Dynamic Programming

Volume I: Foundations

QuantEcon Book II

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Preface

This textbook is about the theory of dynamic programming and its applications in economics and finance, as well as adjacent fields such as operations research. Its main aim is to distill recent innovations in the theory of dynamic programming into textbook form, while also providing applications and code that will help a reader approach the research frontier. The book is aimed primarily at graduate students in economics and finance, as well as researchers in these fields. Advanced undergraduates with good quantitative backgrounds will find most chapters are accessible.

While the book contains classical results on dynamic programming that are found in texts such as Bellman (1957), Denardo (1981), Bertsimas and Tsitsiklis (1997), Puterman (2005), and Stokey and Lucas (1989), it also describes extensions to the basic model that have become increasingly popular within economics and finance over the last few decades. In addition, the text tries to explain some of the innovations created by researchers and practitioners as they wrestled with how to formulate and solve modern decision problems.

The extensions mentioned above include recursive preference models, robust control, models with time varying-discount rates and other more sophisticated preference features. Such settings often fail to satisfy the standard contraction-mapping restrictions upon which traditional methods are based. To this end, the key theoretical chapter (Chapter 7) is presented in abstract setting that builds on the framework in Bertsekas (2022b). Taking this approach allows us to obtain a high degree of generality while also offering transparency in proofs. A number of results are new.

Since the main theoretical results Chapters 1–6 are special cases of those found in Chapter 7, we considered writing the textbook in reverse order, starting with the general case in Chapter 7 and then progressing to special cases. However, our experience teaching this material tells us that students find the general results challenging on first pass, but considerably easier after they have practiced dynamic programming through the earlier chapters. That said, advanced readers with a strong knowledge of dynamic programming might want to jump straight to Chapter 7 and then work backwards according to their interests.

Instructors wishing to use this book as a text for undergraduate students can start with Chapter 1, skim through Chapter 2, work through Chapters 3–6, and skip Chapter 7 entirely. For such a course the topic of convex and concave operators in Chapter 2 can be avoided, as can the discussion on topological conjugacy, along with the treatment of recursive preferences in §4.3.

This book deals only with finite state and action spaces. More general models are left to Volume II. The reason for this division is that, for the most part, the theory for general models is essentially the same as that for finite state models, with almost all of the difference involving qualifications and conditions to ensure that maximization and integration make sense. In our opinion, the best way to learn dynamic programming is to cover the finite case first, where these qualifications are not necessary. Without these distractions, the core theory of dynamic programming is especially clear.

Another feature of the text is that computer code is a first-class citizen. The code embedded in the textbook is written in Julia and can be found at

`https://github.com/QuantEcon/book-dp1`

We chose Julia because it is open source and because Julia allows us to write computer code that is as close as possible to the relevant mathematical equations. Please note that all of the Julia code in the text is written to maximize clarity rather than speed.

At the time of writing, we are in the process of implementing matching Python code, which can also be found at the repository listed above. We find Python very practical for efficient dynamic programming, although implementations are sometimes not as clean as Julia, and tend to be very library specific (which is why we preferred Julia for programs embedded in the text).

Readers should find it straightforward to port our Python and Julia code to other platforms should they wish to do so.

While writing this book, we worked hard to mix rigorous theory with exciting applications. Despite the various layers of abstractions used to unify the theory, all of the results we present are entirely practical, being motivated by important optimization problems from economics and finance.

This textbook is one of a series being written in partnership with the QuantEcon organization, with funding generously provided by Schmidt Futures (see acknowledgments below). There is a small amount of overlap with the first book in the series, Sargent and Stachurski (2022), particularly on the topic of Markov chains. Although repetition is generally undesirable, we decided nonzero overlap would be optimal, since it saves readers from having to jump between two documents.

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Common Symbols

$\mathbb{1}\{P\}$	indicator, equal to 1 if statement P is true and 0 otherwise
$\alpha := 1$	α is defined as equal to 1
$f \equiv 1$	function f is everywhere equal to 1
$\wp(A)$	the power set of A; that is, the collection of all subsets of set A
$[n]$	$\{1, \ldots, n\}$
$\mathbb{C}$	the complex numbers
$\mathbb{N}$, $\mathbb{Z}$ and $\mathbb{R}$	the natural numbers, integers and real numbers respectively
$\mathbb{Z}_+$, $\mathbb{R}_+$, etc.	the nonnegative elements of $\mathbb{Z}$, $\mathbb{R}$, etc.
$\lvert x\rvert$ for $x \in \mathbb{R}$	the absolute value of x
$\lvert\lambda\rvert$ for $\lambda \in \mathbb{C}$	the modulus of λ (i.e., $\sqrt{a^2 + b^2}$ when $\lambda = a + ib$)
$\lvert B\rvert$ for set B	the cardinality of (i.e., number of elements in) B
$\mathbb{R}^n$	all n-tuples of real numbers
$x \leqslant y \quad (x, y \in \mathbb{R}^n)$	$x_i \leqslant y_i$ for $i = 1, \ldots n$ (pointwise partial order)
$x \ll y \quad (x, y \in \mathbb{R}^n)$	$x_i < y_i$ for $i = 1, \ldots n$
$\mathscr{D}(F)$	the set of distributions (or probability mass functions) on F
$\mathbb{R}^M$	all functions from M to $\mathbb{R}$
$i\mathbb{R}^M$	the set of increasing functions in $\mathbb{R}^M$
$\langle a, b\rangle$	the inner product of vectors a and b
$\vee_{\alpha\in A} u_\alpha$	supremum of $\{u_\alpha\}_{\alpha\in A}$
$\wedge_{\alpha\in A} u_\alpha$	infimum of $\{u_\alpha\}_{\alpha\in A}$
IID	independent and identically distributed
$X \stackrel{d}{=} Y$	X and Y have the same distribution
$X \sim F$	X has distribution F
$F \preceq_{\mathrm{F}} G$	G first order stochastically dominates F

Common Abbreviations

SDF	Stochastic discount factor (see §4.2.1.2 and §4.2.1.3)
MDP	Markov decision process (see §6.1.1.1)
VFI	Value function iteration (see §6.1.3.1)
HPI	Howard policy iteration (see §6.1.3.2)
OPI	Optimistic policy iteration (see §6.1.3.4)
RDP	Recursive decision process (see §7.1.1)
ADP	Abstract dynamic program (see §7.3.2)
SDP	Stable dynamic program (see §7.3.3)

Chapter 1

Introduction

The temporal structure of a typical dynamic program is

```
an initial state X_0 is given
t ← 0
while t < T do
    the controller of the system observes the current state X_t
    the controller chooses an action A_t
    the controller receives a reward R_t that depends on the current state and
      action
    the state updates to X_{t+1}
    t ← t + 1
end
```

The state X_t is typically a vector listing the current values of a set of variables deemed relevant to choosing the current action. The action A_t is a vector describing choices of a set of decision variables. If $T < \infty$ then the problem is called a **finite horizon** problem. Otherwise it is called an **infinite horizon** problem. Figure 1.1 illustrates the first two rounds of the dynamic program. As shown in the figure, the rule for the state update depends on the current state and action. The update rule can also depend on shocks or other random elements.

For decision makers facing such a system, dynamic programming provides a way to maximize expected *lifetime* reward that aggregates the reward sequence $(R_t)_{t \geqslant 0}$. The exact nature of the aggregation rule varies across applications, but a typical case takes an expected discounted sum, such as $\mathbb{E} \sum_{t \geqslant 0} \beta^t R_t$ for some $\beta \in (0, 1)$.

Figure 1.1: A dynamic program

Example 1.0.1. A manager wants to set prices and inventories to maximize a firm's **expected present value** (EPV), which, given interest rate r, is defined as

$$\mathbb{E}\left[\pi_0 + \frac{1}{1+r}\pi_1 + \left(\frac{1}{1+r}\right)^2 \pi_2 + \cdots\right]. \tag{1.1}$$

In such a problem, X_t will be a vector that quantifies the size of the inventories, prices set by competitors and other factors relevant to profit maximization. The action A_t will specify current prices and orders of new stock. The current reward R_t is current profit π_t, and the profit stream $(\pi_t)_{t\geqslant 0}$ is aggregated into lifetime rewards via (1.1).

Dynamic programming has a *vast* array of applications, from robotics and artificial intelligence to the sequencing of DNA. Dynamic programming is used every day to control aircraft, route shipping, test products, recommend information on media platforms and solve major research problems. Some companies now produce specialized computer chips that are designed for specific dynamic programs.

Within economics and finance, dynamic programming is applied to topics including unemployment, monetary policy, fiscal policy, asset pricing, firm investment, wealth dynamics, inventory control, commodity pricing, sovereign default, the division of labor, natural resource extraction, human capital accumulation, retirement decisions, portfolio choice, and dynamic pricing. We discuss some of these applications in the chapters below.

The core theory of dynamic programming is relatively simple and concise. But implementation can be computationally demanding. That situation provides one of the major challenges facing the field of dynamic programming.

Example 1.0.2. To illustrate how computationally demanding problems arise, consider again Example 1.0.1, now supposing that the store in question is a book store and, for each book, the retailer chooses to hold between 0 and 10 copies. If there are 100 books to choose from, then the number of possible combinations for her inventories is 11^{100}, about 20 orders of magnitude larger than the number of atoms in the known universe. In reality there are probably many more books to choose from, as well as other factors in the business environment that affect the choices of the retailer.

In this book we discuss fundamental theory, traditional economic applications and modern applications with large state spaces and computationally demanding environments. We also cover recent trends towards more sophisticated specifications of lifetime rewards, often called recursive preferences. Throughout the text, theory and computation are combined, since, for interesting problems, brute-force computation is futile, while theory alone provides limited insight. The interplay between interesting applications, fundamental theory, computational methods and evolving hardware capability makes dynamic programming exciting.

1.1 Bellman Equations

In this section we introduce the recursive structure of dynamic programming in a simple setting. After solving a finite-horizon model, we consider an infinite-horizon version and explain how it produces a system of nonlinear equations. Then we turn to methods for solving such systems.

1.1.1 Finite-Horizon Job Search

We begin with a celebrated model of job search created by McCall (1970). McCall analyzed the decision problem of an unemployed worker in terms of current and likely future wage offers, impatience, and the availability of unemployment compensation. Here we study a simple version of the model in which essential ideas of dynamic programming are particularly clear.

Readers who are familiar with Bellman equations can skim this section quickly and proceed directly to fixed point theory in §1.2.

1.1.1.1 A Two-Period Problem

Imagine someone who begins her working life at time $t = 1$ without employment. While unemployed, she receives a new job offer paying wage W_t at each date t. She

can accept the offer and work permanently at that wage level or reject the offer, receive unemployment compensation c, and draw a new off next period. We assume that the wage offer sequence $\{W_t\}$ is IID and nonnegative, with distribution φ. In particular,

- $\mathsf{W} \subset \mathbb{R}_+$ is a finite set of possible wage outcomes and
- $\varphi \colon \mathsf{W} \to [0, 1]$ is a probability distribution on W, assigning a probability $\varphi(w)$ to each possible wage outcome w.

The worker is impatient. Impatience is parameterized by a time discount factor $\beta \in (0, 1)$, so that the present value of a next-period payoff of y dollars is βy. Since $\beta < 1$, the worker will be tempted to accept reasonable offers, rather than waiting for a better one. A key question is how long to wait.

Suppose as a first step that working life is just two periods. To solve our problem we work backwards, starting at the final date $t = 2$, after W_2 has been observed.[1] If she is already employed, the agent has no decision to make: she continues working at her current wage. If she is unemployed, then she should take the largest of c and W_2.

Now we step back to $t = 1$. At this time, having received offer W_1, the unemployed worker's options are (a) accept W_1 and receive it in both periods or (b) reject it, receive unemployment compensation c, and then, in the second period, choose the maximum of W_2 and c.

Let's assume that the agent seeks to maximize expected present value. The EPV of option (a) is $W_1 + \beta W_1$, which is also called the **stopping value**. The EPV of option (b), also called the **continuation value**, is

$$h_1 := c + \beta \sum_{w' \in \mathsf{W}} v_2(w')\varphi(w') \quad \text{where} \quad v_2(w) := \max\{c, w\}. \tag{1.2}$$

The optimal choice at $t = 1$ is now clear: accept the offer if $W_1 + \beta W_1 \geqslant h_1$ and reject otherwise. A decision tree is shown in Figure 1.2.

1.1.1.2 Value Functions

A key idea in dynamic programming is to use "value functions" to track maximal rewards from a given state at a given time. The **time 2 value function** v_2 defined in

[1] Solving the last period first and then working back in time is called **backward induction**. Starting with the last period makes sense because there is no future to consider.

Figure 1.2: Decision tree for a two period problem

Figure 1.3: The value function v_1 and the reservation wage

(1.2) returns the maximum value obtained in the final stage for each possible realization of the time 2 wage offer. The **time 1 value function** v_1 evaluated at $w \in \mathsf{W}$ is

$$v_1(w) := \max\left\{w + \beta w,\ c + \beta \sum_{w' \in \mathsf{W}} v_2(w')\varphi(w')\right\}. \tag{1.3}$$

It represents the present value of expected lifetime income after receiving the first offer w, conditional on choosing optimally in both periods.

The value function is shown in Figure 1.3. Figure 1.3 also shows the **reservation wage**.

$$w_1^* := \frac{h_1}{1+\beta}, \tag{1.4}$$

It is the w that solves the indifference condition

$$w + \beta w = c + \beta \sum_{w' \in \mathsf{W}} v_2(w')\varphi(w'),$$

and equates the value of stopping to the value of continuing. For an offer W_1 above w_1^*, the stopping value exceeds the continuation value. For an offer below the reservation wage, the reverse is true. Hence, the optimal choice for the agent at $t = 1$ is described entirely by the reservation wage.

Parameters and functions underlying the figure are shown in Listing 1.

Studying (1.4) is already instructive. For example, we can see that higher unemployment compensation c shifts up the continuation value h_1 and increases the reservation wage. As a result, the agent will, on average, spend more time unemployed when unemployment compensation is higher.

Exercise 1.1.1. If unemployment compensation increases unemployment duration, should we conclude that increasing such compensation is detrimental to society? Provide some thoughts on this question based on intuition from the McCall model.

1.1.1.3 Three Periods

Now let's suppose that the agent works in period $t = 0$ as well as $t = 1, 2$. Figure 1.4 shows the decision tree for the three periods. Notice that the subtree containing nodes 1 and 2 is exactly the same as the whole decision tree for the two-period problem in Figure 1.2. We will use this to find optimal actions.

At $t = 0$, the value of accepting the current offer W_0 is $W_0 + \beta W_0 + \beta^2 W_0$, while maximal value of rejecting and waiting, is c plus, after discounting by β, the maximum value that can be obtained by behaving optimally from $t = 1$. Fortunately, this value has already been calculated: it is just $v_1(W_1)$, as given in (1.3)!

Maximal time zero value $v_0(w)$ is the maximum of the value of these two options, given $W_0 = w$, so we can write

$$v_0(w) = \max \left\{ w + \beta\, w + \beta^2\, w,\ c + \beta \sum_{w' \in \mathsf{W}} v_1(w')\varphi(w') \right\}. \tag{1.5}$$

By plugging v_1 from (1.3) into this expression, we can determine v_0, as well as the optimal action, which is the one that achieves the largest value in the max term in (1.5).

Figure 1.4 illustrates how the backward induction process works. The last period value function v_2 is trivial to obtain. With v_2 in hand we can compute v_1. With v_1 in hand we can compute v_0. Once all the value functions are available, we can calculate whether to accept or reject at each point in time.

Exercise 1.1.2. The optimal action at time $t = 0$ is determined by a time zero reservation wage w_0^*, where the agent should accept the time zero wage offer if and only if W_0 exceeds w_0^*. Calculate w_0^* for this problem, by analogy with w_1^* in (1.4).

```julia
using Distributions

"Creates an instance of the job search model, stored as a NamedTuple."
function create_job_search_model(;
        n=50,         # wage grid size
        w_min=10.0,   # lowest wage
        w_max=60.0,   # highest wage
        a=200,        # wage distribution parameter
        b=100,        # wage distribution parameter
        β=0.96,       # discount factor
        c=10.0        # unemployment compensation
    )
    w_vals = collect(LinRange(w_min, w_max, n+1))
    ϕ = pdf(BetaBinomial(n, a, b))
    return (; n, w_vals, ϕ, β, c)
end

" Computes lifetime value at t=1 given current wage w_1 = w. "
function v_1(w, model)
    (; n, w_vals, ϕ, β, c) = model
    h_1 = c + β * max.(c, w_vals)'ϕ
    return max(w + β * w, h_1)
end

" Computes reservation wage at t=1. "
function res_wage(model)
    (; n, w_vals, ϕ, β, c) = model
    h_1 = c + β * max.(c, w_vals)'ϕ
    return h_1 / (1 + β)
end
```

Listing 1: Computing v_1 and w_1^* (`two_period_job_search.jl`)

Figure 1.4: Decision tree for the job seeker

Notice how we broke the three period problem down into a pair of two period problems, given by the two equations (1.3) and (1.5). Breaking many-period problems down into a sequence of two period problems is the essence of dynamic programming. The recursive relationships between v_0 and v_1 in (1.5), as well as between v_1 and v_2 in (1.3), are examples of what are called **Bellman equations**. We will see many other examples shortly.

Exercise 1.1.3. Extend the above arguments to T time periods, where T can be any finite number. Using Julia or any other suitable programming language, write a function that takes T as an argument and returns $(w_0^*, \ldots, w_T^*)$, the sequence of reservation wages for each period.

1.1.2 Infinite Horizon

Next we consider an infinite horizon, which is in some ways more challenging and someways simpler and cleaner. On one hand, the lack of a terminal period means that we cannot do backward induction. On the other hand, the infinite horizon means that the agent always faces an infinite future, so the current decision is not time dependent—and hence more straightforward. This will become clearer as the section unfolds.[2]

With the above discussion in mind, let us consider a worker who aims to maximize

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t R_t, \tag{1.6}$$

where $R_t \in \{c, W_t\}$ is earnings at time t. As before, jobs are permanent, so accepting a job at a given wage means earning that wage in every subsequent period.

Let's clarify our assumptions:

Assumption 1.1.1. The wage process satisfies $\{W_t\} \overset{\text{IID}}{\sim} \varphi$ where $\varphi \in \mathscr{D}(\mathsf{W})$ and $\mathsf{W} \subset \mathbb{R}_+$ with $|\mathsf{W}| < \infty$. The parameters c and β are positive and $\beta < 1$.

Here and below, for any finite or countable set F, the symbol $\mathscr{D}(F)$ indicates the set of distributions (or probability mass functions) on F.

[2]Incidentally, imposing an infinite horizon is not the same as assuming humans live forever. Rather, it corresponds to the idea that humans have no specific "termination" date. More generally, we can understand an infinite horizon as an approximation to a finite horizon when observations are recorded at relatively high frequency and no clear termination date exists.

1.1.2.1 Intuition

As with the finite state case, applying dynamic programming involves a two step procedure that first assigns values to states and then deduces optimal actions given those values. We begin with an intuitive discussion and then formalize the main ideas.

To trade off current and future rewards optimally, we need to compare current payoffs we get from our two choices with the states that those choices lead to and the maximum value that can be extracted from those states. But how do we calculate the maximum value that can be extracted from each state when lifetime is infinite?

Consider first the present expected lifetime value of being employed with wage $w \in \mathsf{W}$. This case is easy because, under the current assumptions, workers who accept a job are employed forever and have no remaining choices to exercise. Lifetime payoff is

$$w + \beta w + \beta^2 w + \cdots = \frac{w}{1-\beta}. \tag{1.7}$$

How about maximum present expected lifetime value attainable when entering the current period unemployed with wage offer w in hand? Denote this (as yet unknown) value by $v^*(w)$. We call v^* the **value function**. While v^* is not trivial to pin down, the task is not impossible. Our first step in the right direction is to observe that it satisfies **Bellman's equation**

$$v^*(w) = \max\left\{\frac{w}{1-\beta},\ c + \beta \sum_{w' \in \mathsf{W}} v^*(w')\varphi(w')\right\} \tag{1.8}$$

at every $w \in \mathsf{W}$. (Here w' is the offer next period.)

Our reasoning is as follows: The first term inside the max operation is the **stopping value**, or lifetime payoff from accepting current offer w. The second term inside the max operation is the **continuation value**, or current expected value of rejecting and behaving optimally thereafter. Maximal value is obtained by selecting the largest of these two alternatives.

At this point, you should note the similarity between (1.8) and our finite horizon Bellman equations (1.3) and (1.5). The only real difference is that the value function is no longer time-dependent. To repeat, this is because the worker always looks forward toward an infinite horizon, regardless of the current date.

Mathematically, (1.8) is viewed as an equation to be solved for a function $v^* \in \mathbb{R}^{\mathsf{W}}$, the set of all functions from W to $\mathbb{R}$. Once we have solved for v^* (assuming this is possible), optimal choices can be made by observing current w and then choosing the largest of the two alternatives on the right-hand side of (1.8), just as we did in the

finite horizon case. This idea—that optimal choices can be made by computing the value function and maximizing the right-hand side of the Bellman equation—is called **Bellman's principle of optimality**, and will be a cornerstone of what follows. Later we prove it carefully in a very general setting.

The first step of this approach is to solve for v^*. For this problem we use fixed point theory, which is the subject of the next section. Later, in §1.3, we return to the job search problem and apply fixed point theory to solving for v^*.

1.2 Stability and Contractions

In this section we cover enough fixed point theory to solve the infinite horizon job search problem. (In Chapter 2 we consider more general results.) Readers who are familiar with the Neumann series lemma (geometric series of matrices) and Banach's fixed point theorem can skim this section and proceed to §1.3.

1.2.1 Vector Space

To begin, we recall some fundamental properties of real numbers, finite-dimensional vector space, basic topology and equivalence of norms.

1.2.1.1 Real and Complex Vectors

For the most part, we are interested in vectors where the elements are real numbers (as opposed to complex numbers). Prior to investigating such vectors, let us recall several definitions concerning the real line $\mathbb{R}$.

Given $a, b \in \mathbb{R}$, let $a \vee b := \max\{a, b\}$ and $a \wedge b := \min\{a, b\}$. The **absolute value** of $a \in \mathbb{R}$ is defined as $|a| := a \vee (-a)$. The notions of supremum, infimum, maximum and minimum for subsets of the real line are defined in Appendix §A, as are real sequences and the usual definition of convergence of real numbers.

A **real-valued vector** $u = (u_i)_{i=1}^n$ can be understood either as a function from $[n] := \{1, \dots, n\}$ to $\mathbb{R}$, with u_i as the value of the function at $i \in [n]$, or a finite real sequence $(u_1, \dots, u_n)$, with u_i as the i-th element. We discuss these alternative points of view in §1.2.1.4. The set of all real vectors of length n is denoted by $\mathbb{R}^n$. The **inner product** of n-vectors $u = (u_i)_{i=1}^n$ and $v = (v_i)_{i=1}^n$ is $\langle u, v \rangle := \sum_{i=1}^n u_i v_i$.

The set $\mathbb{C}$ of complex numbers is defined in the appendix to Sargent and Stachurski (2022) and many other places; as is the set $\mathbb{C}^n$ of all complex-valued n-vectors. We assume readers have some idea of what complex numbers are and know how to compute their modulus.

Exercise 1.2.1. Let α, s and t be real numbers. Show that $\alpha \vee (s+t) \leqslant s + \alpha \vee t$ whenever $s \geqslant 0$.

1.2.1.2 Norms

Readers will be familiar with the ordinary **Euclidean norm** on real vector space, defined as

$$\|u\| := \sqrt{\langle u, u \rangle} \qquad (u \in \mathbb{R}^n).$$

We also wish to work with some alternative norms on $\mathbb{R}^n$, which are important for applications of fixed point theory because they provide more flexibility when checking the conditions of various results.

As a first step, we recall that a function $\|\cdot\| \colon \mathbb{R}^n \to \mathbb{R}$ is called a **norm** on $\mathbb{R}^n$ if, for any $\alpha \in \mathbb{R}$ and $u, v \in \mathbb{R}^n$,

(a)	$\|u\| \geqslant 0$	(nonnegativity)
(b)	$\|u\| = 0 \iff u = 0$	(positive definiteness)
(c)	$\|\alpha u\| = \lvert\alpha\rvert \|u\|$ and	(positive homogeneity)
(d)	$\|u + v\| \leqslant \|u\| + \|v\|$	(triangle inequality)

The Euclidean norm is a norm on $\mathbb{R}^n$, as suggested by its name. The Euclidean norm satisfies the **Cauchy–Schwarz inequality**

$$|\langle u, v \rangle| \leqslant \|u\| \cdot \|v\| \quad \text{for all } u, v \in \mathbb{R}^n.$$

This inequality can be used to prove that the triangle inequality is valid for the Euclidean norm (see, e.g., Kreyszig (1978)).

Example 1.2.1. The ℓ_1 **norm** of a vector $u \in \mathbb{R}^n$ is defined by

$$u = (u_1, \ldots, u_n) \mapsto \|u\|_1 := \sum_{i=1}^n |u_i|. \tag{1.9}$$

In machine learning applications, $\|\cdot\|_1$ is sometimes called the "Manhattan norm," and $d_1(u,v) := \|u-v\|_1$ is called the "Manhattan distance" or "taxicab distance" between vectors u and v. We will refer to it more simply as the **ℓ_1 distance** or **ℓ_1 deviation**.

Exercise 1.2.2. Verify that the ℓ_1 norm on $\mathbb{R}^n$ satisfies (a)–(d) above.

The ℓ_1 norm and the Euclidean norm are special cases of the so-called **ℓ_p norm**, which is defined for $p \geqslant 1$ by

$$u = (u_1, \ldots, u_n) \mapsto \|u\|_p := \left(\sum_{i=1}^{n} |u_i|^p\right)^{1/p}. \tag{1.10}$$

It can be shown that $u \mapsto \|u\|_p$ is a norm for all $p \geqslant 1$, as suggested by the name (see, e.g., Kreyszig (1978)). For this norm, the subadditivity in (d) is called **Minkowski's inequality**.

Since the Euclidean case is obtained by setting $p = 2$, the Euclidean norm is also called the ℓ_2 norm, and we write $\|\cdot\|_2$ rather than $\|\cdot\|$ when extra clarity is required.

Exercise 1.2.3. Prove that the **supremum norm**, defined by $\|u\|_\infty := \max_{i=1}^n |u_i|$, is also a norm on $\mathbb{R}^n$.

(The symbol $\|u\|_\infty$ is used because, for all $u \in \mathbb{R}^n$, we have $\|u\|_p \to \|u\|_\infty$ as $p \to \infty$.)

For the next exercise, we recall that the **indicator function** of logical statement P, denoted here by $\mathbb{1}\{P\}$, takes value 1 (resp., 0) if P is true (resp., false). For example, if $x, y \in \mathbb{R}$, then

$$\mathbb{1}\{x \leqslant y\} = \begin{cases} 1 & \text{if } x \leqslant y \\ 0 & \text{otherwise.} \end{cases}$$

If $A \subset S$, where S is any set, then $\mathbb{1}_A(x) := \mathbb{1}\{x \in A\}$ for all $x \in S$.

Exercise 1.2.4. The so-called ℓ_0 "norm" $\|u\|_0 := \sum_{i=1}^n \mathbb{1}\{u_i \neq 0\}$, routinely used in data science applications, is *not* in fact a norm on $\mathbb{R}^n$. Prove this.

1.2.1.3 Equivalence of Vector Norms

One of the most fundamental properties of finite-dimensional normed vector space is that all norms are equivalent. Let's review this result and discuss why it matters.

To begin, recall that when u and $(u_m) := (u_m)_{m\in\mathbb{N}}$ are all elements of $\mathbb{R}^n$, we say that (u_m) **converges** to u and write $u_m \to u$ if

$$\|u_m - u\| \to 0 \text{ as } m \to \infty \text{ for some norm } \|\cdot\| \text{ on } \mathbb{R}^n.$$

It might seem that this definition is imprecise. Don't we need to clarify that the convergence is with respect to a particular norm?

In fact we do not. This is because any two norms $\|\cdot\|_a$ and $\|\cdot\|_b$ on $\mathbb{R}^n$ are **equivalent**, in the sense that there exist finite positive constants M, N such that

$$M\|u\|_a \leqslant \|u\|_b \leqslant N\|u\|_a \quad \text{for all } u \in \mathbb{R}^n. \tag{1.11}$$

(See, e.g., Kreyszig (1978).)

Exercise 1.2.5. Let us write $\|\cdot\|_a \sim \|\cdot\|_b$ if there exist finite M, N such that (1.11) holds. Prove that $\sim$ is an equivalence relation on the set of norms on $\mathbb{R}^n$.

Exercise 1.2.6. Let $\|\cdot\|_a$ and $\|\cdot\|_b$ be any two norms on $\mathbb{R}^n$. Given a point u in $\mathbb{R}^n$ and a sequence (u_m) in $\mathbb{R}^n$, use (1.11) to confirm that $\|u_m - u\|_a \to 0$ implies $\|u_m - u\|_b \to 0$ as $m \to \infty$.

The next exercise reminds us that, in finite dimensions, pointwise convergence and norm convergence are the same thing.

Exercise 1.2.7. Let $\|\cdot\|$ be any norm on $\mathbb{R}^n$. Fixing a point u in $\mathbb{R}^n$ and a sequence (u_m) in $\mathbb{R}^n$, let u^i and u_m^i be the i-th component of u and u_m respectively. Show that $u_m^i \to u^i$ for all $i \in \{1, \dots, n\}$ if and only if $\|u_m - u\| \to 0$.

Recall that a set $C \subset \mathbb{R}^n$ is called **closed** in $\mathbb{R}^n$ if, for all $u \in \mathbb{R}^n$ and sequences $\{u_m\} \subset \mathbb{R}^n$ with $u_m \in C$ for all m such that $u_m \to u$ as $m \to \infty$, we also have $u \in C$. A set G is called **open** if G^c is closed. A self-map T on $U \subset \mathbb{R}^n$ is called **continuous at $u \in U$** if $Tu_m \to Tu$ for any $\{u_m\} \subset U$ with $u_m \to u$; and **continuous** if T is continuous at every $u \in U$. These notions are independent of any norm, since convergence is independent of the choice of norm.

1.2.1.4 Finite-Dimensional Function Space

In this section we clarify notation concerning functions and discuss how sets of real-valued functions are similar to sets of vectors.

If X is any set and u maps X to $\mathbb{R}$, then we call u a **real-valued function** on X and write $u\colon \mathsf{X} \to \mathbb{R}$. Throughout, the symbol $\mathbb{R}^{\mathsf{X}}$ denotes the set of all real-valued functions on X. This is a special case of the symbol B^A, where A and B are sets, which represents the set of all functions from A to B.

Here we clarify an essentially trivial issue that can nonetheless cause some degree of confusion. Let X be any finite set. Since X is finite, we can always impose some enumeration of the elements, so that $\mathsf{X} = \{x_1, \dots, x_n\}$ for some $n \in \mathbb{N}$. The aim of this section is to make the point that $\mathbb{R}^{\mathsf{X}}$ is, in essence, the vector space $\mathbb{R}^n$ expressed in different notation. The next lemma clarifies.

Lemma 1.2.1. *If* $\mathsf{X} = \{x_1, \dots, x_n\}$*, then*

$$\mathbb{R}^{\mathsf{X}} \ni u \quad \longleftrightarrow \quad (u(x_1), \dots, u(x_n)) \in \mathbb{R}^n \tag{1.12}$$

is a one-to-one correspondence between $\mathbb{R}^{\mathsf{X}}$ *and the vector space* $\mathbb{R}^n$*.*

The proof is obvious: The lemma just states that a real-valued function u on X is uniquely identified by the set of values that it takes on X, which is an n-tuple of real numbers. Throughout the text, whenever the supporting set X is finite, we freely use the identification in (1.12), adopting whichever notation—vector or function—is most convenient for the application in question.

If $\|\cdot\|$ is any norm on $\mathbb{R}^n$, then we extend $\|\cdot\|$ to $\mathbb{R}^{\mathsf{X}}$ via the identification in (1.12). That is, for $u \in \mathbb{R}^{\mathsf{X}}$, the value $\|u\|$ is given by the norm of the vector $(u(x_1), \dots, u(x_n)) \in \mathbb{R}^n$.

We say that a subset of $\mathbb{R}^{\mathsf{X}}$ is closed (resp., open, compact, etc.) if the corresponding subset of $\mathbb{R}^n$ is closed (resp., open, compact, etc.)

1.2.1.5 Pointwise Operations on Functions

In general, if $f, g \in \mathbb{R}^{\mathsf{X}}$ and $\alpha, \beta \in \mathbb{R}$, then the expressions $\alpha f + \beta g$, fg, etc., are also elements of $\mathbb{R}^{\mathsf{X}}$, defined at $x \in \mathsf{X}$ by

$$(\alpha f + \beta g)(x) = \alpha f(x) + \beta g(x), \quad (\alpha f)(x) = \alpha f(x), \quad \text{etc.} \tag{1.13}$$

Similarly, $|f|$, $f \vee g$ and $f \wedge g$ are real-valued functions on X defined by

$$|f|(x) = |f(x)|, \quad (f \vee g)(x) = f(x) \vee g(x) \quad \text{and} \quad (f \wedge g)(x) = f(x) \wedge g(x). \tag{1.14}$$

Figure 1.5 illustrates the functions $f \vee g$ and $f \wedge g$ when X is a subset of $\mathbb{R}$.

Figure 1.5: Functions $f \vee g$ and $f \wedge g$

Figure 1.6: The vectors $u \vee v$ and $u \wedge v$ in $\mathbb{R}^2$

When X is finite, functions in $\mathbb{R}^{\mathsf{X}}$ can be understood as vectors (see §1.2.1.4). In this notation, for vectors $u = (u_i)_{i=1}^n$ and $v = (v_i)_{i=1}^n$ in $\mathbb{R}^n$, the definitions in (1.13) become

$$|u| := (|u_i|)_{i=1}^n, \quad u \wedge v := (u_i \wedge v_i)_{i=1}^n \quad \text{and} \quad u \vee v := (u_i \vee v_i)_{i=1}^n. \tag{1.15}$$

Figure 1.6 illustrates in $\mathbb{R}^2$.

Let X be a nonempty set and let $\{v_\sigma\} := \{v_\sigma\}_{\sigma \in \Sigma}$ be a finite subset of $\mathbb{R}^{\mathsf{X}}$ (i.e., the index set Σ is finite). Generalizing the definitions above, we set $\vee_\sigma v_\sigma$ to be the pointwise maximum and $\wedge_\sigma v_\sigma$ to be the pointwise minimum. Thus, for arbitrary

$x \in \mathsf{X}$,

$$\left(\bigvee_\sigma v_\sigma\right)(x) := \max_{\sigma\in\Sigma} v_\sigma(x). \quad \text{and} \quad \left(\bigwedge_\sigma v_\sigma\right)(x) := \min_{\sigma\in\Sigma} v_\sigma(x).$$

1.2.1.6 A Useful Inequality

On the topic of real-valued functions, the following lemma will be helpful when we study dynamic programming.

Lemma 1.2.2. *Let D be a finite set. If f and g are elements of $\mathbb{R}^D$, then*

$$|\max_{z\in D} f(z) - \max_{z\in D} g(z)| \leqslant \max_{z\in D} |f(z) - g(z)|. \tag{1.16}$$

Proof. We focus on the first claim. Fixing $f, g \in \mathbb{R}^D$, we have

$$f = f - g + g \leqslant |f - g| + g$$

$$\therefore \quad \max f \leqslant \max(|f - g| + g) \leqslant \max|f - g| + \max g$$

$$\therefore \quad \max f - \max g \leqslant \max|f - g|$$

Reversing the roles of f and g proves the claim. □

1.2.2 Neumann Series

In this section we discuss geometric series in matrix space, along with the Neumann series lemma, which is one of the most useful results in applied and numerical analysis.

Before starting we recall that if A is $n \times n$, then $\lambda \in \mathbb{C}$ is called an **eigenvalue** of A if there exists a nonzero $e \in \mathbb{C}^n$ such that $Ae = \lambda e$. (Here $\mathbb{C}$ is the set of complex numbers and $\mathbb{C}^n$ is the set of complex n-vectors.) The vector e satisfying this equality is called an **eigenvector** of A and (λ, e) is called an **eigenpair**.

In Julia, we can check for the eigenvalues of a given square matrix A via `eigvals(A)`. The code

```
using LinearAlgebra
A = [0 -1;
     1  0]
println(eigvals(A))
```

produces

```
2-element Vector{ComplexF64}:
 0.0 - 1.0im
 0.0 + 1.0im
```

Here `im` stands for i, the imaginary unit (i.e., $i^2 = -1$), so the eigenvalues of A are $-i$ and i. Fixed point theory is used to solve equations, so let's begin by discussing equations and then circle back to fixed points. One easy equation to understand is the one-dimensional linear equation $u = au + b$, where a, b are given and u is unknown. In this case we have the elementary geometric series result

$$|a| < 1 \quad \Longrightarrow \quad u^* = \frac{b}{1-a} = \sum_{k \geqslant 0} a^k b. \tag{1.17}$$

This scalar result extends naturally to vectors. To show this we suppose that u and b are column vectors in $\mathbb{R}^n$, and that A is an $n \times n$ matrix. We consider the vector equation $u = Au + b$. For the next result, we recall that the **spectral radius** of A is defined as

$$r(A) := \max\{|\lambda| : \lambda \text{ is an eigenvalue of } A\} \tag{1.18}$$

Here $|\lambda|$ indicates the modulus of the complex number λ.

With I as the $n \times n$ identity matrix, we can state the following result, which is the multivariate extension of (1.17):

Theorem 1.2.3 (Neumann Series Lemma)**.** *If $r(A) < 1$, then $I - A$ is nonsingular and $u = Au + b$ has the unique solution*

$$u^* = (I - A)^{-1} b = \sum_{k \geqslant 0} A^k b.$$

It is implicit in Theorem 1.2.3 that the sum $\sum_{k \geqslant 0} A^k$ converges. The code in Listing 2 shows how to compute the spectral radius of an arbitrary matrix A in Julia. The print statement produces `0.5828`, so, for this matrix, $r(A) < 1$.

```julia
using LinearAlgebra
r(A) = maximum(abs(λ) for λ in eigvals(A))  # Spectral radius
A = [0.4 0.1;                               # Test with arbitrary A
     0.7 0.2]
print(r(A))
```

Listing 2: Computing the spectral radius (`compute_spec_rad.jl`)

Exercise 1.2.8. Prove that $r(\alpha B) = |\alpha|\, r(B)$ for all $\alpha \in \mathbb{R}$.

Remark 1.2.1. In this text, we follow the mathematical convention that a vector in $\mathbb{R}^n$ is just an n-tuple of real values. This coincides with the viewpoint of Julia: vectors are, by default, "flat" arrays. At the same time, if we use vectors in matrix algebra, they can be understood as column vectors unless we state otherwise.

The rest of this section works through the proof of the Neumann series lemma, with several parts left as exercises. An intuitive proof of the lemma runs as follows. If $S := \sum_{k \geqslant 0} A^k$, then

$$I + AS = I + A \sum_{k \geqslant 0} A^k = I + A + A^2 + \cdots = S.$$

Rearranging $I + AS = S$ gives $S = (I - A)^{-1}$. Since $u = Au + b$ is equivalent to $(I - A)u = b$, we have $u = (I - A)^{-1} b = Sb$, which matches the claim in the Neumann series lemma.

This argument lacks rigor, however. To complete it, we need to prove that (a) the sum $\sum_{k \geqslant 0} A^k$ converges and (b) the matrix $I - A$ is invertible.

To resolve these issues, we introduce the **matrix norm**

$$\|B\|_\infty := \max_{i,j} |b_{ij}|.$$

Lemma 1.2.4. *If B is any square matrix, then*

$$r(B)^k \leqslant \|B^k\|_\infty \text{ for all } k \in \mathbb{N} \qquad \text{and} \qquad \|B^k\|_\infty^{1/k} \to r(B) \text{ as } k \to \infty.$$

The second result in Lemma 1.2.4 is a version of **Gelfand's formula**.

Exercise 1.2.9. Using Lemma 1.2.4, show that

(i) $r(B) < 1$ implies $\|B^k\|_\infty \to 0$ as $k \to \infty$.

(ii) $r(B) > 1$ implies $\|B^k\|_\infty \to \infty$ as $k \to \infty$.

Exercise 1.2.10. Prove: $r(A) < 1$ implies that the series $\sum_{k\geqslant 0} A^k$ converges, in the sense that every element of the matrix $S_K := \sum_{k=0}^{K} A^k$ converges as $K \to \infty$.

From this last result, one can show that $(I - A)^{-1}$ exists:

Exercise 1.2.11. Prove this claim by showing that, when $\sum_{k\geqslant 0} A^k$ exists, the inverse of $I - A$ exists and indeed $(I - A)^{-1} = \sum_{k\geqslant 0} A^k$.[3]

Listing 3 helps illustrate the result in Exercise 1.2.11, although we truncate the infinite sum $\sum_{k\geqslant 0} A^k$ at 50.

The output is `5.621e-12`, which is essentially zero.

1.2.3 Nonlinear Systems

The equation $u = Au + b$ discussed in the previous section is called a linear system.[4] While the Neumann series lemma is invaluable for such systems, it does not apply to *non*linear problems. The set of techniques to handle nonlinear systems is broad, since there are many types. In this section we present Banach's fixed point theorem, which is perhaps the most widely applied result for handling nonlinear systems. (Later, in Chapter 2, we will introduce other methods.)

1.2.3.1 Fixed Points

One systematic way to look at the problem of solving equations is through the lense of fixed point theory. To recall the basic definitions, we will say that T is a **self-map** on an arbitrary set U if T is a function from U into itself. For a self-map T on U, a point $u^* \in U$ is called a **fixed point** of T in U if $Tu^* = u^*$.

[3]Hint: To prove that A is invertible and $B = A^{-1}$, it suffices to show that $AB = I$. See, for example, Sargent and Stachurski (2022).

[4]A few authors call it *affine* instead, since $u \mapsto Au + b$ is affine rather than linear when $b \neq 0$. We will adhere to standard terminology and call it linear.

```
# Primitives
A = [0.4 0.1;
     0.7 0.2]

# Method one: direct inverse
B_inverse = inv(I - A)

# Method two: power series
function power_series(A)
    B_sum = zeros((2, 2))
    A_power = I
    for k in 1:50
        B_sum += A_power
        A_power = A_power * A
    end
    return B_sum
end

# Print maximal error
print(maximum(abs.(B_inverse - power_series(A))))
```

Listing 3: Matrix inversion vs power series (`power_series.jl`)

Remark 1.2.2. In fixed point theory, it is common to write Tu for the image of u under the function T, rather than $T(u)$. In addition, T is often called an **operator** rather than a function. One reason is that, in the applications that follow, u can itself be a function. In such settings, confusion can be avoided by calling T an operator.

Example 1.2.2. Let $U = \mathbb{R}^n$ and let T be defined by $Tu = Au + b$, where A and b are as in §1.2.2. Since u is a fixed point of T if and only if $u = Au + b$, solving the equation $u = Au + b$ is the same as searching for the fixed point of T.

Example 1.2.3. Every u in set U is fixed under the identity map $I \colon u \mapsto u$.

Example 1.2.4. If $U = \mathbb{N}$ and $Gu = u + 1$, then G has no fixed point.

Figure 1.7 shows another example, for a self-map G on $U := [0, 2]$. Fixed points are numbers $x \in [0, 2]$ where G meets the 45 degree line. In this case there are three.

Exercise 1.2.12. Let U be any set and let T be a self-map on U. Suppose there exists an $\bar{u} \in U$ and an $m \in \mathbb{N}$ such that $T^k u = \bar{u}$ for all $u \in U$ and $k \geqslant m$. Prove that, under this condition, $\bar{u}$ is the unique fixed point of T in U.

Figure 1.7: Graph and fixed points of $G\colon x \mapsto 2.125/(1+x^{-4})$

Exercise 1.2.13. Let T be a self-map on $U \subset \mathbb{R}^d$. Prove the following: If $T^m u \to u^*$ as $m \to \infty$ for some pair $u, u^* \in U$ and, in addition, T is continuous at u^*, then u^* is a fixed point of T.

It turns out that the most natural way to write down general theorems about solving scalar equations, vector equations and more abstract equations is in terms of fixed points. Indeed, an abstract representation of a system of equations is $u = Tu$, where u takes values in an abstract set U and T is a self-map on U. By definition, solutions to this system coincide with fixed points of the mapping T.

When considering fixed points, given a self-map T on U, we typically seek conditions on T and U under which the following properties hold:

- T has at least one fixed point on U (existence)
- T has at most one fixed point on U (uniqueness)
- T has a fixed point on U and the fixed point can be computed using some suitable numerical scheme.

Example 1.2.5. If $U = \mathbb{R}^n$ and T is defined by $Tu = Au + b$, then, by the Neumann series lemma, T has a unique fixed point $u^* \in \mathbb{R}^n$ whenever $r(A) < 1$. Moreover, that

fixed point can be computed, at least approximately, by using either $u^* = (I - A)^{-1}b$ or $u^* = \sum_{k \geqslant 0} A^k b$.

1.2.3.2 Global Stability

A self-map T on U is called **globally stable** on U if T has a unique fixed point u^* in U and, moreover, $T^k u \to u^*$ as $k \to \infty$ for all $u \in U$. Here T^k indicates k compositions of T with itself. Global stability is a very desirable property in the setting of dynamic programming and a number of our results rely on it.

Exercise 1.2.14. As in Example 1.2.5, let $U = \mathbb{R}^n$ and let T be defined by $Tu = Au + b$. Using induction, prove that

$$T^k u = A^k u + A^{k-1} b + A^{k-2} b + \cdots + Ab + b \tag{1.19}$$

for all $u \in U$ and $k \in \mathbb{N}$. Next, show that T is globally stable on U whenever $r(A) < 1$.

Let T be a self-map on $U \subset \mathbb{R}^n$. We call T **invariant** on $C \subset U$ and call C an **invariant set** if T is also a self-map on C; that is, if $u \in C$ implies $Tu \in C$.

Exercise 1.2.15. Let T be a globally stable self-map on $U \subset \mathbb{R}^n$, with fixed point u^*. Prove the following: If C is closed and T is invariant on C, then $u^* \in C$.

1.2.3.3 Banach's Fixed Point Theorem

Next we present one fixed point theorem for nonlinear operators that is among the most important and widely used results in applied analysis: the Banach fixed point theorem.

Let U be a nonempty subset of $\mathbb{R}^n$ and let $\|\cdot\|$ be a norm on $\mathbb{R}^n$. A self-map T on U is called **contraction** on U with respect to $\|\cdot\|$ if there exists a $\lambda < 1$ such that

$$\|Tu - Tv\| \leqslant \lambda \|u - v\| \quad \text{for all} \quad u, v \in U. \tag{1.20}$$

The constant λ is called the **modulus of contraction**.

Exercise 1.2.16. Let T be a contraction on U with respect to some given norm $\|\cdot\|$. Show that, T is continuous on U and has at most one fixed point in U.

Let $\|\cdot\|$ be any norm on $\mathbb{R}^n$. The **operator norm** of an $n \times m$ matrix A is defined as

$$\|A\|_o := \sup\left\{\frac{\|Ax\|}{\|x\|} \ : \ x \in \mathbb{R}^m,\, x \neq 0\right\}. \tag{1.21}$$

Exercise 1.2.17. Prove that $\|A\|_o = \|A\|$ when $m = 1$ (i.e., A is just a vector).

Exercise 1.2.18. Let $U = \mathbb{R}^n$ and let $\|\cdot\|$ be any norm on $\mathbb{R}^n$. Let $Tx = Ax + b$, where A is $n \times n$ and b is $n \times 1$. Prove that T is a contraction of modulus $\|A\|_o$ on U whenever $\|A\|_o < 1$.

The fundamental importance of contractions stems from the following theorem.

Theorem 1.2.5 (Banach's contraction mapping theorem)**.** *If U is closed in $\mathbb{R}^n$ and T is a contraction of modulus λ on U with respect to some norm $\|\cdot\|$ on $\mathbb{R}^n$, then T has a unique fixed point u^* in U and*

$$\|T^n u - u^*\| \leqslant \lambda^n \|u - u^*\| \quad \textit{for all } n \in \mathbb{N} \textit{ and } u \in U. \tag{1.22}$$

In particular, T is globally stable on U.

We complete a proof of Theorem 1.2.5 in stages.

Exercise 1.2.19. Let U and T have the properties stated in Theorem 1.2.5. Fix $u_0 \in U$ and let $u_m := T^m u_0$. Show that

$$\|u_m - u_k\| \leqslant \sum_{i=m}^{k-1} \lambda^i \|u_0 - u_1\|$$

holds for all $m, k \in \mathbb{N}$ with $m < k$.

Exercise 1.2.20. Using the results in Exercise 1.2.19, prove that (u_m) is a Cauchy sequence in $\mathbb{R}^n$.

Exercise 1.2.21. Using Exercise 1.2.20, argue that (u_m) hence has a limit $u^* \in \mathbb{R}^n$. Prove that $u^* \in U$.

Proof of Theorem 1.2.5. In the exercises we proved existence of a point $u^* \in U$ such that $T^m u \to u^*$. The fact that u^* is a fixed point of T now follows from Exercise 1.2.13 and Exercise 1.2.16. Uniqueness is implied by Exercise 1.2.16. The bound (1.22) follows from iteration on the contraction inequality (1.20) while setting $v = u^*$. □

Observe that Banach's contraction mapping theorem extends directly to operators on $\mathbb{R}^{\mathsf{X}}$ when X is finite. Indeed, if $|\mathsf{X}| = n$, C is closed in $\mathbb{R}^{\mathsf{X}}$ and T is a contraction on $C \subset \mathbb{R}^{\mathsf{X}}$, in the sense that, for some $\lambda < 1$,

$$\|Tf - Tg\| \leqslant \lambda \|f - g\| \quad \text{for all} \quad f, g \in C$$

then T has a unique fixed point f^* in C and

$$\|T^n f - f^*\| \leqslant \lambda^n \|f - f^*\| \quad \text{for all } n \in \mathbb{N} \text{ and } f \in \mathbb{R}^{\mathsf{X}}.$$

There is no need to supply a new proof: we just need to identify functions in $\mathbb{R}^{\mathsf{X}}$ with vectors in $\mathbb{R}^n$ under the correspondence (1.12).

Exercise 1.2.22. Let U be a closed subset of $\mathbb{R}^n$ with the property that $u, v \in U$ implies $u \vee v \in U$. Let T_1 and T_2 be contraction maps on U under the supremum norm $\|\cdot\|_\infty$. Prove that the self-map $T : U \to U$ defined by $Tu := (T_1 u) \vee (T_2 u)$ is also contraction on U under the supremum norm.

1.2.4 Successive Approximation

Consider a self-map T on $U \subset \mathbb{R}^n$. We seek algorithms that compute fixed points of T whenever they exist.

1.2.4.1 Iteration

If T is globally stable on U, then a natural algorithm for approximating the unique fixed point u^* of T in U is to pick any $u \in U$ and iterate with T for some finite number of steps:

```
fix u_0 ∈ U and τ > 0
k ← 0
ε ← τ + 1
while ε > τ do
    u_{k+1} ← T u_k
    ε ← ‖u_{k+1} − u_k‖
    k ← k + 1
end
return u_k
```

Figure 1.8: Successive approximation from different initial conditions

By the definition of global stability, $(u_k)_{k\geqslant 0}$ converges to u^*. The algorithm just described is called either **successive approximation** or **fixed point iteration**. Listing 4 provides a function that implements this procedure. Distance between points is measured using the ℓ_∞ norm.

Listing 5 applies successive approximation to the map $Tu = Au + b$ using the function defined in `s_approx.jl`. Figure 1.8 shows the sequence of iterates generated by four runs of the successive approximation algorithm, each with a different starting condition u_0. The map and parameters are the same as in Listing 5. It is clear from the figure that a good choice of initial condition (i.e., close to the fixed point) accelerates convergence.

Of course for $Tu = Au + b$ with $r(A) < 1$, there is a more direct method to compute the fixed point: the Neumann series lemma tells us that $u^* = (I - A)^{-1}b$ so we can apply a numerical linear equation solver. However, successive approximation is still used, even for this case. One reason is that $(I - A)^{-1}$ can be very large, making application of a linear solver problematic. Another is that we might be satisfied with a quick approximation of the fixed point, computed with a few iterations of T. Both of these situations arise when we study dynamic programming.

```
"""
Computes the approximate fixed point of T via successive approximation.

"""
function successive_approx(T,                       # Operator (callable)
                           u_0;                     # Initial condition
                           tolerance=1e-6,          # Error tolerance
                           max_iter=10_000,         # Max iteration bound
                           print_step=25)           # Print at multiples
    u = u_0
    error = Inf
    k = 1

    while (error > tolerance) & (k <= max_iter)
        u_new = T(u)
        error = maximum(abs.(u_new - u))
        if k % print_step == 0
            println("Completed iteration $k with error $error.")
        end
        u = u_new
        k += 1
    end

    if error <= tolerance
        println("Terminated successfully in $k iterations.")
    else
        println("Termination Warning: Error is greater than tolerance.")
    end

    return u
end
```

Listing 4: Successive approximation (`s_approx.jl`)

```
include("s_approx.jl")
using LinearAlgebra

# Compute the fixed point of Tu = Au + b via linear algebra
A, b = [0.4 0.1; 0.7 0.2], [1.0; 2.0]
u_star = (I - A) \ b  # compute (I - A)^{-1} * b

# Compute the fixed point via successive approximation
T(u) = A * u + b
u_0 = [1.0; 1.0]
u_star_approx = successive_approx(T, u_0)

# Test for approximate equality (prints "true")
print(isapprox(u_star, u_star_approx, rtol=1e-5))
```

Listing 5: Using successive approximations to compute u^* (`linear_iter.jl`)

1.2.4.2 A One-Dimensional Example

To illustrate successive approximations in a nonlinear setting, we use the Solow–Swan growth model, which is a typical starting point for analysis of economic growth in undergraduate studies. For the version we present, the fixed point can be computed with pencil and paper, so successive approximation is unnecessary. At the same time, it will be useful to have this simple example when we discuss rates of convergence.

One version of the Solow–Swan growth dynamics is

$$k_{t+1} = sf(k_t) + (1-\delta)k_t, \qquad t = 0, 1, \dots, \tag{1.23}$$

where k_t is capital stock per worker, $f\colon (0,\infty) \to (0,\infty)$ is a production function, $s > 0$ is a savings rate and $\delta \in (0,1)$ is a rate of depreciation. If we set $g(k) := sf(k) + (1-\delta)k$, then iterating with g from some starting point k_0 (i.e., setting $k_{t+1} = g(k_t)$ for all $t \geqslant 0$) generates the sequence in (1.23). At the same time, we can understand this process as using successive approximation to compute the fixed point of g.

Exercise 1.2.23. Let $f(k) = Ak^\alpha$ with $A > 0$ and $0 < \alpha < 1$. Show that, while the Solow-Swan map $g(k) = sk^\alpha + (1-\delta)k$ sends $U := (0,\infty)$ into itself, g is *not* a contraction on U. [Hint: use the definition of the derivative of g as a limit and consider the derivative $g'(k)$ for k close to zero.]

Although the model specified in Exercise 1.2.23 does not generate a contraction, it is globally stable. The next exercise asks you to prove this.

Exercise 1.2.24. Show that, in the setting of Exercise 1.2.23, the unique fixed point of g in U is

$$k^* := \left(\frac{sA}{\delta}\right)^{1/(1-\alpha)}$$

Prove that, for $k \in U$,

(i) $k \leqslant k^*$ implies $k \leqslant g(k) \leqslant k^*$ and

(ii) $k^* \leqslant k$ implies $k^* \leqslant g(k) \leqslant k$.

Conclude that g is globally stable on U. (Why?)

Figure 1.9 illustrates the dynamics in a 45 degree diagram when $f(k) = Ak^\alpha$. In the top subfigure, $A = 2.0$, $\alpha = 0.3$, $s = 0.3$ and $\delta = 0.4$. The function g is plotted alongside the 45 degree line. Readers will recall that, when $g(k_t)$ lies strictly above the 45 degree line, then $k_{t+1} = g(k_t) > k_t$ and so capital per worker rises. If $g(k_t) < k_t$ then it falls. One trajectory $\{k_t\}_{t \geqslant 0}$, produced by starting from a particular choice of k_0, is traced out in the figure.

The bottom subfigure is similar, with parameters adjusted to $A = 3.0$, $\alpha = 0.05$, $s = 0.4$ and $\delta = 0.6$.

The figure helps illustrate the fact that k^* is the unique fixed point of g in U and all sequences converge to it. The second statement can be rephrased as: successive approximation successfully computes the fixed point of g by stepping through the time path of capital.

1.3 Infinite-Horizon Job Search

Now we are armed with useful fixed point methods, let's return to the job search problem first discussed in §1.1.2 and solve for optimal choices more carefully.

1.3.1 Values and Policies

In this section we solve for the value function of the infinite horizon job search problem and use it to make optimal choices.

Figure 1.9: Successive approximation for the Solow–Swan model

1.3.1.1 Optimal Choices

In §1.1.2.1 we proposed a strategy for solving the infinite-horizon job search problem, which required computing the value function v^*. You will recall that v^* solves the Bellman equation, which is

$$v^*(w) = \max\left\{\frac{w}{1-\beta},\ c + \beta \sum_{w' \in \mathsf{W}} v^*(w')\varphi(w')\right\} \qquad (w \in \mathsf{W}). \tag{1.24}$$

Suppose for the moment that we can compute v^*, and let

$$h^* := c + \beta \sum_{w'} v^*(w')\varphi(w') \tag{1.25}$$

be the infinite-horizon **continuation value**. The continuation value is the maximal lifetime value that the agent can receive, contingent on deciding to continue today.

With h^* in hand, the optimal decision at any given time, facing current wage draw $w \in \mathsf{W}$, is as follows:

(i) If $w/(1-\beta) \geqslant h^*$, then accept the job offer.

(ii) If not, then reject and wait for the next offer.

This decision maximizes lifetime value given the current offer.

(We will prove below that this decision process is optimal as claimed. For now, however, we focus on computing v^* and h^*.)

1.3.1.2 The Bellman Operator

The metho proposed above requires that we solve for v^*. To do so, we introduce an operator T, called the **Bellman operator**, such that any fixed point of T solves the Bellman equation and vice versa. This is true by construction for T defined at $v \in \mathbb{R}^{\mathsf{W}}$ by

$$(Tv)(w) = \max\left\{\frac{w}{1-\beta},\ c + \beta \sum_{w' \in \mathsf{W}} v(w')\varphi(w')\right\} \qquad (w \in \mathsf{W}). \tag{1.26}$$

Let $V := \mathbb{R}_+^{\mathsf{W}}$ and let $\|\cdot\|_\infty$ be the supremum norm on V. We measure the distance between two elements f, g of V by $\|f - g\| = \max_{w \in \mathsf{W}} |f(w) - g(w)|$. Under this norm distance, we have the following result.

Proposition 1.3.1. *T is a contraction of modulus β on V.*

A proof of Proposition 1.3.1 is given below. An implication of the proposition is that $T^k v \to v^*$ as $k \to \infty$ for any $v \in V$, so we can compute v^* to any required degree of accuracy by successive approximation.

Our proof of Proposition 1.3.1 uses the elementary bound

$$|\alpha \vee x - \alpha \vee y| \leqslant |x - y| \qquad (\alpha, x, y \in \mathbb{R}) \tag{1.27}$$

Exercise 1.3.1. Verify that (1.27) always holds. [Exercise 1.2.1 might be helpful.]

Proof of Proposition 1.3.1. Take any f, g in V and fix any $w \in \mathsf{W}$. Apply the bound in (1.27) to get

$$\begin{aligned} |(Tf)(w) - (Tg)(w)| &\leqslant \left| c + \beta \sum_{w'} f(w')\varphi(w') - \left(c + \beta \sum_{w'} g(w')\varphi(w') \right) \right| \\ &= \beta \left| \sum_{w'} [f(w') - g(w')]\varphi(w') \right|. \end{aligned}$$

Apply the triangle inequality to obtain

$$|(Tf)(w) - (Tg)(w)| \leqslant \beta \sum_{w'} |f(w') - g(w')|\varphi(w') \leqslant \beta \|f - g\|_\infty.$$

Taking the supremum over all w on the left hand side of this expression leads to

$$\|Tf - Tg\|_\infty \leqslant \beta \|f - g\|_\infty.$$

Since f, g were arbitrary elements of V, the contraction claim is verified. □

1.3.1.3 Optimal Policies

As will become clear over the next few chapters, the entire field of dynamic programming revolves around finding optimal policies. In order to prepare ourselves for this perspective, we briefly introduce the notion of policies and relate them to the job search application.

In general, for a dynamic program, choices by the controller aim to maximize lifetime rewards and consist of a state-contingent sequence $(A_t)_{t \geqslant 0}$ specifying how the agent acts at each point in time. Since agents are not clairvoyant, it is natural to assume that A_t can depend on present and past events but not future ones. In other words, A_t is a function of past state-action pairs (A_{t-i}, X_{t-i}) for $i \geqslant 1$ and the current state X_t. That is,

$$A_t = \sigma_t(X_t, A_{t-1}, X_{t-1}, A_{t-2}, X_{t-2}, \ldots, A_0, X_0)$$

for some function σ_t. In the language of dynamic programming, σ_t is called a time t **policy function**.

A key insight of dynamic programming is that, in some contexts the problem can be set up so that *the current state X_t is sufficient to determine the optimal current action*.

Example 1.3.1. In Example 1.0.1, the retailer chooses stock orders and prices in each period. Every quantity relevant to this decision belongs in the current state, contingent on keeping the problem tractable. The current state might include not just the level of current inventories and various measures of business conditions, but also information such as the rate at which inventories have changed over each of the past six months.

If the current state X_t is enough to determine the current action, then policies are just maps from states to actions. That is, we can write $A_t = \sigma(X_t)$ for some function σ. A policy function that depends only on the current state is often called a **Markov policy**. Since all policies we consider will be Markov policies, we refer to them more concisely as "policies."

Remark 1.3.1. In the last paragraph, we dropped the time subscript on σ with no loss of generality because we can always include the date t in the current state i.e., if Y_t is

the state without time, then we can set $X_t = (t, Y_t)$). Whether this is necessary depends on the problem at hand. For the job search model with finite horizon, the date matters because the opportunity for future earnings decreases with the date. For the infinite horizon version of the problem, in which an the agent always looks forward toward an infinite horizon, the only current information that matters to the agent at time t is the wage offer W_t. As a result, the calendar date t does not affect the agent's decision at time t, so there is no need to include time in the state.

In the job search model, the state is the current wage offer and possible actions are to accept or to reject the current offer. With 0 interpreted as reject and 1 understood as accept, the action space is $\{0, 1\}$, so a policy is a map σ from W to $\{0, 1\}$. Let Σ be the set of all such maps.

A policy is an "instruction manual" for the agent: for an agent following $\sigma \in \Sigma$, if current wage offer is w, the agent always responds with $\sigma(w) \in \{0, 1\}$. The policy dictates whether the agent accepts or rejects at any given wage.

For each $v \in V$, a **v-greedy policy** is a $\sigma \in \Sigma$ satisfying

$$\sigma(w) = \mathbb{1}\left\{\frac{w}{1-\beta} \geqslant c + \beta \sum_{w' \in \mathsf{W}} v(w')\varphi(w')\right\} \quad \text{for all } w \in \mathsf{W}. \tag{1.28}$$

Equation (1.28) says that an agent accepts if $w/(1-\beta)$ exceeds the continuation value computed using v and rejects otherwise. Our discussion of optimal choices in §1.3.1.1 can now be summarized as the recommendation

Adopt a v^*-greedy policy.

This statement is sometimes called Bellman's principle of optimality.

Inserting v^* into (1.28) and rearranging, we can express a v^*-greedy policy via

$$\sigma^*(w) = \mathbb{1}\{w \geqslant w^*\} \quad \text{where } w^* := (1-\beta)h^*. \tag{1.29}$$

The quantity w^* in (1.29) is called the **reservation wage**, and parallels the reservation wage that we introduced for the finite-horizon problem. Equation (1.29) states that value maximization requires accepting an offer if and only if it exceeds the reservation wage. Thus, w^* provides a scalar description of an optimal policy.

1.3.2 Computation

Let's turn to computation. In §1.3.2.1, we apply a standard dynamic programming method, called value function iteration. Below, in §1.3.2.2, we apply a more specialized method that uses the structure of the job search problem to accelerate computation.

1.3.2.1 Value Function Iteration

Recall that, by Proposition 1.3.1, we can compute an approximate optimal policy by applying successive approximation via the Bellman operator. In the language of dynamic programming, this is called **value function iteration**. Algorithm 1 provides a full description.

Algorithm 1: Value function iteration for job search

```
input v_0 ∈ V, an initial guess of v*
input τ, a tolerance level for error
ε ← τ + 1
k ← 0
while ε > τ do
    for w ∈ W do
        v_{k+1}(w) ← (T v_k)(w)
    end
    ε ← ||v_k − v_{k+1}||_∞
    k ← k + 1
end
Compute a v_k-greedy policy σ
return σ
```

While $T^k v$ never attains v^* in most cases, we can obtain a close approximation by monitoring distances between successive iterates, waiting until they become small enough. Later we will study how these distances depend on k, the number of iterations, as well as the parameters.

Listing 6 implements value function iteration for the infinite-horizon job search model, using the function for successive approximation from Listing 4.

Figure 1.10 shows a sequence of iterates $\{T^k v\}$ when $v \equiv 0$ and parameters are as given in Listing 1 (page 8). Iterates $0, 1$ and 2 are shown, in addition to a limiting function (iterate 1000). If you experiment with different initial conditions, you will see that they all converge to the same limit.

```
include("two_period_job_search.jl")
include("s_approx.jl")

" The Bellman operator. "
function T(v, model)
    (; n, w_vals, ϕ, β, c) = model
    return [max(w / (1 - β), c + β * v'ϕ) for w in w_vals]
end

" Get a v-greedy policy. "
function get_greedy(v, model)
    (; n, w_vals, ϕ, β, c) = model
    σ = w_vals ./ (1 - β) .>= c .+ β * v'ϕ  # Boolean policy vector
    return σ
end

" Solve the infinite-horizon IID job search model by VFI. "
function vfi(model=default_model)
    (; n, w_vals, ϕ, β, c) = model
    v_init = zero(model.w_vals)
    v_star = successive_approx(v -> T(v, model), v_init)
    σ_star = get_greedy(v_star, model)
    return v_star, σ_star
end
```

Listing 6: Value function iteration (`iid_job_search.jl`)

Figure 1.10: A sequence of iterates of the Bellman operator

Figure 1.11 shows an approximation of v^* computed using the code in Listing 6, along with the stopping reward $w/(1-\beta)$ and the corresponding continuation value (1.25). As anticipated, the value function is the pointwise supremum of the stopping reward and the continuation value. The agent chooses to accept an offer only when that offer exceeds some value close to 43.5.

1.3.2.2 Computing the Continuation Value Directly

The technique we employed to solve the job search model in §1.3.1 follows a standard approach to dynamic programming. But for this particular problem, there is an easier way to compute the optimal policy that sidesteps calculating the value function. This section explains how.

Recall that the value function satisfies the Bellman equation

$$v^*(w) = \max\left\{\frac{w}{1-\beta},\ c + \beta \sum_{w'} v^*(w')\varphi(w')\right\} \qquad (w \in \mathsf{W}), \tag{1.30}$$

and that the continuation value is given by (1.25). We can use h^* to eliminate v^* from (1.30). First we insert h^* on the right hand side of (1.30) and then we replace w with w', which gives $v^*(w') = \max\{w'/(1-\beta), h^*\}$. Then we take mathematical

Figure 1.11: The approximate value function for job search

expectations of both sides, multiply by β and add c to obtain

$$h^* = c + \beta \sum_{w'} \max\left\{\frac{w'}{1-\beta}, h^*\right\} \varphi(w'). \tag{1.31}$$

To obtain the unknown value h^*, we introduce the mapping $g\colon \mathbb{R}_+ \to \mathbb{R}_+$ defined by

$$g(h) = c + \beta \sum_{w'} \max\left\{\frac{w'}{1-\beta}, h\right\} \varphi(w'). \tag{1.32}$$

By construction, h^* solves (1.31) if and only if h^* is a fixed point of g.

Exercise 1.3.2. Show that g is a contraction map on $\mathbb{R}_+$. Conclude that h^* is the unique fixed point of g in $\mathbb{R}_+$.

Figure 1.12 shows the function g using the discrete wage offer distribution and parameters as adopted previously. The unique fixed point is h^*.

Exercise 1.3.2 implies that we can compute h^* by choosing arbitrary $h \in \mathbb{R}_+$ and iterating with g. Doing so produces a value of approximately 1086. (The associated reservation wage is $w^* = (1-\beta)h^* \approx 43.4$.) Computation of h^* using this method is much faster than value function iteration because the fixed point problem is in $\mathbb{R}_+$ rather than $\mathbb{R}_+^n$.

With h^* in hand we have solved the dynamic programming problem, since a policy

Figure 1.12: Computing the continuation value as the fixed point of g

σ^* is v^*-greedy if and only if it satisfies

$$\sigma^*(w) = \mathbb{1}\left\{\frac{w}{1-\beta} \geqslant h^*\right\} \qquad (w \in \mathbb{R}_+). \tag{1.33}$$

Exercise 1.3.3. As a computational exercise, compare the value function v^* computed via

$$v^*(w) = \max\left\{\frac{w}{1-\beta}, h^*\right\}$$

with our previous result, shown in Figure 1.11. You should find them essentially identical.

1.4 Chapter Notes

Dynamic programming is often attributed to Richard Bellman (1920–1984). Both the term "dynamic programming" and the methodology were popularized by Bellman (1957). According to his autobiography, Bellman chose the name dynamic programming to avoid giving the impression that he was conducting mathematical research within RAND Corporation. His ultimate boss, Secretary of Defence Charles Wilson, apparently disliked such research (Bellman (1984)).

The job search model was introduced by McCall (1970). The McCall model and its extensions transformed economists' way of thinking about labor markets (see,

e.g., Lucas (1978b)). Influential extensions to the job search model include Burdett (1978), Jovanovic (1979), Pissarides (1979), Jovanovic (1984), Mortensen (1986), Ljungqvist (2002) and Chetty (2008). Rogerson et al. (2005) provides a useful survey.

For background on elementary real analysis, the book by Bartle and Sherbert (2011) is excellent. Discussions of Banach's theorem and the Neumann series lemma can be found in Cheney (2013) and Atkinson and Han (2005). Martins-da Rocha and Vailakis (2010) provides an extension to Banach's theorem that requires only local contractivity.

Chapter 2

Fixed Points

Chapter 1 emphasized the importance of fixed point theory for dynamic programming and reviewed some fixed point results. This chapter contains a more extensive discussion that ranges from fundamental theory to algorithms.

Some of the fixed point theory we discuss is related to order. An investment in order-theoretic concepts will prove valuable not only for fixed point methods but also for understanding the main concepts in dynamic programming. (Chapter 7 will show that core components of dynamic programming can be expressed in terms of simple order-theoretic constructs.)

2.1 Order and Fixed Points

We begin with partial orders and then analyze fixed points of operators acting on partially ordered sets.

2.1.1 Partial Orders

Our first task is to define partially ordered sets.

2.1.1.1 Partially Ordered Sets

A **partial order** on a nonempty set P is a relation $\preceq$ on $P \times P$ that, for any p, q, r in P, satisfies

$p \preceq p$	(reflexivity)
$p \preceq q$ and $q \preceq p$ implies $p = q$ and	(antisymmetry)
$p \preceq q$ and $q \preceq r$ implies $p \preceq r$	(transitivity)

When paired with a partial order $\preceq$, the set P (or the pair $(P, \preceq)$) is called a **partially ordered set**. For convenience, we sometimes write $p \preceq q$ as $q \succeq p$. Also, $p \preceq q \preceq r$ means $p \preceq q$ and $q \preceq r$.

Example 2.1.1. The usual order $\leqslant$ on $\mathbb{R}$ is a partial order on $\mathbb{R}$.

Exercise 2.1.1. Let P be any set and consider the relation induced by equality, so that $p \preceq q$ if and only if $p = q$. Show that this relation is a partial order on P.

Exercise 2.1.2. Let M be any set. Show that $\subset$ is a partial order on $\wp(M)$, the set of all subsets of M.

A partial order $\preceq$ on P is called a **total order** if, for all $p, q \in P$, either $p \preceq q$ or $q \preceq p$.

Example 2.1.2. The usual order $\leqslant$ on $\mathbb{R}$ is a total order, as is the same order on $\mathbb{N}$.

Exercise 2.1.3. Is the partial order defined in Exercise 2.1.2 a total order? Either prove that it is or provide a counterexample.

A subset B of a partially ordered set $(P, \preceq)$ is called **increasing** if $x \in B$, $y \in P$ and $x \preceq y$ implies $y \in B$. The set B is called **decreasing** if $x \in B$, $y \in P$ and $y \preceq x$ implies $y \in B$.

