frac{N_{j,t}^m}{\theta}
\]

The symbols \( N_{j,t}^c \) and \( N_{j,t}^m \) will denote the measures of \( \Omega^c \) and \( \Omega^m \) respectively.

### 16.4.2 New Varieties

To introduce a new variety, a firm must hire \( f \) units of labor per variety in each country.

Monopolist profits must be less than or equal to zero in expectation, so
\[ N_{j,t}^m \geq 0, \quad \pi_{j,t}^m := (p_{j,t}^m - \psi)y_{j,t}^m - f \leq 0 \quad \text{and} \quad \pi_{j,t}^m N_{j,t}^m = 0 \]

With further manipulations, this becomes

\[ N_{j,t}^m = \theta(M_{j,t} - N_{j,t}^c) \geq 0, \quad \frac{1}{\sigma} \left[ \frac{\alpha L_j}{\theta(M_{j,t} + \rho M_{k,t})} + \frac{\alpha L_k}{\theta(M_{j,t} + M_{k,t}/\rho)} \right] \leq f \]

### 16.4.3 Law of Motion

With \( \delta \) as the exogenous probability of a variety becoming obsolete, the dynamic equation for the measure of firms becomes

\[ N_{j,t+1}^c = \delta(N_{j,t}^c + N_{j,t}^m) = \delta(N_{j,t}^c + \theta(M_{j,t} - N_{j,t}^c)) \]

We will work with a normalized measure of varieties

\[ n_{j,t} := \frac{\theta\sigma f N_{j,t}^c}{\alpha(L_1 + L_2)}, \quad i_{j,t} := \frac{\theta\sigma f N_{j,t}^m}{\alpha(L_1 + L_2)}, \quad m_{j,t} := \frac{\theta\sigma f M_{j,t}}{\alpha(L_1 + L_2)} = n_{j,t} + i_{j,t} \]

We also use \( s_j := \frac{L_j}{L_1 + L_2} \) to be the share of labor employed in country \( j \).

We can use these definitions and the preceding expressions to obtain a law of motion for \( n_t := (n_{1,t}, n_{2,t}) \).

In particular, given an initial condition, \( n_0 = (n_{1,0}, n_{2,0}) \in \mathbb{R}^2_+ \), the equilibrium trajectory, \( \{n_t\}_{t=0}^{\infty} = \{(n_{1,t}, n_{2,t})\}_{t=0}^{\infty} \), is obtained by iterating on \( n_{t+1} = F(n_t) \) where \( F: \mathbb{R}^2_+ \rightarrow \mathbb{R}^2_+ \) is given by

\[
F(n_t) = \begin{cases} 
\delta(\theta s_1(\rho) + (1 - \theta)n_{1,t}), & \text{for } n_t \in D_{LL} \\
\delta n_{1,t}, & \text{for } n_t \in D_{HH} \\
\delta(\theta h_1(n_{2,t}) + (1 - \theta)n_{2,t}), & \text{for } n_t \in D_{HL} \\
\delta(\theta h_1(n_{2,t}) + (1 - \theta)n_{1,t}, \delta n_{2,t}), & \text{for } n_t \in D_{LH}
\end{cases}
\]

Here

\[ D_{LL} := \{(n_1, n_2) \in \mathbb{R}^2_+ \mid n_1 \leq s_j(\rho)\} \]
\[ D_{HH} := \{(n_1, n_2) \in \mathbb{R}^2_+ \mid n_1 \geq h_j(\rho)\} \]
\[ D_{HL} := \{(n_1, n_2) \in \mathbb{R}^2_+ \mid n_1 \geq s_1(\rho) \text{ and } n_2 \leq h_2(n_1)\} \]
\[ D_{LH} := \{(n_1, n_2) \in \mathbb{R}^2_+ \mid n_1 \leq h_1(n_2) \text{ and } n_2 \geq s_2(\rho)\} \]

while

\[ s_1(\rho) = 1 - s_2(\rho) = \min\left\{ \frac{s_1 - \rho s_2}{1 - \rho}, 1 \right\} \]

and \( h_j(n_k) \) is defined implicitly by the equation

\[ 1 = \frac{s_j}{h_j(n_k) + \rho n_k} + \frac{s_k}{h_j(n_k) + n_k/\rho} \]
Rewriting the equation above gives us a quadratic equation in terms of $h_j(n_k)$.

Since we know $h_j(n_k) > 0$ then we can just solve the quadratic equation and return the positive root.

This gives us

$$h_j(n_k)^2 + \left( (\rho + \frac{1}{\rho})n_k - s_j - s_k \right) h_j(n_k) + \left( n_k^2 - \frac{s_j n_k}{\rho} - s_k n_k \rho \right) = 0$$

### 16.5 Simulation

Let’s try simulating some of these trajectories.

We will focus in particular on whether or not innovation cycles synchronize across the two countries.

As we will see, this depends on initial conditions.

For some parameterizations, synchronization will occur for “most” initial conditions, while for others synchronization will be rare.

The computational burden of testing synchronization across many initial conditions is not trivial.

In order to make our code fast, we will use just in time compiled functions that will get called and handled by our class.

These are the `@jit` statements that you see below (review this lecture if you don’t recall how to use JIT compilation).

Here’s the main body of code

```python
In [2]: @jit(nopython=True)
   def _hj(j, nk, s1, s2, θ, δ, ρ):

   # Find out who’s h we are evaluating
   if j == 1:
       sj = s1
       sk = s2
   else:
       sj = s2
       sk = s1

   # Coefficients on the quadratic a x^2 + b x + c = 0
   a = 1.0
   b = ((ρ + 1 / ρ) * nk - sj - sk)
   c = (nk * nk - (sj * nk) / ρ - sk * ρ * nk)

   # Positive solution of quadratic form
   root = (-b + np.sqrt(b * b - 4 * a * c)) / (2 * a)

   return root
```
@jit(nopython=True)
def DLL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
    """Determine whether (n1, n2) is in the set DLL"
    return (n1 <= s1_ρ) and (n2 <= s2_ρ)

@jit(nopython=True)
def DHH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
    """Determine whether (n1, n2) is in the set DHH"
    return (n1 >= _hj(1, n2, s1, s2, θ, δ, ρ)) and (n2 >= _hj(2, n1, s1, s2, θ, δ, ρ))

@jit(nopython=True)
def DHL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
    """Determine whether (n1, n2) is in the set DHL"
    return (n1 >= s1_ρ) and (n2 <= _hj(2, n1, s1, s2, θ, δ, ρ))

@jit(nopython=True)
def DLH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
    """Determine whether (n1, n2) is in the set DLH"
    return (n1 <= _hj(1, n2, s1, s2, θ, δ, ρ)) and (n2 >= s2_ρ)

@jit(nopython=True)
def one_step(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
    """Takes a current value for (n_{1, t}, n_{2, t}) and returns the values (n_{1, t+1}, n_{2, t+1}) according to the law of motion."
    # Depending on where we are, evaluate the right branch
    if DLL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
        n1_tp1 = δ * (θ * s1_ρ + (1 - θ) * n1)
        n2_tp1 = δ * (1 - θ) * n2
    elif DHH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
        n1_tp1 = δ * n1
        n2_tp1 = δ * n2
    elif DHL(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
        n1_tp1 = δ * n1
        n2_tp1 = δ * _hj(2, n1, s1, s2, θ, δ, ρ) + (1 - θ) * n2
    elif DLH(n1, n2, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
        n1_tp1 = δ * _hj(1, n2, s1, s2, θ, δ, ρ) + (1 - θ) * n1
        n2_tp1 = δ * n2
    return n1_tp1, n2_tp1

@jit(nopython=True)
def n_generator(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ):
    """Given an initial condition, continues to yield new values of n1 and n2"
    n1_t, n2_t = n1_0, n2_0
    while True:
        n1_tp1, n2_tp1 = one_step(n1_t, n2_t, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)
        yield (n1_tp1, n2_tp1)
        n1_t, n2_t = n1_tp1, n2_tp1

@jit(nopython=True)
def _pers_till_sync(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ, maxiter, npers):
Takes initial values and iterates forward to see whether the histories eventually end up in sync.

If countries are symmetric then as soon as the two countries have the same measure of firms then they will be synchronized -- However, if they are not symmetric then it is possible they have the same measure of firms but are not yet synchronized. To address this, we check whether firms stay synchronized for `npers` periods with Euclidean norm

Parameters
----------

- **n1_0**: scalar(Float)
  - Initial normalized measure of firms in country one
- **n2_0**: scalar(Float)
  - Initial normalized measure of firms in country two
- **maxiter**: scalar(Int)
  - Maximum number of periods to simulate
- **npers**: scalar(Int)
  - Number of periods we would like the countries to have the same measure for

Returns
-------

- **synchronized**: scalar(Bool)
  - Did the two economies end up synchronized
- **pers_2_sync**: scalar(Int)
  - The number of periods required until they synchronized

```python
# Initialize the status of synchronization
synchronized = False
pers_2_sync = maxiter
iters = 0

# Initialize generator
n_gen = n_generator(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)

# Will use a counter to determine how many times in a row
# the firm measures are the same
nsync = 0

while (not synchronized) and (iters < maxiter):
    # Increment the number of iterations and get next values
    iters += 1
    n1_t, n2_t = next(n_gen)

    # Check whether same in this period
    if abs(n1_t - n2_t) < 1e-8:
        nsync += 1
    # If not, then reset the nsync counter
    else:
        nsync = 0

    # If we have been in sync for npers then stop and countries
    # became synchronized nsync periods ago
    if nsync > npers:
        synchronized = True
        pers_2_sync = iters - nsync
```
return synchronized, pers_2_sync

@jit(nopython=True)
def _create_attraction_basis(s1_ρ, s2_ρ, s1, s2, θ, δ, ρ, maxiter, npers, npts):
    # Create unit range with npts
    synchronized, pers_2_sync = False, θ
    unit_range = np.linspace(0.0, 1.0, npts)

    # Allocate space to store time to sync
    time_2_sync = np.empty((npts, npts))
    # Iterate over initial conditions
    for i, n1_0 in enumerate(unit_range):
        for j, n2_0 in enumerate(unit_range):
            synchronized, pers_2_sync = _pers_till_sync(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ, maxiter, npers)
            time_2_sync[i, j] = pers_2_sync
    return time_2_sync

# == Now we define a class for the model == #
class MSGSync:
    ""
    The paper "Globalization and Synchronization of Innovation Cycles" presents a two-country model with endogenous innovation cycles. Combines elements from Deneckere Judd (1985) and Helpman Krugman (1985) to allow for a model with trade that has firms which can introduce new varieties into the economy.

    We focus on being able to determine whether the two countries eventually synchronize their innovation cycles. To do this, we only need a few of the many parameters. In particular, we need the parameters listed below

    Parameters
    --------
    s1 : scalar(Float)
        Amount of total labor in country 1 relative to total worldwide labor
    θ : scalar(Float)
        A measure of how much more of the competitive variety is used in production of final goods
    δ : scalar(Float)
        Percentage of firms that are not exogenously destroyed every period
    ρ : scalar(Float)
        Measure of how expensive it is to trade between countries
    ""
def __init__(self, s1=0.5, θ=2.5, δ=0.7, ρ=0.2):
    # Store model parameters
    self.s1, self.θ, self.δ, self.ρ = s1, θ, δ, ρ

    # Store other cutoffs and parameters we use
    self.s2 = 1 - s1
    self.s1_ρ = self._calc_s1_ρ()
    self.s2_ρ = 1 - self.s1_ρ
def _unpack_params(self):
    return self.s1, self.s2, self.θ, self.δ, self.ρ

def _calc_s1_ρ(self):
    # Unpack params
    s1, s2, θ, δ, ρ = self._unpack_params()

    # s_1(ρ) = min(val, 1)
    val = (s1 - ρ * s2) / (1 - ρ)
    return min(val, 1)

def simulate_n(self, n1_0, n2_0, T):
    # Unpack parameters
    s1, s2, θ, δ, ρ = self._unpack_params()
    s1_ρ, s2_ρ = self.s1_ρ, self.s2_ρ

    # Allocate space
    n1 = np.empty(T)
    n2 = np.empty(T)

    # Create the generator
    n1[0], n2[0] = n1_0, n2_0
    n_gen = n_generator(n1_0, n2_0, s1_ρ, s2_ρ, s1, s2, θ, δ, ρ)

    # Simulate for T periods
    for t in range(1, T):
        # Get next values
        n1_tp1, n2_tp1 = next(n_gen)

        # Store in arrays
        n1[t] = n1_tp1
        n2[t] = n2_tp1
    return n1, n2

def pers_till_sync(self, n1_0, n2_0, maxiter=500, npers=3):
    # Takes initial values and iterates forward to see whether
If countries are symmetric then as soon as the two countries have the same measure of firms then they will be synchronized. However, if they are not symmetric then it is possible they have the same measure of firms but are not yet synchronized. To address this, we check whether firms stay synchronized for \( \text{`npers`} \) periods with Euclidean norm.

Parameters
---------

- \( n_1_0 \) : scalar(Float)
  Initial normalized measure of firms in country one
- \( n_2_0 \) : scalar(Float)
  Initial normalized measure of firms in country two
- \( \maxiter \) : scalar(Int)
  Maximum number of periods to simulate
- \( \npers \) : scalar(Int)
  Number of periods we would like the countries to have the same measure for

Returns
-------

- \( \text{synchronized} \) : scalar(Bool)
  Did the two economies end up synchronized
- \( \text{pers}_2\text{ Sync} \) : scalar(Int)
  The number of periods required until they synchronized

# Unpack parameters
\begin{align*}
  \text{s1, s2, } \theta, \delta, \rho &= \text{self.\_unpack_params()} \\
  \text{s1}_\rho, \text{s2}_\rho &= \text{self.s1}_\rho, \text{self.s2}_\rho
\end{align*}

\text{return } \text{\_pers\_till\_sync}(n_1_0, n_2_0, s1_\rho, s2_\rho, \\
  s1, s2, \theta, \delta, \rho, \maxiter, \npers)

\textbf{def create_attraction\_basis(self, maxiter=250, npers=3, npts=50):} \\
Creates an attraction basis for values of \( n \) on \([0, 1] \times [0, 1]\) with \( npts \) in each dimension

# Unpack parameters
\begin{align*}
  \text{s1, s2, } \theta, \delta, \rho &= \text{self.\_unpack_params()} \\
  \text{s1}_\rho, \text{s2}_\rho &= \text{self.s1}_\rho, \text{self.s2}_\rho
\end{align*}

\text{ab} = \text{_create\_attraction\_basis}(s1_\rho, s2_\rho, s1, s2, \theta, \delta, \\
  \rho, \maxiter, \npers, \npts)

\textbf{return } \text{ab

16.5.1 Time Series of Firm Measures

We write a short function below that exploits the preceding code and plots two time series. Each time series gives the dynamics for the two countries. The time series share parameters but differ in their initial condition. Here’s the function
In [3]: def plot_timeseries(n1_0, n2_0, s1=0.5, θ=2.5, δ=0.7, p=0.2, ax=none, title=''): 
    ""
    Plot a single time series with initial conditions
    ""
    if ax is None:
        fig, ax = plt.subplots()
    # Create the MSG Model and simulate with initial conditions
    model = MSGSync(s1, θ, δ, p)
    n1, n2 = model.simulate_n(n1_0, n2_0, 25)
    ax.plot(np.arange(25), n1, label='$n_1$', lw=2)
    ax.plot(np.arange(25), n2, label='$n_2$', lw=2)
    ax.legend()
    ax.set(title=title, ylim=(0.15, 0.8))
    return ax

# Create figure
fig, ax = plt.subplots(2, 1, figsize=(10, 8))
plot_timeseries(0.15, 0.35, ax=ax[0], title='Not Synchronized')
plot_timeseries(0.4, 0.3, ax=ax[1], title='Synchronized')
fig.tight_layout()
plt.show()
In the first case, innovation in the two countries does not synchronize.

In the second case, different initial conditions are chosen, and the cycles become synchronized.

### 16.5.2 Basin of Attraction

Next, let’s study the initial conditions that lead to synchronized cycles more systematically. We generate time series from a large collection of different initial conditions and mark those conditions with different colors according to whether synchronization occurs or not.

The next display shows exactly this for four different parameterizations (one for each subfigure).
As you can see, larger values of $\rho$ translate to more synchronization.

You are asked to replicate this figure in the exercises.

In the solution to the exercises, you’ll also find a figure with sliders, allowing you to experiment with different parameters.

Here’s one snapshot from the interactive figure.
16.6 Exercises

16.6.1 Exercise 1

Replicate the figure shown above by coloring initial conditions according to whether or not synchronization occurs from those conditions.

16.7 Solutions

In [4]:
```python
def plot_attraction_basis(s1=0.5, θ=2.5, δ=0.7, ρ=0.2, npts=250, ax=None):
    if ax is None:
        fig, ax = plt.subplots()

        # Create attraction basis
        unitrange = np.linspace(0, 1, npts)
        model = MSGSync(s1, θ, δ, ρ)
        ab = model.create_attraction_basis(npts=npts)
        cf = ax.pcolormesh(unitrange, unitrange, ab, cmap="viridis")

        return ab, cf
```

```python
fig = plt.figure(figsize=(14, 12))

# Left - Bottom - Width - Height
ax0 = fig.add_axes((0.05, 0.475, 0.38, 0.35), label="axes0")
ax1 = fig.add_axes((0.5, 0.475, 0.38, 0.35), label="axes1")
ax2 = fig.add_axes((0.05, 0.05, 0.38, 0.35), label="axes2")
ax3 = fig.add_axes((0.5, 0.05, 0.38, 0.35), label="axes3")
```
\[ \text{params} = [\[0.5, 2.5, 0.7, 0.2\], \\
[0.5, 2.5, 0.7, 0.4\], \\
[0.5, 2.5, 0.7, 0.6\], \\
[0.5, 2.5, 0.7, 0.8]] \]

ab0, cf0 = plot_attraction_basis(params[0], npts=500, ax=ax0)
ab1, cf1 = plot_attraction_basis(params[1], npts=500, ax=ax1)
ab2, cf2 = plot_attraction_basis(params[2], npts=500, ax=ax2)
ab3, cf3 = plot_attraction_basis(params[3], npts=500, ax=ax3)

cbar_ax = fig.add_axes([0.9, 0.075, 0.03, 0.725])
plt.colorbar(cf0, cax=cbar_ax)

ax0.set_title(r"$s_1=0.5$, $\theta=2.5$, $\delta=0.7$, $\rho=0.2$", fontsize=22)
ax1.set_title(r"$s_1=0.5$, $\theta=2.5$, $\delta=0.7$, $\rho=0.4$", fontsize=22)
ax2.set_title(r"$s_1=0.5$, $\theta=2.5$, $\delta=0.7$, $\rho=0.6$", fontsize=22)
ax3.set_title(r"$s_1=0.5$, $\theta=2.5$, $\delta=0.7$, $\rho=0.8$", fontsize=22)

fig.suptitle("Synchronized versus Asynchronized 2-cycles",
 x=0.475, y=0.915, size=26)
plt.show()
16.7. SOLUTIONS

16.7.1 Interactive Version

Additionally, instead of just seeing 4 plots at once, we might want to manually be able to change $\rho$ and see how it affects the plot in real-time. Below we use an interactive plot to do this.

Note, interactive plotting requires the `ipywidgets` module to be installed and enabled.

```
In [5]: def interact_attraction_basis(\rho=0.2, maxiter=250, npts=250):
    # Create the figure and axis that we will plot on
    fig, ax = plt.subplots(figsize=(12, 10))

    # Create model and attraction basis
    s1, \theta, \delta = 0.5, 2.5, 0.75
    model = MSGSync(s1, \theta, \delta, \rho)
    ab = model.create_attraction_basis(maxiter=maxiter, npts=npts)

    # Color map with colormesh
    unitrange = np.linspace(0, 1, npts)
    cf = ax.pcolormesh(unitrange, unitrange, ab, cmap="viridis")
    cbar_ax = fig.add_axes([0.95, 0.15, 0.05, 0.7])
    plt.colorbar(cf, cax=cbar_ax)
    plt.show()
    return None

In [6]: fig = interact(interact_attraction_basis,
                        \rho=(0.0, 1.0), 0.05),
                        maxiter=(50, 5000, 50),
                        npts=(25, 750, 25))
```
Chapter 17  

Coase’s Theory of the Firm

17.1 Contents

- Overview 17.2
- The Model 17.3
- Equilibrium 17.4
- Existence, Uniqueness and Computation of Equilibria 17.5
- Implementation 17.6
- Exercises 17.7
- Solutions 17.8

17.2 Overview

In 1937, Ronald Coase wrote a brilliant essay on the nature of the firm [16].
Coase was writing at a time when the Soviet Union was rising to become a significant industrial power.
At the same time, many free-market economies were afflicted by a severe and painful depression.
This contrast led to an intensive debate on the relative merits of decentralized, price-based allocation versus top-down planning.
In the midst of this debate, Coase made an important observation: even in free-market economies, a great deal of top-down planning does in fact take place.
This is because firms form an integral part of free-market economies and, within firms, allocation is by planning.
In other words, free-market economies blend both planning (within firms) and decentralized production coordinated by prices.
The question Coase asked is this: if prices and free markets are so efficient, then why do firms even exist?
Couldn’t the associated within-firm planning be done more efficiently by the market?

We’ll use the following imports:

In [1]: import numpy as np
17.2.1 Why Firms Exist

On top of asking a deep and fascinating question, Coase also supplied an illuminating answer: firms exist because of transaction costs.

Here’s one example of a transaction cost:

Suppose agent A is considering setting up a small business and needs a web developer to construct and help run an online store.

She can use the labor of agent B, a web developer, by writing up a freelance contract for these tasks and agreeing on a suitable price.

But contracts like this can be time-consuming and difficult to verify

- How will agent A be able to specify exactly what she wants, to the finest detail, when she herself isn’t sure how the business will evolve?
- And what if she isn’t familiar with web technology? How can she specify all the relevant details?
- And, if things go badly, will failure to comply with the contract be verifiable in court?

In this situation, perhaps it will be easier to employ agent B under a simple labor contract.

The cost of this contract is far smaller because such contracts are simpler and more standard.

The basic agreement in a labor contract is: B will do what A asks him to do for the term of the contract, in return for a given salary.

Making this agreement is much easier than trying to map every task out in advance in a contract that will hold up in a court of law.

So agent A decides to hire agent B and a firm of nontrivial size appears, due to transaction costs.

17.2.2 A Trade-Off

Actually, we haven’t yet come to the heart of Coase’s investigation.

The issue of why firms exist is a binary question: should firms have positive size or zero size?

A better and more general question is: what determines the size of firms?

The answer Coase came up with was that “a firm will tend to expand until the costs of organizing an extra transaction within the firm become equal to the costs of carrying out the same transaction by means of an exchange on the open market...” ([16], p. 395).

But what are these internal and external costs?

In short, Coase envisaged a trade-off between

- transaction costs, which add to the expense of operating between firms, and
- diminishing returns to management, which adds to the expense of operating within firms
We discussed an example of transaction costs above (contracts).

The other cost, diminishing returns to management, is a catch-all for the idea that big operations are increasingly costly to manage.

For example, you could think of management as a pyramid, so hiring more workers to implement more tasks requires expansion of the pyramid, and hence labor costs grow at a rate more than proportional to the range of tasks.

Diminishing returns to management makes in-house production expensive, favoring small firms.

17.2.3 Summary

Here’s a summary of our discussion:

- Firms grow because transaction costs encourage them to take some operations in house.
- But as they get large, in-house operations become costly due to diminishing returns to management.
- The size of firms is determined by balancing these effects, thereby equalizing the marginal costs of each form of operation.

17.2.4 A Quantitative Interpretation

Coase’s ideas were expressed verbally, without any mathematics.

In fact, his essay is a wonderful example of how far you can get with clear thinking and plain English.

However, plain English is not good for quantitative analysis, so let’s bring some mathematical and computation tools to bear.

In doing so we’ll add a bit more structure than Coase did, but this price will be worth paying.

Our exposition is based on [39].

17.3 The Model

The model we study involves production of a single unit of a final good.

Production requires a linearly ordered chain, requiring sequential completion of a large number of processing stages.

The stages are indexed by $t \in [0, 1]$, with $t = 0$ indicating that no tasks have been undertaken and $t = 1$ indicating that the good is complete.

17.3.1 Subcontracting

The subcontracting scheme by which tasks are allocated across firms is illustrated in the figure below
In this example,

- Firm 1 receives a contract to sell one unit of the completed good to a final buyer.
- Firm 1 then forms a contract with firm 2 to purchase the partially completed good at stage $t_1$, with the intention of implementing the remaining $1 - t_1$ tasks in-house (i.e., processing from stage $t_1$ to stage 1).
- Firm 2 repeats this procedure, forming a contract with firm 3 to purchase the good at stage $t_2$.
- Firm 3 decides to complete the chain, selecting $t_3 = 0$.

At this point, production unfolds in the opposite direction (i.e., from upstream to downstream).

- Firm 3 completes processing stages from $t_3 = 0$ up to $t_2$ and transfers the good to firm 2.
- Firm 2 then processes from $t_2$ up to $t_1$ and transfers the good to firm 1,
- Firm 1 processes from $t_1$ to 1 and delivers the completed good to the final buyer.

The length of the interval of stages (range of tasks) carried out by firm $i$ is denoted by $\ell_i$.

Each firm chooses only its upstream boundary, treating its downstream boundary as given.

The benefit of this formulation is that it implies a recursive structure for the decision problem for each firm.

In choosing how many processing stages to subcontract, each successive firm faces essentially the same decision problem as the firm above it in the chain, with the only difference being
that the decision space is a subinterval of the decision space for the firm above. We will exploit this recursive structure in our study of equilibrium.

17.3.2 Costs

Recall that we are considering a trade-off between two types of costs. Let’s discuss these costs and how we represent them mathematically.

**Diminishing returns to management** means rising costs per task when a firm expands the range of productive activities coordinated by its managers.

We represent these ideas by taking the cost of carrying out \( \ell \) tasks in-house to be \( c(\ell) \), where \( c \) is increasing and strictly convex. Thus, the average cost per task rises with the range of tasks performed in-house. We also assume that \( c \) is continuously differentiable, with \( c(0) = 0 \) and \( c'(0) > 0 \).

**Transaction costs** are represented as a wedge between the buyer’s and seller’s prices. It matters little for us whether the transaction cost is borne by the buyer or the seller. Here we assume that the cost is borne only by the buyer. In particular, when two firms agree to a trade at face value \( v \), the buyer’s total outlay is \( \delta v \), where \( \delta > 1 \). The seller receives only \( v \), and the difference is paid to agents outside the model.

17.4 Equilibrium

We assume that all firms are *ex-ante* identical and act as price takers. As price takers, they face a price function \( p \), which is a map from \([0, 1]\) to \( \mathbb{R}_+ \), with \( p(t) \) interpreted as the price of the good at processing stage \( t \).

There is a countable infinity of firms indexed by \( i \) and no barriers to entry. The cost of supplying the initial input (the good processed up to stage zero) is set to zero for simplicity.

Free entry and the infinite fringe of competitors rule out positive profits for incumbents, since any incumbent could be replaced by a member of the competitive fringe filling the same role in the production chain. Profits are never negative in equilibrium because firms can freely exit.

17.4.1 Informal Definition of Equilibrium

An equilibrium in this setting is an allocation of firms and a price function such that

1. all active firms in the chain make zero profits, including suppliers of raw materials
2. no firm in the production chain has an incentive to deviate, and
3. no inactive firms can enter and extract positive profits
17.4.2 Formal Definition of Equilibrium

Let’s make this definition more formal.

(You might like to skip this section on first reading)

An allocation of firms is a nonnegative sequence \( \{\ell_i\}_{i \in \mathbb{N}} \) such that \( \ell_i = 0 \) for all sufficiently large \( i \).

Recalling the figures above,

- \( \ell_i \) represents the range of tasks implemented by the \( i \)-th firm

As a labeling convention, we assume that firms enter in order, with firm 1 being the furthest downstream.

An allocation \( \{\ell_i\} \) is called feasible if \( \sum_{i \geq 1} \ell_i = 1 \).

In a feasible allocation, the entire production process is completed by finitely many firms.

Given a feasible allocation, \( \{\ell_i\} \), let \( \{t_i\} \) represent the corresponding transaction stages, defined by

\[
\begin{align*}
    t_0 &= s \\
    t_i &= t_{i-1} - \ell_i
\end{align*}
\]  

In particular, \( t_{i-1} \) is the downstream boundary of firm \( i \) and \( t_i \) is its upstream boundary.

As transaction costs are incurred only by the buyer, its profits are

\[
\pi_i = p(t_{i-1}) - c(\ell_i) - \delta p(t_i)
\]  

Given a price function \( p \) and a feasible allocation \( \{\ell_i\} \), let

- \( \{t_i\} \) be the corresponding firm boundaries,
- \( \{\pi_i\} \) be corresponding profits, as defined in (2).

This price-allocation pair is called an equilibrium for the production chain if

1. \( p(0) = 0 \),
2. \( \pi_i = 0 \) for all \( i \), and
3. \( p(s) - c(s - t) - \delta p(t) \leq 0 \) for any pair \( s, t \) with \( 0 \leq s \leq t \leq 1 \).

The rationale behind these conditions was given in our informal definition of equilibrium above.

17.5 Existence, Uniqueness and Computation of Equilibria

We have defined an equilibrium but does one exist? Is it unique? And, if so, how can we compute it?

17.5.1 A Fixed Point Method

To address these questions, we introduce the operator \( T \) mapping a nonnegative function \( p \) on \([0,1]\) to \( Tp \) via
17.5. EXISTENCE, UNIQUENESS AND COMPUTATION OF EQUILIBRIA

\[ T p(s) = \min_{t \leq s} \{c(s - t) + \delta p(t)\} \quad \text{for all} \quad s \in [0, 1]. \]  

(3)

Here and below, the restriction \(0 \leq t\) in the minimum is understood.

The operator \(T\) is similar to a Bellman operator.

Under this analogy, \(p\) corresponds to a value function and \(\delta\) to a discount factor.

But \(\delta > 1\), so \(T\) is not a contraction in any obvious metric, and in fact, \(T^n p\) diverges for many choices of \(p\).

Nevertheless, there exists a domain on which \(T\) is well-behaved: the set of convex increasing continuous functions \(p: [0, 1] \to \mathbb{R}\) such that \(c'(0)s \leq p(s) \leq c(s)\) for all \(0 \leq s \leq 1\).

We denote this set of functions by \(\mathcal{P}\).

In [39] it is shown that the following statements are true:

1. \(T\) maps \(\mathcal{P}\) into itself.
2. \(T\) has a unique fixed point in \(\mathcal{P}\), denoted below by \(p^*\).
3. For all \(p \in \mathcal{P}\) we have \(T^k p \to p^*\) uniformly as \(k \to \infty\).

Now consider the choice function

\[ t^*(s) := \text{the solution to} \min_{t \leq s} \{c(s - t) + \delta p^*(t)\} \]  

(4)

By definition, \(t^*(s)\) is the cost-minimizing upstream boundary for a firm that is contracted to deliver the good at stage \(s\) and faces the price function \(p^*\).

Since \(p^*\) lies in \(\mathcal{P}\) and since \(c\) is strictly convex, it follows that the right-hand side of (4) is continuous and strictly convex in \(t\).

Hence the minimizer \(t^*(s)\) exists and is uniquely defined.

We can use \(t^*\) to construct an equilibrium allocation as follows:

Recall that firm 1 sells the completed good at stage \(s = 1\), its optimal upstream boundary is \(t^*(1)\).

Hence firm 2’s optimal upstream boundary is \(t^*(t^*(1))\).

Continuing in this way produces the sequence \(\{t^*_i\}\) defined by

\[ t^*_0 = 1 \quad \text{and} \quad t^*_i = t^*(t^*_{i-1}) \]  

(5)

The sequence ends when a firm chooses to complete all remaining tasks.

We label this firm (and hence the number of firms in the chain) as

\[ n^* := \inf\{i \in \mathbb{N} : t^*_i = 0\} \]  

(6)

The task allocation corresponding to (5) is given by \(\ell^*_i := t^*_{i-1} - t^*_i\) for all \(i\).

In [39] it is shown that
1. The value \( n^* \) in (6) is well-defined and finite,

2. the allocation \( \{ \ell_i^* \} \) is feasible, and

3. the price function \( p^* \) and this allocation together forms an equilibrium for the production chain.

While the proofs are too long to repeat here, much of the insight can be obtained by observing that, as a fixed point of \( T \), the equilibrium price function must satisfy

\[
p^*(s) = \min_{t \leq s} \{ c(s - t) + \delta p^*(t) \}
\]

for all \( s \in [0, 1] \) (7)

From this equation, it is clear that so profits are zero for all incumbent firms.

### 17.5.2 Marginal Conditions

We can develop some additional insights on the behavior of firms by examining marginal conditions associated with the equilibrium.

As a first step, let \( \ell^*(s) := s - t^*(s) \).

This is the cost-minimizing range of in-house tasks for a firm with downstream boundary \( s \).

In [39] it is shown that \( t^* \) and \( \ell^* \) are increasing and continuous, while \( p^* \) is continuously differentiable at all \( s \in (0, 1) \) with

\[
(p^*)'(s) = c'(\ell^*(s))
\]

Equation (8) follows from \( p^*(s) = \min_{t \leq s} \{ c(s - t) + \delta p^*(t) \} \) and the envelope theorem for derivatives.

A related equation is the first order condition for \( p^*(s) = \min_{t \leq s} \{ c(s - t) + \delta p^*(t) \} \), the minimization problem for a firm with upstream boundary \( s \), which is

\[
\delta (p^*)'(t^*(s)) = c'(s - t^*(s))
\]

This condition matches the marginal condition expressed verbally by Coase that we stated above:

“A firm will tend to expand until the costs of organizing an extra transaction within the firm become equal to the costs of carrying out the same transaction by means of an exchange on the open market...”

Combining (8) and (9) and evaluating at \( s = t_i \), we see that active firms that are adjacent satisfy

\[
\delta c'(\ell_{i+1}^*) = c'(\ell_i^*)
\]

In other words, the marginal in-house cost per task at a given firm is equal to that of its upstream partner multiplied by gross transaction cost.
This expression can be thought of as a **Coase–Euler equation**, which determines inter-firm efficiency by indicating how two costly forms of coordination (markets and management) are jointly minimized in equilibrium.

### 17.6 Implementation

For most specifications of primitives, there is no closed-form solution for the equilibrium as far as we are aware.

However, we know that we can compute the equilibrium corresponding to a given transaction cost parameter $\delta$ and a cost function $c$ by applying the results stated above.

In particular, we can

1. fix initial condition $p \in \mathcal{P}$,
2. iterate with $T$ until $T^n p$ has converged to $p^*$, and
3. recover firm choices via the choice function (3)

At each iterate, we will use continuous piecewise linear interpolation of functions.

To begin, here’s a class to store primitives and a grid:

```python
In [2]: class ProductionChain:
    def __init__(self, 
        n=1000, 
        delta=1.05, 
        c=lambda t: np.exp(10 * t) - 1):

        self.n, self.delta, self.c = n, delta, c
        self.grid = np.linspace(1e-04, 1, n)
```

Now let’s implement and iterate with $T$ until convergence.

Recalling that our initial condition must lie in $\mathcal{P}$, we set $p_0 = c$

```python
In [3]: def compute_prices(pc, tol=1e-5, max_iter=5000):
    
    """
    Compute prices by iterating with $T$
    * pc is an instance of ProductionChain
    * The initial condition is $p = c$
    """
    delta, c, n, grid = pc.delta, pc.c, pc.n, pc.grid
    p = c(grid)  # Initial condition is $c(s)$, as an array
    new_p = np.empty_like(p)
    error = tol + 1
    i = 0

    while error > tol and i < max_iter:
        for j, s in enumerate(grid):
            
            new_p[j] = pc(p[j], s)
            error = max(error, new_p[j] - p[j])
            p = new_p
            i += 1
```

```
The next function computes optimal choice of upstream boundary and range of task implemented for a firm face price function p_function and with downstream boundary \( s \).

In [4]: def optimal_choices(pc, p_function, s):
   """
   Takes p_func as the true function, minimizes on [0,s]
   Returns optimal upstream boundary t_star and optimal size of firm ell_star
   In fact, the algorithm minimizes on [-1,s] and then takes the max of the minimizer and zero. This results in better results close to zero
   """
   delta, c = pc.delta, pc.c
   f = lambda t: delta * p_function(t) + c(s - t)
   t_star = max(fminbound(f, -1, s), 0)
   ell_star = s - t_star
   return t_star, ell_star

The allocation of firms can be computed by recursively stepping through firms’ choices of their respective upstream boundary, treating the previous firm’s upstream boundary as their own downstream boundary.

In doing so, we start with firm 1, who has downstream boundary \( s = 1 \).

In [5]: def compute_stages(pc, p_function):
   s = 1.0
   transaction_stages = [s]
   while s > 0:
       s, ell = optimal_choices(pc, p_function, s)
       transaction_stages.append(s)
   return np.array(transaction_stages)

Let’s try this at the default parameters.

The next figure shows the equilibrium price function, as well as the boundaries of firms as vertical lines

In [6]: pc = ProductionChain()
   p_star = compute_prices(pc)
transaction_stages = compute_stages(pc, p_star)

fig, ax = plt.subplots()

ax.plot(pc.grid, p_star(pc.grid))
ax.set_xlim(0.0, 1.0)
ax.set_ylim(0.0)

for s in transaction_stages:
    ax.axvline(x=s, c="0.5")

plt.show()
Note that downstream firms choose to be larger, a point we return to below.

17.7 Exercises

17.7.1 Exercise 1

The number of firms is endogenously determined by the primitives.
What do you think will happen in terms of the number of firms as $\delta$ increases? Why?
Check your intuition by computing the number of firms at delta in (1.01, 1.05, 1.1).

17.7.2 Exercise 2

The value added of firm $i$ is $v_i := p^*(t_{i-1}) - p^*(t_i)$.
One of the interesting predictions of the model is that value added is increasing with downstreamness, as are several other measures of firm size.
Can you give any intuition?
Try to verify this phenomenon (value added increasing with downstreamness) using the code above.

17.8 Solutions

17.8.1 Exercise 1

In [8]: for delta in (1.01, 1.05, 1.1):
pc = ProductionChain(delta=delta)
p_star = compute_prices(pc)
transaction_stages = compute_stages(pc, p_star)
num_firms = len(transaction_stages)
print(f"When delta={delta} there are {num_firms} firms")

Iteration converged in 2 steps
When delta=1.01 there are 64 firms
Iteration converged in 2 steps
When delta=1.05 there are 41 firms
Iteration converged in 2 steps
When delta=1.1 there are 35 firms

17.8.2 Exercise 2

Firm size increases with downstreamness because $p^*$, the equilibrium price function, is increasing and strictly convex.

This means that, for a given producer, the marginal cost of the input purchased from the producer just upstream from itself in the chain increases as we go further downstream.

Hence downstream firms choose to do more in house than upstream firms — and are therefore larger.

The equilibrium price function is strictly convex due to both transaction costs and diminishing returns to management.

One way to put this is that firms are prevented from completely mitigating the costs associated with diminishing returns to management — which induce convexity — by transaction costs. This is because transaction costs force firms to have nontrivial size.

Here’s one way to compute and graph value added across firms

In [9]: pc = ProductionChain()
p_star = compute_prices(pc)
stages = compute_stages(pc, p_star)

va = []

for i in range(len(stages) - 1):
    va.append(p_star(stages[i]) - p_star(stages[i+1]))

fig, ax = plt.subplots()
ax.plot(va, label="value added by firm")
ax.set_xticks((5, 25))
ax.set_xticklabels(("downstream firms", "upstream firms"))
plt.show()

Iteration converged in 2 steps
Part IV

Dynamic Linear Economies
Chapter 18

Recursive Models of Dynamic Linear Economies

18.1 Contents

- A Suite of Models 18.2
- Econometrics 18.3
- Dynamic Demand Curves and Canonical Household Technologies 18.4
- Gorman Aggregation and Engel Curves 18.5
- Partial Equilibrium 18.6
- Equilibrium Investment Under Uncertainty 18.7
- A Rosen-Topel Housing Model 18.8
- Cattle Cycles 18.9
- Models of Occupational Choice and Pay 18.10
- Permanent Income Models 18.11
- Gorman Heterogeneous Households 18.12
- Non-Gorman Heterogeneous Households 18.13

“Mathematics is the art of giving the same name to different things” – Henri Poincare

“Complete market economies are all alike” – Robert E. Lucas, Jr., (1989)

“Every partial equilibrium model can be reinterpreted as a general equilibrium model.” – Anonymous

18.2 A Suite of Models

This lecture presents a class of linear-quadratic-Gaussian models of general economic equilibrium designed by Lars Peter Hansen and Thomas J. Sargent [31].

The class of models is implemented in a Python class DLE that is part of quantecon.

Subsequent lectures use the DLE class to implement various instances that have appeared in the economics literature
1. Growth in Dynamic Linear Economies
2. Lucas Asset Pricing using DLE
3. IRFs in Hall Model
4. Permanent Income Using the DLE class
5. Rosen schooling model
6. Cattle cycles
7. Shock Non Invertibility

18.2.1 Overview of the Models

In saying that “complete markets are all alike”, Robert E. Lucas, Jr. was noting that all of them have

- a commodity space.
- a space dual to the commodity space in which prices reside.
- endowments of resources.
- peoples’ preferences over goods.
- physical technologies for transforming resources into goods.
- random processes that govern shocks to technologies and preferences and associated information flows.
- a single budget constraint per person.
- the existence of a representative consumer even when there are many people in the model.
- a concept of competitive equilibrium.
- theorems connecting competitive equilibrium allocations to allocations that would be chosen by a benevolent social planner.

The models have no frictions such as ...

- Enforcement difficulties
- Information asymmetries
- Other forms of transactions costs
- Externalities

The models extensively use the powerful ideas of

- Indexing commodities and their prices by time (John R. Hicks).
- Indexing commodities and their prices by chance (Kenneth Arrow).

Much of the imperialism of complete markets models comes from applying these two tricks.

The Hicks trick of indexing commodities by time is the idea that dynamics are a special case of statics.

The Arrow trick of indexing commodities by chance is the idea that analysis of trade under uncertainty is a special case of the analysis of trade under certainty.

The class of models specify the commodity space, preferences, technologies, stochastic shocks and information flows in ways that allow the models to be analyzed completely using only the tools of linear time series models and linear-quadratic optimal control described in the two lectures Linear State Space Models and Linear Quadratic Control.
There are costs and benefits associated with the simplifications and specializations needed to make a particular model fit within the [31] class
- the costs are that linear-quadratic structures are sometimes too confining.
- benefits include computational speed, simplicity, and ability to analyze many model features analytically or nearly analytically.

A variety of superficially different models are all instances of the [31] class of models
- Lucas asset pricing model
- Lucas-Prescott model of investment under uncertainty
- Asset pricing models with habit persistence
- Rosen-Topel equilibrium model of housing
- Rosen schooling models
- Rosen-Murphy-Scheinkman model of cattle cycles
- Hansen-Sargent-Tallarini model of robustness and asset pricing
- Many more ...

The diversity of these models conceals an essential unity that illustrates the quotation by Robert E. Lucas, Jr., with which we began this lecture.

18.2.2 Forecasting?

A consequence of a single budget constraint per person plus the Hicks-Arrow tricks is that households and firms need not forecast.

But there exist equivalent structures called recursive competitive equilibria in which they do appear to need to forecast.

In these structures, to forecast, households and firms use:
- equilibrium pricing functions, and
- knowledge of the Markov structure of the economy’s state vector.

18.2.3 Theory and Econometrics

For an application of the [31] class of models, the outcome of theorizing is a stochastic process, i.e., a probability distribution over sequences of prices and quantities, indexed by parameters describing preferences, technologies, and information flows.

Another name for that object is a likelihood function, a key object of both frequentist and Bayesian statistics.

There are two important uses of an equilibrium stochastic process or likelihood function.

The first is to solve the direct problem.

The direct problem takes as inputs values of the parameters that define preferences, technologies, and information flows and as an output characterizes or simulates random paths of quantities and prices.

The second use of an equilibrium stochastic process or likelihood function is to solve the inverse problem.

The inverse problem takes as an input a time series sample of observations on a subset of prices and quantities determined by the model and from them makes inferences about the
parameters that define the model’s preferences, technologies, and information flows.

18.2.4 More Details

A [31] economy consists of lists of matrices that describe peoples’ household technologies, their preferences over consumption services, their production technologies, and their information sets.

There are complete markets in history-contingent commodities.

Competitive equilibrium allocations and prices

- satisfy equations that are easy to write down and solve
- have representations that are convenient econometrically

Different example economies manifest themselves simply as different settings for various matrices.

[31] use these tools:

- A theory of recursive dynamic competitive economies
- Linear optimal control theory
- Recursive methods for estimating and interpreting vector autoregressions

The models are flexible enough to express alternative senses of a representative household

- A single ‘stand-in’ household of the type used to good effect by Edward C. Prescott.
- Heterogeneous households satisfying conditions for Gorman aggregation into a representative household.
- Heterogeneous household technologies that violate conditions for Gorman aggregation but are still susceptible to aggregation into a single representative household via ‘non-Gorman’ or ‘mongrel’ aggregation.

These three alternative types of aggregation have different consequences in terms of how prices and allocations can be computed.

In particular, can prices and an aggregate allocation be computed before the equilibrium allocation to individual heterogeneous households is computed?

- Answers are “Yes” for Gorman aggregation, “No” for non-Gorman aggregation.

In summary, the insights and practical benefits from economics to be introduced in this lecture are

- Deeper understandings that come from recognizing common underlying structures.
- Speed and ease of computation that comes from unleashing a common suite of Python programs.

We’ll use the following mathematical tools

- Stochastic Difference Equations (Linear).
- Duality: LQ Dynamic Programming and Linear Filtering are the same things mathematically.
- The Spectral Factorization Identity (for understanding vector autoregressions and non-Gorman aggregation).

So here is our roadmap.

We’ll describe sets of matrices that pin down
• Information
• Technologies
• Preferences

Then we’ll describe
• Equilibrium concept and computation
• Econometric representation and estimation

18.2.5 Stochastic Model of Information Flows and Outcomes

We’ll use stochastic linear difference equations to describe information flows and equilibrium outcomes.

The sequence \(\{w_t : t = 1, 2, \ldots\}\) is said to be a martingale difference sequence adapted to \(\{J_t : t = 0, 1, \ldots\}\) if \(E(w_{t+1} | J_t) = 0\) for \(t = 0, 1, \ldots\).

The sequence \(\{w_t : t = 1, 2, \ldots\}\) is said to be conditionally homoskedastic if \(E(w_{t+1}w_{t+1}' | J_t) = I\) for \(t = 0, 1, \ldots\).

We assume that the \(\{w_t : t = 1, 2, \ldots\}\) process is conditionally homoskedastic.

Let \(\{x_t : t = 1, 2, \ldots\}\) be a sequence of \(n\)-dimensional random vectors, i.e. an \(n\)-dimensional stochastic process.

The process \(\{x_t : t = 1, 2, \ldots\}\) is constructed recursively using an initial random vector \(x_0 \sim N(\tilde{x}_0, \Sigma_0)\) and a time-invariant law of motion:

\[
x_{t+1} = Ax_t + Cw_{t+1}
\]

for \(t = 0, 1, \ldots\) where \(A\) is an \(n\) by \(n\) matrix and \(C\) is an \(n\) by \(N\) matrix.

Evidently, the distribution of \(x_{t+1}\) conditional on \(x_t\) is \(N(Ax_t, CC')\).

18.2.6 Information Sets

Let \(J_0\) be generated by \(x_0\) and \(J_t\) be generated by \(x_0, w_1, \ldots, w_t\), which means that \(J_t\) consists of the set of all measurable functions of \(\{x_0, w_1, \ldots, w_t\}\).

18.2.7 Prediction Theory

The optimal forecast of \(x_{t+1}\) given current information is

\[
E(x_{t+1} | J_t) = Ax_t
\]

and the one-step-ahead forecast error is

\[
x_{t+1} - E(x_{t+1} | J_t) = Cw_{t+1}
\]

The covariance matrix of \(x_{t+1}\) conditioned on \(J_t\) is

\[
E(x_{t+1} - E(x_{t+1} | J_t))(x_{t+1} - E(x_{t+1} | J_t))' = CC'
\]
A nonrecursive expression for \( x_t \) as a function of \( x_0, w_1, w_2, \ldots, w_t \) is

\[
x_t = Ax_{t-1} + Cw_t
\]

\[
= A^2x_{t-2} + ACw_{t-1} + Cw_t
\]

\[
= \left[ \sum_{\tau=0}^{t-1} A^\tau Cw_{t-\tau} \right] + A^tx_0
\]

Shift forward in time:

\[
x_{t+j} = \sum_{s=0}^{j-1} A^s Cw_{t+j-s} + A^jx_t
\]

Projecting on the information set \( \{x_0, w_t, w_{t-1}, \ldots, w_1\} \) gives

\[
E_t x_{t+j} = A^jx_t
\]

where \( E_t(\cdot) \equiv E(\cdot) \mid x_0, w_t, w_{t-1}, \ldots, w_1 = E(\cdot) \mid J_t \), and \( x_t \) is in \( J_t \).

It is useful to obtain the covariance matrix of the \( j \)-step-ahead prediction error \( x_{t+j} - E_t x_{t+j} = \sum_{s=0}^{j-1} A^s Cw_{t-s+j} \).

Evidently,

\[
E_t(x_{t+j} - E_t x_{t+j})(x_{t+j} - E_t x_{t+j})' = \sum_{k=0}^{j-1} A^k CC'A'^k \equiv v_j
\]

\( v_j \) can be calculated recursively via

\[
v_1 = CC'
\]

\[
v_j = CC' + Av_{j-1}A', \quad j \geq 2
\]

### 18.2.8 Orthogonal Decomposition

To decompose these covariances into parts attributable to the individual components of \( w_t \), we let \( i_\tau \) be an \( N \)-dimensional column vector of zeroes except in position \( \tau \), where there is a one. Define a matrix \( v_{j,\tau} \)

\[
v_{j,\tau} = \sum_{k=0}^{j-1} A^k Ci_\tau C'A'^k.
\]

Note that \( \sum_{\tau=1}^N i_\tau i_\tau' = I \), so that we have

\[
\sum_{\tau=1}^N v_{j,\tau} = v_j
\]

Evidently, the matrices \( \{v_{j,\tau}, \tau = 1,\ldots, N\} \) give an orthogonal decomposition of the covariance matrix of \( j \)-step-ahead prediction errors into the parts attributable to each of the components \( \tau = 1,\ldots, N \).
18.2.9 Taste and Technology Shocks

\[ E(w_t \mid J_{t-1}) = 0 \text{ and } E(w_t w_t' \mid J_{t-1}) = I \text{ for } t = 1, 2, \ldots \]

\[ b_t = U_b z_t \text{ and } d_t = U_d z_t, \]

where \( U_b \) and \( U_d \) are matrices that select entries of \( z_t \). The law of motion for \( \{z_t : t = 0, 1, \ldots\} \) is

\[ z_{t+1} = A_{22} z_t + C_2 w_{t+1} \text{ for } t = 0, 1, \ldots \]

where \( z_0 \) is a given initial condition. The eigenvalues of the matrix \( A_{22} \) have absolute values that are less than or equal to one.

Thus, in summary, our model of information and shocks is

\[
\begin{align*}
  z_{t+1} &= A_{22} z_t + C_2 w_{t+1} \\
  b_t &= U_b z_t \\
  d_t &= U_d z_t.
\end{align*}
\]

We can now briefly summarize other components of our economies, in particular

- Production technologies
- Household technologies
- Household preferences

18.2.10 Production Technology

Where \( c_t \) is a vector of consumption rates, \( k_t \) is a vector of physical capital goods, \( g_t \) is a vector of intermediate productions goods, \( d_t \) is a vector of technology shocks, the production technology is

\[
\begin{align*}
  \Phi_c c_t + \Phi g_t + \Phi_i i_t &= \Gamma k_{t-1} + d_t \\
  k_t &= \Delta_k k_{t-1} + \Theta_k i_t \\
  g_t \cdot g_t &= \ell_t^2
\end{align*}
\]

Here \( \Phi_c, \Phi_g, \Phi_i, \Gamma, \Delta_k, \Theta_k \) are all matrices conformable to the vectors they multiply and \( \ell_t \) is a disutility generating resource supplied by the household.

For technical reasons that facilitate computations, we make the following.

**Assumption:** \( [\Phi_c, \Phi_g] \) is nonsingular.

18.2.11 Household Technology

Households confront a technology that allows them to devote consumption goods to construct a vector \( h_t \) of household capital goods and a vector \( s_t \) of utility generating house services

\[
\begin{align*}
  s_t &= \Lambda h_{t-1} + \Pi c_t \\
  h_t &= \Delta_h h_{t-1} + \Theta_h c_t
\end{align*}
\]
where \( \Lambda, \Pi, \Delta_h, \Theta_h \) are matrices that pin down the household technology.

We make the following

**Assumption:** The absolute values of the eigenvalues of \( \Delta_h \) are less than or equal to one.

Below, we’ll outline further assumptions that we shall occasionally impose.

### 18.2.12 Preferences

Where \( b_t \) is a stochastic process of preference shocks that will play the role of demand shifters, the representative household orders stochastic processes of consumption services \( s_t \) according to

\[
\left( \frac{1}{2} \right) E \sum_{t=0}^{\infty} \beta^t [(s_t - b_t) \cdot (s_t - b_t) + \ell_t^2] |J_0|, \quad 0 < \beta < 1
\]

We now proceed to give examples of production and household technologies that appear in various models that appear in the literature.

First, we give examples of production Technologies

\[
\Phi_c c_t + \Phi_g g_t + \Phi_i i_t = \Gamma k_{t-1} + d_t
\]

\[
| g_t | \leq \ell_t
\]

so we’ll be looking for specifications of the matrices \( \Phi_c, \Phi_g, \Phi_i, \Gamma, \Delta_k, \Theta_k \) that define them.

### 18.2.13 Endowment Economy

There is a single consumption good that cannot be stored over time.

In time period \( t \), there is an endowment \( d_t \) of this single good.

There is neither a capital stock, nor an intermediate good, nor a rate of investment.

So \( c_t = d_t \).

To implement this specification, we can choose \( A_{22}, C_2, \) and \( U_d \) to make \( d_t \) follow any of a variety of stochastic processes.

To satisfy our earlier rank assumption, we set:

\[
c_t + i_t = d_{1t}
\]

\[
g_t = \phi_1 i_t
\]

where \( \phi_1 \) is a small positive number.

To implement this version, we set \( \Delta_k = \Theta_k = 0 \) and

\[
\Phi_c = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad \Phi_i = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad \Phi_g = \begin{bmatrix} 0 & -1 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad d_t = \begin{bmatrix} d_{1t} \\ 0 \end{bmatrix}
\]
We can use this specification to create a linear-quadratic version of Lucas’s (1978) asset pricing model.

### 18.2.14 Single-Period Adjustment Costs

There is a single consumption good, a single intermediate good, and a single investment good. The technology is described by

\[
\begin{align*}
  c_t &= \gamma k_{t-1} + d_{1t}, \quad \gamma > 0 \\
  \phi_1 i_t &= g_t + d_{2t}, \quad \phi_1 > 0 \\
  \ell_t^2 &= g_t^2 \\
  k_t &= \delta k_{t-1} + i_t, \quad 0 < \delta_k < 1
\end{align*}
\]

Set

\[
\begin{align*}
  \Phi_c &= \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad \Phi_g = \begin{bmatrix} 0 \\ -1 \end{bmatrix}, \quad \Phi_i = \begin{bmatrix} 0 \\ \phi_1 \end{bmatrix} \\
  \Gamma &= \begin{bmatrix} \gamma \\ 0 \end{bmatrix}, \quad \Delta_k = \delta_k, \quad \Theta_k = 1
\end{align*}
\]

We set $A_{22}, C_2$ and $U_d$ to make $(d_{1t}, d_{2t})' = d_t$ follow a desired stochastic process.

Now we describe some examples of preferences, which as we have seen are ordered by

\[
- \left( \frac{1}{2} \right) E \sum_{t=0}^{\infty} \beta^t \left[ (s_t - b_t) \cdot (s_t - b_t) + (\ell_t)^2 \right] \mid J_0 , \quad 0 < \beta < 1
\]

where household services are produced via the household technology

\[
h_t = \Delta_h h_{t-1} + \Theta_h c_t
\]

and we make

**Assumption:** The absolute values of the eigenvalues of $\Delta_h$ are less than or equal to one.

Later we shall introduce **canonical** household technologies that satisfy an ‘invertibility’ requirement relating sequences \{s_t\} of services and \{c_t\} of consumption flows.

And we’ll describe how to obtain a canonical representation of a household technology from one that is not canonical.

Here are some examples of household preferences.

**Time Separable preferences**

\[
- \frac{1}{2} E \sum_{t=0}^{\infty} \beta^t \left[ (c_t - b_t)^2 + (\ell_t^2) \right] \mid J_0 , \quad 0 < \beta < 1
\]
CHAPTER 18. RECURSIVE MODELS OF DYNAMIC LINEAR ECONOMIES

Consumer Durables

\[ h_t = \delta_h h_{t-1} + c_t , \ 0 < \delta_h < 1 \]

Services at \( t \) are related to the stock of durables at the beginning of the period:

\[ s_t = \lambda h_{t-1} , \ \lambda > 0 \]

Preferences are ordered by

\[ -\frac{1}{2} E \sum_{t=0}^{\infty} \beta^t \left[ (\lambda h_{t-1} - b_t)^2 + \ell_t^2 \right] | J_0 \]

Set \( \Delta_h = \delta_h, \Theta_h = 1, \Lambda = \lambda, \Pi = 0 \).

**Habit Persistence**

\[ -\left( \frac{1}{2} \right) E \sum_{t=0}^{\infty} \beta^t \left[ (c_t - \lambda(1 - \delta_h) \sum_{j=0}^{\infty} \delta_h^j c_{t-j-1} - b_t)^2 + \ell_t^2 \right] | J_0 \]

\( 0 < \beta < 1 , \ 0 < \delta_h < 1 , \ \lambda > 0 \)

Here the effective bliss point \( b_t + \lambda(1 - \delta_h) \sum_{j=0}^{\infty} \delta_h^j c_{t-j-1} \) shifts in response to a moving average of past consumption.

**Initial Conditions**

Preferences of this form require an initial condition for the geometric sum \( \sum_{j=0}^{\infty} \delta_h^j c_{t-j-1} \) that we specify as an initial condition for the 'stock of household durables,' \( h_{-1} \).

Set

\[ h_t = \delta_h h_{t-1} + (1 - \delta_h)c_t , \ 0 < \delta_h < 1 \]

\[ h_t = (1 - \delta_h) \sum_{j=0}^{t} \delta_h^j c_{t-j} + \delta_h^{t+1} h_{-1} \]

\[ s_t = -\lambda h_{t-1} + c_t , \ \lambda > 0 \]

To implement, set \( \Lambda = -\lambda, \ \Pi = 1, \ \Delta_h = \delta_h, \ \Theta_h = 1 - \delta_h \).

**Seasonal Habit Persistence**

\[ -\left( \frac{1}{2} \right) E \sum_{t=0}^{\infty} \beta^t \left[ (c_t - \lambda(1 - \delta_h) \sum_{j=0}^{\infty} \delta_h^j c_{t-j-4} - b_t)^2 + \ell_t^2 \right] \]

\( 0 < \beta < 1 , \ 0 < \delta_h < 1 , \ \lambda > 0 \)

Here the effective bliss point \( b_t + \lambda(1 - \delta_h) \sum_{j=0}^{\infty} \delta_h^j c_{t-j-4} \) shifts in response to a moving average of past consumptions of the same quarter.
To implement, set
\[
\tilde{h}_t = \delta \tilde{h}_{t-4} + (1 - \delta_h) c_t , \quad 0 < \delta_h < 1
\]
This implies that
\[
h_t = \begin{bmatrix} \tilde{h}_t \\ \tilde{h}_{t-1} \\ \tilde{h}_{t-2} \\ \tilde{h}_{t-3} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & \delta_h \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \tilde{h}_{t-1} \\ \tilde{h}_{t-2} \\ \tilde{h}_{t-3} \\ \tilde{h}_{t-4} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ (1 - \delta_h) \end{bmatrix} c_t
\]
with consumption services
\[
s_t = - \begin{bmatrix} 0 & 0 & 0 & -\lambda \end{bmatrix} h_{t-1} + c_t , \quad \lambda > 0
\]

**Adjustment Costs.**

Recall
\[-\left(\frac{1}{2}\right) E \sum_{t=0}^{\infty} \beta^t [(c_t - b_{1t})^2 + \lambda^2 (c_t - c_{t-1})^2 + \ell_t^2] \mid J_0 \]
\[0 < \beta < 1 , \quad \lambda > 0
\]
To capture adjustment costs, set
\[
h_t = c_t
\]
\[
s_t = \begin{bmatrix} 0 \\ -\lambda \end{bmatrix} h_{t-1} + \begin{bmatrix} 1 \end{bmatrix} c_t
\]
so that
\[
s_{1t} = c_t
\]
\[
s_{2t} = \lambda (c_t - c_{t-1})
\]
We set the first component \(b_{1t}\) of \(b_t\) to capture the stochastic bliss process and set the second component identically equal to zero.

Thus, we set \(\Delta_h = 0, \Theta_h = 1\)

\[
\Lambda = \begin{bmatrix} 0 \\ -\lambda \end{bmatrix} , \quad \Pi = \begin{bmatrix} 1 \end{bmatrix}
\]

**Multiple Consumption Goods**
Λ = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \text{and} \quad \Pi = \begin{bmatrix} π_1 & 0 \\ π_2 & π_3 \end{bmatrix}

\frac{1}{2} \beta^t (Πc_t - b_t)'(Πc_t - b_t)

\begin{align*}
mu_t &= -β^t[ΠΠc_t - Π'b_t] \\
c_t &= -(ΠΠ)^{-1}β^{-t}mu_t + (ΠΠ)^{-1}Π'b_t
\end{align*}

This is called the Frisch demand function for consumption.

We can think of the vector \( mu_t \) as playing the role of prices, up to a common factor, for all dates and states.

The scale factor is determined by the choice of numeraire.

Notions of substitutes and complements can be defined in terms of these Frisch demand functions.

Two goods can be said to be substitutes if the cross-price effect is positive and to be complements if this effect is negative.

Hence this classification is determined by the off-diagonal element of \(- (ΠΠ)^{-1}\), which is equal to \( π_2π_3 / \det(ΠΠ) \).

If \( π_2 \) and \( π_3 \) have the same sign, the goods are substitutes.

If they have opposite signs, the goods are complements.

To summarize, our economic structure consists of the matrices that define the following components:

**Information and shocks**

\begin{align*}
z_{t+1} &= A_{22}z_t + C_2w_{t+1} \\
b_t &= U_kz_t \\
d_t &= U_qz_t
\end{align*}

**Production Technology**

\begin{align*}
Φ_c c_t + Φ_g g_t + Φ_i i_t &= Γk_{t-1} + d_t \\
k_t &= Δ_kk_{t-1} + Θ_ki_t \\
g_t \cdot g_t &= ℓ_t^2
\end{align*}

**Household Technology**

\begin{align*}
s_t &= Λh_{t-1} + Πc_t \\
h_t &= Δ_hh_{t-1} + Θ_hc_t
\end{align*}

**Preferences**
18.2. A SUITE OF MODELS

\[
\left(\frac{1}{2}\right) E \sum_{t=0}^{\infty} \beta^t [(s_t - b_t) \cdot (s_t - b_t) + \ell_t^2] | J_0, \ 0 < \beta < 1
\]

*Next steps:* we move on to discuss two closely connected concepts

- A Planning Problem or Optimal Resource Allocation Problem
- Competitive Equilibrium

18.2.15 Optimal Resource Allocation

Imagine a planner who chooses sequences \(\{c_t, i_t, g_t\}_{t=0}^{\infty}\) to maximize

\[-(1/2)E \sum_{t=0}^{\infty} \beta^t [(s_t - b_t) \cdot (s_t - b_t) + g_t \cdot g_t] | J_0\]

subject to the constraints

- \(\Phi c_t + \Phi g_t + \Phi i_t = \Gamma_{k-1} + d_t,\)
- \(k_t = \Delta_k k_{t-1} + \Theta_i k_t,\)
- \(h_t = \Delta_h h_{t-1} + \Theta_h c_t,\)
- \(s_t = \Lambda h_{t-1} + \Pi c_t,\)
- \(z_{t+1} = A_{22} z_t + C_2 w_{t+1}, \ b_t = U_b z_t, \ \text{and} \ d_t = U_d z_t\)

and initial conditions for \(h_{-1}, k_{-1},\) and \(z_0.\)

Throughout, we shall impose the following **square summability** conditions

\[E \sum_{t=0}^{\infty} \beta^t h_t \cdot h_t | J_0 < \infty \ \text{and} \ \sum_{t=0}^{\infty} \beta^t k_t \cdot k_t | J_0 < \infty\]

Define:

\[L_0^2 = \{ \{y_t\} : y_t \text{ is a random variable in } J_t \ \text{and} \ \sum_{t=0}^{\infty} \beta^t y_t^2 | J_0 < +\infty\}\]

Thus, we require that each component of \(h_t\) and each component of \(k_t\) belong to \(L_0^2.\)

We shall compare and utilize two approaches to solving the planning problem

- Lagrangian formulation
- Dynamic programming

18.2.16 Lagrangian Formulation

Form the Lagrangian
\[ \mathcal{L} = -E \sum_{t=0}^{\infty} \beta^t \left[ \left( \frac{1}{2} \right) \left( (s_t - b_t) \cdot (s_t - b_t) + g_t \cdot g_t \right) \ight. \\
+ M_t^d' \cdot (\Phi_c c_t + \Phi_g g_t + \Phi_i i_t - \Gamma k_{t-1} - d_t) \\
+ M_t^k' \cdot (k_t - \Delta k_{t-1} - \Theta k_i t) \\
+ M_t^h' \cdot (h_t - \Delta h_{t-1} - \Theta h c_t) \\
\left. + M_t^s' \cdot (s_t - \Lambda h_{t-1} - \Pi c_t) \right] \right| J_0 \]

The planner maximizes \( \mathcal{L} \) with respect to the quantities \( \{c_t, i_t, g_t\} \) and minimizes with respect to the Lagrange multipliers \( M_t^d, M_t^k, M_t^h, M_t^s \).

First-order necessary conditions for maximization with respect to \( c_t, g_t, h_t, i_t, k_t, \) and \( s_t \), respectively, are:

\[-\Phi_c' M_t^d + \Theta_k' M_t^h + \Pi'M_t^s = 0, \]
\[-g_t - \Phi_g' M_t^d = 0, \]
\[-M_t^h + \beta E(\Delta h_{t+1} M_t^{h+1} + \Lambda'M_t^{s+1}) \mid J_t = 0, \]
\[-\Phi_i' M_t^d + \Theta_k M_t^k = 0, \]
\[-M_t^k + \beta E(\Delta k_{t+1} M_t^{k+1} + \Gamma' M_t^{d+1}) \mid J_t = 0, \]
\[-s_t + b_t - M_t^s = 0 \]

for \( t = 0, 1, \ldots \).

In addition, we have the complementary slackness conditions (these recover the original transition equations) and also transversality conditions

\[ \lim_{t \to \infty} \beta^t E[M_t^k k_t] \mid J_0 = 0 \]
\[ \lim_{t \to \infty} \beta^t E[M_t^h h_t] \mid J_0 = 0 \]

The system formed by the FONCs and the transition equations can be handed over to Python.

Python will solve the planning problem for fixed parameter values.

Here are the Python Ready Equations

\[-\Phi_c' M_t^d + \Theta_k' M_t^h + \Pi'M_t^s = 0, \]
\[-g_t - \Phi_g' M_t^d = 0, \]
\[-M_t^h + \beta E(\Delta h_{t+1} M_t^{h+1} + \Lambda'M_t^{s+1}) \mid J_t = 0, \]
\[-\Phi_i' M_t^d + \Theta_k M_t^k = 0, \]
\[-M_t^k + \beta E(\Delta k_{t+1} M_t^{k+1} + \Gamma' M_t^{d+1}) \mid J_t = 0, \]
\[-s_t + b_t - M_t^s = 0 \]
\[ \Phi_c c_t + \Phi_g g_t + \Phi_i i_t = \Gamma k_{t-1} + d_t, \]
\[ k_t = \Delta k_{t-1} + \Theta k_i t, \]
\[ h_t = \Delta h_{t-1} + \Theta h c_t, \]
\[ s_t = \Lambda h_{t-1} + \Pi c_t, \]
\[ z_{t+1} = A z_t + C w_{t+1}, \]
\[ b_t = U_b z_t, \quad \text{and} \quad d_t = U_d z_t. \]
The Lagrange multipliers or shadow prices satisfy

\[ M_t^s = b_t - s_t \]

\[ M_t^h = E \left[ \sum_{\tau=1}^{\infty} \beta^\tau (\Delta_h^\tau)^{-1} A'M_{t+\tau}^s \mid J_t \right] \]

\[ M_t^d = \left[ \frac{\Phi_c'}{\Phi_g'} \right]^{-1} \left[ \Theta_h' M_t^h + \Pi'M_t^s \right] - g_t \]

\[ M_t^k = E \left[ \sum_{\tau=1}^{\infty} \beta^\tau (\Delta_k^\tau)^{-1} \Gamma'M_{t+\tau}^d \mid J_t \right] \]

\[ M_t^i = \Theta_k M_t^k \]

Although it is possible to use matrix operator methods to solve the above Python ready equations, that is not the approach we’ll use.

Instead, we’ll use dynamic programming to get recursive representations for both quantities and shadow prices.

18.2.17 Dynamic Programming

Dynamic Programming always starts with the word let.

Thus, let \( V(x_0) \) be the optimal value function for the planning problem as a function of the initial state vector \( x_0 \).

(Thus, in essence, dynamic programming amounts to an application of a guess and verify method in which we begin with a guess about the answer to the problem we want to solve. That’s why we start with let \( V(x_0) \) be the (value of the) answer to the problem, then establish and verify a bunch of conditions \( V(x_0) \) has to satisfy if indeed it is the answer)

The optimal value function \( V(x) \) satisfies the Bellman equation

\[ V(x_0) = \max_{c_0, i_0, g_0} \left[ -0.5(s_0 - b_0) \cdot (s_0 - b_0) + g_0 \cdot g_0 \right] + \beta EV(x_1) \]

subject to the linear constraints

\[ \Phi_c c_0 + \Phi_g g_0 + \Phi_i i_0 = \Gamma k_{-1} + d_0, \]

\[ k_0 = \Delta_k k_{-1} + \Theta_k i_0, \]

\[ h_o = \Delta_h h_{-1} + \Theta_h c_0, \]

\[ s_0 = \Lambda h_{-1} + \Pi c_0, \]

\[ z_1 = A_{22} z_0 + C_2 w_1, \]

\[ b_0 = U_b z_0 \quad \text{and} \quad d_0 = U_d z_0 \]

Because this is a linear-quadratic dynamic programming problem, it turns out that the value function has the form

\[ V(x) = x'Px + \rho \]
Thus, we want to solve an instance of the following linear-quadratic dynamic programming problem:

Choose a contingency plan for \( \{x_{t+1}, u_t\}_{t=0}^\infty \) to maximize

\[
-E \sum_{t=0}^\infty \beta^t [x_t'Rx_t + u_t'Qu_t + 2u_t'W'x_t], \quad 0 < \beta < 1
\]

subject to

\[
x_{t+1} = Ax_t + Bu_t + Cw_{t+1}, \quad t \geq 0
\]

where \( x_0 \) is given; \( x_t \) is an \( n \times 1 \) vector of state variables, and \( u_t \) is a \( k \times 1 \) vector of control variables.

We assume \( w_{t+1} \) is a martingale difference sequence with \( Ew_tw'_t = I \), and that \( C \) is a matrix conformable to \( x \) and \( w \).

The optimal value function \( V(x) \) satisfies the Bellman equation

\[
V(x_t) = \max_{u_t} \left\{ -(x_t'Rx_t + u_t'Qu_t + 2u_t'Wx_t) + \beta E_t V(x_{t+1}) \right\}
\]

where maximization is subject to

\[
x_{t+1} = Ax_t + Bu_t + Cw_{t+1}, \quad t \geq 0
\]

\[
V(x_t) = -x_t'Px_t - \rho
\]

\( P \) satisfies

\[
P = R + \beta A'PA - (\beta A'PB + W)(Q + \beta B'PB)^{-1}(\beta B'PA + W')
\]

This equation in \( P \) is called the **algebraic matrix Riccati equation**.

The optimal decision rule is \( u_t = -Fx_t \), where

\[
F = (Q + \beta B'PB)^{-1}(\beta B'PA + W')
\]

The optimum decision rule for \( u_t \) is independent of the parameters \( C \), and so of the noise statistics.

Iterating on the Bellman operator leads to

\[
V_{j+1}(x_t) = \max_{u_t} \left\{ -(x_t'Rx_t + u_t'Qu_t + 2u_t'Wx_t) + \beta E_t V_j(x_{t+1}) \right\}
\]

\[
V_j(x_t) = -x_t'P_jx_t - \rho_j
\]

where \( P_j \) and \( \rho_j \) satisfy the equations.
18.2. A SUITE OF MODELS

\[ P_{j+1} = R + \beta A' P_j A - (\beta A' P_j B + W)(Q + \beta B' P_j B)^{-1}(\beta B' P_j A + W') \]

\[ \rho_{j+1} = \beta \rho_j + \beta \text{ trace } P_j C C' \]

We can now state the planning problem as a dynamic programming problem

\[
\max_{\{u_t, x_{t+1}\}} -E \sum_{t=0}^{\infty} \beta^t [x_t' R x_t + u_t' Q u_t + 2 u_t' W' x_t], \quad 0 < \beta < 1
\]

where maximization is subject to

\[ x_{t+1} = A x_t + B u_t + C w_{t+1}, \quad t \geq 0 \]

\[ x_t = \begin{bmatrix} h_{t-1} \\ k_{t-1} \\ z_t \end{bmatrix}, \quad u_t = \begin{bmatrix} i_t \end{bmatrix} \]

where

\[
A = \begin{bmatrix} \Delta_h & \Theta_h U_c[\Phi_c \Phi_g]^{-1} \Gamma & \Theta_h U_c[\Phi_c \Phi_g]^{-1} U_d \\ 0 & \Delta_k & 0 \\ 0 & 0 & A_{22} \end{bmatrix}
\]

\[
B = \begin{bmatrix} -\Theta_h U_c[\Phi_c \Phi_g]^{-1} \Phi_i \\ \Theta_k \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 \\ 0 \\ C_2 \end{bmatrix}
\]

\[
\begin{bmatrix} x_t \\ u_t \end{bmatrix}' S \begin{bmatrix} x_t \\ u_t \end{bmatrix} = \begin{bmatrix} x_t \\ u_t \end{bmatrix}' \begin{bmatrix} R & W \\ W' & Q \end{bmatrix} \begin{bmatrix} x_t \\ u_t \end{bmatrix}
\]

\[ S = (G'G + H'H)/2 \]

\[ H = [\Lambda : \Pi U_c[\Phi_c \Phi_g]^{-1} \Gamma : \Pi U_c[\Phi_c \Phi_g]^{-1} U_d - U_b : -\Pi U_c[\Phi_c \Phi_g]^{-1} \Phi_i] \]

\[ G = U_g[\Phi_c \Phi_g]^{-1}[0 : \Gamma : U_d : -\Phi_i]. \]

**Lagrange multipliers as gradient of value function**

A useful fact is that Lagrange multipliers equal gradients of the planner’s value function

\[ M^k_t = M_k x_t \] and \[ M^h_t = M_h x_t \] where

\[ M_k = 2\beta[0 \ I \ 0] PA^o \]

\[ M_h = 2\beta[0 \ 0 \ I] PA^o \]

\[ M^s_t = M_s x_t \] where \[ M_s = (S_b - S_s) \] and \[ S_b = [0 \ 0 \ U_b] \]
\[ M_t^d = M_d x_t \quad \text{where} \quad M_d = \begin{bmatrix} \Phi'_d & \Theta' h M_h + \Pi' M_s \\ \Phi'_g & -S_g \end{bmatrix}^{-1} \]

\[ M_t^c = M_c x_t \quad \text{where} \quad M_c = \Theta'_h M_h + \Pi' M_s \]

\[ M_t^i = M_i x_t \quad \text{where} \quad M_i = \Theta'_k M_k \]

We will use this fact and these equations to compute competitive equilibrium prices.

### 18.2.18 Other mathematical infrastructure

Let’s start with describing the commodity space and pricing functional for our competitive equilibrium.

For the commodity space, we use

\[ L_0^2 = \{ y_t : y_t \text{ is a random variable in } J_t \text{ and } E \sum_{t=0}^{\infty} \beta^t y_t^2 | J_0 < +\infty \} \]

For pricing functionals, we express values as inner products

\[ \pi(c) = E \sum_{t=0}^{\infty} \beta^t p^0_t \cdot c_t | J_0 \]

where \( p^0_t \) belongs to \( L_0^2 \).

With these objects in our toolkit, we move on to state the problem of a Representative Household in a competitive equilibrium.

### 18.2.19 Representative Household

The representative household owns endowment process and initial stocks of \( h \) and \( k \) and chooses stochastic processes for \( \{c_t, s_t, h_t, \ell_t\}_{t=0}^{\infty} \), each element of which is in \( L_0^2 \), to maximize

\[ - \frac{1}{2} E_0 \sum_{t=0}^{\infty} \beta^t \left[ (s_t - b_t) \cdot (s_t - b_t) + \ell_t^2 \right] \]

subject to

\[ E \sum_{t=0}^{\infty} \beta^t p^0_t \cdot c_t | J_0 = E \sum_{t=0}^{\infty} \beta^t (u^0_t \ell_t + \alpha^0_t \cdot d_t) | J_0 + v_0 \cdot k_{-1} \]

\[ s_t = \Lambda h_{t-1} + \Pi c_t \]

\[ h_t = \Delta h_{t-1} + \Theta h c_t, \quad h_{-1}, k_{-1} \text{ given} \]

We now describe the problems faced by two types of firms called type I and type II.
18.2. SUITE OF MODELS

18.2.20 Type I Firm

A type I firm rents capital and labor and endowments and produces $c_t, i_t$.
It chooses stochastic processes for $\{c_t, i_t, k_t, \ell_t, g_t, d_t\}$, each element of which is in $L^2_0$, to maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t (p_0^t \cdot c_t + q_0^t \cdot i_t - r_0^t \cdot k_{t-1} - w_0^t \ell_t - \alpha_0^t \cdot d_t)$$

subject to

$$\Phi_c c_t + \Phi_g g_t + \Phi_i i_t = \Gamma k_{t-1} + d_t$$

$$-\ell_t^2 + g_t \cdot g_t = 0$$

18.2.21 Type II Firm

A firm of type II acquires capital via investment and then rents stocks of capital to the $c, i$-producing type I firm.

A type II firm is a price taker facing the vector $v_0$ and the stochastic processes $\{r_0^t, q_0^t\}$. The firm chooses $k_{-1}$ and stochastic processes for $\{k_t, i_t\}_{t=0}^{\infty}$ to maximize

$$E \sum_{t=0}^{\infty} \beta^t (r_0^t \cdot k_{t-1} - q_0^t \cdot i_t) \mid J_0 - v_0 \cdot k_{-1}$$

subject to

$$k_t = \Delta_k k_{t-1} + \Theta_k i_t$$

18.2.22 Competitive Equilibrium: Definition

We can now state the following.

Definition: A competitive equilibrium is a price system $[v_0, \{p_0^t, w_0^t, \alpha_0^t, q_0^t, \ell_0^t\}_{t=0}^{\infty}]$ and an allocation $\{c_t, i_t, k_t, \ell_t, g_t, d_t\}_{t=0}^{\infty}$ that satisfy the following conditions:

- Each component of the price system and the allocation resides in the space $L^2_0$.
- Given the price system and given $h_{-1}$, $k_{-1}$, the allocation solves the representative household’s problem and the problems of the two types of firms.

Versions of the two classical welfare theorems prevail under our assumptions.

We exploit that fact in our algorithm for computing a competitive equilibrium.

Step 1: Solve the planning problem by using dynamic programming.

The allocation (i.e., quantities) that solve the planning problem are the competitive equilibrium quantities.

Step 2: use the following formulas to compute the equilibrium price system
\[ p_0^t = \left[ \Pi' M_i + \Theta_h M_h^k \right] / \mu_0^w = M_i / \mu_0^w \]

\[ w_0^t = | S_g x_t | / \mu_0^w \]

\[ r_0^t = \Gamma' M_d / \mu_0^w \]

\[ q_0^t = \Theta_k M_i^k / \mu_0^w = M_i / \mu_0^w \]

\[ \alpha_0^t = M_i^d / \mu_0^w \]

\[ v_0 = \Gamma' M_0^d / \mu_0^w + \Delta'_k M_0^k / \mu_0^w \]

**Verification:** With this price system, values can be assigned to the Lagrange multipliers for each of our three classes of agents that cause all first-order necessary conditions to be satisfied at these prices and at the quantities associated with the optimum of the planning problem.

### 18.2.23 Asset pricing

An important use of an equilibrium pricing system is to do asset pricing.

Thus, imagine that we are presented a dividend stream: \( \{y_t\} \in L_0^2 \) and want to compute the value of a perpetual claim to this stream.

To value this asset we simply take price times quantity and add to get an asset value:

\[ a_0 = E \sum_{t=0}^{\infty} \beta^t p_0^t \cdot y_t \mid J_0. \]

To compute \( a_0 \) we proceed as follows.

We let

\[ y_t = U_a x_t \]

\[ a_0 = E \sum_{t=0}^{\infty} \beta^t x'_t Z_a x_t \mid J_0 \]

\[ Z_a = U'_a M_c / \mu_0^w \]

We have the following convenient formulas:

\[ a_0 = x'_0 \mu_a x_0 + \sigma_a \]

\[ \mu_a = \sum_{\tau=0}^{\infty} \beta^\tau (A^\circ)^\tau Z_a A^{\circ\tau} \]

\[ \sigma_a = \frac{\beta}{1 - \beta} \text{trace} \left( Z_a \sum_{\tau=0}^{\infty} \beta^\tau (A^\circ)^\tau CC' (A^\circ)^\tau \right) \]
18.2.24 Re-Opening Markets

We have assumed that all trading occurs once-and-for-all at time $t = 0$. If we were to re-open markets at some time $t > 0$ at time $t$ wealth levels implicitly defined by time $0$ trades, we would obtain the same equilibrium allocation (i.e., quantities) and the following time $t$ price system

$$L_t^2 = \{y_s\}_{s=t}^{\infty}: y_s \text{ is a random variable in } J_s \text{ for } s \geq t$$

and $E \sum_{s=t}^{\infty} \beta^{s-t} y_s^2 | J_t < +\infty]$.

$$p_s^t = M_c x_s / [\bar{e}_j M_c x_t], \quad s \geq t$$

$$w_s^t = S_g x_s / [\bar{e}_j M_c x_t], \quad s \geq t$$

$$r_s^t = \Gamma' M_d x_s / [\bar{e}_j M_c x_t], \quad s \geq t$$

$$q_s^t = M_i x_s / [\bar{e}_j M_c x_t], \quad s \geq t$$

$$\alpha_s^t = M_d x_s / [\bar{e}_j M_c x_t], \quad s \geq t$$

$$v_t = [\Gamma' M_d + \Delta' k M_k] x_t / [\bar{e}_j M_c x_t]$$

18.3 Econometrics

Up to now, we have described how to solve the direct problem that maps model parameters into an (equilibrium) stochastic process of prices and quantities.

Recall the inverse problem of inferring model parameters from a single realization of a time series of some of the prices and quantities.

Another name for the inverse problem is econometrics.

An advantage of the [31] structure is that it comes with a self-contained theory of econometrics.

It is really just a tale of two state-space representations.

Here they are:

Original State-Space Representation:

$$x_{t+1} = A^o x_t + C w_{t+1}$$

$$y_t = G x_t + v_t$$

where $v_t$ is a martingale difference sequence of measurement errors that satisfies $E v_t v_t' = R, E w_{t+1} v_s' = 0$ for all $t + 1 \geq s$ and
\( x_0 \sim \mathcal{N}(\hat{x}_0, \Sigma_0) \)

**Innovations Representation:**

\[
\begin{align*}
\hat{x}_{t+1} &= A^{o}\hat{x}_t + K_t a_t \\
y_t &= G\hat{x}_t + a_t,
\end{align*}
\]

where \( a_t = y_t - E[y_t|y^{t-1}] \), \( Ea_t a'_t \equiv \Omega_t = G\Sigma_t G' + R \).

Compare numbers of shocks in the two representations:

- \( n_w + n_y \) versus \( n_y \)

Compare spaces spanned

- \( H(y^t) \subset H(w^t, u^t) \)
- \( H(y^t) = H(a^t) \)

**Kalman Filter:**

Kalman gain:

\[
K_t = A^{o}\Sigma_t G' (G\Sigma_t G' + R)^{-1}
\]

**Riccati Difference Equation:**

\[
\Sigma_{t+1} = A^{o}\Sigma_t A^{o'} + C C' \\
- A^{o}\Sigma_t G' (G\Sigma_t G' + R)^{-1}G\Sigma_t A^{o'}
\]

**Innovations Representation as Whitener**

Whitening Filter:

\[
\begin{align*}
a_t &= y_t - G\hat{x}_t \\
\hat{x}_{t+1} &= A^{o}\hat{x}_t + K_t a_t
\end{align*}
\]

can be used recursively to construct a record of innovations \( \{a_t\}_{t=0}^T \) from an \( (\hat{x}_0, \Sigma_0) \) and a record of observations \( \{y_t\}_{t=0}^T \).

**Limiting Time-Invariant Innovations Representation**

\[
\begin{align*}
\Sigma &= A^{o}\Sigma A^{o'} + C C' \\
- A^{o}\Sigma G' (G\Sigma G' + R)^{-1}G\Sigma A^{o'} \\
K &= A^{o}\Sigma_t G' (G\Sigma G' + R)^{-1}
\end{align*}
\]

\[
\begin{align*}
\hat{x}_{t+1} &= A^{o}\hat{x}_t + K a_t \\
y_t &= G\hat{x}_t + a_t
\end{align*}
\]

where \( Ea_t a'_t \equiv \Omega = G\Sigma G' + R \).
18.3.1 Factorization of Likelihood Function

Sample of observations \( \{y_s\}_{s=0}^T \) on a \((n_y \times 1)\) vector.

\[
f(y_T, y_{T-1}, \ldots, y_0) = f_T(y_T|y_{T-1}, \ldots, y_0)f_{T-1}(y_{T-1}|y_{T-2}, \ldots, y_0) \cdots f_1(y_1|y_0)f_0(y_0)
\]

\[
= g_T(a_T)g_{T-1}(a_{T-1}) \cdots g_1(a_1)f_0(y_0).
\]

Gaussian Log-Likelihood:

\[
-\frac{1}{2} \sum_{t=0}^T \left\{ n_y \ln(2\pi) + \ln|\Omega_t| + a_t'\Omega_t^{-1}a_t \right\}
\]

18.3.2 Covariance Generating Functions

Autocovariance: \( C_x(\tau) = E x_t x_{t-\tau}' \).

Generating Function: \( S_x(z) = \sum_{\tau=-\infty}^\infty C_x(\tau)z^\tau, z \in \mathbb{C} \).

18.3.3 Spectral Factorization Identity

Original state-space representation has too many shocks and implies:

\[
S_y(z) = G(zI - A^o)^{-1}CC'(z^{-1}I - (A^o)')^{-1}G' + R
\]

Innovations representation has as many shocks as dimension of \( y_t \) and implies

\[
S_y(z) = [G(zI - A^o)^{-1}K + I][G\Sigma G' + R][K'(z^{-1}I - A^o')^{-1}G' + I]
\]

Equating these two leads to:

\[
G(zI - A^o)^{-1}CC'(z^{-1}I - A^o')^{-1}G' + R = [G(zI - A^o)^{-1}K + I][G\Sigma G' + R][K'(z^{-1}I - A^o')^{-1}G' + I].
\]

**Key Insight:** The zeros of the polynomial \( \det(G(zI - A^o)^{-1}K + I) \) all lie inside the unit circle, which means that \( a_t \) lies in the space spanned by square summable linear combinations of \( y_t \).

**Key Property:** Invertibility

18.3.4 Wold and Vector Autoregressive Representations

Let’s start with some lag operator arithmetic.

The lag operator \( L \) and the inverse lag operator \( L^{-1} \) each map an infinite sequence into an infinite sequence according to the transformation rules

\[
Lx_t \equiv x_{t-1}
\]
\[ L^{-1}x_t \equiv x_{t+1} \]

A Wold moving average representation for \( \{y_t\} \) is

\[ y_t = [G(I - A^oL)^{-1}KL + I]a_t \]

Applying the inverse of the operator on the right side and using

\[ [G(I - A^oL)^{-1}KL + I]^{-1} = I - G[I - (A^o - KG)L]^{-1}KL \]

gives the vector autoregressive representation

\[ y_t = \sum_{j=1}^{\infty} G(A^o - KG)^{j-1}Ky_{t-j} + a_t \]

### 18.4 Dynamic Demand Curves and Canonical Household Technologies

#### 18.4.1 Canonical Household Technologies

\[ h_t = \Delta h_{t-1} + \Theta hc_t \]
\[ s_t = \Lambda h_{t-1} + \Pi c_t \]
\[ b_t = Ub_z_t \]

**Definition:** A household service technology \((\Delta_h, \Theta_h, \Pi, \Lambda, U_b)\) is said to be **canonical** if

- \(\Pi\) is nonsingular, and
- the absolute values of the eigenvalues of \((\Delta_h - \Theta_h\Pi^{-1}\Lambda)\) are strictly less than \(1/\sqrt{\beta}\).

**Key invertibility property:** A canonical household service technology maps a service process \(\{s_t\}\) in \(L_0^2\) into a corresponding consumption process \(\{c_t\}\) for which the implied household capital stock process \(\{h_t\}\) is also in \(L_0^2\).

An inverse household technology:

\[ c_t = -\Pi^{-1}\Delta h_{t-1} + \Pi^{-1}s_t \]
\[ h_t = (\Delta_h - \Theta_h\Pi^{-1}\Lambda)h_{t-1} + \Theta_h\Pi^{-1}s_t \]

The restriction on the eigenvalues of the matrix \((\Delta_h - \Theta_h\Pi^{-1}\Lambda)\) keeps the household capital stock \(\{h_t\}\) in \(L_0^2\).

#### 18.4.2 Dynamic Demand Functions

\[ p_t^0 \equiv \Pi^{-1/\gamma'} \left[ p_t^0 - \Theta h E_t \sum_{\tau=1}^{\infty} \beta^\tau (\Delta_h' - \Lambda'\Pi^{-1}\Lambda'\Theta_h')^{-1}\Lambda'\Pi^{-1}\gamma' p_{t+\tau}^0 \right] \]

\[ s_{i,t} = \Delta h_{i,t-1} \]
\[ h_{i,t} = \Delta h_{i,t-1} \]
where \( h_{t-1} = h_{-1} \).

\[
W_0 = E_0 \sum_{t=0}^{\infty} \beta^t (u_0^t \ell_t + \alpha_0^t \cdot d_t) + v_0 \cdot k_{-1}
\]

\[
\mu_0^w = \frac{E_0 \sum_{t=0}^{\infty} \beta^t \rho_t^0 \cdot (b_t - s_{i,t}) - W_0}{E_0 \sum_{t=0}^{\infty} \beta^t \rho_t^0 \cdot \rho_t^0}
\]

\[
c_t = -\Pi^{-1} h_{t-1} + \Pi^{-1} b_t - \Pi^{-1} \mu_0^w E_t \{\Pi' \Pi - \Pi' \Theta_h' \}
\]

\[
[I - (\Delta'_h - \Lambda' \Pi' \Theta_h') \beta L^{-1} - \Lambda' \Pi' \beta L^{-1}] p_t^0
\]

\[
h_t = \Delta h h_{t-1} + \Theta h c_t
\]

This system expresses consumption demands at date \( t \) as functions of: (i) time-\( t \) conditional expectations of future scaled Arrow-Debreu prices \( \{p_{0+s}\}_{s=0}^{\infty} \); (ii) the stochastic process for the household’s endowment \( \{d_t\} \) and preference shock \( \{b_t\} \), as mediated through the multiplier \( \mu_0^w \) and wealth \( W_0 \); and (iii) past values of consumption, as mediated through the state variable \( h_{t-1} \).

### 18.5 Gorman Aggregation and Engel Curves

We shall explore how the dynamic demand schedule for consumption goods opens up the possibility of satisfying Gorman’s (1953) conditions for aggregation in a heterogeneous consumer model.

The first equation of our demand system is an Engel curve for consumption that is linear in the marginal utility \( \mu_0^2 \) of individual wealth with a coefficient on \( \mu_0^w \) that depends only on prices.

The multiplier \( \mu_0^w \) depends on wealth in an affine relationship, so that consumption is linear in wealth.

In a model with multiple consumers who have the same household technologies \( (\Delta_h, \Theta_h, \Lambda, \Pi) \) but possibly different preference shock processes and initial values of household capital stocks, the coefficient on the marginal utility of wealth is the same for all consumers.

Gorman showed that when Engel curves satisfy this property, there exists a unique community or aggregate preference ordering over aggregate consumption that is independent of the distribution of wealth.

#### 18.5.1 Re-Opened Markets

\[
\rho_t^i = \Pi^{-1'} \left[ p_t^i - \Theta_h' E_t \sum_{\tau=1}^{\infty} \beta^\tau (\Delta'_h - \Lambda' \Pi' \Theta_h' \tau^{-1} \Lambda' \Pi' \rho_{t+\tau}^i) \right]
\]

\[
s_{i,t} = \Lambda h_{i,t-1}
\]

\[
h_{i,t} = \Delta h h_{i,t-1},
\]

where now \( h_{i,t-1} = h_{t-1} \). Define time \( t \) wealth \( W_t \).
\[ W_t = E_t \sum_{j=0}^{\infty} \beta^j (w_{t+j} \ell_{t+j} + \alpha_{t+j} \cdot d_{t+j}) + v_t \cdot k_{t-1} \]

\[ \mu^w_t = \frac{E_t \sum_{j=0}^{\infty} \beta^j \rho_{t+j} \cdot (b_{t+j} - s_{i,t+j}) - W_t}{E_t \sum_{t=0}^{\infty} \beta \rho_{t+j} \cdot \rho_{t+j}^t} \]

\[ c_t = -\Pi^{-1} \Delta h_{t-1} + \Pi^{-1} b_t - \Pi^{-1} \mu^w_t E_t \{ \Pi^{\prime -1} - \Pi^{\prime -1} \Theta^h \} \]

\[ h_t = \Delta h_{h_{t-1}} + \Theta_h c_t \]

18.5.2 Dynamic Demand

Define a time \( t \) continuation of a sequence \( \{z_t\}_{t=0}^{\infty} \) as the sequence \( \{z_{\tau}\}_{\tau=t}^{\infty} \). The demand system indicates that the time \( t \) vector of demands for \( c_t \) is influenced by:

Through the multiplier \( \mu^w_t \), the time \( t \) continuation of the preference shock process \( \{b_t\} \) and the time \( t \) continuation of \( \{s_{i,t}\} \).

The time \( t-1 \) level of household durables \( h_{t-1} \).

Everything that affects the household’s time \( t \) wealth, including its stock of physical capital \( k_{t-1} \) and its value \( v_t \), the time \( t \) continuation of the factor prices \( \{w_t, \alpha_t\} \), the household’s continuation endowment process, and the household’s continuation plan for \( \{\ell_t\} \).

The time \( t \) continuation of the vector of prices \( \{p^t_t\} \).

18.5.3 Attaining a Canonical Household Technology

Apply the following version of a factorization identity:

\[ \tilde{\Pi} + \beta^{1/2} L \tilde{\Lambda} (I - \beta^{1/2} L \Delta_h)^{-1} \Theta^h \]

The factorization identity guarantees that the \( \tilde{\Lambda}, \tilde{\Pi} \) representation satisfies both requirements for a canonical representation.

18.6 Partial Equilibrium

Now we’ll provide quick overviews of examples of economies that fit within our framework.

We provide details for a number of these examples in subsequent lectures:

1. Growth in Dynamic Linear Economies
2. Lucas Asset Pricing using DLE
3. IRFs in Hall Model
4. Permanent Income Using the DLE class
5. Rosen schooling model
6. Cattle cycles
7. Shock Non Invertibility

We’ll start with an example of a partial equilibrium in which we posit demand and supply curves.

Suppose that we want to capture the dynamic demand curve:

\[
 c_t = -\Pi^{-1} \Delta h_{t-1} + \Pi^{-1} b_t - \Pi^{-1} \mu_0 \{ \Pi' \theta_h \} \theta_h' \theta_h^{-1} \beta L^{-1} \Lambda' \Pi' \theta_h' \theta_h^{-1} \beta L^{-1} \}
\]

From material described earlier in this lecture, we know how to reverse engineer preferences that generate this demand system.

- note how the demand equations are cast in terms of the matrices in our standard preference representation.

Now let’s turn to supply.

A representative firm takes as given and beyond its control the stochastic process \( \{ p_t \}_{t=0}^{\infty} \).

The firm sells its output \( c_t \) in a competitive market each period.

Only spot markets convene at each date \( t \geq 0 \).

The firm also faces an exogenous process of cost disturbances \( d_t \).

The firm chooses stochastic processes \( \{ c_t, g_t, i_t, k_t \}_{t=0}^{\infty} \) to maximize

\[
 E_0 \sum_{t=0}^{\infty} \beta^t \{ p_t \cdot c_t - g_t \cdot g_t/2 \}
\]

subject to given \( k_{-1} \) and

\[
 \Phi_c c_t + \Phi_i i_t + \Phi_g g_t = \Gamma k_{t-1} + d_t \\
 k_t = \Delta k_{t-1} + \Theta_k i_t.
\]

### 18.7 Equilibrium Investment Under Uncertainty

A representative firm maximizes

\[
 E \sum_{t=0}^{\infty} \beta^t \{ p_t c_t - g_t^2/2 \}
\]

subject to the technology

\[
 c_t = \gamma k_{t-1} \\
 k_t = \delta k_{t-1} + i_t \\
 g_t = f_i i_t + f_d d_t
\]
where \(d_t\) is a cost shifter, \(\gamma > 0\), and \(f_1 > 0\) is a cost parameter and \(f_2 = 1\). Demand is governed by

\[
p_t = \alpha_0 - \alpha_1 c_t + u_t
\]

where \(u_t\) is a demand shifter with mean zero and \(\alpha_0, \alpha_1\) are positive parameters. Assume that \(u_t, d_t\) are uncorrelated first-order autoregressive processes.

### 18.8 A Rosen-Topel Housing Model

\[
R_t = b_t + \alpha h_t
\]
\[
p_t = E_t \sum_{\tau = 0}^{\infty} (\beta \delta h) \tau R_{t+\tau}
\]

where \(h_t\) is the stock of housing at time \(t\), \(R_t\) is the rental rate for housing, \(p_t\) is the price of new houses, and \(b_t\) is a demand shifter; \(\alpha < 0\) is a demand parameter, and \(\delta h\) is a depreciation factor for houses.

We cast this demand specification within our class of models by letting the stock of houses \(h_t\) evolve according to

\[
h_t = \delta h h_{t-1} + c_t, \quad \delta h \in (0, 1)
\]

where \(c_t\) is the rate of production of new houses.

Houses produce services \(s_t\) according to \(s_t = \lambda h_t\) or \(s_t = \lambda h_{t-1} + \pi c_t\), where \(\lambda = \lambda h, \pi = \lambda\).

We can take \(\bar{\lambda} \rho^0_t = R_t\) as the rental rate on housing at time \(t\), measured in units of time \(t\) consumption (housing).

Demand for housing services is

\[
s_t = b_t - \mu_0 \rho^0_t
\]

where the price of new houses \(p_t\) is related to \(\rho^0_t\) by \(\rho^0_t = \pi^{-1}[p_t - \beta \delta h E_t p_{t+1}]\).

### 18.9 Cattle Cycles

Rosen, Murphy, and Scheinkman (1994). Let \(p_t\) be the price of freshly slaughtered beef, \(m_t\) the feeding cost of preparing an animal for slaughter, \(\bar{h}_t\) the one-period holding cost for a mature animal, \(\gamma_1 \bar{h}_t\) the one-period holding cost for a yearling, and \(\gamma_0 \bar{h}_t\) the one-period holding cost for a calf.

The cost processes \(\{\bar{h}_t, m_t\}_{t=0}^{\infty}\) are exogenous, while the stochastic process \(\{p_t\}_{t=0}^{\infty}\) is determined by a rational expectations equilibrium. Let \(\bar{x}_t\) be the breeding stock, and \(\bar{y}_t\) be the total stock of animals.

The law of motion for cattle stocks is

\[
\bar{x}_t = (1 - \delta) \bar{x}_{t-1} + g \bar{x}_{t-3} - c_t
\]
where $c_t$ is a rate of slaughtering. The total head-count of cattle

$$\bar{y}_t = \bar{x}_t + g\bar{x}_{t-1} + g\bar{x}_{t-2}$$

is the sum of adults, calves, and yearlings, respectively.

A representative farmer chooses $\{c_t, \bar{x}_t\}$ to maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t \{p_t c_t - \bar{h}_t \bar{x}_t - (\gamma_0 \bar{h}_t)(g\bar{x}_{t-1}) - (\gamma_1 \bar{h}_t)(g\bar{x}_{t-2}) - m_t c_t - \Psi(\bar{x}_t, \bar{x}_{t-1}, \bar{x}_{t-2}, c_t)\}$$

where

$$\Psi = \frac{\psi_1}{2} \bar{x}_t^2 + \frac{\psi_2}{2} \bar{x}_{t-1}^2 + \frac{\psi_3}{2} \bar{x}_{t-2}^2 + \frac{\psi_4}{2} c_t^2$$

Demand is governed by

$$c_t = \alpha_0 - \alpha_1 p_t + \tilde{d}_t$$

where $\alpha_0 > 0$, $\alpha_1 > 0$, and $\{\tilde{d}_t\}_{t=0}^{\infty}$ is a stochastic process with mean zero representing a demand shifter.

For more details see Cattle cycles

18.10 Models of Occupational Choice and Pay

We’ll describe the following pair of schooling models that view education as a time-to-build process:

- Rosen schooling model for engineers
- Two-occupation model

18.10.1 Market for Engineers

Ryoo and Rosen’s (2004) [56] model consists of the following equations:

first, a demand curve for engineers

$$w_t = -\alpha_d N_t + \epsilon_{1t}, \alpha_d > 0$$

second, a time-to-build structure of the education process

$$N_{t+k} = \delta_N N_{t+k-1} + n_t, 0 < \delta_N < 1$$

third, a definition of the discounted present value of each new engineering student

$$v_t = \beta^k E_0 \sum_{j=0}^{\infty} (\beta \delta_N)^j w_{t+k+j}.$$
and fourth, a supply curve of new students driven by \(v_t\)

\[ n_t = \alpha_s v_t + \epsilon_{2t}, \quad \alpha_s > 0 \]

Here \(\{\epsilon_{1t}, \epsilon_{2t}\}\) are stochastic processes of labor demand and supply shocks.

**Definition:** A partial equilibrium is a stochastic process \(\{w_t, N_t, v_t, n_t\}_{t=0}^{\infty}\) satisfying these four equations, and initial conditions \(N_{-1}, n_{-s}, s = 1, \ldots, -k\).

We sweep the time-to-build structure and the demand for engineers into the household technology and putting the supply of new engineers into the technology for producing goods.

\[
s_t = \begin{bmatrix} \lambda_1 & 0 & \ldots & 0 \\ 0 & 0 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & 0 \\ h_{k+1,t} \end{bmatrix} \begin{bmatrix} h_{1,t-1} \\ h_{2,t-1} \\ \vdots \\ h_{k,t-1} \end{bmatrix} + 0 \cdot c_t
\]

This specification sets Rosen’s \(N_t = h_{1,t-1}, n_t = c_t, h_{\tau+1,t-1} = n_{t-\tau}, \tau = 1, \ldots, k\), and uses the home-produced service to capture the demand for labor. Here \(\lambda_1\) embodies Rosen’s demand parameter \(\alpha_d\).

- The supply of new workers becomes our consumption.
- The dynamic demand curve becomes Rosen’s dynamic supply curve for new workers.

**Remark:** This has an Imai-Keane flavor.

For more details and Python code see Rosen schooling model.

### 18.10.2 Skilled and Unskilled Workers

First, a demand curve for labor

\[
\begin{bmatrix} w_{ut} \\ w_{st} \end{bmatrix} = \alpha_d \begin{bmatrix} N_{ut} \\ N_{st} \end{bmatrix} + \epsilon_{1t}
\]

where \(\alpha_d\) is a \((2 \times 2)\) matrix of demand parameters and \(\epsilon_{1t}\) is a vector of demand shifters second, time-to-train specifications for skilled and unskilled labor, respectively:

\[
N_{st+k} = \delta_N N_{st+k-1} + n_{st}
\]

\[N_{at} = \delta_N N_{at-1} + n_{at};\]

where \(N_{st}, N_{at}\) are stocks of the two types of labor, and \(n_{st}, n_{at}\) are entry rates into the two occupations.

third, definitions of discounted present values of new entrants to the skilled and unskilled occupations, respectively:
\[ v_{st} = E_t \beta^k \sum_{j=0}^{\infty} (\beta \delta) w_{st+k+j} \]
\[ v_{ut} = E_t \sum_{j=0}^{\infty} (\beta \delta) w_{ut+j} \]

where \( w_{ut}, w_{st} \) are wage rates for the two occupations; and fourth, supply curves for new entrants:

\[ \begin{bmatrix} n_{st} \\ n_{ut} \end{bmatrix} = \alpha_s \begin{bmatrix} v_{ut} \\ v_{st} \end{bmatrix} + \epsilon_{2t} \]

**Short Cut**

As an alternative, Siow simply used the equalizing differences condition

\[ v_{ut} = v_{st} \]

### 18.11 Permanent Income Models

We’ll describe a class of permanent income models that feature

- Many consumption goods and services
- A single capital good with \( R\beta = 1 \)
- The physical production technology

\[ \phi_c \cdot c_t + i_t = \gamma k_{t-1} + e_t \]
\[ k_t = k_{t-1} + i_t \]
\[ \phi_i i_t - g_t = 0 \]

**Implication One:**

Equality of Present Values of Moving Average Coefficients of \( c \) and \( e \)

\[ k_{t-1} = \beta \sum_{j=0}^{\infty} \beta^j (\phi_c \cdot c_{t+j} - e_{t+j}) \Rightarrow \]
\[ k_{t-1} = \beta \sum_{j=0}^{\infty} \beta^j E(\phi_c \cdot c_{t+j} - e_{t+j}) | J_t \Rightarrow \]
\[ \sum_{j=0}^{\infty} \beta^j (\phi_c)' \chi_j = \sum_{j=0}^{\infty} \beta^j \epsilon_j \]

where \( \chi_j w_t \) is the response of \( c_{t+j} \) to \( w_t \) and \( \epsilon_j w_t \) is the response of endowment \( e_{t+j} \) to \( w_t \):

**Implication Two:**

Martingales
\[ M^k_t = E(M^k_{t+1} | J_t) \]
\[ M^e_t = E(M^e_{t+1} | J_t) \]

and

\[ M^c_t = (\Phi_c)' M^d_t = \phi_c M^d_t \]

For more details see Permanent Income Using the DLE class.

**Testing Permanent Income Models:**

We have two types of implications of permanent income models:

- Equality of present values of moving average coefficients.
- Martingale \( M^k_t \).

These have been tested in work by Hansen, Sargent, and Roberts (1991) [57] and by Attanasio and Pavoni (2011) [6].

### 18.12 Gorman Heterogeneous Households

We now assume that there is a finite number of households, each with its own household technology and preferences over consumption services.

Household \( j \) orders preferences over consumption processes according to

\[ - \left( \frac{1}{2} \right) E \sum_{t=0}^{\infty} \beta^t \left[ (s_{jt} - b_{jt}) \cdot (s_{jt} - b_{jt}) + \ell_{jt}^2 \right] | J_0 \]

\[ s_{jt} = \Lambda h_{jt-1} + \Pi c_{jt} \]

\[ h_{jt} = \Delta h_{jt-1} + \Theta h c_{jt} \]

and \( h_{j,-1} \) is given

\[ b_{jt} = U_{bj} z_t \]

\[ E \sum_{t=0}^{\infty} \beta^t p_t^0 \cdot c_{jt} | J_0 = E \sum_{t=0}^{\infty} \beta^t (w_t^0 \ell_{jt} + \alpha_t^0 \cdot d_{jt}) | J_0 + v_0 \cdot k_{j,-1}, \]

where \( k_{j,-1} \) is given. The \( j \)th consumer owns an endowment process \( d_{jt} \), governed by the stochastic process \( d_{jt} = U_{dj} z_t \).

We refer to this as a setting with Gorman heterogeneous households.

This specification confines heterogeneity among consumers to:

- differences in the preference processes \( \{b_{jt}\} \), represented by different selections of \( U_{bj} \)
- differences in the endowment processes \( \{d_{jt}\} \), represented by different selections of \( U_{dj} \)
- differences in \( h_{j,-1} \) and
• differences in $k_{j,-1}$

The matrices $\Lambda, \Pi, \Delta_h, \Theta_h$ do not depend on $j$.

This makes everybody’s demand system have the form described earlier, with different $\mu_{w}^0$’s (reflecting different wealth levels) and different $b_{jt}$ preference shock processes and initial conditions for household capital stocks.

**Punchline:** there exists a representative consumer.

We can use the representative consumer to compute a competitive equilibrium aggregate allocation and price system.

With the equilibrium aggregate allocation and price system in hand, we can then compute allocations to each household.

**Computing Allocations to Individuals:**

Set

$$\ell_{jt} = (\mu_{0j}^w/\mu_{0a})\ell_{at}$$

Then solve the following equation for $\mu_{0j}^w$:

$$\mu_{0j}^w E_0 \sum_{t=0}^{\infty} \beta^t \{ (\rho_t^0 \cdot \rho_t^0) + (w_t^0/\mu_{0a}^w)\ell_{at} \} = E_0 \sum_{t=0}^{\infty} \beta^t \{ (b_{jt} - s_{jt}) - \alpha_t^0 \cdot d_{jt} \} - v_0 k_{j,-1}$$

$$s_{jt} - b_{jt} = \mu_{0j}^w \rho_t^0$$

$$c_{jt} = -\Pi^{-1} \Delta h_{j,t-1} + \Pi^{-1} s_{jt}$$

$$h_{jt} = (\Delta_h - \Theta_h \Pi^{-1} \Lambda) h_{j,t-1} + \Pi^{-1} \Theta h s_{jt}$$

Here $h_{j,-1}$ given.

### 18.13 Non-Gorman Heterogeneous Households

We now describe a less tractable type of heterogeneity across households that we dub **Non-Gorman heterogeneity**.

Here is the specification:

Preferences and Household Technologies:

$$-\frac{1}{2} E \sum_{t=0}^{\infty} \beta^t [(s_{it} - b_{it}) \cdot (s_{it} - b_{it}) + \ell_{it}^2] \mid J_0$$

$$s_{it} = \Lambda_i h_{it-1} + \Pi_i c_{it}$$

$$h_{it} = \Delta_{h_i} h_{it-1} + \Theta_{h_i} c_{it}, \ i = 1, 2.$$ 

$$b_{it} = U_{bi} z_t$$
\[ z_{t+1} = A_{22}z_t + C_2w_{t+1} \]

**Production Technology**

\[ \Phi_t(c_t + c_{2t}) + \Phi_g g_t + \Phi_i i_t = \Gamma k_{t-1} + d_{1t} + d_{2t} \]

\[ k_t = \Delta k_{t-1} + \Theta k_{it} \]

\[ g_t \cdot g_t = \ell^2_t, \quad \ell_t = \ell_{1t} + \ell_{2t} \]

\[ d_{it} = U_{d_i}z_t, \quad i = 1, 2 \]

**Pareto Problem:**

\[ -\frac{1}{2} \lambda E \sum_{t=0}^{\infty} \beta^t [(s_{1t} - b_{1t}) \cdot (s_{1t} - b_{1t}) + \ell^2_{1t}] \]

\[ -\frac{1}{2} (1 - \lambda) E \sum_{t=0}^{\infty} \beta^t [(s_{2t} - b_{2t}) \cdot (s_{2t} - b_{2t}) + \ell^2_{2t}] \]

**Mongrel Aggregation: Static**

There is what we call a kind of **mongrel aggregation** in this setting.

We first describe the idea within a simple static setting in which there is a single consumer static inverse demand with implied preferences:

\[ c_t = \Pi^{-1}b_t - \mu_0 \Pi^{-1} \Pi^{-1'} p_t \]

An inverse demand curve is

\[ p_t = \mu_0^{-1} \Pi' b_t - \mu_0^{-1} \Pi' c_t \]

Integrating the marginal utility vector shows that preferences can be taken to be

\[ (-2\mu_0)^{-1}(\Pi c_t - b_t) \cdot (\Pi c_t - b_t) \]

**Key Insight:** Factor the inverse of a ‘covariance matrix’. 

Now assume that there are two consumers, \( i = 1, 2 \), with demand curves

\[ c_{it} = \Pi_i^{-1}b_{it} - \mu_0 \Pi_i^{-1} \Pi_i^{-1'} p_t \]

\[ c_{1t} + c_{2t} = (\Pi_1^{-1}b_{1t} + \Pi_2^{-1}b_{2t}) - (\mu_0 \Pi_1^{-1} \Pi_1^{-1'} + \mu_0 \Pi_2^{-1} \Pi_2^{-1'}) p_t \]

Setting \( c_{1t} + c_{2t} = c_t \) and solving for \( p_t \) gives
18.13. NON-GORMAN HETEROGENEOUS HOUSEHOLDS 363

\[ p_t = (\mu_{01}\Pi_1^{-1}\Pi_1^{-1} + \mu_{02}\Pi_2^{-1}\Pi_2^{-1})^{-1}(\Pi_1^{-1}b_{1t} + \Pi_2^{-1}b_{2t}) \]
\[ - (\mu_{01}\Pi_1^{-1}\Pi_1^{-1} + \mu_{02}\Pi_2^{-1}\Pi_2^{-1})^{-1}c_t \]

**Punchline:** choose \( \Pi \) associated with the aggregate ordering to satisfy

\[ \mu_0^{-1}\Pi\Pi = (\mu_{01}\Pi_1^{-1}\Pi_1^{-1} + \mu_{02}\Pi_2^{-1}\Pi_2^{-1})^{-1} \]

**Dynamic Analogue:**

We now describe how to extend mongrel aggregation to a dynamic setting.

The key comparison is

- Static: factor a covariance matrix-like object
- Dynamic: factor a spectral-density matrix-like object

**Programming Problem for Dynamic Mongrel Aggregation:**

Our strategy for deducing the mongrel preference ordering over \( c_t = c_{1t} + c_{2t} \) is to solve the programming problem: choose \( \{c_{1t}, c_{2t}\} \) to maximize the criterion

\[ \sum_{t=0}^{\infty} \beta^t [\lambda(s_{1t} - b_{1t}) \cdot (s_{1t} - b_{1t}) + (1 - \lambda)(s_{2t} - b_{2t}) \cdot (s_{2t} - b_{2t})] \]

subject to

\[ h_{jt} = \Delta_j h_{j,t-1} + \Theta_j c_{jt}, j = 1, 2 \]
\[ s_{jt} = \Delta_j s_{j,t-1} + \Pi_j c_{jt}, j = 1, 2 \]
\[ c_{1t} + c_{2t} = c_t \]

subject to \( (h_{1,-1}, h_{2,-1}) \) given and \( \{b_{1t}\}, \{b_{2t}\}, \{c_t\} \) being known and fixed sequences.

Substituting the \( \{c_{1t}, c_{2t}\} \) sequences that solve this problem as functions of \( \{b_{1t}, b_{2t}, c_t\} \) into the objective determines a mongrel preference ordering over \( \{c_t\} = \{c_{1t} + c_{2t}\} \).

In solving this problem, it is convenient to proceed by using Fourier transforms. For details, please see [31] where they deploy a

**Secret Weapon:** Another application of the spectral factorization identity.

**Concluding remark:** The [31] class of models described in this lecture are all complete markets models. We have exploited the fact that complete market models are all alike to allow us to define a class that gives the same name to different things in the spirit of Henri Poincare.

Could we create such a class for incomplete markets models?

That would be nice, but before trying it would be wise to contemplate the remainder of a statement by Robert E. Lucas, Jr., with which we began this lecture.

“Complete market economies are all alike but each incomplete market economy is incomplete in its own individual way.” Robert E. Lucas, Jr., (1989)
Chapter 19

Growth in Dynamic Linear Economies

19.1 Contents

- Common Structure 19.2
- A Planning Problem 19.3
- Example Economies 19.4

This is another member of a suite of lectures that use the quantecon DLE class to instantiate models within the [31] class of models described in detail in *Recursive Models of Dynamic Linear Economies*.

In addition to what’s included in Anaconda, this lecture uses the quantecon library.

