

Econ 202A Macroeconomics: Section 2

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Section 2

1. Neoclassical Growth Model (a.k.a., Ramsey-Cass-Koopmans Model)
 - Phase Diagram
 - Numerical Solution: Finite Difference Method + Newton's Method
2. Neoclassical Growth Model in Recursive Representation
 - Hamilton-Jacobi-Bellman (HJB) equations
3. Numerical Solution: Finite Difference Method
 - Explicit Method
 - Implicit Method

Section 2-1:

Neoclassical Growth Model

Neoclassical Growth Model Overview

- Two endogenous variables $c(t)$, $k(t)$

- Two dynamic equations:

$$\frac{\dot{c}(t)}{c(t)} = \frac{f'(k(t)) - \rho - \theta g}{\theta}$$

$$\dot{k}(t) = f(k(t)) - c(t) - (n + g)k(t)$$

- Two boundary conditions:
 - $k(0)$ given (initial condition)
 - Intertemporal budget constraint with equality (terminal condition)
- It is the fact that dynamic system has a terminal condition (rather than full set of initial conditions) that makes the system “forward looking”.

Figure 1: Dynamic System (Steinsson 2024)

Phase Diagram

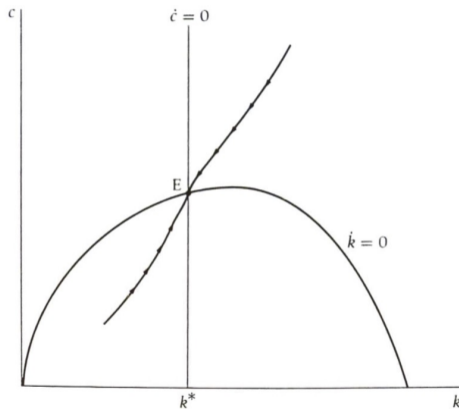


FIGURE 2.5 The saddle path

Source: Romer (2019)

Figure 2: Dynamics of $c(t)$ and $k(t)$

- Phase diagram has many paths
- All of them satisfy the two dynamic equations
- Which one of these paths will the economy take?
- Answer determined by boundary conditions
 - Boundary condition #1: Initial condition for k
 - But there is no initial condition for c !!!
 - $c(0)$ is a choice of the household
- So, how do we determine $c(0)$?
 - Boundary condition #2: Intertemporal budget constraint holds with equality

Figure 3: Which Path Will the Economy Take? (Steinsson 2024)

Terminal Boundary Conditions

- Intertemporal budget constraint with equality:

$$\int_0^{\infty} e^{-R(t)} e^{-(n+g)t} c(t) dt = k(0) + \int_0^{\infty} e^{-R(t)} e^{-(n+g)t} [f(k(t)) - (n+g)k(t)] dt \\ - \lim_{t \rightarrow \infty} e^{-R(t)} e^{-(n+g)t} k(t)$$

⇒ When solving models like the Neoclassical Growth Model, numerically with a finite time horizon, imposing that **capital converges to a steady-state level k_{ss} at the terminal point**, $k(T) = k_{ss}$, approximates both the transversality condition and the intertemporal budget constraint over an infinite horizon.

Determination of $c(0)$

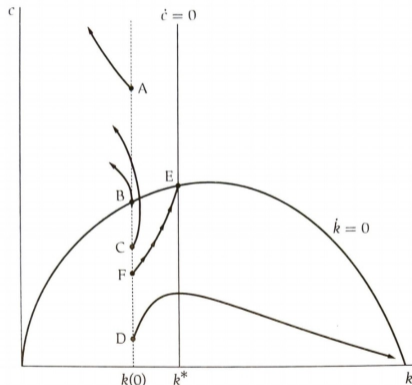


FIGURE 2.4 The behavior of c and k for various initial values of c

Source: Romer (2019)

Figure 4: Determination of $c(0)$

For any positive initial level of k , there is a unique level of c that is consistent with households' intertemporal optimization, the dynamics of the capital stock, households' budget constraint, and the requirement that k not be negative. The function giving this initial c as a function of k is known as the saddle path. For any starting value of k , the initial c must be the value on the saddle path. (Romer, 2022)

Exercise: Numerically Solve the Neoclassical Growth Model

Solve the Neoclassical Growth model with the following system of equations:

$$\frac{\dot{c}(t)}{c(t)} = \frac{f'(k(t)) - \rho - \theta g}{\theta} \quad (1)$$

$$\dot{k}(t) = f(k(t)) - c(t) - (n + g)k(t) \quad (2)$$

where the initial condition for capital is $K_0 = 10$, and the intertemporal budget constraint with equality is imposed as the terminal condition.

Key Challenges

1. Solving a **system** of differential equations for both consumption and capital.

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1. Solving a **system** of differential equations for both consumption and capital.
2. Dealing with both initial and **terminal** boundary conditions.

Shooting Algorithm

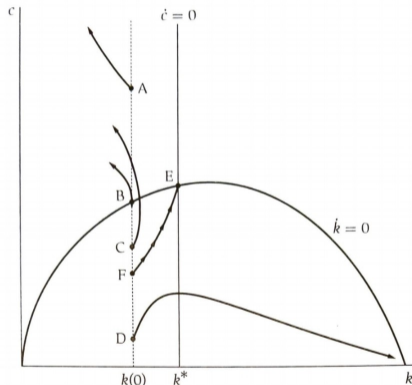


FIGURE 2.4 The behavior of c and k for various initial values of c

Source: Romer (2019)

Figure 5: Shooting Algorithm Idea

Steps of Shooting Algorithm

1. **Guess an Initial Value for Consumption, $c(0)$.**

Start by guessing an initial value for consumption, $c(0)$. Since $k(0)$ is already given, you can use both $k(0)$ and the guessed $c(0)$ to begin the forward integration.