Exercise 2.1.4. Describe the set of increasing sets in $(\mathbb{R}, \leqslant)$.

2.1.1.2 Pointwise Orders

Most partial orders that we care about in this book are *pointwise* orders. All such orders are special cases of the following example.

Example 2.1.3 (Pointwise order over functions)**.** Let X be any set. For f, g in $\mathbb{R}^{\mathsf{X}}$, we write $f \leqslant g$ if $f(x) \leqslant g(x)$ for all $x \in \mathsf{X}$. The relation $\leqslant$ on $\mathbb{R}^{\mathsf{X}}$ is a partial order called the **pointwise order** on $\mathbb{R}^{\mathsf{X}}$. For example, looking at Figure 1.5 on page 17, we can see that $f \leqslant f \vee g$ and $g \leqslant f \vee g$. This makes sense, since $f \vee g$ is the pointwise maximum of the two functions.

Figure 2.1: Pointwise we have $u \leqslant v$ and $u \ll v$ but not $w \leqslant v$

Example 2.1.4. Let X be any set. For f, g in $\mathbb{R}^{\mathsf{X}}$, we write $f \ll g$ if $f(x) < g(x)$ for all $x \in$ X. The relation $\ll$ is *not* a partial order on $\mathbb{R}^{\mathsf{X}}$, since reflexivity fails.

The preceeding examples extend immediately to vectors, since vectors are just real-valued functions under the identification in Lemma 1.2.1 (page 16). In particular, for vectors $u = (u_1, \ldots, u_n)$ and $v = (v_1, \ldots, v_n)$ in $\mathbb{R}^n$, we write

- $u \leqslant v$ if $u_i \leqslant v_i$ for all $i \in [n]$ and
- $u \ll v$ if $u_i < v_i$ for all $i \in [n]$.

Statements $u \geqslant v$ and $u \gg v$ are defined analogously. Figure 2.1 illustrates. As above, the relation $\leqslant$ is called the **pointwise order** on $\mathbb{R}^n$ (while $\ll$ is not a partial order).

In Figure 2.1 we can also see that $\leqslant$ is not a total order on $\mathbb{R}^n$. For example, neither $v \leqslant w$ nor $w \leqslant v$, since $w_1 > v_1$ but $w_2 < v_2$.

Exercise 2.1.5. Limits in $\mathbb{R}$ preserve weak inequalities. Use this property to prove that the same is true in $\mathbb{R}^n$. In particular, show that, for vectors $a, b \in \mathbb{R}^n$ and sequence (u_k) in $\mathbb{R}^n$ with $a \leqslant u_k \leqslant b$ for all $k \in \mathbb{N}$ and $u_k \to u \in \mathbb{R}^n$, we have $a \leqslant u \leqslant b$.

Example 2.1.5 (Pointwise order over matrices)**.** Analogous to vectors, for $n \times k$ matrices $A = (a_{ij})$ and $B = (b_{ij})$, we write

- $A \leqslant B$ if $a_{ij} \leqslant b_{ij}$ for all i, j.
- $A \ll B$ if $a_{ij} < b_{ij}$ for all i, j.

The relation $\leqslant$ is a partial order on $\mathbb{M}^{n \times k}$, the set of real-valued $n \times k$ matrices. As for vectors, we call this the **pointwise order**.

Exercise 2.1.6. Explain why the pointwise order introduced in Example 2.1.5 is also a special case of the order in Example 2.1.3.

Given a partially ordered set $(P, \preceq)$ and two elements a, b of P, the **order interval** $[a, b]$ is defined as all $p \in P$ such that $a \preceq p \preceq b$. (If $a \preceq b$ fails, the order interval is empty.)

Exercise 2.1.7. Let $C[0,1]$ be the set of continuous functions on $[0,1]$, partially ordered by the pointwise order $\leqslant$. Let f_i, g_i be elements of $C[0,1]$ for $i = 1, 2$. Show that the intersection of the two order intervals $[f_1, f_2]$ and $[g_1, g_2]$ is an order interval in $C[0,1]$.

Exercise 2.1.8. Prove the next two facts:

(i) If B is $m \times k$ and $B \geqslant 0$, then $|Bu| \leqslant B|u|$ for all $k \times 1$ column vectors u.

(ii) If A is $n \times n$ with $A \geqslant 0$ and (u_k) is a sequence in $\mathbb{R}^n$ satisfying $u_{k+1} \leqslant Au_k$ for all $k \geqslant 0$, then $u_k \leqslant A^k u_0$.

Exercise 2.1.9. Let A be $n \times k$ and let u and v be k-vectors. Prove that $A \gg 0$, $u \leqslant v$ and $u \neq v$ implies $Au \ll Av$.

2.1.1.3 Inequalities and Identities

The following inequalities and identities hold.

Lemma 2.1.1. *If X is finite and $f, g, h \in \mathbb{R}^{\mathsf{X}}$, then the following statements are true:*

(i) $|f + g| \leqslant |f| + |g|$.

(ii) $(f \wedge g) + h = (f + h) \wedge (g + h)$ *and* $(f \vee g) + h = (f + h) \vee (g + h)$.

(iii) $(f \vee g) \wedge h = (f \wedge h) \vee (g \wedge h)$ *and* $(f \wedge g) \vee h = (f \vee h) \wedge (g \vee h)$.

(iv) $|f \wedge h - g \wedge h| \leqslant |f - g|$.

(v) $|f \vee h - g \vee h| \leqslant |f - g|$.

These results follow immediately from proofs of analogous results when $f, g, h \in \mathbb{R}$. For example, by the the usual triangle inequality for scalars, we have $|f(x)+g(x)| \leqslant |f(x)| + |g(x)|$ for all $x \in \mathsf{X}$. This is equivalent to the statement $|f + g| \leqslant |f + g|$ in (i).

Similarly, inequality (v) follows directly from a corresponding scalar inequality that was already proved in Exercise 1.3.1, page 32.

A complete proof of lemma 2.1.1 can be found in Theorem 30.1 of Aliprantis and Burkinshaw (1998).

It is also true that, if $f, g, h \in \mathbb{R}_+^{\mathsf{X}}$, then

$$(f + g) \wedge h \leqslant (f \wedge h) + (g \wedge h). \tag{2.1}$$

Exercise 2.1.10. Prove: If $a, b, c \in \mathbb{R}_+$, then $|a \wedge c - b \wedge c| \leqslant |a - b| \wedge c$.

2.1.1.4 Least and Greatest Elements

In dynamic programming, our aim is to maximize lifetime value (or minimize lifetime cost), which is a function over the state space, rather than a number. Thus, the objective takes values in a partially ordered set (a set of functions over the state space). This leads us to consider "least" and "greatest" elements, rather than traditional maxima and minima (definitions of which can be found in Appendix A).

In particular, given a partially ordered set $(P, \preceq)$ and $A \subset P$, we say that

- $\ell \in P$ is a **least element** of A if $\ell \in A$ and $a \succeq \ell$ for all $a \in A$, and
- $g \in P$ is a **greatest element** of A if $g \in A$ and $a \preceq g$ for all $a \in A$.

Exercise 2.1.11. Let P be any partially ordered set and fix $A \subset P$. Prove that A has at most one greatest element and at most one least element.

Example 2.1.6. Let X be a nonempty set and V be a subset of $\mathbb{R}^{\mathsf{X}}$. We consider V as a partially ordered set, ordered by the pointwise order $\leqslant$. Let $\{v_\sigma\} := \{v_\sigma\}_{\sigma \in \Sigma}$ be a finite collection of functions in V. Let $\vee_\sigma v_\sigma$ be the pointwise maximum (as defined in §1.2.1.5). Clearly, if $\vee_\sigma v_\sigma \in \{v_\sigma\}$, then $\vee_\sigma v_\sigma$ is the greatest element of $\{v_\sigma\}$.

Exercise 2.1.12. Adopt the setting of Example 2.1.6 and prove the following: If $\{v_\sigma\}$ has a greatest element, then that greatest element is $\vee_\sigma v_\sigma$.

Figure 2.2 helps to illustrate Example 2.1.6. The function $\vee_\sigma v_\sigma$ is denoted by v^*. In this case, $\{v_\sigma\}$ has no greatest element, since neither $v_{\sigma'} \leqslant v_{\sigma''}$ nor $v_{\sigma''} \leqslant v_{\sigma'}$.

Figure 2.2: v^* is the upper envelope of $\{v_\sigma\}_{\sigma\in\Sigma}$

Exercise 2.1.13. Let M be a nonempty set and let $\wp(M)$ be the set of all subsets of M, partially ordered by $\subset$. Let $\{A_i\} := \{A_i\}_{i\in I}$ be a subset of $\wp(M)$, so that $A_i \in \wp(M)$ for each i in arbitrary (nonempty) index set I. Let $S := \bigcup_i A_i$. Then S is the greatest element of $\{A_i\}$ if and only if $S \in \{A_i\}$.

Example 2.1.7. Adopt the setting of Exercise 2.1.13 and suppose that $\{A_i\}$ is the set of bounded subsets of $\mathbb{R}^n$. Since the union of all such sets is $\mathbb{R}^n$ (which is not bounded), $\{A_i\}$ has no greatest element. Indeed, if G is the greatest element of $\{A_i\}$, then G contains every bounded subset of $\mathbb{R}^n$. But then G is not bounded. Contradiction.

If A is totally ordered, then a greatest element g of A is also called a **maximum** of A, while a least element ℓ of A is also called a **minimum**. See Appendix A for more about maxima and minima.

2.1.2 Order-Preserving Maps

Given two partially ordered sets $(P, \preceq)$ and $(Q, \trianglelefteq)$, a map T from P to Q is called **order-preserving** if, given $p, p' \in P$, we have

$$p \preceq p' \quad \Longrightarrow \quad Tp \trianglelefteq Tp'. \tag{2.2}$$

T is called **order-reversing** if, instead,

$$p \preceq p' \quad \Longrightarrow \quad Tp' \trianglelefteq Tp. \tag{2.3}$$

Example 2.1.8. Let $\leqslant$ be the pointwise order on $\mathbb{R}^n$. If A is $n \times n$ with $A \geqslant 0$, then $T\colon \mathbb{R}^n \to \mathbb{R}^n$ defined by $Tu = Au + b$ is order preserving on $\mathbb{R}^n$, since $u \leqslant v$ implies $v - u \geqslant 0$, and hence $A(v-u) \geqslant 0$. But then $Au \leqslant Av$ and hence $Tu \leqslant Tv$.

Example 2.1.9. Given $a \leqslant b$ in $\mathbb{R}$, let $C[a,b]$ be all continuous functions from $[a,b]$ to $\mathbb{R}$ and let $\leqslant$ be the pointwise order on $C[a,b]$. Let

$$I(f) := \int_a^b f(x)dx \qquad (f \in C[a,b]).$$

Since $f \leqslant g$ implies $\int_a^b f(x)dx \leqslant \int_a^b g(x)dx$, the map I is order-preserving on $C[a,b]$.

Regarding the definitions in (2.2)–(2.3), when $(Q, \trianglelefteq) = (\mathbb{R}, \leqslant)$, it is common to say "increasing" instead of order-preserving, and "decreasing" instead of order-reversing. We adopt this terminology. In particular, given partially ordered set $(P, \preceq)$, we call $h \in \mathbb{R}^P$

- **increasing** if $p \preceq p'$ implies $h(p) \leqslant h(p')$ and
- **decreasing** if $p \preceq p'$ implies $h(p) \geqslant h(p')$.

We use the symbol $i\mathbb{R}^P$ for the set of increasing functions in $\mathbb{R}^P$.[1]

Exercise 2.1.14. Prove: If P is any partially ordered set and $f, g \in i\mathbb{R}^P$, then

(i) $\alpha f + \beta g \in i\mathbb{R}^P$ whenever $\alpha, \beta \geqslant 0$.

(ii) $f \vee g \in i\mathbb{R}^P$ and $f \wedge g \in i\mathbb{R}^P$.

Exercise 2.1.15. Given finite P, show that $i\mathbb{R}^P$ is closed in $\mathbb{R}^P$.

Exercise 2.1.16. Let $(P, \preceq)$ be a partially ordered set and let A be an order-preserving self-map on P. Prove that A^k is order-preserving on P for any $k \in \mathbb{N}$.

[1] Why not just use "increasing" and "decreasing" in all cases, rather than adopting the fancier terminology "order-preserving" and "order-reversing"? The short answer is that, for a general partial order, the concepts of order-preserving and order-reversing can be very different from the usual notions of increasing and decreasing function.

Exercise 2.1.17. Let X be a random variable mapping Ω to finite X. Define $\ell\colon \mathbb{R}^{\mathsf{X}} \to \mathbb{R}$ by $\ell h = \mathbb{E}h(X)$. Show that ℓ is increasing when $\mathbb{R}^{\mathsf{X}}$ has the pointwise order.

Exercise 2.1.18. Let A be $n \times k$. Show that the map $u \mapsto Au$ is order-preserving on $\mathbb{R}^k$, under the usual pointwise order, whenever $A \geqslant 0$.

Exercise 2.1.19. Let A and B be $n \times n$ with $0 \leqslant A \leqslant B$. Prove that $A^k \leqslant B^k$ for all $k \in \mathbb{N}$ and, in addition, that $r(A) \leqslant r(B)$.

As usual, if $h\colon P \to Q$ and $P, Q \subset \mathbb{R}$, then we will call h

- **strictly increasing** if $x < y$ implies $h(x) < h(y)$, and
- **strictly decreasing** if $x < y$ implies $h(x) > h(y)$.

2.1.3 Parametric Monotonicity

We are often interested in whether a change in a parameter shifts an outcome up or down. For example, the parameter in question might appear in a central bank decision rule for pegging an interest rate, and we want to know whether increasing that parameter will increase steady state inflation. By providing sufficient conditions for monotone shifts in fixed points, results in this section can help answer such questions.

Let $(P, \preceq)$ be a partially ordered set. Given two self-maps S and T on a set P, we write $S \preceq T$ if $Su \preceq Tu$ for every $u \in P$ and say that T **dominates** S on P.

Example 2.1.10. Let $P = \mathbb{R}^n_+$ with the pointwise order on vectors, let $Sx = Ax + b$ and $Tx = Bx + b$, where $b \in \mathbb{R}^n$ and A and B are $n \times n$. If $A \leqslant B$, then, for any $x \in \mathbb{R}^n_+$, we have $Ax \leqslant Bx$. Hence $Sx \leqslant Tx$ and T dominates S on P.

Exercise 2.1.20. Let $(P, \preceq)$ be a partially ordered set and let S and T be order-preserving self-maps such that $S \preceq T$. Show that $S^k \preceq T^k$ holds for all $k \in \mathbb{N}$.

Exercise 2.1.21. Let $(P, \preceq)$ be a partially ordered set, let $\mathcal{S}$ be the set of all self-maps on P and, as above, write $S \preceq T$ if T dominates S on P. Show that $\preceq$ is a partial order on $\mathcal{S}$.

One might assume that, in a setting where T dominates S, the fixed points of T will be larger. This can hold, as in Figure 2.3, but it can also fail, as in Figure 2.4. One

Figure 2.3: Ordered fixed points when global stability holds

difference between these two scenarios is that, in the case of Figure 2.3, the map T is globally stable. This leads us to our next result.

Proposition 2.1.2. *Let S and T be self-maps on $M \subset \mathbb{R}^n$ and let $\leqslant$ be the pointwise order. If T dominates S on M and, in addition, T is order-preserving and globally stable on M, then its unique fixed point dominates any fixed point of S.*

Proof of Proposition 2.1.2. Assume the conditions of the proposition and let u_T be the unique fixed point of T. Let u_S be any fixed point of S. Since $S \leqslant T$, we have $u_S = Su_S \leqslant Tu_S$. Applying T to both sides of this inequality and using the order-preserving property of T and transitivity of $\leqslant$ gives $u_S \leqslant T^2 u_S$. Continuing in this fashion yields $u_S \leqslant T^k u_S$ for all $k \in \mathbb{N}$. Taking the limit in k and using the fact that $\leqslant$ is closed under limits gives $u_S \leqslant u_T$. □

As an application of Proposition 2.1.2, consider again the Solow–Swan growth model $k_{t+1} = g(k_t) := sf(k_t) + (1-\delta)k_t$. We saw in §1.2.4.2 that if $f(k) = Ak^\alpha$ where $A > 0$ and $\alpha \in (0,1)$, then g is globally stable on $M := (0,\infty)$. Clearly $k \mapsto g(k)$ is order-preserving on M. If we now increase, say, the savings rate s, then g will be shifted up everywhere, implying, via Proposition 2.1.2, that the fixed point will also rise. Exercise 2.1.22 asks you to step through the details.

Exercise 2.1.22. Let $g(k) = sAk^\alpha + (1-\delta)k$ where all parameters are strictly positive, $\alpha \in (0,1)$ and $\delta \leqslant 1$. Let $k^*(s, A, \alpha, \delta)$ be the unique fixed point of g in M. Without using the expression we derived for k^* previously (Exercise 1.2.24), show that

Figure 2.4: Reverse-ordered fixed points when global stability fails

(i) $k^*(s, A, \alpha, \delta)$ is increasing in s and A.

(ii) $k^*(s, A, \alpha, \delta)$ is decreasing in δ.

Figure 2.5 helps illustrate the results of Exercise 2.1.22. The top left sub-figure shows the default parameterization, with $A = 2.0$, $s = \alpha = 0.3$ and $\delta = 0.4$. The other sub-figures show how the steady state changes as parameters shift from that default.

Exercise 2.1.23. In (1.32) on page 38, we defined a map g such that the optimal continuation value h^* is a fixed point. Using this construction, prove that h^* is increasing in β.

Figure 2.6 gives an illustration of the result in Exercise 2.1.23. Here an increase in β leads to a larger continuation value. This seems reasonable, since larger β indicates more concern for outcomes in future periods.

While the examples of parametric monotonicity given above are all one-dimensional, we will soon see that Proposition 2.1.2 can be applied in high-dimensional settings as well.

2.1.4 Order Intervals and Fixed Points

In this section we prove a simple but useful version of perhaps the most important fixed point theorem in all of order theory, typically attributed to Bronislaw Knaster

Figure 2.5: Parametric monotonicity for the Solow-Swan model

Figure 2.6: Parametric monotonicity in β for the continuation value

(1893–1980) and Alfred Tarski (1901–1983). The theorem provides existence of fixed points for order-preserving maps under certain assumptions, as well as restrictions on the structure of the set of all fixed points.

Let $P = [0, 1]$ and try to draw an increasing function T that maps P to itself and yet fails to touch the 45 degree line. You will find that it's impossible. The next theorem generalizes this idea:

Theorem 2.1.3 (Knaster–Tarski). *Let X be a finite set. If $I = [\varphi, \psi]$ is a nonempty order interval in $(\mathbb{R}^{\mathsf{X}}, \leqslant)$ and T is an order-preserving self-map on $(I, \leqslant)$, then the set of fixed points of T is nonempty and contains a least and greatest element $u^* \leqslant u^{**}$. Moreover,*

$$T^k\varphi \leqslant u^* \leqslant u^{**} \leqslant T^k\psi \quad \textit{for all } k \geqslant 0. \tag{2.4}$$

Proof. Let U be all $u \in I$ such that $u \leqslant Tu$. Let $u^{**} := \sup_{u \in U} u(x)$. By Theorem A.2.1 on page 264, the function u^{**} is a well defined element of I. (The set U is nonempty because $\varphi \in U$.) We claim that u^{**} is a fixed point, for which it suffices to obtain the two inequalities $u^{**} \leqslant Tu^{**}$ and $Tu^{**} \leqslant u^{**}$.

Regarding the first inequality, given any $u \in U$, we have $u \leqslant u^{**}$, and hence $Tu \leqslant Tu^{**}$. But $u \in U$ also implies $u \leqslant Tu$, so $u \leqslant Tu^{**}$. Since this bound holds for all $u \in U$, it follows from the definition of the supremum that $u^{**} \leqslant Tu^{**}$. This gives us one of our inequalities.

To complete the argument, we use the last inequality to obtain $Tu^{**} \leqslant TTu^{**}$, which implies that $Tu^{**} \in U$. Since u^{**} is a pointwise supremum over U, this yields $Tu^{**} \leqslant u^{**}$. We can now conclude that $Tu^{**} = u^*$.

Let D be all $u \in I$ such that $Tu \leqslant u$. Let $u^* := \inf_{u \in U} u(x)$. Using analogous arguments with inequalities reversed shows that u^* is also a fixed point.

Now let $\bar{u}$ be any fixed point of T. Since $\bar{u} \in U$, we have $\bar{u} \leqslant u^{**}$. Since $\bar{u} \in D$, we also have $u^* \leqslant \bar{u}$. In particular, for any fixed point $\bar{u}$ of T in I, we have $u^* \leqslant \bar{u} \leqslant u^{**}$. □

Relative to Banach's contraction mapping theorem, the main weakness of Theorem 2.1.3 is that it yields only existence. Uniqueness and stability can fail—as you can easily convince yourself by sketching the one-dimensional case $I = [0, 1]$. In the next section we seek additional conditions that guarantee uniqueness and stability.

2.1.5 Concavity, Convexity and Stability

In this section we introduce a set of sufficient conditions for global stability that replace contractivity with shape properties on the operator such as concavity and convexity. These results have many useful applications in economics and finance.

Figure 2.7: Global stability induced by increasing concave functions

2.1.5.1 The One-Dimensional Case

To build intuition, we start with the one-dimensional case, where the fixed-point problem can be visualized and proofs are relatively simple. We show how concavity and monotonicity can be paired to achieve stability.

We have in fact already seen how this pairing can produce a unique stable fixed point. Figure 4.6 showed just such a scenario, for the one-dimensional version of the operator U. In addition, §1.2.4.2 we studied a discrete time Solow–Swan model and proved global stability of g on U when $g(k) := sf(k) + (1 - \delta)k$ and $U := (0, \infty)$, with $f(k) = Ak^\alpha$, $0 < \alpha, \delta < 1$ and $A > 0$. However, the proof we constructed was quite specialized. Here is a more general result.

Proposition 2.1.4. *Let g be an increasing concave self-map on $U := (0, \infty)$. If, for all $x \in U$, there exists a pair $a, b \in U$ with $a \leqslant x \leqslant b$, $a < g(a)$ and $g(b) \leqslant b$, then g is globally stable on U.*

The proof is below. Figure 2.7 gives one example, where $g(x) = 1 + \sqrt{x}/2$. For a function such as this one, given any positive number x, we can find a number $a < x$ that gets mapped strictly up (i.e., $g(a)$ is above the 45 line) and a point $b > x$ that gets mapped strictly down (i.e., $g(b)$ is below the 45 degree line). Under iteration all trajectories converge to the unique fixed point x^*.

Before reading the proof we recommend you sketch your own examples to see why the different conditions are required.

Exercise 2.1.24. Prove that the map g and set U defined in the discussion of the Solow-Swan model above Proposition 2.1.4 satisfies the conditions of the proposition.

Exercise 2.1.25. Dropping the Cobb-Douglas specification on production, suppose $g(k) = sf(k) + (1-\delta)k$ where $0 < s, \delta < 1$ and f is a strictly positive increasing concave production function on $U = (0, \infty)$ satisfying the **Inada conditions**

$$f'(k) \to \infty \text{ as } k \to 0 \quad \text{and} \quad f'(k) \to 0 \text{ as } k \to \infty,$$

Use Proposition 2.1.4 to prove that g is globally stable on U.

Exercise 2.1.26. Fajgelbaum et al. (2017) study a law of motion for aggregate uncertainty given by

$$s_{t+1} = g(s_t) \quad \text{where} \quad g(s) := \rho^2 \left[\frac{1}{s} + a^2 \frac{1}{\eta} \right]^{-1} + \gamma.$$

Let a, η and γ be positive constants and assume $0 < \rho < 1$. Prove that g is globally stable on $M := (0, \infty)$.

Proof of Proposition 2.1.4. First we prove existence of a fixed point $x^* \in U$. Fix $x \in U$. Suppose first that $x \leqslant g(x)$. Since g is increasing, we then have $g(x) \leqslant g^2(x)$. Continuing in this fashion (or using induction) shows that $(g^n(x))$ is monotone increasing. Moreover, there exists a $b \in U$ such that $x \leqslant b$ and $g(b) \leqslant b$. Hence $g(x) \leqslant g(b) \leqslant b$. Continuing in this fashion (or using induction) yields $g^n(x) \leqslant b$ for all n. We now see that $(g^n(x))$ is increasing and bounded above. Thus, there exists an $x^* \in U$ such that $(x_n) := (g^n(x))$ converges to x^*. Since g is concave and, therefore, continuous on any open set, the result in Exercise 1.2.13 implies that $x^* = g(x^*)$.

We have treated the case $x \leqslant g(x)$ and shown existence of a fixed point. If, instead, $x \geqslant g(x)$, then $(g^n(x))$ is shown to be decreasing and bounded by a symmetric argument. In the same way, we obtain a fixed point x^* with $g^n(x) \to x^*$.

To show the uniqueness of the fixed point, assume $g(x) = x$ and $g(y) = y$ for some $x, y \in U$. We claim that $x = y$. To see this, suppose without loss of generality that $x \leqslant y$. By assumption, there exists an $a \in U$ such that $a \leqslant x \leqslant y$ and $g(a) > a$. Because $a \leqslant x \leqslant y$, we can take $\lambda \in [0, 1]$ such that $x = \lambda a + (1-\lambda)y$. If $\lambda > 0$, then concavity of g and $g(a) > a$ implies the contradiction

$$g(x) = g(\lambda a + (1-\lambda)y) \geqslant \lambda g(a) + (1-\lambda)g(y) > \lambda a + (1-\lambda)y = x = g(x).$$

Hence $\lambda = 0$. Since $x = \lambda a + (1-\lambda)y$, this yields $x = y$.

We have proved existence of a unique fixed point in U to which every trajectory converges. □

2.1.5.2 The Multidimensional Case

Proposition 2.1.4 extends naturally to multiple dimensions. In this section we present a multidimensional version that covers both convex and concave functions.

In order to state our result, we extend the definition of convexity and concavity to vector-valued self-maps. In fact the conditions look identical to those for scalar-valued functions: a self-map T on a convex subset D of $\mathbb{R}^n$ is called **convex** if

$$T(\lambda u + (1-\lambda)v) \leqslant \lambda Tu + (1-\lambda)Tv \text{ whenever } u, v \in D \text{ and } \lambda \in [0,1];$$

and **concave** if

$$\lambda Tu + (1-\lambda)Tv \leqslant T(\lambda u + (1-\lambda)v) \text{ whenever } u, v \in D \text{ and } \lambda \in [0,1].$$

Here $\leqslant$ is, as usual, the pointwise order.

We are now ready to state our next fixed point result, which was first proved in an infinite-dimensional setting by Du (1990).

Theorem 2.1.5 (Du)**.** *Let X be a finite set, let $I := [\varphi, \psi]$ be a nonempty order interval in $(\mathbb{R}^{\mathsf{X}}, \leqslant)$ and let T be a self-map on I. If T is order-preserving, then T is globally stable on I under any one of (i)–(iv) below.*

(i) *T is concave and $T\varphi \gg \varphi$, or*

(ii) *T is concave and there exists an $\delta > 0$ such that $T\varphi \geqslant \varphi + \delta(\psi - \varphi)$, or*

(iii) *T is convex and $T\psi \ll \psi$, or*

(iv) *T is convex and there exists an $\delta > 0$ such that $T\psi \leqslant \psi - \delta(\psi - \varphi)$.*

Conditions (i) and (ii) are very similar: both require that T is concave and maps φ up strictly. In fact (ii) holds whenever (i) holds, so (ii) is the weaker (but slightly more complicated) condition. Conditions (iii) and (iv) are similar, after replacing concavity with convexity. Figure 2.8 illustrates the convex and the concave versions of the result in the simple case $n = 1$. We encourage you to sketch your own variations to get a feeling for why the different conditions are needed.

Figure 2.8: Du's theorem: convex and concave cases

Exercise 2.1.27. The presentation in Du (1990) and Zhang (2012) requires that δ in conditions (ii) and (iv) is in $(0, 1)$. Show that this restriction is unnecessary for the conclusions of Theorem 2.1.5 to hold.

Exercise 2.1.28. Let F and G be self-maps on convex $D \subset \mathbb{R}^n$. Show that $T := F \circ G$ is concave on D whenever F and G are order-preserving and concave on D.

A full proof of Theorem 2.1.5 can be found in Du (1990) or Theorem 2.1.2 and Corollary 2.1.1 of Zhang (2012). Here we prove only uniqueness.

Proof of uniqueness for Theorem 2.1.5. We focus in this proof on the concave case. Let I be as in Theorem 2.1.5 and suppose that T is an order-preserving concave self map on I with $T\varphi \gg \varphi$. By Theorem 2.1.3, T has a least and greatest fixed point in I, which we denote by u^* and u^{**} respectively. Let

$$\lambda := \min_{x \in \mathsf{X}} \frac{u^*(x) - \varphi(x)}{u^{**}(x) - \varphi(x)}$$

and let $\bar{x}$ be a minimizer. It follows immediately from its definition that λ obeys $0 \leqslant \lambda \leqslant 1$ and

$$u^*(x) \geqslant \lambda u^{**}(x) + (1 - \lambda)\varphi(x) \quad \text{for all } x \in \mathsf{X} \text{ with equality at } \bar{x}.$$

As a result, applying the stated properties of T, we have

$$u^* = Tu^* \geqslant T(\lambda u^{**} + (1 - \lambda)\varphi) \geqslant \lambda u^{**} + (1 - \lambda)T\varphi.$$

Suppose now that $\lambda < 1$. Since $T\varphi \gg \varphi$, we get $u^* \gg \lambda u^{**} + (1-\lambda)\varphi$ and evaluating this at $\bar{x}$ yields

$$u^*(\bar{x}) > \lambda u^{**}(\bar{x}) + (1-\lambda)\varphi(\bar{x}) = u^*(\bar{x}),$$

which is a contradition. Hence $\lambda = 1$ and, therefore, $u^* \geqslant u^{**}$. Since all fixed points $\bar{u}$ of T in I obey $u^* \leqslant \bar{u} \leqslant u^{**}$, we see that $u^* = u^{**}$ is the unique fixed point of T in I. □

2.2 Stability and Algorithms

We are interested not only in existence and uniqueness of fixed points but also in how to compute them. In this section we discuss alternative methods for computing fixed points and their rates of convergence. We also treat some useful results on stability theory.

2.2.1 Conjugate Maps

Next we treat an extremely useful technique for simplifying analysis of stability and fixed points. This method will have multiple applications in what follows.

Suppose we are concerned with the dynamics induced by an operator T mapping $\mathbb{R}^n$ into itself. For example, we might want to know if a unique fixed point of T exists, or if iterates of T always converge to a fixed point. Discussion above suggests that, in order to address these questions, we should apply fixed point theory to T.

Sometimes, however, there is an easier approach: transform T into a "simpler" operator $\hat{T}$ and then study the fixed point properties of $\hat{T}$. Of course, for this idea to work, we need to be sure that any properties we discover about $\hat{T}$ can be translated back to properties of T, the operator that we are actually interested in.

This section explains the notion of topological conjugacy, which originates in the field of dynamical systems theory, and can be used effectively for the problem just described. Later in this text, we will apply the methodology to operators that arise in recursive preference and dynamic programming contexts.

To explain the idea, let U and $\hat{U}$ be two subsets of $\mathbb{R}^n$. A function Φ from U to $\hat{U}$ is called a **homeomorphism** if it is continuous, a bijection, and its inverse Φ^{-1} is also continuous.

Example 2.2.1. The map $\Phi u = \ln u$ from $(0, \infty)$ to $\mathbb{R}$ is a homeomorphism, with continuous inverse $\Phi^{-1} y = \exp(y)$.

Example 2.2.2. Let Φ be an $n \times n$ matrix. We can regard Φ as a map sending column vector u into column vector Φu. This map is a homeomorphism from $\mathbb{R}^n$ to itself if and only if Φ is nonsingular.

A **dynamical system** is a pair (U, T), where U is a subset of $\mathbb{R}^n$ and T is a self-map on U. Two dynamical systems (U, T) and $(\hat{U}, \hat{T})$ are said to be

- **conjugate** under Φ if Φ is a bijection from U into $\hat{U}$ such that $T = \Phi^{-1} \circ \hat{T} \circ \Phi$ on U, and
- **topologically conjugate** under Φ if they are conjugate under Φ and, in addition, Φ is a homeomorphism.

Conjugacy of (U, T) and $(\hat{U}, \hat{T})$ under Φ can be understood as follows: shifting a point $u \in U$ to Tu using the map T is equivalent to moving u into $\hat{U}$ via $\hat{u} = \Phi u$, applying $\hat{T}$, and then moving the result back using Φ^{-1}:

$$\begin{tikzcd} u \arrow[r, "T"] \arrow[d, "\Phi"] & Tu \\ \hat{u} \arrow[r, "\hat{T}"] & \hat{T}\hat{u} \arrow[u, "\Phi^{-1}"'] \end{tikzcd}$$

Example 2.2.3. Let A be an $n \times n$ **diagonalizable matrix**, meaning that there exists a diagonal matrix D and a nonsingular matrix P such that $A = P^{-1}DP$. (The matrices D and P can be complex-valued.) Analogous to Example 2.2.2, we can regard A as a map on $\mathbb{R}^n$ and D and a map on $\mathbb{C}^n$, the set of complex n-vectors The identity $A = P^{-1}DP$ implies that the dynamical systems $(A, \mathbb{R}^n)$ and $(D, \mathbb{C}^n)$ are topologically conjugate.

Exercise 2.2.1. Let $U := ((0, \infty), |\cdot|)$ and $\hat{U} := (\mathbb{R}, |\cdot|)$. Let $Tu = Au^\alpha$, where $A > 0$ and $\alpha \in \mathbb{R}$, and let $\hat{T}\hat{u} = \ln A + \alpha\hat{u}$. Show that T and $\hat{T}$ are topologically conjugate under $\Phi := \ln$.

Exercise 2.2.2. Show that if (U, T) and $(\hat{U}, \hat{T})$ are conjugate under Φ, then $u \in U$ is a fixed point of T on U if and only if $\Phi u \in \hat{U}$ is a fixed point of $\hat{T}$ on $\hat{U}$.

Exercise 2.2.3. Continuing in the setting of Exercise 2.2.2, let $u^* \in U$ be a fixed point of T and let u be any point in U. Show, in addition, that $\lim_{k\to\infty} T^k u = u^*$ if and only if $\lim_{k\to\infty} \hat{T}^k \Phi u = \Phi u^*$.

From the preceding exercises we can state the following useful result:

Proposition 2.2.1. *If (U,T) and $(\hat{U},\hat{T})$ are topologically conjugate, then (U,T) is globally stable if and only if $(\hat{U},\hat{T})$ is globally stable. The unique fixed points $u^* \in U$ and $\hat{u}^* \in \hat{U}$ satisfy $\hat{u}^* = \Phi u^*$.*

2.2.2 Local Stability

In §1.2.3.2 we investigated global stability, which is relatively strict. Here we introduce local stability and provide a standard sufficient condition in the case where the map is smooth.

Let U be a subset of $\mathbb{R}^n$ and let T be a self-map on U. A fixed point u^* of T in U is called **locally stable** for the dynamical system (U,T) if there exists an open set $O \subset U$ such that $u^* \in O$ and $T^k u \to u^*$ as $k \to \infty$ for every $u \in O$. In other words, the domain of attraction for u^* contains an open neighborhood of u^*.

Example 2.2.4. Recalling Figure 1.9 on page 31, the fixed point k^* of self-map g on $\mathbb{R}_+$ is locally stable, since sequences generated from all nearby initial conditions converge to k^* under iteration by g. We verify this below.

Exercise 2.2.4. Returning to the setting of Exercise 2.2.2, let (U,T) and $(\hat{U},\hat{T})$ be topologically conjugate and let u^* be a fixed point of T in U. Show that u^* is locally stable for (U,T) if and only if Φu^* is locally stable for $(\hat{U},\hat{T})$.

One way to verify the claim in Example 2.2.4 is to show that $|g'(k^*) < 1|$, which implies that the first-order linear approximation at k^*, given by

$$\hat{g}(k) := g(k^*) + g'(k^*)(k - k^*) := k^* + g'(k^*)(k - k^*),$$

is a contraction of modulus $|g'(k^*)|$. Since k^* is clearly a fixed point, all iterations generated by the approximation $\hat{g}$ converge to k^*. Moreover, since g and g' are similar in a neighborhood of k^*, the same is true for iterates of g starting close to k^*.

The next theorem formalizes this argument, while extending it to multiple dimensions. In stating the theorem, we take T to be a self-map on U with fixed point u^* in U and assume that T is continuously differentiable on U. We recall that the **Jacobian** of T at $u \in U$ is

$$J_T(u) := \begin{pmatrix} \frac{\partial T_1}{\partial u_1}(u) & \cdots & \frac{\partial T_1}{\partial u_n}(u) \\ & \cdots & \\ \frac{\partial T_n}{\partial u_1}(u) & \cdots & \frac{\partial T_n}{\partial u_n}(u) \end{pmatrix} \quad \text{where} \quad Tu = \begin{pmatrix} T_1 u \\ \vdots \\ T_n u \end{pmatrix}.$$

We set $\hat{T}$ to be the first-order approximation to T at u^*:

$$\hat{T}u = u^* + J_T(u^*)(u - u^*) \qquad (u \in U).$$

Theorem 2.2.2 (Hartman–Grobman)**.** *If $J_T(u^*)$ is nonsingular and contains no eigenvalues on the unit circle in $\mathbb{C}$, then there exists an open neighborhood O of u^* such that (O, T) and $(O, \hat{T})$ are topologically conjugate.*

Combining this theorem with the result of Exercise 2.2.4, we see that, under the conditions of the theorem, u^* is globally stable for (O, T), and hence locally stable for (U, T), whenever $(O, \hat{T})$ is globally stable. By the Neumann series lemma, the first-order approximation will be globally stable whenever $J_T(u^*)$ has spectral radius less than one. Thus, we have

Corollary 2.2.3. *Under the conditions of Theorem 2.2.2, the fixed point u^* is locally stable whenever $r(J_T(u^*)) < 1$.*

2.2.3 Convergence Rates

One key issue when comparing fixed point computation strategies is relative rates of convergence. In what follows, given some norm $\|\cdot\|$ on $\mathbb{R}^n$, we say that sequence $(u_k)_{k\geqslant 0} \subset \mathbb{R}^n$ converges to $u^* \in \mathbb{R}^n$ **at rate at least** q if $q \geqslant 1$ and, for some $\beta \in (0, \infty)$ and $N \in \mathbb{N}$, we have

$$\|u_{k+1} - u^*\| \leqslant \beta \|u_k - u^*\|^q \quad \text{for all } k \geqslant N.$$

If, in addition,

$$\limsup_{k\to\infty} \frac{\|u_{k+1} - u^*\|}{\|u_k - u^*\|^q} = \beta$$

then we say that convergence occurs **at rate** q. If $q = 2$ then we say that convergence is (at least) **quadratic**. If $q = 1$ and $\beta < 1$, then we say that convergence is (at least) **linear**. Note that, in many sources, "at rate q" is expressed as **Q-order** q.

Example 2.2.5. Let T be a contraction of modulus λ on closed set $U \subset \mathbb{R}^n$. If u^* is the unique fixed point of T in U and $u_k := T^k u_0$, then (u_k) converges at least linearly to u^*, since $\|u_{k+1} - u^*\| = \|Tu_k - Tu^*\| \leqslant \lambda \|u_k - u^*\|$.

Orders of convergence are studied in the neighborhood of zero, implying that higher orders are faster. For example, suppose $\varepsilon_k := \|u_k - u^*\|$ is the size of the error and u_k converges to u^* quadratically. If, say, $\varepsilon_k = 10^{-5}$, then $\varepsilon_{k+1} \approx \beta 10^{-10}$. Provided that β is not large, the number of accurate digits roughly doubles at each step.

Successive approximation of fixed points typically converges at a linear rate. To see this in one dimension, try the following exercise.

Exercise 2.2.5. Let $T\colon U \to U$ where T is twice continuously differentiable and U is an open interval in $\mathbb{R}$. Suppose that T has a fixed point $u^* \in U$ and $u_k := T^k u_0$ converges to u^* as $k \to \infty$. Prove that the rate of convergence is linear whenever $0 < |T'u^*| < 1$. In completing the proof, you might find it helpful to use the fact that, by a second order Taylor expansion, there is a $v \in (u_k, u^*)$ such that

$$Tu_k = u^* + T'u^*(u_k - u^*) + \frac{T''v}{2}(u_k - u^*)^2. \tag{2.5}$$

(The assumption $0 < |T'u^*| < 1$ in Exercise 2.2.5 is a mild one. For example, given the convergence of successive approximation to the fixed point, we expect $|T'u^*| < 1$, since this inequality implies that u^* is locally stable.)

2.2.4 Gradient-Based Methods

While successive approximation always converges when global stability holds, faster algorithms can often be obtained by leveraging extra information, such as gradients. One particularly useful gradient-based technique is Newton's method. We have a particular interest in Newton's method because it relates to one of the core algorithms for solving dynamic programs (as will be discussed in §6.1.3.2).

Note that, while Newton's method is usually used to solve for roots of a given function, the discussion below uses a modified version adapted to the problem of finding fixed points.

2.2.4.1 Newton Fixed Point Iteration

To illustrate the method, suppose first that T is a differentiable self-map on an open set $U \subset \mathbb{R}^n$ and that our aim is to find a fixed point of T. Our plan is to start with a guess u_0 of the fixed point and then update it to u_1. To do this we use the first-order approximation $\hat{T}$ of T around u_0 and solve for the fixed point of $\hat{T}$—which we can do exactly since $\hat{T}$ is linear. We take this new point as u_1 and then continue.

If T is one-dimensional then $\hat{T}u := Tu_0 + T'u_0(u_1 - u_0)$. For $n > 1$ we replace $T'u_0$ with the Jacobian of T at u_0, which we write as $J_T(u_0)$. We then solve $\hat{T}u_1 = u_1$ for u_1,

Figure 2.9: The first step of Newton's method applied to T

which gives

$$u_1 = (I - J_T(u_0))^{-1}(Tu_0 - J_T(u_0)u_0) \qquad (I \text{ is the } n \times n \text{ identity}).$$

Figure 2.9 shows u_0 and u_1 when $n = 1$ and $Tu = 1 + u/(u+1)$ and $u_0 = 0.5$. The value u_1 is the fixed point of the first-order approximation $\hat{T}$. In this case it is closer to the fixed point than u_0, as desired.

Newton's (fixed point) method continues in the same manner, from u_1 to u_2 and so on, leading to the sequence of points

$$u_{k+1} = Qu_k \quad \text{where} \quad Qu := (I - J_T(u))^{-1}(Tu - J_T(u)u) \qquad k = 0, 1, \ldots \tag{2.6}$$

Notice that we do not need to write a new solver, since the successive approximation function in Listing 4 can be applied to Q defined in (2.6).

2.2.4.2 Rates of Convergence

Figure 2.10 shows both the Newton approximation sequence and the successive approximation sequence applied to the problem of computing the fixed point k^* of the Solow–Swan model. We use two different initial conditions (top and bottom subfigures). For these initial conditions, both sequences converge but the Newton sequences approach the fixed point faster.

Figure 2.10: Newton's method applied to the Solow–Swan update rule

This fast rate of convergence can be confirmed theoretically for the Newton scheme: under mild conditions, there exists a neigborhood of the fixed point within which the Newton iterates converge quadratically. See, for example, Theorem 5.4.1 of Atkinson and Han (2005). This fast rate of convergence will be significant when we study certain dynamic programming algorithms (see §6.1.3.3).

2.2.4.3 Speed vs Robustness

When comparing numerical methods, we often observe a trade-off between speed and robustness. In essence, the reason is that speed is obtained by successfully exploiting the structure of a given problem (differentiability, convexity, monotonicity, etc.). This requires assumptions on the existence of suitable structure. Such requirements can be violated, which negatively impacts the robustness of fast methods.

Relative to other algorithms, successive approximation tends to be robust but slow. We saw one illustration of the relatively slow rate of convergence in Figure 2.10. But we can also see its relatively strong robustness properties via the same example, by inspecting Figure 2.11, which compares the update rule of successive approximation (the function g) with the update rule for Newton's method (the function Q in (2.6)). Also plotted is the dashed 45 degree line.

Figure 2.11: Robustness of successive approximation vs Newton's method

The parameterization for the model is the same as the top subfigure in Figure 1.9. As previously discussed, the shape of g implies global convergence of successive approximation. However, Q is simultaneously well-behaved near the fixed point (i.e., very flat and hence strongly contractive) and also badly behaved away from the fixed point. This illustrates the fact that Newton's method is fast but generally less robust.

2.2.4.4 Parallelization

We have discussed rates of convergence for fixed point methods. Mathematicians and computer scientists also analyze algorithms via **worst case complexity**, which measures the number of fundamental operations (e.g., addition and multiplication of floating point numbers) when the algorithm acts on data that is least favorable for high performance. One of the reasons these measures are viewed as attractive is because they are independent of the software and hardware platforms on which the algorithms are implemented.

At the same time, varying software and hardware can make an enormous difference, not just to the absolute performance of algorithms but also to the *relative* performance. For example, while a single update step in successive approximation can often be partially parallelized, the nature of the algorithm is inherently serial, in the sense that the $(k+1)$-th iterate cannot be computed until iterate k is available. Moreover,

because the rate of convergence is often slow, there can be many serial steps that are hard to parallelize over.

Newton's method is also serial to some degree, since we are just iterating with a different map (the operator Q in (2.6)). However, because it involves inverting matrices in potentially high dimensions, each step is computationally intensive. At the same time, since the rate of convergence is faster, we have a smaller number of steps. In this sense, the algorithm is less serial—it involves a smaller number of more expensive steps. Because it is less serial, Newton's method offers far more potential for parallelization. Thus, the speed gain associated with Newton's method can become extremely large when using massively parallel computer architecture.

2.2.5 Eventual Contractions

To conclude this chapter, we briefly discuss a result that extends Banach's fixed point theorem, discussed in §1.2.3.3, to multi-step contractions. To state the result we take U to be a subset of $\mathbb{R}^n$ and define a self-map T on U to be **eventually contracting** if there exists a $k \in \mathbb{N}$ and a norm $\|\cdot\|$ such that T^k is a contraction on U under $\|\cdot\|$.

Theorem 2.2.4. *If U is closed and T is eventually contracting, then T is globally stable on U.*

Exercise 2.2.6. Prove Theorem 2.2.4. [Hint: Theorem 1.2.5 is self-improving, in the sense that it implies this seemingly stronger result.]

It is helpful to recognize the connection between Theorem 2.2.4 and the Neumann series lemma. If $U = \mathbb{R}^n$ and $Tu = Au + b$ with $r(A) < 1$, then

$$\|T^k u - T^k v\|_\infty = \|A^k u - A^k v\|_\infty = \|A^k(u - v)\|_\infty \leqslant \|A^k\|_\infty \|u - v\|_\infty.$$

Since $r(A) < 1$, we can choose k such that $\|A^k\|_\infty < 1$ (see Exercise 1.2.9). Hence T is eventually contracting and Theorem 2.2.4 yields global stability. We do not need to call on the Neumann series lemma.

On one hand, eventual contractions have much wider scope than the Neumann series lemma, since they can also be applied in nonlinear settings. On the other, the Neumann series lemma is preferred when applicable, since it provides inverse and power series representations of the fixed point.

2.3 Chapter Notes

For background on elementary real analysis, the textbook by Bartle and Sherbert (2011) is excellent. More advanced textbooks on fixed points and numerical analysis include Cheney (2013) and Atkinson and Han (2005). Good background on order-theoretic fixed point methods can be found in Guo et al. (2004) and Zhang (2012). Some applications of Theorem 2.1.5 in network analysis can be found in Sargent and Stachurski (2022).

Chapter 3

Markov Dynamics

Our next task is to review Markov dynamics, which provide an essential workhorse in economics and finance. In fact almost every kind of stochastic process studied in these fields can be represented as a Markov process under a suitable choice for the state space. Moreover, well structured dynamic programs have an inherent Markov structure, related to the idea that the current state contains all information sufficient to choose the current action (see the discussion in §1.3.1.3).

3.1 Foundations

In this section, we state and discuss foundational properties of Markov models. After recalling the basic properties of nonnegative matrices and their powers, we show how these properties connect to transition probabilities and laws of motion for Markov chains.

3.1.1 Nonnegative Matrices

Our first step is to review basic properties of nonnegative matrices. The key theoretical result for this section is the Perron–Frobenius theorem.

3.1.1.1 Nonnegative Matrices and their Powers

In what follows, we call a matrix A **nonnegative** and write $A \geqslant 0$ if all the elements of A are nonnegative. We call A **positive**, and we write $A \gg 0$, if every element of A is

strictly positive. A nonnegative square matrix A is called **irreducible** if $\sum_{k\in\mathbb{N}} A^k \gg 0$. This is obviously stronger than nonnegativity but weaker than positivity. An interpretation in terms of connected networks is given in Chapter 1 of Sargent and Stachurski (2022).

Let A be $n \times n$. It is not always true that the spectral radius $r(A)$ is an eigenvalue.[1] However, when $A \geqslant 0$, we have the following:

Theorem 3.1.1 (Perron–Frobenius)**.** *If $A \geqslant 0$, then $r(A)$ is an eigenvalue of A with nonnegative, real-valued right and left eigenvectors. In particular, we can find a nonnegative, nonzero column vector e and a nonnegative, nonzero row vector ε such that*

$$Ae = r(A)e \quad \text{and} \quad \varepsilon A = r(A)\varepsilon. \tag{3.1}$$

If A is irreducible, then these eigenvectors are everywhere positive and unique. Moreover, if A is positive, then with e and ε normalized so that $\langle \varepsilon, e \rangle = 1$, we have

$$r(A)^{-t}A^t \to e\,\varepsilon \qquad (t \to \infty). \tag{3.2}$$

The convergence in (3.2) provides a sharp characterization of large powers of A. In §3.1.2, we will illustrate its significance by applying it to a model of employment and unemployment flows.

Remark 3.1.1. Note that, in general, if v is a positive real-valued eigenvector for A, then so is αv for all $\alpha > 0$. Hence the uniqueness statement in the Perron–Frobenius theorem is only up to positive multiples. It tells us that if e is the right eigenvector corresponding to $r(A)$ and $\hat{e}$ is another positive vector satisfying $A\hat{e} = r(A)\hat{e}$, then $\hat{e} = \alpha e$ for some $\alpha > 0$. A similar statement holds for the left eigenvalue ε.

Remark 3.1.2. The assumption that A is positive in the last part of the Perron–Frobenius theorem can be replaced by a weaker assumption without changing the convergence in (3.2). A complete statement and full proof of the theorem can be found in Meyer (2000).

Using the Perron–Frobenius theorem, we can provide useful bounds on the spectral radius of a nonnegative matrix. In what follows, fix $n \times n$ matrix $A = (a_{ij})$ and set

- $\operatorname{rowsum}_i(A) := \sum_j a_{ij}$ = the i-th row sum of A and
- $\operatorname{colsum}_j(A) := \sum_i a_{ij}$ = the j-th column sum of A.

[1] For example, if $A = \operatorname{diag}(-1, 0)$ then the eigenvalues of A are $\{-1, 0\}$. Hence $r(A) = |-1| = 1$, which is not an eigenvalue of A.

Lemma 3.1.2. *If $A \geqslant 0$, then*

(i) $\min_i \operatorname{rowsum}_i(A) \leqslant r(A) \leqslant \max_i \operatorname{rowsum}_i(A)$ *and*

(ii) $\min_j \operatorname{colsum}_j(A) \leqslant r(A) \leqslant \max_j \operatorname{colsum}_j(A)$.

Exercise 3.1.1. Prove Lemma 3.1.2. (Hint: Since e and ε are nonnegative and nonzero, and since eigenvectors are defined only up to nonzero multiples, you can assume that both of these vectors sum to 1.)

The next result is called a "local" spectral radius theorem. While it is similar to Gelfand's formula (page 20), it replaces the matrix norm in that result with an arbitrary vector norms. This can be more convenient, as we will see below.

Lemma 3.1.3. *Let $\|\cdot\|$ be any norm on $\mathbb{R}^n$. If A is $n \times n$, h is $n \times 1$, $A \geqslant 0$ and $h \gg 0$, then*

$$\|A^k h\|^{1/k} \to r(A) \qquad (k \to \infty). \tag{3.3}$$

Lemma 3.1.3 tells us that, eventually, for any positive h, the norm of the vector $A^k h$ grows at rate $r(A)$. A proof can be found in Krasnoselskii (1964) or Theorem B1 of Borovička and Stachurski (2020).

3.1.1.2 Stochastic Matrices

Let $\mathbb{1}$ be a column vector of ones. An $n \times n$ matrix P is called **stochastic** if

$$P \geqslant 0 \quad \text{and} \quad P\mathbb{1} = \mathbb{1}.$$

In other words, P is nonnegative and has unit row sums.

Exercise 3.1.2. Let P, Q be $n \times n$ stochastic matrices. Prove the following facts.

(i) PQ is also stochastic.

(ii) $r(P) = 1$.

(iii) There exists a row vector $\psi \in \mathbb{R}^n_+$ such that $\psi\mathbb{1} = 1$ and $\psi P = \psi$.

(iv) If P is irreducible, then the vector ψ in (iii) is everwhere positive and unique, in the sense that no other vector $\psi \in \mathbb{R}^n_+$ satisfies $\psi\mathbb{1} = 1$ and $\psi P = \psi$.

The vector ψ in part (iii) of Exercise 3.1.2 is called a **stationary distribution** for P. Such distributions play an important role in the theory of Markov chains and we discuss their interpretation and significance in §3.2.1.

Exercise 3.1.3. Given stochastic matrix P and constant $\varepsilon > 0$, prove the following result: There exists no $h \in \mathbb{R}^{\mathsf{X}}$ with $Ph \geqslant h + \varepsilon$.

3.1.2 Application: A Lake Model of Employment

In this section we illustrate the power of the Perron–Frobenius theorem by showing how it helps us analyze a model of employment and unemployment flows in a large population.

The model is sometimes called a "lake model" because there are two pools of workers: those who are currently employed and those who are currently unemployed but still seeking work. The flows between states are as follows:

- Workers exit the labor market at rate d.
- New workers enter the labor market at rate b.
- Employed workers separate from their jobs and become unemployed at rate α.
- Unemployed workers find jobs at rate λ.

We assume that all of these parameters lie in $(0, 1)$. New workers are initially unemployed.

The resulting rates of transition between the two pools are shown in Figure 3.1. For example, the rate of flow from employment to unemployment is $\alpha(1 - d)$, which equals the fraction of employed workers who remained in the labor market and separated from their jobs.

Let e_t and u_t be the number of employed and unemployed workers at time t respectively. The total population (of workers) is $n_t := e_t + u_t$. In view of the rates stated above, the number of unemployed workers evolves according to

$$u_{t+1} = (1 - d)\alpha e_t + (1 - d)(1 - \lambda)u_t + bn_t.$$

These three terms on the right correspond to the newly unemployed (due to separation), the unemployed who failed to find jobs last period, and new entrants into the labor force. The number of employed workers evolves according to

$$e_{t+1} = (1 - d)(1 - \alpha)e_t + (1 - d)\lambda u_t.$$

Evolution of the time series for u_t, e_t and n_t is illustrated in Figure 3.2. The parameters were set to $\alpha = 0.01$, $\lambda = 0.1$, $d = 0.02$, and $b = 0.025$. The initial population of

Figure 3.1: Lake model transition dynamics

unemployed and employed workers was set to $u_0 = 0.6$ and $e_0 = 1.2$ respectively. The series grow over the long run due to net population growth.

Can we say more about the dynamics of this system? For example, what long run unemployment rate should we expect? Also, do long run outcomes depend heavily on the initial conditions u_0 and e_0? Or are there some general statements we can make, which hold regardless of the initial state.

To begin to address these questions, we first organize the linear system for (e_t) and (u_t) by setting

$$x_t := \begin{pmatrix} u_t \\ e_t \end{pmatrix} \quad \text{and} \quad A := \begin{pmatrix} (1-d)(1-\lambda)+b & (1-d)\alpha+b \\ (1-d)\lambda & (1-d)(1-\alpha) \end{pmatrix}. \tag{3.4}$$

With these definitions, we can write the dynamics as $x_{t+1} = Ax_t$. As a result, $x_t = A^t x_0$, where $x_0 = (u_0 \; e_0)^\top$.

The overall growth rate of the total labor force is $g = b - d$, in the sense that $n_{t+1} = (1+g)n_t$ for all t.

Exercise 3.1.4. Confirm this claim by using the equation $x_{t+1} = Ax_t$.

Exercise 3.1.5. Prove that $r(A) = 1+g$. [Hint: Use one of the results in §3.1.1.1.]

Exercise 3.1.6. By the Perron-Frobenius theorem, $1+g$ is an eigenvalue (in fact the dominant eigenvalue) of A. Show that $\mathbb{1}^\top := (1 \; 1)$ is a left eigenvector corresponding to this eigenvalue.

Figure 3.2: Time series for e_t, u_t and n_t, (`lake_2.jl`)

Exercise 3.1.7. Prove that the unique right eigenvector $\bar{x}$ satisfying $A\bar{x} = r(A)\bar{x}$ and $\mathbb{1}^\top \bar{x} = 1$ is given by

$$\bar{x} := \begin{pmatrix} \bar{u} \\ \bar{e} \end{pmatrix} \quad \text{with} \quad \bar{u} := \frac{1 + g - (1-d)(1-\alpha)}{1 + g - (1-d)(1-\alpha) + (1-d)\lambda} \tag{3.5}$$

and $\bar{e} := 1 - \bar{u}$.

In the language of Perron–Frobenius theory, the right eigenvector $\bar{x}$ is sometimes called the **dominant eigenvector**, since it corresponds to the dominant (i.e., largest) eigenvalue $r(A)$. It is also true that this eigenvector plays an important role in determining long run outcomes. In the remainder of this section we illustrate this fact.

To begin, recall that $\alpha\bar{x}$ is also a right eigenvector corresponding to the eigenvalue $r(A)$ when $\alpha > 0$. The set $D := \{x \in \mathbb{R}^2 : x = \alpha\bar{x} \text{ for some } \alpha > 0\}$ is shown as a dashed black line in Figure 3.3. The figure also shows two time paths, each of the form $(x_t)_{t \geqslant 0} = (A^t x_0)_{t \geqslant 0}$, generated from two different initial conditions. In both cases, we see that both paths converge to D over time. The figure suggests that all paths share strong similarities in the long run, with those similarities determined by the dominant eigenvector $\bar{x}$.

To see why this is so, we return (3.2) from to the Perron–Frobenius theorem, which

Figure 3.3: Time paths $x_t = A^t x_0$ for two choices of x_0 (`lake_1.jl`)

tells us, since $A \gg 0$, we have

$$A^t \approx r(A)^t \cdot \bar{x}\mathbb{1}^\top = (1+g)^t \begin{pmatrix} \bar{u} & \bar{u} \\ \bar{e} & \bar{e} \end{pmatrix} \quad \text{for large } t.$$

As a result, for any initial condition $x_0 = (u_0 \; e_0)^\top$, we have

$$A^t x_0 \approx (1+g)^t \begin{pmatrix} \bar{u} & \bar{u} \\ \bar{e} & \bar{e} \end{pmatrix} \begin{pmatrix} u_0 \\ e_0 \end{pmatrix} = (1+g)^t (u_0 + e_0) \begin{pmatrix} \bar{u} \\ \bar{e} \end{pmatrix} = n_t \bar{x},$$

where $n_t = (1+g)^t n_0$ and $n_0 = u_0 + e_0$. This says that, regardless of the initial condition, the state x_t scales along $\bar{x}$ at the rate of population growth. This is precisely what we saw in Figure 3.3.

We can give an additional interpretation to the components $\bar{u}$ and $\bar{e}$ of $\bar{x}$. Since n_t is the size of the workforce at time t, the rate of unemployment is u_t/n_t. As just shown, for large t this is close to $(n_t\bar{u})/n_t = \bar{u}$. Hence $\bar{u}$ is the long term rate of unemployment along the stable growth path. Similarly, the other component $\bar{e}$ of the dominant eigenvector is the long run employment rate for this economy.

In summary, the dominant eigenvector provides with both the long-run rate of unemployment and the stable growth path, to which all trajectories with positive initial conditions converge over time.

Remark 3.1.3. A more careful analysis of this problem would require us to think carefully about how the underlying rates α, λ, b and d are determined. For the hiring rate λ, we could use the job search model to fix the rate at which workers are matched to jobs. In particular, with w^* as the reservation wage, we could set

$$\lambda = \mathbb{P}\{w_t \geqslant w^*\} = \sum_{w \in \mathsf{W}} \varphi(\mathbb{1}\{w \geqslant w^*\}).$$

Doing so would allow us to study the crucial rate λ in terms of fundamental primitives, such as unemployment compensation and impatience of individual agents.

3.1.3 Markov Chains

In this section we define Markov chains and discuss some fundamental properties.

3.1.3.1 Defining Markov Chains

Let X be a finite set with elements $x_1, \ldots, x_n$. We will consider random processes $(X_t)_{t \geqslant 0}$ taking values in X and, in this setting, X is called the **state space** of the process. Our particular interest is Markov chains, each one of which will be generated by some stochastic matrix P. In particular, the element P_{ij} gives the probability of the chain moving from x_i to x_j.

In what follows, the ideas are clearer if we write $x, x', \ldots$ for arbitrary elements of X and $P(x, x')$ for the probability of moving from x to x'. To formalizes this notation, we note that each stochastic $n \times n$ matrix $P = (P_{ij})$ can be identified with a function P on $\mathsf{X} \times \mathsf{X}$ via $P(x_i, x_j) := P_{ij}$. This map is obviously one-to-one, and the resulting function P on $\mathsf{X} \times \mathsf{X}$ obeys

$$P \geqslant 0 \quad \text{and} \quad \sum_{x' \in \mathsf{X}} P(x, x') = 1 \text{ for all } x \in \mathsf{X}. \tag{3.6}$$

In view of the one-to-one correspondence, we will call any $P \in \mathbb{R}^{\mathsf{X} \times \mathsf{X}}$ satisfying (3.6) a **stochastic matrix** on X. The spectral radius of such a function is defined as the spectral radius of the corresponding matrix, and so on.

The set of **distributions** on X is written as $\mathscr{D}(\mathsf{X})$ and contains all $\varphi \in \mathbb{R}_+^{\mathsf{X}}$ with $\sum_{x \in \mathsf{X}} \varphi(x) = 1$. With this notation, (3.6) can also be written as

$$P(x, \cdot) \in \mathscr{D}(\mathsf{X}) \quad \text{for all } x \in \mathsf{X}.$$

Since we can identify any $f \in \mathbb{R}^{\mathsf{X}}$ with a corresponding vector in $\mathbb{R}^n$ (see page 16), the set $\mathscr{D}(\mathsf{X})$ can also be thought of as a subset of $\mathbb{R}^n$. This set of vectors (i.e., the nonnegative vectors that sum to unity) is sometimes called the **unit simplex**. In matrix expressions, we view distributions *as row vectors*. This convention will simplify notation in what follows.

Let $(X_t)_{t \geqslant 0}$ be a sequence of random variables taking values in X. We say that (X_t) is a **Markov chain** on X if there exists a stochastic matrix P on X such that

$$\mathbb{P}\{X_{t+1} = x' \mid X_0, X_1, \ldots, X_t\} = P(X_t, x') \quad \text{for all} \quad t \geqslant 0,\ x' \in \mathsf{X}. \tag{3.7}$$

In this context, P is called the **transition matrix** of the Markov chain.

To simplify terminology, we also call an X-valued random process $(X_t)_{t \geqslant 0}$ **P-Markov** when it satisfies (3.7). We call either X_0 or its distribution ψ_0 the **initial condition** of (X_t) depending on context.

The definition of a Markov chain says two things:

(i) When updating to X_{t+1} from X_t, earlier states are not required.

(ii) The matrix P encodes all of the information required to perform the update, given the current state X_t.

One way to think about Markov chains is algorithmically: Let P be a stochastic matrix and let ψ_0 be an element of $\mathscr{D}(\mathsf{X})$. Now generate (X_t) via Algorithm 2. The resulting sequence is P-Markov with initial condition ψ_0.

Algorithm 2: Generation of P-Markov (X_t) with initial condition ψ_0

```
t ← 0
X_t ← a draw from ψ_0
while t < ∞ do
    X_{t+1} ← a draw from the distribution P(X_t, ·)
    t ← t + 1
end
```

3.1.3.2 Application: S-s Dynamics

As an example, let us consider a firm whose inventory behavior follows S-s dynamics, meaning that the firm waits until its inventory of a given product falls below some level $s > 0$ and then replenishes by buying some fixed amount. This kind of behavior is reasonable if ordering inventory involves a fixed cost. (Later, in §6.2.1, we will show

how S-s behavior arises naturally in a model where the firm chooses its inventory path to maximize its present value.)

To implement S-s dynamics, we suppose that a firm's inventory $(X_t)_{t \geqslant 0}$ of a given product obeys

$$X_{t+1} = \max\{X_t - D_{t+1}, 0\} + S\mathbb{1}\{X_t \leqslant s\},$$

where

- $(D_t)_{t \geqslant 1}$ is an exogenous IID demand process with $D_t \stackrel{d}{=} \varphi \in \mathscr{D}(\mathbb{Z}_+)$ for all t and
- S is the amount of stock ordered every time that inventory falls below s.

For the distribution φ of the demand process we take the geometric distribution, so that $\varphi(d) = \mathbb{P}\{D_t = d\} = p(1-p)^d$ for $d \in \mathbb{Z}_+$.

Exercise 3.1.8. A suitable state space for this model is $\mathsf{X} := \{0, \dots, S + s\}$, since

$$X_t \in \mathsf{X} \implies \mathbb{P}\{X_{t+1} \in \mathsf{X}\} = 1$$

for all t. Verify this claim.

If we define

$$h(x, d) = \max\{x - d, 0\} + S\mathbb{1}\{x \leqslant s\},$$

so that $X_{t+1} = h(X_t, D_{t+1})$ for all t, then the transition matrix can be expressed as

$$P(x, x') = \mathbb{P}\{h(x, D_{t+1}) = x'\} = \sum_{d \geqslant 0} \mathbb{1}\{h(x, d) = x'\}\varphi(d)$$

for $(x, x') \in \mathsf{X} \times \mathsf{X}$. In calculations we can truncate the infinite sum and still obtain a good approximation to P.

Listing 7 provides Julia code that implements the model, simulates inventory paths and computes other objects of interest. Since the state space $\mathsf{X} = \{x_1, \dots, x_n\}$ corresponds to $\{0, \dots, S + s\}$, we have $x_i = i - 1$. This convention is used when computing `P[i, j]`, which corresponds to $P(x_i, x_j)$. The code in the listing is used to produce the simulation of inventories in Figure 3.4.

The function `compute_mc` returns an instance of a `MarkovChain` object, which can store both the state X and the transition probabilities. The `QuantEcon.jl` library defines this data type and provides functions that act on it, in order to facilitate simulation of Markov chains, computation of stationary distributions and other related tasks.

```julia
using Distributions, IterTools, QuantEcon

function create_inventory_model(; S=100,  # Order size
                                  s=10,   # Order threshold
                                  p=0.4)  # Demand parameter
    ϕ = Geometric(p)
    h(x, d) = max(x - d, 0) + S*(x <= s)
    return (; S, s, p, ϕ, h)
end

"Simulate the inventory process."
function sim_inventories(model; ts_length=200)
    (; S, s, p, ϕ, h) = model
    X = Vector{Int32}(undef, ts_length)
    X[1] = S  # Initial condition
    for t in 1:(ts_length-1)
        X[t+1] = h(X[t], rand(ϕ))
    end
    return X
end

"Compute the transition probabilities and state."
function compute_mc(model; d_max=100)
    (; S, s, p, ϕ, h) = model
    n = S + s + 1  # Size of state space
    state_vals = collect(0:(S + s))
    P = Matrix{Float64}(undef, n, n)
    for (i, j) in product(1:n, 1:n)
        P[i, j] = sum((h(i-1, d) == j-1)*pdf(ϕ, d) for d in 0:d_max)
    end
    return MarkovChain(P, state_vals)
end

"Compute the stationary distribution of the model."
function compute_stationary_dist(model)
    mc = compute_mc(model)
    return mc.state_values, stationary_distributions(mc)[1]
end
```

Listing 7: An implementation of S-s inventory dynamics (`inventory_sim.jl`)

Figure 3.4: Inventory simulation (`inventory_sim.jl`)

3.1.3.3 Higher Order Transition Matrices

Given a finite state space X, $k \geqslant 0$ and transition matrix P, let P^k is the k-th power of P. (If $k = 0$, then P^k is the identity matrix.) Since the set of stochastic matrices is closed under multiplication (Exercise 3.1.2), P^k is a stochastic matrix on X for all $k \geqslant 0$. In this context, P^k is called the **k-step transition matrix** corresponding to P. In what follows, $P^k(x, x')$ denotes the (x, x')-th element of P^k.

The k-step transition matrix has the following interpretation: If (X_t) is P-Markov, then, for any $t, k \in \mathbb{Z}_+$ and $x, x' \in \mathsf{X}$,

$$P^k(x, x') = \mathbb{P}\{X_{t+k} = x' \,|\, X_t = x\}. \tag{3.8}$$

In other words, P^k provides the k-step transition probabilities for the P-Markov chain (X_t), as suggested by its name.

This claim can be verified by induction. Fix $t \geqslant 0$. The claim is obviously true when $k = 0, 1$. Suppose the claim is also true at k and now consider the case $k + 1$. By the law of total probability, for given $x, x' \in \mathsf{X}$, we have

$$\mathbb{P}\{X_{t+k+1} = x' \,|\, X_t = x\} = \sum_z \mathbb{P}\{X_{t+k+1} = x' \,|\, X_{t+k} = z\}\mathbb{P}\{X_{t+k} = z \,|\, X_t = x\}.$$

The induction hypothesis allows us to use (3.8) at k, so the last equation becomes

$$\mathbb{P}\{X_{t+k+1} = x' \mid X_t = x\} = \sum_z P^k(x,z)P(z,x') = P^{k+1}(x,x').$$

The law (3.8) is now verified at $k+1$, completing our proof by induction.

We can now give the following useful characterization of irreducibility:

Lemma 3.1.4. *Let P be a stochastic matrix on X. The following statements are equivalent:*

(i) *P is irreducible.*

(ii) *For any P-chain (X_t) and any $x, x' \in \mathsf{X}$, there exists a $k \geqslant 0$ such that*

$$\mathbb{P}\{X_k = x' \mid X_0 = x\} > 0.$$

In other words, irreducibility of P is equivalent to the statement that P-chains eventually visit any state from any other state with positive probability.

Proof of Lemma 3.1.4. Let P be a stochastic matrix on X. Recall that P is irreducible if and only if $\sum_{k\geqslant 0} P^k \gg 0$. This is equivalent to the statement that, for each $(x,x') \in \mathsf{X}\times\mathsf{X}$, there exists a $k \geqslant 0$ such that $P^k(x,x') > 0$, which is in turn equivalent to part (ii) of Lemma 3.1.4. □

Exercise 3.1.9. Using Lemma 3.1.4, prove that the stochastic matrix associated with the S-s inventory dynamics in §3.1.3.2 is irreducible.

Several libraries have code for testing irreducibility. For Julia, `QuantEcon.jl` is one such package. See Listing 8 for an example of a call to this functionality. In this case, irreducibility fails because state 2 is an **absorbing state**. Once entered, the probability of ever leaving this state is zero. (A subset Y of X with this property is called an **absorbing set**.)

3.2 Dynamics

In this section we review some aspects of Markov dynamics, including stationarity, ergodicity and conditional expectations.

```
using QuantEcon
P = [0.1 0.9;
     0.0 1.0]
mc = MarkovChain(P)
print(is_irreducible(mc))
```

Listing 8: Testing irreducibility (`is_irreducible.jl`)

3.2.1 Stationarity and Ergodicity

Fix a stochastic matrix P on X and let (X_t) be a P-chain. Let ψ_t be the distribution of X_t for all t. For each $t \geqslant 0$, these distributions obey the recursion

$$\psi_{t+1}(x') = \sum_{x \in \mathsf{X}} P(x, x')\psi_t(x) \quad \text{for all } x \in \mathsf{X}. \tag{3.9}$$

This just states that

$$\mathbb{P}\{X_{t+1} = x'\} = \sum_{x \in \mathsf{X}} \mathbb{P}\{X_{t+1} = x' \mid X_t = x\}\mathbb{P}\{X_t = x\}$$

for all $x, x' \in \mathsf{X}$, which is true by the law of total probability. Using matrix algebra, with each ψ_t regarded as a row vector, (3.9) can also be written as $\psi_{t+1} = \psi_t P$. Iterating on this equation, we get $\psi_t = \psi_0 P^t$ for all t. In summary,

$$(X_t)_{t \geqslant 0} \text{ is } P\text{-Markov with } X_0 \stackrel{d}{=} \psi_0 \implies X_t \stackrel{d}{=} \psi_0 P^t \text{ for all } t \geqslant 0. \tag{3.10}$$

Note 3.2.1. The fundamental relation $\psi_{t+1} = \psi_t P$ and the result (3.10) require that each ψ_t is a row vector. In what follows, we always treat marginal distributions of $(X_t)_{t \geqslant 0}$ as row vectors.