```python
In [1]: !pip install --upgrade quantecon
```

This lecture describes several complete market economies having a common linear-quadratic-Gaussian structure.

Three examples of such economies show how the DLE class can be used to compute equilibria of such economies in Python and to illustrate how different versions of these economies can or cannot generate sustained growth.

We require the following imports

```python
In [2]: import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
from quantecon import LQ, DLE
```

19.2 Common Structure

Our example economies have the following features

- Information flows are governed by an exogenous stochastic process $z_t$ that follows

$$z_{t+1} = A_{22}z_t + C_2w_{t+1}$$
where $w_{t+1}$ is a martingale difference sequence.

- Preference shocks $b_t$ and technology shocks $d_t$ are linear functions of $z_t$
  \[ b_t = U_b z_t \]
  \[ d_t = U_d z_t \]

- Consumption and physical investment goods are produced using the following technology
  \[ \Phi_c c_t + \Phi_g g_t + \Phi_i i_t = \Gamma k_{t-1} + d_t \]
  \[ k_t = \Delta_k k_{t-1} + \Theta_k i_t \]
  \[ g_t \cdot g_t = l_t^2 \]

where $c_t$ is a vector of consumption goods, $g_t$ is a vector of intermediate goods, $i_t$ is a vector of investment goods, $k_t$ is a vector of physical capital goods, and $l_t$ is the amount of labor supplied by the representative household.

- Preferences of a representative household are described by
  \[ -\frac{1}{2} \mathbb{E} \sum_{t=0}^{\infty} \beta^t [(s_t - b_t) \cdot (s_t - b_t) + g_t \cdot g_t], \quad 0 < \beta < 1 \]
  \[ s_t = \Lambda h_{t-1} + \Pi c_t \]
  \[ h_t = \Delta_h h_{t-1} + \Theta_h c_t \]

where $s_t$ is a vector of consumption services, and $h_t$ is a vector of household capital stocks.

Thus, an instance of this class of economies is described by the matrices
\[ \{ A_{22}, C_2, U_b, U_d, \Phi_c, \Phi_g, \Phi_i, \Gamma, \Delta_k, \Theta_k, \Lambda, \Pi, \Delta_h, \Theta_h \} \]
and the scalar $\beta$.

### 19.3 A Planning Problem

The first welfare theorem asserts that a competitive equilibrium allocation solves the following planning problem.

Choose $\{c_t, s_t, i_t, h_t, k_t, g_t\}_{t=0}^{\infty}$ to maximize
\[ -\frac{1}{2} \mathbb{E} \sum_{t=0}^{\infty} \beta^t [(s_t - b_t) \cdot (s_t - b_t) + g_t \cdot g_t] \]
subject to the linear constraints
\[ \Phi_c c_t + \Phi_g g_t + \Phi_i i_t = \Gamma k_{t-1} + d_t \]
\[ k_t = \Delta_k k_{t-1} + \Theta_k i_t \]
19.4. EXAMPLE ECONOMIES

\[ h_t = \Delta h_{t-1} + \Theta h_t \]

\[ s_t = \Lambda h_{t-1} + \Pi c_t \]

and

\[ z_{t+1} = A_{22} z_t + C_2 w_{t+1} \]

\[ b_t = U_b z_t \]

\[ d_t = U_d z_t \]

The DLE class in Python maps this planning problem into a linear-quadratic dynamic programming problem and then solves it by using QuantEcon’s LQ class.

(See Section 5.5 of Hansen & Sargent (2013) [31] for a full description of how to map these economies into an LQ setting, and how to use the solution to the LQ problem to construct the output matrices in order to simulate the economies)

The state for the LQ problem is

\[ x_t = \begin{bmatrix} h_{t-1} \\ k_{t-1} \\ z_t \end{bmatrix} \]

and the control variable is \( u_t = i_t \).

Once the LQ problem has been solved, the law of motion for the state is

\[ x_{t+1} = (A - BF)x_t + Cw_{t+1} \]

where the optimal control law is \( u_t = -Fx_t \).

Letting \( A^o = A - BF \) we write this law of motion as

\[ x_{t+1} = A^o x_t + Cw_{t+1} \]

19.4 Example Economies

Each of the example economies shown here will share a number of components. In particular, for each we will consider preferences of the form

\[ -\frac{1}{2} \mathbb{E} \sum_{t=0}^{\infty} \beta^t [(s_t - b_t)^2 + l_t^2], 0 < \beta < 1 \]

\[ s_t = \lambda h_{t-1} + \pi c_t \]
CHAPTER 19. GROWTH IN DYNAMIC LINEAR ECONOMIES

\[ h_t = \delta_h h_{t-1} + \theta_h c_t \]

\[ b_t = U_b z_t \]

Technology of the form

\[ c_t + i_t = \gamma_1 k_{t-1} + d_{1t} \]

\[ k_t = \delta_k k_{t-1} + i_t \]

\[ g_t = \phi_1 i_t, \phi_1 > 0 \]

\[ \begin{bmatrix} d_{1t} \\ 0 \end{bmatrix} = U_d z_t \]

And information of the form

\[ z_{t+1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.8 & 0 \\ 0 & 0 & 0.5 \end{bmatrix} z_t + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} w_{t+1} \]

\[ U_b = \begin{bmatrix} 30 & 0 & 0 \end{bmatrix} \]

\[ U_d = \begin{bmatrix} 5 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]

We shall vary \( \{\lambda, \pi, \delta_h, \theta_h, \gamma_1, \delta_k, \phi_1\} \) and the initial state \( x_0 \) across the three economies.

19.4.1 Example 1: Hall (1978)

First, we set parameters such that consumption follows a random walk. In particular, we set

\[ \lambda = 0, \pi = 1, \gamma_1 = 0.1, \phi_1 = 0.00001, \delta_k = 0.95, \beta = \frac{1}{1.05} \]

(In this economy \( \delta_h \) and \( \theta_h \) are arbitrary as household capital does not enter the equation for consumption services We set them to values that will become useful in Example 3)

It is worth noting that this choice of parameter values ensures that \( \beta (\gamma_1 + \delta_k) = 1 \).

For simulations of this economy, we choose an initial condition of

\[ x_0 = \begin{bmatrix} 5 & 150 & 1 & 0 & 0 \end{bmatrix} \]
In [3]: # Parameter Matrices

\[
\begin{align*}
\gamma_1 &= 0.1 \\
\phi_1 &= 1e-5 \\
\phi_c, \phi_g, \phi_i, \gamma, \delta_k, \theta_k &= (np.array([[1]], [0])), \\
& (np.array([[0]], [1])), \\
& (np.array([[1], [-\phi_1]]), \\
& (np.array([[\gamma_1]], [0])), \\
& (np.array([[.95]]), \\
& (np.array([[1]])) \\
\beta, \lambda, \pi, \delta, \phi &= (np.array([[1 / 1.05]]), \\
& (np.array([[0]])), \\
& (np.array([[1]])), \\
& (np.array([[.9]])), \\
& (np.array([[1]])) - np.array([[.9]]))
\end{align*}
\]

\[
\begin{align*}
\text{a22, c2, ub, ud} &= (np.array([[1, 0, 0], \\
& [0, .8, 0], \\
& [0, 0, .5]]), \\
& np.array([[0, 0], \\
& [1, 0], \\
& [0, 1]]), \\
& np.array([[30, 0, 0]]), \\
& np.array([[5, 1, 0], \\
& [0, 0, 0]]))
\end{align*}
\]

# Initial condition
\[
x_0 = np.array([[5], [150], [1], [0], [0]])
\]

info1 = (a22, c2, ub, ud)
tech1 = (\phi_c, \phi_g, \phi_i, \gamma, \delta_k, \theta_k)
pref1 = (\beta, \lambda, \pi, \delta, \phi)

These parameter values are used to define an economy of the DLE class.

In [4]: econ1 = DLE(info1, tech1, pref1)

We can then simulate the economy for a chosen length of time, from our initial state vector \(x_0\)

In [5]: econ1.compute_sequence(x0, ts_length=300)

The economy stores the simulated values for each variable. Below we plot consumption and investment

In [6]: # This is the right panel of Fig 5.7.1 from p.105 of HS2013

plt.plot(econ1.c[0], label='Cons.')
plt.plot(econ1.i[0], label='Inv. ')
plt.legend()
plt.show()
Inspection of the plot shows that the sample paths of consumption and investment drift in ways that suggest that each has or nearly has a random walk or unit root component.

This is confirmed by checking the eigenvalues of $A^o$

In [7]: `econ1.endo, econ1.exo`

Out[7]: `(array([0.9, 1.]), array([1. , 0.8, 0.5]))`

The endogenous eigenvalue that appears to be unity reflects the random walk character of consumption in Hall’s model.

- Actually, the largest endogenous eigenvalue is very slightly below 1.
- This outcome comes from the small adjustment cost $\phi_1$.

In [8]: `econ1.endo[1]`

Out[8]: `0.9999999999904767`

The fact that the largest endogenous eigenvalue is strictly less than unity in modulus means that it is possible to compute the non-stochastic steady state of consumption, investment and capital.

In [9]: `econ1.compute_steadystate()`
   `np.set_printoptions(precision=3, suppress=True)`
   `print(econ1.css, econ1.iss, econ1.kss)`

```
[[4.999]] [[-0.001]] [[-0.021]]
```

However, the near-unity endogenous eigenvalue means that these steady state values are of little relevance.
19.4.2 Example 2: Altered Growth Condition

We generate our next economy by making two alterations to the parameters of Example 1.

- First, we raise $\phi_1$ from 0.00001 to 1.
  - This will lower the endogenous eigenvalue that is close to 1, causing the economy to head more quickly to the vicinity of its non-stochastic steady-state.
- Second, we raise $\gamma_1$ from 0.1 to 0.15.
  - This has the effect of raising the optimal steady-state value of capital.

We also start the economy off from an initial condition with a lower capital stock

$$x_0 = \begin{bmatrix} 5 & 20 & 1 & 0 & 0 \end{bmatrix}$$

Therefore, we need to define the following new parameters

In [10]: $\gamma_2 = 0.15$
$\gamma_{22} = \text{np.array([[0.15], [0]])}$

$\phi_{12} = 1$
$\phi_{12} = \text{np.array([[1], [-0.12]])}$

$\text{tech2} = (\phi_c, \phi_g, \phi_{i2}, \gamma_{22}, \delta_k, \theta_k)$

$x_{02} = \text{np.array([[5], [20], [1], [0], [0]])}$

Creating the DLE class and then simulating gives the following plot for consumption and investment

In [11]: $\text{econ2} = \text{DLE(info1, tech2, pref1)}$
$\text{econ2.compute_sequence(x02, ts_length=300)}$

plt.plot(econ2.c[0], label='Cons.')
plt.plot(econ2.i[0], label='Inv. ')
plt.legend()
plt.show()
Simulating our new economy shows that consumption grows quickly in the early stages of the sample.

However, it then settles down around the new non-stochastic steady-state level of consumption of 17.5, which we find as follows

In [12]: econ2.compute_steadystate()
   print(econ2.css, econ2.iss, econ2.kss)

[[17.5]] [[6.25]] [[125.]]

The economy converges faster to this level than in Example 1 because the largest endogenous eigenvalue of \( A^\circ \) is now significantly lower than 1.

In [13]: econ2.endo, econ2.exo

Out[13]: (array([0.9 , 0.952]), array([1. , 0.8, 0.5]))

19.4.3 Example 3: A Jones-Manuelli (1990) Economy

For our third economy, we choose parameter values with the aim of generating sustained growth in consumption, investment and capital.

To do this, we set parameters so that Jones and Manuelli’s “growth condition” is just satisfied.

In our notation, just satisfying the growth condition is actually equivalent to setting \( \beta (\gamma_1 + \delta_k) = 1 \), the condition that was necessary for consumption to be a random walk in Hall’s model.

Thus, we lower \( \gamma_1 \) back to 0.1.
In our model, this is a necessary but not sufficient condition for growth.

To generate growth we set preference parameters to reflect habit persistence.

In particular, we set $\lambda = -1$, $\delta_h = 0.9$ and $\theta_h = 1 - \delta_h = 0.1$.

This makes preferences assume the form

$$-\frac{1}{2}e^{\sum_{t=0}^{\infty} \beta t [(c_t - b_t - (1 - \delta_h) \sum_{j=0}^{\infty} \delta_h^j c_{t-j-1})^2 + l_t^2]}$$

These preferences reflect habit persistence

- the effective “bliss point” $b_t + (1 - \delta_h) \sum_{j=0}^{\infty} \delta_h^j c_{t-j-1}$ now shifts in response to a moving average of past consumption

Since $\delta_h$ and $\theta_h$ were defined earlier, the only change we need to make from the parameters of Example 1 is to define the new value of $\lambda$.

In [14]:

```python
l_λ2 = np.array([-1])
pref2 = (β, l_λ2, π_h, δ_h, θ_h)
```

In [15]:

```python
econ3 = DLE(info1, tech1, pref2)
```

We simulate this economy from the original state vector

In [16]:

```python
econ3.compute_sequence(x0, ts_length=300)
```

# This is the right panel of Fig 5.10.1 from p.110 of HS2013
```python
plt.plot(econ3.c[0], label='Cons.')
plt.plot(econ3.i[0], label='Inv.')</nplt.legend()
plt.show()
```
Thus, adding habit persistence to the Hall model of Example 1 is enough to generate sustained growth in our economy.

The eigenvalues of $\mathbf{A}_0$ in this new economy are

$$\text{In [17]: } \text{econ3.endo, econ3.exo}$$

$$\text{Out[17]: } \text{(array([1.+0.j, 1.-0.j]), array([1., 0.8, 0.5]))}$$

We now have two unit endogenous eigenvalues. One stems from satisfying the growth condition (as in Example 1).

The other unit eigenvalue results from setting $\lambda = -1$.

To show the importance of both of these for generating growth, we consider the following experiments.

### 19.4.4 Example 3.1: Varying Sensitivity

Next we raise $\lambda$ to -0.7

$$\text{In [18]: } \lambda_3 = \text{np.array([[[-0.7]]])}$$

$$\text{pref3} = (\beta, \lambda_3, \pi_h, \delta_h, \theta_h)$$

$$\text{econ4 = DLE(info1, tech1, pref3)}$$

$$\text{econ4.compute_sequence(x0, ts_length=300)}$$

$$\text{plt.plot(econ4.c[0], label='Cons.'')}$$

$$\text{plt.plot(econ4.i[0], label='Inv.'), plt.legend() \text{plt.show()}}$$

![Graph showing consumption and investment over time](image-url)
We no longer achieve sustained growth if $\lambda$ is raised from -1 to -0.7.
This is related to the fact that one of the endogenous eigenvalues is now less than 1.

In [19]: econ4. endo, econ4. exo

Out[19]: (array([0.97, 1.]), array([1., 0.8, 0.5]))

19.4.5 Example 3.2: More Impatience

Next let’s lower $\beta$ to 0.94

In [20]: $\beta_2$ = np.array([[0.94]])
   pref4 = ($\beta_2$, l_λ, π_h, δ_h, $\theta_h$)
   econ5 = DLE(info1, tech1, pref4)
   econ5.compute_sequence(x0, ts_length=300)
   plt.plot(econ5.c[0], label='Cons.' )
   plt.plot(econ5.i[0], label='Inv.' )
   plt.legend()
   plt.show()

Growth also fails if we lower $\beta$, since we now have $\beta(\gamma_1 + \delta_k) < 1$.
Consumption and investment explode downwards, as a lower value of $\beta$ causes the representative consumer to front-load consumption.
This explosive path shows up in the second endogenous eigenvalue now being larger than one.
In [21]: econ5.endo, econ5.exo

Out[21]: (array([0.9, 1.013]), array([1., 0.8, 0.5]))
Chapter 20

Lucas Asset Pricing Using DLE

20.1 Contents

- Asset Pricing Equations 20.2
- Asset Pricing Simulations 20.3

This is one of a suite of lectures that use the quantecon DLE class to instantiate models within the [31] class of models described in detail in Recursive Models of Dynamic Linear Economies.

In addition to what’s in Anaconda, this lecture uses the quantecon library

In [1]: !pip install --upgrade quantecon

This lecture uses the DLE class to price payout streams that are linear functions of the economy’s state vector, as well as risk-free assets that pay out one unit of the first consumption good with certainty.

We assume basic knowledge of the class of economic environments that fall within the domain of the DLE class.

Many details about the basic environment are contained in the lecture Growth in Dynamic Linear Economies.

We’ll also need the following imports

In [2]: import numpy as np
import matplotlib.pyplot as plt
from quantecon import LQ
from quantecon import DLE
%matplotlib inline

We use a linear-quadratic version of an economy that Lucas (1978) [44] used to develop an equilibrium theory of asset prices:

Preferences

$$\frac{1}{2} \mathbb{E} \sum_{t=0}^{\infty} \beta^t ([c_t - b_t]^2 + l_t^2) J_t$$
CHAPTER 20. LUCAS ASSET PRICING USING DLE

\[ s_t = c_t \]

\[ b_t = U_b z_t \]

**Technology**

\[ c_t = d_{1t} \]

\[ k_t = \delta_b k_{t-1} + i_t \]

\[ g_t = \phi_1 i_t, \phi_1 > 0 \]

\[ \begin{bmatrix} d_{1t} \\ 0 \end{bmatrix} = U_d z_t \]

**Information**

\[
   z_{t+1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.8 & 0 \\ 0 & 0 & 0.5 \end{bmatrix} z_t + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} w_{t+1}
\]

\[ U_b = \begin{bmatrix} 30 & 0 & 0 \end{bmatrix} \]

\[ U_d = \begin{bmatrix} 5 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]

\[ x_0 = \begin{bmatrix} 5 & 150 & 1 & 0 & 0 \end{bmatrix} \]

### 20.2 Asset Pricing Equations

[31] show that the time t value of a permanent claim to a stream \( y_s = U_a x_s, s \geq t \) is:

\[ a_t = (x_t' \mu_a x_t + \sigma_a)/(\bar{\varepsilon}_t M_c x_t) \]

with

\[ \mu_a = \sum_{\tau=0}^{\infty} \beta^\tau (A^\sigma)' Z_a A^{\sigma \tau} \]

\[ \sigma_a = \frac{\beta}{1 - \beta} \text{trace}(Z_a \sum_{\tau=0}^{\infty} \beta^\tau (A^\sigma)' C C' (A^\sigma')^\tau) \]

where
20.3. Asset Pricing Simulations

\[ Z_a = U'_a M_c \]

The use of \( \bar{e}_1 \) indicates that the first consumption good is the numeraire.

### 20.3 Asset Pricing Simulations

In [3]:
```
gam = 0
\gamma = np.array([[gam], [0]])
ϕ_c = np.array([[1], [0]])
ϕ_g = np.array([[0], [1]])
ϕ_1 = 1e-4
\delta_k = np.array([[0], [-ϕ_1]])
θ_k = np.array([[1]])
ϕ = np.array([[1 / 1.05]])
ud = np.array([[5, 1, 0],
               [0, 0, 0]])
a22 = np.array([[1, 0, 0],
                [0, 0.8, 0],
                [0, 0, 0.5]])
c2 = np.array([[0, 1, 0],
               [0, 0, 1]]).T
l_\lambda = np.array([[0]])
π_h = np.array([[1]])
δ_h = np.array([[0.9]]) - δ_h
θ_h = np.array([[1]]) - δ_h
ub = np.array([[30, 0, 0]])
x0 = np.array([[5, 150, 1, 0, 0]]).T
```

info1 = (a22, c2, ub, ud)
technology1 = (ϕ_c, ϕ_g, ϕ_1, \gamma, \delta_k, θ_k)

After specifying a “Pay” matrix, we simulate the economy.

The particular choice of “Pay” used below means that we are pricing a perpetual claim on the endowment process \( d_{1t} \).

In [5]:
```
econ1 = DLE(info1, technology1, pref1)
```

In [6]:
```
### Fig 7.12.1 from p.147 of HS2013
plt.plot(econ1.Pay_Price, label='Price of Tree')
plt.legend()
plt.show()
```
The next plot displays the realized gross rate of return on this “Lucas tree” as well as on a risk-free one-period bond:

```
In [7]:  ### Left panel of Fig 7.12.2 from p.148 of HS2013
    plt.plot(econ1.Pay_Gross, label='Tree')
    plt.plot(econ1.R1_Gross, label='Risk-Free')
    plt.legend()
    plt.show()
```
In [8]: np.corrcoef(econ1.Pay_Gross[1:, 0], econ1.R1_Gross[1:, 0])

Out[8]: array([[ 1. , -0.51574716],
             [-0.51574716,  1. ]])

Above we have also calculated the correlation coefficient between these two returns.

To give an idea of how the term structure of interest rates moves in this economy, the next
plot displays the net rates of return on one-period and five-period risk-free bonds:

In [9]: ### Right panel of Fig 7.12.2 from p.148 of HS2013
plt.plot(econ1.R1_Net, label='One-Period')
plt.plot(econ1.R5_Net, label='Five-Period')
plt.legend()
plt.show()
In [11]: ```python
### Left panel of Fig 7.12.3 from p.148 of HS2013
plt.plot(econ2.Pay_Gross, label='Tree')
plt.plot(econ2.R1_Gross, label='Risk-Free')
plt.legend()
plt.show()
```

```
Out[11]:
```

The correlation between these two gross rates is now more negative.

Next, we again plot the *net* rates of return on one-period and five-period risk-free bonds:

In [12]: ```python
np.corrcoef(econ2.Pay_Gross[1:, 0], econ2.R1_Gross[1:, 0])
```

```
Out[12]:
```

The correlation between these two gross rates is now more negative.

Next, we again plot the *net* rates of return on one-period and five-period risk-free bonds:
We can see the tendency of the term structure to slope up when rates are low (and down when rates are high) has been accentuated relative to the first instance of our economy.
Chapter 21

IRFs in Hall Models

21.1 Contents

- Example 1: Hall (1978) 21.2
- Example 2: Higher Adjustment Costs 21.3
- Example 3: Durable Consumption Goods 21.4

This is another member of a suite of lectures that use the quantecon DLE class to instantiate models within the \([31]\) class of models described in detail in Recursive Models of Dynamic Linear Economies.

In addition to what’s in Anaconda, this lecture uses the quantecon library.

In [1]: !pip install --upgrade quantecon

We’ll make these imports:

In [2]: import numpy as np
   import matplotlib.pyplot as plt
   %matplotlib inline
   from quantecon import LQ
   from quantecon import DLE

This lecture shows how the DLE class can be used to create impulse response functions for three related economies, starting from Hall (1978) [24].

Knowledge of the basic economic environment is assumed.

See the lecture “Growth in Dynamic Linear Economies” for more details.

21.2 Example 1: Hall (1978)

First, we set parameters to make consumption (almost) follow a random walk.

We set

\[ \lambda = 0, \pi = 1, \gamma_1 = 0.1, \phi_1 = 0.00001, \delta_k = 0.95, \beta = \frac{1}{1.05} \]
(In this example $\delta_h$ and $\theta_h$ are arbitrary as household capital does not enter the equation for consumption services.

We set them to values that will become useful in Example 3)

It is worth noting that this choice of parameter values ensures that $\beta(\gamma_1 + \delta_k) = 1$.

For simulations of this economy, we choose an initial condition of:

$$x_0 = \begin{bmatrix} 5 & 150 & 1 & 0 & 0 \end{bmatrix}$$

In [3]: $\gamma_1 = 0.1$
   $\gamma = \text{np.array}([\gamma_1, 0])$
   $\phi_c = \text{np.array}([1, 0])$
   $\phi_g = \text{np.array}([0, 1])$
   $\phi_i = 1e-5$
   $\phi_k = \text{np.array}([0.95])$
   $\theta_k = \text{np.array}([1])$
   $\beta = \text{np.array}([1 / 1.05])$
   $\lambda = \text{np.array}([0])$
   $\pi_h = \text{np.array}([1])$
   $\delta_h = \text{np.array}([0.9])$
   $\theta_h = \text{np.array}([1])$
   $a22 = \text{np.array}([[1, 0, 0],
                          [0, 0.8, 0],
                          [0, 0, 0.5]])$
   $c2 = \text{np.array}([[0, 0],
                        [1, 0],
                        [0, 1]])$
   $ud = \text{np.array}([[5, 1, 0],
                         [0, 0, 0]])$
   $ub = \text{np.array}([[30, 0, 0]])$
   $x0 = \text{np.array}([[5, 150], [1], [0], [0]])$

   info1 = (a22, c2, ub, ud)
   tech1 = ($\phi_c$, $\phi_g$, $\phi_i$, $\gamma$, $\delta_k$, $\theta_k$)
   pref1 = ($\beta$, $\lambda$, $\pi_h$, $\delta_h$, $\theta_h$)

These parameter values are used to define an economy of the DLE class.

We can then simulate the economy for a chosen length of time, from our initial state vector $x_0$.

The economy stores the simulated values for each variable. Below we plot consumption and investment:

In [4]: econ1 = DLE(info1, tech1, pref1)
   econ1.compute_sequence(x0, ts_length=300)

   # This is the right panel of Fig 5.7.1 from p.105 of HS2013
   plt.plot(econ1.c[0], label='Cons.')
   plt.plot(econ1.i[0], label='Inv.')
   plt.legend()
   plt.show()
The DLE class can be used to create impulse response functions for each of the endogenous variables: \( \{c_t, s_t, h_t, i_t, k_t, g_t\} \).

If no selector vector for the shock is specified, the default choice is to give IRFs to the first shock in \( w_{t+1} \).

Below we plot the impulse response functions of investment and consumption to an endowment innovation (the first shock) in the Hall model:

```
In [5]: econ1.irf(ts_length=40, shock=None)
# This is the left panel of Fig 5.7.1 from p.105 of HS2013
plt.plot(econ1.c_Irf, label='Cons.')
plt.plot(econ1.i_Irf, label='Inv.')
plt.legend()
plt.show()
```
It can be seen that the endowment shock has permanent effects on the level of both consumption and investment, consistent with the endogenous unit eigenvalue in this economy. Investment is much more responsive to the endowment shock at shorter time horizons.

21.3 Example 2: Higher Adjustment Costs

We generate our next economy by making only one change to the parameters of Example 1: we raise the parameter associated with the cost of adjusting capital, $\phi_1$, from 0.00001 to 0.2. This will lower the endogenous eigenvalue that is unity in Example 1 to a value slightly below 1.

In [6]:
$\phi_{12} = 0.2$

$\phi_{12} = \text{np.array([[1], [-\phi_{12}]]]}$

$\text{tech2} = (\phi_c, \phi_g, \phi_{12}, \gamma, \delta_k, \theta_k)$

econ2 = DLE(info1, tech2, pref1)
econ2.compute_sequence(x0, ts_length = 300)

# This is the right panel of Fig 5.8.1 from p.106 of HS2013
plt.plot(econ2.c[0], label='Cons. ')
plt.plot(econ2.i[0], label='Inv. ')
plt.legend()
plt.show()
21.3. EXAMPLE 2: HIGHER ADJUSTMENT COSTS

In [7]: econ2.irf(ts_length=40, shock=None)
   # This is the left panel of Fig 5.8.1 from p.106 of HS2013
   plt.plot(econ2.c_irf, label='Cons.')
   plt.plot(econ2.i_irf, label='Inv. ')
   plt.legend()
   plt.show()

In [8]: econ2.endo
CHAPTER 21. IRFS IN HALL MODELS

Out[8]: array([0.9 , 0.99657126])

In [9]: econ2.compute_steadystate()
   print(econ2.css, econ2.iss, econ2.kss)

[[5.]] [[2.12173041e-12]] [[4.2434517e-11]]

The first graph shows that there seems to be a downward trend in both consumption and investment.

This is a consequence of the decrease in the largest endogenous eigenvalue from unity in the earlier economy, caused by the higher adjustment cost.

The present economy has a nonstochastic steady state value of 5 for consumption and 0 for both capital and investment.

Because the largest endogenous eigenvalue is still close to 1, the economy heads only slowly towards these mean values.

The impulse response functions now show that an endowment shock does not have a permanent effect on the levels of either consumption or investment.

21.4 Example 3: Durable Consumption Goods

We generate our third economy by raising $\phi_1$ further, to 1.0. We also raise the production function parameter from 0.1 to 0.15 (which raises the non-stochastic steady state value of capital above zero).

We also change the specification of preferences to make the consumption good durable.

Specifically, we allow for a single durable household good obeying:

$$h_t = \delta h_{t-1} + c_t, \quad 0 < \delta_h < 1$$

Services are related to the stock of durables at the beginning of the period:

$$s_t = \lambda h_{t-1}, \lambda > 0$$

And preferences are ordered by:

$$-\frac{1}{2} E \sum_{t=0}^{\infty} \beta^t [(\lambda h_{t-1} - b_t)^2 + I_t^2] J_0$$

To implement this, we set $\lambda = 0.1$ and $\pi = 0$ (we have already set $\theta_h = 1$ and $\delta_h = 0.9$).

We start from an initial condition that makes consumption begin near around its non-stochastic steady state.

In [10]: $\phi_13 = 1$
   $\phi_13 = np.array([[1], [-\phi_13]])$
\[ \gamma_{12} = 0.15 \]
\[ \gamma_2 = \text{np.array([[0.12], [0]])} \]
\[ l_\lambda2 = \text{np.array([[0.1]])} \]
\[ \pi_h2 = \text{np.array([[0]])} \]
\[ x01 = \text{np.array([[150], [100], [1], [0], [0]])} \]
\[ \text{tech3} = (\phi_c, \phi_g, \phi_i3, \gamma_2, \delta_k, \theta_k) \]
\[ \text{pref2} = (\beta, l_\lambda2, \pi_h2, \delta_h, \theta_h) \]
\[ \text{econ3} = \text{DLE(info1, tech3, pref2)} \]
\[ \text{econ3.compute_sequence(x01, ts_length=300)} \]

In contrast to Hall’s original model of Example 1, it is now investment that is much smoother than consumption.

This illustrates how making consumption goods durable tends to undo the strong consumption smoothing result that Hall obtained.
The impulse response functions confirm that consumption is now much more responsive to an endowment shock (and investment less so) than in Example 1.

As in Example 2, the endowment shock has permanent effects on neither variable.
Chapter 22

Permanent Income Model using the DLE Class

22.1 Contents

- The Permanent Income Model 22.2

This lecture is part of a suite of lectures that use the quantecon DLE class to instantiate models within the [31] class of models described in detail in Recursive Models of Dynamic Linear Economies.

In addition to what’s included in Anaconda, this lecture uses the quantecon library.

In [1]: !pip install --upgrade quantecon

This lecture adds a third solution method for the linear-quadratic-Gaussian permanent income model with $\beta R = 1$, complementing the other two solution methods described in Optimal Savings I: The Permanent Income Model and Optimal Savings II: LQ Techniques and this Jupyter notebook http://nbviewer.jupyter.org/github/QuantEcon/QuantEcon.notebooks/blob/master/permanent_income.ipynb.

The additional solution method uses the DLE class.

In this way, we map the permanent income model into the framework of Hansen & Sargent (2013) “Recursive Models of Dynamic Linear Economies” [31].

We’ll also require the following imports

In [2]: import quantecon asqe
import numpy as np
import scipy.linalg asla
import matplotlib.pyplot asplt
%matplotlib inline
from quantecon import DLE
np.set_printoptions(suppress=True, precision=4)

22.2 The Permanent Income Model

The LQ permanent income model is an example of a savings problem.
A consumer has preferences over consumption streams that are ordered by the utility functional

$$E_0 \sum_{t=0}^{\infty} \beta^t u(c_t)$$  \hspace{1cm} (1)$$

where $E_t$ is the mathematical expectation conditioned on the consumer’s time $t$ information, $c_t$ is time $t$ consumption, $u(c)$ is a strictly concave one-period utility function, and $\beta \in (0, 1)$ is a discount factor.

The LQ model gets its name partly from assuming that the utility function $u$ is quadratic:

$$u(c) = -.5(c - \gamma)^2$$

where $\gamma > 0$ is a bliss level of consumption.

The consumer maximizes the utility functional (1) by choosing a consumption, borrowing plan $\{c_t, b_{t+1}\}_{t=0}^{\infty}$ subject to the sequence of budget constraints

$$c_t + b_t = R^{-1}b_{t+1} + y_t, t \geq 0$$  \hspace{1cm} (2)$$

where $y_t$ is an exogenous stationary endowment process, $R$ is a constant gross risk-free interest rate, $b_t$ is one-period risk-free debt maturing at $t$, and $b_0$ is a given initial condition.

We shall assume that $R^{-1} = \beta$.

Equation (2) is linear.

We use another set of linear equations to model the endowment process.

In particular, we assume that the endowment process has the state-space representation

$$z_{t+1} = A_{22}z_t + C_2w_{t+1}$$
$$y_t = U_y z_t$$  \hspace{1cm} (3)$$

where $w_{t+1}$ is an IID process with mean zero and identity contemporaneous covariance matrix, $A_{22}$ is a stable matrix, its eigenvalues being strictly below unity in modulus, and $U_y$ is a selection vector that identifies $y$ with a particular linear combination of the $z_t$.

We impose the following condition on the consumption, borrowing plan:

$$E_0 \sum_{t=0}^{\infty} \beta^t b_t^2 < +\infty$$  \hspace{1cm} (4)$$

This condition suffices to rule out Ponzi schemes.

(We impose this condition to rule out a borrow-more-and-more plan that would allow the household to enjoy bliss consumption forever)

The state vector confronting the household at $t$ is

$$x_t = \begin{bmatrix} z_t \\ b_t \end{bmatrix}$$
where $b_t$ is its one-period debt falling due at the beginning of period $t$ and $z_t$ contains all variables useful for forecasting its future endowment.

We assume that $\{y_t\}$ follows a second order univariate autoregressive process:

$$y_{t+1} = \alpha + \rho_1 y_t + \rho_2 y_{t-1} + \sigma w_{t+1}$$

### 22.2.1 Solution with the DLE Class

One way of solving this model is to map the problem into the framework outlined in Section 4.8 of [31] by setting up our technology, information and preference matrices as follows:

**Technology:**
$$\phi_c = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad \phi_g = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad \phi_i = \begin{bmatrix} -1 \\ -0.00001 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} -1 \\ 0 \end{bmatrix}, \quad \Delta_k = 0, \quad \Theta_k = R.$$

**Information:**
$$A_{22} = \begin{bmatrix} 1 & 0 & 0 \\ \alpha & \rho_1 & \rho_2 \\ 0 & 1 & 0 \end{bmatrix}, \quad C_2 = \begin{bmatrix} 0 \\ \sigma \\ 0 \end{bmatrix}, \quad U_b = \begin{bmatrix} \gamma & 0 & 0 \end{bmatrix}, \quad U_d = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

**Preferences:**
$$\Lambda = 0, \quad \Pi = 1, \quad \Delta_h = 0, \quad \Theta_h = 0.$$

We set parameters
$$\alpha = 10, \beta = 0.95, \rho_1 = 0.9, \rho_2 = 0, \sigma = 1$$
(The value of $\gamma$ does not affect the optimal decision rule)

The chosen matrices mean that the household’s technology is:

$$c_t + k_{t-1} = i_t + y_t$$

$$\frac{k_t}{R} = i_t$$

$$l_t^2 = (0.00001)^2 i_t$$

Combining the first two of these gives the budget constraint of the permanent income model, where $k_t = b_{t+1}$.

The third equation is a very small penalty on debt-accumulation to rule out Ponzi schemes.

We set up this instance of the DLE class below:

In [3]: $\alpha, \beta, \rho_1, \rho_2, \sigma = 10, 0.95, 0.9, 0, 1$

```python
\gamma = np.array([[\gamma], [0]])
\phi_c = np.array([[1], [0]])
\phi_g = np.array([[0], [1]])
\phi_i = 1e-5
\phi_1 = np.array([[\phi_1], [\phi_1]])
\phi_k = np.array([[\phi_k], [\phi_k]])
\theta_k = np.array([[1 / \beta]])
\beta = np.array([[\beta]])
\lambda_k = np.array([[\lambda]])
\sigma_h = np.array([[1]])
```
\[ \delta_h = \text{np.array([[0]])} \]
\[ \theta_h = \text{np.array([[0]])} \]
\[ a22 = \text{np.array([[1, 0, 0], [\varphi_{-1}, \varphi_2], [0, 1, 0]])} \]
\[ c2 = \text{np.array([[0], [0], [0]])} \]
\[ u = \text{np.array([[0, 1, 0], [0, 0, 0]])} \]
\[ x0 = \text{np.array([[0], [0], [1], [0], [0]])} \]
\[ \text{info1} = (a22, c2, ub, ud) \]
\[ \text{tech1} = (\phi_c, \phi_g, \phi_i, \gamma, \delta_k, \theta_k) \]
\[ \text{pref1} = (\beta, 1_\lambda, \pi_h, \delta_h, \theta_h) \]
\[ \text{econ1} = \text{DLE(info1, tech1, pref1)} \]

To check the solution of this model with that from the \textbf{LQ} problem, we select the \( S_c \) matrix from the \textbf{DLE} class.

The solution to the \textbf{DLE} economy has:

\[ c_t = S_c x_t \]

In [4]: econ1.Sc

Out[4]: array([[ 0. , -0.05 , 65.5172, 0.3448, 0. ]])

The state vector in the \textbf{DLE} class is:

\[
\begin{bmatrix}
  h_{t-1} \\
  k_{t-1} \\
  z_{t-1}
\end{bmatrix}
\]

where \( k_{t-1} = b_t \) is set up to be \( b_t \) in the permanent income model.

The state vector in the \textbf{LQ} problem is \( [z_t, b_t] \).

Consequently, the relevant elements of econ1.Sc are the same as in \(-F\) occur when we apply other approaches to the same model in the lecture \textit{Optimal Savings II: LQ Techniques} and this Jupyter notebook \texttt{http://nbviewer.jupyter.org/github/QuantEcon/QuantEcon.notebooks/blob/master/permanent_income.ipynb}.

The plot below quickly replicates the first two figures of that lecture and that notebook to confirm that the solutions are the same

In [5]: fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(16, 5))

    for i in range(25):
        econ1.compute_sequence(x0, ts_length=150)
        ax1.plot(econ1.c[0], c='g')
22.2. THE PERMANENT INCOME MODEL

```python
ax1.plot(econ1.d[0], c='b')
ax1.plot(econ1.c[0], label='Consumption', c='g')
ax1.plot(econ1.d[0], label='Income', c='b')
ax1.legend()

for i in range(25):
    econ1.compute_sequence(x0, ts_length=150)
    ax2.plot(econ1.k[0], color='r')
ax2.plot(econ1.k[0], label='Debt', c='r')
ax2.legend()
plt.show()
```
Chapter 23

Rosen Schooling Model

23.1 Contents

- A One-Occupation Model 23.2
- Mapping into HS2013 Framework 23.3

This lecture is yet another part of a suite of lectures that use the quantecon DLE class to instantiate models within the [31] class of models described in detail in Recursive Models of Dynamic Linear Economies.

In addition to what’s included in Anaconda, this lecture uses the quantecon library

In [1]: !pip install --upgrade quantecon

We’ll also need the following imports:

In [2]: import numpy as np
import matplotlib.pyplot as plt
from quantecon import LQ
from collections import namedtuple
from quantecon import DLE
from math import sqrt
%mplexinline

23.2 A One-Occupation Model

Ryoo and Rosen’s (2004) [56] partial equilibrium model determines

- a stock of “Engineers” $N_t$
- a number of new entrants in engineering school, $n_t$
- the wage rate of engineers, $w_t$

It takes $k$ periods of schooling to become an engineer.

The model consists of the following equations:

- a demand curve for engineers:

$$w_t = -\alpha_d N_t + \epsilon_{dt}$$
• a time-to-build structure of the education process:

\[ N_{t+k} = \delta_N N_{t+k-1} + n_t \]

• a definition of the discounted present value of each new engineering student:

\[ v_t = \beta \sum_{j=0}^{\infty} (\beta \delta_N)^j w_{t+k+j} \]

• a supply curve of new students driven by present value \( v_t \):

\[ n_t = \alpha_s v_t + \epsilon_{st} \]

### 23.3 Mapping into HS2013 Framework

We represent this model in the [31] framework by

• sweeping the time-to-build structure and the demand for engineers into the household technology, and

• putting the supply of engineers into the technology for producing goods

#### 23.3.1 Preferences

\[ \Pi = 0, \Lambda = [\alpha_d \ 0 \ \cdots \ 0], \Delta_h = \begin{bmatrix} \delta_N & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & 0 & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}, \Theta_h = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \]

where \( \Lambda \) is a \( k+1 \times 1 \) matrix, \( \Delta_h \) is a \( k_1 \times k+1 \) matrix, and \( \Theta_h \) is a \( k+1 \times 1 \) matrix.

This specification sets \( N_t = h_{1t-1}, n_t = c_t, h_{\tau+1,t-1} = n_{t-(k-\tau)} \) for \( \tau = 1, \ldots, k \).

Below we set things up so that the number of years of education, \( k \), can be varied.

#### 23.3.2 Technology

To capture Ryoo and Rosen’s [56] supply curve, we use the physical technology:

\[ c_t = i_t + d_{1t} \]

\[ \psi_1 i_t = g_t \]

where \( \psi_1 \) is inversely proportional to \( \alpha_s \).

#### 23.3.3 Information

Because we want \( b_t = \epsilon_{dt} \) and \( d_{1t} = \epsilon_{st} \), we set
\[
A_{22} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \rho_s & 0 \\ 0 & 0 & \rho_d \end{bmatrix},
C_2 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix},
U_b = [30 \quad 0 \quad 1],
U_d = \begin{bmatrix} 10 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}
\]

where \(\rho_s\) and \(\rho_d\) describe the persistence of the supply and demand shocks.

In [3]: Information = namedtuple('Information', ['a22', 'c2', 'ub', 'ud'])
Technology = namedtuple('Technology', ['ϕ_c', 'ϕ_g', 'ϕ_i', 'γ', 'δ_k', 'θ_k'])
Preferences = namedtuple('Preferences', ['β', 'l_λ', 'π_h', 'δ_h', 'θ_h'])

### 23.3.4 Effects of Changes in Education Technology and Demand

We now study how changing
- the number of years of education required to become an engineer and
- the slope of the demand curve

affects responses to demand shocks.

To begin, we set \(k = 4\) and \(\alpha_d = 0.1\)

In [4]: \# Number of periods of schooling required to become an engineer

\[
\begin{array}{l}
\beta = \text{np.array}([1 / 1.05]) \\
\alpha_d = \text{np.array}([[0.1]]) \\
\alpha_s = 1 \\
\varepsilon_1 = 1e-7 \\
\lambda_1 = \text{np.ones}((1, k)) * \varepsilon_1 \\
\text{# Use of } \varepsilon_1 \text{ is trick to acquire detectability, see HS2013 p. 228 footnote 4} \\
\lambda = \text{np.hstack}((\alpha_d, \lambda_1)) \\
\pi_h = \text{np.array}([[0]]) \\
\delta_n = \text{np.array}([[0.95]]) \\
d1 = \text{np.vstack}((\delta_n, \text{np.zeros}((k - 1, 1)))) \\
d2 = \text{np.hstack}((d1, \text{np.eye}(k))) \\
\delta_h = \text{np.vstack}((d2, \text{np.zeros}((1, k + 1)))) \\
\theta_h = \text{np.vstack}((\text{np.zeros}((k, 1)), \text{np.ones}((1, 1)))) \\
\psi_1 = 1 / \alpha_s \\
\phi_c = \text{np.array}([[1], [0]]) \\
\phi_g = \text{np.array}([[0], [-1]]) \\
\phi_i = \text{np.array}([[-1], [\psi_1]]) \\
\gamma = \text{np.array}([[0], [0]]) \\
\delta_k = \text{np.array}([[0]]) \\
\theta_k = \text{np.array}([[0]]) \\
\rho_s = 0.8 \\
\rho_d = 0.8 \\
a22 = \text{np.array}([[1, 0, 0], [0, \rho_s, 0], [0, \rho_d, 0]])
\end{array}
\]
$$[\theta, \theta, \varphi_d]$$

c2 = np.array([[0, 0], [2, 0], [0, 1]])
ub = np.array([[0, 0], [2, 1]])
ud = np.array([[2, 0], [2, 0]])

info1 = Information(a22, c2, ub, ud)
technology1 = Technology($\phi_c$, $\phi_g$, $\phi_l$, $\gamma$, $\delta_k$, $\theta_k$)
preference1 = Preferences($\beta$, $\lambda_\lambda$, $\pi_h$, $\delta_h$, $\theta_h$)
econ1 = DLE(info1, technology1, preference1)

We create three other instances by:

1. Raising $\alpha_d$ to 2
2. Raising $k$ to 7
3. Raising $k$ to 10

In [5]:

```python
alpha_d = np.array([[2]])
lambda_ = np.hstack((alpha_d, lambda_l))
preference2 = Preferences($\beta$, $\lambda_\lambda$, $\pi_h$, $\delta_h$, $\theta_h$)
econ2 = DLE(info1, technology1, preference2)
alpha_d = np.array([[0.1]])
k = 7
lambda_1 = np.ones((1, k)) * epsilon_1
lambda_ = np.hstack((alpha_d, lambda_l))
d1 = np.vstack((delta_n, np.zeros((k - 1, 1))))
d2 = np.hstack((d1, np.eye(k)))
delta_h = np.vstack((d2, np.zeros((1, k + 1))))
theta_h = np.vstack((np.zeros((k, 1)),
np.ones((1, 1))))

preference3 = Preferences($\beta$, $\lambda_\lambda$, $\pi_h$, $\delta_h$, $\theta_h$)
econ3 = DLE(info1, technology1, preference3)
k = 10
lambda_1 = np.ones((1, k)) * epsilon_1
lambda_ = np.hstack((alpha_d, lambda_l))
d1 = np.vstack((delta_n, np.zeros((k - 1, 1))))
d2 = np.hstack((d1, np.eye(k)))
delta_h = np.vstack((d2, np.zeros((1, k + 1))))
theta_h = np.vstack((np.zeros((k, 1)),
np.ones((1, 1))))

preference4 = Preferences($\beta$, $\lambda_\lambda$, $\pi_h$, $\delta_h$, $\theta_h$)
econ4 = DLE(info1, technology1, preference4)
shock_demand = np.array([[0], [1]])
econ1.irf(ts_length=25, shock=shock_demand)
econ2.irf(ts_length=25, shock=shock_demand)
econ3.irf(ts_length=25, shock=shock_demand)
econ4.irf(ts_length=25, shock=shock_demand)
23.3. MAPPING INTO HS2013 FRAMEWORK

The first figure plots the impulse response of $n_t$ (on the left) and $N_t$ (on the right) to a positive demand shock, for $\alpha_d = 0.1$ and $\alpha_d = 2$.

When $\alpha_d = 2$, the number of new students $n_t$ rises initially, but the response then turns negative.

A positive demand shock raises wages, drawing new students into the profession.

However, these new students raise $N_t$.

The higher is $\alpha_d$, the larger the effect of this rise in $N_t$ on wages.

This counteracts the demand shock’s positive effect on wages, reducing the number of new students in subsequent periods.

Consequently, when $\alpha_d$ is lower, the effect of a demand shock on $N_t$ is larger

The next figure plots the impulse response of $n_t$ (on the left) and $N_t$ (on the right) to a positive demand shock, for $k = 4$, $k = 7$ and $k = 10$ (with $\alpha_d = 0.1$)

In [6]: fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
ax1.plot(econ1.c_irf, label='$\alpha_d = 0.1$')
ax1.plot(econ2.c_irf, label='$\alpha_d = 2$')
ax1.legend()
ax1.set_title('Response of $n_t$ to a demand shock')

ax2.plot(econ1.h_irf[:, 0], label='$\alpha_d = 0.1$')
ax2.plot(econ2.h_irf[:, 0], label='$\alpha_d = 2$')
ax2.legend()
ax2.set_title('Response of $N_t$ to a demand shock')
plt.show()
Both panels in the above figure show that raising $k$ lowers the effect of a positive demand shock on entry into the engineering profession.

Increasing the number of periods of schooling lowers the number of new students in response to a demand shock.

This occurs because with longer required schooling, new students ultimately benefit less from the impact of that shock on wages.
Chapter 24

Cattle Cycles

24.1 Contents

- The Model 24.2
- Mapping into HS2013 Framework 24.3

This is another member of a suite of lectures that use the quanteco DLE class to instantiate models within the [31] class of models described in detail in Recursive Models of Dynamic Linear Economies.

In addition to what’s in Anaconda, this lecture uses the quanteco library.

In [1]: !pip install --upgrade quanteco

This lecture uses the DLE class to construct instances of the “Cattle Cycles” model of Rosen, Murphy and Scheinkman (1994) [53].

That paper constructs a rational expectations equilibrium model to understand sources of recurrent cycles in US cattle stocks and prices.

We make the following imports:

In [2]: import numpy as np
   import matplotlib.pyplot as plt
   from quanteco import LQ
   from collections import namedtuple
   from quanteco import DLE
   from math import sqrt
   %matplotlib inline

24.2 The Model

The model features a static linear demand curve and a “time-to-grow” structure for cattle.

Let $p_t$ be the price of slaughtered beef, $m_t$ the cost of preparing an animal for slaughter, $h_t$ the holding cost for a mature animal, $\gamma_1 h_t$ the holding cost for a yearling, and $\gamma_0 h_t$ the holding cost for a calf.

The cost processes $\{h_t, m_t\}_{t=0}^\infty$ are exogenous, while the price process $\{p_t\}_{t=0}^\infty$ is determined within a rational expectations equilibrium.
Let $x_t$ be the breeding stock, and $y_t$ be the total stock of cattle.

The law of motion for the breeding stock is

$$x_t = (1 - \delta)x_{t-1} + gx_{t-3} - c_t$$

where $g < 1$ is the number of calves that each member of the breeding stock has each year, and $c_t$ is the number of cattle slaughtered.

The total headcount of cattle is

$$y_t = x_t + gx_{t-1} + gx_{t-2}$$

This equation states that the total number of cattle equals the sum of adults, calves and yearlings, respectively.

A representative farmer chooses $\{c_t, x_t\}$ to maximize:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \{p_t c_t - h_t x_t - \gamma_0 h_t (gx_{t-1}) - \gamma_1 h_t (gx_{t-2}) - m_t c_t - \frac{\psi_1}{2} x_t^2 - \frac{\psi_2}{2} x_{t-1}^2 - \frac{\psi_3}{2} x_{t-3}^2 - \frac{\psi_4}{2} c_t^2\}$$

subject to the law of motion for $x_t$, taking as given the stochastic laws of motion for the exogenous processes, the equilibrium price process, and the initial state $[x_{-1}, x_{-2}, x_{-3}]$.

**Remark** The $\psi_j$ parameters are very small quadratic costs that are included for technical reasons to make well posed and well behaved the linear quadratic dynamic programming problem solved by the fictitious planner who in effect chooses equilibrium quantities and shadow prices.

Demand for beef is governed by

$$c_t = a_0 - a_1 p_t + \tilde{d}_t$$

where $\tilde{d}_t$ is a stochastic process with mean zero, representing a demand shifter.

### 24.3 Mapping into HS2013 Framework

#### 24.3.1 Preferences

We set $\Lambda = 0, \Delta_h = 0, \Theta_h = 0, \Pi = \alpha_i^{-1}$ and $b_t = \Pi \tilde{d}_t + \Pi \alpha_0$.

With these settings, the FOC for the household’s problem becomes the demand curve of the “Cattle Cycles” model.

#### 24.3.2 Technology

To capture the law of motion for cattle, we set

$$\Delta_k = \begin{bmatrix} (1 - \delta) & 0 & g \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad \Theta_k = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

(where $i_t = -c_t$).
24.3. MAPPING INTO HS2013 FRAMEWORK

To capture the production of cattle, we set

\[
\Phi_c = \begin{bmatrix}
1 & f_1 & 0 \\
0 & 0 & 0 \\
-f_7 & 0 & 0
\end{bmatrix}, \quad \Phi_g = \begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}, \quad \Phi_i = \begin{bmatrix}
1 \\
0 \\
0
\end{bmatrix}, \quad \Gamma = \begin{bmatrix}
0 & 0 & 0 \\
f_1(1 - \delta) & 0 & gf_1 \\
f_3 & 0 & 0 \\
0 & f_5 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

24.3.3 Information

We set

\[
A_{22} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \rho_1 & 0 & 0 \\
0 & 0 & \rho_2 & 0 \\
0 & 0 & 0 & \rho_3
\end{bmatrix}, \quad C_2 = \begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 15
\end{bmatrix}, \quad U_b = \begin{bmatrix}
\Pi \alpha_0 & 0 & 0 \Pi
\end{bmatrix}, \quad U_d = \begin{bmatrix}
0 & f_2u_h \\
f_4u_h & f_6u_h \\
f_8u_h
\end{bmatrix}
\]

To map this into our class, we set

\[
f_2 = \frac{\psi_1}{2}, \quad f_2^2 = \frac{\psi_2}{2}, \quad f_3^2 = \frac{\psi_3}{2}, \quad 2f_1f_2 = 1, \quad 2f_3f_4 = \gamma_0g, \quad 2f_5f_6 = \gamma_1g.
\]

In [3]: # We define namedtuples in this way as it allows us to check, for example, # what matrices are associated with a particular technology.

```
Information = namedtuple('Information', ['a22', 'c2', 'ub', 'ud'])
Technology = namedtuple('Technology', ['\phi_c', '\phi_g', '\phi_i', '\gamma', '\delta_k', '\theta_k'])
Preferences = namedtuple('Preferences', ['\beta', 'l_\lambda', '\pi_h', '\delta_h', '\theta_h'])
```

We set parameters to those used by [53]

In [4]: \[\beta = np.array([[0.099]])\]
\[l_\lambda = np.array([[0]])\]
\[a1 = 0.5\]
\[\pi_h = np.array([[1 / (sqrt(a1))]])\]
\[\delta_h = np.array([[0]])\]
\[\theta_h = np.array([[0]])\]

\[\delta = 0.1\]
\[g = 0.85\]
\[f_1 = 0.001\]
\[f_3 = 0.001\]
\[f_5 = 0.001\]
\[f_7 = 0.001\]

\[\phi_c = np.array([[1], [f1], [0], [0], [-f7]])\]
\[\phi_g = np.array([[0, 0, 0, 0],
[1, 0, 0, 0],
[0, 1, 0, 0],
[0, 0, 1, 0]]),
```
\[
\phi_i = \text{np.array}([[1], [0], [0], [0], [0]])
\]
\[
\gamma = \text{np.array}([[0, 0, 0], [f1 * (1 - \delta), 0, g * f1], [f3, 0, 0], [0, f5, 0], [0, 0, 0]])
\]
\[
\delta_k = \text{np.array}([[1 - \delta, 0, g], [1, 0, 0], [0, 1, 0]])
\]
\[
\theta_k = \text{np.array}([[1], [0], [0]])
\]
\[
\rho_1 = 0, \rho_2 = 0, \rho_3 = 0.6
\]
\[
a0 = 500, \gamma_0 = 0.4, \gamma_1 = 0.7
\]
\[
f2 = 1 / (2 * f1), f4 = \gamma_0 * g / (2 * f3), f6 = \gamma_1 * g / (2 * f5), f8 = 1 / (2 * f7)
\]
\[
a22 = \text{np.array}([[1, 0, 0, 0], [0, \rho_1, 0, 0], [0, 0, \rho_2, 0], [0, 0, 0, \rho_3]])
\]
\[
c2 = \text{np.array}([[0, 0, 0], [1, 0, 0], [0, 1, 0], [0, 0, 15]])
\]
\[
ub = \text{np.array}([[\pi h * a0, 0, 0, \pi h]])
\]
\[
uh = \text{np.array}([[50, 1, 0, 0]])
\]
\[
um = \text{np.array}([[100, 0, 1, 0]])
\]
\[
ud = \text{np.vstack}([[0, 0, 0, 0], [f2 * uh, f4 * uh, f6 * uh, f8 * um]])
\]

Notice that we have set \(\rho_1 = \rho_2 = 0\), so \(h_t\) and \(m_t\) consist of a constant and a white noise component.

We set up the economy using tuples for information, technology and preference matrices below.

We also construct two extra information matrices, corresponding to cases when \(\rho_3 = 1\) and \(\rho_3 = 0\) (as opposed to the baseline case of \(\rho_3 = 0.6\)).

In [5]: info1 = Information(a22, c2, ub, ud)
    tech1 = Technology(\(\phi_c\), \(\phi_g\), \(\phi_i\), \(\gamma\), \(\delta_k\), \(\theta_k\))
    pref1 = Preferences(\(\beta\), \(\hat{\lambda}\), \(\pi h\), \(\delta h\), \(\theta h\))

\[
\rho_3_2 = 1
\]
\[
a22_2 = \text{np.array}([[1, 0, 0, 0]]),
\]
[0, ρ1, 0, 0],
[0, 0, ρ2, 0],
[0, 0, 0, ρ3_2])

info2 = Information(a22_2, c2, ub, ud)

ρ3_3 = 0
a22_3 = np.array([[
1, 0, 0, 0],
[0, ρ1, 0, 0],
[0, 0, ρ2, 0],
[0, 0, 0, ρ3_3]])

info3 = Information(a22_3, c2, ub, ud)

# Example of how we can look at the matrices associated with a given namedtuple
info1.a22

Out[5]: array([[1., 0., 0., 0.],
               [0., 0., 0., 0.],
               [0., 0., 0., 0.],
               [0., 0., 0., 0.6]])

In [6]: # Use tuples to define DLE class
econ1 = DLE(info1, tech1, pref1)
econ2 = DLE(info2, tech1, pref1)
econ3 = DLE(info3, tech1, pref1)

# Calculate steady-state in baseline case and use to set the initial condition
econ1.compute_steadystate(nnc=4)
x0 = econ1.zz

In [7]: econ1.compute_sequence(x0, ts_length=100)

[53] use the model to understand the sources of recurrent cycles in total cattle stocks.
Plotting $y_t$ for a simulation of their model shows its ability to generate cycles in quantities

In [8]: # Calculation of $y_t$
totalstock = econ1.k[0] + g * econ1.k[1] + g * econ1.k[2]
fig, ax = plt.subplots()
ax.plot(totalstock)
ax.set_xlim((-1, 100))
aset_title('Total number of cattle')
plt.show()
In their Figure 3, [53] plot the impulse response functions of consumption and the breeding stock of cattle to the demand shock, $\tilde{d}_t$, under the three different values of $\rho_3$.

We replicate their Figure 3 below.

```python
In [9]: shock_demand = np.array([[0], [0], [1]])

econ1.irf(ts_length=25, shock=shock_demand)
econ2.irf(ts_length=25, shock=shock_demand)
econ3.irf(ts_length=25, shock=shock_demand)

fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
ax1.plot(econ1.c_irf, label='$\rho=0.6$')
ax1.plot(econ2.c_irf, label='$\rho=1$')
ax1.plot(econ3.c_irf, label='$\rho=0$')
ax1.set_title('Consumption response to demand shock')
ax1.legend()

ax2.plot(econ1.k_irf[:, 0], label='$\rho=0.6$')
ax2.plot(econ2.k_irf[:, 0], label='$\rho=1$')
ax2.plot(econ3.k_irf[:, 0], label='$\rho=0$')
ax2.set_title('Breeding stock response to demand shock')
ax2.legend()
plt.show()
24.3. MAPPING INTO HS2013 FRAMEWORK

The above figures show how consumption patterns differ markedly, depending on the persistence of the demand shock:

- If it is purely transitory ($\rho_3 = 0$) then consumption rises immediately but is later reduced to build stocks up again.
- If it is permanent ($\rho_3 = 1$), then consumption falls immediately, in order to build up stocks to satisfy the permanent rise in future demand.

In Figure 4 of their paper, [53] plot the response to a demand shock of the breeding stock and the total stock, for $\rho_3 = 0$ and $\rho_3 = 0.6$.

We replicate their Figure 4 below:

```python
In [10]: total1_irf = econ1.k_irf[:, 0] + g * econ1.k_irf[:, 1] + g * econ1.k_irf[:, 2]
total3_irf = econ3.k_irf[:, 0] + g * econ3.k_irf[:, 1] + g * econ3.k_irf[:, 2]

fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
ax1.plot(econ1.k_irf[:, 0], label='Breeding Stock')
ax1.plot(total1_irf, label='Total Stock')
ax1.set_title('\$\rho=0.6\$')

ax2.plot(econ3.k_irf[:, 0], label='Breeding Stock')
ax2.plot(total3_irf, label='Total Stock')
ax2.set_title('\$\rho=0\$')
plt.show()
```
The fact that $y_t$ is a weighted moving average of $x_t$ creates a humped shape response of the total stock in response to demand shocks, contributing to the cyclicality seen in the first graph of this lecture.
Chapter 25

Shock Non Invertibility

25.1 Contents

- Overview 25.2
- Model 25.3
- Code 25.4

25.2 Overview

This is another member of a suite of lectures that use the quantecon DLE class to instantiate models within the [31] class of models described in detail in Recursive Models of Dynamic Linear Economies.

In addition to what’s in Anaconda, this lecture uses the quantecon library.

In [1]: !pip install --upgrade quantecon

We’ll make these imports:

In [2]: import numpy as np
import quantecon as qe
import matplotlib.pyplot as plt
from quantecon import LQ
from quantecon import DLE
from math import sqrt
%matplotlib inline

This lecture can be viewed as introducing an early contribution to what is now often called a news and noise issue.

In particular, it analyzes a shock-invertibility issue that is endemic within a class of permanent income models.

Technically, the invertibility problem indicates a situation in which histories of the shocks in an econometrician’s autoregressive or Wold moving average representation span a smaller information space than do the shocks that are seen by the agents inside the econometrician’s model.
This situation sets the stage for an econometrician who is unaware of the problem and consequently misinterprets shocks and likely responses to them.

A shock-invertibility that is technically close to the one studied here is discussed by Eric Leeper, Todd Walker, and Susan Yang \[ ? \] in their analysis of fiscal foresight.

A distinct shock-invertibility issue is present in the special LQ consumption smoothing model in quantecon lecture.

### 25.3 Model

We consider the following modification of Robert Hall’s (1978) model \[24\] in which the endowment process is the sum of two orthogonal autoregressive processes:

**Preferences**

\[
-\frac{1}{2} \mathbb{E} \sum_{t=0}^{\infty} \beta^t [(c_t - b_t)^2 + I_t^2] J_0
\]

\[s_t = c_t\]

\[b_t = U_b z_t\]

**Technology**

\[c_t + i_t = \gamma k_{t-1} + d_t\]

\[k_t = \delta k_{t-1} + i_t\]

\[g_t = \phi_1 i_t, \phi_1 > 0\]

\[g_t \cdot g_t = I_t^2\]

**Information**

\[
U_b = \begin{bmatrix} 30 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}
\]

\[U_d = \begin{bmatrix} 5 & 1 & 1 & 0.8 & 0.6 & 0.4 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}\]
The preference shock is constant at 30, while the endowment process is the sum of a constant and two orthogonal processes. Specifically:

\[ d_t = 5 + d_{1t} + d_{2t} \]

\[ d_{1t} = 0.9d_{1t-1} + w_{1t} \]

\[ d_{2t} = 4w_{2t} + 0.8(4w_{2t-1}) + 0.6(4w_{2t-2}) + 0.4(4w_{2t-3}) \]

\( d_{1t} \) is a first-order AR process, while \( d_{2t} \) is a third-order pure moving average process.

In [3]:
\[ \gamma_1 = 0.05 \]
\[ \psi_c = np.array([[\gamma_1], [0]]) \]
\[ \psi_g = np.array([[1], [0]]) \]
\[ \phi_1 = 0.00001 \]
\[ \psi_i = np.array([[1], [-\phi_1]]) \]
\[ \sigma_k = np.array([[1]]) \]
\[ \theta_k = np.array([[1]]) \]
\[ \beta = np.array([[1 / 1.05]]) \]
\[ l_\lambda = np.array([[0]]) \]
\[ \tau_h = np.array([[1]]) \]
\[ \delta_h = np.array([[1]]) - \delta_h \]
\[ u_d = np.array([[5, 1, 0.8, 0.6, 0.4],
                  [0, 0, 0, 0, 0]]) \]
\[ a_{22} = np.zeros((6, 6)) \]

# Chase's great trick
\[ a_{22}[[0, 1, 3, 4, 5], [0, 1, 2, 3, 4]] = np.array([[1.0, 0.9, 1.0, 1.0, 1.0]]) \]
\[ c_2 = np.zeros((6, 2)) \]
\[ c_{2f}[[1, 2], [0, 1]] = np.array([[1.0, 4.0]]) \]
\[ ub = np.array([[30, 0, 0, 0, 0]]) \]
\[ x_0 = np.array([[5], [150], [1], [0], [0], [0], [0], [0], [0]]) \]

\[ \text{info1} = (a_{22}, c_2, ub, u_d) \]
\[ \text{tech1} = (\psi_c, \psi_g, \psi_i, \gamma, \sigma_k, \theta_k) \]
\[ \text{pref1} = (\beta, l_\lambda, \tau_h, \delta_h, \theta_h) \]

\[ \text{econ1} = \text{DLE(info1, tech1, pref1)} \]

We define the household’s net of interest deficit as \( c_t - d_t \).

Hall’s model imposes “expected present-value budget balance” in the sense that

\[ \mathbb{E} \sum_{j=0}^{\infty} \beta^j(c_{t+j} - d_{t+j})|J_t = \beta^{-1}k_{t-1} \forall t \]

If we define the moving average representation of \( (c_t, c_t - d_t) \) in terms of the \( w_t \)s to be:

\[
\begin{bmatrix}
  c_t \\
  c_t - d_t
\end{bmatrix} =
\begin{bmatrix}
  \sigma_1(L) \\
  \sigma_2(L)
\end{bmatrix} w_t
\]
then Hall’s model imposes the restriction $\sigma_2(\beta) = [0 \ 0]$.

The agent inside this model sees histories of both components of the endowment process $d_{1t}$ and $d_{2t}$.

The econometrician has data on the history of the pair $[c_t, d_t]$, but not directly on the history of $w_t$.

The econometrician obtains a Wold representation for the process $[c_t, c_t - d_t]$:

\[
\begin{bmatrix}
  c_t \\
  c_t - d_t
\end{bmatrix} = 
\begin{bmatrix}
  \sigma_1^*(L) \\
  \sigma_2^*(L)
\end{bmatrix} u_t
\]

The Appendix of chapter 8 of [31] explains why the impulse response functions in the Wold representation estimated by the econometrician do not resemble the impulse response functions that depict the response of consumption and the deficit to innovations to agents’ information.

Technically, $\sigma_2(\beta) = [0 \ 0]$ implies that the history of $u_t$s spans a smaller linear space than does the history of $w_t$s.

This means that $u_t$ will typically be a distributed lag of $w_t$ that is not concentrated at zero lag:

\[
   u_t = \sum_{j=0}^{\infty} \alpha_j w_{t-j}
\]

Thus, the econometrician’s news $u_t$ potentially responds belatedly to agents’ news $w_t$.

### 25.4 Code

We will construct Figures from Chapter 8 Appendix E of [31] to illustrate these ideas:

```python
In [4]: # This is Fig 8.E.1 from p.188 of HS2013

econ1.irf(ts_length=40, shock=None)
fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
ax1.plot(econ1.c_irf, label='Consumption')
ax1.plot(econ1.c_irf - econ1.d_irf[:,0].reshape(40,1), label='Deficit')
ax1.legend()
ax1.set_title('Response to $w_{1t}$')
shock2 = np.array([[0], [1]])
econ1.irf(ts_length=40, shock=shock2)
ax2.plot(econ1.c_irf, label='Consumption')
ax2.plot(econ1.c_irf - econ1.d_irf[:,0].reshape(40, 1), label='Deficit')
ax2.legend()
ax2.set_title('Response to $w_{2t}$')
plt.show()
```
The above figure displays the impulse response of consumption and the deficit to the endowment innovations.

Consumption displays the characteristic “random walk” response with respect to each innovation.

Each endowment innovation leads to a temporary surplus followed by a permanent net-of-interest deficit.

The temporary surplus just offsets the permanent deficit in terms of expected present value.

In [5]:
G_HS = np.vstack([econ1.Sc, econ1.Sc-econ1.Sd[:, :].reshape(1, 8)])
H_HS = 1e-8 * np.eye(2)  # Set very small so there is no measurement error
lss_hs = qe.LinearStateSpace(econ1.A0, econ1.C, G_HS, H_HS)

hs_kal = qe.Kalman(lss_hs)
w_lss = hs_kal.whitener_lss()
ma_coefs = hs_kal.stationary_coefficients(50, 'ma')

# This is Fig 8.E.2 from p.189 of HS2013

ma_coefs = ma_coefs
jj = 50
y1_w1 = np.empty(jj)
y2_w1 = np.empty(jj)
y1_w2 = np.empty(jj)
y2_w2 = np.empty(jj)

for t in range(jj):
y1_w1[t] = ma_coefs[t][0, 0]
y1_w2[t] = ma_coefs[t][0, 1]
y2_w1[t] = ma_coefs[t][1, 0]
y2_w2[t] = ma_coefs[t][1, 1]

# This scales the impulse responses to match those in the book
y1_w1 = sqrt(hs_kal.stationary_innovation_covar()[0, 0]) * y1_w1
y2_w1 = sqrt(hs_kal.stationary_innovation_covar()[0, 0]) * y2_w1
y1_w2 = sqrt(hs_kal.stationary_innovation_covar()[1, 1]) * y1_w2
y2_w2 = sqrt(hs_kal.stationary_innovation_covar()[1, 1]) * y2_w2

fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
ax1.plot(y1_w1, label='Consumption')
ax1.plot(y2_w1, label='Deficit')
The above figure displays the impulse response of consumption and the deficit to the innovations in the econometrician’s Wold representation

- this is the object that would be recovered from a high order vector autoregression on the econometrician’s observations.

Consumption responds only to the first innovation

- this is indicative of the Granger causality imposed on the \([c_t, c_t - d_t]\) process by Hall’s model: consumption Granger causes \(c_t - d_t\), with no reverse causality.

In [6]: # This is Fig 8.E.3 from p.189 of HS2013

```python
jj = 20
irf_wlss = w_lss.impulse_response(jj)
ycoefs = irf_wlss[1]
# Pull out the shocks
a1_w1 = np.empty(jj)
a1_w2 = np.empty(jj)
a2_w1 = np.empty(jj)
a2_w2 = np.empty(jj)

for t in range(jj):
    a1_w1[t] = ycoefs[t][0, 0]
    a1_w2[t] = ycoefs[t][0, 1]
    a2_w1[t] = ycoefs[t][1, 0]
    a2_w2[t] = ycoefs[t][1, 1]
```

```python
fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(12, 4))
ap1.plot(a1_w1, label='Consumption innov.')
ap1.plot(a2_w1, label='Deficit innov.')
ap1.set_title('Response to \(wu_{1t}\)')
ap1.legend()
```
The above figure displays the impulse responses of $u_t$ to $w_t$, as depicted in:

$$u_t = \sum_{j=0}^{\infty} \alpha_j w_{t-j}$$

While the responses of the innovations to consumption are concentrated at lag zero for both components of $w_t$, the responses of the innovations to $(c_t - d_t)$ are spread over time (especially in response to $w_{1t}$).

Thus, the innovations to $(c_t - d_t)$ as revealed by the vector autoregression depend on what the economic agent views as "old news".
Part V

Classic Linear Models
Chapter 26

Von Neumann Growth Model (and a Generalization)

26.1 Contents

- Notation 26.2
- Model Ingredients and Assumptions 26.3
- Dynamic Interpretation 26.4
- Duality 26.5
- Interpretation as Two-player Zero-sum Game 26.6

This lecture uses the class `Neumann` to calculate key objects of a linear growth model of John von Neumann [67] that was generalized by Kemeny, Morgenstern and Thompson [38].

Objects of interest are the maximal expansion rate (\(\alpha\)), the interest factor (\(\beta\)), the optimal intensities (\(x\)), and prices (\(p\)).

In addition to watching how the towering mind of John von Neumann formulated an equilibrium model of price and quantity vectors in balanced growth, this lecture shows how fruitfully to employ the following important tools:

- a zero-sum two-player game
- linear programming
- the Perron-Frobenius theorem

We’ll begin with some imports:

```python
In [2]: import numpy as np
    import matplotlib.pyplot as plt
    from scipy.linalg import solve
    from scipy.optimize import fsolve, linprog
    from textwrap import dedent
    %matplotlib inline
    np.set_printoptions(precision=2)
```

The code below provides the `Neumann` class

```python
In [2]: class Neumann(object):
```
CHAPTER 26. VON NEUMANN GROWTH MODEL (AND A GENERALIZATION)

This class describes the Generalized von Neumann growth model as it was discussed in Kemeny et al. (1956, ECTA) and Gale (1960, Chapter 9.5):

Let:
n ... number of goods
m ... number of activities
A ... input matrix is m-by-n
    $a_{i,j}$ - amount of good $j$ consumed by activity $i$
B ... output matrix is m-by-n
    $b_{i,j}$ - amount of good $j$ produced by activity $i$
x ... intensity vector (m-vector) with non-negative entries
    $x'B$ - the vector of goods produced
    $x'A$ - the vector of goods consumed
p ... price vector (n-vector) with non-negative entries
    $Bp$ - the revenue vector for every activity
    $Ap$ - the cost of each activity

Both A and B have non-negative entries. Moreover, we assume that
(1) Assumption I (every good which is consumed is also produced):
    for all $j$, $b_{.,j} > 0$, i.e. at least one entry is strictly positive
(2) Assumption II (no free lunch):
    for all $i$, $a_{i,.} > 0$, i.e. at least one entry is strictly positive

Parameters
----------
A : array_like or scalar(float)
    Part of the state transition equation. It should be `n x n`
B : array_like or scalar(float)
    Part of the state transition equation. It should be `n x k`

```
def __init__(self, A, B):
    self.A, self.B = list(map(self.convert, (A, B)))
    self.m, self.n = self.A.shape

    # Check if (A, B) satisfy the basic assumptions
    assert self.A.shape == self.B.shape, 'The input and output matrices \ must have the same dimensions!'
    assert (self.A >= 0).all() and (self.B >= 0).all(), 'The input and \ output matrices must have only non-negative entries!'

    # (1) Check whether Assumption I is satisfied:
    if (np.sum(B, 0) <= 0).any():
        self.AI = False
    else:
        self.AI = True

    # (2) Check whether Assumption II is satisfied:
    if (np.sum(A, 1) <= 0).any():
        self.AII = False
    else:
        self.AII = True

def __repr__(self):
    return self.__str__()
def __str__(self):
    me = ""
    Generalized von Neumann expanding model:
    - number of goods : \{n\}
    - number of activities : \{m\}

    Assumptions:
    - AI: every column of B has a positive entry : \{AI\}
    - AII: every row of A has a positive entry : \{AII\}

    # Irreducible : \{irr\}
    return dedent(me.format(n=self.n, m=self.m,
                              AI=self.AI, AII=self.AII))

def convert(self, x):
    ""
    Convert array_like objects (lists of lists, floats, etc.) into well-formed 2D NumPy arrays
    ""
    return np.atleast_2d(np.asarray(x))

def bounds(self):
    ""
    Calculate the trivial upper and lower bounds for alpha (expansion rate) and beta (interest factor). See the proof of Theorem 9.8 in Gale (1960)
    ""
    n, m = self.n, self.m
    A, B = self.A, self.B

    f = lambda α: ((B - α * A) @ np.ones((n, 1))).max()
    g = lambda β: (np.ones((1, m)) @ (B - β * A)).min()

    UB = np.asscalar(fsolve(f, 1))  # Upper bound for α, β
    LB = np.asscalar(fsolve(g, 2))  # Lower bound for α, β
    return LB, UB

def zerosum(self, γ, dual=False):
    ""
    Given gamma, calculate the value and optimal strategies of a two-player zero-sum game given by the matrix

    \[ M(\gamma) = B - \gamma * A \]

    Row player maximizing, column player minimizing

    Zero-sum game as an LP (primal --> α)

    max (0', 1) @ (x', v)
    subject to
Zero-sum game as an LP (dual --> beta)

\[
\begin{align*}
\min (0', 1) @ (p', u) \\
\text{subject to} \\
[M, -\text{ones}(m, 1)] @ (p', u)' &= 0 \\
(p', u) @ (\text{ones}(n, 1), 0) &= 1 \\
(p', u) &= (0', -\infty)
\end{align*}
\]

Outputs:
--------
value: scalar
value of the zero-sum game
strategy: vector
if dual = False, it is the intensity vector,
if dual = True, it is the price vector

```python
A, B, n, m = self.A, self.B, self.n, self.m
M = B - γ * A

if dual == False:
    # Solve the primal LP (for details see the description)
    # (1) Define the problem for v as a maximization (linprog minimizes)
    c = np.hstack([np.zeros(m), -1])

    # (2) Add constraints :
    # ... non-negativity constraints
    bounds = tuple(m * [(0, None)] + [(None, None)])
    # ... inequality constraints
    A_iq = np.hstack([-M.T, np.ones((m, 1))])
    b_iq = np.zeros((m, 1))
    # ... normalization
    A_eq = np.hstack([np.ones(n), 0]).reshape(1, m + 1)
    b_eq = 1
    res = linprog(c, A_ub=A_iq, b_ub=b_iq, A_eq=A_eq, b_eq=b_eq, 
                  bounds=bounds, options=dict(bland=True, tol=1e-7))

else:
    # Solve the dual LP (for details see the description)
    # (1) Define the problem for v as a maximization (linprog minimizes)
    c = np.hstack([np.zeros(n), 1])

    # (2) Add constraints :
    # ... non-negativity constraints
    bounds = tuple(n * [(0, None)] + [(None, None)])
    # ... inequality constraints
    A_iq = np.hstack([M, -np.ones((m, 1))])
    b_iq = np.zeros((m, 1))
    # ... normalization
    A_eq = np.hstack([np.ones(n), 0]).reshape(1, n + 1)
```

b_eq = 1

res = linprog(c, A_ub=A_iq, b_ub=b_iq, A_eq=A_eq, b_eq=b_eq,
             bounds=bounds, options=dict(bland=True, tol=1e-7))

if res.status != 0:
    print(res.message)

# Pull out the required quantities
value = res.x[-1]
strategy = res.x[:-1]

return value, strategy

def expansion(self, tol=1e-8, maxit=1000):
    ""
    The algorithm used here is described in Hamburger-Thompson-Weil
    (1967, ECTA). It is based on a simple bisection argument and utilizes
    the idea that for a given $\gamma (= \alpha$ or $\beta$), the matrix $M = B - \gamma \cdot A$
    defines a two-player zero-sum game, where the optimal strategies are
    the (normalized) intensity and price vector.

    Outputs:
    -------
    alpha: scalar
    ""
    LB, UB = self.bounds()

    for iter in range(maxit):
        \gamma = (LB + UB) / 2
        ZS = self.zerosum(\gamma=\gamma)
        V = ZS[0]  # value of the game with $\gamma$

        if V >= 0:
            LB = \gamma
        else:
            UB = \gamma

        if abs(UB - LB) < tol:
            \gamma = (UB + LB) / 2
            x = self.zerosum(\gamma=\gamma)[1]
            p = self.zerosum(\gamma=\gamma, dual=True)[1]
            break

    return \gamma, x, p

def interest(self, tol=1e-8, maxit=1000):
    ""
    The algorithm used here is described in Hamburger-Thompson-Weil
    (1967, ECTA). It is based on a simple bisection argument and utilizes
    the idea that for a given gamma (= alpha or beta),
    the matrix $M = B - \gamma \cdot A$ defines a two-player zero-sum game,
    where the optimal strategies are the (normalized) intensity and price vector.
CHAPTER 26. VON NEUMANN GROWTH MODEL (AND A GENERALIZATION)

Outputs:
--------
**beta: scalar**
"""optimal interest rate"

LB, UB = self.bounds()

for iter in range(maxit):
    γ = (LB + UB) / 2
    ZS = self.zerosum(γ=γ, dual=True)
    V = ZS[0]
    if V > 0:
        LB = γ
    else:
        UB = γ
    if abs(UB - LB) < tol:
        γ = (UB + LB) / 2
        p = self.zerosum(γ=γ, dual=True)[1]
        x = self.zerosum(γ=γ)[1]
        break

return γ, x, p

26.2 Notation

We use the following notation.

**0** denotes a vector of zeros.

We call an \( n \)-vector positive and write \( x \gg 0 \) if \( x_i > 0 \) for all \( i = 1, 2, \ldots, n \).

We call a vector non-negative and write \( x \geq 0 \) if \( x_i \geq 0 \) for all \( i = 1, 2, \ldots, n \).

We call a vector semi-positive and written \( x > 0 \) if \( x \geq 0 \) and \( x \neq 0 \).

For two conformable vectors \( x \) and \( y \), \( x \gg y \), \( x \geq y \) and \( x > y \) mean \( x - y \gg 0 \), \( x - y \geq 0 \), and \( x - y > 0 \), respectively.

We let all vectors in this lecture be column vectors; \( x^T \) denotes the transpose of \( x \) (i.e., a row vector).

Let \( \iota_n \) denote a column vector composed of \( n \) ones, i.e. \( \iota_n = (1, 1, \ldots, 1)^T \).

Let \( e^i \) denote a vector (of arbitrary size) containing zeros except for the \( i \) th position where it is one.

We denote matrices by capital letters. For an arbitrary matrix \( A \), \( a_{i,j} \) represents the entry in its \( i \) th row and \( j \) th column.

\( a_{-j} \) and \( a_i \) denote the \( j \) th column and \( i \) th row of \( A \), respectively.
26.3 Model Ingredients and Assumptions

A pair \((A, B)\) of \(m \times n\) non-negative matrices defines an economy.

- \(m\) is the number of activities (or sectors)
- \(n\) is the number of goods (produced and/or consumed).
- \(A\) is called the input matrix; \(a_{i,j}\) denotes the amount of good \(j\) consumed by activity \(i\)
- \(B\) is called the output matrix; \(b_{i,j}\) represents the amount of good \(j\) produced by activity \(i\)

Two key assumptions restrict economy \((A, B)\):

- **Assumption I:** (every good that is consumed is also produced)
  \[b_{j} > 0 \quad \forall j = 1, 2, \ldots, n\]
- **Assumption II:** (no free lunch)
  \[a_{i} > 0 \quad \forall i = 1, 2, \ldots, m\]

A semi-positive intensity \(m\)-vector \(x\) denotes levels at which activities are operated.

Therefore,

- vector \(x^T A\) gives the total amount of goods used in production
- vector \(x^T B\) gives total outputs

An economy \((A, B)\) is said to be productive, if there exists a non-negative intensity vector \(x \geq 0\) such that \(x^T B > x^T A\).

The semi-positive \(n\)-vector \(p\) contains prices assigned to the \(n\) goods.

The \(p\) vector implies cost and revenue vectors

- the vector \(Ap\) tells costs of the vector of activities
- the vector \(Bp\) tells revenues from the vector of activities

Satisfaction or a property of an input-output pair \((A, B)\) called irreducibility (or indecomposability) determines whether an economy can be decomposed into multiple “sub-economies”.

**Definition:** For an economy \((A, B)\), the set of goods \(S \subset \{1, 2, \ldots, n\}\) is called an independent subset if it is possible to produce every good in \(S\) without consuming goods from outside \(S\). Formally, the set \(S\) is independent if \(\exists T \subset \{1, 2, \ldots, m\}\) (a subset of activities) such that \(a_{i,j} = 0 \ \forall i \in T\) and \(j \in S^c\) and for all \(j \in S\), \(\exists i \in T\) for which \(b_{i,j} > 0\). The economy is irreducible if there are no proper independent subsets.

We study two examples, both in Chapter 9.6 of Gale [22]

**In [3]:**

1. **Irreducible \((A, B)\) example: \(\alpha_\theta = \beta_\theta\)**
   \[
   A1 = \text{np.array}([[0, 1, 0, 0],
                         [1, 0, 0, 1],
                         [0, 0, 1, 0]])
   \]
   \[
   B1 = \text{np.array}([[1, 0, 0, 0],
                         [0, 0, 2, 0],
                         [0, 1, 0, 1]])
   \]

2. **Reducible \((A, B)\) example: \(\beta_\theta < \alpha_\theta\)**
   \[
   A2 = \text{np.array}([[0, 1, 0, 0, 0],
                         [1, 0, 1, 0, 0],
                         [0, 0, 0, 0, 0]])
   \]
26.4 Dynamic Interpretation

Attach a time index $t$ to the preceding objects, regard an economy as a dynamic system, and study sequences

$$\{(A_t, B_t)\}_{t \geq 0}, \quad \{x_t\}_{t \geq 0}, \quad \{p_t\}_{t \geq 0}$$

An interesting special case holds the technology process constant and investigates the dynamics of quantities and prices only.

Accordingly, in the rest of this lecture, we assume that $(A_t, B_t) = (A, B)$ for all $t \geq 0$.

A crucial element of the dynamic interpretation involves the timing of production.
We assume that production (consumption of inputs) takes place in period $t$, while the consequent output materializes in period $t + 1$, i.e., consumption of $x_t^T A$ in period $t$ results in $x_t^T B$ amounts of output in period $t + 1$.

These timing conventions imply the following feasibility condition:

$$x_t^T B \geq x_{t+1}^T A \quad \forall t \geq 1$$

which asserts that no more goods can be used today than were produced yesterday.

Accordingly, $A_p_t$ tells the costs of production in period $t$ and $B_p_t$ tells revenues in period $t + 1$.

### 26.4.1 Balanced Growth

We follow John von Neumann in studying “balanced growth”.

Let $./$ denote an elementwise division of one vector by another and let $\alpha > 0$ be a scalar.

Then balanced growth is a situation in which

$$x_{t+1}/x_t = \alpha, \quad \forall t \geq 0$$

With balanced growth, the law of motion of $x$ is evidently $x_{t+1} = \alpha x_t$ and so we can rewrite the feasibility constraint as

$$x_t^T B \geq \alpha x_t^T A \quad \forall t$$

In the same spirit, define $\beta \in \mathbb{R}$ as the interest factor per unit of time.

We assume that it is always possible to earn a gross return equal to the constant interest factor $\beta$ by investing “outside the model”.

Under this assumption about outside investment opportunities, a no-arbitrage condition gives rise to the following (no profit) restriction on the price sequence:

$$\beta A_p_t \geq B_p_t \quad \forall t$$

This says that production cannot yield a return greater than that offered by the outside investment opportunity (here we compare values in period $t + 1$).

The balanced growth assumption allows us to drop time subscripts and conduct an analysis purely in terms of a time-invariant growth rate $\alpha$ and interest factor $\beta$.

### 26.5 Duality

Two problems are connected by a remarkable dual relationship between technological and valuation characteristics of the economy:

**Definition:** The technological expansion problem (TEP) for the economy $(A, B)$ is to find a semi-positive $m$-vector $x > 0$ and a number $\alpha \in \mathbb{R}$ that satisfy
\[
\max_{\alpha} \alpha \\
\text{s.t. } x^T B \geq \alpha x^T A
\]

Theorem 9.3 of David Gale’s book [22] asserts that if Assumptions I and II are both satisfied, then a maximum value of \( \alpha \) exists and that it is positive.

The maximal value is called the \textit{technological expansion rate} and is denoted by \( \alpha_0 \). The associated intensity vector \( x_0 \) is the \textit{optimal intensity vector}.

**Definition:** The economic expansion problem* (EEP) for \((A, B)\) is to find a semi-positive \( n \)-vector \( p > 0 \) and a number \( \beta \in \mathbb{R} \) that satisfy

\[
\min_{\beta} \beta \\
\text{s.t. } Bp \leq \beta A p
\]

Assumptions I and II imply existence of a minimum value \( \beta_0 > 0 \) called the \textit{economic expansion rate}.

The corresponding price vector \( p_0 \) is the \textit{optimal price vector}.

Because the criterion functions in the \textit{technological expansion} problem and the \textit{economical expansion problem} are both linearly homogeneous, the optimality of \( x_0 \) and \( p_0 \) are defined only up to a positive scale factor.

For convenience (and to emphasize a close connection to zero-sum games), we normalize both vectors \( x_0 \) and \( p_0 \) to have unit length.

A standard duality argument (see Lemma 9.4. in (Gale, 1960) [22]) implies that under Assumptions I and II, \( \beta_0 \leq \alpha_0 \).

But to deduce that \( \beta_0 \geq \alpha_0 \), Assumptions I and II are not sufficient.

Therefore, von Neumann [67] went on to prove the following remarkable “duality” result that connects TEP and EEP.

**Theorem 1 (von Neumann):** If the economy \((A, B)\) satisfies Assumptions I and II, then there exist \( (\gamma^*, x_0, p_0) \), where \( \gamma^* \in [\beta_0, \alpha_0] \subset \mathbb{R} \), \( x_0 > 0 \) is an \( m \)-vector, \( p_0 > 0 \) is an \( n \)-vector, and the following arbitrage true

\[
x_0^T B \geq \gamma^* x_0^T A \\
B p_0 \leq \gamma^* A p_0 \\
x_0^T (B - \gamma^* A) p_0 = 0
\]

**Note**

*Proof (Sketch):* Assumption I and II imply that there exist \( (\alpha_0, x_0) \) and \( (\beta_0, p_0) \) that solve the TEP and EEP, respectively. If \( \gamma^* > \alpha_0 \), then by definition of \( \alpha_0 \), there cannot exist a semi-positive \( x \) that satisfies \( x^T B \geq \gamma^* x^T A \). Similarly, if \( \gamma^* < \beta_0 \), there is no semi-positive \( p \) for which \( Bp \leq \gamma^* A p \). Let \( \gamma^* \in [\beta_0, \alpha_0] \), then \( x_0^T B \geq \alpha_0 x_0^T A \geq \gamma^* x_0^T A \). Moreover, \( B p_0 \leq \beta_0 A p_0 \leq \gamma^* A p_0 \). These two inequalities imply \( x_0 (B - \gamma^* A) p_0 = 0 \).

Here the constant \( \gamma^* \) is both an expansion factor and an interest factor (not necessarily optimal).
26.6 Interpretation as Two-Player Zero-Sum Game

We have already encountered and discussed the first two inequalities that represent feasibility and no-profit conditions.

Moreover, the equality \( x_0^T (B - \gamma^* A) p_0 = 0 \) concisely expresses the requirements that if any good grows at a rate larger than \( \gamma^* \) (i.e., if it is oversupplied), then its price must be zero; and that if any activity provides negative profit, it must be unused.

Therefore, the conditions stated in Theorem I encode all equilibrium conditions.

So Theorem I essentially states that under Assumptions I and II there always exists an equilibrium \( (\gamma^*, x_0, p_0) \) with balanced growth.

Note that Theorem I is silent about uniqueness of the equilibrium. In fact, it does not rule out (trivial) cases with \( x_0^T B p_0 = 0 \) so that nothing of value is produced.

To exclude such uninteresting cases, Kemeny, Morgenstern and Thompson [38] add an extra requirement

\[
x_0^T B p_0 > 0
\]

and call the associated equilibria economic solutions.

They show that this extra condition does not affect the existence result, while it significantly reduces the number of (relevant) solutions.

26.6 Interpretation as Two-player Zero-sum Game

To compute the equilibrium \( (\gamma^*, x_0, p_0) \), we follow the algorithm proposed by Hamburger, Thompson and Weil (1967), building on the key insight that an equilibrium (with balanced growth) can be solves a particular two-player zero-sum game. First, we introduce some notation.

Consider the \( m \times n \) matrix \( C \) as a payoff matrix, with the entries representing payoffs from the minimizing column player to the maximizing row player and assume that the players can use mixed strategies. Thus,

- the row player chooses the \( m \)-vector \( x > 0 \) subject to \( i_m^T x = 1 \)
- the column player chooses the \( n \)-vector \( p > 0 \) subject to \( i_n^T p = 1 \).

**Definition:** The \( m \times n \) matrix game \( C \) has the solution \( (x^*, p^*, V(C)) \) in mixed strategies if

\[
(x^*)^T C e_j \geq V(C) \quad \forall j \in \{1, \ldots, n\} \quad \text{and} \quad (e_i^*)^T C p^* \leq V(C) \quad \forall i \in \{1, \ldots, m\}
\]

The number \( V(C) \) is called the value of the game.

From the above definition, it is clear that the value \( V(C) \) has two alternative interpretations:

- by playing the appropriate mixed strategy, the maximizing player can assure himself at least \( V(C) \) (no matter what the column player chooses)
- by playing the appropriate mixed strategy, the minimizing player can make sure that the maximizing player will not get more than \( V(C) \) (irrespective of what is the maximizing player’s choice)

A famous theorem of Nash (1951) tells us that there always exists a mixed strategy Nash equilibrium for any finite two-player zero-sum game.
Moreover, von Neumann’s Minmax Theorem \([66]\) implies that

\[
V(C) = \max_x \min_p x^T Cp = \min_p \max_x x^T Cp = (x^*)^T Cp^*
\]

### 26.6.1 Connection with Linear Programming (LP)

Nash equilibria of a finite two-player zero-sum game solve a linear programming problem. To see this, we introduce the following notation

- For a fixed \(x\), let \(v\) be the value of the minimization problem: \(v \equiv \min_p x^T Cp = \min_j x^T Ce^j\)
- For a fixed \(p\), let \(u\) be the value of the maximization problem: \(u \equiv \max_x x^T Cp = \max_i (e_i)^T Cp\)

Then the \textit{max-min problem} (the game from the maximizing player’s point of view) can be written as the \textit{primal} LP

\[
\begin{align*}
0 \leq x^T C & \leq x^T C \\
x & \geq 0 \\
\eta^T x & = 1
\end{align*}
\]

while the \textit{min-max problem} (the game from the minimizing player’s point of view) is the \textit{dual} LP

\[
\begin{align*}
0 \leq C & \leq p \geq 0 \\
\eta^T p & = 1
\end{align*}
\]

Hamburger, Thompson and Weil \([25]\) view the input-output pair of the economy as payoff matrices of two-player zero-sum games. Using this interpretation, they restate Assumption I and II as follows

\[
V(−A) < 0 \quad \text{and} \quad V(B) > 0
\]

**Note**

\textit{Proof (Sketch):} \(\star \Rightarrow V(B) > 0\) implies \(x_0^T B \gg 0\), where \(x_0\) is a maximizing vector. Since \(B\) is non-negative, this requires that each column of \(B\) has at least one positive entry, which is Assumption I. \(\star \Leftarrow\) From Assumption I and the fact that \(p > 0\), it follows that \(Bp > 0\). This implies that the maximizing player can always choose \(x\) so that \(x^T Bp > 0\) so that it must be the case that \(V(B) > 0\).

In order to (re)state Theorem I in terms of a particular two-player zero-sum game, we define a matrix for \(\gamma \in \mathbb{R}\)

\[
M(\gamma) \equiv B - \gamma A
\]
For fixed $\gamma$, treating $M(\gamma)$ as a matrix game, calculating the solution of the game implies

- If $\gamma > \alpha_0$, then for all $x > 0$, there $\exists j \in \{1, \ldots, n\}$, s.t. $[x^T M(\gamma)]_j < 0$ implying that $V(M(\gamma)) < 0$.
- If $\gamma < \beta_0$, then for all $p > 0$, there $\exists i \in \{1, \ldots, m\}$, s.t. $[(M(\gamma)p)]_i > 0$ implying that $V(M(\gamma)) > 0$.
- If $\gamma \in \{\beta_0, \alpha_0\}$, then (by Theorem I) the optimal intensity and price vectors $x_0$ and $p_0$ satisfy

$$x_0^T M(\gamma) \geq 0^T \quad \text{and} \quad M(\gamma)p_0 \leq 0$$

That is, $(x_0, p_0, 0)$ is a solution of the game $M(\gamma)$ so that $V(M(\beta_0)) = V(M(\alpha_0)) = 0$.

Proof (Sketch): If $x'$ is optimal for a maximizing player in game $M(\gamma')$, then $(x')^T M(\gamma') \geq 0^T$ and so for all $\gamma < \gamma'$.

$$(x')^T M(\gamma) = (x')^T M(\gamma') + (x')^T (\gamma' - \gamma)A \geq 0^T$$

hence $V(M(\gamma)) \geq 0$. If $p''$ is optimal for a minimizing player in game $M(\gamma'')$, then $M(\gamma)p \leq 0$ and so for all $\gamma'' < \gamma$

$$M(\gamma)p'' = M(\gamma'') + (\gamma'' - \gamma)Ap'' \leq 0$$

hence $V(M(\gamma)) \leq 0$.

It is clear from the above argument that $\beta_0, \alpha_0$ are the minimal and maximal $\gamma$ for which $V(M(\gamma)) = 0$.

Furthermore, Hamburger et al. [25] show that the function $\gamma \mapsto V(M(\gamma))$ is continuous and nonincreasing in $\gamma$.

This suggests an algorithm to compute $(\alpha_0, x_0)$ and $(\beta_0, p_0)$ for a given input-output pair $(A, B)$.

26.6.2 Algorithm

Hamburger, Thompson and Weil [25] propose a simple bisection algorithm to find the minimal and maximal roots (i.e. $\beta_0$ and $\alpha_0$) of the function $\gamma \mapsto V(M(\gamma))$.

Step 1

First, notice that we can easily find trivial upper and lower bounds for $\alpha_0$ and $\beta_0$.

- TEP requires that $x^T (B - \alpha A) \geq 0^T$ and $x > 0$, so if $\alpha$ is so large that $\max_i \{(B - \alpha A)\epsilon_{ni}\} < 0$, then TEP ceases to have a solution.

Accordingly, let $UB$ be the $\alpha^*$ that solves $\max_i \{(B - \alpha^* A)\epsilon_{ni}\} = 0$. 

• Similar to the upper bound, if $\beta$ is so low that $\min_j[[u^T_m(B - \beta A)]_j] > 0$, then the EEP has no solution and so we can define $\text{LB}$ as the $\beta^*$ that solves $\min_j[[u^T_m(B - \beta^* A)]_j] = 0$.

The bounds method calculates these trivial bounds for us

**In [6]:** n1.bounds()

```
/home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:98:
DeprecationWarning: np.asscalar(a) is deprecated since NumPy v1.16, use a.item() instead
/home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:99:
DeprecationWarning: np.asscalar(a) is deprecated since NumPy v1.16, use a.item() instead
```

**Out[6]:** (1.0, 2.0)

**Step 2**

Compute $\alpha_0$ and $\beta_0$

- Finding $\alpha_0$
  1. Fix $\gamma = \frac{UB + LB}{2}$ and compute the solution of the two-player zero-sum game associated with $M(\gamma)$. We can use either the primal or the dual LP problem.
  2. If $V(M(\gamma)) \geq 0$, then set $LB = \gamma$, otherwise let $UB = \gamma$.
  3. Iterate on 1. and 2. until $|UB - LB| < \epsilon$.

- Finding $\beta_0$
  1. Fix $\gamma = \frac{UB + LB}{2}$ and compute the solution of the two-player zero-sum game associated with $M(\gamma)$. We can use either the primal or the dual LP problem.
  2. If $V(M(\gamma)) > 0$, then set $LB = \gamma$, otherwise let $UB = \gamma$.
  3. Iterate on 1. and 2. until $|UB - LB| < \epsilon$.

**Existence:** Since $V(M(LB)) > 0$ and $V(M(UB)) < 0$ and $V(M(\cdot))$ is a continuous, nonincreasing function, there is at least one $\gamma \in [LB, UB]$, s.t. $V(M(\gamma)) = 0$.

The zerosum method calculates the value and optimal strategies associated with a given $\gamma$.

**In [7]:** $\gamma = 2$

```
print(f'Value of the game with $\gamma = {\gamma}$')
pprint(n1.zerosum(\gamma=\gamma)[0])
print('Intensity vector (from the primal)')
pprint(n1.zerosum(\gamma=\gamma)[1])
print('Price vector (from the dual)')
pprint(n1.zerosum(\gamma=\gamma, dual=True)[1])
```

```
Value of the game with $\gamma = 2$
-0.24000000097850305
Intensity vector (from the primal)
[0.32 0.28 0.4 ]
Price vector (from the dual)
[4.00e-01 3.20e-01 2.80e-01 2.54e-10]
```
26.6. INTERPRETATION AS TWO-PLAYER ZERO-SUM GAME

In [8]: numb_grid = 100
   γ_grid = np.linspace(0.4, 2.1, numb_grid)
   value_ex1_grid = np.asarray([n1.zerosum(γ=γ_grid[i])[0]  
                                for i in range(numb_grid)])
   value_ex2_grid = np.asarray([n2.zerosum(γ=γ_grid[i])[0]  
                                for i in range(numb_grid)])

fig, axes = plt.subplots(1, 2, figsize=(14, 5), sharey=True)
fig.suptitle(r'The function $V(M(\gamma))$', fontsize=16)
for ax, grid, N, i in zip(axes, (value_ex1_grid, value_ex2_grid),
                           (n1, n2), (1, 2)):
    ax.plot(γ_grid, grid)
    ax.set(title=f'Example {i}', xlabel='$\gamma$')
    ax.axhline(0, c='k', lw=1)
    ax.axvline(N.bounds()[0], c='r', ls='--', label='lower bound')
    ax.axvline(N.bounds()[1], c='g', ls='--', label='upper bound')
plt.show()
The \textit{expansion} method implements the bisection algorithm for $\alpha_0$ (and uses the primal LP problem for $x_0$)

In \[9\]: $\alpha_0$, x, p = n1.expansion()

\begin{verbatim}
print(f'\alpha_0 = {x_0}')
print(f'x_0 = {x}')
print(f'The corresponding p from the dual = {p}')
\end{verbatim}

\[
\alpha_0 = 1.2599210478365421
\]
\[
x_0 = [0.33 0.26 0.41]
\]
The corresponding p from the dual = [4.13e-01 3.27e-01 2.60e-01 1.82e-10]

The \textit{interest} method implements the bisection algorithm for $\beta_0$ (and uses the dual LP problem for $p_0$)

In \[10\]: $\beta_0$, x, p = n1.interest()

\begin{verbatim}
print(f'\beta_0 = {\beta_0}')
print(f'p_0 = {p}')
print(f'The corresponding x from the primal = {x}')
\end{verbatim}

\[
\beta_0 = 1.2599210478365421
\]
\[
p_0 = [4.13e-01 3.27e-01 2.60e-01 1.82e-10]
\]
The corresponding x from the primal = [0.33 0.26 0.41]

Of course, when $\gamma^*$ is unique, it is irrelevant which one of the two methods we use – both work.

In particular, as will be shown below, in case of an irreducible $(A, B)$ (like in Example 1), the maximal and minimal roots of $V(M(\gamma))$ necessarily coincide implying a “full duality” result, i.e. $\alpha_0 = \beta_0 = \gamma^*$ so that the expansion (and interest) rate $\gamma^*$ is unique.
26.6.3 Uniqueness and Irreducibility

As an illustration, compute first the maximal and minimal roots of $V(M(\cdot))$ for our Example 2 that has a reducible input-output pair $(A, B)$

```
In [11]: α₀, x, p = n2.expansion()
   print(f'α₀ = {α₀}')
   print(f'x₀ = {x}')
   print(f'The corresponding p from the dual = {p}')

   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:98:
   DeprecationWarning: np.asscalar(a) is deprecated since NumPy v1.16, use a.item() instead
   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:99:
   DeprecationWarning: np.asscalar(a) is deprecated since NumPy v1.16, use a.item() instead
   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:158:
   OptimizeWarning: Unknown solver options: bland

   α₀ = 1.1343231122911552
   x₀ = [1.67e-11 1.83e-11 3.24e-01 2.61e-01 4.15e-01]
   The corresponding p from the dual = [5.04e-01 4.96e-01 2.96e-12 2.24e-12 3.08e-12 3.56e-12]
```

```
In [12]: β₀, x, p = n2.interest()
   print(f'β₀ = {β₀}')
   print(f'p₀ = {p}')
   print(f'The corresponding x from the primal = {x}')

   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:98:
   DeprecationWarning: np.asscalar(a) is deprecated since NumPy v1.16, use a.item() instead
   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:99:
   DeprecationWarning: np.asscalar(a) is deprecated since NumPy v1.16, use a.item() instead
   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:158:
   OptimizeWarning: Unknown solver options: bland

   β₀ = 1.2579826879933175
   p₀ = [5.11e-01 4.89e-01 2.73e-08 2.17e-08 1.80e-08 2.66e-09]
   The corresponding x from the primal = [1.61e-09 1.65e-09 3.27e-01 2.60e-01 4.12e-01]
```

As we can see, with a reducible $(A, B)$, the roots found by the bisection algorithms might differ, so there might be multiple $γ^*$ that make the value of the game with $M(γ^*)$ zero. (see the figure above).
Indeed, although the von Neumann theorem assures existence of the equilibrium, Assump-
tions I and II are not sufficient for uniqueness. Nonetheless, Kemeny et al. (1967) show that
there are at most finitely many economic solutions, meaning that there are only finitely many
$\gamma^*$ that satisfy $V(M(\gamma^*)) = 0$ and $x_0^T B p_0 > 0$ and that for each such $\gamma^*_i$, there is a self-
contained part of the economy (a sub-economy) that in equilibrium can expand independently
with the expansion coefficient $\gamma^*_i$.

The following theorem (see Theorem 9.10. in Gale [22]) asserts that imposing irreducibility is
sufficient for uniqueness of $(\gamma^*, x_0, p_0)$.

**Theorem II:** Adopt the conditions of Theorem 1. If the economy $(A, B)$ is irreducible, then
$\gamma^* = \alpha_0 = \beta_0$.

### 26.6.4 A Special Case

There is a special $(A, B)$ that allows us to simplify the solution method significantly by invok-
ing the powerful Perron-Frobenius theorem for non-negative matrices.

**Definition:** We call an economy simple if it satisfies

- $n = m$
- Each activity produces exactly one good
- Each good is produced by one and only one activity.

These assumptions imply that $B = I_n$, i.e., that $B$ can be written as an identity matrix (pos-
sibly after reshuffling its rows and columns).

The simple model has the following special property (Theorem 9.11. in Gale [22]): if $x_0$ and
$\alpha_0 > 0$ solve the TEP with $(A, I_n)$, then

$$
 x_0^T = \alpha_0 x_0^T A \quad \iff \quad x_0^T A = \left( \frac{1}{\alpha_0} \right) x_0^T 
$$

The latter shows that $1/\alpha_0$ is a positive eigenvalue of $A$ and $x_0$ is the corresponding non-
negative left eigenvector.

The classic result of **Perron and Frobenius** implies that a non-negative matrix has a non-
negative eigenvalue-eigenvector pair.

Moreover, if $A$ is irreducible, then the optimal intensity vector $x_0$ is positive and unique up to
multiplication by a positive scalar.

Suppose that $A$ is reducible with $k$ irreducible subsets $S_1, \ldots, S_k$. Let $A_i$ be the submatrix
corresponding to $S_i$ and let $\alpha_i$ and $\beta_i$ be the associated expansion and interest factors, re-
spectively. Then we have

$$
 \alpha_0 = \max_i \{ \alpha_i \} \quad \text{and} \quad \beta_0 = \min_i \{ \beta_i \}
$$
Part VI

Time Series Models
Chapter 27

Covariance Stationary Processes

27.1 Contents

- Overview 27.2
- Introduction 27.3
- Spectral Analysis 27.4
- Implementation 27.5

In addition to what’s in Anaconda, this lecture will need the following libraries:

```
In [1]: !pip install --upgrade quantecon
```

27.2 Overview

In this lecture we study covariance stationary linear stochastic processes, a class of models routinely used to study economic and financial time series.

This class has the advantage of being

1. simple enough to be described by an elegant and comprehensive theory
2. relatively broad in terms of the kinds of dynamics it can represent

We consider these models in both the time and frequency domain.

27.2.1 ARMA Processes

We will focus much of our attention on linear covariance stationary models with a finite number of parameters.

In particular, we will study stationary ARMA processes, which form a cornerstone of the standard theory of time series analysis.

Every ARMA process can be represented in linear state space form.

However, ARMA processes have some important structure that makes it valuable to study them separately.
27.2.2 Spectral Analysis

Analysis in the frequency domain is also called spectral analysis.

In essence, spectral analysis provides an alternative representation of the autocovariance function of a covariance stationary process.

Having a second representation of this important object

• shines a light on the dynamics of the process in question
• allows for a simpler, more tractable representation in some important cases

The famous Fourier transform and its inverse are used to map between the two representations.

27.2.3 Other Reading

For supplementary reading, see

• [43], chapter 2
• [59], chapter 11
• John Cochrane’s notes on time series analysis, chapter 8
• [60], chapter 6
• [17], all

Let’s start with some imports:

```python
In [2]: import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
import quantecon as qe
```

27.3 Introduction

Consider a sequence of random variables \( \{X_t\} \) indexed by \( t \in \mathbb{Z} \) and taking values in \( \mathbb{R} \).

Thus, \( \{X_t\} \) begins in the infinite past and extends to the infinite future — a convenient and standard assumption.

As in other fields, successful economic modeling typically assumes the existence of features that are constant over time.

If these assumptions are correct, then each new observation \( X_t, X_{t+1}, ... \) can provide additional information about the time-invariant features, allowing us to learn from as data arrive.

For this reason, we will focus in what follows on processes that are stationary — or become so after a transformation (see for example this lecture).

27.3.1 Definitions

A real-valued stochastic process \( \{X_t\} \) is called covariance stationary if

1. Its mean \( \mu := \mathbb{E}X_t \) does not depend on \( t \).
27.3. INTRODUCTION

2. For all $k$ in $\mathbb{Z}$, the $k$-th autocovariance $\gamma(k) := \mathbb{E}(X_t - \mu)(X_{t+k} - \mu)$ is finite and depends only on $k$.

The function $\gamma : \mathbb{Z} \to \mathbb{R}$ is called the *autocovariance function* of the process.

Throughout this lecture, we will work exclusively with zero-mean (i.e., $\mu = 0$) covariance stationary processes.

The zero-mean assumption costs nothing in terms of generality since working with non-zero-mean processes involves no more than adding a constant.

27.3.2 Example 1: White Noise

Perhaps the simplest class of covariance stationary processes is the white noise processes. A process $\{\varepsilon_t\}$ is called a *white noise process* if

1. $\mathbb{E}\varepsilon_t = 0$
2. $\gamma(k) = \sigma^2 1\{k = 0\}$ for some $\sigma > 0$

(Here $1\{k = 0\}$ is defined to be 1 if $k = 0$ and zero otherwise)

White noise processes play the role of building blocks for processes with more complicated dynamics.

27.3.3 Example 2: General Linear Processes

From the simple building block provided by white noise, we can construct a very flexible family of covariance stationary processes — the *general linear processes*

$$X_t = \sum_{j=0}^{\infty} \psi_j \varepsilon_{t-j}, \quad t \in \mathbb{Z} \quad (1)$$

where

- $\{\varepsilon_t\}$ is white noise
- $\{\psi_t\}$ is a square summable sequence in $\mathbb{R}$ (that is, $\sum_{t=0}^{\infty} \psi_t^2 < \infty$)

The sequence $\{\psi_t\}$ is often called a linear filter.

Equation (1) is said to present a moving average process or a moving average representation.

With some manipulations, it is possible to confirm that the autocovariance function for (1) is

$$\gamma(k) = \sigma^2 \sum_{j=0}^{\infty} \psi_j \psi_{j+k} \quad (2)$$

By the Cauchy-Schwartz inequality, one can show that $\gamma(k)$ satisfies equation (2).

Evidently, $\gamma(k)$ does not depend on $t$. 
27.3.4 Wold Representation

Remarkably, the class of general linear processes goes a long way towards describing the entire class of zero-mean covariance stationary processes.

In particular, **Wold's decomposition theorem** states that every zero-mean covariance stationary process \{\(X_t\)\} can be written as

\[
X_t = \sum_{j=0}^{\infty} \psi_j \epsilon_{t-j} + \eta_t
\]

where

- \{\(\epsilon_t\)\} is white noise
- \{\(\psi_t\)\} is square summable
- \(\psi_0\epsilon_t\) is the one-step ahead prediction error in forecasting \(X_t\) as a linear least-squares function of the infinite history \(X_{t-1}, X_{t-2}, \ldots\)
- \(\eta_t\) can be expressed as a linear function of \(X_{t-1}, X_{t-2}, \ldots\) and is perfectly predictable over arbitrarily long horizons

For the method of constructing a Wold representation, intuition, and further discussion, see [59], p. 286.

27.3.5 AR and MA

General linear processes are a very broad class of processes.

It often pays to specialize to those for which there exists a representation having only finitely many parameters.

(Experience and theory combine to indicate that models with a relatively small number of parameters typically perform better than larger models, especially for forecasting)

One very simple example of such a model is the first-order autoregressive or AR(1) process

\[
X_t = \phi X_{t-1} + \epsilon_t \quad \text{where} \quad |\phi| < 1 \quad \text{and} \quad \{\epsilon_t\} \text{ is white noise}
\]

By direct substitution, it is easy to verify that \(X_t = \sum_{j=0}^{\infty} \phi^j \epsilon_{t-j}\).

Hence \{\(X_t\)\} is a general linear process.

Applying (2) to the previous expression for \(X_t\), we get the AR(1) autocovariance function

\[
\gamma(k) = \phi^k \frac{\sigma^2}{1 - \phi^2}, \quad k = 0, 1, \ldots
\]

The next figure plots an example of this function for \(\phi = 0.8\) and \(\phi = -0.8\) with \(\sigma = 1\).

```
In [3]: num_rows, num_cols = 2, 1
    fig, axes = plt.subplots(num_rows, num_cols, figsize=(10, 8))
    plt.subplots_adjust(hspace=0.4)
    for i, phi in enumerate((0.8, -0.8)):
        ax = axes[i]
```
Another very simple process is the MA(1) process (here MA means “moving average”)

\[ X_t = \epsilon_t + \theta \epsilon_{t-1} \]

You will be able to verify that

\[ \gamma(0) = \sigma^2(1 + \theta^2), \quad \gamma(1) = \sigma^2 \theta, \quad \text{and} \quad \gamma(k) = 0 \quad \forall \ k > 1 \]

The AR(1) can be generalized to an AR(p) and likewise for the MA(1).

Putting all of this together, we get the

**27.3.6 ARMA Processes**

A stochastic process \( \{X_t\} \) is called an autoregressive moving average process, or ARMA\((p, q)\), if it can be written as

\[ X_t = \phi X_{t-1} + \theta \epsilon_{t-1} + \epsilon_t \]
where \( \{ \epsilon_t \} \) is white noise.

An alternative notation for ARMA processes uses the lag operator \( L \).

**Def.** Given arbitrary variable \( Y_t \), let \( L^k Y_t := Y_{t-k} \).

It turns out that

- lag operators facilitate succinct representations for linear stochastic processes
- algebraic manipulations that treat the lag operator as an ordinary scalar are legitimate

Using \( L \), we can rewrite (5) as

\[
L^0 X_t - \phi_1 L^1 X_t - \cdots - \phi_p L^p X_t = L^0 \epsilon_t + \theta_1 L^1 \epsilon_t + \cdots + \theta_q L^q \epsilon_t
\]

If we let \( \phi(z) \) and \( \theta(z) \) be the polynomials

\[
\phi(z) := 1 - \phi_1 z - \cdots - \phi_p z^p \quad \text{and} \quad \theta(z) := 1 + \theta_1 z + \cdots + \theta_q z^q
\]

then (6) becomes

\[
\phi(L) X_t = \theta(L) \epsilon_t
\]

In what follows we **always assume** that the roots of the polynomial \( \phi(z) \) lie outside the unit circle in the complex plane.

This condition is sufficient to guarantee that the ARMA\((p, q)\) process is covariance stationary.

In fact, it implies that the process falls within the class of general linear processes described above.

That is, given an ARMA\((p, q)\) process \( \{ X_t \} \) satisfying the unit circle condition, there exists a square summable sequence \( \{ \psi_t \} \) with \( X_t = \sum_{j=0}^{\infty} \psi_j \epsilon_{t-j} \) for all \( t \).

The sequence \( \{ \psi_t \} \) can be obtained by a recursive procedure outlined on page 79 of [17].

The function \( t \mapsto \psi_t \) is often called the **impulse response function**.

**27.4 Spectral Analysis**

Autocovariance functions provide a great deal of information about covariance stationary processes.

In fact, for zero-mean Gaussian processes, the autocovariance function characterizes the entire joint distribution.

Even for non-Gaussian processes, it provides a significant amount of information.

It turns out that there is an alternative representation of the autocovariance function of a covariance stationary process, called the **spectral density**.

At times, the spectral density is easier to derive, easier to manipulate, and provides additional intuition.
27.4. SPECTRAL ANALYSIS

27.4.1 Complex Numbers

Before discussing the spectral density, we invite you to recall the main properties of complex numbers (or skip to the next section).

It can be helpful to remember that, in a formal sense, complex numbers are just points $(x, y) \in \mathbb{R}^2$ endowed with a specific notion of multiplication.

When $(x, y)$ is regarded as a complex number, $x$ is called the real part and $y$ is called the imaginary part.

The *modulus* or *absolute value* of a complex number $z = (x, y)$ is just its Euclidean norm in $\mathbb{R}^2$, but is usually written as $|z|$ instead of $\|z\|$.

The product of two complex numbers $(x, y)$ and $(u, v)$ is defined to be $(xu - vy, xv + yu)$, while addition is standard pointwise vector addition.

When endowed with these notions of multiplication and addition, the set of complex numbers forms a field — addition and multiplication play well together, just as they do in $\mathbb{R}$.

The complex number $(x, y)$ is often written as $x + iy$, where $i$ is called the imaginary unit and is understood to obey $i^2 = -1$.

The $x + iy$ notation provides an easy way to remember the definition of multiplication given above, because, proceeding naively,

$$(x + iy)(u + iv) = xu - yv + i(xv + yu)$$

Converted back to our first notation, this becomes $(xu - vy, xv + yu)$ as promised.

Complex numbers can be represented in the polar form $re^{i\omega}$ where

$$re^{i\omega} := r(\cos(\omega) + i \sin(\omega)) = x + iy$$

where $x = r \cos(\omega), y = r \sin(\omega)$, and $\omega = \arctan(y/x)$ or $\tan(\omega) = y/x$.

27.4.2 Spectral Densities

Let $\{X_t\}$ be a covariance stationary process with autocovariance function $\gamma$ satisfying $\sum_k \gamma(k)^2 < \infty$.

The *spectral density* $f$ of $\{X_t\}$ is defined as the discrete time Fourier transform of its autocovariance function $\gamma$.

$$f(\omega) := \sum_{k \in \mathbb{Z}} \gamma(k)e^{-i\omega k}, \quad \omega \in \mathbb{R}$$

(Some authors normalize the expression on the right by constants such as $1/\pi$ — the convention chosen makes little difference provided you are consistent).

Using the fact that $\gamma$ is even, in the sense that $\gamma(t) = \gamma(-t)$ for all $t$, we can show that

$$f(\omega) = \gamma(0) + 2 \sum_{k \geq 1} \gamma(k) \cos(\omega k)$$

(9)

It is not difficult to confirm that $f$ is
• real-valued
• even \( f(\omega) = f(-\omega) \), and
• 2\( \pi \)-periodic, in the sense that \( f(2\pi + \omega) = f(\omega) \) for all \( \omega \)

It follows that the values of \( f \) on \([0, \pi]\) determine the values of \( f \) on all of \( \mathbb{R} \) — the proof is an exercise.

For this reason, it is standard to plot the spectral density only on the interval \([0, \pi]\).

27.4.3 Example 1: White Noise

Consider a white noise process \( \{\epsilon_t\} \) with standard deviation \( \sigma \).

It is easy to check that in this case \( f(\omega) = \sigma^2 \). So \( f \) is a constant function.

As we will see, this can be interpreted as meaning that “all frequencies are equally present”.

(White light has this property when frequency refers to the visible spectrum, a connection that provides the origins of the term “white noise”)

27.4.4 Example 2: AR and MA and ARMA

It is an exercise to show that the MA(1) process \( X_t = \theta \epsilon_{t-1} + \epsilon_t \) has a spectral density

\[
f(\omega) = \sigma^2 (1 + 2\theta \cos(\omega) + \theta^2)
\]  

(10)

With a bit more effort, it’s possible to show (see, e.g., p. 261 of [59]) that the spectral density of the AR(1) process \( X_t = \phi X_{t-1} + \epsilon_t \) is

\[
f(\omega) = \frac{\sigma^2}{1 - 2\phi \cos(\omega) + \phi^2}
\]  

(11)

More generally, it can be shown that the spectral density of the ARMA process (5) is

\[
f(\omega) = \left| \frac{\theta(e^{i\omega})}{\phi(e^{i\omega})} \right|^2 \sigma^2
\]  

(12)

where

• \( \sigma \) is the standard deviation of the white noise process \( \{\epsilon_t\} \).
• the polynomials \( \phi(\cdot) \) and \( \theta(\cdot) \) are as defined in (7).

The derivation of (12) uses the fact that convolutions become products under Fourier transformations.

The proof is elegant and can be found in many places — see, for example, [59], chapter 11, section 4.

It’s a nice exercise to verify that (10) and (11) are indeed special cases of (12).

27.4.5 Interpreting the Spectral Density

Plotting (11) reveals the shape of the spectral density for the AR(1) model when \( \phi \) takes the values 0.8 and -0.8 respectively.
In [4]: def ar1_sd(ϕ, ω):
   return 1 / (1 - 2 * ϕ * np.cos(ω) + ϕ**2)

ωs = np.linspace(0, np.pi, 180)
num_rows, num_cols = 2, 1
fig, axes = plt.subplots(num_rows, num_cols, figsize=(10, 8))
plt.subplots_adjust(hspace=0.4)

# Autocovariance when phi = 0.8
for i, ϕ in enumerate((0.8, -0.8)):
    ax = axes[i]
    sd = ar1_sd(ϕ, ωs)
    ax.plot(ωs, sd, 'b-', alpha=0.6, lw=2,
            label='spectral density, $\phi = {\phi:.2}$')
    ax.legend(loc='upper center')
    ax.set(xlabel='frequency', xlim=(0, np.pi))
plt.show()

These spectral densities correspond to the autocovariance functions for the AR(1) process shown above.

Informally, we think of the spectral density as being large at those $\omega \in [0, \pi]$ at which the autocovariance function seems approximately to exhibit big damped cycles.

To see the idea, let’s consider why, in the lower panel of the preceding figure, the spectral density for the case $\phi = -0.8$ is large at $\omega = \pi$.

Recall that the spectral density can be expressed as
When we evaluate this at $\omega = \pi$, we get a large number because $\cos(\pi k)$ is large and positive when $(-0.8)^k$ is positive, and large in absolute value and negative when $(-0.8)^k$ is negative. Hence the product is always large and positive, and hence the sum of the products on the right-hand side of (13) is large.

These ideas are illustrated in the next figure, which has $k$ on the horizontal axis.

In [5]: $\phi = -0.8$

```
times = list(range(16))
y1 = [0**k / (1 - 0**2) for k in times]
y2 = [np.cos(np.pi * k) for k in times]
y3 = [a * b for a, b in zip(y1, y2)]

num_rows, num_cols = 3, 1
fig, axes = plt.subplots(num_rows, num_cols, figsize=(10, 8))
plt.subplots_adjust(hspace=0.25)

# Autocovariance when $\phi = -0.8$
ax = axes[0]
ax.plot(times, y1, 'bo-', alpha=0.6, label='$\gamma(k)$')
ax.legend(loc='upper right')
ax.set(xlim=(0, 15), yticks=(-2, 0, 2))
ax.hlines(0, 0, 15, linestyle='--', alpha=0.5)

# Cycles at frequency $\pi$
ax = axes[1]
ax.plot(times, y2, 'bo-', alpha=0.6, label='$\cos(\pi k)$')
ax.legend(loc='upper right')
ax.set(xlim=(0, 15), yticks=(-1, 0, 1))
ax.hlines(0, 0, 15, linestyle='--', alpha=0.5)

# Product
ax = axes[2]
ax.stem(times, y3, label='$\gamma(k) \cos(\pi k)$')
ax.legend(loc='upper right')
ax.set(xlim=(0, 15), ylim=(-3, 3), yticks=(-1, 0, 1, 2, 3))
ax.hlines(0, 0, 15, linestyle='--', alpha=0.5)
ax.set_xlabel('k')
plt.show()
```

UserWarning: In Matplotlib 3.3 individual lines on a stem plot will be added as a LineCollection instead of individual lines. This significantly improves the performance of a stem plot. To remove this warning and switch to the new behaviour, set the "use_line_collection" keyword argument to True.
On the other hand, if we evaluate \( f(\omega) \) at \( \omega = \pi/3 \), then the cycles are not matched, the sequence \( \gamma(k) \cos(\omega k) \) contains both positive and negative terms, and hence the sum of these terms is much smaller.

In [6]: \( \phi = -0.8 \)

```python
import matplotlib.pyplot as plt
import numpy as np

times = list(range(16))
y1 = [\phi**k / (1 - \phi)**2 for k in times]
y2 = [np.cos(np.pi * k/3) for k in times]
y3 = [a * b for a, b in zip(y1, y2)]

num_rows, num_cols = 3, 1
fig, axes = plt.subplots(num_rows, num_cols, figsize=(10, 8))
plt.subplots_adjust(hspace=0.25)

# Autocovariance when phi = -0.8
ax = axes[0]
ax.plot(times, y1, 'bo-', alpha=0.6, label='\( \gamma(k) \)')
ax.legend(loc='upper right')
ax.set(xlim=(0, 15), yticks=(-2, 0, 2))
ax.hlines(0, 0, 15, linestyle='--', alpha=0.5)

# Cycles at frequency \( \pi \)
ax = axes[1]
ax.plot(times, y2, 'bo-', alpha=0.6, label='\( \cos(\pi k/3) \)')
ax.legend(loc='upper right')
ax.set(xlim=(0, 15), yticks=(-1, 0, 1))
ax.hlines(0, 0, 15, linestyle='--', alpha=0.5)
```
# Product

```
ax = axes[2]
ax.stem(times, y3, label='$\gamma(k) \cos(\pi k/3)$')
ax.legend(loc='upper right')
ax.set_xlim(0, 15), ylim=(-3, 3), yticks=(-1, 0, 1, 2, 3))
ax.hlines(0, 0, 15, linestyle='--', alpha=0.5)
ax.set_xlabel('$k$')
plt.show()
```

In summary, the spectral density is large at frequencies $\omega$ where the autocovariance function exhibits damped cycles.

## 27.4.6 Inverting the Transformation

We have just seen that the spectral density is useful in the sense that it provides a frequency-based perspective on the autocovariance structure of a covariance stationary process.
Another reason that the spectral density is useful is that it can be “inverted” to recover the autocovariance function via the inverse Fourier transform.

In particular, for all \( k \in \mathbb{Z} \), we have

\[
\gamma(k) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(\omega)e^{i\omega k} d\omega
\]  

(14)

This is convenient in situations where the spectral density is easier to calculate and manipulate than the autocovariance function.

(For example, the expression (12) for the ARMA spectral density is much easier to work with than the expression for the ARMA autocovariance)

### 27.4.7 Mathematical Theory

This section is loosely based on [59], p. 249-253, and included for those who

- would like a bit more insight into spectral densities
- and have at least some background in Hilbert space theory

Others should feel free to skip to the next section — none of this material is necessary to progress to computation.

Recall that every separable Hilbert space \( H \) has a countable orthonormal basis \( \{h_k\} \).

The nice thing about such a basis is that every \( f \in H \) satisfies

\[
f = \sum_k \alpha_k h_k \quad \text{where} \quad \alpha_k := \langle f, h_k \rangle
\]  

(15)

where \( \langle \cdot, \cdot \rangle \) denotes the inner product in \( H \).

Thus, \( f \) can be represented to any degree of precision by linearly combining basis vectors.

The scalar sequence \( \alpha = \{\alpha_k\} \) is called the Fourier coefficients of \( f \), and satisfies \( \sum_k |\alpha_k|^2 < \infty \).

In other words, \( \alpha \) is in \( \ell_2 \), the set of square summable sequences.

Consider an operator \( T \) that maps \( \alpha \in \ell_2 \) into its expansion \( \sum_k \alpha_k h_k \in H \).

The Fourier coefficients of \( T\alpha \) are just \( \alpha = \{\alpha_k\} \), as you can verify by confirming that \( \langle T\alpha, h_k \rangle = \alpha_k \).

Using elementary results from Hilbert space theory, it can be shown that

- \( T \) is one-to-one — if \( \alpha \) and \( \beta \) are distinct in \( \ell_2 \), then so are their expansions in \( H \).
- \( T \) is onto — if \( f \in H \) then its preimage in \( \ell_2 \) is the sequence \( \alpha \) given by \( \alpha_k = \langle f, h_k \rangle \).
- \( T \) is a linear isometry — in particular, \( \langle \alpha, \beta \rangle = \langle T\alpha, T\beta \rangle \).

Summarizing these results, we say that any separable Hilbert space is isometrically isomorphic to \( \ell_2 \).

In essence, this says that each separable Hilbert space we consider is just a different way of looking at the fundamental space \( \ell_2 \).

With this in mind, let’s specialize to a setting where
• $\gamma \in \ell_2$ is the autocovariance function of a covariance stationary process, and $f$ is the spectral density.

• $H = L_2$, where $L_2$ is the set of square summable functions on the interval $[-\pi, \pi]$, with inner product $\langle g, h \rangle = \int_{-\pi}^{\pi} g(\omega)h(\omega) d\omega$.

• $\{h_k\}$ is the orthonormal basis for $L_2$ given by the set of trigonometric functions.

\[ h_k(\omega) = \frac{e^{i\omega k}}{\sqrt{2\pi}}, \quad k \in \mathbb{Z}, \quad \omega \in [-\pi, \pi] \]

Using the definition of $T$ from above and the fact that $f$ is even, we now have

\[ T\gamma = \sum_{k \in \mathbb{Z}} \gamma(k) \frac{e^{i\omega k}}{\sqrt{2\pi}} = \frac{1}{\sqrt{2\pi}} f(\omega) \] (16)

In other words, apart from a scalar multiple, the spectral density is just a transformation of $\gamma \in \ell_2$ under a certain linear isometry — a different way to view $\gamma$.

In particular, it is an expansion of the autocovariance function with respect to the trigonometric basis functions in $L_2$.

As discussed above, the Fourier coefficients of $T\gamma$ are given by the sequence $\gamma$, and, in particular, $\gamma(k) = \langle T\gamma, h_k \rangle$.

Transforming this inner product into its integral expression and using (16) gives (14), justifying our earlier expression for the inverse transform.

### 27.5 Implementation

Most code for working with covariance stationary models deals with ARMA models.

Python code for studying ARMA models can be found in the `tsa` submodule of `statsmodels`.

Since this code doesn’t quite cover our needs — particularly vis-a-vis spectral analysis — we’ve put together the module `arma.py`, which is part of `QuantEcon.py` package.

The module provides functions for mapping ARMA$(p,q)$ models into their

1. impulse response function
2. simulated time series
3. autocovariance function
4. spectral density

#### 27.5.1 Application

Let’s use this code to replicate the plots on pages 68–69 of [43].

Here are some functions to generate the plots

```python
In [7]: def plot_impulse_response(arma, ax=None):
    if ax is None:
```
27.5. IMPLEMENTATION

```python
ax = plt.gca()
yi = arma.impulse_response()
ax.stem(list(range(len(yi))), yi)
ax.set(xlim=(-0.5), ylim=(min(yi)-0.1, max(yi)+0.1),
       title='Impulse response', xlabel='time', ylabel='response')
return ax

def plot_spectral_density(arma, ax=None):
    if ax is None:
        ax = plt.gca()
w, spect = arma.spectral_density(two_pi=False)
ax.semilogy(w, spect)
ax.set(xlim=(0, np.pi), ylim=(0, np.max(spect)),
       title='Spectral density', xlabel='frequency', ylabel='spectrum')
return ax

def plot_autocovariance(arma, ax=None):
    if ax is None:
        ax = plt.gca()
acov = arma.autocovariance()
ax.stem(list(range(len(acov))), acov)
ax.set(xlim=(-0.5, len(acov) - 0.5), title='Autocovariance',
       xlabel='time', ylabel='autocovariance')
return ax

def plot_simulation(arma, ax=None):
    if ax is None:
        ax = plt.gca()
x_out = arma.simulation()
ax.plot(x_out)
ax.set(title='Sample path', xlabel='time', ylabel='state space')
return ax

def quad_plot(arma):
    """Plots the impulse response, spectral_density, autocovariance,
    and one realization of the process.
    """
    num_rows, num_cols = 2, 2
    fig, axes = plt.subplots(num_rows, num_cols, figsize=(12, 8))
    plot_functions = [plot_impulse_response,
                      plot_spectral_density,
                      plot_autocovariance,
                      plot_simulation]
    for plot_func, ax in zip(plot_functions, axes.flatten()):
        plot_func(arma, ax)
plt.tight_layout()
plt.show()
```

Now let’s call these functions to generate plots.

As a warmup, let’s make sure things look right when we for the pure white noise model $X_t = \epsilon_t$.

In [8]: $\phi = 0.0$
   $\theta = 0.0$
If we look carefully, things look good: the spectrum is the flat line at $10^0$ at the very top of the spectrum graphs, which is at it should be.

Also

- the variance equals $1 = \int_{-\pi}^{\pi} 1 d\omega$ as it should.
- the covariogram and impulse response look as they should.
it is actually challenging to visualize a time series realization of white noise – a sequence of surprises – but this too looks pretty good.

To get some more examples, as our laboratory we’ll replicate quartets of graphs that [43] use to teach “how to read spectral densities”.

Ljungqvist and Sargent’s first model is $X_t = 1.3X_{t-1} - .7X_{t-2} + \epsilon_t$

In [9]: $\phi = 1.3, \theta = 0.0$

arma = qe.ARMA($\phi$, $\theta$)
quad_plot(arma)
Ljungqvist and Sargent’s second model is \( X_t = .9X_{t-1} + \epsilon_t \)

\[
\phi = 0.9 \\
\theta = -0.0 \\
\text{arma} = \\text{ge.ARM}(\phi, \theta) \\
\text{quad_plot(arma)}
\]

Ljungqvist and Sargent’s third model is \( X_t = .8X_{t-4} + \epsilon_t \)
In [11]: $\phi = 0., 0., 0., .8$
   \[ \theta = -0.7 \]
   
   arma = qe.ARMAR$(\phi, \theta)$
   
   quad_plot(arma)

   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:5:
   UserWarning: In Matplotlib 3.3 individual lines on a stem plot will be added as a LineCollection instead of individual lines. This significantly improves the performance of a stem plot. To remove this warning and switch to the new behaviour, set the "use_line_collection" keyword argument to True.

   /home/ubuntu/anaconda3/lib/python3.7/site-packages/numpy/core/_asarray.py:85:
   ComplexWarning: Casting complex values to real discards the imaginary part
   return array(a, dtype, copy=False, order=order)
   
   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:16:
   UserWarning: Attempted to set non-positive bottom ylim on a log-scaled axis. Invalid limit will be ignored.
   app.launch_new_instance()
   
   /home/ubuntu/anaconda3/lib/python3.7/site-packages/matplotlib/transforms.py:923:
   ComplexWarning: Casting complex values to real discards the imaginary part
   self._points[:, 1] = interval
   
   /home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:23:
   UserWarning: In Matplotlib 3.3 individual lines on a stem plot will be added as a LineCollection instead of individual lines. This significantly improves the performance of a stem plot. To remove this warning and switch to the new behaviour, set the "use_line_collection" keyword argument to True.

   Ljungqvist and Sargent’s fourth model is $X_t = .98X_{t-1} + \epsilon_t - .7\epsilon_{t-1}$

In [12]: $\phi = .98$
   \[ \theta = -0.7 \]
   
   arma = qe.ARMAR$(\phi, \theta)$
   
   quad_plot(arma)
27.5.2 Explanation

The call

```
arma = ARMA(\phi, \theta, \sigma)
```

creates an instance `arma` that represents the ARMA\((p, q)\) model.
\[ X_t = \phi_1 X_{t-1} + \ldots + \phi_p X_{t-p} + \epsilon_t + \theta_1 \epsilon_{t-1} + \ldots + \theta_q \epsilon_{t-q} \]

If \( \phi \) and \( \theta \) are arrays or sequences, then the interpretation will be

- \( \phi \) holds the vector of parameters \((\phi_1, \phi_2, \ldots, \phi_p)\).
- \( \theta \) holds the vector of parameters \((\theta_1, \theta_2, \ldots, \theta_q)\).

The parameter \( \sigma \) is always a scalar, the standard deviation of the white noise.

We also permit \( \phi \) and \( \theta \) to be scalars, in which case the model will be interpreted as

\[ X_t = \phi X_{t-1} + \epsilon_t + \theta \epsilon_{t-1} \]

The two numerical packages most useful for working with ARMA models are `scipy.signal` and `numpy.fft`.

The package `scipy.signal` expects the parameters to be passed into its functions in a manner consistent with the alternative ARMA notation (8).

For example, the impulse response sequence \( \{\psi_t\} \) discussed above can be obtained using `scipy.signal.dimpulse`, and the function call should be of the form

\[ \text{times, } \psi = \text{dimpulse}((\text{ma_poly, ar_poly, 1}), \text{n=impulse\_length}) \]

where `ma_poly` and `ar_poly` correspond to the polynomials in (7) — that is,

- `ma_poly` is the vector \((1, \theta_1, \theta_2, \ldots, \theta_q)\)
- `ar_poly` is the vector \((1, -\phi_1, -\phi_2, \ldots, -\phi_p)\)

To this end, we also maintain the arrays `ma_poly` and `ar_poly` as instance data, with their values computed automatically from the values of `phi` and `theta` supplied by the user.

If the user decides to change the value of either `theta` or `phi` ex-post by assignments such as `arma.phi = (0.5, 0.2)` or `arma.theta = (0, -0.1)`, then `ma_poly` and `ar_poly` should update automatically to reflect these new parameters.

This is achieved in our implementation by using descriptors.

### 27.5.3 Computing the Autocovariance Function

As discussed above, for ARMA processes the spectral density has a simple representation that is relatively easy to calculate.

Given this fact, the easiest way to obtain the autocovariance function is to recover it from the spectral density via the inverse Fourier transform.

Here we use NumPy’s Fourier transform package `np.fft`, which wraps a standard Fortran-based package called FFTPACK.

A look at the `np.fft` documentation shows that the inverse transform `np.fft.ifft` takes a given sequence \( A_0, A_1, \ldots, A_{n-1} \) and returns the sequence \( a_0, a_1, \ldots, a_{n-1} \) defined by

\[ a_k = \frac{1}{n} \sum_{t=0}^{n-1} A_t e^{ik2\pi t/n} \]

Thus, if we set \( A_t = f(\omega_t) \), where \( f \) is the spectral density and \( \omega_t := 2\pi t/n \), then
\[ a_k = \frac{1}{n} \sum_{t=0}^{n-1} f(\omega_t) e^{i\omega_t k} = \frac{1}{2\pi} \sum_{t=0}^{n-1} f(\omega_t) e^{i\omega_t k}, \quad \omega_t := \frac{2\pi t}{n} \]

For \( n \) sufficiently large, we then have

\[ a_k \approx \frac{1}{2\pi} \int_0^{2\pi} f(\omega) e^{i\omega k} d\omega = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(\omega) e^{i\omega k} d\omega \]

(You can check the last equality)

In view of (14), we have now shown that, for \( n \) sufficiently large, \( a_k \approx \gamma(k) \) — which is exactly what we want to compute.
Chapter 28

Estimation of Spectra

28.1 Contents

- Overview 28.2
- Periodograms 28.3
- Smoothing 28.4
- Exercises 28.5
- Solutions 28.6

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

28.2 Overview

In a previous lecture, we covered some fundamental properties of covariance stationary linear stochastic processes.

One objective for that lecture was to introduce spectral densities — a standard and very useful technique for analyzing such processes.

In this lecture, we turn to the problem of estimating spectral densities and other related quantities from data.

Estimates of the spectral density are computed using what is known as a periodogram — which in turn is computed via the famous fast Fourier transform.

Once the basic technique has been explained, we will apply it to the analysis of several key macroeconomic time series.

For supplementary reading, see [59] or [17].

Let’s start with some standard imports:

In [2]: import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
from quantecon import ARMA, periodogram, ar_periodogram

465
28.3 Periodograms

Recall that the spectral density $f$ of a covariance stationary process with autocorrelation function $\gamma$ can be written

$$f(\omega) = \gamma(0) + 2 \sum_{k \geq 1} \gamma(k) \cos(\omega k), \quad \omega \in \mathbb{R}$$

Now consider the problem of estimating the spectral density of a given time series, when $\gamma$ is unknown.

In particular, let $X_0, \ldots, X_{n-1}$ be $n$ consecutive observations of a single time series that is assumed to be covariance stationary.

The most common estimator of the spectral density of this process is the periodogram of $X_0, \ldots, X_{n-1}$, which is defined as

$$I(\omega) := \frac{1}{n} \left| \sum_{t=0}^{n-1} X_t e^{it\omega} \right|^2, \quad \omega \in \mathbb{R} \quad (1)$$

(Recall that $|z|$ denotes the modulus of complex number $z$)

Alternatively, $I(\omega)$ can be expressed as

$$I(\omega) = \frac{1}{n} \left\{ \left[ \sum_{t=0}^{n-1} X_t \cos(\omega t) \right]^2 + \left[ \sum_{t=0}^{n-1} X_t \sin(\omega t) \right]^2 \right\}$$

It is straightforward to show that the function $I$ is even and $2\pi$-periodic (i.e., $I(\omega) = I(-\omega)$ and $I(\omega + 2\pi) = I(\omega)$ for all $\omega \in \mathbb{R}$).

From these two results, you will be able to verify that the values of $I$ on $[0, \pi]$ determine the values of $I$ on all of $\mathbb{R}$.

The next section helps to explain the connection between the periodogram and the spectral density.

28.3.1 Interpretation

To interpret the periodogram, it is convenient to focus on its values at the Fourier frequencies

$$\omega_j := \frac{2\pi j}{n}, \quad j = 0, \ldots, n - 1$$

In what sense is $I(\omega_j)$ an estimate of $f(\omega_j)$?

The answer is straightforward, although it does involve some algebra.

With a bit of effort, one can show that for any integer $j > 0$,

$$\sum_{t=0}^{n-1} e^{it\omega_j} = \sum_{t=0}^{n-1} \exp \left\{ it \frac{2\pi j}{n} \right\} = 0$$
Letting $\bar{X}$ denote the sample mean $n^{-1}\sum_{t=0}^{n-1} X_t$, we then have

$$nI(\omega_j) = \left| \sum_{t=0}^{n-1} (X_t - \bar{X}) e^{it\omega_j} \right|^2 = \sum_{t=0}^{n-1} (X_t - \bar{X}) e^{it\omega_j} \sum_{r=0}^{n-1} (X_r - \bar{X}) e^{-ir\omega_j}$$

By carefully working through the sums, one can transform this to

$$nI(\omega_j) = \sum_{t=0}^{n-1} (X_t - \bar{X})^2 + 2 \sum_{k=1}^{n-1} \sum_{t=k}^{n-1} (X_t - \bar{X})(X_{t-k} - \bar{X}) \cos(\omega_j k)$$

Now let

$$\hat{\gamma}(k) := \frac{1}{n} \sum_{t=k}^{n-1} (X_t - \bar{X})(X_{t-k} - \bar{X}), \quad k = 0, 1, \ldots, n - 1$$

This is the sample autocovariance function, the natural “plug-in estimator” of the autocovariance function $\gamma$.

(“Plug-in estimator” is an informal term for an estimator found by replacing expectations with sample means)

With this notation, we can now write

$$I(\omega_j) = \hat{\gamma}(0) + 2 \sum_{k=1}^{n-1} \hat{\gamma}(k) \cos(\omega_j k)$$

Recalling our expression for $f$ given above, we see that $I(\omega_j)$ is just a sample analog of $f(\omega_j)$.

### 28.3.2 Calculation

Let’s now consider how to compute the periodogram as defined in (1).

There are already functions available that will do this for us — an example is `statsmodels.tsa.stattools.periodogram` in the `statsmodels` package.

However, it is very simple to replicate their results, and this will give us a platform to make useful extensions.

The most common way to calculate the periodogram is via the discrete Fourier transform, which in turn is implemented through the fast Fourier transform algorithm.

In general, given a sequence $a_0, \ldots, a_{n-1}$, the discrete Fourier transform computes the sequence

$$A_j := \sum_{t=0}^{n-1} a_t \exp \left\{ i2\pi \frac{tj}{n} \right\}, \quad j = 0, \ldots, n - 1$$

With `numpy.fft.fft` imported as `fft` and $a_0, \ldots, a_{n-1}$ stored in NumPy array `a`, the function call `fft(a)` returns the values $A_0, \ldots, A_{n-1}$ as a NumPy array.

It follows that when the data $X_0, \ldots, X_{n-1}$ are stored in array $X$, the values $I(\omega_j)$ at the Fourier frequencies, which are given by
\[
\frac{1}{n} \left| \sum_{t=0}^{n-1} X_t \exp\left\{i2\pi \frac{tj}{n}\right\} \right|^2, \quad j = 0, \ldots, n - 1
\]

can be computed by \texttt{np.abs(fft(X))**2 / len(X)}.

Note: The NumPy function \texttt{abs} acts elementwise, and correctly handles complex numbers (by computing their modulus, which is exactly what we need).

A function called \texttt{periodogram} that puts all this together can be found \texttt{here}.

Let’s generate some data for this function using the \texttt{ARMA} class from \texttt{QuantEcon.py} (see the lecture on linear processes for more details).

Here’s a code snippet that, once the preceding code has been run, generates data from the process

\[
X_t = 0.5X_{t-1} + \epsilon_t - 0.8\epsilon_{t-2}
\]

where \(\{\epsilon_t\}\) is white noise with unit variance, and compares the periodogram to the actual spectral density

```python
In [3]: n = 40 # Data size
    : \phi, \theta = 0.5, (0, -0.8) # AR and MA parameters
    : lp = ARMA(\phi, \theta)
    : X = lp.simulation(ts_length=n)

    fig, ax = plt.subplots()
    x, y = periodogram(X)
    ax.plot(x, y, 'b-', lw=2, alpha=0.5, label='periodogram')
    x_sd, y_sd = lp.spectral_density(two_pi=False, res=120)
    ax.plot(x_sd, y_sd, 'r-', lw=2, alpha=0.8, label='spectral density')
    ax.legend()
    plt.show()
```

/home/ubuntu/anaconda3/lib/python3.7/site-packages/numpy/core/_asarray.py:85: ComplexWarning: Casting complex values to real discards the imaginary part
return array(a, dtype, copy=False, order=order)
This estimate looks rather disappointing, but the data size is only 40, so perhaps it’s not surprising that the estimate is poor.

However, if we try again with $n = 1200$ the outcome is not much better.

The periodogram is far too irregular relative to the underlying spectral density.

This brings us to our next topic.
28.4 Smoothing

There are two related issues here.

One is that, given the way the fast Fourier transform is implemented, the number of points \( \omega \) at which \( I(\omega) \) is estimated increases in line with the amount of data.

In other words, although we have more data, we are also using it to estimate more values.

A second issue is that densities of all types are fundamentally hard to estimate without parametric assumptions.

Typically, nonparametric estimation of densities requires some degree of smoothing.

The standard way that smoothing is applied to periodograms is by taking local averages.

In other words, the value \( I(\omega_j) \) is replaced with a weighted average of the adjacent values

\[
I(\omega_{j-p}), I(\omega_{j-p+1}), \ldots, I(\omega_j), \ldots, I(\omega_{j+p})
\]

This weighted average can be written as

\[
I_s(\omega_j) := \sum_{\ell=-p}^{p} w(\ell) I(\omega_{j+\ell})
\]  

(3)

where the weights \( w(-p), \ldots, w(p) \) are a sequence of \( 2p + 1 \) nonnegative values summing to one.

In general, larger values of \( p \) indicate more smoothing — more on this below.

The next figure shows the kind of sequence typically used.

Note the smaller weights towards the edges and larger weights in the center, so that more distant values from \( I(\omega_j) \) have less weight than closer ones in the sum (3).