Consistent with our definition of stationary distributions in §3.1.1.2, a distribution $\psi^* \in \mathscr{D}(\mathsf{X})$ is called **stationary** for P if

$$\sum_{x \in \mathsf{X}} P(x, x')\psi^*(x) = \psi^*(x') \quad \text{for all } x \in \mathsf{X}.$$

Since distributions are regarded as row vectors, we can write this expression more simply as $\psi^* P = \psi^*$. In view of (3.9), if ψ^* is stationary and X_t has distribution ψ^*, then so does X_{t+1}, and hence X_{t+k} for all $k \geqslant 1$.

We saw in Exercise 3.1.2 that every stochastic matrix on X has at least one stationary distribution, and that uniqueness in $\mathscr{D}(\mathsf{X})$ holds whenever P is irreducible. The next result is also fundamental.

Theorem 3.2.1. *If P is irreducible with stationary distribution ψ^*, then, for any P-Markov chain (X_t) and any $x \in \mathsf{X}$, we have*

$$\mathbb{P}\left\{\lim_{k\to\infty} \frac{1}{k}\sum_{t=0}^{k-1} \mathbb{1}\{X_t = x\} = \psi^*(x)\right\} = 1. \tag{3.11}$$

A proof of (3.11) can be found in Brémaud (2020).

Property (3.11) tells us that, with probability one (i.e., for almost every P-Markov chain that we generate), the fraction of time that the chain spends in any given state is, in the limit, equal to the probability assigned to that state by the stationary distribution. Markov chains with this property are sometimes said to be **ergodic**.

Since the S-s inventory model from §3.1.3.2 is irreducible, the ergodicity result from Theorem 3.2.1 applies. In particular, the model has only one stationary distribution ψ^* in $\mathscr{D}(\mathsf{X})$, where $\mathsf{X} = \{0, \dots, S + s\}$, and (3.11) is valid whenever (X_t) is generated by the model. Figure 3.5 illustrates this by plotting both the stationary distribution ψ^* (which is computed using the code in Listing 7), and the value $m(y) := \frac{1}{k}\sum_{t=0}^{k-1} \mathbb{1}\{X_t = y\}$ at each $y \in \mathsf{X}$. The value of k is set to $1,000,000$. As predicted by the theorem, the fraction of time spent by the chain in each state is close to the probability assigned by ψ^*.

Exercise 3.2.1. Let (X_t) be P-Markov on X with $X_0 \stackrel{d}{=} \psi_0$. Show that

$$\mathbb{E}h(X_t) = \psi_0 P^t h = \langle \psi_0 P^t, h \rangle \quad \text{for all } t \in \mathbb{N} \text{ and } h \in \mathbb{R}^{\mathsf{X}}. \tag{3.12}$$

3.2.1.1 Application: Day Laborer

Suppose that a day laborer is either unemployed ($X_t = 1$) or employed ($X_t = 2$) in each period. In state 1 he is hired with probability $\alpha \in (0, 1)$. In state 2 he is fired with probability $\beta \in (0, 1)$. The corresponding state space and transition matrix are

$$\mathsf{X} = \{1, 2\} \quad \text{and} \quad P = \begin{pmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{pmatrix}. \tag{3.13}$$

Figure 3.5: Ergodicity (`inventory_sim.jl`)

Listing 9 provides a function to update from X_t to X_{t+1}, using the fact that `rand()` generates a draw from the uniform distribution on $[0, 1)$.

Exercise 3.2.2. Explain why Listing 9 updates the current state according to the probabilities in P.

Exercise 3.2.3. P is positive it must be irreducible, so P has the unique stationary distribution in $\psi^* \in \mathscr{D}(\mathsf{X})$. Show that ψ^* is given by

$$\psi^* = \frac{1}{\alpha + \beta} \begin{pmatrix} \beta & \alpha \end{pmatrix}. \tag{3.14}$$

It is also true that $\psi P^t \to \psi^*$ as $t \to \infty$ for any $\psi \in \mathscr{D}(\mathsf{X})$. In other words, the operator P when understood as the mapping $\psi \mapsto \psi P$, is globally stable on $\mathscr{D}(\mathsf{X})$

Exercise 3.2.4. Prove this using the Perron–Frobenius theorem. (More generally, show that this global stability result holds for any positive stochastic matrix P.)

Exercise 3.2.5. Fix $\alpha = 0.3$ and $\beta = 0.2$. Compute the sequence (ψP^t) for different choices of ψ and confirm that your results are consistent with the claim that $\psi P^t \to \psi^*$ as $t \to \infty$ for any $\psi \in \mathscr{D}(\mathsf{X})$.

```
function create_laborer_model(; α=0.3, β=0.2)
    return (; α, β)
end

function laborer_update(x, model)  # update X from t to t+1
    (; α, β) = model
    if x == 1
        x′ = rand() < α ? 2 : 1
    else
        x′ = rand() < β ? 1 : 2
    end
    return x′
end
```

Listing 9: Updating the state of the day laborer (`laborer_sim.jl`)

Exercise 3.2.6. Since P is irreducible, ergodicity holds. Simulate a long realization Markov of a P-Markov chain from an arbitrary initial condition and confirm that your results are consistent with (3.11).

3.2.2 Approximation

It can be helpful to reduce continuous state Markov models to finite state models in order to simplify numerical calculations. The most common targets for this form of discretization are the **linear Gaussian AR(1)** models, where $(X_t)_{t \geqslant 0}$ evolves in $\mathbb{R}$ according to

$$X_{t+1} = \rho X_t + b + \nu \varepsilon_{t+1}, \quad (\varepsilon_t) \overset{\text{IID}}{\sim} N(0,1). \tag{3.15}$$

Here we discuss one technique for discretizing (3.15), often called **Tauchen's method**, and use it to illustrate concepts related to stationarity.[2]

We assume throughout that $|\rho| < 1$. Under this assumption, (3.15) has a unique **stationary distribution** ψ^* given by

$$\psi^* = N(\mu_x, \sigma_x^2) \quad \text{with} \quad \mu_x := \frac{b}{1-\rho} \quad \text{and} \quad \sigma_x^2 := \frac{\nu^2}{1-\rho^2}.$$

[2]We feature Tauchen's method because of its simplicity. At the same time, we acknowledge that Tauchen's method is limited and its performance can be sub-optimal in some cases. For a more general discretization method and a survey of the literature, see Farmer and Toda (2017).

This means that ψ^* has the following property:

$$X_t \stackrel{d}{=} \psi^* \text{ and } X_{t+1} = \rho X_t + b + \nu\varepsilon_{t+1} \text{ implies } X_{t+1} \stackrel{d}{=} \psi^*.$$

Exercise 3.2.7. Suppose that $X_t \stackrel{d}{=} \psi^*$, $\varepsilon_{t+1} \stackrel{d}{=} N(0,1)$ and X_t and ε_{t+1} are independent. Prove that $\rho X_t + b + \nu\varepsilon_{t+1}$ has distribution ψ^*. Is this always true if we drop the independence assumption made above?

When $|\rho| < 1$, this model is ergodic in a similar sense to (3.11) on page 81: on average, realizations of the process spend most of their time in regions of the state where the stationary distribution puts high probability mass. (You can check this via simulations if you wish.) Hence, in the discretization that follows, the discrete state space will be centered in this area.

Exercise 3.2.8. Set $b = 0$ in (3.15) and let F be the $N(0,\nu^2)$ cdf. Show that

$$\mathbb{P}\{t - \delta < X_{t+1} \leqslant t + \delta \,|\, X_t = x\} = F(t - \rho x + \delta) - F(t - \rho x - \delta) \tag{3.16}$$

for all $\delta, t \in \mathbb{R}$.

We start with the case $b = 0$. As a first step, we choose n as the number of states for the discrete approximation and m as an integer that parameterizes the width of the state space. Then we create a state space $\mathsf{X} := \{x_1, \ldots, x_n\} \subset \mathbb{R}$ as a linear grid that brackets the stationary mean on both sides by m standard deviations:

- set $x_1 = -m\,\sigma_x$,
- set $x_n = m\,\sigma_x$ and
- set $x_{i+1} = x_i + s$ where $s = (x_n - x_1)/(n-1)$ and i in $[n-1]$.

The next step is to create an $n \times n$ matrix P computed to approximate the dynamics in (3.15). For $i, j \in [n]$,

(i) if $j = 1$, then set $P(x_i, x_j) = F(x_1 - \rho x_i + s/2)$.

(ii) If $j = n$, then set $P(x_i, x_j) = 1 - F(x_n - \rho x_i - s/2)$.

(iii) Otherwise, set $P(x_i, x_j) = F(x_j - \rho x_i + s/2) - F(x_j - \rho x_i - s/2)$.

The first two are boundary rules and the third applies Exercise 3.2.8.

Exercise 3.2.9. Prove that $\sum_{j=1}^n P(x_i, x_j) = 1$ for all $i \in [n]$.

Figure 3.6: Comparison of $\psi^* = N(\mu_x, \sigma_x^2)$ and its discrete approximant

Finally, if $b \neq 0$, then we shift the state space to center it on the mean μ_x of the stationary distribution $N(\mu_x, \sigma_x^2)$. This is done by replacing x_i with $x_i + \mu_x$ for each i.

Julia routines for computing X and P can be found in the library QuantEcon.jl.

Figure 3.6 compares the continuous stationary distribution ψ^* and the unique stationary distribution of the discrete approximation when X and P are constructed as above, under the parameterization $\rho = 0.9$, $b = 0.0$, $\nu = 1.0$. The discretization parameters were set to $n = 15$ and $m = 3$.

3.2.3 Expectations

In this section we discuss how to take conditional expectations with respect to Markov chains. The theory will be essential for the study of finite MDPs, since, in these models, lifetime rewards are expectations of flow reward functions with respect to Markov chains.

3.2.3.1 Conditional Expectations

Let P be any stochastic matrix on X. For each $h \in \mathbb{R}^{\mathsf{X}}$, we define

$$(Ph)(x) = \sum_{x' \in \mathsf{X}} h(x')P(x, x') \qquad (x \in \mathsf{X}). \tag{3.17}$$

Noting that $P(x, \cdot)$ is the distribution of X_{t+1} given $X_t = x$, we can equivalently write

$$(Ph)(x) = \mathbb{E}[h(X_{t+1}) \,|\, X_t = x], \tag{3.18}$$

where (X_t) is any P-Markov chain on X. In terms of matrix algebra, viewing h has an $n \times 1$ column vector, the expression $(Ph)(x)$ is one element of the vector Ph obtained by premultiplying h by P.

The interpretation in (3.18) extends to powers of P. In particular, we have

$$(P^k h)(x) = \sum_{x' \in \mathsf{X}} h(x') P^k(x, x') = \mathbb{E}[h(X_{t+k}) \mid X_t = x]. \tag{3.19}$$

Exercise 3.2.10. Show that

(i) Every constant function $h \in \mathbb{R}^{\mathsf{X}}$ is a fixed point of P (i.e., $Ph = h$).

(ii) $\max_x |Ph(x)| \leqslant \max_x |h(x)|$ for all $h \in \mathbb{R}^{\mathsf{X}}$.

3.2.3.2 The Law of Iterated Expectations

The **law of iterated expectations** appears time and again in dynamic modeling, particularly in economics and finance. One common version of the law is that if X and Y are two random variables, then $\mathbb{E}[\mathbb{E}[Y \mid X]] = \mathbb{E}[Y]$. Let's show this in the Markov case when predicting future values.

Let (X_t) be P-Markov with $X_0 \stackrel{d}{=} \psi_0$. Fix $t, k \in \mathbb{N}$. Set $\mathbb{E}_t := \mathbb{E}[\cdot \mid X_t]$. We claim that

$$\mathbb{E}[\mathbb{E}_t[h(X_{t+k})]] = \mathbb{E}[h(X_{t+k})] \quad \text{for any } h \in \mathbb{R}^{\mathsf{X}}. \tag{3.20}$$

To see this, recall that $\mathbb{E}[h(X_{t+k}) \mid X_t = x] = (P^k h)(x)$. Hence $\mathbb{E}[h(X_{t+k}) \mid X_t] = (P^k h)(X_t)$. Therefore,

$$\mathbb{E}[\mathbb{E}_t[h(X_{t+k})]] = \mathbb{E}[(P^k h)(X_t)] = \sum_{x'} (P^k h)(x') \psi_t(x') = \sum_{x'} (P^k h)(x') (\psi_0 P^t)(x').$$

Since $\psi_0 P^t$ is a row vector, we can write the last expression as

$$\psi_0 P^t P^k h = \psi_0 P^{t+k} h = \psi_{t+k} h = \mathbb{E} h(X_{t+k}).$$

Hence (3.20) holds.

3.2.4 Monotonicity

In this section we connect Markov chains to order theory via stochastic dominance. These ideas will have many applications in what follows.

3.2.4.1 Increasing Functions

Let X be a finite set partially ordered by $\preceq$. In what follows, $i\mathbb{R}^{\mathsf{X}}$ is the set of increasing functions in $\mathbb{R}^{\mathsf{X}}$. Thus, for $h \in \mathbb{R}^{\mathsf{X}}$,

$$h \in i\mathbb{R}^{\mathsf{X}} \quad \iff \quad x, y \in \mathsf{X} \text{ and } x \preceq y \text{ implies } h(x) \leqslant h(y).$$

Example 3.2.1. If $\mathsf{X} = \{1, \ldots, n\}$ and $\preceq$ is the usual order $\leqslant$ on $\mathbb{R}$, then $x \mapsto 2x$ and $x \mapsto \mathbb{1}\{2 \leqslant x\}$ are in $i\mathbb{R}^{\mathsf{X}}$ but $x \mapsto -x$ and $x \mapsto \mathbb{1}\{x \leqslant 2\}$ are not.

The next exercise shows that an increasing function can be represented as the sum of increasing binary functions. This fact will be valuable when we characterize orders over distributions, in §3.2.4.2.

Exercise 3.2.11. Let $\mathsf{X} = \{x_1, \ldots, x_n\}$ where $x_k \preceq x_{k+1}$ for all k. Show that, for any $u \in i\mathbb{R}^{\mathsf{X}}$, there exist $s_1, \ldots, s_n$ in $\mathbb{R}_+$ such that $u(x) = \sum_{k=1}^{n} s_k \mathbb{1}\{x \geqslant x_k\}$ for all $x \in \mathsf{X}$.

3.2.4.2 Stochastic Dominance

It is useful to have a partial order over distributions, which can tell us when one distribution is "larger" than another. One of many possible applications for such an order is as follows: we could apply our parametric monotonicity results from §2.1.3 to study what kinds of modifications to the wage offer distribution (e.g., shifts up under the stated partial order) would lead the worker in §1.3 to increase their reservation wage.

There are in fact many partial orders over distributions in the literature. In this section we consider the most important of all of these orders, which is called "first order stochastic dominance."

To start to consider stochastic dominance, let's look at an example. Recall that a random variable X is binomial $B(n, 0.5)$ if it counts the number of heads in n flips of a fair coin. Figure 3.7 shows two probability mass functions, one of distribution $\varphi \stackrel{d}{=} X \sim B(10, 0.5)$ and another of $\psi \stackrel{d}{=} Y \sim B(18, 0.5)$. Since Y counts over more flips, we expect it to take larger values, in some sense, and we also expect its distribution ψ to reflect this. But how can we make this idea precise?

The standard order over distributions, which captures this idea, is defined as follows: Given finite set X partially ordered by $\preceq$ and $\varphi, \psi \in \mathscr{D}(\mathsf{X})$, we say that ψ **stochastically dominates** φ and write $\varphi \preceq_{\mathbf{F}} \psi$ if

$$\sum_x u(x)\varphi(x) \leqslant \sum_x u(x)\psi(x) \quad \text{for every } u \text{ in } i\mathbb{R}^{\mathsf{X}} \tag{3.21}$$

Figure 3.7: Two binomial distributions

The relation $\preceq_{\mathrm{F}}$ is also called **first order stochastic dominance** to differentiate it from other forms of stochastic order.

Example 3.2.2. Consider the distributions $\varphi = B(10, 0.5)$ and $\psi = B(18, 0.5)$ defined above. For the outcome space we take $\mathsf{X} = \{0, \ldots, 18\}$. It is not hard to see that $\varphi \preceq_{\mathrm{F}} \psi$ holds. Indeed, if we take $W_1, \ldots, W_{18}$ to be IID binary random variables with $\mathbb{P}\{W_i = 1\} = 0.5$ for all i, then $X := \sum_{i=1}^{10} W_i$ has distribution φ and $Y := \sum_{i=1}^{18} W_i$ has distribution ψ. In addition, we can see that $X \leqslant Y$ with probability one (i.e., for any outcome of the draws $W_1, \ldots, W_{18}$). Hence, for any given $u \in i\mathbb{R}^{\mathsf{X}}$, we have $u(X) \leqslant u(Y)$ with probability one. Hence $\mathbb{E}u(X) \leqslant \mathbb{E}u(Y)$ holds, which is the same statement as (3.21).

One way to understand the definition of first order stochastic dominance is as follows: Suppose we have an agent whose preferences over outcomes in X are determined by a utility function $u \in \mathbb{R}^{\mathsf{X}}$. Suppose in addition that the agent prefers more to less, in the sense that $u \in i\mathbb{R}^{\mathsf{X}}$, and that the agent ranks lotteries over X according to expected utility. In other words, the agent evaluates $\varphi \in \mathscr{D}(\mathsf{X})$ according to $\sum_x u(x)\varphi(x)$. Then the agent (weakly) prefers ψ to φ whenever $\varphi \preceq_{\mathrm{F}} \psi$.

We can go one step further. Consider now the class $\mathscr{A}$ of *all* agents who (a) have preferences over outcomes in X, (b) prefer more to less, and (c) rank lotteries over X according to expected utility. Then $\varphi \preceq_{\mathrm{F}} \psi$ if and only if every agent in $\mathscr{A}$ prefers ψ to φ.

Remark 3.2.1. The last paragraph helps illustrate the significance of stochastic dominance in economics. It is standard to assume that economic agents have increasing

utility functions and use expected utility to evaluate lotteries. In such an environment, a policy maker who can engineer an upward shift in a lottery, as measured by stochastic dominance, will make all agents better off. Such a change is unambiguously welfare enhancing.

EXERCISE 3.2.12. The simplest setting in which we can study stochastic dominance is where $\mathsf{X} = \{1, 2\}$ and X is partially ordered by $\leqslant$. In this case, $\varphi \preceq_{\mathrm{F}} \psi$ if and only φ puts more mass on 1 than ψ, and, equivalently, less mass on 2. That is,

$$\varphi \preceq_{\mathrm{F}} \psi \iff \psi(1) \leqslant \varphi(1) \iff \varphi(2) \leqslant \psi(2).$$

Verify the equivalence of these statements.

There is another perspective on stochastic dominance that can be relatively intuitive. To state it, we first introduce the notation

$$G^{\varphi}(y) := \sum_{x \succeq y} \varphi(x) \qquad (\varphi \in \mathscr{D}(\mathsf{X}),\ y \in \mathsf{X}).$$

For a given distribution φ, the function G^{φ} is sometimes called the **counter** CDF (counter cumulative distribution function) of φ.

Lemma 3.2.2. *For each $\varphi, \psi \in \mathscr{D}(\mathsf{X})$, the following statements hold:*

(i) $\varphi \preceq_F \psi \implies G^{\varphi} \leqslant G^{\psi}$.

(ii) *If X is totally ordered by $\preceq$, then $G^{\varphi} \leqslant G^{\psi} \implies \varphi \preceq_F \psi$.*

The proof is given on page 269. Figure 3.8 helps to illustrate. Here $\mathsf{X} \subset \mathbb{R}$ and φ and ψ are distributions on X. We can see that $\varphi \preceq_{\mathrm{F}} \psi$ because the counter CDFs are ordered, in the sense that $G^{\varphi} \leqslant G^{\psi}$ pointwise on X.

Lemma 3.2.3. *Stochastic dominance is a partial order on $\mathscr{D}(\mathsf{X})$.*

EXERCISE 3.2.13. Prove the transitivity component of Lemma 3.2.3. That is, prove that $\preceq_{\mathrm{F}}$ is transitive on $\mathscr{D}(\mathsf{X})$.

3.2.4.3 Monotone Markov Chains

Let X be a finite set partially ordered by $\preceq$. A stochastic matrix P on $\mathsf{X} \times \mathsf{X}$ is called **monotone increasing** if

$$x, y \in \mathsf{X} \text{ and } x \preceq y \qquad \implies \qquad P(x, \cdot) \preceq_{\mathrm{F}} P(y, \cdot).$$

Figure 3.8: Visualization of $\varphi \preceq_{\mathrm{F}} \psi$

In other words, P is monotone increasing if shifting up the current state shifts up the next period state, in the sense that its distribution increases in the stochastic dominance ordering on $\mathscr{D}(\mathsf{X})$. Below, we will see that monotonicity of stochastic matrices is closely related to monotonicity in value functions in some important applications.

Monotonicity in stochastic matrices is related to positive autocorrelation. To illustrate the idea, consider the AR(1) model $X_{t+1} = \rho X_t + \sigma \varepsilon_{t+1}$ from §3.2.2 and suppose we apply Tauchen discretization, mapping the parameters ρ, σ and a discretization size n into an $n \times n$ stochastic matrix P on state space $\mathsf{X} = \{x_1, \ldots, x_n\} \subset \mathbb{R}$. If $\rho \geqslant 0$, so that positive autocorrelation holds, then P is monotone increasing.

Exercise 3.2.14. Verify this claim.

Exercise 3.2.15. In §3.2.1.1 we discussed a setting where

$$\mathsf{X} = \{1, 2\} \quad \text{and} \quad P_w = \begin{pmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{pmatrix}$$

for some $\alpha, \beta \in [0, 1]$. Show that P_w is monotone increasing if and only if $\alpha + \beta \leqslant 1$.

Exercise 3.2.16. Prove that P is monotone increasing if and only if P is invariant on $i\mathbb{R}^{\mathsf{X}}$; that is, if $h \in i\mathbb{R}^{\mathsf{X}}$ implies $Ph \in i\mathbb{R}^{\mathsf{X}}$.

EXERCISE 3.2.17. Prove: If P is monotone increasing then so is P^t for all $t \in \mathbb{N}$.

3.3 Job Search Revisited

In this section we return to the job search problem Chapter 1, aiming to drop some of the restrictive assumptions we made in that chapter. First we show how the analysis and fixed point theory extends to the case of Markov wage offers. Then we discuss how the solution gains additional structure when the stochastic matrix for Markov wage offers is monotone increasing. Finally, we will remove the unrealistic assumption that no job separation occurs.

3.3.1 Job Search with Markov State

Our first step is to allow wage draws to be correlated rather than IID and analyze optimality in this setting.

3.3.1.1 Value Function Iteration

We assume that the wage process (W_t) is P-Markov on finite set $\mathsf{W} \subset \mathbb{R}_+$, where P is a stochastic matrix. The value function v^* is defined in an analogous manner to the IID case: $v^*(w)$ is the maximum lifetime value that can be obtained when the current wage offer is w.

Just as for the IID case, the value function satisfies the Bellman equation (see (1.24) on page 31), which in the present setting states becomes

$$v^*(w) = \max\left\{\frac{w}{1-\beta},\ c + \beta \sum_{w' \in \mathsf{W}} v^*(w')P(w,w')\right\} \qquad (w \in \mathsf{W}). \tag{3.22}$$

(We will prove this claim carefully in Chapter 5.) In all of what follows we assume $\beta \in (0,1)$.

The Bellman operator corresponding to (3.22) is

$$(Tv)(w) = \max\left\{\frac{w}{1-\beta},\ c + \beta \sum_{w' \in \mathsf{W}} v(w')P(w,w')\right\} \qquad (w \in \mathsf{W}).$$

Let $V := \mathbb{R}_+^{\mathsf{W}}$ and endow V with the supremum norm, so that the distance between two elements f, g of V is measured by $\|f - g\| = \max_{w \in \mathsf{W}} |f(w) - g(w)|$.

Exercise 3.3.1. Prove that T is an order-preserving self-map on V.

Exercise 3.3.2. Prove that T is a contraction of modulus β on V.

We recommend you read the proof of the next lemma, since the same style of argument is repeated many times in the text.

Lemma 3.3.1. *The value function v^* is increasing on W whenever P is monotone increasing.*

Proof. Let iV be the increasing functions in V and suppose that P is monotone increasing. The operator T is a self-map on iV in this setting, since $v \in iV$ implies $h(w) := c + \beta \sum_{w' \in \mathsf{W}} v(w')P(w, w')$ is in iV. Hence, for such a v, both h and the stopping value function $e(w) := w/(1 - \beta)$ are in iV. It follows that $Tv = \max\{h, e\}$ is in iV.

Since iV is a closed subset of V and T is a self-map on iV, the fixed point v^* is in iV (cf., Exercise 1.2.15 on page 24). □

In view of the contraction property established in Exercise 3.3.2, we can use value function iteration to (i) solve for an approximation v to the value function and (ii) compute the v-greedy policy, which approximates the optimal policy. Code for implementing this procedure is shown in Listing 10. The definition of a v-greedy policy is analogous to that for the IID case (see (1.28) on page 34).

3.3.1.2 Continuation Values

The continuation value h^* from the IID case (defined on page 31) is now replaced by a **continuation value function**, given by

$$h^*(w) := c + \beta \sum_{w' \in \mathsf{W}} v^*(w')P(w, w') \qquad (w \in \mathsf{W}).$$

The continuation value depends on w because the current wage offer helps predict the wage offer next period, which in turn affects the value of continuing. The functions $w \mapsto w/(1 - \beta)$, h^* and v^* corresponding to the default model in Listing 10 are shown in Figure 3.9.

```julia
using QuantEcon, LinearAlgebra
include("s_approx.jl")

"Creates an instance of the job search model with Markov wages."
function create_markov_js_model(;
        n=200,       # wage grid size
        ρ=0.9,       # wage persistence
        ν=0.2,       # wage volatility
        β=0.98,      # discount factor
        c=1.0        # unemployment compensation
    )
    mc = tauchen(n, ρ, ν)
    w_vals, P = exp.(mc.state_values), mc.p
    return (; n, w_vals, P, β, c)
end

" The Bellman operator Tv = max{e, c + β P v} with e(w) = w / (1-β)."
function T(v, model)
    (; n, w_vals, P, β, c) = model
    h = c .+ β * P * v
    e = w_vals ./ (1 - β)
    return max.(e, h)
end

" Get a v-greedy policy."
function get_greedy(v, model)
    (; n, w_vals, P, β, c) = model
    σ = w_vals / (1 - β) .>= c .+ β * P * v
    return σ
end

"Solve the infinite-horizon Markov job search model by VFI."
function vfi(model)
    v_init = zero(model.w_vals)
    v_star = successive_approx(v -> T(v, model), v_init)
    σ_star = get_greedy(v_star, model)
    return v_star, σ_star
end
```

Listing 10: Job search with Markov state (`markov_js.jl`)

Figure 3.9: Value, stopping, and continuation for Markov job search

Exercise 3.3.3. Explain why the continuation value function is increasing in Figure 3.9. If possible, provide a mathematical explanation and economic intuition.

Exercise 3.3.4. Using the Bellman equation (3.22), show that h^* obeys

$$h^*(w) := c + \beta \sum_{w' \in \mathsf{W}} \max\left\{\frac{w'}{1-\beta}, h^*(w')\right\} P(w, w') \qquad (w \in \mathsf{W}).$$

Exercise 3.3.5. Let Q be the operator on V defined at $h \in V$ by

$$(Qh)(w) := c + \beta \sum_{w' \in \mathsf{W}} \max\left\{\frac{w'}{1-\beta}, h(w')\right\} P(w, w') \qquad (w \in \mathsf{W}). \tag{3.23}$$

Prove that Q is (a) an order-preserving self-map on V and (b) a contraction of modulus β on V under the supremum norm.

Exercise 3.3.5 suggests to us a way to solve the job search problem without using value function iteration: iterate with Q to obtain the continuation value function h^*

and then use the policy

$$\sigma^*(w) = \mathbb{1}\left\{\frac{w'}{1-\beta} \geqslant h^*(w)\right\} \qquad (w \in \mathsf{W}),$$

which tells the agent to accept when the current stopping value exceeds the current continuation value.

In this particular case, the two approaches (iterating with T vs iterating with Q) are relatively similar, and, in general, neither offers any particular advantage over the other. However, we already saw in the IID case that the approach based on continuation values can be much more efficient in some settings (see the discussion in §1.3.2.2). We will investigate the relative merits of the two approaches more systematically in Chapter 5.

3.3.2 Job Search with Separation

As a final application for this chapter, we modify the job search problem discussed in §3.3.1 by adding one natural extension: separation occurs. In particular, an existing match between worker and firm terminates with probability α every period. (The modification is an extension because, under $\alpha = 0$, we recover the permanent job scenario from §3.3.1.)

Once separation enters the picture, the agent comes to view the loss of a job as a capital loss, and a spell of unemployment as an investment in searching for an acceptable job. In what follows, the wage process and discount factor are unchanged from §3.3.1. As before, $V := \mathbb{R}_+^{\mathsf{W}}$ is endowed with the supremum norm.

The value function for an unemployed worker is denoted by v_u^*. This function satisfies the recursion

$$v_u^*(w) = \max\left\{v_e^*(w),\ c + \beta \sum_{w' \in \mathsf{W}} v_u^*(w')P(w,w')\right\} \qquad (w \in \mathsf{W}). \tag{3.24}$$

The function v_e^* that appears in this equation is the value function for employed agents. In particular, $v_e^*(w)$ is the lifetime value of obtained by an agent who starts the period employed at wage w. The function v_e^* satisfies the recursion

$$v_e^*(w) = w + \beta\left[\alpha \sum_{w'} v_u^*(w')P(w,w') + (1-\alpha)v_e^*(w)\right] \qquad (w \in \mathsf{W}). \tag{3.25}$$

This equation states that value accruing to an employed agent is current wage plus the discounted expected value next of being either employed or unemployed next period, weighted by their probabilities.

We claim that, when $0 < \alpha, \beta < 1$, the equations (3.24) and (3.25) both have unique solutions in V. To help prove this, we solve (3.25) in terms of $v_e^*(w)$ to obtain

$$v_e^*(w) = \frac{1}{1-\beta(1-\alpha)} \left(w + \alpha\beta (P v_u^*)(w) \right). \tag{3.26}$$

(Recall $(Ph)(w) := \sum_{w'} h(w')P(w,w')$ for $h \in \mathbb{R}^{\mathsf{W}}$ and $w \in \mathsf{W}$.) Substituting into (3.24) yields

$$v_u^*(w) = \max \left\{ \frac{1}{1-\beta(1-\alpha)} \left(w + \alpha\beta (P v_u^*)(w) \right), \; c + \beta \, (P v_u^*)(w) \right\}. \tag{3.27}$$

Exercise 3.3.6. Prove that there exists a unique $v_u^* \in V$ that solves (3.27). Propose a convergent method for solving for both v_u^* and v_e^*. [Hint, if you need it: Look at Exercise 1.2.22 on page 26.]

Figure 3.10 shows the value function v_u^* for an unemployed worker, which is the fixed point of (3.27), as well as the stopping and continuation values, which are given by

$$s^*(w) := \frac{1}{1-\beta(1-\alpha)} \left(w + \alpha\beta (P v_u^*)(w) \right) \quad \text{and} \quad h_e^*(w) := c + \beta \, (P v_u^*)(w)$$

respectively, for each $w \in \mathsf{W}$. Parameters are as in Listing 11. The value function v_u^* is the pointwise maximum (i.e., $v_u^* = s^* \vee h^*$). The agent's optimal policy while unemployed is

$$\sigma^*(w) := \mathbb{1}\{s^*(w) \geqslant h^*(w)\}.$$

As before, the smallest w such that $\sigma^*(w) = 1$ is called the **reservation wage**.

Figure 3.11 shows how the reservation wage changes with α. To produce this figure we solved the model for the reservation wage at 10 values of α in an evenly spaced grid ranging 0 to 1. Not surprisingly, the reservation wage falls with α, since time spent unemployed is a capital investment in better wages, and the value of this investment declines as the separation rate rises.

Exercise 3.3.7. Replicate Figure 3.11.

```julia
using QuantEcon, LinearAlgebra

"Creates an instance of the job search model with separation."
function create_js_with_sep_model(;
        n=200,          # wage grid size
        ρ=0.9, ν=0.2,   # wage persistence and volatility
        β=0.98, α=0.1,  # discount factor and separation rate
        c=1.0)          # unemployment compensation
    mc = tauchen(n, ρ, ν)
    w_vals, P = exp.(mc.state_values), mc.p
    return (; n, w_vals, P, β, c, α)
end
```

Listing 11: Job search with separation model (`markov_js_with_sep.jl`)

Figure 3.10: Value function with job separation

Figure 3.11: The reservation wage vs separation rate

3.4 Chapter Notes

Many excellent textbooks on Markov chains exist, including Norris (1998), Häggström et al. (2002) and Privault (2013). Sargent and Stachurski (2022) provides a relatively comprehensive treatment from a network perspective. This perspective is a very natural one for Markov chains. More economic applications are discussed in Stokey and Lucas (1989) and Ljungqvist and Sargent (2018). Meyer (2000) gives a detailed account of the theory of nonnegative matrices. Another useful reference is Horn and Johnson (2012).

The systematic study of monotone Markov chains was initiated by Daley (1968). Monotone Markov methods have many important applications in economics. See, for example, Hopenhayn and Prescott (1992), Kamihigashi and Stachurski (2014), Jaśkiewicz and Nowak (2014), Balbus et al. (2014), Foss et al. (2018) and Hu and Shmaya (2019).

Chapter 4

Valuation

Following our introduction in Chapter 1, we laid foundations for dynamic programming theory by studying fixed point theory (Chapter 2) and Markov dynamics (Chapter 3). Before we begin solving dynamic programs, there is one more foundational topic that we need to treat: how to combine a reward sequence $(R_t)_{t \geqslant 0}$ into lifetime value. This topic is essential to the theory of dynamic programming because dynamic programming is a form of optimization and lifetime value provides the objective that we try to optimize.

In applications, the most common way to combine a reward sequence $(R_t)_{t \geqslant 0}$ into time zero lifetime value V_0 is via a geometric sum with constant discount rate, so that $V_0 = \mathbb{E} \sum_{t \geqslant 0} \beta^t R_t$ for some positive constant β. We saw this in (1.1) on page 2, where combined a profit stream $(\pi_t)_{t \geqslant 0}$ into expected present value of the firm, and again in (1.6) on page 10, where a worker evaluated lifetime earnings in a similar way. Below, in §4.1.1, we investigate this form of lifetime valuation (linear with constant discount rate) in a systematic way.

Next we investigate extensions to the traditional approach to valuation, which are becoming increasingly popular in quantitative work. One extension uses time-varying discount rates, discussed below in §4.1.2. Another involves dropping the linear assumption, so that lifetime value can no longer be written as a geometric sum. Instead, lifetime value is computed from a recursive representation that is typically nonlinear. We discuss this "recursive preference" approach in §4.3.

By the end of this chapter we will be able to define and compute lifetime value using traditional and modern approaches. This will allow us to formally define optimality (unlike our treatment of job search in Chapter 1, where the discussion was purely intuitive). We will then be ready to start maximizing lifetime value, beginning in Chapter 5.

4.1 Linear Valuation

In this section we discuss linear valuation under fixed and time-varying discount rates.

4.1.1 Fixed Discount Rates

Our first topic is valuation with fixed discount rates, which is relatively straightforward. We begin with theory and then investigate two simple applications.

4.1.1.1 Theory

Consider the problem of computing the expectation of a discounted sum of future measurements. These sums take the form

$$v(x) := \mathbb{E}_x \sum_{t \geqslant 0} \beta^t h(X_t) := \mathbb{E}\left[\sum_{t \geqslant 0} \beta^t h(X_t) \mid X_0 = x\right] \tag{4.1}$$

for some constant $\beta \in \mathbb{R}_+$ and $h \in \mathbb{R}^{\mathsf{X}}$, where (X_t) is P-Markov on finite set X. Here $\mathbb{E}_x$ indicates we are conditioning on $X_0 = x$.

Lemma 4.1.1. *If $\beta \in (0,1)$, then $v(x)$ in (4.1) is finite for all $x \in \mathsf{X}$, the matrix $I - \beta P$ is invertible and*

$$v = \sum_{t \geqslant 0} (\beta P)^t h = (I - \beta P)^{-1} h. \tag{4.2}$$

Proof. Under the stated conditions we have

$$\mathbb{E}_x \sum_{t \geqslant 0} \beta^t h(X_t) = \sum_{t \geqslant 0} \beta^t \mathbb{E}_x h(X_t) = \sum_{t \geqslant 0} \beta^t (P^t h)(x), \tag{4.3}$$

where the first equality in (4.3) uses linearity of expectations and the second follows from (3.19) and the assumption that (X_t) is P-Markov starting at x.[1] Applying the Neumann Series Lemma (p. 19) to the matrix βP, we see that $\sum_{t \geqslant 0} (\beta P)^t = (I - \beta P)^{-1}$. The lemma is applicable because $r(\beta P) = \beta r(P) = \beta < 1$, as follows from Exercise 3.1.2. □

[1] Regarding the first equality, care must be taken when pushing mathematical expectations through infinite sums. In the present setting, justification can be provided by appealing to the dominated convergence theorem, which is one of the fundamental results of measure theory. See, for example, Williams (1991).

4.1.1.2 Application: Valuation of Firms

Consider a firm that receives profit stream $(\pi_t)_{t \geqslant 0}$. For a shareholder, the total valuation of the firm is the expected present value of its profit stream. Suppose for now that the interest rate is constant at $r > 0$. With $\beta := 1/(1+r)$, total valuation is

$$V_0 = \mathbb{E} \sum_{t=0}^{\infty} \beta^t \pi_t. \tag{4.4}$$

To compute this value, we need a model of how profits evolve. A common strategy is to set $\pi_t = \pi(X_t)$ for some fixed $\pi \in \mathbb{R}^{\mathsf{X}}$, where $(X_t)_{t \geqslant 0}$ is a state process. After the function π and the dynamics of (X_t) have been estimated, the value V_0 in (4.4) can be computed.

Here we assume that (X_t) is P-Markov for some stochastic matrix P defined on a finite set X. Then, conditioning on $X_0 = x$, we can write the value as

$$v(x) := \mathbb{E}_x \sum_{t=0}^{\infty} \beta^t \pi_t := \mathbb{E} \left[\sum_{t=0}^{\infty} \beta^t \pi_t \,|\, X_0 = x \right].$$

By Lemma 4.1.1, the value $v(x)$ is finite and the function $v \in \mathbb{R}^{\mathsf{X}}$ can be obtained by

$$v = \sum_{t \geqslant 0} \beta^t P^t \pi = (I - \beta P)^{-1} \pi.$$

It seems natural that valuation will be increasing if higher states generate higher profits and also predict higher states in the future. The next exercise confirms this.

Exercise 4.1.1. Let X be partially ordered and suppose that $\pi \in i\mathbb{R}^{\mathsf{X}}$ and that P is monotone increasing. (See §3.2.4 for terminology and notation.) Prove that, under these conditions, v is increasing on X.

4.1.1.3 Application: Valuing Consumption Streams

Household choices over consumption and savings are one of the central topics of economic modeling. To model choices we need to attach values to different consumption paths. Here, a **consumption path** is a nonnegative random sequence $(C_t)_{t \geqslant 0}$. In what follows we consider consumption paths such that $C_t = c(X_t)$ for all $t \geqslant 0$, where $c \in \mathbb{R}_+^{\mathsf{X}}$ and $(X_t)_{t \geqslant 0}$ is P-Markov on finite set X. Thus, consumption streams are stationary functions of a finite state Markov chain.

In the standard **additively separable** model of consumer preferences with constant geometric discounting, the time zero value of a consumption stream $(C_t)_{t \geqslant 0}$, given current state $X_0 = x \in \mathsf{X}$, is

$$v(x) = \mathbb{E}_x \sum_{t \geqslant 0} \beta^t u(C_t). \tag{4.5}$$

Here

- $\beta \in (0, 1)$ is a discount factor,
- $\mathbb{E}_x := \mathbb{E}[\,\cdot \mid X_0 = x]$, and
- $u \colon \mathbb{R}_+ \to \mathbb{R}$ is called the **flow utility function**.

Dependence of $v(x)$ on x is due to the fact that the initial condition $X_0 = x$ influences the Markov state process and, therefore, the time path of consumption.

Using $C_t = c(X_t)$ and defining $r := u \circ c$ we can write $v(x) = \mathbb{E}_x \sum_{t \geqslant 0} \beta^t r(X_t)$. By Lemma 4.1.1, this sum is finite and v can be expressed as

$$v = (I - \beta P)^{-1} r. \tag{4.6}$$

Figure 4.1 shows an example when u has the constant relative risk aversion (**CRRA**) specification

$$u(c) = \frac{c^{1-\gamma}}{1-\gamma} \qquad (c \geqslant 0,\ \gamma > 0), \tag{4.7}$$

while $c(x) = \exp(x)$, so that consumption takes the form $C_t = \exp(X_t)$, and $(X_t)_{t \geqslant 0}$ is a Tauchen discretization (see §3.2.2) of $X_{t+1} = \rho X_t + \nu W_{t+1}$ where $(W_t)_{t \geqslant 1}$ is IID and standard normal. The parameters are $n = 25$, $\beta = 0.98$, $\rho = 0.96$, $\nu = 0.05$ and $\gamma = 2$. We set $r = u \circ c$ and solved for v via (4.6).

Exercise 4.1.2. Replicate Figure 4.1.

Exercise 4.1.3. The value function in Figure 4.1 appears to be increasing in the state x. Prove this for the CRRA model when $\rho \geqslant 0$.

4.1.2 Time-Varying Discount Rates

Time-varying discount rates have become an increasingly popular tool in economics and finance, as a way to bring model outputs closer to the data. In this section we

Figure 4.1: The value of $(C_t)_{t\geqslant 0}$ given $X_t = x$

provide background discussion and then show how to modify the standard linear valuation model to handle time-varying discount rates.

4.1.2.1 Motivation

When we discussed firm valuation in §4.1.1.2, we assumed that the interest rate is constant. A quick look at the data shows that this assumption is dubious at best. Interest rates are stochastic and time-varying, even for safe assets like US Treasury bills. To illustrate this, Figure 4.2 shows the nominal interest rate on 1 Year Treasury bills since the 1950s, while Figure 4.3 shows dynamics of the real interest rate for 10 year T-bills since 2012. Clearly both the nominal and the real interest rates are significantly time varying.

Should a given firm's profit stream be discounted by nominal or real interest rates? The answer depends on the costs and revenue stream of the firm, and how closely they co-move with inflation. In practice, most discounting exercises use nominal rates, such as one or two year Treasury bills. In addition, some use an alternative firm-specific rate called weighted average cost of capital, which measures average cost of raising funds from bonds, common stock, and other sources. At this point, what matters for us is that *all* of these alternative discount rates exhibit significant variation over time.

Example 4.1.1. When a period of rising interest rates is anticipated by the market, the share prices of newer and more technology-heavy firms typically face strong head-winds. This is because the profit streams from such firms are usually biased towards

Figure 4.2: Nominal US interest rates (`plot_interest_rates_nominal.jl`)

Figure 4.3: Real US interest rates (`plot_interest_rates_real.jl`)

the future, in the sense that dividends are initially low or zero (while profits are reinvested) and eventually high (if the business model is successful). A period of rising interest rates indicates that such profit streams should be heavily discounted.

We have just motivated time-varying discount rates for the firm problem. How about the consumer problem discussed in §4.1.1.3? Here, too, time-varying discount rates have become popular in quantitative work, particularly in macroeconomics. (An early example is Krusell and Smith (1998) and more citations are provided in §4.4.) One reason is that the traditional macroeconomic modeling approach, which loads all shocks on the supply side, leads to model outputs that deviate from data in substantial ways. Time-varying discount rates introduce fluctuations that originate on the demand side.

4.1.2.2 Theory

In order to handle time-varying discount rates, we now present and prove a general result on geometric sums. Throughout this section, we work in the following setting:

- X is a finite set and P is a stochastic matrix on X.
- h is in $\mathbb{R}^{\mathsf{X}}$ and b is a map from $\mathsf{X} \times \mathsf{X}$ to $\mathbb{R}$.
- $(X_t)_{t \geqslant 0}$ is P-Markov and $B_t = b(X_{t-1}, X_t)$.

Also, let K be the matrix on X defined by $K(x, x') := b(x, x')P(x, x')$.

Given $x \in \mathsf{X}$ we write $\mathbb{E}_x$ for $\mathbb{E}[\cdot \,|\, X_0 = x]$. With the convention $\prod_{i=1}^{0} B_i := 1$, we have the following key result.

Theorem 4.1.2. *If $r(K) < 1$, then*

$$v(x) := \mathbb{E}_x \sum_{t=0}^{\infty} \left(\prod_{i=1}^{t} B_i \right) h(X_t) \tag{4.8}$$

is finite for all $x \in \mathsf{X}$. Moreover, v is the only element of $\mathbb{R}^{\mathsf{X}}$ that satisfies

$$v(x) = h(x) + \sum_{x'} v(x') K(x, x') \qquad (x \in \mathsf{X}). \tag{4.9}$$

Finally, $I - K$ is nonsingular and $v = (I - K)^{-1} h$.

Theorem 4.1.2 generalizes Lemma 4.1.1 on page 100. Indeed, if $b \equiv \beta \in (0, 1)$, then $r(K) = \beta r(P) = \beta < 1$, and the result in Theorem 4.1.2 reduces to Lemma 4.1.1.

One way to prove Theorem 4.1.2 is via the law of iterated expectations: With $\mathbb{E}_{X_1}$ denoting expectation conditioned on X_1, we have

$$\begin{aligned}\mathbb{E}_x \sum_{t=1}^{\infty}\left(\prod_{i=1}^{t} B_i\right) h(X_t) &= \mathbb{E}_x\, \mathbb{E}_{X_1} \sum_{t=1}^{\infty}\left(\prod_{i=1}^{t} B_i\right) h(X_t) \\ &= \mathbb{E}_x\, B_1 \mathbb{E}_{X_1} \sum_{t=1}^{\infty}\left(\prod_{i=2}^{t} B_i\right) h(X_t).\end{aligned}$$

By the definition of v in (4.8), the right-hand side is just

$$\mathbb{E}_x\, B_1 v(X_1) = \mathbb{E}_x\, b(X_0, X_1) v(X_1) = \sum_{x'} b(x, x') v(x') P(x, x') = \sum_{x'} v(x') K(x, x').$$

As a consequence, applying (4.8) again,

$$v(x) = h(x) + \mathbb{E}_x \sum_{t=1}^{\infty}\left(\prod_{i=1}^{t} B_i\right) h(X_t) = h(x) + \sum_{x'} v(x') K(x, x'),$$

which is (4.9). In vector form, the last equation becomes $v = h + Kv$. Using $r(K) < 1$ and applying the Neumann series lemma gives nonsingularity of $I - K$ and the representation $v = (I - K)^{-1} h$.

The proof above uses a somewhat sophisticated version of the law of iterated expectations, which we have not proved in this text. To keep this book as self-contained as possible, we provide an alternative proof of Theorem 4.1.2 on page 270, which uses a longer but more straightforward approach.

4.1.2.3 Application: Firm Valuation with Stochastic Interest Rates

Now we can return to the firm valuation problem, while allowing the interest rate to follow a stochastic process $(r_t)_{t \geqslant 0}$. Under the convention that the interest rate over the period between t and $t+1$ is known at time t and written as r_t, the time zero expected present value of time t profit π_t is

$$\mathbb{E}\left\{\beta_0 \cdots \beta_{t-1} \cdot \pi_t\right\} \qquad \text{where } \beta_t := \frac{1}{1 + r_t}.$$

The expected present value of the firm is, therefore,

$$V_0 = \mathbb{E} \sum_{t=0}^{\infty}\left(\prod_{i=0}^{t-1} \beta_i\right) \pi_t \qquad \text{where } \prod_{i=0}^{-1} \beta_i := 1. \tag{4.10}$$

Suppose that $\beta_t = \beta(X_t)$ for some $\beta \in \mathbb{R}^{\mathsf{X}}$, so that randomness in interest rates is a function of the same Markov state that influences profits. There is very little loss of generality in making this assumption. (In fact, the two processes can still be completely independent. For example, if we take X_t to have the form $X_t = (Y_t, Z_t)$, where (Y_t) and (Z_t) are independent Markov chains, then we can take β_t to be a function of Y_t and π_t to be a function of Z_t. The resulting interest and profit processes are independent.)

Conditioning on $X_0 = x$, the value in (4.10) becomes

$$v(x) = \mathbb{E} \sum_{t=0}^{\infty} \left(\prod_{i=0}^{t-1} \beta(X_i) \right) \pi(X_t) \tag{4.11}$$

With $K(x, x') := \beta(x)P(x, x')$, we have

Proposition 4.1.3. *If $r(K) < 1$, then the firm valuation (4.11) is finite for all $x \in \mathsf{X}$ and*

$$v = (I - K)^{-1}\pi.$$

Exercise 4.1.4. Verify Proposition 4.1.3 via Theorem 4.1.2.

Exercise 4.1.5. Let X be partially ordered and assume $r(K) < 1$. Prove that v is in $i\mathbb{R}^{\mathsf{X}}$ whenever P is monotone increasing and $\beta, \pi \in i\mathbb{R}^{\mathsf{X}}$.

4.2 Asset Pricing

In this section we provide a brief introduction to the standard theory of asset pricing in a Markov environment. While the topic of asset pricing is fascinating in its own right, our main aim is to provide additional practice in handling linear valuation problems. (Readers who lack interest in asset pricing and wish to push ahead with their study of dynamic programming can skip to §4.3.)

4.2.1 Introduction to Asset Pricing

We first discuss risk-neutral pricing and show why this assumption is typically implausible. Next, we introduce stochastic discount factors and stationary asset pricing.

4.2.1.1 Risk-Neutral Pricing?

Consider the problem of assigning a current price Π_t to an asset that confers on its owner the right to payoff G_{t+1}. The payoff is stochastic and realized next period. One simple idea is to use the **risk-neutral pricing**, which implies that

$$\Pi_t = \mathbb{E}_t \, \beta \, G_{t+1} \tag{4.12}$$

for some constant discount factor $\beta \in (0, 1)$. If the payoff is in k periods, then we modify the price to $\mathbb{E}_t \, \beta^k \, G_{t+k}$. In essence, risk-neutral pricing says that cost equals expected reward, discounted to present value by compounding a constant rate of discount.

Example 4.2.1. Let S_t be the price of a stock at each point in time t. A **European call option** gives its owner the right to purchase the stock at price K at time $t + k$. There is no obligation to exercise the option, so the payoff at $t + k$ is $\max\{S_{t+k} - K, 0\}$. Under risk-neutral pricing, the time t price of this option is

$$\Pi_t = \mathbb{E}_t \, \beta^k \, \max\{S_{t+k} - K, 0\}.$$

Although risk neutrality allows for simple pricing, assuming risk neutrality for all investors is *not* consistent with the data.

To give one example, suppose that we take the asset that pays G_{t+1} in (4.12) and replace it with another asset that pays $H_{t+1} = G_{t+1} + \varepsilon_{t+1}$, where ε_{t+1} is independent of G_{t+1}, $\mathbb{E}_t \, \varepsilon_{t+1} = 0$ and $\operatorname{Var} \varepsilon_{t+1} > 0$. In effect, we are adding risk to the original payoff without changing its mean.

Under risk neutrality, the price of this new asset is

$$\Pi_t^H = \mathbb{E}_t \, \beta \, [G_{t+1} + \varepsilon_{t+1}] = \Pi_t + \beta \, \mathbb{E}_t \, \varepsilon_{t+1} = \Pi_t.$$

Thus, H_{t+1} and G_{t+1} are priced identically, even though their means are both $\mathbb{E}_t G_{t+1}$ and their variances satisfy

$$\operatorname{Var} H_{t+1} = \operatorname{Var} G_{t+1} + \operatorname{Var} \varepsilon_{t+1} > \operatorname{Var} G_{t+1}.$$

This outcome contradicts the fact that, in asset markets, investors typically demand some compensation for bearing risk.

A helpful way to think about the same point is to consider the rate of return $r_{t+1} := (G_{t+1} - \Pi_t)/\Pi_t$ on holding an asset with payoff G_{t+1}. From (4.12) we have $\mathbb{E}_t \, \beta(1 + r_{t+1}) =$

1, or

$$\mathbb{E}_t\, r_{t+1} = \frac{1-\beta}{\beta}.$$

Since the right-hand side does not depend on G_{t+1}, risk neutrality implies that all assets have the same expected rate of return. But this contradicts the fact that, on average, riskier assets tend to have higher rates of return—which are needed to incentivize investors to bear risk.

Example 4.2.2. The **risk premium** on a given asset is defined as the expected rate of return minus the rate of return on a risk-free asset. If we assume risk neutrality then, by the preceding discussion, the risk premium is zero for all assets. However, calculations based on post-war US data show that the average risk premium for equities is around 8% per annum (see, e.g., Cochrane (2009)).

4.2.1.2 A Stochastic Discount Factor

To go beyond risk neutral-pricing, let's start with a model containing one asset and one agent. Due to the simplicity of the model, we will find it straightforward to price the asset and compare it to the risk neutral case.

In the model, a representative agent takes the price Π_t of a risky asset as given and solves

$$\max_{0\leqslant\alpha\leqslant 1}\{u(C_t)+\beta\mathbb{E}_t u(C_{t+1})\}$$
$$\text{subject to} \quad C_t = E_t - \Pi_t\alpha \quad \text{and} \quad C_{t+1} = E_{t+1} + \alpha G_{t+1}.$$

Here

- u is a flow utility function,
- G_{t+1} is the payoff of the asset and Π_t is the time-t price,
- β is a constant discount factor measuring impatience of the agent,
- E_t and E_{t+1} are endowments and
- α is the share of the asset purchased by the agent.

Rewriting as $\max_\alpha\{u(E_t-\Pi_t\alpha)+\beta\mathbb{E}_t u(E_{t+1}+\alpha G_{t+1})\}$ and differentiating with respect to α leads to the first order condition

$$u'(E_t-\Pi_t\alpha)\Pi_t = \beta\mathbb{E}_t u'(E_{t+1}+\alpha G_{t+1})G_{t+1}.$$

Rearranging gives us

$$\Pi_t = \mathbb{E}_t \left[\beta \frac{u'(C_{t+1})}{u'(C_t)} G_{t+1} \right]. \tag{4.13}$$

Comparing (4.13) with (4.12), we see that the payoff is now multiplied by a positive random variable rather than a constant. This term

$$M_{t+1} := \beta \frac{u'(C_{t+1})}{u'(C_t)} \tag{4.14}$$

is called the **stochastic discount factor** or **pricing kernel** of the model. We call this particular form of the pricing kernel shown in (4.14) the **Lucas stochastic discount factor** (Lucas SDF) in honor of Lucas (1978a).

Example 4.2.3. If u is linear, so that $u(c) = ac + b$ for some $a, b \in \mathbb{R}$, then $u'(c) = a$ for all c, so $M_{t+1} = \beta$. In other words, if utility has no curvature, then pricing is risk neutral.

Example 4.2.4. If utility has the CRRA form $u(c) = c^{1-\gamma}/(1-\gamma)$ for some $\gamma > 0$, then the Lucas SDF takes the form

$$M_{t+1} = \beta \left(\frac{C_{t+1}}{C_t} \right)^{-\gamma}, \tag{4.15}$$

which we can also write as $M_{t+1} = \beta \exp(-\gamma g_{t+1})$ when $g_{t+1} := \ln(C_{t+1}/C_t)$ is the growth rate of consumption. Thus the SDF is a positive random variable taking relatively small values in states of the world where consumption growth is high.

In the CRRA case, the Lucas SDF applies heavier discounting to assets that concentrate payoffs in states of the world where the agent is already enjoying strong consumption growth. Conversely, the agent attaches higher weights to future payoffs that occur when consumption growth is low. This is because such payoffs hedge against the risk of drawing low consumption states.

4.2.1.3 A General Specification

The standard neoclassical theory of asset pricing generalizes the Lucas discounting specification by assuming only that there exists a positive random variable M_{t+1} such that the price of an asset with payoff G_{t+1} is

$$\Pi_t = \mathbb{E}_t M_{t+1} G_{t+1} \qquad (t \geqslant 0). \tag{4.16}$$

As above, M_{t+1} is called the **stochastic discount factor** (SDF). Equation 4.16 generalizes (4.13) by refraining from placing a specification on the SDF (apart from assuming positivity).

In fact, it can be shown that there exists an SDF M_{t+1} such that (4.16) is always valid under relatively weak assumptions. In particular, a single SDF M_{t+1} can be used to price *any* asset in the market, so if H_{t+1} is a second stochastic payoff then the current price of an asset with this payoff is $\mathbb{E}_t M_{t+1} H_{t+1}$.

We skip a proof of these claims, since our main interest is in understanding forward looking equations in Markov environments, which are needed for our discussion of dynamic programming below. References for asset pricing theory with full proofs are listed in §3.4.

4.2.1.4 Markov Pricing

A common assumption in quantitative applications is that all underlying randomness is driven by a Markov model. In this spirit, we take (X_t) to be P-Markov on finite state X, where P is a given stochastic matrix, and suppose further that the SDF and payoff have the forms

$$M_{t+1} = m(X_t, X_{t+1}) \quad \text{and} \quad G_{t+1} = g(X_t, X_{t+1})$$

for fixed functions m, g mapping $\mathsf{X} \times \mathsf{X}$ to $\mathbb{R}_+$. Since m is arbitrary at this point, we are not assuming any particular specification for the SDF.

In this setting, conditioning on $X_t = x$, the standard asset pricing equation $\Pi_t = \mathbb{E}_t M_{t+1} G_{t+1}$ becomes

$$\pi(x) = \sum_{x' \in \mathsf{X}} m(x, x') g(x, x') P(x, x') \qquad (x \in \mathsf{X}), \tag{4.17}$$

where $\pi(x)$ is the price of the asset conditional on $X_t = x$. (That is, $\Pi_t = \pi(X_t)$.)

4.2.1.5 Pricing a Stationary Dividend Stream

Now we are ready to look at pricing a stationary cash flow over an infinite horizon. This is one of the most fundamental problems in asset pricing. We will apply the Markov structure assumed in §4.2.1.4. In all that follows, (X_t) is P-Markov.

We seek the time t price, denoted by Π_t, for an **ex-dividend contract** on the dividend stream $(D_t)_{t \geqslant 0}$. The contract provides the owner with the right to the dividend stream. The "ex-dividend" component means that, should the contract be traded at

time t, the dividend paid at time t goes to the seller rather than the buyer. As a result, purchasing at t and selling at $t+1$ pays $\Pi_{t+1} + D_{t+1}$. Hence, applying the fundamental asset pricing equation, at time t price Π_t of the contract must satisfy

$$\Pi_t = \mathbb{E}_t M_{t+1}(\Pi_{t+1} + D_{t+1}). \tag{4.18}$$

We assume the existence of a $d \in \mathbb{R}_+^{\mathsf{X}}$ such that $D_t = d(X_t)$ for all t. Using (4.17), we can write this as

$$\pi(x) = \sum_{x'} m(x, x')(\pi(x') + d(x'))P(x, x') \qquad (x \in \mathsf{X}), \tag{4.19}$$

or, equivalently,

$$\pi = A\pi + Ad \quad \text{when } A(x, x') := m(x, x')P(x, x'). \tag{4.20}$$

By the Neumann series lemma, the solution to this system of equations is

$$\pi^* = (I - A)^{-1}Ad = \sum_{k=1}^{\infty} A^k d \quad \text{when } r(A) < 1. \tag{4.21}$$

The vector π^* is called an **equilibrium price function**.

Exercise 4.2.1. As discussed in §4.2.1.1, the case $m \equiv \beta$ for some $\beta \in \mathbb{R}_+$ is called the risk-neutral case. Provide a condition on β under which $r(A) < 1$.

Exercise 4.2.2. Confirm that $(\Pi_t)_{t \geqslant 0}$ generated by $\Pi_t = \pi^*(X_t)$ solves (4.18).

Remark 4.2.1. We can call A an **Arrow–Debreu discount operator**. Its powers apply discounting: the valuation of any random payoff g in k periods is $A^k g$.

Exercise 4.2.3. Derive the price for a **cum-dividend contract** on the dividend stream $(D_t)_{t \geqslant 0}$, with the model otherwise unchanged. Under this contract, should the right to the dividend stream be traded at time t, the dividend paid at time t goes to the buyer rather than the seller.

4.2.1.6 Forward Sum Representation

Asset prices can be expressed as infinite sums under the assumptions stated above. Let's show this for cum-dividend contracts (although the case of ex-dividend contracts

is similar). In Exercise 4.2.3 you found that the state-contingent price vector π for a cum-dividend contract on the dividend stream $(D_t)_{t\geqslant 0}$ obeys

$$\pi = d + A\pi \quad \text{when } A(x, x') := m(x, x')P(x, x'). \tag{4.23}$$

As before, $D_t = d(X_t)$ and $(X_t)_{t\geqslant 0}$ is P-Markov. Applying the uniqueness component of Theorem 4.1.2, we see that the function π also obeys

$$\pi(x) = \mathbb{E}_x \left\{ \sum_{t=0}^{\infty} \left[\prod_{i=1}^{t} M_i \right] D_t \right\}$$

where $M_{t+1} := m(X_t, X_{t+1})$ and $\prod_{i=1}^{0} M_i := 1$. This expression agrees with our intuition: The price of the contract is the expected present value of the dividend stream, with the time t dividend discounted by the composite factor $M_1 \cdots M_t$.

4.2.2 Nonstationary Dividends

Until now, our discussion of asset pricing has assumed that dividends are stationary. However, dividends typically grow over time, along with other economic measures such as GDP. In this section we solve for the price of a dividend stream when dividends exhibit random growth.

4.2.2.1 Price-Dividend Ratios

A standard model of dividend growth is

$$\ln \frac{D_{t+1}}{D_t} = \kappa(X_t, \eta_{t+1}) \qquad t = 0, 1, \ldots,$$

where κ is a fixed function, (X_t) is the state process and (η_t) is IID. We let φ be the density of each η_t and assume that (X_t) is P-Markov on a finite set X. Let's suppose as before that the SDF obeys $M_{t+1} = m(X_t, X_{t+1})$ for some positive function m.

Since dividends grow over time, so will the price of the asset. As such, we should no longer seek a fixed function π such that $\Pi_t = \pi(X_t)$ for all t, since the resulting price process (Π_t) will fail to grow. Instead, we try to solve for the **price-dividend ratio** $V_t := \Pi_t / D_t$, which we hope will be stationary.

Exercise 4.2.4. Using $\Pi_t = \mathbb{E}_t \left[M_{t+1}(D_{t+1} + \Pi_{t+1}) \right]$, show that

$$V_t = \mathbb{E}_t \left[M_{t+1} \exp(\kappa(X_t, \eta_{t+1})) \left(1 + V_{t+1}\right) \right]. \tag{4.24}$$

After conditioning on $X_t = x$, (4.24) leads us to conjecture existence of a function v such that

$$v(x) = \sum_{x' \in \mathsf{X}} m(x, x') \int \exp(\kappa(x, \eta)) \varphi(\mathrm{d}\eta) \, [1 + v(x')] \, P(x, x') \tag{4.25}$$

for all $x \in \mathsf{X}$. We understand (4.25) as an equation to be solved for the unknown object $v \in \mathbb{R}^{\mathsf{X}}$. If we can find a solution v^* to (4.25), then setting $V_t = v^*(X_t)$ yields a process (V_t) that obeys (4.24).

Exercise 4.2.5. Let

$$A(x, x') := m(x, x') \int \exp(\kappa(x, \eta)) \varphi(\mathrm{d}\eta) P(x, x') \qquad (x, x' \in \mathsf{X}). \tag{4.26}$$

Show that (4.24) has a unique solution v^* in $\mathbb{R}^{\mathsf{X}}$ when $r(A) < 1$, and

$$v^* = (I - A)^{-1} A \mathbb{1} = \sum_{t \geqslant 1} A^t \mathbb{1}. \tag{4.27}$$

The price-dividend process (V_t^*) defined by $V_t^* = v^*(X_t)$ solves (4.24). The price can be recovered via $\Pi_t = V_t^* D_t$.

4.2.2.2 Application: Markov Growth with a Lucas SDF

As an example, suppose that dividend growth obeys

$$\kappa(X_t, \eta_{d,t+1}) = \mu_d + X_t + \sigma_d \, \eta_{d,t+1}$$

where $(\eta_{d,t})_{t \geqslant 0}$ is IID and standard normal. Consumption growth is given by

$$\ln \frac{C_{t+1}}{C_t} = \mu_c + X_t + \sigma_c \, \eta_{c,t+1},$$

where $(\eta_{c,t})_{t \geqslant 0}$ is also IID and standard normal. We use the Lucas SDF in (4.15), implying that

$$M_{t+1} = \beta \left(\frac{C_{t+1}}{C_t} \right)^{-\gamma} = \beta \exp(-\gamma(\mu_c + X_t + \sigma_c \eta_{c,t+1}))$$

```julia
using QuantEcon, LinearAlgebra

"Creates an instance of the asset pricing model with Markov state."
function create_asset_pricing_model(;
        n=200,                # state grid size
        ρ=0.9, ν=0.2,         # state persistence and volatility
        β=0.99, γ=2.5,        # discount and preference parameter
        μ_c=0.01, σ_c=0.02, # consumption growth mean and volatility
        μ_d=0.02, σ_d=0.1)  # dividend growth mean and volatility
    mc = tauchen(n, ρ, ν)
    x_vals, P = exp.(mc.state_values), mc.p
    return (; x_vals, P, β, γ, μ_c, σ_c, μ_d, σ_d)
end
```

Listing 12: Asset pricing model with Lucas SDF (`pd_ratio.jl`)

Exercise 4.2.6. Using (4.26), show that

$$A(x, x') = \beta \exp\left(-\gamma\mu_c + \mu_d + (1-\gamma)x + \frac{\gamma^2\sigma_c^2 + \sigma_d^2}{2}\right) P(x, x').$$

Figure 4.4 shows the price-dividend ratio function v^* for the specification given in Listing 12, as well as for an alternative mean dividend growth rate μ_d. The state process is a Tauchen discretization of an AR(1) process with positive autocorrelation. An increase in the state predicts higher dividends, which tends to increase the price. At the same time, higher x also predicts higher consumption growth, which acts negatively on the price. For values of γ greater than 1, the second effect dominates and the price-dividend ratio slopes down.

Exercise 4.2.7. Complete the code in Listing 12 and replicate Figure 4.4. Add a test to your code that checks $r(A) < 1$ before computing the price-dividend ratio.

4.2.3 Incomplete Markets

In §4.2.1.5, the problem of solving for the equilibrium price vector π was treated using the Neumann series lemma. However, there are various modifications to the basic model where nonlinearities make use of the Neumann series lemma impossible.

Figure 4.4: Price-dividend ratio as a function of the state

For example, Harrison and Kreps (1978) analyze a setting with heterogeneous beliefs and incomplete markets, leading to failure of the standard asset pricing equation. This results in a nonlinear equation for prices.

We treat the model only briefly. There are two types of agents. Type i believes that the state updates according to stochastic matrix P_i for $i = 1, 2$. In addition, agents are risk-neutral, so $m(x, y) \equiv \beta \in (0, 1)$. Harrison and Kreps (1978) show that, for their model, the equilibrium condition (4.19) becomes

$$\pi(x) = \max_i \beta \sum_{x'} [\pi(x') + d(x')] P_i(x, x') \tag{4.28}$$

for $x \in S$ and $i \in \{1, 2\}$. Setting aside the details that lead to this equation, our objective is simply: obtain a vector of prices π that solves (4.28).

As a first step, we introduce an operator $T \colon \mathbb{R}^n_+ \to \mathbb{R}^n_+$ that maps π to $T\pi$ via

$$(T\pi)(x) = \max_i \beta \sum_{x'} [\pi(x') + d(x')] P_i(x, x') \qquad (x \in S). \tag{4.29}$$

We are assuming $d \geqslant 0$, so T is indeed a self-map on $\mathbb{R}^n_+$.

By construction, a vector $\pi \in \mathbb{R}^n_+$ is a fixed point of T if and only if it is a vector of prices that solves (4.28). Hence, we have successfully converted our equilibrium problem into a fixed point problem.

We aim to show that T is a contraction. To this end, pick any $p, q \in \mathbb{R}^n_+$. Applying the inequality from Lemma 1.2.2 on page 18, we obtain

$$|(Tp)(x) - (Tq)(x)| \leqslant \beta \max_i \left| \sum_{x'} [p(x') + d(x')] P_i(x, x') - \sum_{x'} [q(x') - d(x')] P_i(x, x') \right|.$$

Using the triangle inequality and canceling terms leads to

$$|(Tp)(x) - (Tq)(x)| \leqslant \beta \max_{i \in \{1,2\}} \sum_{x'} |p(x') - q(x')| P_i(x, x') \leqslant \beta \|p - q\|_\infty.$$

Since this bound holds for all x, we can take the maximum with respect to x and obtain

$$\|Tp - Tq\|_\infty \leqslant \beta \|p - q\|_\infty.$$

In other words, on $\mathbb{R}^n_+$, the map T is a contraction of modulus β with respect to the sup norm.

Since $\mathbb{R}^n_+$ is a closed subset of $\mathbb{R}^n$, we conclude that T has a unique fixed point in this set. Hence, the system (4.28) has a unique solution π^* in $\mathbb{R}^n_+$, representing equilibrium prices. This fixed point can be computed by successive approximation.

4.3 Recursive Preferences

In this section we continue with the problem of computing the lifetime value of a given reward process. Our aim is to introduce more general specifications of lifetime value. In particular, we consider *recursive preferences*, which provide a much richer way of specifying how rewards are aggregated into total lifetime value. Such preferences are increasingly popular but also involve nontrivial technical problems. We will show how common specifications of recursive utility can be handled via fixed point theory.

Once we have understood the process of translating recursive preferences into lifetime value, we will move on to maximizing lifetime value—that is, dynamic programming.

4.3.1 Motivation: Optimal Savings

Here we motivate recursive preference models by analyzing consumption decisions.

4.3.1.1 A Recursive View of the Standard Model

The additively separable model of valuation in §4.1.1.3 can be studied from a purely recursive point of view. As a starting point, we state that the value V_t of current and future consumption is defined at each point in time t by the recursion

$$V_t = u(C_t) + \beta \, \mathbb{E}_t V_{t+1}. \tag{4.30}$$

The random variables V_t and V_{t+1} are the unknown objects in this expression. The expectation $\mathbb{E}_t$ is conditional on knowledge of $X_0, \ldots, X_t$.

Since consumption is a function of $(X_t)_{t \geqslant 0}$ and, by the Markov property, the future and past are independent after conditioning on the present, it is natural to guess that V_t will depend on the Markov chain only through X_t. Hence we guess there is a solution of (4.30) takes the form $V_t = v(X_t)$ for some $v \in \mathbb{R}^{\mathsf{X}}$.

Remark 4.3.1. Here v is an *ansatz*, meaning "educated guess." First we guess the form of a solution and then we try to verify that the guess is correct. So long as we carry out the second step, there is no loss of rigor caused by starting with a guess.

Under this conjecture, (4.30) can be rewritten as $v(X_t) = u(c(X_t)) + \beta \mathbb{E}_t v(X_{t+1})$. Conditioning on $X_t = x$ and using $r := u \circ c$, this becomes

$$v(x) = r(x) + \beta \, \mathbb{E}_x \, v(X_{t+1}) = r(x) + \beta (Pv)(x) \qquad (x \in \mathsf{X}). \tag{4.31}$$

In vector form, we get $v = r + \beta P v$. From the Neumann Series Lemma, the solution is $v^* = (I - \beta P)^{-1} r$, which is identical to (4.6) on page 102.

Exercise 4.3.1. Verify our guess: Show $(V_t^*)_{t \geqslant 0}$ obeys (4.30) when $V_t^* := v^*(X_t)$.

In summary, (4.30) and the sequential representation (4.5) specify the same valuation for consumption paths.

Does the recursive formulation in §4.3.1.1 seem unnecessary, given that we are led to the same result that we obtained from the more direct sequential approach used in §4.1.1.3? The reason we compare the two approaches is to contrast the current situation with other settings where alternative preferences over consumption paths imply that the sequential approach has no natural counterpart—and we are forced to proceed recursively.

Preferences that do not preserve additive separability and hence have no sequential counterpart are usually called **recursive preferences**.

Remark 4.3.2. This terminology is somewhat confusing, since, as we have just agreed, additively separable preferences also admit a recursive specification. The key point to remember is that, for most forms of recursive preferences, lifetime utility can *only* be expressed recursively. We will present our first example in §4.3.2.