```
In [4]: def hanning_window(M):
    w = [0.5 - 0.5 * np.cos(2 * np.pi * n/(M-1)) for n in range(M)]
    return w

window = hanning_window(25) / np.abs(sum(hanning_window(25)))
x = np.linspace(-12, 12, 25)
fig, ax = plt.subplots(figsize=(9, 7))
ax.plot(x, window)
ax.set_title("Hanning window")
ax.set_ylabel("Weights")
ax.set_xlabel("Position in sequence of weights")
plt.show()
```
28.4. SMOOTHING

28.4.1 Estimation with Smoothing

Our next step is to provide code that will not only estimate the periodogram but also provide smoothing as required.

Such functions have been written in estspec.py and are available once you’ve installed QuantEcon.py.

The GitHub listing displays three functions, smooth(), periodogram(), ar_periodogram(). We will discuss the first two here and the third one below.

The periodogram() function returns a periodogram, optionally smoothed via the smooth() function.

Regarding the smooth() function, since smoothing adds a nontrivial amount of computation, we have applied a fairly terse array-centric method based around np.convolve.

Readers are left either to explore or simply to use this code according to their interests.

The next three figures each show smoothed and unsmoothed periodograms, as well as the population or “true” spectral density.

(The model is the same as before — see equation (2) — and there are 400 observations)
From the top figure to bottom, the window length is varied from small to large.

![Graphs showing window lengths](image)

In looking at the figure, we can see that for this model and data size, the window length chosen in the middle figure provides the best fit.

Relative to this value, the first window length provides insufficient smoothing, while the third gives too much smoothing.

Of course in real estimation problems, the true spectral density is not visible and the choice of appropriate smoothing will have to be made based on judgement/priors or some other theory.

### 28.4.2 Pre-Filtering and Smoothing

In the code listing, we showed three functions from the file `estspec.py`.

The third function in the file (`ar_periodogram()`) adds a pre-processing step to periodogram smoothing.
First, we describe the basic idea, and after that we give the code.

The essential idea is to

1. Transform the data in order to make estimation of the spectral density more efficient.
2. Compute the periodogram associated with the transformed data.
3. Reverse the effect of the transformation on the periodogram, so that it now estimates the spectral density of the original process.

Step 1 is called *pre-filtering* or *pre-whitening*, while step 3 is called *recoloring*.

The first step is called pre-whitening because the transformation is usually designed to turn the data into something closer to white noise.

Why would this be desirable in terms of spectral density estimation?

The reason is that we are smoothing our estimated periodogram based on estimated values at nearby points — recall (3).

The underlying assumption that makes this a good idea is that the true spectral density is relatively regular — the value of $I(\omega)$ is close to that of $I(\omega')$ when $\omega$ is close to $\omega'$.

This will not be true in all cases, but it is certainly true for white noise.

For white noise, $I$ is as regular as possible — it is a constant function.

In this case, values of $I(\omega')$ at points $\omega'$ near to $\omega$ provided the maximum possible amount of information about the value $I(\omega)$.

Another way to put this is that if $I$ is relatively constant, then we can use a large amount of smoothing without introducing too much bias.

### 28.4.3 The AR(1) Setting

Let’s examine this idea more carefully in a particular setting — where the data are assumed to be generated by an AR(1) process.

(More general ARMA settings can be handled using similar techniques to those described below)

Suppose in particular that $\{X_t\}$ is covariance stationary and AR(1), with

$$X_{t+1} = \mu + \phi X_t + \epsilon_{t+1}$$  \hspace{1cm} (4)

where $\mu$ and $\phi \in (-1, 1)$ are unknown parameters and $\{\epsilon_t\}$ is white noise.

It follows that if we regress $X_{t+1}$ on $X_t$ and an intercept, the residuals will approximate white noise.

Let

- $g$ be the spectral density of $\{\epsilon_t\}$ — a constant function, as discussed above
- $I_0$ be the periodogram estimated from the residuals — an estimate of $g$
- $f$ be the spectral density of $\{X_t\}$ — the object we are trying to estimate

In view of an earlier result we obtained while discussing ARMA processes, $f$ and $g$ are related by
\[ f(\omega) = \left| \frac{1}{1 - e^{i\omega}} \right|^2 g(\omega) \] (5)

This suggests that the recoloring step, which constructs an estimate \( I \) of \( f \) from \( I_0 \), should set

\[ I(\omega) = \left| \frac{1}{1 - \hat{\phi}e^{i\omega}} \right|^2 I_0(\omega) \]

where \( \hat{\phi} \) is the OLS estimate of \( \phi \).

The code for \texttt{ar_periodogram()} — the third function in \texttt{estspec.py} — does exactly this. (See the code here).

The next figure shows realizations of the two kinds of smoothed periodograms:

1. “standard smoothed periodogram”, the ordinary smoothed periodogram, and

2. “AR smoothed periodogram”, the pre-whitened and recolored one generated by \texttt{ar_periodogram()}

The periodograms are calculated from time series drawn from (4) with \( \mu = 0 \) and \( \phi = -0.9 \). Each time series is of length 150.

The difference between the three subfigures is just randomness — each one uses a different
draw of the time series.

In all cases, periodograms are fit with the “hamming” window and window length of 65. Overall, the fit of the AR smoothed periodogram is much better, in the sense of being closer to the true spectral density.

### 28.5 Exercises

#### 28.5.1 Exercise 1

Replicate this figure (modulo randomness).

The model is as in equation (2) and there are 400 observations.

For the smoothed periodogram, the window type is “hamming”.

28.5.2 Exercise 2

Replicate this figure (modulo randomness).

The model is as in equation (4), with $\mu = 0$, $\phi = -0.9$ and 150 observations in each time series.

All periodograms are fit with the “hamming” window and window length of 65.

28.6 Solutions

28.6.1 Exercise 1

In [5]: ## Data
n = 400
$\phi$ = 0.5
$\theta$ = 0, -0.8
lp = ARMA($\phi$, $\theta$)
X = lp.simulation(ts_length=n)

fig, ax = plt.subplots(3, 1, figsize=(10, 12))

for i, wl in enumerate((15, 55, 175)): # Window lengths
    x, y = periodogram(X)
    ax[i].plot(x, y, 'b-', lw=2, alpha=0.5, label='periodogram')

    x_sd, y_sd = lp.spectral_density(two_pi=False, res=120)
    ax[i].plot(x_sd, y_sd, 'r-', lw=2, alpha=0.8, label='spectral density')

    x, y_smoothed = periodogram(X, window='hamming', window_len=wl)
    ax[i].plot(x, y_smoothed, 'k-', lw=2, label='smoothed periodogram')

    ax[i].legend()
    ax[i].set_title(f'window length = {wl}')</n
plt.show()
28.6.2 Exercise 2

In [6]: \( lp = ARMA(-0.9) \)
   \( \text{wl} = 65 \)

\[
\text{fig, ax = plt.subplots(3, 1, figsize=(10,12))}
\]

\[
\text{for } i \text{ in range(3):}
\quad X = lp.simulation(ts_length=150)
\quad ax[i].set_xlim(0, np.pi)
\quad x_sd, y_sd = lp.spectral_density(two_pi=False, res=180)
\]
```python
ax[i].semilogy(x_sd, y_sd, 'r-', lw=2, alpha=0.75,
        label='spectral density')

x, y_smoothed = periodogram(X, window='hamming', window_len=wl)
ax[i].semilogy(x, y_smoothed, 'k-', lw=2, alpha=0.75,
        label='standard smoothed periodogram')

x, y_ar = ar_periodogram(X, window='hamming', window_len=wl)
ax[i].semilogy(x, y_ar, 'b-', lw=2, alpha=0.75,
        label='AR smoothed periodogram')

ax[i].legend(loc='upper left')
plt.show()
```
CHAPTER 28. ESTIMATION OF SPECTRA
Chapter 29

Additive and Multiplicative Functionals

29.1 Contents

- Overview 29.2
- A Particular Additive Functional 29.3
- Dynamics 29.4
- Code 29.5
- More About the Multiplicative Martingale 29.6

In addition to what’s in Anaconda, this lecture will need the following libraries:

```
In [1]: !pip install --upgrade quantecon
```

29.2 Overview

Many economic time series display persistent growth that prevents them from being asymptotically stationary and ergodic.

For example, outputs, prices, and dividends typically display irregular but persistent growth. Asymptotic stationarity and ergodicity are key assumptions needed to make it possible to learn by applying statistical methods.

Are there ways to model time series that have persistent growth that still enable statistical learning based on a law of large numbers for an asymptotically stationary and ergodic process?

The answer provided by Hansen and Scheinkman [32] is yes.

They described two classes of time series models that accommodate growth.

They are

1. additive functionals that display random “arithmetic growth”
2. multiplicative functionals that display random “geometric growth”

These two classes of processes are closely connected.
If a process \( \{y_t\} \) is an additive functional and \( \phi_t = \exp(y_t) \), then \( \{\phi_t\} \) is a multiplicative functional.

Hansen and Sargent [30] (chs. 5 and 8) describe discrete time versions of additive and multiplicative functionals.

In this lecture, we describe both additive functionals and multiplicative functionals.

We also describe and compute decompositions of additive and multiplicative processes into four components:

1. a constant
2. a trend component
3. an asymptotically stationary component
4. a martingale

We describe how to construct, simulate, and interpret these components.

More details about these concepts and algorithms can be found in Hansen and Sargent [30].

Let’s start with some imports:

```python
In [2]:
import numpy as np
import scipy as sp
import scipy.linalg as la
import quantecon as qe
import matplotlib.pyplot as plt
%matplotlib inline
from scipy.stats import norm, lognorm
```

### 29.3 A Particular Additive Functional

Hansen and Sargent [30] describe a general class of additive functionals.

This lecture focuses on a subclass of these: a scalar process \( \{y_t\}_{t=0}^{\infty} \) whose increments are driven by a Gaussian vector autoregression.

Our special additive functional displays interesting time series behavior while also being easy to construct, simulate, and analyze by using linear state-space tools.

We construct our additive functional from two pieces, the first of which is a first-order vector autoregression (VAR)

\[
x_{t+1} = Ax_t + Bz_{t+1}
\]

(1)

Here
- \( x_t \) is an \( n \times 1 \) vector,
- \( A \) is an \( n \times n \) stable matrix (all eigenvalues lie within the open unit circle),
- \( z_{t+1} \sim N(0, I) \) is an \( m \times 1 \) IID shock,
- \( B \) is an \( n \times m \) matrix, and
- \( x_0 \sim N(\mu_0, \Sigma_0) \) is a random initial condition for \( x \).
The second piece is an equation that expresses increments of \(\{y_t\}_{t=0}^\infty\) as linear functions of:

- a scalar constant \(\nu\),
- the vector \(x_t\), and
- the same Gaussian vector \(z_{t+1}\) that appears in the VAR (1).

In particular,

\[
y_{t+1} - y_t = \nu + Dx_t + Fz_{t+1}\tag{2}
\]

Here \(y_0 \sim N(\mu_y, \Sigma_y)\) is a random initial condition for \(y\).

The nonstationary random process \(\{y_t\}_{t=0}^\infty\) displays systematic but random arithmetic growth.

### 29.3.1 Linear State-Space Representation

A convenient way to represent our additive functional is to use a linear state space system.

To do this, we set up state and observation vectors:

\[
\hat{x}_t = \begin{bmatrix} 1 \\ x_t \\ y_t \end{bmatrix} \text{ and } \hat{y}_t = \begin{bmatrix} x_t \\ y_t \end{bmatrix}
\]

Next we construct a linear system

\[
\begin{bmatrix} 1 \\ x_{t+1} \\ y_{t+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & A & 0 \\ \nu & D & 1 \end{bmatrix} \begin{bmatrix} 1 \\ x_t \\ y_t \end{bmatrix} + \begin{bmatrix} 0 \\ B \\ F \end{bmatrix} z_{t+1}
\]

This can be written as:

\[
\begin{align*}
\hat{x}_{t+1} &= \hat{A}\hat{x}_t + \hat{B}z_{t+1} \\
\hat{y}_t &= \hat{D}\hat{x}_t
\end{align*}
\]

which is a standard linear state space system.

To study it, we could map it into an instance of `LinearStateSpace` from `QuantEcon.py`.

But here we will use a different set of code for simulation, for reasons described below.

### 29.4 Dynamics

Let’s run some simulations to build intuition.

In doing so we’ll assume that \(z_{t+1}\) is scalar and that \(\tilde{x}_t\) follows a 4th-order scalar autoregression.
\[ \tilde{x}_{t+1} = \phi_1 \tilde{x}_t + \phi_2 \tilde{x}_{t-1} + \phi_3 \tilde{x}_{t-2} + \phi_4 \tilde{x}_{t-3} + \sigma z_{t+1} \]  

(3)
in which the zeros \( z \) of the polynomial
\[ \phi(z) = (1 - \phi_1 z - \phi_2 z^2 - \phi_3 z^3 - \phi_4 z^4) \]
are strictly greater than unity in absolute value.

(Being a zero of \( \phi(z) \) means that \( \phi(z) = 0 \))

Let the increment in \( \{y_t\} \) obey
\[ y_{t+1} - y_t = \nu + \tilde{x}_t + \sigma z_{t+1} \]

with an initial condition for \( y_0 \).

While (3) is not a first order system like (1), we know that it can be mapped into a first order system.

- For an example of such a mapping, see this example.

In fact, this whole model can be mapped into the additive functional system definition in (1) – (2) by appropriate selection of the matrices \( A, B, D, F \).

You can try writing these matrices down now as an exercise — correct expressions appear in the code below.

29.4.1 Simulation

When simulating we embed our variables into a bigger system.

This system also constructs the components of the decompositions of \( y_t \) and of \( \exp(y_t) \) proposed by Hansen and Scheinkman [32].

All of these objects are computed using the code below

In [3]:
```python
from AMF_LSS_VAR:

This class transforms an additive (multiplicative)
functional into a QuantEcon linear state space system.

def __init__(self, A, B, D, F=None, nu=None):
    # Unpack required elements
    self.nx, self.nk = B.shape
    self.A, self.B = A, B

    # Checking the dimension of D (extended from the scalar case)
    if len(D.shape) > 1 and D.shape[0] != 1:
        self.nm = D.shape[0]
        self.D = D
    elif len(D.shape) > 1 and D.shape[0] == 1:
        self.nm = 1
        self.D = D
    else:
```

```
self.nm = 1
self.D = np.expand_dims(D, 0)

# Create space for additive decomposition
self.add_decomp = None
self.mult_decomp = None

# Set F
if not np.any(F):
    self.F = np.zeros((self.nk, 1))
else:
    self.F = F

# Set ν
if not np.any(ν):
    self.ν = np.zeros((self.nm, 1))
elif type(ν) == float:
    self.ν = np.asarray([[ν]])
elif len(ν.shape) == 1:
    self.ν = np.expand_dims(ν, 1)
else:
    self.ν = ν

if self.ν.shape[0] != self.D.shape[0]:
    raise ValueError("The dimension of ν is inconsistent with D!")

# Construct BIG state space representation
self.lss = self.construct_ss()

def construct_ss(self):
    ""
    This creates the state space representation that can be passed
    into the quantecon LSS class.
    ""

    # Pull out useful info
    nx, nk, nm = self.nx, self.nk, self.nm
    if self.add_decomp:
        ν, H, g = self.add_decomp
    else:
        ν, H, g = self.additive_decomp()

    # Auxiliary blocks with 0's and 1's to fill out the lss matrices
    nx0c = np.zeros((nx, 1))
    nx0r = np.zeros(nx)
    nx1 = np.ones(nx)
    nk0 = np.zeros(nk)
    ny0c = np.zeros((nm, 1))
    ny0r = np.zeros(nm)
    ny1m = np.eye(nm)
    ny0m = np.zeros((nm, nm))
    nx0m = np.zeros_like(D)

    # Build A matrix for LSS
    # Order of states is: [1, t, xt, yt, mt]
    A1 = np.hstack([1, 0, nx0r, ny0r, ny0r])  # Transition for 1
    A2 = np.hstack([1, 1, nx0r, ny0r, ny0r])  # Transition for t
    # Transition for x_{t+1}
A3 = np.hstack([nx0c, nx0c, A, nyx0m.T, nyx0m.T])
# Transition for y_{t+1}
A4 = np.hstack([ν, ny0c, D, ny1m, ny0m])
# Transition for m_{t+1}
A5 = np.hstack([ny0c, ny0c, nyx0m, ny0m, ny1m])
Abar = np.vstack([A1, A2, A3, A4, A5])

# Build B matrix for LSS
Bbar = np.vstack([nk0, nk0, B, F, H])

# Build G matrix for LSS
# Order of observation is: [xt, yt, mt, st, tt]
# Selector for x_{t}
G1 = np.hstack([nx0c, nx0c, np.eye(nx), nyx0m.T, nyx0m.T])
G2 = np.hstack([ny0c, ny0c, nyx0m, ny1m, ny0m])
# Selector for \gamma_{t}
G3 = np.hstack([ny0c, ny0c, nyx0m, ny0m, ny1m])
# Selector for stationary
G4 = np.hstack([ny0c, ny0c, -g, ny0m, ny0m])
# Selector for trend
G5 = np.hstack([ny0c, ν, nyx0m, ny0m, ny0m])
Gbar = np.vstack([G1, G2, G3, G4, G5])

# Build H matrix for LSS
Hbar = np.zeros((Gbar.shape[0], nk))

# Build LSS type
x0 = np.hstack([1, 0, nx0r, ny0r, ny0r])
S0 = np.zeros((len(x0), len(x0)))
lss = qe.lss.LinearStateSpace(Abar, Bbar, Gbar, Hbar, μ_0=x0, Σ_0=S0)

return lss

def additive_decomp(self):
    """
    Return values for the martingale decomposition
    - ν : unconditional mean difference in Y
    - H : coefficient for the (linear) martingale component (κ_a)
    - g : coefficient for the stationary component g(x)
    - Y_0 : it should be the function of X_0 (for now set it to 0.0)
    """
    I = np.identity(self.nx)
    A_res = la.solve(I - self.A, I)
g = self.D @ A_res
    H = self.F + self.D @ A_res @ self.B

    return self.ν, H, g

def multiplicative_decomp(self):
    """
    Return values for the multiplicative decomposition (Example 5.4.4.)
    - ν_tilde : eigenvalue
    - H : vector for the Jensen term
    """
    ν, H, g = self.additive_decomp()
    ν_tilde = ν + (.5)*np.expand_dims(np.diag(H @ H.T), 1)
29.4. DYNAMICS

```
return \tilde{\nu}, H, g

def loglikelihood_path(self, x, y):
    k, T = y.shape
    FF = F @ F.T
    FFinv = la.inv(FF)
    temp = y[:, 1:] - y[:, :-1] - D @ x[:, :-1]
    obs = temp * FFinv * temp
    obssum = np.cumsum(obs)
    scalar = (np.log(la.det(FF)) + k*np.log(2*np.pi))*np.arange(1, T)
    return -0.5*(obssum + scalar)

def loglikelihood(self, x, y):
    llh = self.loglikelihood_path(x, y)
    return llh[-1]
```

Plotting

The code below adds some functions that generate plots for instances of the `AMF_LSS_VAR` class.

```
In [4]: def plot_given_paths(amf, T, ypath, mpath, spath, tpath, mbounds, sbounds, horline=0, show_trend=True):

    # Allocate space
    trange = np.arange(T)

    # Create figure
    fig, ax = plt.subplots(2, 2, sharey=True, figsize=(15, 8))

    # Plot all paths together
    ax[0, 0].plot(trange, ypath[0, :], label="y_t", color="k")
    ax[0, 0].plot(trange, mpath[0, :], label="m_t", color="m")
    ax[0, 0].plot(trange, spath[0, :], label="s_t", color="g")
    if show_trend:
        ax[0, 0].plot(trange, tpath[0, :], label="t_t", color="r")
    ax[0, 0].axhline(horline, color="k", linestyle="--")
    ax[0, 0].set_title("One Path of All Variables")
    ax[0, 0].legend(loc="upper left")

    # Plot Martingale Component
    ax[0, 1].plot(trange, mpath[0, :], "m")
    ax[0, 1].plot(trange, mpath.T, alpha=0.45, color="m")
    ub = mbounds[1, :]
    lb = mbounds[0, :]
    ax[0, 1].fill_between(trange, lb, ub, alpha=0.25, color="m")
    ax[0, 1].set_title("Martingale Components for Many Paths")
    ax[0, 1].axhline(horline, color="k", linestyle="--")

    # Plot Stationary Component
    ax[1, 0].plot(spath[0, :], color="g")
    ax[1, 0].plot(spath.T, alpha=0.25, color="g")
```
ub = sbounds[1, :]
lb = sbounds[0, :]
ax[1, 0].fill_between(trange, lb, ub, alpha=0.25, color="g")
ax[1, 0].axhline(horline, color="k", linestyle="-.")
ax[1, 0].set_title("Stationary Components for Many Paths")

# Plot Trend Component
if show_trend:
    ax[1, 1].plot(tpath.T, color="r")
ax[1, 1].set_title("Trend Components for Many Paths")
ax[1, 1].axhline(horline, color="k", linestyle="--")

return fig

def plot_additive(amf, T, npaths=25, show_trend=True):
    ""
    Plots for the additive decomposition.
    Acts on an instance amf of the AMF_LSS_VAR class
    ""
    # Pull out right sizes so we know how to increment
    nx, nk, nm = amf.nx, amf.nk, amf.nm

    # Allocate space (nm is the number of additive functionals -
    # we want npaths for each)
    mpath = np.empty((nm*npaths, T))
    mbounds = np.empty((nm*2, T))
    spath = np.empty((nm*npaths, T))
    sbounds = np.empty((nm*2, T))
    tpath = np.empty((nm*npaths, T))
    ypath = np.empty((nm*npaths, T))

    # Simulate for as long as we wanted
    moment_generator = amf.lss.moment_sequence()
    # Pull out population moments
    for t in range(T):
        tmoms = next(moment_generator)
        ymeans = tmoms[1]
        yvar = tmoms[3]

        # Lower and upper bounds - for each additive functional
        for ii in range(nm):
            li, ui = ii+2, (ii+1)*2
            mscale = np.sqrt(yvar[nx+nm*ii, nx+nm*ii])
            sscale = np.sqrt(yvar[nx+2*nm*ii, nx+2*nm*ii])
            if mscale == 0.0:
                mscale = 1e-12  # avoids a RuntimeWarning from calculating
                ppf
            if sscale == 0.0:  # of normal distribution with std dev = 0.
                sscale = 1e-12  # sets std dev to small value instead
            madd_dist = norm(ymeans[nx+nm*ii], mscale)
            sadd_dist = norm(ymeans[nx+2*nm*ii], sscale)

            mbounds[li:ui, t] = madd_dist.ppf([0.01, .99])
            sbounds[li:ui, t] = sadd_dist.ppf([0.01, .99])

            # Pull out paths
```python
for n in range(npaths):
    x, y = amf.lss.simulate(T)
    for ii in range(nm):
        ypath[npaths*ii+n, :] = y[nx+ii, :]
        mpath[npaths*ii+n, :] = y[nx+nm + ii, :]
        spath[npaths*ii+n, :] = y[nx+2*nm + ii, :]
        tpath[npaths*ii+n, :] = y[nx+3*nm + ii, :]

add_figs = []

for ii in range(nm):
    li, ui = npaths*(ii), npaths*(ii+1)
    LI, UI = 2*(ii), 2*(ii+1)
    add_figs.append(plot_given_paths(amf, T,
                                       ypath[li:ui,:],
                                       mpath[li:ui,:],
                                       spath[li:ui,:],
                                       tpath[li:ui,:],
                                       mbounds[LI:UI,:],
                                       sbounds[LI:UI,:],
                                       show_trend=show_trend))

add_figs[ii].suptitle(f'Additive decomposition of $y_{\{ii+1\}}$',
                       fontsize=14)

return add_figs

def plot_multiplicative(amf, T, npaths=25, show_trend=True):
    ""
    Plots for the multiplicative decomposition
    ""
    # Pull out right sizes so we know how to increment
    nx, nk, nm = amf.nx, amf.nk, amf.nm
    # Matrices for the multiplicative decomposition
    ν_tilde, H, g = amf.multiplicative_decomp()

    # Allocate space (nm is the number of functionals -
    # we want npaths for each)
    mpath_mult = np.empty((nm*npaths, T))
    mbounds_mult = np.empty((nm*2, T))
    spath_mult = np.empty((nm*npaths, T))
    sbounds_mult = np.empty((nm*2, T))
    tpath_mult = np.empty((nm*npaths, T))
    ypath_mult = np.empty((nm*npaths, T))

    # Simulate for as long as we wanted
    moment_generator = amf.lss.moment_sequence()
    # Pull out population moments
    for t in range(T):
        tmoms = next(moment_generator)
        ymeans = tmoms[1]
        yvar = tmoms[3]

        # Lower and upper bounds - for each multiplicative functional
        for ii in range(nm):
            li, ui = ii*2, (ii+1)*2
```

Mdist = lognorm(np.sqrt(yvar[nx+nm+ii, nx+nm+ii]).item(),
    scale=np.exp(ymeans[nx+nm+ii] \
        - t * (.5)
    )[ii]
    ).item()

Sdist = lognorm(np.sqrt(yvar[nx+2*nm+ii, nx+2*nm+ii]).item(),
    scale=np.exp(-ymeans[nx+2*nm+ii]).item())
mbounds_mult[li:ui, t] = Mdist.ppf([.01, .99])
sbounds_mult[li:ui, t] = Sdist.ppf([.01, .99])

# Pull out paths
for n in range(npaths):
    x, y = amf.lss.simulate(T)
    for ii in range(nm):
        ypath_mult[npaths*ii+n, :] = np.exp(y[nx+ii, :])
        mpath_mult[npaths*ii+n, :] = np.exp(y[nx+nm + ii, :] \
            - np.arange(T) * (.5)
        )[ii]
        spath_mult[npaths*ii+n, :] = 1/np.exp(-y[nx+2*nm + ii, :])
        tpath_mult[npaths*ii+n, :] = np.exp(y[nx+3*nm + ii, :] \
            + np.arange(T) * (.5)
        )[ii]

mult_figs = []
for ii in range(nm):
    li, ui = npaths*(ii), npaths*(ii+1)
    LI, UI = 2*(ii), 2*(ii+1)

    mult_figs.append(plot_given_paths(amf,T,
        ypath_mult[li:ui,:],
        mpath_mult[li:ui,:],
        spath_mult[li:ui,:],
        tpath_mult[li:ui,:],
        mbounds_mult[LI:UI,:],
        sbounds_mult[LI:UI,:],
        1,
        show_trend=show_trend))

    mult_figs[ii].suptitle(f'Multiplicative decomposition of \$
    \mathbf{y}_{(' + \$ii+1)$', fontsize=14)

return mult_figs

def plot_martingale_paths(amf, T, mpath, mbounds, horline=1, \
    show_trend=False):
    # Allocate space
    trange = np.arange(T)
# Create figure
fig, ax = plt.subplots(1, 1, figsize=(10, 6))

# Plot Martingale Component
ub = mbounds[1, :]
lb = mbounds[0, :]
ad.fill_between(trange, lb, ub, color="#ffccff")
ad.axhline(horline, color="k", linestyle="--")
ad.plot(trange, mpath.T, linewidth=0.25, color="#4c4c4c")

return fig

def plot_martingales(amf, T, npaths=25):
    # Pull out right sizes so we know how to increment
    nx, nk, nm = amf.nx, amf.nk, amf.nm
    # Matrices for the multiplicative decomposition
    v_tilde, H, g = amf.multiplicative_decomp()
    # Allocate space (nm is the number of functionals -
    # we want npaths for each)
    mpath_mult = np.empty((nm*npaths, T))
    mbounds_mult = np.empty((nm*2, T))
    # Simulate for as long as we wanted
    moment_generator = amf.lss.moment_sequence()
    # Pull out population moments
    for t in range(T):
        tmoms = next(moment_generator)
        ymeans = tmoms[1]
        yvar = tmoms[3]

        # Lower and upper bounds - for each functional
        for ii in range(nm):
            li, ui = ii*2, (ii+1)*2
            Mdist = lognorm(np.sqrt(yvar[nx+nm+ii, nx+nm+ii]).item(),
                            scale= np.exp(ymean[nx+nm+ii] - t *.5)
                            * np.expand_dims(np.diag(H @ H.T), 1)[ii]
                        ).item()
            mbounds_mult[li:ui, t] = Mdist.ppf([.01, .99])

    # Pull out paths
    for n in range(npaths):
        x, y = amf.lss.simulate(T)
        for ii in range(nm):
            mpath_mult[npaths*ii+n, :] = np.exp(y[nx+nm + ii, :] - np.arange(T) * (.5)
                                                * np.expand_dims(np.diag(H @ H.T), 1)[ii]
                )

    mart_figs = []
for ii in range(nm):
    li, ui = npaths*(ii), npaths*(ii+1)
    LI, UI = 2*(ii), 2*(ii+1)
    mart_figs.append(plot_martingale_paths(amf, T, mpath_mult[li:ui, :],
                                           mbounds_mult[LI:UI, :],
                                           horline=1))
    mart_figs[ii].set_title(f'Martingale components for many paths of \$y_{ii+1}\$', fontsize=14)

return mart_figs

For now, we just plot $y_t$ and $x_t$, postponing until later a description of exactly how we compute them.

In [5]: $\phi_1, \phi_2, \phi_3, \phi_4 = 0.5, -0.2, 0, 0.5$
$\sigma = 0.01$
$v = 0.01$  # Growth rate

# A matrix should be n x n
A = np.array([[\phi_1, \phi_2, \phi_3, \phi_4],
              [ 1,  0,  0,  0],
              [ 0,  1,  0,  0],
              [ 0,  0,  1,  0]])

# B matrix should be n x k
B = np.array([[\sigma, 0, 0, 0]]).T
D = np.array([1, 0, 0, 0]) @ A
F = np.array([1, 0, 0, 0]) @ B

amf = AMF_LSS_VAR(A, B, D, F, v=v)

T = 150
x, y = amf.lss.simulate(T)

fig, ax = plt.subplots(2, 1, figsize=(10, 9))

ax[0].plot(np.arange(T), y[amf.nx, :], color='k')
ax[0].set_title('Path of $y_t$')
ax[1].plot(np.arange(T), y[0, :], color='g')
ax[1].axhline(0, color='k', linestyle='-.')
ax[1].set_title('Associated path of $x_t$')
plt.show()
Notice the irregular but persistent growth in $y_t$.

### 29.4.2 Decomposition

Hansen and Sargent [30] describe how to construct a decomposition of an additive functional into four parts:

- a constant inherited from initial values $x_0$ and $y_0$
- a linear trend
- a martingale
- an (asymptotically) stationary component

To attain this decomposition for the particular class of additive functionals defined by (1) and (2), we first construct the matrices

\[
H := F + D(I - A)^{-1}B \\
g := D(I - A)^{-1}
\]

Then the Hansen-Scheinkman [32] decomposition is
CHAPTER 29. ADDITIVE AND MULTIPLICATIVE FUNCTIONALS

\[
y_t = \nu t + \sum_{j=1}^{t} Hz_j - gx_t + g x_0 + y_0
\]

Martingale component

At this stage, you should pause and verify that \( y_{t+1} - y_t \) satisfies (2).

It is convenient for us to introduce the following notation:

- \( \tau_t = \nu t \), a linear, deterministic trend
- \( m_t = \sum_{j=1}^{t} Hz_j \), a martingale with time \( t + 1 \) increment \( Hz_{t+1} \)
- \( s_t = gx_t \), an (asymptotically) stationary component

We want to characterize and simulate components \( \tau_t, m_t, s_t \) of the decomposition.

A convenient way to do this is to construct an appropriate instance of a linear state space system by using LinearStateSpace from QuantEcon.py.

This will allow us to use the routines in LinearStateSpace to study dynamics.

To start, observe that, under the dynamics in (1) and (2) and with the definitions just given,

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_t \\
y_t \\
\nu \\
m_t \\
s_t
\end{bmatrix}
= \begin{bmatrix}
1 & 1 & 0 & 0 & 0 \\
0 & 0 & A & 0 & 0 \\
\nu & 0 & D & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_t \\
y_t \\
\nu \\
m_t \\
s_t
\end{bmatrix}
+ \begin{bmatrix}
0 \\
x_t \\
y_t \\
\nu \\
\nu
\end{bmatrix}
\begin{bmatrix}
B \\
F \\
F \\
H
\end{bmatrix}
\]

and

\[
\begin{bmatrix}
x_t \\
y_t \\
\tau_t \\
m_t \\
s_t
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & I & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & -g & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_t \\
y_t \\
\tau_t \\
m_t \\
s_t
\end{bmatrix}
\]

With

\[
\begin{bmatrix}
1 \\
x_t \\
y_t \\
\tau_t \\
m_t
\end{bmatrix}
= \begin{bmatrix}
1 \\
x_t \\
y_t \\
\tau_t \\
m_t
\end{bmatrix}
\]

we can write this as the linear state space system

\[
\begin{align*}
\tilde{x}_{t+1} &= \tilde{A}\tilde{x}_t + \tilde{B}z_{t+1} \\
\tilde{y}_t &= \tilde{D}\tilde{x}_t
\end{align*}
\]

By picking out components of \( \tilde{y}_t \), we can track all variables of interest.
29.5 Code

The class `AMF_LSS_VAR` mentioned above does all that we want to study our additive functional.

In fact, `AMF_LSS_VAR` does more because it allows us to study an associated multiplicative functional as well.

(A hint that it does more is the name of the class – here AMF stands for “additive and multiplicative functional” – the code computes and displays objects associated with multiplicative functionals too.)

Let’s use this code (embedded above) to explore the example process described above.

If you run the code that first simulated that example again and then the method call you will generate (modulo randomness) the plot

```python
In [6]: plot_additive(amf, T)
plt.show()
```

When we plot multiple realizations of a component in the 2nd, 3rd, and 4th panels, we also plot the population 95% probability coverage sets computed using the LinearStateSpace class.

We have chosen to simulate many paths, all starting from the same non-random initial conditions $x_0, y_0$ (you can tell this from the shape of the 95% probability coverage shaded areas).

Notice tell-tale signs of these probability coverage shaded areas
- the purple one for the martingale component $m_t$ grows with $\sqrt{t}$
- the green one for the stationary component $s_t$ converges to a constant band

29.5.1 Associated Multiplicative Functional

Where \( \{y_t\} \) is our additive functional, let \( M_t = \exp(y_t) \).
As mentioned above, the process \( \{M_t\} \) is called a **multiplicative functional**.

Corresponding to the additive decomposition described above we have a multiplicative decomposition of \( M_t \)

\[
\frac{M_t}{M_0} = \exp(t\nu) \exp\left(\sum_{j=1}^{t} H \cdot Z_j\right) \exp\left(D(I - A)^{-1}x_0 - D(I - A)^{-1}x_0\right)
\]

or

\[
\frac{M_t}{M_0} = \exp(\tilde{\nu}t) \left( \frac{\tilde{M}_t}{\tilde{M}_0} \right) \left( \frac{\tilde{e}(X_0)}{\tilde{e}(x_t)} \right)
\]

where

\[
\tilde{\nu} = \nu + \frac{H \cdot H}{2}, \quad \tilde{M}_t = \exp\left(\sum_{j=1}^{t} \left(H \cdot z_j - \frac{H \cdot H}{2}\right)\right), \quad \tilde{M}_0 = 1
\]

and

\[
\tilde{e}(x) = \exp[g(x)] = \exp[D(I - A)^{-1}x]
\]

An instance of class **AMF_LSS_VAR** (above) includes this associated multiplicative functional as an attribute.

Let’s plot this multiplicative functional for our example.

If you run the code that first simulated that example again and then the method call in the cell below you’ll obtain the graph in the next cell.

In [7]: `plot_multiplicative(amf, T)`
`plt.show()`
As before, when we plotted multiple realizations of a component in the 2nd, 3rd, and 4th panels, we also plotted population 95% confidence bands computed using the LinearStateSpace class.

Comparing this figure and the last also helps show how geometric growth differs from arithmetic growth.

The top right panel of the above graph shows a panel of martingales associated with the panel of $M_t = \exp(y_t)$ that we have generated for a limited horizon $T$.

It is interesting to how the martingale behaves as $T \to +\infty$.

Let’s see what happens when we set $T = 12000$ instead of 150.

29.5.2 Peculiar Large Sample Property

Hansen and Sargent [30] (ch. 8) describe the following two properties of the martingale component $\tilde{M}_t$ of the multiplicative decomposition

- while $E_0\tilde{M}_t = 1$ for all $t \geq 0$, nevertheless ...
- as $t \to +\infty$, $\tilde{M}_t$ converges to zero almost surely

The first property follows from the fact that $\tilde{M}_t$ is a multiplicative martingale with initial condition $\tilde{M}_0 = 1$.

The second is a peculiar property noted and proved by Hansen and Sargent [30].

The following simulation of many paths of $\tilde{M}_t$ illustrates both properties

In [8]:
np.random.seed(10021987)
plot_martingales(amf, 12000)
plt.show()
The dotted line in the above graph is the mean $\tilde{E}_M^t = 1$ of the martingale.

It remains constant at unity, illustrating the first property.

The purple 95 percent frequency coverage interval collapses around zero, illustrating the second property.

### 29.6 More About the Multiplicative Martingale

Let’s drill down and study probability distribution of the multiplicative martingale $\{\tilde{M}_t\}_{t=0}^\infty$ in more detail.

As we have seen, it has representation

$$\tilde{M}_t = \exp\left( \sum_{j=1}^t \left( H \cdot z_j - \frac{H \cdot H}{2} \right) \right), \quad \tilde{M}_0 = 1$$

where $H = [F + D(I - A)^{-1} B]$.

It follows that $\log \tilde{M}_t \sim \mathcal{N}\left(-\frac{t H \cdot H}{2}, tH \cdot H\right)$ and that consequently $\tilde{M}_t$ is log normal.

#### 29.6.1 Simulating a Multiplicative Martingale Again

Next, we want a program to simulate the likelihood ratio process $\{\tilde{M}_t\}_{t=0}^\infty$.

In particular, we want to simulate 5000 sample paths of length $T$ for the case in which $x$ is a scalar and $[A, B, D, F] = [0.8, 0.001, 1.0, 0.01]$ and $\nu = 0.005$.

After accomplishing this, we want to display and study histograms of $\tilde{M}_T$ for various values of $T$.

Here is code that accomplishes these tasks.

#### 29.6.2 Sample Paths

Let’s write a program to simulate sample paths of $\{x_t, y_t\}_{t=0}^\infty$.

We’ll do this by formulating the additive functional as a linear state space model and putting the LinearStateSpace class to work.

In [9]:  ```python
class AMF_LSS_VAR:
    """
    This class is written to transform a scalar additive functional into a linear state space system.
    """
    def __init__(self, A, B, D, F=0.0, \nu=0.0):
        # Unpack required elements

        # Create space for additive decomposition
        self.add_decomp = None
        self.mult_decomp = None
    ```
# Construct BIG state space representation
self.lss = self.construct_ss()

def construct_ss(self):
    
    This creates the state space representation that can be passed into the quantecon LSS class.
    
    # Pull out useful info
    nx, nk, nm = 1, 1, 1
    if self.add_decomp:
        ν, H, g = self.add_decomp
    else:
        ν, H, g = self.additive_decomp()

    # Build A matrix for LSS
    # Order of states is: [1, t, xt, yt, mt]
    A1 = np.hstack([1, 0, 0, 0, 0])   # Transition for 1
    A2 = np.hstack([1, 1, 0, 0, 0])   # Transition for t
    A3 = np.hstack([0, 0, A, 0, 0])   # Transition for x_{t+1}
    A4 = np.hstack([ν, 0, D, 1, 0])   # Transition for y_{t+1}
    A5 = np.hstack([0, 0, 0, 0, 1])   # Transition for m_{t+1}
    Abar = np.vstack([A1, A2, A3, A4, A5])

    # Build B matrix for LSS
    Bbar = np.vstack([0, 0, B, F, H])

    # Build G matrix for LSS
    # Order of observation is: [xt, yt, mt, st, tt]
    G1 = np.hstack([0, 0, 1, 0, 0])   # Selector for x_{t}
    G2 = np.hstack([0, 0, 0, 1, 0])   # Selector for y_{t}
    G3 = np.hstack([0, 0, -g, 0, 0])  # Selector for stationary
    G4 = np.hstack([0, ν, 0, 0, 0])   # Selector for trend
    Gbar = np.vstack([G1, G2, G3, G4, G5])

    # Build H matrix for LSS
    Hbar = np.zeros((1, 1))

    # Build LSS type
    x0 = np.hstack([1, 0, 0, 0, 0])
    S0 = np.zeros((5, 5))
    lss = qe.lss.LinearStateSpace(Abar, Bbar, Gbar, Hbar, x0=x0, Sigma_0=S0)

    return lss

def additive_decomp(self):
    
    Return values for the martingale decomposition (Proposition 4.3.3.)
    - ν : unconditional mean difference in Y
    - H : coefficient for the (linear) martingale component
    - (kappa_a)
    - g : coefficient for the stationary component g(x)
    - Y_Θ : it should be the function of X_Θ (for now set it to 0.0)
A_res = 1 / (1 - self.A)
g = self.D * A_res
return self.ν, H, g

def multiplicative_decomp(self):
    """
    Return values for the multiplicative decomposition (Example 5.4.4.)
    - \( \nu_{\text{tilde}} \) : eigenvalue
    - \( H \) : vector for the Jensen term
    """
    ν, H, g = self.additive_decomp()
    ν_tilde = ν + (.5) * H**2
    return ν_tilde, H, g

def loglikelihood_path(self, x, y):
    T = y.T.size
    FF = F**2
    FFinv = 1 / FF
    temp = y[1:] - y[:-1] - D * x[:-1]
    obs = temp * FFinv * temp
    obssum = np.cumsum(obs)
    scalar = (np.log(FF) + np.log(2 * np.pi)) * np.arange(1, T)
    return (-0.5) * (obssum + scalar)

def loglikelihood(self, x, y):
    llh = self.loglikelihood_path(x, y)
    return llh[-1]

The heavy lifting is done inside the AMF_LSS_VAR class.

The following code adds some simple functions that make it straightforward to generate sample paths from an instance of AMF_LSS_VAR.

In [10]: def simulate_xy(amf, T):
    """Simulate individual paths.""
    foo, bar = amf.lss.simulate(T)
    x = bar[0, :]
    y = bar[1, :]
    return x, y

def simulate_paths(amf, T=150, I=5000):
    """Simulate multiple independent paths.""
    storeX = np.empty((I, T))
    storeY = np.empty((I, T))
    for i in range(I):
        # Do specific simulation
        x, y = simulate_xy(amf, T)
# Fill in our storage matrices
storeX[i, :] = x
storeY[i, :] = y

return storeX, storeY

def population_means(amf, T=150):
    # Allocate Space
    xmean = np.empty(T)
    ymean = np.empty(T)

    # Pull out moment generator
    moment_generator = amf.lss.moment_sequence()
    for tt in range(T):
        tmoms = next(moment_generator)
        ymeans = tmoms[1]
        xmean[tt] = ymeans[0]
        ymean[tt] = ymeans[1]

    return xmean, ymean

Now that we have these functions in our toolkit, let’s apply them to run some simulations.

In [11]: def simulate_martingale_components(amf, T=1000, I=5000):
    # Get the multiplicative decomposition
    ν, H, g = amf.multiplicative_decomp()

    # Allocate space
    add_mart_comp = np.empty((I, T))

    # Simulate and pull out additive martingale component
    for i in range(I):
        foo, bar = amf.lss.simulate(T)

        # Martingale component is third component
        add_mart_comp[i, :] = bar[2, :]

    mul_mart_comp = np.exp(add_mart_comp - (np.arange(T) * H**2)/2)

    return add_mart_comp, mul_mart_comp

# Build model
amf_2 = AMF_LSS_VAR(0.8, 0.001, 1.0, 0.01, 0.005)
amc, mmc = simulate_martingale_components(amf_2, 1000, 5000)
amcT = amc[:, -1]
mmcT = mmc[:, -1]

print("The (min, mean, max) of additive Martingale component in period T is")
print(f"\t({np.min(amcT)}, {np.mean(amcT)}, {np.max(amcT)})")

print("The (min, mean, max) of multiplicative Martingale component in period T is")
print(f"\t({np.min(mmcT)}, {np.mean(mmcT)}, {np.max(mmcT)})")
The (min, mean, max) of additive Martingale component in period T is
(-1.8379907335579106, 0.011040789361757435, 1.4697384727035145)
The (min, mean, max) of multiplicative Martingale component in period T is
(0.14222026893384476, 1.006753060146832, 3.8858858377907133)

Let's plot the probability density functions for \(\tilde{M}_t\) for \(t = 100, 500, 1000, 10000, 100000\).
Then let's use the plots to investigate how these densities evolve through time.
We will plot the densities of \(\tilde{M}_t\) for different values of \(t\).
Note: \texttt{scipy.stats.lognorm} expects you to pass the standard deviation first (\(tH \cdot H\)) and then the exponent of the mean as a keyword argument \texttt{scale (scale=np.exp(-t * H2 / 2))}.
  - See the documentation here.
This is peculiar, so make sure you are careful in working with the log normal distribution.
Here is some code that tackles these tasks

In [12]:

```python
def Mtilde_t_density(amf, t, xmin=1e-8, xmax=5.0, npts=5000):
    # Pull out the multiplicative decomposition
    \(\tilde{\nu}, H, g = amf.multiplicative_decomp()\)
    \(H2 = H^2\)
    
    # The distribution
    mdist = lognorm(np.sqrt(t*H2), scale=np.exp(-t*g/2))
    x = np.linspace(xmin, xmax, npts)
    pdf = mdist.pdf(x)

    return x, pdf

def logMtilde_t_density(amf, t, xmin=-10.0, xmax=10.0, npts=5000):
    # Pull out the multiplicative decomposition
    \(\tilde{\nu}, H, g = amf.multiplicative_decomp()\)
    \(H2 = H^2\)
    
    # The distribution
    lmdist = norm(-t*H2/2, np.sqrt(t*H2))
    x = np.linspace(xmin, xmax, npts)
    pdf = lmdist.pdf(x)

    return x, pdf
```

times_to_plot = [10, 100, 500, 1000, 2500, 5000]
dens_to_plot = map(lambda t: Mtilde_t_density(amf_2, t, xmin=1e-8, xmax=6.), times_to_plot)
ldens_to_plot = map(lambda t: logMtilde_t_density(amf_2, t, xmin=-10.0, xmax=10.0), times_to_plot)

fig, ax = plt.subplots(3, 2, figsize=(14, 14))
ax = ax.flatten()
These probability density functions help us understand mechanics underlying the peculiar property of our multiplicative martingale:

- As $T$ grows, most of the probability mass shifts leftward toward zero.
- For example, note that most mass is near 1 for $T = 10$ or $T = 100$ but most of it is near 0 for $T = 5000$.
- As $T$ grows, the tail of the density of $\tilde{M}_T$ lengthens toward the right.
- Enough mass moves toward the right tail to keep $E\tilde{M}_T = 1$ even as most mass in the distribution of $\tilde{M}_T$ collapses around 0.
29.6.3 Multiplicative Martingale as Likelihood Ratio Process

This lecture studies likelihood processes and likelihood ratio processes. A likelihood ratio process is a multiplicative martingale with mean unity. Likelihood ratio processes exhibit the peculiar property that naturally also appears in this lecture.
Chapter 30

Classical Control with Linear Algebra

30.1 Contents

• Overview 30.2
• A Control Problem 30.3
• Finite Horizon Theory 30.4
• The Infinite Horizon Limit 30.5
• Undiscounted Problems 30.6
• Implementation 30.7
• Exercises 30.8

30.2 Overview

In an earlier lecture Linear Quadratic Dynamic Programming Problems, we have studied how to solve a special class of dynamic optimization and prediction problems by applying the method of dynamic programming. In this class of problems

• the objective function is \textit{quadratic} in \textit{states} and \textit{controls}.
• the one-step transition function is \textit{linear}.
• shocks are IID Gaussian or martingale differences.

In this lecture and a companion lecture Classical Filtering with Linear Algebra, we study the classical theory of linear-quadratic (LQ) optimal control problems.

The classical approach does not use the two closely related methods – dynamic programming and Kalman filtering – that we describe in other lectures, namely, Linear Quadratic Dynamic Programming Problems and A First Look at the Kalman Filter.

Instead, they use either

• \textit{z}-transform and lag operator methods, or
• matrix decompositions applied to linear systems of first-order conditions for optimum problems.

In this lecture and the sequel Classical Filtering with Linear Algebra, we mostly rely on elementary linear algebra.
The main tool from linear algebra we’ll put to work here is LU decomposition.

We’ll begin with discrete horizon problems.

Then we’ll view infinite horizon problems as appropriate limits of these finite horizon problems.

Later, we will examine the close connection between LQ control and least-squares prediction and filtering problems.

These classes of problems are connected in the sense that to solve each, essentially the same mathematics is used.

Let’s start with some standard imports:

```python
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
```

### 30.2.1 References

Useful references include [68], [27], [49], [5], and [48].

### 30.3 A Control Problem

Let $L$ be the lag operator, so that, for sequence $\{x_t\}$ we have $Lx_t = x_{t-1}$.

More generally, let $L^k x_t = x_{t-k}$ with $L^0 x_t = x_t$ and

$$d(L) = d_0 + d_1 L + \ldots + d_m L^m$$

where $d_0, d_1, \ldots, d_m$ is a given scalar sequence.

Consider the discrete-time control problem

$$\max_{\{y_t\}} \lim_{N \to \infty} \sum_{t=0}^{N} \beta^t \left\{ a_t y_t - \frac{1}{2} h y_t^2 - \frac{1}{2} [d(L) y_t]^2 \right\},$$

(1)

where

- $h$ is a positive parameter and $\beta \in (0, 1)$ is a discount factor.
- $\{a_t\}_{t \geq 0}$ is a sequence of exponential order less than $\beta^{-1/2}$, by which we mean $\lim_{t \to \infty} \beta^{1/2} a_t = 0$.

Maximization in (1) is subject to initial conditions for $y_{-1}, y_{-2} \ldots, y_{-m}$.

Maximization is over infinite sequences $\{y_t\}_{t \geq 0}$.

### 30.3.1 Example

The formulation of the LQ problem given above is broad enough to encompass many useful models.
As a simple illustration, recall that in LQ Control: Foundations we consider a monopolist facing stochastic demand shocks and adjustment costs.

Let’s consider a deterministic version of this problem, where the monopolist maximizes the discounted sum

\[ \sum_{t=0}^{\infty} \beta^t \pi_t \]

and

\[ \pi_t = p_t q_t - cq_t - \gamma(q_{t+1} - q_t)^2 \]

with

\[ p_t = \alpha_0 - \alpha_1 q_t + d_t \]

In this expression, \( q_t \) is output, \( c \) is average cost of production, and \( d_t \) is a demand shock.

The term \( \gamma(q_{t+1} - q_t)^2 \) represents adjustment costs.

You will be able to confirm that the objective function can be rewritten as (1) when

1. \( a_t := \alpha_0 + d_t - c \)
2. \( h := 2\alpha_1 \)
3. \( d(L) := \sqrt{2\gamma(I - L)} \)

Further examples of this problem for factor demand, economic growth, and government policy problems are given in ch. IX of [59].

### 30.4 Finite Horizon Theory

We first study a finite \( N \) version of the problem.

Later we will study an infinite horizon problem solution as a limiting version of a finite horizon problem.

(This will require being careful because the limits as \( N \to \infty \) of the necessary and sufficient conditions for maximizing finite \( N \) versions of (1) are not sufficient for maximizing (1))

We begin by

1. fixing \( N > m \),
2. differentiating the finite version of (1) with respect to \( y_0, y_1, \ldots, y_N \), and
3. setting these derivatives to zero.

For \( t = 0, \ldots, N - m \) these first-order necessary conditions are the Euler equations.

For \( t = N - m + 1, \ldots, N \), the first-order conditions are a set of terminal conditions.

Consider the term

\[ J = \sum_{t=0}^{N} \beta^t [d(L)y_t][d(L)y_t] \]

\[ = \sum_{t=0}^{N} \beta^t (d_0 y_t + d_1 y_{t-1} + \cdots + d_m y_{t-m}) (d_0 y_t + d_1 y_{t-1} + \cdots + d_m y_{t-m}) \]
Differentiating $J$ with respect to $y_t$ for $t = 0, 1, \ldots, N - m$ gives

$$
\frac{\partial J}{\partial y_t} = 2\beta^t d_0 (L)y_t + 2\beta^{t+1} d_1 (L)y_{t+1} + \cdots + 2\beta^{t+m} d_m (L)y_{t+m}
= 2\beta^t \left( d_0 + d_1 \beta L^{-1} + d_2 \beta^2 L^{-2} + \cdots + d_m \beta^m L^{-m} \right) d(L)y_t
$$

We can write this more succinctly as

$$
\frac{\partial J}{\partial y_t} = 2\beta^t d(\beta L^{-1})d(L)y_t
$$

(2)

Differentiating $J$ with respect to $y_t$ for $t = N - m + 1, \ldots, N$ gives

$$
\frac{\partial J}{\partial y_N} = 2\beta^N d_0 (L)y_N
\frac{\partial J}{\partial y_{N-1}} = 2\beta^{N-1} \left[ d_0 + \beta d_1 L^{-1} \right] d(L)y_{N-1}
\vdots
\frac{\partial J}{\partial y_{N-m+1}} = 2\beta^{N-m+1} \left[ d_0 + \beta L^{-1} d_1 + \cdots + \beta^{m-1} L^{-m+1} d_{m-1} \right] d(L)y_{N-m+1}
$$

(3)

With these preliminaries under our belts, we are ready to differentiate (1).

Differentiating (1) with respect to $y_t$ for $t = 0, \ldots, N - m$ gives the Euler equations

$$
[h + d(\beta L^{-1})d(L)]y_t = a_t, \quad t = 0, 1, \ldots, N - m
$$

(4)

The system of equations (4) forms a $2 \times m$ order linear difference equation that must hold for the values of $t$ indicated.

Differentiating (1) with respect to $y_t$ for $t = N - m + 1, \ldots, N$ gives the terminal conditions

$$
\beta^N (a_N - hy_N - d_0 (L)y_N) = 0
\beta^{N-1} \left( a_{N-1} - hy_{N-1} - \left( d_0 + \beta d_1 L^{-1} \right) d(L)y_{N-1} \right) = 0
\vdots
\beta^{N-m+1} \left( a_{N-m+1} - hy_{N-m+1} - \left( d_0 + \beta L^{-1} d_1 + \cdots + \beta^{m-1} L^{-m+1} d_{m-1} \right) d(L)y_{N-m+1} \right) = 0
$$

(5)

In the finite $N$ problem, we want simultaneously to solve (4) subject to the $m$ initial conditions $y_{-1}, \ldots, y_{-m}$ and the $m$ terminal conditions (5).

These conditions uniquely pin down the solution of the finite $N$ problem.

That is, for the finite $N$ problem, conditions (4) and (5) are necessary and sufficient for a maximum, by concavity of the objective function.

Next, we describe how to obtain the solution using matrix methods.
30.4. Matrix Methods

Let’s look at how linear algebra can be used to tackle and shed light on the finite horizon LQ control problem.

A Single Lag Term

Let’s begin with the special case in which \( m = 1 \).

We want to solve the system of \( N + 1 \) linear equations

\[
\begin{align*}
[h + d (\beta L^{-1}) d (L)] y_t &= a_t, \quad t = 0, 1, \ldots, N - 1 \\
\beta^N [a_N - h y_N - d_0 d (L) y_N] &= 0
\end{align*}
\]

where \( d(L) = d_0 + d_1 L \).

These equations are to be solved for \( y_0, y_1, \ldots, y_N \) as functions of \( a_0, a_1, \ldots, a_N \) and \( y_{-1} \).

Let

\[
\phi(L) = \phi_0 + \phi_1 L + \beta \phi_1 L^{-1} = h + d(\beta L^{-1}) d(L) = (h + d_0^2 + d_1^2) + d_1 d_0 L + d_1 d_0 \beta L^{-1}
\]

Then we can represent (6) as the matrix equation

\[
\begin{bmatrix}
(\phi_0 - d_1^2) & \phi_1 & 0 & 0 & \cdots & \cdots & 0 \\
\beta \phi_1 & \phi_0 & \phi_1 & 0 & \cdots & \cdots & 0 \\
0 & \beta \phi_1 & \phi_0 & \phi_1 & \cdots & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\
0 & \cdots & \cdots & \beta \phi_1 & \phi_0 & \phi_1 \\
0 & \cdots & \cdots & 0 & \beta \phi_1 & \phi_0
\end{bmatrix}
\begin{bmatrix}
y_N \\
y_{N-1} \\
y_{N-2} \\
\vdots \\
y_1 \\
y_0
\end{bmatrix}
= \begin{bmatrix}
a_N \\
a_{N-1} \\
a_{N-2} \\
\vdots \\
a_1 \\
a_0 - \phi_1 y_{-1}
\end{bmatrix}
\]

or

\[
W \bar{y} = \bar{a}
\]

Notice how we have chosen to arrange the \( y_t \)’s in reverse time order.

The matrix \( W \) on the left side of (7) is “almost” a Toeplitz matrix (where each descending diagonal is constant).

There are two sources of deviation from the form of a Toeplitz matrix

1. The first element differs from the remaining diagonal elements, reflecting the terminal condition.

2. The sub-diagonal elements equal \( \beta \) time the super-diagonal elements.

The solution of (8) can be expressed in the form

\[
\bar{y} = W^{-1} \bar{a}
\]

which represents each element \( y_t \) of \( \bar{y} \) as a function of the entire vector \( \bar{a} \).
That is, \( y_t \) is a function of past, present, and future values of \( a \)'s, as well as of the initial condition \( y_{-1} \).

**An Alternative Representation**

An alternative way to express the solution to (7) or (8) is in so-called feedback-feedforward form.

The idea here is to find a solution expressing \( y_t \) as a function of past \( y \)'s and current and future \( a \)'s.

To achieve this solution, one can use an LU decomposition of \( W \).

There always exists a decomposition of \( W \) of the form \( W = LU \) where

- \( L \) is an \( (N + 1) \times (N + 1) \) lower triangular matrix.
- \( U \) is an \( (N + 1) \times (N + 1) \) upper triangular matrix.

The factorization can be normalized so that the diagonal elements of \( U \) are unity.

Using the LU representation in (9), we obtain

\[
U \hat{y} = L^{-1} \hat{a}
\]

Since \( L^{-1} \) is lower triangular, this representation expresses \( y_t \) as a function of

- lagged \( y \)'s (via the term \( U \hat{y} \)), and
- current and future \( a \)'s (via the term \( L^{-1} \hat{a} \))

Because there are zeros everywhere in the matrix on the left of (7) except on the diagonal, super-diagonal, and sub-diagonal, the \( LU \) decomposition takes

- \( L \) to be zero except in the diagonal and the leading sub-diagonal.
- \( U \) to be zero except on the diagonal and the super-diagonal.

Thus, (10) has the form

\[
\begin{bmatrix}
1 & U_{12} & 0 & 0 & \ldots & 0 & 0 \\
0 & 1 & U_{23} & 0 & \ldots & 0 & 0 \\
0 & 0 & 1 & U_{34} & \ldots & 0 & 0 \\
0 & 0 & 0 & 1 & \ldots & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & 0 & 0 & \ldots & 1 & U_{N,N+1} \\
0 & 0 & 0 & 0 & \ldots & 0 & 1
\end{bmatrix}
\begin{bmatrix}
y_N \\
y_{N-1} \\
y_{N-2} \\
y_{N-3} \\
\vdots \\
y_1 \\
y_0
\end{bmatrix}
= 
\begin{bmatrix}
L_{11}^{-1} & 0 & 0 & \ldots & 0 \\
L_{21}^{-1} & L_{22}^{-1} & 0 & \ldots & 0 \\
L_{31}^{-1} & L_{32}^{-1} & L_{33}^{-1} & \ldots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
L_{N,1}^{-1} & L_{N,2}^{-1} & L_{N,3}^{-1} & \ldots & 0 \\
L_{N+1,1}^{-1} & L_{N+1,2}^{-1} & L_{N+1,3}^{-1} & \ldots & L_{N+1,N+1}^{-1}
\end{bmatrix}
\begin{bmatrix}
a_N \\
a_{N-1} \\
a_{N-2} \\
\vdots \\
a_1 \\
a_0 - \phi_1 y_{-1}
\end{bmatrix}
\]

where \( L_{ij}^{-1} \) is the \((i,j)\) element of \( L^{-1} \) and \( U_{ij} \) is the \((i,j)\) element of \( U \).

Note how the left side for a given \( t \) involves \( y_t \) and one lagged value \( y_{t-1} \) while the right side involves all future values of the forcing process \( a_t, a_{t+1}, \ldots, a_N \).
Additional Lag Terms

We briefly indicate how this approach extends to the problem with \( m > 1 \).

Assume that \( \beta = 1 \) and let \( D_{m+1} \) be the \((m + 1) \times (m + 1)\) symmetric matrix whose elements are determined from the following formula:

\[
D_{jk} = d_0 d_{k-j} + d_1 d_{k-j+1} + \ldots + d_{j-1} d_{k-1}, \quad k \geq j
\]

Let \( I_{m+1} \) be the \((m + 1) \times (m + 1)\) identity matrix.

Let \( \phi_j \) be the coefficients in the expansion \( \phi(L) = h + d(L^{-1})d(L) \).

Then the first order conditions (4) and (5) can be expressed as:

\[
(D_{m+1} + hI_{m+1}) \begin{bmatrix} y_N \\ y_{N-1} \\ \vdots \\ y_{N-m} \end{bmatrix} = \begin{bmatrix} a_N \\ a_{N-1} \\ \vdots \\ a_{N-m} \end{bmatrix} + M \begin{bmatrix} y_{N-m+1} \\ y_{N-m-2} \\ \vdots \\ y_{N-2m} \end{bmatrix}
\]

where \( M \) is \((m + 1) \times m\) and

\[
M_{ij} = \begin{cases} D_{i-j, m+1} & \text{for } i > j \\ 0 & \text{for } i \leq j \end{cases}
\]

\[
\phi_m y_{N-1} + \phi_{m-1} y_{N-2} + \ldots + \phi_0 y_{N-m-1} + \phi_1 y_{N-m-2} + \ldots + \phi_m y_{N-2m-1} = a_{N-m-1}
\]

\[
\phi_m y_{N-2} + \phi_{m-1} y_{N-3} + \ldots + \phi_0 y_{N-m-2} + \phi_1 y_{N-m-3} + \ldots + \phi_m y_{N-2m-2} = a_{N-m-2}
\]

\[
\vdots
\]

\[
\phi_m y_m + \phi_{m-1} y_{m-1} + \phi_{m-2} + \ldots + \phi_0 y_0 + \phi_1 y_{-1} + \ldots + \phi_m y_{-m} = a_0
\]

As before, we can express this equation as \( W \tilde{y} = \tilde{a} \).

The matrix on the left of this equation is “almost” Toeplitz, the exception being the leading \( m \times m \) submatrix in the upper left-hand corner.

We can represent the solution in feedback-feedforward form by obtaining a decomposition \( LU = W \), and obtain

\[
U \tilde{y} = L^{-1} \tilde{a}
\]

\[
\sum_{j=0}^{t} U_{t+j-N+1, -t+N+j+1} y_{t-j} = \sum_{j=0}^{N-t} L_{-t+N+1, -t+N+1-j} \tilde{a}_{t+j},
\]

\[
t = 0, 1, \ldots, N
\]

where \( L_{t,s}^{-1} \) is the element in the \((t, s)\) position of \( L \), and similarly for \( U \).
The left side of equation (11) is the “feedback” part of the optimal control law for \( y_t \), while the right-hand side is the “feedforward” part.

We note that there is a different control law for each \( t \).

Thus, in the finite horizon case, the optimal control law is time-dependent.

It is natural to suspect that as \( N \to \infty \), (11) becomes equivalent to the solution of our infinite horizon problem, which below we shall show can be expressed as

\[
c(L)y_t = c(\beta L^{-1})^{-1}a_t,
\]

so that as \( N \to \infty \) we expect that for each fixed \( t, U_{t,t-j}^{-1} \to c_j \) and \( L_{t,t+j} \) approaches the coefficient on \( L^{-j} \) in the expansion of \( c(\beta L^{-1})^{-1} \).

This suspicion is true under general conditions that we shall study later.

For now, we note that by creating the matrix \( W \) for large \( N \) and factoring it into the \( LU \) form, good approximations to \( c(L) \) and \( c(\beta L^{-1})^{-1} \) can be obtained.

### 30.5 The Infinite Horizon Limit

For the infinite horizon problem, we propose to discover first-order necessary conditions by taking the limits of (4) and (5) as \( N \to \infty \).

This approach is valid, and the limits of (4) and (5) as \( N \) approaches infinity are first-order necessary conditions for a maximum.

However, for the infinite horizon problem with \( \beta < 1 \), the limits of (4) and (5) are, in general, not sufficient for a maximum.

That is, the limits of (5) do not provide enough information uniquely to determine the solution of the Euler equation (4) that maximizes (1).

As we shall see below, a side condition on the path of \( y_t \) that together with (4) is sufficient for an optimum is

\[
\sum_{t=0}^{\infty} \beta^t h y_t^2 < \infty
\]  

(12)

All paths that satisfy the Euler equations, except the one that we shall select below, violate this condition and, therefore, evidently lead to (much) lower values of (1) than does the optimal path selected by the solution procedure below.

Consider the characteristic equation associated with the Euler equation

\[
h + d(\beta z^{-1})d(z) = 0
\]  

(13)

Notice that if \( \tilde{z} \) is a root of equation (13), then so is \( \beta \tilde{z}^{-1} \).

Thus, the roots of (13) come in “\( \beta \)-reciprocal” pairs.

Assume that the roots of (13) are distinct.

Let the roots be, in descending order according to their moduli, \( z_1, z_2, \ldots, z_{2m} \).
From the reciprocal pairs property and the assumption of distinct roots, it follows that $|z_j| > \sqrt{\beta}$ for $j \leq m$ and $|z_j| < \sqrt{\beta}$ for $j > m$.

It also follows that $z_{2m-j} = \beta^{-1}z_{j+1}$, $j = 0, 1, \ldots, m - 1$.

Therefore, the characteristic polynomial on the left side of (13) can be expressed as

$$h + d(\beta z^{-1})d(z) = z^{-m}z_0(z - z_1) \cdots (z - z_m)(z - z_{m+1}) \cdots (z - z_{2m})$$

$$= z^{-m}z_0(z - z_1)(z - z_2) \cdots (z - z_m)(z - \beta z_{m}^{-1}) \cdots (z - \beta z_2^{-1})(z - \beta z_1^{-1}) \quad (14)$$

where $z_0$ is a constant.

In (14), we substitute $(z - z_j) = -z_j(1 - \frac{1}{z_j}z)$ and $(z - \beta z_j^{-1}) = z(1 - \frac{\beta}{z_j}z^{-1})$ for $j = 1, \ldots, m$ to get

$$h + d(\beta z^{-1})d(z) = (-1)^m(z_0z_1 \cdots z_m)(1 - \frac{1}{z_1}z)(1 - \frac{1}{z_m}z)(1 - \frac{1}{z_1}\beta z_{m}^{-1}) \cdots (1 - \frac{1}{z_m}\beta z_1^{-1})$$

Now define $c(z) = \sum_{j=0}^{m} c_j z^j$ as

$$c(z) = \left[(-1)^m z_0 \cdots z_m\right]^{1/2} \left(1 - \frac{z}{z_1}\right) \left(1 - \frac{z}{z_2}\right) \cdots \left(1 - \frac{z}{z_m}\right) \quad (15)$$

Notice that (14) can be written

$$h + d(\beta z^{-1})d(z) = c(\beta z^{-1})c(z) \quad (16)$$

It is useful to write (15) as

$$c(z) = c_0(1 - \lambda_1 z) \cdots (1 - \lambda_m z) \quad (17)$$

where

$$c_0 = \left[(-1)^m z_0 \cdots z_m\right]^{1/2}; \quad \lambda_j = \frac{1}{z_j}, \quad j = 1, \ldots, m$$

Since $|z_j| > \sqrt{\beta}$ for $j = 1, \ldots, m$ it follows that $|\lambda_j| < 1/\sqrt{\beta}$ for $j = 1, \ldots, m$.

Using (17), we can express the factorization (16) as

$$h + d(\beta z^{-1})d(z) = c_0^2(1 - \lambda_1 z) \cdots (1 - \lambda_m z)(1 - \lambda_1\beta z^{-1}) \cdots (1 - \lambda_m\beta z^{-1})$$

In sum, we have constructed a factorization (16) of the characteristic polynomial for the Euler equation in which the zeros of $c(z)$ exceed $\beta^{1/2}$ in modulus, and the zeros of $c(\beta z^{-1})$ are less than $\beta^{1/2}$ in modulus.

Using (16), we now write the Euler equation as

$$c(\beta L^{-1})c(L)y_t = a_t$$
The unique solution of the Euler equation that satisfies condition (12) is

\[ c(L)y_t = c(\beta L^{-1})^{-1}a_t \]  

(18)

This can be established by using an argument paralleling that in chapter IX of [59].

To exhibit the solution in a form paralleling that of [59], we use (17) to write (18) as

\[ (1 - \lambda_1 L) \cdots (1 - \lambda_m L)y_t = \frac{c_0^{-2}a_t}{(1 - \beta \lambda_1 L^{-1}) \cdots (1 - \beta \lambda_m L^{-1})} \]  

(19)

Using partial fractions, we can write the characteristic polynomial on the right side of (19) as

\[ \sum_{j=1}^{m} \frac{A_j}{1 - \lambda_j \beta L^{-1}} \quad \text{where} \quad A_j := \frac{c_0^{-2}}{\prod_{i \neq j}(1 - \frac{\lambda_i}{\lambda_j})} \]

Then (19) can be written

\[ (1 - \lambda_1 L) \cdots (1 - \lambda_m L)y_t = \sum_{j=1}^{m} \frac{A_j}{1 - \lambda_j \beta L^{-1}}a_t \]

or

\[ (1 - \lambda_1 L) \cdots (1 - \lambda_m L)y_t = \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} (\lambda_j \beta)^k a_{t+k} \]  

(20)

Equation (20) expresses the optimum sequence for \( y_t \) in terms of \( m \) lagged \( y \)'s, and \( m \) weighted infinite geometric sums of future \( a_t \)'s.

Furthermore, (20) is the unique solution of the Euler equation that satisfies the initial conditions and condition (12).

In effect, condition (12) compels us to solve the “unstable” roots of \( h + d(\beta z^{-1})d(z) \) forward (see [59]).

The step of factoring the polynomial \( h + d(\beta z^{-1})d(z) \) into \( c(\beta z^{-1})c(z) \), where the zeros of \( c(z) \) all have modulus exceeding \( \sqrt{\beta} \), is central to solving the problem.

We note two features of the solution (20)

1. Since \( |\lambda_j| < 1/\sqrt{\beta} \) for all \( j \), it follows that \( (\lambda_j \beta) < \sqrt{\beta} \).
2. The assumption that \( \{a_t\} \) is of exponential order less than \( 1/\sqrt{\beta} \) is sufficient to guarantee that the geometric sums of future \( a_t \)'s on the right side of (20) converge.

We immediately see that those sums will converge under the weaker condition that \( \{a_t\} \) is of exponential order less than \( \phi^{-1} \) where \( \phi = \max \{\beta \lambda_i, i = 1, \ldots, m\} \).

Note that with \( a_t \) identically zero, (20) implies that in general \( |y_t| \) eventually grows exponentially at a rate given by \( \max_i |\lambda_i| \).

The condition \( \max_i |\lambda_i| < 1/\sqrt{\beta} \) guarantees that condition (12) is satisfied.

In fact, \( \max_i |\lambda_i| < 1/\sqrt{\beta} \) is a necessary condition for (12) to hold.

Were (12) not satisfied, the objective function would diverge to \( -\infty \), implying that the \( y_t \) path could not be optimal.
For example, with $a_t = 0$, for all $t$, it is easy to describe a naive (nonoptimal) policy for \( \{y_t, t \geq 0\} \) that gives a finite value of (17).

We can simply let $y_t = 0$ for $t \geq 0$.

This policy involves at most $m$ nonzero values of $hy^2$ and $[d(L)y_t]^2$, and so yields a finite value of (1).

Therefore it is easy to dominate a path that violates (12).

### 30.6 Undiscounted Problems

It is worthwhile focusing on a special case of the LQ problems above: the undiscounted problem that emerges when $\beta = 1$.

In this case, the Euler equation is

\[
\left(h + d(L^{-1})d(L)\right)y_t = a_t
\]

The factorization of the characteristic polynomial (16) becomes

\[
\left(h + d(z^{-1})d(z)\right) = c(z^{-1})c(z)
\]

where

\[
c(z) = c_0(1 - \lambda_1 z)\ldots(1 - \lambda_m z)
\]

\[
c_0 = \begin{bmatrix} (-1)^m z_0 z_1 \ldots z_m \end{bmatrix}
\]

\[
|\lambda_j| < 1 \text{ for } j = 1, \ldots, m
\]

\[
\lambda_j = \frac{1}{z_j} \text{ for } j = 1, \ldots, m
\]

\[
z_0 = \text{constant}
\]

The solution of the problem becomes

\[
(1 - \lambda_1 L)\ldots(1 - \lambda_m L)y_t = \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} \lambda_j^k a_{t+k}
\]

### 30.6.1 Transforming Discounted to Undiscounted Problem

Discounted problems can always be converted into undiscounted problems via a simple transformation.

Consider problem (1) with $0 < \beta < 1$.

Define the transformed variables

\[
\tilde{a}_t = \beta^{t/2}a_t, \quad \tilde{y}_t = \beta^{t/2}y_t
\]

Then notice that $\beta^t [d(L)y_t]^2 = [\tilde{d}(L)\tilde{y}_t]^2$ with $\tilde{d}(L) = \sum_{j=0}^{m} \tilde{d}_j L^j$ and $\tilde{d}_j = \beta^{j/2}d_j$. 

Then the original criterion function (1) is equivalent to

$$\lim_{N \to \infty} \sum_{t=0}^{N} \{ \tilde{a}_t \tilde{y}_t - \frac{1}{2} h \tilde{y}_t^2 - \frac{1}{2} [\tilde{d}(L) \tilde{y}_t]^2 \}$$  \hspace{1cm} (22)

which is to be maximized over sequences \( \{ \tilde{y}_t, \ t = 0, \ldots \} \) subject to \( \tilde{y}_{-1}, \ldots, \tilde{y}_{-m} \) given and \( \{ \tilde{a}_t, \ t = 1, \ldots \} \) a known bounded sequence.

The Euler equation for this problem is \([h + \tilde{d}(L^{-1}) \tilde{d}(L)] \tilde{y}_t = \tilde{a}_t\).

The solution is

$$(1 - \tilde{\lambda}_1 z) \cdots (1 - \tilde{\lambda}_m z) \tilde{y}_t = \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k \tilde{a}_{t+k}$$

or

$$\tilde{y}_t = \tilde{f}_1 \tilde{y}_{t-1} + \cdots + \tilde{f}_m \tilde{y}_{t-m} + \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k \tilde{a}_{t+k},$$  \hspace{1cm} (23)

where \( \tilde{c}(z^{-1}) \tilde{c}(z) = h + \tilde{d}(z^{-1}) \tilde{d}(z) \), and where

$$[(\tilde{c}(z^{-1}) \tilde{c}(z) = h + \tilde{d}(z^{-1}) \tilde{d}(z), \text{ where } |\tilde{\lambda}_j| < 1$$

We leave it to the reader to show that (23) implies the equivalent form of the solution

$$y_t = f_1 y_{t-1} + \cdots + f_m y_{t-m} + \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} (\lambda_j \beta)^k a_{t+k}$$

where

$$f_j = \tilde{f}_j \beta^{-j/2}, \ A_j = \tilde{A}_j, \ \lambda_j = \tilde{\lambda}_j \beta^{-1/2}$$  \hspace{1cm} (24)

The transformations (21) and the inverse formulas (24) allow us to solve a discounted problem by first solving a related undiscounted problem.

### 30.7 Implementation

Here’s the code that computes solutions to the LQ problem using the methods described above.

```python
import numpy as np
import scipy.stats as spst
import scipy.linalg as la

class LQFilter:
    def __init__(self, d, h, y_m, r=None, h_eps=None, beta=None):
```

In [2]: import numpy as np
import scipy.stats as spst
import scipy.linalg as la

class LQFilter:
    def __init__(self, d, h, y_m, r=None, h_eps=None, beta=None):
```
Parameters
----------

- **d**: list or numpy.array (1-D or a 2-D column vector)
  - The order of the coefficients: \([d_0, d_1, \ldots, d_m]\)
- **h**: scalar
  - Parameter of the objective function (corresponding to the quadratic term)
- **y_m**: list or numpy.array (1-D or a 2-D column vector)
  - Initial conditions for \(y\)
- **r**: list or numpy.array (1-D or a 2-D column vector)
  - The order of the coefficients: \([r_0, r_1, \ldots, r_k]\)
  - (optional, if not defined -> deterministic problem)
- **\(\beta\)**: scalar
  - Discount factor (optional, default value is one)

```python
self.h = h
self.d = np.asarray(d)
self.m = self.d.shape[0] - 1

self.y_m = np.asarray(y_m)

if self.m == self.y_m.shape[0]:
    self.y_m = self.y_m.reshape(self.m, 1)
else:
    raise ValueError("y_m must be of length m = {self.m:d}\)

#---------------------------------------------
# Define the coefficients of \(\phi\) upfront
#---------------------------------------------
ϕ = np.zeros(2 * self.m + 1)
for i in range(-self.m, self.m + 1):
    ϕ[self.m - i] = np.sum(np.diag(self.d.reshape(self.m + 1, 1) \ @ self.d.reshape(1, self.m + 1),
                                  k=-i)
                         )

ϕ[self.m] = ϕ[self.m] + self.h
self.ϕ = ϕ

#---------------------------------------------
# If \(r\) is given calculate the vector \(\phi_r\)
#---------------------------------------------
if r is None:
    pass
else:
    self.r = np.asarray(r)
    self.k = self.r.shape[0] - 1
    ϕ_r = np.zeros(2 * self.k + 1)
    for i in range(-self.k, self.k + 1):
        ϕ_r[self.k - i] = np.sum(np.diag(self.r.reshape(self.k + 1, 1) \ @ self.r.reshape(1, self.k + 1),
                                          k=-i)
                                )

if h_eps is None:
```
self.ϕ_r = ϕ_r
else:
    ϕ_r[self.k] = ϕ_r[self.k] + h_eps
self.ϕ_r = ϕ_r

# If β is given, define the transformed variables
if β is None:
    self.β = 1
else:
    self.β = β
self.d = self.β**((np.arange(self.m + 1)/2) * self.d)
self.y_m = self.y_m * (self.β**((- np.arange(1, self.m + 1)/2)) \  
    .reshape(self.m, 1))

def construct_W_and_Wm(self, N):
    """This constructs the matrices W and W_m for a given number of periods N """
    m = self.m
d = self.d

    W = np.zeros((N + 1, N + 1))
    W_m = np.zeros((N + 1, m))

    #---------------------------------------
    # Terminal conditions
    #---------------------------------------
    D_m1 = np.zeros((m + 1, m + 1))
    M = np.zeros((m + 1, m))

    # (1) Construct the D_{m+1} matrix using the formula
    for j in range(m + 1):
        for k in range(j, m + 1):
            D_m1[j, k] = d[:j + 1] @ d[k - j: k + 1]

            # Make the matrix symmetric
            D_m1 = D_m1 + D_m1.T - np.diag(np.diag(D_m1))

    # (2) Construct the M matrix using the entries of D_m1
    for j in range(m):
        for i in range(j + 1, m + 1):
            M[i, j] = D_m1[i - j - 1, m]

    # Euler equations for t = 0, 1, ..., N-(m+1)
    phi = self.ϕ

    W[:,(m + 1), :,(m + 1)] = D_m1 + self.h * np.eye(m + 1)
    W[:,(m + 1), (m + 1):(2 * m + 1)] = M

    for i, row in enumerate(np.arange(m + 1, N + 1 - m)): 
30.7. IMPLEMENTATION

```python
W[row, (i + 1):(2 * m + 2 + i) = \phi

for i in range(1, m + 1):
    W[N - m + i, -(2 * m + 1 - i):] = \phi[:i]

for i in range(m):
    W_m[N - i, :(m - i)] = \phi[(m + 1 + i):]

return W, W_m

def roots_of_characteristic(self):
    """
    This function calculates z_0 and the 2m roots of the characteristic
equation associated with the Euler equation (1.7)
    """
    m = self.m
    \phi = self.\phi
    # Calculate the roots of the 2m-polynomial
    roots = np.roots(\phi)
    # Sort the roots according to their length (in descending order)
    roots_sorted = roots[np.argsort(abs(roots))[:-1]]
    z_0 = \phi.sum() / np.poly1d(roots, True)(1)
    z_1_to_m = roots_sorted[:m]  # We need only those outside the
    # unit circle
    \lambda = 1 / z_1_to_m
    return z_1_to_m, z_0, \lambda

def coeffs_of_c(self):
    """
    This function computes the coefficients \{c_j, j = 0, 1, ..., m\} for
\(c(z) = \sum_{j = 0}^{m} c_j z^j\)
    Based on the expression (1.9). The order is
    \(\cdots, c_\text{coeffs} = [c_0, c_1, ..., c_{m-1}, c_m]\)
    z_1_to_m, z_0 = self.roots_of_characteristic()[:2]
    c_0 = (z_0 * np.prod(z_1_to_m).real * (-1)**self.m)**.5
    c_coeffs = np.poly1d(z_1_to_m, True).c * z_0 / c_0
    return c_coeffs[:-1]

def solution(self):
    """
    This function calculates \{\lambda_j, j=1,\ldots,m\} and \{A_j, j=1,\ldots,m\}
    of the expression (1.15)
    """
```
\[ \lambda = \text{self.roots_of_characteristic()}[2] \]
\[ c_0 = \text{self.coeffs_of_c()}[-1] \]

\[ A = \text{np.zeros}(\text{self.m}, \text{dtype=complex}) \]
\[ \text{for j in range}(\text{self.m}): \]
\[ \text{denom} = 1 - \frac{\lambda[\text{j}]}{\lambda[\text{j}]} \]
\[ A[\text{j}] = c_0^2 / \text{np.prod}(\text{denom}[\text{np.arange}(\text{self.m}) != \text{j}]) \]

\[ \text{return } \lambda, A \]

```python
def construct_V(self, N):
    '''
    This function constructs the covariance matrix for \( x^N \) (see section 6)
    for a given period \( N \)
    '''
    V = \text{np.zeros}((N, N))
    \( \phi_r \) = self.\( \phi_r \)
    \[ \text{for i in range}(N): \]
    \[ \text{for j in range}(N): \]
    \[ \text{if } \text{abs}(i-j) <= \text{self.k}: \]
    \[ V[i, j] = \phi_r[\text{self.k + abs(i-j)}] \]
    \[ \text{return } V \]
```

```python
def simulate_a(self, N):
    '''
    Assuming that the u's are normal, this method draws a random path for \( x^N \)
    '''
    V = self.construct_V(N + 1)
    d = spst.multivariate_normal(np.zeros(N + 1), V)
    \[ \text{return } d.\text{rvs()} \]
```

```python
def predict(self, a_hist, t):
    '''
    This function implements the prediction formula discussed in section 6 (1.59)
    It takes a realization for \( a^N \), and the period in which the prediction is formed
    Output: \( E[\bar{a} | a_t, a_{t-1}, ..., a_1, a_0] \)
    '''
    N = np.asarray(a_hist).shape[0] - 1
    a_hist = np.asarray(a_hist).reshape(N + 1, 1)
    V = self.construct_V(N + 1)
    aux_matrix = np.zeros((N + 1, N + 1))
    aux_matrix[:,(t + 1)] = np.eye(t + 1)
    L = la.cholesky(V).T
    Ea_hist = la.inv(L) @ aux_matrix @ L @ a_hist
    \[ \text{return } Ea_hist \]
```
def optimal_y(self, a_hist, t=None):
    ""
    - if t is NOT given it takes a_hist (list or numpy.array) as a
deterministic a_t
    - if t is given, it solves the combined control prediction problem
      (section 7)(by default, t == None -> deterministic)

    for a given sequence of a_t (either deterministic or a particular
realization), it calculates the optimal y_t sequence using the method
of the lecture

    Note:------
    scipy.linalg.lu normalizes L, U so that L has unit diagonal elements
To make things consistent with the lecture, we need an auxiliary
diagonal matrix D which renormalizes L and U
""

    N = np.asarray(a_hist).shape[0] - 1
    W, W_m = self.construct_W_and_Wm(N)
    L, U = la.lu(W, permute_l=True)
    D = np.diag(1 / np.diag(U))
    U = D @ U
    L = L @ np.diag(1 / np.diag(D))
    J = np.fliplr(np.eye(N + 1))
    if t is None:  # If the problem is deterministic
        a_hist = J @ np.asarray(a_hist).reshape(N + 1, 1)
        a_bar = a_hist - W_m @ self.y_m  # a_bar from the lecture
        Uy = np.linalg.solve(L, a_bar)  # U @ y_bar = L^{-1}
        y_bar = np.linalg.solve(U, Uy)  # y_bar = U^{-1}L^{-1}
        J = np.fliplr(np.eye(N + self.m + 1))
        y_hist = J @ np.vstack([y_bar, self.y_m])
        if self.β != 1:
            y_hist = y_hist * (self.β**((np.arange(N + 1) / 2))[:-1] \ 
                              .reshape(N + 1, 1))
        return y_hist, L, U, y_bar
    else:  # If the problem is stochastic and we look at it
Ea_hist = self.predict(a_hist, t).reshape(N + 1, 1)
Ea_hist = J @ Ea_hist

a_bar = Ea_hist - W_m @ self.y_m  # a_bar from the lecture
Uy = np.linalg.solve(L, a_bar) # U @ y_bar = L^{-1}
y_bar = np.linalg.solve(U, Uy) # y_bar = U^{-1}L^{-1}

# Reverse the order of y_bar with the matrix J
J = np.flip(np.eye(N + self.m + 1))
# y_hist : concatenated y_m and y_bar
y_hist = J @ np.vstack([y_bar, self.y_m])

return y_hist, L, U, y_bar

30.7.1 Example

In this application, we’ll have one lag, with

\[ d(L)y_t = \gamma(I - L)y_t = \gamma(y_t - y_{t-1}) \]

Suppose for the moment that \( \gamma = 0 \).

Then the intertemporal component of the LQ problem disappears, and the agent simply
wants to maximize \( a_t y_t - h y_t^2 / 2 \) in each period.

This means that the agent chooses \( y_t = a_t / h \).

In the following we’ll set \( h = 1 \), so that the agent just wants to track the \( \{a_t\} \) process.

However, as we increase \( h = 1 \), so that the agent just wants to track the \( \{a_t\} \) process.

Hence \( \{y_t\} \) evolves as a smoothed version of \( \{a_t\} \).

The \( \{a_t\} \) sequence we’ll choose as a stationary cyclic process plus some white noise.

Here’s some code that generates a plot when \( \gamma = 0.8 \)

```python
In [3]: # Set seed and generate a_t sequence
np.random.seed(123)
n = 100
a_seq = np.sin(np.linspace(0, 5 * np.pi, n)) + 2 + 0.1 * np.random.randn(n)

def plot_simulation(\gamma=0.8, m=\text{1}, \text{h}=1, y_m=2):
    d = \gamma * np.asarray([1, -1])
y_m = np.asarray(y_m).reshape(m, 1)

testlq = LQFilter(d, h, y_m)
y_hist, L, U, y = testlq.optimal_y(a_seq)
y = y[::-1]  # Reverse y

# Plot simulation results
fig, ax = plt.subplots(figsize=(10, 6))
p_args = \{'lw' : 2, 'alpha' : 0.6\}

time = range(len(y))
ax.plot(time, a_seq / h, \'k-o\', ms=4, lw=2, alpha=0.6, label='\$a_t\$')
```

# Set seed and generate a_t sequence
np.random.seed(123)
n = 100
a_seq = np.sin(np.linspace(0, 5 * np.pi, n)) + 2 + 0.1 * np.random.randn(n)

def plot_simulation(\gamma=0.8, m=\text{1}, \text{h}=1, y_m=2):
    d = \gamma * np.asarray([1, -1])
y_m = np.asarray(y_m).reshape(m, 1)

testlq = LQFilter(d, h, y_m)
y_hist, L, U, y = testlq.optimal_y(a_seq)
y = y[::-1]  # Reverse y

# Plot simulation results
fig, ax = plt.subplots(figsize=(10, 6))
p_args = \{'lw' : 2, 'alpha' : 0.6\}

time = range(len(y))
ax.plot(time, a_seq / h, \'k-o\', ms=4, lw=2, alpha=0.6, label='\$a_t\$')
30.7. IMPLEMENTATION

```python
ax.plot(time, y, 'b-o', ms=4, lw=2, alpha=0.6, label='$y_t$')
ax.set(title=r'Dynamics with $\gamma = \gamma$',
       xlabel='Time',
       xlim=(0, max(time)))
ax.legend()
ax.grid()
plt.show()

plot_simulation()
```

Here's what happens when we change $\gamma$ to 5.0

In [4]: plot_simulation($\gamma$=5)
And here’s $\gamma = 10$

In [5]: `plot_simulation(\gamma=10)`
30.8 Exercises

30.8.1 Exercise 1

Consider solving a discounted version \((\beta < 1)\) of problem (1), as follows.

Convert (1) to the undiscounted problem (22).

Let the solution of (22) in feedback form be

\[
(1 - \tilde{\lambda}_1 L) \cdots (1 - \tilde{\lambda}_m L) \tilde{y}_t = \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k \tilde{a}_{t+k}
\]

or

\[
\tilde{y}_t = \tilde{f}_1 \tilde{y}_{t-1} + \cdots + \tilde{f}_m \tilde{y}_{t-m} + \sum_{j=1}^{m} \tilde{A}_j \sum_{k=0}^{\infty} \tilde{\lambda}_j^k \tilde{a}_{t+k}
\]  \hspace{1cm} (25)

Here

- \( h + \tilde{d}(z^{-1}) \tilde{d}(z) = \tilde{c}(z^{-1}) \tilde{c}(z) \)
- \( \tilde{c}(z) = [(-1)^m \tilde{z}_0 \tilde{z}_1 \cdots \tilde{z}_m]^{1/2} (1 - \tilde{\lambda}_1 z) \cdots (1 - \tilde{\lambda}_m z) \)

where the \( \tilde{z}_j \) are the zeros of \( h + \tilde{d}(z^{-1}) \tilde{d}(z) \).

Prove that (25) implies that the solution for \( y_t \) in feedback form is

\[
y_t = f_1 y_{t-1} + \cdots + f_m y_{t-m} + \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} \lambda_j^k a_{t+k}
\]

where \( f_j = \tilde{f}_j \beta^{-j/2}, A_j = \tilde{A}_j, \) and \( \lambda_j = \tilde{\lambda}_j \beta^{-1/2} \).

30.8.2 Exercise 2

Solve the optimal control problem, maximize

\[
\sum_{t=-1}^{2} \left\{ a_t y_t - \frac{1}{2} \left[ (1 - 2L) y_t \right]^2 \right\}
\]

subject to \( y_{-1} \) given, and \( \{a_t\} \) a known bounded sequence.

Express the solution in the “feedback form” (20), giving numerical values for the coefficients.

Make sure that the boundary conditions (5) are satisfied.

(Note: this problem differs from the problem in the text in one important way: instead of \( h > 0 \) in (1), \( h = 0 \). This has an important influence on the solution.)

30.8.3 Exercise 3

Solve the infinite time-optimal control problem to maximize
\[
\lim_{N \to \infty} \sum_{t=0}^{N} \frac{1}{2} [(1 - 2L)y_t]^2,
\]

subject to \( y_{-1} \) given. Prove that the solution is

\[ y_t = 2y_{t-1} = 2^{t+1}y_{-1} \quad t > 0 \]

**30.8.4 Exercise 4**

Solve the infinite time problem, to maximize

\[
\lim_{N \to \infty} \sum_{t=0}^{N} (0.0000001) y_t^2 - \frac{1}{2} [(1 - 2L)y_t]^2
\]

subject to \( y_{-1} \) given. Prove that the solution \( y_t = 2y_{t-1} \) violates condition (12), and so is not optimal.

Prove that the optimal solution is approximately \( y_t = 0.5y_{t-1} \).
Chapter 31

Classical Prediction and Filtering
With Linear Algebra

31.1 Contents

- Overview 31.2
- Finite Dimensional Prediction 31.3
- Combined Finite Dimensional Control and Prediction 31.4
- Infinite Horizon Prediction and Filtering Problems 31.5
- Exercises 31.6

31.2 Overview

This is a sequel to the earlier lecture Classical Control with Linear Algebra.

That lecture used linear algebra – in particular, the LU decomposition – to formulate and solve a class of linear-quadratic optimal control problems.

In this lecture, we’ll be using a closely related decomposition, the Cholesky decomposition, to solve linear prediction and filtering problems.

We exploit the useful fact that there is an intimate connection between two superficially different classes of problems:

- deterministic linear-quadratic (LQ) optimal control problems
- linear least squares prediction and filtering problems

The first class of problems involves no randomness, while the second is all about randomness. Nevertheless, essentially the same mathematics solves both types of problem.

This connection, which is often termed “duality,” is present whether one uses “classical” or “recursive” solution procedures.

In fact, we saw duality at work earlier when we formulated control and prediction problems recursively in lectures LQ dynamic programming problems, A first look at the Kalman filter, and The permanent income model.

A useful consequence of duality is that

- With every LQ control problem, there is implicitly affiliated a linear least squares pre-
• With every linear least squares prediction or filtering problem there is implicitly affiliated a LQ control problem.

An understanding of these connections has repeatedly proved useful in cracking interesting applied problems.

For example, Sargent [59] [chs. IX, XIV] and Hansen and Sargent [27] formulated and solved control and filtering problems using z-transform methods.

In this lecture, we begin to investigate these ideas by using mostly elementary linear algebra.

This is the main purpose and focus of the lecture.

However, after showing matrix algebra formulas, we’ll summarize classic infinite-horizon formulas built on z-transform and lag operator methods.

And we’ll occasionally refer to some of these formulas from the infinite dimensional problems as we present the finite time formulas and associated linear algebra.

We’ll start with the following standard import:

```python
import numpy as np
```

### 31.2.1 References

Useful references include [68], [27], [49], [5], and [48].

### 31.3 Finite Dimensional Prediction

Let \((x_1, x_2, \ldots, x_T)^\prime = x\) be a \(T \times 1\) vector of random variables with mean \(\mathbb{E}x = 0\) and covariance matrix \(\mathbb{E}xx^\prime = V\).

Here \(V\) is a \(T \times T\) positive definite matrix.

The \(i, j\) component \(Ex_i x_j\) of \(V\) is the **inner product** between \(x_i\) and \(x_j\).

We regard the random variables as being ordered in time so that \(x_t\) is thought of as the value of some economic variable at time \(t\).

For example, \(x_t\) could be generated by the random process described by the Wold representation presented in equation (16) in the section below on infinite dimensional prediction and filtering.

In that case, \(V_{ij}\) is given by the coefficient on \(z^{i-j}\) in the expansion of \(g_x(z) = d(z) d(z^{-1}) + h\), which equals \(h + \sum_{k=0}^{\infty} d_k d_{k+i-j}\).

We want to construct \(j\) step ahead linear least squares predictors of the form

\[
\hat{E} [x_T | x_{T-j}, x_{T-j+1}, \ldots, x_1]
\]

where \(\hat{E}\) is the linear least squares projection operator.

(Sometimes \(\hat{E}\) is called the wide-sense expectations operator)

To find linear least squares predictors it is helpful first to construct a \(T \times 1\) vector \(\varepsilon\) of random variables that form an orthonormal basis for the vector of random variables \(x\).
The key insight here comes from noting that because the covariance matrix $V$ of $x$ is a positive definite and symmetric, there exists a (Cholesky) decomposition of $V$ such that

$$V = L^{-1}(L^{-1})'$$

and

$$LVL' = I$$

where $L$ and $L^{-1}$ are both lower triangular.

Form the $T \times 1$ random vector $\varepsilon = Lx$.

The random vector $\varepsilon$ is an orthonormal basis for $x$ because

- $L$ is nonsingular
- $\E\varepsilon\varepsilon' = L\E xx'L' = I$
- $x = L^{-1}\varepsilon$

It is enlightening to write out and interpret the equations $Lx = \varepsilon$ and $L^{-1}\varepsilon = x$.

First, we’ll write $Lx = \varepsilon$

$$
L_{11}x_1 = \varepsilon_1 \\
L_{21}x_1 + L_{22}x_2 = \varepsilon_2 \\
\vdots \\
L_{T1}x_1 \ldots + L_{TT}x_T = \varepsilon_T
$$

or

$$
\sum_{j=0}^{t-1} L_{t,t-j}x_{t-j} = \varepsilon_t, \quad t = 1, 2, \ldots, T
$$

Next, we write $L^{-1}\varepsilon = x$

$$
x_1 = L_{11}^{-1}\varepsilon_1 \\
x_2 = L_{22}^{-1}\varepsilon_2 + L_{21}^{-1}\varepsilon_1 \\
\vdots \\
x_T = L_{T1}^{-1}\varepsilon_T + L_{T,T-1}^{-1}\varepsilon_{T-1} \ldots + L_{T,1}^{-1}\varepsilon_1
$$

or

$$
x_t = \sum_{j=0}^{t-1} L_{t,t-j}^{-1} \varepsilon_{t-j}
$$

where $L_{i,j}^{-1}$ denotes the $i,j$ element of $L^{-1}$.

From (2), it follows that $\varepsilon_t$ is in the linear subspace spanned by $x_t, x_{t-1}, \ldots, x_1$.

From (4) it follows that that $x_t$ is in the linear subspace spanned by $\varepsilon_t, \varepsilon_{t-1}, \ldots, \varepsilon_1$. 
Equation (2) forms a sequence of autoregressions that for \( t = 1, \ldots, T \) express \( x_t \) as linear functions of \( x_s, s = 1, \ldots, t - 1 \) and a random variable \((L_{t,t})^{-1}\varepsilon_t\) that is orthogonal to each component of \( x_s, s = 1, \ldots, t - 1 \).

(Here \((L_{t,t})^{-1}\) denotes the reciprocal of \( L_{t,t} \) while \( L_{t,t}^{-1} \) denotes the \( t, t \) element of \( L^{-1} \)).

The equivalence of the subspaces spanned by \( \varepsilon_t, \ldots, \varepsilon_1 \) and \( x_t, \ldots, x_1 \) means that for \( t - 1 \geq m \geq 1 \)

\[
\hat{E}[x_t \mid x_{t-m}, x_{t-m-1}, \ldots, x_1] = \hat{E}[x_t \mid \varepsilon_{t-m}, \varepsilon_{t-m-1}, \ldots, \varepsilon_1] \quad (5)
\]

To proceed, it is useful to drill down and note that for \( t - 1 \geq m \geq 1 \) we can rewrite (4) in the form of the moving average representation

\[
x_t = \sum_{j=0}^{m-1} L_{t,t-j}^{-1} \varepsilon_{t-j} + \sum_{j=m}^{t-1} L_{t,t-j}^{-1} \varepsilon_{t-j} \quad (6)
\]

Representation (6) is an orthogonal decomposition of \( x_t \) into a part \( \sum_{j=m}^{t-1} L_{t,t-j}^{-1} \varepsilon_{t-j} \) that lies in the space spanned by \( [x_{t-m}, x_{t-m+1}, \ldots, x_1] \) and an orthogonal component \( \sum_{j=m}^{t-1} L_{t,t-j}^{-1} \varepsilon_{t-j} \) that does not lie in that space but instead in a linear space known as its orthogonal complement.

It follows that

\[
\hat{E}[x_t \mid x_{t-m}, x_{t-m-1}, \ldots, x_1] = \sum_{j=0}^{m-1} L_{t,t-j}^{-1} \varepsilon_{t-j}
\]

### 31.3.1 Implementation

Here’s the code that computes solutions to LQ control and filtering problems using the methods described here and in :doc: lu_tricks.

```python
import numpy as np
import scipy.stats as spst
import scipy.linalg as la

class LQFilter:
    def __init__(self, d, h, y_m, r=None, h_eps=None, β=None):
        
        Parameters
        ----------
        d : list or numpy.array (1-D or a 2-D column vector)
            The order of the coefficients: \([d_0, d_1, \ldots, d_m]\)
        h : scalar
            Parameter of the objective function (corresponding to the quadratic term)
        y_m : list or numpy.array (1-D or a 2-D column vector)
            Initial conditions for \( y \)
        r : list or numpy.array (1-D or a 2-D column vector)
            The order of the coefficients: \([r_0, r_1, \ldots, r_k]\)
```

(optional, if not defined -> deterministic problem)

\( \beta : \text{scalar} \)

Discount factor (optional, default value is one)

```
self.h = h
self.d = np.asarray(d)
self.m = self.d.shape[0] - 1

self.y_m = np.asarray(y_m)
if self.m == self.y_m.shape[0]:
    self.y_m = self.y_m.reshape(self.m, 1)
else:
    raise ValueError("y_m must be of length m = {self.m:d}")

#---------------------------------------------
# Define the coefficients of \( \phi \) upfront
#---------------------------------------------
φ = np.zeros(2 * self.m + 1)
for i in range(-self.m, self.m + 1):
    φ[self.m - i] = np.sum(np.diag(self.d.reshape(self.m + 1, 1) @ self.d.reshape(1, self.m + 1),
                                   k=-i))

φ[self.m] = φ[self.m] + self.h
self.φ = φ

#-----------------------------------------------------
# If r is given calculate the vector \( \phi_r \)
#-----------------------------------------------------
if r is None:
    pass
else:
    self.r = np.asarray(r)
    self.k = self.r.shape[0] - 1
    φ_r = np.zeros(2 * self.k + 1)
    for i in range(-self.k, self.k + 1):
        φ_r[self.k - i] = np.sum(np.diag(self.r.reshape(self.k + 1, 1) @ self.r.reshape(1, self.k + 1),
                                          k=-i))

    if h_eps is None:
        self.φ_r = φ_r
    else:
        φ_r[self.k] = φ_r[self.k] + h_eps
        self.φ_r = φ_r

#-----------------------------------------------------
# If \( \beta \) is given, define the transformed variables
#-----------------------------------------------------
if β is None:
    self.β = 1
else:
    self.β = β
```python
self.d = self.β**(np.arange(self.m + 1)/2) * self.d
self.y_m = self.y_m * (self.β**(-np.arange(1, self.m + 1)/2))
    .reshape(self.m, 1)

def construct_W_and_Wm(self, N):
    """
    This constructs the matrices W and W_m for a given number of periods N
    """
    m = self.m
d = self.d
W = np.zeros((N + 1, N + 1))
W_m = np.zeros((N + 1, m))

#---------------------------------------
# Terminal conditions
#---------------------------------------
D_m1 = np.zeros((m + 1, m + 1))
M = np.zeros((m + 1, m))

# (1) Construct the D_{m+1} matrix using the formula
for j in range(m + 1):
    for k in range(j, m + 1):
        D_m1[j, k] = d[:j + 1] @ d[k - j: k + 1]
# Make the matrix symmetric
D_m1 = D_m1 + D_m1.T - np.diag(np.diag(D_m1))

# (2) Construct the M matrix using the entries of D_m1
for j in range(m):
    for i in range(j + 1, m + 1):
        M[i, j] = D_m1[i - j - 1, m]

#----------------------------------------------
# Euler equations for t = 0, 1, ..., N-(m+1)
#----------------------------------------------
ϕ = self.ϕ
W[:(m + 1), :(m + 1)] = D_m1 + self.h * np.eye(m + 1)
W[:(m + 1), (m + 1):(2 * m + 1)] = M

for i, row in enumerate(np.arange(m + 1, N + 1 - m)):
    W[row, (i + 1):(2 * m + 2 + i)] = ϕ

for i in range(1, m + 1):
    W[N - m + i, -(2 * m + 1 - i):] = ϕ[:i]

for i in range(m):
    W_m[N - i, :(m - i)] = ϕ[(m + 1 + i):]

return W, W_m

def roots_of_characteristic(self):
    """
```
This function calculates \( z_0 \) and the \( 2m \) roots of the characteristic equation associated with the Euler equation (1.7)

Note: 
-----
`numpy.poly1d(roots, True)` defines a polynomial using its roots that can be evaluated at any point. If \( x_1, x_2, \ldots, x_m \) are the roots then 

\[
p(x) = (x - x_1)(x - x_2)...(x - x_m)
\]

```python
m = self.m
ϕ = self.ϕ

# Calculate the roots of the 2m-polynomial
roots = np.roots(ϕ)
# Sort the roots according to their length (in descending order)
roots_sorted = roots[np.argsort(abs(roots))[:-1]]

z_0 = ϕ.sum() / np.poly1d(roots, True)(1)
z_1_to_m = roots_sorted[:m] # We need only those outside the unit circle
```

\( λ = 1 / z_1_to_m \)

```python
def coeffs_of_c(self):
    ""
    This function computes the coefficients \{c_j, j = 0, 1, ..., m\} for 
    \( c(z) = \sum_{j = 0}^{m} c_j z^j \)
    
    Based on the expression (1.9). The order is 
    \[ c_coeffs = [c_0, c_1, ..., c_{m-1}, c_m] \]
    
    z_1_to_m, z_0 = self.roots_of_characteristic()[2]
    c_0 = (z_0 * np.prod(z_1_to_m).real * (-1)**self.m)**(.5)
    c_coeffs = np.poly1d(z_1_to_m, True).c * z_0 / c_0
    return c_coeffs[:-1]
```

def solution(self):
    ""
    This function calculates \{λ_j, j=1,...,m\} and \{A_j, j=1,...,m\}
    of the expression (1.15)
    
    \[ λ = self.roots_of_characteristic()[:2] \]
    \[ c_0 = self.coeffs_of_c()[-1] \]
    
    A = np.zeros(self.m, dtype=complex)
    for j in range(self.m):
        denom = 1 - λ/λ[j]
        A[j] = c_0**(-2) / np.prod(denom[np.arange(self.m) != j])
    
    return λ, A
```

def construct_V(self, N):
    """
This function constructs the covariance matrix for $x^N$ (see section 6) for a given period $N$.