4.3.1.2 Limitations of Additive Separability

Why do we need exotic preferences that can only be expressed recursively? The reason is that such models allow us to capture choices, values and behavior that cannot be replicated using traditional additively separable models.

One limitation of additive separability is that agents are risk-neutral in future utility (see, e.g., (4.30), where current value depends linearly on future value). Although risk aversion over consumption can be built in through curvature of u, this same curvature also determines the intertemporal elasticity of intertemporal substitution, meaning that the two aspects of preferences cannot be isolated. (We elaborate on this point in §4.3.4.3.) In many settings, risk-neutrality in future values implies that model outputs cannot explain decisions made by economic agents in the real world. (See §4.4 for more discussion.)

Another issue with additive separability is that agents with such preferences are indifferent to variations in the joint distribution of rewards, provided that marginal distributions are unchanged. To get a sense of what this means, we present a simple scenario with random consumption. In this scenario, you accept a new job and will be employed by this firm for the rest of your life. Your daily consumption will be entirely determined by your daily wage. Your boss offers you two options:

(A) Your boss will flip a coin at the start of your first day on the job. If the coin is heads, you will receive \$10,000 a day for the rest of your life. If the coin is tails, you will receive \$1 per day for the rest of your life.

(B) Your boss will flip a coin at the start of every day. If the coin is heads, you will receive \$10,000. If the coin is tails, you will receive \$1.

If you find that you have a strict preference between options A and B, then your utility cannot be modeled using additively separable preferences.

To see why, let φ be a probability distribution that represents the lottery described above, putting mass 0.5 on 10,000 and mass 0.5 on 1. Under option A, consumption $(C_t)_{t\geqslant 1}$ is given by $C_t = C_1$ for all t, where $C_1 \sim \varphi$. Under option B, consumption $(C_t)_{t\geqslant 1}$

is an IID sequence drawn from φ. Either way, lifetime utility is

$$\mathbb{E}\sum_{t\geqslant 1}\beta^t u(C_t) = \sum_{t\geqslant 1}\beta^t \mathbb{E}u(C_t) = \frac{\bar{u}}{1-\beta},$$

where $\bar{u} := \mathbb{E}u(C_1) = u(1)/2 + u(10,000)/2$.

The critical part of this argument is the passing of expectations through the sum, which uses additive separability. The implication is that lifetime utility depends only on the marginal distribution of each C_t, rather than on the joint distribution of the stochastic process $(C_t)_{t\geqslant 0}$.

4.3.2 Risk-Sensitive Preferences

Having motivated recursive preferences, let's turn to our first example: **risk-sensitive preferences**. For the consumption problem described in §4.3.1.1, imposing risk-sensitive preferences means replacing the recursion $v = r + \beta P v$ for v with

$$v(x) = r(x) + \beta\frac{1}{\theta}\ln\left\{\sum_{x'}\exp(\theta v(x'))P(x,x')\right\} \qquad (x \in \mathsf{X}). \tag{4.32}$$

As before, $r(x) = u(c(x))$ represents current utility when the current state is x. The parameter θ is a nonzero constant in $\mathbb{R}$.

In (4.32), we see that the transform $f(v) = \exp(\theta v)$ is applied to v before the expectation is taken. After the expectation is computed, the transform is reversed via $f^{-1}(v) = (1/\theta)\ln(v)$. We show below that the agent can be either risk-averse or risk-loving with respect to future outcomes, depending on the value of θ.

We understand (4.32) as the "definition" of lifetime utility under risk-sensitive preferences. In particular, the function v solving (4.32) gives lifetime value conditional on each current state, given θ and other primitives. Note that, under (4.32), there is no neat sequential representation analogous to $v(x) = \mathbb{E}_x\sum_t \beta^t u(C_t)$ from the additively separable case, due to the nonlinearities introduced by risk sensitivity.

In the previous paragraph we wrote "definition" in scare quotes because we can't be sure we have a definition at this point. Just because we write down a recursive expression for lifetime utility doesn't mean that corresponding lifetime utility is actually well defined. (For example, we can happily write down the recursive vector equation $v = v + \mathbb{1}$ but no solution for this equation exists.) One aim of this chapter is to provide conditions under which recursions like (4.32) have unique and well-defined solutions.

4.3.2.1 Entropic Risk Measures

To understand (4.32), we need to understand the "expectation-like" expression on the right hand side of (4.32), which replaces the ordinary conditional expectation $\sum_{x'} v(x')P(x,x')$ from the additively separable case. To this end, we define, for arbitrary random variable ξ and $\theta \in \mathbb{R}$,

$$\mathscr{E}_\theta[\xi] := \frac{1}{\theta} \ln \{\mathbb{E}[\exp(\theta\xi)]\}.$$

The value $\mathscr{E}_\theta[\xi]$ is called the **entropic risk-adjusted expectation** of ξ given θ.

Exercise 4.3.2. Prove that, for any random variable ξ any nonzero θ and any constant c, we have $\mathscr{E}_\theta[\xi + c] = \mathscr{E}_\theta[\xi] + c$.

The key idea behind the entropic risk-adjusted expectation measure is that decreasing θ lowers appetite for risk and increasing θ does the opposite.

Exercise 4.3.3. Prove that, if ξ is normally distributed, then

$$\mathscr{E}_\theta[\xi] = \mathbb{E}[\xi] + \theta\frac{\mathrm{Var}[\xi]}{2}. \tag{4.33}$$

Expression (4.33) above shows that, for the Gaussian case, $\mathscr{E}_\theta[\xi]$ equals the mean plus a term that penalizes variance when $\theta < 0$ and rewards it when $\theta > 0$.

More generally, we have the following result.

Lemma 4.3.1. *For any random variable ξ taking values in X, we have*

(i) $\mathscr{E}_\theta[\xi] \leqslant \mathbb{E}[\xi]$ *for all* $\theta < 0$.

(ii) $\mathscr{E}_\theta[\xi] \geqslant \mathbb{E}[\xi]$ *for all* $\theta > 0$.

Moreover, both of these inequalities are strict when $\mathrm{Var}[\xi] > 0$.

Proof. Fix $\theta \in \mathbb{R}$ and let $f\colon \mathbb{R} \to (0,\infty)$ be defined by $f(x) = \exp(\theta x)$. Note that $f'(x) = \theta\exp(\theta x)$ and $f''(x) = \theta^2\exp(\theta x)$. Thus f is convex and either increasing or decreasing depending on whether θ is positive or negative. Then $\mathscr{E}_\theta[\xi] = f^{-1}(\mathbb{E}f(\xi))$. By Jensen's inequality,

$$\mathbb{E}[f(\xi)] \geqslant f(\mathbb{E}[\xi]).$$

If $\theta > 0$, then f^{-1} is increasing, so applying f^{-1} to both sides gives $\mathscr{E}_\theta[\xi] \geqslant \mathbb{E}[\xi]$. If $\theta < 0$, then f^{-1} is decreasing, so applying f^{-1} to both sides gives $\mathscr{E}_\theta[\xi] \leqslant \mathbb{E}[\xi]$. This

proves the two weak inequalities in Lemma 4.3.1. To obtain strict inequalties we can apply the same argument using a strict version of Jensen's inequality (see, e.g., Liao and Berg (2018)), which is valid when $\mathrm{Var}[\xi] > 0$. □

4.3.2.2 Existence and Uniqueness

Let's return to investigating lifetime utility under risk-sensitive preferences. To this end, we introduce the **risk-sensitive Koopmans operator** K_θ on $\mathbb{R}^{\mathsf{X}}$ via

$$(K_\theta\, v)(x) = r(x) + \beta \frac{1}{\theta} \ln \left\{ \sum_{x' \in \mathsf{X}} \exp(\theta v(x')) P(x, x') \right\} \qquad (x \in \mathsf{X}). \tag{4.34}$$

Evidently, for given θ, a function $v \in \mathbb{R}^{\mathsf{X}}$ solves the risk-sensitive preference lifetime utility specification (4.32) if and only if v is a fixed point of K_θ. This explains the significance of the following result:

Proposition 4.3.2. *If $\beta \in (0, 1)$ and $\theta \neq 0$, then K_θ is globally stable on $\mathbb{R}^{\mathsf{X}}$.*

The proof of Proposition 4.3.2 is held back: we will prove a more general result in §4.3.4. For now we note the following implications.

(i) For each nonzero θ, lifetime utility is both well-defined and uniquely defined for risk-sensitive preference (i.e., (4.32) has a unique solution).

(ii) The unique solution, denoted henceforth by v^*, can be computed by successive approximation using K_θ.

4.3.2.3 The Gaussian Case

As a simple but tractable case, let's suppose that $r(x) = x$ and that $X_{t+1} = \rho X_t + \sigma W_{t+1}$ where $(W_t)_{t \geqslant 1}$ is IID and standard normal. Here $|\rho| < 1$ and $\sigma \geqslant 0$ controls volatility of the state. Rather than discretizing the state process, we leave it as continuous and proceed by hand.

In this setting, the functional equation (4.32) for v becomes

$$v(x) = x + \beta \mathscr{E}_\theta[v(\rho x + \sigma W)] \tag{4.35}$$

for each $x \in \mathsf{X}$, where W is standard normal.

Since $\rho x + \sigma W$ is Gaussian, the expression (4.33) for the risk-adjusted expectation of a normal random variable leads us to conjecture that the solution v will be linear, in the sense that $v(x) = ax + b$ for some $a, b \in \mathbb{R}$. This conjecture turns out to be correct:

Figure 4.5: Approximate and true solutions in the Gaussian case

Exercise 4.3.4. Verify that $v(x) = ax + b$ solves (4.35) when

$$a := \frac{1}{1 - \rho\beta} \quad \text{and} \quad b := \theta \frac{\beta}{1 - \beta} \frac{(a\sigma)^2}{2}.$$

We can see that, under the stated assumptions, lifetime value v is increasing in the state variable x. However, the impact of the parameters generally depends on θ. For example, if $\theta > 0$, increasing σ shifts up lifetime utility. If $\theta < 0$, then lifetime value decreases with σ. This is as we expect: lifetime utility is affected positively or negatively by volatility, depending on whether or not the agent is risk averse or risk loving.

Figure 4.5 shows the true solution $v(x) = ax + b$ to the risk-sensitive lifetime utility model, as well as an approximate fixed point from a discrete approximation. The discrete approximation is computed by applying successive approximation to K_θ after discretizing the state process via Tauchen's method. The parameters and discretization are shown in Listing 13.

Exercise 4.3.5. Replicate Figure 4.5.

Exercise 4.3.6. Dropping the Gaussian assumption, suppose now that consumption is IID with $C_t = c(X_t)$ where $(X_t)_{t \geqslant 0}$ is IID with distribution φ on finite set X. Thus,

```
using LinearAlgebra, QuantEcon

function create_rs_utility_model(;
        n=180,      # size of state space
        β=0.95,     # time discount factor
        ρ=0.96,     # correlation coef in AR(1)
        σ=0.1,      # volatility
        θ=-1.0)     # risk aversion
    mc = tauchen(n, ρ, σ, 0, 10)  # n_std = 10
    x_vals, P = mc.state_values, mc.p
    r = x_vals      # special case u(c(x)) = x
    return (; β, θ, ρ, σ, r, x_vals, P)
end
```

Listing 13: Risk sensitive utility model parameters (`rs_utility.jl`)

the operator K_θ becomes

$$(K_\theta v)(x) = r(x) + \beta \frac{1}{\theta} \ln \left\{ \sum_{x' \in \mathsf{X}} \exp(\theta v(x')) \varphi(x') \right\} \qquad (x \in \mathsf{X}).$$

While iterating on K_θ is convergent, there is a more efficient method, which reduces to solving a one-dimensional equation. Propose such a method and confirm that it is convergent. [Hint: Consider reviewing §5.2.2.2.]

4.3.3 Epstein–Zin Preferences

One of the most popular specifications of recursive preferences in quantitative research is Epstein–Zin utility. This class of preferences has been used to study asset pricing, business cycles, monetary policy, fiscal policy, optimal taxation, climate policy, pension plans, and many other topics. In this section we introduce the Epstein–Zin specification and discuss how to solve it. We will see that the specification, while highly nonlinear, is nonetheless well behaved.

4.3.3.1 Specification

With **Epstein–Zin** preferences, the additively separable relationship $V_t = u(C_t) + \beta \mathbb{E}_t V_{t+1}$ is replaced by

$$V_t = \left\{ (1-\beta) C_t^\alpha + \beta [\mathbb{E}_t V_{t+1}^\gamma]^{\alpha/\gamma} \right\}^{1/\alpha}, \tag{4.36}$$

where γ and α are nonzero parameters. As for risk-sensitive preferences, lack of additive separability implies that there is no neat sequential representation for lifetime value. As a result, we must work directly with the recursive expression (4.36).

Assume as before that $C_t = c(X_t)$, where $c \in \mathbb{R}_+^{\mathsf{X}}$ and $(X_t)_{t \geqslant 0}$ is P-Markov on finite set X. Hence we conjecture a solution of the form $V_t = v(X_t)$ for some $v \in V := \mathbb{R}_+^{\mathsf{X}}$. Under this conjecture, the **Epstein–Zin Koopmans operator** corresponding to (4.36) is

$$(Kv)(x) = \left\{ (1-\beta) c(x)^\alpha + \beta \left[\sum_{x'} v(x')^\gamma P(x, x') \right]^{\alpha/\gamma} \right\}^{1/\alpha} \qquad (x \in \mathsf{X}), \tag{4.37}$$

As discussed further in §4.3.4.2, the parameter γ governs risk aversion with respect to temporal gambles (where outcomes are resolved in the next period), while $\beta \in (0, 1)$ controls impatience and α parametrizes the intertemporal elasticity of substitution. The fact that all three parameters have distinct interpretations assists calibration or estimation exercises, where parameters are mapped to values in order to run quantitative exercises. This is one of the attractive features of Epstein–Zin preferences.

The first question we need to address is whether or not Epstein–Zin preferences are well defined. In particular, what conditions do we need on primitives such that the Koopmans operator K in (4.37) has a unique fixed point?

4.3.3.2 Properties of the Koopmans Operator

Let's begin by slightly generalizing (4.37) and writing it in vector form as

$$Kv = \left\{ r + \beta [P v^\gamma]^{\alpha/\gamma} \right\}^{1/\alpha} \tag{4.38}$$

where $r \in \mathbb{R}^{\mathsf{X}}$. This version reduces to (4.37) when $r = (1-\beta) c^\alpha$.

Let $r_1 := \min_x r(x)$ and $r_2 := \max_x r(x)$. In all of the remainder of this section, we suppose that the following holds:

Assumption 4.3.1. The primitives obey $0 < \beta < 1$, $\gamma < 0 < \alpha$, and $r_1 > 0$.

Remark 4.3.3. In the asset pricing literature, where Epstein–Zin specifications are common, parameters obeying $\gamma < 0 < \alpha$ are standard. The assumption $r \gg 0$ is required to avoid taking negative exponents of zero. This assumption is innocuous for quantitative work because r_1 can be taken arbitrarily close to zero.

While the assumption $\beta < 1$ cannot be dropped in what follows, other conditions on α and γ can be handled using methods similar to those developed below.

Let $V := [v_1, v_2]$ where $v_1 := m_1 \mathbb{1}$ and $v_2 := m_2 \mathbb{1}$ with

$$m_1 := \left(\frac{r_1/2}{1-\beta}\right)^{1/\alpha} \quad \text{and} \quad m_2 := \left(\frac{2r_2}{1-\beta}\right)^{1/\alpha}.$$

(Recall that the order-interval $[v_1, v_2]$ is all $f \in \mathbb{R}^{\mathsf{X}}$ such that $v_1 \leqslant f \leqslant v_2$.)

Lemma 4.3.3. *The operator K in (4.38) is an order-preserving self-map on V. Moreover,*

$$Kv_1 \gg v_1 \quad \textit{and} \quad Kv_2 \ll v_2. \tag{4.39}$$

Proof. Since $\gamma < 0 < \alpha$ and $P \geqslant 0$, for any $v, w \in V$, we have

$$v \leqslant w \implies v^\gamma \geqslant w^\gamma \implies Pv^\gamma \geqslant Pw^\gamma \implies [Pv^\gamma]^{\alpha/\gamma} \leqslant [Pw^\gamma]^{\alpha/\gamma}.$$

Hence $Kv \leqslant Kw$ and K is order-preserving. As a result, the claim that K is a self-map on V will be complete if we can show that $Kv_1 \geqslant v_1$ and $Kv_2 \leqslant v_2$. These weak inequalities will hold if we can prove (4.39).

To see that (4.39) holds, observe that

$$Kv_1 = \left\{r + \beta \frac{r_1/2}{1-\beta}\right\}^{1/\alpha} \geqslant \left\{r_1 + \beta \frac{r_1/2}{1-\beta}\right\}^{1/\alpha} > \left\{\frac{r_1/2}{1-\beta}\right\}^{1/\alpha}.$$

Hence $Kv_1 \gg v_1$. A similar argument shows that $Kv_2 \ll v_2$. □

4.3.3.3 A Conjugate Operator

When studying existence and uniqueness, it turns out to be easier to rearrange the fixed point problem via a smooth transformation. This transforms K into a new operator, which we label $\hat{K}$. This operator is simpler to work with than K, because it decomposes the Epstein–Zin update rule into two parts: a linear map P and a separate nonlinear component. Having transformed K into $\hat{K}$, we will then show that $\hat{K}$ is stable and $\hat{K}$ and K are topologically conjugate (§2.2.1). This proves stability of K.

To begin we let $w := v^\gamma$ and $\theta := \gamma/\alpha$. With this notation, the fixed point of K in (4.38) becomes $w = \left\{r + \beta(Pw)^{1/\theta}\right\}^\theta$. Let $\hat{K}$ be the corresponding fixed point operator, which we write as

$$\hat{K}w := F(Pw) \quad \text{with} \quad F(t) := \left\{r + \beta t^{1/\theta}\right\}^\theta. \tag{4.40}$$

The function F in (4.40) is applied to the vector Pw pointwise (i.e., element by element). F is a self-map on $(0, \infty)$.

Recalling that $w = v^\gamma$, we can translate any fixed point w of $\hat{K}$ into a fixed point v of K via $v = w^{1/\gamma}$. In fact we have the following much stronger result. In stating it we let Φ be defined at $v \in \mathbb{R}^{\mathsf{X}}$ with $v \gg 0$ by $\Phi v = v^\gamma$.

Lemma 4.3.4. *If $\hat{V} := \Phi V$, then Φ is a homeomorphism from V to $\hat{V}$ and (V, K) and $(\hat{V}, \hat{K})$ are topologically conjugate under Φ.*

Proof. Fix $v \in V$. Φ is continuous from V onto $\hat{V}$, with continuous inverse $\Phi^{-1}w = w^{1/\gamma}$. Hence Φ is a homeomorphism. In addition, for $v \in V$ and any $x \in \mathsf{X}$,

$$\hat{K}\Phi v = \left\{r + \beta(P\Phi v)^{1/\theta}\right\}^\theta = \left\{r + \beta[P(v^\gamma)]^{\alpha/\gamma}\right\}^{\gamma/\alpha} = \Phi K v$$

Thus, $\hat{K}\Phi v = \Phi K v$ for all $v \in V$, or $\hat{K}\Phi = \Phi K$. Rearranging gives $K = \Phi^{-1}\hat{K}\Phi$, so (V, K) and $(\hat{V}, \hat{K})$ are topologically conjugate, as claimed. □

4.3.3.4 Stability of the Conjugate Operator

Since K and $\hat{K}$ are conjugate maps, we can now study stability of K by analyzing the more tractable operator $\hat{K}$.

One idea is to seek conditions under which $\hat{K}$ is a contraction map. Unfortunately, this approach fails under many useful parameterizations. To see why, suppose that X contains a single element, so that r is a constant, P is the identity and w is a scalar satisfying $\hat{K}w = F(w) = \left\{r + \beta w^{1/\theta}\right\}^\theta$. This map is shown in Figure 4.6 when $\theta = 5$, $r = 0.5$ and $\beta = 0.5$. The figure shows that the function $\hat{K}$ has infinite slope in the neighborhood of zero. Functions with slopes greater than one are not contractions.[2]

Exercise 4.3.7. Prove that, under the figures stated in the previous paragraph, the function $F(t) = \left\{r + \beta t^{1/\theta}\right\}^\theta$ satisfies $F'(t) \to \infty$ and $t \downarrow 0$.

[2]We could try to truncate the interval to a neighborhood of the fixed point and hope that $\hat{K}$ is a contraction when restricted to this interval. But in higher dimensions we are not even sure that a fixed point exists for a broad range of parameters, which makes this idea hard to implement.

Figure 4.6: Shape properties of $\hat{K}$ in one dimension

Although the discussion so far does not tell us how to proceed, Figure 4.6 is still promising. If we restrict attention to the interval $(0, \infty)$, this one-dimensional version of $\hat{K}$ is seen to be globally stable. Moreover, we can see that the shape properties of $\hat{K}$ are helping us here—in particular, the fact that $\hat{K}$ is concave and increasing.

Exercise 4.3.8. Prove that, when $\theta < 0$, the function

$$F(t) := \left\{ r + \beta t^{1/\theta} \right\}^{\theta} \tag{4.41}$$

is increasing and concave on $(0, \infty)$.

From the shape properties of F and the Markov properties of P, we can now derive the following result.

Lemma 4.3.5. *The operator $\hat{K}$ is concave and order-preserving on $\hat{V}$.*

Proof. Exercise 4.3.8 tells us that F is increasing and concave on $(0, \infty)$. Moreover, $w \mapsto Pw$ is order-preserving and linear on all of $\mathbb{R}^{\mathsf{X}}$, and hence order-preserving and concave on $\hat{V}$. As a result, the composition $\hat{K} := F \circ P$ is order-preserving and concave on $\hat{V}$. □

Since $\hat{K}$ is concave and order-preserving, a natural next step is to apply Du's theorem (page 55). To this end, observe that the set $\hat{V} = \Phi V$ is all $w \in \mathbb{R}^{\mathsf{X}}$ such that

$v_1 \leqslant w^{1/\gamma} \leqslant v_2$. Equivalently, since $\gamma < 0$,

$$\hat{V} = [w_1, w_2] \quad \text{where} \quad w_1 := v_2^\gamma \quad \text{and} \quad w_2 := v_1^\gamma.$$

Lemma 4.3.6. *The operator $\hat{K}$ satisfies $\hat{K}w_1 \gg w_1$ and $\hat{K}w_2 \ll w_2$.*

Proof. Recall from Lemma 4.3.3 that $Kv_2 \ll v_2$. Since $w_1 = \Phi v_2$, we have $\hat{K}w_1 = \hat{K}\Phi v_2 = \Phi K v_2 \gg \Phi v_2 = w_1$. The proof that $\hat{K}w_2 \ll w_2$ is similar. □

We can now prove

Proposition 4.3.7. *Under Assumption 4.3.1, the Epstein–Zin Koopmans operator* (4.38) *is globally stable on V.*

Proof of Proposition 4.3.7. By Lemmas 4.3.5–4.3.6, combined with the fixed point result in Du's theorem, the operator $\hat{K}$ is globally stable on $\hat{V}$ under Assumption 4.3.1. By this fact and Proposition 2.2.1, the operator K is globally stable on V under the same conditions. □

Proposition 4.3.7 implies that Epstein–Zin utility (which is defined as the fixed point of K) is well-defined under the stated conditions and, moreover, that the fixed point can be computed via successive approximation. Listing 14 provides code for performing this operation. Figure 4.7 shows convergence of the sequence of iterates to the fixed point v^*, under the parameters in Listing 14, given an initial condition v_0. The figure plots every 10th iterate, repeated 100 times.

4.3.4 A General Representation

It will be helpful in what follows if we can define recursive preferences more generally, rather than just listing examples. There are various constructions available in the literature. Many are quite tedious for applied researchers hoping to do quantitative work. Here we give a parsimonious definition that relies on Markov structure.

4.3.4.1 An Operator-Theoretic View

What is the most general definition of recursive utility? One answer is as follows: Given a finite set X and a function class $V \subset \mathbb{R}^{\mathsf{X}}$, we define a **Koopmans operator** to be any globally stable order-preserving self-map K on V. A solution to the recursive

```julia
include("s_approx.jl")
using LinearAlgebra, QuantEcon

function create_ez_utility_model(;
        n=200,      # size of state space
        ρ=0.96,     # correlation coef in AR(1)
        σ=0.1,      # volatility
        β=0.99,     # time discount factor
        α=0.75,     # EIS parameter
        γ=-2.0)     # risk aversion parameter

    mc = tauchen(n, ρ, σ, 0, 5)
    x_vals, P = mc.state_values, mc.p
    c = exp.(x_vals)

    return (; β, ρ, σ, α, γ, c, x_vals, P)
end

function K(v, model)
    (; β, ρ, σ, α, γ, c, x_vals, P) = model

    R = (P * (v.^γ)).^(1/γ)
    return ((1 - β) * c.^α + β * R.^α).^(1/α)
end

function compute_ez_utility(model)
    v_init = ones(length(model.x_vals))
    v_star = successive_approx(v -> K(v, model),
                               v_init,
                               tolerance=1e-10)
    return v_star
end
```

Listing 14: Epstein–Zin utility model and Koopmans operator (`ez_utility.jl`)

Figure 4.7: Convergence of Koopmans iterates for Epstein–Zin utility

utility problem, also called **lifetime utility**, is a fixed point of K in V. Given such a v, the value $v(x)$ is interpreted as lifetime value conditional on $X_0 = x$.

The next examples illustrate the fact that the statement $v = Kv$ is just an abstract representation of the statement that lifetime value v is defined as the solution to a (possibly nonlinear) equation in value space.

Example 4.3.1. Recall that, in the case of additively separable preferences, lifetime value is given by $(V_t)_{t \geqslant 0}$ where $V_t = u(C_t) + \beta \mathbb{E}_t V_{t+1}$ for all t. In §4.3.1.1 we reduced this problem to one of finding a $v \in V := \mathbb{R}^{\mathsf{X}}$ such that $v = r + \beta P v$. Equivalently, v is the fixed point of $Kv := r + \beta P v$. The operator K is globally stable and order-preserving whenever $\beta \in (0, 1)$, and therefore a Koopmans operator

Example 4.3.2. The operator K_θ defined in (4.34) is such that lifetime value under risk-sensitive preferences corresponds to a $v \in \mathbb{R}^{\mathsf{X}}$ satisfying $v = K_\theta v$. K_θ is order-preserving and also globally stable under standard parameterizations (Proposition 4.3.2). This justifies the name "risk-sensitive Koopmans operator" that we applied in §4.3.2.

Our definition of a Koopmans operator is nonstandard and hence requires some justification. On one hand, we cannot place many restrictions on an operator K that yields lifetime utility as a fixed point, since there are many varied forms of recursive

preferences. On the other hand, we suppose that a uniform increase in future values will increase current value. (In fact, we see this property in all applications we consider.) This monotonicity justifies the assumption that K is order-preserving.

Regarding global stability, it is natural to assume that K has a unique fixed point, since that fixed point defines lifetime value. If K fails to have a unique fixed point then the recursive preference specification is not well posed. Our assumption of global stability strengthens existence and uniqueness by requiring global convergence to the fixed point under iteration. This condition is also natural, since $K^T w$ computes utility over T periods with terminal condition $w \in V$. Hence global stability is just the requirement that finite-horizon utility converges to infinite-horizon utility as the time horizon converges to infinity.

Example 4.3.3. To illustrate this last point, consider again the additively separable preferences $V_t = u(C_t) + \beta \mathbb{E}_t V_{t+1}$ in Example 4.3.1. Suppose that the time horizon is finite, with some exogenous terminal value $V_T = w(X_T)$ at time T. Iterating forward from V_0 gives

$$V_0 = u(C_0) + \beta \mathbb{E}_0 V_1 = u(C_0) + \beta \mathbb{E}_0 \left[u(C_1) + \beta \mathbb{E}_1 V_2 \right] = u(C_0) + \beta \mathbb{E}_0 u(C_1) + \beta^2 \mathbb{E}_0 V_2.$$

Continuing forward until time T yields

$$V_0 = \sum_{t=0}^{T-1} \beta^t \mathbb{E}_0 u(C_t) + \beta^T \mathbb{E}_0 V_T.$$

Shifting to functional form and using $r = u \circ c$, the last expression becomes

$$v = \sum_{t=0}^{T-1} (\beta P)^t r + (\beta P)^T w.$$

By Exercise 1.2.14 on page 24, this is just $K^T w$ when K is the associated Koopmans operator $Kv := r + \beta P v$ and, moreover, $K^T w \to v^* := (I - \beta P)^{-1} r$. Thus, global stability of K tells us that a finite-horizon valuation with arbitrary terminal condition w converges to the infinite-horizon valuation.

4.3.4.2 Risk-Adjusted Expectations

The operator-theoretic definition of Koopmans operators in §4.3.4.1 is general but also rather abstract. Typically, in a Markov representation of recursive utility, we can construct the Koopmans operator by combining four key components: Markov

dynamics, current rewards, an aggregation function and risk-adjusted expectation operators.

In the remainder of this section, we will build Koopmans operators from these primitives and connect them to applications. We start by defining the last of the primitives: risk-adjusted expectation operators.

Given $V \subset \mathbb{R}^{\mathsf{X}}$, we define a **risk-adjusted expectation operator** on V to be a map R from $V \times \mathscr{D}(\mathsf{X})$ to $\mathbb{R}$ such that, for all $v, w \in V$ and $\varphi \in \mathscr{D}(\mathsf{X})$,

(i) $v \leqslant w$ implies $R(v, \varphi) \leqslant R(w, \varphi)$ and

(ii) $R(\lambda \mathbb{1}, \varphi) = \lambda$ for all $\lambda \geqslant 0$.

One special case of a risk-adjusted expectation operator is ordinary expectations:

Exercise 4.3.9. Let $V = \mathbb{R}^{\mathsf{X}}$. Show that $R_E(v, \varphi) := \sum_{x \in \mathsf{X}} v(x)\varphi(x)$ is a risk-adjusted expectation operator on V.

Another example is found in the risk-adjusted expectation we used to study risk-sensitive preferences.

Example 4.3.4. Let $V = \mathbb{R}^{\mathsf{X}}$. The function

$$R_e(v, \varphi) := \frac{1}{\theta} \ln \left\{ \sum_{x \in \mathsf{X}} \exp(\theta v(x)) \varphi(x) \right\}$$

is a risk-adjusted expectation on V for all $\theta \neq 0$. R_e is called the **entropic risk-adjusted expectation operator**.

Exercise 4.3.10. Confirm that R_e is in fact a risk-adjusted expectations operator.

Example 4.3.5. As a third example, let $V = \mathbb{R}_+^{\mathsf{X}}$. The map

$$R_\gamma(v, \varphi) := \left\{ \sum_{x \in \mathsf{X}} v^\gamma(x) \varphi(x) \right\}^{1/\gamma} \tag{4.42}$$

is a risk-adjusted expectation operator on V for all $\gamma \neq 0$.[3] The map R_γ is sometimes called the **Kreps-Porteus expectations operator**.

We met R_γ in §4.3.3, when we discussed Epstein–Zin preferences.

Exercise 4.3.11. Confirm that $\mathbb{R}_\gamma$ is a risk-adjusted expectations operator.

[3]The function v^γ is defined by $v^\gamma(x) = (v(x))^\gamma$ for all x. We restrict attention to $V = \mathbb{R}_+^{\mathsf{X}}$ to ensure that (4.42) is well defined. If $\gamma < 0$ and $v(x) = 0$ for some $x \in \mathsf{X}$ we set $R_\gamma(v, \varphi) := 0$.

4.3.4.3 Aggregation

We mentioned in §4.3.4.1 that the Koopmans operators usually involve four key components: Markov dynamics, current rewards, an aggregation function and risk-adjusted expectation operators. More formally, we combine

(i) A stochastic matrix P on X,

(ii) an **aggregator** $A\colon \mathbb{R}^2 \to \mathbb{R}$ such that $y \mapsto A(c, y)$ is increasing for all $c \in \mathbb{R}$,

(iii) a reward function $r \in \mathbb{R}^{\mathsf{X}}$, and

(iv) a risk-adjusted expectation operator R on $V \times \mathscr{D}(\mathsf{X})$.

We then set

$$(Kv)(x) = A[r(x), R(v, P(x, \cdot))] \qquad (v \in V,\ x \in \mathsf{X}). \tag{4.43}$$

Example 4.3.6 (Min aggregator)**.** One aggregator sometimes used in the literature is the **Leontief aggregator** $A(c, y) = \min\{(1-\beta)c, \beta y\}$. Under this specification, the Koopmans operator (4.43) becomes

$$(Kv)(x) = \min\{r(x), R(v, P(x, \cdot))\}.$$

Exercise 4.3.12. Prove that K is order-preserving on V.

Example 4.3.7. In the case of risk-sensitive preferences, the risk-sensitive Koopmans operator defined on page 122 can be expressed as

$$(K_\theta v)(x) = r(x) + \beta R_e(v, P(x, \cdot)) \qquad (x \in \mathsf{X}),$$

where R_e is the entropic risk-adjusted expectations operator. This is a special case of (4.43) with $V = \mathbb{R}^{\mathsf{X}}$, and aggregator $A(c, y) = c + \beta y$.

Example 4.3.8. The Epstein–Zin preferences Koopmans operator can be expressed as

$$(Kv)(x) = \left\{(1-\beta)c(x)^\alpha + \beta R_\gamma(v, P(x, \cdot))^\alpha\right\}^{1/\alpha} \qquad (x \in \mathsf{X}), \tag{4.44}$$

where R_γ is the Kreps–Porteus expectations operator, as defined in (4.42). This is a version of (4.43) when the aggregator is defined by

$$A(c, y) := ((1-\beta)c^\alpha + \beta y^\alpha)^{1/\alpha} \tag{4.45}$$

is called the **CES aggregator**, where CES stands for constant elasticity of substitution.

The CES aggregator from the preceding example is so-named because, in a static utility maximization problem where c and y are two goods and preferences are given by (4.45), the elasticity of substitution is constant and given by $1/(1-\alpha)$. In the present setting, $1/(1-\alpha)$ is usually called the **elasticity of intertemporal substitution** (EIS), since the trade-off is between current and next-period rewards. The next exercise explains.

Exercise 4.3.13. Consider $A(c, y) = ((1-\beta)c^\alpha + \beta y^\alpha)^{1/\alpha}$ as a utility function over current and future goods c and y. Then

$$\text{EIS} := \frac{d\ln(y/c)}{d\ln(A_c/A_y)} \quad \text{where} \quad A_c := \frac{\partial A(c,y)}{\partial c} \quad \text{and} \quad A_y := \frac{\partial A(c,y)}{\partial y}.$$

Confirm that EIS $= 1/(1-\alpha)$.

4.3.4.4 Stability

For K in (4.43) to qualify as a Koopmans operator we need it to be globally stable on V. We discussed special cases of stability above. Here we present one more general result. In stating it, we define a risk-adjusted expectations operator R on V to be **subadditive** when

$$R(v + \lambda\mathbb{1}, \varphi) \leqslant R(v, \varphi) + \lambda \tag{4.46}$$

for all $v \in V$, $\varphi \in \mathscr{D}(\mathsf{X})$ and $\lambda \in \mathbb{R}_+$.

Lemma 4.3.8. *When R is subadditive and $\varphi \in \mathscr{D}(\mathsf{X})$ we have*

$$|R(v, \varphi) - R(w, \varphi)| \leqslant |v - w| \qquad (v, w \in \mathbb{R}^{\mathsf{X}}).$$

Proof. Let the primitives be as stated. Fix $v, w \in V$. By monotonicity and subadditivity of R, we have

$$R(v, \varphi) = R(v - w + w, \varphi) \leqslant R(\|v - w\|\mathbb{1} + w, \varphi) \leqslant R(w, \varphi) + \|v - w\|.$$

Rearranging gives $R(v, \varphi) - R(w, \varphi) \leqslant |v - w|$. Reversing the roles of v and w proves the claim in Lemma 4.3.8. □

While the subadditive condition (4.46) is nontrivial, it holds for some useful cases, such as the entropic risk-adjusted expectation operator defined on page 133:

Lemma 4.3.9. *The entropic risk-adjusted expectations operator R_e is subadditive.*

Proof. Fix $v \in V$, $\varphi \in \mathscr{D}(\mathsf{X})$ and $\lambda \in \mathbb{R}_+$. Let X be a draw from φ. We have

$$R_e(v + \lambda \mathbb{1}, \varphi) = \frac{1}{\theta} \ln \{\mathbb{E} \exp[\theta(v(X) + \lambda)]\} = \frac{1}{\theta} \ln \{\mathbb{E} \exp[\theta v(X)] \cdot \exp(\theta\lambda)\}.$$

Since $\ln(ab) = \ln a + \ln b$ for $a, b > 0$, condition (4.46) holds. □

Take $r \in \mathbb{R}^{\mathsf{X}}$ to be a given reward function, P to be an arbitrary stochastic matrix on X, R be a risk-adjusted expectations operator on $V := \mathbb{R}^{\mathsf{X}}$ and let A be an aggregator. We now have the following stability result.

Proposition 4.3.10. *If $A(c, y) = c + \beta y$ for some $\beta \in (0, 1)$ and R is subadditive, then the associated operator $(Kv)(x) = r(x) + \beta R(v, P(x, \cdot))$ is globally stable on V.*

Proof. Let the primitives be as stated. For any $f \in \mathbb{R}^{\mathsf{X}}$, we write the function $x \mapsto R(f, P(x, \cdot))$ as $R(f, P)$. Fix $v, w \in V$. By subadditivity of R, we have

$$|Kv - Kw| = \beta |R(v, P) - R(w, P)| \leqslant \beta |v - w|,$$

where the last inequality is by Lemma 4.3.8. Taking the supremum over x shows that K is a contraction of modulus β with respect to the supremum norm on V. Hence global stability holds. □

Exercise 4.3.14. Show that the claim in Proposition 4.3.10 remains true of we replace the additive aggregator $A(c, y) = c + \beta y$ with the Leontief aggregator $A(c, y) = \min\{(1 - \beta)c, \beta y\}$. [Hint: Look at the second last inequality in Lemma 2.1.1.]

4.4 Chapter Notes

The discounted additively separable preference structure introduced in §4.3.1 is originally due to Samuelson (1939). An axiomatic foundation was supplied by Koopmans (1960). A critical review can be found in Frederick et al. (2002). Examples of modeling exercises using time-varying discount rates include Krusell and Smith (1998), Christiano et al. (2014), Albuquerque et al. (2016), Basu and Bundick (2017), de Groot et al. (2018), Schorfheide et al. (2018), Toda (2019), Hills et al. (2019) and Hubmer et al. (2020). Theoretical discussion of dynamic programming with time-varying discount rates can be found in Stachurski and Zhang (2021) and Toda (2021).

The fundamental neoclassical theory of asset pricing is discussed in many sources, including Hansen and Renault (2010), Ross (2009), Cochrane (2009), Duffie (2010)

and Campbell (2017). Neoclassical finance is thoughtful and elegant, and also deeply flawed, in the sense that we can find any number of ways in which financial markets deviate from its predictions. Nonetheless, the theory is extremely valuable as a benchmark from which analysis can proceed, as well as a way to communicate ideas.

In §4.3.1.2 we presented an artificial scenario to motivate recursive preferences. Do the deficiencies in additively separability really matter for economic modeling? Evidence suggests that the answer is affirmative. In macroeconomics and asset pricing in particular, researchers increasingly use non-separable preferences in order to bringing model outputs closer to the data. For example, many quantitative models of asset pricing rely heavily on Epstein–Zin preferences. Representative examples include Bansal and Yaron (2004), Bansal et al. (2012), and Schorfheide et al. (2018). Theoretical properties and solution methods are discussed in Epstein and Zin (1991), Pohl et al. (2018) and De Groot et al. (2022).

An accessible introduction to recursive preference models can be found in Backus et al. (2004). Our use of the term "Koopmans operator," which is used by some authors but not entirely standard, honors early contributions by Nobel laureate Tjalling Koopmans on recursive preferences.

There is a strong connection between risk-sensitive preferences and the literature on robust control. See, for example, Cagetti et al. (2002) or Hansen and Sargent (2007). Risk-sensitivity is studied in an optimal growth setting by Bäuerle and Jaśkiewicz (2018). Risk-sensitivity is also used in applications of reinforcement learning, where the underlying state process is not known. See, for example, Shen et al. (2014), Majumdar et al. (2017) or Gao et al. (2021).

Some recursive preference specifications involve ambiguity aversion. An introduction to this literature and its applications can be found in Klibanoff et al. (2009), Hayashi and Miao (2011), Hansen and Miao (2018), Bommier et al. (2019) and Hansen and Sargent (2020).

Another deviation from the standard additively separable model of Samuelson (1939) is hyperbolic discounting. Important references include Rubinstein (2003), Diamond and Köszegi (2003), Dasgupta and Maskin (2005), Karp (2005), Cao and Werning (2018), Balbus et al. (2018), Hens and Schindler (2020), Jaśkiewicz and Nowak (2021), Drugeon and Wigniolle (2021), and Balbus et al. (2022),

The theoretical properties of recursive preference models are studied in many papers, including Boyd (1990), Hansen and Scheinkman (2009), Marinacci and Montrucchio (2010), Bloise and Vailakis (2018), Marinacci and Montrucchio (2019), Pohl et al. (2019), Balbus (2020), Borovička and Stachurski (2020), and Christensen (2022). The paper by Marinacci and Montrucchio (2019) provides a useful alternative approach to existence of unique fixed points in the setting of order-preserving maps.

Chapter 5

Optimal Stopping

In the previous chapter we completed a careful study of computing lifetime rewards. In this chapter we return to the problem of maximizing lifetime rewards by choosing optimal policies. This discussion will formalize and extend our treatment of job search in §3.3.

The class of problems we consider in this chapter all involve choosing when to act in the face of risk and uncertainty. The job search model studied in Chapters 1–3 is, of course, one such application. Others include if or when to exit or enter a market, default on a loan, exploit some new technology, or exercise a real or financial option.

All of these problems can be solved using dynamic programming. Moreover, they have common features that allow us to find sharp characterizations of optimality. Finally, they offer an excellent introduction to dynamic programming because the binary choice (stop or continue) makes the recursive representations particularly clear.

5.1 Introduction to Optimal Stopping

In this section we begin with the standard theory of optimal stopping and then consider alternative approaches, based around continuation values and threshold policies. One key objective is to provide a rigorous discussion of optimality, which improves on our intuitive analysis in the context of job search in §1.3.

5.1.1 Theory

Our first step is to set out the fundamental theory of discrete time infinite-horizon optimal stopping problems.

5.1.1.1 The Stopping Problem

Let X be a finite set. An **optimal stopping problem** with state space X consists of

(i) a stochastic matrix P on X,

(ii) a discount factor $\beta \in (0, 1)$,

(iii) a **continuation reward function** $c \in \mathbb{R}^{\mathsf{X}}$, and

(iv) an **exit reward function** $e \in \mathbb{R}^{\mathsf{X}}$.

Given a P-Markov chain $(X_t)_{t \geqslant 0}$, the problem evolves as follows: An agent observes the state X_t in each period and decides whether to continue or stop. If she chooses to stop, she receives $e(X_t)$ and the process terminates. If she decides to continue, then she receives $c(X_t)$ and the process repeats next period. Lifetime rewards are given by

$$\mathbb{E} \sum_{t \geqslant 0} \beta^t R_t,$$

where R_t equals $c(X_t)$ while the agent continues, $e(X_t)$ when the agent stops, and zero thereafter.

Example 5.1.1. In the infinite-horizon job search problem from Chapter 1, the wage offer process (W_t) is IID with common distribution φ on finite set W, and the choice is between accepting the job offer and receiving unemployment compensation and waiting till next period. This is an optimal stopping problem with state space $\mathsf{X} = \mathsf{W}$ and stochastic matrix P having all rows equal to φ, so that all draws are IID from φ. The exit reward function is $e(x) = x/(1 - \beta)$ and the continuation reward function is constant and equal to unemployment compensation.

Example 5.1.2. Consider an infinite-horizon American call option, which provides the right to buy a given asset at strike price K at each future point in time. The market price of the asset is given by $S_t = s(X_t)$, where (X_t) is P-Markov on finite set X. The interest rate is $r > 0$. The decision of when to exercise is an optimal stopping problem, with exit corresponding to exercise of the option. The discount factor is $1/(1+r)$, the exit reward function is $e(x) = s(x) - K$ and the continuation reward is zero.[1]

As for the job search problem, the actions of the agent will be expressed in terms of a **policy function**, which is a map σ from X to $\{0, 1\}$. The interpretation is that, on observing state x at any given time, the agent responds with action $\sigma(x)$, where 0

[1] We are studying American options in discrete time. Options with discrete exercise times are sometimes called **Bermudan options**. References for the continuous time case are provided in §5.3.

means "continue" and 1 means "stop." Implicit in this formulation is the assumption that the current state contains enough information for the agent to decide whether or not to stop.

Let Σ be the set of functions from X to $\{0, 1\}$. Let $v_\sigma(x)$ denote the expected lifetime value of following policy σ now and in every future period, given current state $x \in \mathsf{X}$. We call v_σ the **σ-value function**. Below, in §5.1.1.3, we show that v_σ is well defined and describe how to calculate it.

The function v_σ is an essential object in what follows, since our aim is to choose a policy that maximizes lifetime value. In particular, a policy $\sigma^* \in \Sigma$ is called **optimal** if

$$v_{\sigma^*}(x) = \max_{\sigma \in \Sigma} v_\sigma(x) \quad \text{for all } x \in \mathsf{X}. \tag{5.1}$$

5.1.1.2 Policy Valuation

Fixing $\sigma \in \Sigma$, let us think about how to pin down the σ-value function v_σ. Recall that $v_\sigma(x)$ is the lifetime value of following σ conditional on state x. Some thought will convince you that v_σ must satisfy

$$v_\sigma(x) = \sigma(x)e(x) + (1 - \sigma(x)) \left[c(x) + \beta \sum_{x' \in \mathsf{X}} v_\sigma(x')P(x, x') \right] \quad \text{for all } x \in \mathsf{X}. \tag{5.2}$$

To see this, suppose first that $\sigma(x) = 1$. In this case, (5.2) states that $v_\sigma(x) = e(x)$, which is what we expect: choosing to stop yields the exit reward. If instead $\sigma(x) = 0$, then (5.2) becomes

$$v_\sigma(x) = c(x) + \beta \sum_{x' \in \mathsf{X}} v_\sigma(x')P(x, x'), \tag{5.3}$$

which is what we expect: the value of continuing is the current reward plus the discounted expected reward obtained by continuing with policy σ next period.

Now all that remains is to solve (5.2) for the function v_σ. To do this, we set

$$r_\sigma(x) := \sigma(x)e(x) + (1 - \sigma(x))c(x) \quad \text{and} \quad P_\sigma(x, x') := (1 - \sigma(x))P(x, x').$$

With this notation, we can write (5.2) pointwise as $v_\sigma = r_\sigma + \beta P_\sigma v_\sigma$. If $r(\beta P_\sigma) < 1$, then we have

$$v_\sigma = (I - \beta P_\sigma)^{-1} r_\sigma. \tag{5.4}$$

Exercise 5.1.1. Confirm that $r(\beta P_\sigma) < 1$ holds for any optimal stopping problem.

By Exercise 5.1.1 and the Neumann series lemma, v_σ is uniquely defined by (5.4).

5.1.1.3 Policy Operators

For the proofs below, it is helpful to view v_σ as the fixed point of a certain operator. In particular, we pair each $\sigma \in \Sigma$ with a corresponding **policy operator**, denoted by T_σ, and defined at $v \in \mathbb{R}^{\mathsf{X}}$ by

$$(T_\sigma v)(x) = \sigma(x)e(x) + (1 - \sigma(x)) \left[c(x) + \beta \sum_{x' \in \mathsf{X}} v(x')P(x, x') \right] \tag{5.5}$$

for each $x \in \mathsf{X}$.

Exercise 5.1.2. Prove that, for any $\sigma \in \Sigma$, the operator T_σ is order-preserving with respect to the pointwise partial order $\leqslant$ on $\mathbb{R}^{\mathsf{X}}$.

Using the notation defined in §5.1.1.2, we can also write define T_σ via

$$T_\sigma v = r_\sigma + \beta P_\sigma v.$$

Hence $v \in \mathbb{R}^{\mathsf{X}}$ is a fixed point of T_σ if and only if $v = r_\sigma + \beta P_\sigma v$. Thus, by $r(\beta P_\sigma) < 1$ and (5.4), the policy value function v_σ is the unique fixed point of T_σ in $\mathbb{R}^{\mathsf{X}}$. The next result shows that, in addition, iterates of T_σ converge to v_σ.

Proposition 5.1.1. *For any $\sigma \in \Sigma$, the policy operator T_σ is a contraction of modulus β on $\mathbb{R}^{\mathsf{X}}$ under to the supremum norm.*

Exercise 5.1.3. Prove Proposition 5.1.1.

5.1.1.4 The Value Function

In the job search problem, we found the optimal policy by computing the fixed point of the Bellman operator. Here we do the same while also explaining more carefully the relationship between optimality and the fixed point of the Bellman operator.

First we define the **value function** v^* of the optimal stopping problem as

$$v^*(x) := \max_{\sigma \in \Sigma} v_\sigma(x) \qquad (x \in \mathsf{X}). \tag{5.6}$$

In particular, $v^*(x)$ is the maximal lifetime value available to an agent facing current state x. In view of the discussion in §1.2.1.5, we can also write $v^* = \vee_\sigma v_\sigma$.

How should we obtain the value function, given that solving the maximization in (5.6) is, in general, a hard problem? Our steps are as follows: We

(i) introduce Bellman's equation for the optimal stopping problem, which is

$$v(x) = \max\left\{e(x), c(x) + \beta \sum_{x' \in \mathsf{X}} v(x')P(x, x')\right\} \qquad (x \in \mathsf{X}), \tag{5.7}$$

(ii) prove that Bellman's equation has a unique solution in $\mathbb{R}^{\mathsf{X}}$, and, finally,

(iii) show that this solution equals the value function, as defined in (5.6).

These steps are completed in §5.1.1.5 below.

5.1.1.5 The Bellman Operator

The **Bellman operator** for the optimal stopping problem is the operator T such that any fixed point of T solves Bellman's equation and vice versa. This is true by construction for T defined by $v \mapsto Tv$,

$$(Tv)(x) = \max\left\{e(x),\ c(x) + \beta \sum_{x' \in \mathsf{X}} v(x')P(x, x')\right\} \qquad (x \in \mathsf{X}). \tag{5.8}$$

Pointwise, we can express T via $Tv = e \vee (c + \beta Pv)$.

Exercise 5.1.4. Prove that T is an order preserving self-map on $\mathbb{R}^{\mathsf{X}}$.

Here is the main result for this section:

Proposition 5.1.2. *For the optimal stopping problem defined in §5.1.1.1,*

(i) *T is a contraction map of modulus β on $\mathbb{R}^{\mathsf{X}}$, under the supremum norm $\|\cdot\|_\infty$ and*

(ii) *the unique fixed point of T on $\mathbb{R}^{\mathsf{X}}$ is the value function v^*.*

Exercise 5.1.5. Prove the claim in (i) of Proposition 5.1.2.

Proof of Proposition 5.1.2. With the result of Exercise 5.1.5 in hand, we need only show that the unique fixed point of T in $\mathbb{R}^{\mathsf{X}}$, denoted by $\bar{v}$, is equal to $v^* = \vee_\sigma v_\sigma$. We show $\bar{v} \leqslant v^*$ and then $\bar{v} \geqslant v^*$.

For the first inequality, let $\sigma \in \Sigma$ be defined by

$$\sigma(x) = \mathbb{1}\left\{e(x) \geqslant c(x) + \beta \sum_{x' \in \mathsf{X}} \bar{v}(x')P(x, x')\right\} \quad \text{for all } x \in \mathsf{X}.$$

Observe that, for this choice of σ, we have, for any $x \in \mathsf{X}$,

$$\begin{aligned}(T_\sigma \bar{v})(x) &= \sigma(x)e(x) + (1-\sigma(x))\left[c(x) + \beta \sum_{x' \in \mathsf{X}} \bar{v}(x')P(x,x')\right] \\ &= \max\left\{e(x),\ c(x) + \beta \sum_{x' \in \mathsf{X}} \bar{v}(x')P(x,x')\right\} = (T\bar{v})(x) = \bar{v}(x).\end{aligned}$$

In particular, $T_\sigma \bar{v} = T\bar{v} = \bar{v}$. But the only fixed point of T_σ in $\mathbb{R}^{\mathsf{X}}$ is v_σ, so it must be the case that $\bar{v} = v_\sigma$. But then $\bar{v} \leqslant v^*$, by the definition of v^*. This is our first inequality.

Regarding the second inequality, fix $\sigma \in \Sigma$ and observe that $Tv \geqslant T_\sigma v$ for all $v \in \mathbb{R}^{\mathsf{X}}$. Since T is order-preserving and globally stable, Proposition 2.1.2 on page 49 implies that $v_\sigma \leqslant \bar{v}$. Taking the maximum over $\sigma \in \Sigma$ yields $v^* \leqslant \bar{v}$. □

5.1.1.6 Optimal Policies

Paralleling the definition provided in the discussion of job search (§1.3), for each $v \in \mathbb{R}^{\mathsf{X}}$, we call $\sigma \in \Sigma$ **v-greedy** if

$$\sigma(x) = \mathbb{1}\left\{e(x) \geqslant c(x) + \beta \sum_{x' \in \mathsf{X}} v(x')P(x,x')\right\} \quad \text{for all } x \in \mathsf{X}. \tag{5.9}$$

A v-greedy policy uses v to assign values to states and then chooses to stop or continue based on the action that generates a higher payoff.

With this language in place, our informal argument in §1.1.2.1 that optimal choices can be made using the value function becomes precise in the next proposition.

Proposition 5.1.3. *Policy $\sigma \in \Sigma$ is optimal if and only if it is v^*-greedy.*

Proposition 5.1.3 is a version of **Bellman's principle of optimality**.

Corollary 5.1.4. *The optimal stopping problem has exactly one optimal policy.*

Proof. This follows directly from Proposition 5.1.3, since, given v^*, the greedy policy

$$\sigma^*(x) := \mathbb{1}\left\{e(x) \geqslant c(x) + \beta \sum_{x' \in \mathsf{X}} v^*(x')P(x,x')\right\} \qquad (x \in \mathsf{X}) \tag{5.10}$$

is clearly uniquely defined. □

5.1.1.7 Value Function Iteration

The theory stated above tells us that successive approximation using the Bellman operator converges to v^* and v^*-greedy policies are optimal. These facts make value function iteration (VFI) a natural algorithm for solving optimal stopping problems. Since VFI for optimal stopping problems is directly analogous VFI for job search, as shown on page 35, we do not repeat it here.

5.1.2 Firm Valuation with Exit

In Chapter 4 we discussed firm valuation under a range of scenarios. In each case, value was obtained as expected present value of the cash flow generated by profits, which is a standard and well-used methodology. It does, however, ignore an important fact: firms have the option to cease operations and sell all remaining assets. In this section, we consider firm valuation in the presence of this exit option.

5.1.2.1 Optional Exit

Consider a firm where productivity is exogenous and evolves according to a Q-Markov chain (Z_t) on finite set $\mathsf{Z} \subset \mathbb{R}$. Profits are given by $\pi_t = \pi(Z_t)$ for some fixed $\pi \in \mathbb{R}^{\mathsf{Z}}$. At the start of each period, the firm decides whether to remain in operation, receiving current profit π_t, or to exit, receiving scrap value $s > 0$ for sale of physical assets. Discounting is at fixed rate r and $\beta := 1/(1+r)$. We assume that $r > 0$.

Let Σ be all $\sigma\colon \mathsf{Z} \to \{0, 1\}$. For given $\sigma \in \Sigma$ and $v \in \mathbb{R}^{\mathsf{Z}}$, the corresponding policy operator is

$$(T_\sigma v)(z) = \sigma(z)s + (1 - \sigma(z)\left[\pi(z) + \beta \sum_{z'} v(z')Q(z, z')\right] \qquad (z \in \mathsf{Z}).$$

We saw in §5.1.1.2–§5.1.1.3 that T_σ has a unique fixed point v_σ and that $v_\sigma(z)$ represents the value of following policy σ forever, conditional on $Z_0 = z$.

The Bellman operator for the firm's problem is the order-preserving self-map T on $\mathbb{R}^{\mathsf{Z}}$ defined by

$$(Tv)(z) = \max\left\{s, \pi(z) + \beta \sum_{z'} v(z')Q(z, z')\right\} \quad (z \in \mathsf{Z}).$$

Pointwise, T can be written as $Tv = s \vee (\pi + \beta Qv)$.

Figure 5.1: Value function for firms with exit option

Let v^* be the value function for this problem. By Proposition 5.1.2, v^* is the unique fixed point of T in $\mathbb{R}^{\mathsf{Z}}$ and the unique solution to Bellman's equation. Moreover, successive approximation from any $v \in \mathbb{R}^{\mathsf{Z}}$ converges to v^*. Finally, by Proposition 5.1.3, a policy is optimal if and only if it is v^*-greedy.

Figure 5.1 shows the value function v^*, along with the stopping value s and the continuation value function $h^* = \pi + \beta Q v^*$, under the parameterization given in Listing 15. As implied by Bellman's equation, v^* is the pointwise maximum of s and h^*. The v^*-greedy policy $\sigma^*(z) = \mathbb{1}\{s \geqslant h^*(z)\}$ instruct the firm to exit when the continuation value of the firm falls below the scrap value.

Exercise 5.1.6. Replicate Figure 5.1 by using the parameters in Listing 15 and applying value function iteration. Reviewing the code for job search on page 93 should be helpful.

5.1.2.2 Exit vs No-Exit

If we define w by $w(z) = \mathbb{E}_z \sum_{t \geqslant 0} \beta^t \pi_t$ for all $z \in \mathsf{Z}$, then $w(z)$ is the value of the firm given $Z_0 = z$ when the firm never exits. In other words, w evaluates the firm according to expected present value of the profit stream. Figure 5.2 shows w, denoted as the no-exit value, based on the parameterization in Listing 15.

In Figure 5.2, we see that $w \leqslant v^*$ on Z. Let's now prove that this is always true.

```
"Creates an instance of the firm exit model."
function create_exit_model(;
        n=200,                  # productivity grid size
        ρ=0.95, μ=0.1, ν=0.1,   # persistence, mean and volatility
        β=0.98, s=100.0         # discount factor and scrap value
    )
    mc = tauchen(n, ρ, ν, μ)
    z_vals, Q = mc.state_values, mc.p
    return (; n, z_vals, Q, β, s)
end
```

Listing 15: Firm exit model (`firm_exit.jl`)

Figure 5.2: Firm value with and without exit

To show $w \leqslant v^*$, first observe that $w = (I - \beta Q)^{-1}\pi$, by $\beta < 1$ and Lemma 4.1.1 on page 100. Rearranging gives $w = \pi + \beta Q w$.

Now note that under the policy $\sigma \equiv 0$, where the firm never chooses to exit, we have $T_\sigma v = \pi + \beta Q v$. Hence the unique fixed point of T_σ is w. As a result, $w = v_\sigma$ for $\sigma \equiv 0$. But $v^* \geqslant v_\sigma$ for all $\sigma \in \Sigma$. This proves that $w \leqslant v^*$.

In terms of intuition, choosing to never exit is a feasible policy. Since v^* involves maximization of firm value over the set of all feasible policies, it must be at least as large.

Exercise 5.1.7. Prove the following: If $Q \gg 0$ and $s > w(z)$ for at least one $z \in \mathsf{Z}$, then $w \ll v^*$. Provide some intuition for this result.

Exercise 5.1.8. Consider a version of the model of firm value with exit where productivity is constant but prices are stochastic. In particular, the prices process (P_t) for the final good is Q-Markov. Suppose further that one-period profits for a given price p are $\max_{\ell \geqslant 0} \pi(\ell, p)$, where ℓ is labor input. Suppose that $\pi(\ell, p) = p\ell^{1/2} - w\ell$, where the wage rate w is constant. Write down Bellman's equation for this model.

5.1.3 Monotonicity

In this section we consider monotonicity in values and actions. In doing so, we return to the general optimal stopping problem described in §5.1.1, with X as the state space, e as the exit reward function and c as the continuation reward function.

5.1.3.1 Monotone Values

Let v^* be the value function of the optimal stopping problem defined by X, P, β, c and e. We define the corresponding **continuation value function** h^* to be

$$h^*(x) := c(x) + \beta \sum_{x' \in \mathsf{X}} v^*(x') P(x, x') \qquad (x \in \mathsf{X}). \tag{5.11}$$

(Please be sure to avoid confusing the continuation reward function c and the continuation value function h^*.)

Let X be partially ordered and let $i\mathbb{R}^{\mathsf{X}}$ be the increasing functions in $\mathbb{R}^{\mathsf{X}}$.

Lemma 5.1.5. *If $e, c \in i\mathbb{R}^{\mathsf{X}}$ and P is monotone increasing, then h^* and v^* are both increasing.*

Proof. Let the stated conditions hold. The Bellman operator can be written pointwise as $Tv = e \vee (c + \beta Pv)$. Since P is monotone increasing, P is invariant on $i\mathbb{R}^{\mathsf{X}}$. It follows from this fact and the conditions on e and c that T is invariant on $i\mathbb{R}^{\mathsf{X}}$. Hence, by Exercise 1.2.15 on page 24, v^* is in $i\mathbb{R}^{\mathsf{X}}$. Since $h^* = c + \beta Pv^*$, the same is true for h^*. □

Example 5.1.3. Consider the firm problem with exit, as described in §5.1.2, with Bellman operator $Tv = s \vee (\pi + \beta Qv)$. Since s is constant, it follows directly that v^* and h^* are both increasing functions when $\pi \in i\mathbb{R}^{\mathsf{Z}}$ and Q is monotone increasing.

5.1.3.2 Monotone Actions

The optimal policy in the IID job search problem takes the form $\sigma^*(w) = \mathbb{1}\{w \geqslant w^*\}$ for all $w \in \mathsf{W}$, where $w^* := (1-\beta)h^*$ is the reservation wage and h^* is the continuation value (see page 34). This optimal policy is of threshold type: once the wage offer exceeds the threshold, the agent always stops.

Since threshold policies are convenient, let us now try to characterize them.

Throughout this section, we take X to be a subset of $\mathbb{R}$. Elements of X are ordered by $\leqslant$, the usual order on $\mathbb{R}$.

Exercise 5.1.9. Prove that the optimal policy σ^* is decreasing on X whenever e is decreasing on X and h^* is increasing on X.

For a binary function on $\mathsf{X} \subset \mathbb{R}$, the condition that σ^* is decreasing means that the controller exists when x is sufficiently small and continues otherwise.

Example 5.1.4. In the firm problem with exit, as described in §5.1.2, h^* is increasing whenever $\pi \in i\mathbb{R}^{\mathsf{Z}}$ and Q is monotone increasing. Since the scrap value is constant, Exercise 5.1.9 applies under these conditions. Hence the optimal policy is decreasing. This reasoning agrees with Figure 5.1, where exit is optimal when the state is small and continuing is optimal when z is large. This makes sense, since Q is monotone increasing, so low current values of z predict low future values of z (and the profits associated with continuing will also be low).

Exercise 5.1.10. Show that the conditions of Exercise 5.1.9 hold when e is constant on X, c is increasing on X and P is monotone increasing.

Exercise 5.1.11. Prove that the optimal policy σ^* is increasing on X whenever e is increasing on X and h^* is decreasing on X.

Example 5.1.5. In the IID job search problem, $e(w) = w/(1-\beta)$ is increasing and h^* is constant. Hence the result in Exercise 5.1.11 applies. This is why the optimal policy $\sigma^*(w) = \mathbb{1}\{w \geqslant (1-\beta)h^*\}$ is increasing. The agent accepts all sufficiently large wage offers.

In the settings of Exercises 5.1.9–5.1.11, the optimal policy is either increasing or decreasing. Since X is totally ordered, monotonicity implies that the policy is of threshold type. For example, if σ^* is increasing, then we take x^* to be the smallest $x \in \mathsf{X}$ such that $\sigma^*(x) = 1$. For such an x^* we have

$$x < x^* \implies \sigma^*(x) = 0 \quad \text{and} \quad x \geqslant x^* \implies \sigma^*(x) = 1.$$

Remark 5.1.1. The conditions in Exercises 5.1.9–5.1.11 are sufficient but not necessary for monotone policies. For example, Figure 3.9 on 94 provides an example of a setting where the policy is increasing (the agent accepts for sufficiently large wage offers) even though both $e(x) = x/(1-\beta)$ and h^* are strictly increasing.

5.1.4 Continuation Values

In §1.3.2.2 we used a "continuation value" approach to solving the job search problem with IID draws, which involved computing the continuation value h^* directly and then setting the optimal policy to $\sigma^*(w) = \mathbb{1}\{w/(1-\beta) \geqslant h^*\}$. We saw that this approach is more efficient than first computing the value function, since the continuation value is one-dimensional rather than $|\mathsf{W}|$-dimensional.

In §3.3.1.2, we tried the same approach for the job search problem with Markov state, where wage draws are correlated. We found that there is no clear benefit to the continuation value approach in that setting, since the continuation value function has the same dimensionality as the value function.

These observations motivate us to explore continuation value methods more carefully. In this section, we state the continuation value approach for the general optimal stopping problem and verify convergence. We will see that, while all relevant state components must be included in the value function, purely transitory components do not affect continuation values. Hence the continuation value approach is at least as efficient and sometimes radically more so.

Another asymmetry between value functions and continuation value functions is that the latter are typically smoother. For example, in job search problems, the value function is usually kinked at the reservation wage, while the continuation value function is smooth. Relative smoothness comes from taking expectations over stochastic

transitions, since integration is a smoothing operation. Like lower dimensionality, increased smoothness helps with both analysis and computation.

5.1.4.1 Useful Techniques

Let h^* be the continuation value function for the optimal stopping problem, as defined in (5.11). To compute h^* directly we begin with the optimal stopping version of Bellman's equation evaluated at v^* and rewrite it as

$$v^*(x') = \max\{e(x'), h^*(x')\} \qquad (x' \in \mathsf{X}). \tag{5.12}$$

Taking expectations of both sides of this equation conditional on current state x produces $\sum_{x' \in \mathsf{X}} v^*(x')P(x,x') = \sum_{x' \in \mathsf{X}} \max\{e(x'), h^*(x')\} P(x,x')$. Multiplying by β, adding $c(x)$, and using the definition of h^*, we get

$$h^*(x) = c(x) + \beta \sum_{x' \in \mathsf{X}} \max\{e(x'), h^*(x')\} P(x,x') \qquad (x \in \mathsf{X}). \tag{5.13}$$

This expression motivates us to introduce the **continuation value operator** $C \colon \mathbb{R}^{\mathsf{X}} \to \mathbb{R}^{\mathsf{X}}$ via

$$(Ch)(x) = c(x) + \beta \sum_{x' \in \mathsf{X}} \max\{e(x'), h(x')\} P(x,x') \qquad (x \in \mathsf{X}). \tag{5.14}$$

Proposition 5.1.6. *The operator C is a contraction of modulus β on $\mathbb{R}^{\mathsf{X}}$. Moreover, the unique fixed point of C in $\mathbb{R}^{\mathsf{X}}$ is h^*.*

Proposition 5.1.6 provides us with an alternative method to compute the optimal policy, which does not involve value function iteration:

(i) Use successive approximation with C to compute h^* (at least approximately) and

(ii) Calculate σ^* via $\sigma^*(x) = \mathbb{1}\{e(x) \geqslant h^*(x)\}$ for each $x \in \mathsf{X}$.

In §5.1.4.2 we discuss settings where this approach is advantageous.

Proof of Proposition 5.1.6. Fix $f, g \in \mathbb{R}^{\mathsf{X}}$ and $x \in \mathsf{X}$. By the triangle inequality and the bound $|\alpha \vee x - \alpha \vee y| \leqslant |x - y|$ from page 32, we have

$$\begin{aligned} |(Cf)(x) - (Cg)(x)| &\leqslant \beta \sum_{x' \in \mathsf{X}} |\max\{e(x'), f(x')\} - \max\{e(x'), g(x')\}| \, P(x,x') \\ &\leqslant \beta \sum_{x' \in \mathsf{X}} |f(x') - g(x')| \, P(x,x'). \end{aligned}$$

The right-hand side is dominated by $\beta\|f-g\|_\infty$. Taking the maximum on the left-hand side gives

$$\|Cf - Cg\|_\infty \leqslant \beta\|f - g\|_\infty,$$

which confirms that C is a contraction of modulus β on $\mathbb{R}^{\mathsf{X}}$.

From the contraction property, we know that C has exactly one fixed point in $\mathbb{R}^{\mathsf{X}}$. Let $\bar{h}$ be this function. We claim that $\bar{h} = h^*$.

Let $\bar{v} := e \vee \bar{h}$. (We use functional notation here and for the rest of the proof, so that operations and relations are all pointwise.) To show that $\bar{h} = h^*$, it suffices to show that $\bar{v} = v^*$. Indeed, if $\bar{v} = v^*$, then

$$\bar{h} = C\bar{h} = c + \beta P(e \vee \bar{h}) = c + \beta P\bar{v} = c + \beta Pv^* = h^*.$$

To see that $\bar{v} = v^*$, we again use $\bar{h} = C\bar{h}$ to obtain

$$e \vee \bar{h} = e \vee (C\bar{h}) = e \vee \left[c + \beta P(e \vee \bar{h})\right].$$

Using $\bar{v} = e \vee \bar{h}$, we can write this as $\bar{v} = e \vee [c + \beta P\bar{v}]$. This is just Bellman's equation in functional notation. As v^* is the only solution to Bellman's equation in $\mathbb{R}^{\mathsf{X}}$ (Proposition 5.1.3), we have $\bar{v} = v^*$, as claimed. □

5.1.4.2 Dimensionality Reduction

In the discussion at the start of §5.1.4, we mentioned that switching from value function iteration to continuation value iteration can greatly reduce the dimensionality of the problem in some cases. Here we try to pin down the cases where this works.

To begin, let W and Z be two finite sets and suppose that $\varphi \in \mathscr{D}(\mathsf{W})$ and Q is a stochastic matrix on Z. Let (W_t) be IID with distribution φ and let (Z_t) be an Q-Markov chain on Z. If (W_t) and (Z_t) are independent, then (X_t) defined by $X_t = (W_t, Z_t)$ is P-Markov on X, where

$$P(x, x') = P((w, z), (w', z')) = \varphi(w')Q(z, z').$$

Suppose that the continuation reward depends only on z. In this case, we can write the Bellman operator as

$$(Tv)(w, z) = \max\left\{e(w, z),\ c(z) + \beta \sum_{w' \in \mathsf{W}} \sum_{z' \in \mathsf{Z}} v(w', z')\varphi(w')Q(z, z')\right\}. \tag{5.15}$$

Since the right-hand side depends on both w and z, the Bellman operator acts in an n-dimensional space, where $n := |\mathsf{X}| = |\mathsf{W}| + |\mathsf{Z}|$.

However, if we inspect the right-hand side of (5.15), we see that the continuation value function depends only on z. Dependence on w is absent because w does not help predict w'. Thus, the continuation value function is an object in $|\mathsf{Z}|$-dimensional space. The continuation value operator

$$(Ch)(z) = c(z) + \beta \sum_{w' \in \mathsf{X}} \sum_{z' \in \mathsf{X}} \max\{e(w', z'), h(z')\} \, \varphi(w') Q(z, z') \qquad (z \in \mathsf{Z}) \tag{5.16}$$

acts in this lower dimensional-space.

Example 5.1.6. We can embed the IID the job search problem into this setting by taking (W_t) to be the wage offer process and (Z_t) to be constant. This is why the IID case offers a large dimensionality reduction when we switch to continuation values.

More examples of dimensionality reduction are shown in the applications below.

5.1.4.3 Application to Firm Value

Consider the firm valuation problem from §5.1.2 but suppose now that scrap value fluctuates over time, according to the prices of the underlying assets. For simplicity let's assume that scrap value at each time t is given by the IID sequence (S_t), where each S_t has density φ on $\mathbb{R}_+$. The corresponding Bellman operator is

$$(Tv)(z, s) = \max\left\{ s, \pi(z) + \beta \sum_{z'} \int v(z', s') \varphi(s') \, \mathrm{d}s' Q(z, z') \right\}.$$

We can convert this problem to a finite state space optimal stopping problem by discretizing the distribution φ onto a finite grid contained in $\mathbb{R}_+$. However, a better approach is to switch to the continuation value operator, since continuation values depend only on z.

Exercise 5.1.12. Write down the continuation value operator for this function as a mapping from $\mathbb{R}^{\mathsf{Z}}$ to itself.