```python
V = np.zeros((N, N))
ϕ_r = self.ϕ_r

for i in range(N):
    for j in range(N):
        if abs(i-j) <= self.k:
            V[i, j] = ϕ_r[self.k + abs(i-j)]

return V
```

def simulate_a(self, N):
    """Assuming that the u's are normal, this method draws a random path for $x^N$.""
    V = self.construct_V(N + 1)
    d = spst.multivariate_normal(np.zeros(N + 1), V)
    return d.rvs()

def predict(self, a_hist, t):
    """This function implements the prediction formula discussed in section 6 (1.59). It takes a realization for $a^N$, and the period in which the prediction is formed.

Output: $E[\bar{a}_t \mid a_t, a_{t-1}, ..., a_1, a_0]$""

N = np.asarray(a_hist).shape[0] - 1
a_hist = np.asarray(a_hist).reshape(N + 1, 1)
V = self.construct_V(N + 1)

aux_matrix = np.zeros((N + 1, N + 1))
aux_matrix[:][:, :t+1] = np.eye(t + 1)
L = np.cholesky(V).T
Ea_hist = L @ aux_matrix @ L @ a_hist

return Ea_hist

def optimal_y(self, a_hist, t=None):
    """- if t is NOT given it takes a_hist (list or numpy.array) as a deterministic a_t
- if t is given, it solves the combined control prediction problem (section 7) (by default, t == None -> deterministic)

for a given sequence of a_t (either deterministic or a particular realization), it calculates the optimal $y_t$ sequence using the method of the lecture

Note:
scipy.linalg.lu normalizes $L$, $U$ so that $L$ has unit diagonal elements.

To make things consistent with the lecture, we need an auxiliary diagonal matrix $D$ which renormalizes $L$ and $U$.

```python
N = np.asarray(a_hist).shape[0] - 1
W, W_m = self.construct_W_and_Wm(N)

L, U = la.lu(W, permute_l=True)
D = np.diag(1 / np.diag(U))
U = D @ U
L = L @ np.diag(1 / np.diag(D))

J = np.fliplr(np.eye(N + 1))
if t is None:  # If the problem is deterministic
    a_hist = J @ np.asarray(a_hist).reshape(N + 1, 1)
    #---------------------------------------------------------------
    # Transform the 'a' sequence if $\beta$ is given
    #---------------------------------------------------------------
    if self.\beta != 1:
        a_hist = a_hist * (self.\beta**((np.arange(N + 1) / 2))[:,::-1]  
                          .reshape(N + 1, 1))

    a_bar = a_hist - W_m @ self.y_m  # a_bar from the lecture
    Uy = np.linalg.solve(L, a_bar)  # U @ y_bar = L^{-1}
    y_bar = np.linalg.solve(U, Uy)  # y_bar = U^{-1}L^{-1}

    # Reverse the order of y_bar with the matrix J
    J = np.fliplr(np.eye(N + self.m + 1))
    y_hist = J @ np.vstack([y_bar, self.y_m])
    #---------------------------------------------------------------
    # Transform the optimal sequence back if $\beta$ is given
    #---------------------------------------------------------------
    if self.\beta != 1:
        y_hist = y_hist * (self.\beta**((- np.arange(-self.m, N + 1)/2))[:,::-1]  
                          .reshape(N + 1 + self.m, 1))

    return y_hist, L, U, y_bar
else:  # If the problem is stochastic and we look at it
    Ea_hist = self.predict(a_hist, t).reshape(N + 1, 1)
    Ea_hist = J @ Ea_hist

    a_bar = Ea_hist - W_m @ self.y_m  # a_bar from the lecture
    Uy = np.linalg.solve(L, a_bar)  # U @ y_bar = L^{-1}
    y_bar = np.linalg.solve(U, Uy)  # y_bar = U^{-1}L^{-1}

    # Reverse the order of y_bar with the matrix J
    J = np.fliplr(np.eye(N + self.m + 1))
    y_hist = J @ np.vstack([y_bar, self.y_m])
```

The code snippet normalizes $L$ and $U$ using `scipy.linalg.lu` and then renormalizes them using a diagonal matrix $D$. It also constructs an auxiliary diagonal matrix $D$ which renormalizes $L$ and $U$. The code then checks if the problem is deterministic and applies transformations to the sequence if $\beta$ is given.
Let’s use this code to tackle two interesting examples.

### 31.3.2 Example 1

Consider a stochastic process with moving average representation

\[ x_t = (1 - 2L)\varepsilon_t \]

where \( \varepsilon_t \) is a serially uncorrelated random process with mean zero and variance unity.

If we were to use the tools associated with infinite dimensional prediction and filtering to be described below, we would use the Wiener-Kolmogorov formula (21) to compute the linear least squares forecasts \( \mathbb{E}[x_{t+j} \mid x_t, x_{t-1}, \ldots] \), for \( j = 1, 2 \).

But we can do everything we want by instead using our finite dimensional tools and setting \( d = r \), generating an instance of LQFilter, then invoking pertinent methods of LQFilter.

```python
m = 1
y_m = np.asarray([0]).reshape(m, 1)
d = np.asarray([1, -2])
r = np.asarray([1, -2])
h = 0.0
example = LQFilter(d, h, y_m, r)
```

The Wold representation is computed by `example.coefficients_of_c()`.

Let’s check that it “flips roots” as required

```python
In [4]: example.coeffs_of_c()
```

```
Out[4]: array([ 2., -1.])
```

```python
In [5]: example.roots_of_characteristic()
```

```
Out[5]: (array([2.]), -2.0, array([0.5]))
```

Now let’s form the covariance matrix of a time series vector of length \( N \) and put it in \( V \).

Then we’ll take a Cholesky decomposition of \( V = L^{-1}L^{-1} \) and use it to form the vector of “moving average representations” \( x = L^{-1}\varepsilon \) and the vector of “autoregressive representations” \( Lx = \varepsilon \).

```python
V = example.construct_V(N=5)
print(V)
```

```
[[ 5. -2.  0.  0.  0.]
 [-2.  5. -2.  0.  0.]
 [ 0. -2.  5. -2.  0.]
 [ 0.  0. -2.  5. -2.]
 [ 0.  0.  0. -2.  5.]]
```
Notice how the lower rows of the “moving average representations” are converging to the appropriate infinite history Wold representation to be described below when we study infinite horizon-prediction and filtering

In [7]: `Li = np.linalg.cholesky(V)`
`print(Li)`

```
[[ 2.23606798  0.        0.        0.        0.        ]
 [-0.89442719  2.04939015  0.        0.        0.        ]
 [ 0.         -0.97590007  2.01186954  0.        0.        ]
 [ 0.         0.        -0.97590007  2.01186954  0.        ]
 [ 0.         0.        0.         -0.99853265  2.000733    ]]
```

Notice how the lower rows of the “autoregressive representations” are converging to the appropriate infinite-history autoregressive representation to be described below when we study infinite horizon-prediction and filtering

In [8]: `L = np.linalg.inv(Li)`
`print(L)`

```
[[ 0.44721360  0.        0.        0.        0.        ]
 [ 0.19518001  0.48795004  0.        0.        0.        ]
 [ 0.09467621  0.23669053  0.49705012  0.        0.        ]
 [ 0.04698977  0.11747443  0.24669630  0.49926632  0.        ]
 [ 0.02345182  0.05862954  0.12312203  0.24917554  0.49981682]]
```

### 31.3.3 Example 2

Consider a stochastic process $X_t$ with moving average representation

$$X_t = (1 - \sqrt{2} L^2) \varepsilon_t$$

where $\varepsilon_t$ is a serially uncorrelated random process with mean zero and variance unity.

Let’s find a Wold moving average representation for $x_t$ that will prevail in the infinite-history context to be studied in detail below.

To do this, we’ll use the Wiener-Kolomogorov formula (21) presented below to compute the linear least squares forecasts $\hat{E}[X_{t+j} | X_{t-1}, ...]$ for $j = 1, 2, 3$.

We proceed in the same way as in example 1

In [9]: `m = 2`
`y_m = np.asarray([0, 0]).reshape(m, 1)`
`d = np.asarray([1, 0, -np.sqrt(2)])`
`r = np.asarray([1, 0, -np.sqrt(2)])`
`h = 0.0`
`example = LQFilter(d, h, y_m, r=d)`
`example.coeffs_of_c()`

Out[9]: `array([ 1.41421356,  0.        , -1.        ])`
In [10]: example.roots_of_characteristic()

Out[10]:
(array([ 1.18920712, -1.18920712]),
      array([-1.41421356,  0.84089642, -0.84089642]))

In [11]: V = example.construct_V(N=8)
print(V)

[[ 3.  0. -1.41421356  0.  0.  0.]
 [ 0.  3.  0. -1.41421356  0.  0.]
 [-1.41421356 0.  3.  0. -1.41421356 0.]
 [ 0. -1.41421356 0.  3.  0. -1.41421356]
 [ 0.  0.    0.  0. -1.41421356 0.]
 [-1.41421356 0.  0.  0. -1.41421356 0.]
 [ 0.  0.  0. -1.41421356 0.  3.]
 [ 0.  0.  0.  0.  0. -1.41421356]
 [ 0.  0.  0.  0.  0.  3.]]

In [12]: Li = np.linalg.cholesky(V)
print(Li[-3:, :])

[[ 0.  0.  0. -0.9258201  0.  1.46385011]
 [ 0.  0.  0.  0. -0.96609178  0.]
 [ 1.43759058 0.  0. -0.96609178  0.]
 [ 0.  0.  0.  0.  0. -0.96609178]
 [ 0.  0.  0.  0.  0.  1.43759058]]

In [13]: L = np.linalg.inv(Li)
print(L)

[[0.57735027  0.  0.  0.  0.  0.]
 [0.  0.57735027  0.  0.  0.  0.]
 [0.  0.  0.65465367  0.  0.  0.]
 [0.  0.  0.  0.65465367  0.  0.]
 [0.  0.  0.  0.  0.68313005  0.]
 [0.  0.  0.  0.  0.  0.69560834]]
31.3.4 Prediction

It immediately follows from the “orthogonality principle” of least squares (see [5] or [59] [ch. X]) that

$$
\hat{E}[x_t \mid x_{t-m}, x_{t-m+1}, \ldots, x_1] = \sum_{j=m}^{t-1} L_{t-j}^{-1} \varepsilon_{t-j}
$$

(7)

$$
= [L_{t,1}^{-1} L_{t,2}^{-1}, \ldots, L_{t,t-m}^{-1} 0 0 \ldots 0] \Sigma x
$$

This can be interpreted as a finite-dimensional version of the Wiener-Kolmogorov \( m \)-step ahead prediction formula.

We can use (7) to represent the linear least squares projection of the vector \( x \) conditioned on the first \( s \) observations \( [x_s, x_{s-1} \ldots, x_1] \).

We have

$$
\hat{E}[x \mid x_s, x_{s-1}, \ldots, x_1] = L^{-1} \begin{bmatrix} I_s & 0 \\ 0 & 0 \end{bmatrix} \Sigma x
$$

(8)

This formula will be convenient in representing the solution of control problems under uncertainty.

Equation (4) can be recognized as a finite dimensional version of a moving average representation.

Equation (2) can be viewed as a finite dimension version of an autoregressive representation.

Notice that even if the \( x_t \) process is covariance stationary, so that \( V \) is such that \( V_{ij} \) depends only on \( |i - j| \), the coefficients in the moving average representation are time-dependent, there being a different moving average for each \( t \).

If \( x_t \) is a covariance stationary process, the last row of \( L^{-1} \) converges to the coefficients in the Wold moving average representation for \( \{x_t\} \) as \( T \to \infty \).

Further, if \( x_t \) is covariance stationary, for fixed \( k \) and \( j > 0 \), \( L_{T-k,T-j}^{-1} \) converges to \( L_{T-k,T-k-j}^{-1} \) as \( T \to \infty \).

That is, the “bottom” rows of \( L^{-1} \) converge to each other and to the Wold moving average coefficients as \( T \to \infty \).

This last observation gives one simple and widely-used practical way of forming a finite \( T \) approximation to a Wold moving average representation.

First, form the covariance matrix \( \Sigma x x' = V \), then obtain the Cholesky decomposition \( L^{-1} L^{-1}' \) of \( V \), which can be accomplished quickly on a computer.

The last row of \( L^{-1} \) gives the approximate Wold moving average coefficients.

This method can readily be generalized to multivariate systems.

31.4 Combined Finite Dimensional Control and Prediction

Consider the finite-dimensional control problem, maximize
\[
\mathbb{E} \sum_{t=0}^{N} \left\{ a_t y_t - \frac{1}{2} h y_t^2 - \frac{1}{2} [d(L)y_t]^2 \right\}, \quad h > 0
\]

where \(d(L) = d_0 + d_1 L + \ldots + d_m L^m\), \(L\) is the lag operator, \(\tilde{a} = [a_N, a_{N-1}, \ldots, a_1, a_0]'\) a random vector with mean zero and \(\mathbb{E} \tilde{a} \tilde{a}' = V\).

The variables \(y_{-1}, \ldots, y_{-m}\) are given.

Maximization is over choices of \(y_0, y_1, \ldots, y_N\), where \(y_t\) is required to be a linear function of \(\{y_{t-s-1}, t+m-1 \geq 0; a_{t-s}, t \geq s \geq 0\}\).

We saw in the lecture Classical Control with Linear Algebra that the solution of this problem under certainty could be represented in the feedback-feedforward form

\[
U \tilde{y} = L^{-1} \tilde{a} + K \begin{bmatrix} y_{-1} \\ \vdots \\ y_{-m} \end{bmatrix}
\]

for some \((N+1) \times m\) matrix \(K\).

Using a version of formula (7), we can express \(\mathbb{E} [\tilde{a} | a_s, a_{s-1}, \ldots, a_0]\) as

\[
\mathbb{E} [\tilde{a} | a_s, a_{s-1}, \ldots, a_0] = \tilde{U}^{-1} \begin{bmatrix} 0 \\ 0 \\ I_{(s+1)} \end{bmatrix} \tilde{U} \tilde{a}
\]

where \(I_{(s+1)}\) is the \((s+1) \times (s+1)\) identity matrix, and \(V = \tilde{U}^{-1} \tilde{U}^{-1}'\), where \(\tilde{U}\) is the upper triangular Cholesky factor of the covariance matrix \(V\).

(We have reversed the time axis in dating the \(a\)'s relative to earlier)

The time axis can be reversed in representation (8) by replacing \(L\) with \(L^T\).

The optimal decision rule to use at time \(0 \leq t \leq N\) is then given by the \((N - t + 1)^{th}\) row of

\[
U \tilde{y} = L^{-1} \tilde{U}^{-1} \begin{bmatrix} 0 \\ 0 \\ I_{(t+1)} \end{bmatrix} \tilde{U} \tilde{a} + K \begin{bmatrix} y_{-1} \\ \vdots \\ y_{-m} \end{bmatrix}
\]

### 31.5 Infinite Horizon Prediction and Filtering Problems

It is instructive to compare the finite-horizon formulas based on linear algebra decompositions of finite-dimensional covariance matrices with classic formulas for infinite horizon and infinite history prediction and control problems.

These classic infinite horizon formulas used the mathematics of \(z\)-transforms and lag operators.

We’ll meet interesting lag operator and \(z\)-transform counterparts to our finite horizon matrix formulas.

We pose two related prediction and filtering problems.

We let \(Y_t\) be a univariate \(m^{th}\) order moving average, covariance stationary stochastic process,
\[ Y_t = d(L)u_t \]  

(9)

where \( d(L) = \sum_{j=0}^{m} d_j L^j \), and \( u_t \) is a serially uncorrelated stationary random process satisfying

\[
\mathbb{E} u_t = 0 \\
\mathbb{E} u_t u_s = \begin{cases} 
1 & \text{if } t = s \\
0 & \text{otherwise}
\end{cases}
\]

(10)

We impose no conditions on the zeros of \( d(z) \).

A second covariance stationary process is \( X_t \) given by

\[ X_t = Y_t + \varepsilon_t \]  

(11)

where \( \varepsilon_t \) is a serially uncorrelated stationary random process with \( \mathbb{E} \varepsilon_t = 0 \) and \( \mathbb{E} \varepsilon_t \varepsilon_s = 0 \) for all distinct \( t \) and \( s \).

We also assume that \( \mathbb{E} \varepsilon_t u_s = 0 \) for all \( t \) and \( s \).

The **linear least squares prediction problem** is to find the \( L_2 \) random variable \( \hat{X}_{t+j} \) among linear combinations of \( \{X_t, X_{t-1}, \ldots\} \) that minimizes \( \mathbb{E}(\hat{X}_{t+j} - X_{t+j})^2 \).

That is, the problem is to find a \( \gamma_j(L) = \sum_{k=0}^{\infty} \gamma_{jk} L^k \) such that \( \sum_{k=0}^{\infty} |\gamma_{jk}|^2 < \infty \) and \( \mathbb{E}[\gamma_j(L)X_t - X_{t+j}]^2 \) is minimized.

The **linear least squares filtering problem** is to find a \( b(L) = \sum_{j=0}^{\infty} b_j L^j \) such that \( \sum_{j=0}^{\infty} |b_j|^2 < \infty \) and \( \mathbb{E}[b(L)X_t - Y_t]^2 \) is minimized.

Interesting versions of these problems related to the permanent income theory were studied by [48].

### 31.5.1 Problem Formulation

These problems are solved as follows.

The covariograms of \( Y \) and \( X \) and their cross covariogram are, respectively,

\[
C_X(\tau) = \mathbb{E} X_t X_{t-\tau} \\
C_Y(\tau) = \mathbb{E} Y_t Y_{t-\tau} \quad \tau = 0, \pm 1, \pm 2, \ldots \\
C_{Y,X}(\tau) = \mathbb{E} Y_t X_{t-\tau}
\]

(12)

The covariance and cross-covariance generating functions are defined as

\[
g_X(z) = \sum_{\tau=-\infty}^{\infty} C_X(\tau) z^\tau \\
g_Y(z) = \sum_{\tau=-\infty}^{\infty} C_Y(\tau) z^\tau \\
g_{Y,X}(z) = \sum_{\tau=-\infty}^{\infty} C_{Y,X}(\tau) z^\tau
\]

(13)
The generating functions can be computed by using the following facts.

Let \( v_{1t} \) and \( v_{2t} \) be two mutually and serially uncorrelated white noises with unit variances. That is,
\[
\mathbb{E}v_{1t}^2 = \mathbb{E}v_{2t}^2 = 1, \quad \mathbb{E}v_{1t}v_{2s} = 0 \quad \text{for all } t \text{ and } s, \quad \mathbb{E}v_{1t}v_{1t-j} = \mathbb{E}v_{2t}v_{2t-j} = 0 \quad \text{for all } j \neq 0.
\]

Let \( x_t \) and \( y_t \) be two random processes given by
\[
y_t = A(L)v_{1t} + B(L)v_{2t} \\
x_t = C(L)v_{1t} + D(L)v_{2t}
\]

Then, as shown for example in [59] [ch. XI], it is true that
\[
g_y(z) = A(z)A(z^{-1}) + B(z)B(z^{-1}) \\
g_x(z) = C(z)C(z^{-1}) + D(z)D(z^{-1}) \\
g_{yx}(z) = A(z)C(z^{-1}) + B(z)D(z^{-1})
\]

Applying these formulas to (9) – (12), we have
\[
g_Y(z) = d(z)d(z^{-1}) \\
g_X(z) = d(z)d(z^{-1}) + h \\
g_{YX}(z) = d(z)d(z^{-1})
\]

The key step in obtaining solutions to our problems is to factor the covariance generating function \( g_X(z) \) of \( X_t \).

The solutions of our problems are given by formulas due to Wiener and Kolmogorov.

These formulas utilize the Wold moving average representation of the \( X_t \) process,
\[
X_t = c(L)\eta_t
\]
where \( c(L) = \sum_{j=0}^{m} c_j L^j \), with
\[
c_0\eta_t = X_t - \hat{\mathbb{E}}[X_t|X_{t-1}, X_{t-2}, ...]
\]

Here \( \hat{\mathbb{E}} \) is the linear least squares projection operator.

Equation (17) is the condition that \( c_0\eta_t \) can be the one-step-ahead error in predicting \( X_t \) from its own past values.

Condition (17) requires that \( \eta_t \) lie in the closed linear space spanned by \([X_t, X_{t-1}, ...] \).

This will be true if and only if the zeros of \( c(z) \) do not lie inside the unit circle.

It is an implication of (17) that \( \eta_t \) is a serially uncorrelated random process and that normalization can be imposed so that \( \mathbb{E}\eta_t^2 = 1 \).

Consequently, an implication of (16) is that the covariance generating function of \( X_t \) can be expressed as
\[
g_X(z) = c(z)c(z^{-1})
\]
It remains to discuss how \( c(L) \) is to be computed.

Combining (14) and (18) gives

\[
d(z) d(z^{-1}) + h = c(z) c(z^{-1})
\]  

Therefore, we have already shown constructively how to factor the covariance generating function \( g_X(z) = d(z) d(z^{-1}) + h \).

We now introduce the **annihilation operator**: 

\[
\left[ \sum_{j=-\infty}^{\infty} f_j L^j \right]_+ \equiv \sum_{j=0}^{\infty} f_j L^j
\]  

In words, \([ \ldots ]_+ \) means “ignore negative powers of \( L \).”

We have defined the solution of the prediction problem as 

\[
\hat{E}[X_{t+j} | X_t, X_{t-1}, \ldots] = \gamma_j(L)X_t.
\]

Assuming that the roots of \( c(z) = 0 \) all lie outside the unit circle, the Wiener-Kolmogorov formula for \( \gamma_j(L) \) holds:

\[
\gamma_j(L) = \left[ \frac{c(L)}{L^j} \right]_+ c(L)^{-1}
\]  

(21)

We have defined the solution of the filtering problem as 

\[
\hat{E}[Y_t | X_t, X_{t-1}, \ldots] = b(L)X_t.
\]

The Wiener-Kolomogorov formula for \( b(L) \) is

\[
b(L) = \left[ \frac{g_Y X(L)}{c(L^{-1})} \right]_+ c(L)^{-1}
\]

or

\[
b(L) = \left[ \frac{d(L)d(L^{-1})}{c(L^{-1})} \right]_+ c(L)^{-1}
\]  

(22)

Formulas (21) and (22) are discussed in detail in [69] and [59].

The interested reader can there find several examples of the use of these formulas in economics. Some classic examples using these formulas are due to [48].

As an example of the usefulness of formula (22), we let \( X_t \) be a stochastic process with Wold moving average representation

\[
X_t = c(L) \eta_t
\]

where \( \mathbb{E} \eta_t^2 = 1 \), and \( c_0 \eta_t = X_t - \hat{E}[X_t | X_{t-1}, \ldots] \), \( c(L) = \sum_{j=0}^{m} c_j L \).

Suppose that at time \( t \), we wish to predict a geometric sum of future \( X \)’s, namely

\[
y_t = \sum_{j=0}^{\infty} \delta^j X_{t+j} = \frac{1}{1 - \delta L^{-1}} X_t
\]
given knowledge of $X_t, X_{t-1}, \ldots$.

We shall use (22) to obtain the answer.

Using the standard formulas (14), we have that

$$g_{yz}(z) = (1 - \delta z^{-1})c(z)c(z^{-1})$$

$$g_z(z) = c(z)c(z^{-1})$$

Then (22) becomes

$$b(L) = \left[ \frac{c(L)}{1 - \delta L^{-1}} \right] + c(L)^{-1}$$

In order to evaluate the term in the annihilation operator, we use the following result from [27].

**Proposition** Let

- $g(z) = \sum_{j=0}^{\infty} g_j z^j$ where $\sum_{j=0}^{\infty} |g_j|^2 < +\infty$.
- $h(z^{-1}) = (1 - \delta_1 z^{-1}) \ldots (1 - \delta_n z^{-1})$, where $|\delta_j| < 1$, for $j = 1, \ldots, n$.

Then

$$\left[ \frac{g(z)}{h(z^{-1})} \right]_+ = \frac{g(z)}{h(z^{-1})} - \sum_{j=1}^{n} \frac{\delta_j g(\delta_j)}{\prod_{k \neq j}^{n} (\delta_j - \delta_k)} \left( \frac{1}{z - \delta_j} \right)$$

and, alternatively,

$$\left[ \frac{g(z)}{h(z^{-1})} \right]_+ = \sum_{j=1}^{n} B_j \left( \frac{z g(z) - \delta_j g(\delta_j)}{z - \delta_j} \right)$$

where $B_j = 1/\prod_{k \neq j}^{n} (1 - \delta_k / \delta_j)$.

Applying formula (25) of the proposition to evaluating (23) with $g(z) = c(z)$ and $h(z^{-1}) = 1 - \delta z^{-1}$ gives

$$b(L) = \left[ \frac{L c(L) - \delta c(\delta)}{L - \delta} \right] c(L)^{-1}$$

or

$$b(L) = \left[ \frac{1 - \delta c(\delta) L^{-1} c(L)^{-1}}{1 - \delta L^{-1}} \right]$$

Thus, we have

$$\hat{E} \left[ \sum_{j=0}^{\infty} \delta^j X_{t+j} | X_t, x_{t-1}, \ldots \right] = \left[ \frac{1 - \delta c(\delta) L^{-1} c(L)^{-1}}{1 - \delta L^{-1}} \right] X_t$$

This formula is useful in solving stochastic versions of problem 1 of lecture Classical Control with Linear Algebra in which the randomness emerges because $\{a_t\}$ is a stochastic process.
The problem is to maximize

\[ \mathbb{E}_0 \lim_{N \to \infty} \sum_{t=0}^{N} \beta^t \left[ a_t y_t - \frac{1}{2} h y_t^2 - \frac{1}{2} [d(L)y_t]^2 \right] \]  

(27)

where \( \mathbb{E}_t \) is mathematical expectation conditioned on information known at \( t \), and where \( \{a_t\} \) is a covariance stationary stochastic process with Wold moving average representation

\[ a_t = c(L) \eta_t \]

where

\[ c(L) = \sum_{j=0}^{\tilde{n}} c_j L^j \]

and

\[ \eta_t = a_t - \hat{E}[a_t|a_{t-1},...] \]

The problem is to maximize (27) with respect to a contingency plan expressing \( y_t \) as a function of information known at \( t \), which is assumed to be \((y_{t-1}, y_{t-2}, ..., a_t, a_{t-1}, ...)\).

The solution of this problem can be achieved in two steps.

First, ignoring the uncertainty, we can solve the problem assuming that \( \{a_t\} \) is a known sequence.

The solution is, from above,

\[ c(L)y_t = c(\beta L^{-1})^{-1} a_t \]

or

\[ (1 - \lambda_1 L) ... (1 - \lambda_m L)y_t = \sum_{j=1}^{m} A_j \sum_{k=0}^{\infty} (\lambda_j \beta)^k a_{t+k} \]  

(28)

Second, the solution of the problem under uncertainty is obtained by replacing the terms on the right-hand side of the above expressions with their linear least squares predictors.

Using (26) and (28), we have the following solution

\[ (1 - \lambda_1 L) ... (1 - \lambda_m L)y_t = \sum_{j=1}^{m} A_j \left[ 1 - \beta \lambda_j c(\beta L^{-1})^{-1} c(L)^{-1} \right] a_t \]

Blaschke factors

The following is a useful piece of mathematics underlying “root flipping”.

Let \( \pi(z) = \sum_{j=0}^{m} \pi_j z^j \) and let \( z_1, ..., z_k \) be the zeros of \( \pi(z) \) that are inside the unit circle, \( k < m \).

Then define
\[
\theta(z) = \pi(z) \left( \frac{z_1 z - 1}{z - z_1} \right) \left( \frac{z_2 z - 1}{z - z_2} \right) \cdots \left( \frac{z_k z - 1}{z - z_k} \right)
\]

The term multiplying \( \pi(z) \) is termed a “Blaschke factor”.

Then it can be proved directly that

\[
\theta(z^{-1})\theta(z) = \pi(z^{-1})\pi(z)
\]

and that the zeros of \( \theta(z) \) are not inside the unit circle.

### 31.6 Exercises

#### 31.6.1 Exercise 1

Let \( Y_t = (1 - 2L)u_t \) where \( u_t \) is a mean zero white noise with \( \mathbb{E}u_t^2 = 1 \). Let

\[
X_t = Y_t + \varepsilon_t
\]

where \( \varepsilon_t \) is a serially uncorrelated white noise with \( \mathbb{E}\varepsilon_t^2 = 9 \), and \( \mathbb{E}\varepsilon_t u_s = 0 \) for all \( t \) and \( s \).

Find the Wold moving average representation for \( X_t \).

Find a formula for the \( A_1j \)'s in

\[
\mathbb{E}\hat{X}_{t+1} \mid X_t, X_{t-1}, \ldots = \sum_{j=0}^{\infty} A_{1j}X_{t-j}
\]

Find a formula for the \( A_{2j} \)'s in

\[
\hat{X}_{t+2} \mid X_t, X_{t-1}, \ldots = \sum_{j=0}^{\infty} A_{2j}X_{t-j}
\]

#### 31.6.2 Exercise 2

**Multivariable Prediction:** Let \( Y_t \) be an \( (n \times 1) \) vector stochastic process with moving average representation

\[
Y_t = D(L)U_t
\]

where \( D(L) = \sum_{j=0}^{m} D_j L^j \), \( D_j \) an \( n \times n \) matrix, \( U_t \) an \( (n \times 1) \) vector white noise with \( \mathbb{E}U_t = 0 \) for all \( t \), \( \mathbb{E}U_t'U_s' = 0 \) for all \( s \neq t \), and \( \mathbb{E}U_t'U_t' = I \) for all \( t \).

Let \( \varepsilon_t \) be an \( n \times 1 \) vector white noise with mean 0 and contemporaneous covariance matrix \( H \), where \( H \) is a positive definite matrix.

Let \( X_t = Y_t + \varepsilon_t \).

Define the covariograms as \( C_X(\tau) = \mathbb{E}X_tX_{t-\tau}, C_Y(\tau) = \mathbb{E}Y_tY_{t-\tau}, C_{X,Y}(\tau) = \mathbb{E}X_tY_{t-\tau} \).
31.6. EXERCISES

Then define the matrix covariance generating function, as in (21), only interpret all the objects in (21) as matrices.

Show that the covariance generating functions are given by

\[ g_y(z) = D(z)D(z^{-1})' \]
\[ g_X(z) = D(z)D(z^{-1})' + H \]
\[ g_{YX}(z) = D(z)D(z^{-1})' \]

A factorization of \( g_X(z) \) can be found (see [54] or [69]) of the form

\[ D(z)D(z^{-1})' + H = C(z)C(z^{-1})', \quad C(z) = \sum_{j=0}^{m} C_j z^j \]

where the zeros of \( |C(z)| \) do not lie inside the unit circle.

A vector Wold moving average representation of \( X_t \) is then

\[ X_t = C(L)\eta_t \]

where \( \eta_t \) is an \( (n \times 1) \) vector white noise that is “fundamental” for \( X_t \).

That is, \( X_t - \hat{\mathbb{E}}[X_t \mid X_{t-1}, X_{t-2} \ldots] = C_0 \eta_t \).

The optimum predictor of \( X_{t+j} \) is

\[ \hat{\mathbb{E}}[X_{t+j} \mid X_t, X_{t-1}, \ldots] = \left[ \frac{C(L)}{L^j} \right] \eta_t \]

If \( C(L) \) is invertible, i.e., if the zeros of \( \det C(z) \) lie strictly outside the unit circle, then this formula can be written

\[ \hat{\mathbb{E}}[X_{t+j} \mid X_t, X_{t-1}, \ldots] = \left[ \frac{C(L)}{L^j} \right] C(L)^{-1} X_t \]
Part VII

Asset Pricing and Finance
Chapter 32

Asset Pricing II: The Lucas Asset Pricing Model

32.1 Contents

- Overview 32.2
- The Lucas Model 32.3
- Exercises 32.4
- Solutions 32.5

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install interpolation

32.2 Overview

As stated in an earlier lecture, an asset is a claim on a stream of prospective payments.

What is the correct price to pay for such a claim?

The elegant asset pricing model of Lucas [44] attempts to answer this question in an equilibrium setting with risk-averse agents.

While we mentioned some consequences of Lucas’ model earlier, it is now time to work through the model more carefully and try to understand where the fundamental asset pricing equation comes from.

A side benefit of studying Lucas’ model is that it provides a beautiful illustration of model building in general and equilibrium pricing in competitive models in particular.

Another difference to our first asset pricing lecture is that the state space and shock will be continuous rather than discrete.

Let’s start with some imports:

In [2]: import numpy as np
   from interpolation import interp
   from numba import njit, prange
   from scipy.stats import lognorm
import matplotlib.pyplot as plt
%matplotlib inline

32.3 The Lucas Model

Lucas studied a pure exchange economy with a representative consumer (or household), where

- Pure exchange means that all endowments are exogenous.
- Representative consumer means that either
  - there is a single consumer (sometimes also referred to as a household), or
  - all consumers have identical endowments and preferences

Either way, the assumption of a representative agent means that prices adjust to eradicate desires to trade.

This makes it very easy to compute competitive equilibrium prices.

32.3.1 Basic Setup

Let’s review the setup.

Assets

There is a single “productive unit” that costlessly generates a sequence of consumption goods \( \{y_t\}_{t=0}^{\infty} \).

Another way to view \( \{y_t\}_{t=0}^{\infty} \) is as a consumption endowment for this economy.

We will assume that this endowment is Markovian, following the exogenous process

\[
y_{t+1} = G(y_t, \xi_{t+1})
\]

Here \( \{\xi_t\} \) is an IID shock sequence with known distribution \( \phi \) and \( y_t \geq 0 \).

An asset is a claim on all or part of this endowment stream.

The consumption goods \( \{y_t\}_{t=0}^{\infty} \) are nonstorable, so holding assets is the only way to transfer wealth into the future.

For the purposes of intuition, it’s common to think of the productive unit as a “tree” that produces fruit.

Based on this idea, a “Lucas tree” is a claim on the consumption endowment.

Consumers

A representative consumer ranks consumption streams \( \{c_t\} \) according to the time separable utility functional

\[
\mathbb{E} \sum_{t=0}^{\infty} \beta^t u(c_t)
\]  

(1)

Here
32.3. THE LUCAS MODEL

- $\beta \in (0, 1)$ is a fixed discount factor.
- $u$ is a strictly increasing, strictly concave, continuously differentiable period utility function.
- $\mathbb{E}$ is a mathematical expectation.

32.3.2 Pricing a Lucas Tree

What is an appropriate price for a claim on the consumption endowment?

We’ll price an ex-dividend claim, meaning that

- the seller retains this period’s dividend
- the buyer pays $p_t$ today to purchase a claim on
  - $y_{t+1}$ and
  - the right to sell the claim tomorrow at price $p_{t+1}$

Since this is a competitive model, the first step is to pin down consumer behavior, taking prices as given.

Next, we’ll impose equilibrium constraints and try to back out prices.

In the consumer problem, the consumer’s control variable is the share $\pi_t$ of the claim held in each period.

Thus, the consumer problem is to maximize (1) subject to

$$c_t + \pi_{t+1}p_t \leq \pi_t y_t + \pi_t p_t$$

along with $c_t \geq 0$ and $0 \leq \pi_t \leq 1$ at each $t$.

The decision to hold share $\pi_t$ is actually made at time $t - 1$.

But this value is inherited as a state variable at time $t$, which explains the choice of subscript.

The Dynamic Program

We can write the consumer problem as a dynamic programming problem.

Our first observation is that prices depend on current information, and current information is really just the endowment process up until the current period.

In fact, the endowment process is Markovian, so that the only relevant information is the current state $y \in \mathbb{R}_+$ (dropping the time subscript).

This leads us to guess an equilibrium where price is a function $p$ of $y$.

Remarks on the solution method

- Since this is a competitive (read: price taking) model, the consumer will take this function $p$ as given.
- In this way, we determine consumer behavior given $p$ and then use equilibrium conditions to recover $p$.
- This is the standard way to solve competitive equilibrium models.

Using the assumption that price is a given function $p$ of $y$, we write the value function and constraint as
$v(\pi, y) = \max_{c, \pi'} \left\{ u(c) + \beta \int v(\pi', G(y, z))\phi(dz) \right\}$

subject to

$$c + \pi'p(y) \leq \pi y + \pi p(y) \tag{2}$$

We can invoke the fact that utility is increasing to claim equality in (2) and hence eliminate the constraint, obtaining

$$v(\pi, y) = \max_{\pi'} \left\{ u[\pi(y + p(y)) - \pi'p(y)] + \beta \int v(\pi', G(y, z))\phi(dz) \right\} \tag{3}$$

The solution to this dynamic programming problem is an optimal policy expressing either $\pi'$ or $c$ as a function of the state $(\pi, y)$.

- Each one determines the other, since $c(\pi, y) = \pi(y + p(y)) - \pi'(\pi, y)p(y)$

**Next Steps**

What we need to do now is determine equilibrium prices.

It seems that to obtain these, we will have to

1. Solve this two-dimensional dynamic programming problem for the optimal policy.
2. Impose equilibrium constraints.
3. Solve out for the price function $p(y)$ directly.

However, as Lucas showed, there is a related but more straightforward way to do this.

**Equilibrium Constraints**

Since the consumption good is not storable, in equilibrium we must have $c_t = y_t$ for all $t$.

In addition, since there is one representative consumer (alternatively, since all consumers are identical), there should be no trade in equilibrium.

In particular, the representative consumer owns the whole tree in every period, so $\pi_t = 1$ for all $t$.

Prices must adjust to satisfy these two constraints.

**The Equilibrium Price Function**

Now observe that the first-order condition for (3) can be written as

$$u'(c)p(y) = \beta \int v'_1(\pi', G(y, z))\phi(dz)$$

where $v'_1$ is the derivative of $v$ with respect to its first argument.
32.3. THE LUCAS MODEL

To obtain \( v'_1 \) we can simply differentiate the right-hand side of (3) with respect to \( \pi \), yielding

\[
v'_1(\pi, y) = u'(c)(y + p(y))
\]

Next, we impose the equilibrium constraints while combining the last two equations to get

\[
p(y) = \beta \int \frac{u'[G(y, z)]}{u'(y)}[G(y, z) + p(G(y, z))]\phi(dz)
\]  

(4)

In sequential rather than functional notation, we can also write this as

\[
p_t = \mathbb{E}_t \left[ \beta \frac{u'(c_{t+1})}{u'(c_t)}(y_{t+1} + p_{t+1}) \right]
\]  

(5)

This is the famous consumption-based asset pricing equation.

Before discussing it further we want to solve out for prices.

32.3.3 Solving the Model

Equation (4) is a functional equation in the unknown function \( p \).

The solution is an equilibrium price function \( p^* \).

Let’s look at how to obtain it.

Setting up the Problem

Instead of solving for it directly we’ll follow Lucas’ indirect approach, first setting

\[
f(y) := u'(y)p(y)
\]  

(6)

so that (4) becomes

\[
f(y) = h(y) + \beta \int f[G(y, z)]\phi(dz)
\]  

(7)

Here \( h(y) := \beta \int u'[G(y, z)]G(y, z)\phi(dz) \) is a function that depends only on the primitives.

Equation (7) is a functional equation in \( f \).

The plan is to solve out for \( f \) and convert back to \( p \) via (6).

To solve (7) we’ll use a standard method: convert it to a fixed point problem.

First, we introduce the operator \( T \) mapping \( f \) into \( Tf \) as defined by

\[
(Tf)(y) = h(y) + \beta \int f[G(y, z)]\phi(dz)
\]  

(8)

In what follows, we refer to \( T \) as the Lucas operator.

The reason we do this is that a solution to (7) now corresponds to a function \( f^* \) satisfying

\[
(Tf^*)(y) = f^*(y) \text{ for all } y.
\]
In other words, a solution is a fixed point of $T$.

This means that we can use fixed point theory to obtain and compute the solution.

**A Little Fixed Point Theory**

Let $cb\mathbb{R}_+$ be the set of continuous bounded functions $f : \mathbb{R}_+ \rightarrow \mathbb{R}_+$.

We now show that

1. $T$ has exactly one fixed point $f^*$ in $cb\mathbb{R}_+$.
2. For any $f \in cb\mathbb{R}_+$, the sequence $T^k f$ converges uniformly to $f^*$.

(Note: If you find the mathematics heavy going you can take 1–2 as given and skip to the next section)

Recall the Banach contraction mapping theorem.

It tells us that the previous statements will be true if we can find an $\alpha < 1$ such that

$$
\|Tf - Tg\| \leq \alpha \|f - g\|, \quad \forall f, g \in cb\mathbb{R}_+ \tag{9}
$$

Here $\|h\| := \sup_{x \in \mathbb{R}_+} |h(x)|$.

To see that (9) is valid, pick any $f, g \in cb\mathbb{R}_+$ and any $y \in \mathbb{R}_+$.

Observe that, since integrals get larger when absolute values are moved to the inside,

$$
|Tf(y) - Tg(y)| = \left| \beta \int f[G(y, z)]\phi(dz) - \beta \int g[G(y, z)]\phi(dz) \right|
\leq \beta \int |f[G(y, z)] - g[G(y, z)]|\phi(dz)
\leq \beta \int \|f - g\|\phi(dz)
= \beta \|f - g\|
$$

Since the right-hand side is an upper bound, taking the sup over all $y$ on the left-hand side gives (9) with $\alpha := \beta$.

**32.3.4 Computation – An Example**

The preceding discussion tells that we can compute $f^*$ by picking any arbitrary $f \in cb\mathbb{R}_+$ and then iterating with $T$.

The equilibrium price function $p^*$ can then be recovered by $p^*(y) = f^*(y)/u'(y)$.

Let’s try this when $\ln y_{t+1} = \alpha \ln y_t + \sigma \epsilon_{t+1}$ where $\{\epsilon_t\}$ is IID and standard normal.

Utility will take the isoelastic form $u(c) = c^{1-\gamma}/(1-\gamma)$, where $\gamma > 0$ is the coefficient of relative risk aversion.

We will set up a LucasTree class to hold parameters of the model.
In [3]: ```

class LucasTree:
    
    """
    Class to store parameters of the Lucas tree model.
    """

    def __init__(self,
        γ=2,  # CRRA utility parameter
        β=0.95,  # Discount factor
        α=0.90,  # Correlation coefficient
        σ=0.1,  # Volatility coefficient
        grid_size=100):
        self.γ, self.β, self.α, self.σ = γ, β, α, σ

        # Set the grid interval to contain most of the mass of the
        # stationary distribution of the consumption endowment
        ssd = self.σ / np.sqrt(1 - self.α**2)
        grid_min, grid_max = np.exp(-4 * ssd), np.exp(4 * ssd)
        self.grid = np.linspace(grid_min, grid_max, grid_size)
        self.grid_size = grid_size

        # Set up distribution for shocks
        self.ϕ = lognorm(σ)
        self.draws = self.ϕ.rvs(500)

        self.h = np.empty(self.grid_size)
        for i, y in enumerate(self.grid):
            self.h[i] = β * np.mean((y**α * self.draws)**(1 - γ))

The following function takes an instance of the LucasTree and generates a jitted version of the Lucas operator

In [4]: ```
def operator_factory(tree, parallel_flag=True):
    
    """
    Returns approximate Lucas operator, which computes and returns the
    updated function Tf on the grid points.

    tree is an instance of the LucasTree class
    """

    grid, h = tree.grid, tree.h
    α, β = tree.α, tree.β
    z_vec = tree.draws

    @njit(parallel=parallel_flag)
    def Tf(f):
        """
        The Lucas operator
        """

        # Turn f into a function
        Af = lambda x: interp(grid, f, x)

        Tf = np.empty_like(f)
# Apply the $T$ operator to $f$ using Monte Carlo integration

```python
for i in prange(len(grid)):
    y = grid[i]
    Tf[i] = h[i] + β * np.mean(Af(y**α * z_vec))
return Tf
```

```
return T
```

To solve the model, we write a function that iterates using the Lucas operator to find the fixed point.

```
In [5]: def solve_model(tree, tol=1e-6, max_iter=500):
    ""
    Compute the equilibrium price function associated with Lucas tree
    * tree is an instance of LucasTree
    ""
    # Simplify notation
    grid, grid_size = tree.grid, tree.grid_size
    γ = tree.γ
    T = operator_factory(tree)
    i = 0
    f = np.ones_like(grid)  # Initial guess of $f$
    error = tol + 1
    while error > tol and i < max_iter:
        Tf = T(f)
        error = np.max(np.abs(Tf - f))
        f = Tf
        i += 1
    price = f * grid**γ  # Back out price vector
    return price
```

Solving the model and plotting the resulting price function

```
In [6]: tree = LucasTree()
price_vals = solve_model(tree)
fig, ax = plt.subplots(figsize=(10, 6))
ax.plot(tree.grid, price_vals, label='$p^*(y)$')
ax.set_xlabel('$y$')
ax.set_ylabel('price')
ax.legend()
plt.show()
```
We see that the price is increasing, even if we remove all serial correlation from the endowment process.

The reason is that a larger current endowment reduces current marginal utility.

The price must therefore rise to induce the household to consume the entire endowment (and hence satisfy the resource constraint).

What happens with a more patient consumer?

Here the orange line corresponds to the previous parameters and the green line is price when $\beta = 0.98$. 
We see that when consumers are more patient the asset becomes more valuable, and the price of the Lucas tree shifts up.

Exercise 1 asks you to replicate this figure.

### 32.4 Exercises

#### 32.4.1 Exercise 1

Replicate the figure to show how discount factors affect prices.

### 32.5 Solutions

#### 32.5.1 Exercise 1

```python
In [7]: fig, ax = plt.subplots(figsize=(10, 6))

for β in (.95, 0.98):
    tree = LucasTree(β=β)
    grid = tree.grid
    price_vals = solve_model(tree)
    label = rf'$\beta = {{β}}$'
    ax.plot(grid, price_vals, lw=2, alpha=0.7, label=label)

ax.legend(loc='upper left')
ax.set(xlabel='$y$', ylabel='price', xlim=(min(grid), max(grid)))
plt.show()
```

![Graph showing how discount factors affect prices.](image)
Chapter 33

Two Modifications of Mean-Variance Portfolio Theory

33.1 Contents

- Overview 33.2
- Appendix 33.3

33.2 Overview

33.2.1 Remarks About Estimating Means and Variances

The famous Black-Litterman (1992) \([11]\) portfolio choice model that we describe in this lecture is motivated by the finding that with high or moderate frequency data, means are more difficult to estimate than variances.

A model of robust portfolio choice that we’ll describe also begins from the same starting point.

To begin, we’ll take for granted that means are more difficult to estimate than covariances and will focus on how Black and Litterman, on the one hand, an robust control theorists, on the other, would recommend modifying the mean-variance portfolio choice model to take that into account.

At the end of this lecture, we shall use some rates of convergence results and some simulations to verify how means are more difficult to estimate than variances.

Among the ideas in play in this lecture will be

- Mean-variance portfolio theory
- Bayesian approaches to estimating linear regressions
- A risk-sensitivity operator and its connection to robust control theory

Let’s start with some imports:

```
In [1]: import numpy as np
import scipy as sp
import scipy.stats as stat
import matplotlib.pyplot as plt
```
33.2.2 Adjusting Mean-variance Portfolio Choice Theory for Distrust of Mean Excess Returns

This lecture describes two lines of thought that modify the classic mean-variance portfolio choice model in ways designed to make its recommendations more plausible.

As we mentioned above, the two approaches build on a common and widespread hunch – that because it is much easier statistically to estimate covariances of excess returns than it is to estimate their means, it makes sense to contemplated the consequences of adjusting investors’ subjective beliefs about mean returns in order to render more sensible decisions.

Both of the adjustments that we describe are designed to confront a widely recognized embarrassment to mean-variance portfolio theory, namely, that it usually implies taking very extreme long-short portfolio positions.

33.2.3 Mean-variance Portfolio Choice

A risk-free security earns one-period net return \( r_f \).

An \( n \times 1 \) vector of risky securities earns an \( n \times 1 \) vector \( \bar{r} - r_f \mathbf{1} \) of excess returns, where \( \mathbf{1} \) is an \( n \times 1 \) vector of ones.

The excess return vector is multivariate normal with mean \( \mu \) and covariance matrix \( \Sigma \), which we express either as

\[
\bar{r} - r_f \mathbf{1} \sim \mathcal{N}(\mu, \Sigma)
\]

or

\[
\bar{r} - r_f \mathbf{1} = \mu + C\epsilon
\]

where \( \epsilon \sim \mathcal{N}(0, I) \) is an \( n \times 1 \) random vector.

Let \( w \) be an \( n \times 1 \) vector of portfolio weights.

A portfolio consisting \( w \) earns returns

\[
w'(\bar{r} - r_f \mathbf{1}) \sim \mathcal{N}(w'\mu, w'\Sigma w)
\]

The mean-variance portfolio choice problem is to choose \( w \) to maximize

\[
U(\mu, \Sigma; w) = w'\mu - \frac{\delta}{2}w'\Sigma w
\]  

where \( \delta > 0 \) is a risk-aversion parameter. The first-order condition for maximizing (1) with respect to the vector \( w \) is

\[
\mu = \delta \Sigma w
\]
which implies the following design of a risky portfolio:

\[ w = (\delta \Sigma)^{-1} \mu \]  

(2)

### 33.2.4 Estimating the Mean and Variance

The key inputs into the portfolio choice model (2) are

- estimates of the parameters \( \mu, \Sigma \) of the random excess return vector \( \tilde{r} - r_f 1 \)
- the risk-aversion parameter \( \delta \)

A standard way of estimating \( \mu \) is maximum-likelihood or least squares; that amounts to estimating \( \mu \) by a sample mean of excess returns and estimating \( \Sigma \) by a sample covariance matrix.

### 33.2.5 The Black-Litterman Starting Point

When estimates of \( \mu \) and \( \Sigma \) from historical sample means and covariances have been combined with reasonable values of the risk-aversion parameter \( \delta \) to compute an optimal portfolio from formula (2), a typical outcome has been \( w \)'s with extreme long and short positions.

A common reaction to these outcomes is that they are so unreasonable that a portfolio manager cannot recommend them to a customer.

In [2]: `np.random.seed(12)`

```
N = 10                                # Number of assets
T = 200                               # Sample size

# random market portfolio (sum is normalized to 1)
w_m = np.random.rand(N)
w_m = w_m / (w_m.sum())

# True risk premia and variance of excess return (constructed # so that the Sharpe ratio is 1)
μ = (np.random.randn(N) + 5) / 100     # Mean excess return (risk premium)
S = np.random.randn(N, N)              # Random matrix for the covariance matrix
V = S @ S.T                             # Turn the random matrix into symmetric psd
Σ = V * (w_m @ μ)**2 / (w_m @ V @ w_m)

# Risk aversion of market portfolio holder
δ = 1 / np.sqrt(w_m @ Σ @ w_m)

# Generate a sample of excess returns
excess_return = stats.multivariate_normal(μ, Σ)
sample = excess_return.rvs(T)

# Estimate μ and Σ
μ_est = sample.mean().reshape(N, 1)
Σ_est = np.cov(sample.T)

w = np.linalg.solve(δ * Σ_est, μ_est)
```
Black and Litterman’s responded to this situation in the following way:

- They continue to accept (2) as a good model for choosing an optimal portfolio $w$.
- They want to continue to allow the customer to express his or her risk tolerance by setting $\delta$.
- Leaving $\Sigma$ at its maximum-likelihood value, they push $\mu$ away from its maximum value in a way designed to make portfolio choices that are more plausible in terms of conforming to what most people actually do.

In particular, given $\Sigma$ and a reasonable value of $\delta$, Black and Litterman reverse engineered a vector $\mu_{BL}$ of mean excess returns that makes the $w$ implied by formula (2) equal the actual market portfolio $w_m$, so that

$$w_m = (\delta \Sigma)^{-1} \mu_{BL}$$
33.2. OVERVIEW

33.2.6 Details

Let’s define

\[ w'_m \mu \equiv (r_m - r_f) \]

as the (scalar) excess return on the market portfolio \( w_m \).

Define

\[ \sigma^2 = w'_m \Sigma w_m \]

as the variance of the excess return on the market portfolio \( w_m \).

Define

\[ \text{SR}_m = \frac{r_m - r_f}{\sigma} \]

as the **Sharpe-ratio** on the market portfolio \( w_m \).

Let \( \delta_m \) be the value of the risk aversion parameter that induces an investor to hold the market portfolio in light of the optimal portfolio choice rule (2).

Evidently, portfolio rule (2) then implies that \( r_m - r_f = \delta_m \sigma^2 \) or

\[ \delta_m = \frac{r_m - r_f}{\sigma^2} \]

or

\[ \delta_m = \frac{\text{SR}_m}{\sigma} \]

Following the Black-Litterman philosophy, our first step will be to back a value of \( \delta_m \) from

- an estimate of the Sharpe-ratio, and
- our maximum likelihood estimate of \( \sigma \) drawn from our estimates or \( w_m \) and \( \Sigma \)

The second key Black-Litterman step is then to use this value of \( \delta \) together with the maximum likelihood estimate of \( \Sigma \) to deduce a \( \mu_{BL} \) that verifies portfolio rule (2) at the market portfolio \( w = w_m \)

\[ \mu_m = \delta_m \Sigma w_m \]

The starting point of the Black-Litterman portfolio choice model is thus a pair \((\delta_m, \mu_m)\) that tells the customer to hold the market portfolio.

---

In [3]: # Observed mean excess market return
   \[ r_m = w_m \odot \mu_{\text{est}} \]

   # Estimated variance of the market portfolio
   \[ \sigma_m = w_m \odot \Sigma_{\text{est}} \odot w_m \]

   # Sharpe-ratio
33.2.7 Adding Views

Black and Litterman start with a baseline customer who asserts that he or she shares the market’s views, which means that he or she believes that excess returns are governed by

\[ \bar{r} - r_f \mathbf{1} \sim \mathcal{N}(\mu_{BL}, \Sigma) \] (3)
Black and Litterman would advise that customer to hold the market portfolio of risky securities.

Black and Litterman then imagine a consumer who would like to express a view that differs from the market’s.

The consumer wants appropriately to mix his view with the market’s before using (2) to choose a portfolio.

Suppose that the customer’s view is expressed by a hunch that rather than (3), excess returns are governed by

$$\tilde{r} - r_f 1 \sim \mathcal{N}(\tilde{\mu}, \tau \Sigma)$$

where $\tau > 0$ is a scalar parameter that determines how the decision maker wants to mix his view $\tilde{\mu}$ with the market’s view $\mu_{BL}$.

Black and Litterman would then use a formula like the following one to mix the views $\tilde{\mu}$ and $\mu_{BL}$

$$\tilde{\mu} = (\Sigma^{-1} + (\tau \Sigma)^{-1})^{-1}(\Sigma^{-1}\mu_{BL} + (\tau \Sigma)^{-1}\tilde{\mu}) \quad (4)$$

Black and Litterman would then advise the customer to hold the portfolio associated with these views implied by rule (2):

$$\tilde{w} = (\delta \Sigma)^{-1}\tilde{\mu}$$

This portfolio $\tilde{w}$ will deviate from the portfolio $w_{BL}$ in amounts that depend on the mixing parameter $\tau$.

If $\tilde{\mu}$ is the maximum likelihood estimator and $\tau$ is chosen heavily to weight this view, then the customer’s portfolio will involve big short-long positions.

```python
In [4]: def black_litterman(\lambda, \mu_1, \mu_2, \Sigma_1, \Sigma_2):
   
   """This function calculates the Black-Litterman mixture mean excess return and covariance matrix """
   \Sigma_1_inv = np.linalg.inv(\Sigma_1)
   \Sigma_2_inv = np.linalg.inv(\Sigma_2)
   
   \mu_tilde = np.linalg.solve(\Sigma_1_inv + \lambda \times \Sigma_2_inv, 
                           \Sigma_1_inv \otimes \mu_1 + \lambda \times \Sigma_2_inv \otimes \mu_2)
   
   return \mu_tilde
   
\tau = 1
\mu_tilde = black_litterman(1, \mu_m, \mu_est, \Sigma_est, \tau \times \Sigma_est)

# The Black-Litterman recommendation for the portfolio weights
w_tilde = np.linalg.solve(\delta \times \Sigma_est, \mu_tilde)

\tau_slider = FloatSlider(min=0.05, max=10, step=0.5, value=\tau)

@interact(\tau=\tau_slider)
def BL_plot(\tau):
   
def BL_plot(\tau):
```
Consider the following Bayesian interpretation of the Black-Litterman recommendation.

33.2.8 Bayes Interpretation of the Black-Litterman Recommendation

Consider the following Bayesian interpretation of the Black-Litterman recommendation.
The prior belief over the mean excess returns is consistent with the market portfolio and is given by

\[ \mu \sim \mathcal{N}(\mu_{BL}, \Sigma) \]

Given a particular realization of the mean excess returns \( \mu \) one observes the average excess returns \( \hat{\mu} \) on the market according to the distribution

\[ \hat{\mu} \mid \mu, \Sigma \sim \mathcal{N}(\mu, \tau \Sigma) \]

where \( \tau \) is typically small capturing the idea that the variation in the mean is smaller than the variation of the individual random variable.

Given the realized excess returns one should then update the prior over the mean excess returns according to Bayes rule.

The corresponding posterior over mean excess returns is normally distributed with mean

\[ (\Sigma^{-1} + (\tau \Sigma)^{-1})^{-1}(\Sigma^{-1}\mu_{BL} + (\tau \Sigma)^{-1}\hat{\mu}) \]

The covariance matrix is

\[ (\Sigma^{-1} + (\tau \Sigma)^{-1})^{-1} \]

Hence, the Black-Litterman recommendation is consistent with the Bayes update of the prior over the mean excess returns in light of the realized average excess returns on the market.

**33.2.9 Curve Decolletage**

Consider two independent “competing” views on the excess market returns

\[ r_e \sim \mathcal{N}(\mu_{BL}, \Sigma) \]

and

\[ r_e \sim \mathcal{N}(\hat{\mu}, \tau \Sigma) \]

A special feature of the multivariate normal random variable \( Z \) is that its density function depends only on the (Euclidean) length of its realization \( z \).

Formally, let the \( k \)-dimensional random vector be

\[ Z \sim \mathcal{N}(\mu, \Sigma) \]

then

\[ \tilde{Z} \equiv \Sigma(Z - \mu) \sim \mathcal{N}(0, I) \]

and so the points where the density takes the same value can be described by the ellipse
where \( \ddot{d} \in \mathbb{R}_+ \) denotes the (transformation) of a particular density value.

The curves defined by equation (5) can be labeled as iso-likelihood ellipses

**Remark:** More generally there is a class of density functions that possesses this feature, i.e.

\[
\exists g : \mathbb{R}_+ \mapsto \mathbb{R}_+ \quad \text{and} \quad c \geq 0, \quad \text{s.t. the density } f \text{ of } Z \text{ has the form } f(z) = cg(z \cdot z)
\]

This property is called **spherical symmetry** (see p 81 in Leamer (1978) [42]).

In our specific example, we can use the pair \((\tilde{d}_1, \tilde{d}_2)\) as being two “likelihood” values for which the corresponding iso-likelihood ellipses in the excess return space are given by

\[
(\tilde{r}_e - \mu_{BL})'\Sigma^{-1}(\tilde{r}_e - \mu_{BL}) = \tilde{d}_1
\]

\[
(\tilde{r}_e - \bar{\mu})'((\tau \Sigma)^{-1}(\tilde{r}_e - \bar{\mu}) = \tilde{d}_2
\]

Notice that for particular \( \tilde{d}_1 \) and \( \tilde{d}_2 \) values the two ellipses have a tangency point.

These tangency points, indexed by the pairs \((\tilde{d}_1, \tilde{d}_2)\), characterize points \( \tilde{r}_e \) from which there exists no deviation where one can increase the likelihood of one view without decreasing the likelihood of the other view.

The pairs \((\tilde{d}_1, \tilde{d}_2)\) for which there is such a point outlines a curve in the excess return space. This curve is reminiscent of the Pareto curve in an Edgeworth-box setting.

Dickey (1975) [19] calls it a **curve decolletage**.

Leamer (1978) [42] calls it an **information contract curve** and describes it by the following program: maximize the likelihood of one view, say the Black-Litterman recommendation while keeping the likelihood of the other view at least at a prespecified constant \( \tilde{d}_2 \)

\[
\tilde{d}_1(\tilde{d}_2) \equiv \max_{\tilde{r}_e} (\tilde{r}_e - \mu_{BL})'\Sigma^{-1}(\tilde{r}_e - \mu_{BL})
\]

subject to \((\tilde{r}_e - \bar{\mu})'((\tau \Sigma)^{-1}(\tilde{r}_e - \bar{\mu}) \geq \tilde{d}_2
\]

Denoting the multiplier on the constraint by \( \lambda \), the first-order condition is

\[
2(\tilde{r}_e - \mu_{BL})'\Sigma^{-1} + \lambda(\tilde{r}_e - \bar{\mu})'((\tau \Sigma)^{-1}(\tilde{r}_e - \bar{\mu}) = 0
\]

which defines the **information contract curve** between \( \mu_{BL} \) and \( \hat{\mu} \)

\[
\tilde{r}_e = (\Sigma^{-1} + \lambda(\tau \Sigma)^{-1})^{-1}(\Sigma^{-1}\mu_{BL} + \lambda(\tau \Sigma)^{-1}\hat{\mu})
\] (6)

Note that if \( \lambda = 1 \), (6) is equivalent with (4) and it identifies one point on the information contract curve.

Furthermore, because \( \lambda \) is a function of the minimum likelihood \( \tilde{d}_2 \) on the RHS of the constraint, by varying \( \tilde{d}_2 \) (or \( \lambda \)), we can trace out the whole curve as the figure below illustrates.
In [5]: np.random.seed(1987102)

N = 2  # Number of assets
T = 200  # Sample size
τ = 0.8

# Random market portfolio (sum is normalized to 1)
w_m = np.random.rand(N)
w_m = w_m / (w_m.sum())

μ = (np.random.randn(N) + 5) / 100
S = np.random.randn(N, N)
V = S @ S.T
Σ = V * (w_m @ μ)**2 / (w_m @ V @ w_m)

excess_return = stat.multivariate_normal(μ, Σ)
sample = excess_return.rvs(T)

μ_est = sample.mean().reshape(N, 1)
Σ_est = np.cov(sample.T)

σ_m = w_m @ Σ_est @ w_m
d_m = (w_m @ μ_est) / σ_m
μ_m = (d_m * Σ_est @ w_m).reshape(N, 1)

N_r1, N_r2 = 100, 100
r1 = np.linspace(-.04, .1, N_r1)
r2 = np.linspace(-.02, .15, N_r2)

λ_grid = np.linspace(.001, 20, 100)
curve = np.asarray([black_litterman(λ, μ_m, μ_est, Σ_est, τ * Σ_est).flatten() for λ in λ_grid])

λ_slider = FloatSlider(min=.1, max=7, step=.5, value=1)

@interact(λ=λ_slider)
def decolletage(λ):
    dist_r_BL = stat.multivariate_normal(μ_m.squeeze(), Σ_est)
dist_r_hat = stat.multivariate_normal(μ_est.squeeze(), τ * Σ_est)

    X, Y = np.meshgrid(r1, r2)
    Z_BL = np.zeros((N_r1, N_r2))
    Z_hat = np.zeros((N_r1, N_r2))

    for i in range(N_r1):
        for j in range(N_r2):
            Z_BL[i, j] = dist_r_BL.pdf(np.hstack([X[i, j], Y[i, j]]))
            Z_hat[i, j] = dist_r_hat.pdf(np.hstack([X[i, j], Y[i, j]]))

    μ_tilde = black_litterman(λ, μ_m, μ_est, Σ_est, τ * Σ_est).flatten()

    fig, ax = plt.subplots(figsize=(10, 6))
    ax.contourf(X, Y, Z_hat, cmap='viridis', alpha=.4)
    ax.contourf(X, Y, Z_BL, cmap='viridis', alpha=.4)
    ax.contourf(μ_tilde, cmap='viridis', alpha=.9)
    ax.contourf(μ_tilde, cmap='viridis', alpha=.9)
Note that the line that connects the two points $\hat{\mu}$ and $\mu_{BL}$ is linear, which comes from the fact that the covariance matrices of the two competing distributions (views) are proportional to each other.

To illustrate the fact that this is not necessarily the case, consider another example using the same parameter values, except that the “second view” constituting the constraint has covariance matrix $\tau I$ instead of $\tau \Sigma$.

This leads to the following figure, on which the curve connecting $\hat{\mu}$ and $\mu_{BL}$ are bending.

In [6]: $\lambda_{grid} = \text{np.linspace}(0.001, 20000.0, 1000)$
$\text{curve} = \text{np.asarray}([\text{black_litterman}(\lambda, \mu_m, \mu_est, \Sigma_est, \tau \ast \text{np.eye}(N)).\text{flatten()} \text{ for } \lambda \text{ in } \lambda_{grid}])$

$\lambda_{slider} = \text{FloatSlider}([\text{min}=5, \text{max}=1500, \text{step}=100, \text{value}=200])$

@interact($\lambda=\lambda_{slider}$)
def decolletage($\lambda$):
    $\text{dist}_r_{BL} = \text{stat.mutilvariate_normal}(\mu_m.\text{squeeze()}, \Sigma_{est})$
    $\text{dist}_r_{hat} = \text{stat.mutilvariate_normal}(\mu_{est}.\text{squeeze()}, \tau \ast \text{np.eye}(N))$
33.2. OVERVIEW

\[
X, Y = \text{np.meshgrid}(r1, r2) \\
Z_{BL} = \text{np.zeros}((N_r1, N_r2)) \\
Z_{hat} = \text{np.zeros}((N_r1, N_r2)) \\
\]

\[
\text{for } i \text{ in range}(N_r1): \\
\quad \text{for } j \text{ in range}(N_r2): \\
\quad \quad Z_{BL}[i, j] = \text{dist}_r_{BL}.pdf(\text{np.hstack([X[i, j], Y[i, j]]))} \\
\quad \quad Z_{hat}[i, j] = \text{dist}_r_{hat}.pdf(\text{np.hstack([X[i, j], Y[i, j]]))} \\
\mu_{\tilde{}} = \text{black_litterman}(\lambda, \mu_m, \mu_{est}, \Sigma_{est}, \tau \times \text{np.eye}(N)).flatten() \\
\]

```
fig, ax = plt.subplots(figsize=(10, 6))
ax.contourf(X, Y, Z_hat, cmap='viridis', alpha=.4)
ax.contourf(X, Y, Z_BL, cmap='viridis', alpha=.4)
ax.contourf(X, Y, Z_BL, [dist_r_BL.pdf(\mu_{\tilde{}}),], cmap='viridis', alpha=.9)
ax.contourf(X, Y, Z_hat, [dist_r_hat.pdf(\mu_{\tilde{}}),], cmap='viridis', alpha=.9)
ax.scatter(\mu_{est}[0], \mu_{est}[1])
ax.scatter(\mu_m[0], \mu_m[1])
ax.scatter(\mu_{\tilde{}}[0], \mu_{\tilde{}}[1], c='k', s=20*3)
ax.plot(curve[:, 0], curve[:, 1], c='k')
ax.axhline(0, c='k', alpha=.8)
ax.axvline(0, c='k', alpha=.8)
xax.set_xlabel('Excess return on the first asset, $r_{e, 1}$')
xax.set_ylabel('Excess return on the second asset, $r_{e, 2}$')
xax.text(\mu_{est}[0] + 0.003, \mu_{est}[1], r'$\hat{\mu}$')
xax.text(\mu_m[0] + 0.003, \mu_m[1] + 0.005, r'$\mu_{BL}$')
plt.show()
```
33.2.10 Black-Litterman Recommendation as Regularization

First, consider the OLS regression

$$\min_\beta \|X\beta - y\|^2$$

which yields the solution

$$\hat{\beta}_{OLS} = (X'X)^{-1}X'y$$

A common performance measure of estimators is the mean squared error (MSE).

An estimator is “good” if its MSE is relatively small. Suppose that $\beta_0$ is the “true” value of the coefficient, then the MSE of the OLS estimator is

$$\text{mse}(\hat{\beta}_{OLS}, \beta_0) := \mathbb{E}\|\hat{\beta}_{OLS} - \beta_0\|^2 = \mathbb{E}\|\hat{\beta}_{OLS} - \mathbb{E}\beta_{OLS}\|^2 + \|\mathbb{E}\hat{\beta}_{OLS} - \beta_0\|^2$$

From this decomposition, one can see that in order for the MSE to be small, both the bias and the variance terms must be small.

For example, consider the case when $X$ is a $T$-vector of ones (where $T$ is the sample size), so $\hat{\beta}_{OLS}$ is simply the sample average, while $\beta_0 \in \mathbb{R}$ is defined by the true mean of $y$.

In this example the MSE is

$$\text{mse}(\hat{\beta}_{OLS}, \beta_0) = \frac{1}{T^2}\mathbb{E}\left(\sum_{t=1}^{T}(y_t - \beta_0)\right)^2 + 0_{\text{bias}}$$

However, because there is a trade-off between the estimator’s bias and variance, there are cases when by permitting a small bias we can substantially reduce the variance so overall the MSE gets smaller.

A typical scenario when this proves to be useful is when the number of coefficients to be estimated is large relative to the sample size.

In these cases, one approach to handle the bias-variance trade-off is the so called Tikhonov regularization.

A general form with regularization matrix $\Gamma$ can be written as

$$\min_\beta \left\{\|X\beta - y\|^2 + \|\Gamma(\beta - \bar{\beta})\|^2\right\}$$

which yields the solution

$$\hat{\beta}_{Reg} = (X'X + \Gamma')^{-1}(X'y + \Gamma'\bar{\beta})$$

Substituting the value of $\hat{\beta}_{OLS}$ yields

$$\hat{\beta}_{Reg} = (X'X + \Gamma')^{-1}(X'X\hat{\beta}_{OLS} + \Gamma'\bar{\beta})$$
Often, the regularization matrix takes the form $\Gamma = \lambda I$ with $\lambda > 0$ and $\tilde{\beta} = 0$.

Then the Tikhonov regularization is equivalent to what is called ridge regression in statistics.

To illustrate how this estimator addresses the bias-variance trade-off, we compute the MSE of the ridge estimator

$$\text{mse}(\hat{\beta}_{\text{ridge}}, \beta_0) = \frac{1}{(T + \lambda)^2} \mathbb{E} \left( \sum_{t=1}^{T} (y_t - \beta_0) \right)^2 + \left( \frac{\lambda}{T + \lambda} \right)^2 \beta_0^2$$

The ridge regression shrinks the coefficients of the estimated vector towards zero relative to the OLS estimates thus reducing the variance term at the cost of introducing a “small” bias.

However, there is nothing special about the zero vector. When $\tilde{\beta} \neq 0$ shrinkage occurs in the direction of $\tilde{\beta}$.

Now, we can give a regularization interpretation of the Black-Litterman portfolio recommendation.

To this end, simplify first the equation (4) characterizing the Black-Litterman recommendation

$$\tilde{\mu} = (\Sigma^{-1} + (\tau \Sigma)^{-1})(\Sigma^{-1}\mu_{BL} + (\tau \Sigma)^{-1}\hat{\mu})$$

$$= (1 + \tau^{-1})^{-1}\Sigma\Sigma^{-1}(\mu_{BL} + \tau^{-1}\hat{\mu})$$

$$= (1 + \tau^{-1})^{-1}(\mu_{BL} + \tau^{-1}\hat{\mu})$$

In our case, $\hat{\mu}$ is the estimated mean excess returns of securities. This could be written as a vector autoregression where

- $y$ is the stacked vector of observed excess returns of size $(NT \times 1) - N$ securities and $T$ observations.
- $X = \sqrt{\tau}^{-1}(I_N \otimes \iota_T)$ where $I_N$ is the identity matrix and $\iota_T$ is a column vector of ones.

Correspondingly, the OLS regression of $y$ on $X$ would yield the mean excess returns as coefficients.

With $\Gamma = \sqrt{\tau}^{-1}(I_N \otimes \iota_T)$ we can write the regularized version of the mean excess return estimation

$$\hat{\beta}_{\text{Reg}} = (X'X + \Gamma'\Gamma)^{-1}(X'X\hat{\beta}_{\text{OLS}} + \Gamma'\Gamma\tilde{\beta})$$

$$= (1 + \tau)^{-1}X'X(X'X)^{-1}(\hat{\beta}_{\text{OLS}} + \tau\tilde{\beta})$$

$$= (1 + \tau)^{-1}(\hat{\beta}_{\text{OLS}} + \tau\tilde{\beta})$$

$$= (1 + \tau^{-1})^{-1}(\tau^{-1}\hat{\beta}_{\text{OLS}} + \tilde{\beta})$$

Given that $\hat{\beta}_{\text{OLS}} = \hat{\mu}$ and $\tilde{\beta} = \mu_{BL}$ in the Black-Litterman model, we have the following interpretation of the model’s recommendation.

The estimated (personal) view of the mean excess returns, $\hat{\mu}$ that would lead to extreme short-long positions are “shrunk” towards the conservative market view, $\mu_{BL}$, that leads to the more conservative market portfolio.

So the Black-Litterman procedure results in a recommendation that is a compromise between
the conservative market portfolio and the more extreme portfolio that is implied by estimated “personal” views.

33.2.11 Digression on A Robust Control Operator

The Black-Litterman approach is partly inspired by the econometric insight that it is easier to estimate covariances of excess returns than the means.

That is what gave Black and Litterman license to adjust investors’ perception of mean excess returns while not tampering with the covariance matrix of excess returns.

The robust control theory is another approach that also hinges on adjusting mean excess returns but not covariances.

Associated with a robust control problem is what Hansen and Sargent \cite{29}, \cite{26} call a T operator.

Let’s define the T operator as it applies to the problem at hand.

Let $x$ be an $n \times 1$ Gaussian random vector with mean vector $\mu$ and covariance matrix $\Sigma = CC'$. This means that $x$ can be represented as

$$x = \mu + C\epsilon$$

where $\epsilon \sim \mathcal{N}(0, I)$.

Let $\phi(\epsilon)$ denote the associated standardized Gaussian density.

Let $m(\epsilon, \mu)$ be a likelihood ratio, meaning that it satisfies

- $m(\epsilon, \mu) > 0$
- $\int m(\epsilon, \mu)\phi(\epsilon)d\epsilon = 1$

That is, $m(\epsilon, \mu)$ is a non-negative random variable with mean 1.

Multiplying $\phi(\epsilon)$ by the likelihood ratio $m(\epsilon, \mu)$ produces a distorted distribution for $\epsilon$, namely

$$\tilde{\phi}(\epsilon) = m(\epsilon, \mu)\phi(\epsilon)$$

The next concept that we need is the entropy of the distorted distribution $\tilde{\phi}$ with respect to $\phi$.

Entropy is defined as

$$\text{ent} = \int \log m(\epsilon, \mu)m(\epsilon, \mu)\phi(\epsilon)d\epsilon$$

or

$$\text{ent} = \int \log m(\epsilon, \mu)\tilde{\phi}(\epsilon)d\epsilon$$

That is, relative entropy is the expected value of the likelihood ratio $m$ where the expectation is taken with respect to the twisted density $\tilde{\phi}$. 
Relative entropy is non-negative. It is a measure of the discrepancy between two probability distributions.

As such, it plays an important role in governing the behavior of statistical tests designed to discriminate one probability distribution from another.

We are ready to define the $T$ operator.

Let $V(x)$ be a value function.

Define

$$
T(V(x)) = \min_{m(\epsilon, \mu)} \int m(\epsilon, \mu) [V(\mu + C\epsilon) + \theta \log m(\epsilon, \mu)]\phi(\epsilon) d\epsilon
$$

$$
= -\log \theta \int \exp \left( \frac{-V(\mu + C\epsilon)}{\theta} \right) \phi(\epsilon) d\epsilon
$$

This asserts that $T$ is an indirect utility function for a minimization problem in which an evil agent chooses a distorted probability distribution $\tilde{\phi}$ to lower expected utility, subject to a penalty term that gets bigger the larger is relative entropy.

Here the penalty parameter

$$
\theta \in [\theta, +\infty]
$$

is a robustness parameter when it is $+\infty$, there is no scope for the minimizing agent to distort the distribution, so no robustness to alternative distributions is acquired As $\theta$ is lowered, more robustness is achieved.

**Note:** The $T$ operator is sometimes called a *risk-sensitivity* operator.

We shall apply $T$ to the special case of a linear value function $w'(\bar{r} - r_f 1)$ where $\bar{r} - r_f 1 \sim N(\mu, \Sigma)$ or $\bar{r} - r_f 1 = \mu + C\epsilon$ and $\epsilon \sim N(0, I)$.

The associated worst-case distribution of $\epsilon$ is Gaussian with mean $v = -\theta^{-1}C'w$ and covariance matrix $I$ (When the value function is affine, the worst-case distribution distorts the mean vector of $\epsilon$ but not the covariance matrix of $\epsilon$).

For utility function argument $w'(\bar{r} - r_f 1)$

$$
T(\bar{r} - r_f 1) = w'\mu + \zeta - \frac{1}{2\theta} w'\Sigma w
$$

and entropy is

$$
\frac{v'v}{2} = \frac{1}{2\theta^2} w'C'w
$$

### 33.2.12 A Robust Mean-variance Portfolio Model

According to criterion (1), the mean-variance portfolio choice problem chooses $w$ to maximize

$$
E[w(\bar{r} - r_f 1)] - \text{var}[w(\bar{r} - r_f 1)]
$$

which equals


\[ w'\mu - \frac{\delta}{2}w'\Sigma w \]

A robust decision maker can be modeled as replacing the mean return \( E[w(\vec{r} - r_f)] \) with the risk-sensitive

\[ T[w(\vec{r} - r_f)] = w'\mu - \frac{1}{2\theta}w'\Sigma w \]

that comes from replacing the mean \( \mu \) of \( \vec{r} - r_f \) with the worst-case mean

\[ \mu - \theta^{-1}\Sigma w \]

Notice how the worst-case mean vector depends on the portfolio \( w \).

The operator \( T \) is the indirect utility function that emerges from solving a problem in which an agent who chooses probabilities does so in order to minimize the expected utility of a maximizing agent (in our case, the maximizing agent chooses portfolio weights \( w \)).

The robust version of the mean-variance portfolio choice problem is then to choose a portfolio \( w \) that maximizes

\[ T[w(\vec{r} - r_f)] - \frac{\delta}{2}w'\Sigma w \]

or

\[ w'(\mu - \theta^{-1}\Sigma w) - \frac{\delta}{2}w'\Sigma w \] (7)

The minimizer of (7) is

\[ w_{\text{rob}} = \frac{1}{\delta + \gamma} \Sigma^{-1}\mu \]

where \( \gamma \equiv \theta^{-1} \) is sometimes called the risk-sensitivity parameter.

An increase in the risk-sensitivity parameter \( \gamma \) shrinks the portfolio weights toward zero in the same way that an increase in risk aversion does.

### 33.3 Appendix

We want to illustrate the “folk theorem” that with high or moderate frequency data, it is more difficult to estimate means than variances.

In order to operationalize this statement, we take two analog estimators:

- sample average: \( \bar{X}_N = \frac{1}{N} \sum_{i=1}^{N} X_i \)
- sample variance: \( S_N = \frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X}_N)^2 \)

to estimate the unconditional mean and unconditional variance of the random variable \( X \), respectively.
To measure the “difficulty of estimation”, we use mean squared error (MSE), that is the average squared difference between the estimator and the true value.

Assuming that the process \( \{X_i\} \) is ergodic, both analog estimators are known to converge to their true values as the sample size \( N \) goes to infinity.

More precisely for all \( \varepsilon > 0 \)

\[
\lim_{N \to \infty} P \{|\bar{X}_N - \mathbb{E}X| > \varepsilon\} = 0
\]

and

\[
\lim_{N \to \infty} P \{|S_N - \mathbb{V}X| > \varepsilon\} = 0
\]

A necessary condition for these convergence results is that the associated MSEs vanish as \( N \) goes to infinity, or in other words,

\[
\text{MSE}(\bar{X}_N, \mathbb{E}X) = o(1) \quad \text{and} \quad \text{MSE}(S_N, \mathbb{V}X) = o(1)
\]

Even if the MSEs converge to zero, the associated rates might be different. Looking at the limit of the relative MSE (as the sample size grows to infinity)

\[
\frac{\text{MSE}(S_N, \mathbb{V}X)}{\text{MSE}(\bar{X}_N, \mathbb{E}X)} = \frac{o(1)}{o(1)} \to B \quad (N \to \infty)
\]

can inform us about the relative (asymptotic) rates.

We will show that in general, with dependent data, the limit \( B \) depends on the sampling frequency.

In particular, we find that the rate of convergence of the variance estimator is less sensitive to increased sampling frequency than the rate of convergence of the mean estimator.

Hence, we can expect the relative asymptotic rate, \( B \), to get smaller with higher frequency data, illustrating that “it is more difficult to estimate means than variances”.

That is, we need significantly more data to obtain a given precision of the mean estimate than for our variance estimate.

### 33.3.1 A Special Case – IID Sample

We start our analysis with the benchmark case of IID data. Consider a sample of size \( N \) generated by the following IID process,

\[ X_i \sim \mathcal{N}(\mu, \sigma^2) \]

Taking \( \bar{X}_N \) to estimate the mean, the MSE is

\[
\text{MSE}(\bar{X}_N, \mu) = \frac{\sigma^2}{N}
\]

Taking \( S_N \) to estimate the variance, the MSE is


\[ \text{MSE}(S_N, \sigma^2) = \frac{2\sigma^4}{N-1} \]

Both estimators are unbiased and hence the MSEs reflect the corresponding variances of the estimators. Furthermore, both MSEs are \( o(1) \) with a (multiplicative) factor of difference in their rates of convergence:

\[ \frac{\text{MSE}(S_N, \sigma^2)}{\text{MSE}(X_N, \mu)} = \frac{N2\sigma^2}{N-1} \xrightarrow{N \to \infty} 2\sigma^2 \]

We are interested in how this (asymptotic) relative rate of convergence changes as increasing sampling frequency puts dependence into the data.

### 33.3.2 Dependence and Sampling Frequency

To investigate how sampling frequency affects relative rates of convergence, we assume that the data are generated by a mean-reverting continuous time process of the form

\[ dX_t = -\kappa(X_t - \mu)dt + \sigma dW_t \]

where \( \mu \) is the unconditional mean, \( \kappa > 0 \) is a persistence parameter, and \( \{W_t\} \) is a standardized Brownian motion.

Observations arising from this system in particular discrete periods \( T(h) \equiv \{nh : n \in \mathbb{Z}\} \) with \( h > 0 \) can be described by the following process

\[ X_{t+1} = (1 - \exp(-\kappa h))\mu + \exp(-\kappa h)X_t + \epsilon_{t,h} \]

where

\[ \epsilon_{t,h} \sim \mathcal{N}(0, \Sigma_h) \quad \text{with} \quad \Sigma_h = \frac{\sigma^2(1 - \exp(-2\kappa h))}{2\kappa} \]

We call \( h \) the \textit{frequency} parameter, whereas \( n \) represents the number of \textit{lags} between observations.

Hence, the effective distance between two observations \( X_t \) and \( X_{t+n} \) in the discrete time notation is equal to \( h \cdot n \) in terms of the underlying continuous time process.

Straightforward calculations show that the autocorrelation function for the stochastic process \( \{X_t\}_{t \in T(h)} \) is

\[ \Gamma_h(n) \equiv \text{corr}(X_{t+hn}, X_t) = \exp(-\kappa hn) \]

and the auto-covariance function is

\[ \gamma_h(n) \equiv \text{cov}(X_{t+hn}, X_t) = \frac{\exp(-\kappa hn)\sigma^2}{2\kappa}. \]
It follows that if \( n = 0 \), the unconditional variance is given by \( \gamma_h(0) = \frac{\sigma^2}{2\kappa} \) irrespective of the sampling frequency.

The following figure illustrates how the dependence between the observations is related to the sampling frequency:

- For any given \( h \), the autocorrelation converges to zero as we increase the distance – \( n \) – between the observations. This represents the “weak dependence” of the \( X \) process.
- Moreover, for a fixed lag length, \( n \), the dependence vanishes as the sampling frequency goes to infinity. In fact, letting \( h \) go to \( \infty \) gives back the case of IID data.

```python
In [7]:
mu = .0
x = .1
sigma = .5
var_uncond = sigma**2 / (2 * x)
n_grid = np.linspace(0, 40, 100)
autocorr_h1 = np.exp(-x * n_grid * 1)
autocorr_h2 = np.exp(-x * n_grid * 2)
autocorr_h5 = np.exp(-x * n_grid * 5)
autocorr_h1000 = np.exp(-x * n_grid * 1e8)

fig, ax = plt.subplots(figsize=(8, 4))
ax.plot(n_grid, autocorr_h1, label=r'$h=1$', c='darkblue', lw=2)
ax.plot(n_grid, autocorr_h2, label=r'$h=2$', c='darkred', lw=2)
ax.plot(n_grid, autocorr_h5, label=r'$h=5$', c='orange', lw=2)
ax.plot(n_grid, autocorr_h1000, label=r'"h=\infty"', c='darkgreen', lw=2)
ax.legend()
ax.grid()
ax.set(title=r'Autocorrelation functions, $\Gamma_h(n)$',
       xlabel=r'Lags between observations, \( n \)')
plt.show()
```
33.3.3 Frequency and the Mean Estimator

Consider again the AR(1) process generated by discrete sampling with frequency \( h \). Assume that we have a sample of size \( N \) and we would like to estimate the unconditional mean – in our case the true mean is \( \mu \).

Again, the sample average is an unbiased estimator of the unconditional mean

\[
\mathbb{E}[X_{\bar{N}}] = \frac{1}{N} \sum_{i=1}^{N} \mathbb{E}[X_i] = \mathbb{E}[X_0] = \mu
\]

The variance of the sample mean is given by

\[
\text{𝕍}(\bar{X}_N) = \frac{1}{N^2} \left( \sum_{i=1}^{N} \text{𝕍}(X_i) + 2 \sum_{i=1}^{N-1} \sum_{s=i+1}^{N} \text{cov}(X_i, X_s) \right)
\]

\[
= \frac{1}{N^2} \left( N \gamma(0) + 2 \sum_{i=1}^{N-1} i \cdot \gamma(h \cdot (N-i)) \right)
\]

\[
= \frac{1}{N^2} \left( N \sigma^2 \gamma(2\kappa) + 2 \sum_{i=1}^{N-1} i \cdot \exp(-\kappa h (N-i)) \sigma^2 \right)
\]

It is explicit in the above equation that time dependence in the data inflates the variance of the mean estimator through the covariance terms. Moreover, as we can see, a higher sampling frequency—smaller \( h \)—makes all the covariance terms larger, everything else being fixed. This implies a relatively slower rate of convergence of the sample average for high-frequency data.

Intuitively, the stronger dependence across observations for high-frequency data reduces the “information content” of each observation relative to the IID case.

We can upper bound the variance term in the following way

\[
\text{𝕍}(\bar{X}_N) = \frac{1}{N^2} \left( N \sigma^2 + 2 \sum_{i=1}^{N-1} i \cdot \exp(-\kappa h (N-i)) \sigma^2 \right)
\]

\[
\leq \frac{\sigma^2}{2\kappa N} \left( 1 + 2 \sum_{i=1}^{N-1} \cdot \exp(-\kappa h (i)) \right)
\]

\[
= \frac{\sigma^2}{2\kappa N} \text{IID case} \left( 1 + 2 \cdot \frac{1 - \exp(-\kappa h)^{N-1}}{1 - \exp(-\kappa h)} \right)
\]

Asymptotically the \( \exp(-\kappa h)^{N-1} \) vanishes and the dependence in the data inflates the benchmark IID variance by a factor of

\[
\left( 1 + 2 \cdot \frac{1}{1 - \exp(-\kappa h)} \right)
\]

This long run factor is larger the higher is the frequency (the smaller is \( h \)).
Therefore, we expect the asymptotic relative MSEs, \( B \), to change with time-dependent data. We just saw that the mean estimator’s rate is roughly changing by a factor of

\[
\left(1 + \frac{1}{1 - \exp(-\kappa h)}\right)
\]

Unfortunately, the variance estimator’s MSE is harder to derive. Nonetheless, we can approximate it by using (large sample) simulations, thus getting an idea about how the asymptotic relative MSEs changes in the sampling frequency \( h \) relative to the IID case that we compute in closed form.

In [8]:
```python
def sample_generator(h, N, M):
    \( \phi = (1 - \exp(-x * h)) * \mu \)
    \( \varphi = \exp(-x * h) \)
    \( s = \sigma^2 \times (1 - \exp(-2 * x * h)) / (2 * x) \)

    mean_uncond = \mu
    std_uncond = np.sqrt(\sigma^2 / (2 * x))

    \( \epsilon_path = \text{norm}(0, \sqrt{s}) \cdot \text{rvs}(\text{M, N}) \)

    y_path = np.zeros((\text{M, N + 1}))
    y_path[:, 0] = \text{norm(mean_uncond, std_uncond).rvs(M)}

    for i in range(N):
        y_path[:, i + 1] = \( \phi + \varphi \cdot y_path[:, i] + \epsilon_path[:, i] \)

    return y_path
```

In [9]:
```python
# Generate large sample for different frequencies
N_app, M_app = 1000, 30000  # Sample size, number of simulations
h_grid = np.linspace(.1, 80, 30)

var_est_store = []
mean_est_store = []
labels = []

for h in h_grid:
    labels.append(h)
    sample = sample_generator(h, N_app, M_app)
    mean_est_store.append(np.mean(sample, 1))
    var_est_store.append(np.var(sample, 1))

var_est_store = np.array(var_est_store)
mean_est_store = np.array(mean_est_store)

# Save mse of estimators
mse_mean = np.var(mean_est_store, 1) + (np.mean(mean_est_store, 1) - \mu)**2
mse_var = np.var(var_est_store, 1) - \text{var_uncond)**2

benchmark_rate = 2 * var_uncond  # IID case

# Relative MSE for large samples
rate_h = mse_var / mse_mean
```
The above figure illustrates the relationship between the asymptotic relative MSES and the sampling frequency.

- We can see that with low-frequency data – large values of \( h \) – the ratio of asymptotic rates approaches the IID case.
- As \( h \) gets smaller – the higher the frequency – the relative performance of the variance estimator is better in the sense that the ratio of asymptotic rates gets smaller. That is, as the time dependence gets more pronounced, the rate of convergence of the mean estimator’s MSE deteriorates more than that of the variance estimator.
Chapter 34

Irrelevance of Capital Structures with Complete Markets

34.1 Contents

- Introduction 34.2
- Competitive equilibrium 34.3
- Code 34.4

In addition to what’s in Anaconda, this lecture will need the following libraries:

```
In [1]: !pip install --upgrade quantecon
!pip install interpolation
!conda install -y -c plotly plotly plotly-orca
```

34.2 Introduction

This is a prolegomenon to another lecture Equilibrium Capital Structures with Incomplete Markets about a model with incomplete markets authored by Bisin, Clementi, and Gottardi [? ].

We adopt specifications of preferences and technologies very close to Bisin, Clemente, and Gottardi’s but unlike them assume that there are complete markets in one-period Arrow securities.

This simplification of BCG’s setup helps us by

- creating a benchmark economy to compare with outcomes in BCG’s incomplete markets economy
- creating a good guess for initial values of some equilibrium objects to be computed in BCG’s incomplete markets economy via an iterative algorithm
- illustrating classic complete markets outcomes that include
  - indeterminacy of consumers’ portfolio choices
  - indeterminacy of firms’ financial structures that underlies a Modigliani-Miller theorem [? ]
- introducing Big K, little k issues in a simple context that will recur in the BCG incomplete markets environment

A Big K, little k analysis also played roles in this quantecon lecture as well as here and here.
34.2.1 Setup

The economy lasts for two periods, \( t = 0, 1 \).

There are two types of consumers named \( i = 1, 2 \).

A scalar random variable \( \epsilon \) with probability density \( g(\epsilon) \) affects both

- the return in period 1 from investing \( k \geq 0 \) in physical capital in period 0.
- exogenous period 1 endowments of the consumption good for agents of types \( i = 1 \) and \( i = 2 \).

Type \( i = 1 \) and \( i = 2 \) agents’ period 1 endowments are correlated with the return on physical capital in different ways.

We discuss two arrangements:

- a command economy in which a benevolent planner chooses \( k \) and allocates goods to the two types of consumers in each period and each random second period state
- a competitive equilibrium with markets in claims on physical capital and a complete set (possibly a continuum) of one-period Arrow securities that pay period 1 consumption goods contingent on the realization of random variable \( \epsilon \).

34.2.2 Endowments

There is a single consumption good in period 0 and at each random state \( \epsilon \) in period 1.

Economy-wide endowments in periods 0 and 1 are

\[
\begin{align*}
&\text{period 0} \\
&\text{period 1 in state } \epsilon \\
\end{align*}
\]

\[w_0 \quad w_1(\epsilon)\]

Soon we’ll explain how aggregate endowments are divided between type \( i = 1 \) and type \( i = 2 \) consumers.

We don’t need to do that in order to describe a social planning problem.

34.2.3 Technology:

Where \( \alpha \in (0, 1) \) and \( A > 0 \)

\[
\begin{align*}
c_0^1 + c_0^2 + k &= w_0^1 + w_0^2 \\
c_1^1(\epsilon) + c_1^2(\epsilon) &= w_1^1(\epsilon) + w_1^2(\epsilon) + e^A k^\alpha, \quad k \geq 0
\end{align*}
\]

34.2.4 Preferences:

A consumer of type \( i \) orders period 0 consumption \( c_0^i \) and state \( \epsilon \), period 1 consumption \( c_1^i(\epsilon) \) by

\[
u^i = u(c_0^i) + \beta \int u(c_1^i(\epsilon))g(\epsilon)d\epsilon, \quad i = 1, 2
\]

\( \beta \in (0, 1) \) and the one-period utility function is
34.2. INTRODUCTION

\[ u(c) = \begin{cases} \frac{c^{1-\gamma}}{1-\gamma} & \text{if } \gamma \neq 1 \\ \log c & \text{if } \gamma = 1 \end{cases} \]

34.2.5 Parameterizations

Following BCG, we shall employ the following parameterizations:

\[ \epsilon \sim \mathcal{N}(\mu, \sigma^2) \]

\[ u(c) = \frac{c^{1-\gamma}}{1-\gamma} \]

\[ w_i^1(\epsilon) = e^{-\chi_i \mu - 5\chi_i^2 \sigma^2 + \chi_i \epsilon}, \quad \chi_i \in [0, 1] \]

Sometimes instead of assuming \( \epsilon \sim g(\epsilon) = \mathcal{N}(0, \sigma^2) \), we’ll assume that \( g(\cdot) \) is a probability mass function that serves as a discrete approximation to a standardized normal density.

34.2.6 Pareto criterion and planning problem

The planner’s objective function is

\[ \text{obj} = \phi_1 u^1 + \phi_2 u^2, \quad \phi_i \geq 0, \quad \phi_1 + \phi_2 = 1 \]

where \( \phi_i \geq 0 \) is a Pareto weight that the planner attaches to a consumer of type \( i \).

We form the following Lagrangian for the planner’s problem:

\[
L = \sum_{i=1}^{2} \phi_i \left[ u(c_i^1) + \beta \int u(c_1^1(\epsilon)) g(\epsilon) d\epsilon \right] \\
+ \lambda_0 \left[ w_0^1 + w_0^2 - k - c_0^1 - c_0^2 \right] \\
+ \beta \int \lambda_1(\epsilon) \left[ w_1^1(\epsilon) + w_1^2(\epsilon) + e^\epsilon A k^\alpha - c_1^1(\epsilon) - c_1^2(\epsilon) \right] g(\epsilon) d\epsilon
\]

First-order necessary optimality conditions for the planning problem are:

\[
c_0^1 : \quad \phi_1 u'(c_0^1) - \lambda_0 = 0 \\
c_0^2 : \quad \phi_2 u'(c_0^2) - \lambda_0 = 0 \\
c_1^1(\epsilon) : \quad \phi_1 \beta u'(c_1^1(\epsilon)) g(\epsilon) - \beta \lambda_1(\epsilon) g(\epsilon) = 0 \\
c_1^2(\epsilon) : \quad \phi_2 \beta u'(c_1^2(\epsilon)) g(\epsilon) - \beta \lambda_1(\epsilon) g(\epsilon) = 0 \\
k : \quad -\lambda_0 + \beta \alpha A k^{\alpha-1} \int \lambda_1(\epsilon) e^\epsilon g(\epsilon) d\epsilon = 0
\]

The first four equations imply that

\[
\frac{u'(c_1^1(\epsilon))}{u'(c_0^1)} = \frac{u'(c_1^2(\epsilon))}{u'(c_0^2)} = \frac{\lambda_1(\epsilon)}{\lambda_0} = \frac{\phi_2}{\phi_1} 
\]
These together with the fifth first-order condition for the planner imply the following equation that determines an optimal choice of capital

\[ 1 = \beta \alpha A k^{\alpha - 1} \int \frac{u'(c_1^i(\epsilon))}{u'(c_0^i)} e^\epsilon g(\epsilon) d\epsilon \]

for \( i = 1, 2 \).

### 34.2.7 Helpful observations and bookkeeping

Evidently,

\[ u'(c) = c^{-\gamma} \]

and

\[ \frac{u'(c_1)}{u'(c_2)} = \left( \frac{c_1}{c_2} \right)^{-\gamma} = \frac{\phi_2}{\phi_1} \]

where it is to be understood that this equation holds for \( c_1 = c_0^1 \) and \( c_2 = c_0^2 \) and also for \( c_1 = c_1(\epsilon) \) and \( c_2 = c_2(\epsilon) \) for all \( \epsilon \).

With the same understanding, it follows that

\[ \left( \frac{c_1}{c_2} \right) = \left( \frac{\phi_2}{\phi_1} \right)^{-\gamma^{-1}} \]

Let \( c = c_1 + c_2 \).

It follows from the preceding equation that

\[ c_1 = \eta c \]
\[ c_2 = (1 - \eta)c \]

where \( \eta \in [0, 1] \) is a function of \( \phi_1 \) and \( \gamma \).

Consequently, we can write the planner’s first-order condition for \( k \) as

\[ 1 = \beta \alpha A k^{\alpha - 1} \int \left( \frac{w_1(\epsilon) + A k^{\alpha} e^\epsilon}{w_0 - k} \right)^{-\gamma} e^\epsilon g(\epsilon) d\epsilon \]

which is one equation to be solved for \( k \geq 0 \).

Anticipating a Big K, little k idea widely used in macroeconomics, to be discussed in detail below, let \( K \) be the value of \( k \) that solves the preceding equation so that

\[ 1 = \beta \alpha A K^{\alpha - 1} \int \left( \frac{w_1(\epsilon) + A K^{\alpha} e^\epsilon}{w_0 - K} \right)^{-\gamma} g(\epsilon)e^\epsilon d\epsilon \]

The associated optimal consumption allocation is
34.3. COMPETITIVE EQUILIBRIUM

\[ C_0 = w_0 - K \]
\[ C_1(\epsilon) = w_1(\epsilon) + AK^\alpha e^\epsilon \]
\[ c_0^1 = \eta C_0 \]
\[ c_0^2 = (1 - \eta)C_0 \]
\[ c_1^1(\epsilon) = \eta C_1(\epsilon) \]
\[ c_1^2(\epsilon) = (1 - \eta)C_1(\epsilon) \]

where \( \eta \in [0, 1] \) is the consumption share parameter mentioned above that is a function of the Pareto weight \( \phi_1 \) and the utility curvature parameter \( \gamma \).

Remarks

The relative Pareto weight parameter \( \eta \) does not appear in equation (1) that determines \( K \). Neither does it influence \( C_0 \) or \( C_1(\epsilon) \), which depend solely on \( K \).

The role of \( \eta \) is to determine how to allocate total consumption between the two types of consumers.

Thus, the planner’s choice of \( K \) does not interact with how it wants to allocate consumption.

34.3 Competitive equilibrium

We now describe a competitive equilibrium for an economy that has specifications of consumer preferences, technology, and aggregate endowments that are identical to those in the preceding planning problem.

While prices do not appear in the planning problem – only quantities do – prices play an important role in a competitive equilibrium.

To understand how the planning economy is related to a competitive equilibrium, we now turn to the Big K, little k distinction.

34.3.1 Measures of agents and firms

We follow BCG in assuming that there are unit measures of

- consumers of type \( i = 1 \)
- consumers of type \( i = 2 \)
- firms with access to the production technology that converts \( k \) units of time 0 good into \( Ak^\alpha e^\epsilon \) units of the time 1 good in random state \( \epsilon \)

Thus, let \( \omega \in [0,1] \) index a particular consumer of type \( i \).

Then define Big \( C^i \) as

\[ C^i = \int_0^1 c^i(\omega)d\omega \]

In the same spirit, let \( \zeta \in [0,1] \) index a particular firm. Then define Big \( K \) as
CHAPTER 34. IRRELEVANCE OF CAPITAL STRUCTURES WITH COMPLETE MARKETS

\[ K = \int_{0}^{1} k(\zeta) d\zeta \]

The assumption that there are continua of our three types of agents plays an important role making each individual agent into a powerless \textbf{price taker}:

- an individual consumer chooses its own (infinitesimal) part \( c^i(\omega) \) of \( C^i \) taking prices as given
- an individual firm chooses its own (infinitesimal) part \( k(\zeta) \) of \( K \) taking prices as
- equilibrium prices depend on the \textbf{Big K}, \textbf{Big C} objects \( K \) and \( C \)

Nevertheless, in equilibrium, \( K = k, C^i = c^i \)

The assumption about measures of agents is thus a powerful device for making a host of competitive agents take as given equilibrium prices that are determined by the independent decisions of hosts of agents who behave just like they do.

\section*{Ownership}

Consumers of type \( i \) own the following exogenous quantities of the consumption good in periods 0 and 1:

\[
\begin{align*}
w_i^0, & \quad i = 1, 2 \\
w_i^1(\epsilon) & \quad i = 1, 2
\end{align*}
\]

where

\[
\begin{align*}
\sum_i w_i^0 & = w_0 \\
\sum_i w_i^1(\epsilon) & = w_1(\epsilon)
\end{align*}
\]

Consumers also own shares in a firm that operates the technology for converting nonnegative amounts of the time 0 consumption good one-for-one into a capital good \( k \) that produces \( Ak^{\alpha}e^{\epsilon} \) units of the time 1 consumption good in time 1 state \( \epsilon \).

Consumers of types \( i = 1, 2 \) are endowed with \( \theta_i^0 \) shares of a firm and

\[ \theta_0^1 + \theta_0^2 = 1 \]

\section*{Asset markets}

At time 0, consumers trade the following assets with other consumers and with firms:

- equities (also known as stocks) issued by firms
- one-period Arrow securities that pay one unit of consumption at time 1 when the shock \( \epsilon \) assumes a particular value

Later, we’ll allow the firm to issue bonds too, but not now.
34.3. COMPETITIVE EQUILIBRIUM

34.3.2 Objects appearing in a competitive equilibrium

Let
- \( a^i(\epsilon) \) be consumer \( i \)'s purchases of claims on time 1 consumption in state \( \epsilon \)
- \( q(\epsilon) \) be a pricing kernel for one-period Arrow securities
- \( \theta^i_0 \geq 0 \) be consumer \( i \)'s initial share of the firm, \( \sum_i \theta^i_0 = 1 \)
- \( \theta^i \) be the fraction of a firm’s shares purchased by consumer \( i \) at time \( t = 0 \)
- \( -\bar{a}^i(\epsilon; \theta^i) \) be debt limits constraining consumer \( i \)'s issues of claims on time 1 consumption in state \( \epsilon \)
- \( V \) be the value of the representative firm
- \( \tilde{V} \) be the value of equity issued by the representative firm
- \( K, C_0 \) be two scalars and \( C_1(\epsilon) \) a function that we use to construct a guess about an equilibrium pricing kernel for Arrow securities

We proceed to describe constrained optimum problems faced by consumers and a representative firm in a competitive equilibrium.

34.3.3 A representative firm’s problem

A representative firm takes Arrow security prices \( q(\epsilon) \) as given.

The firm purchases capital \( k \geq 0 \) from consumers at time 0 and finances itself by issuing equity at time 0.

The firm produces time 1 goods \( Ak^\alpha e^\epsilon \) in state \( \epsilon \) and pays all of these earnings to owners of its equity.

The value of a firm’s equity at time 0 can be computed by multiplying its state-contingent earnings by their Arrow securities prices and then adding over all contingencies:

\[
\tilde{V} = \int Ak^\alpha e^\epsilon q(\epsilon) d\epsilon
\]

Owners of a firm want it to choose \( k \) to maximize

\[
V = -k + \int Ak^\alpha e^\epsilon q(\epsilon) d\epsilon
\]

The firm’s first-order necessary condition for an optimal \( k \) is

\[
-1 + \alpha Ak^{\alpha-1} \int e^\epsilon q(\epsilon) d\epsilon = 0
\]

The time 0 value of a representative firm is

\[
V = -k + \tilde{V}
\]

The right side equals the value of equity minus the cost of the time 0 goods that it purchases and uses as capital.
34.3.4 A consumer’s problem

We now pose a consumer’s problem in a competitive equilibrium.

As a price taker, each consumer faces a given Arrow securities pricing kernel \( q(\epsilon) \), a given value of a firm \( V \) that has chosen capital stock \( k \), a price of equity \( \tilde{V} \), and prospective next period random dividends \( Ak^\alpha e^\epsilon \).

Consumer \( i \) also confronts a state-by-state borrowing limit that restricts quantities of Arrow securities that he can issue.

If we evaluate consumer \( i \)’s time 1 budget constraint at zero consumption \( c^i_1(\epsilon) = 0 \) and solve for \(-a^i(\epsilon)\) we obtain

\[
-a^i(\epsilon; \theta^i) = w^i_1(\epsilon) + \theta^i Ak^\alpha e^\epsilon
\]  

(2)

The quantity \(-a^i(\epsilon; \theta^i)\) is the maximum amount that it is feasible for consumer \( i \) to repay to his Arrow security creditors at time 1 in state \( \epsilon \).

To arrange trading with one-period Arrow securities, we must impose on agent \( i \) the state-by-state debt limits

\[-a^i(\epsilon) \leq -\bar{a}^i(\epsilon; \theta^i)\]

Notice that consumer \( i \)’s borrowing limit defined in (2) depends on

- his endowment \( w^i_1(\epsilon) \) at time 1 in state \( \epsilon \)
- his share \( \theta^i \) of a representative firm’s dividends

These constitute the two sources of collateral that back the consumer’s issues of Arrow securities that pay off in state \( \epsilon \).

Consumer \( i \) chooses a scalar \( c^i_0 \) and a function \( c^i_1(\epsilon) \) to maximize

\[u(c^i_0) + \beta \int u(c^i_1(\epsilon))g(\epsilon)d\epsilon\]

subject to his state-by-state debt limits and time 0 and time 1 budget constraints

\[
c^i_0 \leq w^i_0 + \theta^i_0 V - \int q(\epsilon)a^i(\epsilon)d\epsilon - \theta^i\tilde{V}
\]

\[
c^i_1(\epsilon) \leq w^i_1(\epsilon) + \theta^i Ak^\alpha e^\epsilon + a^i(\epsilon)
\]

Attach Lagrange multiplier \( \lambda^i_0 \) to the budget constraint at time 0, scaled Lagrange multipliers \( \beta \lambda^i_1(\epsilon)g(\epsilon) \) to the budget constraint at time 1 and state \( \epsilon \), and scaled Lagrange multiplier \( \beta \phi^i_1(\epsilon)g(\epsilon) \) to the debt limit at time 1 and state \( \epsilon \), then form the Lagrangian
\[ L^i = u(c^i_0) + \beta \int u'(c^i_1(\epsilon))g(\epsilon)d\epsilon \]
\[ + \lambda^i_0[w^i_0 + \theta^i_0 - \int q(\epsilon)a^i(\epsilon)d\epsilon - \theta^i \tilde{V} - c^i_0] \]
\[ + \beta \int \lambda^i_1(\epsilon)[w^i_1(\epsilon) + \theta^i Ak^\alpha e^\epsilon + a^i(\epsilon)c^i_1(\epsilon)]g(\epsilon)d\epsilon \]
\[ + \beta \int \phi^i_1(\epsilon)[-\bar{a}^i(\epsilon; \theta^i) + a^i(\epsilon)]g(\epsilon)d\epsilon \]

Off corners, first-order necessary conditions for an optimum with respect to \(c^i_0, c^i_1(\epsilon),\) and \(a^i(\epsilon)\) are

\[ c^i_0 : \quad u'(c^i_0) - \lambda^i_0 = 0 \]
\[ c^i_1(\epsilon) : \quad \beta u'(c^i_1(\epsilon))g(\epsilon) - \beta \lambda^i_1(\epsilon)g(\epsilon) = 0 \]
\[ a^i(\epsilon) : \quad - \lambda^i_0 q(\epsilon) + \beta \lambda^i_1(\epsilon) = 0 \]

These equations imply that consumer \(i\) adjusts its consumption plan to satisfy

\[ q(\epsilon) = \beta \left( \frac{u'(c^i_1(\epsilon))}{u'(c^i_0)} \right) g(\epsilon) \quad (3) \]

To deduce a restriction on equilibrium prices, we solve the period 1 budget constraint to express \(a^i(\epsilon)\) as

\[ a^i(\epsilon) = c^i_1(\epsilon) - w^i_1(\epsilon) - \theta^i Ak^\alpha e^\epsilon \]

then substitute the expression on the right side into the time 0 budget constraint and rearrange to get the single intertemporal budget constraint

\[ w^i_0 + \theta^i_0 V + \int w^i_1(\epsilon)q(\epsilon)d\epsilon + \theta^i \left[ Ak^\alpha \int e^\epsilon q(\epsilon)d\epsilon - \tilde{V} \right] \geq c^i_0 + \int c^i_1(\epsilon)q(\epsilon)d\epsilon \quad (4) \]

The right side of inequality (4) is the present value of consumer \(i\)’s consumption while the left side is the present value of consumer \(i\)’s endowment when consumer \(i\) buys \(\theta^i\) shares of equity. From inequality (4), we deduce two findings.

1. **No arbitrage profits condition:**

Unless

\[ \tilde{V} = Ak^\alpha \int e^\epsilon q(\epsilon)d\epsilon \quad (5) \]

an arbitrage opportunity would be open.

If

\[ \tilde{V} > Ak^\alpha \int e^\epsilon q(\epsilon)d\epsilon \]
the consumer could afford an arbitrarily high present value of consumption by setting $\theta^i$ to an arbitrarily large negative number.

If

$$\bar{V} < Ak^\alpha \int e^\epsilon q(\epsilon) d\epsilon$$

the consumer could afford an arbitrarily high present value of consumption by setting $\theta^i$ to be arbitrarily large positive number.

Since resources are finite, there can exist no such arbitrage opportunity in a competitive equilibrium.

Therefore, it must be true that the following no arbitrage condition prevails:

$$\bar{V} = \int Ak^\alpha e^\epsilon q(\epsilon; K) d\epsilon$$

Equation (6) asserts that the value of equity equals the value of the state-contingent dividends $Ak^\alpha e^\epsilon$ evaluated at the Arrow security prices $q(\epsilon; K)$ that we have expressed as a function of $K$.

We’ll say more about this equation later.

2. Indeterminacy of portfolio

When the no-arbitrage pricing equation (6) prevails, a consumer of type $i$’s choice $\theta^i$ of equity is indeterminate.

Consumer of type $i$ can offset any choice of $\theta^i$ by setting an appropriate schedule $a^i(\epsilon)$ for purchasing state-contingent securities.

34.3.5 Computing competitive equilibrium prices and quantities

Having computed an allocation that solves the planning problem, we can readily compute a competitive equilibrium via the following steps that, as we’ll see, relies heavily on the Big $K$, little $k$, Big $C$, little $c$ logic mentioned earlier:

- a competitive equilibrium allocation equals the allocation chosen by the planner
- competitive equilibrium prices and the value of a firm’s equity are encoded in shadow prices from the planning problem that depend on Big $K$ and Big $C$.

To substantiate that this procedure is valid, we proceed as follows.

With $K$ in hand, we make the following guess for competitive equilibrium Arrow securities prices

$$q(\epsilon; K) = \beta \left( \frac{u'(w_1(\epsilon) + AK^\alpha e^\epsilon)}{u'(w_0 - K)} \right)^{-\gamma}$$

(7)

To confirm the guess, we begin by considering its consequences for the firm’s choice of $k$.

With Arrow securities prices (7), the firm’s first-order necessary condition for choosing $k$ becomes
\[-1 + \alpha A k^{\alpha - 1} \int e^\epsilon q(\epsilon; K) d\epsilon = 0 \tag{8}\]

which can be verified to be satisfied if the firm sets

\[k = K\]

because by setting \(k = K\) equation (8) becomes equivalent with the planner’s first-order condition (1) for setting \(K\).

To pose a consumer’s problem in a competitive equilibrium, we require not only the above guess for the Arrow securities pricing kernel \(q(\epsilon)\) but the value of equity \(\tilde{V}\):

\[\tilde{V} = \int A K^{\alpha} e^\epsilon q(\epsilon; K) d\epsilon \tag{9}\]

Let \(\tilde{V}\) be the value of equity implied by Arrow securities price function (7) and formula (9).

At the Arrow securities prices \(q(\epsilon)\) given by (7) and equity value \(\tilde{V}\) given by (9), consumer \(i = 1, 2\) choose consumption allocations and portfolios that satisfy the first-order necessary conditions

\[\beta \left( \frac{u'_{c_i^1(\epsilon)}}{u'_{c_i^0(\epsilon)}} \right) g(\epsilon) = q(\epsilon; K)\]

It can be verified directly that the following choices satisfy these equations

\[c^1_0 + c^2_0 = C_0 = w_0 - K\]
\[c^1_0(\epsilon) + c^2_0(\epsilon) = C_1(\epsilon) = w_1(\epsilon) + A k^\alpha e^\epsilon\]
\[\frac{c^2_1(\epsilon)}{c^1_1(\epsilon)} = \frac{c^2_0}{c^1_0} = \frac{1 - \eta}{\eta}\]

for an \(\eta \in (0, 1)\) that depends on consumers’ endowments \([w^1_0, w^2_0, w^1_1(\epsilon), w^2_1(\epsilon), \theta^1_0, \theta^2_0]\).

**Remark:** Multiple arrangements of endowments \([w^1_0, w^2_0, w^1_1(\epsilon), w^2_1(\epsilon), \theta^1_0, \theta^2_0]\) associated with the same distribution of wealth \(\eta\). Can you explain why? **Hint:** Think about the portfolio indeterminacy finding above.

### 34.3.6 Modigliani-Miller theorem

We now allow a firm to issue both bonds and equity.

Payouts from equity and bonds, respectively, are

\[d^e(k, b; \epsilon) = \max \{e^\epsilon A k^\alpha - b, 0\}\]
\[d^b(k, b; \epsilon) = \min \left\{ \frac{e^\epsilon A k^\alpha - b}{b}, 1 \right\}\]

Thus, one unit of the bond pays one unit of consumption at time 1 in state \(\epsilon\) if \(A k^\alpha e^\epsilon - b \geq 0\), which is true when \(\epsilon \geq \epsilon^* = \log_\frac{b}{A k^\alpha} \), and pays \(\frac{A k^\alpha e^\epsilon}{b}\) units of time 1 consumption in state \(\epsilon\) when \(\epsilon < \epsilon^*\).
The value of the firm is now the sum of equity plus the value of bonds, which we denote

\[ \tilde{V} + bp(k, b) \]

where \( p(k, b) \) is the price of one unit of the bond when a firm with \( k \) units of physical capital issues \( b \) bonds.

We continue to assume that there are complete markets in Arrow securities with pricing kernel \( q(\epsilon) \).

A version of the no-arbitrage-in-equilibrium argument that we presented earlier implies that the value of equity and the price of bonds are

\[
\tilde{V} = Ak^\alpha \int_{-\infty}^{\infty} e^\epsilon q(\epsilon) d\epsilon - b \int_{-\infty}^{\infty} q(\epsilon) d\epsilon
\]

\[
p(k, b) = \frac{Ak^\alpha}{b} \int_{-\infty}^{\epsilon^*} e^\epsilon q(\epsilon) d\epsilon + \int_{\epsilon^*}^{\infty} q(\epsilon) d\epsilon
\]

Consequently, the value of the firm is

\[ \tilde{V} + p(k, b)b = Ak^\alpha \int_{-\infty}^{\infty} e^\epsilon q(\epsilon) d\epsilon, \]

which is the same expression that we obtained above when we assumed that the firm issued only equity.

We thus obtain a version of the celebrated Modigliani-Miller theorem about firms’ finance:

**Modigliani-Miller theorem:**

- The value of a firm is independent the mix of equity and bonds that it uses to finance its physical capital.
- The firm’s decision about how much physical capital to purchase does not depend on whether it finances those purchases by issuing bonds or equity.
- The firm’s choice of whether to finance itself by issuing equity or bonds is indeterminant.

Please note the role of the assumption of complete markets in Arrow securities in substantiating these claims.

In *Equilibrium Capital Structures with Incomplete Markets*, we will assume that markets are (very) incomplete – we’ll shut down markets in almost all Arrow securities.

That will pull the rug from underneath the Modigliani-Miller theorem.

### 34.4 Code

We create a class object `BCG_complete_markets` to compute equilibrium allocations of the complete market BCG model given a list of parameter values.

It consists of 4 functions that do the following things:

- **opt_k** computes the planner’s optimal capital \( K \)
  - First, create a grid for capital.
34.4. CODE

Then for each value of capital stock in the grid, compute the left side of the planner’s first-order necessary condition for $k$, that is,

$$\beta \alpha AK^{\alpha-1} \int \left( \frac{w_1(\epsilon) + AK^\alpha e^\epsilon}{w_0 - K} \right)^{-\gamma} e^\epsilon g(\epsilon) d\epsilon - 1 = 0$$

Find $k$ that solves this equation.

- $q$ computes Arrow security prices as a function of the productivity shock $\epsilon$ and capital $K$: 
  $$q(\epsilon; K) = \beta \left( \frac{u'(w_1(\epsilon) + AK^\alpha e^\epsilon)}{u'(w_0 - K)} \right)$$

- $V$ solves for the firm value given capital $k$:
  $$V = -k + \int Ak^\alpha e^\epsilon q(\epsilon; K) d\epsilon$$

- `opt_c` computes optimal consumptions $c^0_1$ and $c^i(\epsilon)$:
  - The function first computes weight $\eta$ using the budget constraint for agent 1:
  $$w_1^0 + \theta_0^0 V + \int w_1^1(\epsilon) q(\epsilon) d\epsilon = c^1_0 + \int c_1(\epsilon) q(\epsilon) d\epsilon = \eta \left( C_0 + \int C_1(\epsilon) q(\epsilon) d\epsilon \right)$$
  where
  $$C_0 = w_0 - K$$
  $$C_1(\epsilon) = w_1(\epsilon) + AK^\alpha e^\epsilon$$
  - It computes consumption for each agent as
    $$c^1_0 = \eta C_0$$
    $$c^2_0 = (1 - \eta) C_0$$
    $$c^1_1(\epsilon) = \eta C_1(\epsilon)$$
    $$c^2_1(\epsilon) = (1 - \eta) C_1(\epsilon)$$

The list of parameters includes:

- $\chi_1, \chi_2$: Correlation parameters for agents 1 and 2. Default values are 0 and 0.9, respectively.
- $w^1_0, w^2_0$: Initial endowments. Default values are 1.
- $\theta^1_0, \theta^2_0$: Consumers’ initial shares of a representative firm. Default values are 0.5.
- $\psi$: CRRA risk parameter. Default value is 3.
- $\alpha$: Returns to scale production function parameter. Default value is 0.6.
- $A$: Productivity of technology. Default value is 2.5.
- $\mu, \sigma$: Mean and standard deviation of the log of the shock. Default values are -0.025 and 0.4, respectively.
- $\beta$: time preference discount factor. Default value is .96.
- `nb_points_integ`: number of points used for integration through Gauss-Hermite quadrature: default value is 10

In [2]: import pandas as pd
     import numpy as np
     import matplotlib.pyplot as plt
     from scipy.stats import norm
     from numba import njit, prange
     from quantecon.optimize import root_finding
     %matplotlib inline
In [3]: #======== Class: BCG for complete markets =========#
class BCG_complete_markets:

    # init method or constructor
    def __init__(self,
        a1 = 0,
        a2 = 0.9,
        w10 = 1,
        w20 = 1,
        a10 = 0.5,
        a20 = 0.5,
        a = 3,
        a = 0.6,
        A = 2.5,
        a = -0.025,
        a = 0.4,
        a = 0.96,
        nb_points_integ = 10):

    #======== Setup =========#
    # Risk parameters
    self.a1 = a1
    self.a2 = a2

    # Other parameters
    self.a = a
    self.A = A
    self.a = a
    self.a = a
    self.a = a

    # Utility
    self.u = lambda c: (c**(1-a)) / (1-a)

    # Production
    self.f = njit(lambda k: A * (k ** a))
    self.Y = lambda a, k: np.exp(a) * self.f(k)

    # Initial endowments
    self.w10 = w10
    self.w20 = w20
    self.w0 = w10 + w20

    # Initial holdings
    self.a10 = a10
    self.a20 = a20

    # Endowments at t=1
    w11 = njit(lambda a: np.exp(-a1*2 - 0.5*(a1**2)*(a**2) + a1))
    w21 = njit(lambda a: np.exp(-a2*2 - 0.5*(a2**2)*(a**2) + a2))
    self.w11 = w11
    self.w21 = w21

    self.w1 = njit(lambda a: w11(a) + w21(a))

    # Normal PDF
    self.g = lambda x: norm.pdf(x, loc=a, scale=a)
# Integration

```python
x, self.weights = np.polynomial.hermite.hermgauss(nb_points_integ)
self.points_integral = np.sqrt(2) * \[ x + \]

self.k_foc = k_foc_factory(self)
```

# Function: solve for optimal k
```python
def opt_k(self, plot=False):
    w0 = self.w0

    # Grid for k
    kgrid = np.linspace(1e-4, w0-1e-4, 100)

    # get FONC values for each k in the grid
    kfoc_list = []
    for k in kgrid:
        kfoc = self.k_foc(k, self.\]1, self.\]2)
        kfoc_list.append(kfoc)

    # Plot FONC for k
    if plot:
        fig, ax = plt.subplots(figsize=(8, 7))
        ax.plot(kgrid, kfoc_list, color='blue', label=r'FONC for k')
        ax.axhline(0, color='red', linestyle='--')
        ax.legend()
        ax.set_xlabel(r'k')
        plt.show()

    # Find k that solves the FONC
    kk = root_finding.newton_secant(self.k_foc, 1e-2, args=(self.\]1,  
                                           self.\]2)).root

    return kk
```

# Function: Compute Arrow security price
```python
def q(self, k):
    \[ = self.\]
    \[ = self.\]
    w0 = self.w0
    w1 = self.w1
    fk = self.f(k)
    g = self.g

    return \[ * ((w1(\[) + np.exp(\[)*fk) / (w0 - k))**(-\[)
```

# Function: compute firm value V
```python
def V(self, k):
    q = self.q
    fk = self.f(k)
    weights = self.weights
    integ = lambda \[: np.exp(\[) * fk * q(\[, k)
```
```
return -k + np.sum(weights * integ(self.points_integral)) / np.sqrt(np.pi)

#======== Optimal c ========
# Function: Compute optimal consumption choices c
def opt_c(self, k=None, plot=False):
    w1 = self.w1
    w0 = self.w0
    w10 = self.w10
    w11 = self.w11
    w10 = self.w10
    w11 = self.w11
    Y = self.Y
    q = self.q
    V = self.V
    weights = self.weights

    if k is None:
        k = self.opt_k()

    # Solve for the ratio of consumption i from the intertemporal B.C.
    f_k = self.f(k)
    c1 = lambda i: (w1(i) + np.exp(i)*f_k)*q(i,k)
    denom = np.sum(weights * c1(self.points_integral)) / np.sqrt(np.pi) + (w0 - k)
    w10q = lambda i: w10(i)*q(i,k)
    num = w10 + w10 * V(k) + np.sum(weights * w10q(self.points_integral)) / np.sqrt(np.pi)

    i = num / denom

    # Consumption choices
    c10 = i * (w0 - k)
    c20 = (1-i) * (w0 - k)
    c11 = lambda i: (c10) * (w1(i) + Y(i,k))
    c21 = lambda i: (1-i) * (w1(i) + Y(i,k))

    return c10, c20, c11, c21

def k_foc_factory(model):
    f = model.f
    A = model.A
    w0 = model.w0
    w11 = njit(lambda i, i1: np.exp(-i1*i - 0.5*(i1**2)*(i**2) + i1**2))
    w21 = njit(lambda i, i2: np.exp(-i2*i - 0.5*(i2**2)*(i**2) + i2**2))
```
34.4. CODE

```python
w1 = njit(lambda d1, d2: w11(d1, d2) + w21(d1, d2))

@njit
def integrand(d1, d2, k=1e-4):
    fk = f(k)
    return (w1(d1, d2) + np.exp(d1) * fk) ** (-d1) * np.exp(d2)

@njit
def k_foc(k, d1, d2):
    int_k = np.sum(weights * integrand(points_integral, d1, d2, k)) / np.sqrt(np.pi)
    mul = d * d * A * k ** (d - 1) / ((w0 - k) ** (-d))
    val = mul * int_k - 1
    return val

34.4.1 Examples

Below we provide some examples of how to use BCG_complete markets.

1st example

In the first example, we set up instances of BCG complete markets models.
We can use either default parameter values or set parameter values as we want.
The two instances of the BCG complete markets model, mdl1 and mdl2, represent
the model with default parameter settings and with agent 2’s income correlation altered to be
\( \chi_2 = -0.9 \), respectively.

In [4]: # Example: BCG model for complete markets
mdl1 = BCG_complete_markets()
mdl2 = BCG_complete_markets(d2=-0.9)

Let’s plot the agents’ time-1 endowments with respect to shocks to see the difference in the
two models:

In [5]: #==== Figure 1: HH endowments and firm productivity ====#
# Realizations of innovation from -3 to 3
epsgrid = np.linspace(-1, 1, 1000)

fig, ax = plt.subplots(1, 2, figsize=(15,7))
ax[0].plot(epsgrid, mdl1.w11(epsgrid), color='black', label='Agent 1’s endowment')
ax[0].plot(epsgrid, mdl1.w21(epsgrid), color='blue', label='Agent 2’s endowment')
ax[0].plot(epsgrid, mdl1.Y(epsgrid, 1), color='red', label='Production with $k=1$')
ax[0].set_xlim([-1, 1])
ax[0].set_ylim([0, 7])
```

Let’s also compare the optimal capital stock, $k$, and optimal time-0 consumption of agent 2, $c_{02}$, for the two models:

In [6]: # Print optimal $k$

kk_1 = mdl1.opt_k()
kk_2 = mdl2.opt_k()

print('The optimal $k$ for model 1: {:.5f}'.format(kk_1))
print('The optimal $k$ for model 2: {:.5f}'.format(kk_2))

# Print optimal time-0 consumption for agent 2

c20_1 = mdl1.opt_c(k=kk_1)[1]
c20_2 = mdl2.opt_c(k=kk_2)[1]

print('The optimal $c_{02}$ for model 1: {:.5f}'.format(c20_1))
print('The optimal $c_{02}$ for model 2: {:.5f}'.format(c20_2))
2nd example

In the second example, we illustrate how the optimal choice of $k$ is influenced by the correlation parameter $\chi_i$.

We will need to install the plotly package for 3D illustration. See https://plotly.com/python/getting-started/ for further instructions.

```
In [7]: # Mesh grid of
N = 30
ι1grid, ι2grid = np.meshgrid(np.linspace(-1,1,N),
                           np.linspace(-1,1,N))

k_foc = k_foc_factory(mdl1)

# Create grid for k
kgrid = np.zeros_like(ι1grid)

w0 = mdl1.w0

@njit(parallel=True)
def fill_k_grid(kgrid):
    # Loop: Compute optimal k and
    for i in prange(N):
        for j in prange(N):
            X1 = ι1grid[i, j]
            X2 = ι2grid[i, j]
            k = root_finding.newton_secant(k_foc, 1e-2, args=(X1, X2)).root
            kgrid[i, j] = k

In [8]: %time
fill_k_grid(kgrid)

CPU times: user 2.52 s, sys: 7.28 ms, total: 2.53 s
Wall time: 2.52 s

In [9]: %time
# Second-run
fill_k_grid(kgrid)

CPU times: user 24.5 ms, sys: 125 µs, total: 24.7 ms
Wall time: 12.9 ms

In [10]: ### Example: Plot optimal k with different correlations ###

    from IPython.display import Image
    # Import plotly
```
```python
import plotly.graph_objs as go

# Plot optimal k
fig = go.Figure(data=[go.Surface(x=grid, y=grid, z=kgrid)])
fig.update_layout(scene=dict(xaxis_title='x - 1',
yaxis_title='y - 2',
zaxis_title='z - k',
aspectratio=dict(x=1, y=1, z=1)))
fig.update_layout(width=500,
                   height=500,
                   margin=dict(l=50, r=50, b=65, t=90))
fig.update_layout(scene_camera=dict(eye=dict(x=2, y=-2, z=1.5)))

# Export to PNG file
Image(fig.to_image(format="png"))
# fig.show() will provide interactive plot when running
# notebook locally
```

Out[10]:
Chapter 35

Equilibrium Capital Structures with Incomplete Markets

35.1 Contents

- Introduction 35.2
- Asset Markets 35.3
- Equilibrium verification 35.4
- Pseudo Code 35.5
- Code 35.6
- Examples 35.7
- A picture worth a thousand words 35.8

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: pip install --upgrade quantecon
   !pip install interpolation
   !conda install -y -c plotly plotly plotly-orca

35.2 Introduction

This is an extension of an earlier lecture Irrelevance of Capital Structures with Complete Markets about a complete markets model.

In contrast to that lecture, this one describes an instance of a model authored by Bisin, Clementi, and Gottardi [?] in which financial markets are incomplete.

Instead of being able to trade equities and a full set of one-period Arrow securities as they can in Irrelevance of Capital Structures with Complete Markets, here consumers and firms trade only equity and a bond.

It is useful to watch how outcomes differ in the two settings.

In the complete markets economy in Irrelevance of Capital Structures with Complete Markets

- there is a unique stochastic discount factor that prices all assets
- consumers’ portfolio choices are indeterminate
- firms’ financial structures are indeterminate, so the model embodies an instance of a Modigliani-Miller irrelevance theorem [?]
• the aggregate of all firms’ financial structures are indeterminate, a consequence of there being redundant assets

In the incomplete markets economy studied here

• there is a not a unique equilibrium stochastic discount factor
• different stochastic discount factors price different assets
• consumers’ portfolio choices are determinate
• while individual firms’ financial structures are indeterminate, thus conforming to part of a Modigliani-Miller theorem, [? ], the aggregate of all firms’ financial structures is determinate.

A Big K, little k analysis played an important role in the previous lecture Irrelevance of Capital Structures with Complete Markets.

A more subtle version of a Big K, little k features in the BCG incomplete markets environment here.

We use it to convey the heart of what BCG call a rational conjectures equilibrium in which conjectures are about equilibrium pricing functions in regions of the state space that an average consumer or firm does not visit in equilibrium.

Note that the absence of complete markets means that we can compute competitive equilibrium prices and allocations by first solving the simple planning problem that we did in Irrelevance of Capital Structures with Complete Markets.

Instead, we compute an equilibrium by solving a system of simultaneous inequalities.

(Here we do not address the interesting question of whether there is a different planning problem that we could use to compute a competitive equilibrium allocation.)

35.2.1 Setup

We adopt specifications of preferences and technologies used by Bisin, Clemente, and Gottardi (2018) and in our earlier lecture on a complete markets version of their model.

The economy lasts for two periods, \( t = 0, 1 \).

There are two types of consumers named \( i = 1, 2 \).

A scalar random variable \( \epsilon \) affects both

• a representative firm’s physical return \( f(k)e^\epsilon \) in period 1 from investing \( k \geq 0 \) in capital in period 0.
• period 1 endowments \( w_i(\epsilon) \) of the consumption good for agents \( i = 1 \) and \( i = 2 \).

35.2.2 Ownership

A consumer of type \( i \) is endowed with \( w_0^i \) units of the time 0 good and \( w_1^i(\epsilon) \) of the time 1 good when the random variable takes value \( \epsilon \).

At the start of period 0, a consumer of type \( i \) also owns \( \theta_0^i \) shares of a representative firm.
35.2. INTRODUCTION

35.2.3 Measures of agents and firms

As in the companion lecture Irrelevance of Capital Structures with Complete Markets that studies a complete markets version of the model, we follow BCG in assuming that there are unit measures of

- consumers of type $i = 1$
- consumers of type $i = 2$
- firms with access to a production technology that converts $k$ units of time 0 good into $Ak^\alpha e^\epsilon$ units of the time 1 good in random state $\epsilon$

Thus, let $\omega \in [0, 1]$ index a particular consumer of type $i$.

Then define Big $C^i$ as

$$C^i = \int_0^1 c^i(\omega) d\omega$$

with components

$$C^i_0 = \int_0^1 c^i_0(\omega) d\omega$$
$$C^i_1(\epsilon) = \int_0^1 c^i_1(\epsilon; \omega) d\omega$$

In the same spirit, let $\zeta \in [0, 1]$ index a particular firm and let firm $\zeta$ purchase $k(\zeta)$ units of capital and issue $b(\zeta)$ bonds.

Then define Big $K$ and Big $B$ as

$$K = \int_0^1 k(\zeta) d\zeta, \quad B = \int_0^1 b(\zeta) d\zeta$$

The assumption that there are equal measures of our three types of agents justifies our assumption that each individual agent is a powerless price taker:

- an individual consumer chooses its own (infinitesimal) part $c^i(\omega)$ of $C^i$ taking prices as given
- an individual firm chooses its own (infinitesimal) part $k(\zeta)$ of $K$ and $b(\zeta)$ of $B$ taking pricing functions as given
- However, equilibrium prices depend on the Big $K$, Big $B$, Big $C$ objects $K$, $B$, and $C$

The assumption about measures of agents is a powerful device for making a host of competitive agents take as given the equilibrium prices that turn out to be determined by the decisions of hosts of agents who are just like them.

We call an equilibrium symmetric if

- all type $i$ consumers choose the same consumption profiles so that $c^i(\omega) = C^i$ for all $\omega \in [0, 1]$
- all firms choose the same levels of $k$ and $b$ so that $k(\zeta) = K$, $b(\zeta) = B$ for all $\zeta \in [0, 1]$

In this lecture, we restrict ourselves to describing symmetric equilibria.
35.2.4 Endowments

Per capital economy-wide endowments in periods 0 and 1 are

\[ w_0 = w_1^1 + w_0^2 \]
\[ w_1(\epsilon) = w_1^1(\epsilon) + w_1^2(\epsilon) \text{ in state } \epsilon \]

35.2.5 Feasibility:

Where \( \alpha \in (0, 1) \) and \( A > 0 \)

\[ C_0^1 + C_0^2 = w_0^1 + w_0^2 - K \]
\[ C_1^1(\epsilon) + C_1^2(\epsilon) = w_1^1(\epsilon) + w_1^2(\epsilon) + e^\epsilon \int_0^1 f(k(\zeta))d\zeta, \quad k \geq 0 \]

where \( f(k) = Ak^\alpha, A > 0, \alpha \in (0, 1) \).

35.2.6 Parameterizations

Following BCG, we shall employ the following parameterizations:

\[ \epsilon \sim N(\mu, \sigma^2) \]
\[ u(\epsilon) = \frac{\epsilon^{1-\gamma}}{1-\gamma} \]
\[ w_i^1(\epsilon) = e^{-\chi_i \mu - 5\chi_i \sigma^2 + \chi_i \epsilon}, \quad \chi_i \in [0, 1] \]

Sometimes instead of assuming \( \epsilon \sim g(\epsilon) = N(0, \sigma^2) \), we’ll assume that \( g(\cdot) \) is a probability mass function that serves as a discrete approximation to a standardized normal density.

35.2.7 Preferences:

A consumer of type \( i \) orders period 0 consumption \( c_0^i \) and state \( \epsilon \)-period 1 consumption \( c_1^i(\epsilon) \) by

\[ u_i^1 = u(c_0^i) + \beta \int u(c_1^i(\epsilon))g(\epsilon)d\epsilon, \quad i = 1, 2 \]

\( \beta \in (0, 1) \) and the one-period utility function is

\[ u(\epsilon) = \begin{cases} 
\frac{\epsilon^{1-\gamma}}{1-\gamma} & \text{if } \gamma \neq 1 \\
\log \epsilon & \text{if } \gamma = 1
\end{cases} \]

35.2.8 Risk-sharing motives

The two types of agents’ period 1 endowments have different correlations with the physical return on capital.
35.3. Asset Markets

Markets are incomplete: ex cathedra we the model builders declare that only equities and bonds issued by representative firms can be traded.

Let $\theta^i$ and $\xi^i$ be a consumer of type $i$’s post-trade holdings of equity and bonds, respectively.

A firm issues bonds promising to pay $b$ units of consumption at time $t = 1$ and purchases $k$ units of physical capital at time $t = 0$.

When $e^\prime Ak^\alpha < b$ at time 1, the firm defaults and its output is divided equally among bondholders.

Evidently, when the productivity shock $\epsilon < e^\prime = \log \left( \frac{b}{Ak^\alpha} \right)$, the firm defaults on its debt.

Payoffs to equity and debt at date 1 as functions of the productivity shock $\epsilon$ are thus

$$
d^e(k, b; \epsilon) = \max \{ e^\prime Ak^\alpha - b, 0 \}
$$

$$
d^b(k, b; \epsilon) = \min \left\{ \frac{e^\prime Ak^\alpha}{b}, 1 \right\}
$$

A firm faces a bond price function $p(k, b)$ when it issues $b$ bonds and purchases $k$ units of physical capital.

A firm’s equity is worth $q(k, b)$ when it issues $b$ bonds and purchases $k$ units of physical capital.

A firm regards an equity-pricing function $q(k, b)$ and a bond pricing function $p(k, b)$ as exogenous in the sense that they are not affected by its choices of $k$ and $b$.

Consumers face equilibrium prices $\hat{q}$ and $\hat{p}$ for bonds and equities, where $\hat{q}$ and $\hat{p}$ are both scalars.

Consumers are price takers and only need to know the scalars $\hat{q}, \hat{p}$.

Firms are price function takers and must know the functions $q(k, b), p(k, b)$ in order completely to pose their optimum problems.

35.3.1 Consumers

Each consumer of type $i$ is endowed with $w^i_0$ of the time 0 consumption good, $w^i_1(\epsilon)$ of the time 1, state $\epsilon$ consumption good and also owns a fraction $\theta^i_0 \in (0, 1)$ of the initial value of a representative firm, where $\theta^i_0 + \theta^i_2 = 1$.

The initial value of a representative firm is $V$ (an object to be determined in a rational expectations equilibrium).

Consumer $i$ buys $\theta^i$ shares of equity and buys bonds worth $\hat{p}\xi^i$ where $\hat{p}$ is the bond price.
CHAPTER 35. EQUILIBRIUM CAPITAL STRUCTURES WITH INCOMPLETE MARKETS

Being a price-taker, a consumer takes \( V, \bar{q}, \bar{p}, \) and \( K,B \) as given.

Consumers know that equilibrium payoff functions for bonds and equities take the form

\[
\begin{align*}
d^e(K,B;\epsilon) &= \max \left\{ e^\alpha AK^\alpha - B, 0 \right\} \\
d^b(K,B;\epsilon) &= \min \left\{ \frac{e^\alpha AK^\alpha}{B}, 1 \right\}
\end{align*}
\]

Consumer \( i \)'s optimization problem is

\[
\begin{align*}
\max_{c_0^i,\theta^i,\xi^i,c_1^i(\epsilon)} & \quad u(c_0^i) + \beta \int u(c_1^i(\epsilon))g(\epsilon) \, d\epsilon \\
\text{subject to} & \quad c_0^i = w_0^i + \theta_0^i V - \bar{q}^i \theta^i - \bar{p}^i \xi^i, \\
& \quad c_1^i(\epsilon) = w_1^i(\epsilon) + \theta^i d^e(K,B;\epsilon) + \xi^i d^b(K,B;\epsilon) \quad \forall \epsilon, \\
& \quad \theta^i \geq 0, \xi^i \geq 0.
\end{align*}
\]

The last two inequalities impose that the consumer cannot short sell either equity or bonds.

In a rational expectations equilibrium, \( \bar{q} = q(K,B) \) and \( \bar{p} = p(K,B) \)

We form consumer \( i \)'s Lagrangian:

\[
L_i := u(c_0^i) + \beta \int u(c_1^i(\epsilon))g(\epsilon) \, d\epsilon \\
+ \lambda_0^i [w_0^i + \theta_0^i V - \bar{q}^i \theta^i - \bar{p}^i \xi^i] \\
+ \beta \int \lambda_1^i(\epsilon) [w_1^i(\epsilon) + \theta^i d^e(K,B;\epsilon) + \xi^i d^b(K,B;\epsilon) - c_1^i(\epsilon)] g(\epsilon) \, d\epsilon
\]

Consumer \( i \)'s first-order necessary conditions for an optimum include:

\[
\begin{align*}
c_0^i : & \quad u'(c_0^i) = \lambda_0^i \\
c_1^i(\epsilon) : & \quad u'(c_1^i(\epsilon)) = \lambda_1^i(\epsilon) \\
\theta^i : & \quad \beta \int \lambda_1^i(\epsilon)d^e(K,B;\epsilon)g(\epsilon) \, d\epsilon \leq \lambda_0^i \bar{q} \quad (= \text{ if } \theta^i > 0) \\
\xi^i : & \quad \beta \int \lambda_1^i(\epsilon)d^b(K,B;\epsilon)g(\epsilon) \, d\epsilon \leq \lambda_0^i \bar{p} \quad (= \text{ if } \theta^i > 0)
\end{align*}
\]

We can combine and rearrange consumer \( i \)'s first-order conditions to become:

\[
\begin{align*}
\bar{q} \geq \beta \int \frac{u'(c_1^i(\epsilon))}{u'(c_0^i)}d^e(K,B;\epsilon)g(\epsilon) \, d\epsilon \quad (= \text{ if } \theta^i > 0) \\
\bar{p} \geq \beta \int \frac{u'(c_1^i(\epsilon))}{u'(c_0^i)}d^b(K,B;\epsilon)g(\epsilon) \, d\epsilon \quad (= \text{ if } \theta^i > 0)
\end{align*}
\]

These inequalities imply that in a symmetric rational expectations equilibrium consumption allocations and prices satisfy

\[
\begin{align*}
\bar{q} &= \max_{i} \beta \int \frac{u'(c_1^i(\epsilon))}{u'(c_0^i)}d^e(K,B;\epsilon)g(\epsilon) \, d\epsilon \\
\bar{p} &= \max_{i} \beta \int \frac{u'(c_1^i(\epsilon))}{u'(c_0^i)}d^b(K,B;\epsilon)g(\epsilon) \, d\epsilon
\end{align*}
\]
35.3.2 Pricing functions

When individual firms solve their optimization problems, they take big \( C^i \)'s as fixed objects that they don’t influence.

A representative firm faces a price function \( q(k, b) \) for its equity and a price function \( p(k, b) \) per unit of bonds that satisfy

\[
q(k, b) = \max_i \beta \int \frac{u'(C^1_i(\epsilon))}{u'(C^0_0)} d\epsilon(k, b; \epsilon) g(\epsilon) d\epsilon
\]

\[
p(k, b) = \max_i \beta \int \frac{u'(C^1_i(\epsilon))}{u'(C^0_0)} d\epsilon(k, b; \epsilon) g(\epsilon) d\epsilon
\]

where the payoff functions are described by equations (1).

Notice the appearance of big \( C^i \)'s on the right sides of these two equations that define equilibrium pricing functions.

The two price functions describe outcomes not only for equilibrium choices \( K, B \) of capital \( k \) and debt \( b \), but also for any out-of-equilibrium pairs \( (k, b) \neq (K, B) \).

The firm is assumed to know both price functions.

This means that the firm understands that its choice of \( k, b \) influences how markets price its equity and debt.

This package of assumptions is sometimes called rational conjectures (about price functions).

BCG give credit to Makowski for emphasizing and clarifying how rational conjectures are components of rational expectations equilibria.

35.3.3 Firms

The firm chooses capital \( k \) and debt \( b \) to maximize its market value:

\[
V \equiv \max_{k, b} -k + q(k, b) + p(k, b)b
\]

Attributing value maximization to the firm is a good idea because in equilibrium consumers of both types want a firm to maximize its value.

In the special quantitative examples studied here

- consumers of types \( i = 1, 2 \) both hold equity
- only consumers of type \( i = 2 \) hold debt; consumers of type \( i = 1 \) hold none.

These outcomes occur because we follow BCG and set parameters so that a type 2 consumer’s stochastic endowment of the consumption good in period 1 is more correlated with the firm’s output than is a type 1 consumer’s.

This gives consumers of type 2 a motive to hedge their second period endowment risk by holding bonds (they also choose to hold some equity).

These outcomes mean that the pricing functions end up satisfying
CHAPTER 35. EQUILIBRIUM CAPITAL STRUCTURES WITH INCOMPLETE MARKETS

\[ q(k, b) = \beta \int u'(C_1^i(\epsilon)) \frac{d^c(k, b; \epsilon)}{d^c(C_0^i)} \, d\epsilon = \beta \int u'(C_1^2(\epsilon)) \frac{d^c(k, b; \epsilon)}{d^c(C_0^2)} \, d\epsilon \]

\[ p(k, b) = \beta \int u'(C_2^i(\epsilon)) \frac{d^b(k, b; \epsilon)}{d^b(C_0^2)} \, d\epsilon \]

Recall that \( \epsilon^*(k, b) \equiv \log \left( \frac{b A_k}{A_k} \right) \) is a firm’s default threshold.

We can rewrite the pricing functions as:

\[ q(k, b) = \beta \int_{\epsilon^*}^{\infty} u'(C_1^i(\epsilon)) \frac{d^c(k, b; \epsilon)}{d^c(C_0^i)} (e^\epsilon A_k^\alpha - b) \, d\epsilon, \quad i = 1, 2 \]

\[ p(k, b) = \beta \int_{-\infty}^{\epsilon^*} u'(C_2^i(\epsilon)) \frac{d^b(k, b; \epsilon)}{d^b(C_0^2)} e^\epsilon A_k^\alpha \, d\epsilon + \beta \int_{\epsilon^*}^{\infty} u'(C_2^2(\epsilon)) \frac{d^b(k, b; \epsilon)}{d^b(C_0^2)} g(\epsilon) \, d\epsilon \]

**Firm’s optimization problem**

The firm’s optimization problem is

\[ V \equiv \max_{k, b} \{-k + q(k, b) + p(k, b)b\} \]

The firm’s first-order necessary conditions with respect to \( k \) and \( b \), respectively, are

\[ k: \quad -1 + \frac{\partial q(k, b)}{\partial k} + b \frac{\partial p(k, b)}{\partial k} = 0 \]

\[ b: \quad \frac{\partial q(k, b)}{\partial b} + p(k, b) + b \frac{\partial p(k, b)}{\partial b} = 0 \]

We use the Leibniz integral rule several times to arrive at the following derivatives:

\[ \frac{\partial q(k, b)}{\partial k} = \beta A_k^\alpha \int_{\epsilon^*}^{\infty} u'(C_1^i(\epsilon)) \frac{e^\epsilon g(\epsilon) \, d\epsilon}{u'(C_0^i)}, \quad i = 1, 2 \]

\[ \frac{\partial q(k, b)}{\partial b} = -\beta \int_{\epsilon^*}^{\infty} u'(C_1^i(\epsilon)) \frac{g(\epsilon) \, d\epsilon}{u'(C_0^i)}, \quad i = 1, 2 \]

\[ \frac{\partial p(k, b)}{\partial k} = \beta A_k^\alpha \int_{-\infty}^{\epsilon^*} \frac{u'(C_2^i(\epsilon))}{u'(C_0^2)} g(\epsilon) \, d\epsilon \]

\[ \frac{\partial p(k, b)}{\partial b} = -\beta A_k^\alpha \frac{1}{b^2} \int_{-\infty}^{\epsilon^*} \frac{u'(C_2^i(\epsilon))}{u'(C_0^2)} e^\epsilon g(\epsilon) \, d\epsilon \]

**Special case:** We confine ourselves to a special case in which both types of consumer hold positive equities so that \( \frac{\partial q(k, b)}{\partial k} \) and \( \frac{\partial q(k, b)}{\partial b} \) are related to rates of intertemporal substitution for both agents.

Substituting these partial derivatives into the above first-order conditions for \( k \) and \( b \), respectively, we obtain the following versions of those first order conditions:
35.4 Equilibrium verification

On page 5 of BCG (2018), the authors say

If the price conjectures corresponding to the plan chosen by firms in equilibrium are correct, that is equal to the market prices \( \hat{q} \) and \( \hat{p} \), it is immediate to verify that the rationality of the conjecture coincides with the agents’ Euler equations.

Here BCG are describing how they go about verifying that when they set little \( k \), little \( b \) from the firm’s first-order conditions equal to the big \( K \), big \( B \) at the big \( C \)’s that appear in the pricing functions, then

- consumers’ Euler equations are satisfied if little \( c \)’s are equated to Big \( C \)’s
- firms’ first-order necessary conditions for \( k, b \) are satisfied.
- \( \hat{q} = q(K, B) \) and \( \hat{p} = p(K, B) \).

35.5 Pseudo Code

Before displaying our Python code for computing a BCG incomplete markets equilibrium, we’ll sketch some pseudo code that describes its logical flow.

Here goes:

1. Set upper and lower bounds for firm value as \( V_h \) and \( V_l \), for capital as \( k_h \) and \( k_l \), and for debt as \( b_h \) and \( b_l \).
2. Conjecture firm value \( V = \frac{1}{2}(V_h + V_l) \)
3. Conjecture debt level \( b = \frac{1}{2}(b_h + b_l) \).
4. Conjecture capital \( k = \frac{1}{2}(k_h + k_l) \).
5. Compute the default threshold \( \epsilon^*(k, b) \equiv \log\left(\frac{b}{A k^\alpha}\right) \).
6. (In this step we abuse notation by freezing \( V, k, b \) and in effect temporarily treating them as Big \( K, B \) values. Thus, in this step 6 little \( k \), \( b \) are frozen at guessed at value of \( K, B \).) Fixing the values of \( V, b \) and \( k \), compute optimal choices of consumption \( c^i \) with consumers’ FOCs. Assume that only agent 2 holds debt: \( \xi^2 = b \) and that both agents hold equity: \( 0 < \theta^i < 1 \) for \( i = 1, 2 \).
7. Set high and low bounds for equity holdings for agent 1 as \( \theta^1_h \) and \( \theta^1_l \). Guess \( \theta^1 = \frac{1}{2}(\theta^1_h + \theta^1_l) \), and \( \theta^2 = 1 - \theta^1 \). While \( |\theta^1_h - \theta^1_l| \) is large:
• Compute agent 1’s valuation of the equity claim with a fixed-point iteration:
  \[ q_1 = \beta \int \frac{u'(c^1_1(\epsilon))}{u'(c^0_1)} d\epsilon (k; b; \epsilon) g(\epsilon) \, d\epsilon \]
  where
  \[ c^1_1(\epsilon) = w^1_1(\epsilon) + \theta^1 d^e(k; b; \epsilon) \]
  and
  \[ c^0_1 = u^1_0 + \theta^1 V - q_1 \theta^1 \]

• Compute agent 2’s valuation of the bond claim with a fixed-point iteration:
  \[ p = \beta \int \frac{u'(c^2_1(\epsilon))}{u'(c^0_2)} d\epsilon (k; b; \epsilon) g(\epsilon) \, d\epsilon \]
  where
  \[ c^2_1(\epsilon) = w^2_1(\epsilon) + \theta^2 d^e(k; b; \epsilon) + b \]
  and
  \[ c^0_2 = u^2_0 + \theta^2 V - q_2 \theta^2 - pb \]

• Compute agent 2’s valuation of the equity claim with a fixed-point iteration:
  \[ q_2 = \beta \int \frac{u'(c^2_1(\epsilon))}{u'(c^0_2)} d\epsilon (k; b; \epsilon) g(\epsilon) \, d\epsilon \]
  where
  \[ c^2_1(\epsilon) = w^2_1(\epsilon) + \theta^2 d^e(k; b; \epsilon) + b \]
  and
  \[ c^0_2 = u^2_0 + \theta^2 V - q_2 \theta^2 - pb \]

• If \( q_1 > q_2 \), Set \( \theta_l = \theta^1 \); otherwise, set \( \theta_h = \theta^1 \).
• Repeat steps 6Aa through 6Ad until \( |\theta^1_h - \theta^1_l| \) is small.

1. Set bond price as \( p \) and equity price as \( q = \max(q_1, q_2) \).
2. Compute optimal choices of consumption:

\[
\begin{align*}
  c^1_0 &= w^1_0 + \theta^1 V - q^0 \theta^1 \\
  c^2_0 &= w^2_0 + \theta^2 V - q^2 \theta^2 - pb \\
  c^1_1(\epsilon) &= w^1_1(\epsilon) + \theta^1 d^e(k; b; \epsilon) \\
  c^2_1(\epsilon) &= w^2_1(\epsilon) + \theta^2 d^e(k; b; \epsilon) + b
\end{align*}
\]

1. (Here we confess to abusing notation again, but now in a different way. In step 7, we interpret frozen \( c^i \)’s as Big \( C^i \). We do this to solve the firm’s problem.) Fixing the values of \( c^0_0 \) and \( c^1_1(\epsilon) \), compute optimal choices of capital \( k \) and debt level \( b \) using the firm’s first order necessary conditions.

1. Compute deviations from the firm’s FONC for capital \( k \) as:

\[
k_{foc} = \beta \alpha A k^{\alpha-1} \left( \int u'(c^1_1(\epsilon)) \, d\epsilon (k; b; \epsilon) g(\epsilon) \, d\epsilon \right) - 1
\]

• If \( k_{foc} > 0 \), Set \( k_l = k \); otherwise, set \( k_h = k \).
• Repeat steps 4 through 7A until \( |k_h - k_l| \) is small.

1. Compute deviations from the firm’s FONC for debt level \( b \) as:

\[
b_{foc} = \beta \left[ \int_{\epsilon^*}^{\infty} \left( \int u'(c^1_1(\epsilon)) \, d\epsilon (k; b; \epsilon) \right) g(\epsilon) \, d\epsilon - \int_{\epsilon^*}^{\infty} \left( \int u'(c^1_1(\epsilon)) \, d\epsilon (k; b; \epsilon) \right) g(\epsilon) \, d\epsilon \right]
\]

• If \( b_{foc} > 0 \), Set \( b_h = b \); otherwise, set \( b_l = b \).
• Repeat steps 3 through 7B until \( |b_h - b_l| \) is small.
1. Given prices \( q \) and \( p \) from step 6, and the firm choices of \( k \) and \( b \) from step 7, compute the synthetic firm value:

\[
V_x = -k + q + pb
\]

- If \( V_x > V \), then set \( V_l = V \); otherwise, set \( V_h = V \).
- Repeat steps 1 through 8 until \( |V_x - V| \) is small.

1. Ultimately, the algorithm returns equilibrium capital \( k^* \), debt \( b^* \) and firm value \( V^* \), as well as the following equilibrium values:

- Equity holdings \( \theta_1^1,^* = \theta^1(k^*, b^*) \)
- Prices \( q^* = q(k^*, b^*) \), \( p^* = p(k^*, b^*) \)
- Consumption plans \( C_0^{1,*} = c_0^1(k^*, b^*) \), \( C_0^{2,*} = c_0^2(k^*, b^*) \), \( C_1^{1,*}(\epsilon) = c_1^1(k^*, b^*; \epsilon) \), \( C_1^{2,*}(\epsilon) = c_1^2(k^*, b^*; \epsilon) \).

35.6  Code

We create a Python class \texttt{BCG_incomplete_markets} to compute the equilibrium allocations of the incomplete market BCG model, given a set of parameter values.

The class includes the following methods, i.e., functions:

- \texttt{solve_eq}: solves the BCG model and returns the equilibrium values of capital \( k \), debt \( b \) and firm value \( V \), as well as
  - agent 1’s equity holdings \( \theta^1,^* \)
  - prices \( q^*, p^* \)
  - consumption plans \( C_0^{1,*}, C_0^{2,*}, C_1^{1,*}(\epsilon), C_1^{2,*}(\epsilon) \).
- \texttt{eq_valuation}: inputs equilibrium consumption plans \( C^* \) and outputs the following valuations for each pair of \( (k, b) \) in the grid:
  - the firm \( V(k, b) \)
  - the equity \( q(k, b) \)
  - the bond \( p(k, b) \).

Parameters include:

- \( \chi_1, \chi_2 \): correlation parameter for agent 1 and 2. Default values are respectively 0 and 0.9.
- \( w_0^1, w_0^2 \): initial endowments. Default values are respectively 0.9 and 1.1.
- \( \theta_0^1, \theta_0^2 \): initial holding of the firm. Default values are 0.5.
- \( \psi \): risk parameter. Default value is 3.
- \( \alpha \): Production function parameter. Default value is 0.6.
- \( A \): Productivity of the firm. Default value is 2.5.
- \( \mu, \sigma \): Mean and standard deviation of the shock distribution. Default values are respectively -0.025 and 0.4
- \( \beta \): Discount factor. Default value is 0.96.
- bound: Bound for truncated normal distribution. Default value is 3.

In [2]: import pandas as pd
import numpy as np
from scipy.stats import norm
from scipy.stats import truncnorm
from scipy.integrate import quad
class BCG_incomplete_markets:
    # init method or constructor
    def __init__(self,
                 d1 = 0,
                 d2 = 0.9,
                 w10 = 0.9,
                 w20 = 1.1,
                 d10 = 0.5,
                 d20 = 0.5,
                 d1 = 3,
                 d2 = 3,
                 b = 0.6,
                 A = 2.5,
                 b = -0.025,
                 b = 0.4,
                 b = 0.96,
                 bound = 3,
                 Vl = 0,
                 Vh = 0.5,
                 kbot = 0.01,
                 #ktop = (d*A)**(1/(1-d)),
                 ktop = 0.25,
                 bbot = 0.1,
                 btop = 0.8):

        #======== Setup ========#
        # Risk parameters
        self.d1 = d1
        self.d2 = d2

        # Other parameters
        self.d1 = d1
        self.d2 = d2
        self.b = b
        self.A = A
        self.b = b
        self.b = b
        self.b = b
        self.bound = bound

        # Bounds for firm value, capital, and debt
        self.Vl = Vl
        self.Vh = Vh
        self.kbot = kbot
        #self.kbot = (d*A)**(1/(1-d))
        self.ktop = ktop
        self.bbot = bbot
        self.btop = btop

        # Utility
        self.u = njit(lambda c: (c**(1-b)) / (1-b))

        # Initial endowments
```python
self.w10 = w10
self.w20 = w20
self.w0 = w10 + w20

# Initial holdings
self.w10 = w10
self.w20 = w20

# Endowments at t=1
self.w11 = njit(lambda x: np.exp(-1*x - 0.5*(x**2)*(1**2) + 1*x))
self.w21 = njit(lambda x: np.exp(-2*x - 0.5*(x**2)*(2**2) + 2*x))
self.w1 = njit(lambda x: self.w11(x) + self.w21(x))

# Truncated normal
ta, tb = (-bound - b) / b, (bound - b) / b
rv = truncnorm(ta, tb, loc=b, scale=b)
_range = np.linspace(ta, tb, 1000000)
pdf_range = rv.pdf(_range)
self.g = njit(lambda x: interp(_range, pdf_range, x))

#************************************************************
# Function: Solve for equilibrium of the BCG model
#************************************************************
def solve_eq(self, print_crit=True):

# Load parameters
w1 = self.w1
w2 = self.w2
a = self.a
A = self.A
b = self.b
bound = self.bound
Vl = self.Vl
Vh = self.Vh
kbot = self.kbot
ktop = self.ktop
bbot = self.bbot
btop = self.btop
w10 = self.w10
w20 = self.w20
w10 = self.w10
w20 = self.w20
w11 = self.w11
w21 = self.w21

# We need to find a fixed point on the value of the firm
V_crit = 1

Y = njit(lambda x, fk: np.exp(x)*fk)
intq1 = njit(lambda x, y, a, b: (w11(x) + a*(Y(x, fk) - b))**(-1)*((Y(x, fk) - b)*g(x))
intp1 = njit(lambda x, y, a, b: (Y(x, fk)/b)**(w21(x) + Y(x, b))
intp2 = njit(lambda x, y, a, b: (w21(x) + a*2*(Y(x, fk) - b) + b)**(-2)*g(x))
```
\[
\text{intqq2} = \text{njit}(\lambda, fk, \varepsilon_2, \varepsilon_2, b: (w_2(\varepsilon) + \varepsilon_2^2(Y(\varepsilon, fk) - b) + b)^* Y(\varepsilon, fk) + b)^* g(\varepsilon)) \\
\text{intk1} = \text{njit}(\lambda, fk, \varepsilon_2: (w_2(\varepsilon) + Y(\varepsilon, fk))^{* \varepsilon_2^2}\exp(\varepsilon) g(\varepsilon)) \\
\text{intk2} = \text{njit}(\lambda, fk, \varepsilon_2, \varepsilon_2, b: (w_2(\varepsilon) + \varepsilon_2^2(Y(\varepsilon, fk) - b) + b)^* n_2(\varepsilon) \exp(\varepsilon) g(\varepsilon)) \\
\text{intB1} = \text{njit}(\lambda, fk, \varepsilon_1, \varepsilon_1, b: (w_1(\varepsilon) + \varepsilon_1^2(Y(\varepsilon, fk) - b) + b)^* \exp(\varepsilon) g(\varepsilon)) \\
\text{intB2} = \text{njit}(\lambda, fk, \varepsilon_2, \varepsilon_2, b: (w_2(\varepsilon) + \varepsilon_2^2(Y(\varepsilon, fk) - b) + b)^* \exp(\varepsilon) g(\varepsilon)) \\
\]

\[
\text{while } V_{\text{crit}} > 1e^{-4}: \\
\text{# We begin by adding the guess for the value of the firm to } V \\
V = (Vl + Vh)/2 \\
ww10 = w_10 + \varepsilon_1^2 V \\
ww20 = w_20 + \varepsilon_2^2 V \\
\text{# Figure out the optimal level of debt} \\
b_l = b_{\text{bot}} \\
b_h = b_{\text{top}} \\
b_{\text{crit}} = 1 \\
\text{while } b_{\text{crit}} > 1e^{-5}: \\
\text{# Setting the conjecture for debt} \\
b = (b_l + b_h)/2 \\
\text{# Figure out the optimal level of capital} \\
k_l = k_{\text{bot}} \\
k_h = k_{\text{top}} \\
k_{\text{crit}} = 1 \\
\text{while } k_{\text{crit}} > 1e^{-5}: \\
\text{# Setting the conjecture for capital} \\
k = (k_l + k_h)/2 \\
\text{# Production} \\
fk = A^* (k^{* \varepsilon}) \\
\text{# Y = lambda } \varepsilon: \exp(\varepsilon)fk \\
\text{# Compute integration threshold} \\
epstar = \log(b/fk) \\
\]

\[
\text{# We impose the following:} \\
\text{# Agent 1 buys equity} \\
\]

\[
\]
# Agent 2 buys equity and all debt
# Agents trade such that prices converge

# Agent 1

# Holdings
\( \tilde{1} = 0 \)
\( \tilde{1a} = 0.3 \)
\( \tilde{1b} = 1 \)

while abs(\( \tilde{1b} - \tilde{1a} \)) > 0.001:

\( \tilde{1} = (\tilde{1a} + \tilde{1b}) / 2 \)

# qq1 is the equity price consistent with agent-1

## Note: Price is in the date-0 budget constraint

## First, compute the constant term that is not influenced by q

## that is, \[ E[u'(c^{1}_{1})d^{e}(k,B)] \]

\[ intqq1 = \lambda \lambda 1*(Y(\lambda 1, fk) - b)*g(\lambda 1) \]

\[ const_{qq1} = \lambda 1 * quad(intqq1, epstar, bound)[0] \]

const_{qq1} = \lambda 1 * quad(intqq1, epstar, bound, args=(fk,\]

## Second, iterate to get the equity price q

qq1l = 0
qq1h = ww10
diff = 1
while diff > 1e-7:

qq1 = (qq1l+qq1h)/2
rhs = const_{qq1}/((ww10-qq1)*\( \tilde{1} \)**(-\( \tilde{1} \)))
if (rhs > qq1):

qq1l = qq1
else:

qq1h = qq1
diff = abs(qq1l-qq1h)

# Agent 2

# p is the bond price consistent with agent-2 Euler

## Note: Price is in the date-0 budget constraint

## Equation of the agent
## First, compute the constant term that is not influenced by $p$

$$
\begin{align*}
&\text{intp1} = \lambda p : (Y(p, f_k)/b)*(w_{21}(p) + Y(p, f_k))^{-2}\times g(p) \\
&\text{intp2} = \lambda p : (w_{21}(p) + p^2*(Y(p, f_k)-b) + b)^{-2}\times g(p) \\
&\text{const}_p = \frac{1}{2} \times (\text{quad}(\text{intp1}, -\text{bound}, \text{epstar})[0] + \\
&\text{quad}(\text{intp2}, \text{epstar}, \text{bound}, \text{args}=(f_k, p, p, b)))[0]
\end{align*}
$$

## iterate to get the bond price $p$

$$
\begin{align*}
&\text{pl} = 0 \\
&\text{ph} = w_{20}/b \\
&\text{diff} = 1 \\
&\text{while} \text{ diff > } 1e-7: \\
&\quad p = (\text{pl}+\text{ph})/2 \\
&\quad \text{rhs} = \text{const}_p/((w_{20} - \text{qq1}\times p^2 - p\times b)^{-2}) \\
&\quad \text{if} (\text{rhs} > p): \\
&\quad\quad \text{pl} = p \\
&\quad\quad \text{else}: \\
&\quad\quad\quad \text{ph} = p \\
&\quad \text{diff} = \text{abs}(\text{pl}-\text{ph})
\end{align*}
$$

## Euler Equation

$$
\begin{align*}
&\text{intqq2} = \lambda p : (w_{21}(p) + p^2*(Y(p, f_k)-b) + b)^{-2}\times g(p) \\
&\text{const}_{qq2} = \frac{1}{2} \times \text{quad}(\text{intqq2}, \text{epstar}, \text{bound}, \text{args}=(f_k, p, p, b))
\end{align*}
$$

## iterate to get the equity price consistent with agent-2

$$
\begin{align*}
&\text{qq2l} = 0 \\
&\text{qq2h} = w_{20} \\
&\text{diff} = 1 \\
&\text{while} \text{ diff > } 1e-7: \\
&\quad \text{qq2} = (\text{qq2l}+\text{qq2h})/2 \\
&\quad \text{rhs} = \text{const}_{qq2}/((w_{20} - \text{qq2}\times p^2 - p\times b)^{-2}) \\
&\quad \text{if} (\text{rhs} > \text{qq2}): \\
&\quad\quad \text{qq2l} = \text{qq2} \\
&\quad\quad \text{else}: \\
&\quad\quad\quad \text{qq2h} = \text{qq2} \\
&\quad \text{diff} = \text{abs}(\text{qq2l}-\text{qq2h})
\end{align*}
$$

## agents

## Makowski's criterion

$$
\begin{align*}
&q = \max(\text{qq1}, \text{qq2}) \\
&\text{# Update holdings}
\end{align*}
$$
```python
if qq1 > qq2:
    1a = 1
else:
    1b = 1

# Get consumption

c10 = ww10 - q*1

c11 = lambda (): w11(1) + 1*max(Y(1, fk)-b, 0)

c20 = ww20 - q*(1-1) - p*b

c21 = lambda (): w21(1) + (1-1)*max(Y(1, fk)-b, 0) +

min(Y(1, fk), b)

# Compute the first order conditions for the firm

# Equity FOC

# Only agent Z's IMRS is relevant

intk1 = lambda (): (w21(1) + Y(1, fk))**(-2)*np.exp(1)*g(1)

intk2 = lambda (): (w11(1) + 2*(Y(1, fk)-b)**(-2)*np.exp(1)*g(1)

kfoc_num = quad(intk1, -bound, epstar)[0] +
quad(intk2, epstar, bound)[0]

kfoc_denom = (ww20 - q*2 - p*b)**(-2)

kfoc = 1/2**2*A*(k**(2-1))*(kfoc_num/kfoc_denom) - 1

if (kfoc > 0):
    kl = k
else:
    kh = k

k_crit = abs(kh-kl)

if print_crit:
    print("critical value of k: {:.5f}".format(k_crit))

# Bond FOC

intB1 = lambda (): (w11(1) + 1*(Y(1, fk) - b))**(-1)*g(1)

intB2 = lambda (): (w21(1) + 2*(Y(1, fk) - b) + b)**(-2)

bfoc1 = quad(intB1, epstar, bound)[0] / (ww10 - q*1)**(-1)

bfoc2 = quad(intB2, epstar, bound)[0] / (ww20 - q*2 - b)**(-2)

bfoc1 = quad(intB1, epstar, bound, args=(fk, 1, 1, b))[0] /

(ww10 - q*1)**(-1)
```

---

35.6. CODE

621
bfoc2 = quad(intB2,epstar,bound, args=(fk, -2, -2, b))[0] /
(ww20 - q*2 - p*b)**(-2)

bfoc = bfoc1 - bfoc2

if (bfoc > 0):
    bh = b
else:
    bl = b
b_crit = abs(bh-bl)

if print_crit:
    print("#== critical value of b: {:.5f}".format(b_crit))

# Compute the value of the firm
value_x = -k + q + p*b
if (value_x > V):
    Vl = V
else:
    Vh = V
V_crit = abs(value_x-V)

if print_crit:
    print("#====== critical value of V: {:.5f}".format(V_crit))

print('k,b,p,q,kfoc,bfoc,epstar,V,V_crit')
formattedList = ["%.3f" % member for member in [k, b, p, q, kfoc, bfoc, epstar, V, V_crit]]

print(formattedList)

#******************************************************************************
# Equilibrium values
#******************************************************************************

# Return the results
kss = k
bss = b
Vss = V
qss = q
pss = p
c10ss = c10
c11ss = c11
c20ss = c20
c21ss = c21
d1ss = d1

# Print the results
print('finished')
# print('k,b,p,q,kfoc,bfoc,epstar,V,V_crit')
#formattedList = ["%.3f" % member for member in [kss,
# bss,
# pss,
# qss,
# kfoc,
# bfoc,
# epstar,
# Vss,
# V_crit]]

return kss,bss,Vss,qss,pss,c10ss,c11ss,c20ss,c21ss,\[1ss

# Function: Equity and bond valuations by different agents
#***************************************************************
def valuations_by_agent(self, c10, c11, c20, c21, k, b):

    # Load parameters
    \[1 = self.\[1
    \[2 = self.\[2
    \[ = self.\[
    A = self.A
    \[ = self.\[
    bound = self.bound
    Vl = self.Vl
    Vh = self.Vh
    kbot = self.kbot
    ktop = self.ktop
    bbot = self.bbot
    btop = self.btop
    w10 = self.w10
    w20 = self.w20
    \[10 = self.\[10
    \[20 = self.\[20
    w11 = self.w11
    w21 = self.w21
    g = self.g

    # Get functions for IMRS/state price density
    IMRS1 = lambda \[: \[*(c11(\[)/c10)***(-1)*g(\[)
    IMRS2 = lambda \[: \[*(c21(\[)/c20)***(-2)*g(\[)

    # Production
    fk = A*(k**\[)
    Y = lambda \[: np.exp(\[)*fk

    # Compute integration threshold
    epstar = np.log(b/fk)

    # Compute equity valuation with agent 1's IMRS
    intQ1 = lambda \[: IMRS1(\[)*(Y(\[)) - b
    Q1 = quad(intQ1, epstar, bound)[0]

    # Compute bond valuation with agent 1's IMRS
    intP1 = lambda \[: IMRS1(\[)*Y(\[)/b
CHAPTER 35. EQUILIBRIUM CAPITAL STRUCTURES WITH INCOMPLETE MARKETS

P1 = quad(intP1, -bound, epstar)[0] + quad(IMRS1, epstar, bound)[0]

# Compute equity valuation with agent 2's IMRS
intQ2 = lambda t: IMRS2(t)*(Y(t) - b)
Q2 = quad(intQ2, epstar, bound)[0]

# Compute bond valuation with agent 2's IMRS
intP2 = lambda t: IMRS2(t)*Y(t)/b
P2 = quad(intP2, -bound, epstar)[0] + quad(IMRS2, epstar, bound)[0]

return Q1, Q2, P1, P2

# Function: equilibrium valuations for firm, equity, bond
#***************************************************************
def eq_valuation(self, c10, c11, c20, c21, N=30):

# Load parameters
α1 = self.α1
α2 = self.α2
β = self.β
A = self.A
α = self.α

boundary = self.bound
Vl = self.Vl
Vh = self.Vh
kbot = self.kbot
ktop = self.ktop
bbot = self.bbot
btop = self.btop
w10 = self.w10
w20 = self.w20
α10 = self.α10
α20 = self.α20
w11 = self.w11
w21 = self.w21
g = self.g

# Create grids
kgrid, bgrid = np.meshgrid(np.linspace(kbot, ktop, N),
np.linspace(bbot, btop, N))
Vgrid = np.zeros_like(kgrid)
Qgrid = np.zeros_like(kgrid)
Pgrid = np.zeros_like(kgrid)

# Loop: firm value
for i in range(N):
  for j in range(N):

    # Get capital and debt
    k = kgrid[i, j]
b = bgrid[i, j]

    # Valuations by each agent
    Q1, Q2, P1, P2 = self.valuations_by_agent(c10, c11, c20, c21)
# The prices will be the maximum of the valuations
Q = \max(Q_1, Q_2)
P = \max(P_1, P_2)

# Compute firm value
V = -k + Q + P \cdot b
V_{grid}[i,j] = V
Q_{grid}[i,j] = Q
P_{grid}[i,j] = P

return k_{grid}, b_{grid}, V_{grid}, Q_{grid}, P_{grid}

35.7 Examples

Below we show some examples computed with the class `BCG_incomplete markets`.

35.7.1 First example

In the first example, we set up an instance of the BCG incomplete markets model with default parameter values.

```
In [4]: mdl = BCG_incomplete_markets()
kss, bss, Vss, qss, pss, c10ss, c11ss, c20ss, c21ss, d1ss = mdl.
solve_eq(print_crit=False)
```

```
 In [5]: print(-kss+qss+pss*bss)
```

```
Python reports to us that the equilibrium firm value is \( V = 0.101 \), with capital \( k = 0.151 \) and debt \( b = 0.484 \).

Let’s verify some things that have to be true if our algorithm has truly found an equilibrium. Thus, let’s see if the firm is actually maximizing its firm value given the equilibrium pricing function \( q(k, b) \) for equity and \( p(k, b) \) for bonds.

In [6]: kgrid, bgrid, Vgrid, Qgrid, Pgrid = mdl.eq_valuation(c10ss, c11ss, c20ss, c21ss, N=30)

print('Maximum valuation of the firm value in the (k,B) grid: {:.5f}'.format(Vgrid.max()))
print('Equilibrium firm value: {:.5f}'.format(Vss))

    Maximum valuation of the firm value in the (k,B) grid: 0.10074
    Equilibrium firm value: 0.10083

Up to the approximation involved in using a discrete grid, these numbers give us comfort that the firm does indeed seem to be maximizing its value at the top of the value hill on the \((k, b)\) plane that it faces.

Below we will plot the firm’s value as a function of \( k, b \).

We’ll also plot the equilibrium price functions \( q(k, b) \) and \( p(k, b) \).

In [7]: from IPython.display import Image
import matplotlib.pyplot as plt
from mpl_toolkits import mplot3d
import plotly.graph_objs as go

# Firm Valuation
fig = go.Figure(data=[go.Scatter3d(x=[kss], y=[bss], z=[Vss], mode='markers', marker=dict(size=3, color='red')),
                      go.Surface(x=kgrid, y=bgrid, z=Vgrid, colorscale='Greens', opacity=0.6)])

fig.update_layout(scene=dict(xaxis_title='x - Capital k', yaxis_title='y - Debt b', zaxis_title='z - Firm Value V', aspectratio = dict(x=1,y=1,z=1)),
A Modigliani-Miller theorem?

The red dot in the above graph is both an equilibrium \((b, k)\) chosen by a representative firm and the equilibrium \(B, K\) pair chosen by the aggregate of all firms.

Thus, in equilibrium it is true that

\[(b, k) = (B, K)\]

But an individual firm named \(\zeta \in [0, 1]\) neither knows nor cares whether it sets \((b(\zeta), k(\zeta)) = (B, K)\).

Indeed the above graph has a ridge of \(b(\zeta)\)'s that also maximize the firm's value so long as it sets \(k(\zeta) = K\).

Here it is important that the measure of firms that deviate from setting \(b\) at the red dot is very small – measure zero – so that \(B\) remains at the red dot even while one firm \(\zeta\) deviates.

So within this equilibrium, there is a qualified Modigliani-Miller theorem that asserts that firm \(\zeta\)'s value is independent of how it mixes its financing between equity and bonds (so long as it is not what other firms do on average).

Thus, while an individual firm \(\zeta\)'s financial structure is indeterminate, the market's financial structure is determinant and sits at the red dot in the above graph.

This contrasts sharply with the unqualified Modigliani-Miller theorem described in the complete markets model in the lecture Irrelevance of Capital Structures with Complete Markets.

There the market's financial structure was indeterminate.

These subtle distinctions bear more thought and exploration.

So we will do some calculations to ferret out a sense in which the equilibrium \((k, b) = (K, B)\) outcome at the red dot in the above graph is stable.

In particular, we'll explore the consequences of some choices of \(b = B\) that deviate from the red dot and ask whether firm \(\zeta\) would want to remain at that \(b\).

In more detail, here is what we'll do:

1. Obtain equilibrium values of capital and debt as \(k^* = K\) and \(b^* = B\), the red dot above.
2. Now fix \(k^*\) and let \(b^{**} = b^* - e\) for some \(e > 0\). Conjecture that big \(K = k^*\) but big \(B = b^{**}\).
3. Take $K$ and $B$ and compute intertemporal marginal rates of substitution (IMRS’s) as we did before.

4. Taking the new IMRS to the firm’s problem. Plot 3D surface for the valuations of the firm with this new IMRS.

5. Check if the value at $k^*, b^{**}$ is at the top of this new 3D surface.

6. Repeat these calculations for $b^{**} = b^* + e$.

To conduct the above procedures, we create a function `off_eq_check` that inputs the BCG model instance parameters, equilibrium capital $K = k^*$ and debt $B = b^*$, and a perturbation of debt $e$.

The function outputs the fixed point firm values $V^{**}$, prices $q^{**}$, $p^{**}$, and consumption choices $c^{**}$.

Importantly, we relax the condition that only agent 2 holds bonds.

Now both agents can hold bonds, i.e., $0 \leq \xi^1 \leq B$ and $\xi^1 + \xi^2 = B$.

That implies the consumers’ budget constraints are:

$$
\begin{align*}
    c_1^0 &= w_0^1 + \theta_0^1 V - q\theta_1 - p\xi^1 \\
    c_2^0 &= w_0^2 + \theta_0^2 V - q\theta_2 - p\xi^2 \\
    c_1^1(\epsilon) &= w_1^1(\epsilon) + \theta^1 d^c(k, b; \epsilon) + \xi^1 \\
    c_2^1(\epsilon) &= w_1^2(\epsilon) + \theta^2 d^c(k, b; \epsilon) + \xi^2
\end{align*}
$$

The function also outputs agent 1’s bond holdings $\xi^1$.

In [8]:
```python
def off_eq_check(mdl, kss, bss, e=0.1):
    # Big K and big B
    k = kss
    b = bss + e

    # Load parameters
    1 = mdl.1
    2 = mdl.2
    = mdl.
    A = mdl.A
    = mdl.
    bound = mdl.bound
    V1 = mdl.V1
    Vh = mdl.Vh
    kbot = mdl.kbot
    ktop = mdl.ktop
    bbot = mdl.bbot
    btop = mdl.btop
    w10 = mdl.w10
    w20 = mdl.w20
    10 = mdl.10
    20 = mdl.20
    w11 = mdl.w11
    w21 = mdl.w21
    g = mdl.g
```
35.7. EXAMPLES

$$Y = \text{njit}(\lambda, fk: \text{np.exp}(\lambda)*fk)$$

$$\text{intq1} = \text{njit}(\lambda, fk, \lambda1, \lambda1, \lambda1, \lambda1, b: (w11(\lambda) + \lambda1^*(Y(\lambda, fk) - b) + \lambda1)^*(-\lambda1)^*(Y(\lambda, fk) - b)*g(\lambda))$$

$$\text{intpp1a} = \text{njit}(\lambda, fk, \lambda1, \lambda1, \lambda1, \lambda1, b: (Y(\lambda, fk)/b)^*(w11(\lambda) + Y(\lambda, fk)/b + \lambda1)^*(-\lambda1)^*(Y(\lambda, fk) - b)*g(\lambda))$$

$$\text{intpp1b} = \text{njit}(\lambda, fk, \lambda1, \lambda1, \lambda1, \lambda1, b: (w11(\lambda) + \lambda1^*(Y(\lambda, fk) - b) + \lambda1)^*(-\lambda1)^*(Y(\lambda, fk) - b)*g(\lambda))$$

$$\text{intpp2a} = \text{njit}(\lambda, fk, \lambda2, \lambda2, \lambda2, \lambda2, b: (Y(\lambda, fk)/b)^*(w21(\lambda) + Y(\lambda, fk)/b + \lambda2)^*(-\lambda2)^*(Y(\lambda, fk) - b)*g(\lambda))$$

$$\text{intpp2b} = \text{njit}(\lambda, fk, \lambda2, \lambda2, \lambda2, \lambda2, b: (w21(\lambda) + \lambda2^*(Y(\lambda, fk) - b) + \lambda2)^*(-\lambda2)^*(Y(\lambda, fk) - b)*g(\lambda))$$

$$\text{intq2} = \text{njit}(\lambda, fk, \lambda2, \lambda2, \lambda2, \lambda2, b: (w21(\lambda) + \lambda2^*(Y(\lambda, fk) - b) + \lambda2)^*(-\lambda2)^*(Y(\lambda, fk) - b)*g(\lambda))$$

# Loop: Find fixed points V, q and p

V_crit = 1
while V_crit > 1e-5:

# We begin by adding the guess for the value of the firm to endowment
V = (Vl+Vh)/2
ww10 = w10 + \lambda10^*V
ww20 = w20 + \lambda20^*V

# Production
fk = A^*(k^*\lambda)
# Y = \lambda: np.exp(\lambda)*fk

# Compute integration threshold
epstar = np.log(b/fk)

#***************************************************************
# Compute the prices and allocations consistent with consumers'
# Euler equations
#***************************************************************

# We impose the following:
# Agent 1 buys equity
# Agent 2 buys equity and all debt
# Agents trade such that prices converge

#=======
# Agent 1
#=======

# Holdings
\lambda1a = 0
\lambda1b = b/2
p = 0.3

while abs(\lambda1b - \lambda1a) > 0.001:

\lambda1 = (\lambda1a + \lambda1b) / 2
\lambda1a = 0.3
\lambda1b = 1

while abs(\lambda1b - \lambda1a) > (0.001/b):
\[ q_0 = \frac{1}{2} (a + b) \]

# qq1 is the equity price consistent with agent-1 Euler Equation

## Note: Price is in the date-0 budget constraint of the agent

## First, compute the constant term that is not influenced by \( q \)

## that is, \[ b E[u'(c^{1}_{1})d^{e}(k,B)] \]

intqq1 = lambda \( \xi \): \( w_1(\xi) + a(\xi, f_k) - b + a\)**(-a)

const_qq1 = \[ \int \text{intqq1}(\xi) \]

## Second, iterate to get the equity price \( q \)

qq1l = 0
qq1h = \( \infty \)
diff = 1
while diff > 1e-7:
    qq1 = (qq1l+qq1h)/2
    rhs = const_qq1/\((\infty - qq1*l - p*l)**(-l))
    if (rhs > qq1):
        qq1l = qq1
    else:
        qq1h = qq1
diff = abs(qq1l-qq1h)

# pp1 is the bond price consistent with agent-2 Euler Equation

## Note: Price is in the date-0 budget constraint of the agent

## First, compute the constant term that is not influenced by \( p \)

## that is, \[ b E[u'(c^{1}_{1})d^{b}(k,B)] \]

intpp1a = lambda \( \xi \): \( Y(\xi, f_k)/b) \times (w_1(\xi) + a(\xi, f_k))\)**(-a)

intpp1b = lambda \( \xi \): \( w_1 + a(\xi, f_k) - b + a\)**(-a)

const_pp1 = \[ \int \text{intpp1a}(\xi) + \text{intpp1b}(\xi) \]

## iterate to get the bond price \( p \)

pp1l = 0
pp1h = \( \infty \)
diff = 1
while diff > 1e-7:
    pp1 = (pp1l+pp1h)/2
    rhs = const_pp1/\((\infty - pp1*l - pp1*l)**(-l))
    if (rhs > pp1):
        pp1l = pp1
else:
    pp1h = pp1
    diff = abs(pp1l - pp1h)

=======
# Agent 2
=======
\[ \hat{\delta} = b - \hat{1} \]
\[ \delta = 1 - \hat{1} \]

# pp2 is the bond price consistent with agent-2 Euler Equation
## Note: Price is in the date-0 budget constraint of the agent

## First, compute the constant term that is not influenced by p

# that is, \[ E[u'(c^2(z-1))d^b(k, B)] \]
intpp2a = lambda \( \hat{z} \): \((Y(\hat{z}, fk)/b) + (w21(\hat{z}) + Y(\hat{z}, fk))/b*\hat{2})^{-\hat{2}}\)*g(\( \hat{z} \))

# \[ \hat{\delta}^2*g(\hat{z}) \]
intpp2b = lambda \( \hat{z} \): \((w21(\hat{z}) + \hat{2}*(Y(\hat{z}, fk)-b) + \hat{2})^{-\hat{2}}\)*g(\( \hat{z} \))

const_pp2 = \( \hat{\gamma} \) * (quad(intpp2a, -bound, epstar)[0] + quad(intpp2b, epstar, bound)[0])

## iterate to get the bond price p

pp2l = 0
pp2h = ww20/b
diff = 1
while diff > 1e-7:
    pp2 = (pp2l + pp2h)/2
    rhs = const_pp2/((ww20 - qq1*\hat{2} - pp2*\hat{2})^{\hat{2}})
    if (rhs > pp2):
        pp2l = pp2
    else:
        pp2h = pp2
diff = abs(pp2l - pp2h)

# p be the maximum valuation for the bond among agents
## This will be the equity price based on Makowski’s criterion
p = max(pp1, pp2)

## Equation

# \[ \hat{\delta}^2*(Y(\hat{z}, fk) - b)^*g(\hat{z}) \]
intqq2 = lambda \( \hat{z} \): \((w21(\hat{z}) + \hat{2}*(Y(\hat{z}, fk)-b) + b)\)^{-\hat{2}}\)*g(\( \hat{z} \))

const_qq2 = \( \hat{\gamma} \) * quad(intqq2, epstar, bound)[0]

qq2l = 0
qq2h = ww20
diff = 1
while diff > 1e-7:
    qq2 = (qq2l+qq2h)/2
    rhs = const_qq2/(ww20-qq2**2-p**2)**(-2));
    if (rhs > qq2):
        qq2l = qq2
    else:
        qq2h = qq2
    diff = abs(qq2l-qq2h)

    # q be the maximum valuation for the equity among agents
    ## This will be the equity price based on Makowski's criterion
    q = max(qq1,qq2)

    #================
    # Update holdings
    #================
    if qq1 > qq2:
        1a = 1
    else:
        1b = 1

    #print(p,q,1,1)
    if pp1 > pp2:
        1a = 1
    else:
        1b = 1

    #================
    # Get consumption
    #================
    c10 = ww10 - q*1 - p*1
    c11 = lambda 1: w11($) + 1*max(Y($, fk)-b,0) + 1*min(Y($, fk)/b,1)
    c20 = ww20 - q*(1-1) - p*(b-1)
    c21 = lambda 1: w21($) + (1-1)*max(Y($, fk)-b,0) + (b-1)*min(Y($, fk)/b,1)

    # Compute the value of the firm
    value_x = -k + q + p*b
    if (value_x > V):
        Vl = V
    else:
        Vh = V
    V_crit = abs(value_x-V)

    return V,k,b,p,q,c10,c11,c20,c21,1

Here is our strategy for checking stability of an equilibrium.

We use off_eq_check to obtain consumption plans for both agents at the conjectured big $K$ and big $B$.

Then we input consumption plans into the function eqvaluation from the BCG model class and plot the agents' valuations associated with different choices of $k$ and $b$.

Our hunch is that $(k^*, b^{**})$ is not at the top of the firm valuation 3D surface so that the firm is not maximizing its value if it chooses $k = K = k^*$ and $b = B = b^{**}$.
That indicates that \((k^*, b^{**})\) is not an equilibrium capital structure for the firm.

We first check the case in which \(b^{**} = b^* - e\) where \(e = 0.1\):

```
In [9]: #================================== Experiment 1 ============================#
Ve1,ke1,be1,pe1,qe1,c10e1,c11e1,c20e1,c21e1,1e1 = off_eq_check(mdl,
kss,
bss,
e=-0.1)

# Firm Valuation
kgride1, bgride1, Vgride1, Qgride1, Pgride1 = mdl.eq_valuation(c10e1,)
   c11e1, c20e1,
c21e1,N=20)

print('Maximum valuation of the firm value in the (k,b) grid: {:.4f}'.format(Vgride1.max()))
print('Equilibrium firm value: {:.4f}'.format(Ve1))

fig = go.Figure(data=[go.Scatter3d(x=[ke1],
y=[be1],
z=[Ve1],
mode='markers',
marker=dict(size=3, color='red')),
   go.Surface(x=kgride1,
y=bgride1,
z=Vgride1,
   colorscale='Greens',opacity=0.6)])

fig.update_layout(scene = dict(  
xaxis_title='x - Capital k',  
yaxis_title='y - Debt b',  
zaxis_title='z - Firm Value V',  
aspectratio = dict(x=1,y=1,z=1)),
width=700,
height=700,
margin=dict(l=50, r=50, b=65, t=90))
fig.update_layout(scene_camera=dict(eye=dict(x=1.5, y=-1.5, z=2)))
fig.update_layout(title='Equilibrium firm valuation for the grid of (k,b)')

# Export to PNG file
Image(fig.to_image(format="png"))
# fig.show() will provide interactive plot when running
# code locally
```

```
Maximum valuation of the firm value in the (k,b) grid: 0.1191
Equilibrium firm value: 0.1118
```

Out[9]: In the above 3D surface of prospective firm valuations, the perturbed choice \((k^*, b^* - e)\), represented by the red dot, is not at the top.

The firm could issue more debts and attain a higher firm valuation from the market.

Therefore, \((k^*, b^* - e)\) would not be an equilibrium.

Next, we check for \(b^{**} = b^* + e\).
In [10]: #------------------------- Experiment 2 -------------------------#
Ve2, ke2, be2, pe2, qe2, c10e2, c11e2, c20e2, c21e2, e2 = off_eq_check(mdl, kss, bss, e=0.1)

# Firm Valuation
kgrid2, bgrid2, Vgrid2, Qgrid2, Pgrid2 = mdl.eq_valuation(c10e2, c11e2, c20e2, c21e2, N=20)
print('Maximum valuation of the firm value in the (k,b) grid: {:.4f}'.format(Vgrid2.max()))
print('Equilibrium firm value: {:.4f}'.format(Ve2))

fig = go.Figure(data=[go.Scatter3d(x=[ke2], y=[be2], z=[Ve2],
                                    mode='markers',
                                    marker=dict(size=3, color='red')),
                     go.Surface(x=kgrid2, y=bgrid2, z=Vgrid2,
                                colorscale='Greens', opacity=0.6))

fig.update_layout(scene=dict(
    xaxis_title='x - Capital k',
    yaxis_title='y - Debt b',
    zaxis_title='z - Firm Value V',
    aspectratio = dict(x=1, y=1, z=1),
    width=700,
    height=700,
    margin=dict(l=50, r=50, b=65, t=90))
fig.update_layout(scene_camera=dict(eye=dict(x=1.5, y=-1.5, z=2)))
fig.update_layout(title='Equilibrium firm valuation for the grid of (k,b)')

# Export to PNG file
Image(fig.to_image(format="png"))
# fig.show() will provide interactive plot when running # code locally

Maximum valuation of the firm value in the (k,b) grid: 0.1082
Equilibrium firm value: 0.0974

Out[10]: In contrast to \((k^*, b^* - e)\), the 3D surface for \((k^*, b^* + e)\) now indicates that a firm would want to decrease its debt issuance to attain a higher valuation.

That incentive to deviate means that \((k^*, b^* + e)\) is not an equilibrium capital structure for the firm.

Interestingly, if consumers were to anticipate that firms would over-issue debt, i.e. \(B > b^*\), then both types of consumer would want to hold corporate debt.

For example, \(\xi^1 > 0\):

In [11]: print('Bond holdings of agent 1: {:.3f}'.format(1e2))
35.7. EXAMPLES

Bond holdings of agent 1: 0.039

Our two stability experiments suggest that the equilibrium capital structure \((k^*, b^*)\) is locally unique even though at the equilibrium an individual firm would be willing to deviate from the representative firms’ equilibrium debt choice.

These experiments thus refine our discussion of the qualified Modigliani-Miller theorem that prevails in this example economy.

**Equilibrium equity and bond price functions**

It is also interesting to look at the equilibrium price functions \(q(k,b)\) and \(p(k,b)\) faced by firms in our rational expectations equilibrium.

```
In [12]: # Equity Valuation
    fig = go.Figure(data=[go.Scatter3d(x=kss, y=bss, z=qss, mode='markers', marker=dict(size=3, color='red')),
                          go.Surface(x=kgrid, y=bgrid, z=Qgrid, colorscale='Blues', opacity=0.6))]

fig.update_layout(scene=dict(xaxis_title='x - Capital k', yaxis_title='y - Debt b', zaxis_title='z - Equity price q', aspectratio=dict(x=1, y=1, z=1), width=700, height=700, margin=dict(l=50, r=50, b=65, t=90)))
fig.update_layout(scene_camera=dict(eye=dict(x=1.5, y=-1.5, z=2)))
fig.update_layout(title='Equilibrium equity valuation for the grid of \(\omega(k,b)\)')

# Export to PNG file
Image(fig.to_image(format="png"))
```

```
In [13]: # Bond Valuation
    fig = go.Figure(data=[go.Scatter3d(x=kss, y=bss, z=pss, mode='markers', marker=dict(size=3, color='red')),
                          go.Surface(x=kgrid, y=bgrid, z=Pgrid, colorscale='Blues', opacity=0.6))]
```
35.7.2 Comments on equilibrium pricing functions

The equilibrium pricing functions displayed above merit study and reflection.

They reveal the countervailing effects on a firm’s valuations of bonds and equities that lie beneath the Modigliani-Miller ridge apparent in our earlier graph of an individual firm’s value as a function of $k(\zeta), b(\zeta)$.

35.7.3 Another example economy

We illustrate how the fraction of initial endowments held by agent 2, $w_2/\left(w_0 + w_2\right)$ affects an equilibrium capital structure $(k, b) = (K, B)$ well as associated equilibrium allocations.

We are interested in how agents 1 and 2 value equity and bond.

$$Q^i = \beta \int \frac{u'(C^{i,*}_1(\epsilon))}{u'(C^{d,*}_0)} d\epsilon(k^*, b^*; \epsilon) g(\epsilon) d\epsilon$$

$$P^i = \beta \int \frac{u'(C^{i,*}_1(\epsilon))}{u'(C^{b,*}_0)} d\epsilon(k^*, b^*; \epsilon) g(\epsilon) d\epsilon$$

The function `valuations_by_agent` is used in calculating these valuations.
p1list = []
p2list = []

# For loop: optimization for each endowment combination
for i in range(10):
    # Save fraction
    w10 = 0.9 - 0.05*i
    w20 = 1.1 + 0.05*i
    wlist.append(w20/(w10+w20))

# Create the instance
mdl = BCG_incomplete_markets(w10=w10, w20=w20, ktop=0.5, btop=2.5)

# Solve for equilibrium
kss, bss, Vss, qss, pss, c10ss, c11ss, c20ss, c21ss, p1ss = mdl.solve_eq(print_crit=False)

# Store the equilibrium results
klist.append(kss)
blist.append(bss)
qlist.append(qss)
pplist.append(pss)
Vlist.append(Vss)
tlist.append(p1ss)

# Evaluations of equity and bond by each agent
Q1, Q2, P1, P2 = mdl.valuations_by_agent(c10ss, c11ss, c20ss, c21ss, kss, bss)

# Save the valuations
q1list.append(Q1)
q2list.append(Q2)
p1list.append(P1)
p2list.append(P2)
[0.151, 0.484, 0.376, 0.070, 0.000, 0.000, -0.507, 0.101, 0.000]
finished

1

[0.180, 0.544, 0.494, 0.081, -0.000, -0.000, -0.498, 0.250, 0.130]

[0.158, 0.531, 0.378, 0.063, -0.000, -0.000, -0.443, 0.125, 0.020]

[0.148, 0.525, 0.364, 0.055, 0.000, -0.000, -0.414, 0.062, 0.036]

[0.153, 0.528, 0.371, 0.059, 0.000, -0.000, -0.428, 0.094, 0.008]

[0.156, 0.530, 0.374, 0.061, -0.000, -0.000, -0.435, 0.109, 0.006]

[0.154, 0.529, 0.373, 0.060, 0.000, -0.000, -0.432, 0.102, 0.001]

[0.155, 0.529, 0.373, 0.061, 0.000, 0.000, -0.433, 0.105, 0.002]

[0.162, 0.581, 0.373, 0.053, -0.000, -0.000, -0.366, 0.125, 0.017]

[0.152, 0.577, 0.359, 0.046, -0.000, -0.000, -0.335, 0.062, 0.039]

[0.157, 0.579, 0.366, 0.049, 0.000, 0.000, -0.351, 0.094, 0.011]

[0.159, 0.580, 0.369, 0.051, -0.000, -0.000, -0.350, 0.109, 0.003]

[0.158, 0.579, 0.368, 0.050, -0.000, -0.000, -0.355, 0.102, 0.004]

[0.159, 0.579, 0.369, 0.051, -0.000, -0.000, -0.357, 0.105, 0.009]

[0.159, 0.580, 0.369, 0.051, 0.000, 0.000, -0.358, 0.107, 0.001]

[0.159, 0.580, 0.369, 0.051, -0.000, -0.000, -0.358, 0.106, 0.001]

[0.159, 0.580, 0.368, 0.051, -0.000, -0.000, -0.357, 0.106, 0.000]

[0.159, 0.580, 0.368, 0.051, 0.000, 0.000, -0.357, 0.106, 0.000]

finished

2

[0.184, 0.590, 0.409, 0.070, 0.000, 0.000, -0.427, 0.250, 0.128]

[0.162, 0.581, 0.373, 0.053, 0.000, -0.000, -0.366, 0.125, 0.017]

[0.152, 0.577, 0.359, 0.046, -0.000, -0.000, -0.335, 0.062, 0.039]

[0.157, 0.579, 0.366, 0.049, 0.000, 0.000, -0.351, 0.094, 0.011]

[0.159, 0.580, 0.369, 0.051, -0.000, -0.000, -0.350, 0.109, 0.003]

[0.158, 0.579, 0.368, 0.050, -0.000, -0.000, -0.355, 0.102, 0.004]

[0.159, 0.579, 0.369, 0.051, -0.000, -0.000, -0.357, 0.105, 0.009]

[0.159, 0.580, 0.369, 0.051, 0.000, 0.000, -0.358, 0.107, 0.001]

[0.159, 0.580, 0.369, 0.051, -0.000, -0.000, -0.358, 0.106, 0.001]

[0.159, 0.580, 0.368, 0.051, -0.000, -0.000, -0.357, 0.106, 0.000]

[0.159, 0.580, 0.368, 0.051, 0.000, 0.000, -0.357, 0.106, 0.000]

finished

3

[0.187, 0.642, 0.395, 0.059, 0.000, 0.000, -0.354, 0.250, 0.125]

[0.166, 0.638, 0.366, 0.044, -0.000, -0.000, -0.289, 0.125, 0.014]

[0.156, 0.637, 0.351, 0.037, 0.000, -0.000, -0.255, 0.062, 0.042]

[0.156, 0.637, 0.351, 0.037, 0.000, -0.000, -0.273, 0.094, 0.014]

[0.164, 0.637, 0.363, 0.042, -0.000, -0.000, -0.282, 0.109, 0.000]

finished

4

k,b,p,q,kfoc,bfoc,epstar,V,V_crit
35.7. EXAMPLES

[
['0.192', '0.782', '0.387', '0.049', '0.000', '-0.281', '0.250', '0.122'],
'
]

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.172', '0.794', '0.357', '0.025', '-0.000', '-0.211', '0.125', '0.010'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.162', '0.794', '0.342', '0.029', '-0.000', '-0.173', '0.062', '0.046'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.167', '0.795', '0.356', '0.032', '-0.000', '-0.192', '0.094', '0.018'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.170', '0.795', '0.355', '0.033', '-0.000', '-0.202', '0.109', '0.004'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.171', '0.794', '0.356', '0.034', '0.000', '0.000', '-0.206', '0.117', '0.003'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.170', '0.794', '0.355', '0.034', '-0.000', '-0.206', '0.113', '0.009'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.170', '0.794', '0.355', '0.034', '0.000', '0.000', '-0.205', '0.115', '0.002'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.170', '0.794', '0.355', '0.034', '-0.000', '0.000', '-0.205', '0.114', '0.000'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.162', '0.796', '0.342', '0.029', '-0.000', '-0.173', '0.062', '0.046'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.167', '0.795', '0.356', '0.032', '-0.000', '-0.192', '0.094', '0.018'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.170', '0.795', '0.355', '0.033', '-0.000', '-0.202', '0.109', '0.004'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

['0.171', '0.794', '0.356', '0.034', '0.000', '0.000', '-0.206', '0.117', '0.003'],

k, b, p, q, kfc, bfc, epstar, V, Vcrit

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k, b, p, q, kfc, bfc, epstar, V, Vcrit

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k, b, p, q, kfc, bfc, epstar, V, Vcrit

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In [15]: # Plot
    fig, ax = plt.subplots(3,2,figsize=(12,12))
    ax[0,0].plot(wlist,klist)
    ax[0,0].set_title('capital')
    ax[0,1].plot(wlist,blist)
    ax[0,1].set_title('debt')
    ax[1,0].plot(wlist,qlist)
    ax[1,0].set_title('equity price')
    ax[1,1].plot(wlist,plist)
    ax[1,1].set_title('bond price')
    ax[2,0].plot(wlist,Vlist)
    ax[2,0].set_title('firm value')
    ax[2,0].set_xlabel('fraction of initial endowment held by agent $\omega^2$,fontsize=13)

    # Create a list of Default thresholds
    A = mdl.A
    \[ = mdl.\[ 
    epslist = []
    for i in range(len(wlist)):
        bb = blist[i]
        kk = klist[i]
        eps = np.log(bb/(A*kk**\[))
        epslist.append(eps)

    # Plot (cont.)
    ax[2,1].plot(wlist,epslist)
    ax[2,1].set_title(r'default threshold $\epsilon^*$')
    ax[2,1].set_xlabel('fraction of initial endowment held by agent $\omega^2$,fontsize=13)

plt.show()
35.8 A picture worth a thousand words

Please stare at the above panels.

They describe how equilibrium prices and quantities respond to alterations in the structure of society's hedging desires across economies with different allocations of the initial endowment to our two types of agents.

Now let's see how the two types of agents value bonds and equities, keeping in mind that the type that values the asset highest determines the equilibrium price (and thus the pertinent set of Big C's).

In [16]: # Comparing the prices
fig, ax = plt.subplots(1, 3, figsize=(16, 6))

ax[0].plot(wlist, q1list, label='agent 1', color='green')
ax[0].plot(wlist, q2list, label='agent 2', color='blue')
ax[0].plot(wlist, qlist, label='equity price', color='red', linestyle='--')
It is rewarding to stare at the above plots too.

In equilibrium, equity valuations are the same across the two types of agents but bond valuations are not.

Agents of type 2 value bonds more highly (they want more hedging).

Taken together with our earlier plot of equity holdings, these graphs confirm our earlier conjecture that while both type of agents hold equities, only agents of type 2 holds bonds.
Part VIII

Dynamic Programming Squared
Chapter 36

Stackelberg Plans

36.1 Contents

- Overview 36.2
- Duopoly 36.3
- The Stackelberg Problem 36.4
- Stackelberg Plan 36.5
- Recursive Representation of Stackelberg Plan 36.6
- Computing the Stackelberg Plan 36.7
- Exhibiting Time Inconsistency of Stackelberg Plan 36.8
- Recursive Formulation of the Follower’s Problem 36.9
- Markov Perfect Equilibrium 36.10
- MPE vs. Stackelberg 36.11

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

36.2 Overview

This notebook formulates and computes a plan that a Stackelberg leader uses to manipulate forward-looking decisions of a Stackelberg follower that depend on continuation sequences of decisions made once and for all by the Stackelberg leader at time 0.

To facilitate computation and interpretation, we formulate things in a context that allows us to apply dynamic programming for linear-quadratic models.

From the beginning, we carry along a linear-quadratic model of duopoly in which firms face adjustment costs that make them want to forecast actions of other firms that influence future prices.

Let’s start with some standard imports:

In [2]: import numpy as np
import numpy.linalg as la
import quantecon as qe
from quantecon import LQ
import matplotlib.pyplot as plt
%matplotlib inline
36.3 Duopoly

Time is discrete and is indexed by $t = 0, 1, ...$

Two firms produce a single good whose demand is governed by the linear inverse demand curve

$$p_t = a_0 - a_1 (q_{1t} + q_{2t})$$

where $q_{it}$ is output of firm $i$ at time $t$ and $a_0$ and $a_1$ are both positive.

$q_{10}, q_{20}$ are given numbers that serve as initial conditions at time $0$.

By incurring a cost of change

$$\gamma v_{it}^2$$

where $\gamma > 0$, firm $i$ can change its output according to

$$q_{it+1} = q_{it} + v_{it}$$

Firm $i$’s profits at time $t$ equal

$$\pi_{it} = p_t q_{it} - \gamma v_{it}^2$$

Firm $i$ wants to maximize the present value of its profits

$$\sum_{t=0}^{\infty} \beta^t \pi_{it}$$

where $\beta \in (0, 1)$ is a time discount factor.

36.3.1 Stackelberg Leader and Follower

Each firm $i = 1, 2$ chooses a sequence $\vec{q}_i = \{q_{it+1}\}_{t=0}^{\infty}$ once and for all at time $0$.

We let firm 2 be a Stackelberg leader and firm 1 be a Stackelberg follower.

The leader firm 2 goes first and chooses $\{q_{2t+1}\}_{t=0}^{\infty}$ once and for all at time $0$.

Knowing that firm 2 has chosen $\{q_{2t+1}\}_{t=0}^{\infty}$, the follower firm 1 goes second and chooses $\{q_{1t+1}\}_{t=0}^{\infty}$ once and for all at time $0$.

In choosing $\vec{q}_2$, firm 2 takes into account that firm 1 will base its choice of $\vec{q}_1$ on firm 2’s choice of $\vec{q}_2$.

36.3.2 Abstract Statement of the Leader’s and Follower’s Problems

We can express firm 1’s problem as

$$\max_{\vec{q}_1} \Pi_1(\vec{q}_1; \vec{q}_2)$$
where the appearance behind the semi-colon indicates that $\vec{q}_2$ is given.

Firm 1’s problem induces the best response mapping

$$\vec{q}_t = B(\vec{q}_2)$$

(Here $B$ maps a sequence into a sequence)

The Stackelberg leader’s problem is

$$\max_{\vec{q}_2} \Pi_2(B(\vec{q}_2), \vec{q}_2)$$

whose maximizer is a sequence $\vec{q}_2$ that depends on the initial conditions $q_{10}, q_{20}$ and the parameters of the model $a_0, a_1, \gamma$.

This formulation captures key features of the model

- Both firms make once-and-for-all choices at time 0.
- This is true even though both firms are choosing sequences of quantities that are indexed by time.
- The Stackelberg leader chooses first within time 0, knowing that the Stackelberg follower will choose second within time 0.

While our abstract formulation reveals the timing protocol and equilibrium concept well, it obscures details that must be addressed when we want to compute and interpret a Stackelberg plan and the follower’s best response to it.

To gain insights about these things, we study them in more detail.

36.3.3 Firms’ Problems

Firm 1 acts as if firm 2’s sequence $\{q_{2t+1}\}_{t=0}^{\infty}$ is given and beyond its control.

Firm 2 knows that firm 1 chooses second and takes this into account in choosing $\{q_{2t+1}\}_{t=0}^{\infty}$.

In the spirit of working backward, we study firm 1’s problem first, taking $\{q_{2t+1}\}_{t=0}^{\infty}$ as given.

We can formulate firm 1’s optimum problem in terms of the Lagrangian

$$L = \sum_{t=0}^{\infty} \beta^t \left[ a_0 q_{1t} - a_1 q_{1t}^2 - a_1 q_{1t} q_{2t} - \gamma v_{1t}^2 + \lambda_t [q_{1t} + v_{1t} - q_{1t+1}] \right]$$

Firm 1 seeks a maximum with respect to $\{q_{1t+1}, v_{1t}\}_{t=0}^{\infty}$ and a minimum with respect to $\{\lambda_t\}_{t=0}^{\infty}$.

We approach this problem using methods described in Ljungqvist and Sargent RMT5 chapter 2, appendix A and Macroeconomic Theory, 2nd edition, chapter IX.

First-order conditions for this problem are

$$\frac{\partial L}{\partial q_{1t}} = a_0 - 2a_1 q_{1t} - a_1 q_{2t} + \lambda_t - \beta^{-1} \lambda_{t-1} = 0, \quad t \geq 1$$

$$\frac{\partial L}{\partial v_{1t}} = -2\gamma v_{1t} + \lambda_t = 0, \quad t \geq 0$$
These first-order conditions and the constraint \( q_{1t+1} = q_{1t} + v_{1t} \) can be rearranged to take the form
\[
v_{1t} = \frac{\beta a_0}{2\gamma} - \frac{\beta a_1}{\gamma} q_{1t+1} - \frac{\beta a_1}{2\gamma} q_{2t+1}
\]
\[
q_{t+1} = q_{1t} + v_{1t}
\]
We can substitute the second equation into the first equation to obtain
\[
(q_{1t+1} - q_{1t}) = \beta(q_{1t+2} - q_{1t+1}) + c_0 - c_1 q_{1t+1} - c_2 q_{2t+1}
\]
where \( c_0 = \frac{\beta a_0}{2\gamma}, c_1 = \frac{\beta a_1}{\gamma}, c_2 = \frac{\beta a_1}{2\gamma} \).

This equation can in turn be rearranged to become the second-order difference equation
\[
q_{1t} + (1 + \beta + c_1)q_{1t+1} - \beta q_{1t+2} = c_0 - c_2 q_{2t+1} \tag{1}
\]
Equation (1) is a second-order difference equation in the sequence \( \vec{q}_1 \) whose solution we want.

It satisfies two boundary conditions:
- an initial condition that \( q_{1,0} \), which is given
- a terminal condition requiring that \( \lim_{T \to +\infty} \beta^T q_{1t}^2 < +\infty \)

Using the lag operators described in chapter IX of *Macroeconomic Theory, Second edition (1987)*, difference equation (1) can be written as
\[
\beta(1 - \frac{1 + \beta + c_1}{\beta} L + \beta^{-1} L^2)q_{1t+2} = -c_0 + c_2 q_{2t+1}
\]
The polynomial in the lag operator on the left side can be factored as
\[
(1 - \frac{1 + \beta + c_1}{\beta} L + \beta^{-1} L^2) = (1 - \delta_1 L)(1 - \delta_2 L) \tag{2}
\]
where \( 0 < \delta_1 < 1 < \frac{1}{\sqrt{\beta}} < \delta_2 \).

Because \( \delta_2 > \frac{1}{\sqrt{\beta}} \) the operator \( (1 - \delta_2 L) \) contributes an unstable component if solved backwards but a stable component if solved forwards.

Mechanically, write
\[
(1 - \delta_2 L) = -\delta_2 L(1 - \delta_2^{-1} L^{-1})
\]
and compute the following inverse operator
\[
\left[-\delta_2 L(1 - \delta_2^{-1} L^{-1})\right]^{-1} = -\delta_2(1 - \delta_2^{-1} L^{-1})^{-1}
\]
Operating on both sides of equation (2) with \( \beta^{-1} \) times this inverse operator gives the follower’s decision rule for setting \( q_{1t+1} \) in the feedback-feedforward form.
\[
q_{1t+1} = \delta_1 q_{1t} - c_0 \delta_2^{-1} \beta^{-1} \frac{1}{1 - \delta_2^{-1}} + c_2 \delta_2^{-1} \beta^{-1} \sum_{j=0}^{\infty} \delta_2^j q_{2t+j+1}, \quad t \geq 0 \tag{3}
\]
The problem of the Stackelberg leader firm 2 is to choose the sequence \( \{q_{2t+1}\}_{t=0}^{\infty} \) to maximize its discounted profits

\[
\sum_{t=0}^{\infty} \beta^t \{(a_0 - a_1(q_{1t} + q_{2t}))q_{2t} - \gamma(q_{2t+1} - q_{2t})^2\}
\]

subject to the sequence of constraints (3) for \( t \geq 0 \).

We can put a sequence \( \{\theta_t\}_{t=0}^{\infty} \) of Lagrange multipliers on the sequence of equations (3) and formulate the following Lagrangian for the Stackelberg leader firm 2’s problem

\[
\tilde{L} = \sum_{t=0}^{\infty} \beta^t \{(a_0 - a_1(q_{1t} + q_{2t}))q_{2t} - \gamma(q_{2t+1} - q_{2t})^2\} + \sum_{t=0}^{\infty} \beta^t \theta_t \left[ \delta_1 q_{1t} - c_0 \delta_2^{-1} \beta^{-1} \frac{1}{1 - \delta_2^{-1}} + c_2 \delta_2^{-1} \beta^{-1} \sum_{j=0}^{\infty} \delta_2^{-j} q_{2t+j+1} - q_{1t+1} \right]
\]

subject to initial conditions for \( q_{1t}, q_{2t} \) at \( t = 0 \).

**Comments:** We have formulated the Stackelberg problem in a space of sequences.

The max-min problem associated with Lagrangian (4) is unpleasant because the time \( t \) component of firm 1’s payoff function depends on the entire future of its choices of \( \{q_{1t+j}\}_{j=0}^{\infty} \).

This renders a direct attack on the problem cumbersome.

Therefore, below, we will formulate the Stackelberg leader’s problem recursively.

We’ll put our little duopoly model into a broader class of models with the same conceptual structure.

### 36.4 The Stackelberg Problem

We formulate a class of linear-quadratic Stackelberg leader-follower problems of which our duopoly model is an instance.

We use the optimal linear regulator (a.k.a. the linear-quadratic dynamic programming problem described in LQ Dynamic Programming problems) to represent a Stackelberg leader’s problem recursively.

Let \( z_t \) be an \( n_z \times 1 \) vector of **natural state variables**.

Let \( x_t \) be an \( n_x \times 1 \) vector of endogenous forward-looking variables that are physically free to jump at \( t \).

In our duopoly example \( x_t = v_{1t} \), the time \( t \) decision of the Stackelberg follower.

Let \( u_t \) be a vector of decisions chosen by the Stackelberg leader at \( t \).

The \( z_t \) vector is inherited physically from the past.

But \( x_t \) is a decision made by the Stackelberg follower at time \( t \) that is the follower’s best response to the choice of an entire sequence of decisions made by the Stackelberg leader at time \( t = 0 \).

Let
\[ y_t = \begin{bmatrix} z_t \\ x_t \end{bmatrix} \]

Represent the Stackelberg leader's one-period loss function as

\[ r(y, u) = y' R y + u' Q u \]

Subject to an initial condition for \( z_0 \), but not for \( x_0 \), the Stackelberg leader wants to maximize

\[ -\sum_{t=0}^{\infty} \beta^t r(y_t, u_t) \tag{5} \]

The Stackelberg leader faces the model

\[
\begin{bmatrix}
I & 0 \\
G_{21} & G_{22}
\end{bmatrix}
\begin{bmatrix}
z_{t+1} \\
x_{t+1}
\end{bmatrix} =
\begin{bmatrix}
\tilde{A}_{11} & \tilde{A}_{12} \\
\tilde{A}_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
z_t \\
x_t
\end{bmatrix} + \tilde{B} u_t
\tag{6}
\]

We assume that the matrix \( \begin{bmatrix} I & 0 \\ G_{21} & G_{22} \end{bmatrix} \) on the left side of equation (6) is invertible, so that we can multiply both sides by its inverse to obtain

\[
\begin{bmatrix}
z_{t+1} \\
x_{t+1}
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
z_t \\
x_t
\end{bmatrix} + B u_t 
\tag{7}
\]

or

\[ y_{t+1} = Ay_t + Bu_t \tag{8} \]

### 36.4.1 Interpretation of the Second Block of Equations

The Stackelberg follower's best response mapping is summarized by the second block of equations of (7).

In particular, these equations are the first-order conditions of the Stackelberg follower’s optimization problem (i.e., its Euler equations).

These Euler equations summarize the forward-looking aspect of the follower’s behavior and express how its time \( t \) decision depends on the leader’s actions at times \( s \geq t \).

When combined with a stability condition to be imposed below, the Euler equations summarize the follower’s best response to the sequence of actions by the leader.

The Stackelberg leader maximizes (5) by choosing sequences \( \{u_t, x_t, z_{t+1}\} \) subject to (8) and an initial condition for \( z_0 \).

Note that we have an initial condition for \( z_0 \) but not for \( x_0 \).

\( x_0 \) is among the variables to be chosen at time 0 by the Stackelberg leader.

The Stackelberg leader uses its understanding of the responses restricted by (8) to manipulate the follower’s decisions.
36.4. THE STACKELBERG PROBLEM

36.4.2 More Mechanical Details

For any vector $a_t$, define $\tilde{a}_t = [a_t, a_{t+1} \ldots]$.

Define a feasible set of $(\tilde{y}_1, \tilde{u}_0)$ sequences

$$\Omega(y_0) = \{(\tilde{y}_1, \tilde{u}_0) : y_{t+1} = Ay_t + Bu_t, \forall t \geq 0\}$$

Please remember that the follower’s Euler equation is embedded in the system of dynamic equations $y_{t+1} = Ay_t + Bu_t$.

Note that in the definition of $\Omega(y_0)$, $y_0$ is taken as given.

Although it is taken as given in $\Omega(y_0)$, eventually, the $x_0$ component of $y_0$ will be chosen by the Stackelberg leader.

36.4.3 Two Subproblems

Once again we use backward induction.

We express the Stackelberg problem in terms of two subproblems.

Subproblem 1 is solved by a continuation Stackelberg leader at each date $t \geq 0$.

Subproblem 2 is solved by the Stackelberg leader at $t = 0$.

The two subproblems are designed

- to respect the protocol in which the follower chooses $\tilde{q}_1$ after seeing $\tilde{q}_2$ chosen by the leader
- to make the leader choose $\tilde{q}_2$ while respecting that $\tilde{q}_1$ will be the follower’s best response to $\tilde{q}_2$
- to represent the leader’s problem recursively by artfully choosing the state variables confronting and the control variables available to the leader

Subproblem 1

$$v(y_0) = \max_{(\tilde{y}_1, \tilde{u}_0) \in \Omega(y_0)} \sum_{t=0}^{\infty} \beta^t r(y_t, u_t)$$

Subproblem 2

$$w(z_0) = \max_{x_0} v(y_0)$$

Subproblem 1 takes the vector of forward-looking variables $x_0$ as given.

Subproblem 2 optimizes over $x_0$.

The value function $w(z_0)$ tells the value of the Stackelberg plan as a function of the vector of natural state variables at time 0, $z_0$.

36.4.4 Two Bellman Equations

We now describe Bellman equations for $v(y)$ and $w(z_0)$. 
Subproblem 1

The value function $v(y)$ in subproblem 1 satisfies the Bellman equation

$$v(y) = \max_{u,y^*} \{-r(y, u) + \beta v(y^*)\} \tag{9}$$

where the maximization is subject to

$$y^* = Ay + Bu$$

and $y^*$ denotes next period’s value. Substituting $v(y) = -y'P y$ into Bellman equation (9) gives

$$-y'P y = \max_{u,y^*} \{-y'Ry - u'Qu - \beta y'^*P y^*\}$$

which as in lecture linear regulator gives rise to the algebraic matrix Riccati equation

$$P = R + \beta A'PA - \beta^2 A'PB(Q + \beta B'PB)^{-1}B'PA$$

and the optimal decision rule coefficient vector

$$F = \beta(Q + \beta B'PB)^{-1}B'PA$$

where the optimal decision rule is

$$u_t = -Fy_t$$

Subproblem 2

We find an optimal $x_0$ by equating to zero the gradient of $v(y_0)$ with respect to $x_0$:

$$-2P_{21}z_0 - 2P_{22}x_0 = 0,$$

which implies that

$$x_0 = -P_{22}^{-1}P_{21}z_0$$

36.5 Stackelberg Plan

Now let’s map our duopoly model into the above setup. We will formulate a state space system

$$y_t = \begin{bmatrix} z_t \\ x_t \end{bmatrix}$$

where in this instance $x_t = v_{1t}$, the time $t$ decision of the follower firm 1.
36.5. **STACKELBERG PLAN**

36.5.1 Calculations to Prepare Duopoly Model

Now we’ll proceed to cast our duopoly model within the framework of the more general linear-quadratic structure described above. That will allow us to compute a Stackelberg plan simply by enlisting a Riccati equation to solve a linear-quadratic dynamic program.

As emphasized above, firm 1 acts as if firm 2’s decisions \( \{ q_{2t+1}, v_{2t} \}_{t=0}^{\infty} \) are given and beyond its control.

36.5.2 Firm 1’s Problem

We again formulate firm 1’s optimum problem in terms of the Lagrangian

\[
L = \sum_{t=0}^{\infty} \beta^t \left( a_0 q_{1t} - a_1 q_{1t}^2 - a_1 q_{1t} q_{2t} - \gamma v_{1t}^2 + \lambda_t (q_{1t} + v_{1t} - q_{1t+1}) \right)
\]

Firm 1 seeks a maximum with respect to \( \{ q_{1t+1}, v_{1t} \}_{t=0}^{\infty} \) and a minimum with respect to \( \{ \lambda_t \}_{t=0}^{\infty} \).

First-order conditions for this problem are

\[
\frac{\partial L}{\partial q_{1t}} = a_0 - 2a_1 q_{1t} - a_1 q_{2t} + \lambda_t - \beta^{-1} \lambda_{t-1} = 0, \quad t \geq 1
\]

\[
\frac{\partial L}{\partial v_{1t}} = -2\gamma v_{1t} + \lambda_t = 0, \quad t \geq 0
\]

These first-order order conditions and the constraint \( q_{1t+1} = q_{1t} + v_{1t} \) can be rearranged to take the form

\[
v_{1t} = \beta v_{1t+1} + \frac{\beta a_0}{2\gamma} - \frac{\beta a_1}{\gamma} q_{1t+1} - \frac{\beta a_1}{2\gamma} q_{2t+1}
\]

\[
q_{t+1} = q_{1t} + v_{1t}
\]

We use these two equations as components of the following linear system that confronts a Stackelberg continuation leader at time \( t \)

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
\frac{\beta a_0}{2\gamma} - \frac{\beta a_1}{2\gamma} & -\frac{\beta a_1}{\gamma} & \beta
\end{bmatrix}
\begin{bmatrix}
q_{2t+1} \\
q_{1t+1} \\
v_{1t+1}
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
q_{2t} \\
q_{1t} \\
v_{1t}
\end{bmatrix}
+ \begin{bmatrix}
1 \\
0 \\
0 \\
0
\end{bmatrix}
v_{2t}
\]

Time \( t \) revenues of firm 2 are \( \pi_{2t} = a_0 q_{2t} - a_1 q_{2t}^2 - a_1 q_{1t} q_{2t} \) which evidently equal

\[
z_t' R_1 z_t = \begin{bmatrix}
1 & q_{2t} & q_{1t}
\end{bmatrix}
\begin{bmatrix}
0 & \frac{a_0}{2} & 0 \\
\frac{a_0}{2} & -a_1 & -\frac{a_1}{2} \\
0 & -\frac{a_1}{2} & 0
\end{bmatrix}
\begin{bmatrix}
1 \\
q_{2t} \\
q_{1t}
\end{bmatrix}
\]

If we set \( Q = \gamma \), then firm 2’s period \( t \) profits can then be written
CHAPTER 36. STACKELBERG PLANS

\[ y'_t R y_t - Qv^2_{2t} \]

where

\[ y_t = \begin{bmatrix} z_t \\ x_t \end{bmatrix} \]

with \( x_t = v_{1t} \) and

\[ R = \begin{bmatrix} R_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \]

We’ll report results of implementing this code soon.

But first, we want to represent the Stackelberg leader’s optimal choices recursively.

It is important to do this for several reasons:

• properly to interpret a representation of the Stackelberg leader’s choice as a sequence of history-dependent functions
• to formulate a recursive version of the follower’s choice problem

First, let’s get a recursive representation of the Stackelberg leader’s choice of \( \bar{q}_2 \) for our duopoly model.

36.6 Recursive Representation of Stackelberg Plan

In order to attain an appropriate representation of the Stackelberg leader’s history-dependent plan, we will employ what amounts to a version of the **Big K, little k** device often used in macroeconomics by distinguishing \( z_t \), which depends partly on decisions \( x_t \) of the followers, from another vector \( \bar{z}_t \), which does not.

We will use \( \bar{z}_t \) and its history \( \bar{z}_t = [\bar{z}_t, \bar{z}_{t-1}, \ldots, \bar{z}_0] \) to describe the sequence of the Stackelberg leader’s decisions that the Stackelberg follower takes as given.

Thus, we let \( \bar{y}_t = [\bar{z}'_t \ \bar{x}'_t] \) with initial condition \( \bar{z}_0 = z_0 \) given.

That we distinguish \( \bar{z}_t \) from \( z_t \) is part and parcel of the **Big K, little k** device in this instance.

We have demonstrated that a Stackelberg plan for \( \{u_t\}_{t=0}^\infty \) has a recursive representation

\[
\begin{align*}
\bar{x}_0 &= -P_{-21}^{-1}P_{21} \bar{z}_0 \\
u_t &= -F\bar{y}_t, \quad t \geq 0 \\
\bar{y}_{t+1} &= (A - BF)\bar{y}_t, \quad t \geq 0
\end{align*}
\]

From this representation, we can deduce the sequence of functions \( \sigma = \{\sigma_t(\bar{z}_t)\}_{t=0}^\infty \) that comprise a Stackelberg plan.

For convenience, let \( \bar{A} \equiv A - BF \) and partition \( \bar{A} \) conformably to the partition \( y_t = \begin{bmatrix} \bar{z}_t \\ \bar{x}_t \end{bmatrix} \) as

\[
\begin{bmatrix}
\bar{A}_{11} & \bar{A}_{12} \\
\bar{A}_{21} & \bar{A}_{22}
\end{bmatrix}
\]
Let \( H_0^0 \equiv -P_{22}^{-1}P_{21} \) so that \( \tilde{x}_0 = H_0^0 z_0 \).

Then iterations on \( \tilde{y}_{t+1} = \tilde{A}\tilde{y}_t \) starting from initial condition \( \tilde{y}_0 = \begin{bmatrix} \tilde{z}_0 \\ H_0^0 z_0 \end{bmatrix} \) imply that for \( t \geq 1 \)

\[
x_t = \sum_{j=1}^{t} H_j^t \tilde{z}_{t-j}
\]

where

\[
\begin{align*}
H_1^t &= \tilde{A}_{21} \\
H_2^t &= \tilde{A}_{22}\tilde{A}_{21} \\
&\vdots \\
H_{t-1}^t &= \tilde{A}_{22}^{-2}\tilde{A}_{21} \\
H_t^t &= \tilde{A}_{22}^{-1}(\tilde{A}_{21} + \tilde{A}_{22}H_0^0)
\end{align*}
\]

An optimal decision rule for the Stackelberg’s choice of \( u_t \) is

\[
u_t = -F\tilde{y}_t = -\begin{bmatrix} F_z & F_x \end{bmatrix} \begin{bmatrix} \tilde{z}_t \\ x_t \end{bmatrix}
\]

or

\[
u_t = -F_z \tilde{z}_t - F_x \sum_{j=1}^{t} H_j^t z_{t-j} = \sigma_t(\tilde{z}^t)
\]

Representation (10) confirms that whenever \( F_x \neq 0 \), the typical situation, the time \( t \) component \( \sigma_t \) of a Stackelberg plan is \textbf{history-dependent}, meaning that the Stackelberg leader’s choice \( u_t \) depends not just on \( \tilde{z}_t \) but on components of \( \tilde{z}^{t-1} \).

36.6.1 Comments and Interpretations

After all, at the end of the day, it will turn out that because we set \( \tilde{z}_0 = z_0 \), it will be true that \( z_t = \tilde{z}_t \) for all \( t \geq 0 \).

Then why did we distinguish \( \tilde{z}_t \) from \( z_t \)?

The answer is that if we want to present to the Stackelberg \textbf{follower} a history-dependent representation of the Stackelberg \textbf{leader}’s sequence \( \tilde{q}_2 \), we must use representation (10) cast in terms of the history \( \tilde{z}^t \) and \textbf{not} a corresponding representation cast in terms of \( z^t \).

36.6.2 Dynamic Programming and Time Consistency of follower’s Problem

Given the sequence \( \tilde{q}_2 \) chosen by the Stackelberg leader in our duopoly model, it turns out that the Stackelberg \textbf{follower}’s problem is recursive in the \textit{natural} state variables that confront a follower at any time \( t \geq 0 \).

This means that the follower’s plan is time consistent.
To verify these claims, we’ll formulate a recursive version of a follower’s problem that builds on our recursive representation of the Stackelberg leader’s plan and our use of the Big K, little k idea.

### 36.6.3 Recursive Formulation of a Follower’s Problem

We now use what amounts to another “Big K, little k” trick (see rational expectations equilibrium) to formulate a recursive version of a follower’s problem cast in terms of an ordinary Bellman equation.

Firm 1, the follower, faces \( \{ q_{2t} \}_{t=0}^{\infty} \) as a given quantity sequence chosen by the leader and believes that its output price at \( t \) satisfies

\[
p_t = a_0 - a_1 (q_{1t} + q_{2t}), \quad t \geq 0
\]

Our challenge is to represent \( \{ q_{2t} \}_{t=0}^{\infty} \) as a given sequence.

To do so, recall that under the Stackelberg plan, firm 2 sets output according to the \( q_{2t} \) component of

\[
y_{t+1} = \begin{bmatrix} 1 \\ q_{2t} \\ q_{1t} \\ x_t \end{bmatrix}
\]

which is governed by

\[
y_{t+1} = (A - BF) y_t
\]

To obtain a recursive representation of a \( \{ q_{2t} \} \) sequence that is exogenous to firm 1, we define a state \( \tilde{y}_t \)

\[
\tilde{y}_t = \begin{bmatrix} 1 \\ q_{2t} \\ \tilde{q}_{1t} \\ \tilde{x}_t \end{bmatrix}
\]

that evolves according to

\[
\tilde{y}_{t+1} = (A - BF) \tilde{y}_t
\]

subject to the initial condition \( \tilde{q}_{10} = q_{10} \) and \( \tilde{x}_0 = x_0 \) where \( x_0 = -P_{21}^{-1} P_{22} \) as stated above.

Firm 1’s state vector is

\[
X_t = \begin{bmatrix} \tilde{y}_t \\ q_{1t} \end{bmatrix}
\]

It follows that the follower firm 1 faces law of motion
36.6. RECURSIVE REPRESENTATION OF STACKELBERG PLAN

\[
\begin{bmatrix}
\tilde{y}_{t+1} \\
q_{t+1}
\end{bmatrix} =
\begin{bmatrix}
A - BF & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\tilde{y}_t \\
q_t
\end{bmatrix} +
\begin{bmatrix}
0 \\
1
\end{bmatrix}x_t
\] (11)

This specification assures that from the point of view of a firm 1, \(q_{2t}\) is an exogenous process.

Here

- \(\tilde{q}_{1t}, \tilde{x}_t\) play the role of \textbf{Big K}
- \(q_{1t}, x_t\) play the role of \textbf{little k}

The time \(t\) component of firm 1’s objective is

\[
\tilde{X}_t' \tilde{R} x_t - x_t^2 \tilde{Q} =
\begin{bmatrix}
1 \\
q_{2t} \\
\tilde{q}_{1t} \\
\tilde{x}_t
\end{bmatrix}
\begin{bmatrix}
0 & 0 & 0 & 0 & \frac{a_0}{2} \\
0 & 0 & 0 & 0 & -\frac{a_1}{2} \\
0 & 0 & 0 & 0 & 0 \\
\frac{a_0}{2} & -\frac{a_1}{2} & 0 & 0 & -a_1
\end{bmatrix}
\begin{bmatrix}
1 \\
q_{2t} \\
\tilde{q}_{1t} \\
\tilde{x}_t \\
q_{1t}
\end{bmatrix} - \gamma x_t^2
\]

Firm 1’s optimal decision rule is

\[x_t = -\tilde{F} X_t\]

and it’s state evolves according to

\[\tilde{X}_{t+1} = (\tilde{A} - \tilde{B} \tilde{F}) X_t\]

under its optimal decision rule.

Later we shall compute \(\tilde{F}\) and verify that when we set

\[X_0 =
\begin{bmatrix}
1 \\
q_{20} \\
q_{10} \\
x_0 \\
q_{10}
\end{bmatrix}\]

we recover

\[x_0 = -\tilde{F} X_0\]

which will verify that we have properly set up a recursive representation of the follower’s problem facing the Stackelberg leader’s \(\bar{q}_2\).

36.6.4 Time Consistency of Follower’s Plan

Since the follower can solve its problem using dynamic programming its problem is recursive in what for it are the \textbf{natural state variables}, namely
It follows that the follower’s plan is time consistent.

### 36.7 Computing the Stackelberg Plan

Here is our code to compute a Stackelberg plan via a linear-quadratic dynamic program as outlined above:

```python
In [3]: # Parameters
    a0 = 10
    a1 = 2
    β = 0.96
    γ = 120
    n = 300
    tol0 = 1e-8
    tol1 = 1e-16
    tol2 = 1e-2
    βs = np.ones(n)
    βs[1:] = β
    βs = βs.cumprod()

In [4]: # In LQ form
    Alhs = np.eye(4)
    # Euler equation coefficients
    Alhs[3, :] = β * a0 / (2 * γ), -β * a1 / (2 * γ), -β * a1 / γ, β
    Arhs = np.eye(4)
    Arhs[2, 3] = 1
    Alhsinv = la.inv(Alhs)
    A = Alhsinv @ Arhs
    B = Alhsinv @ np.array([0, 1, 0, 0]).T
    R = np.array([[0, -a0 / 2, 0, 0],
                  [-a0 / 2, a1, 1, 0],
                  [0, a1 / 2, 0, 0],
                  [0, 0, 0, 0]])
    Q = np.array([[γ]])

    # Solve using QE's LQ class
    # LQ solves minimization problems which is why the sign of R and Q was changed
    lq = LQ(Q, R, A, B, beta=β)
    P, F, d = lq.stationary_values(method='doubling')
```
36.7. COMPUTING THE STACKELBERG PLAN

\[ P_{22} = P[3:, 3:] \]
\[ P_{21} = P[3:, :3] \]
\[ P_{22}^{-1} = la.inv(P_{22}) \]
\[ H_{0,0} = -P_{22}^{-1} \odot P_{21} \]

# Simulate forward

\[ \pi_{\text{leader}} = \text{np.zeros}(n) \]
\[ z0 = \text{np.array}([[1, 1, 1]]).T \]
\[ x0 = H_{0,0} \odot z0 \]
\[ y0 = \text{np.vstack}((z0, x0)) \]
\[ y_t, u_t = \text{lq.compute_sequence}(y0, ts_length=n)[::2] \]
\[ \pi_{\text{matrix}} = (R + F \cdot T \odot Q \odot F) \]

for t in range(n):
    \[ \pi_{\text{leader}}[t] = -(y_t[:, t].T \odot \pi_{\text{matrix}} \odot y_t[:, t]) \]

# Display policies

print("Computed policy for Stackelberg leader\n")
print(f"F = {F}"")

Computed policy for Stackelberg leader

\[ F = \begin{bmatrix} -1.58004454 & 0.29461313 & 0.67480938 & 6.53970594 \end{bmatrix} \]

36.7.1 Implied Time Series for Price and Quantities

The following code plots the price and quantities

In [5]:
q_leader = y_t[1, :-1]
q_follower = y_t[2, :-1]
q = q_leader + q_follower  # Total output, Stackelberg
p = a0 - a1 * q  # Price, Stackelberg

fig, ax = plt.subplots(figsize=(9, 5.8))
ax.plot(range(n), q_leader, 'b-', lw=2, label='leader output')
ax.plot(range(n), q_follower, 'r-', lw=2, label='follower output')
ax.plot(range(n), p, 'g-', lw=2, label='price')
ax.set_title('Output and prices, Stackelberg duopoly')
ax.legend(frameon=False)
ax.set_xlabel('t')
plt.show()
36.7.2 Value of Stackelberg Leader

We'll compute the present value earned by the Stackelberg leader. We'll compute it two ways (they give identical answers – just a check on coding and thinking).

In [6]:
```python
v_leader_forward = np.sum(\beta_s * \pi_leader)
v_leader_direct = -yt[:, 0].T @ P @ yt[:, 0]
```

# Display values
```python
print("Computed values for the Stackelberg leader at t=0:\n")
print(f"v_leader_forward(forward sim) = {v_leader_forward:.4f}"")
print(f"v_leader_direct (direct) = {v_leader_direct:.4f}"")
```

Computed values for the Stackelberg leader at t=0:

\[ v_{\text{leader\_forward}}(\text{forward\_sim}) = 150.0316 \]
\[ v_{\text{leader\_direct}}(\text{direct}) = 150.0324 \]

In [7]: # Manually checks whether \( P \) is approximately a fixed point
```python
P_next = (R + F.T @ Q @ F + \beta * (A - B @ F).T @ P @ (A - B @ F))
(P - P_next < tol0).all()
```

Out[7]: True

In [8]: # Manually checks whether two different ways of computing the value function give approximately the same answer
36.8 Exhibiting Time Inconsistency of Stackelberg Plan

In the code below we compare two values

- the continuation value $-y_t P y_t$ earned by a continuation Stackelberg leader who inherits state $y_t$ at $t$
- the value of a reborn Stackelberg leader who inherits state $z_t$ at $t$ and sets $x_t = -P_{22}^{-1} P_{21}$

The difference between these two values is a tell-tale sign of the time inconsistency of the Stackelberg plan.

In [9]: # Compute value function over time with a reset at time $t$

```python
v_expanded = -((y0.T @ R @ y0 + ut[:, 0].T @ Q @ ut[:, 0] +
    β * (y0.T @ (A - B @ F).T @ P @ (A - B @ F) @ y0)))
(v_leader_direct - v_expanded < tol0)[0, 0]
```

Out[9]: True

In [10]: fig, axes = plt.subplots(3, 1, figsize=(10, 7))

```python
axes[0].plot(range(n+1), (- F @ yt).flatten(), 'bo',
    label='Stackelberg leader', ms=2)
axes[0].plot(range(n+1), (- F @ yt_reset).flatten(), 'ro',
    label='continuation leader at t', ms=2)
axes[0].set(title=r'Leader control variable $u_{\cdot t}$', xlabel='t')
axes[0].legend()

axes[1].plot(range(n+1), yt[3, :], 'bo', ms=2)
axes[1].plot(range(n+1), yt_reset[3, :], 'ro', ms=2)
axes[1].set(title=r'Follower control variable $x_{\cdot t}$', xlabel='t')

axes[2].plot(range(n), vt_leader, 'bo', ms=2)
axes[2].plot(range(n), vt_reset_leader, 'ro', ms=2)
axes[2].set(title=r'Leader value function $v(y_{\cdot t})$', xlabel='t')
```

plt.tight_layout()
plt.show()
CHAPTER 36. STACKELBERG PLANS

36.9 Recursive Formulation of the Follower’s Problem

We now formulate and compute the recursive version of the follower’s problem.

We check that the recursive Big $K$, little $k$ formulation of the follower’s problem produces the same output path $\tilde{q}_1$ that we computed when we solved the Stackelberg problem.

In [11]:

\[
\begin{align*}
A_{\text{tilde}} &= \text{np.eye}(5) \\
A_{\text{tilde}}[4:, 4:] &= A - B @ F \\
R_{\text{tilde}} &= \text{np.array}([[\theta, \theta, \theta, -a_0 / 2], \\
&[\theta, \theta, \theta, a_1 / 2], \\
&[\theta, \theta, \theta, \theta], \\
&[-a_0 / 2, a_1 / 2, \theta, \theta]]) \\
Q_{\text{tilde}} &= Q \\
B_{\text{tilde}} &= \text{np.array}([[\theta, \theta, \theta, 1]])^T \\
lq_{\text{tilde}} &= \text{lq}(Q_{\text{tilde}}, R_{\text{tilde}}, A_{\text{tilde}}, B_{\text{tilde}}, \beta) \\
P_{\text{tilde}}, F_{\text{tilde}}, d_{\text{tilde}} &= \text{lq}_{\text{tilde}}.\text{stationary_values}(\text{method}='\text{doubling}') \\
y_{\text{tilde}} &= \text{np.vstack}((y_0, y_0[2])) \\
y_{\text{tilde}} &= \text{lq}_{\text{tilde}}.\text{compute_sequence}(y_{\text{tilde}}, \text{ts_length}=n)[0]
\end{align*}
\]

In [12]:

# Checks that the recursive formulation of the follower's problem gives
# the same solution as the original Stackelberg problem
fig, ax = plt.subplots()
36.9. RECURSIVE FORMULATION OF THE FOLLOWER’S PROBLEM

ax.plot(yt_tilde[4], 'r', label="q_tilde")
ax.plot(yt_tilde[2], 'b', label="q")
ax.legend()
plt.show()

Note: Variables with \_tilde are obtained from solving the follower’s problem – those without are from the Stackelberg problem.

```
In [13]: # Maximum absolute difference in quantities over time between
   # the first and second solution methods
Out[13]: 6.661338147750939e-16

In [14]: # x0 == x0_tilde
   yt[:, 0][-1] - (yt_tilde[:, 1] - yt_tilde[:, 0])[-1] < tol0
Out[14]: True
```

36.9.1 Explanation of Alignment

If we inspect the coefficients in the decision rule $-\tilde{F}$, we can spot the reason that the follower chooses to set $x_t = \tilde{x}_t$ when it sets $x_t = -\tilde{F}X_t$ in the recursive formulation of the follower problem.

Can you spot what features of $\tilde{F}$ imply this?