Exercise 5.1.13. In §3.2.4.2 we defined stochastic dominance for distributions on finite sets. For densities φ and ψ on $\mathbb{R}_+$, the definition is similar: we say that ψ stochastically dominates φ and write $\varphi \preceq_{\mathrm{F}} \psi$ if $\int u(x)\varphi(x) \, \mathrm{d}x \leqslant \int u(x)\psi(x) \, \mathrm{d}x$ for

every u in $i\mathbb{R}^{\mathsf{X}}$.[2] With this definition, show that if φ_a and φ_b are two alternative distributions for scrap value and $\varphi_a \preceq_{\mathrm{F}} \varphi_b$, then $\sigma_a^* \geqslant \sigma_b^*$ pointwise on Z, where σ_i^* is the optimal policy corresponding to distribution φ_i for $i \in \{a, b\}$. Interpret this result.

5.2 Further Applications

In this section we discuss some further applications of optimal stopping and apply the results described above.

5.2.1 American Options

American options were introduced briefly in Example 5.1.2 on page 139. Here we investigate this class of derivatives more carefully. We focus on American call options, which provide the right to buy a given asset (e.g., 1,000 shares in some underlying equity) at any time during some specified period at some fixed **strike price** K. The market price of the asset at time t is denoted by S_t.

The infinite horizon case was discussed in Example 5.1.2. However, options without termination dates—also called perpetual options—are rare in practice. Hence we focus on the finite-horizon case. We are interested in computing the expected value of holding the option when discounting with a fixed interest rate. This is a standard approach to pricing American options.

Finite horizon American options can be solved by backward induction, analogous to the finite horizon job search problem discussed in Chapter 1. Alternatively, we can embed finite horizon options into the theory of infinite-horizon optimal stopping. This second approach is convenient for us, since the theory of infinite-horizon optimal stopping has already been presented.

To perform this embedding, we take $T \in \mathbb{N}$ to be a fixed integer indicating the date of expiration. The option is purchased at $t = 0$ and can be exercised at $t \in \mathbb{N}$ with $t \leqslant T$. To include t in the current state, we set

$$\mathsf{T} := \{1, \ldots, T+1\} \quad \text{and} \quad m(t) := \min\{t+1, T+1\} \text{ for all } t \in \mathsf{T}.$$

[2]Actually, in most definitions, u is also restricted to be bounded and measurable, in order to ensure that the integrals are finite. These technicalities can be ignored in the exercise.

The idea is that time is updated via $t' = m(t)$, so that time increments at each update until $t = T + 1$. After that we hold t constant. Bounding time at $T + 1$ keeps the state space finite.

We assume that the stock price S_t evolves according to

$$S_t = Z_t + W_t \quad \text{where} \quad (W_t)_{t \geqslant 0} \overset{\text{IID}}{\sim} \varphi \in \mathscr{D}(\mathsf{W}).$$

Here $(Z_t)_{t \geqslant 0}$ is Q-Markov on finite set Z for some stochastic matrix Q and W is also finite. This means that the share price is affected by a persistent and purely transient component. We choose parameters such that $(Z_t)_{t \geqslant 0}$ is close to a random walk, implying that price changes are difficult to predict.

To convert these update rules into an optimal stopping problem, as defined in §5.1.1.1, we need to specify the state and clarify the stochastic matrix P on X that maps to the state process. We set the state space to $\mathsf{X} := \mathsf{T} \times \mathsf{W} \times \mathsf{Z}$ and

$$P((t, w, z), (t', w', z')) := \mathbb{1}\{t' = m(t)\} \varphi(w') Q(z, z').$$

In other words, time updates deterministically via $t' = m(t)$ and z' and w' are drawn independently from $Q(z, \cdot)$ and φ respectively.

As in the perpetual option case, the continuation reward is zero and the discount rate is $\beta := 1/(1 + r)$, where $r > 0$ is a fixed risk-free rate. The exit reward can be expressed as $\mathbb{1}\{t \leqslant T\}(S_t - K)$. In other words, exercise at time t earns the owner $S_t - K$ up to expiry and zero thereafter. In terms of the state (t, z), the exit reward is

$$e(t, w, z) := \mathbb{1}\{t \leqslant T\}[z + w - K].$$

Bellman's equation can be written as

$$v(t, w, z) = \max \left\{ e(t, w, z),\ \beta \sum_{w'} \sum_{z'} v(t', w', z') \varphi(w') Q(z, z') \right\},$$

where $t' = m(t)$. This relationship neatly captures the value of the option: It is the maximum of current exercise value and the discounted expected value of carrying the option over to the next period.

Since the problem described above is an optimal stopping problem in the sense of §5.1.1.1, all of the optimality results described above apply. In particular, iterates of the Bellman operator converge to the value function v^* and, moreover, a policy is optimal if and only if it is v^*-greedy.

We can do better than value function iteration. Since $(W_t)_{t \geqslant 0}$ is IID and appears

```julia
using QuantEcon, LinearAlgebra, IterTools

"Creates an instance of the option model with log S_t = Z_t + W_t."
function create_american_option_model(;
        n=100, μ=10.0,  # Markov state grid size and mean value
        ρ=0.98, ν=0.2,  # persistence and volatility for Markov state
        s=0.3,          # volatility parameter for W_t
        r=0.01,         # interest rate
        K=10.0, T=200)  # strike price and expiration date
    t_vals = collect(1:T+1)
    mc = tauchen(n, ρ, ν)
    z_vals, Q = mc.state_values .+ μ, mc.p
    w_vals, φ, β = [-s, s], [0.5, 0.5], 1 / (1 + r)
    e(t, i_w, i_z) = (t ≤ T) * (z_vals[i_z] + w_vals[i_w] - K)
    return (; t_vals, z_vals, w_vals, Q, φ, T, β, K, e)
end
```

Listing 16: Pricing and American option (`american_option.jl`)

only in the exit reward, we can reduce dimensionality by switching to the continuation value operator, which, in this case, can be expressed as

$$(Ch)(t,z) = \beta \sum_{z'} \sum_{w'} \max\{e(t',w',z'),\, h(t',z')\}\, \varphi(w')Q(z,z'). \tag{5.17}$$

As proved in §5.1.4, the unique fixed point of C is the continuation value function h^*, and $C^k h \to h^*$ as $k \to \infty$ for all $h \in \mathbb{R}^{\mathsf{X}}$. With the fixed point in hand, we can compute the optimal policy as

$$\sigma^*(t,w,z) = \mathbb{1}\{e(t,w,z) \geqslant h^*(t,z)\}.$$

Here $\sigma^*(t,w,z) = 1$ indicates exercise of the option at time t.

Figure 5.3 provides a visual representation of optimal actions under the default parameterization described in Listing 16. Each of the three figures show contour lines of the net exit reward $f(t,w,z) := e(t,w,z) - h^*(w,z)$, viewed as a function of (w,z), when t is held fixed. The date t for each subfigure is shown in the title. The optimal policy exercises the option when $f(t,w,z) \geqslant 0$.

In each subfigure, the **exercise region**, which is the set (w,z) such that $f(t,w,z) \geqslant 0$, correspond to the northeast part of the figure, where w and z are both large. The boundary between exercise and continuing is the zero contour line, which is shown in

black. Notice that the size of the the exercise region expands with t. This is because the value of waiting decreases when the set of possible exercise dates declines.

Figure 5.4 provides some simulations of the stock price process $(S_t)_{t \geqslant 0}$ over the lifetime of the option, again using the default parameterization described in Listing 16. The blue region in the top part of each subfigure is the values of the stock price $S_t = Z_t + W_t$ such that $S_t \geqslant K$. An option traded in this configuration (where the price of the underlying exceeds the strike price) is said to be "in the money." The figure also shows the optimal exercise date in each of the simulations, which is the first t such that $e(t, W_t, Z_t) \geqslant h^*(W_t, Z_t)$.

5.2.2 Research and Development

Consider a firm that engages in costly research and development (R&D) in order to develop a new product. The dynamic problem faced by the firm is whether to hold back and continue investing in the project or stop and bring the product to market. For simplicity, we assume here that the value of bringing the product to market is a one-off payoff $\pi_t = \pi(X_t)$, where (X_t) is Markov chain on finite set X with stochastic matrix P. The flow cost of investing in R&D is C_t per period, where (C_t) is a stochastic process. Future payoffs are discounted at rate $r > 0$ and we set $\beta := 1/(1+r)$.

5.2.2.1 Constant R&D Costs

As a first take on this problem, suppose that $C_t \equiv c \in \mathbb{R}_+$ for all t. This is an optimal stopping problem with exit reward $e = \pi$ and constant continuation reward $-c$. Bellman's equation for this problem is

$$v(x) = \max \left\{ \pi(x), -c + \beta \sum_{x'} v(x') P(x, x') \right\} \qquad (x \in \mathsf{X}). \tag{5.18}$$

Exercise 5.2.1. Write down the continuation value operator for this problem. Prove that the continuation value function h^* is increasing in x whenever $\pi \in i\mathbb{R}^{\mathsf{X}}$ and P is monotone increasing.

Exercise 5.2.2. Prove that the optimal policy σ^* is increasing whenever π is increasing and (X_t) is IID (so that all rows of P are identical). Provide economic intuition for this result.

Figure 5.3: Exercise region for the American option

Figure 5.4: Simulations for the American option process

5.2.2.2 IID R&D Costs

Let's suppose now that $(C_t)_{t\geqslant 0}$ is IID with common distribution $\varphi \in \mathscr{D}(\mathsf{W})$. Bellman's equation becomes

$$v(c,x) = \max\left\{\pi(x), -c + \beta \sum_{x'}\sum_{c'} v(c',x')\varphi(c')P(x,x')\right\}. \tag{5.19}$$

Since (C_t) is IID, we would ideally like to integrate it out in the manner of §5.1.4.2, thereby lowering the dimensionality of the problem. However, if we look at the continuation value associated with (5.19), we get

$$h(c,x) := -c + \beta \sum_{x'}\sum_{c'} v(c',x')\varphi(c')P(x,x'),$$

which still depends on c.

Fortunately, with a bit more thought, we can find a way to eliminate c. To this end, we define

$$g(x) := \sum_{x'}\sum_{c'} v(c',x')\varphi(c')P(x,x'), \tag{5.20}$$

which is the expected discounted value in state x. Rewriting Bellman's equation using g and replacing (c,x) with (c',x') gives

$$v(c',x') = \max\left\{\pi(x'), -c' + \beta g(x')\right\}.$$

Averaging over (c',x') and using the definition of g again gives

$$g(x) = \sum_{x'}\sum_{c'} \max\left\{\pi(x'), -c' + \beta g(x')\right\}\varphi(c')P(x,x'). \tag{5.21}$$

This is a functional equation in g, which depends only on x. To solve it, we introduce the operator R defined by

$$(Rg)(x) = \sum_{x'}\sum_{c'} \max\left\{\pi(x'), -c' + \beta g(x')\right\}\varphi(c')P(x,x') \quad (x \in \mathsf{X}).$$

Exercise 5.2.3. Prove that R is a contraction of modulus β on $\mathbb{R}^{\mathsf{X}}$.

From Exercise 5.2.3, we see that (5.21) has a unique solution in $\mathbb{R}^{\mathsf{X}}$, which we denote by g^*, and that g^* can be computed by successive approximation. With g^* in

hand, we can compute the optimal policy via

$$\sigma^*(c, x) = \mathbb{1}\left\{\pi(x), -c + \beta g^*(x)\right\}.$$

Remark 5.2.1. The technique we just used works by solving for the expected value function, as defined in (5.20). In §6.3 we analyze this method again in a more general setting and discuss its convergence properties.

5.3 Chapter Notes

Numerous textbooks treat optimal stopping in depth, although most use continuous time. Peskir and Shiryaev (2006) and Shiryaev (2007) are useful examples.

There are many applications of optimal stopping in economics and finance, with influential early research papers including McCall (1970), Jovanovic (1982), Hopenhayn (1992), and Ericson and Pakes (1995). In more recent literature, Arellano (2008) considers borrowing on international financial markets with the option of sovereign default (see §7.2.1.4). Riedel (2009) studies optimal stopping under Knightian uncertainty. Fajgelbaum et al. (2017) include an optimal stopping problem for firms in a model of uncertainty traps.

The firm problem with optimal exit is routinely used to analyze firm dynamics and firm size distributions in equilibrium models with heterogeneous firms. Hopenhayn (1992) is a classic reference. Perla and Tonetti (2014) study a variation where growth is created by firms at the bottom of the productivity distribution imitating more productive firms. Carvalho and Grassi (2019) analyze business cycles in a setting of firm growth with exit and a Pareto distribution of firms.

Regarding American options, the perpetual case is studied in Mordecki (2002). Practical methods for solving American option models are provided in Longstaff and Schwartz (2001), Rogers (2002), and Kohler et al. (2010).

Replacement problems are an important kind of optimal stopping problem not treated in this chapter. A classic early example is the paper by Rust (1987), which uses dynamic programming to consider optimal replacement of engine parts and structural estimation to fit parameters. Some discussion of structural estimation is provided in §6.3.1.

Chapter 6

Markov Decision Processes

In this chapter we study a class of discrete time, infinite horizon dynamic programs called Markov decision processes (MDPs). This class of problems is broad enough to encompass a very large range of applications, including the optimal stopping problems we analyzed in Chapter 5. It also provides the standard departure point for reinforcement learning, which combines statistical and artificial intelligence methods with dynamic programming in order to handle real-world settings where information on the underlying model is incomplete.

6.1 Definition and Properties

In this section we define MDPs and investigate their fundamental properties.[1]

6.1.1 The MDP Model

MDPs are dynamic programs characterized by two features: rewards are additively separable and the discount rate is constant. (Additive separability was defined and discussed in §4.3.)

In what follows we require the following definition: A **correspondence** Γ from one set X to another set A is a function from X into $\wp(\mathsf{A})$, the set of all subsets of A. The correspondence is called **nonempty** if $\Gamma(x) \neq \emptyset$ for all $x \in \mathsf{X}$. For example, the map Γ defined by $\Gamma(x) = [-x, x]$ is a nonempty correspondence from $\mathbb{R}$ to $\mathbb{R}$.

[1] As usual, we stick to finite states and actions, leaving general state-action problems to Volume II. Note, however, that, at least in principle, finite states and actions can closely approximate the continuous case. For example, in the interval $[0, 1]$, there are more than one billion 64-bit floating point numbers.

6.1.1.1 Definition

We study a controller who interacts with a state process $(X_t)_{t\geqslant 0}$ by choosing an action path $(A_t)_{t\geqslant 0}$ to maximize expected discounted rewards

$$\mathbb{E}\sum_{t\geqslant 0}\beta^t r(X_t, A_t), \tag{6.1}$$

taking an initial state X_0 as given. As with all dynamic programs, we insist that the controller is not clairvoyant: he or she cannot choose actions that depend on future states.

To formalize the problem, we fix a finite set X, henceforth called the **state space**, and a finite set A, henceforth called the **action space**. Given X and A, we define a (finite) **Markov decision process** (**MDP**) to be a tuple (Γ, β, r, P) containing

(i) a nonempty correspondence Γ from $\mathsf{X} \to \mathsf{A}$, referred to as the **feasible correspondence**, which in turn defines the **feasible state-action pairs**

$$\mathsf{G} := \{(x, a) \in \mathsf{X}\times\mathsf{A} : a \in \Gamma(x)\},$$

(ii) a constant β in $(0, 1)$, referred to as the **discount factor**,

(iii) a function r from G to $\mathbb{R}$, referred to as the **reward function**, and

(iv) a **stochastic kernel** P from G to X; that is, P is a map from $\mathsf{G}\times\mathsf{X}$ to $\mathbb{R}_+$ satisfying

$$\sum_{x'\in\mathsf{X}} P(x, a, x') = 1 \quad \text{for all } (x, a) \text{ in } \mathsf{G}.$$

The feasible correspondence restricts actions, in the sense that $\Gamma(x) \subset \mathsf{A}$ is the set of actions available to the controller in state x. Given a feasible state-action pair (x, a), reward $r(x, a)$ is received and the next period state x' is selected from $P(x, a, \cdot)$, which is an element of $\mathscr{D}(\mathsf{X})$. The dynamics and reward flow are summarized in Algorithm 3.

Bellman's equation associated with this problem is

$$v(x) = \max_{a\in\Gamma(x)}\left\{r(x, a) + \beta\sum_{x'\in\mathsf{X}} v(x')P(x, a, x')\right\} \qquad (x \in \mathsf{X}). \tag{6.2}$$

This can be understood as an equation in the unknown function $v \in \mathbb{R}^{\mathsf{X}}$. Below we define the value function v^* as maximal lifetime rewards and show that v^* is the unique solution to Bellman's equation in $\mathbb{R}^{\mathsf{X}}$.

Algorithm 3: MDP dynamics: states, actions, and rewards

```
t ← 0
input X_0
while t < ∞ do
    observe X_t
    choose action A_t
    receive reward r(X_t, A_t)
    draw X_{t+1} from P(X_t, A_t, ·)
    t ← t + 1
end
```

As for optimal stopping, Bellman's equation reduces an infinite-horizon problem to a two period problem. Current actions influence the two terms on the right hand side: current rewards and expected discounted value from future states. In every case we examine, there is a trade-off between maximizing current rewards and influencing the distribution $P(x, a, \cdot)$ of the next period state in order to obtain high future rewards.

6.1.1.2 Example: Cake Eating

Many dynamic programming problems in economics involve a trade-off between current and future consumption. The simplest example in this class is the "cake eating" problem, where initial household wealth is given but no labor income is received. Wealth evolves according to

$$W_{t+1} = R(W_t - C_t) \qquad (t = 0, 1, \ldots)$$

Here R is a gross rate of interest, so that investing d dollars today returns Rd next period, and C_t is current consumption. The agent seeks to maximize

$$\mathbb{E} \sum_{t \geqslant 0} \beta^t u(C_t) \quad \text{given } W_0 = w.$$

We assume that $C_t \geqslant 0$ and $W_t \geqslant 0$, so that the agent cannot borrow. Consumption level C_t generates utility $u(C_t)$. Assuming that wealth takes values in a finite set $\mathsf{W} \subset \mathbb{R}_+$, Bellman's equation for this problem can be written as

$$v(w) = \max_{0 \leqslant w' \leqslant Rw} \left\{ u\left(w - \frac{w'}{R}\right) + \beta v(w') \right\}. \tag{6.3}$$

In (6.3) we are using $w' = R(w - c)$ to obtain $c = (w - w'/R)$. The household uses (6.3) to trade-off current utility of consumption against the value of future wealth.

This model can be framed as an MDP with W as the state space. The action A_t is the choice of next period wealth W_{t+1}. Thus, the action space is also W. The feasible correspondence is

$$\Gamma(w) = \{a \in \mathsf{W} : a \leqslant Rw\} \qquad (w \in \mathsf{W}),$$

implying that $\mathsf{G} = \{(w, a) \in \mathsf{W} \times \mathsf{W} : a \leqslant Rw\}$. The current reward is utility of consumption, or

$$r(w, a) = u\left(w - \frac{a}{R}\right) \qquad ((w, a) \in \mathsf{G}).$$

The stochastic kernel is $P(w, a, w') = \mathbb{1}\{w' = a\}$. This just states that next period wealth w' is equal to the action a with probability one.

6.1.1.3 Example: Job Search

The optimal stopping problem we studied in Chapter 5 can be framed as an MDP. Here we show this for the job search problem with Markov state discussed in §3.3.1. As before, W is the set of wage outcomes. Since we need the symbol P for other purposes, we let Q be the stochastic matrix for wages, so that $(W_t)_{t \geqslant 0}$ is Q-Markov on W.

Remark 6.1.1. The fact that optimal stopping problems are a special case of the MDP model is significant because it allows us to apply results obtained for MDPs to optimal stopping. At the same time, expressing an optimal stopping problem as an MDP requires an additional state variable, which complicates the exposition. We provide the details for completeness but readers can skip to §6.1.2 without losing continuity.

To express the job search problem as an MDP, we let $\mathsf{X} = \{0, 1\} \times \mathsf{W}$ be the state space. typical element is (e, w), with e representing either unemployment ($e = 0$) or employment ($e = 1$) and w being the current wage offer. The action $a \in \mathsf{A} := \{0, 1\}$ indicates rejection or acceptance of the current wage offer.

To reflect the assumption that workers never leave the firm, we require $a \geqslant e$. Thus, the feasible correspondence is

$$\Gamma(x) = \Gamma(e, w) = \{a \in \{0, 1\} : a \geqslant e\}.$$

The set of feasible state-action pairs is, therefore, $\mathsf{G} = \{((e, w), a) \in \mathsf{X} \times \mathsf{A} : a \geqslant e\}$. The reward function is

$$r(x, a) = r((e, w), a) = aw + (1 - a)c.$$

Regarding the stochastic kernel, we need to define state transition probabilities for all feasible state-action pairs. Letting $P[(e,w),a,(e',w')]$ be the probability of transitioning to state (e',w') given current state (e,w) and current action $a \leqslant e$, we set

$$P[(0,w),a,(e',w')] = \mathbb{1}\{e'=a\} \cdot [\, a\mathbb{1}\{w'=w\} + (1-a)Q(w,w') \,] \tag{6.4}$$

and $P[(1,w),1,(e',w')] = \mathbb{1}\{e'=1\}\mathbb{1}\{w'=w\}$. Equation (6.4) says that if $a=0$ then $e'=0$ and the next wage is drawn from $Q(w,w')$, while if $a=1$ then $e'=1$ and the next wage is w.

Exercise 6.1.1. Verify that P is a stochastic kernel from G to X.

To double check that these definitions are correct, we can verify that they lead to the same Bellman equations that we saw in §3.3.1.

Exercise 6.1.2. Show that, under the definitions of Γ, r and P just provided, we have $v(1,w) = w + \beta\mathbb{E}v(1,w)$.

The last exercise implies that $v(1,w) = w/(1-\beta)$, which is what we expect for lifetime value of an agent employed with wage w.

Exercise 6.1.3. Show that, under these definitions of Γ, r and P, Bellman's equation for $v(0,w)$ agrees with the one we obtained for an unemployed agent on page 91.

Exercise 6.1.4. Extending this analysis, show that the job search with separation model from §3.3.2 is also an MDP.

6.1.2 Optimality

In this section we return to the general MDP setting of §6.1.1.1, define optimal policies and state our main optimality result. As was the case for job search, actions are governed by policies, which are maps from states to actions (see, in particular, §1.3.1.3, where policies were introduced).

6.1.2.1 Policies and Value

Given a fixed MDP (Γ,β,r,P), the set of **feasible policies** is

$$\Sigma := \{\sigma \in \mathsf{A}^{\mathsf{X}} : \sigma(x) \in \Gamma(x) \text{ for all } x \in \mathsf{X}\}. \tag{6.6}$$

If we select a particular policy σ from Σ, it is understood that we respond to state X_t with action $A_t := \sigma(X_t)$ at every date t. As a result, the state evolves by drawing X_{t+1} from $P(X_t, \sigma(X_t), \cdot)$ at each $t \geqslant 0$. In other words, $(X_t)_{t\geqslant 0}$ is P_σ-Markov for P_σ defined by

$$P_\sigma(x, x') := P(x, \sigma(x), x') \qquad (x, x' \in \mathsf{X}).$$

Fixing a policy "closes the loop" in the state transition process and sets a given Markov chain for the state.

Under the policy σ, rewards at state x are $r(x, \sigma(x))$. If we introduce the notation

$$r_\sigma(x) := r(x, \sigma(x)) \qquad (x \in \mathsf{X})$$

and $\mathbb{E}_x := \mathbb{E}[\,\cdot\,|X_0 = x]$, then the lifetime value of following σ starting from state x can be written as

$$v_\sigma(x) = \mathbb{E}_x \sum_{t\geqslant 0} \beta^t r_\sigma(X_t) \quad \text{where } (X_t) \text{ is } P_\sigma\text{-Markov with } X_0 = x. \tag{6.7}$$

Since $\beta < 1$, applying Lemma 4.1.1 on page 100 to this expression yields

$$v_\sigma = \sum_{t\geqslant 0} \beta^t P_\sigma^t r_\sigma = (I - \beta P_\sigma)^{-1} r_\sigma. \tag{6.8}$$

Another way to compute v_σ is by making use of the **policy operator** T_σ defined at $v \in \mathbb{R}^{\mathsf{X}}$ by

$$(T_\sigma v)(x) = r(x, \sigma(x)) + \beta \sum_{x'\in\mathsf{X}} v(x') P(x, \sigma(x), x') \qquad (x \in \mathsf{X}). \tag{6.9}$$

(This definition is analogous to the policy operator defined for the optimal stopping problem in §5.1.1.3.) In vector notation, we can express the operator via

$$T_\sigma v = r_\sigma + \beta P_\sigma v. \tag{6.10}$$

The next exercise shows how T_σ can be put to work.

Exercise 6.1.5. Fixing σ in Σ, prove that

(i) T_σ is an order-preserving self-map on $\mathbb{R}^{\mathsf{X}}$,

(ii) T_σ is a contraction on $\mathbb{R}^{\mathsf{X}}$ of modulus β under the norm $\|\cdot\|_\infty$,

(iii) the σ-value function v_σ is the unique fixed point of T_σ in $\mathbb{R}^{\mathsf{X}}$, and

(iv) $T_\sigma^k v \to v_\sigma$ as $k \to \infty$ for all $v \in \mathbb{R}^{\mathsf{X}}$.

Computationally, this means that we can pick $v \in \mathbb{R}^{\mathsf{X}}$ and iterate with T_σ to obtain an approximation to v_σ.

Exercise 6.1.6. Prove that, when the initial condition for iteration is $v \equiv 0 \in \mathbb{R}^{\mathsf{X}}$, the k-th iterate $T_\sigma^k v$ is equal to the truncated sum $\sum_{t=0}^{k-1} \beta^t P_\sigma^t r_\sigma$.

Remark 6.1.2. When computing v_σ, should we use the expression $(I - \beta P_\sigma)^{-1} r_\sigma$ in (6.8) or should we iterate with T_σ? For small state spaces, the first option is typically faster. However, it is easy to write down dynamic programming problems where X is very large (see, e.g., Example 1.0.2 on page 2). If, say, X has 10^9 elements, then $I - \beta P_\sigma$ is $10^9 \times 10^9$. Matrices of this size are difficult to invert—or even store in memory. In such settings, iterating with T_σ is often faster.

The next exercise provides some additional intuition for policy operators.

Exercise 6.1.7. Fix $\sigma \in \Sigma$ and let (X_t) be P_σ-Markov with initial condition $x \in \mathsf{X}$. Prove that, for given $v \in \mathbb{R}^{\mathsf{X}}$, and $k \in \mathbb{N}$, we have

$$(T_\sigma^k v)(x) = \mathbb{E}_x \left[\sum_{t=1}^{k-1} \beta^t r(X_t, \sigma(X_t)) + \beta^k v(X_k) \right].$$

In other words, show that $(T_\sigma^k v)(x)$ is the payoff from following policy σ and starting in state x when lifetime is truncated to the finite horizon k and v provides a terminal payoff in each state.

6.1.2.2 Defining Optimality

The **value function** is defined as $v^* := \vee_{\sigma \in \Sigma} v_\sigma$, where, as usual, the maximum is pointwise. More explicitly,

$$v^*(x) = \max_{\sigma \in \Sigma} v_\sigma(x) \qquad (x \in \mathsf{X}). \tag{6.11}$$

This is consistent with our definition of the value function in the optimal stopping case (see page 141). It is the maximal lifetime value we can extract from each state using optimal behaviour. The maximum in (6.11) exists at each x because Σ is a finite set.

A policy $\sigma \in \Sigma$ is called **optimal** if $v_\sigma = v^*$. In other words, a policy is optimal if its lifetime value is maximal at each state.

Looking again at Figure 2.2, we see that, as drawn, there is no optimal policy, since v^* differs from both $v_{\sigma'}$ and $v_{\sigma''}$. Below, in Proposition 6.1.1, we will show that such an outcome is **not** possible for MDPs. In other words, an optimal policy always exists.

Our optimality results are easier to follow with some additional terminology. To start, given $v \in \mathbb{R}^{\mathsf{X}}$, we define a policy $\sigma \in \Sigma$ to be **v-greedy** if

$$\sigma(x) \in \operatorname*{argmax}_{a \in \Gamma(x)} \left\{ r(x,a) + \beta \sum_{x' \in \mathsf{X}} v(x') P(x,a,x') \right\} \quad \text{for all } x \in \mathsf{X}. \tag{6.12}$$

In essence, a v-greedy policy treats v as the correct value function and sets all actions accordingly.

The **Bellman operator** for the MDP is the self-map T on $\mathbb{R}^{\mathsf{X}}$ defined by

$$(Tv)(x) = \max_{a \in \Gamma(x)} \left\{ r(x,a) + \beta \sum_{x'} v(x') P(x,a,x') \right\} \qquad (x \in \mathsf{X}). \tag{6.13}$$

Obviously $Tv = v$ if and only if v satisfies Bellman's equation (6.2).

Exercise 6.1.8. Given $v \in \mathbb{R}^{\mathsf{X}}$, prove that

(i) at least one v-greedy policy exists,

(ii) $\sigma \in \Sigma$ is v-greedy if and only if $T_\sigma v = Tv$, and

(iii) $(Tv)(x) = \max_{\sigma \in \Sigma} (T_\sigma v)(x)$ for all $x \in \mathsf{X}$.

The last part of Exercise 6.1.8 tells us that T is the pointwise maximum of $\{T_\sigma\}_{\sigma \in \Sigma}$, which can be expressed as $T = \vee_\sigma T_\sigma$. Figure 6.1 illustrates this relationship in one dimension.

Exercise 6.1.9. Prove that T is a contraction of modulus β on $\mathbb{R}^{\mathsf{X}}$ under the norm $\|\cdot\|_\infty$. [Hint: Apply Lemma 1.2.2 on page 18 along with Exercise 6.1.8.]

6.1.2.3 Optimality Theory

We can now state our main optimality result for MDPs:

Proposition 6.1.1. *For the MDP described in §6.1.1.1,*

(i) *the value function v^* is the unique solution to Bellman's equation in $\mathbb{R}^{\mathsf{X}}$,*

Figure 6.1: T is the pointwise maximum of $\{T_\sigma\}_{\sigma \in \Sigma}$ (one-dimensional setting)

(ii) $\lim_{k \to \infty} T^k v = v^*$ *for all* $v \in \mathbb{R}^{\mathsf{X}}$,

(iii) *a feasible policy is optimal if and only it is* v^**-greedy, and*

(iv) *at least one optimal policy exists.*

We prove the results of Proposition 6.1.1 in a more general setting in Chapter 7, as part of a larger set of results. Nonetheless, for those who want a direct proof, we provide one here:

Proof. In Exercise 6.1.9 we showed that T is a contraction mapping on the closed set $\mathbb{R}^{\mathsf{X}}$. Hence T is globally stable on $\mathbb{R}^{\mathsf{X}}$ and therefore has a unique fixed point $\bar{v} \in \mathbb{R}^{\mathsf{X}}$. Our first claim is that $\bar{v} = v^*$. We show $\bar{v} \leqslant v^*$ and then $\bar{v} \geqslant v^*$.

For the first inequality, let $\sigma \in \Sigma$ be $\bar{v}$-greedy. Recalling Exercise 6.1.8, we have $T_\sigma \bar{v} = T\bar{v} = \bar{v}$. Hence $\bar{v}$ is also a fixed point of T_σ. But the only fixed point of T_σ in $\mathbb{R}^{\mathsf{X}}$ is v_σ, so $\bar{v} = v_\sigma$. But then $\bar{v} \leqslant v^*$, since, by definition, $v^* = \vee_\sigma v_\sigma$. This is our first inequality.

Regarding the second inequality, fix $\sigma \in \Sigma$ and observe that $Tv \geqslant T_\sigma v$ for all $v \in \mathbb{R}^{\mathsf{X}}$. Since T is order-preserving and globally stable, Proposition 2.1.2 on page 49 implies that $v_\sigma \leqslant \bar{v}$. Taking the supremum over $\sigma \in \Sigma$ yields $v^* \leqslant \bar{v}$.

Hence v^* is a fixed point of T in $\mathbb{R}^{\mathsf{X}}$. Since T is globally stable on $\mathbb{R}^{\mathsf{X}}$, the remaining claims in parts (i)–(ii) follow immediately.

Regarding part (iii), it follows from Exercise 6.1.8 and part (i) of this theorem that

$$\sigma \text{ is } v^*\text{-greedy} \quad \iff \quad T_\sigma v^* = Tv^* \quad \iff \quad T_\sigma v^* = v^*.$$

The right hand side of this expression tells us that v^* is a fixed point of T_σ. But the only fixed point of T_σ is v_σ, so the right hand side is equivalent to the statement $v_\sigma = v^*$. Hence, by this chain of logic and the definition of optimality,

$$\sigma \text{ is } v^*\text{-greedy} \iff v^* = v_\sigma \iff \sigma \text{ is optimal} \tag{6.14}$$

Hence (iii) holds.

Part (iv) is left as an exercise immediately below. □

Exercise 6.1.10. Prove that, in Proposition 6.1.1, (iii) implies (iv).

Figure 6.2 illustrates Proposition 6.1.1 in a very simple case, where X is a singleton $\{x\}$. We write v instead of $v(x)$ for the value of state x and place v on the horizontal axis. In the figure, the set of policies is $\Sigma = \{\sigma', \sigma''\}$. For given $\sigma \in \Sigma$, the map T_σ is an affine function $T_\sigma v = r_\sigma + \beta P_\sigma v$ and the fixed point is v_σ. The Bellman operator T is the upper envelope of the functions $\{T_\sigma\}$, as shown in (ii) of Exercise 6.1.8. By definition,

(i) v^* is the largest of these fixed points, which equals $v_{\sigma''}$, and

(ii) σ'' is the optimal policy, since $v_{\sigma''} = v^*$.

In accordance with Proposition 6.1.1, v^* is also the fixed point of the Bellman operator.

It is important to understand the significance of (iii) in Proposition 6.1.1. Greedy policies are relatively easy to compute, in the sense that solving (6.12) at each x is easier than trying to directly solve the problem of maximizing lifetime value, since Σ is in general far larger than $\Gamma(x)$. Part (iii) tells us that solving the overall problem reduces to computing a v-greedy policy with the right choice of v. As for optimal stopping problems, that choice is the value function v^*. Intuitively, v^* assigns the "correct" value to each state, in the sense of maximal lifetime value the controller can extract, so using v^* to calculate greedy policies leads to the optimal outcome.

Figure 6.2: Illustration of optimality for MDPs

6.1.3 Algorithms

In previous chapters we solved job search and optimal stopping problems using value function iteration. In this section we present a generalization suitable for aribtrary MDPs and then discuss two important alternatives.

6.1.3.1 Value Function Iteration

Value function iteration (VFI) for MDPs is similar to VFI for the job search model (see page 35): we use successive approximation on T to compute an approximation v_k to the value function v^* and then take a v_k-greedy policy. The general procedure is given by Algorithm 4.

The fact that the sequence $(v_k)_{k \geqslant 0}$ produced by VFI converges to v^* is immediate from Proposition 6.1.1 (as the tolerance τ is taken toward zero). It is also true that the greedy policy produced in the last step is approximately optimal when τ is small. Further details on convergence are deferred to Chapter 7, where we examine VFI in a more general setting.

VFI is robust, easy to understand and easy to implement. These factors explain its

Algorithm 4: Value function iteration for MDPs

```
input v_0 ∈ ℝ^X, an initial guess of v*
input τ, a tolerance level for error
ε ← τ + 1
k ← 0
while ε > τ do
    for x ∈ X do
        v_{k+1}(x) ← (T v_k)(x)
    end
    ε ← ‖v_k − v_{k+1}‖_∞
    k ← k + 1
end
Compute a v_k-greedy policy σ
return σ
```

enduring popularity. At the same time, in terms of efficiency, VFI is often dominated by alternative algorithms, the most important of which are discussed below.

6.1.3.2 Howard Policy Iteration

Unlike VFI, **Howard policy iteration (HPI)** (or just **policy iteration**) computes optimal policies by iterating between computing the value of a given policy and computing the greedy policy associated with that value. The full technique is described in Algorithm 5.[2]

A visualization of HPI is given in Figure 6.3, where σ is the initial choice. Next we compute the lifetime value v_σ, and then the v_σ-greedy policy σ', and so on. The computation of lifetime value is called the **policy evaluation** step, while the computation of greedy policies is called **policy improvement**.

HPI has two very attractive features. One is that, in a finite state setting, the algorithm always converges to an exact optimal policy in a finite number of steps, regardless of the initial condition. We provide a proof of this fact in a more general setting in Chapter 7. The second is that the rate of convergence is faster that VFI, as shown below in §6.1.3.3.

[2]Notice that we use the norm distance $\|\sigma_k - \sigma_{k+1}\|_\infty$ between policies. This requires that all policies are either real-valued or vector-valued, which is not a strong assumption. (In particular, the vector-valued case allows for multiple actions.) If $\sigma_k(x)$ is a vector for each x, then $\sigma_k - \sigma_{k+1}$ is a multi-dimensional array, and the supremum norm distance is just the maximum deviation over all states and actions.

Algorithm 5: Howard policy iteration for MDPs

```
input σ_0 ∈ Σ, an initial guess of σ*
k ← 0
ε ← 1
while ε > 0 do
    v_k ← the σ_k-value function (I − βP_{σ_k})^{−1} r_{σ_k}
    σ_{k+1} ← a v_k-greedy policy
    ε ← ‖σ_k − σ_{k+1}‖_∞
    k ← k + 1
end
return σ_k
```

Figure 6.3: Howard policy iteration algorithm (HPI)

Figure 6.4: HPI as a version of Newton's method

Figure 6.4 gives another illustration, presented in the one-dimensional setting that we used for Figure 6.2. In this illustration, we imagine that there are many optimal policies, and hence many functions in $\{T_\sigma\}$, so that their upper envelope, which is the Bellman operator, becomes a smoother curve. The figure shows the update from v_σ to the next lifetime value $v_{\sigma'}$, via the following two steps:

(i) Take σ' to be v_σ-greedy, which means that $T_{\sigma'} v_\sigma = T v_\sigma$ (see Exercise 6.1.8).

(ii) Take $v_{\sigma'}$ to be the fixed point of $T_{\sigma'}$.

The next step, from $v_{\sigma'}$ to $v_{\sigma''}$ is analogous.

Comparison of this figure with Figure 2.9 on page 62 suggests that HPI is an implementation of Newton's method, applied to the Bellman operator. We confirm this in §6.1.3.3.

6.1.3.3 HPI as Newton Iteration

In discussing the connection between HPI and Newton iteration, one issue we need to deal with is the fact that T is not always differentiable, at seen in Figure 6.2. At the same time, T is convex, and this leads us to consider *subgradients* as a substitute for

Figure 6.5: Subgradients of convex functions

derivatives. Once we admit this modification, HPI and Newton iteration are identical, as we now show.

First, we recall that, given a self-map T from $S \subset \mathbb{R}^n$ to itself, an $n \times n$ matrix D is called a **subgradient** of T at $v \in S$ if

$$Tu \geqslant Tv + D(u - v) \quad \text{for all } u \in S. \tag{6.15}$$

Figure 6.5 illustrates the definition in one dimension, where D is just a scalar determining the slope of a tangent line at v. In the left subfigure, T_1 is convex and differentiable at v, which means that only one subgradient exists (since any other choice of slope implies that the inequality in (6.15) will fail for some u). In the right subfigure, T_2 is convex but nondifferentiable at v, so multiple subgradients exist.

In the next result, we take (Γ, β, r, P) to be a given MDP and let T be the associated Bellman operator.

Lemma 6.1.2. *If $v \in \mathbb{R}^{\mathsf{X}}$ and $\sigma \in \Sigma$ is v-greedy, then βP_σ is a subgradient of T at v.*

Proof. Fix $v \in \mathbb{R}^{\mathsf{X}}$ and let σ be v-greedy. Using $T \geqslant T_\sigma$ and $T_\sigma v = Tv$, we have

$$Tu = Tv + Tu - Tv \geqslant Tv + T_\sigma u - T_\sigma v.$$

Applying the definition of T_σ now gives

$$Tu \geqslant Tv + \beta P_\sigma u - \beta P_\sigma v = Tv + \beta P_\sigma (u - v).$$

Hence βP_σ is a subgradient of T at v, as claimed. □

Now let's consider Newton's method applied to the problem of finding the fixed point of T. Since T is nondifferentiable and convex, we replace the Jacobian in Newton's method (see (2.6) on page 62) with the subdifferential. This leads us to iterate

on

$$v_{k+1} = Qv_k \quad \text{where} \quad Qv := (I - \beta P_\sigma)^{-1}(Tv - \beta P_\sigma v).$$

In the definition of Q, the policy σ is v-greedy. Using $Tv = T_\sigma v$, the map Q reduces to $Qv := (I - \beta P_\sigma)^{-1} r_\sigma$, which is exactly the update step to produce the next σ-value function in HPI (i.e., the lifetime value of a v-greedy policy).

The fact that HPI is a version of Newton's method suggests that its iterates $(v_k)_{k \geqslant 0}$ enjoy quadratic convergence. This is indeed the case: under mild conditions one can show there exists a constant N such that, for all $k \geqslant 0$,

$$\|v_{k+1} - v_k\| \leqslant N \|v_k - v_{k-1}\|^2 \tag{6.16}$$

(see, e.g., Puterman (2005), Theorem 6.4.8). Hence HPI enjoys both a fast convergence rate and the robustness of global convergence.

At the same time, HPI is not always optimal in terms of efficiency, since the size of the constant term in (6.16) also matters. This term can be large because, at each step, the update from v_σ to $v_{\sigma'}$ requires computing the exact lifetime value $v_{\sigma'}$ of the v_σ-greedy policy σ'. Computing this fixed point exactly can be computationally expensive in high dimensions.

One way around this issue is to forgo computing the fixed point $v_{\sigma'}$ exactly, replacing it with an approximation. The next section takes up this idea.

6.1.3.4 Optimistic Policy Iteration

Optimistic policy iteration (OPI) is an algorithm that borrows from both VFI and HPI. In short, the algorithm is the same as HPI except that, instead of computing the full value v_σ of a given policy, the approximation $T_\sigma^m v$ discussed in Exercise 6.1.5 is used instead. Algorithm 6 provides details.

In the algorithm, the policy operator T_{σ_k} is applied m times to generate an approximation of v_{σ_k}. The constant step size m can also be replaced with a sequence $(m_k) \subset \mathbb{N}$. In either case, for MDPs, convergence to an optimal policy is guaranteed. We prove this in a more general setting in Chapter 7.

Notice that, as $m \to \infty$, the algorithm increasingly approximates Howard policy iteration, since $T_{\sigma_k}^m v_k$ converges to v_{σ_k}. At the same time, if $m = 1$, the algorithm is essentially the same as VFI. Hence, with intermediate m, OPI can be seen as a kind of "convex combination' of HPI and VFI.

In many practical dynamic programming problems, a reasonable choice of m will lead to faster convergence than both VFI and HPI. We investigate these ideas in the applications below.

Algorithm 6: Optimistic policy iteration for MDPs

```
input v_0 ∈ R^X, an initial guess of v*
input τ, a tolerance level for error
input m ∈ N, a step size
k ← 0
ε ← τ + 1
while ε > τ do
    σ_k ← a v_k-greedy policy
    v_{k+1} ← T^m_{σ_k} v_k
    ε ← ||v_k − v_{k+1}||_∞
    k ← k + 1
end
return σ_k
```

6.2 Applications

This section gives several applications of the MDP model to economic problems. The applications illustrate the ease with which MDPs can be implemented numerically and solved on a computer (provided that the state and action spaces are not too large).

6.2.1 Optimal Inventories

In §3.1.3.2 we studied a firm whose inventory behavior follows S-s dynamics. In this section we show how S-s behavior arises naturally in optimizing model, where the firm chooses its inventory path to maximize profits in each period. To keep the problem relatively simple, we ignore exit options (so that firm value is the expected present value of profits), and that the firm only sells one product.

6.2.1.1 Environment

Given a demand process $(D_t)_{t\geqslant 0}$, inventory $(X_t)_{t\geqslant 0}$ of the product obeys

$$X_{t+1} = m(X_t - D_{t+1}) + A_t, \quad \text{where } m(y) := y \vee 0. \tag{6.17}$$

The term A_t is units of stock ordered this period, which take one period to arrive. We assume that the firm can store at most K items at one time, so the state space is $\mathsf{X} := \{0, \ldots, K\}$.

Profits are given by

$$\pi_t := X_t \wedge D_{t+1} - cA_t - \kappa \mathbb{1}\{A_t > 0\}.$$

We take the minimum of current stock and demand because orders in excess of inventory are assumed to be lost rather than backfilled. Here c is unit product cost and κ is a fixed cost of ordering inventory. We assume IID demand with common distribution $\varphi \in \mathscr{D}(\mathbb{Z}+)$.

With $\beta := 1/(1+r)$ and $r > 0$, the value of the firm is

$$V_0 = \mathbb{E} \sum_{t \geqslant 0} \beta^t \pi_t \tag{6.18}$$

Managers of the firm try to maximize shareholder value. Let's now consider their optimization problem.

6.2.1.2 Optimization

Bellman's equation for this dynamic program is

$$v(x) = \max_{a \in \Gamma(x)} \left\{ \sum_{d \geqslant 0} (x \wedge d)\varphi(d) - ca - \kappa \mathbb{1}\{a > 0\} + \beta \sum_{d \geqslant 0} v(m(x-d)+a)\varphi(d) \right\}$$

at each $x \in \mathsf{X}$, where

$$\Gamma(x) := \{0, \ldots, K - x\} \tag{6.19}$$

is the set of feasible actions a when the current inventory state is x. Bellman's equation states that optimal value is attained when the firm chooses a to balance current expected profits with the value of a higher inventory next period.

Exercise 6.2.1. Write down the Bellman operator for this model and prove that this operator is a contraction of modulus β on $\mathbb{R}^{\mathsf{X}}$ when paired with the supremum norm $\|v\|_\infty := \max_{x \in \mathsf{X}} |v(x)|$.

6.2.1.3 Representation as an MDP

We can map our inventory problem into a finite state MDP with state space X and action space $\mathsf{A} := \mathsf{X}$. The feasible correspondence Γ is as given in (6.19) and the

reward function is current profits, or

$$r(x, a) := \sum_{d \geqslant 0} (x \wedge d)\varphi(d) - ca - \kappa \mathbb{1}\{a > 0\}. \tag{6.21}$$

The stochastic kernel from the set of feasible state-action pairs G induced by Γ is, in view of (6.17),

$$P(x, a, x') := \mathbb{P}\{m(x - D_{t+1}) + a = x'\}. \tag{6.22}$$

Exercise 6.2.2. Suppose that the demand shock has geometric distribution on $\mathbb{Z}_+$ with parameter p. Write down an expression for the stochastic kernel (6.22) using only x, a, x' and the parameters of the model.

Since the inventory model is an MDP, all of the optimality and convergence results in Proposition 6.1.1 apply. In particular, the unique fixed point of the Bellman operator is the value function v^*, and a policy σ^* is optimal if and only if σ^* is v^*-greedy.

6.2.1.4 Computation

Let's now solve this model numerically. As in Exercise 6.2.2, we take φ to be the geometric distribution on $\mathbb{Z}_+$ with parameter p. We use the default parameter values shown in Listing 17. The code listing also presents an implementation of the Bellman operator. We use the `OffSetArrays` package to index arrays on the custom set `0:K`, since this corresponds to the state space.

Figure 6.6 exhibits an approximation of the value function v^*, computed by iterating with T starting at $v \equiv 1$. Figure 6.6 also shows the approximate optimal policy, obtained as a v^*-greedy policy:

$$\sigma^*(x) \in \operatorname*{argmax}_{a \in \Gamma(x)} \left\{ r(x, a) + \beta \sum_{d \geqslant 0} v^*(m(x - d) + a)\varphi(d) \right\}$$

The plot of the optimal policy shows that there is a threshold region below which the firm orders large batches and above which the firm orders nothing. This is intuitive, since the firm wishes to economize on the fixed cost of ordering. Figure 6.7 shows a simulation of inventory dynamics under the optimal policy, starting from $X_0 = 0$. The time path closely approximates the S-s dynamics discussed in §3.1.3.2.

Exercise 6.2.3. Compute the optimal policy by extending the code given in Listing 17. Replicate Figure 6.7, modulo randomness, by sampling from a geometric dis-

```
using Distributions, OffsetArrays
m(x) = max(x, 0)  # Convenience function

function create_inventory_model(; β=0.98,     # discount factor
                                  K=40,       # maximum inventory
                                  c=0.2, κ=2, # cost paramters
                                  p=0.6)      # demand parameter
    ϕ(d) = (1 - p)^d * p  # demand pdf
    return (; β, K, c, κ, p, ϕ)
end

"The function B(x, a, v) = r(x, a) + β Σ_x′ v(x′) P(x, a, x′)."
function B(x, a, v, model; d_max=100)
    (; β, K, c, κ, p, ϕ) = model
    reward = sum(min(x, d)*ϕ(d) for d in 0:d_max) - c * a - κ * (a > 0)
    continuation_value = β * sum(v[m(x - d) + a] * ϕ(d) for d in 0:d_max)
    return reward + continuation_value
end

"The Bellman operator."
function T(v, model)
    (; β, K, c, κ, p, ϕ) = model
    new_v = similar(v)
    for x in 0:K
        Γx = 0:(K - x)
        new_v[x], _ = findmax(B(x, a, v, model) for a in Γx)
    end
    return new_v
end

"Get a v-greedy policy.  Returns a zero-based array."
function get_greedy(v, model)
    (; β, K, c, κ, p, ϕ) = model
    σ_star = OffsetArray(zeros(Int32, K+1), 0:K)
    for x in 0:K
        Γx = 0:(K - x)
        _, a_idx = findmax(B(x, a, v, model) for a in Γx)
        σ_star[x] = Γx[a_idx]
    end
    return σ_star
end
```

Listing 17: Solving the optimal inventory model (`inventory_dp.jl`)

Figure 6.6: The value function and optimal policy for the inventory problem

Figure 6.7: Optimal inventory dynamics

tribution and implementing the dynamics in (6.17). At each X_t, the action A_t should be chosen according to the optimal policy $\sigma^*(X_t)$.

6.2.2 Optimal Savings with Labor Income

As our next example of an MDP, we modify the cake eating problem in §6.1.1.2 to add labor income. Wealth evolves according to

$$W_{t+1} = R(W_t + Y_t - C_t) \qquad (t = 0, 1, \ldots), \tag{6.24}$$

where (W_t) takes values in finite set $\mathsf{W} \subset \mathbb{R}_+$ and (Y_t) is a Markov chain on finite set Y with transition matrix Q. Other parts of the problem are unchanged.

The Bellman operator can be written as

$$(Tv)(w, y) = \max_{w' \in \Gamma(w,y)} \left\{ u\left(w + y - \frac{w'}{R}\right) + \beta \sum_{y' \in \mathsf{Y}} v(w', y') Q(y, y') \right\}. \tag{6.25}$$

6.2.2.1 MDP Representation

To frame this problem as an MDP, we set the state to $x := (w, y)$, representing current wealth and income, taking values in the state space $\mathsf{X} := \mathsf{W} \times \mathsf{Y}$. The action is savings s, which takes values in W and equals w'. The feasible correspondence is the set of feasible savings values

$$\Gamma(w, y) = \{s \in \mathsf{W} : s \leqslant R(w + y)\}.$$

The current reward is utility of consumption $r(w, s) = u(w + y - s/R)$. The stochastic kernel is

$$P((w, y), s, (w', y')) = \mathbb{1}\{w' = s\} Q(y, y').$$

Since the problem can be framed as an MDP, all of the optimality results in Proposition 6.1.1 apply.

6.2.2.2 Implementation

To implement the algorithms discussed in §6.1.3, we use the Bellman operator (6.25), and the corresponding definition of a v-greedy policy, which is

$$\sigma((w,y) \in \operatorname*{argmax}_{w' \in \Gamma(w,y)} \left\{ u\left(w + y - \frac{w'}{R}\right) + \beta \sum_{y' \in \mathsf{Y}} v(w',y')Q(y,y') \right\}$$

for all (w,y). The policy operator for given $\sigma \in \Sigma$ is

$$(T_\sigma v)(w,y) = u\left(w + y - \frac{\sigma(w,y)}{R}\right) + \beta \sum_{y' \in \mathsf{Y}} v(\sigma(w,y),y')Q(y,y'). \tag{6.26}$$

Code for implementing the model and these two operators is given in Listing 18. Income is constructed as a discretized AR(1) process using the method from §3.2.2. Exponentiation is applied to the grid so that income takes positive values.

The function `get_value` in Listing 19 uses the expression $v_\sigma = (I - \beta P_\sigma)^{-1} r_\sigma$ from (6.8) to obtain the value of a given policy σ. The matrix P_σ and vector r_σ take the form

$$\begin{aligned} P_\sigma((w,y),(w',y')) &= \mathbb{1}\{\sigma(w,y) = w'\}Q(y,y') \\ r_\sigma(w,y) &= u(w + y - \sigma(w,y)/R) \end{aligned}$$

In order to use regular matrix algebra routines for this computation, we have mapped the indices `i, j` for state (w_i, y_j) into a single index m, as in $x_m = (w_i, y_j)$. The single index m steps through all points in the state space $\mathsf{X} = \mathsf{W} \times \mathsf{Y}$.

Remark 6.2.1. When mapping to a single index, we take into account the fact Julia uses Fortran style **column major** indexing of arrays. This means that when a two-dimensional array `a` with elements `a[i,j]` and indices `i in 1:wn` and `j in 1:yn` is flattened into a linear array `b` with elements `b[m]` and indices `m in 1:(wn*yn)`, the indices of `b` obey `m = i + (j-1) wn`. Visually, the columns of `a` are stacked vertically into one long column. From single index `m` we can recover `i` via `(m-1)%wn + 1` and `j` via `div(m-1, wn) + 1`.

6.2.2.3 Solution and Timings

Since all of the results for MDPs are in effect, we know that the value function v^* is the unique fixed point of the Bellman operator in $\mathbb{R}^{\mathsf{X}}$, and that value function iteration,

```
using QuantEcon, LinearAlgebra, IterTools

function create_savings_model(; R=1.01, β=0.98, γ=2.5,
                                w_min=0.01, w_max=5.0, w_size=200,
                                ρ=0.9, ν=0.1, y_size=5)
    w_grid = LinRange(w_min, w_max, w_size)
    mc = tauchen(y_size, ρ, ν)
    y_grid, Q = exp.(mc.state_values), mc.p
    return (; β, R, γ, w_grid, y_grid, Q)
end

"B(w, y, w′) = u(R*w + y - w′) + β Σ_y′ v(w′, y′) Q(y, y′)."
function B(i, j, k, v, model)
    (; β, R, γ, w_grid, y_grid, Q) = model
    w, y, w′ = w_grid[i], y_grid[j], w_grid[k]
    u(c) = c^(1-γ) / (1-γ)
    c = w + y - (w′ / R)
    @views value = c > 0 ? u(c) + β * dot(v[k, :], Q[j, :]) : -Inf
    return value
end

"The Bellman operator."
function T(v, model)
    w_idx, y_idx = (eachindex(g) for g in (model.w_grid, model.y_grid))
    v_new = similar(v)
    for (i, j) in product(w_idx, y_idx)
        v_new[i, j] = maximum(B(i, j, k, v, model) for k in w_idx)
    end
    return v_new
end

"The policy operator."
function T_σ(v, σ, model)
    w_idx, y_idx = (eachindex(g) for g in (model.w_grid, model.y_grid))
    v_new = similar(v)
    for (i, j) in product(w_idx, y_idx)
        v_new[i, j] = B(i, j, σ[i, j], v, model)
    end
    return v_new
end
```

Listing 18: Discrete optimal savings model (`finite_opt_saving_0.jl`)

```
include("finite_opt_saving_0.jl")

"Compute a v-greedy policy."
function get_greedy(v, model)
    w_idx, y_idx = (eachindex(g) for g in (model.w_grid, model.y_grid))
    σ = Matrix{Int32}(undef, length(w_idx), length(y_idx))
    for (i, j) in product(w_idx, y_idx)
        _, σ[i, j] = findmax(B(i, j, k, v, model) for k in w_idx)
    end
    return σ
end


"Get the value v_σ of policy σ."
function get_value(σ, model)
    # Unpack and set up
    (; β, R, γ, w_grid, y_grid, Q) = model
    wn, yn = length(w_grid), length(y_grid)
    n = wn * yn
    u(c) = c^(1-γ) / (1-γ)
    # Function to extract (i, j) from m = i + (j-1)*wn"
    single_to_multi(m) = (m-1)%wn + 1, div(m-1, wn) + 1
    # Allocate and create single index versions of P_σ and r_σ
    P_σ = zeros(n, n)
    r_σ = zeros(n)
    for m in 1:n
        i, j = single_to_multi(m)
        w, y, w′ = w_grid[i], y_grid[j], w_grid[σ[i, j]]
        r_σ[m] = u(w + y - w′/R)
        for m′ in 1:n
            i′, j′ = single_to_multi(m′)
            if i′ == σ[i, j]
                P_σ[m, m′] = Q[j, j′]
            end
        end
    end
    # Solve for the value of σ
    v_σ = (I - β * P_σ) \ r_σ
    # Return as multi-index array
    return reshape(v_σ, wn, yn)
```

Listing 19: Discrete optimal savings model (`finite_opt_saving_1.jl`)

```
include("s_approx.jl")
include("finite_opt_saving_1.jl")

"Value function iteration routine."
function value_iteration(model, tol=1e-5)
    vz = zeros(length(model.w_grid), length(model.y_grid))
    v_star = successive_approx(v -> T(v, model), vz, tolerance=tol)
    return get_greedy(v_star, model)
end

"Howard policy iteration routine."
function policy_iteration(model)
    wn, yn = length(model.w_grid), length(model.y_grid)
    σ = ones(Int32, wn, yn)
    i, error = 0, 1.0
    while error > 0
        v_σ = get_value(σ, model)
        σ_new = get_greedy(v_σ, model)
        error = maximum(abs.(σ_new - σ))
        σ = σ_new
        i = i + 1
        println("Concluded loop $i with error $error.")
    end
    return σ
end

"Optimistic policy iteration routine."
function optimistic_policy_iteration(model; tolerance=1e-5, m=100)
    v = zeros(length(model.w_grid), length(model.y_grid))
    error = tolerance + 1
    while error > tolerance
        last_v = v
        σ = get_greedy(v, model)
        for i in 1:m
            v = T_σ(v, σ, model)
        end
        error = maximum(abs.(v - last_v))
    end
    return get_greedy(v, model)
end
```

Listing 20: Discrete optimal savings model (`finite_opt_saving_2.jl`)

Figure 6.8: Timings for alternative algorithms, savings model

Howard policy iteration and optimistic policy iteration all converge. Listing 20 implements these three algorithms. Since the state and action space are finite, Howard policy iteration is guaranteed to return an exact optimal policy.

Figure 6.8 shows the wall time taken to solve the finite optimal savings model under the default parameters when executed on a standard laptop machine. Time is measured in seconds. The horizonal axis corresponds to the step parameter m in optimistic policy iteration (Algorithm 6). The two other algorithms do not depend on m and hence their timings are constant. The figure shows that policy iteration is an order of magnitude faster than value function iteration and optimistic policy iteration is even faster than policy iteration for moderate values of m.

Although the timings are comparable, run-times are always dependent on implementation and relative speed varies significantly with the way that the algorithms are written, the extent to which parallelization can be exploited and the parameters and description of the problem. However, our results are consistent with other applications in this text: optimistic policy iteration dominates both value function iteration and Howard policy iteration for many choices of the step size m.

6.2.3 Optimal Investment

As our next application, we consider a monopolist facing correlated, stochastically evolving demand and adjustment costs. The trade-off in this dynamic programming

problem involves balancing adjustment of capacity to meet demand against the costs associated with that adjustment.

6.2.3.1 Problem Description

We assume that the monopolist produces a single product and faces an inverse demand function of the form

$$P_t = a_0 - a_1 Y_t + Z_t,$$

where a_0, a_1 are positive parameters, Y_t is output, P_t is price and the demand shock Z_t follows

$$Z_{t+1} = \rho Z_t + \sigma \eta_{t+1}, \qquad \{\eta_t\} \overset{\text{IID}}{\sim} N(0,1).$$

Current profits are given by

$$\pi_t := P_t Y_t - c Y_t - \gamma (Y_{t+1} - Y_t)^2.$$

Here $\gamma(Y_{t+1} - Y_t)^2$ represents adjustment costs associated with changing production scale, parameterized by γ, and c is unit cost of current production. Costs are convex, so rapid changes to capacity are expensive.

The monopolist chooses (Y_t) to maximize the expected present value of its profit flow, which we write as

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t \pi_t. \tag{6.27}$$

Here $\beta = 1/(1+r)$, where $r > 0$ is a fixed interest rate.

One way to start thinking about the optimal time path of output is to consider what would happen if $\gamma = 0$. Without adjustment costs there is no intertemporal trade-off, so the monopolist should choose output to maximize current profit in each period. The implied level of output at time t is

$$\bar{Y}_t := \frac{a_0 - c + Z_t}{2a_1}. \tag{6.28}$$

Exercise 6.2.4. Show that $\bar{Y}_t$ maximizes current profit when $\gamma = 0$.

For $\gamma > 0$, we expect the following behavior.

- If γ is close to zero, then the optimal output path Y_t will track the time path of $\bar{Y}_t$ relatively closely, while

- if γ is larger, then Y_t will be significantly smoother than $\bar{Y}_t$, as the monopolist seeks to avoid adjustment costs.

6.2.3.2 MDP Representation

We can represent this problem as an MDP. To do so we let Y be a grid contained in $\mathbb{R}_+$ that lists possible output values. To conform to the finite state setting, we discretize the shock process (Z_t) using Tauchen's method, as described in §3.2.2. For convenience we again use (Z_t) to represent the discrete process, which is a finite Markov chain on $\mathsf{Z} \subset \mathbb{R}$ with transition matrix Q.

The state space for this MDP is $\mathsf{X} = \mathsf{Y} \times \mathsf{Z}$, while the action space is Y. The feasible correspondence is defined by $\Gamma(x) = \mathsf{Y}$, meaning that choice of output is not restricted by the state. Thus, the feasible policy set Σ is all $\sigma \colon \mathsf{Y} \times \mathsf{Z} \to \mathsf{Y}$.

We write (y, z) for the current state, q for the action (which chooses next period output) and (y', z') for the next period state. The current reward function is current profits, which we can write as

$$r((y, z), q) = (a_0 - a_1 y + z - c)y - \gamma(q - y)^2.$$

The stochastic kernel is

$$P((y, z), q, (y', z')) = \mathbb{1}\{y' = q\}Q(z, z').$$

The term $\mathbb{1}\{y' = q\}$ is just a formal statement of the idea that next period output y' is equal to our current choice q for next period output. With these definitions, the problem defines an MDP and all of the optimality theory for MDPs applies.

6.2.3.3 Implementation

The Bellman operator for this problem can be expressed as

$$(Tv)(y, z) = \max_{y' \in \mathbb{R}} \left\{ r(y, z, y') + \beta \sum_{z' \in \mathsf{Z}} v(y', z')Q(z, z') \right\}.$$

Given $\sigma \in \Sigma$, we can express the policy operator as

$$(T_\sigma v)(y, z) = r(y, z, \sigma(y, z)) + \beta \sum_{z' \in \mathsf{Z}} v(\sigma(y, z), z')Q(z, z').$$

A v-greedy policy is a $\sigma \in \Sigma$ that obeys

$$\sigma(y, z) = \operatorname*{argmax}_{y' \in \mathsf{Y}} \left\{ r(y, z, y') + \beta \sum_{z' \in \mathsf{Z}} v(y', z') Q(z, z') \right\}.$$

By combining iteration with the policy operator and computation of greedy policies, we can implement optimistic policy iteration, compute the optimal policy σ^*, and study the output choices generated by this policy. We are particularly interested in how output responds to randomly generated demand shocks over time.

Figure 6.9 shows the result of a simulation designed to shed light on how output responds to demand. After choosing a initial values (Y_1, Z_1) and generating a Q-Markov chain $(Z_t)_{t=1}^T$, we simulated optimal output via $Y_{t+1} = \sigma^*(Y_t, Z_t)$. The default parameters are shown in Listing 21. In the figure, the adjustment cost parameter γ is varied as shown in the title. In addition to the optimal output path, the path of $(\bar{Y}_t)$ as defined in (6.28) is also presented.

The figure shows how increasing γ promotes smoothing, as predicted in our discussion above. For small γ, adjustment costs have only minor impact on choices, so output closely follows $(\bar{Y}_t)$, the optimal path when output responds immediately to demand shocks. Conversely, larger values of γ make adjustment expensive, so the operator responds relatively slowly to changes in demand.

Figure 6.10 compares timings for two of the three different algorithms we have discussed: value function iteration (VFI) and optimistic policy iteration (OPI). The timings are for the model shown in Listing 21. As in Figure 6.8, which gave timings for the optimal savings model, the horizonal axis shows m, which is the step parameter in OPI (Algorithm 6). VFI does not depend on m and hence its timings are constant. The vertical axis is time in seconds. In this figure, we do not show the result for Howard policy iteration (HPI) because the time taken was around 12 times larger than VFI.

Note that HPI is far slower than VFI, in contrast to our findings for the optimal savings problem. One might suspect this is due to the fact that HPI computes the exact optimal policy (whereas VFI is not guarateed to do so) but this is not the case. Indeed, in this instance, HPI, VFI and OPI all returned the same policy, which is equal to the optimal policy. Rather, the main difference is in the discount factors. VFI can be very slow when the discount factor is close to one. (This is because VFI convergence is linear in β, whereas HPI convergence is quadratic.) This was the setting of the optimal savings case (where $\beta = 0.99$). Here, however, $r = 0.04$ and $\beta = 1/(1 + r)$, so β is relatively small and VFI performs quite well.

More important is the fact that OPI dominates both VFI and HPI in terms of speed

Figure 6.9: Simulation of optimal output with different adjustment costs

```
using QuantEcon, LinearAlgebra, IterTools
include("s_approx.jl")

function create_investment_model(;
        r=0.04,                                # Interest rate
        a_0=10.0, a_1=1.0,                     # Demand parameters
        γ=25.0, c=1.0,                         # Adjustment and unit cost
        y_min=0.0, y_max=20.0, y_size=100,     # Grid for output
        ρ=0.9, ν=1.0,                          # AR(1) parameters
        z_size=25)                             # Grid size for shock
    β = 1/(1+r)
    y_grid = LinRange(y_min, y_max, y_size)
    mc = tauchen(y_size, ρ, ν)
    z_grid, Q = mc.state_values, mc.p
    return (; β, a_0, a_1, γ, c, y_grid, z_grid, Q)
```

Listing 21: Discrete optimal investment model (`finite_lq.jl`)

for almost all values of m, which is consistent with our findings for the optimal savings model. At $m = 60$, OPI is more than 20 times faster than VFI. (We also note that OPI is easier to implement than HPI, since we do not have the single-index problem discussed in Remark 6.2.1 on page 183. The details of the implementation are very similar to those show for the optimal savings case in Listings 18–20.)

Exercise 6.2.5. Consider a firm that maximizes expected present value in a setting where future profits are discounted at rate $\beta = 1/(1+r)$, the only production input is labor and hiring involves fixed costs. Let ℓ_t be employment at the firm at time t. Current profits are given by

$$\pi_t = pZ_t\ell_t^\alpha - w\ell_t - \kappa\mathbb{1}\{\ell_{t+1} \neq \ell_t\},$$

where p is the output price, w is the wage rate, α is a production parameter, the productivity shock is Q-Markov on Z and κ is a fixed cost of hiring and firing. This fixed cost induces lumpy adjustment, as shown in Figure 6.11. Show that this model is an MDP. Write down Bellman's equation and the procedure for optimistic policy iteration in the context of this model. Replicate Figure 6.11, modulo randomness, using the parameters shown in Listing 22.

Figure 6.10: Timings for alternative algorithms, investment model

```
using QuantEcon, LinearAlgebra, IterTools

function create_hiring_model(;
        r=0.04,                                # Interest rate
        κ=1.0,                                 # Adjustment cost
        α=0.4,                                 # Production parameter
        p=1.0, w=1.0,                          # Price and wage
        l_min=0.0, l_max=30.0, l_size=100,     # Grid for labor
        ρ=0.9, ν=0.4, b=1.0,                   # AR(1) parameters
        z_size=100)                            # Grid size for shock
    β = 1/(1+r)
    l_grid = LinRange(l_min, l_max, l_size)
    mc = tauchen(z_size, ρ, ν, b, 6)
    z_grid, Q = mc.state_values, mc.p
    return (; β, κ, α, p, w, l_grid, z_grid, Q)
end
```

Listing 22: Firm hiring model (`firm_hiring.jl`)

Figure 6.11: Optimal shifts in the stock of labor

6.3 Modified Bellman Equations

Direct application of MDP theory is sometimes suboptimal. For example, we saw in §1.3.2.2 that solving the job search problem with IID wage draws is best accomplished by generating a recursion on the continuation value, which reduces dimensionality for iterative solution methods. Separately, in §5.2.2.2, we saw how a different kind of manipulation of Bellman's equation also increased efficiency.

Now we aim to study these kinds of modifications systematically. We begin by providing other examples of how manipulating Bellman's equation can facilitate computation and analysis. Then we establish a solid theoretical foundation for these kinds of manipulations, and to show how similar ideas can also be applied to policy operators and greedy policies.

6.3.1 Structural Estimation

As a first illustration of the ideas in this section, we discuss the connection between certain estimation problems and dynamic programs. Our focus is on the kinds of modifications that econometricians often make to Bellman equations, and how these modifications affect computation and optimality.

6.3.1.1 What is Structural Estimation?

Structural estimation is a branch of quantitative social science in which researchers model the decision problems of economic agents in order to understand observed outcomes. In many instances, the underlying decision problem presents a dynamic program. The first step of the modeling approach is to formulate the dynamic program in terms of functional forms and parameters. Next, parameters are adjusted to bring the model outputs as close as possible to analogous data generated in the real world.

The benefit of structural estimation over estimation of less fully articulated models is the hope to discover objects that are invariant to some hypothetical interventions that the analysis wants to investigate. This process is facilitated by embedding underlying decision problems, which permits studying how agents inside the model want to react to some hypothetical intervention, such as a change in the taxation regime that they confront.

Example 6.3.1. Gillingham et al. (2022) study the used car market in Denmark by modeling consumers who trade cars in the new and used car markets. By modeling the consumers' decision problems, the authors are able to investigate how consumers would react to a hypothetical modification in automobile taxes. The study finds that Denmark automobile taxes exceed the maximizer of the Laffer curve: the government could raise tax revenue by lowering tax rates.

Efficient solution methods are paramount in structural estimation because the underlying dynamic program will need to be solved many times in order to search the parameter space for a good fit to the data. Moreover, these dynamic programs are often high-dimensional, due to the need to handle preference shocks. (In this field, researchers often assume that agents are affected by unobservable preference or reward shocks, in order to rationalize the fact that different choices are sometimes made in the same state of the world.)

In order to maintain focus on dynamic programming, we will not describe the details of the estimation step required for structural estimation (although §6.4 contains references for those who wish to learn about that). Instead, we focus on the kinds of dynamic programs treated in structural estimation and techniques for solving them efficiently.

6.3.1.2 An Illustration

Let us look at an example of a dynamic program with preference shocks used in structural estimation, which is taken from a study of labor supply by married women

(Keane et al., 2011). The model considers the decision problem of a married woman whose husband is already working. The couple have young children and the mother is deciding whether or not to return to work. Here utility function is

$$u(c, d, \xi) = c + (\alpha n + \xi)(1 - d),$$

where c is consumption, α is a parameter, n is the number of children, ξ is a preference shock and d is the action variable. The action is binary, with $d = 1$ representing the decision to work in the current period and $d = 0$ representing the decision to abstain.[3]

The budget constraint for the household is

$$c_t = f_t + w_t d_t - \pi n d_t,$$

where f_t is the father's income, w_t is the mother's wage and π is the cost of child care. Wages are assumed to depend on human capital h_t, which increases with experience. In particular,

$$w_t = \gamma h_t + \eta_t, \quad \text{with} \quad h_t = h_{t-1} + d_{t-1}.$$

Here η_t is random and γ is a parameter. We assume that $(f_t)_{t \geqslant 0}$ is F-Markov on some finite set. In the model, $(\xi_t)_{t \geqslant 0}$ and $(\eta_t)_{t \geqslant 0}$ are IID. We denote their joint distribution by φ.

With discounting constant at rate β, the problem of maximizing expected discounted utility is an MDP with Bellman's equation

$$v(f, h, \xi) = \max_d \left\{ c + (\alpha n + \xi)(1 - d) + \beta \sum_{f', \xi', \eta'} v(f', h + d, \xi', \eta') F(f, f') \varphi(\xi', \eta') \right\}.$$

While we can proceed directly with a technique such as VFI to obtain optimal choices, let us consider how to simplify the procedure.

One way that we can simplify is by reducing number of states. A hint comes from looking at the expected value function

$$g(f, h, d) := \sum_{f', \xi', \eta'} v(f', h + d, \xi', \eta') F(f, f') \varphi(\xi', \eta')$$

While this function also depends on three arguments, we know that d is binary. Hence we can break it down into two functions $g(f, h, 0)$ and $g(f, h, 1)$, each of which depends

[3]There are some questionable assumptions here, such as the fact that the woman is the primary carer, and that she derives no utility from children in periods where she decides to work. See in Keane et al. (2011) for further discussion.

only on the pair (f, h).