Hint: remember the components of $X_t$

```
In [15]: # Policy function in the follower's problem
   F_tilde.round(4)
```
Out[15]: array([[-0., 0., -0.1032, -1., 0.1032]])

In [16]: # Value function in the Stackelberg problem

Out[16]: array([[ 963.54083615, -194.60534465, -511.62197962, -5258.22585724],
        [ -194.60534465, 37.3535753 , 81.97712513, 784.76471234],
        [ -511.62197962, 81.97712513, 247.34333344, 2517.05126111],
        [-5258.22585724, 784.76471234, 2517.05126111, 25556.16504097]])

In [17]: # Value function in the follower's problem

Out[17]: array([[-1.81991134e+01, 2.58003020e+00, 1.56048755e+01,
            1.51229815e+02, -5.00000000e+00],
           [ 2.58003020e+00, -9.69465925e-01, -5.26007958e+00,
            -5.09764310e+01, 1.00000000e+00],
           [ 1.56048755e+01, -5.26007958e+00, -3.22759027e+01,
            -3.12791908e+02, -1.23823802e+01],
           [ 1.51229815e+02, -5.09764310e+01, -3.12791908e+02,
            -3.03132584e+03, -1.20000000e+02],
           [-5.00000000e+00, 1.00000000e+00, -1.23823802e+01,
            -1.20000000e+02, 1.43823802e+01]])

In [18]: # Manually check that P is an approximate fixed point

    (P - ((R + F.T @ Q @ F) + β * (A - B @ F).T @ P @ (A - B @ F)) < tol0).all()

Out[18]: True

In [19]: # Compute `P_guess` using `F_tilde_star`

    F_tilde_star = -np.array([0, 0, 0, 1, 0])
    P_guess = np.zeros((5, 5))

    for i in range(1000):
        P_guess = ((R_tilde + F_tilde_star.T @ Q @ F_tilde_star) +
                   β * (A_tilde - B_tilde @ F_tilde_star).T @ P_guess)

In [20]: # Value function in the follower's problem

    -(y0_tilde.T @ P_tilde @ y0_tilde)[0, 0]

Out[20]: 112.65590740578058

In [21]: # Value function with `P_guess`

    -(y0_tilde.T @ P_guess @ y0_tilde)[0, 0]

Out[21]: 112.6559074057807

In [22]: # Compute policy using policy iteration algorithm

    F_iter = (β * la.inv(Q + β * B_tilde.T @ P_guess @ B_tilde)
              @ B_tilde.T @ P_guess @ A_tilde)
for i in range(100):
    # Compute P_iter
    P_iter = np.zeros((5, 5))
    for j in range(1000):
        P_iter = ((R_tilde + F_iter.T @ Q @ F_iter) + \n        \beta (A_tilde - B_tilde @ F_iter).T @ P_iter @ \n        (A_tilde - B_tilde @ F_iter))

    # Update F_iter
    F_iter = (\beta * la.inv(Q + \beta * B_tilde.T @ P_iter @ B_tilde) @ B_tilde.T @ P_iter @ A_tilde)

    dist_vec = (P_iter - ((R_tilde + F_iter.T @ Q @ F_iter) + \n        \beta (A_tilde - B_tilde @ F_iter).T @ P_iter @ \n        (A_tilde - B_tilde @ F_iter)))

    if np.max(np.abs(dist_vec)) < 1e-8:
        dist_vec2 = (F_iter - ((R_tilde + F_iter.T @ Q @ F_iter) + \n            \beta * (A_tilde - B_tilde @ F_iter).T @ P_iter @ B_tilde) @ B_tilde.T @ P_iter @ A_tilde))
        if np.max(np.abs(dist_vec2)) < 1e-8:
            F_iter =
        else:
            print("The policy didn't converge: try increasing the number of \n            outer loop iterations")
    else:
        print("`P_iter` didn't converge: try increasing the number of inner \n            loop iterations")

In [23]: # Simulate the system using `F_tilde_star` and check that it gives the
           # same result as the original solution

    yt_tilde_star = np.zeros((n, 5))
    yt_tilde_star[0, :) = y0_tilde.flatten()

    for t in range(n-1):
        yt_tilde_star[t+1, :] = (A_tilde - B_tilde @ F_tilde_star) \n        @ yt_tilde_star[t, :]

    fig, ax = plt.subplots()
    ax.plot(yt_tilde_star[:, 4], 'r', label="q_tilde")
    ax.plot(yt_tilde[2], 'b', label="q")
    ax.legend()
    plt.show()
36.10 Markov Perfect Equilibrium

The state vector is

\[ z_t = \begin{bmatrix} 1 \\ q_{2t} \\ q_{1t} \end{bmatrix} \]

and the state transition dynamics are

\[ z_{t+1} = A z_t + B_1 v_{1t} + B_2 v_{2t} \]

where \( A \) is a 3 × 3 identity matrix and

\[ B_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \]

The Markov perfect decision rules are

\[ v_{1t} = -F_1 z_t, \quad v_{2t} = -F_2 z_t \]
and in the Markov perfect equilibrium, the state evolves according to

\[ z_{t+1} = (A - B_1 F_1 - B_2 F_2)z_t \]

In [25]: # In LQ form
A = np.eye(3)
B1 = np.array([[0], [0], [1]])
B2 = np.array([[0], [1], [0]])
R1 = np.array([[0, -a0 / 2, 0], [0, 0, a1 / 2], [-a0 / 2, a1 / 2, 0]])
R2 = np.array([[0, -a0 / 2, 0], [-a0 / 2, a1, a1 / 2], [0, a1 / 2, 0]])
Q1 = Q2 = \gamma
S1 = S2 = W1 = W2 = M1 = M2 = 0.0

# Solve using QE's nnash function
F1, F2, P1, P2 = qe.nnash(A, B1, B2, R1, R2, Q1, Q2, S1, S2, W1, W2, M1, M2, beta=β, tol=tol1)

# Simulate forward
AF = A - B1 @ F1 - B2 @ F2
z = np.empty((3, n))
z[:, 0] = 1, 1, 1
for t in range(n-1):
    z[:, t+1] = AF @ z[:, t]

# Display policies
print("Computed policies for firm 1 and firm 2:
")
print(f"F1 = {F1}"
print(f"F2 = {F2}"

Computed policies for firm 1 and firm 2:
F1 = [[-0.22701363 0.03129874 0.09447113]]
F2 = [[-0.22701363 0.09447113 0.03129874]]

In [26]: q1 = z[1, :]
q2 = z[2, :]
q = q1 + q2 # Total output, MPE
p = a0 - a1 * q # Price, MPE

fig, ax = plt.subplots(figsize=(9, 5.8))
ax.plot(range(n), q, 'b-', lw=2, label='total output')
ax.plot(range(n), p, 'g-', lw=2, label='price')
ax.set_title('Output and prices, duopoly MPE')
ax.legend(frameon=False)
ax.set_xlabel('t')
plt.show()
In [27]: # Computes the maximum difference between the two quantities of the two firms
    np.max(np.abs(q1 - q2))

Out[27]: 6.8833827526759706e-15

In [28]: # Compute values
    u1 = (-F1 @ z).flatten()
    u2 = (-F2 @ z).flatten()

    π_1 = p * q1 - γ * (u1) ** 2
    π_2 = p * q2 - γ * (u2) ** 2

    v1_forward = np.sum(βs * π_1)
    v2_forward = np.sum(βs * π_2)

    v1_direct = (-z[:, 0].T @ P1 @ z[:, 0])
    v2_direct = (-z[:, 0].T @ P2 @ z[:, 0])

# Display values
print("Computed values for firm 1 and firm 2:

    v1(forward sim) = {v1_forward:.4f}; v1 (direct) = {v1_direct:.4f}
    v2 (forward sim) = {v2_forward:.4f}; v2 (direct) = {v2_direct:.4f}"
)

Computed values for firm 1 and firm 2:
    v1(forward sim) = 133.3303; v1 (direct) = 133.3296
    v2 (forward sim) = 133.3303; v2 (direct) = 133.3296
In [29]: # Sanity check
Λ1 = A - B2 @ F2
lq1 = qe.LQ(Q1, R1, A1, B1, beta=β)
P1_ih, F1_ih, d = lq1.stationary_values()
v2_direct_alt = - z[:; θ].T @ lq1.P @ z[:; θ] + lq1.d
(np.abs(v2_direct - v2_direct_alt) < tol2).all()

Out[29]: True

36.11 MPE vs. Stackelberg

In [30]: vt_MPE = np.zeros(n)
vt_follower = np.zeros(n)

for t in range(n):
    vt_MPE[t] = -z[:, t].T @ P1 @ z[:, t]
    vt_follower[t] = -yt_tilde[:, t].T @ P_tilde @ yt_tilde[:, t]

fig, ax = plt.subplots()
ax.plot(vt_MPE, 'b', label='MPE')
ax.plot(vt_leader, 'r', label='Stackelberg leader')
ax.plot(vt_follower, 'g', label='Stackelberg follower')
ax.set_title(r'MPE vs. Stackelberg Value Function')
ax.set_xlabel('t')
ax.legend(loc=(1.05, 0))
plt.show()

In [31]: # Display values
print("Computed values:\n")
print(f"vt_leader(y0) = {vt_leader[0]:.4f}"")
print(f"vt_follower(y0) = {vt_follower[0]:.4f}"")
print(f"vt_MPE(y0) = {vt_MPE[0]:.4f}"
Computed values:

\[
\begin{align*}
vt_{\text{leader}}(y_0) &= 150.0324 \\
vt_{\text{follower}}(y_0) &= 112.6559 \\
vt_{\text{MPE}}(y_0) &= 133.3296
\end{align*}
\]

In [32]: # Compute the difference in total value between the Stackelberg and the MPE

\[
vt_{\text{leader}}[0] + vt_{\text{follower}}[0] - 2 \times vt_{\text{MPE}}[0]
\]

Out[32]: -3.970942562087714
Chapter 37

Ramsey Plans, Time Inconsistency, Sustainable Plans

37.1 Contents

- Overview 37.2
- The Model 37.3
- Structure 37.4
- Intertemporal Influences 37.5
- Four Models of Government Policy 37.6
- A Ramsey Planner 37.7
- A Constrained-to-a-Constant-Growth-Rate Ramsey Government 37.8
- Markov Perfect Governments 37.9
- Equilibrium Outcomes for Three Models of Government Policy Making 37.10
- A Fourth Model of Government Decision Making 37.11
- Sustainable or Credible Plan 37.12
- Whose Credible Plan is it? 37.13
- Comparison of Equilibrium Values 37.14
- Note on Dynamic Programming Squared 37.15

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

37.2 Overview

This lecture describes a linear-quadratic version of a model that Guillermo Calvo [13] used to illustrate the time inconsistency of optimal government plans.

Like Chang [14], we use the model as a laboratory in which to explore the consequences of different timing protocols for government decision making.

The model focuses attention on intertemporal tradeoffs between

- welfare benefits that anticipated deflation generates by increasing a representative agent’s liquidity as measured by his or her real money balances, and
- costs associated with distorting taxes that must be used to withdraw money from the economy in order to generate anticipated deflation
The model features

- rational expectations
- costly government actions at all dates $t \geq 1$ that increase household utilities at dates before $t$
- two Bellman equations, one that expresses the private sector’s expectation of future inflation as a function of current and future government actions, another that describes the value function of a Ramsey planner

A theme of this lecture is that timing protocols affect outcomes.

We’ll use ideas from papers by Cagan [12], Calvo [13], Stokey [62], [63], Chari and Kehoe [15], Chang [14], and Abreu [1] as well as from chapter 19 of [43].

In addition, we’ll use ideas from linear-quadratic dynamic programming described in Linear Quadratic Control as applied to Ramsey problems in Stackelberg problems.

In particular, we have specified the model in a way that allows us to use linear-quadratic dynamic programming to compute an optimal government plan under a timing protocol in which a government chooses an infinite sequence of money supply growth rates once and for all at time 0.

We’ll start with some imports:

```python
In [2]: import numpy as np
from quantecon import LQ
import matplotlib.pyplot as plt
%matplotlib inline
```

### 37.3 The Model

There is no uncertainty.

Let:

- $p_t$ be the log of the price level
- $m_t$ be the log of nominal money balances
- $\theta_t = p_{t+1} - p_t$ be the net rate of inflation between $t$ and $t + 1$
- $\mu_t = m_{t+1} - m_t$ be the net rate of growth of nominal balances

The demand for real balances is governed by a perfect foresight version of the Cagan [12] demand function:

$$m_t - p_t = -\alpha(p_{t+1} - p_t), \quad \alpha > 0 \quad (1)$$

for $t \geq 0$.

Equation (1) asserts that the demand for real balances is inversely related to the public’s expected rate of inflation, which here equals the actual rate of inflation.

(When there is no uncertainty, an assumption of rational expectations simplifies to perfect foresight).

(See [58] for a rational expectations version of the model when there is uncertainty)

Subtracting the demand function at time $t$ from the demand function at $t + 1$ gives:
37.3. THE MODEL

\[ \mu_t - \theta_t = -\alpha \theta_{t+1} + \alpha \theta_t \]

or

\[ \theta_t = \frac{\alpha}{1 + \alpha} \theta_{t+1} + \frac{1}{1 + \alpha} \mu_t \]  

(2)

Because \( \alpha > 0 \), \( 0 < \frac{\alpha}{1 + \alpha} < 1 \).

**Definition:** For a scalar \( x_t \), let \( L^2 \) be the space of sequences \( \{x_t\}_{t=0}^{\infty} \) satisfying

\[ \sum_{t=0}^{\infty} x_t^2 < +\infty \]

We say that a sequence that belongs to \( L^2 \) is **square summable**.

When we assume that the sequence \( \tilde{\mu} = \{\mu_t\}_{t=0}^{\infty} \) is square summable and we require that the sequence \( \tilde{\theta} = \{\theta_t\}_{t=0}^{\infty} \) is square summable, the linear difference equation (2) can be solved forward to get:

\[ \theta_t = \frac{1}{1 + \alpha} \sum_{j=0}^{\infty} \left( \frac{\alpha}{1 + \alpha} \right)^j \mu_{t+j} \]

(3)

**Insight:** In the spirit of Chang [14], note that equations (1) and (3) show that \( \theta_t \) intermediates how choices of \( \mu_{t+j} \), \( j = 0, 1, ... \) impinge on time \( t \) real balances \( m_t - p_t = -\alpha \theta_t \).

We shall use this insight to help us simplify and analyze government policy problems.

That future rates of money creation influence earlier rates of inflation creates optimal government policy problems in which timing protocols matter.

We can rewrite the model as:

\[
\begin{bmatrix}
1 \\
\theta_{t+1}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
0 & \frac{1 + \alpha}{\alpha}
\end{bmatrix}
\begin{bmatrix}
1 \\
\theta_t
\end{bmatrix} +
\begin{bmatrix}
0 \\
-\frac{1}{\alpha}
\end{bmatrix} \mu_t
\]

or

\[ x_{t+1} = Ax_t + B\mu_t \]

(4)

We write the model in the state-space form (4) even though \( \theta_0 \) is to be determined and so is not an initial condition as it ordinarily would be in the state-space model described in Linear Quadratic Control.

We write the model in the form (4) because we want to apply an approach described in Stackelberg problems.

Assume that a representative household’s utility of real balances at time \( t \) is:

\[ U(m_t - p_t) = a_0 + a_1(m_t - p_t) - \frac{a_2}{2}(m_t - p_t)^2, \quad a_0 > 0, a_1 > 0, a_2 > 0 \]

(5)

The “bliss level” of real balances is then \( \frac{a_1}{a_2} \).
The money demand function (1) and the utility function (5) imply that utility maximizing or bliss level of real balances is attained when:

\[ \theta_t = \theta^* = -\frac{a_1}{a_2 \alpha} \]

Below, we introduce the discount factor \( \beta \in (0, 1) \) that a representative household and a benevolent government both use to discount future utilities.

(If we set parameters so that \( \theta^* = \log(\beta) \), then we can regard a recommendation to set \( \theta_t = \theta^* \) as a “poor man’s Friedman rule” that attains Milton Friedman’s optimal quantity of money)

Via equation (3), a government plan \( \vec{\mu} = \{\mu_t\}_{t=0}^{\infty} \) leads to an equilibrium sequence of inflation outcomes \( \vec{\theta} = \{\theta_t\}_{t=0}^{\infty} \).

We assume that social costs \( c_2 \mu_t^2 \) are incurred at \( t \) when the government changes the stock of nominal money balances at rate \( \mu_t \).

Therefore, the one-period welfare function of a benevolent government is:

\[ -s(\theta_t, \mu_t) = -r(x_t, \mu_t) = \begin{bmatrix} 1 \\ \theta_t \end{bmatrix}^T \begin{bmatrix} a_0 & -\frac{a_1 \alpha}{2} \\ -\frac{a_1 \alpha}{2} & -\frac{a_2 \alpha^2}{2} \end{bmatrix} \begin{bmatrix} 1 \\ \theta_t \end{bmatrix} - \frac{c}{2} \mu_t^2 = -x_t'R x_t - Q \mu_t^2 \] (6)

Household welfare is summarized by:

\[ v_0 = -\sum_{t=0}^{\infty} \beta^t r(x_t, \mu_t) = -\sum_{t=0}^{\infty} \beta^t s(\theta_t, \mu_t) \] (7)

We can represent the dependence of \( v_0 \) on \( (\vec{\theta}, \vec{\mu}) \) recursively via the linear difference equation

\[ v_t = -s(\theta_t, \mu_t) + \beta v_{t+1} \] (8)

### 37.4 Structure

The following structure is induced by private agents’ behavior as summarized by the demand function for money (1) that leads to equation (3) that tells how future settings of \( \mu \) affect the current value of \( \theta \).

Equation (3) maps a policy sequence of money growth rates \( \vec{\mu} = \{\mu_t\}_{t=0}^{\infty} \in L^2 \) into an inflation sequence \( \vec{\theta} = \{\theta_t\}_{t=0}^{\infty} \in L^2 \).

These, in turn, induce a discounted value to a government sequence \( \vec{v} = \{v_t\}_{t=0}^{\infty} \in L^2 \) that satisfies the recursion

\[ v_t = -s(\theta_t, \mu_t) + \beta v_{t+1} \]

where we have called \( s(\theta_t, \mu_t) = r(x_t, \mu_t) \) as above.

Thus, we have a triple of sequences \( \vec{\mu}, \vec{\theta}, \vec{v} \) associated with a \( \vec{\mu} \in L^2 \).

At this point \( \vec{\mu} \in L^2 \) is an arbitrary exogenous policy.
To make $\bar{\mu}$ endogenous, we require a theory of government decisions.

37.5 Intertemporal Influences

Criterion function (7) and the constraint system (4) exhibit the following structure:

- Setting $\mu_t \neq 0$ imposes costs $\frac{1}{2} \mu_t^2$ at time $t$ and at no other times; but
- The money growth rate $\mu_t$ affects the representative household’s one-period utilities at all dates $s = 0, 1, \ldots, t$.

That settings of $\mu$ at one date affect household utilities at earlier dates sets the stage for the emergence of a time-inconsistent optimal government plan under a Ramsey (also called a Stackelberg) timing protocol.

We’ll study outcomes under a Ramsey timing protocol below.

But we’ll also study the consequences of other timing protocols.

37.6 Four Models of Government Policy

We consider four models of policymakers that differ in

- what a policymaker is allowed to choose, either a sequence $\bar{\mu}$ or just a single period $\mu_t$.
- when a policymaker chooses, either at time 0 or at times $t \geq 0$.
- what a policymaker assumes about how its choice of $\mu_t$ affects private agents’ expectations about earlier and later inflation rates.

In two of our models, a single policymaker chooses a sequence $\{\mu_t\}_{t=0}^{\infty}$ once and for all, taking into account how $\mu_t$ affects household one-period utilities at dates $s = 0, 1, \ldots, t - 1$

- these two models thus employ a Ramsey or Stackelberg timing protocol.

In two other models, there is a sequence of policymakers, each of whom sets $\mu_t$ at one $t$ only

- Each such policymaker ignores effects that its choice of $\mu_t$ has on household one-period utilities at dates $s = 0, 1, \ldots, t - 1$.

The four models differ with respect to timing protocols, constraints on government choices, and government policymakers’ beliefs about how their decisions affect private agents’ beliefs about future government decisions.

The models are

- A single Ramsey planner chooses a sequence $\{\mu_t\}_{t=0}^{\infty}$ once and for all at time 0.
- A single Ramsey planner chooses a sequence $\{\mu_t\}_{t=0}^{\infty}$ once and for all at time 0 subject to the constraint that $\mu_t = \mu$ for all $t \geq 0$.
- A sequence of separate policymakers chooses $\mu_t$ for $t = 0, 1, 2, \ldots$
  - a time $t$ policymaker chooses $\mu_t$ only and forecasts that future government decisions are unaffected by its choice.
- A sequence of separate policymakers chooses $\mu_t$ for $t = 0, 1, 2, \ldots$
  - a time $t$ policymaker chooses only $\mu_t$ but believes that its choice of $\mu_t$ shapes private agents’ beliefs about future rates of money creation and inflation, and through them, future government actions.
37.7 A Ramsey Planner

First, we consider a Ramsey planner that chooses $\{\mu_t, \theta_t\}_{t=0}^{\infty}$ to maximize (7) subject to the law of motion (4).

We can split this problem into two stages, as in Stackelberg problems and [43] Chapter 19. In the first stage, we take the initial inflation rate $\theta_0$ as given, and then solve the resulting LQ dynamic programming problem.

In the second stage, we maximize over the initial inflation rate $\theta_0$.

Define a feasible set of $(\bar{x}_1, \bar{\mu}_0)$ sequences:

$$\Omega(x_0) = \{(\bar{x}_1, \bar{\mu}_0) : x_{t+1} = Ax_t + B\mu_t, \forall t \geq 0\}$$

37.7.1 Subproblem 1

The value function

$$J(x_0) = \max_{(\bar{x}_1, \bar{\mu}_0) \in \Omega(x_0)} - \sum_{t=0}^{\infty} \beta^t r(x_t, \mu_t)$$

satisfies the Bellman equation

$$J(x) = \max_{\mu, x'} \{-r(x, \mu) + \beta J(x')\}$$

subject to:

$$x' = Ax + B\mu$$

As in Stackelberg problems, we map this problem into a linear-quadratic control problem and then carefully use the optimal value function associated with it.

Guessing that $J(x) = -x'Px$ and substituting into the Bellman equation gives rise to the algebraic matrix Riccati equation:

$$P = R + \beta A'PA - \beta^2 A'PB(Q + \beta B'PB)^{-1}B'PA$$

and the optimal decision rule

$$\mu_t = -Fx_t$$

where

$$F = \beta(Q + \beta B'PB)^{-1}B'PA$$

The QuantEcon LQ class solves for $F$ and $P$ given inputs $Q, R, A, B,$ and $\beta$. 

37.7.2 Subproblem 2

The value of the Ramsey problem is

\[ V = \max_{x_0} J(x_0) \]

The value function

\[ J(x_0) = -[1 \theta_0] \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} [1 \theta_0] = -P_{11} - 2P_{21} \theta_0 - P_{22} \theta_0^2 \]

Maximizing this with respect to \( \theta_0 \) yields the FOC:

\[ -2P_{21} - 2P_{22} \theta_0 = 0 \]

which implies

\[ \theta_0^* = -\frac{P_{21}}{P_{22}} \]

37.7.3 Representation of Ramsey Plan

The preceding calculations indicate that we can represent a Ramsey plan \( \bar{\mu} \) recursively with the following system created in the spirit of Chang [14]:

\[ \begin{align*}
\theta_0 &= \theta_0^* \\
\mu_t &= b_0 + b_1 \theta_t \\
\theta_{t+1} &= d_0 + d_1 \theta_t
\end{align*} \tag{9} \]

To interpret this system, think of the sequence \( \{\theta_t\}_{t=0}^{\infty} \) as a sequence of synthetic promised inflation rates that are just computational devices for generating a sequence \( \bar{\mu} \) of money growth rates that are to be substituted into equation (3) to form actual rates of inflation.

It can be verified that if we substitute a plan \( \bar{\mu} = \{\mu_t\}_{t=0}^{\infty} \) that satisfies these equations into equation (3), we obtain the same sequence \( \bar{\theta} \) generated by the system (9).

(Here an application of the Big \( K \), little \( k \) trick could once again be enlightening)

Thus, our construction of a Ramsey plan guarantees that promised inflation equals actual inflation.

Multiple roles of \( \theta_t \)

The inflation rate \( \theta_t \) that appears in the system (9) and equation (3) plays three roles simultaneously:

- In equation (3), \( \theta_t \) is the actual rate of inflation between \( t \) and \( t + 1 \).
- In equation (2) and (3), \( \theta_t \) is also the public’s expected rate of inflation between \( t \) and \( t + 1 \).
- In system (9), \( \theta_t \) is a promised rate of inflation chosen by the Ramsey planner at time 0.
37.7.4 Time Inconsistency

As discussed in Stackelberg problems and Optimal taxation with state-contingent debt, a continuation Ramsey plan is not a Ramsey plan.

This is a concise way of characterizing the time inconsistency of a Ramsey plan. The time inconsistency of a Ramsey plan has motivated other models of government decision making that alter either

- the timing protocol and/or
- assumptions about how government decision makers think their decisions affect private agents’ beliefs about future government decisions

37.8 A Constrained-to-a-Constant-Growth-Rate Ramsey Government

We now consider the following peculiar model of optimal government behavior.

We have created this model in order to highlight an aspect of an optimal government policy associated with its time inconsistency, namely, the feature that optimal settings of the policy instrument vary over time.

Instead of allowing the Ramsey government to choose different settings of its instrument at different moments, we now assume that at time $0$, a Ramsey government at time $0$ once and for all chooses a constant sequence $\mu_t = \bar{\mu}$ for all $t \geq 0$ to maximize

$$U(-\alpha \bar{\mu}) - \frac{c}{2} \bar{\mu}^2$$

Here we have imposed the perfect foresight outcome implied by equation (2) that $\theta_t = \bar{\mu}$ when the government chooses a constant $\mu$ for all $t \geq 0$.

With the quadratic form (5) for the utility function $U$, the maximizing $\bar{\mu}$ is

$$\bar{\mu} = -\frac{\alpha a_1}{\alpha^2 a_2 + c}$$

**Summary:** We have introduced the constrained-to-a-constant $\mu$ government in order to highlight time-variation of $\mu_t$ as a telltale sign of time inconsistency of a Ramsey plan.

37.9 Markov Perfect Governments

We now change the timing protocol by considering a sequence of government policymakers, the time $t$ representative of which chooses $\mu_t$ and expects all future governments to set $\mu_{t+j} = \bar{\mu}$.

This assumption mirrors an assumption made in a different setting Markov Perfect Equilibrium.

Further, a government policymaker at $t$ believes that $\bar{\mu}$ is unaffected by its choice of $\mu_t$. The time $t$ rate of inflation is then:
\[ \theta_t = \frac{\alpha}{1 + \alpha} \bar{\mu} + \frac{1}{1 + \alpha} \mu_t \]

The time \( t \) government policymaker then chooses \( \mu_t \) to maximize:

\[ W = U(-\alpha \theta_t) - \frac{c}{2} \mu_t^2 + \beta V(\bar{\mu}) \]

where \( V(\bar{\mu}) \) is the time 0 value \( v_0 \) of recursion (8) under a money supply growth rate that is forever constant at \( \bar{\mu} \).

Substituting for \( U \) and \( \theta_t \) gives:

\[ W = a_0 + a_1(-\frac{\alpha^2}{1 + \alpha} \bar{\mu} - \frac{\alpha}{1 + \alpha} \mu_t) - \frac{a_2}{2}((-\frac{\alpha^2}{1 + \alpha} \bar{\mu} - \frac{\alpha}{1 + \alpha} \mu_t)^2 - \frac{c}{2} \mu_t^2 + \beta V(\bar{\mu}) \]

The first-order necessary condition for \( \mu_t \) is then:

\[ -\frac{\alpha}{1 + \alpha} a_1 - a_2(-\frac{\alpha^2}{1 + \alpha} \bar{\mu} - \frac{\alpha}{1 + \alpha} \mu_t)(-\frac{\alpha}{1 + \alpha} - c) = 0 \]

Rearranging we get:

\[ \mu_t = \frac{-a_1}{1 + \alpha} - \frac{\alpha^2 a_2}{1 + \alpha} c + \frac{\alpha}{1 + \alpha} a_2 \]

A Markov Perfect Equilibrium (MPE) outcome sets \( \mu_t = \bar{\mu} \):

\[ \mu_t = \bar{\mu} = \frac{-a_1}{1 + \alpha} - \frac{\alpha^2 a_2}{1 + \alpha} c + \frac{\alpha}{1 + \alpha} a_2 \]

In light of results presented in the previous section, this can be simplified to:

\[ \bar{\mu} = -\frac{\alpha a_1}{\alpha^2 a_2 + (1 + \alpha) c} \]

### 37.10 Equilibrium Outcomes for Three Models of Government Policy Making

Below we compute sequences \( \{\theta_t, \mu_t\} \) under a Ramsey plan and compare these with the constant levels of \( \theta \) and \( \mu \) in a) a Markov Perfect Equilibrium, and b) a Ramsey plan in which the planner is restricted to choose \( \mu_t = \bar{\mu} \) for all \( t \geq 0 \).

We denote the Ramsey sequence as \( \theta^R, \mu^R \) and the MPE values as \( \theta^{MPE}, \mu^{MPE} \).

The bliss level of inflation is denoted by \( \theta^* \).

First, we will create a class ChangLQ that solves the models and stores their values.
def __init__(self, α, α₀, α₁, α₂, c, T=1000, θ_n=200):
    # Record parameters
    self.α, self.α₀, self.α₁ = α, α₀, α₁
    self.α₂, self.c, self.T, self.θ_n = α₂, c, T, θ_n
    # Create β using "Poor Man's Friedman Rule"
    self.β = np.exp(-α₁ / (α * α₂))
    # Solve the Ramsey Problem #
    # LQ Matrices
    R = -np.array([[α₀, -α₁ * α + 2],
                   [-α₁ * α / 2, -α₂ * α**2 / 2]])
    Q = -np.array([[-c / 2]])
    A = np.array([[1, θ], [θ, (1 + α) / α]])
    B = np.array([[0], [-1 / α]])
    # Solve LQ Problem (Subproblem 1)
    lq = LQ(Q, R, A, B, beta=self.β)
    self.P, self.F, self.d = lq.stationary_values()
    # Solve Subproblem 2
    self.θ_R = -self.P[0, 1] / self.P[1, 1]
    # Find bliss level of θ
    self.θ_B = np.log(self.β)
    # Solve the Markov Perfect Equilibrium
    self.μ_MPE = -α₁ / ((1 + α) / α * c + α / (1 + α)
                     + α₂ + α**2 / (1 + α) * α₂)
    self.μ_MPE = self.μ_MPE
    self.μ_check = -α * α₁ / (α₂ * α**2 + c)
    # Calculate value under MPE and Check economy
    self.J_MPE = (α₀ + α₁ * (-α * self.μ_MPE) - α₂ / 2
                  + α * self.μ_MPE)**2 - c / 2 * self.μ_MPE**2) / (1 - self.β)
    self.J_check = (α₀ + α₁ * (-α * self.μ_check) - α₂/2
                    + α * self.μ_check)**2 - c / 2 * self.μ_check**2) \n                    / (1 - self.β)
    # Simulate Ramsey plan for large number of periods
    θ_series = np.vstack((np.ones((1, T)), np.zeros((1, T))))
    μ_series = np.zeros(T)
    J_series = np.zeros(T)
    θ_series[1, 0] = self.θ_R
    μ_series[0] = -self.F.dot(θ_series[:, 0])
    J_series[0] = -θ_series[0, 0] @ self.P @ θ_series[:, 0].T
    for i in range(1, T):
        θ_series[:, i] = (A - B @ self.F) @ θ_series[:, i-1]
        μ_series[i] = -self.F @ θ_series[:, i]
        J_series[i] = -θ_series[:, i] @ self.P @ θ_series[:, i].T
    self.J_series = J_series
    self.μ_series = μ_series
    self.θ_series = θ_series
# Find the range of $\theta$ in Ramsey plan

\[ \theta_{LB} = \min(\theta_{series}[:,]) \]
\[ \theta_{LB} = \min(\theta_{LB}, \text{self.}\theta_{B}) \]
\[ \theta_{UB} = \max(\theta_{series}[:,]) \]
\[ \theta_{UB} = \max(\theta_{UB}, \text{self.}\theta_{MPE}) \]
\[ \theta_{range} = \theta_{UB} - \theta_{LB} \]
\[
\text{self.}\theta_{LB} = \theta_{LB} - 0.05 \times \theta_{range} \\
\text{self.}\theta_{UB} = \theta_{UB} + 0.05 \times \theta_{range} \\
\text{self.}\theta_{range} = \theta_{range}
\]

# Find value function and policy functions over range of $\theta$

\[ \theta_{space} = \text{np.linspace(} \text{self.}\theta_{LB}, \text{self.}\theta_{UB}, 200) \]
\[ J_{space} = \text{np.zeros(}200) \]
\[ \text{check_space} = \text{np.zeros(}200) \]
\[ \mu_{space} = \text{np.zeros(}200) \]
\[ \theta_{prime} = \text{np.zeros(}200) \]

for \( i \) in range(200):

\[ J_{space}[i] = -\text{np.array}((1, \theta_{space}[i])) \backslash \theta \text{self.}P \backslash \text{np.array}((1, \theta_{space}[i])).T \]
\[ \mu_{space}[i] = -\text{self.}F \backslash \text{np.array}((1, \theta_{space}[i])) \]
\[ x_{prime}[i] = (A - B @ \text{self.}F) \backslash \text{np.array}((1, \theta_{space}[i])) \]
\[ \theta_{prime}[i] = x_{prime}[i] \]
\[ \text{check_space}[i] = (\alpha_0 + \alpha_1 \times (\alpha \times \theta_{space}[i]) - \alpha 2/2 \times (\alpha \times \theta_{space}[i])**2 - c/2 \times \theta_{space}[i]**2) / (1 - \text{self.}\beta) \]

\[ J_{LB} = \min(J_{space}) \]
\[ J_{UB} = \max(J_{space}) \]
\[ J_{range} = J_{UB} - J_{LB} \]
\[ \text{self.}J_{LB} = J_{LB} - 0.05 \times J_{range} \]
\[ \text{self.}J_{UB} = J_{UB} + 0.05 \times J_{range} \]
\[ \text{self.}J_{range} = J_{range} \]
\[ \text{self.}J_{space} = J_{space} \]
\[ \text{self.}\theta_{space} = \theta_{space} \]
\[ \text{self.}\mu_{space} = \mu_{space} \]
\[ \text{self.}\theta_{prime} = \theta_{prime} \]
\[ \text{self.}\check_{space} = \check_{space} \]

We will create an instance of ChangLQ with the following parameters

In [4]: clq = ChangLQ(\(a=1, \alpha 0=1, \alpha 1=0.5, \alpha 2=3, c=2\))

\[ \text{clq.}\beta \]

Out[4]: 0.8464817248906141

The following code generates a figure that plots the value function from the Ramsey Planner’s problem, which is maximized at $\theta_{R0}$.

The figure also shows the limiting value $\theta_{R}^R$ to which the inflation rate $\theta_{t}$ converges under the Ramsey plan and compares it to the MPE value and the bliss value.

In [5]: def plot_value_function(clq):

    "Method to plot the value function over the relevant range of $\theta$"

    Here clq is an instance of ChangLQ
The next code generates a figure that plots the value function from the Ramsey Planner's
problem as well as that for a Ramsey planner that must choose a constant \( \mu \) (that in turn equals an implied constant \( \theta \)).

In [6]:

```python
def compare_ramsey_check(clq):
    
    """
    Method to compare values of Ramsey and Check
    
    Here clq is an instance of ChangLQ
    """
    fig, ax = plt.subplots()
    check_min = min(clq.check_space)
    check_max = max(clq.check_space)
    check_range = check_max - check_min
    check_LB = check_min - 0.05 * check_range
    check_UB = check_max + 0.05 * check_range
    ax.set_xlim([clq.\theta_LB, clq.\theta_UB])
    ax.set_ylim([check_LB, check_UB])
    ax.plot(clq.\theta_space, clq.J_space, lw=2, label=r"$J(\theta)$")
    plt.xlabel(r"$\theta$", fontsize=18)
    ax.plot(clq.\theta_space, clq.check_space, lw=2, label=r"$V^{\check{}}(\theta)$")
    plt.legend(fontsize=14, loc='upper left')
    \theta_points = [clq.\theta_space[np.argmax(clq.J_space)],
                    clq.\mu_check]
    labels = [r"$\theta^R$", r"$\theta^\check{}$"]
    for \theta, label in zip(\theta_points, labels):
        ax.scatter(\theta, check_LB + 0.02 * check_range, 60, 'k', 'v')
        ax.annotate(label,
                   xy=(\theta, check_LB + 0.01 * check_range),
                   xytext=(\theta - 0.02 * check_range,
                           check_LB + 0.08 * check_range),
                   fontsize=18)
    plt.tight_layout()
    plt.show()

compare_ramsey_check(clq)
```
The next code generates figures that plot the policy functions for a continuation Ramsey planner.

The left figure shows the choice of $\theta'$ chosen by a continuation Ramsey planner who inherits $\theta$.

The right figure plots a continuation Ramsey planner's choice of $\mu$ as a function of an inherited $\theta$.

\[\text{In [7]: def plot-policy-functions(clq):}\]
\[
\text{Method to plot the policy functions over the relevant range of } \theta
\]
\[
\text{Here clq is an instance of ChangLQ}
\]
\[
\text{fig, axes = plt.subplots(1, 2, figsize=(12, 4))}
\]
\[
\text{labels} = [r"$\theta_0^R$", r"$\theta_{\infty}^R$"]
\]
\[
ax = axes[0]
ax.set_ylim([clq.\theta_LB, clq.\theta_UB])
ax.plot(clq.\theta_space, clq.\theta_prime,
        label=r"$\theta'(\theta)$", lw=2)
ax.plot(x, x, 'k--', lw=2, alpha=\theta) 
ax.set_ylabel(r"$\theta'$", fontsize=18)
\]
\[
\theta_points = [clq.\theta_space[np.argmax(clq.J_space)],
                clq.\theta_series[1, -1]]
\]
\[
\text{for } \theta, \text{ label in zip(\theta_points, labels):}
        ax.scatter(\theta, clq.\theta_LB + 0.02 * clq.\theta_range, 60, 'k', 'v')
        ax.annotate(label,
}
The following code generates a figure that plots sequences of $\mu$ and $\theta$ in the Ramsey plan and compares these to the constant levels in a MPE and in a Ramsey plan with a government restricted to set $\mu_t$ to a constant for all $t$.

In [8]:

```python
def plot_ramsey_MPE(clq, T=15):
    
    Method to plot Ramsey plan against Markov Perfect Equilibrium
    
    Here clq is an instance of ChangLQ
    
    fig, axes = plt.subplots(1, 2, figsize=(12, 4))
    
    plots = [clq.\theta_series[1, 0:T], clq.\mu_series[0:T]]
    MPEs = [clq.\theta_MPE, clq.\mu_MPE]
    labels = [r"\theta", r"\mu"]
```
37.10.1 Time Inconsistency of Ramsey Plan

The variation over time in $\tilde{\mu}_t$ chosen by the Ramsey planner is a symptom of time inconsistency.

- The Ramsey planner reaps immediate benefits from promising lower inflation later to be achieved by costly distorting taxes.
- These benefits are intermediated by reductions in expected inflation that precede the reductions in money creation rates that rationalize them, as indicated by equation (3).
- A government authority offered the opportunity to ignore effects on past utilities and to reoptimize at date $t \geq 1$ would, if allowed, want to deviate from a Ramsey plan.

**Note:** A modified Ramsey plan constructed under the restriction that $\mu_t$ must be constant over time is time consistent (see $\tilde{\mu}$ and $\tilde{\theta}$ in the above graphs).

37.10.2 Meaning of Time Inconsistency

In settings in which governments actually choose sequentially, many economists regard a time inconsistent plan implausible because of the incentives to deviate that occur along the plan.

A way to summarize this defect in a Ramsey plan is to say that it is not credible because there endure incentives for policymakers to deviate from it.

For that reason, the Markov perfect equilibrium concept attracts many economists.
37.11. A FOURTH MODEL OF GOVERNMENT DECISION MAKING

- A Markov perfect equilibrium plan is constructed to insure that government policymakers who choose sequentially do not want to deviate from it. The *no incentive to deviate from the plan* property is what makes the Markov perfect equilibrium concept attractive.

37.10.3 Ramsey Plans Strike Back

Research by Abreu [1], Chari and Kehoe [15] [62], and Stokey [63] discovered conditions under which a Ramsey plan can be rescued from the complaint that it is not credible. They accomplished this by expanding the description of a plan to include expectations about adverse consequences of deviating from it that can serve to deter deviations.

We turn to such theories of sustainable plans next.

37.11 A Fourth Model of Government Decision Making

This is a model in which

- The government chooses \( \{\mu_t\}_{t=0}^\infty \) not once and for all at \( t = 0 \) but chooses to set \( \mu_t \) at time \( t \), not before.
- private agents’ forecasts of \( \{\mu_{t+j+1}, \theta_{t+j+1}\}_{j=0}^\infty \) respond to whether the government at \( t \) confirms or disappoints their forecasts of \( \mu_t \) brought into period \( t \) from period \( t - 1 \).
- the government at each time \( t \) understands how private agents’ forecasts will respond to its choice of \( \mu_t \).
- at each \( t \), the government chooses \( \mu_t \) to maximize a continuation discounted utility of a representative household.

37.11.1 A Theory of Government Decision Making

\( \tilde{\mu} \) is chosen by a sequence of government decision makers, one for each \( t \geq 0 \).

We assume the following within-period and between-period timing protocol for each \( t \geq 0 \):

- at time \( t - 1 \), private agents expect that the government will set \( \mu_t = \tilde{\mu}_t \), and more generally that it will set \( \mu_{t+j} = \tilde{\mu}_{t+j} \) for all \( j \geq 0 \).
- The forecasts \( \{\tilde{\mu}_{t+j}\}_{j=0}^\infty \) determine a \( \theta_t = \tilde{\theta}_t \) and an associated log of real balances \( m_t - p_t = -\alpha \tilde{\theta}_t \) at \( t \).
- Given those expectations and an associated \( \theta_t = \tilde{\theta}_t \), at \( t \) a government is free to set \( \mu_t \in \mathbb{R} \).
- If the government at \( t \) confirms private agents’ expectations by setting \( \mu_t = \tilde{\mu}_t \) at time \( t \), private agents expect the continuation government policy \( \{\tilde{\mu}_{t+j+1}\}_{j=0}^\infty \) and therefore bring expectation \( \tilde{\theta}_{t+1} \) into period \( t + 1 \).
- If the government at \( t \) disappoints private agents by setting \( \mu_t \neq \tilde{\mu}_t \), private agents expect \( \{\mu^A_j\}_{j=0}^\infty \) as the continuation policy for \( t + 1 \), i.e., \( \{\mu_{t+j+1}\} = \{\mu^A_j\}_{j=0}^\infty \) and therefore expect an associated \( \theta^A_0 \) for \( t + 1 \). Here \( \tilde{\mu}^A = \{\mu^A_j\}_{j=0}^\infty \) is an alternative government plan to be described below.
37.11.2 Temptation to Deviate from Plan

The government’s one-period return function \( s(\theta, \mu) \) described in equation (6) above has the property that for all \( \theta \)

\[-s(\theta, 0) \geq -s(\theta, \mu)\]

This inequality implies that whenever the policy calls for the government to set \( \mu \neq 0 \), the government could raise its one-period payoff by setting \( \mu = 0 \).

Disappointing private sector expectations in that way would increase the government’s current payoff but would have adverse consequences for subsequent government payoffs because the private sector would alter its expectations about future settings of \( \mu \).

The temporary gain constitutes the government’s temptation to deviate from a plan.

If the government at \( t \) is to resist the temptation to raise its current payoff, it is only because it forecasts adverse consequences that its setting of \( \mu_t \) would bring for continuation government payoffs via alterations in the private sector’s expectations.

37.12 Sustainable or Credible Plan

We call a plan \( \tilde{\mu} \) sustainable or credible if at each \( t \geq 0 \) the government chooses to confirm private agents’ prior expectation of its setting for \( \mu_t \).

The government will choose to confirm prior expectations only if the long-term loss from disappointing private sector expectations – coming from the government’s understanding of the way the private sector adjusts its expectations in response to having its prior expectations at \( t \) disappointed – outweigh the short-term gain from disappointing those expectations.

The theory of sustainable or credible plans assumes throughout that private sector expectations about what future governments will do are based on the assumption that governments at times \( t \geq 0 \) always act to maximize the continuation discounted utilities that describe those governments’ purposes.

This aspect of the theory means that credible plans always come in pairs:

- a credible (continuation) plan to be followed if the government at \( t \) confirms private sector expectations
- a credible plan to be followed if the government at \( t \) disappoints private sector expectations

That credible plans come in pairs threaten to bring an explosion of plans to keep track of

- each credible plan itself consists of two credible plans
- therefore, the number of plans underlying one plan is unbounded

But Dilip Abreu showed how to render manageable the number of plans that must be kept track of.

The key is an object called a self-enforcing plan.

37.12.1 Abreu’s Self-Enforcing Plan

A plan \( \tilde{\mu}^A \) (here the superscript \( A \) is for Abreu) is said to be self-enforcing if
• the consequence of disappointing private agents’ expectations at time $j$ is to restart plan $\mu^A$ at time $j + 1$
• the consequence of restarting the plan is sufficiently adverse that it forever deters all deviations from the plan

More precisely, a government plan $\bar{\mu}^A$ with equilibrium inflation sequence $\bar{\theta}^A$ is self-enforcing if

$$v^A_j = -s(\theta^A_j, \mu^A_j) + \beta v^A_{j+1} \geq -s(\theta^A_j, 0) + \beta v^A_0 \equiv v^{A,D}_j, \quad j \geq 0 \quad (10)$$

(Here it is useful to recall that setting $\mu = 0$ is the maximizing choice for the government’s one-period return function)

The first line tells the consequences of confirming private agents’ expectations by following the plan, while the second line tells the consequences of disappointing private agents’ expectations by deviating from the plan.

A consequence of the inequality stated in the definition is that a self-enforcing plan is credible.

Self-enforcing plans can be used to construct other credible plans, including ones with better values.

Thus, where $\bar{v}^A$ is the value associated with a self-enforcing plan $\bar{\mu}^A$, a sufficient condition for another plan $\bar{\mu}$ associated with inflation $\bar{\theta}$ and value $\bar{v}$ to be credible is that

$$v_j = -s(\theta_j, \mu_j) + \beta v_{j+1} \geq -s(\theta_j, 0) + \beta v^A_0 \quad \forall j \geq 0 \quad (11)$$

For this condition to be satisfied it is necessary and sufficient that

$$-s(\theta_j, 0) - (-s(\theta_j, \mu_j)) < \beta(v_{j+1} - v^A_0)$$

The left side of the above inequality is the government’s gain from deviating from the plan, while the right side is the government’s loss from deviating from the plan.

A government never wants to deviate from a credible plan.

Abreu taught us that key step in constructing a credible plan is first constructing a self-enforcing plan that has a low time 0 value.

The idea is to use the self-enforcing plan as a continuation plan whenever the government’s choice at time $t$ fails to confirm private agents’ expectation.

We shall use a construction featured in Abreu ([1]) to construct a self-enforcing plan with low time 0 value.

### 37.12.2 Abreu Carrot-Stick Plan

Abreu ([1]) invented a way to create a self-enforcing plan with a low initial value.

Imitating his idea, we can construct a self-enforcing plan $\bar{\mu}$ with a low time 0 value to the government by insisting that future government decision makers set $\mu_t$ to a value yielding
low one-period utilities to the household for a long time, after which government decisions
thereafter yield high one-period utilities.

- Low one-period utilities early are a **stick**
- High one-period utilities later are a **carrot**

Consider a candidate plan $\bar{\mu}^A$ that sets $\mu^A_t = \bar{\mu}$ (a high positive number) for $T_A$ periods, and then reverts to the Ramsey plan.

Denote this sequence by $\{\mu^A_t\}_{t=0}^\infty$.

The sequence of inflation rates implied by this plan, $\{\theta^A_t\}_{t=0}^\infty$, can be calculated using:

$$\theta^A_t = \frac{1}{1+\alpha} \sum_{j=0}^\infty \left( \frac{\alpha}{1+\alpha} \right)^j \mu^A_{t+j}$$

The value of $\{\theta^A_t, \mu^A_t\}_{t=0}^\infty$ at time 0 is

$$v^A_0 = -\sum_{t=0}^{T_A-1} \beta^t s(\theta^A_t, \mu^A_t) + \beta^{T_A} J(\theta^R_0)$$

For an appropriate $T_A$, this plan can be verified to be self-enforcing and therefore credible.

### 37.12.3 Example of Self-Enforcing Plan

The following example implements an Abreu stick-and-carrot plan.

The government sets $\mu^A_t = 0.1$ for $t = 0, 1, \ldots, 9$ and then starts the Ramsey plan.

We have computed outcomes for this plan.

For this plan, we plot the $\theta^A, \mu^A$ sequences as well as the implied $v^A$ sequence.

Notice that because the government sets money supply growth high for 10 periods, inflation starts high.

Inflation gradually slowly declines because people expect the government to lower the money growth rate after period 10.

From the 10th period onwards, the inflation rate $\theta^A_t$ associated with this Abreu plan starts the Ramsey plan from its beginning, i.e., $\theta^A_{t+10} = \theta^R_t \ \forall t \geq 0$.

In [9]: def abreu_plan(clq, T=1000, T_A=10, μ_bar=0.1, T_Plot=20):

    # Append Ramsey \( \mu \) series to stick \( \mu \) series
    clq.μ_A = np.append(np.ones(T_A) * μ_bar, clq.μ_series[:T_A])

    # Calculate implied stick \( \theta \) series
    clq.θ_A = np.zeros(T)
    discount = np.zeros(T)
    for t in range(T):
        discount[t] = (clq.α / (1 + clq.α))**t
    for t in range(T):
        length = clq.μ_A[t:].shape[0]
        clq.θ_A[t] = 1 / (clq.α + 1) * sum(clq.μ_A[t:] * discount[0:length])
# Calculate utility of stick plan

\[ U_A = \text{np.zeros}(T) \]

**for** t **in** range(T):

\[ U_A[t] = \text{clq.} \beta^{**t} \times (\text{clq.} \alpha_0 + \text{clq.} \alpha_1 \times (-\text{clq.} \theta_A[t]) \]
\[ - \text{clq.} \alpha_2 / 2 \times (-\text{clq.} \theta_A[t])^{**2} - \text{clq.} c \times \text{clq.} \mu_A[t] \times 2 \]

\[ \text{clq.} V_A = \text{np.zeros}(T) \]

**for** t **in** range(T):

\[ \text{clq.} V_A[t] = \sum(U_A[t:] / \text{clq.} \beta^{**t}) \]

# Make sure Abreu plan is self-enforcing

\[ \text{clq.} V_{dev} = \text{np.zeros}(T_{Plot}) \]

**for** t **in** range(T_{Plot}):

\[ \text{clq.} V_{dev}[t] = (\text{clq.} \alpha_0 + \text{clq.} \alpha_1 \times (-\text{clq.} \theta_A[t]) \]
\[ - \text{clq.} \alpha_2 / 2 \times (-\text{clq.} \theta_A[t])^{**2} \]
\[ + \text{clq.} \beta \times \text{clq.} V_A[0] \]

fig, axes = plt.subplots(3, 1, figsize=(8, 12))

axes[2].plot(clq.V_dev[0:T_{Plot}], label="$V^{A, D}_t$", c="orange")

plots = [clq.\theta_A, clq.\mu_A, clq.V_A]
layers = [r"$\theta_t^{A}$", r"$\mu_t^{A}$", r"$V_t^{A}$"]

**for** plot, ax, label **in** zip(plots, axes, labels):

ax.plot(plot[0:T_{Plot}], label=label)
ax.set(xlabel="$T$", ylabel=label)
ax.legend()

plt.tight_layout()
plt.show()

abreu_plan(clq)
To confirm that the plan $\tilde{\mu}^A$ is self-enforcing, we plot an object that we call $V_{t}^{A,D}$, defined in the key inequality in the second line of equation (10) above.

$V_{t}^{A,D}$ is the value at $t$ of deviating from the self-enforcing plan $\tilde{\mu}^A$ by setting $\mu_t = 0$ and then
restarting the plan at \( v_0^A \) at \( t + 1 \):

\[
v_t^{A,D} = -s(\theta_j, 0) + \beta v_0^A
\]

In the above graph \( v_t^A > v_t^{A,D} \), which confirms that \( \bar{\mu}^A \) is a self-enforcing plan.

We can also verify the inequalities required for \( \bar{\mu}^A \) to be self-confirming numerically as follows

```python
In [10]: np.all(clq.V_A[0:20] > clq.V_dev[0:20])
```

```
Out[10]: True
```

Given that plan \( \bar{\mu}^A \) is self-enforcing, we can check that the Ramsey plan \( \bar{\mu}^R \) is credible by verifying that:

\[
v_t^R \geq -s(\theta_t^R, 0) + \beta v_0^A, \quad \forall t \geq 0
\]

```python
In [11]: def check_ramsey(clq, T=1000):
   # Make sure Ramsey plan is sustainable
   R_dev = np.zeros(T)
   for t in range(T):
       R_dev[t] = (clq.a0 + clq.a1 * (-clq.\theta_series[1, t])
                   - clq.a2 / 2 * (-clq.\theta_series[1, t])**2) \
                   + clq.\beta \* clq.V_A[0]
   return np.all(clq.J_series > R_dev)

check_ramsey(clq)
```

```
Out[11]: True
```

### 37.12.4 Recursive Representation of a Sustainable Plan

We can represent a sustainable plan recursively by taking the continuation value \( v_t \) as a state variable.

We form the following 3-tuple of functions:

\[
\hat{\mu}_t = \nu_\mu(v_t)
\]

\[
\theta_t = \nu_\theta(v_t)
\]

\[
v_{t+1} = \nu_v(v_t, \mu_t)
\]

In addition to these equations, we need an initial value \( v_0 \) to characterize a sustainable plan.

The first equation of (12) tells the recommended value of \( \hat{\mu}_t \) as a function of the promised value \( v_t \).

The second equation of (12) tells the inflation rate as a function of \( v_t \).

The third equation of (12) updates the continuation value in a way that depends on whether the government at \( t \) confirms private agents’ expectations by setting \( \mu_t \) equal to the recommended value \( \hat{\mu}_t \), or whether it disappoints those expectations.
37.13 Whose Credible Plan is it?

A credible government plan \( \tilde{\mu} \) plays multiple roles.

- It is a sequence of actions chosen by the government.
- It is a sequence of private agents’ forecasts of government actions.

Thus, \( \tilde{\mu} \) is both a government policy and a collection of private agents’ forecasts of government policy.

Does the government choose policy actions or does it simply confirm prior private sector forecasts of those actions?

An argument in favor of the government chooses interpretation comes from noting that the theory of credible plans builds in a theory that the government each period chooses the action that it wants.

An argument in favor of the simply confirm interpretation is gathered from staring at the key inequality (11) that defines a credible policy.

37.14 Comparison of Equilibrium Values

We have computed plans for

- an ordinary (unrestricted) Ramsey planner who chooses a sequence \( \{\mu_t\}_{t=0}^{\infty} \) at time 0
- a Ramsey planner restricted to choose a constant \( \mu \) for all \( t \geq 0 \)
- a Markov perfect sequence of governments

Below we compare equilibrium time zero values for these three.

We confirm that the value delivered by the unrestricted Ramsey planner exceeds the value delivered by the restricted Ramsey planner which in turn exceeds the value delivered by the Markov perfect sequence of governments.

In [12]: clq.J_series[0]

Out[12]: 6.67918822960449

In [13]: clq.J_check

Out[13]: 6.676729524674898

In [14]: clq.J_MPE

Out[14]: 6.663435886995107

We have also computed credible plans for a government or sequence of governments that choose sequentially.

These include

- a self-enforcing plan that gives a low initial value \( v_0 \).
- a better plan – possibly one that attains values associated with Ramsey plan – that is not self-enforcing.
37.15 Note on Dynamic Programming Squared

The theory deployed in this lecture is an application of what we nickname dynamic programming squared.

The nickname refers to the fact that a value satisfying one Bellman equation is itself an argument in a second Bellman equation.

Thus, our models have involved two Bellman equations:

- equation (1) expresses how $\theta_t$ depends on $\mu_t$ and $\theta_{t+1}$
- equation (4) expresses how value $v_t$ depends on $(\mu_t, \theta_t)$ and $v_{t+1}$

A value $\theta$ from one Bellman equation appears as an argument of a second Bellman equation for another value $v$. 
Chapter 38

Optimal Taxation with State-Contingent Debt

38.1 Contents

- Overview 38.2
- A Competitive Equilibrium with Distorting Taxes 38.3
- Recursive Formulation of the Ramsey Problem 38.4
- Examples 38.5

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

38.2 Overview

This lecture describes a celebrated model of optimal fiscal policy by Robert E. Lucas, Jr., and Nancy Stokey [45].

The model revisits classic issues about how to pay for a war.

Here a war means a more or less temporary surge in an exogenous government expenditure process.

The model features

- a government that must finance an exogenous stream of government expenditures with either
  - a flat rate tax on labor, or
  - purchases and sales from a full array of Arrow state-contingent securities
- a representative household that values consumption and leisure
- a linear production function mapping labor into a single good
- a Ramsey planner who at time $t = 0$ chooses a plan for taxes and trades of Arrow securities for all $t \geq 0$

After first presenting the model in a space of sequences, we shall represent it recursively in terms of two Bellman equations formulated along lines that we encountered in Dynamic Stackelberg models.
As in Dynamic Stackelberg models, to apply dynamic programming we shall define the state vector artfully.

In particular, we shall include forward-looking variables that summarize optimal responses of private agents to a Ramsey plan.

See Optimal taxation for analysis within a linear-quadratic setting.

Let’s start with some standard imports:

```python
In [2]:
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
```

### 38.3 A Competitive Equilibrium with Distorting Taxes

For \( t \geq 0 \), a history \( s^t = [s_t, s_{t-1}, \ldots, s_0] \) of an exogenous state \( s_t \) has joint probability density \( \pi_t(s^t) \).

We begin by assuming that government purchases \( g_t(s^t) \) at time \( t \geq 0 \) depend on \( s^t \).

Let \( c_t(s^t), \ell_t(s^t), \) and \( n_t(s^t) \) denote consumption, leisure, and labor supply, respectively, at history \( s^t \) and date \( t \).

A representative household is endowed with one unit of time that can be divided between leisure \( \ell_t \) and labor \( n_t \):

\[
\ell_t(s^t) + n_t(s^t) = 1
\]

Output equals \( n_t(s^t) \) and can be divided between \( c_t(s^t) \) and \( g_t(s^t) \)

\[
c_t(s^t) + g_t(s^t) = n_t(s^t)
\]

A representative household’s preferences over \( \{c_t(s^t), \ell_t(s^t)\}_{t=0}^{\infty} \) are ordered by

\[
\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t) u[c_t(s^t), \ell_t(s^t)]
\]

where the utility function \( u \) is increasing, strictly concave, and three times continuously differentiable in both arguments.

The technology pins down a pre-tax wage rate to unity for all \( t, s^t \).

The government imposes a flat-rate tax \( \tau_t(s^t) \) on labor income at time \( t \), history \( s^t \).

There are complete markets in one-period Arrow securities.

One unit of an Arrow security issued at time \( t \) at history \( s^t \) and promising to pay one unit of time \( t+1 \) consumption in state \( s_{t+1} \) costs \( p_{t+1}(s_{t+1}|s^t) \).

The government issues one-period Arrow securities each period.

The government has a sequence of budget constraints whose time \( t \geq 0 \) component is

\[
g_t(s^t) = \tau_t(s^t) n_t(s^t) + \sum_{s_{t+1}} p_{t+1}(s_{t+1}|s^t) b_{t+1}(s_{t+1}|s^t) - b_t(s_t|s^{t-1})
\]
38.3. A COMPETITIVE EQUILIBRIUM WITH DISTORTING TAXES

where

- $p_{t+1}(s_{t+1}|s^t)$ is a competitive equilibrium price of one unit of consumption at date $t + 1$ in state $s_{t+1}$ at date $t$ and history $s^t$.
- $b_t(s_t|s^{t-1})$ is government debt falling due at time $t$, history $s^t$.

Government debt $b_0(s_0)$ is an exogenous initial condition.

The representative household has a sequence of budget constraints whose time $t \geq 0$ component is

$$c_t(s^t) + \sum_{s_{t+1}} p_t(s_{t+1}|s^t) b_{t+1}(s_{t+1}|s^t) = [1 - \tau_t(s^t)] n_t(s^t) + b_t(s_t|s^{t-1}) \quad \forall t \geq 0 \quad (5)$$

A government policy is an exogenous sequence $\{g(s_t)\}_{t=0}^{\infty}$, a tax rate sequence $\{\tau_t(s^t)\}_{t=0}^{\infty}$, and a government debt sequence $\{b_{t+1}(s_{t+1})\}_{t=0}^{\infty}$.

A feasible allocation is a consumption-labor supply plan $\{c_t(s^t), n_t(s^t)\}_{t=0}^{\infty}$ that satisfies (2) at all $t, s^t$.

A price system is a sequence of Arrow security prices $\{p_{t+1}(s_{t+1}|s^t)\}_{t=0}^{\infty}$.

The household faces the price system as a price-taker and takes the government policy as given.

The household chooses $\{c_t(s^t), \ell_t(s^t)\}_{t=0}^{\infty}$ to maximize (3) subject to (5) and (1) for all $t, s^t$.

A competitive equilibrium with distorting taxes is a feasible allocation, a price system, and a government policy such that

- Given the price system and the government policy, the allocation solves the household’s optimization problem.
- Given the allocation, government policy, and price system, the government’s budget constraint is satisfied for all $t, s^t$.

Note: There are many competitive equilibria with distorting taxes.

They are indexed by different government policies.

The Ramsey problem or optimal taxation problem is to choose a competitive equilibrium with distorting taxes that maximizes (3).

38.3.1 Arrow-Debreu Version of Price System

We find it convenient sometimes to work with the Arrow-Debreu price system that is implied by a sequence of Arrow securities prices.

Let $q^0_t(s^t)$ be the price at time 0, measured in time 0 consumption goods, of one unit of consumption at time $t$, history $s^t$.

The following recursion relates Arrow-Debreu prices $\{q^0_t(s^t)\}_{t=0}^{\infty}$ to Arrow securities prices $\{p_{t+1}(s_{t+1}|s^t)\}_{t=0}^{\infty}$

$$q^0_{t+1}(s^{t+1}) = p_{t+1}(s_{t+1}|s^t)q^0_t(s^t) \quad s.t. \quad q^0_0(s^0) = 1 \quad (6)$$

Arrow-Debreu prices are useful when we want to compress a sequence of budget constraints into a single intertemporal budget constraint, as we shall find it convenient to do below.
38.3.2 Primal Approach

We apply a popular approach to solving a Ramsey problem, called the **primal approach**.

The idea is to use first-order conditions for household optimization to eliminate taxes and prices in favor of quantities, then pose an optimization problem cast entirely in terms of quantities.

After Ramsey quantities have been found, taxes and prices can then be unwound from the allocation.

The primal approach uses four steps:

1. Obtain first-order conditions of the household’s problem and solve them for \( \{q_0^t(s^t), \tau_t(s^t)\}_{t=0}^{\infty} \) as functions of the allocation \( \{c_t(s^t), n_t(s^t)\}_{t=0}^{\infty} \).

2. Substitute these expressions for taxes and prices in terms of the allocation into the household’s present-value budget constraint.

   - This intertemporal constraint involves only the allocation and is regarded as an **implementability constraint**.

3. Find the allocation that maximizes the utility of the representative household (3) subject to the feasibility constraints (1) and (2) and the implementability condition derived in step 2.

   - This optimal allocation is called the **Ramsey allocation**.

4. Use the Ramsey allocation together with the formulas from step 1 to find taxes and prices.

38.3.3 The Implementability Constraint

By sequential substitution of one one-period budget constraint (5) into another, we can obtain the household’s present-value budget constraint:

\[
\sum_{t=0}^{\infty} \sum_{s^t} q_0^t(s^t)c_t(s^t) = \sum_{t=0}^{\infty} \sum_{s^t} q_0^t(s^t)[1 - \tau_t(s^t)]n_t(s^t) + b_0
\]  

\( \{q_0^t(s^t)\}_{t=1}^{\infty} \) can be interpreted as a time 0 Arrow-Debreu price system.

To approach the Ramsey problem, we study the household’s optimization problem.

First-order conditions for the household’s problem for \( \ell_t(s^t) \) and \( b_t(s_{t+1}|s^t) \), respectively, imply

\[
(1 - \tau_t(s^t)) = \frac{u_\ell(s^t)}{u_c(s^t)}
\]  

and

\[
p_{t+1}(s_{t+1}|s^t) = \beta \pi(s_{t+1}|s^t) \left( \frac{u_c(s_{t+1})}{u_c(s^t)} \right)
\]
where \( \pi(s_{t+1} | s^t) \) is the probability distribution of \( s_{t+1} \) conditional on history \( s^t \).

Equation (9) implies that the Arrow-Debreu price system satisfies

\[
q_t^0(s^t) = \beta^t \pi_t(s^t) \frac{u_c(s^t)}{u_c(s^0)}
\]

Using the first-order conditions (8) and (9) to eliminate taxes and prices from (7), we derive the implementability condition

\[
\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t)[u_c(s^t)c_t(s^t) - u_\ell(s^t)n_t(s^t)] - u_c(s^0)b_0 = 0
\]

The Ramsey problem is to choose a feasible allocation that maximizes

\[
\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t)u[c_t(s^t), 1 - n_t(s^t)]
\]

subject to (11).

### 38.3.4 Solution Details

First, define a “pseudo utility function”

\[
V[c_t(s^t), n_t(s^t), \Phi] = u[c_t(s^t), 1 - n_t(s^t)] + \Phi[u_c(s^t)c_t(s^t) - u_\ell(s^t)n_t(s^t)]
\]

where \( \Phi \) is a Lagrange multiplier on the implementability condition (7).

Next form the Lagrangian

\[
J = \sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t)\left\{V[c_t(s^t), n_t(s^t), \Phi] + \theta_t(s^t)\left[n_t(s^t) - c_t(s^t) - g_t(s_i)\right]\right\} - \Phi u_c(0)b_0
\]

where \( \{\theta_t(s^t); \forall s^t\}_{t \geq 0} \) is a sequence of Lagrange multipliers on the feasible conditions (2).

Given an initial government debt \( b_0 \), we want to maximize \( J \) with respect to \( \{c_t(s^t), n_t(s^t); \forall s^t\}_{t \geq 0} \) and to minimize with respect to \( \{\theta(s^t); \forall s^t\}_{t \geq 0} \).

The first-order conditions for the Ramsey problem for periods \( t \geq 1 \) and \( t = 0 \), respectively, are

\[
c_t(s^t): (1 + \Phi)u_c(s^t) + \Phi[u_{cc}(s^t)c_t(s^t) - u_{\ell\ell}(s^t)n_t(s^t)] - \theta_t(s^t) = 0, \quad t \geq 1
\]

\[
n_t(s^t): - (1 + \Phi)u_\ell(s^t) - \Phi[u_{\ell\ell}(s^t)c_t(s^t) - u_{\ell\ell}(s^t)n_t(s^t)] + \theta_t(s^t) = 0, \quad t \geq 1
\]
CHAPTER 38. OPTIMAL TAXATION WITH STATE-CONTINGENT DEBT

\[ c_0(s^0, b_0): (1 + \Phi)u_c(c, 1 - c - g) + \Phi [cu_{cc}(c, 1 - c - g) - (c + g)u_{tc}(c, 1 - c - g)] = (1 + \Phi)u_{tc}(c, 1 - c - g) + \Phi [cu_{tc}(c, 1 - c - g) - (c + g)u_{tc}(c, 1 - c - g)] \]

\[ n_0(s^0, b_0): - (1 + \Phi)u_{t\ell}(s^0, b_0) = 0 \]

Please note how these first-order conditions differ between \( t = 0 \) and \( t \geq 1 \).

It is instructive to use first-order conditions \((15)\) for \( t \geq 1 \) to eliminate the multipliers \( \theta_t(s^t) \).

For convenience, we suppress the time subscript and the index \( s_t \) and obtain

\[ (1 + \Phi)u_c(c, 1 - c - g) + \Phi [cu_{cc}(c, 1 - c - g) - (c + g)u_{tc}(c, 1 - c - g)] = (1 + \Phi)u_{tc}(c, 1 - c - g) + \Phi [cu_{tc}(c, 1 - c - g) - (c + g)u_{tc}(c, 1 - c - g)] \]

(17)

where we have imposed conditions \((1)\) and \((2)\).

Equation \((17)\) is one equation that can be solved to express the unknown \( c \) as a function of the exogenous variable \( g \).

We also know that time \( t = 0 \) quantities \( c_0 \) and \( n_0 \) satisfy

\[ (1 + \Phi)u_c(c, 1 - c - g) + \Phi [cu_{cc}(c, 1 - c - g) - (c + g)u_{tc}(c, 1 - c - g)] = (1 + \Phi)u_{tc}(c, 1 - c - g) + \Phi [cu_{tc}(c, 1 - c - g) - (c + g)u_{tc}(c, 1 - c - g)] + \Phi (u_{cc} - u_{c\ell})b_0 \]

(18)

Notice that a counterpart to \( b_0 \) does not appear in \((17)\), so \( c \) does not depend on it for \( t \geq 1 \).

But things are different for time \( t = 0 \).

An analogous argument for the \( t = 0 \) equations \((16)\) leads to one equation that can be solved for \( c_0 \) as a function of the pair \((g(s_0), b_0)\).

These outcomes mean that the following statement would be true even when government purchases are history-dependent functions \( g_t(s^t) \) of the history of \( s^t \).

**Proposition:** If government purchases are equal after two histories \( s^t \) and \( \tilde{s}^\tau \) for \( t, \tau \geq 0 \), i.e., if

\[ g_t(s^t) = g_{\tau}(\tilde{s}^\tau) = g \]

then it follows from \((17)\) that the Ramsey choices of consumption and leisure, \((c_t(s^t), \ell_t(s^t))\) and \((c_{\tau}(\tilde{s}^\tau), \ell_{\tau}(\tilde{s}^\tau))\), are identical.

The proposition asserts that the optimal allocation is a function of the currently realized quantity of government purchases \( g \) only and does not depend on the specific history that preceded that realization of \( g \).

38.3.5 The Ramsey Allocation for a Given Multiplier

Temporarily take \( \Phi \) as given.

We shall compute \( c_0(s^0, b_0) \) and \( n_0(s^0, b_0) \) from the first-order conditions \((16)\).
Evidently, for \( t \geq 1 \), \( c \) and \( n \) depend on the time \( t \) realization of \( g \) only.

But for \( t = 0 \), \( c \) and \( n \) depend on both \( g_0 \) and the government’s initial debt \( b_0 \).

Thus, while \( b_0 \) influences \( c_0 \) and \( n_0 \), there appears no analogous variable \( b_t \) that influences \( c_t \) and \( n_t \) for \( t \geq 1 \).

The absence of \( b_t \) as a determinant of the Ramsey allocation for \( t \geq 1 \) and its presence for \( t = 0 \) is a symptom of the \textit{time-inconsistency} of a Ramsey plan.

\( \Phi \) has to take a value that assures that the household and the government’s budget constraints are both satisfied at a candidate Ramsey allocation and price system associated with that \( \Phi \).

### 38.3.6 Further Specialization

At this point, it is useful to specialize the model in the following ways.

We assume that \( s \) is governed by a finite state Markov chain with states \( s \in \{1, \ldots, S\} \) and transition matrix \( \Pi \), where

\[
\Pi(s'|s) = \text{Prob}(s_{t+1} = s'|s_t = s)
\]

Also, assume that government purchases \( g \) are an exact time-invariant function \( g(s) \) of \( s \).

We maintain these assumptions throughout the remainder of this lecture.

### 38.3.7 Determining the Multiplier

We complete the Ramsey plan by computing the Lagrange multiplier \( \Phi \) on the implementability constraint (11).

Government budget balance restricts \( \Phi \) via the following line of reasoning.

The household’s first-order conditions imply

\[
(1 - \tau_t(s^t)) = \frac{u_l(s^t)}{u_c(s^t)} \tag{19}
\]

and the implied one-period Arrow securities prices

\[
p_{t+1}(s_{t+1}|s^t) = \beta \Pi(s_{t+1}|s_t) \frac{u_c(s^{t+1})}{u_c(s^t)} \tag{20}
\]

Substituting from (19), (20), and the feasibility condition (2) into the recursive version (5) of the household budget constraint gives

\[
u_c(s^t)[n_t(s^t) - g_t(s^t)] + \beta \sum_{s_{t+1}} \Pi(s_{t+1}|s_t) u_c(s^{t+1}) b_{t+1}(s_{t+1}|s^t) = u_l(s^t)n_t(s^t) + u_c(s^t)b_t(s_t|s^{t-1}) \tag{21}
\]

Define \( x_t(s^t) = u_c(s^t)b_t(s_t|s^{t-1}) \).
Notice that $x_t(s^t)$ appears on the right side of (21) while $\beta$ times the conditional expectation of $x_{t+1}(s^{t+1})$ appears on the left side.

Hence the equation shares much of the structure of a simple asset pricing equation with $x_t$ being analogous to the price of the asset at time $t$.

We learned earlier that for a Ramsey allocation $c_t(s^t), n_t(s^t)$ and $b_t(s_t|s^{t-1})$, and therefore also $x_t(s^t)$, are each functions of $s_t$ only, being independent of the history $s^{t-1}$ for $t \geq 1$.

That means that we can express equation (21) as

$$u_c(s)[n(s) - g(s)] + \beta \sum_{s'} \Pi(s'|s)x'(s') = u_l(s)n(s) + x(s)$$

where $s'$ denotes a next period value of $s$ and $x'(s')$ denotes a next period value of $x$.

Equation (22) is easy to solve for $x(s)$ for $s = 1, \ldots, S$.

If we let $\tilde{n}, \tilde{g}, \tilde{x}$ denote $S \times 1$ vectors whose $i$th elements are the respective $n, g, x$ values when $s = i$, and let $\Pi$ be the transition matrix for the Markov state $s$, then we can express (22) as the matrix equation

$$\tilde{u}_c(\tilde{n} - \tilde{g}) + \beta \Pi \tilde{x} = \tilde{u}_l \tilde{n} + \tilde{x}$$

This is a system of $S$ linear equations in the $S \times 1$ vector $x$, whose solution is

$$\tilde{x} = (I - \beta \Pi)^{-1}[\tilde{u}_c(\tilde{n} - \tilde{g}) - \tilde{u}_l \tilde{n}]$$

In these equations, by $\tilde{u}_c \tilde{n}$, for example, we mean element-by-element multiplication of the two vectors.

After solving for $\tilde{x}$, we can find $b(s_t|s^{t-1})$ in Markov state $s_t = s$ from $b(s) = \frac{x(s)}{u_c(s)}$ or the matrix equation

$$\tilde{b} = \frac{\tilde{x}}{\tilde{u}_c}$$

where division here means an element-by-element division of the respective components of the $S \times 1$ vectors $\tilde{x}$ and $\tilde{u}_c$.

Here is a computational algorithm:

1. Start with a guess for the value for $\Phi$, then use the first-order conditions and the feasibility conditions to compute $c(s_t), n(s_t)$ for $s \in [1, \ldots, S]$ and $c_0(s_0, b_0)$ and $n_0(s_0, b_0)$, given $\Phi$.

   - these are $2(S + 1)$ equations in $2(S + 1)$ unknowns.

1. Solve the $S$ equations (24) for the $S$ elements of $\tilde{x}$.

   - these depend on $\Phi$. 

38.3. A COMPETITIVE EQUILIBRIUM WITH DISTORTING TAXES

1. Find a $\Phi$ that satisfies

$$u_{c,0}b_0 = u_{c,0}(n_0 - g_0) - u_{t,0}n_0 + \beta \sum_{s=1}^{S} \Pi(s|s_0)x(s)$$

by gradually raising $\Phi$ if the left side of (26) exceeds the right side and lowering $\Phi$ if the left side is less than the right side.

2. After computing a Ramsey allocation, recover the flat tax rate on labor from (8) and the implied one-period Arrow securities prices from (9).

In summary, when $g_t$ is a time-invariant function of a Markov state $s_t$, a Ramsey plan can be constructed by solving $3S + 3$ equations in $S$ components each of $\bar{c}$, $\bar{n}$, and $\bar{x}$ together with $n_0$, $c_0$, and $\Phi$.

### 38.3.8 Time Inconsistency

Let $\{\tau_t(s^t)\}_{t=0}^{\infty}, \{b_{t+1}(s_{t+1}|s^t)\}_{t=0}^{\infty}$ be a time 0, state $s_0$ Ramsey plan.

Then $\{\tau_j(s^j)\}_{j=t}^{\infty}, \{b_{j+1}(s_{j+1}|s^j)\}_{j=t}^{\infty}$ is a time $t$, history $s^t$ continuation of a time 0, state $s_0$ Ramsey plan.

A time $t$, history $s^t$ Ramsey plan is a Ramsey plan that starts from initial conditions $s^t, b_t(s_t|s^{t-1})$.

A time $t$, history $s^t$ continuation of a time 0, state 0 Ramsey plan is not a time $t$, history $s^t$ Ramsey plan.

The means that a Ramsey plan is not time consistent.

Another way to say the same thing is that a Ramsey plan is time inconsistent.

The reason is that a continuation Ramsey plan takes $u_{c,t}b_t(s_t|s^{t-1})$ as given, not $b_t(s_t|s^{t-1})$.

We shall discuss this more below.

### 38.3.9 Specification with CRRA Utility

In our calculations below and in a subsequent lecture based on an extension of the Lucas-Stokey model by Aiyagari, Marcet, Sargent, and Seppälä (2002) [3], we shall modify the one-period utility function assumed above.

(We adopted the preceding utility specification because it was the one used in the original [45] paper)

We will modify their specification by instead assuming that the representative agent has utility function

$$u(c, n) = \frac{c^{1-\sigma}}{1-\sigma} - \frac{n^{1+\gamma}}{1+\gamma}$$

where $\sigma > 0$, $\gamma > 0$.

We continue to assume that

$$c_t + g_t = n_t$$
We eliminate leisure from the model.

We also eliminate Lucas and Stokey’s restriction that \( \ell_t + n_t \leq 1 \).

We replace these two things with the assumption that labor \( n_t \in [0, +\infty] \).

With these adjustments, the analysis of Lucas and Stokey prevails once we make the following replacements

\[
\begin{align*}
    u_{\ell}(c, \ell) &\sim -u_n(c, n) \\
    u_c(c, \ell) &\sim u_c(c, n) \\
    u_{\ell,\ell}(c, \ell) &\sim u_{nn}(c, n) \\
    u_{c,\ell}(c, \ell) &\sim u_{c,c}(c, n) \\
    u_{c,\ell}(c, \ell) &\sim 0
\end{align*}
\]

With these understandings, equations (17) and (18) simplify in the case of the CRRA utility function.

They become

\[
(1 + \Phi)[u_c(c) + u_n(c + g)] + \Phi[cu_{cc}(c) + (c + g)u_{nn}(c + g)] = 0
\]

and

\[
(1 + \Phi)[u_c(c_0) + u_n(c_0 + g_0)] + \Phi[c_0u_{cc}(c_0) + (c_0 + g_0)u_{nn}(c_0 + g_0)] - \Phi u_{c,c}(c_0)b_0 = 0
\]

In equation (27), it is understood that \( c \) and \( g \) are each functions of the Markov state \( s \).

In addition, the time \( t = 0 \) budget constraint is satisfied at \( c_0 \) and initial government debt \( b_0 \):

\[
b_0 + g_0 = \tau_0(c_0 + g_0) + \frac{\bar{b}}{R_0}
\]

where \( R_0 \) is the gross interest rate for the Markov state \( s_0 \) that is assumed to prevail at time \( t = 0 \) and \( \tau_0 \) is the time \( t = 0 \) tax rate.

In equation (29), it is understood that

\[
\tau_0 = 1 - \frac{u_{l,0}}{u_{c,0}}
\]

\[
R_0 = \beta \sum_{s=1}^{S} \Pi(s|s_0) \frac{u_c(s)}{u_{c,0}}
\]

### 38.3.10 Sequence Implementation

The above steps are implemented in a class called \( \text{SequentialAllocation} \):

```python
import numpy as np
from scipy.optimize import root
from quantecon import MarkovChain
```
class SequentialAllocation:
    
    Class that takes CESutility or BGPutility object as input returns planner's allocation as a function of the multiplier on the implementability constraint $\mu$.

def __init__(self, model):
    # Initialize from model object attributes
    self.\beta, self.\pi, self.G = model.\beta, model.\pi, model.G
    self.mc, self.\Theta = MarkovChain(self.\pi), model.\Theta
    self.S = len(model.\pi)  # Number of states
    self.model = model

    # Find the first best allocation
    self.find_first_best()

def find_first_best(self):
    # Find the first best allocation
    model = self.model
    S, \Theta, G = self.S, self.\Theta, self.G
    Uc, Un = model.Uc, model.Un

def res(z):
    c = z[:S]
    n = z[S:]
    return np.hstack([\Theta * Uc(c, n) + Un(c, n), \Theta * n - c - G])

    res = root(res, 0.5 * np.ones(2 * S))

    if not res.success:
        raise Exception('Could not find first best')

    self.cFB = res.x[:S]
    self.nFB = res.x[S:]

    # Multiplier on the resource constraint
    self.\XiFB = Uc(self.cFB, self.nFB)
    self.zFB = np.hstack([self.cFB, self.nFB, self.\XiFB])

def time1_allocation(self, \mu):
    # Computes optimal allocation for time $t >= 1$ for a given $\mu$
    model = self.model
    S, \Theta, G = self.S, self.\Theta, self.G
    Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn

def FOC(z):
    c = z[:S]
    n = z[S:2 * S]
    \Xi = z[2 * S:]
# FOC of $c$

```python
return np.hstack([Uc(c, n) - μ * (Ucc(c, n) * c + Uc(c, n)) - Ξ,
                 Un(c, n) - μ * (Unn(c, n) * n + Un(c, n)) \
                 + Θ * Ξ,  # FOC of $n$
                 Θ * n - c - G])
```

# Find the root of the first-order condition
```python
res = root(FOC, self.zFB)
if not res.success:
    raise Exception('Could not find LS allocation."

z = res.x
```

```
c, n, Ξ = z[:S], z[S:2 * S], z[2 * S:]
```

# Compute $x$
```python
I = Uc(c, n) * c + Un(c, n) * n
x = np.dot(np.linalg.solve(np.eye(S) - self.β * self.π), I)
```

```
return c, n, x, Ξ
```

def time0_allocation(self, B_, s_0):
    '''
    Finds the optimal allocation given initial government debt $B_*$ and
    state $s_0$.
    '''
    model, π, Θ, G, β = self.model, self.π, self.Θ, self.G, self.β
    Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn

    # First order conditions of planner's problem
    def FOC(z):
        μ, c, n, Ξ = z
        xprime = self.time1_allocation(μ)[2]
        return np.hstack([Uc(c, n) - μ * (Ucc(c, n) * (c - B_) + Uc(c, n)) - Ξ,
                           Un(c, n) - μ * (Unn(c, n) * n + Un(c, n)) \
                           + Un(c, n)) + Θ[s_0] * Ξ,
                           (Θ * n - c - G)[s_0]])
```

# Find root
```python
res = root(FOC, np.array([0, self.cFB[s_0], self.nFB[s_0], self.ΞFB[s_0]]))
if not res.success:
    raise Exception('Could not find time 0 LS allocation."

return res.x
```

def time1_value(self, μ):
    '''
    Find the value associated with multiplier $μ$.
    '''
    c, n, x, Ξ = self.time1_allocation(μ)
    U = self.model.U(c, n)
    V = np.linalg.solve(np.eye(self.S) - self.β * self.π, U)
    return c, n, x, V

def Τ(self, c, n):
Computes \( T \) given \( c, n \)

```python
model = self.model
Uc, Un = model.Uc(c, n), model.Un(c, n)
return 1 + Un / (self.\( \Theta \) * Uc)
```

```python
def simulate(self, B_, s_0, T, sHist=None):
    model, \( \pi \), \( \beta \) = self.model, self.\( \pi \), self.\( \beta \)
Uc = model.Uc
if sHist is None:
    sHist = self.mc.simulate(T, s_0)

    cHist, nHist, Bhist, THist, \( \mu \)Hist = np.zeros((5, T))
    RHist = np.zeros(T - 1)

    # Time 0
    \( \mu \), cHist[0], nHist[0], _ = self.time0_allocation(B_, s_0)
    THist[0] = self.T(cHist[0], nHist[0])[s_0]
    Bhist[0] = B_
    \( \mu \)Hist[0] = \( \mu \)

    # Time 1 onward
    for t in range(1, T):
        c, n, x, \( \Xi \) = self.time1_allocation(\( \mu \))
        T = self.T(c, n)
        u_c = Uc(c, n)
        s = sHist[t]
        Eu_c = \( \pi \)[sHist[t - 1]] \( \otimes \) u_c
        cHist[t], nHist[t], Bhist[t], THist[t] = c[s], n[s], x[s] / Eu_c
        RHist[t - 1] = Uc(cHist[t - 1], nHist[t - 1]) / (\( \beta \) * Eu_c)
        \( \mu \)Hist[t] = \( \mu \)

    return np.array([cHist, nHist, Bhist, THist, sHist, \( \mu \)Hist, RHist])
```

38.4 Recursive Formulation of the Ramsey Problem

\( x_t(s^t) = u_c(s^t)b_t(s_t|s^{t-1}) \) in equation (21) appears to be a purely “forward-looking” variable. But \( x_t(s^t) \) is also a natural candidate for a state variable in a recursive formulation of the Ramsey problem.

38.4.1 Intertemporal Delegation

To express a Ramsey plan recursively, we imagine that a time 0 Ramsey planner is followed by a sequence of continuation Ramsey planners at times \( t = 1, 2, \ldots \).

A “continuation Ramsey planner” at times \( t \geq 1 \) has a different objective function and faces different constraints and state variables than does the Ramsey planner at time \( t = 0 \).
A key step in representing a Ramsey plan recursively is to regard the marginal utility scaled government debts \( x_t(s^t) = u_c(s^t)b_t(s_t|s^{t-1}) \) as predetermined quantities that continuation Ramsey planners at times \( t \geq 1 \) are obligated to attain.

Continuation Ramsey planners do this by choosing continuation policies that induce the representative household to make choices that imply that

\[
  u_c(s^t)b_t(s_t|s^{t-1}) = x_t(s^t).
\]

A time \( t \geq 1 \) continuation Ramsey planner faces \( x_t, s_t \) as state variables.

A time \( t \geq 1 \) continuation Ramsey planner delivers \( x_t \) by choosing a suitable \( n_t, c_t \) pair and a list of \( s_{t+1} \)-contingent continuation quantities \( x_{t+1} \) to bequeath to a time \( t + 1 \) continuation Ramsey planner.

While a time \( t \geq 1 \) continuation Ramsey planner faces \( x_t, s_t \) as state variables, the time 0 Ramsey planner faces \( b_0 \), not \( x_0 \), as a state variable.

Furthermore, the Ramsey planner cares about \((c_0(s_0), \ell_0(s_0))\), while continuation Ramsey planners do not.

The time 0 Ramsey planner hands a state-contingent function that make \( x_1 \) a function of \( s_1 \) to a time 1 continuation Ramsey planner.

These lines of delegated authorities and responsibilities across time express the continuation Ramsey planners’ obligations to implement their parts of the original Ramsey plan, designed once-and-for-all at time 0.

### 38.4.2 Two Bellman Equations

After \( s_t \) has been realized at time \( t \geq 1 \), the state variables confronting the time \( t \) continuation Ramsey planner are \((x_t, s_t)\).

- Let \( V(x, s) \) be the value of a continuation Ramsey plan at \( x_t = x, s_t = s \) for \( t \geq 1 \).
- Let \( W(b, s) \) be the value of a Ramsey plan at time 0 at \( b_0 = b \) and \( s_0 = s \).

We work backward by presenting a Bellman equation for \( V(x, s) \) first, then a Bellman equation for \( W(b, s) \).

### 38.4.3 The Continuation Ramsey Problem

The Bellman equation for a time \( t \geq 1 \) continuation Ramsey planner is

\[
  V(x, s) = \max_{n, \{x'(s')\}} u(n - g(s), 1 - n) + \beta \sum_{s' \in S} \Pi(s'|s) V(x', s')
\]  

(30)

where maximization over \( n \) and the \( S \) elements of \( x'(s') \) is subject to the single implementability constraint for \( t \geq 1 \).

\[
  x = u_c(n - g(s)) - u_l n + \beta \sum_{s' \in S} \Pi(s'|s) x'(s')
\]  

(31)

Here \( u_c \) and \( u_l \) are today’s values of the marginal utilities.

For each given value of \( x, s \), the continuation Ramsey planner chooses \( n \) and \( x'(s') \) for each \( s' \in S \).
Associated with a value function $V(x, s)$ that solves Bellman equation (30) are $S + 1$ time-invariant policy functions

$$n_t = f(x_t, s_t), \quad t \geq 1$$
$$x_{t+1}(s_{t+1}) = h(s_{t+1}; x_t, s_t), \quad s_{t+1} \in S, \quad t \geq 1$$

### 38.4.4 The Ramsey Problem

The Bellman equation for the time 0 Ramsey planner is

$$W(b_0, s_0) = \max_{n_0, \{x(s_1)\}} u(n_0 - g_0, 1 - n_0) + \beta \sum_{s_1 \in S} \Pi(s_1 | s_0) V(x'(s_1), s_1)$$

(33)

where maximization over $n_0$ and the $S$ elements of $x'(s_1)$ is subject to the time 0 implementability constraint

$$u_{c, 0} b_0 = u_{c, 0}(n_0 - g_0) - u_{l, 0} n_0 + \beta \sum_{s_1 \in S} \Pi(s_1 | s_0) x'(s_1)$$

(34)

coming from restriction (26).

Associated with a value function $W(b_0, n_0)$ that solves Bellman equation (33) are $S + 1$ time 0 policy functions

$$n_0 = f_0(b_0, s_0)$$
$$x_1(s_1) = h_0(s_1; b_0, s_0)$$

(35)

Notice the appearance of state variables $(b_0, s_0)$ in the time 0 policy functions for the Ramsey planner as compared to $(x_t, s_t)$ in the policy functions (32) for the time $t \geq 1$ continuation Ramsey planners.

The value function $V(x_t, s_t)$ of the time $t$ continuation Ramsey planner equals

$$E_t \sum_{\tau = t}^{\infty} \beta^{\tau-t} u(c_t, l_t),$$

where the consumption and leisure processes are evaluated along the original time 0 Ramsey plan.

### 38.4.5 First-Order Conditions

Attach a Lagrange multiplier $\Phi_1(x, s)$ to constraint (31) and a Lagrange multiplier $\Phi_0$ to constraint (26).

Time $t \geq 1$: the first-order conditions for the time $t \geq 1$ constrained maximization problem on the right side of the continuation Ramsey planner’s Bellman equation (30) are

$$\beta \Pi(s' | s) V_x(x', s') - \beta \Pi(s' | s) \Phi_1 = 0$$

(36)

for $x'(s')$ and

$$(1 + \Phi_1)(u_c - u_l) + \Phi_1 [n(u_{ll} - u_{lc}) + (n - g(s))(u_{cc} - u_{lc})] = 0$$

(37)

for $n$. 

Given $\Phi_1$, equation (37) is one equation to be solved for $n$ as a function of $s$ (or of $g(s)$).

Equation (36) implies $V_x(x', s') = \Phi_1$, while an envelope condition is $V_x(x, s) = \Phi_1$, so it follows that

$$V_x(x', s') = V_x(x, s) = \Phi_1(x, s)$$  \hspace{1cm} (38)

Time $t = 0$: For the time 0 problem on the right side of the Ramsey planner’s Bellman equation (33), first-order conditions are

$$V_x(x(s_1), s_1) = \Phi_0$$  \hspace{1cm} (39)

for $x(s_1), s_1 \in S$, and

$$(1 + \Phi_0)[u_{c,0} - u_{n,0}] + \Phi_0[n_0(u_{ll,0} - u_{lc,0}) + (n_0 - g(s_0))(u_{cc,0} - u_{cl,0})] - \Phi_0(u_{cc,0} - u_{cl,0})b_0 = 0$$  \hspace{1cm} (40)

Notice similarities and differences between the first-order conditions for $t \geq 1$ and for $t = 0$.

An additional term is present in (40) except in three special cases

- $b_0 = 0$, or
- $u_c$ is constant (i.e., preferences are quasi-linear in consumption), or
- initial government assets are sufficiently large to finance all government purchases with interest earnings from those assets so that $\Phi_0 = 0$

Except in these special cases, the allocation and the labor tax rate as functions of $s_t$ differ between dates $t = 0$ and subsequent dates $t \geq 1$.

Naturally, the first-order conditions in this recursive formulation of the Ramsey problem agree with the first-order conditions derived when we first formulated the Ramsey plan in the space of sequences.

### 38.4.6 State Variable Degeneracy

Equations (39) and (40) imply that $\Phi_0 = \Phi_1$ and that

$$V_x(x_t, s_t) = \Phi_0$$  \hspace{1cm} (41)

for all $t \geq 1$.

When $V$ is concave in $x$, this implies state-variable degeneracy along a Ramsey plan in the sense that for $t \geq 1$, $x_t$ will be a time-invariant function of $s_t$.

Given $\Phi_0$, this function mapping $s_t$ into $x_t$ can be expressed as a vector $\vec{x}$ that solves equation (34) for $n$ and $c$ as functions of $g$ that are associated with $\Phi = \Phi_0$.

### 38.4.7 Manifestations of Time Inconsistency

While the marginal utility adjusted level of government debt $x_t$ is a key state variable for the continuation Ramsey planners at $t \geq 1$, it is not a state variable at time 0.
38.4. RECURSIVE FORMULATION OF THE RAMSEY PROBLEM

The time 0 Ramsey planner faces $b_0$, not $x_0 = u_{c,0}b_0$, as a state variable.

The discrepancy in state variables faced by the time 0 Ramsey planner and the time $t \geq 1$ continuation Ramsey planners captures the differing obligations and incentives faced by the time 0 Ramsey planner and the time $t \geq 1$ continuation Ramsey planners.

- The time 0 Ramsey planner is obligated to honor government debt $b_0$ measured in time 0 consumption goods.
- The time 0 Ramsey planner can manipulate the value of government debt as measured by $u_{c,0}b_0$.
- In contrast, time $t \geq 1$ continuation Ramsey planners are obligated not to alter values of debt, as measured by $u_{c,t}b_t$, that they inherit from a preceding Ramsey planner or continuation Ramsey planner.

When government expenditures $g_t$ are a time-invariant function of a Markov state $s_t$, a Ramsey plan and associated Ramsey allocation feature marginal utilities of consumption $u_c(s_t)$ that, given $\Phi$, for $t \geq 1$ depend only on $s_t$, but that for $t = 0$ depend on $b_0$ as well.

This means that $u_c(s_t)$ will be a time-invariant function of $s_t$ for $t \geq 1$, but except when $b_0 = 0$, a different function for $t = 0$.

This in turn means that prices of one-period Arrow securities $p_{t+1}(s_{t+1}|s_t) = p(s_{t+1}|s_t)$ will be the same time-invariant functions of $(s_{t+1}, s_t)$ for $t \geq 1$, but a different function $p_0(s_1|s_0)$ for $t = 0$, except when $b_0 = 0$.

The differences between these time 0 and time $t \geq 1$ objects reflect the Ramsey planner’s incentive to manipulate Arrow security prices and, through them, the value of initial government debt $b_0$.

38.4.8 Recursive Implementation

The above steps are implemented in a class called RecursiveAllocation

```python
In [4]: import numpy as np
       from scipy.interpolate import UnivariateSpline
       from scipy.optimize import fmin_slsqp
       from quantecon import MarkovChain
       from scipy.optimize import root

class RecursiveAllocation:
    '''
    Compute the planner’s allocation by solving Bellman equation.
    '''

    def __init__(self, model, µgrid):
        self.β, self.π, self.G = model.β, model.π, model.G
        self.mc, self.S = MarkovChain(self.π), len(model.π)  # Number of states
        self.Θ, self.model, self.µgrid = model.Θ, model, µgrid

        # Find the first best allocation
        self.solve_time1_bellman()
```

CHAPTER 38. OPTIMAL TAXATION WITH STATE-CONTINGENT DEBT

```python
self.T.time_0 = True  # Bellman equation now solves time 0 problem

def solve_time1_bellman(self):
    '''
    Solve the time 1 Bellman equation for calibration model and initial
    grid \( \mu_{grid0} \)
    '''
    model, \( \mu_{grid0} \) = self.model, self.\( \mu \)grid
    S = len(model.\( \pi \))

    # First get initial fit
    pp = SequentialAllocation(model)
    c, n, x, V = map(np.vstack, zip(*map(lambda \( \mu \): pp.time1_value(\( \mu \)), \( \mu \)grid0)))

    Vf, cf, nf, xprimef = {}, {}, {}, {}
    for s in range(2):
        ind = np.argsort(x[:, s])  # Sort x
        # Sort arrays according to x
        c, n, x, V = c[ind], n[ind], x[ind], V[ind]
        cf[s] = UnivariateSpline(x[:, s], c[:, s])
        nf[s] = UnivariateSpline(x[:, s], n[:, s])
        Vf[s] = UnivariateSpline(x[:, s], V[:, s])

        for sprime in range(S):
            xprimef[s, sprime] = UnivariateSpline(x[:, s], x[:, s])

    policies = [cf, nf, xprimef]

    # Create xgrid
    xbar = [x.min(0).max(), x.max(0).min()]
    xgrid = np.linspace(xbar[0], xbar[1], len(\( \mu \)grid0))
    self.xgrid = xgrid

    # Now iterate on bellman equation
    T = BellmanEquation(model, xgrid, policies)
    diff = 1
    while diff > 1e-7:
        PF = T(Vf)
        Vfnew, policies = self.fit_policy_function(PF)
        diff = 0
        for s in range(S):
            diff = max(diff, np.abs((Vf[s](xgrid) - Vfnew[s](xgrid)) / Vf[s](xgrid)).max())
        Vf = Vfnew

    # Store value function policies and Bellman Equations
    self.Vf = Vf
    self.policies = policies
    self.T = T

def fit_policy_function(self, PF):
    '''
    Fits the policy functions PF using the points xgrid using
    UnivariateSpline
    '''
    xgrid, S = self.xgrid, self.S
```
38.4. RECURSIVE FORMULATION OF THE RAMSEY PROBLEM

```python
Vf, cf, nf, xprimef = {}, {}, {}, {}
for s in range(S):
    PFvec = np.vstack(tuple(map(lambda x: PF(x, s), xgrid)))
    Vf[s] = UnivariateSpline(xgrid, PFvec[:, 0], s=0)
    cf[s] = UnivariateSpline(xgrid, PFvec[:, 1], s=0, k=1)
    nf[s] = UnivariateSpline(xgrid, PFvec[:, 2], s=0, k=1)
    for sprime in range(S):
        xprimef[s, sprime] = UnivariateSpline(xgrid, PFvec[:, 3 + sprime], s=0, k=1)
return Vf, [cf, nf, xprimef]

def T(self, c, n):
    '''
    Computes T given c, n
    '''
    model = self.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)
    return 1 + Un / (self.Θ * Uc)

def time0_allocation(self, B_, s0):
    '''
    Finds the optimal allocation given initial government debt B_ and state s_0
    '''
    PF = self.T(self.Vf)
    z0 = PF(B_, s0)
    c0, n0, xprime0 = z0[1], z0[2], z0[3]:
    return c0, n0, xprime0

def simulate(self, B_, s_0, T, sHist=None):
    '''
    Simulates Ramsey plan for T periods
    '''
    model, π = self.model, self.π
    Uc = model.Uc
    cf, nf, xprimef = self.policies
    if sHist is None:
        sHist = self.mc.simulate(T, s_0)
    cHist, nHist, Bhist, THist, μHist = np.zeros((S, T))
    RHist = np.zeros(T - 1)

    # Time 0
    cHist[0], nHist[0], xprime = self.time0_allocation(B_, s_0)
    THist[0] = self.T(cHist[0], nHist[0])[s_0]
    Bhist[0] = B_
    μHist[0] = 0

    # Time 1 onward
    for t in range(1, T):
        s, x = sHist[t], xprime[sHist[t]]
        c, n, xprime = np.empty(self.S), nf[s](x), np.empty(self.S)
```

for shat in range(self.S):
    c[shat] = cf[shat](x)
for sprime in range(self.S):
    xprime[sprime] = xprimef[s, sprime](x)

T = self.T(c, n)[s]
u_c = Uc(c, n)
Eu_c = π[shHist[t - 1]] @ u_c
μHist[t] = self.Vf[s](x, 1)

RHist[t - 1] = Uc(chHist[t - 1], nHist[t - 1]) / (self.β * Eu_c)

cHist[t], nHist[t], Bhist[t], THist[t] = c[s], n, x / u_c[s], T

return np.array([cHist, nHist, Bhist, THist, sHist, μHist, RHist])

class BellmanEquation:
    '''
    Bellman equation for the continuation of the Lucas-Stokey Problem
    '''

    def __init__(self, model, xgrid, policies0):
        self.β, self.π, self.G = model.β, model.π, model.G
        self.S = len(model.π)  # Number of states
        self.Θ, self.model = model.Θ, model

        self.xbar = [min(xgrid), max(xgrid)]
        self.time_0 = False

        self.z0 = {}
        cf, nf, xprimef = policies0
        for s in range(self.S):
            for x in xgrid:
                xprime0 = np.empty(self.S)
                for sprime in range(self.S):
                    xprime0[sprime] = xprimef[s, sprime](x)
                self.z0[x, s] = np.hstack([cf[s](x), nf[s](x), xprime0])

        self.find_first_best()

    def find_first_best(self):
        '''
        Find the first best allocation
        '''
        model = self.model

        def res(z):
            c = z[:S]
            n = z[S:]
            return np.hstack([Θ * Uc(c, n) + Un(c, n), Θ * n - c - G])

        res = root(res, 0.5 * np.ones(2 * S))
        if not res.success:
raise Exception('Could not find first best')

self.cFB = res.x[:S]
self.nFB = res.x[S:]
IFB = Uc(self.cFB, self.nFB) * self.cFB + Un(self.cFB, self.nFB) *

self.nFB
self.xFB = np.linalg.solve(np.eye(S) - self.β * self.π, IFB)
self.zFB = {}

for s in range(S):
    self.zFB[s] = np.hstack([self.cFB[s], self.nFB[s], self.xFB])

def __call__(self, Vf):
    
    Given continuation value function, next period return value function,
    this period return T(V) and optimal policies
    
    if not self.time_0:
        def PF(x, s):
            return self.get_policies_time1(x, s, Vf)
    else:
        def PF(B_, s0):
            return self.get_policies_time0(B_, s0, Vf)
    return PF

def get_policies_time1(self, x, s, Vf):
    
    Finds the optimal policies
    
    model, β, Θ, = self.model, self.β, self.Θ,
    U, Uc, Un = model.U, model.Uc, model.Un

    def objf(z):
        c, n, xprime = z[0], z[1], z[2:]
        Vprime = np.empty(S)
        for sprime in range(S):
            Vprime[sprime] = Vf[sprime](xprime[sprime])
        return -(U(c, n) + β * π[s] @ Vprime)

    def cons(z):
        c, n, xprime = z[0], z[1], z[2:]
        return np.hstack([x - Uc(c, n) * c - Un(c, n) * n - β * π[s]
            @ xprime,
            (Θ * n - c - G)[s]])

    out, fx, _, imode, smode = fmin_slsqp(objf,
        self.z0[x, s],
        f_eqcons=cons,
        bounds=([0, 100], [0, 100])
         + [self.xbar] * S,
        full_output=True,
        iprint=0,
        acc=1e-10)

    if imode > 0:
        raise Exception(smode)
self.z[:, x, s] = out
return np.hstack([-fx, out])

def get_policies_time0(self, B_, s0, Vf):
    r
    Finds the optimal policies
    r
    model, β, Θ, = self.model, self.β, self.Θ,
    U, Uc, Un = model.U, model.Uc, model.Un

def objf(z):
    c, n, xprime = z[0], z[1], z[2:]
    Vprime = np.empty(S)
    for sprime in range(S):
        Vprime[sprime] = Vf[sprime](xprime[sprime])

    return -(U(c, n) + β * π[s0] @ Vprime)

def cons(z):
    c, n, xprime = z[0], z[1], z[2:]
    return np.hstack([-Uc(c, n) * (c - B_) - Un(c, n) * n - β * π[s0]
                      @ xprime,
                      (Θ * n - c - G)[s0]])

out, fx, _, imode, smode = fmin_slsqp(objf, self.zFB[s0],
                                       f_eqcons=cons,
                                       bounds=[(θ, 100), (θ, 100)]
                                                + [self.xbar] * S,
                                       full_output=True, iprint=0,
                                       acc=1e-10)

    if imode > 0:
        raise Exception(smode)

    return np.hstack([-fx, out])

38.5 Examples

38.5.1 Anticipated One-Period War

This example illustrates in a simple setting how a Ramsey planner manages risk.

Government expenditures are known for sure in all periods except one

- For \( t < 3 \) and \( t > 3 \) we assume that \( g_t = g_l = 0.1 \).
- At \( t = 3 \) a war occurs with probability 0.5.
- If there is war, \( g_3 = g_h = 0.2 \)
- If there is no war \( g_3 = g_l = 0.1 \)

We define the components of the state vector as the following six \((t, g)\) pairs:

\((0, g_l), (1, g_l), (2, g_l), (3, g_l), (3, g_h), (t \geq 4, g_l)\).

We think of these 6 states as corresponding to \( s = 1, 2, 3, 4, 5, 6 \).
The transition matrix is

\[
\Pi = \begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0.5 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 & 0
\end{pmatrix}
\]

Government expenditures at each state are

\[
g = \begin{pmatrix}
0.1 \\
0.1 \\
0.1 \\
0.1 \\
0.2 \\
0.1
\end{pmatrix}
\]

We assume that the representative agent has utility function

\[
u(c,n) = \frac{c^{1-\sigma} - n^{1+\gamma}}{1-\sigma - 1+\gamma}
\]

and set \(\sigma = 2\), \(\gamma = 2\), and the discount factor \(\beta = 0.9\).

Note: For convenience in terms of matching our code, we have expressed utility as a function of \(n\) rather than leisure \(l\).

This utility function is implemented in the class CRRAutility

In [5]: `import numpy as np`

```python
class CRRAutility:
    def __init__(self, 
                  \beta=0.9, 
                  \sigma=2, 
                  \gamma=2, 
                  \pi=0.5*np.ones((2, 2)), 
                  G=np.array([0.1, 0.2]), 
                  \Theta=np.ones(2), 
                  transfers=False):
        self.\beta, self.\sigma, self.\gamma = \beta, \sigma, \gamma 
        self.\pi, self.G, self.\Theta, self.transfers = \pi, G, \Theta, transfers

    # Utility function
    def U(self, c, n):
        \sigma = self.\sigma
        if \sigma == 1.:
            U = np.log(c)
        else:
            U = (c**(1 - \sigma) - 1) / (1 - \sigma)
        return U - n**(\gamma) / (1 + self.\gamma)
```
We set initial government debt $b_0 = 1$.

We can now plot the Ramsey tax under both realizations of time $t = 3$ government expenditures

- black when $g_3 = .1$, and
- red when $g_3 = .2$

```python
In [6]: time_π = np.array([[0, 1, 0, 0, 0, 0],
                        [0, 0, 1, 0, 0, 0],
                        [0, 0, 0, 0.5, 0.5, 0],
                        [0, 0, 0, 0, 0, 1],
                        [0, 0, 0, 0, 0, 1]])

time_G = np.array([0.1, 0.1, 0.1, 0.2, 0.1, 0.1])

# Θ can in principle be random

time_Θ = np.ones(6)

time_example = CRRAutility(π=time_π, G=time_G, Θ=time_Θ)

# Solve sequential problem

time_allocation = SequentialAllocation(time_example)

sHist_h = np.array([[0, 1, 2, 3, 5, 5]])

sHist_l = np.array([[0, 1, 2, 4, 5, 5]])

sim_seq_h = time_allocation.simulate(1, 0, 7, sHist_h)

sim_seq_l = time_allocation.simulate(1, 0, 7, sHist_l)

# Government spending paths


sim_seq_h[4] = time_example.G[sHist_h]

# Output paths


sim_seq_h[5] = time_example.Θ[sHist_h] * sim_seq_h[1]

fig, axes = plt.subplots(3, 2, figsize=(14, 10))


for ax, title, sim_l, sim_h in zip(axes.flatten(),
                                    titles, sim_seq_l, sim_seq_h):
    ax.set(title=title)
    ax.plot(sim_l, '-ok', sim_h, '-or', alpha=0.7)
    ax.grid()
```
38.5. EXAMPLES

plt.tight_layout()
plt.show()

Tax smoothing

• the tax rate is constant for all \( t \geq 1 \)
  
  – For \( t \geq 1, t \neq 3 \), this is a consequence of \( g_t \) being the same at all those dates.
  
  – For \( t = 3 \), it is a consequence of the special one-period utility function that we have assumed.
  
  – Under other one-period utility functions, the time \( t = 3 \) tax rate could be either higher or lower than for dates \( t \geq 1, t \neq 3 \).

• the tax rate is the same at \( t = 3 \) for both the high \( g_t \) outcome and the low \( g_t \) outcome.

We have assumed that at \( t = 0 \), the government owes positive debt \( b_0 \).

It sets the time \( t = 0 \) tax rate partly with an eye to reducing the value \( u_{c,0}b_0 \) of \( b_0 \).

It does this by increasing consumption at time \( t = 0 \) relative to consumption in later periods.

This has the consequence of lowering the time \( t = 0 \) value of the gross interest rate for risk-free loans between periods \( t \) and \( t + 1 \), which equals

\[
R_t = \frac{u_{c,t}}{\beta E_t[u_{c,t+1}]}
\]

A tax policy that makes time \( t = 0 \) consumption be higher than time \( t = 1 \) consumption evidently decreases the risk-free rate one-period interest rate, \( R_t \), at \( t = 0 \).

Lowering the time \( t = 0 \) risk-free interest rate makes time \( t = 0 \) consumption goods cheaper.
relative to consumption goods at later dates, thereby lowering the value $u_{c_0}b_0$ of initial government debt $b_0$.

We see this in a figure below that plots the time path for the risk-free interest rate under both realizations of the time $t = 3$ government expenditure shock.

The following plot illustrates how the government lowers the interest rate at time 0 by raising consumption

In [7]: fix, ax = plt.subplots(figsize=(8, 5))
ax.set_title('Gross Interest Rate')
ax.plot(sim_seq_l[-1], '-ok', sim_seq_h[-1], '-or', alpha=0.7)
ax.grid()
plt.show()

38.5.2 Government Saving

At time $t = 0$ the government evidently dissaves since $b_1 > b_0$.

- This is a consequence of it setting a lower tax rate at $t = 0$, implying more consumption at $t = 0$.

At time $t = 1$, the government evidently saves since it has set the tax rate sufficiently high to allow it to set $b_2 < b_1$.

- Its motive for doing this is that it anticipates a likely war at $t = 3$.

At time $t = 2$ the government trades state-contingent Arrow securities to hedge against war at $t = 3$.

- It purchases a security that pays off when $g_3 = g_h$.
- It sells a security that pays off when $g_3 = g_l$.
38.5. EXAMPLES

- These purchases are designed in such a way that regardless of whether or not there is a war at \( t = 3 \), the government will begin period \( t = 4 \) with the same government debt.
- The time \( t = 4 \) debt level can be serviced with revenues from the constant tax rate set at times \( t \geq 1 \).

At times \( t \geq 4 \) the government rolls over its debt, knowing that the tax rate is set at a level that raises enough revenue to pay for government purchases and interest payments on its debt.

38.5.3 Time 0 Manipulation of Interest Rate

We have seen that when \( b_0 > 0 \), the Ramsey plan sets the time \( t = 0 \) tax rate partly with an eye toward lowering a risk-free interest rate for one-period loans between times \( t = 0 \) and \( t = 1 \).

By lowering this interest rate, the plan makes time \( t = 0 \) goods cheap relative to consumption goods at later times.

By doing this, it lowers the value of time \( t = 0 \) debt that it has inherited and must finance.

38.5.4 Time 0 and Time-Inconsistency

In the preceding example, the Ramsey tax rate at time 0 differs from its value at time 1.

To explore what is going on here, let’s simplify things by removing the possibility of war at time \( t = 3 \).

The Ramsey problem then includes no randomness because \( g_t = g_t \) for all \( t \).

The figure below plots the Ramsey tax rates and gross interest rates at time \( t = 0 \) and time \( t \geq 1 \) as functions of the initial government debt (using the sequential allocation solution and a CRRA utility function defined above)

In [8]:
```python
tax_sequence = SequentialAllocation(CRRAutility(G=0.15,
π=np.ones((1, 1)),
Θ=np.ones(1)))
n = 100
tax_policy = np.empty((n, 2))
interest_rate = np.empty((n, 2))
gov_debt = np.linspace(-1.5, 1, n)

for i in range(n):
tax_policy[i] = tax_sequence.simulate(gov_debt[i], Θ, 2)[3]
interest_rate[i] = tax_sequence.simulate(gov_debt[i], Θ, 3)[-1]

fig, axes = plt.subplots(2, 1, figsize=(10,8), sharex=True)
titles = ['Tax Rate', 'Gross Interest Rate']

for ax, title, plot in zip(axes, titles, [tax_policy, interest_rate]):
    ax.plot(gov_debt, plot[:, 0], gov_debt, plot[:, 1], lw=2)
    ax.set(title=title, xlim=(min(gov_debt), max(gov_debt)))
ax.grid()

axes[0].legend(('Time $t=0$', 'Time $t \geq 1$'))
axes[1].set_xlabel('Initial Government Debt')
```

The figure indicates that if the government enters with positive debt, it sets a tax rate at \( t = 0 \) that is less than all later tax rates. By setting a lower tax rate at \( t = 0 \), the government raises consumption, which reduces the value \( u_{c,0}b_{0} \) of its initial debt. It does this by increasing \( c_{0} \) and thereby lowering \( u_{c,0} \).

Conversely, if \( b_{0} < 0 \), the Ramsey planner sets the tax rate at \( t = 0 \) higher than in subsequent periods.

A side effect of lowering time \( t = 0 \) consumption is that it lowers the one-period interest rate at time \( t = 0 \) below that of subsequent periods.

There are only two values of initial government debt at which the tax rate is constant for all \( t \geq 0 \).

The first is \( b_{0} = 0 \)

- Here the government can’t use the \( t = 0 \) tax rate to alter the value of the initial debt.

The second occurs when the government enters with sufficiently large assets that the Ramsey planner can achieve first best and sets \( \tau_{t} = 0 \) for all \( t \).

It is only for these two values of initial government debt that the Ramsey plan is time-consistent.
Another way of saying this is that, except for these two values of initial government debt, a continuation of a Ramsey plan is not a Ramsey plan.

To illustrate this, consider a Ramsey planner who starts with an initial government debt $b_1$ associated with one of the Ramsey plans computed above.

Call $\tau^R_1$ the time $t = 0$ tax rate chosen by the Ramsey planner confronting this value for initial government debt government.

The figure below shows both the tax rate at time 1 chosen by our original Ramsey planner and what a new Ramsey planner would choose for its time $t = 0$ tax rate.

In [9]:
```python
tax_sequence = SequentialAllocation(CRRAutility(G=0.15,
                                   \pi=np.ones((1, 1)),
                                   \Theta=np.ones(1)))

n = 100
tax_policy = np.empty((n, 2))
\tau_reset = np.empty((n, 2))
gov_debt = np.linspace(-1.5, 1, n)

for i in range(n):
    tax_policy[i] = tax_sequence.simulate(gov_debt[i], \Theta, 2)[3]
    \tau_reset[i] = tax_sequence.simulate(gov_debt[i], \Theta, 1)[3]

fig, ax = plt.subplots(figsize=(10, 6))
ax.plot(gov_debt, tax_policy[:, 1], gov_debt, \tau_reset, lw=2)
ax.set(xlabel='Initial Government Debt', title='Tax Rate',
       xlim=(min(gov_debt), max(gov_debt)))
ax.legend(((r'$\tau_1$', r'$\tau^R_1$'))
ax.grid()

fig.tight_layout()
plt.show()
The tax rates in the figure are equal for only two values of initial government debt.

### 38.5.5 Tax Smoothing and non-CRRA Preferences

The complete tax smoothing for \( t \geq 1 \) in the preceding example is a consequence of our having assumed CRRA preferences.

To see what is driving this outcome, we begin by noting that the Ramsey tax rate for \( t \geq 1 \) is a time-invariant function \( \tau(\Phi, g) \) of the Lagrange multiplier on the implementability constraint and government expenditures.

For CRRA preferences, we can exploit the relations \( U_{cc}c = -\sigma U_c \) and \( U_{nn}n = \gamma U_n \) to derive

\[
\frac{(1 + (1 - \sigma)\Phi)U_c}{(1 + (1 - \gamma)\Phi)U_n} = 1
\]

from the first-order conditions.

This equation immediately implies that the tax rate is constant.

For other preferences, the tax rate may not be constant.

For example, let the period utility function be

\[
u(c, n) = \log(c) + 0.69 \log(1 - n)\]

We will create a new class LogUtility to represent this utility function

```python
In [10]: import numpy as np
class LogUtility:
    def __init__(self,
        β=0.9,
        ψ=0.69,
        π=0.5*np.ones((2, 2)),
        G=np.array([0.1, 0.2]),
        Θ=np.ones(2),
        transfers=False):
        self.β, self.ψ, self.π = β, ψ, π
        self.G, self.Θ, self.transfers = G, Θ, transfers

    # Utility function
    def U(self, c, n):
        return np.log(c) + self.ψ * np.log(1 - n)

    # Derivatives of utility function
    def Uc(self, c, n):
        return 1 / c

    def Ucc(self, c, n):
        return -c**(-2)

    def Un(self, c, n):
        return -self.ψ / (1 - n)
```
def Unn(self, c, n):
    return -self.ψ / (1 - n)**2

Also, suppose that $g_t$ follows a two-state IID process with equal probabilities attached to $g_l$ and $g_h$.

To compute the tax rate, we will use both the sequential and recursive approaches described above.

The figure below plots a sample path of the Ramsey tax rate.

In [11]:
```
log_example = LogUtility()
# Solve sequential problem
seq_log = SequentialAllocation(log_example)

# Initialize grid for value function iteration and solve
μ_grid = np.linspace(-0.6, 0.0, 200)
# Solve recursive problem
bel_log = RecursiveAllocation(log_example, μ_grid)

T = 20
sHist = np.array([0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 0])

# Simulate
sim_seq = seq_log.simulate(0.5, 0, T, sHist)
sim_bel = bel_log.simulate(0.5, 0, T, sHist)

# Government spending paths
sim_seq[4] = log_example.G[sHist]

# Output paths
```

fig, axes = plt.subplots(3, 2, figsize=(14, 10))

for ax, title, sim_s, sim_b in zip(axes.flatten(), titles, sim_seq, sim_bel):
    ax.plot(sim_s, '-ob', sim_b, '-xk', alpha=0.7)
    ax.set(title=title)
    ax.grid()

axes.flatten()[0].legend(['Sequential', 'Recursive'])
fig.tight_layout()
plt.show()
As should be expected, the recursive and sequential solutions produce almost identical allocations.

Unlike outcomes with CRRA preferences, the tax rate is not perfectly smoothed.

Instead, the government raises the tax rate when $g_t$ is high.

### 38.5.6 Further Comments

A related lecture describes an extension of the Lucas-Stokey model by Aiyagari, Marcet, Sargent, and Seppälä (2002) \[3\].

In the AMSS economy, only a risk-free bond is traded.

That lecture compares the recursive representation of the Lucas-Stokey model presented in this lecture with one for an AMSS economy.

By comparing these recursive formulations, we shall glean a sense in which the dimension of the state is lower in the Lucas Stokey model.

Accompanying that difference in dimension will be different dynamics of government debt.
Chapter 39

Optimal Taxation without State-Contingent Debt

39.1 Contents

- Overview 39.2
- Competitive Equilibrium with Distorting Taxes 39.3
- Recursive Version of AMSS Model 39.4
- Examples 39.5

Software Requirement:

This lecture requires the use of some older software versions to run. If you would like to execute this lecture please download the following amss_environment.yml file. This specifies the software required and an environment can be created using conda:

Open a terminal:

conda env create --file amss_environment.yml
conda activate amss

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install --upgrade quantecon

39.2 Overview

Let’s start with following imports:

In [2]: import numpy as np
   import matplotlib.pyplot as plt
   %matplotlib inline
   from scipy.optimize import root, fmin_slsqp
   from scipy.interpolate import UnivariateSpline
   from quantecon import MarkovChain

In an earlier lecture, we described a model of optimal taxation with state-contingent debt due to Robert E. Lucas, Jr., and Nancy Stokey [45].
Aiyagari, Marcet, Sargent, and Seppälä [3] (hereafter, AMSS) studied optimal taxation in a model without state-contingent debt.

In this lecture, we

- describe assumptions and equilibrium concepts
- solve the model
- implement the model numerically
- conduct some policy experiments
- compare outcomes with those in a corresponding complete-markets model

We begin with an introduction to the model.

39.3 Competitive Equilibrium with Distorting Taxes

Many but not all features of the economy are identical to those of the Lucas-Stokey economy. Let’s start with things that are identical.

For \( t \geq 0 \), a history of the state is represented by \( s^t = [s_t, s_{t-1}, \ldots, s_0] \).

Government purchases \( g(s) \) are an exact time-invariant function of \( s \).

Let \( c_t(s^t), \ell_t(s^t) \), and \( n_t(s^t) \) denote consumption, leisure, and labor supply, respectively, at history \( s^t \) at time \( t \).

Each period a representative household is endowed with one unit of time that can be divided between leisure \( \ell_t \) and labor \( n_t \):

\[
n_t(s^t) + \ell_t(s^t) = 1
\]  

(1)

Output equals \( n_t(s^t) \) and can be divided between consumption \( c_t(s^t) \) and \( g(s_t) \)

\[
c_t(s^t) + g(s_t) = n_t(s^t)
\]  

(2)

Output is not storable.

The technology pins down a pre-tax wage rate to unity for all \( t, s^t \).

A representative household’s preferences over \( \{c_t(s^t), \ell_t(s^t)\}_t^{\infty} \) are ordered by

\[
\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t) u[c_t(s^t), \ell_t(s^t)]
\]  

(3)

where

- \( \pi_t(s^t) \) is a joint probability distribution over the sequence \( s^t \), and
- the utility function \( u \) is increasing, strictly concave, and three times continuously differentiable in both arguments.

The government imposes a flat rate tax \( \tau_t(s^t) \) on labor income at time \( t \), history \( s^t \).

Lucas and Stokey assumed that there are complete markets in one-period Arrow securities; also see smoothing models.

It is at this point that AMSS [3] modify the Lucas and Stokey economy.
AMSS allow the government to issue only one-period risk-free debt each period.

Ruling out complete markets in this way is a step in the direction of making total tax collections behave more like that prescribed in \[7\] than they do in \[45\].

### 39.3.1 Risk-free One-Period Debt Only

In period \(t\) and history \(s^t\), let

- \(b_{t+1}(s^t)\) be the amount of the time \(t + 1\) consumption good that at time \(t\) the government promised to pay
- \(R_t(s^t)\) be the gross interest rate on risk-free one-period debt between periods \(t\) and \(t + 1\)
- \(T_t(s^t)\) be a non-negative lump-sum transfer to the representative household Section ??

That \(b_{t+1}(s^t)\) is the same for all realizations of \(s_{t+1}\) captures its risk-free character.

The market value at time \(t\) of government debt maturing at time \(t + 1\) equals \(b_{t+1}(s^t)\) divided by \(R_t(s^t)\).

The government’s budget constraint in period \(t\) at history \(s^t\) is

\[
b_t(s^{t-1}) = \tau_t^n(s^t)n_c(s^t) - g_t(s^t) - T_t(s^t) + \frac{b_{t+1}(s^t)}{R_t(s^t)} \equiv z(s^t) + \frac{b_{t+1}(s^t)}{R_t(s^t)},
\]

where \(z(s^t)\) is the net-of-interest government surplus.

To rule out Ponzi schemes, we assume that the government is subject to a natural debt limit (to be discussed in a forthcoming lecture).

The consumption Euler equation for a representative household able to trade only one-period risk-free debt with one-period gross interest rate \(R_t(s^t)\) is

\[
\frac{1}{R_t(s^t)} = \sum_{s_{t+1}|s^t} \beta \pi_{t+1}(s^{t+1}|s^t) u_c(s^{t+1}) u_c(s^t) b_{t+1}(s^t) \]

Substituting this expression into the government’s budget constraint (4) yields:

\[
b_t(s^{t-1}) = z(s^t) + \beta \sum_{s_{t+1}|s^t} \pi_{t+1}(s^{t+1}|s^t) u_c(s^{t+1}) u_c(s^t) b_{t+1}(s^t)
\]

Components of \(z(s^t)\) on the right side depend on \(s^t\), but the left side is required to depend on \(s^{t-1}\) only.

**This is what it means for one-period government debt to be risk-free.**

Therefore, the sum on the right side of equation (5) also has to depend only on \(s^{t-1}\).

This requirement will give rise to measurability constraints on the Ramsey allocation to be discussed soon.

If we replace \(b_{t+1}(s^t)\) on the right side of equation (5) by the right side of next period’s budget constraint (associated with a particular realization \(s_t\)) we get
\[ b_t(s^{t-1}) = z(s^t) + \sum_{s^{t+1}|s^t} \beta \pi_{t+1}(s^{t+1}|s^t) \frac{u_c(s^{t+1})}{u_c(s^t)} \left[ z(s^{t+1}) + \frac{b_{t+2}(s^{t+1})}{R_{t+1}(s^{t+1})} \right] \]

After making similar repeated substitutions for all future occurrences of government indebtedness, and by invoking the natural debt limit, we arrive at:

\[ b_t(s^{t-1}) = \sum_{j=0}^{\infty} \sum_{s^{t+j}|s^t} \beta^j \pi_{t+j}(s^{t+j}|s^t) \frac{u_c(s^{t+j})}{u_c(s^t)} z(s^{t+j}) \] (6)

Now let’s

- substitute the resource constraint into the net-of-interest government surplus, and
- use the household’s first-order condition \( 1 - \tau^n(s^t) = \frac{u_c(s^t)}{u_c(s^t)} \) to eliminate the labor tax rate so that we can express the net-of-interest government surplus \( z(s^t) \) as

\[ z(s^t) = \left[ 1 - \frac{u_c(s^t)}{u_c(s^t)} \right] [c_t(s^t) + g_t(s^t)] - g_t(s^t) - T_t(s^t). \] (7)

If we substitute the appropriate versions of the right side of (7) for \( z(s^{t+j}) \) into equation (6), we obtain a sequence of implementability constraints on a Ramsey allocation in an AMSS economy.

Expression (6) at time \( t = 0 \) and initial state \( s^0 \) was also an implementability constraint on a Ramsey allocation in a Lucas-Stokey economy:

\[ b_0(s^{-1}) = E_0 \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^j)}{u_c(s^0)} z(s^j) \] (8)

Indeed, it was the only implementability constraint there.

But now we also have a large number of additional implementability constraints

\[ b_t(s^{t-1}) = E_t \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^{t+j})}{u_c(s^t)} z(s^{t+j}) \] (9)

Equation (9) must hold for each \( s^t \) for each \( t \geq 1 \).

### 39.3.2 Comparison with Lucas-Stokey Economy

The expression on the right side of (9) in the Lucas-Stokey (1983) economy would equal the present value of a continuation stream of government surpluses evaluated at what would be competitive equilibrium Arrow-Debreu prices at date \( t \).

In the Lucas-Stokey economy, that present value is measurable with respect to \( s^t \).

In the AMSS economy, the restriction that government debt be risk-free imposes that that same present value must be measurable with respect to \( s^{t-1} \).

In a language used in the literature on incomplete markets models, it can be said that the AMSS model requires that at each \( (t, s^t) \) what would be the present value of continuation
government surpluses in the Lucas-Stokey model must belong to the marketable subspace of the AMSS model.

### 39.3.3 Ramsey Problem Without State-contingent Debt

After we have substituted the resource constraint into the utility function, we can express the Ramsey problem as being to choose an allocation that solves

$$\max_{\{c_t(s^t), b_{t+j}(s^t)\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t u(c_t(s^t), 1 - c_t(s^t) - g_t(s_t))$$

where the maximization is subject to

$$\mathbb{E}_0 \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^j)}{u_c(s^0)} z(s^j) \geq b_0(s^{-1}) \tag{10}$$

and

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^{t+j})}{u_c(s^t)} z(s^{t+j}) = b_t(s^{t-1}) \quad \forall s^t \tag{11}$$

given $b_0(s^{-1})$.

### Lagrangian Formulation

Let $\gamma_0(s^0)$ be a non-negative Lagrange multiplier on constraint (10).

As in the Lucas-Stokey economy, this multiplier is strictly positive when the government must resort to distortionary taxation; otherwise it equals zero.

A consequence of the assumption that there are no markets in state-contingent securities and that a market exists only in a risk-free security is that we have to attach stochastic processes $\{\gamma_t(s^t)\}_{t=1}^{\infty}$ of Lagrange multipliers to the implementability constraints (11).

Depending on how the constraints bind, these multipliers can be positive or negative:

$$\gamma_t(s^t) \geq (\leq) 0 \quad \text{if the constraint binds in this direction}$$

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{u_c(s^{t+j})}{u_c(s^t)} z(s^{t+j}) \geq (\leq) b_t(s^{t-1})$$

A negative multiplier $\gamma_t(s^t) < 0$ means that if we could relax constraint (11), we would like to increase the beginning-of-period indebtedness for that particular realization of history $s^t$.

That would let us reduce the beginning-of-period indebtedness for some other history Section ??.

These features flow from the fact that the government cannot use state-contingent debt and therefore cannot allocate its indebtedness efficiently across future states.
39.3.4 Some Calculations

It is helpful to apply two transformations to the Lagrangian. Multiply constraint \((10)\) by \(u_c(s^t)\) and the constraints \((11)\) by \(\beta^t u_c(s^t)\).

Then a Lagrangian for the Ramsey problem can be represented as

\[
J = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ u(c_t(s^t), 1 - c_t(s^t) - g_t(s_t)) + \gamma_t(s^t) \right\}
\]

\[
= \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ u(c_t(s^t), 1 - c_t(s^t) - g_t(s_t)) + \Psi_t(s^t) z(s^t) - \gamma_t(s^t) u_c(s^t) b_t(s^{t-1}) \right\}
\]

where

\[
\Psi_t(s^t) = \Psi_{t-1}(s^{t-1}) + \gamma_t(s^t) \quad \text{and} \quad \Psi_{-1}(s^{1}) = 0
\]

In \((12)\), the second equality uses the law of iterated expectations and Abel’s summation formula (also called \textit{summation by parts}, see this page).

First-order conditions with respect to \(c_t(s^t)\) can be expressed as

\[
u_c(s^t) - u_c(s^t) + \Psi_t(s^t) \left\{ [u_{cc}(s^t) - u_{cd}(s^t)] z(s^t) + u_c(s^t) z_c(s^t) \right\}
- \gamma_t(s^t) [u_{cc}(s^t) - u_{cd}(s^t)] b_t(s^{t-1}) = 0
\]

and with respect to \(b_t(s^t)\) as

\[
\mathbb{E}_t \left[ \gamma_{t+1}(s^{t+1}) u_c(s^{t+1}) \right] = 0
\]

If we substitute \(z(s^t)\) from \((7)\) and its derivative \(z_c(s^t)\) into the first-order condition \((14)\), we find two differences from the corresponding condition for the optimal allocation in a Lucas-Stokey economy with state-contingent government debt.

1. The term involving \(b_t(s^{t-1})\) in the first-order condition \((14)\) does not appear in the corresponding expression for the Lucas-Stokey economy.

   • This term reflects the constraint that beginning-of-period government indebtedness must be the same across all realizations of next period’s state, a constraint that would not be present if government debt could be state contingent.

1. The Lagrange multiplier \(\Psi_t(s^t)\) in the first-order condition \((14)\) may change over time in response to realizations of the state, while the multiplier \(\Phi\) in the Lucas-Stokey economy is time-invariant.

We need some code from our an earlier lecture on optimal taxation with state-contingent debt sequential allocation implementation:
In [3]:
import numpy as np
from scipy.optimize import root
from quantecon import MarkovChain

class SequentialAllocation:
    
    # Class that takes CESutility or BGUtility object as input returns planner's allocation as a function of the multiplier on the implementability constraint $\mu$.

    def __init__(self, model):
        
        # Initialize from model object attributes
        self.\beta, self.\pi, self.G = model.\beta, model.\pi, model.G
        self.mc, self.\Theta = MarkovChain(self.\pi), model.\Theta
        self.S = len(model.\pi)  # Number of states
        self.model = model

        # Find the first best allocation
        self.find_first_best()

    def find_first_best(self):
        
        # Find the first best allocation

        model = self.model
        S, \Theta, G = self.S, self.\Theta, self.G
        Uc, Un = model.Uc, model.Un

        def res(z):
            c = z[:S]
            n = z[S:]
            return np.hstack([\Theta * Uc(c, n) + Un(c, n), \Theta * n - c - G])

        res = root(res, 0.5 * np.ones(2 * S))

        if not res.success:
            raise Exception('Could not find first best')

        self.cFB = res.x[:S]
        self.nFB = res.x[S:]

        # Multiplier on the resource constraint
        self.\Xi_FB = Uc(self.cFB, self.nFB)
        self.zFB = np.hstack([self.cFB, self.nFB, self.\Xi_FB])

    def time1_allocation(self, $\mu$):
        
        # Computes optimal allocation for time $t \geq 1$ for a given $\mu$

        model = self.model
        S, \Theta, G = self.S, self.\Theta, self.G
        Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn

        def FOC(z):
c = z[:S]
n = z[S:2 * S]
Ξ = z[2 * S:]

# FOC of c
return np.hstack([Uc(c, n) - μ * (Ucc(c, n) * c + Uc(c, n)) - Ξ,
                 Un(c, n) - μ * (Unn(c, n) * n + Un(c, n)) \
                 + Θ * Ξ,  # FOC of n
                 Θ * n - c - G])

# Find the root of the first-order condition
res = root(FOC, self.zFB)
if not res.success:
    raise Exception('Could not find LS allocation.')
z = res.x

c, n, Ξ = z[:S], z[S:2 * S], z[2 * S:]

# Compute x
I = Uc(c, n) * c + Un(c, n) * n
x = np.linalg.solve(np.eye(S) - self.β * self.π, I)

return c, n, x, Ξ

def time0_allocation(self, B_, s_0):
    '''
    Finds the optimal allocation given initial government debt B_ and
    state s_0
    '''
    model, π, Θ, G, β = self.model, self.π, self.Θ, self.G, self.β
    Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn

    # First order conditions of planner’s problem
    def FOC(z):
        μ, c, n, Ξ = z
        xprime = self.time1_allocation(μ)[2]
        return np.hstack([Uc(c, n) * (c - B_) + Un(c, n) * n + β * π[s_0] \
                          + xprime,
                          Uc(c, n) - μ * (Ucc(c, n) \
                          * (c - B_) + Uc(c, n)) - Ξ,
                          Un(c, n) - μ * (Unn(c, n) * n \
                          + Un(c, n)) + Θ[s_0] * Ξ,
                          (Θ * n - c - G)[s_0]])

    # Find root
    res = root(FOC, np.array([0, self.cFB[s_0], self.nFB[s_0], self.ΞFB[s_0]]))
    if not res.success:
        raise Exception('Could not find time 0 LS allocation.')

    return res.x

def time1_value(self, μ):
    '''
    Find the value associated with multiplier μ
    '''
    c, n, x, Ξ = self.time1_allocation(μ)
    U = self.model.U(c, n)
    V = np.linalg.solve(np.eye(self.S) - self.β * self.π, U)
    return c, n, x, V
def T(self, c, n):
    '''
    Computes T given c, n
    '''
    model = self.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)
    return 1 + Un / (self.Θ * Uc)

def simulate(self, B_, s_0, T, sHist=None):
    '''
    Simulates planners policies for T periods
    '''
    model, π, β = self.model, self.π, self.β
    Uc = model.Uc

    if sHist is None:
        sHist = self.mc.simulate(T, s_0)

    cHist, nHist, Bhist, THist, μHist = np.zeros((5, T))
    RHist = np.zeros(T - 1)

    # Time 0
    μ, cHist[0], nHist[0], _ = self.time0_allocation(B_, s_0)
    THist[0] = self.T(cHist[0], nHist[0])[s_0]
    Bhist[0] = B_
    μHist[0] = μ

    # Time 1 onward
    for t in range(1, T):
        c, n, x, Ξ = self.time1_allocation(μ)
        T = self.T(c, n)
        u_c = Uc(c, n)
        s = sHist[t]
        Eu_c = π[sHist[t - 1]] ⊗ u_c
        cHist[t], nHist[t], Bhist[t], THist[t] = c[s], n[s], x[s] / Eu_c
        RHist[t - 1] = Uc(cHist[t - 1], nHist[t - 1]) / (β * Eu_c)
        μHist[t] = μ

    return np.array([cHist, nHist, Bhist, THist, sHist, μHist, RHist])

To analyze the AMSS model, we find it useful to adopt a recursive formulation using techniques like those in our lectures on dynamic Stackelberg models and optimal taxation with state-contingent debt.

39.4 Recursive Version of AMSS Model

We now describe a recursive formulation of the AMSS economy.

We have noted that from the point of view of the Ramsey planner, the restriction to one-period risk-free securities

- leaves intact the single implementability constraint on allocations (8) from the Lucas-
stookey economy, but

- adds measurability constraints \((6)\) on functions of tails of allocations at each time and history

We now explore how these constraints alter Bellman equations for a time 0 Ramsey planner and for time \(t \geq 1\), history \(s^t\) continuation Ramsey planners.

### 39.4.1 Recasting State Variables

In the AMSS setting, the government faces a sequence of budget constraints

\[
\tau_t(s^t) n_t(s^t) + T_t(s^t) + b_{t+1}(s^t)/R_t(s^t) = g_t + b_t(s^{t-1})
\]

where \(R_t(s^t)\) is the gross risk-free rate of interest between \(t\) and \(t + 1\) at history \(s^t\) and \(T_t(s^t)\) are non-negative transfers.

Throughout this lecture, we shall set transfers to zero (for some issues about the limiting behavior of debt, this makes a possibly important difference from AMSS \([3]\), who restricted transfers to be non-negative).

In this case, the household faces a sequence of budget constraints

\[
b_t(s^{t-1}) + (1 - \tau_t(s^t)) n_t(s^t) = c_t(s^t) + b_{t+1}(s^t)/R_t(s^t)
\]

The household’s first-order conditions are \(u_{c,t} = \beta R_t \mathbb{E}_t u_{c,t+1}\) and \((1 - \tau_t)u_{c,t} = u_{l,t}\).

Using these to eliminate \(R_t\) and \(\tau_t\) from budget constraint \((16)\) gives

\[
b_t(s^{t-1}) + \frac{u_{l,t}(s^t) n_t(s^t)}{u_{c,t}(s^t)} = c_t(s^t) + \frac{\beta(\mathbb{E}_t u_{c,t+1}) b_{t+1}(s^t)}{u_{c,t}(s^t)}
\]

or

\[
u_{c,t}(s^t) b_t(s^{t-1}) + u_{l,t}(s^t) n_t(s^t) = u_{c,t}(s^t) c_t(s^t) + \beta(\mathbb{E}_t u_{c,t+1}) b_{t+1}(s^t)
\]

Now define

\[
x_t \equiv \beta b_{t+1}(s^t) \mathbb{E}_t u_{c,t+1} = u_{c,t}(s^t) \frac{b_{t+1}(s^t)}{R_t(s^t)}
\]

and represent the household’s budget constraint at time \(t\), history \(s^t\) as

\[
\frac{u_{c,t} x_{t-1}}{\beta \mathbb{E}_{t-1} u_{c,t}} = u_{c,t} c_t - u_{l,t} n_t + x_t
\]

for \(t \geq 1\).

### 39.4.2 Measurability Constraints

Write equation \((18)\) as
39.4. **RECURSIVE VERSION OF AMSS MODEL**

\[ b_t(s^{t-1}) = c_t(s^t) - \frac{u_{t,t}(s^t)}{u_{c,t}(s^t)} n_t(s^t) + \frac{\beta(E_t u_{c,t+1})b_{t+1}(s^t)}{u_{c,t}} \]  \hspace{1cm} (21)

The right side of equation (21) expresses the time \( t \) value of government debt in terms of a linear combination of terms whose individual components are measurable with respect to \( s^t \).

The sum of terms on the right side of equation (21) must equal \( b_t(s^{t-1}) \).

That implies that it has to be *measurable* with respect to \( s^{t-1} \).

Eqs. (21) are the *measurability constraints* that the AMSS model adds to the single time 0 implementation constraint imposed in the Lucas and Stokey model.

### 39.4.3 Two Bellman Equations

Let \( \Pi(s|s_-) \) be a Markov transition matrix whose entries tell probabilities of moving from state \( s_- \) to state \( s \) in one period.

Let

- \( V(x_-, s_-) \) be the continuation value of a continuation Ramsey plan at \( x_{t-1} = x_-, s_{t-1} = s_- \) for \( t \geq 1 \)
- \( W(b, s) \) be the value of the Ramsey plan at time 0 at \( b_0 = b \) and \( s_0 = s \)

We distinguish between two types of planners:

For \( t \geq 1 \), the value function for a **continuation Ramsey planner** satisfies the Bellman equation

\[ V(x_-, s_-) = \max_{\{n(s), x(s)\}} \sum_s \Pi(s|s_-)[u(n(s) - g(s), 1 - n(s)) + \beta V(x(s), s)] \]  \hspace{1cm} (22)

subject to the following collection of implementability constraints, one for each \( s \in S \):

\[ \frac{u_c(s)x_-}{\beta \sum_s \Pi(s|s_-)u_c(s)} = u_c(s)(n(s) - g(s)) - u_l(s)n(s) + x(s) \]  \hspace{1cm} (23)

A continuation Ramsey planner at \( t \geq 1 \) takes \( (x_{t-1}, s_{t-1}) = (x_-, s_-) \) as given and before \( s \) is realized chooses \( (n_t(s_i), x_t(s_i)) = (n(s), x(s)) \) for \( s \in S \).

The **Ramsey planner** takes \( (b_0, s_0) \) as given and chooses \( (n_0, x_0) \).

The value function \( W(b_0, s_0) \) for the time \( t = 0 \) Ramsey planner satisfies the Bellman equation

\[ W(b_0, s_0) = \max_{n_0, x_0} u(n_0 - g_0, 1 - n_0) + \beta V(x_0, s_0) \]  \hspace{1cm} (24)

where maximization is subject to

\[ u_{c,0}b_0 = u_{c,0}(n_0 - g_0) - u_{l,0}n_0 + x_0 \]  \hspace{1cm} (25)
39.4.4 Martingale Supercedes State-Variable Degeneracy

Let $\mu(s|s_-)\Pi(s|s_-)$ be a Lagrange multiplier on the constraint (23) for state $s$. After forming an appropriate Lagrangian, we find that the continuation Ramsey planner’s first-order condition with respect to $x(s)$ is

$$\beta V_x(x(s), s) = \mu(s|s_-)$$  \hspace{1cm} (26)

Applying the envelope theorem to Bellman equation (22) gives

$$V_x(x_-, s_-) = \sum_s \Pi(s|s_-) \mu(s|s_-) u_c(s) \beta \sum_{\tilde{s}} \Pi(\tilde{s}|s_-) u_c(\tilde{s})$$  \hspace{1cm} (27)

Equations (26) and (27) imply that

$$V_x(x_-, s_-) = \sum_s \left( \Pi(s|s_-) \frac{u_c(s)}{\beta \sum_{\tilde{s}} \Pi(\tilde{s}|s_-) u_c(\tilde{s})} \right) V_x(x(s), s)$$  \hspace{1cm} (28)

Equation (28) states that $V_x(x, s)$ is a risk-adjusted martingale.

Saying that $V_x(x, s)$ is a risk-adjusted martingale means that $V_x(x, s)$ is a martingale with respect to the probability distribution over $s^t$ sequences that are generated by the twisted transition probability matrix:

$$\tilde{\Pi}(s|s_-) \equiv \Pi(s|s_-) \frac{u_c(s)}{\sum_{\tilde{s}} \Pi(\tilde{s}|s_-) u_c(\tilde{s})}$$

Exercise: Please verify that $\tilde{\Pi}(s|s_-)$ is a valid Markov transition density, i.e., that its elements are all non-negative and that for each $s_-$, the sum over $s$ equals unity.

39.4.5 Absence of State Variable Degeneracy

Along a Ramsey plan, the state variable $x_t = x_t(s^t, b_0)$ becomes a function of the history $s^t$ and initial government debt $b_0$.

In Lucas-Stokey model, we found that

- a counterpart to $V_x(x, s)$ is time-invariant and equal to the Lagrange multiplier on the Lucas-Stokey implementability constraint
- time invariance of $V_x(x, s)$ is the source of a key feature of the Lucas-Stokey model, namely, state variable degeneracy (i.e., $x_t$ is an exact function of $s_t$)

That $V_x(x, s)$ varies over time according to a twisted martingale means that there is no state-variable degeneracy in the AMSS model.

In the AMSS model, both $x$ and $s$ are needed to describe the state.

This property of the AMSS model transmits a twisted martingale component to consumption, employment, and the tax rate.
39.4.6 Digression on Non-negative Transfers

Throughout this lecture, we have imposed that transfers $T_t = 0$.

AMSS [3] instead imposed a nonnegativity constraint $T_t \geq 0$ on transfers.

They also considered a special case of quasi-linear preferences, $u(c, l) = c + H(l)$.

In this case, $V_x(x, s) \leq 0$ is a non-positive martingale.

By the martingale convergence theorem $V_x(x, s)$ converges almost surely.

Furthermore, when the Markov chain $\Pi(s|s_{-})$ and the government expenditure function $g(s)$ are such that $g_t$ is perpetually random, $V_x(x, s)$ almost surely converges to zero.

For quasi-linear preferences, the first-order condition with respect to $n(s)$ becomes

$$(1 - \mu(s|s_{-}))(1 - u_t(s)) + \mu(s|s_{-})n(s)u_l(s) = 0$$

When $\mu(s|s_{-}) = \beta V_x(x(s), x)$ converges to zero, in the limit $u_t(s) = 1 = u_c(s)$, so that $\tau(x(s), s) = 0$.

Thus, in the limit, if $g_t$ is perpetually random, the government accumulates sufficient assets to finance all expenditures from earnings on those assets, returning any excess revenues to the household as non-negative lump-sum transfers.

39.4.7 Code

The recursive formulation is implemented as follows

```python
In [4]: import numpy as np
   from scipy.optimize import fmin_slsqp
   from scipy.optimize import root
   from quantecon import MarkovChain

class RecursiveAllocationAMSS:
   def __init__(self, model, grid, tol_diff=1e-4, tol=1e-4):
      self.\beta, self.\pi, self.G = model.\beta, model.\pi, model.G
      self.mc, self.S = MarkovChain(self.\pi), len(model.\pi)  # Number of states
      self.\Theta, self.model, self.\mugrid = model.\Theta, model, grid
      self.tol_diff, self.tol = tol_diff, tol

   def solve_time1_bellman(self):
      '''
      Solve the time 1 Bellman equation for calibration model and initial grid \mugrid0
      '''
      model, \mugrid0 = self.model, self.\mugrid
      \pi = model.\pi
```
S = len(model.π)

# First get initial fit from Lucas Stokey solution.
# Need to change things to be ex ante
pp = SequentialAllocation(model)
interp = interpolator_factory(2, None)

def incomplete_allocation(μ_, s_):
    c, n, x, V = pp.time1_value(μ_)
    return c, n, π[s_] @ x, π[s_] @ V
cf, nf, xgrid, Vf, xprimef = [], [], [], [], []
for s_ in range(S):
    c, n, x, V = zip(*map(lambda μ: incomplete_allocation(μ, s_), μgrid0))
    c, n, x, V = np.vstack(c).T, np.vstack(n).T, np.hstack(x), np.hstack(V)
    xprimes = np.vstack([x] * S)
    cf.append(interp(x, c))
    nf.append(interp(x, n))
    Vf.append(interp(x, V))
    xgrid.append(x)
    xprimef.append(interp(x, xprimes))

    cf, nf, xprimef = fun_vstack(cf), fun_vstack(nf), fun_vstack(xprimef)
    Vf = fun_hstack(Vf)
policies = [cf, nf, xprimef]

# Create xgrid
x = np.vstack(xgrid).T
xbar = [x.min()[0].max(), x.max()[0].min()]
xgrid = np.linspace(xbar[0], xbar[1], len(μgrid0))
self.xgrid = xgrid

# Now iterate on Bellman equation
T = BellmanEquation(model, xgrid, policies, tol=self.tol)
diff = 1
while diff > self.tol_diff:
    PF = T(Vf)
    Vfnew, policies = self.fit_policy_function(PF)
    diff = np.abs((Vf(xgrid) - Vfnew(xgrid)) / Vf(xgrid)).max()

    print(diff)
    Vf = Vfnew

# Store value function policies and Bellman Equations
self.Vf = Vf
self.policies = policies
self.T = T

def fit_policy_function(self, PF):
    '''
    Fits the policy functions
    '''
    S, xgrid = len(self.π), self.xgrid
    interp = interpolator_factory(3, 0)
    cf, nf, xprimef, Tf, Vf = [], [], [], [], []
    for s_ in range(S):
        PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
Vf.append(interp(xgrid, PFvec[0, :]))
cf.append(interp(xgrid, PFvec[1:1 + S]))
nf.append(interp(xgrid, PFvec[1 + S:1 + 2 * S]))
xprimef.append(interp(xgrid, PFvec[1 + 2 * S:1 + 3 * S]))
Tf.append(interp(xgrid, PFvec[1 + 3 * S:]))
policies = fun_vstack(cf), fun_vstack(nf), fun_vstack(xprimef), fun_vstack(Tf)
Vf = fun_hstack(Vf)
return Vf, policies

def T(self, c, n):
    '''Computes T given c and n'''
    model = self.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)
    return 1 + Un / (self.Θ * Uc)

def time0_allocation(self, B_, s0):
    '''Finds the optimal allocation given initial government debt B_ and state s_0'''
    PF = self.T(self.Vf)
    z0 = PF(B_, s0)
    c0, n0, xprime0, T0 = z0[1:]
    return c0, n0, xprime0, T0

def simulate(self, B_, s_0, T, sHist=None):
    '''Simulates planners policies for T periods'''
    model, π = self.model, self.π
    Uc = model.Uc
cf, nf, xprimef, Tf = self.policies
    if sHist is None:
        sHist = simulate_markov(π, s_0, T)
    cHist, nHist, Bhist, xHist, THist, μHist = np.zeros((7, T))
    # Time 0
    cHist[0], nHist[0], xHist[0], THist[0] = self.time0_allocation(B_, s_0)
    μHist[0] = self.Vf[s_0](xHist[0])
    # Time 1 onward
    for t in range(1, T):
        s_, x, s = sHist[t - 1], xHist[t - 1], sHist[t]
        c, n, xprime, T = cf[s_, :](x), nf[s_, :](x), xprimef[s_, :](x), Tf[s_, :](x)
        T = self.T(c, n)[s]
        u_c = Uc(c, n)
        Eu_c = π[s_, :] @ u_c
\[ \mu_{\text{Hist}[t]} = \text{self}.Vf[s](xprime[s]) \]

\[ c_{\text{Hist}[t]}, n_{\text{Hist}[t]}, B_{\text{Hist}[t]}, T_{\text{Hist}[t]} = c[s], n[s], x / \text{Eu}_c, T \]

\[ x_{\text{Hist}[t]}, T_{\text{Hist}[t]} = xprime[s], T[s] \]

return np.array([cHist, nHist, Bhist, THist, THist, \(\mu_{\text{Hist}}, sHist, x_{\text{Hist}}\])

class BellmanEquation:
    
    "Bellman equation for the continuation of the Lucas-Stokey Problem"
    
    def __init__(self, model, xgrid, policies0, tol, maxiter=1000):
        self.\(\beta\), self.\(\pi\), self.\(G\) = model.\(\beta\), model.\(\pi\), model.\(G\)
        self.S = len(model.\(\pi\))  # Number of states
        self.\(\Theta\), self.model, self.tol = model.\(\Theta\), model, tol
        self.maxiter = maxiter
        self.xbar = [min(xgrid), max(xgrid)]
        self.time_0 = False
        self.z0 = {}
        cf, nf, xprimef = policies0
        for s_ in range(self.S):
            for x in xgrid:  
                self.z0[x, s_] = np.hstack([cf[s_, :],](x),
                                          nf[s_, :, :](x),
                                          xprimef[s_, :, :](x),
                                          np.zeros(self.S)])
        
        self.find_first_best()

    def find_first_best(self):
        
        "Find the first best allocation"
        
        model = self.model
        S, \(\Theta\), Uc, Un, G = self.S, self.\(\Theta\), model.Uc, model.Un, self.\(G\)
        
        def res(z):
            c = z[:S]
            n = z[S:]
            return np.hstack([\(\Theta\) * Uc(c, n) + Un(c, n), \(\Theta\) * n - c - G])
        
        res = root(res, 0.5 * np.ones(2 * S))
        if not res.success:
            raise Exception('Could not find first best')
        self.cFB = res.x[:S]
        self.nFB = res.x[S:]
        IFB = Uc(self.cFB, self.nFB) * self.cFB + \n              Un(self.cFB, self.nFB) * self.nFB
        
        self.xFB = np.linalg.solve(np.eye(S) - self.\(\beta\) * self.\(\pi\), IFB)
self.zFB = {}
for s in range(S):
    self.zFB[s] = np.hstack([self.cFB[s], self.nFB[s], self.π[s] @ self.xFB, 0.])

def __call__(self, Vf):
    '''
    Given continuation value function next period return value
    function this period return T(V) and optimal policies
    '''
    if not self.time_0:
        def PF(x, s):
            return self.get_policies_time1(x, s, Vf)
    else:
        def PF(B_, s0):
            return self.get_policies_time0(B_, s0, Vf)
    return PF

def get_policies_time1(self, x, s_, Vf):
    '''Finds the optimal policies
    '''
    U, Uc, Un = model.U, model.Uc, model.Un

def objf(z):
    c, n, xprime = z[:S], z[S:2 * S], z[2 * S:3 * S]
    Vprime = np.empty(S)
    for s in range(S):
        Vprime[s] = Vf[s](xprime[s])
    return -π[s_] @ (U(c, n) + β * Vprime)

def cons(z):
    c, n, xprime, T = z[:S], z[S:2 * S], z[2 * S:3 * S], z[3 * S:]
    u_c = Uc(c, n)
    Eu_c = π[s_] @ u_c
    return np.hstack([x * u_c / Eu_c - u_c * (c - T) - Un(c, n) * n - β * xprime,
                      Θ * n - c - G])

if model.transfers:
    bounds = [[(0., 100)] * S + [(0., 100)] * S +
        [self.xbar] * S + [(0., 100)] * S
else:
    bounds = [[(0., 100)] * S + [(0., 100)] * S +
        [self.xbar] * S + [(0., 0.)] * S
out, fx, _, imode, smode = fmin_slsqp(objf, self.z0[x, s_],
    f_eqcons=cons, bounds=bounds, full_output=True, iprint=0,
    acc=self.tol, iter=self.maxiter)

if imode > 0:
    raise Exception(smode)

self.z0[x, s_] = out
return np.hstack([[-fx, out]])
def get_policies_time0(self, B_, s0, Vf):
    '''
    Finds the optimal policies
    '''
    model, β, θ, G = self.model, self.β, self.θ, self.G
    U, Uc, Un = model.U, model.Uc, model.Un

def objf(z):
    c, n, xprime = z[:-1]
    return -(U(c, n) + β * Vf[s0](xprime))

def cons(z):
    c, n, xprime, T = z
    return np.hstack([-Uc(c, n) * (c - B_ - T) - Un(c, n) * n - β * xprime,
                      (θ * n - c - G)[s0]])

if model.transfers:
    bounds = [(0., 100), (0., 100), self.xbar, (0., 100.)]
else:
    bounds = [(0., 100), (0., 100), self.xbar, (0., 0.)]
out, fx, _, imode, smode = fmin_slsqp(objf, self.zFB[s0],
    f_eqcons=cons, bounds=bounds, full_output=True, iprint=0)

if imode > 0:
    raise Exception(smode)

return np.hstack([-fx, out])

39.5 Examples

We now turn to some examples.

We will first build some useful functions for solving the model

In [5]: import numpy as np
   from scipy.interpolate import UnivariateSpline

class interpolate_wrapper:
    def __init__(self, F):
        self.F = F
    def __getitem__(self, index):
        return interpolate_wrapper(np.asarray(self.F[index]))
    def reshape(self, *args):
        self.F = self.F.reshape(*args)
        return self
    def transpose(self):
self.F = self.F.transpose()

def __len__(self):
    return len(self.F)

def __call__(self, xvec):
    x = np.atleast_1d(xvec)
    shape = self.F.shape
    if len(x) == 1:
        fhat = np.hstack([f(x) for f in self.F.flatten()])
        return fhat.reshape(shape)
    else:
        fhat = np.vstack([f(x) for f in self.F.flatten()])
        return fhat.reshape(np.hstack((shape, len(x))))

class interpolator_factory:
    def __init__(self, k, s):
        self.k, self.s = k, s
    def __call__(self, xgrid, Fs):
        shape, m = Fs.shape[:-1], Fs.shape[-1]
        Fs = Fs.reshape((-1, m))
        F = []
        xgrid = np.sort(xgrid)  # Sort xgrid
        for Fhat in Fs:
            F.append(UnivariateSpline(xgrid, Fhat, k=self.k, s=self.s))
        return interpolate_wrapper(np.array(F).reshape(shape))

def fun_vstack(fun_list):
    Fs = [IW.F for IW in fun_list]
    return interpolate_wrapper(np.vstack(Fs))

def fun_hstack(fun_list):
    Fs = [IW.F for IW in fun_list]
    return interpolate_wrapper(np.hstack(Fs))

def simulate_markov(π, s_0, T):
    sHist = np.empty(T, dtype=int)
    sHist[0] = s_0
    S = len(π)
    for t in range(1, T):
        sHist[t] = np.random.choice(np.arange(S), p=π[sHist[t - 1]])
    return sHist

39.5.1 Anticipated One-Period War

In our lecture on optimal taxation with state contingent debt we studied how the government manages uncertainty in a simple setting.
As in that lecture, we assume the one-period utility function
\[
    u(c, n) = \frac{c^{1-\sigma}}{1-\sigma} - \frac{n^{1+\gamma}}{1+\gamma}
\]

**Note**
For convenience in matching our computer code, we have expressed utility as a function of \(n\) rather than leisure \(l\).

We consider the same government expenditure process studied in the lecture on optimal taxation with state contingent debt.

Government expenditures are known for sure in all periods except one.

- For \(t < 3\) or \(t > 3\) we assume that \(g_t = g_l = 0.1\).
- At \(t = 3\) a war occurs with probability 0.5.
  - If there is war, \(g_3 = g_h = 0.2\).
  - If there is no war \(g_3 = g_l = 0.1\).

A useful trick is to define components of the state vector as the following six \((t, g)\) pairs:

\[(0, g_l), (1, g_l), (2, g_l), (3, g_l), (3, g_h), (t \geq 4, g_l)\]

We think of these 6 states as corresponding to \(s = 1, 2, 3, 4, 5, 6\).

The transition matrix is
\[
P = \begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0.5 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 \\
\end{pmatrix}
\]

The government expenditure at each state is
\[
g = \begin{pmatrix}
0.1 \\
0.1 \\
0.1 \\
0.1 \\
0.2 \\
0.1 \\
\end{pmatrix}
\]

We assume the same utility parameters as in the Lucas-Stokey economy.

This utility function is implemented in the following class.

In [6]: `import numpy as np`

**class CRRAutility:**

```python
    def __init__(self,
```
\[ \beta = 0.9, \]
\[ \sigma = 2, \]
\[ \gamma = 2, \]
\[ \pi = 0.5 \times \text{np.ones}(2, 2), \]
\[ G = \text{np.array}([[0.1, 0.2], [0.1, 0.1]]), \]
\[ \Theta = \text{np.ones}(2), \]
\[ \text{transfers} = \text{False} \]:

```python
self.\beta, self.\sigma, self.\gamma = \beta, \sigma, \gamma
self.\pi, self.G, self.\Theta, self.transfers = \pi, G, \Theta, \text{transfers}
```

# Utility function
```python
def U(self, c, n):
    \sigma = self.\sigma
    if \sigma == 1.:
        U = \text{np.log}(c)
    else:
        U = (c**((1 - \sigma) - 1)) / (1 - \sigma)
    return U - n**((1 + self.\gamma)) / (1 + self.\gamma)
```

# Derivatives of utility function
```python
def Uc(self, c, n):
    return c**(-self.\sigma)

def Ucc(self, c, n):
    return -self.\sigma * c**(-self.\sigma - 1)

def Un(self, c, n):
    return -n**self.\gamma

def Unn(self, c, n):
    return -self.\gamma * n**self.\gamma - 1
```

The following figure plots the Ramsey plan under both complete and incomplete markets for both possible realizations of the state at time \( t = 3 \).

Optimal policies when the government has access to state contingent debt are represented by black lines, while the optimal policies when there is only a risk-free bond are in red.

Paths with circles are histories in which there is peace, while those with triangle denote war.

In [7]: # Initialize \( \mu \) grid for value function iteration
\( \mu \_\text{grid} = \text{np.linspace}(-0.7, 0.01, 200) \)

```python
time_example = CRRUtility()

time_example.\pi = \text{np.array}([[0, 1, 0, 0, 0, 0],
                               [0, 0, 1, 0, 0, 0],
                               [0, 0, 0, 0.5, 0.5, 0],
                               [0, 0, 0, 0, 0, 1],
                               [0, 0, 0, 0, 0, 1],
                               [0, 0, 0, 0, 0, 1]])

time_example.G = \text{np.array}([[0.1, 0.1, 0.1, 0.2, 0.1, 0.1]])

time_example.\Theta = \text{np.ones}(6)  # \Theta \text{ can in principle be random}

time_example.transfers = \text{True}  # Government can use transfers
# Solve sequential problem
time_sequential = SequentialAllocation(time_example)
# Solve recursive problem
time_bellman = RecursiveAllocationAMSS(time_example, μ_grid)

sHist_h = np.array([0, 1, 2, 3, 5, 5])
sHist_l = np.array([0, 1, 2, 4, 5, 5])

sim_seq_h = time_sequential.simulate(1, 0, 7, sHist_h)
sim_bel_h = time_bellman.simulate(1, 0, 7, sHist_h)
sim_seq_l = time_sequential.simulate(1, 0, 7, sHist_l)
sim_bel_l = time_bellman.simulate(1, 0, 7, sHist_l)

# Government spending paths
sim_seq_h[4] = time_example.G[sHist_h]
sim_bel_h[4] = time_example.G[sHist_h]

# Output paths
sim_seq_h[5] = time_example.Θ[sHist_h] * sim_seq_h[1]

fig, axes = plt.subplots(3, 2, figsize=(14, 10))

for ax, title, sim_l, sim_h, bel_l, bel_h in zip(axes.flatten(), titles, sim_seq_l, sim_seq_h, sim_bel_l, sim_bel_h):
    ax.plot(sim_l, '-ok', sim_h, '-^k', bel_l, '-or', bel_h, '-^r', alpha=0.7)
    ax.set(title=title)
    ax.grid()

plt.tight_layout()
plt.show()
0.06173036856270536
0.05366619923680977
0.04689112616399679
0.041151783361805694
0.036240612996977156
0.03296623862767769
0.0283684629875867
0.025192688519675774
0.02240584283749033
0.01947746596861597
0.017777612457184643
0.015863113233478984
0.014157555815666256
0.01265688198653255
0.011323561335112373
0.01013434235262587
0.009067133148757954
0.00813336288612958
0.007289176649859819
0.006541412692256665
0.005872916325737843
0.005262679947231285
0.004739774790763247
0.004253945356076248
0.0038185916441854827
0.003426484729681375
0.00309793645662841626
0.002768326663824867
0.0024984277711437395
0.0022405919962000076
0.0020186945277340827
0.0018171348595572291
0.001636401890175593
0.0014731338929059088
0.0013228186521306716
0.0011965286522741955
0.0010699233146931647
0.0009619663791918545
0.00086610648912693
0.000780179763634053
0.000704404030125401
0.0006357998611731389
0.0005726395927541625
0.0005148786099604965
0.0004655396622616272
0.0004193436460035334
0.000377405559701474667
0.0003393644617534996
0.00030585688397374688
0.00027489392163788453
0.00024661907756555605
0.00022217617613994842
0.000209613638277695678
0.00018111171888136342
0.0001635894087493217
0.00014736944417742374
0.00013236625373264476
0.000118537594583787
0.00010958655893643692
9.594152397376526e-05
How a Ramsey planner responds to war depends on the structure of the asset market.

If it is able to trade state-contingent debt, then at time $t = 2$

- the government purchases an Arrow security that pays off when $g_3 = g_h$
- the government sells an Arrow security that pays off when $g_3 = g_l$
- These purchases are designed in such a way that regardless of whether or not there is a war at $t = 3$, the government will begin period $t = 4$ with the same government debt.

This pattern facilitates smoothing tax rates across states.

The government without state contingent debt cannot do this.

Instead, it must enter time $t = 3$ with the same level of debt falling due whether there is peace or war at $t = 3$.

It responds to this constraint by smoothing tax rates across time.

To finance a war it raises taxes and issues more debt.

To service the additional debt burden, it raises taxes in all future periods.

The absence of state contingent debt leads to an important difference in the optimal tax policy.

When the Ramsey planner has access to state contingent debt, the optimal tax policy is history independent

- the tax rate is a function of the current level of government spending only, given the Lagrange multiplier on the implementability constraint

Without state contingent debt, the optimal tax rate is history dependent.

- A war at time $t = 3$ causes a permanent increase in the tax rate.
Perpetual War Alert

History dependence occurs more dramatically in a case in which the government perpetually faces the prospect of war.

This case was studied in the final example of the lecture on optimal taxation with state-contingent debt.

There, each period the government faces a constant probability, 0.5, of war.

In addition, this example features the following preferences

\[ u(c, n) = \log(c) + 0.69 \log(1 - n) \]

In accordance, we will re-define our utility function.

In [8]: `import numpy as np`

```python
class LogUtility:
    def __init__(self,  
                 β=0.9,  
                 ψ=0.69,  
                 π=0.5*np.ones((2, 2)),  
                 G=np.array([0.1, 0.2]),  
                 Θ=np.ones(2),  
                 transfers=False):
        self.β, self.ψ, self.π = β, ψ, π  
        self.G, self.Θ, self.transfers = G, Θ, transfers

    # Utility function
    def U(self, c, n):
        return np.log(c) + self.ψ * np.log(1 - n)

    # Derivatives of utility function
    def Uc(self, c, n):
        return 1 / c

    def Ucc(self, c, n):
        return -c**(-2)

    def Un(self, c, n):
        return -self.ψ / (1 - n)

    def Unn(self, c, n):
        return -self.ψ / (1 - n)**2
```

With these preferences, Ramsey tax rates will vary even in the Lucas-Stokey model with state-contingent debt.

The figure below plots optimal tax policies for both the economy with state contingent debt (circles) and the economy with only a risk-free bond (triangles).

In [9]: `log_example = LogUtility()`
   `log_example.transfers = True`  # Government can use transfers
log_sequential = SequentialAllocation(log_example)  # Solve sequential

log_bellman = RecursiveAllocationAMSS(log_example, μ_grid)

T = 20
sHist = np.array([[0, 0, 0, 0, 0, 0, 0, 1, 1,
                   0, 0, 1, 1, 1, 1, 1, 1, 0]])

# Simulate
sim_seq = log_sequential.simulate(0.5, 0, T, sHist)
sim_bel = log_bellman.simulate(0.5, 0, T, sHist)

titles = ['Consumption', 'Labor Supply', 'Government Debt',
          'Tax Rate', 'Government Spending', 'Output']

# Government spending paths
sim_seq[4] = log_example.G[sHist]

# Output paths

fig, axes = plt.subplots(3, 2, figsize=(14, 10))

for ax, title, seq, bel in zip(axes.flatten(), titles, sim_seq, sim_bel):
    ax.plot(seq, '-ok', bel, '-^b')
    ax.set(title=title)
    ax.grid()

axes[0, 0].legend(('Complete Markets', 'Incomplete Markets'))
plt.tight_layout()
plt.show()
39.5. EXAMPLES

```python
3 log_sequential = SequentialAllocation(log_example)  #
Solve sequential problem

4 log_bellman = RecursiveAllocationAMSS(log_example, μ_grid)

5 T = 20

<ipython-input-4-cc6b33fcda51> in __init__(self, model, μ_grid, tol_diff, tol)
15 # Find the first best allocation
16 self.solve_time1_bellman()
17 self.T.time_0 = True  # Bellman equation now solves time 0 problem

<ipython-input-4-cc6b33fcda51> in solve_time1_bellman(self)
62 PF = T(Vf)
63 Vfnew, policies = self.fit_policy_function(PF)
64 diff = np.abs((Vf(xgrid) - Vfnew(xgrid)) / Vf(xgrid)).max()

<ipython-input-4-cc6b33fcda51> in fit_policy_function(self, PF)
81 cf, nf, xprimef, Tf, Vf = [], [], [], [], []
82 for s_ in range(S):
83 PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
84 Vf.append(interp(xgrid, PFvec[0, :]))
85 cf.append(interp(xgrid, PFvec[1:1 + S]))

<ipython-input-4-cc6b33fcda51> in <listcomp>(.0)
81 cf, nf, xprimef, Tf, Vf = [], [], [], [], []
82 for s_ in range(S):
83 PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
84 Vf.append(interp(xgrid, PFvec[0, :]))
85 cf.append(interp(xgrid, PFvec[1:1 + S]))

<ipython-input-4-cc6b33fcda51> in PF(x, s)
207 '''
208 if not self.time_0:
209     def PF(x, s): return self.
```

```
def PF(B_, s0): return self.
→ get_policies_time0(B_, s0, Vf)

<ipython-input-4-cc6b33fcda51> in get_policies_time1(self, x, s_, Vf)
• f_eqcons=cons, bounds=bounds,
• full_output=True, iprint=0,
→ 247 acc=self.
tol, iter=self.maxiter)

if imode > 0:

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/slsqp.py in fmin_slsqp(func, x0, eqcons, f_eqcons, ieqcons, f_ieqcons,
bounds, fprime, fprime_eqcons, fprime_ieqcons, args, iter, acc,
• iprint, disp, full_output, epsilon, callback)
204 205 res = _minimize_slsqp(func, x0, args, jac=fprime,
 bounds=bounds,
→ 206 constraints=cons, **opts)
207 208 if full_output: return res['x'], res['fun'], res['nit'],
• res['status'], res['message']

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/slsqp.py in _minimize_slsqp(func, x0, args, jac, bounds, constraints,
• maxiter, ftol, iprint, disp, eps, callback, finite_diff_rel_step,
• **unknown_options)
424 425 if mode == -1: # gradient evaluation required
• 426 g = append(sf.grad(x), 0.0)
• 427 a = _eval_con_normals(x, cons, la, n, m, meq,
• mieq)
428

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/._differentiable_functions.py in grad(self, x)
186 187 if not np.array_equal(x, self.x):
• 188 self._update_x_impl(x)
• 189 return self.g
190


When the government experiences a prolonged period of peace, it is able to reduce government debt and set permanently lower tax rates.

However, the government finances a long war by borrowing and raising taxes. This results in a drift away from policies with state contingent debt that depends on the history of shocks.

This is even more evident in the following figure that plots the evolution of the two policies over 200 periods.
# Government spending paths
sim_seq_long[4] = log_example.G[sHist_long]

# Output paths

fig, axes = plt.subplots(3, 2, figsize=(14, 10))
for ax, title, seq, bel in zip(axes.flatten(), titles, sim_seq_long, sim_bel_long):
    ax.plot(seq, '-k', bel, '-.b', alpha=0.5)
    ax.set(title=title)
    ax.grid()

axes[0, 0].legend(['Complete Markets', 'Incomplete Markets'])
plt.tight_layout()
plt.show()

Footnotes

[1] In an allocation that solves the Ramsey problem and that levies distorting taxes on labor, why would the government ever want to hand revenues back to the private sector? It would not in an economy with state-contingent debt, since any such allocation could be improved by lowering distortionary taxes rather than handing out lump-sum transfers. But, without state-contingent debt there can be circumstances when a government would like to make lump-sum transfers to the private sector.

[2] From the first-order conditions for the Ramsey problem, there exists another realization $\tilde{s}^t$ with the same history up until the previous period, i.e., $\tilde{s}^{t-1} = s^{t-1}$, but where the multiplier on constraint (11) takes a positive value, so $\gamma_{t}(\tilde{s}^t) > 0$. 

NameError: name 'log_bellman' is not defined
Chapter 40

Fluctuating Interest Rates Deliver Fiscal Insurance

40.1 Contents

- Overview 40.2
- Forces at Work 40.3
- Logical Flow of Lecture 40.4
- Example Economy 40.5
- Reverse Engineering Strategy 40.6
- Code for Reverse Engineering 40.7
- Short Simulation for Reverse-engineered: Initial Debt 40.8
- Long Simulation 40.9
- BEGS Approximations of Limiting Debt and Convergence Rate 40.10

Software Requirement:

This lecture requires the use of some older software versions to run. If you would like to execute this lecture please download the following amss_environment.yml file. This specifies the software required and an environment can be created using conda:

Open a terminal:

    conda env create --file amss_environment.yml
    conda activate amss

In addition to what’s in Anaconda, this lecture will need the following libraries:

    In [1]: !pip install --upgrade quantecon

40.2 Overview

This lecture extends our investigations of how optimal policies for levying a flat-rate tax on labor income and issuing government debt depend on whether there are complete markets for debt.

A Ramsey allocation and Ramsey policy in the AMSS [3] model described in optimal taxation
without state-contingent debt generally differs from a Ramsey allocation and Ramsey policy in the Lucas-Stokey [45] model described in optimal taxation with state-contingent debt.

This is because the implementability restriction that a competitive equilibrium with a distorting tax imposes on allocations in the Lucas-Stokey model is just one among a set of implementability conditions imposed in the AMSS model.

These additional constraints require that time $t$ components of a Ramsey allocation for the AMSS model be measurable with respect to time $t - 1$ information.

The measurability constraints imposed by the AMSS model are inherited from the restriction that only one-period risk-free bonds can be traded.

Differences between the Ramsey allocations in the two models indicate that at least some of the measurability constraints of the AMSS model of optimal taxation without state-contingent debt are violated at the Ramsey allocation of a corresponding [45] model with state-contingent debt.

Another way to say this is that differences between the Ramsey allocations of the two models indicate that some of the measurability constraints of the AMSS model are violated at the Ramsey allocation of the Lucas-Stokey model.

Nonzero Lagrange multipliers on those constraints make the Ramsey allocation for the AMSS model differ from the Ramsey allocation for the Lucas-Stokey model.

This lecture studies a special AMSS model in which

- The exogenous state variable $s_t$ is governed by a finite-state Markov chain.
- With an arbitrary budget-feasible initial level of government debt, the measurability constraints
  - bind for many periods, but ....
  - eventually, they stop binding evermore, so ....
  - in the tail of the Ramsey plan, the Lagrange multipliers $\gamma_t(s^t)$ on the AMSS implementability constraints (8) converge to zero.
- After the implementability constraints (8) no longer bind in the tail of the AMSS Ramsey plan
  - history dependence of the AMSS state variable $x_t$ vanishes and $x_t$ becomes a time-invariant function of the Markov state $s_t$.
  - the par value of government debt becomes constant over time so that $b_{t+1}(s^t) = \bar{b}$ for $t \geq T$ for a sufficiently large $T$.
  - $\bar{b} < 0$, so that the tail of the Ramsey plan instructs the government always to make a constant par value of risk-free one-period loans to the private sector.
  - the one-period gross interest rate $R_t(s^t)$ on risk-free debt converges to a time-invariant function of the Markov state $s_t$.
- For a particular $b_0 < 0$ (i.e., a positive level of initial government loans to the private sector), the measurability constraints never bind.
- In this special case
  - the par value $b_{t+1}(s_t) = \bar{b}$ of government debt at time $t$ and Markov state $s_t$ is constant across time and states, but ....
  - the market value $\frac{b}{R_t(s_t)}$ of government debt at time $t$ varies as a time-invariant function of the Markov state $s_t$.
  - fluctuations in the interest rate make gross earnings on government debt $\frac{b}{R_t(s_t)}$ fully insure the gross-of-gross-interest-payments government budget against fluctuations in government expenditures.
  - the state variable $x$ in a recursive representation of a Ramsey plan is a time-
40.3. FORCES AT WORK

invariant function of the Markov state for $t \geq 0$.

- In this special case, the Ramsey allocation in the AMSS model agrees with that in a [45] model in which the same amount of state-contingent debt falls due in all states tomorrow
  - it is a situation in which the Ramsey planner loses nothing from not being able to purchase state-contingent debt and being restricted to exchange only risk-free debt debt.
- This outcome emerges only when we initialize government debt at a particular $b_0 < 0$.

In a nutshell, the reason for this striking outcome is that at a particular level of risk-free government assets, fluctuations in the one-period risk-free interest rate provide the government with complete insurance against stochastically varying government expenditures.

Let’s start with some imports:

```
In [2]: import matplotlib.pyplot as plt
%matplotlib inline
from scipy.optimize import fsolve, fmin
```

40.3 Forces at Work

The forces driving asymptotic outcomes here are examples of dynamics present in a more general class incomplete markets models analyzed in [10] (BEGS).

BEGS provide conditions under which government debt under a Ramsey plan converges to an invariant distribution.

BEGS construct approximations to that asymptotically invariant distribution of government debt under a Ramsey plan.

BEGS also compute an approximation to a Ramsey plan’s rate of convergence to that limiting invariant distribution.

We shall use the BEGS approximating limiting distribution and the approximating rate of convergence to help interpret outcomes here.

For a long time, the Ramsey plan puts a nontrivial martingale-like component into the par value of government debt as part of the way that the Ramsey plan imperfectly smooths distortions from the labor tax rate across time and Markov states.

But BEGS show that binding implementability constraints slowly push government debt in a direction designed to let the government use fluctuations in equilibrium interest rate rather than fluctuations in par values of debt to insure against shocks to government expenditures.

- This is a weak (but unrelenting) force that, starting from an initial debt level, for a long time is dominated by the stochastic martingale-like component of debt dynamics that the Ramsey planner uses to facilitate imperfect tax-smoothing across time and states.
- This weak force slowly drives the par value of government assets to a constant level at which the government can completely insure against government expenditure shocks while shutting down the stochastic component of debt dynamics.
- At that point, the tail of the par value of government debt becomes a trivial martingale: it is constant over time.
40.4 Logical Flow of Lecture

We present ideas in the following order

- We describe a two-state AMSS economy and generate a long simulation starting from a positive initial government debt.
- We observe that in a long simulation starting from positive government debt, the par value of government debt eventually converges to a constant $\bar{b}$.
- In fact, the par value of government debt converges to the same constant level $\bar{b}$ for alternative realizations of the Markov government expenditure process and for alternative settings of initial government debt $b_0$.
- We reverse engineer a particular value of initial government debt $b_0$ (it turns out to be negative) for which the continuation debt moves to $\bar{b}$ immediately.
- We note that for this particular initial debt $b_0$, the Ramsey allocations for the AMSS economy and the Lucas-Stokey model are identical.
- We compute the BEGS approximations to check how accurately they describe the dynamics of the long-simulation.

40.4.1 Equations from Lucas-Stokey (1983) Model

Although we are studying an AMSS [3] economy, a Lucas-Stokey [45] economy plays an important role in the reverse-engineering calculation to be described below.

For that reason, it is helpful to have readily available some key equations underlying a Ramsey plan for the Lucas-Stokey economy.

Recall first-order conditions for a Ramsey allocation for the Lucas-Stokey economy.

For $t \geq 1$, these take the form

$$
(1 + \Phi)u_c(c, 1 - c - g) + \Phi [cu_{c\ell}(c, 1 - c - g) - (c + g)u_{\ell\ell}(c, 1 - c - g)]
= (1 + \Phi)u_\ell(c, 1 - c - g) + \Phi [cu_{\ell\ell}(c, 1 - c - g) - (c + g)u_{\ell\ell}(c, 1 - c - g)]
$$

(1)

There is one such equation for each value of the Markov state $s_t$.

In addition, given an initial Markov state, the time $t = 0$ quantities $c_0$ and $b_0$ satisfy

$$
(1 + \Phi)u_c(c, 1 - c - g) + \Phi [cu_{c\ell}(c, 1 - c - g) - (c + g)u_{\ell\ell}(c, 1 - c - g)]
= (1 + \Phi)u_\ell(c, 1 - c - g) + \Phi [cu_{\ell\ell}(c, 1 - c - g) - (c + g)u_{\ell\ell}(c, 1 - c - g)] + \Phi (u_{cc} - u_{c,\ell})b_0
$$

(2)

In addition, the time $t = 0$ budget constraint is satisfied at $c_0$ and initial government debt $b_0$:

$$
b_0 + g_0 = \tau_0(c_0 + g_0) + \frac{b}{R_0}
$$

(3)

where $R_0$ is the gross interest rate for the Markov state $s_0$ that is assumed to prevail at time $t = 0$ and $\tau_0$ is the time $t = 0$ tax rate.

In equation (3), it is understood that
\[ \tau_0 = 1 - \frac{u_{l,0}}{u_{c,0}} \]

\[ R_0^{-1} = \beta \sum_{s=1}^{S} \Pi(s|s_0) \frac{u_s(s)}{u_{c,0}} \]

It is useful to transform some of the above equations to forms that are more natural for analyzing the case of a CRRA utility specification that we shall use in our example economies.

### 40.4.2 Specification with CRRA Utility

As in lectures optimal taxation without state-contingent debt and optimal taxation with state-contingent debt, we assume that the representative agent has utility function

\[ u(c, n) = \frac{c^{1-\sigma}}{1-\sigma} - \frac{n^{1+\gamma}}{1+\gamma} \]

and set \( \sigma = 2, \gamma = 2 \), and the discount factor \( \beta = 0.9 \).

We eliminate leisure from the model and continue to assume that

\[ c_t + g_t = n_t \]

The analysis of Lucas and Stokey prevails once we make the following replacements

\[ u_{\ell}(c, \ell) \sim -u_n(c, n) \]
\[ u_c(c, \ell) \sim u_c(c, n) \]
\[ u_{\ell,\ell}(c, \ell) \sim u_{nn}(c, n) \]
\[ u_{c,c}(c, \ell) \sim u_{c,c}(c, n) \]
\[ u_{c,\ell}(c, \ell) \sim 0 \]

With these understandings, equations (1) and (2) simplify in the case of the CRRA utility function.

They become

\[ (1 + \Phi)[u_c(c) + u_n(c + g)] + \Phi[cu_{cc}(c) + (c + g)u_{nn}(c + g)] = 0 \]  \( (4) \)

and

\[ (1 + \Phi)[u_c(c_0) + u_n(c_0 + g_0)] + \Phi[c_0u_{cc}(c_0) + (c_0 + g_0)u_{nn}(c_0 + g_0)] - \Phi u_{cc}(c_0)\delta_0 = 0 \] \( (5) \)

In equation (4), it is understood that \( c \) and \( g \) are each functions of the Markov state \( s \).

The CRRA utility function is represented in the following class.

In [3]: `import numpy as np`
class CRRAutility:

def __init__(self, 
    β=0.9, 
    σ=2, 
    γ=2, 
    π=0.5*np.ones((2, 2)), 
    G=np.array([0.1, 0.2]), 
    θ=np.ones(2), 
    transfers=False):
    self.β, self.σ, self.γ = β, σ, γ
    self.π, self.G, self.θ, self.transfers = π, G, θ, transfers

# Utility function
def U(self, c, n):
    σ = self.σ
    if σ == 1.:
        U = np.log(c)
    else:
        U = (c**(1 - σ) - 1) / (1 - σ)
    return U - n***(1 + self.γ) / (1 + self.γ)

# Derivatives of utility function
def Uc(self, c, n):
    return c**(-self.σ)

def Ucc(self, c, n):
    return -self.σ * c**(-self.σ - 1)

def Un(self, c, n):
    return -n**self.γ

def Unn(self, c, n):
    return -self.γ * n**(self.γ - 1)

40.5 Example Economy

We set the following parameter values.
The Markov state $s_t$ takes two values, namely, 0, 1.
The initial Markov state is 0.
The Markov transition matrix is $.5I$ where $I$ is a $2 \times 2$ identity matrix, so the $s_t$ process is IID.
Government expenditures $g(s)$ equal .1 in Markov state 0 and .2 in Markov state 1.
We set preference parameters as follows:

$$
\begin{align*}
\beta &= .9 \\
\sigma &= 2 \\
\gamma &= 2
\end{align*}
$$

Here are several classes that do most of the work for us.
The code is mostly taken or adapted from the earlier lectures optimal taxation without state-contingent debt and optimal taxation with state-contingent debt.

In [4]:
import numpy as np
from scipy.optimize import root
from quantecon import MarkovChain

class SequentialAllocation:

    '''
    Class that takes CESutility or BGUtility object as input returns
    planner’s allocation as a function of the multiplier on the
    implementability constraint μ.
    '''

    def __init__(self, model):
        # Initialize from model object attributes
        self.β, self.π, self.G = model.β, model.π, model.G
        self.mc, self.Θ = MarkovChain(self.π), model.Θ
        self.S = len(model.π)  # Number of states
        self.model = model

        # Find the first best allocation
        self.find_first_best()

def find_first_best(self):

    '''
    Find the first best allocation
    '''
    model = self.model
    S, Θ, G = self.S, self.Θ, self.G
    Uc, Un = model.Uc, model.Un

    def res(z):
        c = z[:S]
        n = z[S:]
        return np.hstack([Θ * Uc(c, n) + Un(c, n), Θ * n - c - G])

    res = root(res, 0.5 * np.ones(2 * S))

    if not res.success:
        raise Exception('Could not find first best')

    self.cFB = res.x[:S]
    self.nFB = res.x[S:]

    # Multiplier on the resource constraint
    self.ΞFB = Uc(self.cFB, self.nFB)
    self.zFB = np.hstack([self.cFB, self.nFB, self.ΞFB])

def time1_allocation(self, μ):

    '''
    Computes optimal allocation for time t >= 1 for a given μ
    '''
    model = self.model
    S, Θ, G = self.S, self.Θ, self.G
Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn

def FOC(z):
    c = z[:S]
    n = z[S:2 * S]
    Ξ = z[2 * S:]
    # FOC of c
    return np.hstack([Uc(c, n) - μ * (Ucc(c, n) * c + Uc(c, n)) - Ξ,
                      Un(c, n) - μ * (Unn(c, n) * n + Un(c, n)) - Ξ,
                      Θ * Ξ])

# Find the root of the first-order condition
res = root(FOC, self.zFB)
if not res.success:
    raise Exception('Could not find LS allocation.')
res = res.x

# Compute x
I = Uc(c, n) * c + Un(c, n) * n
x = np.linalg.solve(np.eye(S) - self.β * self.π, I)
return c, n, x, Ξ

def time0_allocation(self, B_, s_0):
    # Finds the optimal allocation given initial government debt B_ and state s_0
    model, π, Θ, G, β = self.model, self.π, self.Θ, self.G, self.β
    Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn
    # First order conditions of planner's problem
    def FOC(z):
        μ, c, n, Ξ = z
        xprime = self.time1_allocation(μ)[2]
        return np.hstack([Uc(c, n) * (c - B_) + Un(c, n) * n + β * π[s_0] @ xprime,
                          Un(c, n) - μ * (Unn(c, n) * n + Un(c, n)) - Ξ,
                          Θ * n - c - G][s_0]])
    # Find root
    res = root(FOC, np.array([0, self.cFB[s_0], self.nFB[s_0], self.ΞFB[s_0]]))
    if not res.success:
        raise Exception('Could not find time 0 LS allocation.')
    return res.x

def time1_value(self, μ):
    # Find the value associated with multiplier μ
    c, n, x, Ξ = self.time1_allocation(μ)
40.5. EXAMPLE ECONOMY

```python
U = self.model.U(c, n)
V = np.linalg.solve(np.eye(self.S) - self.β * self.π, U)
return c, n, x, V

def T(self, c, n):
    
    Computes T given c, n
    ...

    model = self.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)

    return 1 + Un / (self.Θ * Uc)

def simulate(self, B_, s_0, T, sHist=None):
    
    Simulates planners policies for T periods
    
    model, π, β = self.model, self.π, self.β
    Uc = model.Uc

    if sHist is None:
        sHist = self.mc.simulate(T, s_0)

    cHist, nHist, Bhist, THist, μHist = np.zeros((5, T))
    RHist = np.zeros(T - 1)

    # Time 0
    μ, cHist[0], nHist[0], _ = self.time0_allocation(B_, s_0)
    THist[0] = self.T(cHist[0], nHist[0])[s_0]
    BHist[0] = B_.
    μHist[0] = μ

    # Time 1 onward
    for t in range(1, T):
        c, n, x, Ξ = self.time1_allocation(μ)
        T = self.T(c, n)
        U_c = Uc(c, n)
        s = sHist[t]
        Eu_c = π[sHist[t - 1]] @ U_c
        cHist[t], nHist[t], BHist[t], THist[t] = c[s], n[s], x[s] /
        T[s]
        μHist[t] = μ

    return np.array([cHist, nHist, BHist, THist, sHist, μHist, RHist])

In [5]: import numpy as np
from scipy.optimize import fmin_slsqp
from scipy.optimize import root
from quantecon import MarkovChain

class RecursiveAllocationAMSS:
    
    def __init__(self, model, μgrid, tol_diff=1e-4, tol=1e-4):
        self.β, self.π, self.G = model.β, model.π, model.G
```

In [5]: import numpy as np
from scipy.optimize import fmin_slsqp
from scipy.optimize import root
from quantecon import MarkovChain

class RecursiveAllocationAMSS:
    
    def __init__(self, model, μgrid, tol_diff=1e-4, tol=1e-4):
        self.β, self.π, self.G = model.β, model.π, model.G
self.mc, self.S = MarkovChain(self.π), len(model.π)  # Number of states
self.Θ, self.model, self.μgrid = model.Θ, model, μgrid
self.tol_diff, self.tol = tol_diff, tol

# Find the first best allocation
self.solve_time1_bellman()
self.T.time_0 = True  # Bellman equation now solves time 0 problem

def solve_time1_bellman(self):
    '''
    Solve the time 1 Bellman equation for calibration model and initial grid μgrid0
    '''
    model, μgrid0 = self.model, self.μgrid
    π = model.π
    S = len(model.π)

    # First get initial fit from Lucas Stokey solution.
    # Need to change things to be ex ante
    pp = SequentialAllocation(model)
    interp = interpolator_factory(2, None)

    def incomplete_allocation(μ_, s_):
        return c, n, π[s_] @ x, μ[s_] @ V
    for s_ in range(S):
        c, n, x, V = zip(*map(lambda μ: incomplete_allocation(μ, s_), μgrid0))
        c, n = np.vstack(c).T, np.vstack(n).T
        x, V = np.hstack(x), np.hstack(V)
        xprimes = np.vstack([x]*S)
        cf.append(interp(x, c))
        nf.append(interp(x, n))
        Vf.append(interp(x, V))
        xgrid.append(x)
        xprimef.append(interp(x, xprimes))
    cf, nf, xprimef = fun_vstack(cf), fun_vstack(nf), fun_vstack(xprimef)
    Vf = fun_hstack(Vf)
    policies = [cf, nf, xprimef]

    # Create xgrid
    x = np.vstack(xgrid).T
    xbar = [x.min(0).max(), x.max(0).min()]
    xgrid = np.linspace(xbar[0], xbar[1], len(μgrid0))
    self.xgrid = xgrid

    # Now iterate on Bellman equation
    T = BellmanEquation(model, xgrid, policies, tol=self.tol)
    diff = 1
    while diff > self.tol_diff:
        PF = T(Vf)
        Vfnew, policies = self.fit_policy_function(PF)
        diff = np.abs((Vf(xgrid) - Vfnew(xgrid)) / Vf(xgrid)).max()
        print(diff)
# Store value function policies and Bellman Equations
self.Vf = Vf
self.policies = policies
self.T = T

def fit_policy_function(self, PF):
    ""
    Fits the policy functions
    ""
    S, xgrid = len(self.π), self.xgrid
    interp = interpolator_factory(3, θ)
    cf, nf, xprimef, Tf, Vf = [], [], [], [], []
    for s_ in range(S):
        PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
        Vf.append(interp(xgrid, PFvec[0, :]))
        cf.append(interp(xgrid, PFvec[1:1 + S]))
        nf.append(interp(xgrid, PFvec[1 + S:1 + 2 * S]))
        xprimef.append(interp(xgrid, PFvec[1 + 2 * S:1 + 3 * S]))
        Tf.append(interp(xgrid, PFvec[1 + 3 * S:]))
    policies = fun_vstack(cf), fun_vstack(nf), fun_vstack(xprimef), fun_vstack(Tf)
    Vf = fun_hstack(Vf)
    return Vf, policies

def T(self, c, n):
    ""
    Computes T given c and n
    ""
    model = self.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)
    return 1 + Un / (self.θ * Uc)

def time0_allocation(self, B_, s0):
    ""
    Finds the optimal allocation given initial government debt B_ and state s_0
    ""
    PF = self.T(self.Vf)
    z0 = PF(B_, s0)
    c0, n0, xprime0, T0 = z0[1:]
    return c0, n0, xprime0, T0

def simulate(self, B_, s_0, T, sHist=None):
    ""
    Simulates planners policies for T periods
    ""
    model, π = self.model, self.π
    Uc = model.Uc
    cf, nf, xprimef, Tf = self.policies
    if sHist is None:
        sHist = simulate_markov(π, s_0, T)
        cHist, nHist, Bhist, xHist, THist, THist, μHist = np.zeros((7, T))
    # Time 0
class BellmanEquation:
    '''
    Bellman equation for the continuation of the Lucas-Stokey Problem
    '''

    def __init__(self, model, xgrid, policies0, tol, maxiter=1000):
        self.β, self.π, self.G = model.β, model.π, model.G
        self.S = len(model.π)  # Number of states
        self.Θ, self.model, self.tol = model.Θ, model, tol
        self.maxiter = maxiter

        self.xbar = [min(xgrid), max(xgrid)]
        self.time_0 = False

        self.z0 = {}
        cf, nf, xprimef = policies0

        for s_ in range(self.S):
            for x in xgrid:
                self.z0[x, s_] = np.hstack([cf[x, s_](x),
                                            nf[x, s_](x),
                                            xprimef[x, s_](x),
                                            np.zeros(self.S)])

        self.find_first_best()

def find_first_best(self):
    '''
    Find the first best allocation
    '''
    model = self.model

    cHist[0], nHist[0], xHist[0], THist[0] = self.time_0_allocation(B_,
    \_s_0)
    THist[0] = self.T(cHist[0], nHist[0])[s_0]
    BHist[0] = B_
    \_μHist[0] = self.Vf[s_0](xHist[0])

    # Time 1 onward
    for t in range(1, T):
        s_, x, s = sHist[t - 1], xHist[t - 1], sHist[t]
        c, n, xprime, T = cf[s_, :](x), nf[s_, :](x),
                        xprimef[s_, :](x), Tf[s_, :](x)
        T = self.T(c, n)[s]
        u_c = Uc(c, n)
        Eu_c = π[s_, :] ⊕ u_c

        \_μHist[t] = self.Vf[s](xprime[s])

        cHist[t], nHist[t], BHist[t], THist[t] = c[s], n[s], x / Eu_c, T
        xHist[t], THist[t] = xprime[s], T[s]

        return np.array([cHist, nHist, BHist, THist, \_μHist, sHist, xHist])
def res(z):
c = z[:S]
n = z[S:]
return np.hstack([Θ * Uc(c, n) + Un(c, n), Θ * n - c - G])

res = root(res, 0.5 * np.ones(2 * S))
if not res.success:
    raise Exception('Could not find first best')

self.cFB = res.x[:S]
self.nFB = res.x[S:]
IFB = Uc(self.cFB, self.nFB) * self.cFB + \
    Un(self.cFB, self.nFB) * self.nFB

self.xFB = np.linalg.solve(np.eye(S) - self.β * self.π, IFB)

self.zFB = {}
for s in range(S):
    self.zFB[s] = np.hstack(  
        [self.cFB[s], self.nFB[s], self.π[s] @ self.xFB, 0.])

def __call__(self, Vf):
    '''
    Given continuation value function next period return value function this period return T(V) and optimal policies
    '''
    if not self.time_0:
        def PF(x, s):
            return self.get_policies_time1(x, s, Vf)
    else:
        def PF(B_, s0):
            return self.get_policies_time0(B_, s0, Vf)

    return PF

def get_policies_time1(self, x, s, Vf):
    '''
    Finds the optimal policies
    '''
    U, Uc, Un = model.U, model.Uc, model.Un

def objf(z):
c, n, xprime = z[:S], z[S:2 * S], z[2 * S:3 * S]
Vprime = np.empty(S)
for s in range(S):
    Vprime[s] = Vf[s](xprime[s])
return -π[s_] @ (U(c, n) + β * Vprime)

def cons(z):
c, n, xprime, T = z[:S], z[S:2 * S], z[2 * S:3 * S], z[3 * S:]
u_c = Uc(c, n)
Eu_c = π[s_] @ u_c
return np.hstack([    
    x * u_c / Eu_c - u_c * (c - T) - Un(c, n) * n - β * xprime,    
    Θ * n - c - G])
if model.transfers:
    bounds = [([0., 100]) * \( S \) + ([0., 100]) * \( S \) + \\
      [self.xbar] * \( S \) + ([0., 100]) * \( S \)
else:
    bounds = [([0., 100]) * \( S \) + ([0., 100]) * \( S \) + \\
      [self.xbar] * \( S \) + ([0., 0.]) * \( S \)
out, fx, __, imode, smode = fmin_slsqp(objf, self.z0[x, s_],
  f_eqcons=cons, bounds=bounds,
  full_output=True, iprint=0,
  acc=self.tol, iter=self.maxiter)

if imode > 0:
    raise Exception(smode)
self.z0[x, s_] = out
return np.hstack([-fx, out])

def get_policies_time0(self, B_, s0, Vf):
    '''
    Finds the optimal policies
    '''
    model, \( \beta \), \( \Theta \), \( G \) = self.model, self.\( \beta \), self.\( \Theta \), self.\( G \)
    U, Uc, Un = model.U, model.Uc, model.Un

def objf(z):
    c, n, xprime = z[:-1]
    return -(U(c, n) + \( \beta \) * Vf[s0](xprime))

def cons(z):
    c, n, xprime, T = z
    return np.hstack([
        -Un(c, n) * (c - B_ - T) - Un(c, n) * n - \( \beta \) * xprime,
        \( \Theta \) * n - c - G][s0]])

if model.transfers:
    bounds = [([0., 100]), (0., 100), self.xbar, (0., 100.)]
else:
    bounds = [([0., 100]), (0., 100), self.xbar, (0., 0.)]
out, fx, __, imode, smode = fmin_slsqp(objf, self.zFB[s0],
  f_eqcons=cons, bounds=bounds, full_output=True, iprint=0)

if imode > 0:
    raise Exception(smode)
return np.hstack([-fx, out])

In [6]: import numpy as np
from scipy.interpolate import UnivariateSpline

class interpolate_wrapper:
    def __init__(self, F):
        self.F = F
def __getitem__(self, index):
    return interpolate_wrapper(np.asarray(self.F[index]))

def reshape(self, *args):
    self.F = self.F.reshape(*args)
    return self

def transpose(self):
    self.F = self.F.transpose()
    return self

def __len__(self):
    return len(self.F)

def __call__(self, xvec):
    x = np.atleast_1d(xvec)
    shape = self.F.shape
    if len(x) == 1:
        fhat = np.hstack([f(x) for f in self.F.flatten()])
        return fhat.reshape(shape)
    else:
        fhat = np.vstack([f(x) for f in self.F.flatten()])
        return fhat.reshape(np.hstack((shape, len(x))))

class interpolator_factory:
    def __init__(self, k, s):
        self.k, self.s = k, s
    def __call__(self, xgrid, Fs):
        shape, m = Fs.shape[:-1], Fs.shape[-1]
        Fs = Fs.reshape((-1, m))
        F = []
        xgrid = np.sort(xgrid)  # Sort xgrid
        for Fhat in Fs:
            F.append(UnivariateSpline(xgrid, Fhat, k=self.k, s=self.s))
        return interpolate_wrapper(np.array(F).reshape(shape))

def fun_vstack(fun_list):
    Fs = [IW.F for IW in fun_list]
    return interpolate_wrapper(np.vstack(Fs))

def fun_hstack(fun_list):
    Fs = [IW.F for IW in fun_list]
    return interpolate_wrapper(np.hstack(Fs))

def simulate_markov(π, s_0, T):
    sHist = np.empty(T, dtype=int)
    sHist[0] = s_0
    S = len(π)
    for t in range(1, T):
        sHist[t] = np.random.choice(np.arange(S), p=π[sHist[t - 1]])
40.6 Reverse Engineering Strategy

We can reverse engineer a value \( b_0 \) of initial debt due that renders the AMSS measurability constraints not binding from time \( t = 0 \) onward.

We accomplish this by recognizing that if the AMSS measurability constraints never bind, then the AMSS allocation and Ramsey plan is equivalent with that for a Lucas-Stokey economy in which for each period \( t \geq 0 \), the government promises to pay the same state-contingent amount \( \bar{b} \) in each state tomorrow.

This insight tells us to find a \( b_0 \) and other fundamentals for the Lucas-Stokey [45] model that make the Ramsey planner want to borrow the same value \( \bar{b} \) next period for all states and all dates.

We accomplish this by using various equations for the Lucas-Stokey [45] model presented in optimal taxation with state-contingent debt.

We use the following steps.

**Step 1:** Pick an initial \( \Phi \).

**Step 2:** Given that \( \Phi \), jointly solve two versions of equation (4) for \( c(s), s = 1, 2 \) associated with the two values for \( g(s), s = 1, 2 \).

**Step 3:** Solve the following equation for \( \bar{x} \)

\[
\bar{x} = (I - \beta \Pi)^{-1} [\bar{u}_c(\bar{n} - \bar{g}) - \bar{u}_l \bar{n}]
\]

**Step 4:** After solving for \( \bar{x} \), we can find \( b(s|s^{t-1}) \) in Markov state \( s_t = s \) from \( b(s) = \frac{x(s)}{u_c(s)} \) or the matrix equation

\[
\bar{b} = \frac{\bar{x}}{\bar{u}_c}
\]

**Step 5:** Compute \( J(\Phi) = (b(1) - b(2))^2 \).

**Step 6:** Put steps 2 through 6 in a function minimizer and find a \( \Phi \) that minimizes \( J(\Phi) \).

**Step 7:** At the value of \( \Phi \) and the value of \( \bar{b} \) that emerged from step 6, solve equations (5) and (3) jointly for \( c_0, b_0 \).

40.7 Code for Reverse Engineering

Here is code to do the calculations for us.

```python
In [7]: u = CRRAutility()

def min_\Phi(\Phi):
    g1, g2 = u.G  # Government spending in s=0 and s=1
```

# Solve $\Phi(c)$

```python
def equations(unknowns, $\Phi$):
c1, c2 = unknowns
  # First argument of .Uc and second argument of .Un are redundant
  # Set up simultaneous equations
  eq = lambda c, g: 
    $1 + \Phi$ * (u.Uc(c, 1) - -u.Un(1, c + g)) + \n    $\Phi$ * ((c + g) * u.Unn(1, c + g) + c * u.Ucc(c, 1))
  # Return equation evaluated at s=1 and s=2
  return np.array([eq(c1, g1), eq(c2, g2)]).flatten()
```

global c1  # Update c1 globally
global c2  # Update c2 globally

c1, c2 = fsolve(equations, np.ones(2), args=($\Phi$))

uc = u.Uc(np.array([c1, c2]), 1)  # uc(n - g)
ul = -u.Un([1, np.array([c1 + g1, c2 + g2])]) * [c1 + g1, c2 + g2]
  # Solve for x
x = np.linalg.solve(np.eye((2)) - u.$\beta$ * u.$\pi$, uc * [c1, c2] - ul)

global b  # Update b globally
b = x / uc
loss = (b[0] - b[1])**2

return loss

$\Phi_{star}$ = fmin(min_$\Phi$, .1, ftol=1e-14)

Optimization terminated successfully.
  Current function value: 0.000000
  Iterations: 24
  Function evaluations: 48

To recover and print out $\bar{b}$

In [8]: b_bar = b[0]
b_bar

Out[8]: -1.0757576567504166

To complete the reverse engineering exercise by jointly determining $c_0, b_0$, we set up a function that returns two simultaneous equations.

In [9]: def solve_cb(unknowns, $\Phi$, b_bar, s=1):

    c0, b0 = unknowns
    g0 = u.G[s-1]
    R_0 = u.$\beta$ * u.$\pi$s @ [u.Uc(c1, 1) / u.Uc(c0, 1), u.Uc(c2, 1) / u.Uc(c0, -1)]
\[ R_\theta = 1 / R_\theta \]
\[ \tau_\theta = 1 + u.\text{Un}(1, c_0 + g_0) / u.\text{Uc}(c_0, 1) \]
\[ \text{eq1} = \tau_\theta \ast (c_0 + g_0) + b_{\text{bar}} / R_\theta - b_0 - g_0 \]
\[ \text{eq2} = (1 + \Phi) \ast (u.\text{Uc}(c_0, 1) + u.\text{Un}(1, c_0 + g_0)) \]
\[ - \Phi \ast u.\text{Ucc}(c_0, 1) \ast b_0 \]
\[ \text{return np.array([eq1, eq2], dtype='float64')} \]

To solve the equations for \( c_0, b_0 \), we use SciPy’s fsolve function

In [10]: \( c_0, b_0 = \text{fsolve}(\text{solve_cb}, \text{np.array([1., -1.], dtype='float64')}, \text{args=(} \Phi_{\text{star}}, \text{b[0]}, 1), \text{xtol=1.e-12}) \)
\( c_0, b_0 \)

Out[10]: (0.9344994030900681, -1.0386984075517638)

Thus, we have reverse engineered an initial \( b_0 = -1.038698407551764 \) that ought to render the AMSS measurability constraints slack.

### 40.8 Short Simulation for Reverse-engineered: Initial Debt

The following graph shows simulations of outcomes for both a Lucas-Stokey economy and for an AMSS economy starting from initial government debt equal to \( b_0 = -1.038698407551764 \).

These graphs report outcomes for both the Lucas-Stokey economy with complete markets and the AMSS economy with one-period risk-free debt only.

In [11]: \( \mu_{\text{grid}} = \text{np.linspace(-0.09, 0.1, 100)} \)

   \( \text{log_example = CRRAutility()} \)

   \( \text{log_example.transfers = True} \) \hspace{1cm} # Government can use

   \( \text{log_sequential = SequentialAllocation(log_example)} \) \hspace{1cm} # Solve sequential

   \( \text{log_bellman = RecursiveAllocationAMSS(log_example, \mu_{\text{grid}},} \)

   \hspace{1cm} \text{tol_diff=1e-10, tol=1e-12}) \)

   \( T = 20 \)

   \( \text{sHist = np.array([0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1,} \)

   \hspace{1cm}0, 0, 0, 1, 1, 1, 1, 1, 1, 0]) \)

   \( \text{sim_seq = log_sequential.simulate(-1.03869841, 0, T, sHist)} \)

   \( \text{sim_bel = log_bellman.simulate(-1.03869841, 0, T, sHist)} \)

   \( \text{titles = ['Consumption', 'Labor Supply', 'Government Debt',} \)

   \hspace{1cm} 'Tax Rate', 'Government Spending', 'Output'] \)

   \# Government spending paths
40.8. SHORT SIMULATION FOR REVERSE-ENGINEERED: INITIAL DEBT

\[
\text{sim_seq}[4] = \log\text{example.G}[\text{shHist}]
\]
\[
\text{sim_bel}[4] = \log\text{example.G}[\text{shHist}]
\]

# Output paths
\[
\text{sim_seq}[5] = \log\text{example.Θ}[\text{shHist}] * \text{sim_seq}[1]
\]
\[
\text{sim_bel}[5] = \log\text{example.Θ}[\text{shHist}] * \text{sim_bel}[1]
\]

fig, axes = plt.subplots(3, 2, figsize=(14, 10))

for ax, title, seq, bel in zip(axes.flatten(), titles, sim_seq, sim_bel):
    ax.plot(seq, '-ok', bel, '-^b')
    ax.set(title=title)
    ax.grid()

axes[0, 0].legend(['Complete Markets', 'Incomplete Markets'])
plt.tight_layout()
plt.show()
<ipython-input-5-cc6b33fcda51> in fit_policy_function(self, PF)
    81                     cf, nf, xprimef, Tf, Vf = [], [], [], [], []
    82                     for s_ in range(S):
    --> 83                     PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
    84                     Vf.append(interp(xgrid, PFvec[0, :]))
    85                     cf.append(interp(xgrid, PFvec[1:1 + S]))

<ipython-input-5-cc6b33fcda51> in <listcomp>(.0)
    81                     cf, nf, xprimef, Tf, Vf = [], [], [], [], []
    82                     for s_ in range(S):
    --> 83                     PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
    84                     Vf.append(interp(xgrid, PFvec[0, :]))
    85                     cf.append(interp(xgrid, PFvec[1:1 + S]))

<ipython-input-5-cc6b33fcda51> in PF(x, s)
    207                     """  
    208                     if not self.time_0:
    --> 209                     def PF(x, s): return self.get_policies_time1(x, s, Vf)
    210                     else:
    211                     def PF(B_, s0): return self.get_policies_time0(B_, s0, Vf)

<ipython-input-5-cc6b33fcda51> in get_policies_time1(self, x, s_, Vf)
    245                     #
    246                     f_eqcons=cons, bounds=bounds,
    --> 247                     full_output=True, iprint=0,
    248                     tol, iter=self.maxiter)
    249                     if imode > 0:

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/slsqp.py in fmin_slsqp(func, x0, eqcons, f_eqcons, ieqcons, f_ieqcons, bounds, fprime, fprime_eqcons, fprime_ieqcons, args, iter, acc, iprint, disp, full_output, epsilon, callback)
    204             res = _minimize_slsqp(func, x0, args, jac=fprime, bounds=bounds,  
    205                                      constraints=cons, **opts)
if full_output:
    return res['x'], res['fun'], res['nit'],
    res['status'], res['message']

if mode == -1:  # gradient evaluation required
    g = append(sf.grad(x), 0.0)
    a = _eval_con_normals(x, cons, la, n, m, meq, mieq)

def _update_grad(self):
    if not self.g_updated:
        self._update_grad_impl()
        self.g_updated = True

self.x, f0=self.f,
---
**finite_diff_options)
self._update_grad_impl = update_grad

if np.any((x0 < lb) | (x0 > ub)):
The Ramsey allocations and Ramsey outcomes are identical for the Lucas-Stokey and AMSS economies.

This outcome confirms the success of our reverse-engineering exercises.

Notice how for \( t \geq 1 \), the tax rate is a constant - so is the par value of government debt.

However, output and labor supply are both nontrivial time-invariant functions of the Markov state.

### 40.9 Long Simulation

The following graph shows the par value of government debt and the flat rate tax on labor income for a long simulation for our sample economy.

For the same realization of a government expenditure path, the graph reports outcomes for two economies

- the gray lines are for the Lucas-Stokey economy with complete markets
- the blue lines are for the AMSS economy with risk-free one-period debt only

For both economies, initial government debt due at time 0 is \( b_0 = .5 \).

For the Lucas-Stokey complete markets economy, the government debt plotted is \( b_{t+1}(s_{t+1}) \).

- Notice that this is a time-invariant function of the Markov state from the beginning.

For the AMSS incomplete markets economy, the government debt plotted is \( b_{t+1}(s^t) \).

- Notice that this is a martingale-like random process that eventually seems to converge to a constant \( \bar{b} \approx -1.07 \).
- Notice that the limiting value \( \bar{b} < 0 \) so that asymptotically the government makes a constant level of risk-free loans to the public.
- In the simulation displayed as well as other simulations we have run, the par value of government debt converges to about 1.07 after between 1400 to 2000 periods.

For the AMSS incomplete markets economy, the marginal tax rate on labor income \( \tau_t \) converges to a constant

- labor supply and output each converge to time-invariant functions of the Markov state

In [12]: \( T = 2000 \)  # Set T to 200 periods

```python
sim_seq_long = log_sequential.simulate(0.5, 0, T)
sHist_long = sim_seq_long[-3]
sim_bel_long = log_bellman.simulate(0.5, 0, T, sHist_long)
titles = ['Government Debt', 'Tax Rate']
```
40.10. **BEGS Approximations of Limiting Debt and Convergence Rate**

It is useful to link the outcome of our reverse engineering exercise to limiting approximations constructed by [10].
[10] used a slightly different notation to represent a generalization of the AMSS model. We’ll introduce a version of their notation so that readers can quickly relate notation that appears in their key formulas to the notation that we have used.

BEGS work with objects \( B_t, B_t, R_t, X_t \) that are related to our notation by

\[
\begin{align*}
R_t &= \frac{u_{c,t}}{u_{c,t-1}} R_{t-1} = \frac{u_{c,t}}{\beta E_t u_{c,t}} \\
B_t &= b_{t+1}(s^t) = \frac{R_t(s^t)}{R_t(s^t)} \\
b_t(s^{-1}) &= R_{t-1} B_{t-1} \\
B_t &= u_{c,t} B_t = (\beta E_t u_{c,t+1}) b_{t+1}(s^t) \\
X_t &= u_{c,t}[g_t - \tau_t n_t]
\end{align*}
\]

In terms of their notation, equation (44) of [10] expresses the time \( t \) state \( s \) government budget constraint as

\[
B(s) = R_\tau(s, s_-) B_- + X_{\tau(s)}(s) \tag{8}
\]

where the dependence on \( \tau \) is to remind us that these objects depend on the tax rate and \( s_- \) is last period’s Markov state.

BEGS interpret random variations in the right side of (8) as a measure of fiscal risk composed of

- interest-rate-driven fluctuations in time \( t \) effective payments due on the government portfolio, namely, \( R_\tau(s, s_-) B_- \), and
- fluctuations in the effective government deficit \( X_t \)

### 40.10.1 Asymptotic Mean

BEGS give conditions under which the ergodic mean of \( B_t \) is

\[
B^* = -\frac{\text{cov}^\infty(R, X)}{\text{var}^\infty(R)} \tag{9}
\]

where the superscript \( \infty \) denotes a moment taken with respect to an ergodic distribution.

Formula (9) presents \( B^* \) as a regression coefficient of \( X_t \) on \( R_t \) in the ergodic distribution. This regression coefficient emerges as the minimizer for a variance-minimization problem:

\[
B^* = \arg\min_B \text{var}(RB + X) \tag{10}
\]

The minimand in criterion (10) is the measure of fiscal risk associated with a given tax-debt policy that appears on the right side of equation (8).

Expressing formula (9) in terms of our notation tells us that \( \tilde{b} \) should approximately equal

\[
\tilde{b} = \frac{B^*}{\beta E_t u_{c,t+1}} \tag{11}
\]
40.10. BEGS APPROXIMATIONS OF LIMITING DEBT AND CONVERGENCE RATE

40.10.2 Rate of Convergence

BEGS also derive the following approximation to the rate of convergence to $\mathcal{B}^*$ from an arbitrary initial condition.

$$\frac{E_t(\mathcal{B}_{t+1} - \mathcal{B}^*)}{(\mathcal{B}_t - \mathcal{B}^*)} \approx \frac{1}{1 + \beta^2 \text{var}(\mathcal{R})}$$  \hspace{1cm} (12)

(See the equation above equation (47) in [10])

40.10.3 Formulas and Code Details

For our example, we describe some code that we use to compute the steady state mean and the rate of convergence to it.

The values of $\pi(s)$ are 0.5, 0.5.

We can then construct $\mathcal{X}(s), \mathcal{R}(s), u_c(s)$ for our two states using the definitions above.

We can then construct $\beta E_{t-1} u_c = \beta \sum_s u_c(s) \pi(s)$, $\text{cov}(\mathcal{R}(s), \mathcal{X}(s))$ and $\text{var}(\mathcal{R}(s))$ to be plugged into formula (11).

We also want to compute $\text{var}(\mathcal{X})$.

To compute the variances and covariance, we use the following standard formulas.

Temporarily let $x(s), s = 1, 2$ be an arbitrary random variables.

Then we define

$$\mu_x = \sum_s x(s) \pi(s)$$

$$\text{var}(x) = \left( \sum_s \sum_s x(s)^2 \pi(s) \right) - \mu_x^2$$

$$\text{cov}(x, y) = \left( \sum_s x(s)y(s) \pi(s) \right) - \mu_x \mu_y$$

After we compute these moments, we compute the BEGS approximation to the asymptotic mean $\hat{b}$ in formula (11).

After that, we move on to compute $\mathcal{B}^*$ in formula (9).

We’ll also evaluate the BEGS criterion (8) at the limiting value $\mathcal{B}^*$

$$J(\mathcal{B}^*) = \text{var}(\mathcal{R})(\mathcal{B}^*)^2 + 2\mathcal{B}^* \text{cov}(\mathcal{R}, \mathcal{X}) + \text{var}(\mathcal{X})$$  \hspace{1cm} (13)

Here are some functions that we’ll use to compute key objects that we want

```python
In [13]: def mean(x):
    """Returns mean for x given initial state""
    x = np.array(x)
    return x @ u.pi[s]

def variance(x):
```
CHAPTER 40. FLUCTUATING INTEREST RATES DELIVER FISCAL INSURANCE

```python
x = np.array(x)
return x**2 @ u.π[s] - mean(x)**2

def covariance(x, y):
x, y = np.array(x), np.array(y)
return x * y @ u.π[s] - mean(x) * mean(y)

Now let's form the two random variables \( R, X \) appearing in the BEGS approximating formulas.

In [14]: u = CRRAtility()

s = 0
c = [0.940580824225584, 0.8943592757759343]  # Vector for \( c \)
g = u.G  # Vector for \( g \)
n = c + g  # Total population
τ = lambda s: 1 + u.Un(1, n[s]) / u.Uc(c[s], 1)

R_s = lambda s: u.Uc(c[s], n[s]) / (u.β * (u.Uc(c[0], n[0]) * u.π[0, 0] + u.Uc(c[1], n[1]) * u.π[1, 0])))
X_s = lambda s: u.Uc(c[s], n[s]) * (g[s] - τ(s) * n[s])

R = [R_s(0), R_s(1)]
X = [X_s(0), X_s(1)]

print(f"R, X = \{"R_s(0), R_s(1)\}, \{"X_s(0), X_s(1)\}")

R, X = [1.055169547122964, 1.1670526750992583], [0.06357685646224803, 0.19251010100512958]

Now let's compute the ingredient of the approximating limit and the approximating rate of convergence.

In [15]: bstar = -covariance(R, X) / variance(R)
div = u.β * (u.Uc(c[0], n[0]) * u.π[0, 0] + u.Uc(c[1], n[1]) * u.π[1, 1])
bhat = bstar / div
bhat

Out[15]: -1.0757585378303758

Print out \( \hat{b} \) and \( \bar{b} \)

In [16]: bhat, b_bar

Out[16]: (-1.0757585378303758, -1.0757576567504166)

So we have

In [17]: bhat - b_bar

Out[17]: -8.810799592140484e-07
These outcomes show that $\hat{b}$ does a remarkably good job of approximating $\bar{b}$.

Next, let’s compute the BEGS fiscal criterion that $\hat{b}$ is minimizing

In [18]: $J_{\text{min}} = \text{variance}(R) \cdot b_{\text{star}}^2 + 2 \cdot b_{\text{star}} \cdot \text{covariance}(R, X) + \text{variance}(X)$

Out[18]: $-9.020562075079397e-17$

This is machine zero, a verification that $\hat{b}$ succeeds in minimizing the nonnegative fiscal cost criterion $J(B^*)$ defined in BEGS and in equation (13) above.

Let’s push our luck and compute the mean reversion speed in the formula above equation (47) in [10].

In [19]: $\text{den}_2 = 1 + (u \cdot \beta^2) \cdot \text{variance}(R)$

$\text{speedrever} = 1/\text{den}_2$

print(f’Mean reversion speed = {speedrever}’)

Mean reversion speed = 0.9974715478249827

Now let’s compute the implied meantime to get to within 0.01 of the limit

In [20]: $t_{\text{time}} = \text{np.log}(.01) / \text{np.log(speedrever)}$

print(f’Time to get within .01 of limit = {t_{\text{time}}}’)

Time to get within .01 of limit = 1819.0360880098472

The slow rate of convergence and the implied time of getting within one percent of the limiting value do a good job of approximating our long simulation above.
CHAPTER 40. FLUCTUATING INTEREST RATES DELIVER FISCAL INSURANCE
Chapter 41

Fiscal Risk and Government Debt

41.1 Contents

- Overview 41.2
- The Economy 41.3
- Long Simulation 41.4
- Asymptotic Mean and Rate of Convergence 41.5

Software Requirement:

This lecture requires the use of some older software versions to run. If you would like to execute this lecture please download the following amss_environment.yml file. This specifies the software required and an environment can be created using conda:

Open a terminal:

```
conda env create --file amss_environment.yml
conda activate amss
```

In addition to what’s in Anaconda, this lecture will need the following libraries:

```
In [1]: !pip install --upgrade quantecon
```

41.2 Overview

This lecture studies government debt in an AMSS economy [3] of the type described in Optimal Taxation without State-Contingent Debt.

We study the behavior of government debt as time $t \to +\infty$.

We use these techniques

- simulations
- a regression coefficient from the tail of a long simulation that allows us to verify that the asymptotic mean of government debt solves a fiscal-risk minimization problem
- an approximation to the mean of an ergodic distribution of government debt
- an approximation to the rate of convergence to an ergodic distribution of government debt
We apply tools applicable to more general incomplete markets economies that are presented on pages 648 - 650 in section III.D of [10] (BEGS).

We study an economy with three Markov states driving government expenditures.

- In a previous lecture, we showed that with only two Markov states, it is possible that eventually endogenous interest rate fluctuations support complete markets allocations and Ramsey outcomes.
- The presence of three states prevents the full spanning that eventually prevails in the two-state example featured in Fiscal Insurance via Fluctuating Interest Rates.

The lack of full spanning means that the ergodic distribution of the par value of government debt is nontrivial, in contrast to the situation in Fiscal Insurance via Fluctuating Interest Rates where the ergodic distribution of the par value is concentrated on one point.

Nevertheless, [10] (BEGS) establish for general settings that include ours, the Ramsey planner steers government assets to a level that comes as close as possible to providing full spanning in a precise a sense defined by BEGS that we describe below.

We use code constructed in a previous lecture.

**Warning:** Key equations in [10] section III.D carry typos that we correct below.

Let’s start with some imports:

```python
In [2]: import matplotlib.pyplot as plt
%matplotlib inline
from scipy.optimize import minimize
```

### 41.3 The Economy

As in Optimal Taxation without State-Contingent Debt and Optimal Taxation with State-Contingent Debt, we assume that the representative agent has utility function

\[
    u(c, n) = \frac{c^{1-\sigma}}{1-\sigma} - \frac{n^{1+\gamma}}{1+\gamma}
\]

We work directly with labor supply instead of leisure.

We assume that

\[
    c_t + g_t = n_t
\]

The Markov state \(s_t\) takes three values, namely, 0, 1, 2.

The initial Markov state is 0.

The Markov transition matrix is \((1/3)I\) where \(I\) is a 3 \(\times\) 3 identity matrix, so the \(s_t\) process is IID.

Government expenditures \(g(s)\) equal .1 in Markov state 0, .2 in Markov state 1, and .3 in Markov state 2.

We set preference parameters
\[ \beta = 0.9 \]
\[ \sigma = 2 \]
\[ \gamma = 2 \]

The following Python code sets up the economy

```python
In [3]: import numpy as np

class CRRAutility:
    def __init__(self, 
        β=0.9,
        σ=2,
        γ=2,
        π=0.5*np.ones((2, 2)),
        G=np.array([0.1, 0.2]),
        Θ=np.ones(2),
        transfers=False):
        self.β, self.σ, self.γ = β, σ, γ
        self.π, self.G, self.Θ, self.transfers = π, G, Θ, transfers

    # Utility function
    def U(self, c, n):
        σ = self.σ
        if σ == 1.:
            U = np.log(c)
        else:
            U = (c**(1 - σ) - 1) / (1 - σ)
        return U - n**((1 + self.γ) / (1 + self.γ))

    # Derivatives of utility function
    def Uc(self, c, n):
        return c**(-self.σ)

    def Ucc(self, c, n):
        return -self.σ * c**(-self.σ - 1)

    def Un(self, self, c, n):
        return -n**self.γ

    def Unn(self, self, c, n):
        return -self.γ * n**(self.γ - 1)
```

41.3.1 First and Second Moments

We’ll want first and second moments of some key random variables below.

The following code computes these moments; the code is recycled from Fiscal Insurance via Fluctuating Interest Rates.

```python
In [4]: def mean(x, s):
        '''Returns mean for x given initial state'''
```
41.4 Long Simulation

To generate a long simulation we use the following code.

We begin by showing the code that we used in earlier lectures on the AMSS model. Here it is

```python
import numpy as np
from scipy.optimize import root
from quantecon import MarkovChain

class SequentialAllocation:
    '''
    Class that takes CESutility or BGPutility object as input returns planner's allocation as a function of the multiplier on the implementability constraint µ.
    '''
    def __init__(self, model):
        # Initialize from model object attributes
        self.β, self.π, self.G = model.β, model.π, model.G
        self.mc, self.Θ = MarkovChain(self.π), model.Θ
        self.S = len(model.π)  # Number of states
        self.model = model

        # Find the first best allocation
        self.find_first_best()

def find_first_best(self):
    '''
    Find the first best allocation
    '''
    model = self.model
    S, Θ, G = self.S, self.Θ, self.G
    Uc, Un = model.Uc, model.Un

    def res(z):
        c = z[:S]
        n = z[S:]
        return np.hstack([Θ * Uc(c, n) + Un(c, n), Θ * n - c - G])
```

```
res = root(res, 0.5 * np.ones(2 * S))

if not res.success:
    raise Exception('Could not find first best')

self.cFB = res.x[:S]
sel.fnFB = res.x[S:]

# Multiplier on the resource constraint
self.ΞFB = Uc(self.cFB, self.nFB)
self.zFB = np.hstack([self.cFB, self.nFB, self.ΞFB])

def time1_allocation(self, μ):
    ... Computed optimal allocation for time t >= 1 for a given μ ...
    model = self.model
    S, Θ, G = self.S, self.Θ, self.G
    Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn

    def FOC(z):
        c = z[:S]
        n = z[S:2 * S]
        Ξ = z[2 * S:]
        # FOC of c
        return np.hstack([Uc(c, n) - μ * (Ucc(c, n) * c + Uc(c, n)) - Ξ,
                          Un(c, n) - μ * (Unn(c, n) * n + Un(c, n)) \n                          + Θ * Ξ,  # FOC of n
                          Θ * n - c - G])

    # Find the root of the first-order condition
    res = root(FOC, self.zFB)
    if not res.success:
        raise Exception('Could not find LS allocation.')
    z = res.x
    c, n, Ξ = z[:S], z[S:2 * S], z[2 * S:]

    # Compute x
    I = Uc(c, n) * c + Un(c, n) * n
    x = np.linalg.solve(np.eye(S) - self.β * self.π, I)

    return c, n, x, Ξ

def time0_allocation(self, B_, s_0):
    ... Finds the optimal allocation given initial government debt B_ and state s_0 ...
    model, π, Θ, G, β = self.model, self.π, self.Θ, self.G, self.β
    Uc, Ucc, Un, Unn = model.Uc, model.Ucc, model.Un, model.Unn

    # First order conditions of planner's problem
    def FOC(z):
        μ, c, n, Ξ = z
        xprime = self.time1_allocation(μ)[2]
        return np.hstack([Uc(c, n) * (c - B_) + Un(c, n) * n + β * π[s_0] \n                          @ xprime,
                          Uc(c, n) - μ * (Ucc(c, n))]}
\[ \begin{align*}
\* (c - B) + U_c(c, n) - \Xi,
Un(c, n) - \mu \* (Un(c, n) \* n
+ Un(c, n)) + \Theta[s_0] * \Xi,
(\Theta * n - c - G)[s_0]\end{align*} \]

# Find root
res = root(FOC, np.array(
    [0, self.cFB[s_0], self.nFB[s_0], self.ΞFB[s_0]]))
if not res.success:
    raise Exception('Could not find time 0 LS allocation.')

return res.x

def time1_value(self, μ):
    
    Find the value associated with multiplier μ
    
    c, n, x, Ξ = self.time1_allocation(μ)
    U = self.model.U(c, n)
    V = np.linalg.solve(np.eye(self.S) - self.β * self.π, U)
    return c, n, x, V

def Τ(self, c, n):
    
    Computes Τ given c, n
    
    model = self.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)
    return 1 + Un / (self.Θ * Uc)

def simulate(self, B_, s_0, T, sHist=None):
    
    Simulates planners policies for T periods
    
    model, π, β = self.model, self.π, self.β
    Uc = model.Uc

    if sHist is None:
        sHist = self.mc.simulate(T, s_0)
    
    cHist, nHist, Bhist, ΤHist, μHist = np.zeros((5, T))
    RHist = np.zeros(T - 1)

    # Time 0
    μ, cHist[0], nHist[0], _ = self.time0_allocation(B_, s_0)
    THist[0] = self.Τ(cHist[0], nHist[0])[s_0]
    Bhist[0] = B_
    μHist[0] = μ

    # Time 1 onward
    for t in range(1, T):
        c, n, x, Ξ = self.time1_allocation(μ)
        T = self.Τ(c, n)
        u_c = Uc(c, n)
        s = sHist[t]
        Eu_c = π[sHist[t - 1]] @ u_c
\[ \begin{align*}
\text{cHist}[t], \text{nHist}[t], \text{Bhist}[t], \text{THist}[t] &= \text{c}[s], \text{n}[s], \text{x}[s] \\
\text{RHist}[t - 1] &= \text{Uc(cHist}[t - 1], \text{nHist}[t - 1]) / (\beta^* \text{Eu_c})
\end{align*} \]

\[ \mu_{\text{Hist}}[t] = \mu \]

\[ \text{return np.array([cHist, nHist, Bhist, THist, sHist, }^* \mu_{\text{Hist}}, \text{RHist}] \]

In [6]: import numpy as np
from scipy.optimize import fmin_slsqp
from scipy.optimize import root
from quantecon import MarkovChain

**class RecursiveAllocationAMSS:**

```python
def __init__(self, model, \mu_grid, tol_diff=1e-4, tol=1e-4):
    self.\beta, self.\pi, self.G = model.\beta, model.\pi, model.G
    self.mc = MarkovChain(self.\pi), len(model.\pi) # Number of states

# Find the first best allocation
self.solve_time1_bellman()
self.T.time_0 = True # Bellman equation now solves time 0 problem

def solve_time1_bellman(self):
    '''
    Solve the time 1 Bellman equation for calibration model and initial grid \mu_0
    '''
    model, \mu_grid0 = self.model, self.\mu_grid
    \pi = model.\pi
    S = len(model.\pi)

    # First get initial fit from Lucas Stokey solution.
    # Need to change things to be ex ante
    pp = SequentialAllocation(model)
    interp = interpolator_factory(2, None)

def incomplete_allocation(\mu_, s_):
    c, n, x, V = pp.time1_value(\mu_)
    return c, n, \pi[s_] @ x, \pi[s_] @ V

cf, nf, xgrid, Vf, xprimef = [], [], [], [], []
for s_ in range(S):
    c, n, x, V = zip(*map(lambda \mu: incomplete_allocation(\mu, s_), \mu_grid0))
    cf.append(interp(x, c))
    nf.append(interp(x, n))
    Vf.append(interp(x, V))
    xgrid.append(x)
    xprimef.append(interp(x, xprimes))
cf, nf, xprimef = fun_vstack(cf), fun_vstack(nf), fun_vstack(xprimef)
```
Vf = fun_hstack(Vf)
policies = [cf, nf, xprimef]

# Create xgrid
x = np.vstack(xgrid).T
xbar = [x.min(0).max(), x.max(0).min()]
xgrid = np.linspace(xbar[0], xbar[1], len(μgrid0))
self.xgrid = xgrid

# Now iterate on Bellman equation
T = BellmanEquation(model, xgrid, policies, tol=self.tol)
diff = 1
while diff > self.tol_diff:
    PF = T(Vf)
    Vfnew, policies = self.fit_policy_function(PF)
    diff = np.abs((Vf(xgrid) - Vfnew(xgrid)) / Vf(xgrid)).max()
    print(diff)
    Vf = Vfnew

# Store value function policies and Bellman Equations
self.Vf = Vf
self.policies = policies
self.T = T

def fit_policy_function(self, PF):
    ...
    Fits the policy functions ...
    S, xgrid = len(self.π), self.xgrid
    interp = interpolator_factory(3, 0)
    cf, nf, xprimef, Tf, Vf = [], [], [], [], []
    for s_ in range(S):
        PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
        Vf.append(interp(xgrid, PFvec[0, :]))
        cf.append(interp(xgrid, PFvec[1:1 + S]))
        nf.append(interp(xgrid, PFvec[1 + S:1 + 2 * S]))
        xprimef.append(interp(xgrid, PFvec[1 + 2 * S:1 + 3 * S]))
        Tf.append(interp(xgrid, PFvec[1 + 3 * S:]))
    policies = fun_vstack(cf), fun_vstack(nf), fun_vstack(xprimef), fun_vstack(Tf)
    Vf = fun_hstack(Vf)
    return Vf, policies

def T(self, c, n):
    ...
    Computes T given c and n ...
    model = self.model
    Uc, Un = model.Uc(c, n), model.Un(c, n)
    return 1 + Un / (self.Θ * Uc)

def time0_allocation(self, B_, s0):
    ...
    Finds the optimal allocation given initial government debt B_ and state s_0
PF = self.T(self.Vf)
z0 = PF(B_, s0)
c0, n0, xprime0, T0 = z0[1:]
return c0, n0, xprime0, T0

def simulate(self, B_, s_0, T, sHist=None):
    '''
    Simulates planners policies for T periods
    '''
    model, π = self.model, self.π
    Uc = model.Uc
cf, nf, xprimef, Tf = self.policies

    if sHist is None:
        sHist = simulate_markov(π, s_0, T)

    cHist, nHist, Bhist, xHist, THist, μHist = np.zeros((7, T))

    # Time 0
    cHist[0], nHist[0], xHist[0], THist[0] = self.time0_allocation(B_, s_0)
    Bhist[0] = B_
    μHist[0] = self.Vf[s_0](xHist[0])

    # Time 1 onward
    for t in range(1, T):
        s_, x, s = sHist[t - 1], xHist[t - 1], sHist[t]
        c, n, xprime, T = cf[s_, :](x), nf[s_, :](x), xprimef[s_, :](x), Tf[s_, :](x)

        T = self.T(c, n)[s]
        u_c = Uc(c, n)
        Eu_c = π[s_, :] @ u_c

        μHist[t] = self.Vf[s](xprime[s])

        cHist[t], nHist[t], Bhist[t], xHist[t], THist[t] = c[s], n[s], x / Eu_c, T
        xHist[t], THist[t] = xprime[s], T[s]

    return np.array([cHist, nHist, Bhist, THist, μHist, sHist, xHist])

class BellmanEquation:
    '''
    Bellman equation for the continuation of the Lucas-Stokey Problem
    '''

    def __init__(self, model, xgrid, policies0, tol, maxiter=1000):
        self.β, self.π, self.G = model.β, model.π, model.G
        self.S = len(model.π)  # Number of states
        self.Θ = model.Θ, model.tol
        self.maxiter = maxiter

        self.xbar = [min(xgrid), max(xgrid)]
        self.time_0 = False
self.z0 = {}
cf, nf, xprimef = policies0

for s_ in range(self.S):
    for x in xgrid:
        self.z0[x, s_] = np.hstack([cf[s_, :](x),
                                   nf[s_, :](x),
                                   xprimef[s_, :](x),
                                   np.zeros(self.S)])

self.find_first_best()

def find_first_best(self):
    '''
    Find the first best allocation
    '''
    model = self.model

def res(z):
    c = z[:S]
    n = z[S:]
    return np.hstack([Θ * Uc(c, n) + Un(c, n), Θ * n - c - G])

res = root(res, 0.5 * np.ones(2 * S))
if not res.success:
    raise Exception('Could not find first best')

self.cFB = res.x[:S]
self.nFB = res.x[S:]
IFB = Uc(self.cFB, self.nFB) * self.cFB + \
    Un(self.cFB, self.nFB) * self.nFB

self.xFB = np.linalg.solve(np.eye(S) - self.π * self.xFB, IFB)

self.zFB = {}
for s in range(S):
    self.zFB[s] = np.hstack([self.cFB[s], self.nFB[s], self.π[s] @ self.xFB, 0.])

__call__(self, Vf):
    '''
    Given continuation value function next period return value
    function this period return T(V) and optimal policies
    '''
    if not self.time_0:
        def PF(x, s): return self.get_policies_time1(x, s, Vf)
    else:
        def PF(B_, s0): return self.get_policies_time0(B_, s0, Vf)
    return PF

def get_policies_time1(self, x, s_, Vf):
    '''
    Finds the optimal policies
    '''
U, Uc, Un = model.U, model.Uc, model.Un

```python
def objf(z):
c, n, xprime = z[:S], z[S:2 * S], z[2 * S:3 * S]

Vprime = np.empty(S)
for s in range(S):
    Vprime[s] = Vf[s](xprime[s])

return -π[s] @ (U(c, n) + β * Vprime)
```

```python
def cons(z):
c, n, xprime, T = z[:S], z[S:2 * S], z[2 * S:3 * S], z[3 * S:]

u_c = π[s] @ u_c

return np.hstack([
    x * u_c / Eu_c - u_c * (c - T) - Un(c, n) * n - β * xprime,
    Θ * n - c - G])
```

```python
if model.transfers:
    bounds = [(0., 100)] * S + [(0., 100)] * S + 
               [self.xbar] * S + [(0., 100.)] * S
else:
    bounds = [(0., 100)] * S + [(0., 100)] * S + 
               [self.xbar] * S + [(0., 0.)] * S

out, fx, _, imode, smode = fmin_slsqp(objf, self.z0[x, s_],
                                        f_eqcons=cons, bounds=bounds,
                                        full_output=True, iprint=0,
                                        acc=self.tol, iter=self.maxiter)

if imode > 0:
    raise Exception(smode)

self.z0[x, s_] = out
return np.hstack([-fx, out])
```

```python
def get_policies_time0(self, B_, s0, Vf):
    
    Finds the optimal policies
    
    model, β, Θ, G = self.model, self.β, self.Θ, self.G
U, Uc, Un = model.U, model.Uc, model.Un

```
out, fx, _, imode, smode = fmin_slsqp(objf, self.zFB[s0],
-f_eqcons=cons,
        bounds=bounds, full_output=True,  
imode > 0:
    raise Exception(smode)
return np.hstack([-fx, out])

In [7]: import numpy as np
from scipy.interpolate import UnivariateSpline

class interpolate_wrapper:
    def __init__(self, F):
        self.F = F
    def __getitem__(self, index):
        return interpolate_wrapper(np.asarray(self.F[index]))
    def reshape(self, *args):
        self.F = self.F.reshape(*args)
        return self
    def transpose(self):
        self.F = self.F.transpose()
    def __len__(self):
        return len(self.F)
    def __call__(self, xvec):
        x = np.atleast_1d(xvec)
        shape = self.F.shape
        if len(x) == 1:
            fhat = np.hstack([f(x) for f in self.F.flatten()])
            return fhat.reshape(shape)
        else:
            fhat = np.vstack([f(x) for f in self.F.flatten()])
            return fhat.reshape(np.hstack((shape, len(x))))

class interpolator_factory:
    def __init__(self, k, s):
        self.k = k,
        self.s = s
    def __call__(self, xgrid, Fs):
        shape, m = Fs.shape[:-1], Fs.shape[-1]
        Fs = Fs.reshape((-1, m))
        F = []
        xgrid = np.sort(xgrid)  # Sort xgrid
        for Fhat in Fs:
            F.append(UnivariateSpline(xgrid, Fhat, k=self.k, s=self.s))
        return interpolate_wrapper(np.array(F).reshape(shape))
def fun_vstack(fun_list):
    Fs = [IW.F for IW in fun_list]
    return interpolate_wrapper(np.vstack(Fs))

def fun_hstack(fun_list):
    Fs = [IW.F for IW in fun_list]
    return interpolate_wrapper(np.hstack(Fs))

def simulate_markov(π, s_0, T):
    sHist = np.empty(T, dtype=int)
    sHist[0] = s_0
    S = len(π)
    for t in range(1, T):
        sHist[t] = np.random.choice(np.arange(S), p=π[sHist[t - 1]])
    return sHist

Next, we show the code that we use to generate a very long simulation starting from initial
government debt equal to -.5.

Here is a graph of a long simulation of 102000 periods.

In [8]: μ_grid = np.linspace(-0.09, 0.1, 100)

log_example = CRRAutility(π=(1 / 3) * np.ones((3, 3)),
                          G=np.array([0.1, 0.2, .3]),
                          Θ=np.ones(3))

log_example.transfers = True  # Government can use transfers
log_sequential = SequentialAllocation(log_example)  # Solve sequential
                            # problem
log_bellman = RecursiveAllocationAMSS(log_example, μ_grid,
                                        tol=1e-12, tol_diff=1e-10)

T = 102000  # Set T to 102000 periods

sim_seq_long = log_sequential.simulate(0.5, 0, T)
sHist_long = sim_seq_long[-3]
sim_bel_long = log_bellman.simulate(0.5, 0, T, sHist_long)
titles = ['Government Debt', 'Tax Rate']

fig, axes = plt.subplots(2, 1, figsize=(10, 8))

for ax, title, id in zip(axes.flatten(), titles, [2, 3]):
    ax.plot(sim_seq_long[id], '-k', sim_bel_long[id], '-.b', alpha=0.5)
    ax.set(title=title)
    ax.grid()

axes[0].legend(('Complete Markets', 'Incomplete Markets'))
plt.tight_layout()
plt.show()

---------------------------------------------------------------------------
ValueError

Traceback (most recent call last)
<ipython-input-8-e8c791a98201> in <module>
  8 log_sequential = SequentialAllocation(log_example)  
  9 log_bellman = RecursiveAllocationAMSS(log_example, μ_grid,
 ---> 10 tol=1e-12,
  11 tole_diff=1e-10)
  12

<ipython-input-6-cc6b33fcda51> in __init__(self, model,
    μ_grid, tol_diff, tol)
 15 # Find the first best allocation
 ---> 17 self.solve_time1_bellman()
 18 self.T.time_0 = True # Bellman equation now 

solves time 0 problem

<ipython-input-6-cc6b33fcda51> in solve_time1_bellman(self)
 62 PF = T(Vf)
 63 
 ---> 64 Vfnew, policies = self.fit_policy_function(PF)
 65 diff = np.abs((Vf(xgrid) - Vfnew(xgrid)) / Vf(xgrid)).max()

<ipython-input-6-cc6b33fcda51> in __init__(self, model,
    μ_grid, tol_diff, tol)
 15 # Find the first best allocation
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solves time 0 problem

<ipython-input-6-cc6b33fcda51> in solve_time1_bellman(self)
 62 PF = T(Vf)
 63 
 ---> 64 Vfnew, policies = self.fit_policy_function(PF)
 65 diff = np.abs((Vf(xgrid) - Vfnew(xgrid)) / Vf(xgrid)).max()
for s_ in range(S):
    PFvec = np.vstack([PF(x, s_) for x in self.xgrid]).T
    Vf.append(interp(xgrid, PFvec[0, :]))
    cf.append(interp(xgrid, PFvec[1:1 + S]))

def PF(x, s):
    '''
    if not self.time_0:
        def PF(x, s): return self.get_policies_time1(x, s, Vf)
    else:
        def PF(B_, s0): return self.get_policies_time0(B_, s0, Vf)

get_policies_time1(x, s, Vf)

get_policies_time0(B_, s0, Vf)

~x, s_, Vf)
~f_eqcons=cons, bounds=bounds,
~full_output=True, iprint=0,
    acc=self.tol, iter=self.maxiter)
    if imode > 0:
        g = append(sf.grad(x), 0.0)
a = _eval_con_normals(x, cons, la, n, m, meq, mieq)

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_differentiable_functions.py in grad(self, x)
  186 if not np.array_equal(x, self.x):
  187     self._update_x_impl(x)
--> 188     self._update_grad()
  189     return self.g
  190

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_differentiable_functions.py in _update_grad(self)
  169 def _update_grad(self):
  170     if not self.g_updated:
--> 171         self._update_grad_impl()
  172         self.g_updated = True
  173

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_numdiff.py in approx_derivative(fun_wrapped, self.x, f0=self.f,
  90     self.ngev += 1
  91     self.g = approx_derivative(fun_wrapped, self.x, f0=self.f,
--> 92     **finite_diff_options)
  93     self._update_grad_impl = update_grad

ValueError: `x0` violates bound constraints.
The long simulation apparently indicates eventual convergence to an ergodic distribution. It takes about 1000 periods to reach the ergodic distribution – an outcome that is forecast by approximations to rates of convergence that appear in [10] and that we discuss in a previous lecture.

We discard the first 2000 observations of the simulation and construct the histogram of the par value of government debt. We obtain the following graph for the histogram of the last 100,000 observations on the par value of government debt.
The black vertical line denotes the sample mean for the last 100,000 observations included in the histogram; the green vertical line denotes the value of \( \frac{\beta^*}{\kappa} \), associated with the sample (presumably) from the ergodic where \( \beta^* \) is the regression coefficient described below; the red vertical line denotes an approximation by \([10]\) to the mean of the ergodic distribution that can be precomputed before sampling from the ergodic distribution, as described below.

Before moving on to discuss the histogram and the vertical lines approximating the ergodic mean of government debt in more detail, the following graphs show government debt and taxes early in the simulation, for periods 1-100 and 101 to 200 respectively.

In [ ]: titles = ['Government Debt', 'Tax Rate']

```python
fig, axes = plt.subplots(4, 1, figsize=(10, 15))

for i, id in enumerate([2, 3]):
    axes[i].plot(sim_seq_long[id][:-1], '-k', sim_long[id][:-1], '-b', alpha=0.5)
    axes[i+2].plot(range(100, 199), sim_seq_long[id][100:199], '-k',
                   range(100, 199), sim_long[id][100:199], '-b',
                   alpha=0.5)
    axes[i].set(title=titles[i])
    axes[i+2].set(title=titles[i])
    axes[i].grid()
    axes[i+2].grid()

axes[0].legend(('Complete Markets', 'Incomplete Markets'))
plt.tight_layout()
plt.show()
```
For the short samples early in our simulated sample of 102,000 observations, fluctuations in government debt and the tax rate conceal the weak but inexorable force that the Ramsey planner puts into both series driving them toward ergodic distributions far from these early observations:

- early observations are more influenced by the initial value of the par value of government debt than by the ergodic mean of the par value of government debt
- much later observations are more influenced by the ergodic mean and are independent of the initial value of the par value of government debt
41.5 Asymptotic Mean and Rate of Convergence

We apply the results of [10] to interpret

- the mean of the ergodic distribution of government debt
- the rate of convergence to the ergodic distribution from an arbitrary initial government debt

We begin by computing objects required by the theory of section III.i of [10].

As in Fiscal Insurance via Fluctuating Interest Rates, we recall that [10] used a particular notation to represent what we can regard as a generalization of the AMSS model.

We introduce some of the [10] notation so that readers can quickly relate notation that appears in their key formulas to the notation that we have used in previous lectures here and here.

BEGS work with objects $B_t, \mathcal{R}_t, \mathcal{X}_t$ that are related to notation that we used in earlier lectures by

$$
\mathcal{R}_t = \frac{u_{c,t}}{u_{c,t-1}} R_{t-1} = \frac{u_{c,t}}{\beta E_{t-1} u_{c,t}}
$$

$$
B_t = \frac{b_{t+1}(s^t)}{R_t(s^t)}
$$

$$
b_{t}(s^{t-1}) = \mathcal{R}_{t-1}B_{t-1}
$$

$$
\mathcal{B}_t = u_{c,t} B_t = (\beta E_t u_{c,t+1}) b_{t+1}(s^t)
$$

$$
\mathcal{X}_t = u_{c,t}[g_{t} - \tau_t n_t]
$$

[10] call $\mathcal{X}_t$ the effective government deficit, and $\mathcal{B}_t$ the effective government debt.

Equation (44) of [10] expresses the time $t$ state $s$ government budget constraint as

$$
\mathcal{B}(s) = \mathcal{R}_t(s, s_-) \mathcal{B}_- + \mathcal{X}_t(s)
$$

(1)

where the dependence on $\tau$ is to remind us that these objects depend on the tax rate; $s_-$ is last period’s Markov state.

BEGS interpret random variations in the right side of (1) as fiscal risks generated by

- interest-rate-driven fluctuations in time $t$ effective payments due on the government portfolio, namely, $\mathcal{R}_t(s, s_-) \mathcal{B}_-$, and
- fluctuations in the effective government deficit $\mathcal{X}_t$

41.5.1 Asymptotic Mean

BEGS give conditions under which the ergodic mean of $\mathcal{B}_t$ approximately satisfies the equation

$$
\mathcal{B}^* = -\frac{\text{cov}^\infty(\mathcal{R}_t, \mathcal{X}_t)}{\text{var}^\infty(\mathcal{R}_t)}
$$

(2)

where the superscript $\infty$ denotes a moment taken with respect to an ergodic distribution.

Formula (2) represents $\mathcal{B}^*$ as a regression coefficient of $\mathcal{X}_t$ on $\mathcal{R}_t$ in the ergodic distribution.
Regression coefficient $B^*$ solves a variance-minimization problem:

$$B^* = \arg\min_B \text{var}^\infty(RB + \mathcal{X})$$  \hspace{1cm} (3)$$

The minimand in criterion (3) measures fiscal risk associated with a given tax-debt policy that appears on the right side of equation (1).

Expressing formula (2) in terms of our notation tells us that the ergodic mean of the par value $b$ of government debt in the AMSS model should approximately equal

$$\hat{b} = \frac{B^*}{\beta E(E_t u_{c,t+1})} = \frac{B^*}{\beta E(u_{c,t+1})}$$  \hspace{1cm} (4)$$

where mathematical expectations are taken with respect to the ergodic distribution.

### 41.5.2 Rate of Convergence

BEGS also derive the following approximation to the rate of convergence to $B^*$ from an arbitrary initial condition.

$$E_t(B_{t+1} - B^*) - (B_t - B^*) \approx 1 + \beta^2 \text{var}^\infty(R)$$  \hspace{1cm} (5)$$

(See the equation above equation (47) in [10])

### 41.5.3 More Advanced Material

The remainder of this lecture is about technical material based on formulas from [10]. The topic is interpreting and extending formula (3) for the ergodic mean $B^*$.

### 41.5.4 Chicken and Egg

Attributes of the ergodic distribution for $B_t$ appear on the right side of formula (3) for the ergodic mean $B^*$.

Thus, formula (3) is not useful for estimating the mean of the ergodic in advance of actually computing the ergodic distribution.

- we need to know the ergodic distribution to compute the right side of formula (3)

So the primary use of equation (3) is how it confirms that the ergodic distribution solves a fiscal-risk minimization problem.

As an example, notice how we used the formula for the mean of $B$ in the ergodic distribution of the special AMSS economy in *Fiscal Insurance via Fluctuating Interest Rates*:

- first we computed the ergodic distribution using a reverse-engineering construction
- then we verified that $B$ agrees with the mean of that distribution
41.5.5 Approximating the Ergodic Mean

[10] propose an approximation to \( B^* \) that can be computed without first knowing the ergodic distribution.

To construct the BEGS approximation to \( B^* \), we just follow steps set forth on pages 648 - 650 of section III.D of [10].

- notation in BEGS might be confusing at first sight, so it is important to stare and digest before computing
- there are also some sign errors in the [10] text that we’ll want to correct


41.5.6 Step by Step

**Step 1:** For a given \( \tau \) we compute a vector of values \( c_\tau(s), s = 1, 2, \ldots, S \) that satisfy

\[
(1 - \tau)c_\tau(s)^{-\sigma} - (c_\tau(s) + g(s))\gamma = 0
\]

This is a nonlinear equation to be solved for \( c_\tau(s), s = 1, \ldots, S \).