These functions are substantially simpler that v when the domain of ξ is large. Hence, it is natural to consider whether or not we can solve our problem using g rather than v.

6.3.1.3 Expected Value Functions

Rather than address this specific question, let's shift to a generic version of the dynamic program used in structural estimation and how it can be solved using expected value methods. Our generic version takes the form

$$v(y, \varepsilon) = \max_{a \in \Gamma(y)} \left\{ r(y, \varepsilon, a) + \beta \sum_{y'} \int v(y', \varepsilon') P(y, a, y') \varphi(\varepsilon') \, \mathrm{d}\varepsilon' \right\} \tag{6.29}$$

for all $y \in \mathsf{Y}$ and $\varepsilon \in \mathsf{E}$. Here Y is a finite set, often determined by discretization of a continuous space, while E, the outcome space for ε, is allowed to be continuous. The state y will be called the endogenous state, while ε is the preference shock. In practice, ε will often be a vector of shocks that can all impact on current rewards. The integral can therefore be multivariate and is over all of E.

The problem represented by (6.29) is a version of a regular MDP, with state $x = (y, \varepsilon)$ taking values in $\mathsf{X} := \mathsf{Y} \times \mathsf{E}$. If we discretize the space E, then all of the optimality theory for MDPs applies. Instead of taking this approach, however, we draw on our discussion of labor choice in §6.3.1.2. In particular, to enhance efficiency, we will work with the **expected value function**

$$g(y, a) := \sum_{y'} \int v(y', \varepsilon') P(y, a, y') \varphi(\varepsilon') \, \mathrm{d}\varepsilon' \tag{6.30}$$

There are several potential advantages associated with working with g rather than v. One is that the set of actions A can be much smaller than the set of states that would be created by discretization of the preference shock space E (especially if ε_t takes values in a high-dimensional space). Another is that the integral provides smoothing, so that g is typically a smooth function. This can greatly assist structural estimation procedures.

6.3.1.4 Optimality via EV Methods

To exploit the relative simplicity of the expected value function, we rewrite Bellman's equation (6.29) as

$$v(y,\varepsilon) = \max_{a\in\Gamma(y)} \{r(y,\varepsilon,a) + \beta g(y,a)\}.$$

Taking expectations of both sides and using (6.30) again gives

$$g(y,a) = \sum_{y'} \int \max_{a'\in\Gamma(y')} \{r(y',\varepsilon',a') + \beta g(y',a')\} P(y,a,y')\varphi(\varepsilon')\,\mathrm{d}\varepsilon'.$$

To solve this functional equation we introduce the **expected value Bellman operator** R defined at $g \in \mathbb{R}^{\mathsf{G}}$ by

$$(Rg)(y,a) = \sum_{y'} \int \max_{a'\in\Gamma(y')} \{r(y',\varepsilon',a') + \beta g(y',a')\} P(y,a,y')\varphi(\varepsilon')\,\mathrm{d}\varepsilon'. \tag{6.31}$$

Here G is the set of feasible state-action pairs (y,a).

Exercise 6.3.1. Prove that R is order-preserving and a contraction of modulus β on $\mathbb{R}^{\mathsf{G}}$ (with respect to the supremum norm).

In what follows, we let g^* be the fixed point of R in $\mathbb{R}^{\mathsf{G}}$. Since R is a contraction map, g^* can be computed by successive approximation. The next result shows that knowing this fixed point is enough to solve the dynamic program.

Proposition 6.3.1. *A policy $\sigma \in \Sigma$ is optimal if and only if*

$$\sigma(y,\varepsilon) \in \operatorname*{argmax}_{a\in\Gamma(y)} \{r(y,\varepsilon,a) + \beta g^*(y,a)\} \qquad \textit{for all } (y,\varepsilon) \in \mathsf{Y}\times\mathsf{E}.$$

The proof of Proposition 6.3.1 is delayed until §6.3.4, where we prove a more general result.

Example 6.3.2. In the labor supply problem in §6.3.1.2, the expected value Bellman operator becomes

$$(Rg)(f,h,d) = \sum_{f',\xi',\eta'} \max_{d'} \{c + (\alpha n + \xi)(1-d') + \beta g(f',h+d,d')\} F(f,f')\varphi(\xi',\eta').$$

Iterating from an arbitrary guess of g converges to the unique fixed point g^* of R. By

Proposition 6.3.1, we can then compute the optimal policy σ^* at (f, h) by taking

$$\sigma^*(f, h) \in \operatorname*{argmax}_d \{c + (\alpha n + \xi)(1 - d') + \beta g^*(f, h, d)\}.$$

6.3.2 Optimal Savings Revisited

In this section we exhibit another problem where framing the decision in terms of expected values is beneficial. The problem is not directly related to structural estimation. Rather, it is a version of the optimal savings problem from §6.2.2 where labor income has both persistent and transient components. In particular, we assume that

$$Y_t = Z_t + \varepsilon_t$$

where $(\varepsilon_t)_{t \geqslant 0}$ is IID with common distribution φ on E, while $(Z_t)_{t \geqslant 0}$ is Q-Markov on Z. Such specifications of labor income are quite common in the literature, since households tend to react differently to transient and "permanent" shocks (see §6.4 for more discussion).

Leaving other parts of the optimal savings problem from §6.2.2 unchanged, Bellman's equation is

$$v(w, z, \varepsilon) = \max_{w' \leqslant R(w+z+\varepsilon)} \left\{ u\left(w + z + \varepsilon - \frac{w'}{R}\right) + \beta \sum_{z', \varepsilon'} v(w', z', \varepsilon') Q(z, z') \varphi(\varepsilon') \right\}.$$

Both w and w' are constrained to a finite set $\mathsf{W} \subset \mathbb{R}_+$. The expected value function for this problem can be expressed as

$$g(z, w') := \sum_{z', \varepsilon'} v(w', z', \varepsilon') Q(z, z') \varphi(\varepsilon'). \tag{6.32}$$

In the remainder of this section, we will say that a savings policy σ is **g-greedy** if

$$\sigma(z, w, \varepsilon) \in \operatorname*{argmax}_{w' \leqslant R(w+z+\varepsilon)} \left\{ u\left(w + z + \varepsilon - \frac{w'}{R}\right) + \beta g(z, w') \right\}.$$

Given that the model is an MDP, we can see immediately that if we replace v in (6.32) with the value function v^*, then a g-greedy policy will be an optimal one.

Using manipulations analogous to those we used in §6.3.1.4, we can rewrite Bell-

man's equation in terms of expected value functions via

$$g(z, w') = \sum_{z',\, \varepsilon'} \max_{w'' \leqslant R(w'+z'+\varepsilon')} \left\{ u\left(w' + z' + \varepsilon' - \frac{w''}{R}\right) + \beta g(z', w'') \right\} Q(z, z')\varphi(\varepsilon').$$

From here we could proceed by introducing an expected value Bellman operator analogous to R in (6.31), proving it to be a contraction map and then showing that greedy policies taken with respect to the fixed point are optimal. All of this can be accomplished without too much difficulty—we prove more general results in §6.3.4.

However, we also know that optimistic policy iteration (OPI) is, in general, more efficient than value function iteration. This motivates us to introduce the modified σ-value operator

$$(R_\sigma g)(z, w') = \sum_{z',\, \varepsilon'} \left\{ u\left(w' + z' + \varepsilon' - \frac{\sigma(w', z', \varepsilon')}{R}\right) + \beta g(z', \sigma(w', z', \varepsilon')) \right\} Q(z, z')\varphi(\varepsilon').$$

This is a variation on the regular σ-value operator T_σ, modified to act on expected value functions.

A suitably modified OPI routine that is adapted from the regular OPI algorithm in §6.1.3.4 can be found in Algorithm 7 on page 208. The routine is convergent. We discuss this in greater detail in §6.3.4.

Figure 6.12 shows optimal savings as a function of z and ε. The paramters are as in Listing 23. The figures show contour plots of the function $(z, \varepsilon) \mapsto \sigma^*(w, z, \varepsilon)$, where σ^* is the optimal policy. The policy was obtained by modified OPI, as discussed above. In the top and bottom figures, w at is fixed at $\min \mathsf{W}$ and $\max \mathsf{W}$ respectively.

6.3.3 Q-Learning

Q-learning is both an algorithm and a branch of reinforcement learning. Reinforcement learning is a sub-field of control and artificial intelligence, concerned with dynamic optimization in a setting where some aspects of the system are unknown to the controller. One (somewhat narrow) way to define reinforcement learning is techniques for the solution of Markov decision problems where the full specification of state dynamics and rewards is not known.

Q-learning is just one of many techniques for reinforcement learning. It uses stochastic approximation techniques to learn the so-called Q-factor, which assigns value to state-action pairs. Remarkably, the Q-learning algorithm allows an agent

Figure 6.12: Optimal savings as a function of (z, ε), given w

```
using QuantEcon, LinearAlgebra, IterTools

function create_savings_model(; R=1.01, β=0.98, γ=2.5,
                                w_min=0.01, w_max=10.0, w_size=100,
                                ρ=0.9, ν=0.1, z_size=20,
                                ϵ_min=-0.25, ϵ_max=0.25, ϵ_size=30)
    ϵ_grid = LinRange(ϵ_min, ϵ_max, ϵ_size)
    ϕ = ones(ϵ_size) * (1 / ϵ_size)  # Uniform distributoin
    w_grid = LinRange(w_min, w_max, w_size)
    mc = tauchen(z_size, ρ, ν)
    z_grid, Q = exp.(mc.state_values), mc.p
    return (; β, R, γ, ϵ_grid, ϕ, w_grid, z_grid, Q)
end
```

Listing 23: Optimal savings parameters (`modified_opt_savings.jl`)

to eventually learn an optimal policy for any finite MDP through observing the state dynamics and one-period rewards.

Q-learning is connected to the topic of this chapter (modifying Bellman's equation) because it relies on the essential equivalence of the Q-factor and Bellman's equation. Here we omit discussion of learning the Q-factor and proceed instead to discuss this equivalence.

To begin, we fix an MDP (Γ, β, r, P) with state space X and action space A. For each $v \in \mathbb{R}^{\mathsf{X}}$, the **$Q$-factor** corresponding to v is the function

$$q(x, a) = r(x, a) + \beta \sum_{x'} v(x')P(x, a, x') \qquad ((x, a) \in \mathsf{G}).$$

We can convert Bellman's equation into an equation in Q-factors by observing that, given such a q, Bellman's equation can be written as $v(x) = \max_{a \in \Gamma(x)} q(x, a)$. Taking the mean and discounting on both sides of this equation gives

$$\beta \sum_{x'} v(x')P(x, a, x') = \beta \sum_{x'} \max_{a' \in \Gamma(x')} q(x', a')P(x, a, x').$$

Adding $r(x, a)$ and using the definition of q again gives

$$q(x, a) = r(x, a) + \beta \sum_{x'} \max_{a' \in \Gamma(x')} q(x', a')P(x, a, x').$$

This functional equation motivates us to introduce the **Q-factor Bellman operator**

$$(Sq)(x, a) = r(x, a) + \beta \sum_{x'} \max_{a' \in \Gamma(x')} q(x', a')P(x, a, x') \qquad ((x, a) \in \mathsf{G}). \tag{6.33}$$

Exercise 6.3.2. Prove that S is order-preserving and a contraction of modulus β on $\mathbb{R}^{\mathsf{G}}$ (with respect to the supremum norm).

In what follows, we let q^* be the unique fixed point of S in $\mathbb{R}^{\mathsf{G}}$.

Proposition 6.3.2. *A policy $\sigma \in \Sigma$ is optimal if and only if*

$$\sigma(x) \in \operatorname*{argmax}_{a \in \Gamma(x)} q^*(x, a) \qquad \textit{for all } (x, a) \in \mathsf{G}.$$

Enthusiastic readers might like to try to prove Proposition 6.3.2 directly. We defer the proof until §6.3.4, where a more general result is obtained.

6.3.4 Operator Factorizations

Our study of structural estimation in §6.3.1, optimal savings in §6.3.2 and Q-learning in §6.3.3 all involved manipulations of the Bellman and policy operators, which aimed to achieve useful alternative views on the respective optimization problems. Rather than continuing to look at applications that apply such ideas, we now develop a general theoretical framework from which to understand manipulations of the Bellman and policy operators for general MDPs. The framework clarifies how and when these techniques can be applied.

6.3.4.1 Refactoring the Bellman Operator

Fix an MDP (Γ, β, r, P) with state space X and action space A. As usual, Σ is the set of feasible policies, G is the feasible state action pairs, T is the Bellman operator and v^* denotes the value function. Our first step is to decompose T into separate parts. To do this we introduce three auxillary operators:

- $E \colon \mathbb{R}^{\mathsf{X}} \to \mathbb{R}^{\mathsf{G}}$ defined by $(Ev)(x, a) = \sum_{x'} v(x')P(x, a, x')$,
- $D \colon \mathbb{R}^{\mathsf{G}} \to \mathbb{R}^{\mathsf{G}}$ defined by $(Dg)(x, a) = r(x, a) + \beta g(x, a)$ and
- $M \colon \mathbb{R}^{\mathsf{G}} \to \mathbb{R}^{\mathsf{X}}$ defined by $(Mq)(x) = \max_{a \in \Gamma(x)} q(x, a)$.

A moment of thought will convince you that the action of the Bellman operator T on a given $v \in \mathbb{R}^{\mathsf{X}}$ is the composition of these three steps:

(i) take conditional expectations given $(x, a) \in \mathsf{G}$ (applying E),

(ii) discount and adding current rewards (applying D), and

(iii) maximize with respect to current action (applying M).

As a result, we can write $T = MDE := M \circ D \circ E$ (apply E first, D second, and M third). This relationship is visualized in Figure 6.13. The action of T is a round trip from the top node, which is the set of value functions.

If we consider Figure 6.13 more carefully, we can consider two other round trips. One is a round trip from the set of expected value functions, obtained by the sequence EMD. The other is a round trip from the set of Q-factors, obtained by the sequence DEM. Let's name these additional round trips R and S respectively, so that, collecting all three,

$$R = EMD, \quad S = DEM, \quad T = MDE. \tag{6.34}$$

Both R and S act on functions in $\mathbb{R}^{\mathsf{G}}$. The next exercise provides an explicit representation of these operators.

Figure 6.13: Multiple Bellman operators (EV = expected value)

Exercise 6.3.3. Show that for any $g, q \in \mathbb{R}^{\mathsf{G}}$ and $(x, a) \in \mathsf{G}$ we have

$$(Rg)(x,a) = \sum_{x'} \max_{a' \in \Gamma(x')} \{r(x',a') + \beta g(x',a')\} P(x,a,x') \quad \text{and}$$
$$(Sq)(x,a) = r(x,a) + \beta \sum_{x'} \max_{a' \in \Gamma(x')} q(x',a') P(x,a,x').$$

Let's now connect our "refactored" Bellman operators R and S to our preceding examples. Inspection of (6.33) will confirm for you that S is exactly the Q-factor Bellman operator. In addition, R is a general version of the expected value Bellman operator defined in (6.31).

Exercise 6.3.4. Show that, for all $k \in \mathbb{N}$, the following relationships hold

- $R^k = ET^{k-1}MD = EMS^{k-1}D$
- $S^k = DR^{k-1}ME = MT^{k-1}ED$
- $T^k = MS^{k-1}DE = MDR^{k-1}E$

(Here, for any operator A, we take A^0 to be the identity map.)

While the equalities in Exercise 6.3.4 can be proved by induction via (6.34), the intuition is straightforward from Figure 6.13. For example, the relationship $R^k = ET^{k-1}MD$ states that round-tripping k times from the space of expected values (EV

function space) is the same as shifting to value function space by applying MD, round-tripping $k-1$ times using T, and then shifting one more step to EV function space via E.

Although the relationships in Exercise 6.3.4 are easy to prove, they are already useful. For example, suppose that R is easier to iterate with than T in a computational setting. Then, to iterate with T k times, we can instead use $T^k = MDR^{k-1}E$: We apply E once, R $k-1$ times, and M and D once each. If k is large, this might be far more efficient.

In the next exercise and all of the remaining section, we let $\|\cdot\| := \|\cdot\|_\infty$, the supremum norm on either $\mathbb{R}^X$ or $\mathbb{R}^G$.

Exercise 6.3.5. Prove the following facts:

(i) $\|Ev - Ev'\| \leqslant \|v - v'\|$ for all $v, v' \in \mathbb{R}^X$,

(ii) $\|Mg - Mg'\| \leqslant \|g - g'\|$ for all $g, g' \in \mathbb{R}^G$, and

(iii) $\|Dq - Dq'\| \leqslant \beta\|q - q'\|$ for all $q, q' \in \mathbb{R}^G$.

In words, we say that E and M are **nonexpansive** on $\mathbb{R}^X$ and $\mathbb{R}^G$ respectively, while D is a contraction on $\mathbb{R}^G$.

Lemma 6.3.3. *The operators R, S and T are all contraction maps of modulus β under the supremum norm.*

Proof. The fact that T is a contraction of modulus β was proved in Proposition 6.1.1, on page 168. We can also prove this more easily now by applying Exercise 6.3.5, which, for arbitrary $v, v' \in \mathbb{R}^X$, gives

$$\|Tv - Tv'\| = \|MDEv - MDEv'\| \leqslant \|MDv - MDv'\| \leqslant \beta\|Mv - Mv'\| \leqslant \beta\|v - v'\|.$$

The proofs for $R = EMD$ and $S = DEM$ are very similar. □

In the next section we clarify the relationship between these operators and prove Propositions 6.3.1 and 6.3.2.

6.3.4.2 Refactorizations and Optimality

From Lemma 6.3.3 we see that R, S and T all have unique fixed points. We denote them by g^*, q^* and v^* respectively, so that

$$Rg^* = g^*, \quad Sq^* = q^*, \quad \text{and} \quad Tv^* = v^*.$$

We already know that v^* is the value function (Proposition 6.1.1). The results below show that the other two fixed points are, like the value function, sufficient to determine optimality.

Proposition 6.3.4. *The fixed points of R, S and T are connected by the following relationships:*

(i) $g^* = Ev^*$,

(ii) $q^* = Dg^*$, *and*

(iii) $v^* = Mq^*$.

Proof. To prove (i), first observe that, in the notation of (6.34), we have $Ev^* = ETv^* = EMDEv^* = REv^*$. Hence Ev^* is a fixed point of R. But R has only one fixed point, which is g^*. Therefore, $g^* = Ev^*$. The proofs of (ii) and (iii) are analogous. □

The results in Proposition 6.3.4 can be written more explicitly as

- $g^*(x,a) = \sum_{x'} v^*(x')P(x,a,x')$ for all $(x,a) \in \mathsf{G}$,
- $q^*(x,a) = r(x,a) + \beta g^*(x,a)$ for all $(x,a) \in \mathsf{G}$, and
- $v^*(x) = \max_{a\in\Gamma(x)} q^*(x,a)$ for all $x \in \mathsf{X}$.

In the next result and the discussion that follows, given $g, q \in \mathbb{R}^{\mathsf{G}}$, we will call $\sigma \in \Sigma$

- **g-greedy** if $\sigma(x) \in \operatorname{argmax}_{a\in\Gamma(y)} \{r(x,a) + \beta g(x,a)\}$ for all $x \in \mathsf{X}$, and
- **q-greedy** if $\sigma(x) \in \operatorname{argmax}_{a\in\Gamma(y)} q(x,a)$ for all $x \in \mathsf{X}$.

These definitions are exact analogs of the v-greedy concept, applied to expected value functions and Q-factors respectively.

Corollary 6.3.5. *For $\sigma \in \Sigma$, the following statements are equivalent:*

(i) *σ is v-greedy when $v = v^*$.*

(ii) *σ is g-greedy when $g = g^*$.*

(iii) *σ is q-greedy when $q = q^*$.*

In particular, σ is optimal if and only if any one (and hence all) of (i)–(iii) holds.

Proof. To see that (i) imples (ii), suppose that σ is v-greedy when $v = v^*$. Then, for arbitrary $x \in \mathsf{X}$.

$$\begin{aligned}\sigma(x) &\in \operatorname*{argmax}_{a \in \Gamma(y)} \left\{ r(x,a) + \beta \sum_{x'} v^*(x') P(x,a,x') \right\} \\ &= \operatorname*{argmax}_{a \in \Gamma(y)} \left\{ r(x,a) + \beta g^*(x,a) \right\}.\end{aligned}$$

Hence σ is g-greedy when $g = g^*$, and (i) implies (ii). The proofs of the remaining equivalences (ii) $\implies$ (iii) $\implies$ (i) are similar. The claim that σ is optimal if and only if if any one of (i)–(iii) holds now follows from Proposition 6.1.1, which tells us that σ is optimal if and only if σ is v^*-greedy. □

Notice that Proposition 6.3.2 is a special case of Corollary 6.3.5.

The results in Corollary 6.3.5 can be understood as "refactored" versions of Bellman's principle of optimality. One consequence of these results is that we can solve a given MDP by modifying VFI to operate on either expected value functions or Q-factors. For example, if we find it more convenient to iterate in expected value space, then (informally) we can proceed as follows:

(i) Fix $g \in \mathbb{R}^{\mathsf{G}}$.

(ii) Iterate with R to obtain $g_k := R^k g \approx g^*$.

(iii) Compute a g_k-greedy policy.

Since $g_k \approx g^*$, the resulting policy will be approximately optimal.

6.3.4.3 Refactored OPI

In Chapter 6 we found that VFI is often outperformed by HPI or OPI. Our next step is to apply these methods to modified versions of Bellman's equation, as discussed in the previous section. This allows us to can combine the advantages of HPI/OPI with the potential efficiency gains obtained by refactoring Bellman's equation.

We illustrate these ideas below by producing a version of OPI that can compute Q-factors and expected value functions. (The same is true for HPI, although we leave details of this construction to interested readers.)

To begin, we introduce a new operator, denoted M_σ, which, for fixed $\sigma \in \Sigma$ and $q \in \mathbb{R}^{\mathsf{G}}$, produces

$$(M_\sigma q)(x) := q(x, \sigma(x)) \qquad (x \in \mathsf{X}).$$

This operator is the policy analog of the maximization operator M defined by $(Mq)(x) = \max_{a \in \Gamma(x)} q(x, a)$ in §6.3.4.1. Analogous to (6.34), we set

$$R_\sigma := E\, M_\sigma\, D, \quad S_\sigma := D\, E\, M_\sigma, \quad T_\sigma := M_\sigma\, D\, E.$$

You can verify that T_σ is the ordinary σ-policy operator (defined in (6.9)). The operators R_σ and S_σ are the expected value and Q-factor equivalents.

Exercise 6.3.6. The relationships in Exercise 6.3.4 continue to hold after we swap R, S, T, M with $R_\sigma, S_\sigma, T_\sigma, M_\sigma$. Confirm the first of these relationships, showing in particular that

$$R_\sigma^k = E\, T_\sigma^{k-1}\, M_\sigma\, D \qquad \text{for all } k \in \mathbb{N}. \tag{6.35}$$

Let's now show that OPI can be successfully modified via these alternative operators. We will focus on the expected value viewpoint (value functions are replaced by expected value functions), which is the most practical in the applications we wish to consider.

Our modified OPI routine is given in Algorithm 7. It makes the obvious modifications to regular OPI, switching to working with expected value functions in $\mathbb{R}^{\mathsf{G}}$ and from iteration with T_σ to iteration with R_σ.

Algorithm 7: Refactored OPI for expected value functions

```
input g_0 ∈ R^G, an initial guess of g*
input τ, a tolerance level for error
input m ∈ N, a step size
k ← 0
ε ← τ + 1
while ε > τ do
    σ_k ← a g_k-greedy policy
    g_{k+1} ← R^m_{σ_k} g_k
    ε ← ||g_k − g_{k+1}||_∞
    k ← k + 1
end
return σ_k
```

Algorithm 7 is globally convergent in the same sense as regular OPI (Algorithm 6 on page 177). In fact, if we pick $v_0 \in \mathbb{R}^{\mathsf{X}}$ and apply regular OPI with this initial condition, as well as applying Algorithm 7 with initial condition $g_0 := Ev_0$, then the sequences $(v_k)_{k \geqslant 0}$ and $(g_k)_{k \geqslant 0}$ generated by the two algorithms are connected via $g_k =$

Ev_k for all $k \geqslant 0$. If greedy policies are unique, then it is also true that the policy sequences generated by the two algorithms are identical.

Let's prove these claims, assuming for convenience that greedy policies are unique. Consider first the claim that $g_k = Ev_k$ for all $k \geqslant 0$. This is true by assumption when $k = 0$. Suppose, as an induction hypothesis, that $g_k = Ev_k$ holds at arbitrary k let σ be g_k-greedy. Then

$$\sigma(x) = \operatorname*{argmax}_{a \in \Gamma(y)} \{r(x,a) + \beta g_k(x,a)\} = \operatorname*{argmax}_{a \in \Gamma(y)} \left\{ r(x,a) + \beta \sum_{x'} v_k(x') P(x,a,x') \right\},$$

where the second equality is by $g_k = Ev_k$. Hence σ is both g_k-greedy and v_k-greedy, and is the next policy selected by both modified and regular OPI. Moreover, updating via Algorithm 7 and applying (6.35), we have

$$g_{k+1} = R_\sigma^m g_k = ET_\sigma^{m-1} M_\sigma D g_k = ET_\sigma^{m-1} M_\sigma D E v_k = ET_\sigma^m v_k.$$

Since σ is v_k-greedy, $T_\sigma^m v_k$ is the next function selected by regular OPI. Hence $v_{k+1} = T_\sigma^m v_k$. Connecting with the last chain of equalities yields $g_{k+1} = Ev_{k+1}$. This completes the proof that $g_k = Ev_k$ for all k. In fact we just showed that the policy functions generated by the algorithms are identical as well.

The preceding discussion provides a justification for the modified OPI algorithm we adopted in §6.3.2.

6.4 Chapter Notes

Detailed treatment of MDPs can be found in Howard (1960), Bellman (1957), Denardo (1981), Puterman (2005), Bertsekas (2012), Hernández-Lerma and Lasserre (2012a, 2012b), and Kochenderfer et al. (2022). The Hernández-Lerma and Lasserre (2012a, 2012b) provide excellent coverage of theory, while Puterman (2005) gives a clear and detailed exposition of algorithms and techniques. Further discussion of the connection between HPI and Newton iteration can be found in Section 6.4 of Puterman (2005).

HPI is routinely used in artificial intelligence applications, including during the training of AlphaZero by DeepMind. Further discussion of these variants of HPI and their connection to Newton iteration can be found in Bertsekas (2021) and Bertsekas (2022a).

For treatments of dynamic programming from the perspective of economics and finance, see, for example, Sargent (1987), Stokey and Lucas (1989), Van and Dana (2003), Bäuerle and Rieder (2011), or Stachurski (2022). The text by Bäuerle and Rieder (2011) is a favorite of ours.

The optimal savings problem is a workhorse in macroeconomics and has been treated extensively in the literature. Early references include Brock and Mirman (1972), Mirman and Zilcha (1975), Schechtman (1976), Deaton and Laroque (1992), and Carroll (1997). For more recent studies, see, for example, Li and Stachurski (2014), Açıkgöz (2018), Light (2018), Lehrer and Light (2018), or Ma et al. (2020). Recent applications involving optimal savings in a representative agent framework include Bianchi (2011), Paciello and Wiederholt (2014), Rendahl (2016), Heathcote and Perri (2018), Paroussos et al. (2019), Erosa and González (2019), Herrendorf et al. (2021), and Michelacci et al. (2022).

Households solving optimal savings problems are often embedded in heterogenous agent models in order to study income distributions, wealth distributions, business cycles and other macroeconomic phenomena. Representative examples include Aiyagari (1994), Huggett (1993), Krusell and Smith (1998), Miao (2006), Algan et al. (2014), Toda (2014), Benhabib et al. (2015), Stachurski and Toda (2019), Toda (2019), Light (2020), Hubmer et al. (2020), or Cao (2020). Continuous time heterogeneous agent models are also popular and a typical example can be found in Kaplan et al. (2018).

The optimal investment problem dates back to Lucas Jr and Prescott (1971). Textbook treatments can be found in Stokey and Lucas (1989) and Dixit and Pindyck (2012). Hayashi (1982) used the optimal investment problem to connect optimal capital accummulation with Tobin's q (which is the ratio between a physical asset's market value and its replacement value). Other influential papers in the field include Lee and Shin (2000), Hassett and Hubbard (2002), Bloom et al. (2007), Bond and Van Reenen (2007), Bloom (2009), and Wang and Wen (2012). Carruth et al. (2000) contains a survey.

Regarding the S-s inventory model, classic papers in the field include Arrow et al. (1951) and Dvoretzky et al. (1952). Optimality of S-s policies under certain conditions was first established by Scarf (1960). Kelle and Milne (1999) study the impact of S-s inventory policies on the supply chain, including connection to the "bullwhip" effect. The connection between S-s inventory policies and macroeconomic fluctuations is studied in Nirei (2006).

The model in Exercise 6.2.5 is loosely adapted from Bagliano and Bertola (2004).

Rust (1994) is a classic and highly readable reference in the area of structural estimation of MDPs. Keane and Wolpin (1997) provides an influential study of the

career choices of young men. Roberts and Tybout (1997) analyze the decision to export in the presence of sunk costs. Keane et al. (2011) give an excellent overview of structural estimation applied to labor market problems. Gentry et al. (2018) review analysis of auctions using structural estimation. Legrand (2019) surveys the use of structural models to study the dynamics of commodity prices. Calsamiglia et al. (2020) use structural estimation to study school choices. Iskhakov et al. (2020) provide a thoughtful discussion on the differences between structural estimation and machine learning. Luo and Sang (2022) propose a new method of structural estimation using sieves.

Theoretical analysis of the benefits of using expected value functions in discrete choice models and other settings can be found in Rust (1994), Norets (2010), and Kristensen et al. (2021).

In §6.3.2 we studied optimal savings and consumption in the present of transient and persistent shocks to labor income. For research in this vein, see, for example, Quah (1990), Carroll (2009), De Nardi et al. (2010), or Lettau and Ludvigson (2014). For empirical work on labor income dynamics, see, for example, Newhouse (2005), Guvenen (2007), Guvenen (2009), or Blundell et al. (2015). For analysis of optimal savings in a very general setting, see Ma et al. (2020) or Ma and Toda (2021).

In §6.3.3 we discussed Q-learning, which was originally proposed by Watkins (1989). A proof of the convergence properties of Q-learning can be found in Melo (2001).

The theory in §6.3.4 on optimality under modifications of Bellman's equation is loosely based on Ma and Stachurski (2021). That paper considers arbitrary modifications in a very general setting.

Chapter 7

Abstract Dynamic Programming

While the MDP model from Chapter 6 is powerful, elegant, and remarkably broad, researchers in economics, finance, and other fields want to push past the boundaries of that framework. Reasons include:

(i) MDP theory cannot be applied to settings where lifetime values are described by nonlinear recursive preferences (see §4.3).

(ii) Computing equilibria in some models of production and economic geography can be computed using dynamic programming but sometimes these programming problems do not fit within the framework of MDPs.[1]

(iii) Dynamic programming problems that include ambiguity and adversarial agents that promote robust decision rules often fail to be MDPs (see, e.g., Cagetti et al. (2002) or Hansen and Sargent (2011)).

To such handle departures from the MDP assumptions, we construct an *abstract dynamic programming* framework, building on an approach to optimization initially developed by Eric Denardo (1937–) and Loring Mitten (1921–2000), and recently extended and promoted by Bertsekas (2022b). Further references are provided in §7.5.

Apart from generality, another motivation for greater abstraction is a desire for clarity: while we have already provided some optimality proofs (such as the proof of Proposition 6.1.1, on optimality for MDPs), the abstract DP framework allows us to strip away extraneous structure and isolate roles of various assumptions.

[1] See, for example, Hsu et al. (2014), Antràs and De Gortari (2020) Kikuchi et al. (2021) or Tyazhelnikov (2022).

We begin our treatment of abstract dynamic programming in §7.1, using a framework that centers on an abstract representation of Bellman's equation. We then state optimality results and show how the can be verified in a range of applications.

Proofs of the optimality results are all deferred until §7.3, where we strip dynamic programs down to their essence by adopting a purely operator-theoretic approach. This "pure" approach will simplify proofs and, at the same time, allow us to extend dynamic programming to an even broader class of applications.

7.1 Recursive Decision Processes

In this section we introduce recursive decision processes, which, by extending the MDP model, allow us to treat not only MDPs but also models with recursive preferences, state-dependent discounting, and other useful features.

7.1.1 Defining RDPs

Consider a generic Bellman equation of the form

$$v(x) = \max_{a \in \Gamma(x)} B(x, a, v). \tag{7.1}$$

Here x is the state, a is an action, Γ is a feasible correspondence, and B is an abstract representation of the right-hand side of a Bellman equation. (Compare with, say, Bellman's equation for the MDP model offered in (6.2) on page 162.) We understand $\Gamma(x)$ as all actions available to the controller in state x. The function v assigns values to states and is a member of some class $V \subset \mathbb{R}^{\mathsf{X}}$.

We introduce two finite sets,

- an **action space** A and
- a **state space** X.

Given X and A, we define a **recursive decision process** (RDP) to be a triple (Γ, V, B) containing

(i) a **feasible correspondence** Γ that is a nonempty correspondence from X to A. Γ in turn defines

- the feasible state-action pairs

$$\mathsf{G} := \{(x, a) \in \mathsf{X} \times \mathsf{A} : a \in \Gamma(x)\},$$

- the set of feasible policies

$$\Sigma := \{\sigma \in \mathsf{A}^{\mathsf{X}} : \sigma(x) \in \Gamma(x) \text{ for all } x \in \mathsf{X}\};$$

(ii) a **value space** V, which is a sublattice of $\mathbb{R}^{\mathsf{X}}$, and

(iii) a **value aggregator** B that maps $\mathsf{G} \times V$ to $\mathbb{R}$ and satisfies the monotonicity condition

$$v, w \in V \text{ and } v \leqslant w \implies B(x, a, v) \leqslant B(x, a, w) \text{ for all } (x, a) \in \mathsf{G}, \tag{7.2}$$

and the consistency condition

$$\sigma \in \Sigma \text{ and } v \in V \implies w \in V \quad \text{where } w(x) := B(x, \sigma(x), v). \tag{7.3}$$

The statement that V is a **sublattice** of $\mathbb{R}^{\mathsf{X}}$ means that $f, g \in V$ implies $f \vee g \in V$ and $f \wedge g \in V$. Throughout, $\leqslant$ represents the pointwise order on $\mathbb{R}^{\mathsf{X}}$.

The definition of the feasible correspondence in (i) is identical to that for the MDP case in Chapter 6. As for (ii), we understand V to be a class of functions that assign values to states. In (iii), the interpretation of the aggregator B is:

> $B(x, a, v)$ = total lifetime rewards, contingent on current action a, current state x, and using v to evaluate future states.

In other words, $B(x, a, v)$ corresponds to the right hand side of Bellman's equation, as in (7.1). Not surprisingly, optimality requires inserting the correct function v into $B(x, a, v)$, so locating and calculating this v is one of our major concerns.

The monotonicity condition (7.2) is natural: if, relative to v, rewards are at least as high for w in every future state, then the total rewards one can extract under w should be at least as high. The consistency condition in (7.3) is required to ensure that, when considering the value of different policies, we remain within the value space V.

Example 7.1.1. A basic "cake eating" problem can be framed as an RDP. Let X be a finite subset of $\mathbb{R}_+$, where $x \in \mathsf{X}$ is understood to be the number of remaining slices of cake. With $\mathsf{A} = \mathsf{X}$, $V = \mathbb{R}^{\mathsf{X}}$, $u \colon \mathbb{R}_+ \to \mathbb{R}$,

$$B(x, x', v) = u(x - x') + \beta v(x')$$

and $\Gamma(x) = \{x' \in \mathsf{X} : x' \leqslant x\}$ we obtain an RDP. The choice x' is the number of remaining slices next period and $u(x - x')$ is the utility from slices enjoyed today.

The monotonicity condition (7.2) clearly holds and the consistency condition (7.3) is trivial in this case, since V is all of $\mathbb{R}^{\mathsf{X}}$.

Generalizing the previous example, we now show that every MDP is an RDP.

Example 7.1.2. Consider an arbitrary MDP (Γ, β, r, P) with state space X and action space A (see, e.g., §6.1.1.1). To frame this model as an RDP, we take Γ as the feasible correspondence for the RDP and $V = \mathbb{R}^{\mathsf{X}}$ as the value space. The aggregator B is

$$B(x, a, v) = r(x, a) + \beta \sum_{x' \in \mathsf{X}} v(x') P(x, a, x') \qquad ((x, a) \in \mathsf{G},\ v \in V). \tag{7.4}$$

(This corresponds to the unmaximized right-hand side of Bellman's equation in (6.2) on page 162.) Now (Γ, V, B) forms an RDP. The monotonicity condition (7.2) clearly holds and the consistency condition (7.3) is trivial, as in Example 7.1.1.

Example 7.1.3 (State-Dependent Discounting)**.** We can add state-dependent discounting to the last example by changing the aggregator to

$$B(x, a, v) = r(x, a) + \sum_{x'} v(x') \beta(x, a, x') P(x, a, x'), \tag{7.5}$$

where β is some nonnegative function from $\mathsf{G} \times \mathsf{X}$ to $\mathbb{R}$. As before we take $V = \mathbb{R}^{\mathsf{X}}$. This model is no longer and MDP but the primitives (Γ, V, B) form an RDP.

Exercise 7.1.1. Verify that (Γ, V, B) as defined in Example 7.1.3 is in fact an RDP.

Example 7.1.4 (Epstein–Zin Preferences)**.** We can modify the MDP in Example 7.1.2 to use the Epstein–Zin aggregator in (4.36) by setting

$$B(x, a, v) = \left\{ r(x, a) + \beta \left[\sum_{x' \in \mathsf{X}} v(x')^{\gamma} P(x, a, x') \right]^{\alpha/\gamma} \right\}^{1/\alpha}, \tag{7.6}$$

where β, γ and α are nonzero parameters. (This matches (4.38) on page 125, apart from the fact that we now have an action to consider.) To avoid undefined exponentiation when $\gamma < 0$, we assume that $r_1 := \min_{(x,a) \in \mathsf{G}} r(x, a)$ is strictly positive and take $V := [v_1, v_2]$ where v_1 and v_2 are defined in §4.3.3.2.

Exercise 7.1.2. Confirm that the Epstein–Zin model from Example 7.1.4 satisfies the monotonicity and consistency conditions in the definition of an RDP. You can assume the parameter restrictions in §4.3.3.2.

Example 7.1.5. We can also modify the MDP in Example 7.1.2 to use risk-sensitive preferences. We do this by taking V to be all of $\mathbb{R}^{\mathsf{X}}$ and setting

$$B(x, a, v) = r(x, a) + \beta \frac{1}{\theta} \ln \left\{ \sum_{x' \in \mathsf{X}} \exp(\theta v(x')) P(x, a, x') \right\} \tag{7.7}$$

for all $(x, a) \in \mathsf{G}$.

Exercise 7.1.3. Confirm that the risk-sensitive model (Γ, V, B) in Example 7.1.5 is an RDP, for all nonzero values of θ.

Example 7.1.6. In §6.1.1.3 we embedded the job search model into the MDP framework but the construction was somewhat awkward. Fortunately, we can also view each optimal stopping problem (including job search) as an RDP; the appropriate embedding is straightforward. Indeed, consider an optimal stopping problem with primitives as described in Chapter 5 and Bellman's equation

$$v(x) = \max \left\{ e(x), c(x) + \beta \sum_{x' \in \mathsf{X}} v(x') P(x, x') \right\} \qquad (x \in \mathsf{X}). \tag{7.8}$$

If we set $V = \mathbb{R}^{\mathsf{X}}$, let $\Gamma(x) = \{0, 1\}$ and

$$B(x, a, v) = a e(x) + (1 - a) \left[c(x) + \beta \sum_{x' \in \mathsf{X}} v(x') P(x, x') \right] \tag{7.9}$$

for $x \in \mathsf{X}$ and $a \in \mathsf{A} := \{0, 1\}$, then (Γ, V, B) is an RDP with Bellman's equation (7.8).

Example 7.1.7. The **shortest path problem** considers optimal traversal of a directed graph $\mathscr{G} = (\mathsf{X}, E)$, where X is the vertices of the graph and E is the edges. A weight function $c \colon E \to (0, \infty)$ associates positive cost to each edge $(x, y) \in E$. The aim is to find the minimum cost path from x to a specified node d for every $x \in \mathsf{X}$. The problem can be solved by applying a Bellman operator of the form

$$(Tv)(x) = \min_{a \in \mathscr{O}(x)} \{c(x, a) + v(a)\} \qquad (x \in \mathsf{X}), \tag{7.10}$$

where $\mathscr{O}(x) := \{y \in \mathsf{X} : (x, y) \in E\}$ is the direct successors of x and $v(a)$ is the minimum cost-to-go from state a. The problem is not an MDP because future values are not discounted. It can, however, can be framed as an RDP, by taking X as the state and action spaces, and by setting the aggregator to $B(x, a, v) = c(x, a) + v(a)$.[2]

[2]For a maximization problem, we would replace $c(x, a)$ with $-c(x, a)$.

7.1.2 Optimality

In this section we present optimality theory for RDPs.

7.1.2.1 Definitions

Let (Γ, V, B) be an RDP with state and action spaces X and A, and let Σ be the set of all feasible policies. For each $\sigma \in \Sigma$ we introduce the **policy operator** T_σ as a map from V to itself defined by

$$(T_\sigma v)(x) = B(x, \sigma(x), v) \qquad (x \in \mathsf{X}). \tag{7.11}$$

The RDP policy operator is a direct generalization of the MDP policy operator defined on page 166, as well as the optimal stopping policy operator defined on page 141.

Exercise 7.1.4. Show that T_σ is an order-preserving self-map on V for all $\sigma \in \Sigma$.

Given $v \in V$, a policy σ is called **greedy** if

$$\sigma(x) \in \operatorname*{argmax}_{a \in \Gamma(x)} B(x, a, v) \qquad \text{for all } x \in \mathsf{X}. \tag{7.12}$$

(Since $\Gamma(x)$ is finite and nonempty at each $x \in \mathsf{X}$, at least one such policy exists.) As with policy operators, the notion of greedy policies extends existing definitions from the optimal stopping and MDP cases.

Exercise 7.1.5. Show that, for each $v \in V$, the set $\{T_\sigma v\}_{\sigma \in \Sigma}$ contains a least and greatest element (see §2.1.1.4).

Given (Γ, V, B), the operator T on V defined by

$$(Tv)(x) = \max_{a \in \Gamma(x)} B(x, a, v) \qquad (x \in \mathsf{X})$$

is called **Bellman's operator**. Analogously, we say that $v \in V$ satisfies **Bellman's equation** if (7.1) holds.

Example 7.1.8. For the Epstein–Zin RDP in (7.6), Bellman's operator is given by

$$(Tv)(x) = \max_{a \in \Gamma(x)} \left\{ r(x, a)^\alpha + \beta \left[\sum_{x' \in \mathsf{X}} v(x')^\gamma P(x, a, x') \right]^{\alpha/\gamma} \right\}^{1/\alpha} \qquad (x \in \mathsf{X}).$$

Exercise 7.1.6. Given an RDP (Γ, V, B) with policy operators $\{T_\sigma\}$ and Bellman operator T, show that, for each $v \in V$, we have $Tv = \vee_{\sigma\in\Sigma} T_\sigma v$.

7.1.2.2 Stable RDPs

We call an RDP (Γ, V, B) **stable** if, for all $\sigma \in \Sigma$, the policy operator T_σ is globally stable on V. One implication is that each T_σ has a unique fixed point, which we denote by v_σ and call the **σ-value function**. We interpret v_σ as representing the lifetime value of following policy σ.

Example 7.1.9. In the MDP case, lifetime value is given by $v_\sigma = (I - \beta P_\sigma)^{-1} r_\sigma$. As discussed in Exercise 6.1.5, v_σ is the unique fixed point of the MDP policy operator $T_\sigma = r_\sigma + \beta P_\sigma$. Hence the RPD definition generalizes the MDP case.

By construction, v_σ obeys

$$v_\sigma(x) = B(x, \sigma(x), v_\sigma) \quad \text{for all } x \in \mathsf{X}. \tag{7.13}$$

For a stable RDP, we define the **value function** v^* via $v^* := \vee_\sigma v_\sigma$. More explicitly,

$$v^*(x) := \max_{\sigma\in\Sigma} v_\sigma(x) \qquad (x \in \mathsf{X}). \tag{7.14}$$

A policy σ is called **optimal** if and only if

$$v_{\sigma^*}(x) \geqslant v_\sigma(x) \quad \text{for all } \sigma \in \Sigma \text{ and all } x \in \mathsf{X}.$$

As was the case when we studied MDPs and optimal stopping, an optimal policy is a policy that generates maximal lifetime value from every possible state.

Exercise 7.1.7. Show that, for a given RDP (Γ, V, B) and fixed $v \in V$, the Bellman operator T obeys

$$(T^k v)(x) = \max_{a\in\Gamma(x)} B(x, a, T^{k-1} v) \tag{7.15}$$

for all $k \in \mathbb{Z}_+$ and all $x \in \mathsf{X}$. (For an easier exercise, check that it works when $k = 2$.) Show, in addition, that for any policy $\sigma \in \Sigma$, the policy operator T_σ obeys

$$(T_\sigma^k v)(x) = \max_{a\in\Gamma(x)} B(x, a, T_\sigma^{k-1} v) \tag{7.16}$$

for all $k \in \mathbb{Z}_+$ and all $x \in \mathsf{X}$.

7.1.2.3 Optimality Results

We can now state our main optimality result for RDPs.

Theorem 7.1.1. *For every stable RDP, the following statements are true:*

(i) *the value function v^* is the unique solution to Bellman's equation in V,*

(ii) *HPI converges to v^* in finitely many steps,*

(iii) *If $v_0 = v_\sigma$ for some $\sigma \in \Sigma$, then the sequence (v_k) generated by OPI converges to v^*.*

(iv) *Bellman's principle of optimality holds, and*

(v) *at least one optimal policy exists.*

The proof of Theorem 7.1.1 is deferred to §7.3.

Example 7.1.10. The optimality results for optimal stopping problems we presented in Chapter 5 are a special case of Theorem 7.1.1, since each policy operator is globally stable on $V := \mathbb{R}^{\mathsf{X}}$ (Proposition 5.1.1).

Example 7.1.11. The optimality results for MDPs we presented in Chapter 6 are a special case of Theorem 7.1.1, since each policy operator is globally stable on $V := \mathbb{R}^{\mathsf{X}}$ (see Exercise 6.1.5 on page 166).

7.1.2.4 Application: Epstein–Zin Utility

Let us continue with the Epstein–Zin RPD (Γ, B, V) introduced in Example 7.1.4. Our aim is to establish stability. Under the stated specification, policy operators take the form

$$(T_\sigma v)(x) = \left\{ r(x, \sigma(x)) + \beta \left(\sum_{x'} v(x')^\gamma P(x, \sigma(x), x') \right)^{\alpha/\gamma} \right\}^{1/\alpha}. \tag{7.18}$$

Letting $r_1 := \min r$ and $r_2 := \max r$, we suppose that Assumption 4.3.1 on page 125 holds, so that $0 < \beta < 1$, $\gamma < 0 < \alpha$, and $r_1 > 0$.

Proposition 7.1.2. *The Epstein–Zin RPD described above is stable.*

Proof. This follows from Proposition 4.3.7 on page 129, which tells us that, under the stated assumptions, every policy operator (7.18) is globally stable on V. □

As a consequence, under the stated assumptions, the conclusions of Theorem 7.1.1 hold. In particular, the fundamental optimality results apply and the standard algorithms converge.

Later, in §7.4.4, we return to Epstein–Zin preferences and provide a sharper and more informative treatment.

7.1.2.5 Further Applications

In Examples 7.1.10–7.1.11 we noted that MDPs and optimal stopping problems are stable RDPs. In §7.1.2.4 we gave conditions under which Epstein–Zin RDPs are stable. In §7.2, to simplify the process of verifying stability (and hence the optimality properties in Theorem 7.1.1), we describe several classes of RDPs that have the stability property and then show how specific applications fit into these classes. Before that, in §7.1.3, we discuss some additional properties of RPDs.

7.1.3 Value Convergence

In general, one hopes that a v-greedy policy will be approximately optimal when v is close to v^*. In this section we provide a weak condition on RPDs under which this hope is realized.

Given an RPD (Γ, V, B) with state space X and action space A, we call the value aggregator B **value-continuous** if, for any $v \in V$ and sequence $(v_k)_{k\geqslant 1}$ in V, we have

$$v_k \to v \quad \Longrightarrow \quad B(x, a, v_k) \to B(x, a, v)$$

as $k \to \infty$, for all $(x, a) \in \mathsf{G}$. (Here $v_k \to v$ means pointwise or norm convergence, which are equivalent by Exercise 1.2.7 on page 15.)

Value-continuity is satisfied by all applications considered in this text.

Example 7.1.12. For any MDP, the deviation $|B(x, a, v_k) - B(x, a, v)|$ is dominated by $\beta\|v_k - v\|_\infty$ for all $(x, a) \in \mathsf{G}$. Since all norms are equivalent in finite-dimensional space, $v_k \to v$ implies $\|v_k - v\|_\infty \to 0$. Hence every MDP is value-continuous.

Now suppose that the RPD is stable, with value function v^*. The next results imply that, under value-continuity, if $v_k \to v^*$, then lifetime value of a v_k-greedy policy converges to the value of an optimal policy.

Proposition 7.1.3. *Let $(v_k)_{k\geqslant 1}$ be a sequence in V such that $v_k \to v^*$ as $k \to \infty$, and let σ_k be v_k-greedy for all k. If B is value-continuous, then $v_{\sigma_k} \to v^*$.*

Proof. Let v and σ_k be as stated. Fix $\varepsilon > 0$ and pick any $x \in \mathsf{X}$. From the definition of greedy policies and the fact that v^* satisfies Bellman's equation, we have

$$v_{\sigma_k}(x) = \max_{a \in \Gamma(x)} B(x, a, v_k) \quad \text{and} \quad v^*(x) = \max_{a \in \Gamma(x)} B(x, a, v^*).$$

Applying Lemma 1.2.2 on page 18 yields

$$|v_{\sigma_k}(x) - v^*(x)| \leqslant \max_{a \in \Gamma(x)} |B(x, a, v_k) - B(x, a, v^*)|.$$

Since pointwise convergence implies uniform convergence on finite sets, we can choose $m \in \mathbb{N}$ such that $k \geqslant m$ implies $|B(x, a, v_k) - B(x, a, v^*)| < \varepsilon$ for all $a \in \Gamma(x)$. From this fact and the previous bound we get $|v_{\sigma_k}(x) - v^*(x)| < \varepsilon$ whenever $k \geqslant m$. Hence v_{σ_k} converges to v^* on X. □

7.2 Types of RDPs

In §7.1 we showed that RDPs have strong optimality properties whenever they are stable. But what conditions are sufficient for this property? We start with a relatively strict condition based on contractivity and then progress to weaker assumptions.

7.2.1 Contracting RDPs

In this section we study RDPs with strong contraction properties. Most traditional dynamic programs fit into this framework.

7.2.1.1 Definition and Examples

Let $\mathscr{R} = (\Gamma, V, B)$ be an RDP with state space X, action space A, and feasible state-action pair set G. We call $\mathscr{R}$ **contracting** if V is closed and there exists a $\beta \in [0, 1)$ such that

$$|B(x, a, v) - B(x, a, w)| \leqslant \beta \|v - w\|_\infty \quad \text{for all } (x, a) \in \mathsf{G} \text{ and } v, w \in V. \tag{7.19}$$

In line with the terminology for contraction maps, we call β the **modulus of contraction** for $\mathscr{R}$ when (7.19) holds.

Example 7.2.1. The optimal stopping RDP from Example 7.1.6 is contracting with modulus β, since $V = \mathbb{R}^{\mathsf{X}}$ and, for B in (7.9), an application of the triangle inequality gives

$$|B(x,a,v) - B(x,a,w)| = (1-a)\beta \left| \sum_{x' \in \mathsf{X}} [v(x') - w(x')] P(x,x') \right| \leqslant \beta \|v - w\|_\infty.$$

Proposition 7.2.1. *If $\mathscr{R}$ is contracting with modulus β, then T and $\{T_\sigma\}_{\sigma \in \Sigma}$ are all contractions of modulus β on V under the norm $\|\cdot\|_\infty$.*

The following corollary is immediate from Banach's contraction mapping theorem.

Corollary 7.2.2. *If $\mathscr{R}$ is contracting, then $\mathscr{R}$ is stable and hence all of the optimality and convergence results in Theorem 7.1.1 apply.*

Proof of Proposition 7.2.1. Let $\mathscr{R} = (\Gamma, V, B)$ be contracting with modulus β. Fix $\sigma \in \Sigma$ and let v and w be elements of V. By (7.19) we have

$$|(T_\sigma v)(x) - (T_\sigma w)(x)| = |B(x,\sigma(x),v) - B(x,\sigma(x),w)| \leqslant \beta \|v - w\|_\infty$$

for every $x \in \mathsf{X}$. Maximizing over x proves that T_σ is a contraction of modulus β with respect to the supremum norm. Since V is closed, it follows from Banach's contraction mapping theorem that T_σ is globally stable on V. □

Exercise 7.2.1. Show that any MDP is a contracting RDP.

Exercise 7.2.2. Prove that the RDP for the state-dependent discounting model in Example 7.1.3 is contracting on $V = \mathbb{R}^{\mathsf{X}}$ whenever there exists a $b < 1$ with $\beta(x,a,x') \leqslant b$ for all $(x,a) \in \mathsf{G}$ and $x' \in \mathsf{X}$.

Next we state a useful sufficient condition for contractivity. We say that RDP (Γ, V, B) satisfies **Blackwell's condition** if $v \in V$ implies $v + \lambda \mathbb{1} \in V$ for every $\lambda \geqslant 0$ and, in addition, there exists a $\beta \in [0,1)$ such that

$$B(x,a,v+\lambda\mathbb{1}) \leqslant B(x,a,v) + \beta\lambda \qquad \text{for all } \lambda \in \mathbb{R}_+ \text{ and all } (x,a) \in \mathsf{G}.$$

Exercise 7.2.3. Prove the following: If $\mathscr{R} = (\Gamma, B, V)$ is an RDP that satisfies Blackwell's condition and V is closed, then $\mathscr{R}$ is contracting with modulus β.

Exercise 7.2.4. Prove that the discrete optimal savings model from §6.2.2 satisfies Blackwell's condition.

7.2.1.2 Global Convergence of VFI

Corollary 7.2.2 tells us that contracting RPDs are stable. Hence, by Proposition 7.3.8, the sequence $(v_k) \subset V$ generated by OPI (and hence VFI) converges to v^*, provided that $v_0 = v_\sigma$ for some $\sigma \in \Sigma$. We can slightly strengthen this result by leveraging the contraction property.

To this end, let $\mathscr{R}$ be a contracting RDP. Proposition 7.2.1 tells us that the associated Bellman operator T is a contraction map on V. Moreover, since $\mathscr{R}$ is a stable RDP, the unique fixed point of T in V is v^*. It follows immediately that $v_k := T^k v \to v^*$ for any $v \in V$.

Exercise 7.2.5. Show that every contracting RDP is value-continuous.

From Exercise 7.2.5 we see that, not only does v_k globally converge to v^*, but, in addition, values of the resulting greedy policies converge to the value of an optimal policy.

7.2.1.3 Error Bounds

The result in §7.2.1.2 shows convergence of policy values generated by VFI under stability and value continuity. We can obtain sharper for contracting RDPs, including error bounds. Here is one such result.

Proposition 7.2.3. *Let (Γ, V, B) be a contracting RDP with modulus of contraction β and Bellman operator T. Fix $v \in V$ and $k \in \mathbb{N}$. If $v_k := T^k v$ and $\sigma \in \Sigma$ is v_k-greedy, then*

$$\|v^* - v_\sigma\|_\infty \leqslant \frac{2\beta}{1-\beta}\|v_k - v_{k-1}\|_\infty. \tag{7.20}$$

Since the VFI algorithm terminates when $\|v_k - v_{k-1}\|_\infty$ falls below a given tolerance, the result in (7.20) directly provides a quantitative bound on the performance of the policy returned by VFI. In the proof we use the fact that T is a contraction of modulus β under the stated assumptions, as shown in Proposition 7.2.1.

Proof of Proposition 7.2.3. Let (Γ, V, B) and v be as stated and let v^* be the value function. Note that

$$\|v^* - v_\sigma\|_\infty \leqslant \|v^* - v_k\|_\infty + \|v_k - v_\sigma\|_\infty. \tag{7.21}$$

To bound the first term on the right-hand side of (7.21), we use the fact that v^* is a fixed point of T, obtaining

$$\|v^* - v_k\|_\infty \leqslant \|v^* - Tv_k\|_\infty + \|Tv_k - v_k\|_\infty \leqslant \beta\|v^* - v_k\|_\infty + \beta\|v_k - v_{k-1}\|_\infty.$$

Hence

$$\|v^* - v_k\|_\infty \leqslant \frac{\beta}{1-\beta}\|v_k - v_{k-1}\|_\infty. \tag{7.22}$$

Now consider the second term on the right-hand side of (7.21). Since σ is v_k-greedy, we have $Tv_k = T_\sigma v_k$, and

$$\|v_k - v_\sigma\|_\infty \leqslant \|v_k - Tv_k\|_\infty + \|Tv_k - v_\sigma\|_\infty \leqslant \|Tv_{k-1} - Tv_k\|_\infty + \|T_\sigma v_k - T_\sigma v_\sigma\|_\infty.$$

$$\therefore \quad \|v_k - v_\sigma\|_\infty \leqslant \beta\|v_{k-1} - v_k\|_\infty + \beta\|v_k - v_\sigma\|_\infty.$$

$$\therefore \quad \|v_k - v_\sigma\|_\infty \leqslant \frac{\beta}{1-\beta}\|v_k - v_{k-1}\|_\infty. \tag{7.23}$$

Together, (7.21), (7.22), and (7.23) give us (7.20). □

7.2.1.4 Application: Optimal Default

In this section we consider a small open economy that borrows in international financial markets in order to smooth consumption and has the option to default. We show that the model is a contractive RDP. (The model is relatively detailed, so impatient readers can skip to the next section.)

In the model, income $(Y_t)_{t\geqslant 0}$ is exogenous Q-Markov on finite set Y. A representative household faces budget constraint

$$C_t = Y_t + b_t - qb_{t+1} \qquad (t \geqslant 0),$$

where C_t is current consumption, q is a discount rate on international markets and b_t measures foreign lending. In particular, purchasing a bond with positive face value b_{t+1} costs qb_{t+1} and repays b_{t+1} next period. Purchasing bond with *negative* face value b_{t+1} pays qb_{t+1} in current consumption goods and promises to deliver b_{t+1} next period.

Trading bonds is managed by a benevolent goverment that wants to maximize household utility. Households discount future utility at rate $\beta \in (0,1)$ and current consumption C_t generates current utility $u(C_t)$. The government faces borrowing constraint $b_t \geqslant -m$ where $m \geqslant 0$.

The government can default on foreign loans. In this case, output available for

consumption drops from Y_t to $h(Y_t)$, where h is a function satisfying $h(y) < y$ for all y. After a country defaults, it loses access to foreign lending.

At the end of each period during which the country is in default, it regains access to international credit markets with probability $\theta \in (0, 1)$. With probability $1 - \theta$ it remains in financial autarky. When a country regains access to foreign borrowing, its debt is reset to zero.

The problem for the government is to maximize expected discounted utility for the households.

We can model this problem as an RDP by considering the value of each state and action. We set the state space X to be the set of all (y, b, d) in $\mathsf{Y} \times \mathsf{B} \times \{0, 1\}$, where B is a finite subset of $[-m, \infty)$ indicating possible choices for bond holdings b_t and d is a binary variable indicating whether or not the country is in default ($d = 0$ means not in default and $d = 1$ means in default).

The value space V is all of $\mathbb{R}^{\mathsf{X}}$. The action space is $(b_a, d_a) \in \mathsf{B} \times \{0, 1\}$ indicating choices for bond holdings and default. The feasible correspondence specifies feasible (b_a, d_a) at given state (y, b, d) and is given by

$$\Gamma(y, b, d) = \begin{cases} \mathsf{B} \times \{0, 1\} & \text{if } d = 0 \text{ and} \\ \{0\} \times \{1\} & \text{if } d = 1. \end{cases}$$

In other words, if $d = 0$, so the country is not in default, the government can choose any $b_a \in \mathsf{B}$ and also any $d_a \in \{0, 1\}$ (i.e., default or not default). If $d = 1$, however, the government has no choices. We represent this by $b_a = 0$ and $d_a = 1$.

The value aggregator takes the form

$$B((y, b, d), (b_a, d_a), v) = \text{value in state } (y, b, d) \text{ under action } (b_a, d_a).$$

To specify it we decompose the problem across cases for d and d_a. First consider the case where $d = 0$ (not currently in default) and $d_a = 0$ (the government chooses not to default). For this case $y + b - qb_a$ is current consumption, so we set

$$B((y, b, 0), (b_a, 0), v) = u(y + b - qb_a) + \beta \sum_{y'} v(y', b_a, 0) Q(y, y') \tag{7.24}$$

Now consider the case where $d = 0$ and $d_a = 1$, so the government chooses to default.

Then current consumption is $h(y)$ and we set

$$B((y,b,0),(b_a,1),v) = u(h(y)) + \beta \left[\theta \sum_{y'} v(y',0,0)Q(y,y') + (1-\theta)\sum_{y'} v(y',0,1)Q(y,y')\right]. \quad (7.25)$$

The term $\sum_{y'} v(y',0,0)Q(y,y')$ is the expected value next period when the country is readmitted to international financial markets (with $b' = 0$ and $d' = 0$), while the term $\sum_{y'} v(y',0,1)Q(y,y')$ is the expected value next period when when default continues (with $b' = 0$ and $d' = 1$.

Since $B((y,b,1),(b_a,0),v)$ is not feasible (a defaulted country cannot itself directly choose to reenter financial markets), the only other possibility that we must consider is $B((y,b,1),(b_a,1),v)$, which is the expected value when the country remains in default. But this is the same as $B((y,b,0),(b_a,1),v)$, as specified above. In other words, the value for a country that stays in default is the same as that for a country that newly enters default.

Exercise 7.2.6. By working through the cases (7.24)–(7.25) for the value aggregator B, show that the model described above is a contractive RDP.

7.2.2 Risk-Sensitive RDPs

In §4.3.2 we introduced risk-sensitive preferences and discussed a recursive utility problem. Now we embed risk-sensitive preferences into a dynamic program. Our task is to apply the preceding optimality results to solve for optimal policies under alternative parameterizations.

7.2.2.1 Optimality Results

We begin with a small extension of the risk-sensitive preference RPD in Example 7.1.5. Our starting point is an MDP (Γ, β, r, P) with state space X and action space A. As usual, $\beta \in (0,1)$. Let $V = \mathbb{R}^{\mathsf{X}}$ and let R be a risk-adjusted expectations operator on V (see §4.3.4.2). For $(x,a) \in \mathsf{G}$ and $v \in V$, let

$$B(x,a,v) := r(x,a) + \beta R(v, P(x,a,\cdot))$$

Exercise 7.2.7. With Γ, V and B as above, verify that (Γ, V, B) forms an RDP.

Recall from §4.3.4.4 that R is called subadditive when $R(v+\lambda\mathbb{1}, \varphi) \leqslant R(v, \varphi)+\lambda$ for all $v \in V$, $\varphi \in \mathscr{D}(\mathsf{X})$ and $\lambda \in \mathbb{R}_+$. The next result shows that subadditivity is sufficient for all of our core optimality results.

Proposition 7.2.4. *If R is is subadditive, then (Γ, V, B) is a contracting RDP.*

Proof. We show that (Γ, V, B) obeys Blackwell's condition. Fix $v \in V$, $(x, a) \in \mathsf{G}$, and $\lambda \geqslant 0$. Applying subadditivity gives

$$B(x, a, v + \lambda\mathbb{1}) = r(x, a) + \beta R(v + \lambda\mathbb{1}, P(x, a, \cdot)) \leqslant r(x, a) + \beta R(v, P(x, a, \cdot)) + \beta\lambda.$$

The right-hand side equals $B(x, a, v) + \beta\lambda$, so Blackwell's condition holds. The claim in Proposition 7.2.4 now follows from Exercise 7.2.3. □

From Corollary 7.2.2 and Proposition 7.2.4, we see that any risk-sensitive RDP with subadditive risk-adjusted expectations operator is stable. Hence all of the fundamental optimality results hold. In addition, VFI and OPI have the relatively strong convergence properties described in §7.2.1.2 and §7.2.1.3.

7.2.2.2 An Example Application

In the Markov job search problem in §3.3.1, the agent is risk-neutral in future payoffs. But studies of asset markets and lab experiments indicate that people are not risk-neutral. To recognize that, let's now consider a job search problem where future wage outcomes are evaluated via entropic risk-adjusted expectations. The associated Bellman operator is

$$(Tv)(w) = \max\left\{\frac{w}{1-\beta},\ c + \frac{\beta}{\theta}\ln\left[\sum_{w'}\exp(\theta v(w'))P(w, w')\right]\right\} \qquad (w \in \mathsf{W}).$$

Here θ is a nonzero parameter and other details are as in §3.3.1. We can represent the problem as an RDP with state space W, action space $\mathsf{A} = \{0, 1\}$, feasible correspondence $\Gamma(w) = \mathsf{A}$, value space $V := \mathbb{R}^{\mathsf{W}}$, and value aggregator

$$B(w, a, v) = a\frac{w}{1-\beta} + (1-a)\left\{c + \frac{\beta}{\theta}\ln\left[\sum_{w'}\exp(\theta v(w'))P(w, w')\right]\right\}.$$

If $\theta < 0$, then the agent is risk-averse with respect to the gamble associated with continuing and waiting for new wage draws. If $\theta > 0$ then the agent is risk-loving with respect to such gambles. For $\theta \approx 0$, the agent is close to risk-neutral.

Figure 7.1 shows how the continuation value, value function and optimal decision vary with θ. Apart from θ, parameters are identical to those in Listing 10 on page 93. Indeed, for θ close to zero, as in the middle sub-figure of Figure 7.1, we see that the value function and reservation wage are almost identical to those from the risk-neutral model in Figure 3.9 on page 94.

As expected, a negative value of θ tends to reduce the continuation value and hence the reservation wage, since the agent's dislike of risk encourages early acceptance of an offer. For positive values of θ the reverse is true, as seen in the bottom sub-figure.

Exercise 7.2.8. Replicate Figure 7.1. The simpest method is to modify the code in Listing 10 and use value function iteration.

7.2.3 Eventually Contracting RDPs

Many RDPs are not contracting. Since there is no single method for handling all types of non-contractive RDPs, we introduce several alternative techniques over the next few sections. The first such technique, treated in this section, handles RDPs that contract "eventually," even though they may fail to contract in one step. We show that these eventually contracting RDPs are stable, so all of the fundamental optimality results apply.

7.2.3.1 Definition and Properties

Let $\mathscr{R} = (\Gamma, V, B)$ be an RDP. We call $\mathscr{R}$ **eventually contracting** if there exists a non-negative matrix L on X such that $r(L) < 1$ and

$$|B(x, a, v) - B(x, a, w)| \leqslant \sum_{x'} |v(x') - w(x')| L(x, x') \quad \text{for all } (x, a) \in \mathsf{G}. \tag{7.26}$$

Exercise 7.2.9. Prove the following: If $\mathscr{R}$ is eventually contracting and, if in addition, $L(x, x') = \beta Q(x, x')$ for some $\beta \in (0, 1)$ and stochastic matrix Q on X, then $\mathscr{R}$ is contracting (in the sense of §7.2.1.1).

Let $\mathscr{R} = (\Gamma, V, B)$ be an RDP. The next result shows that, eventual contractivity is sufficient for all of the fundamental RDP optimality results in Theorem 7.1.1 to hold.

Proposition 7.2.5. *If $\mathscr{R}$ is eventually contracting, then $\mathscr{R}$ is also stable and hence all of the optimality and convergence results in Theorem 7.1.1 apply.*

Figure 7.1: Job search with risk-sensitive preferences

Proof. Let $\mathscr{R}$ be as stated and fix $\sigma \in \Sigma$. Let T_σ be the associated policy operator. We need to show that T_σ is globally stable on V. To this end, fix $v, w \in V$ and pick any $k \in \mathbb{N}$ and $x \in \mathsf{X}$. Combining (7.16) and (7.26) yields

$$\begin{aligned} |(T_\sigma^k v)(x) - (T_\sigma^k w)(x)| &= \left| B(x, \sigma(x), T_\sigma^{k-1} v) - B(x, \sigma(x), T_\sigma^{k-1} w) \right| \\ &\leqslant \sum_{x'} \left| (T_\sigma^{k-1} v)(x') - (T_\sigma^{k-1} w)(x') \right| L(x, x'). \end{aligned}$$

Thus, pointwise on the state space, we have

$$e_k \leqslant L e_{k-1} \quad \text{where} \quad e_k := |T_\sigma^k v - T_\sigma^k w|. \tag{7.27}$$

Since L is nonnegative, the operator $u \mapsto Lu$ is order-preserving on $\mathbb{R}^{\mathsf{X}}$. As a result, we can iterate on (7.27) to obtain $e_k \leqslant L^k e_0$, or

$$|T_\sigma^k v - T_\sigma^k w| \leqslant L^k |v - w| \leqslant L^k \mathbb{1} \|v - w\|_\infty.$$

Taking the supremum on the right and then the left,

$$\|T_\sigma^k v - T_\sigma^k w\|_\infty \leqslant \|L^k \mathbb{1}\|_\infty \|v - w\|_\infty \leqslant \|L^k\|_\infty \|v - w\|_\infty.$$

Here $\|L^k\|_\infty$ is defined via the matrix norm in §1.2.2. Since $r(L) < 1$, we have $\|L^k\|_\infty \to 0$ as $k \to \infty$ (see Exercise 1.2.9 on page 20). Hence T_σ is eventually contracting on V and therefore globally stable (Theorem 2.2.4, page 65). □

7.2.3.2 State-Dependent Discounting

The significance of state-dependent discounting was emphasized in §4.1.2.1, when we considered firm valuation with time-varying interest rates. In Example 7.1.3, we extended an MDP model to include state-dependent discounting an thereby obtained an RDP. In this section we provide weak conditions for stability, and hence optimality, of this RDP. These conditions rely on eventual contractivity.

As in Example 7.1.3, we begin with an MDP (Γ, β, r, P) with state space X and then replace the constant β with a function β from $\mathsf{G} \times \mathsf{X}$ to $\mathbb{R}$, so that the aggregator takes the form

$$B(x, a, v) = r(x, a) + \sum_{x'} v(x') \beta(x, a, x') P(x, a, x'). \tag{7.28}$$

The value space V is all of $\mathbb{R}^{\mathsf{X}}$. The tuple $\mathscr{R} := (\Gamma, V, B)$ forms an RDP (Exercise 7.2.2).

Proposition 7.2.6. *If there exists a nonnegative matrix L on X such that $r(L) < 1$ and if*

$$\beta(x, a, x')P(x, a, x') \leqslant L(x, x') \tag{7.29}$$

for all $(x, a) \in \mathsf{G}$ and $x' \in \mathsf{X}$, then $\mathscr{R}$ is eventually contracting.

Proof. Let $\mathscr{R}$ and L be as stated and fix $(x, a) \in \mathsf{G}$. For given $v, w \in V$, applying the definition (7.28) and the triangle inequality, we have

$$\begin{aligned} |B(x, a, v) - B(x, a, w)| &\leqslant \left| \sum_{x'} [v(x') - w(x')]\beta(x, a, x')P(x, a, x') \right| \\ &\leqslant \sum_{x'} |v(x') - w(x')|\beta(x, a, x')P(x, a, x') \end{aligned}$$

Now (7.29) implies that $\mathscr{R}$ is eventually contracting, as claimed. □

7.2.4 Application: Exogenous Discount Rates

§7.2.3.2 provided general conditions for optimality under state-dependent discounting. In this section we specialize to models where the discount factor process is purely exogenous, as in much of the applied literature. First we try to understand the spectral radius assumption $r(L) < 1$ that we use to get eventual contractivity, and to determine how strict the condition is vis-a-vis applications in economics and finance. Next we apply the model to a problem of inventory management.

7.2.4.1 Exogenous Discounting and the Spectral Radius Condition

To begin, we suppose that the state X_t can be decomposed into a pair (Y_t, Z_t), where $(Y_t)_{t \geqslant 0}$ is endogenous (i.e., affected by the actions of the controller) and $(Z_t)_{t \geqslant 0}$ is exogenous. We suppose further that

(i) Γ is a nonempty correspondence from X to A,

(ii) β is a function that maps Z to $\mathbb{R}_+$,

(iii) r is a function from $\mathsf{G} := \{(y, a) \in \mathsf{Y} \times \mathsf{A} : a \in \Gamma(y)\}$ to $\mathbb{R}$,

(iv) Q is a stochastic matrix on Z and

(v) R is a stochastic kernel from G to Y.

The exogenous process $(Z_t)_{t\geqslant 0}$ is Q-Markov. The discount factor process $(\beta_t)_{t\geqslant 0}$ is defined by $\beta_t := \beta(Z_t)$. Given $Y_t = y$ and current action a, current reward is $r(y, a)$ and Y_{t+1} is drawn from distribution $R(y, a, \cdot)$. Y_{t+1} and Z_{t+1} are updated independently given the time t state and action.

We can frame the model as an RPD (Γ, V, B) with $V = \mathbb{R}^{\mathsf{X}}$ and aggregator

$$B((y, z), a, v) = r((y, z), a) + \beta(z) \sum_{y', z'} v(y', z') R(y, a, y') Q(z, z')$$

Exercise 7.2.10. Show that (Γ, V, B) is an eventually contracting RDP whenever $L(z, z') := \beta(z)Q(z, z')$ satisfies $r(L) < 1$.

It is not difficult to verify that if $\sup \beta < 1$, then the the RPD is not just eventually contracting but contracting. In the present context, we call this case **strict discounting**.

While strict state-dependent discounting is easy to state and understand, there are important cases in which it fails. For example, the real interest rate r_t is sometimes negative, as shown in Figure 4.3 on 104. This means that, when discounting with real rates, the associated discount factor $\beta_t = 1/(1+r_t)$ is sometimes greater than 1. Hence strict discounting fails.

In addition, in the macroeconomic literature, empirically motivated time-varying discount factor specifications lead to models where $\beta_t > 1$ occurs with positive probability. For example, Hills et al. (2019) study a model that can be embedded in the RPD framework just described. Figure 7.2 shows a simulation of one of the discount factor processes used in their model, prior to discretization. The exogenous state and discount factor process takes the form $\beta_t = bZ_t$, where (Z_t) is an exogenous state obeying $Z_{t+1} = 1 - \rho + \rho Z_t + \sigma\varepsilon_{t+1}$ with (ε_t) IID and standard normal. Clearly strict discounting fails for this model too.

Let's now consider the weaker condition $r(L) < 1$ described in Exercise 7.2.10 and check whether it holds. Following Hills et al. (2019), we discretize the dynamics of (Z_t) via a Tauchen approximation, producing a stochastic matrix Q on a finite set Z.[3] The set of values for β_t ranges between 0.95 and 1.04, so that $\beta_t > 1$ remains possible. Nonetheless, with $L(z, z') = \beta(z)Q(z, z')$ we obtain $r(L) = 0.9996$.

It follows from Exercise 7.2.10 and Proposition 7.2.5 that the RPD is stable and the fundamental optimality results apply.

[3]The parameters are $\rho = 0.85$, $\sigma = 0.0062$, and $b = 0.99875$. In line with Hills et al. (2019), we discretize the model via `mc = tauchen(n, ρ, σ, 1 - ρ, m)` with $m = 4.5$ and $n = 15$.

Figure 7.2: Discount factor process $(\beta)_{t \geqslant 0}$ in Hills et al. (2019).

Summarizing, the condition $r(L) < 1$ allows the discount factor occasionally to exceed one provided that its long-run average is strictly less than one. Hence $r(L) < 1$ is a relatively weak condition that includes many applications while still preserving strong optimality results.

7.2.4.2 Inventory Management Revisited

High interest rates tend to suppress investment, while low interest rates promote it. Investment in inventory provides an example. In this section, we modify the inventory management model from §6.2.1 to include time-varying interest rates.

Recall that, in the model of §6.2.1, Bellman's equation takes the form

$$v(x) = \max_{a \in \Gamma(x)} \left\{ r(x,a) + \beta \sum_{d \geqslant 0} v(m(x-d)+a)\varphi(d) \right\} \tag{7.30}$$

at each $x \in \mathsf{X}$, where $\mathsf{X} := \{0, \ldots, K\}$, x is the current inventory level, a is the current inventory order, $r(x,a)$ is current profits (defined in (6.21)), $m(y) := y \vee 0$ and d is an IID demand shock with distribution φ. Let's now add a time-varying discount rate and investigate its impact on optimal choices.

To add time-varying discounting we replace the constant β in (7.30) with a stochastic process (β_t) where $\beta_t = 1/(1+r_t)$. We suppose that the dynamics can be expressed

as $\beta_t = \beta(Z_t)$, where the exogenous process $(Z_t)_{t \geqslant 0}$ is Q-Markov on Z. After relabeling the endogenous state X_t as Y_t and x as y, in line with the notation in §7.2.4.1, the aggregator becomes

$$B((y,z),a,v) = r(y,a) + \beta(z) \sum_{d \geqslant 0} \sum_{z'} v(m(y-d)+a, z')\varphi(d)Q(z,z').$$

If we set

$$R(y,a,y') := \mathbb{P}\{m(y-D)+a = y'\} \quad \text{when} \quad D \sim \varphi,$$

then $R(y,a,y')$ is the probability of realizing next period inventory level y' when the current level is y and the action is a. Hence we can rewrite the aggregator as

$$B((y,z),a,v) = r(y,a) + \beta(z) \sum_{y',z'} v(y',z')R(y,a,y')Q(z,z').$$

This is a version of the RPD with exogenous state-dependent discounting described in §7.2.4.1. Hence, by Exercise 7.2.10, the RPD is stable whenever $r(L) < 1$ for $L(z,z') := \beta(z)Q(z,z')$.

Figure 7.3 shows how inventory evolves under an optimal program when the parameters of the problem are as given in Listing 24. (The code includes a test for $r(L) < 1$.) We set $\beta(z) = z$ and take (Z_t) to be a discretization of an AR(1) process. Figure 7.3 was created by simulating (Z_t) according to Q and inventory (X_t) according to $X_{t+1} = m(X_t - D_{t+1}) + A_t$, where A_t follows the optimal policy.

The outcome is similar to Figure 6.7, in the sense that inventory falls slowly and then jumps up. As before, this lumpy behavior is down to fixed costs. However, a new phenomenon is now present: inventories move up or down on average, trending up as interest rates fall and down as interest rates rise. (The interest rate r_t is calculated via $\beta_t = 1/(1+r_t)$ at each t.) In essence, high interest rates predict future high interest rates due to positive autocorrelation ($\rho > 0$), which in turn devalue future profits and hence encourage managers to economize on stock.

7.2.5 Convex and Concave RDPs

We have seen that RDPs have excellent optimality properties when then are stable; that is, when all policy operators are globally stable self-maps on value space. So far we have looked at conditions for stability based on contractions (§7.2.1) and eventual contractions (§7.2.3). But sometimes both of these approaches fail and we need alternative conditions. In this section we explore such conditions by turning to Du's

Figure 7.3: Inventory dynamics with time-varying interest rates

```
using LinearAlgebra, Distributions, OffsetArrays, QuantEcon

function create_sdd_inventory_model(;
        ρ=0.98, ν=0.002, n_z=20, b=0.97,  # Z state parameters
        K=40, c=0.2, κ=0.8, p=0.6)        # firm and demand parameters
    ϕ(d) = (1 - p)^d * p                  # demand pdf
    mc = tauchen(n_z, ρ, ν)
    z_vals, Q = mc.state_values .+ b, mc.p
    rL = maximum(abs.(eigvals(z_vals .* Q)))
    @assert  rL < 1 "Error: r(L) ≥ 1."    # check r(L) < 1
    return (; K, c, κ, p, ϕ, z_vals, Q)
end
```

Listing 24: Investment model with time-varying discounting (`inventory_sdd.jl`)

theorem (page 55), which provides an alternative approach to global stability of policy operators. Du's theorem is well suited to the task, since it leverages the fact that all policy operators are order-preserving maps.

7.2.5.1 Convex RDPs

Let $\mathscr{R} = (\Gamma, V, B)$ be an RDP. We call $\mathscr{R}$ **convex** if

(i) $V = [v_1, v_2]$ for some pair $v_1 \leqslant v_2$ in $\mathbb{R}^{\mathsf{X}}$,

(ii) for all $(x, a) \in \mathsf{G}$, $\lambda \in [0, 1]$ and v, w in V, we have

$$B(x, a, \lambda v + (1 - \lambda)w) \leqslant \lambda B(x, a, v) + (1 - \lambda)B(x, a, w) \quad \text{and,} \tag{7.31}$$

(iii) there exists a $\delta > 0$ such that

$$B(x, a, v_2) \leqslant v_2(x) - \delta[v_2(x) - v_1(x)] \text{ for all } (x, a) \in \mathsf{G}. \tag{7.32}$$

The following condition is often easier to check than (7.32).

Exercise 7.2.11. Prove that (iii) holds whenever

$$B(x, a, v_2) < v_2(x) \text{ for all } (x, a) \in \mathsf{G}. \tag{7.33}$$

Convexity yields stability, as the next proposition shows.

Proposition 7.2.7. *If $\mathscr{R} = (\Gamma, V, B)$ is a convex RDP, then $\mathscr{R}$ is also stable and hence all of the optimality and convergence results in Theorem 7.1.1 apply.*

Proof. Fix $\sigma \in \Sigma$. By the monotonicity property of RDPs, T_σ is an order-preserving self-map on V. Since (7.31) holds, T_σ is also a convex operator on V. Moreover, $Tv_1 \geqslant v_1$ because $T \colon V \to V$ and, by (7.33), $T_\sigma v_2 \leqslant v_2 - \delta(v_2 - v_1)$. Hence Du's Theorem on page 55 applies and T_σ is globally stable on V. This shows that $\mathscr{R}$ is a stable RDP. □

7.2.5.2 Concave RDPs

Analogous to the convex case, we call $\mathscr{R}$ **concave** if

(i) $V = [v_1, v_2]$ for some pair $v_1 \leqslant v_2$ in $\mathbb{R}^{\mathsf{X}}$,

(ii) for all $(x, a) \in \mathsf{G}$, $\lambda \in [0, 1]$ and v, w in V, we have

$$B(x, a, \lambda v + (1 - \lambda)w) \geqslant \lambda B(x, a, v) + (1 - \lambda)B(x, a, w) \quad \text{and,} \tag{7.34}$$

(iii) there exists a $\delta > 0$ such that

$$B(x, a, v_1) \geqslant v_1(x) + \delta[v_2(x) - v_1(x)] \text{ for all } (x, a) \in \mathsf{G}. \tag{7.35}$$

The following condition is often easier to check than (7.35).

Exercise 7.2.12. Prove that (iii) holds whenever

$$B(x, a, v_1) > v_1(x) \text{ for all } (x, a) \in \mathsf{G}. \tag{7.36}$$

These conditions also yield stability, as the next proposition shows.

Proposition 7.2.8. *If $\mathscr{R} = (\Gamma, V, B)$ is a concave RDP, then $\mathscr{R}$ is also stable and hence all of the optimality and convergence results in Theorem 7.1.1 apply.*

Exercise 7.2.13. Verify Proposition 7.2.8 (modify the proof of Proposition 7.2.7).

As an illustrative application, consider the RDP $\mathscr{R} = (\Gamma, B, V)$ generated by an ordinary MDP (Γ, β, r, P), so that $V = \mathbb{R}^{\mathsf{X}}$ and $B(x, a, v) = r(x, a) + \beta \sum_{x'} v(x')P(x, a, x')$. In §7.2.1 we saw that $\mathscr{R}$ is a contracting RDP. In fact $\mathscr{R}$ is also convex *and* concave if we fix some $\varepsilon > 0$ and redefine V to

$$V := [v_1, v_2] \quad \text{where} \quad v_1 := \frac{r_1 - \varepsilon}{1 - \beta} \text{ and } v_2 := \frac{r_2 + \varepsilon}{1 - \beta}. \tag{7.37}$$

(The functions v_1 and v_2 are constant.) For example, (7.36) holds because, for given $(x, a) \in \mathsf{G}$,

$$B(x, a, v_1) = r(x, a) + \beta \sum_{x'} v_1(x')P(x, a, x') \geqslant r_1 + \beta \frac{r_1 - \varepsilon}{1 - \beta}.$$

The right-hand side can be re-written as $v_1 + \varepsilon$, so (7.36) is confirmed.

Exercise 7.2.14. Complete the proof that $\mathscr{R}$ is both concave and convex.

7.2.6 Application: Adversarial Agents

Many decision problems in economics, finance and artificial intelligence involve determining optimal choices while interacting with an adversarial agent. For example, in a modified MDP setting, Bellman's equation might have the form

$$v(x) = \max_{a \in \Gamma(x)} \min_{d \in D(x)} \left\{ r(x,a,d) + \beta \sum_{x'} v(x') P(x,a,d,x') \right\} \qquad (x \in \mathsf{X}) \tag{7.38}$$

where, for each x, the choice $d \in D(x)$ is made by the opponent (adversarial agent). The object P is a stochastic kernel, in the sense that $P(x,a,d,\cdot)$ is a distribution over X for each feasible (x,a,d). The understanding here is that when the decision maker chooses action $a \in \Gamma(x)$, she does so with the knowledge that the opponent will then choose $d \in D(x)$ to minimize her aggregate value. These kinds of optimization programs arise in the setting of zero sum dynamic games.

This problem becomes an RPD $\mathscr{R} = (\Gamma, B, V)$ when we take $V = \mathbb{R}^{\mathsf{X}}$ and

$$B(x,a,v) = \min_{d \in D(x)} \left\{ r(x,a,d) + \beta \sum_{x'} v(x') P(x,a,d,x') \right\} \qquad ((x,a) \in \mathsf{G}).$$

A closely related problem is **robust control**. While there are many formulations of the problem, a typical situation is one where the controller understands her own reward function but does not know the exact stochastic kernel P that drives the state. Instead, she knows that P belongs to some class $\mathscr{P}$ of stochastic kernels from $\mathsf{G} \times \mathsf{X}$ to X. The aggregator above is then modified to

$$B(x,a,v) = \inf_{P \in \mathscr{P}} \left\{ r(x,a) + \beta \sum_{x'} v(x') P(x,a,x') \right\} \tag{7.39}$$

for $(x,a) \in \mathsf{G}$. When seeking an optimal policy, the controller is trying to maximize rewards under the worst-case scenario.[4]

Let's analyze optimality properties of the robust control model with aggregator B in (7.39). Here, as usual, $\beta \in (0,1)$. We take V is as defined in (7.37) and set $\mathscr{R} = (\Gamma, V, B)$. The set $\mathscr{P}$ of stochastic kernels is entirely arbitrary.

Proposition 7.2.9. *$\mathscr{R}$ is a concave RDP.*

[4]The setting where choices are made across a class of probability distributions without any prior information as to which is more likely is sometimes referred to as **Knightian uncertainty**. Not only does the controller face uncertainty over outcomes, but, in addition, she does not know the probabilities that generate these uncertainties. Robust control is one possible reaction to Knightian uncertainty.

The proof is accomplished in a series of exercises.

Exercise 7.2.15. Let f and g be bounded functions from nonempty set D into $\mathbb{R}$. Prove that

$$\inf_{d \in D} (f(d) + g(d)) \geqslant \inf_{d \in D} f(d) + \inf_{d \in D} g(d).$$

Exercise 7.2.16. Check the following:

- $\mathscr{R}$ is, in fact, an RDP.
- The concavity condition (7.34) holds (hint: apply Exercise 7.2.15).
- The ε bound in (7.36) holds.

We conclude from the discussion above that the robust control RDP is stable, and hence all of the fundamental optimality properties hold.

7.3 Abstract Theory

In §7.1 we introduced RDPs, stated their optimality properties and investigated applications that satisfy the optimality conditions. The main task remaining is to prove the core optimality results in Theorem 7.1.1.

Rather than proving this result directly, we now present a completely abstract version of a dynamic programming problem, focusing purely on policy operators. Doing so allows us to simplify proofs and further extend the reach of dynamic programming theory.

Once the proofs are done, we will return to RPDs and show they are a special case.

7.3.1 Prelude

We saw in §7.1 that a stable RDP yields a set of feasible policies Σ and, for each $\sigma \in \Sigma$, a policy operator T_σ defined on the value space $V \subset \mathbb{R}^{\mathsf{X}}$. Notice that the dynamic programming problem is fully specified by the family of operators $\{T_\sigma\}_{\sigma \in \Sigma}$ and the space V that they act on. From this set of operators we obtain the set of lifetime values $\{v_\sigma\}_{\sigma \in \Sigma}$, with each v_σ uniquely identified as a fixed point of T_σ. These lifetime values define the value function v^* as the pointwise maximum $v^* = \vee_\sigma v_\sigma$. An optimal policy is then defined as a $\sigma \in \Sigma$ obeying $v_\sigma = v^*$.

To shed unnecessary structure before the main optimality proofs, a natural idea is to start directly with an abstract set of "policy operators" $\{T_\sigma\}$ acting on some set V. One can then define lifetime values and optimality as in the previous paragraph and start to investigate conditions on the family of operators $\{T_\sigma\}$ that lead to characterizations of optimality that we hope to obtain.

Although we seek to maximize generality, we need at least some structure on the operator family $\{T_\sigma\}$. At minimum, we need each operator T_σ to have a unique fixed point v_σ that describes the lifetime value of following a given policy. Another useful property of the family $\{T_\sigma\}$ of policy operators, which holds in the RDP case, is that, for each $v \in V$, there is a $\sigma \in \Sigma$ such that $T_\sigma v = \vee_{\tau\in\Sigma} T_\tau v$ pointwise on the state space—in fact every v-greedy policy has this property (see, e.g., Exercise 7.1.5 on page 217).

We use these ideas as our starting point. We take a family $\{T_\sigma\}$ of operators that are order-preserving, admit greedy policies and possess unique fixed points. We then show that, for such a family, we can define optimality and prove that abstract versions of the basic optimality results hold (the value function satisfies Bellman's equation, Bellman's principle of optimality holds, etc.).

7.3.2 Abstract Dynamic Programs

In this section we formalize abstract dynamic programs and present fundamental optimality results. In the discussion below, we use a lattice V as an abstract representation of the value space V from the RDP setting. A **lattice** is a partially ordered set that is closed under the taking of finite suprema and infima. A complete definition is given in §A.3.

For those who are unfamiliar with lattices and wish to proceed directly to the theory, it suffices to continue to view the value space V as a sublattice of $\mathbb{R}^{\mathsf{X}}$, where X is an arbitrary finite set, and to understand the abstract partial order $\preceq$ as the pointwise order $\leqslant$.

7.3.2.1 Set Up

An **abstract dynamic program** (**ADP**) is a pair $(\{T_\sigma\}_{\sigma\in\Sigma}, V)$, where

(i) $V = (V, \preceq)$ is a lattice,

(ii) Σ is a finite set,

(iii) For each $\sigma \in \Sigma$,

Figure 7.4: T_σ satisfies all conditions (one-dimensional setting)

(a) T_σ is an order-preserving self-map on V,

(b) T_σ has a unique fixed point in V, denoted henceforth by v_σ,

(c) $v \in V$ and $T_\sigma v \preceq v$ implies $v_\sigma \preceq v$,

(d) $v \in V$ and $v \preceq T_\sigma v$ implies $v \preceq v_\sigma$,

(iv) for all $v \in V$, the set $\{T_\sigma v\}_{\sigma \in \Sigma}$ contains a least and greatest element

Below, we often write $\{T_\sigma\}$ in place of $\{T_\sigma\}_{\sigma \in \Sigma}$. Elements of Σ are called **policies** and elements of $\{T_\sigma\}$ are called **policy operators**. Analogous to the RDP setting, we call v_σ the **σ-value function**.

For ease of reference, we refer to (iii)-(c) as **downward stability** and (iii)-(d) as **upward stability**. Figure 7.4 gives a stylized illustration of an operator T_σ that satisfies all conditions in (iii) when $V = [0, 1]$. For example, T_σ is downward stable because any v that is mapped down by T_σ (i.e., $T_\sigma v \leqslant v$) satisfies $v_\sigma \leqslant v$.

Property (iv) we call **existence of greedy policies** for reasons that are clarified below. We require existence of a least element of $\{T_\sigma v\}_{\sigma \in \Sigma}$ as well as a greatest element because we want to consider minimization as well as maximization problems (see §7.4.2). For applications that involve only maximization, it is enough that a greatest element exists for all v. Moreover, in this case, one can replace the assumption that V

is a lattice with a weaker condition that V is an **upper semi-lattice**; that is $f \vee g \in V$ whenever $f, g \in V$.

For a given ADP and fixed $v \in V$, a policy $\hat{\sigma}$ in Σ is called **v-greedy** if $T_{\hat{\sigma}} v \succeq T_\sigma v$ for all $\sigma \in \Sigma$. Existence of a greatest element in property (iv) of the definition is equivalent to the statement that a v-greedy policy exists for every $v \in V$.

7.3.2.2 MDPs are ADPs

One reason we constructed ADPs is to generalize MDPs, as defined in Chapter 6. Let's now verify that every MDP is an ADP.

To see this, fix an MDP (Γ, β, r, P) on with state space X, let Σ be the associated feasible policies and let $\{T_\sigma\}_{\sigma \in \Sigma}$ be the policy operators. Our claim is that $(\{T_\sigma\}_{\sigma \in \Sigma}, V)$ is an ADP when V is $\mathbb{R}^{\mathsf{X}}$ and $\preceq$ is the pointwise order $\leqslant$.

Parts (i)–(ii) of the ADP definition hold because $V = \mathbb{R}^{\mathsf{X}}$ is a lattice under the pointwise order $\leqslant$ and Σ is finite. Regarding (iii), we fix $\sigma \in \Sigma$ and recall that $T_\sigma v = r_\sigma + \beta P_\sigma v$ for some $r_\sigma \in \mathbb{R}^{\mathsf{X}}$ and $\beta \in (0, 1)$, where P_σ is a stochastic matrix. We saw in Chapter 6 that T_σ satisfies (iii)-(a) and (iii)-(b). Regarding upward stability, suppose that $v \in \mathbb{R}^{\mathsf{X}}$ and $v \leqslant T_\sigma v$, or, equivalently, $v \leqslant r_\sigma + \beta P_\sigma v$. A simple rearrangement transforms this to $v \leqslant (I - \beta P_\sigma)^{-1} r_\sigma$, or, equivalently $v \leqslant v_\sigma$. A similar argument shows that downward stability also holds.

It only remains to check part (iv) of the definition of ADPs on existence of least and greatest elements. To this end, we fix $v \in V$ and take $\hat{\sigma}$ to be v-greedy in the sense of Chapter 6, so that

$$\hat{\sigma}(x) \in \operatorname*{argmax}_{a \in \Gamma(x)} \left\{ r(x, a) + \beta \sum_{x' \in \mathsf{X}} v(x') P(x, a, x') \right\} \quad \text{for all } x \in \mathsf{X} \tag{7.40}$$

(see §6.1.2.2). If σ is any other feasible policy, then

$$r(x, \hat{\sigma}(x)) + \beta \sum_{x' \in \mathsf{X}} v(x') P(x, \hat{\sigma}(x), x') \geqslant r(x, \sigma(x)) + \beta \sum_{x' \in \mathsf{X}} v(x') P(x, \sigma(x), x')$$

at all x. In operator form, this is $T_{\hat{\sigma}} v \geqslant T_\sigma v$. Since σ is an arbitrary greedy policy, we have shown that $T_{\hat{\sigma}} v$ is the greatest element of $\{T_\sigma v\}_{\sigma \in \Sigma}$.

A similar argument replacing argmax with argmin in (7.40) shows that a least element also exists. This completes the proof that every MDP is an ADP. Later, in §7.3.3, we will show that the same is true for every stable RDP.

7.3.2.3 Values

Consider again a general ADP and let $\{v_\sigma\}_{\sigma\in\Sigma}$ be the set of σ-value functions. In every application we consider, v_σ represents the lifetime value of following policy σ in each period. From these elements we construct the **value function** as the element of V defined by

$$v^* := \bigvee_{\sigma\in\Sigma} v_\sigma. \tag{7.41}$$

In addition,

(i) A policy $\sigma \in \Sigma$ is called **optimal** for the ADP if $v_\sigma = v^*$.

(ii) **Bellman's principle of optimality** is said to hold if the set of optimal policies in Σ is identical to the set of v^*-greedy policies.

All of the definitions given in this section are direct generalizations of definitions that we used for optimal stopping problems, MDPs and RDPs.

Bellman's way of solving dynamic programs was to exploit what is now widely called Bellman's equation. To state the equation, we first define the **Bellman operator** associated with a fixed ADP as the map T on V defined by

$$Tv = \bigvee_{\sigma\in\Sigma} T_\sigma v \qquad (v \in V). \tag{7.42}$$

The definition of the Bellman operator in (7.42) includes all of the Bellman operators we have met as special cases. For example, given an RDP (Γ, V, B) with policy operators $\{T_\sigma\}$, the Bellman operator $(Tv)(x) = \max_{a\in\Gamma(x)} B(x,a,v)$ can also be characterized by the definition in (7.42). (See Exercise 7.1.6 on page 218.)

Exercise 7.3.1. Show that T is an order-preserving self-map on V.

Exercise 7.3.2. Show that (analogous to Exercise 6.1.8 on page 168),

$$Tv = T_\sigma v \iff \sigma \text{ is } v\text{-greedy}. \tag{7.43}$$

A function $v \in V$ is said to satisfy **Bellman's equation** if it is a fixed point of T; that is, if $v = Tv$.

7.3.2.4 An HPI Operator

We define a self-map H on V via

$$Hv = v_\sigma \text{ where } \sigma \text{ is } v\text{-greedy} \tag{7.44}$$

Iterating with H is an abstract version of the Howard policy iteration (HPI) algorithm defined for the MDP case on page 173. In particular, if we fix $\sigma \in \Sigma$ and set $v_k = H^k v_\sigma$, then $(v_k)_{k \geqslant 0}$ is the sequence of σ-value functions generated by HPI.

Below, we say that **HPI converges in finitely many steps** if, for all $\sigma \in \Sigma$, there exists a $K \in \mathbb{N}$ such that $k \geqslant K$ implies $H^k v_\sigma = v^*$.

For the operator H to be well-defined, we need to always select the same v-greedy policy when H is applied to v (since two v-greedy policies can have different lifetime values). Hence, for this purpose, we enumerate the policy set Σ and, when applying H, always choose the first v-greedy policy. (For example, if the set of v-greedy policies is $\{\sigma_2, \sigma_3, \sigma_4\}$, then we choose σ_2 and set $Hv = v_{\sigma_2}$.) This particular choice of convention makes no difference to our results.

7.3.2.5 Optimality Results

We can now state our main result on abstract dynamic programming.

Theorem 7.3.1. *For any ADP, the following statements are true:*

(i) *the value function v^* is the unique solution to Bellman's equation in V,*

(ii) *v^* is the unique fixed point of H in V,*

(iii) *HPI converges in finitely many steps,*

(iv) *Bellman's principle of optimality holds, and*

(v) *at least one optimal policy exists.*

Theorem 7.3.1 informs us that all ADPs have first-rate optimality properties. Bellman's principle of optimality provides a natural characterization of optimal policies, as well as a straightforward way to compute such policies provided we can calculate the value function. The fact that HPI converges to the value function in finite time confirms that this is possible.

The proof of Theorem 7.3.1 is constructed through a sequence of intermediate results in the remainder of this section. We begin with the following lemma.

Lemma 7.3.2. *If v^* satisfies Bellman's equation, then Bellman's principle of optimality holds and at least one optimal policy exists.*

Proof. Suppose v^* satisfies Bellman's equation. To see that Bellman's principle of optimality holds, recall that σ is optimal if and only if $v_\sigma = v^*$. Since v_σ is the unique fixed point of T_σ, this is equivalent to $T_\sigma v^* = v^*$. Since v^* satisfies Bellman's equation, the last statement is equivalent to $T_\sigma v^* = Tv^*$, which is, in turn equivalent to the statement that σ is v^*-greedy. In other words, Bellman's principle of optimality holds.

Existence of an optimal policy is now trivial, since $v^* \in V$ and hence there exists at least one v^*-greedy policy. By Bellman's principle of optimality, every such policy is optimal. □

Lemma 7.3.3. *If $\sigma \in \Sigma$ and $Tv_\sigma = v_\sigma$, then $v_\sigma = v^*$ and σ is optimal.*

Proof. Let v_σ be as stated. To prove optimality of σ, we need to show that $v_\sigma = v^*$. By definition, $v_\sigma \preceq v^*$, so it suffices to obtain $v_\sigma \succeq v^*$. For this we fix $\tau \in \Sigma$ and observe that $v_\sigma = Tv_\sigma \succeq T_\tau v_\sigma$. Hence, by downward stability, $v_\sigma \succeq v_\tau$. Since $\tau \in \Sigma$ was arbitrary, we have $v_\sigma \succeq v^*$. Hence $v_\sigma = v^*$, as claimed. □

The next lemma tells us that if H has a fixed point, then that fixed point is v^*.

Lemma 7.3.4. *If $v \in V$ and $Hv = v$, then*

(i) *v equals the value function v^*, and*

(ii) *the value function satisfies Bellman's equation.*

Proof. Fix $v \in V$ with $Hv = v$ and let σ be the first v-greedy policy, so that $Hv = v_\sigma$. From the last two equations we obtain $v_\sigma = v$. Combining this equality with the greedy characterization $T_\sigma v = Tv$ yields $v_\sigma = T_\sigma v_\sigma = Tv_\sigma$. Lemma 7.3.3 now implies $v = v_\sigma = v^*$. In particular, $v = v^*$, which proves (i). Regarding (ii), substituting $v_\sigma = v^*$ into the previous equation $v_\sigma = Tv_\sigma$ yields $v^* = Tv^*$, so the value function satisfies Bellman's equation. □

Lemma 7.3.5. *For all $\sigma \in \Sigma$ we have $v_\sigma \preceq Hv_\sigma$.*

Proof. Fix $\sigma \in \Sigma$ and let τ be the first v_σ-greedy policy, so that $Hv_\sigma = v_\tau$. The greedy property of τ and the definition of T yield

$$v_\sigma = T_\sigma v_\sigma \preceq Tv_\sigma = T_\tau v_\sigma.$$

Upward stability now gives $v_\sigma \preceq v_\tau = Hv_\sigma$. □

Lemma 7.3.6. *For any $\sigma \in \Sigma$, the sequence $(v_k)_{k \geqslant 0}$ defined by $v_0 = v_\sigma$ and $v_{k+1} = Hv_k$ for $k \geqslant 0$ converges to v^* in finitely many steps. In particular, there exists a $K \in \mathbb{N}$ such that $H^K v_0 = v^*$ and, moreover, $Hv^* = v^*$.*

Proof. Regarding finite termination, observe from Lemma 7.3.5 that $v_{k+1} \succeq v_k$ for all k. Since the sequence (v_k) is contained in the finite set $\{v_\sigma\}_{\sigma \in \Sigma}$, it must be that $v_{K+1} = v_K$ for some $K \in \mathbb{N}$ (since otherwise we have an infinite sequence that never cycles). But then $Hv_K = v_{K+1} = v_K$, so v_K is a fixed point of H. Lemma 7.3.4 now implies that $v_K = v^*$. □

Proof of Theorem 7.3.1. Lemma 7.3.6 implies that HPI converges in finite time and $Hv^* = v^*$. From Lemma 7.3.4 it follows that $Tv^* = v^*$. Since $Tv^* = v^*$, Lemma 7.3.2 now implies that Bellman's principle of optimality holds and at least one optimal policy exists. It remains to show that v^* is the only solution to Bellman's equation in V.

To see this, suppose that $\bar{v} = T\bar{v}$. On one hand, existence of greedy policies implies that there is a policy σ such that $T_\sigma \bar{v} = T\bar{v}$, so $T_\sigma \bar{v} = \bar{v}$ and hence $\bar{v} = v_\sigma \preceq v^*$. On the other hand, given $\sigma \in \Sigma$, we have $T_\sigma \bar{v} \preceq T\bar{v} = \bar{v}$. Downward stability now gives $v_\sigma \preceq \bar{v}$. Since σ was an arbitrarily chosen policy, we have $v^* \preceq \bar{v}$. Hence $\bar{v} = v^*$, which proves the uniqueness claim.

Finally, combining Lemmas 7.3.4 and 7.3.6 proves that v^* is the unique fixed point of H in V. The proof of Theorem 7.3.1 is now complete. □

7.3.3 Stable Dynamic Programs

In the ADP framework of §7.3.2, the underlying space V lacks any form of topology, which means that we cannot discuss convergence of algorithms such as VFI and OPI. Here we add additional structure, including topology, and then study convergence. This process also brings the model closer to applications.

We begin by taking X to be any finite set. Given X, a **stable dynamic program (SDP)** is a pair $(\{T_\sigma\}_{\sigma \in \Sigma}, V)$, where

(i) $V = V$ is a sublattice of $(\mathbb{R}^{\mathsf{X}}, \leqslant)$,

(ii) Σ is a finite set,

(iii) T_σ is a Koopmans operator on V for every $\sigma \in \Sigma$, and

(iv) for all $v \in V$, the set $\{T_\sigma v\}_{\sigma \in \Sigma}$ contains a least and greatest element

(We use the name "stable" because the Koopmans operator assumption implies that each T_σ is globally stable (and order-preserving) on V (see 4.3.4.1).)

Throughout, the symbol v_σ denotes the unique fixed point of T_σ. We use similar terminology as for the case of ADPs. For example, each T_σ is called a policy operator.

Lemma 7.3.7. *Every stable dynamic program is an abstract dynamic program.*

Proof. Since every sublattice of $\mathbb{R}^{\mathsf{X}}$ is a lattice and every Koopmans operator is order preserving, we need only show that all of the policy operators are upward and downward stable (i.e., that (iii)-(c) and (iii)-(d) in the definition of an ADP hold.) To see that this is so, fix $\sigma \in \Sigma$ and $v \in V$. Suppose first that $v \leqslant T_\sigma v$. Iterating on this inequality and using the fact that T_σ is order-preserving gives $v \leqslant T_\sigma^k v$ for all $k \in \mathbb{N}$. Since Koopmans operators are globally stable, taking the limit gives $v \leqslant v_\sigma$. Hence upward stability holds. The proof of downward stability is analogous. □

Since each stable dynamic program is an ADP, all of the fundamental optimality properties in Theorem 7.3.1 hold. An open question is whether value function iteration (VFI) and optimistic policy iteration (OPI) converge. In this section we show that the answer is affirmative: the additional structure provided by stable dynamic programs allows us to prove convergence of both VFI and OPI. Since VFI is a special case of OPI, we now focus on the latter.

Our first step is to slightly generalize the OPI algorithm as it appears for MDPs on page 177, restating it in Algorithm 8.

Algorithm 8: Abstract OPI

```
input v_0 ∈ V, an initial guess of v*
input τ, a tolerance level for error
input m ∈ ℕ, a step size
k ← 0 and ε ← τ + 1
while ε > τ do
    σ_k ← a v_k-greedy policy
    v_{k+1} ← T^m_{σ_k} v_k
    ε ← ‖v_k − v_{k+1}‖
    k ← k + 1
end
return v_k, σ_k
```

The main result of this section is as follows.

Proposition 7.3.8. *If $\mathcal{S}$ is an SDP, v^* is the value function of $\mathcal{S}$, and (v_k) is a sequence in value space generated by OPI Algorithm 8, then*

$$v_0 = v_\sigma \text{ for some } \sigma \in \Sigma \quad \Longrightarrow \quad \lim_{k\to\infty} v_k = v^*.$$

The statement in Proposition 7.3.8 holds for any step size m in the OPI algorithm. Since $m = 1$ is included, VFI is nested as a special case.

The proof of the proposition proceeds through a series of exercises and lemmas. For the purposes of the current section we set

$$V_\Sigma := \{v_\sigma\}_{\sigma\in\Sigma} \quad \text{and} \quad V_u := \{v \in V : Tv \geqslant v\}.$$

In all of the following discussion $\mathcal{S} = (\{T_\sigma\}, V)$ is a stable dynamic program with value function v^* Bellman operator T.

Exercise 7.3.3. Prove that $V_\Sigma \subset V_u$.

Lemma 7.3.9. *If $v \in V_\Sigma$, then $T^k v \to v^*$ as $k \to \infty$.*

Proof. Fix $v \in V_\Sigma$. On one hand, $v \leqslant v^*$ and hence $T^k v \leqslant T^k v^* = v^*$ for all k. On the other hand, if σ is any policy, then $T_\sigma^k v \leqslant T^k v$ for all k. Hence $T_\sigma^k v \leqslant T^k v \leqslant v^*$ for all k. If we now take σ to be an optimal policy, which exists under the stated assumptions, we have $T_\sigma^k v \to v^*$ as $k \to \infty$. Hence $T^k v \to v^*$, as required. □

Next, fixing $\sigma \in \Sigma$, we define the operator W from V to itself via

$$Wv := T_\sigma^m v \quad \text{where} \quad \sigma \text{ is the first } v\text{-greedy policy.}$$

In the definition, "first" is a convention, as discussed after the definition of the operator H in (7.44). In fact W is an approximation of H, since $T_\sigma^m v \to v_\sigma = Hv$ as $m \to \infty$, where converges follows from the global stability property of Koopmans operators.

Lemma 7.3.10. *W is an order-preserving self-map on V_u. Moreover,*

$$v \in V_u \implies Tv \leqslant Wv \leqslant T^m v.$$

Proof. As for the self-map property, pick any $v \in V_u$. Since T and T_σ are order-preserving, $v \leqslant Tv$ and σ is v-greedy, we have

$$Wv = T_\sigma T_\sigma^{m-1} v \leqslant T T_\sigma^{m-1} v \leqslant T T_\sigma^{m-1} T v = T T_\sigma^m v = TWv.$$

Hence $Wv \in V_u$ and W is invariant on V_u.

As for the order-preserving property, this is immediate from the definition, since powers of order-preserving self-maps are order-preserving (Exercise 2.1.16).

As for the inequality $Tv \leqslant Wv$, fix $v \in V_u$. Since T_σ is order-preserving, $v \leqslant Tv$ and σ is v-greedy, we have

$$T_\sigma^{m-1} v \leqslant T_\sigma^{m-1} Tv = T_\sigma^{m-1} T_\sigma v = Wv.$$

Continuing in the same manner gives $T_\sigma^{m-j} v \leqslant Wv$ for $j < m$ and, in particular, $T_\sigma v \leqslant Wv$. Because σ is v-greedy, this yields $Tv \leqslant Wv$.

Regarding the second inequality, we use the fact that $T_\sigma \leqslant T$ on V and T and T_σ are both order-preserving to obtain $Wv = T_\sigma^m v \leqslant T^m \sigma v$ (see Exercise 2.1.20 on page 48). □

Proof of Proposition 7.3.8. Fix $v_0 \in V_\Sigma$. Our first claim is that

$$T^k v_0 \leqslant W^k v_0 \leqslant T^{km} v_0 \quad \text{for all } k \in \mathbb{N}. \tag{7.45}$$

Indeed, this holds for $k = 1$ by $v_0 \in V_u$ and Lemma 7.3.10. Since all operators are order-preserving and invariant on V_u, the extension to arbitrary k follows from Exercise 2.1.20 on page 48.

Now let $(v_k)_{k \geqslant 0}$ be the value sequence generated by OPI. Since $v_k = W^k v_0$, (7.45) holds and $T^i v_0 \to v^*$ as $i \to \infty$, we see that $v_k \to v^*$ as $k \to \infty$. □

7.3.4 Back to RPDs

When we introduced abstract dynamic programs in §7.3.2.1, one of our key aims was to prove Theorem 7.1.1 on page 219, which states the fundamental optimality properties of stable RPDs. At this point we have shown that abstract dynamic programs have most of the desired optimality properties and stable dynamic programs have all of them. As such, the task of proving Theorem 7.1.1 will be complete if we can show that every stable RPD is a stable dynamic program. We now state this result.

Proposition 7.3.11. *Let $\mathscr{R} := (\Gamma, V, B)$ be an RDP with policy operators $\{T_\sigma\}_{\sigma \in \Sigma}$. If $\mathscr{R}$ is stable, then $(\{T_\sigma\}_{\sigma \in \Sigma}, V)$ is a stable dynamic program.*

Proof. By assumption, V is a sublattice of $\mathbb{R}^{\mathsf{X}}$. By Exercise 7.1.4, each T_σ is order-preserving on V. By the stable RDP assumption, each T_σ is globally stable on V. By Exercise 7.1.5, for each $v \in V$, the set $\{T_\sigma v\}$ contains a least and greatest element. Hence $(\{T_\sigma\}, V)$ is a stable dynamic program, as claimed. □

To tidy up this section let's spell out the proof of Theorem 7.1.1.

Proof of Theorem 7.1.1. Let $\mathscr{R} := (\Gamma, V, B)$ be a stable RDP and let $(\{T_\sigma\}, V)$ be the SDP generated by $\mathscr{R}$. Since an SDP is an APD, Theorem 7.3.1 tells us that the value function v^* is the unique solution to Bellman's equation in V, that HPI converges to v^* in finitely many steps, that Bellman's principle of optimality holds, and that at least one optimal policy exists. The only claim we still need to prove is: if $v_0 = v_\sigma$ for some $\sigma \in \Sigma$, then the sequence (v_k) generated by OPI converges to v^*. But this also holds for SDPs, by Proposition 7.3.8. The proof is now complete. □

7.4 Isomorphic Dynamic Programs

One service provided by mathematics is to determine when two different problems are essentially the same. For example, students of algebra study group isomorphisms, which tell us when two groups are identical in terms of their characteristics under group operations. Topologically isomorphisms play a similar role for topological spaces—these kinds of isomorphisms are also called homeomorphisms, which we introduced in §2.2.1. We used homeomorphisms to identify topologically conjugate dynamical systems, which is itself a method for connecting essentially identical dynamic models.

Not surprisingly, it is also useful to have a notion of "isomorphic" dynamic programs. In this section we set out such a notion and show that an isomorphic relationship leads to essentially equivalent optimality properties. We exploit these ideas to study additional dynamic programming problems, including minimization problems and decision problems with ambiguity.

7.4.1 Isomorphic ADPs

We begin by reviewing order isomorphisms and then, in §7.4.1.3, we turn to the topic of "isomorphic" dynamic programs. This section assumes that you are familiar with the material on suprema and infima in §A.3.

7.4.1.1 Order Isomorphisms

Our first step is to identify an isomorphic relationship between sets with partial orders. To this end, let P and $\hat{P}$ be two partially ordered sets and let Φ be a map from P to

$\hat{P}$. The map Φ is called an **order isomorphism** if Φ is bijective and order-preserving. Similarly, Φ is called an **order anti-isomorphism** if Φ is bijective and order-reversing.

Example 7.4.1. If $P = \hat{P} = \mathbb{R}^n_+$ with the usual pointwise order, then Φ mapping $p \in P$ to $p^2 \in \hat{P}$, where the operation $p \mapsto p^2$ acts pointwise, is an order isomorphism, since Φ is bijective and preserves the pointwise order.

Exercise 7.4.1. Let P and $\hat{P}$ be order-isomorphic; that is, there exists an order isomorphism from P to $\hat{P}$. Prove: If P is totally ordered, then so is $\hat{P}$.

Exercise 7.4.2. Check the following claims:

(i) If Φ is an order isomorphism from P to $\hat{P}$, then Φ^{-1} is order-preserving.

(ii) If Φ is an order anti-isomorphism from P to $\hat{P}$, then Φ^{-1} is order-reversing.

Exercise 7.4.3. Let L and $\hat{L}$ be two lattices and let $\{f_i\}_{i \in I}$ be a finite subset of L. Prove the following statements:

(i) If Φ is an order-preserving map from L to $\hat{L}$, then

$$\Phi \bigvee_i f_i = \bigvee_i \Phi f_i \quad \text{and} \quad \Phi \bigwedge_i f_i = \bigwedge_i \Phi f_i.$$

(ii) If Φ is an order-reversing map from L to $\hat{L}$, then

$$\Phi \bigvee_i f_i = \bigwedge_i \Phi f_i \quad \text{and} \quad \Phi \bigwedge_i f_i = \bigvee_i \Phi f_i.$$

7.4.1.2 Minimization Terminology

Up until now all theory and applications have concerned maximization of lifetime values. However, as well as isomorphisms between dynamic programs, we also wish to consider "anti-isomorphisms" that reverse the order of valuations. For this reason, as well as for the desire to state minimization results, now is a good time to introduce minimization terminology.

To improve clarity, whenever we discuss minimization and maximization together, what were previously called optimal policies (which are maximizers) will be called

max-optimal policies. Similarly, greedy policies will be called **max-greedy** policies, value functions will be called **max-value functions** and so on. The minimization case will use the prefix "min-" instead, as per the definitions below.

To begin the theory, $\mathscr{A} := (\{T_\sigma\}, V)$ be an ADP (see §7.3.2). As usual, for each $\sigma \in \Sigma$, the symbol v_σ denotes the σ-value function; that is the unique fixed point of T_σ. A policy $\sigma^* \in \Sigma$ will be called **min-optimal** if $v_{\sigma^*} \leqslant v_\sigma$ for every $\sigma \in \Sigma$. The **min-value function** is

$$u^* := \inf_{\sigma \in \Sigma} v_\sigma.$$

A policy σ is called **v-min-greedy** if $T_\sigma v \leqslant T_\tau v$ for all $\tau \in \Sigma$.

Example 7.4.2. If $\mathscr{A}$ is generated by an RDP (Γ, V, B), then $\sigma \in \Sigma$ is v-min-greedy if and only if

$$\sigma(x) \in \operatorname*{argmin}_{a \in \Gamma(x)} B(x, a, v) \quad \text{at each } x \in \mathsf{X}.$$

One purpose of the following discussion is to find and characterize min-optimal policies for the ADP $(\{T_\sigma\}, V)$. To this end, we define $S \colon V \to V$ via $Sv = \inf_{\sigma \in \Sigma} T_\sigma v$. We call S the **min-Bellman operator**.

Example 7.4.3. In the RDP setting of Example 7.4.2, this definition is equivalent to

$$(Sv)(x) = \min_{a \in \Gamma(x)} B(x, a, v) \qquad (x \in \mathsf{X}). \tag{7.46}$$

Exercise 7.4.4. Show that σ is v-min-greedy if and only if $T_\sigma v = Sv$.

7.4.1.3 Definitions and Results

To begin, we define ADPs $\mathscr{A} = (\{T_\sigma\}_{\sigma \in \Sigma}, V)$ and $\hat{\mathscr{A}} = (\{\hat{T}_\sigma\}_{\sigma \in \Sigma}, \hat{V})$ to be **isomorphic** if $\mathscr{A}$ and $\hat{\mathscr{A}}$ have the same policy sets Σ and, in addition, there exists an order isomorphism Φ from V to $\hat{V}$ such that T_σ and $\hat{T}_\sigma$ are conjugate under Φ for all $\sigma \in \Sigma$. As per the discussion in §2.2.1, the last statement means that

$$T_\sigma = \Phi^{-1} \circ \hat{T}_\sigma \circ \Phi \quad \text{for all } \sigma \in \Sigma. \tag{7.47}$$

In addition, we call $\mathscr{A}$ and $\hat{\mathscr{A}}$ **anti-isomorphic** if the same definition holds after replacing "order isomorphism" with "order anti-isomorphism."

In what follows, for ADPs $\mathscr{A} = (\{T_\sigma\}, V)$ and $\hat{\mathscr{A}} = (\{\hat{T}_\sigma\}, \hat{V})$, we let

- v_σ (resp., $\hat{v}_\sigma$) be the fixed point of T_σ (resp., $\hat{T}_\sigma$),

- T (resp., $\hat{T}$) be the Bellman operator of $\mathscr{A}$ (resp., $\hat{\mathscr{A}}$),
- v^* (resp., $\hat{v}^*$) be the max-value function of $\mathscr{A}$ (resp., $\hat{\mathscr{A}}$) and
- u^* (resp., $\hat{u}^*$) be the min-value function of $\mathscr{A}$ (resp., $\hat{\mathscr{A}}$)

We seek relationships between value functions and optimal properties of isomorphic ADP pairs.

Theorem 7.4.1. *If the ADPs $\mathscr{A}$ and $\hat{\mathscr{A}}$ are isomorphic under Φ, then*

(i) $T = \Phi^{-1} \circ \hat{T} \circ \Phi$ *and* $S = \Phi^{-1} \circ \hat{S} \circ \Phi$ *on* V,

(ii) $\hat{v}^* = \Phi\, v^*$ *and* $\hat{u}^* = \Phi\, u^*$,

(iii) σ *is max-optimal for* $\mathscr{A}$ *if and only if* σ *is max-optimal for* $\hat{\mathscr{A}}$.

(iv) σ *is min-optimal for* $\mathscr{A}$ *if and only if* σ *is min-optimal for* $\hat{\mathscr{A}}$.

Thus, under the isomorphic relationship, the max- and min-value functions are identified under the order-isomorphism and $\mathscr{A}$ and $\hat{\mathscr{A}}$ have identical optimal policies.

Proof of Theorem 7.4.1. Assume the conditions of Theorem 7.4.1. For given $v \in V$, applying the supremum pass-through for order isomorphisms in Exercise 7.4.3 and (7.47) yields

$$Tv = \bigvee_\sigma T_\sigma\, v = \bigvee_\sigma \Phi^{-1}\hat{T}_\sigma\, \Phi\, v = \Phi^{-1} \bigvee_\sigma \hat{T}_\sigma\, \Phi\, v = \Phi^{-1}\hat{T}\, \Phi\, v.$$

Hence (V, T) and $(\hat{V}, \hat{T})$ are conjugate under Φ, and, therefore, their fixed points are connected by $\hat{v}^* = \Phi\, v^*$ (see Exercise 2.2.2 on page 58). Similarly,

$$Sv = \bigwedge_\sigma T_\sigma\, v = \bigwedge_\sigma \Phi^{-1}\hat{T}_\sigma\, \Phi\, v = \Phi^{-1} \bigwedge_\sigma \hat{T}_\sigma\, \Phi\, v = \Phi^{-1}\hat{S}\, \Phi\, v.$$

Hence (V, S) and $(\hat{V}, \hat{S})$ are conjugate under Φ, and therefore $\hat{u}^* = \Phi\, u^*$. Together, these results prove (i)–(ii).

Regarding claim (iii), note that σ is max-optimal for $\mathscr{A}$ if and only if $T_\sigma\, v^* = v^*$, which, by the bijection property of Φ, is also equivalent to $\Phi\, T_\sigma\, v^* = \hat{v}^*$. Using conjugacy, we can also write this as $\hat{T}_\sigma\, \hat{v}^* = \hat{v}^*$, which is equivalent to the statement that σ is max-optimal for $\hat{\mathscr{A}}$.

The proof of (iv) is similar. □

Here is a result for the order-reversing case that corresponds to Theorem 7.4.1:

Theorem 7.4.2. *If the ADPs $\mathscr{A}$ and $\hat{\mathscr{A}}$ are anti-isomorphic under Φ, then*

(i) $T = \Phi^{-1} \circ \hat{S} \circ \Phi$ *and* $S = \Phi^{-1} \circ \hat{T} \circ \Phi$ *on* V,

(ii) $\hat{u}^* = \Phi\, v^*$ *and* $\hat{v}^* = \Phi\, u^*$, *and*

(iii) σ *is max-optimal for* $\mathscr{A}$ *if and only if* σ *is min-optimal for* $\hat{\mathscr{A}}$.

(iv) σ *is min-optimal for* $\mathscr{A}$ *if and only if* σ *is max-optimal for* $\hat{\mathscr{A}}$.

Proof. Assume the conditions of Theorem 7.4.2. For given $v \in V$, applying the properties of order anti-isomorphisms in Exercise 7.4.3, we get

$$Tv = \bigvee_\sigma T_\sigma\, v = \bigvee_\sigma \Phi^{-1}\hat{T}_\sigma\, \Phi v = \Phi^{-1} \bigwedge_\sigma \hat{T}_\sigma\, \Phi v = \Phi^{-1}\hat{S}\, \Phi v.$$

Hence (V, T) and $(\hat{V}, \hat{S})$ are conjugate under Φ. Since $\hat{u}^*$ is the fixed point of $\hat{S}$, we obtain $\hat{u}^* = \Phi v^*$. Similarly, for $v \in V$,

$$Sv = \bigwedge_\sigma T_\sigma\, v = \bigwedge_\sigma \Phi^{-1}\hat{T}_\sigma\, \Phi v = \Phi^{-1} \bigvee_\sigma \hat{T}_\sigma\, \Phi v = \Phi^{-1}\hat{T}\, \Phi v.$$

Since $\hat{v}^*$ is the fixed point of $\hat{T}$, we obtain $\hat{v}^* = \Phi u^*$. This proves claims (i)–(ii).

Regarding claim (iii), note that σ is max-optimal for $\mathscr{A}$ if and only if $T_\sigma\, v^* = v^*$, which, by the bijection property of Φ, is also equivalent to $\Phi T_\sigma\, v^* = \Phi v^* = \hat{u}^*$. Using conjugacy, we can also write this as $T_\sigma \Phi^{-1}\, v^* = \hat{T}_\sigma\, \hat{u}^* = \hat{u}^*$, which is equivalent to the statement that σ is min-optimal for $\hat{\mathscr{A}}$.

The proof of (iv) is similar. □

7.4.1.4 Isomorphic RDPs

The preceding results are simple and broad but the isomorphic (or anti-isomorphic) relationships are not trivial to establish. To this end, let us give conditions on RDPs under which they generate isomorphic (or anti-isomorphic) ADPs. These conditions are more restrictive but easier to check in applications.

In what follows, we call RDPs $\mathscr{R}$ and $\hat{\mathscr{R}}$ **isomorphic** if the ADPs they generate are isomorphic. Likewise, we call $\mathscr{R}$ and $\hat{\mathscr{R}}$ **anti-isomorphic** if the ADPs they generate are anti-isomorphic.

To this end, let $\mathscr{R} = (\Gamma, V, B)$ and $\hat{\mathscr{R}} = (\Gamma, \hat{V}, \hat{B})$ be two RDPs with state space X and action space A. Suppose that

$$V = \mathbb{M}^{\mathsf{X}} \quad \text{and} \quad \hat{V} = \hat{\mathbb{M}}^{\mathsf{X}} \quad \text{where } \mathbb{M}, \hat{\mathbb{M}} \subset \mathbb{R},$$

and, in addition, that φ is a homeomorphism from $\mathbb{M}$ onto $\hat{\mathbb{M}}$ such that

$$B(x, a, v) = \varphi^{-1}[\hat{B}(x, a, \varphi \circ v)] \quad \text{for all } v \in V \text{ and } (x, a) \in \mathsf{G}. \tag{7.48}$$

In this setting, we have the following result:

Proposition 7.4.3. *If φ is increasing on $\mathbb{M}$, then $\mathscr{R}$ and $\hat{\mathscr{R}}$ are isomorphic. If φ is decreasing on $\mathbb{M}$, then $\mathscr{R}$ and $\hat{\mathscr{R}}$ are anti-isomorphic.*

Proof. Let $\mathscr{A}$ and $\hat{\mathscr{A}}$ be the ADPs generated by $\mathscr{R}$ and $\hat{\mathscr{R}}$ respectively. Let Φ be defined by $\Phi v = \varphi \circ v$. Consider the first case in which φ is increasing on $\mathbb{M}$. Since φ is a homeomorphism from $\mathbb{M}$ to $\hat{\mathbb{M}}$, Φ is a homeomorphism from V to $\hat{V}$. Since φ is increasing, Φ is an order isomorphism from V to $\hat{V}$. Moreover, for any $\sigma \in \Sigma$,

$$(T_\sigma v)(x) = B(x, \sigma(x), v) = \varphi^{-1}[\hat{B}(x, \sigma(x), \varphi \circ v)] = \varphi^{-1}[(\hat{T}_\sigma \varphi \circ v)(x)].$$

In other words, $T_\sigma v = \Phi^{-1}\hat{T}_\sigma \Phi v$, so $\mathscr{A}$ and $\hat{\mathscr{A}}$ are isomorphic ADPs. Hence, by definition, $\mathscr{R}$ and $\hat{\mathscr{R}}$ are isomorphic RDPs, as claimed.

The proof of the anti-isomorphic case is analogous and omitted. □

7.4.2 Minimization Problems

In this section we consider minimization problems. We then provide an application that concerns loss minimization in the setting of a negative discount rate.

The next theorem tells us that the ADPs have strong optimality properties vis-a-vis minimization as well as vis-a-vis maximization.

Theorem 7.4.4. *If $\mathscr{A} = (\{T_\sigma\}, V)$ is an ADP with min-value function u^* and min-Bellman operator S, then*

(i) *u^* is the unique fixed point of S in V,*

(ii) *a policy $\sigma \in \Sigma$ is min-optimal if and only if σ is u^*-min greedy, and*

(iii) *at least one min-optimal policy exists.*

Item (iii) is a version of **Bellman's principle of optimality**, rephrased for the minimization case. To Theorem 7.4.4 we can also add a statement that a min-oriented version of HPI converges in finite time; in the interests of brevity, we leave such details aside. Given our preceding work on anti-isomorphic ADPs, we will find that the proof of Theorem 7.4.4 is just a matter of finding the right anti-isomorphism.

Proof of Theorem 7.4.4. We take $\mathscr{A}$ as given and introduce a second ADP $\hat{\mathscr{A}}$ as follows. Let $\preceq$ be the partial order on V, so that $V = (V, \preceq)$, and let $\hat{V}$ be the partially ordered space $(\hat{V}, \hat{\preceq})$, where $\hat{V}$ is a copy of V and $\hat{\preceq}$ is the reversed partial order; that is, for $u, v \in \hat{V}$, we have $u \hat{\preceq} v$ in $\hat{V}$ if and only if $v \preceq u$ in V. Under this reversed partial order, the identity map I from V to $\hat{V}$ defined by $Iv = v$ is an anti-isomorphism. Now we define $\hat{\mathscr{A}}$ as $(\{\hat{T}_\sigma\}, \hat{V})$ where $\hat{V}$ is as just defined and $\hat{T}_\sigma = T_\sigma = I \circ T_\sigma \circ I^{-1}$ for all σ.

By construction, $\mathscr{A}$ and $\hat{\mathscr{A}}$ are anti-isomorphic under the I. From Theorem 7.4.2, we obtain $T = \hat{S}$ and $S = \hat{T}$ on V, while $\hat{u}^* = v^*$ and $\hat{v}^* = u^*$. Since $\hat{v}^*$ is the unique fixed point of $\hat{T}$, it follows that u^* is the unique fixed point of S. This proves claim (i).

Regarding claim (ii), Theorem 7.4.2 tells us that that σ is min-optimal for $\mathscr{A}$ if and only if σ is max-optimal for $\hat{\mathscr{A}}$; which is in turn true if and only if it $\hat{T}_\sigma \hat{v}^* = \hat{v}^*$. From the above identities, this is the same statement as $T_\sigma u^* = u^* = Su^*$, which is equivalent to the statement that σ is u^*-min-greedy.

Regarding (iii), since u^* has at least one min-greedy policy, a min-optimal policy exists. □

7.4.3 Application: Negative Discount Rate Optimality

When discussing MDPs we used β to represent the discount factor. Given β, the **discount rate** or **rate of time preference** is the value ρ that solves $\beta = 1/(1+\rho)$. The standard MDP assumption $\beta < 1$ implies this rate is positive. You will recall from Chapter 6 that the condition $\beta < 1$ is essential to the general theory of MDPs, since it yields global stability of the Bellman and policy operators on $\mathbb{R}^{\mathsf{X}}$ (via the Neumann series lemma or Banach's fixed point theorem).

But behavior consistent with positive discount rates is not universal. For example, negative rates of time preference are commonly inferred when people face unpleasant tasks. Subjects of studies often prefer getting such tasks "over and done with" rather than postponing them. (Negative discount rates are inferred in other settings as well. §7.5 provides background and references.)

In this section, we model optimal choice under a zero or negative discount rate. Taking our cue from the discussion above, we consider a scenario where a task generates disutility but has to be completed. In particular, we assume that

$$B(x, x', v) = c(x, x') + \beta v(x') \qquad (x, x' \in \mathsf{X}) \tag{7.49}$$

where X is a finite set and β is some positive constant. We take X to be both the state and action space, so the action is choosing a feasible next-period state. The function c

gives the cost of transitioning from x to the new state x' and we assume that $c(x, x') > 0$ when $x \neq x'$ and $c(x, x) = 0$ for all x.

(If c is understood as utility rather than cost, then (7.49) generalizes the cake eating problem in Example 7.1.1.)

There are several different interpretations we can give this problem. To focus on one, let's consider the problem of optimal traversal of a network, along the lines of the shortest path problem considered in Example 7.1.7. To repeat, the problem is to traverse a directed graph $\mathscr{G} = (\mathsf{X}, E)$, where X is the vertices of the graph and E is the edges (intuitively, $(x, x') \in E$ means that there exists an "arrow" from x to x'). The aim is to find the minimum cost path from given x to a specified destination node d.

Letting $\mathscr{O}(x) := \{y \in \mathsf{X} : (x, y) \in E\}$ be the direct successors of x, we define the feasible correspondence Γ by setting $\Gamma(x)$ to be all x' such that

$$x' \in \mathscr{O}(x), \qquad x' \neq x, \quad \text{and} \quad c(x, x') + \beta c(x', d) \leqslant c(x, d).$$

The first condition is just feasibility. The second and third conditions are restict choices to "rational" decisions: the first says that the controller cannot stay still, while the second says that the controller should not move to d in two steps when doing so is more costly than moving there in one. The latter two restrictions narrow down the policy space and help us solve the problem even when the discount rate is negative.

We can frame this problem as an RPD $\mathscr{R} = (\Gamma, B, V)$ with Γ, B as just described and

$$V := [v_1, v_2] \quad \text{where} \quad v_1(x) := 0 \quad \text{and} \quad v_2(x) := c(x, d). \tag{7.50}$$

Here is our main result for this section.

Proposition 7.4.5. *$\mathscr{R}$ is a concave RDP.*

It follows that $\mathscr{R}$ is stable and the fundamental optimality results apply (see Proposition 7.2.8). For example, from Theorem 7.4.4, we see that the min-value function u^* is the unique solution to

$$u^*(x) = \min_{x' \in \Gamma(x)} \{c(x, x') + \beta u^*(x')\}$$

in V and a policy $\sigma \in \Sigma$ is min-optimal if and only if

$$\sigma(x) \in \operatorname*{argmin}_{x' \in \Gamma(x)} \{c(x, x') + \beta u^*(x')\}$$

for all $x \in \mathsf{X}$. Notice that, in line with zero or negative discounting, Proposition 7.4.5 permits $\beta \geqslant 1$.

Proof of Proposition 7.4.5. We must first check that $\mathscr{R}$ is an RDP. The only nontrivial assertion is consistency, in the sense that $v_1 \leqslant T_\sigma v \leqslant v_2$ for all $\sigma \in \Sigma$ and all $v \in V$ (this is condition (7.3)). Since T_σ is order-preserving, it suffices to show that $T_\sigma v_1 \geqslant v_1$ and $T_\sigma v_2 \leqslant v_2$. Since $v_1 = 0$, the first inequality is obvious. Regarding the second, fix $\sigma \in \Sigma$ and $x \in \mathsf{X}$. Observe that, by the definition of v_2 and Γ in (7.50),

$$(T_\sigma v_2)(x) = c(x, x') + \beta c(x', d) \leqslant c(x, d) = v_2(x),$$

so $T_\sigma v_2 \leqslant v_2$ is confirmed.

Now we show that $\mathscr{R}$ is also concave. For this we must confirm the concavity property (7.34) on page 237, but this is obvious because our aggregator B in (7.49) is linear in v. We also need to confirm (7.35) on page 237, which, since $v_1 = 0$, reduces to showing existence of a $\delta > 0$ such that $B(x, x', v_1) \geqslant \delta v_2(x)$ for all $(x, x') \in \mathsf{G}$, or, equivalently,

$$c(x, x') \geqslant \delta c(x, d) \text{ for all } (x, x') \in \mathsf{G}. \tag{7.51}$$

To this end, let

$$\delta := \min \left\{ \frac{c(x, x')}{c(x, d)} \ : \ x' \in \Gamma(x) \text{ and } x \neq d \right\}$$

Fix $x \in \mathsf{X}$ and $x' \in \Gamma(x)$. For $x = d$ (7.51) is trivial, since $c(d, d) = 0$. For $x \neq d$ we have $c(x, x') \geqslant \delta c(x, d)$ by the definition of δ, so (7.51) is confirmed for all x. This concludes the proof that $\mathscr{R}$ is a concave RDP. □

Remark 7.4.1. With $\beta = 1$, the argument above provides a new proof of the traditional shortest path problem introduced in Example 7.1.7.

7.4.4 Epstein–Zin Revisited

In this section we return to the Epstein–Zin specification previously treated in §7.1.2.4. Our main purpose is to show that the original model is either isomorphic or anti-isomorphic to a simpler and more tractable model. This observation simplifies analysis and increases numerical stability when we come to computation.

Our specification will be as in Example 7.1.4, with

$$B(x, a, v) = \left\{ r(x, a) + \beta \left(\sum_{x'} v(x')^\gamma P(x, a, x') \right)^{\alpha/\gamma} \right\}^{1/\alpha}, \tag{7.52}$$

As before, $r_1 := \min r$ and $V = \mathbb{M}^{\mathsf{X}}$ where $\mathbb{M}$ is the real interval $\mathbb{M} = [m_1, m_2]$ with as defined in §4.3.3.2.

Assumption 7.4.1. The parameters obey $\min r > 0$, $0 < \beta < 1$ and $\gamma < 0 < \alpha < 1$.

Letting Γ be an arbitrary feasible correspondence, we know from Exercise 7.1.2 that (Γ, V, B) is a well-defined RPD. Now we introduce another RPD that will be simpler to analyze. We set

$$\hat{B}(x, a, v) = B\left(x, a, v^{1/\gamma}\right)^{\gamma} \tag{7.53}$$

Let $\hat{\mathbb{M}} := \mathbb{M}^{\gamma}$ be all m^{γ} where $m \in \mathbb{M}$. Let $\hat{V} := \hat{\mathbb{M}}^{\mathsf{X}}$ and let $\hat{\mathscr{R}} = (\Gamma, \hat{B}, \hat{V})$.

Lemma 7.4.6. *$\mathscr{R} = (\Gamma, B, V)$ and $\hat{\mathscr{R}} = (\Gamma, \hat{B}, \hat{V})$ are anti-isomorphic.*

Proof. The map $\varphi(m) = m^{\gamma}$ is a homeomorphism from $\mathbb{M}$ to $\hat{\mathbb{M}}$ and (7.48) holds under φ. Since $\gamma < 0$, the claim now follows from Proposition 7.4.3. □

Hence, to solve $\mathscr{R}$, we can show that $\hat{\mathscr{R}}$ is stable (which implies that $\mathscr{R}$ is stable, by Proposition **??**) and then solve $\hat{\mathscr{R}}$. Any min-optimal policy for $\hat{\mathscr{R}}$ will be max-optimal for $\mathscr{R}$ (Theorem 7.4.2).

Lemma 7.4.7. *$\hat{\mathscr{R}}$ is a concave RPD.*

Proof. To see this, fix $(x, a) \in \mathsf{G}$ and observe that

$$\hat{B}(x, a, w) = \left\{ r(x, a) + \beta \left(\sum_{x'} w(x') P(x, a, x') \right)^{1/\theta} \right\}^{\theta} = f(\ell(w)),$$

where

$$\theta := \frac{\gamma}{\alpha}, \qquad F(t) := \left\{ r(x, a) + \beta t^{1/\theta} \right\}^{\theta}, \qquad \text{and } \ell(w) := \sum_{x'} w(x') P(x, a, x').$$

Since $\gamma < 0 < \alpha$, we have $\theta < 0$. You showed in Exercise 4.3.8 on page 128 that $F'(t) > 0$ and $F''(t) < 0$ for all $t > 0$. Also, ℓ is order-preserving and linear. Hence $f \circ \ell$ is order-preserving and concave. In other words, $w \mapsto \hat{B}(x, a, w)$ is concave for each fixed $(x, a) \in \mathsf{G}$.

Moreover, $\hat{V} = [w_1, w_2]$ where $w_1 = v_2^{\gamma} = m_2^{\gamma} \mathbb{1}$ with

$$m_2 := \left(\frac{2r_2}{1 - \beta} \right)^{1/\alpha}.$$

so

$$\hat{B}(x, a, w_1) = \left\{ r(x, a) + \beta \frac{2r_2}{1 - \beta} \right\}^{\theta} \geqslant \left\{ r_2 + \beta \frac{2r_2}{1 - \beta} \right\}^{\theta} > \left\{ \frac{2r_2}{1 - \beta} \right\}^{\theta} = m_2^{\gamma}.$$

In other words, $\hat{B}(x, a, w_1) > w_1$ for all $(x, a) \in \mathsf{G}$. Hence $(\Gamma, \hat{V}, \hat{B})$ is a concave RPD. □

7.5 Chapter Notes

This chapter draws on the excellent textbook by Bertsekas (2022b), who in turn credits Mitten (1964) as the first research paper to frame Richard Bellman's dynamic programming problems in an abstract setting. Related contemporaneous publications include Denardo and Mitten (1967) and Denardo (1967). Our central optimality results from this chapter (Theorem 7.3.1 and Theorem 7.1.1) appear to be new, although closely related results appear in Bertsekas (2022b) and other sources.

An algorithm that we neglected to discuss is stochastic gradient descent (or ascent) in policy space. Typically policies are parameterized an approximation architecture that consists of basis functions, activation functions, and compositions of them (e.g., a neural network). In large models, such approximation is used even when the state and action spaces are finite, simply because the curse of dimensionality makes exact representations infeasible. For recent discussions of gradient descent in policy spaces see Nota and Thomas (2019), Mei et al. (2020), and Bhandari and Russo (2022).

Dynamic programming with state state-dependent discounting is now common in macroeconomics and finance. Representative examples include Krusell and Smith (1998), Woodford (2011), Albuquerque et al. (2016), Saijo (2017), Schorfheide et al. (2018), Hills et al. (2019), Fagereng et al. (2019), Hubmer et al. (2020) and Cao (2020). For more on the theory of state-dependent discounting, see Jasso-Fuentes et al. (2020) or Stachurski and Zhang (2021).

Another challenge to the standard model with constant discount rates comes from empirical and experimental studies that find evidence of "hyperbolic discounting," where valuations across time fall rapidly at first and then more slowly. Thoughtful reviews of hyperbolic and quasi-hyperbolic discounting can be found in Frederick et al. (2002) and Rubinstein (2003). Cao and Werning (2018) provide conditions under which predictions from optimal savings models with quasi-hyperbolic discounting are robust. Balbus et al. (2018) analyze uniqueness of time-consistent stationary Markov policies for quasi-hyperbolic households under uncertainty. Balbus et al. (2022) study equilibria in dynamic models with recursive payoffs and generalized discounting. Noor and Takeoka (2022) addresses the topic of optimal discounting.

Al-Najjar and Shmaya (2019) study the connection between Epstein–Zin utility and parameter uncertainty.

Ruszczyński (2010) considers risk averse dynamic programming and time consistency.

The optimal default application in §7.2.1.4 is loosely based on Arellano (2008). Influential contributions to this line of work include, Yue (2010), Chatterjee and Eyigungor (2012), Arellano and Ramanarayanan (2012), Cruces and Trebesch (2013), Ghosh et al. (2013), Gennaioli et al. (2014), and Bocola et al. (2019).

As for negative discounting, Loewenstein and Sicherman (1991) found that the majority of workers they surveyed reported a preference for increasing wage profiles over decreasing ones that yield the same undiscounted sum, even when it was pointed out that the latter could be used to construct a dominating consumption sequence. Loewenstein and Prelec (1991) obtained similar results. In summarizing their study, they argue that, in the context of the choice problems they examined, "sequences of outcomes that decline in value are greatly disliked, indicating a negative rate of time preference" (Loewenstein and Prelec, 1991, p. 351).

Part I

Appendices

Appendix A

Suprema and Infima

This section of the appendix contains an extremely brief review of basic facts concerning sets, functions, suprema and infima. We recommend Bartle and Sherbert (2011) for those who wish to learn more.

A.1 Sets and Functions

A **set** is a collection of objections viewed as a whole. Examples include the set of **natural numbers** $\mathbb{N} := \{1, 2, \ldots\}$ and $[n] := \{1, 2, \ldots, n\}$ when $n \in \mathbb{N}$. The set that contains no elements is called the **empty set** and denoted by $\emptyset$. A set X is called **finite** if we can write $\mathsf{X} = \{x_1, \ldots, x_n\}$ for some $n \in \mathbb{N}$. Note that, according to our definition, every finite set is automatically nonempty.

A **function** f from set A to set B, written $A \ni x \mapsto f(x) \in B$ or $f\colon A \to B$, is a rule associating to each and every element a in A one and only one element $b \in B$. The point b is also written as $f(a)$, and called the **image** of a under f. For $C \subset A$, the set $f(C)$ is the set of all images of points in C, and is called the image of C under f. Also, for $D \subset B$, the set $f^{-1}(D)$ is all points in A that map into D under f, and is called the **preimage** of D under f.