\( S = 3 \) in our case, but we’ll write code for a general integer \( S \).

**Typo alert:** Please note that there is a sign error in equation (42) of [10] – it should be a minus rather than a plus in the middle.

- We have made the appropriate correction in the above equation.

**Step 2:** Knowing \( c_\tau(s), s = 1, \ldots, S \) for a given \( \tau \), we want to compute the random variables

\[
\mathcal{R}_\tau(s) = \frac{c_\tau(s)^{-\sigma}}{\beta \sum_{s'=1}^{S} c_\tau(s')^{-\sigma} \pi(s')}
\]

and

\[
\mathcal{X}_\tau(s) = (c_\tau(s) + g(s))^{1+\gamma} - c_\tau(s)^{1-\sigma}
\]

each for \( s = 1, \ldots, S \).

BEGS call \( \mathcal{R}_\tau(s) \) the effective return on risk-free debt and they call \( \mathcal{X}_\tau(s) \) the effective government deficit.

**Step 3:** With the preceding objects in hand, for a given \( B \), we seek a \( \tau \) that satisfies

\[
B = -\frac{\beta}{1-\beta} E\mathcal{X}_\tau \equiv -\frac{\beta}{1-\beta} \sum_s \mathcal{X}_\tau(s) \pi(s)
\]

This equation says that at a constant discount factor \( \beta \), equivalent government debt \( B \) equals the present value of the mean effective government surplus.

**Typo alert:** there is a sign error in equation (46) of [10] – the left side should be multiplied by \(-1\).

- We have made this correction in the above equation.
For a given $\mathcal{B}$, let a $\tau$ that solves the above equation be called $\tau(\mathcal{B})$.

We’ll use a Python root solver to find a $\tau$ that this equation for a given $\mathcal{B}$.

We’ll use this function to induce a function $\tau(\mathcal{B})$.

**Step 4:** With a Python program that computes $\tau(\mathcal{B})$ in hand, next we write a Python function to compute the random variable.

$$J(\mathcal{B})(s) = \mathcal{R}_{\tau(\mathcal{B})}(s)\mathcal{B} + \mathcal{X}_{\tau(\mathcal{B})}(s), \quad s = 1, \ldots, S$$

**Step 5:** Now that we have a machine to compute the random variable $J(\mathcal{B})(s), s = 1, \ldots, S$, via a composition of Python functions, we can use the population variance function that we defined in the code above to construct a function $\text{var}(J(\mathcal{B}))$.

We put $\text{var}(J(\mathcal{B}))$ into a function minimizer and compute

$$\mathcal{B}^* = \arg\min_{\mathcal{B}} \text{var}(J(\mathcal{B}))$$

**Step 6:** Next we take the minimizer $\mathcal{B}^*$ and the Python functions for computing means and variances and compute

$$\text{rate} = \frac{1}{1 + \beta^2 \text{var}(\mathcal{R}_{\tau(\mathcal{B}^*)})}$$

Ultimate outputs of this string of calculations are two scalars

$$(\mathcal{B}^*, \text{rate})$$

**Step 7:** Compute the divisor

$$\text{div} = \beta E u_{c,t+1}$$

and then compute the mean of the par value of government debt in the AMSS model

$$\hat{b} = \frac{\mathcal{B}^*}{\text{div}}$$

In the two-Markov-state AMSS economy in *Fiscal Insurance via Fluctuating Interest Rates*, $E_t u_{c,t+1} = E u_{c,t+1}$ in the ergodic distribution and we have confirmed that this formula very accurately describes a constant par value of government debt that

- supports full fiscal insurance via fluctuating interest parameters, and
- is the limit of government debt as $t \to +\infty$

In the three-Markov-state economy of this lecture, the par value of government debt fluctuates in a history-dependent way even asymptotically.

In this economy, $\hat{b}$ given by the above formula approximates the mean of the ergodic distribution of the par value of government debt

- this is the red vertical line plotted in the histogram of the last 100,000 observations of our simulation of the par value of government debt plotted above
- the approximation is fairly accurate but not perfect
• so while the approximation circumvents the chicken and egg problem surrounding the much better approximation associated with the green vertical line, it does so by enlarging the approximation error.

### 41.5.7 Execution

Now let’s move on to compute things step by step.

**Step 1**

```python
In [9]: u = CRRAutility(π=(1 / 3) * np.ones((3, 3)),
                        G=np.array([0.1, 0.2, 0.3]),
                        Θ=np.ones(3))

τ = 0.05            # Initial guess of τ (to displays calcs along the way)
S = len(u.G)        # Number of states

def solve_c(c, τ, u):
    return (1 - τ) * c**(-u.σ) - (c + u.G)**u.γ

# .x returns the result from root

Out[9]:

In [10]: root(solve_c, np.ones(S), args=(τ, u)).x

Out[10]:
```

### 41.5.8 Note about Code

Remember that in our code $\pi$ is a $3 \times 3$ transition matrix.

But because we are studying an IID case, $\pi$ has identical rows and we only need to compute objects for one row of $\pi$. 
This explains why at some places below we set $s = 0$ just to pick off the first row of $\pi$ in the calculations.

### 41.5.9 Code

First, let’s compute $\mathcal{R}$ and $\mathcal{X}$ according to our formulas

```python
In [12]: def compute_R_X(\tau, u, s):
    c = root(solve_c, np.ones(S), args=(\tau, u)).x  # Solve for vector of c's
    div = u.\beta * (u.Uc(c[0], n[0]) * u.\pi[s, 0] \
        + u.Uc(c[1], n[1]) * u.\pi[s, 1] \
        + u.Uc(c[2], n[2]) * u.\pi[s, 2])
    R = c**(-u.\sigma) / (div)
    X = (c + u.G)**(1 + u.\gamma) - c**(1 - u.\sigma)
    return R, X

In [13]: c**(-u.\sigma) @ u.\pi

Out[13]: array([1.25997521, 1.25997521, 1.25997521])

In [14]: u.\pi

Out[14]: array([[0.33333333, 0.33333333, 0.33333333],
                [0.33333333, 0.33333333, 0.33333333],
                [0.33333333, 0.33333333, 0.33333333]])

We only want unconditional expectations because we are in an IID case.
So we’ll set $s = 0$ and just pick off expectations associated with the first row of $\pi$

In [15]: s = 0

    R, X = compute_R_X(\tau, u, s)

    Let’s look at the random variables $\mathcal{R}, \mathcal{X}$

In [16]: R

Out[16]: array([1.00116313, 1.10755123, 1.22461897])

In [17]: mean(R, s)

Out[17]: 1.1111111111111112

In [18]: X

Out[18]: array([0.05457803, 0.18259396, 0.33685546])

In [19]: mean(X, s)

Out[19]: 0.19134248445303795

In [20]: X @ u.\pi

Out[20]: array([0.19134248, 0.19134248, 0.19134248])
Step 3

In [21]: `def solve_τ(τ, B, u, s):
      R, X = compute_R,X(τ, u, s)
      return ((u.β - 1) / u.β) * B - X @ u.π[s]

Note that $B$ is a scalar.

Let’s try out our method computing $\tau$

In [22]: s = 0
      B = 1.0
      τ = root(solve_τ, .1, args=(B, u, s)).x[0] # Very sensitive to initial value

Out[22]: 0.2740159773695818

In the above cell, $B$ is fixed at 1 and $\tau$ is to be computed as a function of $B$.
Note that 0.2 is the initial value for $\tau$ in the root-finding algorithm.

Step 4

In [23]: `def min_J(B, u, s):
      # Very sensitive to initial value of $\tau$
      τ = root(solve_τ, .5, args=(B, u, s)).x[0]
      R, X = compute_R,X(τ, u, s)
      return variance(R * B + X, s)

In [24]: min_J(B, u, s)

Out[24]: 0.035564405653720765

Step 6

In [25]: B_star = minimize(min_J, .5, args=(u, s)).x[0]
      B_star

Out[25]: -1.1994845546544417

In [26]: n = c + u.G # Compute labor supply

In [27]: div = u.β * (u.Uc(c[0], n[0]) * u.π[s, 0] \\
       + u.Uc(c[1], n[1]) * u.π[s, 1] \\
       + u.Uc(c[2], n[2]) * u.π[s, 2])

In [28]: B_hat = B_star/div
      B_hat
41.5. ASYMPTOTIC MEAN AND RATE OF CONVERGENCE

Out[28]: -1.057767335514381

In [29]: \( \tau_{\text{star}} = \text{root}(-1.05, \ 0.05, \ \text{args}=(B_{\text{star}}, \ u, \ s)).X[0] \)
\( \tau_{\text{star}} \)

Out[29]: 0.09572904833250909

In [30]: \( R_{\text{star}}, \ X_{\text{star}} = \text{compute_R_X}(\tau_{\text{star}}, \ u, \ s) \)
\( R_{\text{star}}, \ X_{\text{star}} \)

Out[30]: (array([0.9998398, 1.10746593, 1.2260276]), array([0.00202734, 0.12464768, 0.27315316]))

In [31]: \( \text{rate} = 1 / (1 + u.\beta^2 \times \text{variance}(R_{\text{star}}, \ s)) \)
\( \text{rate} \)

Out[31]: 0.9931353437178791

In [32]: \( \text{root}(-1.05, \ 0.05, \ \text{args}=(B_{\text{star}}, \ u)).X[0] \)

Out[32]: array([0.92643823, 0.8802712, 0.83662638])
Chapter 42

Competitive Equilibria of a Model of Chang

42.1 Contents

- Overview 42.2
- Setting 42.3
- Competitive Equilibrium 42.4
- Inventory of Objects in Play 42.5
- Analysis 42.6
- Calculating all Promise-Value Pairs in CE 42.7
- Solving a Continuation Ramsey Planner’s Bellman Equation 42.8

In addition to what’s in Anaconda, this lecture will need the following libraries:

```
In [1]: !pip install polytope
```

42.2 Overview

This lecture describes how Chang [14] analyzed competitive equilibria and a best competitive equilibrium called a Ramsey plan.

He did this by

- characterizing a competitive equilibrium recursively in a way also employed in the dynamic Stackelberg problems and Calvo model lectures to pose Stackelberg problems in linear economies, and then
- appropriately adapting an argument of Abreu, Pearce, and Stachetti [2] to describe key features of the set of competitive equilibria


A textbook version of Chang’s model appears in chapter 25 of [43].

This lecture and Credible Government Policies in Chang Model can be viewed as more sophisticated and complete treatments of the topics discussed in Ramsey plans, time inconsistency, sustainable plans.
Both this lecture and Credible Government Policies in Chang Model make extensive use of an idea to which we apply the nickname dynamic programming squared.

In dynamic programming squared problems there are typically two interrelated Bellman equations

- A Bellman equation for a set of agents or followers with value or value function \( v_a \).
- A Bellman equation for a principal or Ramsey planner or Stackelberg leader with value or value function \( v_p \) in which \( v_a \) appears as an argument.

We encountered problems with this structure in dynamic Stackelberg problems, optimal taxation with state-contingent debt, and other lectures.

We’ll start with some standard imports:

```python
In [2]: import numpy as np
import polytope
import quantecon as qe
import matplotlib.pyplot as plt
%matplotlib inline

`polytope` failed to import `cvxopt.glpk`. will use `scipy.optimize.linprog`
```

42.2.1 The Setting

First, we introduce some notation.

For a sequence of scalars \( \bar{z} \equiv \{z_t\}_{t=0}^{\infty} \), let \( \bar{z}^x = (z_0, ..., z_t), \bar{z}^s = (z_t, z_{t+1}, ...) \).

An infinitely lived representative agent and an infinitely lived government exist at dates \( t = 0, 1, ... \).

The objects in play are

- an initial quantity \( M_{-1} \) of nominal money holdings
- a sequence of inverse money growth rates \( \bar{h} \) and an associated sequence of nominal money holdings \( \bar{M} \)
- a sequence of values of money \( \bar{q} \)
- a sequence of real money holdings \( \bar{m} \)
- a sequence of total tax collections \( \bar{x} \)
- a sequence of per capita rates of consumption \( \bar{c} \)
- a sequence of per capita incomes \( \bar{y} \)

A benevolent government chooses sequences \( (\bar{M}, \bar{h}, \bar{x}) \) subject to a sequence of budget constraints and other constraints imposed by competitive equilibrium.

Given tax collection and price of money sequences, a representative household chooses sequences \( (\bar{c}, \bar{m}) \) of consumption and real balances.

In competitive equilibrium, the price of money sequence \( \bar{q} \) clears markets, thereby reconciling decisions of the government and the representative household.

Chang adopts a version of a model that [13] designed to exhibit time-inconsistency of a Ramsey policy in a simple and transparent setting.

By influencing the representative household’s expectations, government actions at time \( t \) affect components of household utilities for periods \( s \) before \( t \).
When setting a path for monetary expansion rates, the government takes into account how the household’s anticipations of the government’s future actions affect the household’s current decisions.

The ultimate source of time inconsistency is that a time 0 Ramsey planner takes these effects into account in designing a plan of government actions for $t \geq 0$.

42.3 Setting

42.3.1 The Household’s Problem

A representative household faces a nonnegative value of money sequence $\tilde{q}$ and sequences $\tilde{y}, \tilde{x}$ of income and total tax collections, respectively.

The household chooses nonnegative sequences $\tilde{c}, \tilde{M}$ of consumption and nominal balances, respectively, to maximize

$$\sum_{t=0}^{\infty} \beta^t [u(c_t) + v(q_t M_t)]$$

subject to

$$q_t M_t \leq y_t + q_t M_{t-1} - c_t - x_t$$

and

$$q_t M_t \leq \bar{m}$$

Here $q_t$ is the reciprocal of the price level at $t$, which we can also call the value of money.

Chang [14] assumes that

- $u : \mathbb{R}_+ \to \mathbb{R}$ is twice continuously differentiable, strictly concave, and strictly increasing;
- $v : \mathbb{R}_+ \to \mathbb{R}$ is twice continuously differentiable and strictly concave;
- $u'(c)_{c \to 0} = \lim_{m \to 0} v'(m) = +\infty$;
- there is a finite level $m = m^f$ such that $v'(m^f) = 0$

The household carries real balances out of a period equal to $m_t = q_t M_t$.

Inequality (2) is the household’s time $t$ budget constraint.

It tells how real balances $q_t M_t$ carried out of period $t$ depend on income, consumption, taxes, and real balances $q_t M_{t-1}$ carried into the period.

Equation (3) imposes an exogenous upper bound $\bar{m}$ on the household’s choice of real balances, where $\bar{m} \geq m^f$.

42.3.2 Government

The government chooses a sequence of inverse money growth rates with time $t$ component $h_t \equiv \frac{M_{t-1}}{M_t} \in \Pi \equiv [\pi, \overline{\pi}]$, where $0 < \pi < 1 < \frac{1}{\beta} \leq \overline{\pi}$.

The government faces a sequence of budget constraints with time $t$ component
\[ -x_t = q_t(M_t - M_{t-1}) \]

which by using the definitions of \( m_t \) and \( h_t \) can also be expressed as

\[ -x_t = m_t(1 - h_t) \quad (4) \]

The restrictions \( m_t \in [0, \bar{m}] \) and \( h_t \in \Pi \) evidently imply that \( x_t \in X \equiv [(\pi - 1)\bar{m}, (\pi - 1)\bar{m}] \).

We define the set \( E \equiv [0, \bar{m}] \times \Pi \times X \), so that we require that \((m, h, x) \in E\).

To represent the idea that taxes are distorting, Chang makes the following assumption about outcomes for per capita output:

\[ y_t = f(x_t), \quad (5) \]

where \( f : \mathbb{R} \to \mathbb{R} \) satisfies \( f(x) > 0 \), is twice continuously differentiable, \( f''(x) < 0 \), and \( f(x) = f(-x) \) for all \( x \in \mathbb{R} \), so that subsidies and taxes are equally distorting.

Calvo’s and Chang’s purpose is not to model the causes of tax distortions in any detail but simply to summarize the outcome of those distortions via the function \( f(x) \).

A key part of the specification is that tax distortions are increasing in the absolute value of tax revenues.

**Ramsey plan:** A Ramsey plan is a competitive equilibrium that maximizes (1).

Within-period timing of decisions is as follows:

- first, the government chooses \( h_t \) and \( x_t \);
- then given \( \bar{q} \) and its expectations about future values of \( x \) and \( y \)'s, the household chooses \( M_t \) and therefore \( m_t \) because \( m_t = q_t M_t \);
- then output \( y_t = f(x_t) \) is realized;
- finally \( c_t = y_t \)

This within-period timing confronts the government with choices framed by how the private sector wants to respond when the government takes time \( t \) actions that differ from what the private sector had expected.

This consideration will be important in lecture credible government policies when we study credible government policies.

The model is designed to focus on the intertemporal trade-offs between the welfare benefits of deflation and the welfare costs associated with the high tax collections required to retire money at a rate that delivers deflation.

A benevolent time 0 government can promote utility generating increases in real balances only by imposing sufficiently large distorting tax collections.

To promote the welfare increasing effects of high real balances, the government wants to induce gradual deflation.

### 42.3.3 Household’s Problem

Given \( M_{-1} \) and \( \{q_t\}_{t=0}^{\infty} \), the household’s problem is
COMPETITIVE EQUILIBRIUM

\[
\mathcal{L} = \max_{\vec{c}, \vec{M}} \min_{\bar{\lambda}, \vec{\mu}} \sum_{t=0}^{\infty} \beta^t \{ u(c_t) + v(M_t q_t) + \lambda_t [y_t - c_t - x_t + q_t M_{t-1} - q_t M_t] \\
+ \mu_t [\bar{m} - q_t M_t] \}
\]

First-order conditions with respect to \( c_t \) and \( M_t \), respectively, are

\[
u'(c_t) = \lambda_t \\
q_t [u'(c_t) - v'(M_t q_t)] \leq \beta u'(c_{t+1}) q_{t+1}, \quad \text{if } M_t q_t < \bar{m}
\]

The last equation expresses Karush-Kuhn-Tucker complementary slackness conditions (see here).

These insist that the inequality is an equality at an interior solution for \( M_t \).

Using \( h_t = \frac{M_t - 1}{M_t} \) and \( q_t = \frac{m_t}{M_t} \) in these first-order conditions and rearranging implies

\[
m_t [u'(c_t) - v'(m_t)] \leq \beta u'(f(x_{t+1})) m_{t+1} h_{t+1}, \quad \text{if } m_t < \bar{m} \tag{6}
\]

Define the following key variable

\[
\theta_{t+1} \equiv u'(f(x_{t+1})) m_{t+1} h_{t+1} \tag{7}
\]

This is real money balances at time \( t + 1 \) measured in units of marginal utility, which Chang refers to as ‘the marginal utility of real balances’.

From the standpoint of the household at time \( t \), equation (7) shows that \( \theta_{t+1} \) intermediates the influences of \( (\vec{x}_{t+1}, \vec{m}_{t+1}) \) on the household’s choice of real balances \( m_t \).

By “intermediates” we mean that the future paths \( (\vec{x}_{t+1}, \vec{m}_{t+1}) \) influence \( m_t \) entirely through their effects on the scalar \( \theta_{t+1} \).

The observation that the one dimensional promised marginal utility of real balances \( \theta_{t+1} \) functions in this way is an important step in constructing a class of competitive equilibria that have a recursive representation.

A closely related observation pervaded the analysis of Stackelberg plans in lecture dynamic Stackelberg problems.

42.4 Competitive Equilibrium

Definition:

- A \textit{government policy} is a pair of sequences \((\vec{h}, \vec{x})\) where \( h_t \in \Pi \ \forall t \geq 0 \).
- A \textit{price system} is a nonnegative value of money sequence \( \vec{q} \).
- An \textit{allocation} is a triple of nonnegative sequences \((\vec{c}, \vec{m}, \vec{y})\).

It is required that time \( t \) components \((m_t, x_t, h_t) \in E\).

Definition:

Given \( M_{-1} \), a government policy \((\vec{h}, \vec{x})\), price system \( \vec{q} \), and allocation \((\vec{c}, \vec{m}, \vec{y})\) are said to be a \textit{competitive equilibrium} if

- \( m_t = q_t M_t \) and \( y_t = f(x_t) \).
• The government budget constraint is satisfied.
• Given \( \bar{q}, \bar{x}, \bar{y}, (\bar{c}, \bar{m}) \) solves the household’s problem.

42.5 Inventory of Objects in Play

Chang constructs the following objects

1. A set \( \Omega \) of initial marginal utilities of money \( \theta_0 \)
   • Let \( \Omega \) denote the set of initial promised marginal utilities of money \( \theta_0 \) associated with competitive equilibria.
   • Chang exploits the fact that a competitive equilibrium consists of a first period outcome \((h_0, m_0, x_0)\) and a continuation competitive equilibrium with marginal utility of money \( \theta_1 \in \Omega \).

1. Competitive equilibria that have a recursive representation
   • A competitive equilibrium with a recursive representation consists of an initial \( \theta_0 \) and a four-tuple of functions \((h, m, x, \Psi)\) mapping \( \theta \) into this period’s \((h, m, x)\) and next period’s \( \theta \), respectively.
   • A competitive equilibrium can be represented recursively by iterating on
     \[
     h_t = h(\theta_t) \\
     m_t = m(\theta_t) \\
     x_t = x(\theta_t) \\
     \theta_{t+1} = \Psi(\theta_t)
     \]
     starting from \( \theta_0 \)
     The range and domain of \( \Psi(\cdot) \) are both \( \Omega \)

1. A recursive representation of a Ramsey plan
   • A recursive representation of a Ramsey plan is a recursive competitive equilibrium \( \theta_0, (h, m, x, \Psi) \) that, among all recursive competitive equilibria, maximizes \( \sum_{t=0}^{\infty} \beta^t [u(c_t) + v(q_t, M_t)] \).
   • The Ramsey planner chooses \( \theta_0, (h, m, x, \Psi) \) from among the set of recursive competitive equilibria at time 0.
   • Iterations on the function \( \Psi \) determine subsequent \( \theta_t \)’s that summarize the aspects of the continuation competitive equilibria that influence the household’s decisions.
   • At time 0, the Ramsey planner commits to this implied sequence \( \{\theta_t\}_{t=0}^{\infty} \) and therefore to an associated sequence of continuation competitive equilibria.

1. A characterization of time-inconsistency of a Ramsey plan
   • Imagine that after a ‘revolution’ at time \( t \geq 1 \), a new Ramsey planner is given the opportunity to ignore history and solve a brand new Ramsey plan.
   • This new planner would want to reset the \( \theta_t \) associated with the original Ramsey plan to \( \theta_0 \).
   • The incentive to reinitialize \( \theta_t \) associated with this revolution experiment indicates the time-inconsistency of the Ramsey plan.
   • By resetting \( \theta \) to \( \theta_0 \), the new planner avoids the costs at time \( t \) that the original Ramsey planner must pay to reap the beneficial effects that the original Ramsey plan for \( s \geq t \) had achieved via its influence on the household’s decisions for \( s = 0, \ldots, t - 1 \).
42.6 Analysis

A competitive equilibrium is a triple of sequences \((\vec{m}, \vec{x}, \vec{h}) \in E^\infty\) that satisfies (2), (3), and (6).

Chang works with a set of competitive equilibria defined as follows.

**Definition:** \(CE = \{(\vec{m}, \vec{x}, \vec{h}) \in E^\infty\) such that (2), (3), and (6) are satisfied \(\}\).

\(CE\) is not empty because there exists a competitive equilibrium with \(h_t = 1\) for all \(t \geq 1\), namely, an equilibrium with a constant money supply and constant price level.

Chang establishes that \(CE\) is also compact.

Chang makes the following key observation that combines ideas of Abreu, Pearce, and Stacchetti \([2]\) with insights of Kydland and Prescott \([40]\).

**Proposition:** The continuation of a competitive equilibrium is a competitive equilibrium.

That is, \((\vec{m}_t, \vec{x}_t, \vec{h}_t) \in CE\) implies that \((\vec{m}_t, \vec{x}_t, \vec{h}_t) \in CE\) \(\forall \, t \geq 1\).

(Lecture dynamic Stackelberg problems also used a version of this insight)

We can now state that a **Ramsey problem** is to

\[
\max_{(\vec{m}, \vec{x}, \vec{h}) \in E^\infty} \sum_{t=0}^{\infty} \beta^t [u(c_t) + v(m_t)]
\]

subject to restrictions (2), (3), and (6).

Evidently, associated with any competitive equilibrium \((m_0, x_0)\) is an implied value of \(\theta_0 = u'(f(x_0))(m_0 + x_0)\).

To bring out a recursive structure inherent in the Ramsey problem, Chang defines the set

\[
\Omega = \{\theta \in \mathbb{R} \text{ such that } \theta = u'(f(x_0))(m_0 + x_0) \text{ for some } (\vec{m}, \vec{x}, \vec{h}) \in CE\}
\]

Equation (6) inherits from the household’s Euler equation for money holdings the property that the value of \(m_0\) consistent with the representative household’s choices depends on \((\vec{h}_1, \vec{m}_1)\).

This dependence is captured in the definition above by making \(\Omega\) be the set of first period values of \(\theta_0\) satisfying \(\theta_0 = u'(f(x_0))(m_0 + x_0)\) for first period component \((m_0, h_0)\) of competitive equilibrium sequences \((\vec{m}, \vec{x}, \vec{h})\).

Chang establishes that \(\Omega\) is a nonempty and compact subset of \(\mathbb{R}_+\).

Next Chang advances:

**Definition:** \(\Gamma(\theta) = \{(\vec{m}, \vec{x}, \vec{h}) \in CE | \theta = u'(f(x_0))(m_0 + x_0)\}\).

Thus, \(\Gamma(\theta)\) is the set of competitive equilibrium sequences \((\vec{m}, \vec{x}, \vec{h})\) whose first period components \((m_0, h_0)\) deliver the prescribed value \(\theta\) for first period marginal utility.

If we knew the sets \(\Omega, \Gamma(\theta)\), we could use the following two-step procedure to find at least the value of the Ramsey outcome to the representative household:

1. Find the indirect value function \(w(\theta)\) defined as
\[ w(\theta) = \max_{(\tilde{m}, \tilde{x}, \tilde{h}) \in \Gamma(\theta)} \sum_{t=0}^{\infty} \beta^t [u(f(x_t)) + v(m_t)] \]

1. Compute the value of the Ramsey outcome by solving \( \max_{\theta \in \Omega} w(\theta) \).

Thus, Chang states the following

**Proposition:**

\( w(\theta) \) satisfies the Bellman equation

\[ w(\theta) = \max_{x, m, h, \theta'} \{ u(f(x)) + v(m) + \beta w(\theta') \} \]

where maximization is subject to

\[ (m, x, h) \in E \text{ and } \theta' \in \Omega \]

and

\[ \theta = u'(f(x))(m + x) \]

and

\[ -x = m(1 - h) \]

and

\[ m \cdot [u'(f(x)) - v'(m)] \leq \beta \theta', \quad \text{if } m < \tilde{m} \]

Before we use this proposition to recover a recursive representation of the Ramsey plan, note that the proposition relies on knowing the set \( \Omega \).

To find \( \Omega \), Chang uses the insights of Kydland and Prescott [40] together with a method based on the Abreu, Pearce, and Stacchetti [2] iteration to convergence on an operator \( B \) that maps continuation values into values.

We want an operator that maps a continuation \( \theta \) into a current \( \theta \).

Chang lets \( Q \) be a nonempty, bounded subset of \( \mathbb{R} \).

Elements of the set \( Q \) are taken to be candidate values for continuation marginal utilities.

Chang defines an operator

\[ B(Q) = \theta \in \mathbb{R} \text{ such that there is } (m, x, h, \theta') \in E \times Q \]

such that (11), (12), and (13) hold.

Thus, \( B(Q) \) is the set of first period \( \theta' \)'s attainable with \( (m, x, h) \in E \) and some \( \theta' \in Q \).

**Proposition:**

1. \( Q \subset B(Q) \) implies \( B(Q) \subset \Omega \) (‘self-generation’).
2. \( \Omega = B(\Omega) \) (‘factorization’).

The proposition characterizes \( \Omega \) as the largest fixed point of \( B \).

It is easy to establish that \( B(Q) \) is a monotone operator.

This property allows Chang to compute \( \Omega \) as the limit of iterations on \( B \) provided that iterations begin from a sufficiently large initial set.

### 42.6.1 Some Useful Notation

Let \( \tilde{h}^t = (h_0, h_1, \ldots, h_t) \) denote a history of inverse money creation rates with time \( t \) component \( h_t \in \Pi \).

A **government strategy** \( \sigma = \{\sigma_t\}_{t=0}^{\infty} \) is a \( \sigma_0 \in \Pi \) and for \( t \geq 1 \) a sequence of functions \( \sigma_t : \Pi^{t-1} \rightarrow \Pi \).

Chang restricts the government’s choice of strategies to the following space:

\[
CE_\pi = \{ \tilde{h} \in \Pi^{\infty} : \text{there is some } (\tilde{m}, \tilde{x}) \text{ such that } (\tilde{m}, \tilde{x}, \tilde{h}) \in CE \}
\]

In words, \( CE_\pi \) is the set of money growth sequences consistent with the existence of competitive equilibria.

Chang observes that \( CE_\pi \) is nonempty and compact.

**Definition:** \( \sigma \) is said to be **admissible** if for all \( t \geq 1 \) and after any history \( \tilde{h}^{t-1} \), the continuation \( \tilde{h}_t \) implied by \( \sigma \) belongs to \( CE_\pi \).

Admissibility of \( \sigma \) means that anticipated policy choices associated with \( \sigma \) are consistent with the existence of competitive equilibria after each possible subsequent history.

After any history \( \tilde{h}^{t-1} \), admissibility restricts the government’s choice in period \( t \) to the set

\[
CE_\pi^0 = \{ h \in \Pi : \text{there is } \tilde{h} \in CE_\pi \text{ with } \tilde{h} = h_0 \}
\]

In words, \( CE_\pi^0 \) is the set of all first period money growth rates \( h = h_0 \), each of which is consistent with the existence of a sequence of money growth rates \( \tilde{h} \) starting from \( h_0 \) in the initial period and for which a competitive equilibrium exists.

**Remark:** \( CE_\pi^0 = \{ h \in \Pi : \text{there is } (m, \theta') \in [0, \tilde{m}] \times \Omega \text{ such that } mu'[f((h-1)m) - v'(m)] \leq \beta\theta' \text{ with equality if } m < \tilde{m} \} \).

**Definition:** An allocation rule is a sequence of functions \( \alpha = \{\alpha_t\}_{t=0}^{\infty} \) such that \( \alpha_t : \Pi^t \rightarrow [0, \tilde{m}] \times X \).

Thus, the time \( t \) component of \( \alpha_t(h^t) \) is a pair of functions \( (m_t(h^t), x_t(h^t)) \).

**Definition:** Given an admissible government strategy \( \sigma \), an allocation rule \( \alpha \) is called **competitive** if given any history \( \tilde{h}^{t-1} \) and \( h_t \in CE_\pi^0 \), the continuations of \( \sigma \) and \( \alpha \) after \( (\tilde{h}^{t-1}, h_t) \) induce a competitive equilibrium sequence.

### 42.6.2 Another Operator

At this point it is convenient to introduce another operator that can be used to compute a Ramsey plan.
For computing a Ramsey plan, this operator is wasteful because it works with a state vector that is bigger than necessary.

We introduce this operator because it helps to prepare the way for Chang’s operator called \( \tilde{D}(Z) \) that we shall describe in lecture credible government policies.

It is also useful because a fixed point of the operator to be defined here provides a good guess for an initial set from which to initiate iterations on Chang’s set-to-set operator \( \tilde{D}(Z) \) to be described in lecture credible government policies.

Let \( S \) be the set of all pairs \((w, \theta)\) of competitive equilibrium values and associated initial marginal utilities.

Let \( W \) be a bounded set of values in \( \mathbb{R} \).

Let \( Z \) be a nonempty subset of \( W \times \Omega \).

Think of using pairs \((w', \theta')\) drawn from \( Z \) as candidate continuation value, \( \theta \) pairs.

Define the operator

\[
D(Z) = \left\{(w, \theta) : \text{there is } h \in CE^n_0 \right. \\
\left. \text{and a four-tuple } (m(h), x(h), w'(h), \theta'(h)) \in [0, \bar{m}] \times X \times Z \text{ such that} \\
w = u(f(x(h))) + v(m(h)) + \beta w'(h) \right. \\
\left. \theta = u'(f(x(h)))(m(h) + x(h)) \right. \\
x(h) = m(h)(h - 1) \\
\left. m(h)(u'(f(x(h))) - v'(m(h))) \leq \beta \theta'(h) \right. \\
\left. \text{with equality if } m(h) < \bar{m} \} \right.
\]

It is possible to establish.

**Proposition:**

1. If \( Z \subset D(Z) \), then \( D(Z) \subset S \) (‘self-generation’).

2. \( S = D(S) \) (‘factorization’).

**Proposition:**

1. Monotonicity of \( D \): \( Z \subset Z' \) implies \( D(Z) \subset D(Z') \).

2. \( Z \) compact implies that \( D(Z) \) is compact.
It can be shown that $S$ is compact and that therefore there exists a $(w, \theta)$ pair within this set that attains the highest possible value $w$.

This $(w, \theta)$ pair is associated with a Ramsey plan.

Further, we can compute $S$ by iterating to convergence on $D$ provided that one begins with a sufficiently large initial set $S_0$.

As a very useful by-product, the algorithm that finds the largest fixed point $S = D(S)$ also produces the Ramsey plan, its value $w$, and the associated competitive equilibrium.

### 42.7 Calculating all Promise-Value Pairs in CE

Above we have defined the $D(Z)$ operator as:

$$
D(Z) = \{ (w, \theta) : \exists h \in CE^0 \pi \text{ and } (m(h), x(h), w'(h), \theta'(h)) \in [0, \bar{m}] \times X \times Z \text{ such that }
$$

$$
w = u(f(x(h))) + v(m(h)) + \beta w'(h)
$$

$$
\theta = u'(f(x(h)))(m(h) + x(h))
$$

$$
x(h) = m(h)(h - 1)
$$

$$
m(h)(u'(f(x(h))) - v'(m(h))) \leq \beta \theta'(h) \text{ (with equality if } m(h) < \bar{m})\}
$$

We noted that the set $S$ can be found by iterating to convergence on $D$, provided that we start with a sufficiently large initial set $S_0$.

Our implementation builds on ideas in this notebook.

To find $S$ we use a numerical algorithm called the outer hyperplane approximation algorithm. It was invented by Judd, Yeltekin, Conklin [37].

This algorithm constructs the smallest convex set that contains the fixed point of the $D(S)$ operator.

Given that we are finding the smallest convex set that contains $S$, we can represent it on a computer as the intersection of a finite number of half-spaces.

Let $H$ be a set of subgradients, and $C$ be a set of hyperplane levels.

We approximate $S$ by:

$$
\tilde{S} = \{ (w, \theta) | H \cdot (w, \theta) \leq C \}
$$

A key feature of this algorithm is that we discretize the action space, i.e., we create a grid of possible values for $m$ and $h$ (note that $x$ is implied by $m$ and $h$). This discretization simplifies computation of $\tilde{S}$ by allowing us to find it by solving a sequence of linear programs.

The outer hyperplane approximation algorithm proceeds as follows:
1. Initialize subgradients, $H$, and hyperplane levels, $C_0$.

2. Given a set of subgradients, $H$, and hyperplane levels, $C_t$, for each subgradient $h_i \in H$:
   - Solve a linear program (described below) for each action in the action space.
   - Find the maximum and update the corresponding hyperplane level, $C_{t+1}$.

1. If $|C_{t+1} - C_t| > \epsilon$, return to 2.

**Step 1** simply creates a large initial set $S_0$.

Given some set $S_t$, **Step 2** then constructs the set $S_{t+1} = D(S_t)$. The linear program in Step 2 is designed to construct a set $S_{t+1}$ that is as large as possible while satisfying the constraints of the $D(S)$ operator.

To do this, for each subgradient $h_i$, and for each point in the action space $(m_j, h_j)$, we solve the following problem:

$$\max_{[w', \theta']} h_i \cdot (w, \theta)$$

subject to

$$H \cdot (w', \theta') \leq C_t$$

$$w = u(f(x_j)) + v(m_j) + \beta w'$$

$$\theta = u'(f(x_j))(m_j + x_j)$$

$$x_j = m_j(h_j - 1)$$

$$m_j(u'(f(x_j)) - v'(m_j)) \leq \beta \theta' \ (= \text{if } m_j < \bar{m})$$

This problem maximizes the hyperplane level for a given set of actions.

The second part of Step 2 then finds the maximum possible hyperplane level across the action space.

The algorithm constructs a sequence of progressively smaller sets $S_{t+1} \subset S_t \subset S_{t-1} \ldots \subset S_0$.

**Step 3** ends the algorithm when the difference between these sets is small enough.

We have created a Python class that solves the model assuming the following functional forms:

$$u(c) = \log(c)$$

$$v(m) = \frac{1}{500}(m\bar{m} - 0.5m^2)^{0.5}$$
The remaining parameters \( \{ \beta, \bar{m}, \bar{h}, \bar{\bar{h}} \} \) are then variables to be specified for an instance of the Chang class.

Below we use the class to solve the model and plot the resulting equilibrium set, once with \( \beta = 0.3 \) and once with \( \beta = 0.8 \).

(Here we have set the number of subgradients to 10 in order to speed up the code for now - we can increase accuracy by increasing the number of subgradients)

In [3]:

```
Provides a class called ChangModel to solve different parameterizations of the Chang (1998) model.
```

```
import numpy as np
import quantecon asqe
import time
from scipy.spatial import ConvexHull
from scipy.optimize import linprog, minimize, minimize_scalar
from scipy.interpolate import UnivariateSpline
import numpy.polynomial.chebyshev as cheb

class ChangModel:
    """
    Class to solve for the competitive and sustainable sets in the Chang (1998) model, for different parameterizations.
    """
    def __init__(self, \( \beta \), \( \bar{m} \), \( \bar{h} \), \( \bar{\bar{h}} \), \( n_h \), \( n_m \), \( N_g \)):
        # Record parameters
        self.\( \beta \), self.\( \bar{m} \), self.\( \bar{h} \), self.\( \bar{\bar{h}} \), self.\( n_h \), self.\( n_m \), self.\( N_g \) = \( \beta \), \( \bar{m} \), \( \bar{h} \), \( \bar{\bar{h}} \), \( n_h \), \( n_m \), \( N_g \)
        # Create other parameters
        self.m_min = 1e-9
        self.m_max = self.\( \bar{m} \)
        self.N_a = self.\( n_h \)*self.\( n_m \)
        # Utility and production functions
        uc = lambda c: np.log(c)
        uc_p = lambda c: 1/c
        v = lambda m: 1/500 * (\( \bar{m} \) * m - 0.5 * m**2)**0.5
        v_p = lambda m: 0.5/500 * (\( \bar{m} \) * m - 0.5 * m**2)**(-0.5) * (\( \bar{m} \) - m)
        u = lambda h, m: uc(f(h, m)) + v(m)
        def f(h, m):
            x = m * (h - 1)
            f = 180 - (0.4 * x)**2
            return f
        def \( \theta \)(h, m):
            x = m * (h - 1)
```

\[ \theta = \text{uc}_p(f(h, m)) \times (m + x) \]

\[
\text{return } \theta
\]

# Create set of possible action combinations, \( A \)
\[
A1 = \text{np.linspace}(\text{h_min}, \text{h_max}, \text{n_h}).\text{reshape}(\text{n_h}, 1)
\]
\[
A2 = \text{np.linspace}(\text{self.m_min}, \text{self.m_max}, \text{n_m}).\text{reshape}(\text{n_m}, 1)
\]
\[
\text{self.A} = \text{np.concatenate}([\text{np.kron(np.ones((\text{n_m}, 1))), A1}, \text{np.kron(A2, np.ones((\text{n_h}, 1)))}], \text{axis}=1)
\]

# Pre-compute utility and output vectors
\[
\text{self.euler_vec} = -\text{np.multiply(self.A[:, 1], uc}_p(f(\text{self.A[:, 0], self.A[:, 1]})) - \text{v}_p(\text{self.A[:, 1]}))
\]
\[
\text{self.u_vec} = \text{u}(\text{self.A[:, 0], self.A[:, 1]})
\]
\[
\text{self.Θ_vec} = \theta(\text{self.A[:, 0], self.A[:, 1]})
\]
\[
\text{self.f_vec} = f(\text{self.A[:, 0], self.A[:, 1]})
\]
\[
\text{self.bell_vec} = \text{np.multiply(uc}_p(f(\text{self.A[:, 0], self.A[:, 1]}), \text{np.multiply(self.A[:, 1], (self.A[:, 0] - 1) \text{\textbackslash}})
\]
\[
+ \text{np.multiply(self.A[:, 1], v}_p(\text{self.A[:, 1]}))
\]

# Find extrema of (\( w, \theta \)) space for initial guess of equilibrium sets
\[
p\_vec = \text{np.zeros(\text{self.N_a})}
\]
\[
w\_vec = \text{np.zeros(\text{self.N_a})}
\]
\[
\text{for } i \text{ in range(\text{self.N_a})}:
\]
\[
p\_vec[i] = \text{self.Θ_vec[i]}
\]
\[
w\_vec[i] = \text{self.u_vec[i]} / (1 - \beta)
\]
\[
\text{w_space} = \text{np.array}([\text{min(w_vec[\text{-np.isinf(w_vec)]}, \text{max(w_vec[\text{-np.isinf(w_vec)]})}]}
\]
\[
p\_space = \text{np.array}([0, \text{max(p_vec[\text{-np.isinf(w_vec)]})]})
\]
\[
\text{self.p_space} = p\_space
\]

# Set up hyperplane levels and gradients for iterations
\[
def \text{SG_H_V}(\text{N, w_space, p_space}): 
\]
\[
\text{
This function initializes the subgradients, hyperplane levels, and extreme points of the value set by choosing an appropriate origin and radius. It is based on a similar function in QuantEcon's Games.jl.}
\]

# First, create a unit circle. Want points placed on [0, 2\pi]
\[
\text{inc} = 2 * \text{np.pi} / \text{N}
\]
\[
\text{degrees} = \text{np.arange(0, 2 * np.pi, inc)}
\]

# Points on circle
\[
\text{H} = \text{np.zeros}((\text{N}, 2))
\]
\[
\text{for } i \text{ in range(\text{N})}:
\]
\[
\text{x} = \text{degrees[i]}
\]
\[
\text{H}[i, 0] = \text{np.cos(x)}
\]
\[
\text{H}[i, 1] = \text{np.sin(x)}
\]

# Then calculate origin and radius
\[
\text{o} = \text{np.array}([\text{np.mean(w_space), np.mean(p_space)]})
\]
\[
\text{r1} = \text{max}((\text{max(w_space)} - \text{o[0]})**2, (\text{o[0]} - \text{min(w_space)})**2)
\]
42.7. CALCULATING ALL PROMISE-VALUE PAIRS IN CE

\[
r_2 = \max((\max(p_{\text{space}}) - o[1])^2, (o[1] - \min(p_{\text{space}}))^2)
\]

\[
r = \sqrt{r_1 + r_2}
\]

# Now calculate vertices
\[
Z = \text{np.zeros}((2, N))
\]

for i in range(N):
    \[
    Z[0, i] = o[0] + r^H.T[0, i]
    \]
    \[
    Z[1, i] = o[1] + r^H.T[1, i]
    \]

# Corresponding hyperplane levels
\[
C = \text{np.zeros}(N)
\]

for i in range(N):
    \[
    C[i] = \text{np.dot}(Z[:, i], H[i, :])
    \]

return C, H, Z

C, self.H, Z = SG_H_V(N_g, w_space, p_space)

C = C.reshape(N_g, 1)

self.c0_c, self.c0_s, self.c1_c, self.c1_s = np.copy(C), np.copy(C), np.copy(C), np.copy(C)

self.z0_s, self.z0_c, self.z1_s, self.z1_c = np.copy(Z), np.copy(Z), np.copy(Z), np.copy(Z)

# Create dictionaries to save equilibrium set for each iteration

self.c_dic_s, self.c_dic_c = {}, {}

self.c_dic_s[0], self.c_dic_c[0] = self.c0_s, self.c0_c

def solve_worst_spe(self):

    """Method to solve for BR(Z). See p.449 of Chang (1998)""

    p_vec = np.full(self.N_a, np.nan)

c = [1, 0]

# Pre-compute constraints

aineq_mbar = np.vstack((self.H, np.array([0, -self.β])))
bineq_mbar = np.vstack((self.c0_s, 0))

aineq = self.H
bineq = self.c0_s
aeq = [[0, -self.β]]

for j in range(self.N_a):
    # Only try if consumption is possible
    if self.f_vec[j] > 0:
        # If m = mbar, use inequality constraint
        if self.A[j, 1] == self.mbar:
            bineq_mbar[-1] = self.euler_vec[j]
            res = linprog(c, A_ub=aineq_mbar, b_ub=bineq_mbar, bounds=(self.w_bnds_s, self.p_bnds_s))
else:
    beq = self.euler_vec[j]
    res = linprog(c, A_ub=aineq, b_ub=bineq, A_eq=aeq, b_eq=beq,
                  bounds=(self.w_bnds_s, self.p_bnds_s))
    if res.status == 0:
        p_vec[j] = self.u_vec[j] + self.β * res.x[0]
# Max over h and min over other variables (see Chang (1998) p.449)
self.br_z = np.nanmax(np.nanmin(p_vec.reshape(self.n_m, self.n_h), 0))

def solve_subgradient(self):
    """Method to solve for E(Z). See p.449 of Chang (1998)"

    # Pre-compute constraints
    aineq_C_mbar = np.vstack((self.H, np.array([0, -self.β])))
    bineq_C_mbar = np.vstack((self.c0_c, 0))
    aineq_C = self.H
    bineq_C = self.c0_c
    aeq_C = [[0, -self.β]]
    aineq_S_mbar = np.vstack((np.vstack((self.H, np.array([0, -self.β]))),
                               np.array([-self.β, 0])))
    bineq_S_mbar = np.vstack((self.c0_s, np.zeros((2, 1))))
    aineq_S = np.vstack((self.H, np.array([-self.β, 0])))
    bineq_S = np.vstack((self.c0_s, 0))
    aeq_S = [[0, -self.β]]

    # Update maximal hyperplane level
    for i in range(self.N_g):
        c_a1a2_c, t_a1a2_c = np.full((self.N_a, -np.inf), 
                                   np.zeros((self.N_a, 2)))
        c_a1a2_s, t_a1a2_s = np.full((self.N_a, -np.inf), 
                                   np.zeros((self.N_a, 2)))
        c = [-self.H[i, 0], -self.H[i, 1]]
        for j in range(self.N_a):
            if self.f_vec[j] > 0:
                # COMPETITIVE EQUILIBRIA
                # If m = mbar, use inequality constraint
                if self.A[j, 1] == self.mbar:
                    bineq_C_mbar[-1] = self.euler_vec[j]
                    res = linprog(c, A_ub=aineq_C_mbar, b_ub=bineq_C_mbar,
                                  bounds=(self.w_bnds_c, self.p_bnds_c))
                # If m < mbar, use equality constraint
                else:
                    beq_C = self.euler_vec[j]
                    res = linprog(c, A_ub=aineq_C, b_ub=bineq_C, A_eq=beq_C,
                                  bounds=(self.w_bnds_c, self.p_bnds_c))
                    # If m < mbar, use equality constraint
                    else:
                        beq_C = self.euler_vec[j]
                        res = linprog(c, A_ub=aineq_C, b_ub=bineq_C, A_eq=beq_C,
                                      bounds=(self.w_bnds_c, self.p_bnds_c))
                        # If m < mbar, use equality constraint
                        else:
                            beq_C = self.euler_vec[j]
                            res = linprog(c, A_ub=aineq_C, b_ub=bineq_C, A_eq=beq_C,
                                          bounds=(self.w_bnds_c, self.p_bnds_c))
                            # If m < mbar, use equality constraint
                            else:
b_eq = beq_C, bounds=(self.w_bnds_c, \nself.p_bnds_c))

if res.status == 0:
    c_a1a2_c[i] = self.H[i, 0] * (self.u_vec[i] \n+ self.β * res.x[0]) + self.H[i, 1] * self.Θ_vec[i]
    t_a1a2_c[i] = res.x

# SUSTAINABLE EQUILIBRIA
# If m = mbar, use inequality constraint
if self.A[j, 1] == self.mbar:
    bineq_S_mbar = self.euler_vec[j]
    bineq_S_mbar = self.u_vec[j] - self.br_z
    res = linprog(c, A_ub=aineq_S_mbar, b_ub=bineq_S_mbar, \nbounds=(self.w_bnds_s, self.p_bnds_s))
# If m < mbar, use equality constraint
else:
    bineq_S = self.u_vec[j] - self.br_z
    bineq_S = self.euler_vec[j]
    res = linprog(c, A_ub=aineq_S, b_ub=bineq_S, A_eq=aeq_S, \nbounds=(self.w_bnds_s, self.p_bnds_s))

if res.status == 0:
    c_a1a2_s[i] = self.H[i, 0] * (self.u_vec[i] \n+ self.β * res.x[0]) + self.H[i, 1] * self.Θ_vec[i]
    t_a1a2_s[i] = res.x

idx_c = np.where(c_a1a2_c == max(c_a1a2_c))[:, 0]
selz1_c[:, i] = np.array([self.u_vec[idx_c] + self.β * t_a1a2_c[idx_c, 0], self.Θ_vec[idx_c]])
idx_s = np.where(c_a1a2_s == max(c_a1a2_s))[:, 0]
selz1_s[:, i] = np.array([self.u_vec[idx_s] + self.β * t_a1a2_s[idx_s, 0], self.Θ_vec[idx_s]])

for i in range(self.N_g):
    selz1_c[i] = np.dot(selz1_c[:, i], self.H[i, :])
    selz1_s[i] = np.dot(selz1_s[:, i], self.H[i, :])

def solve_sustainable(self, tol=1e-5, max_iter=250):
    """Method to solve for the competitive and sustainable equilibrium sets."

    t = time.time()
    diff = tol + 1
    iters = 0

    print('### ----------------- ###')
    print('Solving Chang Model Using Outer Hyperplane Approximation')
    print('### ----------------- ### \n')

    print('Maximum difference when updating hyperplane levels:')

while diff > tol and iters < max_iter:
    iters = iters + 1
self.solve_worst_spe()
self.solve_subgradient()
diff = max(np.maximum(abs(self.c0_c - self.c1_c),
                      abs(self.c0_s - self.c1_s)))
print(diff)

# Update hyperplane levels
self.c0_c, self.c0_s = np.copy(self.c1_c), np.copy(self.c1_s)

# Update bounds for w and θ
wmin_c, wmax_c = np.min(self.z1_c, axis=1)[0],
                 np.max(self.z1_c, axis=1)[0]
pmin_c, pmax_c = np.min(self.z1_c, axis=1)[1],
                 np.max(self.z1_c, axis=1)[1]

wmin_s, wmax_s = np.min(self.z1_s, axis=1)[0],
                 np.max(self.z1_s, axis=1)[0]
pmin_S, pmax_S = np.min(self.z1_s, axis=1)[1],
                 np.max(self.z1_s, axis=1)[1]

self.w_bnds_s, self.w_bnds_c = (wmin_s, wmax_s), (wmin_c, wmax_c)
self.p_bnds_s, self.p_bnds_c = (pmin_S, pmax_S), (pmin_c, pmax_c)

# Save iteration
self.c_dic_c[iters], self.c_dic_s[iters] = np.copy(self.c1_c), np.copy(self.c1_s)
self.iters = iters

elapsed = time.time() - t
print('Convergence achieved after {} iterations and {} seconds'.format(iters, round(elapsed, 2)))

---

def solve_bellman(self, θ_min, θ_max, order, disp=False, tol=1e-7, maxiters=100):
    """
    Continuous Method to solve the Bellman equation in section 25.3
    """

    mbar = self.mbar

    # Utility and production functions
    uc = lambda c: np.log(c)
    uc_p = lambda c: 1 / c
    v = lambda m: 1 / 500 * (mbar * m - 0.5 * m**2)**0.5
    v_p = lambda m: 0.5/500 * (mbar*m - 0.5 * m**2)**(-0.5) * (mbar - m)
    u = lambda h, m: uc(f(h, m)) + v(m)

    def f(h, m):
        x = m ** (h - 1)
        f = 180 - (0.4 * x)**2
        return f

    def θ(h, m):
        x = m ** (h - 1)
        θ = uc_p(f(h, m)) * (m + x)
        return θ

    # Bounds for Maximization
    lb1 = np.array([self.h_min, θ, θ_min])
42.7. **Calculating all Promise-Value Pairs in CE**

ub1 = np.array([self.h_max, self.mbar - 1e-5, self.mbar])

lb2 = np.array([self.h_min, self.mbar])

ub2 = np.array([self.h_max, self.mbar])

# Initialize Value Function coefficients

# Calculate roots of Chebyshev polynomial
k = np.linspace(order, 1, order)

roots = np.cos((2 * k - 1) * np.pi / (2 * order))

# Scale to approximation space
s = θ_min + (roots - 1) / 2 * (θ_max - θ_min)

# Create a basis matrix
Φ = cheb.chebvander(roots, order - 1)

# Function to minimize and constraints

def p_fun(x):
    scale = -1 + 2 * (x[2] - θ_min) / (θ_max - θ_min)
    p_fun = -(u(x[0], x[1]))
    + self.β * np.dot(cheb.chebvander(scale, order - 1), c)

    return p_fun

def p_fun2(x):
    scale = -1 + 2 * (x[1] - θ_min) / (θ_max - θ_min)
    p_fun = -(u(x[0], mbar))
    + self.β * np.dot(cheb.chebvander(scale, order - 1), c)

    return p_fun

cons1 = ({'type': 'eq', 'fun': lambda x: uc_p(f(x[0], x[1])) * x[1]
             * (x[0] - 1) + v_p(x[1]) * x[1] + self.β * x[2] - θ},
         {'type': 'eq', 'fun': lambda x: uc_p(f(x[0], x[1]))
             * x[0] * x[1] - θ})

cons2 = ({'type': 'ineq', 'fun': lambda x: uc_p(f(x[0], mbar)) * mbar
             * (x[0] - 1) + v_p(mbar) * mbar + self.β * x[1] - θ},
         {'type': 'eq', 'fun': lambda x: uc_p(f(x[0], mbar))
             * x[0] * mbar - θ})

bnds1 = np.concatenate([lb1.reshape(3, 1), ub1.reshape(3, 1)], axis=1)

bnds2 = np.concatenate([lb2.reshape(2, 1), ub2.reshape(2, 1)], axis=1)

# Bellman Iterations

diff = 1

ites = 1

while diff > tol:
    # 1. Maximization, given value function guess
    p_iter1 = np.zeros(order)
    for i in range(order):
        θ = s[i]
        res = minimize(p_fun,
                        lb1 + (ub1-lb1) / 2,
                        method='SLSQP',
                        bounds=bnds1,
                        constraints=cons1,
                        tol=1e-10)
        if res.success == True:
            p_iter1[i] = -p_fun(res.x)

    diff = 1
res = minimize(p_fun2,
    lb2 + (ub2-lb2) / 2,
    method='SLSQP',
    bounds=bnds2,
    constraints=cons2,
    tol=1e-10)
if -p_fun2(res.x) > p_iter1[i] and res.success == True:
    p_iter1[i] = -p_fun2(res.x)

# 2. Bellman updating of Value Function coefficients

# 3. Compute distance and update
diff = np.linalg.norm(c - c1)
if bool(disp == True):
    print(diff)
c = np.copy(c1)
    iters = iters + 1
if iters > maxiters:
    print('Convergence failed after {} iterations'.format(maxiters))
    break

self.θ_grid = s
self.p_iter = p_iter1
self.φ = Φ
self.c = c
print('Convergence achieved after {} iterations'.format(iters))

# Check residuals
θ_grid_fine = np.linspace(θ_min, θ_max, 100)
resid_grid = np.zeros(100)
p_grid = np.zeros(100)
θ_prime_grid = np.zeros(100)
m_grid = np.zeros(100)
h_grid = np.zeros(100)
for i in range(100):
    θ = θ_grid_fine[i]
    res = minimize(p_fun,
        lb1 + (ub1-lb1) / 2,
        method='SLSQP',
        bounds=bnds1,
        constraints=cons1,
        tol=1e-10)
if res.success == True:
    p = -p_fun(res.x)
p_grid[i] = p
θ_prime_grid[i] = res.x[2]
    h_grid[i] = res.x[0]
m_grid[i] = res.x[1]
res = minimize(p_fun2,
    lb2 + (ub2-lb2)/2,
    method='SLSQP',
    bounds=bnds2,
    constraints=cons2,
    tol=1e-10)
if -p_fun2(res.x) > p and res.success == True:
    p = -p_fun2(res.x)
p_grid[i] = p
42.7. CALCULATING ALL PROMISE-VALUE PAIRS IN CE

θ_prime_grid[i] = res.x[1]

h_grid[i] = res.x[0]

m_grid[i] = self.mbar

scale = -1 + 2*(θ - θ_min)/(θ_max - θ_min)

resid_grid[i] = np.dot(cheb.chebvander(scale, order - 1), c) - p

self.resid_grid = resid_grid

self.θ_grid_fine = θ_grid_fine

self.θ_prime_grid = θ_prime_grid

self.m_grid = m_grid

self.h_grid = h_grid

self.p_grid = p_grid

self.x_grid = m_grid * (h_grid - 1)

# Simulate

θ_series = np.zeros(31)

m_series = np.zeros(30)

h_series = np.zeros(30)

# Find initial θ

def ValFun(x):
    scale = -1 + 2*(x - θ_min)/(θ_max - θ_min)

    p_fun = np.dot(cheb.chebvander(scale, order - 1), c)

    return -p_fun

res = minimize(ValFun,
               (θ_min + θ_max)/2,
               bounds=[(θ_min, θ_max)])

θ_series[0] = res.x

# Simulate

for i in range(30):
    θ = θ_series[i]

    res = minimize(p_fun,
                   lb1 + (ub1-lb1)/2,
                   method='SLSQP',
                   bounds=bnds1,
                   constraints=cons1,
                   tol=1e-10)

    if res.success == True:
        p = -p_fun(res.x)

        h_series[i] = res.x[0]

        m_series[i] = res.x[1]

        θ_series[i+1] = res.x[2]

        res2 = minimize(p_fun2,
                        lb2 + (ub2-lb2)/2,
                        method='SLSQP',
                        bounds=bnds2,
                        constraints=cons2,
                        tol=1e-10)

        if -p_fun2(res2.x) > p and res2.success == True:
            h_series[i] = res2.x[0]

            m_series[i] = self.mbar

            θ_series[i+1] = res2.x[1]

    self.θ_series = θ_series

    self.m_series = m_series

    self.h_series = h_series
In [4]: ch1 = ChangModel(\(\beta=0.3\), \(m_{\text{bar}}=30\), \(h_{\text{min}}=0.9\), \(h_{\text{max}}=2\), \(n_h=8\), \(n_m=35\), \(N_g=10\))
ch1.solve_sustainable()

### --------------- ###
Solving Chang Model Using Outer Hyperplane Approximation
### --------------- ###

Maximum difference when updating hyperplane levels:

\[1.9168\]
\[0.66782\]
\[0.49235\]
\[0.32412\]
\[0.19022\]
def plot_competitive(ChangModel):
    
    Method that only plots competitive equilibrium set
    
    poly_C = polytope.Polytope(ChangModel.H, ChangModel.c1_c)
    ext_C = polytope.extreme(poly_C)
    
    fig, ax = plt.subplots(figsize=(7, 5))
    ax.set_xlabel('w', fontsize=16)
    ax.set_ylabel(r'$\theta$', fontsize=18)
    ax.fill(ext_C[:,0], ext_C[:,1], 'r', zorder=0)
    ChangModel.min_theta = min(ext_C[:,1])

ValueError: The algorithm terminated successfully and determined that the problem is infeasible.
```python
ChangModel.max_theta = max(ext_C[:, 1])

# Add point showing Ramsey Plan
idx_Ramsey = np.where(ext_C[:, 0] == max(ext_C[:, 0]))[0][0]
R = ext_C[idx_Ramsey, :]
ax.scatter(R[0], R[1], 150, 'black', 'o', zorder=1)

w_min = min(ext_C[:, 0])

# Label Ramsey Plan slightly to the right of the point
ax.annotate("R", xy=(R[0], R[1]), xytext=(R[0] + 0.03 * (R[0] - w_min), R[1]), fontsize=18)

plt.tight_layout()
plt.show()

plot_competitive(ch1)

In [6]: ch2 = ChangModel(β=0.8, mbar=30, h_min=0.9, h_max=1/0.8,
                        n_h=8, n_m=35, N_g=10)
    ch2.solve_sustainable()

### --------------- ###
Solving Chang Model Using Outer Hyperplane Approximation
### --------------- ###

Maximum difference when updating hyperplane levels:
[0.06369]
[0.02476]
[0.02153]
```
42.7. CALCULATING ALL PROMISE-VALUE PAIRS IN CE

[0.01915]
[0.01795]
[0.01642]
[0.01507]
[0.01284]
[0.01106]
[0.00694]
[0.0085]
[0.00433]
[0.00492]
[0.00303]
[0.00182]

---------------------------------------------------------------------------
ValueError
Traceback (most recent call last)
  in <module>
    ch2 = ChangModel(β=0.8, mbar=30, h_min=0.9, h_max=1/0.8,
    n_h=8, n_m=35, N_g=10)
----> 3 ch2.solve_sustainable()

  in solve_sustainable
    iters = iters + 1
    self.solve_worst_spe()
   --> 271 self.solve_subgradient()
    diff = max(np.maximum(abs(self.c0_c - self.

  in solve_subgradient
    res = linprog(c, A_ub=aineq_S, b_ub=bineq_S, A_eq = aeq_S, 
    bounds=(self.w_bnds_s, 
    --> 234 if res.status == 0:
       c_a1a2_s[j] = self.H[i, 0] * (self.

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_linprog.py in linprog(c, A_ub, b_ub, A_eq, b_eq, bounds, method, 
   callback, options, x0)
CHAPTER 42. COMPETITIVE EQUILIBRIA OF A MODEL OF CHANG

561 ▪
562 ▪
563 ▪
564 ▪
565 ▪

sol = {

-/anaconda3/lib/python3.7/site-packages/scipy/optimize/
-linprog_util.py in _postprocess(x, postsolve_args, complete,
status, message, tol, iteration, disp)
1538     status, message = _check_result(
1539         x, fun, status, slack, con,
1540         bounds, tol, message
1541     )
1542

-/anaconda3/lib/python3.7/site-packages/scipy/optimize/
-linprog_util.py in _check_result(x, fun, status, slack, con,
bounds, tol, message)
1451     # nearly basic feasible solution. Postsolving can make the solution
1452     # basic, however, this solution is NOT optimal
1453     raise ValueError(message)
1454
1455     return status, message

ValueError: The algorithm terminated successfully and determined that the problem is infeasible.

In [7]: plot_competitive(ch2)
42.8 Solving a Continuation Ramsey Planner’s Bellman Equation

In this section we solve the Bellman equation confronting a **continuation Ramsey planner**. The construction of a Ramsey plan is decomposed into two subproblems in [Ramsey plans, time inconsistency, sustainable plans and dynamic Stackelberg problems](#).

- Subproblem 1 is faced by a sequence of continuation Ramsey planners at $t \geq 1$.
- Subproblem 2 is faced by a Ramsey planner at $t = 0$.

The problem is:

$$ J(\theta) = \max_{m, x, \theta'} u(f(x)) + v(m) + \beta J(\theta') $$

subject to:

$$ \theta \leq u'(f(x))x + v'(m)m + \beta \theta' $$

$$ \theta = u'(f(x))(m + x) $$

$$ x = m(h - 1) $$
To solve this Bellman equation, we must know the set $\Omega$.

We have solved the Bellman equation for the two sets of parameter values for which we computed the equilibrium value sets above.

Hence for these parameter configurations, we know the bounds of $\Omega$.

The two sets of parameters differ only in the level of $\beta$.

From the figures earlier in this lecture, we know that when $\beta = 0.3$, $\Omega = [0.0088, 0.0499]$, and when $\beta = 0.8$, $\Omega = [0.0395, 0.2193]$

In [8]:
ch1 = ChangModel($\beta=0.3, \ mbar=30, \ h_{min}=0.99, \ h_{max}=1/0.3, \ n_h=8, \ n_m=35, \ N_g=50$)
ch2 = ChangModel($\beta=0.8, \ mbar=30, \ h_{min}=0.1, \ h_{max}=1/0.8, \ n_h=20, \ n_m=50, \ N_g=50$)

/home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:33:
RuntimeWarning: invalid value encountered in log

In [9]:
ch1.solve_bellman($\theta_{min}=0.01, \ \theta_{max}=0.0499, \ order=30, \ tol=1e-6$)
ch2.solve_bellman($\theta_{min}=0.045, \ \theta_{max}=0.15, \ order=30, \ tol=1e-6$)

/home/ubuntu/anaconda3/lib/python3.7/site-packages/ipykernel_launcher.py:309:
RuntimeWarning: invalid value encountered in log

Convergence achieved after 15 iterations

---------------------------------------------------------------------------
ValueError                                Traceback (most recent call last)
<ipython-input-9-288b772e8fe3> in <module>
     1 ch1.solve_bellman($\theta_{min}=0.01, \ \theta_{max}=0.0499, \ order=30, \ tol=1e-6$)
---> 2 ch2.solve_bellman($\theta_{min}=0.045, \ \theta_{max}=0.15, \ order=30, \ tol=1e-6$)
<ipython-input-3-04bea48ab06f> in solve_bellman(self, $\theta_{min}, \ \theta_{max}, \ order, \ disp, \ tol, \ maxiters$)
     386 bounds=bnds2,
42.8. SOLVING A CONTINUATION RAMSEY PLANNER’S BELLMAN EQUATION

387 constraints=cons2,
388 tol=1e-10)
389 if -p_fun2(res.x) > p_iter1[i] and res.
390 success == True:
391 p_iter1[i] = -p_fun2(res.x)

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/
=> minimize.py in minimize(fun, x0, args, method, jac, hess, hessp,
bounds, constraints, tol, callback, options)
624 elif meth == 'slsqp':
625 return _minimize_slsqp(fun, x0, args, jac, bounds,
--> constraints, constraints,
callback=callback, **options)
627 else:
628 return _minimize_trustregion_constr(fun, x0,:
=> args, jac, hess, hessp,

=> py in _minimize_slsqp(func, x0, args, jac, bounds, constraints,:
> maxiter, ftol, iprint, disp, eps, callback, finite_diff_rel_step,
**unknown_options)
424 425 if mode == -1: # gradient evaluation required
426 --> g = append(sf.grad(x), 0.0)
427 a = _eval_con_normals(x, cons, la, n, m, meq,
=> mieq)
428
~/anaconda3/lib/python3.7/site-packages/scipy/optimize/
=> _differentiable_functions.py in grad(self, x)
186 if not np.array_equal(x, self.x):
187 --> self._update_x_impl(x)
188 self._update_grad()
189 return self.g
190
~/anaconda3/lib/python3.7/site-packages/scipy/optimize/
=> _differentiable_functions.py in _update_grad(self)
169 def _update_grad(self):
170 if not self.g_updated:
--> 171 self._update_grad_impl()
172 self.g_updated = True
173
~/anaconda3/lib/python3.7/site-packages/scipy/optimize/
=> _differentiable_functions.py in update_grad()
First, a quick check that our approximations of the value functions are good.
We do this by calculating the residuals between iterates on the value function on a fine grid:

```
In [10]: max(abs(ch1.resid_grid)), max(abs(ch2.resid_grid))
```

```
---------------------------------------------------------------------------
AttributeError                       Traceback (most recent call last)
<ipython-input-10-17edaece7e64> in <module>
----> 1 max(abs(ch1.resid_grid)), max(abs(ch2.resid_grid))

AttributeError: 'ChangModel' object has no attribute 'resid_grid'
```

The value functions plotted below trace out the right edges of the sets of equilibrium values plotted above:

```
In [11]: fig, axes = plt.subplots(1, 2, figsize=(12, 4))
   ...
   for ax, model in zip(axes, (ch1, ch2)):
       ax.plot(model.θ_grid, model.p_iter)
```
The next figure plots the optimal policy functions; values of $\theta', m, x, h$ for each value of the state $\theta$:

In [12]:
```python
for model in (ch1, ch2):
    fig, axes = plt.subplots(2, 2, figsize=(12, 6), sharex=True)
    fig.suptitle(rf"$\beta = \{model.\beta\}$", fontsize=16)
    plots = [model.\theta_prime_grid, model.m_grid, model.h_grid, model.x_grid]
    labels = [r"$\theta'$", "$m$", "$h$", "$x$"]
    for ax, plot, label in zip(axes.flatten(), plots, labels):
        ax.plot(model.\theta_grid_fine, plot)
```

```
ax.set_xlabel(r"$\theta$", fontsize=14)
ax.set_ylabel(label, fontsize=14)

plt.show()
With the first set of parameter values, the value of $\theta'$ chosen by the Ramsey planner quickly hits the upper limit of $\Omega$.

But with the second set of parameters it converges to a value in the interior of the set.

Consequently, the choice of $\hat{\theta}$ is clearly important with the first set of parameter values.

One way of seeing this is plotting $\theta'(\theta)$ for each set of parameters.

With the first set of parameter values, this function does not intersect the 45-degree line until $\hat{\theta}$, whereas in the second set of parameter values, it intersects in the interior.

```
In [13]: fig, axes = plt.subplots(1, 2, figsize=(12, 4))

    for ax, model in zip(axes, (ch1, ch2)):
        ax.plot(model.\theta-grid-fine, model.\theta-prime-grid, label=r"$\theta'(\theta)$")
        ax.plot(model.\theta-grid-fine, model.\theta-grid-fine, label=r"$\theta$")
        ax.set(xlabel=r"$\theta$", title=rf"$\beta = {model.\beta}$")

    axes[0].legend()
    plt.show()
```

```
AttributeError
```

```
---------------------------------------------------------------------------
AttributeError Traceback (most recent call last)
<ipython-input-13-569b58752de7> in <module>
  2      
  3 for ax, model in zip(axes, (ch1, ch2)):
----> 4     ax.plot(model.\theta-grid-fine, model.\theta-prime-grid, label=r"$\theta'(\theta)$")

AttributeError
```
850

CHAPTER 42. COMPETITIVE EQUILIBRIA OF A MODEL OF CHANG

5
ax.plot(model.θ_grid_fine, model.θ_grid_fine,�
↪label=r"$\theta$")
6
ax.set(xlabel=r"$\theta$", title=rf"$\beta = {model.
↪β}$")

AttributeError: 'ChangModel' object has no attribute�
'θ_grid_fine'

↪

Subproblem 2 is equivalent to the planner choosing the initial value of 𝜃 (i.e. the value which
maximizes the value function).
From this starting point, we can then trace out the paths for {𝜃𝑡 , 𝑚𝑡 , ℎ𝑡 , 𝑥𝑡 }∞
𝑡=0 that support
this equilibrium.
These are shown below for both sets of parameters

In [14]: for model in (ch1, ch2):
fig, axes = plt.subplots(2, 2, figsize=(12, 6))
fig.suptitle(rf"$\beta = {model.β}$")
plots = [model.θ_series, model.m_series, model.h_series, model.
↪

x_series]
labels = [r"$\theta$", "$m$", "$h$", "$x$"]
for ax, plot, label in zip(axes.flatten(), plots, labels):
ax.plot(plot)
ax.set(xlabel='t', ylabel=label)
plt.show()


42.8. SOLVING A CONTINUATION RAMSEY PLANNER’S BELLMAN EQUATION

\[ \hat{\beta} = 0.3 \]

\[ \text{AttributeError Traceback (most recent call last)} \]

\[ <ipython-input-14-9da55787148f> in <module> \]
\[ 4 \quad \text{fig.suptitle(rf'$\beta = \{model.\beta\}$')} \]
\[ 5 \]
\[ ----> 6 \quad \text{plots = [model.\theta_series, model.m_series, model.} \]
\[ \text{h_series, model.x_series]} \]
\[ 7 \quad \text{labels = [r'$\theta$', '$m$', '$h$', '$x$']} \]
\[ 8 \]

\[ \text{AttributeError: 'ChangModel' object has no attribute '}\theta\text{'_series'} \]
42.8.1 Next Steps

In Credible Government Policies in Chang Model we shall find a subset of competitive equilibria that are **sustainable** in the sense that a sequence of government administrations that chooses sequentially, rather than once and for all at time $0$ will choose to implement them.

In the process of constructing them, we shall construct another, smaller set of competitive equilibria.
Chapter 43

Credible Government Policies in a Model of Chang

43.1 Contents

- Overview 43.2
- The Setting 43.3
- Calculating the Set of Sustainable Promise-Value Pairs 43.4

In addition to what’s in Anaconda, this lecture will need the following libraries:

In [1]: !pip install polytope

43.2 Overview

Some of the material in this lecture and competitive equilibria in the Chang model can be viewed as more sophisticated and complete treatments of the topics discussed in Ramsey plans, time inconsistency, sustainable plans.

This lecture assumes almost the same economic environment analyzed in competitive equilibria in the Chang model.

The only change – and it is a substantial one – is the timing protocol for making government decisions.

In competitive equilibria in the Chang model, a Ramsey planner chose a comprehensive government policy once-and-for-all at time 0.

Now in this lecture, there is no time 0 Ramsey planner.

Instead there is a sequence of government decision-makers, one for each $t$.

The time $t$ government decision-maker choose time $t$ government actions after forecasting what future governments will do.

We use the notion of a sustainable plan proposed in [15], also referred to as a credible public policy in [62].

Technically, this lecture starts where lecture competitive equilibria in the Chang model on Ramsey plans within the Chang [14] model stopped.
That lecture presents recursive representations of competitive equilibria and a Ramsey plan for a version of a model of Calvo [13] that Chang used to analyze and illustrate these concepts.

We used two operators to characterize competitive equilibria and a Ramsey plan, respectively.

In this lecture, we define a credible public policy or sustainable plan.

Starting from a large enough initial set $Z_0$, we use iterations on Chang’s set-to-set operator $\tilde{D}(Z)$ to compute a set of values associated with sustainable plans.

Chang’s operator $\tilde{D}(Z)$ is closely connected with the operator $D(Z)$ introduced in lecture competitive equilibria in the Chang model.

- $\tilde{D}(Z)$ incorporates all of the restrictions imposed in constructing the operator $D(Z)$, but ....
- It adds some additional restrictions
  - these additional restrictions incorporate the idea that a plan must be sustainable.
  - sustainable means that the government wants to implement it at all times after all histories.

Let’s start with some standard imports:

```python
import numpy as np
import quantecon as qe
import polytope
import matplotlib.pyplot as plt
%matplotlib inline
```

`polytope` failed to import `cvxopt.glpk`.
will use `scipy.optimize.linprog`

## 43.3 The Setting

We begin by reviewing the set up deployed in competitive equilibria in the Chang model.

Chang’s model, adopted from Calvo, is designed to focus on the intertemporal trade-offs between the welfare benefits of deflation and the welfare costs associated with the high tax collections required to retire money at a rate that delivers deflation.

A benevolent time 0 government can promote utility generating increases in real balances only by imposing an infinite sequence of sufficiently large distorting tax collections.

To promote the welfare increasing effects of high real balances, the government wants to induce gradual deflation.

We start by reviewing notation.

For a sequence of scalars $\tilde{z} = \{z_t\}_{t=0}^{\infty}$, let $\tilde{z} = (z_0, ..., z_t)$, $\tilde{z}_t = (z_t, z_{t+1}, ...)$. An infinitely lived representative agent and an infinitely lived government exist at dates $t = 0, 1, ...$

The objects in play are

- an initial quantity $M_{t-1}$ of nominal money holdings
- a sequence of inverse money growth rates $\hat{h}$ and an associated sequence of nominal money holdings $\hat{M}$
43.3. THE SETTING

- a sequence of values of money \( \bar{q} \)
- a sequence of real money holdings \( \bar{m} \)
- a sequence of total tax collections \( \bar{x} \)
- a sequence of per capita rates of consumption \( \bar{c} \)
- a sequence of per capita incomes \( \bar{y} \)

A benevolent government chooses sequences \((\bar{M}, \bar{h}, \bar{x})\) subject to a sequence of budget constraints and other constraints imposed by competitive equilibrium.

Given tax collection and price of money sequences, a representative household chooses sequences \((\bar{c}, \bar{m})\) of consumption and real balances.

In competitive equilibrium, the price of money sequence \(\bar{q}\) clears markets, thereby reconciling decisions of the government and the representative household.

### 43.3.1 The Household’s Problem

A representative household faces a nonnegative value of money sequence \(\bar{q}\) and sequences \(\bar{y}, \bar{x}\) of income and total tax collections, respectively.

The household chooses nonnegative sequences \(\bar{c}, \bar{M}\) of consumption and nominal balances, respectively, to maximize

\[
\sum_{t=0}^{\infty} \beta^t [u(c_t) + v(q_tM_t)]
\]

subject to

\[
q_tM_t \leq y_t + q_{t-1}M_{t-1} - c_t - x_t
\]

and

\[
q_tM_t \leq \bar{m}
\]

Here \(q_t\) is the reciprocal of the price level at \(t\), also known as the value of money.

Chang [14] assumes that

- \(u : \mathbb{R}_+ \rightarrow \mathbb{R}\) is twice continuously differentiable, strictly concave, and strictly increasing;
- \(v : \mathbb{R}_+ \rightarrow \mathbb{R}\) is twice continuously differentiable and strictly concave;
- \(u'(c)_{c \rightarrow 0} = \lim_{m \rightarrow 0} v'(m) = +\infty;\)
- there is a finite level \(m = m^f\) such that \(v'(m^f) = 0\)

Real balances carried out of a period equal \(m_t = q_tM_t\).

Inequality (2) is the household’s time \(t\) budget constraint.

It tells how real balances \(q_tM_t\) carried out of period \(t\) depend on income, consumption, taxes, and real balances \(q_{t-1}M_{t-1}\) carried into the period.

Equation (3) imposes an exogenous upper bound \(\bar{m}\) on the choice of real balances, where \(\bar{m} \geq m^f\).
43.3.2 Government

The government chooses a sequence of inverse money growth rates with time \( t \) component
\[
\hat{h}_t = \frac{M_t}{M_{t-1}} \in \Pi \equiv [\underline{\pi}, \bar{\pi}]
\]
where \( 0 < \underline{\pi} < 1 < \frac{1}{\beta} \leq \bar{\pi} \).

The government faces a sequence of budget constraints with time \( t \) component
\[
-x_t = q_t(M_t - M_{t-1})
\]
which, by using the definitions of \( m_t \) and \( h_t \), can also be expressed as
\[
-x_t = m_t(1 - h_t)
\]
(4)

The restrictions \( m_t \in [0, \bar{m}] \) and \( h_t \in \Pi \) evidently imply that \( x_t \in X \equiv [(\underline{\pi} - 1)\bar{m}, (\bar{\pi} - 1)\bar{m}] \).

We define the set \( E \equiv [0, \bar{m}] \times \Pi \times X \), so that we require that \((m, h, x) \in E\).

To represent the idea that taxes are distorting, Chang makes the following assumption about outcomes for per capita output:
\[
y_t = f(x_t)
\]
(5)

where \( f : \mathbb{R} \to \mathbb{R} \) satisfies \( f(x) > 0 \), is twice continuously differentiable, \( f''(x) < 0 \), and \( f(x) = f(-x) \) for all \( x \in \mathbb{R} \), so that subsidies and taxes are equally distorting.

The purpose is not to model the causes of tax distortions in any detail but simply to summarize the outcome of those distortions via the function \( f(x) \).

A key part of the specification is that tax distortions are increasing in the absolute value of tax revenues.

The government chooses a competitive equilibrium that maximizes (1).

43.3.3 Within-period Timing Protocol

For the results in this lecture, the timing of actions within a period is important because of the incentives that it activates.

Chang assumed the following within-period timing of decisions:

- first, the government chooses \( h_t \) and \( x_t \);
- then given \( \tilde{q} \) and its expectations about future values of \( x \) and \( y \)'s, the household chooses \( M_t \) and therefore \( m_t \) because \( m_t = q_t M_t \);
- then output \( y_t = f(x_t) \) is realized;
- finally \( c_t = y_t \)

This within-period timing confronts the government with choices framed by how the private sector wants to respond when the government takes time \( t \) actions that differ from what the private sector had expected.

This timing will shape the incentives confronting the government at each history that are to be incorporated in the construction of the \( \tilde{D} \) operator below.
43.3.4 Household’s Problem

Given $M_{-1}$ and $\{q_t\}_{t=0}^\infty$, the household’s problem is

$$
\mathcal{L} = \max_{\tilde{c}, \tilde{M}} \min_{\tilde{\lambda}, \tilde{\mu}} \sum_{t=0}^\infty \beta^t \{u(c_t) + v(M_t q_t) + \lambda_t[y_t - c_t - x_t + q_t M_{t-1} - q_t M_t]
+ \mu_t[\tilde{m} - q_t M_t]\}
$$

First-order conditions with respect to $c_t$ and $M_t$, respectively, are

$$
u'(c_t) = \lambda_t

q_t[u'(c_t) - v'(M_t q_t)] \leq \beta u'(c_{t+1}) q_{t+1}, = \text{ if } M_t q_t < \tilde{m}
$$

Using $h_t = \frac{M_{t+1}}{M_t}$ and $q_t = \frac{m_t}{M_t}$ in these first-order conditions and rearranging implies

$$
m_t[u'(c_t) - v'(m_t)] \leq \beta u'(f(x_{t+1})) m_{t+1} h_{t+1}, = \text{ if } m_t < \tilde{m}
$$

Define the following key variable

$$
\theta_{t+1} \equiv u'(f(x_{t+1})) m_{t+1} h_{t+1}
$$

This is real money balances at time $t + 1$ measured in units of marginal utility, which Chang refers to as ‘the marginal utility of real balances’.

From the standpoint of the household at time $t$, equation (7) shows that $\theta_{t+1}$ intermediates the influences of $(\tilde{x}_{t+1}, \tilde{m}_{t+1})$ on the household’s choice of real balances $m_t$.

By “intermediates” we mean that the future paths $(\tilde{x}_{t+1}, \tilde{m}_{t+1})$ influence $m_t$ entirely through their effects on the scalar $\theta_{t+1}$.

The observation that the one dimensional promised marginal utility of real balances $\theta_{t+1}$ functions in this way is an important step in constructing a class of competitive equilibria that have a recursive representation.

A closely related observation pervaded the analysis of Stackelberg plans in dynamic Stackelberg problems and the Calvo model.

43.3.5 Competitive Equilibrium

**Definition:**
- A *government policy* is a pair of sequences $(\tilde{h}, \tilde{x})$ where $h_t \in \Pi \forall t \geq 0$.
- A *price system* is a non-negative value of money sequence $\tilde{q}$.
- An *allocation* is a triple of non-negative sequences $(\tilde{c}, \tilde{m}, \tilde{y})$.

It is required that time $t$ components $(m_t, x_t, h_t) \in E$.

**Definition:**
Given $M_{-1}$, a government policy $(\tilde{h}, \tilde{x})$, price system $\tilde{q}$, and allocation $(\tilde{c}, \tilde{m}, \tilde{y})$ are said to be a competitive equilibrium if

- $m_t = q_t M_t$ and $y_t = f(x_t)$. 

The government budget constraint is satisfied.
Given \( q, x, y, (\bar{c}, \bar{m}) \) solves the household’s problem.

### 43.3.6 A Credible Government Policy

Chang works with

A **credible government policy with a recursive representation**

- Here there is no time 0 Ramsey planner.
- Instead there is a sequence of governments, one for each \( t \), that choose time \( t \) government actions after forecasting what future governments will do.
- Let \( w = \sum_{t=0}^{\infty} \beta^t [u(c_t) + v(q_t M_t)] \) be a value associated with a particular competitive equilibrium.
- A recursive representation of a credible government policy is a pair of initial conditions \((w_0, \theta_0)\) and a five-tuple of functions

\[
\begin{align*}
    h(w_t, \theta_t), & \quad m(h_t, w_t, \theta_t), \quad x(h_t, w_t, \theta_t), \\
    & \quad \chi(h_t, w_t, \theta_t), \quad \Psi(h_t, w_t, \theta_t)
\end{align*}
\]

mapping \( w_t, \theta_t \) and in some cases \( h_t \) into \( \hat{h}_t, m_t, x_t, w_{t+1}, \) and \( \theta_{t+1} \), respectively.
- Starting from an initial condition \((w_0, \theta_0)\), a credible government policy can be constructed by iterating on these functions in the following order that respects the within-period timing:

\[
\begin{align*}
    \hat{h}_t &= h(w_t, \theta_t) \\
    m_t &= m(h_t, w_t, \theta_t) \\
    x_t &= x(h_t, w_t, \theta_t) \\
    w_{t+1} &= \chi(h_t, w_t, \theta_t) \\
    \theta_{t+1} &= \Psi(h_t, w_t, \theta_t)
\end{align*}
\]

Here it is to be understood that \( \hat{h}_t \) is the action that the government policy instructs the government to take, while \( h_t \) possibly not equal to \( \hat{h}_t \) is some other action that the government is free to take at time \( t \).

The plan is **credible** if it is in the time \( t \) government’s interest to execute it.

Credibility requires that the plan be such that for all possible choices of \( h_t \) that are consistent with competitive equilibria,

\[
\begin{align*}
    u(f(x(\hat{h}_t, w_t, \theta_t))) + v(m(\hat{h}_t, w_t, \theta_t)) + \beta \chi(\hat{h}_t, w_t, \theta_t) \\
    \geq u(f(x(h_t, w_t, \theta_t))) + v(m(h_t, w_t, \theta_t)) + \beta \chi(h_t, w_t, \theta_t)
\end{align*}
\]

so that at each instance and circumstance of choice, a government attains a weakly higher lifetime utility with continuation value \( w_{t+1} = \Psi(h_t, w_t, \theta_t) \) by adhering to the plan and confirming the associated time \( t \) action \( \hat{h}_t \) that the public had expected earlier.

Please note the subtle change in arguments of the functions used to represent a competitive equilibrium and a Ramsey plan, on the one hand, and a credible government plan, on the other hand.

The extra arguments appearing in the functions used to represent a credible plan come from allowing the government to contemplate disappointing the private sector’s expectation about its time \( t \) choice \( \hat{h}_t \).
A credible plan induces the government to confirm the private sector’s expectation.

The recursive representation of the plan uses the evolution of continuation values to deter the government from wanting to disappoint the private sector’s expectations.

Technically, a Ramsey plan and a credible plan both incorporate history dependence.

For a Ramsey plan, this is encoded in the dynamics of the state variable \( \theta_t \), a promised marginal utility that the Ramsey plan delivers to the private sector.

For a credible government plan, we the two-dimensional state vector \((w_t, \theta_t)\) encodes history dependence.

### 43.3.7 Sustainable Plans

A government strategy \( \sigma \) and an allocation rule \( \alpha \) are said to constitute a **sustainable plan** (SP) if:

1. \( \sigma \) is admissible.
2. Given \( \sigma \), \( \alpha \) is competitive.
3. After any history \( \vec{h}_{t-1} \), the continuation of \( \sigma \) is optimal for the government; i.e., the sequence \( \hat{h}_t \) induced by \( \sigma \) after \( \vec{h}_{t-1} \) maximizes over \( CE_\pi \) given \( \alpha \).

Given any history \( \vec{h}_{t-1} \), the continuation of a sustainable plan is a sustainable plan.

Let \( \Theta = \{(\vec{m}, \vec{x}, \vec{h}) \in CE : \text{there is an SP whose outcome is}(\vec{m}, \vec{x}, \vec{h})\} \).

Sustainable outcomes are elements of \( \Theta \).

Now consider the space

\[
S = \left\{(w, \theta) : \text{there is a sustainable outcome } (\vec{m}, \vec{x}, \vec{h}) \in \Theta \right\}
\]

with value

\[
w = \sum_{t=0}^{\infty} \beta^t [u(f(x_t)) + v(m_t)] \text{ and such that } u'(f(x_0))(m_0 + x_0) = \theta
\]

The space \( S \) is a compact subset of \( W \times \Omega \) where \( W = [\underline{w}, \overline{w}] \) is the space of values associated with sustainable plans. Here \( \underline{w} \) and \( \overline{w} \) are finite bounds on the set of values.

Because there is at least one sustainable plan, \( S \) is nonempty.

Now recall the within-period timing protocol, which we can depict \((h, x) \rightarrow m = qM \rightarrow y = c\).

With this timing protocol in mind, the time 0 component of an SP has the following components:

1. A period 0 action \( \hat{h} \in \Pi \) that the public expects the government to take, together with subsequent within-period consequences \( m(\hat{h}), x(\hat{h}) \) when the government acts as expected.

2. For any first-period action \( h \neq \hat{h} \) with \( h \in CE_\pi^0 \), a pair of within-period consequences \( m(h), x(h) \) when the government does not act as the public had expected.
3. For every $h \in \Pi$, a pair $(w'(h), \theta'(h)) \in S$ to carry into next period.

These components must be such that it is optimal for the government to choose $\hat{h}$ as expected; and for every possible $h \in \Pi$, the government budget constraint and the household’s Euler equation must hold with continuation $\theta$ being $\theta'(h)$.

Given the timing protocol within the model, the representative household’s response to a government deviation to $h \neq \hat{h}$ from a prescribed $\hat{h}$ consists of a first-period action $m(h)$ and associated subsequent actions, together with future equilibrium prices, captured by $(w'(h), \theta'(h))$.

At this point, Chang introduces an idea in the spirit of Abreu, Pearce, and Stacchetti [2]. Let $Z$ be a nonempty subset of $W \times \Omega$.

Think of using pairs $(w', \theta')$ drawn from $Z$ as candidate continuation value, promised marginal utility pairs.

Define the following operator:

$$\tilde{D}(Z) = \{(w, \theta) : \text{there is } \hat{h} \in CE^0_\pi \text{ and for each } h \in CE^0_\pi$$
$$\text{a four-tuple } (m(h), x(h), w'(h), \theta'(h)) \in [0, \bar{m}] \times X \times Z$$
$$\text{such that}$$

$$w = u(f(x(\hat{h}))) + v(m(\hat{h})) + \beta w'(\hat{h}) \quad (10)$$

$$\theta = u'(f(x(\hat{h}))) (m(\hat{h}) + x(\hat{h})) \quad (11)$$

and for all $h \in CE^0_\pi$

$$w \geq u(f(x(h))) + v(m(h)) + \beta w'(h) \quad (12)$$

$$x(h) = m(h)(h - 1) \quad (13)$$

and

$$m(h)(u'(f(x(h))) - v' (m(h))) \leq \beta \theta'(h) \quad (14)$$

with equality if $m(h) < \bar{m}$

This operator adds the key incentive constraint to the conditions that had defined the earlier $D(Z)$ operator defined in competitive equilibria in the Chang model.

Condition (12) requires that the plan deter the government from wanting to take one-shot deviations when candidate continuation values are drawn from $Z$.

**Proposition:**

1. If $Z \subset \tilde{D}(Z)$, then $\tilde{D}(Z) \subset S$ ('self-generation').
43.4. **Calculating the Set of Sustainable Promise-Value Pairs**

2. \( S = \tilde{D}(S) \) (‘factorization’).

**Proposition:**

1. Monotonicity of \( \tilde{D} \): \( Z \subset Z' \) implies \( \tilde{D}(Z) \subset \tilde{D}(Z') \).
2. \( Z \) compact implies that \( \tilde{D}(Z) \) is compact.

Chang establishes that \( S \) is compact and that therefore there exists a highest value \( \text{SP} \) and a lowest value \( \text{SP} \).

Further, the preceding structure allows Chang to compute \( S \) by iterating to convergence on \( \tilde{D} \) provided that one begins with a sufficiently large initial set \( Z_0 \).

This structure delivers the following recursive representation of a sustainable outcome:

1. Choose an initial \((w_0, \theta_0) \in S\);
2. Generate a sustainable outcome recursively by iterating on (8), which we repeat here for convenience:

\[
\begin{align*}
\hat{h}_t &= h(w_t, \theta_t) \\
m_t &= m(h_t, w_t, \theta_t) \\
x_t &= x(h_t, w_t, \theta_t) \\
w_{t+1} &= x(h_t, w_t, \theta_t) \\
\theta_{t+1} &= \Psi(h_t, w_t, \theta_t)
\end{align*}
\]

43.4 **Calculating the Set of Sustainable Promise-Value Pairs**

Above we defined the \( \tilde{D}(Z) \) operator as (9).

Chang (1998) provides a method for dealing with the final three constraints.

These incentive constraints ensure that the government wants to choose \( \hat{h} \) as the private sector had expected it to.

Chang’s simplification starts from the idea that, when considering whether or not to confirm the private sector’s expectation, the government only needs to consider the payoff of the *best* possible deviation.

Equally, to provide incentives to the government, we only need to consider the harshest possible punishment.

Let \( h \) denote some possible deviation. Chang defines:

\[
P(h; Z) = \min u(f(x)) + v(m) + \beta w'
\]

where the minimization is subject to

\[
x = m(h - 1)
\]
\[ m(h)(u'(f(x(h))) + v'(m(h))) \leq \beta \theta'(h) \text{ (with equality if } m(h) < \tilde{m}) \]

\[(m, x, w', \theta') \in [0, \tilde{m}] \times X \times Z\]

For a given deviation \( h \), this problem finds the worst possible sustainable value. We then define:

\[ BR(Z) = \max P(h; Z) \text{ subject to } h \in CE^0_n \]

\( BR(Z) \) is the value of the government’s most tempting deviation.

With this in hand, we can define a new operator \( E(Z) \) that is equivalent to the \( \tilde{D}(Z) \) operator but simpler to implement:

\[ E(Z) = \left\{ (w, \theta) : \exists h \in CE^0_n \text{ and } (m(h), x(h), w'(h), \theta'(h)) \in [0, \tilde{m}] \times X \times Z \right\} \]

such that

\[ w = u(f(x(h))) + v(m(h)) + \beta w'(h) \]

\[ \theta = u'(f(x(h)))(m(h) + x(h)) \]

\[ x(h) = m(h)(h - 1) \]

\[ m(h)(u'(f(x(h))) - v'(m(h))) \leq \beta \theta'(h) \text{ (with equality if } m(h) < \tilde{m}) \]

and

\[ w \geq BR(Z) \]
43.4. CALCULATING THE SET OF SUSTAINABLE PROMISE-VALUE PAIRS

**Step 1** simply creates a large initial set $S_0$.

Given some set $S_t$, **Step 2** then constructs the value $BR(S_t)$.

To do this, we solve the following problem for each point in the action space $(m_j, h_j)$:

$$\min_{[w', \theta']} u(f(x_j)) + v(m_j) + \beta w'$$

subject to

$$H \cdot (w', \theta') \leq C_t$$

$$x_j = m_j(h_j - 1)$$

$$m_j(u'(f(x_j)) - v'(m_j)) \leq \beta \theta' \quad (= \text{if } m_j < \bar{m})$$

This gives us a matrix of possible values, corresponding to each point in the action space.

To find $BR(Z)$, we minimize over the $m$ dimension and maximize over the $h$ dimension.

**Step 3** then constructs the set $S_{t+1} = E(S_t)$. The linear program in Step 3 is designed to construct a set $S_{t+1}$ that is as large as possible while satisfying the constraints of the $E(S)$ operator.

To do this, for each subgradient $h_i$, and for each point in the action space $(m_j, h_j)$, we solve the following problem:

$$\max_{[w', \theta']} h_i \cdot (w, \theta)$$

subject to

$$H \cdot (w', \theta') \leq C_t$$

$$w = u(f(x_j)) + v(m_j) + \beta w'$$

$$\theta = u'(f(x_j))(m_j + x_j)$$

$$x_j = m_j(h_j - 1)$$

$$m_j(u'(f(x_j)) - v'(m_j)) \leq \beta \theta' \quad (= \text{if } m_j < \bar{m})$$

$$w \geq BR(Z)$$

This problem maximizes the hyperplane level for a given set of actions.
The second part of Step 3 then finds the maximum possible hyperplane level across the action space. The algorithm constructs a sequence of progressively smaller sets $S_{t+1} \subset S_t \subset S_{t-1} \ldots \subset S_0$.

**Step 4** ends the algorithm when the difference between these sets is small enough.

We have created a Python class that solves the model assuming the following functional forms:

$$u(c) = \log(c)$$

$$v(m) = \frac{1}{500}(m\bar{m} - 0.5m^2)^{0.5}$$

$$f(x) = 180 - (0.4x)^2$$

The remaining parameters $\{\beta, \bar{m}, \bar{h}, \tilde{h}\}$ are then variables to be specified for an instance of the Chang class.

Below we use the class to solve the model and plot the resulting equilibrium set, once with $\beta = 0.3$ and once with $\beta = 0.8$. We also plot the (larger) competitive equilibrium sets, which we described in competitive equilibria in the Chang model.

(We have set the number of subgradients to 10 in order to speed up the code for now. We can increase accuracy by increasing the number of subgradients)

The following code computes sustainable plans

```python
In [3]:

Provides a class called ChangModel to solve different parameterizations of the Chang (1998) model.

```

```python
import numpy as np
import quantecon as qe
import time

from scipy.spatial import ConvexHull
from scipy.optimize import linprog, minimize, minimize_scalar
from scipy.interpolate import UnivariateSpline
import numpy.polynomial.chebyshev as cheb

class ChangModel:
    """Class to solve for the competitive and sustainable sets in the Chang (1998) model, for different parameterizations."
    ""
    def __init__(self, beta, mbar, h_min, h_max, n_h, n_m, N_g):
        # Record parameters
        self.beta, self.mbar, self.h_min, self.h_max = beta, mbar, h_min, h_max
        self.n_h, self.n_m, self.N_g = n_h, n_m, N_g
```
# Create other parameters
self.m_min = 1e-9
self.m_max = self.mbar
self.N_a = self.n_h*self.n_m

# Utility and production functions
uc = lambda c: np.log(c)
uc_p = lambda c: 1/c
v = lambda m: 1/500 * mbar * m - 0.5 * m**2
v_p = lambda m: 0.5/500 * (mbar * m - 0.5 * m**2)**(-0.5) * (mbar - m)
u = lambda h, m: uc(f(h, m)) + v(m)

def f(h, m):
x = m * (h - 1)
f = 180 - (0.4 * x)**2
return f

def θ(h, m):
x = m * (h - 1)
θ = uc_p(f(h, m)) * (m + x)
return θ

# Create set of possible action combinations, A
A1 = np.linspace(h_min, h_max, n_h).reshape(n_h, 1)
A2 = np.linspace(m_min, m_max, n_m).reshape(n_m, 1)
self.A = np.concatenate((np.kron(np.ones((n_m, 1)), A1), np.kron(A2, np.ones((n_h, 1)))), axis=1)

# Pre-compute utility and output vectors
self.euler_vec = -np.multiply(self.A[:, 1], 
    uc_p(f(self.A[:, 0], self.A[:, 1])) - v_p(self.A[:, 1]))
self.u_vec = u(self.A[:, 0], self.A[:, 1])
self.θ_vec = θ(self.A[:, 0], self.A[:, 1])
self.f_vec = f(self.A[:, 0], self.A[:, 1])
self.bell_vec = np.multiply(uc_p(f(self.A[:, 0],
    self.A[:, 1]),
    np.multiply(self.A[:, 1],
    (self.A[:, 0] - 1)))/
    v_p(self.A[:, 1]))

# Find extrema of (w, θ) space for initial guess of equilibrium sets
p_vec = np.zeros(self.N_a)
w_vec = np.zeros(self.N_a)
for i in range(self.N_a):
p_vec[i] = self.θ_vec[i]
w_vec[i] = self.u_vec[i]/(1 - β)

w_space = np.array([min(w_vec[np.isinf(w_vec)]),
    max(w_vec[np.isinf(w_vec)])])
p_space = np.array([0, max(p_vec[np.isinf(w_vec)])])
self.p_space = p_space

# Set up hyperplane levels and gradients for iterations
def SG_H_V(N, w_space, p_space):
    this function initializes the subgradients, hyperplane levels,
    and extreme points of the value set by choosing an appropriate
origin and radius. It is based on a similar function in QuantEcon’s Games.jl

```python
# First, create a unit circle. Want points placed on [0, 2π]
inc = 2 * np.pi / N
degrees = np.arange(0, 2 * np.pi, inc)

# Points on circle
H = np.zeros((N, 2))
for i in range(N):
    x = degrees[i]
    H[i, 0] = np.cos(x)
    H[i, 1] = np.sin(x)

# Then calculate origin and radius
o = np.array([np.mean(w_space), np.mean(p_space)])
r1 = max((max(w_space) - o[0])**2, (o[0] - min(w_space))**2)
r2 = max((max(p_space) - o[1])**2, (o[1] - min(p_space))**2)
r = np.sqrt(r1 + r2)

# Now calculate vertices
Z = np.zeros((2, N))
for i in range(N):
    Z[0, i] = o[0] + r*H.T[0, i]
    Z[1, i] = o[1] + r*H.T[1, i]

# Corresponding hyperplane levels
C = np.zeros(N)
for i in range(N):
    C[i] = np.dot(Z[:, i], H[i, :])
return C, H, Z
```

```python
# Create dictionaries to save equilibrium set for each iteration
self.c_dic_s, self.c_dic_c = {}, {}
```

```python
def solve_worst_spe(self):
    """Method to solve for BR(Z). See p.449 of Chang (1998)""
```
43.4. CALCULATING THE SET OF SUSTAINABLE PROMISE-VALUE PAIRS

\[
p_{\text{vec}} = \text{np.full}(\text{self}.N_a, \text{np.nan})
\]

\[
c = [1, 0]
\]

# Pre-compute constraints
\[
a_{\text{ineq}}_{\text{mbar}} = \text{np.vstack}((\text{self}.H, \text{np.array}([0, -\text{self}.\beta])))
\]
\[
b_{\text{ineq}}_{\text{mbar}} = \text{np.vstack}((\text{self}.c0_s, 0))
\]

\[
a_{\text{ineq}} = \text{self}.H
\]
\[
b_{\text{ineq}} = \text{self}.c0_s
\]
\[
a_{\text{eq}} = [[0, -\text{self}.\beta]]
\]

for j in range(\text{self}.N_a):
    # Only try if consumption is possible
    if \text{self}.f_vec[j] > 0:
        # If \( m = \text{mbar} \), use inequality constraint
        if \text{self}.A[j, 1] == \text{self}.euler_vec[j]:
            \text{bineq}_{\text{mbar}[\text{-1}]} = \text{self}.euler_vec[j]
            \text{res} = \text{linprog}(c, \text{A}_{\text{ub}}=\text{aineq}_{\text{mbar}}, \text{b}_{\text{ub}}=\text{bineq}_{\text{mbar}},
                \text{bounds}=\text{self}.w_{\text{bnds}}_s, \text{self}.p_{\text{bnds}}_s)
        else:
            \text{beq} = \text{self}.euler_vec[j]
            \text{res} = \text{linprog}(c, \text{A}_{\text{ub}}=\text{aineq}, \text{b}_{\text{ub}}=\text{bineq}, \text{A}_{\text{eq}}=\text{aeq},
                \text{b}_{\text{eq}}=\text{beq},
                \text{bounds}=\text{self}.w_{\text{bnds}}_s, \text{self}.p_{\text{bnds}}_s)
    if \text{res}.status == 0:
        \text{p}_{\text{vec}}[j] = \text{self}.u_{\text{vec}}[j] + \text{self}.\beta \times \text{res.x}[0]

# Max over \( h \) and min over other variables (see Chang (1998) p.449)
\text{self}.br_\text{z} = \text{np.nanmax}(\text{np.nanmin}(\text{p}_{\text{vec}}.\text{reshape}(\text{self}.n_m, \text{self}.n_h),
                0))

\text{def} \text{solve_subgradient}(\text{self})::

    \text{Method to solve for } E(Z). \text{ See p.449 of Chang (1998)}

\text{# Pre-compute constraints}
\[
a_{\text{ineq}}_{\text{C}}_{\text{mbar}} = \text{np.vstack}((\text{self}.H, \text{np.array}([0, -\text{self}.\beta])))
\]
\[
b_{\text{ineq}}_{\text{C}}_{\text{mbar}} = \text{np.vstack}((\text{self}.c0_c, 0))
\]

\[
a_{\text{ineq}}_{\text{C}} = \text{self}.H
\]
\[
b_{\text{ineq}}_{\text{C}} = \text{self}.c0_c
\]
\[
a_{\text{eq}}_{\text{C}} = [[0, -\text{self}.\beta]]
\]

\[
a_{\text{ineq}}_{\text{S}}_{\text{mbar}} = \text{np.vstack}((\text{np.vstack}((\text{self}.H, \text{np.array}([0, -\text{self}.\beta]))),
                \text{np.array}([-\text{self}.\beta, 0])))
\]
\[
b_{\text{ineq}}_{\text{S}}_{\text{mbar}} = \text{np.vstack}((\text{self}.c0_s, \text{np.zeros}((2, 1))))
\]

\[
a_{\text{ineq}}_{\text{S}} = \text{np.vstack}((\text{self}.H, \text{np.array}([-\text{self}.\beta, 0])))
\]
\[
b_{\text{ineq}}_{\text{S}} = \text{np.vstack}((\text{self}.c0_s, 0))
\]
\[
a_{\text{eq}}_{\text{S}} = [[0, -\text{self}.\beta]]
\]

# Update maximal hyperplane level
for i in range(\text{self}.N_g):
    \text{c}_{\text{a1a2}}_{\text{c}}, \text{t}_{\text{a1a2}}_{\text{c}} = \text{np.full}(\text{self}.N_a, -\text{np.inf}),
        \text{np.zeros}((\text{self}.N_a, 2))
    \text{c}_{\text{a1a2}}_{\text{s}}, \text{t}_{\text{a1a2}}_{\text{s}} = \text{np.full}(\text{self}.N_a, -\text{np.inf}),
        \text{np.zeros}((\text{self}.N_a, 2))
```python
np.zeros((self.N_a, 2))
c = [-self.H[i, 0], -self.H[i, 1]]

for j in range(self.N_a):
    # Only try if consumption is possible
    if self.f_vec[j] > 0:
        # COMPETITIVE EQUILIBRIA
        # If m = mbar, use inequality constraint
        if self.A[j, 1] == self.mbar:
            bineq_C_mbar[-1] = self.euler_vec[j]
            res = linprog(c, A_ub=aineq_C_mbar, b_ub=bineq_C_mbar,
                          bounds=(self.w_bnds_c, self.p_bnds_c))
        # If m < mbar, use equality constraint
        else:
            beq_C = self.euler_vec[j]
            res = linprog(c, A_ub=aineq_C, b_ub=bineq_C, A_eq=[
                          -self.H[i, 0], -self.H[i, 1]]
                          b_eq = beq_C, bounds=(self.w_bnds_c, 
                          self.p_bnds_c))
        if res.status == 0:
            c_a1a2_c[j] = self.H[i, 0] * (self.u_vec[j] \n                          + self.β * res.x[0]) + self.H[i, 1] * self.Θ_vec[j]
            t_a1a2_c[j] = res.x

        # SUSTAINABLE EQUILIBRIA
        # If m = mbar, use inequality constraint
        if self.A[j, 1] == self.mbar:
            bineq_S_mbar[-1] = self.euler_vec[j]
            bineq_S_mbar[-2] = self.u_vec[j] - self.br_z
            res = linprog(c, A_ub=aineq_S_mbar, b_ub=bineq_S_mbar,
                          bounds=(self.w_bnds_s, self.p_bnds_s))
        # If m < mbar, use equality constraint
        else:
            beq_S = self.euler_vec[j]
            res = linprog(c, A_ub=aineq_S, b_ub=bineq_S, A_eq=[
                          -self.H[i, 0], -self.H[i, 1]]
                          b_eq = beq_S, bounds=(self.w_bnds_s, 
                          self.p_bnds_s))
        if res.status == 0:
            c_a1a2_s[j] = self.H[i, 0] * (self.u_vec[j] \n                          + self.β*res.x[0]) + self.H[i, 1] * self.Θ_vec[j]
            t_a1a2_s[j] = res.x

idx_c = np.where(c_a1a2_c == max(c_a1a2_c))[0][0]
self.z1_c[:, i] = np.array([self.u_vec[idx_c] \n                          + self.β * t_a1a2_c[idx_c, 0],
                          self.Θ_vec[idx_c]])

idx_s = np.where(c_a1a2_s == max(c_a1a2_s))[0][0]
self.z1_s[:, i] = np.array([self.u_vec[idx_s] \n                          + self.β * t_a1a2_s[idx_s, 0],
                          self.Θ_vec[idx_s]])

for i in range(self.N_g):
    self.c1_c[i] = np.dot(self.z1_c[:, i], self.H[i, :])
```

```python
self.c1_s[i] = np.dot(self.z1_s[:, i], self.H[i, :])

def solve_sustainable(self, tol=1e-5, max_iter=250):
    """
    Method to solve for the competitive and sustainable equilibrium sets.
    """
    t = time.time()
    diff = tol + 1
    iters = 0

    print('### ------------------ ###
    print('Solving Chang Model Using Outer Hyperplane Approximation')
    print('### ------------------ ###
    
    print('Maximum difference when updating hyperplane levels:')
    while diff > tol and iters < max_iter:
        iters = iters + 1
        self.solve_worst_spe()
        self.solve_subgradient()
        diff = max(np.maximum(abs(self.c0_c - self.c1_c),
                              abs(self.c0_s - self.c1_s)))
        print(diff)

        # Update hyperplane levels
        self.c0_c, self.c0_s = np.copy(self.c1_c), np.copy(self.c1_s)

        # Update bounds for w and θ
        wmin_c, wmax_c = np.min(self.z1_c, axis=1)[0], 
                         np.max(self.z1_c, axis=1)[0]
        pmin_c, pmax_c = np.min(self.z1_c, axis=1)[1], 
                         np.max(self.z1_c, axis=1)[1]
        wmin_s, wmax_s = np.min(self.z1_s, axis=1)[0], 
                         np.max(self.z1_s, axis=1)[0]
        pmin_s, pmax_s = np.min(self.z1_s, axis=1)[1], 
                         np.max(self.z1_s, axis=1)[1]

        self.w_bnds_s, self.w_bnds_c = (wmin_s, wmax_s), (wmin_c, wmax_c)
        self.p_bnds_s, self.p_bnds_c = (pmin_s, pmax_s), (pmin_c, pmax_c)

        # Save iteration
        self.c_dic_c[iters], self.c_dic_s[iters] = np.copy(self.c1_c), 
                                                  np.copy(self.c1_s)
        self.iters = iters

        elapsed = time.time() - t
        print('Convergence achieved after {} iterations and {} seconds'.format(iters, round(elapsed, 2)))

    def solve_bellman(self, θ_min, θ_max, order, disp=False, tol=1e-7, maxiters=100):
        """
        Continuous Method to solve the Bellman equation in section 25.3
        """
        mbar = self.mbar
```

# Utility and production functions
uc = lambda c: np.log(c)
uc_p = lambda c: 1 / c
v = lambda m: 1 / 500 * (mbar * m - 0.5 * m**2)**0.5
v_p = lambda m: 0.5/500 * (mbar**m - 0.5 * m**2)**(-0.5) * (mbar - m)
u = lambda h, m: uc(f(h, m)) + v(m)

def f(h, m):
x = m * (h - 1)
f = 180 / (0.4 * x)**2
return f

def θ(h, m):
x = m * (h - 1)
θ = uc_p(f(h, m)) * (m + x)
return θ

# Bounds for Maximization
lb1 = np.array([self.h_min, θ, θ_min])
ub1 = np.array([self.h_max, self.mbar - 1e-5, θ_max])
lb2 = np.array([self.h_min, θ_min])
ub2 = np.array([self.h_max, θ_max])

# Initialize Value Function coefficients
# Calculate roots of Chebyshev polynomial
k = np.linspace(order, 2, order)
roots = np.cos((2 * k - 1) * np.pi / (2 * order))
# Scale to approximation space
s = θ_min + (roots - -1) / 2 * (θ_max - θ_min)
# Create a basis matrix
Φ = cheb.chebvander(roots, order - 1)
c = np.zeros(Φ.shape[0])

# Function to minimize and constraints
def p_fun(x):
scale = -1 + 2 * (x[2] - θ_min) / (θ_max - θ_min)
p_fun = - (u(x[0], x[1]) *
            (x[0] - 1) + v_p(x[1]) * x[1] + self.β * x[2] - θ),
         (x[0] - 1) + v(mbar) * mbar + self.β * x[1] - θ),
'type': 'eq', 'fun': lambda x: uc_p(f(x[0], mbar)) * mbar
         * x[0] * mbar - θ)
cons2 = {'type': 'ineq', 'fun': lambda x: uc_p(f(x[0], mbar)) * mbar
        * x[0] - 1) + v_p(mbar) * mbar + self.β * x[1] - θ},
         x[0] * mbar - θ})

bnds1 = np.concatenate([lb1.reshape(3, 1), ub1.reshape(3, 1)], axis=1)


```
bdns2 = np.concatenate([lb2.reshape(2, 1), ub2.reshape(2, 1)], axis=1)

# Bellman Iterations
diff = 1
iters = 1

while diff > tol:
    # 1. Maximization, given value function guess
    p_iter1 = np.zeros(order)
    for i in range(order):
        θ = s[i]
        res = minimize(p_fun,
                        lb1 + (ub1-lb1) / 2,
                        method='SLSQP',
                        bounds=bnds1,
                        constraints=cons1,
                        tol=1e-10)
        if res.success == True:
            p_iter1[i] = -p_fun(res.x)
        res = minimize(p_fun2,
                        lb2 + (ub2-lb2) / 2,
                        method='SLSQP',
                        bounds=bnds2,
                        constraints=cons2,
                        tol=1e-10)
        if -p_fun2(res.x) > p_iter1[i] and res.success == True:
            p_iter1[i] = -p_fun2(res.x)

    # 2. Bellman updating of Value Function coefficients
    c1 = np.linalg.solve(Φ, p_iter1)

    # 3. Compute distance and update
    diff = np.linalg.norm(c - c1)
    if bool(disp == True):
        print(diff)
    c = np.copy(c1)
    iters = iters + 1
    if iters > maxiters:
        print('Convergence failed after {} iterations'.format(maxiters))
        break

    self.θ_grid = s
    self.p_iter = p_iter1
    self.Φ = Φ
    self.c = c
    print('Convergence achieved after {} iterations'.format(iters))

# Check residuals
θ_grid_fine = np.linspace(θ_min, θ_max, 100)
resid_grid = np.zeros(100)
p_grid = np.zeros(100)
θ_prime_grid = np.zeros(100)
m_grid = np.zeros(100)
h_grid = np.zeros(100)
for i in range(100):
    θ = θ_grid_fine[i]
    res = minimize(p_fun,
```
\[ \text{lb1} \div (\text{ub1}-\text{lb1}) / 2, \]
\[
\text{method='SLSQP',}
\quad \text{bounds=bnds1,}
\quad \text{constraints=cons1,}
\quad \text{tol=1e-10} \]

```python
if res.success == True:
    p = -p_fun(res.x)
    p_grid[i] = p
    θ_prime_grid[i] = res.x[2]
    h_grid[i] = res.x[0]
    m_grid[i] = res.x[1]
    res = minimize(p_fun2,
        lb2 + (ub2-lb2)/2,
        method='SLSQP',
        bounds=bnds2,
        constraints=cons2,
        tol=1e-10)
```

```python
if -p_fun2(res.x) > p and res.success == True:
    p = -p_fun2(res.x)
    p_grid[i] = p
    θ_prime_grid[i] = res.x[1]
    h_grid[i] = res.x[0]
    m_grid[i] = self.mbar
    scale = -1 + 2 * (θ - θ_min)/(θ_max - θ_min)
    resid_grid[i] = np.dot(cheb.chebvander(scale, order-1), c) - p
```

```python
self.resid_grid = resid_grid
self.θ_grid_fine = θ_grid_fine
self.θ_prime_grid = θ_prime_grid
self.m_grid = m_grid
self.h_grid = h_grid
self.p_grid = p_grid
self.x_grid = m_grid * (h_grid - 1)
```

```
# Simulate
θ_series = np.zeros(31)
m_series = np.zeros(30)
h_series = np.zeros(30)

# Find initial θ
def ValFun(x):
    scale = -1 + 2*(x - θ_min)/(θ_max - θ_min)
    p_fun = np.dot(cheb.chebvander(scale, order - 1), c)
    return -p_fun

res = minimize(ValFun,
                (θ_min + θ_max)/2,
                bounds=[(θ_min, θ_max)])
θ_series[0] = res.x

# Simulate
for i in range(30):
    θ = θ_series[i]
    res = minimize(p_fun,
                    lb1 + (ub1-lb1)/2,
                    method='SLSQP',
                    bounds=bnds1,
                    constraints=cons1}
```
43.4. CALCULATING THE SET OF SUSTAINABLE PROMISE-VALUE PAIRS

\( \text{tol}=1e-10 \)

```python
if res.success == True:
    p = -p_fun(res.x)
    h_series[i] = res.x[0]
    m_series[i] = res.x[1]
    \( \theta \)_series[i+1] = res.x[2]
res2 = minimize(p_fun2,
    lb2 + (ub2-lb2)/2,  # Constraint update
    method='SLSQP',
    bounds=bnds2,
    constraints=cons2,
    tol=1e-10)
if -p_fun2(res2.x) > p and res2.success == True:
    h_series[i] = res2.x[0]
    m_series[i] = self.mbar
    \( \theta \)_series[i+1] = res2.x[1]
```

43.4.1 Comparison of Sets

The set of \((w, \theta)\) associated with sustainable plans is smaller than the set of \((w, \theta)\) pairs associated with competitive equilibria, since the additional constraints associated with sustainability must also be satisfied.

Let’s compute two examples, one with a low \(\beta\), another with a higher \(\beta\).

**In [4]:**
```
ch1 = ChangModel(\(\beta=0.3\), mbar=30, h_min=0.9, h_max=2, n_h=8, n_m=35, N_g=10)
```

**In [5]:**
```
ch1.solve_sustainable()
```

```python
### --------------- ###
Solving Chang Model Using Outer Hyperplane Approximation
### --------------- ###
Maximum difference when updating hyperplane levels:
[1.9168]
[0.66782]
[0.49235]
[0.32412]
[0.19022]
```

```
ValueError
Traceback (most recent call last)
<ipython-input-5-ce0f3c9d3306> in <module>
----> 1 ch1.solve_sustainable()
```

---
<ipython-input-3-04bea48ab06f> in solve_sustainable(self,)
   269       iters = iters + 1
   270       self.solve_worst_spe()
  --> 271       self.solve_subgradient()
   272       diff = max(np.maximum(abs(self.c0_c - self.
   273       abs(self.c0_s - self.c1_s))))

<ipython-input-3-04bea48ab06f> in solve_subgradient(self)
   231       res = linprog(c, A_ub=aineq_S,
  --> 232       b_ub=bineq_S, A_eq = aeq_S,
   233       b_eq = beq_S,
   234       bounds=(self.w_bnds_s, 
   235       if res.status == 0:
   236       c_a1a2_s[j] = self.H[i, 0] * (self.

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_linprog.py in linprog(c, A_ub, b_ub, A_eq, b_eq, bounds, method,
   561       callback, options, x0)
   562       complete, status,
   563       message, tol,
  --> 564       iteration, disp)
   565       sol = {

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_linprog_util.py in _postprocess(x, postsolve_args, complete,)
   1538       status, message = _check_result(
   1539       x, fun, status, slack, con,
  --> 1540       bounds, tol, message
   1541     )
   1542

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_linprog_util.py in _check_result(x, fun, status, slack, con,  
   1538       status, message = _check_result(
   1539       x, fun, status, slack, con,
  --> 1540       bounds, tol, message
   1541     )
   1542
### 43.4. Calculating the Set of Sustainable Promise-Value Pairs

```python
434. CALCULATING THE SET OF SUSTAINABLE PROMISE-VALUE PAIRS

# nearly basic feasible solution. Postsolving can
# make the solution
# basic, however, this solution is NOT optimal
-> raise ValueError(message)

return status, message

ValueError: The algorithm terminated successfully and
determined that the problem is infeasible.

The following plot shows both the set of \( w, \theta \) pairs associated with competitive equilibria (in red) and the smaller set of \( w, \theta \) pairs associated with sustainable plans (in blue).

In [6]: def plot_equilibria(ChangModel):
   """
   Method to plot both equilibrium sets
   """
   fig, ax = plt.subplots(figsize=(7, 5))
   ax.set_xlabel('w', fontsize=16)
   ax.set_ylabel(r'$\theta$', fontsize=18)
   poly_S = polytope.Polytope(ChangModel.H, ChangModel.c1_s)
   poly_C = polytope.Polytope(ChangModel.H, ChangModel.c1_c)
   ext_C = polytope.extreme(poly_C)
   ext_S = polytope.extreme(poly_S)
   ax.fill(ext_C[:, 0], ext_C[:, 1], 'r', zorder=-1)
   ax.fill(ext_S[:, 0], ext_S[:, 1], 'b', zorder=0)
   # Add point showing Ramsey Plan
   idx_Ramsey = np.where(ext_C[:, 0] == max(ext_C[:, 0]))[0][0]
   R = ext_C[idx_Ramsey, :]
   ax.scatter(R[0], R[1], 150, 'black', 'o', zorder=1)
   w_min = min(ext_C[:, 0])
   # Label Ramsey Plan slightly to the right of the point
   ax.annotate("R", xy=(R[0], R[1]),
               xytext=(R[0] + 0.03 * (R[0] - w_min),
                       R[1]), fontsize=18)
   plt.tight_layout()
   plt.show()

plot_equilibria(ch1)
```
Evidently, the Ramsey plan, denoted by the $R$, is not sustainable.

Let’s raise the discount factor and recompute the sets

In [7]: ch2 = ChangModel($\beta$=0.8, $m_{\bar{a}}$=30, $h_{\min}$=0.9, $h_{\max}$=1/0.8, 
n_h=8, n_m=35, $N_g$=10)

In [8]: ch2.solve_sustainable()

### --------------- ###
Solving Chang Model Using Outer Hyperplane Approximation
### --------------- ###

Maximum difference when updating hyperplane levels:
[0.06369]
[0.02476]
[0.02153]
[0.01915]
[0.01795]
[0.01642]
[0.01507]
[0.01284]
[0.01106]
[0.00694]
[0.0085]
[0.00781]
[0.00433]
[0.00492]
[0.00303]
[0.00182]
ValueError

Traceback (most recent call last)

<ipython-input-8-b1776dca964b> in <module>
----> 1 ch2.solve_sustainable()

<ipython-input-3-04bea48ab06f> in solve_sustainable(self,)
   269     iters = iters + 1
   270     self.solve_worst_spe()
--> 271     self.solve_subgradient()
   272     diff = max(np.maximum(abs(self.c0_c - self.
   273           abs(self.c0_s - self.c1_s)))

<ipython-input-3-04bea48ab06f> in solve_subgradient(self)
   231     res = linprog(c, A_ub=aineq_S,
   232                      b_ub=bineq_S, A_eq = aeq_S,
--> 233                      b_eq = beq_S, bounds=(self.w_bnds_s, \
   234                           self.p_bnds_s))
   235     if res.status == 0:
   236         c_a1a2_s[j] = self.H[i, 0] * (self.

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_linprog.py in linprog(c, A_ub, b_ub, A_eq, b_eq, bounds, method, callback, options, x0)
   561     complete, status,
   562     message, tol,
   563     iteration, disp)

~/anaconda3/lib/python3.7/site-packages/scipy/optimize/_linprog_util.py in _postprocess(x, postsolve_args, complete, status, message, tol, iteration, disp)
   1538     status, message = _check_result(
   1539         x, fun, status, slack, con,
Let’s plot both sets

**In [9]:** plot_equilibria(ch2)

Evidently, the Ramsey plan is now sustainable.
Bibliography