Given a set S and $A \subset S$, we define $S \ni x \mapsto \mathbb{1}_A(x) \in \{0, 1\}$ to be the function that takes the value 1 when $x \in A$ and zero otherwise. This function is called the **indicator function** of A.

A function $f\colon A \to B$ is called **one-to-one** if distinct elements of A are always mapped into distinct elements of B, and **onto** if every element of B is the image under f of at least one point in A. A **bijection** or **one-to-one correspondence** from A to B is a function f from A to B that is both one-to-one and onto.

If $f\colon A \to B$ and $g\colon B \to C$, then the **composition** of f and g is the function $f \circ g$ from A to C defined at $a \in A$ by $(f \circ g)(x) := g(f(a))$.

A.2 Sup, Inf, Max and Min

Given a subset A of $\mathbb{R}$, we call $u \in \mathbb{R}$ an **upper bound** of A if $a \leqslant u$ for all a in A. Let $U(A)$ be the set of all upper bounds of A. An element $\bar{u}$ of $\mathbb{R}$ is called a **supremum** or **least upper bound** of A if

(i) $\bar{u} \in U(A)$ and

(ii) $\bar{u} \leqslant u$ for every $u \in U(A)$.

Example A.2.1. For the set $I := [0,1] \subset \mathbb{R}$, the number 1 is an upper bound of I. Moreover, for if u is an upper bound of I, then $u \geqslant 1$. Hence 1 is the supremum of I.

Example A.2.2. $\mathbb{N}$ has no supremum in $\mathbb{R}$, since the set of upper bounds is empty.

Exercise A.2.1. Show that, for all of the sets $(0,1)$, $[0,1)$ and $(0,1]$, the number 1 is the supremum of the set.

Exercise A.2.2. Fix $A \subset \mathbb{R}$. Prove that, for $s \in U(A)$, we have $s = \sup A$ if and only if, for all $\varepsilon > 0$, there exists a point $a \in A$ with $a > s - \varepsilon$.

Exercise A.2.3. Fix $A \subset \mathbb{R}$. Prove that A has at most one supremum.

One of the most important properties of $\mathbb{R}$ is stated below.

Theorem A.2.1 (Least upper bound property)**.** *Every nonempty subset of $\mathbb{R}$ with an upper bound in $\mathbb{R}$ has a supremum in $\mathbb{R}$.*

Theorem A.2.1 is often taken as axiomatic in formal constructions the real numbers. (Alternatively, one may assume completeness of the reals and then prove Theorem A.2.1 using this property. See, e.g., Bartle and Sherbert (2011).)

For $A \subset \mathbb{R}$, a **lower bound** of A is any number ℓ such that $\ell \leqslant a$ for all $a \in A$. If $i \in \mathbb{R}$ is an lower bound for A and also satisfies $i \geqslant \ell$ for every lower bound ℓ of A, then i is called the **infimum** of A and we write $i = \inf A$. At most one such i exists, and every nonempty subset of $\mathbb{R}$ bounded from below has an infimum.

A number m contained in a subset A of $\mathbb{R}$ is called the **maximum** of A and we write $m = \max A$ if $a \leqslant m$ for every $a \in A$. It is called the **minimum** of A if $a \geqslant m$ for every $a \in A$.

Exercise A.2.4. Prove: If A is a finite subset of $\mathbb{R}$, then $\sup A = \max A$.

Exercise A.2.5. Show that, if A is a closed and bounded subset of $\mathbb{R}$, then A has both a maximum and a minimum.

Exercise A.2.6. Prove the following statements:

(i) If $A \subset B$, then $\sup A \leqslant \sup B$.

(ii) If $s = \sup A$ and $s \in A$, then $s = \max A$.

(iii) If $i = \inf A$ and $i \in A$, then $i = \min A$.

Given an arbitrary set D and a function $f\colon D \to \mathbb{R}$, define

$$\sup_{x\in D} f(x) := \sup\{f(x) : x \in D\} \quad \text{and} \quad \max_{x\in D} f(x) := \max\{f(x) : x \in D\}$$

whenever the latter exists. A point $x^* \in D$ is called a

- **maximizer** of f on D if $x^* \in D$ and $f(x^*) \geqslant f(x)$ for all $x \in D$, and a
- **minimizer** of f on D if $x^* \in D$ and $f(x^*) \leqslant f(x)$ for all $x \in D$.

Equivalently, $x^* \in D$ is a maximizer of f on D if $f(x^*) = \max_{x\in D} f(x)$, and a minimizer if $f(x^*) = \min_{x\in D} f(x)$. We define

$$\operatorname*{argmax}_{x\in D} f(x) := \{x^* \in X : f(x^*) \geqslant f(x) \text{ for all } x \in D\}.$$

The set $\operatorname{argmin}_{x\in D} f(x)$ is defined analogously.

A **real sequence** is a map x from $\mathbb{N}$ to $\mathbb{R}$, with the value of the function at $k \in \mathbb{N}$ typically denoted by x_k rather than $x(k)$. A real sequence $x = (x_k)_{k\geqslant 1} := (x_k)_{k\in\mathbb{N}}$ is said to **converge** to $\bar{x} \in \mathbb{R}$ if, for each $\varepsilon > 0$, there exists an $N \in \mathbb{N}$ such that $|x_k - \bar{x}| < \varepsilon$ for all $k \geqslant N$. In this case we write $\lim_k x_k = x$ or $x_k \to x$ Bartle and Sherbert (2011) give an excellent introduction to real sequences and their basic properties.

Exercise A.2.7. Let (x_k) be a bounded monotone increasing sequence in $\mathbb{R}$. Prove that $\sup_k x_k = \lim_k x_k$.

A.3 Lattices

A.3.1 Suprema and Infima in Partially Ordered Sets

The definitions of suprema and infima on the real line in Appendix A extend naturally to partially ordered sets. For example, given a partially ordered set $(P, \preceq)$ and a nonempty subset A of P, we call $u \in P$ an **upper bound** of A if $a \preceq u$ for all a in A. An element $\bar{u}$ of P is called a **supremum** of A if

(i) $\bar{u}$ is an upper bound of A and

(ii) $\bar{u} \preceq u$ for every upper bound u of A.

If it exists, then

- the supremum of A is typically written as $\sup A$.
- If $A = \{a_i\}_{i \in I}$ for some index set I, we also write $\sup A$ as $\vee_i a_i$.
- If $A = \{a, b\}$, then $\sup A$ is also written as $a \vee b$.

Exercise A.3.1. Prove the following statements in the setting described above:

(i) If $\bar{u}$ is a supremum of A and $\bar{u} \in A$, then $\bar{u}$ is a greatest element (see §2.1.1.4) of A.

(ii) If g is a greatest element of A then $g = \sup A$.

We call $\ell \in P$ a **lower bound** of A if $a \succeq \ell$ for all a in A. An element $\bar{\ell}$ of P is called a **infimum** of A if $\bar{\ell}$ is an upper bound of A and $\bar{\ell} \succeq u$ for every upper bound ℓ of A. We use analogous notation to denote the infimum. For example, if $A = \{a, b\}$, then the infimum $\inf A$ is also written as $a \wedge b$.

Example A.3.1. Let M be a nonempty set and let $\wp(M)$ be the set of all subsets of M, partially ordered by $\subset$. Let $\{A_i\}_{i \in I}$ be a subset of $\wp(M)$, so that $A_i \in \wp(M)$ for each i in nonempty index set I. Then the supremum and infimum of $\{A_i\}_{i \in I}$ in $(\wp(M), \subset)$ are given by

$$\bigvee_i A_i = \bigcup_i A_i \quad \text{and} \quad \bigwedge_i A_i = \bigcap_i A_i$$

respectively. To see the former, observe that $A_j \subset \cup_i A_i$ for all $j \in I$. Hence $\cup_i A_i$ is an upper bound of $\{A_i\}$. Moreover, if $B \subset M$ and $A_j \subset B$ for all $i \in I$, then $\cup_i A_i \subset B$. This proves that $\cup_i A_i$ is the supremum. The proof of the infimum case is similar.

A.3.2 Suprema and the Pointwise Order

Let X be a nonempty set and V be a subset of $\mathbb{R}^{\mathsf{X}}$. We treat V as a partially ordered set, with partial order given by the pointwise order $\leqslant$. Let $\{f_i\} := \{f_i\}_{i \in I}$ be a finite collection of functions in V. As usual, we take $\vee_i f_i$ to be the pointwise maximum of the functions $\{f_i\}$ (see §1.2.1.5).

Lemma A.3.1. *In the setting described above, $\vee_i f_i$ is the supremum of $\{f_i\}$ in V whenever $\vee_i f_i \in V$.*

Proof. Suppose first that $\vee_i f_i \in V$. Then, under the pointwise order $\leqslant$, we have $f_i \leqslant \vee_i f_i$ for all $i \in I$ and $u \in V$. Hence $\vee_i f_i$ is an upper bound of $\{f_i\}$ in V. Moreover, if $u \in V$ and $u \geqslant f_i$ for all $i \in I$, then $u \geqslant \vee_i f_i$. Hence $\vee_i f_i$ is the supremum of $\{f_i\}$ in V, as claimed. □

One corollary of Lemma A.3.1 is that $\vee_i f$ is always the supremum of $\{f_i\}$ in $(\mathbb{R}^{\mathsf{X}}, \leqslant)$.

The discussion above also tells us that we can compute the supremum of a collection of vectors $\{u_i\} \subset \mathbb{R}^n$ by taking the pointwise maximum. Similarly, the infimum is obtained by taking the pointwise infimum.

Exercise A.3.2. Let X be any set and let $\mathbb{R}^{\mathsf{X}}$ have the pointwise order. Is it true that, for a finite subset $F := \{f_i\}_{i \in I}$ of $\mathbb{R}^{\mathsf{X}}$, the set F contains a greatest element.

Remark A.3.1. Lemma A.3.1 tells us that, for $f, g \in \mathbb{R}^{\mathsf{X}}$, the supremum $f \vee g$ is the pointwise maximum and $f \wedge g$ is the pointwise minimum. This agrees with the terminology and notation we introduced in §1.2.1.4.

A.3.3 Existence and Uniqueness

Let P be any partially ordered set and let A be a nonempty subset of P. The following uniqueness results are simple to verify:

Exercise A.3.3. Prove that A has at most one supremum and one infimum in P.

Existence of suprema and infima is less trivial in partially ordered sets than the totally ordered case. For example, we know that $A \subset \mathbb{R}$ has a supremum in $\mathbb{R}$ whenever A is bounded above (Theorem A.2.1). But now let $P = (0, 1)$, partially ordered by the usual order $\leqslant$. The set $A = [1/2, 1)$ is bounded above in $\mathbb{R}$ but has no supremum in P. Indeed, if $s = \sup A$, the $s \in P$ and $a \leqslant s$ for all $s \in A$. This is clearly impossible.

A.3.4 Lattices

A nonempty partially ordered set P is called a **lattice** if, given any two elements p and q of P, both $p \vee q$ and $p \wedge q$ exist in P.

Example A.3.2. As follows from the discussion in §A.3.2, if X is any nonempty set, then the set $\mathbb{R}^{\mathsf{X}}$ paired with the pointwise order $\leqslant$ is a lattice.

Example A.3.3. Let $C[a, b]$ be the set of all continuous functions from $[a, b] \subset \mathbb{R}$ to $\mathbb{R}$. The set $C[a, b]$ is a lattice when paired with the pointwise order. Indeed, given $f, g \in C[a, b]$, the functions $f \vee g$ and $f \wedge g$ are also continuous, and therefore lie in $C[a, b]$.

Example A.3.4. Consider the unit disc $D := \{v \in \mathbb{R}^2 : \|v\| \leqslant 1\}$ endowed with the usual pointwise order. Let $e_1 := (1, 0)$ and $e_2 := (0, 1)$ be the canonical basis vectors in $\mathbb{R}^2$. The set $\{e_1, e_2\}$ lies in D but has no upper bound in D. Hence D is not a lattice.

Exercise A.3.4. Let P be a lattice. Prove that $\wedge_i p_i$ and $\vee_i p_i$ are both in P whenever $\{p_i\}_{i \in I} \subset P$ and I is finite.

Appendix B

Remaining Proofs

Proof of Lemma 3.2.2. Regarding (i), fix $\varphi, \psi \in \mathscr{D}(\mathsf{X})$ with $\varphi \preceq_{\mathrm{F}} \psi$. Pick any $y \in \mathsf{X}$. By transitivity of partial orders, the function $u(x) := \mathbb{1}\{y \preceq x\}$ is in $i\mathbb{R}^{\mathsf{X}}$. Hence $\sum_x u(x)\varphi(x) \leqslant \sum_x u(x)\psi(x)$. Given the definition of u, this is equivalent to $G^{\varphi}(y) \leqslant G^{\psi}(y)$. As y was chosen arbitrarily, we have $G^{\varphi} \leqslant G^{\psi}$ pointwise on X.

Regarding (ii), let $\varphi, \psi \in \mathscr{D}(\mathsf{X})$ be such that $G^{\varphi} \leqslant G^{\psi}$ and let X be totally ordered by $\preceq$. We can write X as $\{x_1, \ldots, x_n\}$ with $x_i \preceq x_{i+1}$ for all i. Pick any $u \in i\mathbb{R}^{\mathsf{X}}$ and let $\alpha_i = u(x_i)$. By Exercise 3.2.11, we can write u as $u(x) = \sum_{i=1}^n s_i \mathbb{1}\{x \geqslant x_i\}$ at each $x \in \mathsf{X}$, where $s_i \geqslant 0$ for all i. Hence

$$\sum_{x \in \mathsf{X}} u(x)\varphi(x) = \sum_{x \in \mathsf{X}} \sum_{i=1}^n s_i \mathbb{1}\{x \geqslant x_i\}\varphi(x) = \sum_{i=1}^n s_i \sum_{x \in \mathsf{X}} \mathbb{1}\{x \geqslant x_i\}\varphi(x) = \sum_{i=1}^n s_i\, G^{\varphi}(x_i).$$

A similar argument gives $\sum_{x \in \mathsf{X}} u(x)\psi(x) = \sum_{i=1}^n s_i\, G^{\psi}(x_i)$. Since $G^{\varphi} \leqslant G^{\psi}$, we have

$$\sum_{x \in \mathsf{X}} u(x)\varphi(x) = \sum_{i=1}^n s_i\, G^{\varphi}(x_i) \leqslant \sum_{i=1}^n s_i\, G^{\psi}(x_i) = \sum_{x \in \mathsf{X}} u(x)\psi(x).$$

We conclude that $\varphi \preceq_{\mathrm{F}} \psi$, as was to be shown. □

Below we prove Theorem 4.1.2. We begin with the following result concerning expectations over products.

Lemma B.0.1. *For each $t \in \mathbb{N}$ and $x \in \mathsf{X}$, we have*

$$\mathbb{E}_x \left\{ \left[\prod_{i=1}^t B_i \right] h(X_t) \right\} = \sum_{x' \in \mathsf{X}} K^t(x, x') h(x'). \tag{B.1}$$

In the proof and remainder of this section, we set $H_t := h(X_t)$ for all t.

Proof. We verify the claim in Lemma B.0.1 using induction on t. The claim holds at $t = 1$ because, for any such h and x,

$$\mathbb{E}_x\left[B_1 H_1\right] = \sum_{x'} b(x, x')h(x')P(x, x') = \sum_{x'} K(x, x')h(x').$$

Now suppose it holds at t. We claim it also holds at $t + 1$. To show this we apply the law of iterated expectations to obtain

$$\mathbb{E}_x\left[B_1 \cdots B_{t+1} H_{t+1}\right] = \mathbb{E}_x\left[\mathbb{E}_t\left[B_1 \cdots B_{t+1} H_{t+1}\right]\right] = \mathbb{E}_x\left[B_1 \cdots B_t \mathbb{E}_t[B_{t+1} H_{t+1}]\right].$$

Since $\mathbb{E}_t B_{t+1} H_{t+1} = \sum_y b(X_t, y)h(y)P(X_t, y)$, we can now write

$$\mathbb{E}_x\left[B_1 \cdots B_{t+1} H_{t+1}\right] = \mathbb{E}_x\left[B_1 \cdots B_t f(X_t)\right] \quad \text{where} \quad f(x) := \sum_y K(x, y)h(y). \tag{B.2}$$

Applying the induction hypothesis (B.1) to the right-hand side of the first equation in (B.2) (with $h = f$), we now have

$$\mathbb{E}_x\left[B_1 \cdots B_{t+1} H_{t+1}\right] = \sum_{x'} K^t(x, x')f(x') = \sum_{x'} K^t(x, x') \sum_y K(x', y)h(y).$$

But $\sum_{x'} K^t(x, x')K(x', y) = K^{t+1}(x, y)$, so (B.1) holds at $t + 1$ as well. The proof is now complete. □

Now we can complete the proof of Theorem 4.1.2.

Proof of Theorem 4.1.2. We fix $x \in \mathsf{X}$ and use Lemma B.0.1 to obtain

$$v(x) = \mathbb{E}_x\left\{\sum_{t=0}^{\infty}\left[\prod_{i=1}^{t} B_i\right] H_t\right\} = \sum_{t=0}^{\infty} \mathbb{E}_x\left\{\left[\prod_{i=1}^{t} B_i\right] H_t\right\} = \sum_{t=0}^{\infty}(K^t h)(x). \tag{B.3}$$

Writing (B.3) pointwise gives, $v = \sum_{t \geqslant 0} K^t h$.[1] By the Neumann series lemma and $r(K) < 1$, this sum converges and equals $(I - K)^{-1}h$. The recursive expression (4.9) follows from $v = (I - K)^{-1}h$, since premultiplying both sides by $I - K$ gives $v = h + Kv$. Finally, if w is an element of $\mathbb{R}^{\mathsf{X}}$ satisfying $w = h + Kw$, then, by the uniqueness component of the Neumann series lemma, $w = v$. In other words, v defined in (4.8) is the only function that satisfies the recursion (4.9). □

[1] In (B.3) we again passed expectations through an infinite sum. This operation takes some care but is valid under the assumption $r(K) < 1$. Footnote 1 on page 100 provides more information.

Appendix C

Solutions to Selected Exercises

Solution to Exercise 1.1.1. Here is one possible answer: On one hand, providing additional unemployment compensation is costly for taxpayers and tends to increase the unemployment rate. On the other hand, unemployment compensation encourages the worker to reject low initial offers, leading to a better lifetime wage. This can enhance worker welfare and expand the tax base. A larger model is needed to disentangle these effects.

Solution to Exercise 1.2.1. Fix α, s and t with $s \geqslant 0$. Suppose first that $\alpha \geqslant s + t$. Then $\alpha \vee (s + t) = \alpha \leqslant \alpha \vee t \leqslant s + \alpha \vee t$, as claimed. Suppose next that $\alpha \leqslant s + t$. Then $\alpha \vee (s + t) = s + t \leqslant s + \alpha \vee t$, as required.

Solution to Exercise 1.2.4. For $\alpha > 0$ we always have $\|\alpha u\|_0 = \|u\|_0$, which violates positive homogeneity.

Solution to Exercise 1.2.12. Let T and U be as stated in the exercise. Regarding uniqueness, suppose that T has two distinct fixed points u and y in U. Since $T^m u = \bar{u}$ and $T^m y = \bar{u}$, we have $T^m u = T^m y$. But u and y are distinct fixed points, so $u = T^m u$ must be distinct from $y = T^m y$. Contradiction.

Regarding the claim that $\bar{u}$ is a fixed point, we recall that $T^k u = \bar{u}$ for $k \geqslant m$. Hence $T^m \bar{u} = \bar{u}$ and $T^{m+1} \bar{u} = \bar{u}$. But then

$$T\bar{u} = TT^m \bar{u} = T^{m+1} \bar{u} = \bar{u},$$

so $\bar{u}$ is a fixed point of T.

Solution to Exercise 1.2.13. Assume the hypotheses of the exercise and let $u_m := T^m u$ for all $m \in \mathbb{N}$. By continuity and $u_m \to u^*$ we have $Tu_m \to Tu^*$. But the sequence (Tu_m) is just (u_m) with the first element omitted, so, given that $u_m \to u^*$, we must have $Tu_m \to u^*$. Since limits are unique, it follows that $u^* = Tu^*$.

Solution to Exercise 1.2.15. Let the stated hypotheses hold and fix $u \in C$. By global stability we have $T^k u \to u^*$. Since T is invariant on C we have $(T^k u)_{k\in\mathbb{N}} \subset C$. Since C is closed, this implies that the limit is in C. In other words, $u^* \in C$, as claimed.

Solution to Exercise 1.2.18. By the definition of the operator norm we have $\|Au\| \leqslant \|A\|_o \|u\|$ for all $u \in \mathbb{R}^n$. If $\|A\|_o < 1$, then T is a contraction of modulus $\|A\|_o$, since, for any $x, y \in U$,

$$\|Ax + b - Ay - b\| = \|A(x - y)\| \leqslant \|A\|_o \|x - y\|.$$

Solution to Exercise 1.2.18. By the definition of the derivative, for any $x \in U := (0, \infty)$, we have

$$\lim_{y\to x} \left| \frac{g(y) - g(x)}{y - x} - g'(x) \right| = 0.$$

Hence, by the reverse triangle inequality, for fixed $\varepsilon > 0$, we can take a $\delta > 0$ such that

$$\left| \frac{g(y) - g(x)}{y - x} \right| > |g'(x)| - \varepsilon = g'(x) - \varepsilon$$

for all $y \in (x - \delta, x + \delta)$. Rearranging gives

$$|g(x) - g(y)| > [g'(x) - \varepsilon]|x - y|$$

for all $y \in (x - \delta, x + \delta)$. But $g'(x) = s\alpha x^{\alpha-1} + 1 - \delta$, which converges to $+\infty$ as $x \to 0$. It follows that, for any $\lambda \in [0, 1)$, we can find a pair x, y such that $|g(x) - g(y)| > \lambda|x - y|$. Hence g is not a contraction map under $|\cdot|$.

Solution to Exercise 1.2.20. From the bound in Exercise 1.2.19, we obtain

$$\|u_m - u_k\| \leqslant \frac{\lambda^m}{1 - \lambda} \lambda^i \|u_0 - u_1\| \qquad (m, k \in \mathbb{N} \text{ with } m < k).$$

Hence (u_m) is Cauchy, as claimed.

Solution to Exercise 1.2.22. Let T_1, T_2 be contraction maps on U of modulus λ_1

and λ_2 respectively. Fix $u, v \in U$. We have

$$\|Tu - Tv\|_\infty = \|(T_1 u) \vee (T_2 u) - (T_1 v) \vee (T_2 v)\|_\infty = \max_i |\max_j (T_j u)_i - \max_j (T_j v)_i|,$$

where i ranges over $1, \ldots, n$ and where j ranges over $1, 2$. Applying Lemma 1.2.2 and reversing the order of maxima gives

$$\|Tu - Tv\|_\infty \leqslant \max_i \max_j |(T_j u)_i - (T_j v)_i| = \max_j \max_i |(T_j u)_i - (T_j v)_i|.$$

From the definition of the supremum norm and our assumptions on T_1, T_2, this becomes

$$\|Tu - Tv\|_\infty \leqslant \max_j \|T_j u - T_j v\|_\infty \leqslant \max_j \lambda_j \|u - v\|_\infty.$$

Hence T is a contraction of modulus $\lambda := \max_j \lambda_j$.

Solution to Exercise 1.3.1. Fix $\alpha, x, y \in \mathbb{R}$. We have $x = x - y + y \leqslant |x - y| + y$. Applying the result in Exercise 1.2.1 yields

$$\alpha \vee x \leqslant |x - y| + \alpha \vee y \quad \iff \quad \alpha \vee x - \alpha \vee y \leqslant |x - y|.$$

Reversing the roles of x and y completes the proof.

Solution to Exercise 2.1.3. Let $M = \{1, 2\}$, let $A = \{1\}$ and let $B = \{2\}$. Then $A \subset B$ and $B \subset A$ both fail. Hence $\subset$ is not a total order on $\wp(M)$.

Solution to Exercise 2.1.6. Just set $\mathsf{X} = [n] \times [k]$.

Solution to Exercise 2.1.7. Let $I_f := [f_1, f_2]$ and $I_g := [g_1, g_2]$. Consider the order interval $I := [f_1 \wedge g_1, f_2 \vee g_2]$. If $h \in I$, then $h \geqslant f_1 \wedge g_1$, so $h \geqslant f_1$ and $h \geqslant g_1$. A similar argument gives $h \leqslant f_2$ and $h \leqslant g_2$. Hence $h \in I_f \cap I_g$. Working in the other direction, it is not difficult to show that $h \in I_f \cap I_g$ implies $h \in I$. Hence $I = I_f \cap I_g$. In particular, $I_f \cap I_g$ is an order interval in $C[0, 1]$.

Solution to Exercise 2.1.8. Regarding the first claim, fix $B \in \mathbb{M}^{m \times k}$ with $b_{ij} \geqslant 0$ for all i, j. Pick any $i \in [m]$ and $u \in \mathbb{R}^k$. By the triangle inequality, we have $|\sum_j b_{ij} u_j| \leqslant \sum_j b_{ij} |u_j|$. Stacking these inequalities yields $|Bu| \leqslant B|u|$, as was to be shown.

Regarding the second, let A and (u_k) be as stated, with $u_{k+1} \leqslant A u_k$ for all k. We aim to prove $u_k \leqslant A^k u_0$ for all k using induction. In doing so, we observe that $u_1 \leqslant A u_0$, so the claim is true at $k = 1$. Suppose now that it holds at $k - 1$. Then $u_k \leqslant$

$Au_{k-1} \leqslant AA^{k-1}u_0 = A^k u_0$, where the last step used nonnegativity of A and the induction hypothesis. The claim is now proved.

Solution to Exercise 2.1.9. Assume the stated conditions. Let $h := v - u$ and let a_{ij} be the i, j-th element of A. We have $h \geqslant 0$ and $h_j > 0$ at some j. Hence $\sum_j a_{ij} h_j > 0$. This says that every row of Ah is strictly positive. In other words $Ah = A(v - u) \gg 0$. The claim follows.

Solution to Exercise 2.1.10. Fix $a, b \in \mathbb{R}_+$ and $c \in \mathbb{R}_+$. By (2.1), we have

$$a \wedge c = (a - b + b) \wedge c \leqslant (|a - b| + b) \wedge c \leqslant |a - b| \wedge c + b \wedge c.$$

Thus, $a \wedge c - b \wedge c \leqslant |a - b| \wedge c$. Reversing the roles of a and b gives $b \wedge c - a \wedge c \leqslant |a - b| \wedge c$. This proves the claim in Exercise 2.1.10.

Solution to Exercise 2.1.11. We prove the claim concerning greatest elements: Suppose that g and g' are greatest elements of A. Then, since both are in A, we have $g \preceq g'$ and $g' \preceq g$. Hence, by asymmetry, $g = g'$.

Solution to Exercise 2.1.12. If $\{v_\sigma\}$ has a greatest element $\bar{v}$, then, since $\bar{v}$ is in the set $\{v_\sigma\}$ and dominates every other function, we have $\bar{v}(x) = \max_\sigma v(x)$ at all x. Hence $\bar{v}$ is the pointwise maximum.

Solution to Exercise 2.1.13. To see this, suppose first that $S \in \{A_i\}$. Since $A_j \subset \cup_i A_i =: S$ for all $j \in I$, the set S is a greatest element of $\{A_i\}$. Conversely, if S is not in $\{A_i\}$, then S is not a greatest element (since the definition directly requires that $S \in \{A_i\}$.

Solution to Exercise 2.1.15. Take $(f_k)_{k \geqslant 1}$ in $i\mathbb{R}^P$ and $f \in \mathbb{R}^P$ with $f_k \to f$ as $k \to \infty$. Since $f_k \to f$ we have $f_k(z) \to f(z)$ for all $z \in P$. (Norm convergence implies pointwise convergence.) Fix $x, y \in P$ with $x \preceq y$. From $(f_k) \subset i\mathbb{R}^P$ we have $f_k(x) \leqslant f_k(y)$ for all k. Since weak inequalities are preserved under limits, $f(x) \leqslant f(y)$. Hence $f \in i\mathbb{R}^P$.

Solution to Exercise 2.1.16. Let A and P be as stated. The claim that A^k is order-preserving on P holds at $k = 1$. Suppose now that it holds at k and fix $p, q \in P$ with $p \preceq q$. By the induction hypothesis and the fact that A is order-preserving, we have $AA^k p \preceq AA^k q$. Hence $A^{k+1} p \preceq A^{k+1} q$. We conclude that A^{k+1} is also order-preserving, as was to be shown.

Solution to Exercise 2.1.18. Fix an $n \times k$ matrix A with $A \geqslant 0$, along with $u, v \in \mathbb{R}^k$. We need to show that $u \leqslant v$ implies $Au \leqslant Av$ for any conformable vectors u, v. This holds because if $u \leqslant v$ we have $v - u \geqslant 0$, so $A(v - u) \geqslant 0$. But then $Av - Au \geqslant 0$, or $Au \leqslant Av$.

Solution to Exercise 2.1.19. Fix square A, B with $0 \leqslant A \leqslant B$. It follows from the rules of matrix multiplication that, for arbitrary nonnegative square matrices E, F, G with $F \leqslant G$, we have $EF \leqslant EG$ and $FE \leqslant GE$. Hence, if $A^k \leqslant B^k$ for some $k \in \mathbb{N}$, then $A^{k+1} = AA^k \leqslant BA^k \leqslant BB^k = B^{k+1}$. Thus, by induction, $A^k \leqslant B^k$ for all $k \in \mathbb{N}$, which verifies the first claim. Regarding the second, it is clear that for nonnegative matrices E, F with $E \leqslant F$ we have $\|E\|_\infty \leqslant \|F\|_\infty$. Hence $\|A^k\|_\infty \leqslant \|B^k\|_\infty$ for all $k \in \mathbb{N}$. Raising both sides to the power $1/k$ and applying Gelfand's lemma verifies $r(A) \leqslant r(B)$.

Solution to Exercise 2.1.20. Let P, S, T be as described in the exercise. We aim to show that $S^k \preceq T^k$ holds for all $k \in \mathbb{N}$. Clearly it holds for $k = 1$. If it also holds at $k - 1$, then, for any $u \in P$, we have $S^k u = SS^{k-1}u \leqslant ST^{k-1}u \leqslant TT^{k-1}u = T^k u$, where we used the induction hypothesis, the order-preserving property of S and the assumption that $S \preceq T$.

Solution to Exercise 2.1.23. Fix $\beta_1 \leqslant \beta_2$. Let g_1 and g_2 be the corresponding fixed point maps, as defined in (1.32). Since $\beta_1 \leqslant \beta_2$, we have $g_1(h) \leqslant g_2(h)$ for all $h \in \mathbb{R}_+$ and, in addition, g_2 is a contraction map (and hence globally stable), Proposition 2.1.2 applies. In particular, the fixed point h_1^* corresponding to β_1 is less than or equal to h_2^*, the fixed point corresponding to β_2.

Solution to Exercise 2.1.27. We begin with the concave case. Suppose there exists a $\delta > 0$ such that $T\varphi \geqslant \varphi + \delta(\psi - \varphi)$. Set $\delta' := \delta/(\delta + 1)$. Then $\delta' \in (0, 1)$ and $\delta' < \delta$, so $T\varphi \geqslant \varphi + \delta'(\psi - \varphi)$. In other words, if the bound holds at arbitrary positive δ, then it holds for some $\delta' \in (0, 1)$.

The case of convex T is similar.

Solution to Exercise 2.2.1. To show that $T = \Phi^{-1} \circ \hat{T} \circ \Phi$ holds, we can equivalently prove that $\Phi \circ T = \hat{T} \circ \Phi$. For $u \in \mathbb{R}$, we have $\Phi T u = \ln A + \alpha \ln u$ and $\hat{T}\Phi u = \ln A + \alpha \ln u$. Hence $\Phi \circ T = \hat{T} \circ \Phi$, as was to be shown.

Solution to Exercise 2.2.2. Let (U, T) and $(\hat{U}, \hat{T})$ be conjugate under Φ, with $\hat{T} \circ \Phi = \Phi \circ T$. The stated equivalence holds because

$$Tu = u \iff \Phi T u = \Phi u \iff \hat{T}\Phi u = \Phi u.$$

Solution to Exercise 2.2.3. From $\hat{T} = \Phi \circ T \circ \Phi^{-1}$ we have $\hat{T}^2 = \Phi \circ T \circ \Phi^{-1} \circ \Phi \circ T \circ \Phi^{-1} = \Phi \circ T^2 \circ \Phi^{-1}$ and, continuing in the same way (or using induction), $\hat{T}^k = \Phi \circ T^k \circ \Phi^{-1}$ for all $k \in \mathbb{N}$. Equivalently, $\hat{T}^k \circ \Phi = \Phi \circ T^k$ for all $k \in \mathbb{N}$. Hence, using continuity of Φ and Φ^{-1},

$$T^k u \to u^* \iff \Phi T^k u \to \Phi u^* \iff \hat{T}^k \Phi u \to \Phi u^*.$$

Solution to Exercise 2.2.5. Since $u_{k+1} = Tu_k$, we have

$$\frac{u_{k+1} - u^*}{u_k - u^*} = T'u^* + \frac{T''v}{2}(u_k - u^*).$$

Taking absolute values and using $u_k \to u^*$ confirms the linear rate claimed in the exercise.

Solution to Exercise 2.2.6. Let U be closed in $\mathbb{R}^n$, let T be a self-map on U and let T^k be a contraction. Let u^* be the unique fixed point of T^k. Fix $\varepsilon > 0$. We can choose m such that $\|T^{mk}Tu^* - u^*\| < \varepsilon$. Then

$$\|TT^{mk}u^* - u^*\| = \|Tu^* - u^*\| < \varepsilon.$$

Since ε was arbitrary we have $\|Tu^* - u^*\| = 0$, implying that u^* is a fixed point of T. The proof that $T^m u \to u^*$ for any u is left to the reader.

Solution to Exercise 3.1.1. Let A be as stated and let e be the right eigenvector in (3.1). Since e is nonnegative and nonzero, and since eigenvectors are defined only up to constant multiples, we can and do assume that $\sum_j e_j = 1$. From $Ae = r(A)e$ we have $\sum_j a_{ij}e_j = r(A)e_i$ for all i. Summing with respect to i gives $\sum_j \operatorname{colsum}_j(A)e_j = r(A)$. Since the elements of e are nonnegative and sum to one, $r(A)$ is a weighted average of the column sums. Hence the second pair of bounds in Lemma 3.1.2 holds. The remaining proof is similar (use the left eigenvector).

Solution to Exercise 3.1.2. Let P and Q be as stated. Evidently $PQ \geqslant 0$. Moreover, $PQ\mathbb{1} = P\mathbb{1} = \mathbb{1}$, so PQ is stochastic. That $r(P) = 1$ follows directly from Lemma 3.1.2. By the Perron–Frobenius theorem, there exists a nonzero, nonnegative row vector φ satisfying $\varphi P = \varphi$. Rescaling φ to $\varphi/(\varphi\mathbb{1})$ gives the desired vector ψ.

The final positivity and uniqueness claim is also by the Perron–Frobenius theorem, and its consequences for irreducible matrices. Indeed, if φ is another nonnegative vector satisfying $\varphi\mathbb{1} = 1$ and $\varphi P = \varphi$, then, by the Perron–Frobenius theorem, $\varphi = \alpha\psi$ for some $\alpha > 0$. But then $\alpha\psi\mathbb{1} = 1$ and $\psi\mathbb{1} = 1$, which gives $\alpha = 1$. Hence $\varphi = \psi$.

Solution to Exercise 3.1.3. Let P and ε have the stated properties. Fix $h \in \mathbb{R}^{\mathsf{X}}$. It suffices to show that for this arbitrary h we can find an $x \in \mathsf{X}$ such that $(Ph)(x) < h(x) + \varepsilon$. This is easy to verify, since, for $\bar{x} \in \operatorname{argmax}_{x \in \mathsf{X}} h(x)$ we have $(Ph)(\bar{x}) = \sum_{x'} h(x')P(\bar{x}, x') \leqslant h(\bar{x})$.

Solution to Exercise 3.1.4. It is straightforward to confirm that both columns of A sum to $1 + g$. As a result, with $\mathbb{1}^\top$ as a row vector of ones, we have

$$n_{t+1} = \mathbb{1}^\top x_{t+1} = \mathbb{1}^\top A x_t = (1+g)\mathbb{1}^\top x_t = (1+g)n_t,$$

as was to be shown.

Solution to Exercise 3.1.8. Let $X_t = x \in \mathsf{X}$, so that $X_{t+1} = \max\{x - D_{t+1}, 0\} + S\mathbb{1}\{x \leqslant s\}$. Evidently X_{t+1} is integer-valued and nonnegative. If $x \leqslant s$, then $X_{t+1} \leqslant \max\{s - D_{t+1}, 0\} + S \leqslant s + S$. Similarly, if $s < x \leqslant S + s$, then $X_{t+1} \leqslant \max\{x - D_{t+1}, 0\} \leqslant S + s$. The claim is verified.

Solution to Exercise 3.1.9. Let $x \in \mathsf{X}$ be the current state at time t and suppose first that $s < x$. The next period state X_{t+1} hits s with positive probability, since $\varphi(d) > 0$ for all $d \in \mathbb{Z}_+$. The state X_{t+2} hits $S + s$ with positive probability, since $\varphi(0) > 0$. From $S + s$, the inventory level reaches any point in $\mathsf{X} = \{0, \ldots, S + s\}$ in one step with positive probability. Hence, from current state x, inventory reaches any other state y with positive probability in three steps.

The logic for the case $x \leqslant s$ is similar and left to the reader.

Solution to Exercise 3.2.1. Fix $t \in \mathbb{N}$. Under the stated hypotheses, we have $X_t \stackrel{d}{=} \psi_0 P^t$ (see (3.10)). Hence

$$\mathbb{E}h(X_t) = \sum_{x'} h(x')\mathbb{P}\{X_t = x'\} = \sum_{x'} h(x')(\psi_0 P^t)(x') = \left\langle \psi_0 P^t, h \right\rangle.$$

Solution to Exercise 3.2.4. Assume P is positive with unique stationary distribution ψ^*. Since $r(P) = 1$, the last part of the Perron–Frobenius theorem tells us that $P^t \to e\,\varepsilon$ as $t \to \infty$, where e and ε are the dominant right and left eigenvectors, normalized such that $\langle e, \varepsilon \rangle = 1$. In this case we know ψ^* is the dominant left eigenvector and $\mathbb{1}$ is the dominant right eigenvector. Moreover, $\psi^* \in \mathscr{D}(\mathsf{X})$ yields $\langle \psi^*, \mathbb{1} \rangle = 1$. Hence, for any $\psi \in \mathscr{D}(\mathsf{X})$, we have

$$\psi P^t \to \psi \mathbb{1}\, \psi^* = \psi^* \quad \text{as} \quad t \to \infty.$$

Hence global stability holds, as claimed.

Solution to Exercise 3.2.8. Since we are conditioning on $X_t = x$, we can replace X_{t+1} with $\rho x + \nu\varepsilon_{t+1}$. The result then follows from $\mathbb{P}\{\alpha < \nu\varepsilon_{t+1} \leqslant \beta\} = F(\beta) - F(\alpha)$.

Solution to Exercise 3.2.11. Set $\alpha_k := u(x_k)$ for all k and $s_k := \alpha_k - \alpha_{k-1}$ with $\alpha_0 := 0$. Fix $x_j \in \mathsf{X}$. Then

$$\sum_{k=1}^{n} s_k \mathbb{1}\{x_j \geqslant x_k\} = \sum_{k=1}^{j} s_k = (\alpha_1 - \alpha_0) + (\alpha_2 - \alpha_1) + \ldots + (\alpha_j - \alpha_{j-1}) = \alpha_j.$$

In other words, $\sum_{k=1}^{n} s_k \mathbb{1}\{x_j \geqslant x_k\} = u(x_j)$. This completes the proofs.

Solution to Exercise 3.2.12. Fix $\varphi, \psi \in \mathsf{X}$ and suppose that $\varphi \preceq_{\mathrm{F}} \psi$. Let $u \in \mathbb{R}^{\mathsf{X}}$ be defined by $u(1) = 0$ and $u(2) = 1$. Then, by the definition of stochastic dominance, we have $\varphi(2) \leqslant \psi(2)$. Since $\varphi(1) = 1 - \varphi(2)$ and $\psi(1) = 1 - \psi(2)$, this inequality is equivalent to $\psi(1) \leqslant \varphi(1)$. Finally, suppose that $\psi(1) \leqslant \varphi(1)$ and fix $u \in i\mathbb{R}^{\mathsf{X}}$. Let $h = u(2) - u(1) \geqslant 0$. Then

$$\sum_x u(x)\varphi(x) = u(1)\varphi(1) + (u(1) + h)(1 - \varphi(1)) = u(1) + h(1 - \varphi(1)).$$

Similarly, $\sum_x u(x)\psi(x) = u(1) + h(1 - \psi(1))$. Since $h \geqslant 0$ and $\psi(1) \leqslant \varphi(1)$, we have $\sum_x u(x)\varphi(x) \leqslant \sum_x u(x)\psi(x)$. Thus, $\varphi \preceq_{\mathrm{F}} \psi$. This chain of implications proves the equivalences in the exercise.

Solution to Exercise 3.2.13. Suppose $f, g, h \in \mathscr{D}(\mathsf{X})$ with $f \preceq_{\mathrm{F}} g$ and $g \preceq_{\mathrm{F}} h$. Fixing $u \in i\mathbb{R}^{\mathsf{X}}$, we have

$$\sum_x u(x)f(x) \leqslant \sum_x u(x)g(x) \quad \text{and} \quad \sum_x u(x)g(x) \leqslant \sum_x u(x)h(x)$$

Hence $\sum_x u(x)f(x) \leqslant \sum_x u(x)h(x)$. Since u was arbitrary in $i\mathbb{R}^{\mathsf{X}}$, we are done.

Solution to Exercise 3.2.14. Using Exercise 3.2.8 and the definition of P, it can be shown that

$$G(x, x_k) := \sum_{j=k}^{n} P(x, x_j) = \mathbb{P}\{x_k - s/2 < X_{t+1} \,|\, X_t = x\}.$$

Rewriting the probability in terms of ε_{t+1}, we get

$$G(x, x_k) = \mathbb{P}\{\varepsilon_{t+1} > (x_k - s/2 - \rho x)/\sigma\}.$$

Since $\rho \geqslant 0$, we can now see that $x \leqslant y$ implies $G(x, x_k) \leqslant G(y, x_k)$ for all k, or, equivalently, $G(x, \cdot) \leqslant G(y, \cdot)$ pointwise on X. By Lemma 3.2.2, this is equivalent to the statement that $P(x, \cdot) \preceq_{\mathrm{F}} P(y, \cdot)$, which confirms that P is monotone increasing.

Solution to Exercise 3.2.15. This matrix P_w is monotone increasing if and only if $(1 - \alpha, \alpha) \preceq_{\mathrm{F}} (\beta, 1 - \beta)$. From Exercise 3.2.12, we know that this is equivalent to $\beta \leqslant 1 - \alpha$, or $\beta + \alpha \leqslant 1$.

Solution to Exercise 3.2.16. Suppose that P is monotone increasing and fix $h \in i\mathbb{R}^{\mathsf{X}}$. We claim that $Ph \in i\mathbb{R}^{\mathsf{X}}$. To see this, pick any $x, y \in \mathsf{X}$ with $x \preceq y$. Since $x \preceq y$ we have $P(x, \cdot) \preceq_{\mathrm{F}} P(y, \cdot)$. Hence $\sum_{x'} h(x')P(x, x') \leqslant \sum_{x'} h(x')P(y, x')$. This shows that $Ph \in i\mathbb{R}^{\mathsf{X}}$.

To see the converse, suppose that P is invariant on $i\mathbb{R}^{\mathsf{X}}$. Fix $x, y \in \mathsf{X}$ with $x \preceq y$. We claim that $P(x, \cdot) \preceq_{\mathrm{F}} P(y, \cdot)$. To see this, fix $u \in i\mathbb{R}^{\mathsf{X}}$. $Pu \in i\mathbb{R}^{\mathsf{X}}$ by invariance, so $(Pu)(x) \leqslant (Pu)(y)$ and hence $\sum_{x'} u(x')P(x, x') \leqslant \sum_{x'} u(x')P(y, x')$. Since u was chosen arbitrarily from $i\mathbb{R}^{\mathsf{X}}$, we have $P(x, \cdot) \preceq_{\mathrm{F}} P(y, \cdot)$. Hence P is monotone increasing, as was to be shown.

Solution to Exercise 3.2.17. Clearly this is true for $t = 1$. Suppose it is also true for arbitrary t. Then, for any $h \in i\mathbb{R}^{\mathsf{X}}$, the function $P^t h$ is again in $i\mathbb{R}^{\mathsf{X}}$. From this it follow that $P^{t+1}h = PP^t h$ is also in $i\mathbb{R}^{\mathsf{X}}$, since P is monotone increasing. This proves that P^{t+1} is invariant on $i\mathbb{R}^{\mathsf{X}}$, and therefore monotone increasing.

Solution to Exercise 3.3.1. To show that T is a self-map on $V := \mathbb{R}_+^{\mathsf{W}}$, we just need to verify that $v \in V$ implies $Tv \in V$, which only requires us to verify that T maps nonnegative functions into nonnegative functions. This is clear from the definition. Regarding the order-preserving property, fix $f, g \in V$ with $f \leqslant g$. We claim that $Tf \leqslant Tg$. Indeed, if $w \in \mathsf{W}$, then $\sum_{w' \in \mathsf{W}} f(w')P(w, w') \leqslant \sum_{w' \in \mathsf{W}} g(w')P(w, w')$, which in turn implies that $(Tf)(w) \leqslant (Tg)(w)$. Since w was an arbitrary wage value, we have $Tf \leqslant Tg$, so T is order preserving.

Solution to Exercise 3.3.3. The code in Listing 10 creates a Markov chain via Tauchen approximation of an AR(1) process with positive autocorrelation parameter. By Exercise 3.2.14, P is monotone increasing. Hence, by Lemma 3.3.1, the value function is increasing. Since $h^* = c + \beta P v^*$, it follows that h^* is increasing. Regarding

intuition, positive autocorrelation in wages means that high current wages predict high future wages. It follows that the value of waiting for future wages rises with current wages.

Solution to Exercise 3.3.6. Let T be the operator on V such that $(Tv_u)(w)$ is the right-hand side of (3.27). To solve the exercise, it suffices to prove that T is a contraction map on V. (Then v_u can be obtained, in the limit, by applying successive approximation to T and, once the approximate fixed point is computed, v_e can be obtained via (3.26).) To show that T is a contraction, we let T_1 and T_2 be the operators on V defined by

$$(T_1 v)(w) = \frac{1}{1-\beta(1-\alpha)}\,(w + \alpha\beta(Pv)(w)) \quad \text{and} \quad (T_2 v)(w) = c + \beta\,(Pv)(w).$$

Since $Tv = (T_1 v) \vee (T_2 v)$, Exercise 1.2.22 on page 26 tells us that T will be a contraction provided that T_1 and T_2 are both contraction maps. For the case of T_2, we have

$$\|T_2 f - T_2 g\|_\infty = \max_w |c + \beta\,(Pf)(w) - c - \beta\,(Pg)(w)| \leqslant \max_w \beta \sum_{w'} |f(w') - g(w')| P(w, w').$$

The last term is dominated by $\beta\|f - g\|_\infty$, so T_2 is a contraction. The proof for T_1 is similar in spirit and hence left to the reader.

Solution to Exercise 4.1.1. Let π and P satisfy the stated conditions. By Exercise 3.2.17, P^t is monotone increasing for all t. By this fact and the assumption $\pi \in i\mathbb{R}^{\mathsf{X}}$, we see that $P^t\pi \in i\mathbb{R}^{\mathsf{X}}$ for all t. Hence $v = \sum_{t\geqslant 0} \beta^t P^t \pi$ is also increasing.

Solution to Exercise 4.1.3. Both u and $\exp$ are increasing on X, so r is in $i\mathbb{R}^{\mathsf{X}}$. Since $\rho \geqslant 0$, the stochastic matrix P is monotone increasing (see §3.2.4.3). Clearly βP shares this property. It follows that $\beta P r \in i\mathbb{R}^{\mathsf{X}}$. Applying βP again, we have $(\beta P)^2 r \in i\mathbb{R}^{\mathsf{X}}$. Continuing in this way, we see that $(\beta P)^k r$ is increasing for all k. Hence $\sum_{k\geqslant 0}(\beta P)^k r$ is increasing. By the Neumann series lemma, this sum is equal to v, so $v \in i\mathbb{R}^{\mathsf{X}}$.

Solution to Exercise 4.1.4. Proposition 4.1.3 follows directly from Theorem 4.1.2 when $B_t = b(X_{t-1}, X_t) = \beta(X_{t-1})$ and $h = \pi$.

Solution to Exercise 4.2.3. Under a cum-dividend contract, purchasing at t and selling at $t+1$ pays $D_t + \Pi_{t+1}$. Hence, applying the fundamental asset pricing equation,

the time t price Π_t of the contract must satisfy

$$\Pi_t = D_t + \mathbb{E}_t M_{t+1} \Pi_{t+1}. \tag{4.22}$$

Proceeding as for the ex-dividend contract, the price conditional on current state x is $\pi(x) = d(x) + \sum_{x'} m(x, x')\pi(x')P(x, x')$. In vector form, this is $\pi = d + A\pi$. Solving out for prices gives $\pi^* = (I - A)^{-1}d$.

Solution to Exercise 4.2.5. We seek a v that solves

$$v(x) = \sum_{x' \in \mathsf{X}} [1 + v(x')] \, A(x, x') \qquad (x, x' \in \mathsf{X}).$$

Treating A as a matrix and v as a column vector, this equation becomes $v = A\mathbb{1} + Av$, where $\mathbb{1}$ is a column vector of ones. By the Neumann series lemma, $r(A) < 1$ implies that this equation has the unique solution $v^* = (I - A)^{-1}A\mathbb{1}$. By the same lemma, v^* has the alternative representation $v^* = \sum_{t \geqslant 0} A^t(A\mathbb{1}) = \sum_{t \geqslant 1} A^t \mathbb{1}$.

Solution to Exercise 4.3.1. Fixing t, rearranging $v^* = (I - \beta P)^{-1}r$ to $v^* = r + \beta P v^*$ and evaluating at X_t gives

$$\begin{aligned} V_t^* = v^*(X_t) &= r(X_t) + \beta \sum_{x'} v^*(x')P(X_t, x') \\ &= u(C_t) + \beta \mathbb{E}[v^*(X_{t+1}) \mid X_t] = u(C_t) + \beta \mathbb{E}_t V_{t+1}^*. \end{aligned}$$

Hence $(V_t^*)_{t \geqslant 0}$ obeys (4.30), as claimed.

Solution to Exercise 4.3.8. This can be confirmed by showing that $F' > 0$ and $F'' < 0$ on $(0, \infty)$. Details are left to the reader.

Solution to Exercise 4.3.13. It is not difficult to show that $(A_c/A_y) = ((1 - \beta)/\beta)(y/c)^{1-\alpha}$. Taking logs and rearranging gives $\ln(y/c) = (1/(1-\alpha)) \ln(A_c/A_y) + k$, where k is a constant. Using the definition in the exercise yields EIS $= 1/(1 - \alpha)$.

Solution to Exercise 5.1.1. Pointwise on X we have $1 - \sigma \leqslant 1$, so $P_\sigma \leqslant P$. By Exercise 2.1.19 on page 48, we then have $r(P_\sigma) \leqslant r(P) = 1$. Hence $r(\beta P_\sigma) = \beta \, r(P_\sigma) \leqslant \beta < 1$.

Solution to Exercise 5.1.2. Fix $\sigma \in \Sigma$. If $f, g \in \mathbb{R}^{\mathsf{X}}$, $f \leqslant g$ and $x \in \mathsf{X}$, then

$$\begin{aligned}(T_\sigma g)(x) - (T_\sigma f)(x) &= (1 - \sigma(x))\beta \sum_{x' \in \mathsf{X}} g(x')P(x, x') - \beta \sum_{x' \in \mathsf{X}} f(x')P(x, x') \\ &= (1 - \sigma(x))\beta \sum_{x' \in \mathsf{X}} (g(x') - f(x'))P(x, x').\end{aligned}$$

Since $g(x') \geqslant f(x')$ for all x' this expression is nonnegative. Hence $(T_\sigma g)(x) \geqslant (T_\sigma f)(x)$ for all x.

Solution to Exercise 5.1.3. Fix $\sigma \in \Sigma$. Given $f, g \in \mathbb{R}^{\mathsf{X}}$ and $x \in \mathsf{X}$, we have

$$\begin{aligned}|(T_\sigma f)(x) - (T_\sigma g)(x)| &= \left| (1 - \sigma(x))\beta \sum_{x' \in \mathsf{X}} (g(x') - f(x'))P(x, x') \right| \\ &\leqslant \beta \left| \sum_{x'} [f(x') - g(x')]P(x, x') \right|.\end{aligned}$$

Applying the triangle inequality and $\sum_{x' \in \mathsf{X}} P(x, x') = 1$, we obtain

$$|(T_\sigma f)(x) - (T_\sigma g)(x)| \leqslant \beta \sum_{x'} |f(x') - g(x')|P(x, x') \leqslant \beta \|f - g\|_\infty.$$

Taking the supremum over all x on the left hand side of this expression leads to

$$\|T_\sigma f - T_\sigma g\|_\infty \leqslant \beta \|f - g\|_\infty.$$

Since f, g were arbitrary elements of $\mathbb{R}^{\mathsf{X}}$, the contraction claim is proved.

Solution to Exercise 5.1.4. Fix $f, g \in \mathbb{R}^{\mathsf{X}}$ with $f \leqslant g$. Since $P \geqslant 0$, we have $Pf \leqslant Pg$. Hence $c + \beta Pf \leqslant c + \beta Pg$. As a result,

$$Tf = e \vee (c + \beta Pf) \leqslant e \vee (c + \beta Pg) = Tg.$$

Solution to Exercise 5.1.5. Take any f, g in $\mathbb{R}^{\mathsf{X}}$ and fix any $x \in \mathsf{X}$. Writing the

operators pointwise and applying the last result in Lemma 2.1.1 (page 44) gives

$$\begin{aligned}|Tf - Tg| &= |e \vee (c + \beta Pf) - e \vee (c + \beta Pg)| \\ &\leqslant |\beta Pf - \beta Pg| \\ &= \beta\, |P(f - g)| \\ &\leqslant \beta P\, |f - g|\,.\end{aligned}$$

(Here the last inequality uses the result in Exercise 2.1.8 on page 44.) Since $P \geqslant 0$ we have $P|f - g| \leqslant P\|f - g\|_\infty \mathbb{1} = \|f - g\|_\infty \mathbb{1}$, so

$$|Tf - Tg| \leqslant \beta \|f - g\|_\infty \mathbb{1}.$$

Taking the maximum on both sides gives $\|Tf - Tg\|_\infty \leqslant \beta \|f - g\|_\infty$. Since f, g were arbitrary elements of $\mathbb{R}^{\mathsf{X}}$, the contraction claim is verified.

Solution to Exercise 5.1.7. First observe that, since $v^* \geqslant w$ and T is order preserving, we have $v^* = Tv^* \geqslant Tw = s \vee (\pi + \beta Qw) = s \vee w$. From this we get $v^* \geqslant s \vee w$ and applying T to both sides gives $v^* \geqslant T(s \vee w)$.

Next, observe that

$$T(s \vee w) = s \vee (\pi + \beta Q(s \vee w)) \geqslant \pi + \beta Q(s \vee w) \gg \pi + \beta Qw = w$$

where the strict inequality is by Exercise 2.1.9 on page 44. We conclude that $v^* \geqslant T(s \vee w) \gg w$, as was to be shown.

Intuitively, the option to exit adds value to firms everywhere in the state space, since $Q \gg 0$ implies that the state can shift to a region of the state space where exit is optimal in a later period.

Solution to Exercise 5.1.8. For the model described, Bellman's equation takes the form

$$v(p) = \max \left\{ s,\ \max_{\ell \geqslant 0} \pi(\ell, p) + \beta \sum_{p'} v(p') Q(p, p') \right\}.$$

Straightforward calculus shows that maximized one-period profits are $\pi(p) = p^2/(4w)$. Hence the final expression is

$$v(p) = \max \left\{ s,\ \frac{p^2}{4w} + \beta \sum_{p'} v(p') Q(p, p') \right\}$$

Solution to Exercise 5.1.9. Fix $x, x' \in \mathsf{X}$ with $x \leqslant x'$. Since σ^* is binary, to show σ^* is decreasing it suffices to show that $\sigma^*(x) = 0$ implies $\sigma^*(x') = 0$. Hence we suppose that $\sigma^*(x) = 0$. This in turn implies that $e(x) < h^*(x)$. As $x \leqslant x'$, e is decreasing and h^* is increasing on X, we have $e(x') < h^*(x')$. Hence $\sigma^*(x') = 0$. We conclude that σ^* is decreasing on X, as claimed.

Solution to Exercise 5.1.11. The solution to Exercise 5.1.11 is similar to that of Exercise 5.1.9 and hence omitted.

Solution to Exercise 5.1.12. Either by manipulating Bellman's equation or appealing to (5.16) on page 152, we see that the continuation value operator is defined at $h \in \mathbb{R}^{\mathsf{Z}}$ by

$$(Ch)(z) = \pi(z) + \beta \sum_{z'} \int \max\{s', h(z')\} \varphi(s') \, \mathrm{d}s' Q(z, z') \qquad (z \in \mathsf{Z}).$$

The next period scrap value S_{t+1} is integrated out and the remaining function depends only on $z \in \mathsf{Z}$.

Solution to Exercise 5.1.13. Let φ_a and φ_b be as stated. For $i \in \{a, b\}$ and $h \in \mathbb{R}^{\mathsf{Z}}$, let

$$(C_i h)(z) = \pi(z) + \beta \sum_{z'} \int \max\{s', h(z')\} \varphi_i(s') \, \mathrm{d}s' Q(z, z').$$

Since, for each $z' \in \mathsf{Z}$, the function $s' \mapsto \max\{s', h(z')\}$ is increasing, we have

$$\sum_{z'} \int \max\{s', h(z')\} \varphi_a(s') \, \mathrm{d}s' Q(z, z') \leqslant \sum_{z'} \int \max\{s', h(z')\} \varphi_b(s') \, \mathrm{d}s' Q(z, z').$$

Hence $C_a h \leqslant C_b h$ for all $h \in \mathbb{R}^{\mathsf{Z}}$. As C_b is order-preserving and globally stable, Proposition 2.1.2 on page 49 implies that the fixed point of C_b dominates the fixed point of C_a. That is, $h_a^* \leqslant h_b^*$. But then, for any $z \in \mathsf{Z}$, we have $h_a^*(z) \leqslant h_b^*(z)$ and hence

$$\sigma_b^*(z) = \mathbb{1}\{s \geqslant h_b^*(z)\} \leqslant \mathbb{1}\{s \geqslant h_a^*(z)\} = \sigma_a^*(z).$$

The interpretation of $\sigma_b^* \leqslant \sigma_a^*$ is that firm exits at fewer states when the scrap value distribution is φ_b^*. This makes sense, since the current scrap value offer s is already known, while future offers are more promising under φ_b^* than φ_a^*. Hence continuing is more attractive.

Solution to Exercise 5.2.1. In view of (5.14), the continuation value opertor for this problem is

$$(Ch)(x) = -c + \beta \sum_{x'} \max\{\pi(x'), h(x')\} P(x, x') \qquad (x \in \mathsf{X}).$$

The monotonicity result for h^* follows from Lemma 5.1.5 on page 147.

Solution to Exercise 5.2.2. If (X_t) is IID with common distribution φ, then the continuation value h^* is constant; in particular, it is the unique solution to

$$h = -c + \beta \sum_{x'} \max\{\pi(x'), h(x')\} \varphi(x').$$

Since constant functions are (weakly) decreasing, Exercise 5.1.11 applies and σ^* is increasing. Intuitively, the value of waiting is independent of the current state, while the value of bringing the product to market is increasing in the current state. Hence, if the firm brings to the product to market in state x, then it should also do so at any $x' \geqslant x$.

Solution to Exercise 6.1.3. When $e = 0$, given the definitions for Γ, r and P stated in §6.1.1.3, Bellman's equation is

$$\begin{aligned} v(0, w) &= \max_{a \in \{0,1\}} \left\{ aw + (1-a)c + \beta \sum_{(e', w')} v(e', w') P[(0, w), a, (e', w')] \right\} \\ &= \max_{a \in \{0,1\}} \left\{ aw + (1-a)c + \beta \left[av(a, w) + (1-a) \sum_{w'} v(a, w') Q(w, w') \right] \right\}, \end{aligned}$$

where the second equation follows from (6.4). (You can see this by checking the cases $a = 0$ and $a = 1$.) Rearranging and using $v(1, w) = w/(1-\beta)$ now gives

$$v(0, w) = \max \left\{ \frac{w}{1-\beta}, c + \beta \sum_{w' \in \mathsf{W}} v(0, w') Q(w', w') \right\}. \tag{6.5}$$

This is Bellman's equation for an unemployed agent from the job search problem we saw previously on page 91.

Solution to Exercise 6.1.5. Fix $\sigma \in \Sigma$. It is obvious that T_σ is a self-map on $\mathbb{R}^{\mathsf{X}}$ and T_σ is clearly order-preserving, since $v \leqslant w$ implies $P_\sigma v \leqslant P_\sigma w$ and hence $T_\sigma v \leqslant T_\sigma w$.

Also, T_σ is a contraction of modulus β on $\mathbb{R}^{\mathsf{X}}$ under the supremum norm, since, for

any v, w in $\mathbb{R}^{\mathsf{X}}$ we have

$$\begin{aligned}|(T_\sigma v)(x) - (T_\sigma w)(x)| &= \beta \left| \sum_y P(x, \sigma(x), y) v(y) - \sum_y P(x, \sigma(x), y) w(y) \right| \\ &\leqslant \sum_y P(x, \sigma(x), y) \beta \ |v(y) - w(y)| \leqslant \beta \|v - w\|_\infty\end{aligned}$$

Taking the supremum over all $x \in \mathsf{X}$ yields the desired result. This contraction property combined with Banach's fixed point theorem implies that T_σ has a unique fixed point.

Now suppose that v is the unique fixed point of T_σ. Then $v = r_\sigma + \beta P_\sigma v$. But then $v = (I - \beta P_\sigma)^{-1} r_\sigma$. Hence $v = v_\sigma$. This establishes all claims in the lemma.

Solution to Exercise 6.1.8. Fix $v \in \mathbb{R}^{\mathsf{X}}$. Part (i) follows from the fact that $\Gamma(x)$ is finite and nonempty at each $x \in \mathsf{X}$. Hence we can select an element a_x^* from the argmax in the definition of a v-greedy policy at each x in X. The resulting policy is v-greedy. For part (ii) we need to show that $\sigma \in \Sigma$ is v-greedy if and only if

$$r(x, \sigma(x)) + \beta \sum_{x'} v(x') P(x, \sigma(x), x') = \max_{a \in \Gamma(x)} \left\{ r(x, a) + \beta \sum_{x'} v(x') P(x, a, x') \right\}$$

for all $x \in \mathsf{X}$. But this immediate from the definition.

Regarding part (iii), it follows from the definitions that $(T_\sigma v)(x) \leqslant (Tv)(x)$ for all $x \in \mathsf{X}$. Conversely, for any v-greedy $\sigma \in \Sigma$, we have $(T_\sigma v)(x) = (Tv)(x)$ for all x. Hence $Tv = \vee_\sigma T_\sigma v$, as was to be shown.

Solution to Exercise 6.1.9. Fix $v, w \in \mathbb{R}^{\mathsf{X}}$ and $x \in \mathsf{X}$. By Exercise 6.1.8 and Lemma 1.2.2, we have

$$\begin{aligned}|(Tv)(x) - (Tw)(x)| &= \left| \max_{\sigma \in \Sigma} (T_\sigma v)(x) - \max_{\sigma \in \Sigma} (T_\sigma w)(x) \right| \\ &\leqslant \max_{\sigma \in \Sigma} |(T_\sigma v)(x) - (T_\sigma w)(x)| = \|T_\sigma v - T_\sigma w\|_\infty.\end{aligned}$$

Applying contractivity of T_σ (Exercise 6.1.5), we get $\|Tv - Tw\|_\infty \leqslant \beta \|v - w\|_\infty$.

Solution to Exercise 6.1.10. Part (iii) of Proposition 6.1.1 implies (iv) because every $v \in \mathbb{R}^{\mathsf{X}}$ has at least one greedy policy (Exercise 6.1.8). In particular, at least one v^*-greedy policy exists.

Solution to Exercise 6.2.1. The Bellman operator is

$$(Tv)(x) = \max_{a \in \Gamma(x)} \left\{ \sum_{d \geqslant 0} (x \wedge d)\varphi(d) - ca - \kappa \mathbb{1}\{a > 0\} + \beta \sum_{d \geqslant 0} v(m(x-d)+a)\varphi(d) \right\} \tag{6.20}$$

This operator is a sup norm contraction mapping on $\mathbb{R}^{\mathsf{X}}$ because, in view of Lemma 1.2.2 on page 18, for any v, w in $\mathbb{R}^{\mathsf{X}}$,

$$\begin{aligned} |(Tv)(x)| - (Tw)(x)| &\leqslant \beta \max_{a \in \Gamma(x)} \left| \sum_{d \geqslant 0} \left[v(m(x-d)+a) - w(m(x-d)+a) \right] \varphi(d) \right| \\ &\leqslant \beta \max_{a \in \Gamma(x)} \sum_{d \geqslant 0} |v(m(x-d)+a) - w(m(x-d)+a)| \, \varphi(d) \end{aligned}$$

Since $\sum_{d \geqslant 0} \varphi(d) = 1$, it follows that, for arbitrary $x \in \mathsf{X}$,

$$|(Tv)(x) - (Tw)(x)| \leqslant \beta \|v - w\|_\infty$$

Taking the supremum over all $x \in \mathsf{X}$ yields the desired result.

Solution to Exercise 6.2.2. The stochastic kernel is

$$P(x, a, y) = \begin{cases} 0 & \text{if } y < a \\ (1-p)^x & \text{if } y = a \\ (1-p)^{x+a-y} p & \text{if } y > a \end{cases} \tag{6.23}$$

The middle case is obtained by observing that the next period state hits y when $y = a$ if and only if $D_{t+1} \geqslant x$ and then using the expression for the PMF of the geometric distribution.

Solution to Exercise 7.1.1. We only need to check that (Γ, V, B) satisfies the monotonicity condition (7.2) and the consistency condition (7.3). The monotonicity condition holds because β is nonnegative, so

$$w \leqslant v \quad \Longrightarrow \quad \sum_{x'} w(x')\beta(x, a, x')P(x, a, x') \leqslant \beta(x) \sum_{x'} v(x')\beta(x, a, x')P(x, a, x') \quad \text{for all } (x, a) \in \mathsf{G}.$$

The consistency condition (7.3) is trivial because V is all of $\mathbb{R}^{\mathsf{X}}$.

Solution to Exercise 7.1.4. Fix $\sigma \in \Sigma$. The claim that T_σ is a self-map on V follows immediately from the consistency condition in (7.3). The order-preserving property

follows from the monotonicity condition in (7.2).

Solution to Exercise 7.1.5. Fix $v \in V$ and consider the set $\{T_\sigma v\}_{\sigma\in\Sigma} \subset V$. We first show that $\{T_\sigma v\}_{\sigma\in\Sigma}$ contains a greatest element. Suppose that $\bar{\sigma}$ is v-greedy. If σ is any other policy, then

$$(T_\sigma v)(x) = B(x, \sigma(x), v) \leqslant (T_{\bar{\sigma}} v)(x) \quad \text{for all } x \in \mathsf{X}.$$

Hence $T_{\bar{\sigma}} v$ is a greatest element of $\{T_\sigma v\}_{\sigma\in\Sigma}$.

The proof that $\{T_\sigma v\}_{\sigma\in\Sigma}$ contains a least element is analogous, after replacing argmax with argmin.

Solution to Exercise 7.1.6. Fix $v \in V$. For any $\sigma \in \Sigma$ and $x \in \mathsf{X}$, we have

$$(Tv)(x) = \max_{a\in\Gamma(x)} B(x, a, v) = \max_{\sigma\in\Sigma} B(x, \sigma(x), v) = \max_{\sigma\in\Sigma} (T_\sigma v)(x).$$

Since x was chosen arbitrarily, we have confirmed that $Tv = \vee_{\sigma\in\Sigma} T_\sigma v$.

Solution to Exercise 7.1.7. Here's a proof for T: The statement

$$(T^k v)(x) = \max_{a\in\Gamma(x)} B(x, a, T^{k-1} v) \tag{7.17}$$

is certainly true when $k = 0$ (and T^0 is the identity). Now suppose it is valid at $k-1$. Then, since $(T^k v)(x) = (T(T^{k-1} v))(x)$ at any given x, we can apply the induction hypothesis to obtain (7.17) for all k. The proof for T_σ is very similar.

Solution to Exercise 7.2.3. Let (Γ, V, B) satisfy Blackwell's condition. Fix $v, w \in V$ and $(x, a) \in \mathsf{G}$. Observe that $v = w + v - w \leqslant w + \|v - w\|_\infty$. By monotonicity of B and Blackwell's condition, we have

$$B(x, a, v) \leqslant B(x, a, w + \|v - w\|_\infty) \leqslant B(x, a, w) + \beta \|v - w\|_\infty.$$

As a result, $B(x, a, v) - B(x, a, w) \leqslant \beta \|v - w\|_\infty$. Reversing the roles of v and w yields

$$|B(x, a, v) - B(x, a, w)| \leqslant \beta \|v - w\|_\infty.$$

Since $\beta < 1$, the RDP is contracting.

Solution to Exercise 7.2.11. When (7.33) holds, by finiteness of G, we can take

an $\varepsilon > 0$ such that

$$B(x, a, v_2) \leqslant v_2(x) - \varepsilon \text{ for all } (x, a) \in \mathsf{G}.$$

We then have

$$\varepsilon \leqslant v_2(x) - B(x, a, v_2) \leqslant v_2(x) - B(x, a, v_1) \leqslant v_2(x) - v_1(x)$$

for all x, so $0 < \varepsilon \leqslant \|v_2 - v_1\|_\infty$. Set $\delta := \varepsilon / \|v_2 - v_1\|_\infty$. From (7.33) we get

$$B(x, a, v_2) \leqslant v_2(x) - \delta \|v_2 - v_1\|_\infty \leqslant v_2(x) - \delta[v_2(x) - v_1(x)]$$

for arbitrary $(x, a) \in \mathsf{G}$. Hence (7.32) holds.

Solution to Exercise 7.3.1. T is a self-map on V because, at each $v \in V$, there exists a policy σ such that $Tv = T_\sigma v$. Hence $Tv \in V$. Regarding the order-preserving property, take $v, w \in V$ with $v \preceq w$. Since T_σ is order-preserving, we have $T_\sigma v \preceq T_\sigma w$ for all $\sigma \in \Sigma$. Hence $T_\sigma v \preceq Tw$ for all $\sigma \in \Sigma$. By the definition of the supremum, we now have $Tv \preceq Tw$.

Solution to Exercise 7.3.3. For all $v \in V_\Sigma$, we have $v = v_\sigma$ for some σ, and hence $Tv \geqslant T_\sigma v = T_\sigma v_\sigma = v_\sigma = v$.

Solution to Exercise 7.4.3. For part (i), we prove the infimum case. (The supremum case is similar.) Let L, $\hat{L}$ and $\{f_i\}_{i \in I}$ be as stated. On one hand, $f_i \succeq \wedge_i f_i$ for all i, so $\Phi f_i \succeq \Phi \wedge_i f_i$ for all i. Hence $\Phi \wedge_i f_i$ is a lower bound and, therefore, $\wedge_i \Phi f_i \succeq \Phi \wedge_i f_i$. On the other hand, for the reverse inequality $\wedge_i \Phi f_i \preceq \Phi \wedge_i f_i$, we observe that $\wedge_i \Phi f_i \preceq \Phi f_i$ for all i. Since Φ^{-1} is order-preserving, this yields $\Phi^{-1} \wedge_i \Phi f_i \preceq f_i$ for all i. Hence $\Phi^{-1} \wedge_i \Phi f_i \preceq \wedge_i f_i$. Applying Φ to both sides yields $\wedge_i \Phi f_i \preceq \Phi \wedge_i f_i$. The proof of part (i) is now done.

Part (ii) is left to the reader.

Solution to Exercise A.3.2. This statement is false. To see this, let $\mathsf{X} = \mathbb{R}$, let $f_1(x) = x$ and let $f_2(x) = -x$. If $g \geqslant f_i$ for $i = 1, 2$, then $g(x) \geqslant |x|$. But then $g \notin \{f_1, f_2\}$.

Solution to Exercise A.3.3. Suppose that s and s' are both suprema of A in P. Then both s and s' are upper bounds, so $s \preceq s'$ and $s' \preceq s$. Hence $s = s'$.

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