2. **Solve the System of Equations Forward.**

Using the guessed value of $c(0)$ and the given $k(0)$, solve the system of differential equations (capital accumulation and Euler equation) forward in time from $t = 0$ to $t = T$.

3. **Check the Terminal Condition.**

After the forward integration, check if the computed value of capital $k(T)$ (or consumption $c(T)$) satisfies the terminal boundary condition.

4. **Adjust the Guess for $c(0)$.**

If the terminal condition is not satisfied, adjust the initial guess for $c(0)$ and repeat the process. Numerical methods like **Newton's method** can be used to iteratively update the guess based on how far the computed terminal value deviates from the desired condition.

5. **Iterate Until Convergence.**

Continue this process of guessing, solving, and checking until the terminal condition is satisfied within a specified tolerance. Once the terminal condition is met, the corresponding value of $c(0)$ is the correct initial value that leads to a solution where both the initial and terminal conditions are satisfied.

Finite Difference Approximations

The finite difference approximations are given as:

$$\frac{c(i+1) - c(i)}{\Delta t} = \frac{f'(k(i)) - \rho - \theta g}{\theta} \cdot c(i) \quad (3)$$

$$\frac{k(i+1) - k(i)}{\Delta t} = f(k(i)) - c(i) - (n + g)k(i) \quad (4)$$

where $i = 1, \dots, I$, $c(i) = c(t_i)$, and $k(i) = k(t_i)$ with a uniform time step size $\Delta t = t_{i+1} - t_i$.

Exercise: Analytically Solve the Steady-State Levels of Capital and Consumption

Solve for the steady-state levels of capital and consumption in the Neoclassical Growth Model, given the following system of equations:

$$\frac{\dot{c}(t)}{c(t)} = \frac{f'(k(t)) - \rho - \theta g}{\theta} \quad (1)$$

$$\dot{k}(t) = f(k(t)) - c(t) - (n + g)k(t) \quad (2)$$

assuming the production function follows a Cobb-Douglas form, $f(k) = AK^\alpha$.

Steady-State Levels of Capital and Consumption

Starting from the Euler equation at steady state:

$$0 = \frac{\dot{c}(t)}{c(t)} = \frac{f'(k(t)) - \rho - \theta g}{\theta} = \frac{\alpha A k^{\alpha-1} - \rho - \theta g}{\theta}$$
$$\therefore k_{ss} = \left(\frac{\rho + \theta g}{\alpha A} \right)^{\frac{1}{\alpha-1}} \quad (5)$$

Now, using the capital accumulation equation at steady state:

$$0 = \dot{k}(t) = f(k(t)) - c(t) - (n + g)k(t)$$
$$c_{ss} = f(k_{ss}) - (n + g)k_{ss} = A k_{ss}^{\alpha} - (n + g)k_{ss}$$
$$\therefore c_{ss} = A k_{ss}^{\alpha} - (n + g)k_{ss} \quad (6)$$

Determination of $c(0)$

- We use Newton's method to find the correct initial consumption $c(0)$ that ensures the terminal capital $k(T)$ converges to the steady-state capital k_{ss} .

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- Newton's method is an iterative numerical technique used to find the roots of a nonlinear function $f(x) = 0$.

Determination of $c(0)$

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- Newton's method is an iterative numerical technique used to find the roots of a nonlinear function $f(x) = 0$.
- In this context:
 - We define a function $f(c(0)) = k_T(c(0)) - k_{ss}$, where $k_T(c(0))$ is the capital at the terminal time given the initial consumption $c(0)$.
 - Newton's method is used to iteratively adjust $c(0)$ so that $f(c(0)) = 0$, meaning $k(T)$ matches the steady-state capital k_{ss} .

Newton's Method

Given an initial guess x_0 , Newton's method iterates according to the following update rule:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

where:

- x_n is the current guess,
- $f(x_n)$ is the function value at x_n ,
- $f'(x_n)$ is the derivative of the function at x_n ,
- x_{n+1} is the updated guess.

Newton's Method

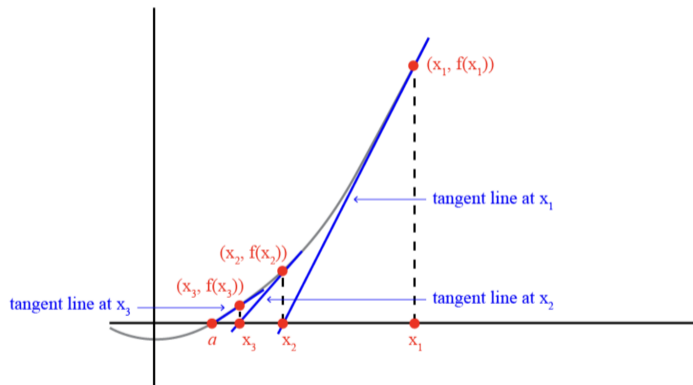


Figure 6: Graphical illustration of Newton's method

Convergence of Newton's Method

- If (i) $f(x)$ is smooth, $f \in C^2$ and (ii) the initial guess x_0 is sufficiently close to the true root x^* , then Newton's method converges quadratically. This means that the error $|x_n - x^*|$ decreases approximately with the square of the previous error at each iteration, leading to very rapid convergence near the solution.

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- If the initial guess is far from the root or if $f'(x)$ is close to zero, convergence may be slow or fail altogether.
- Selecting a well-informed initial guess improves convergence reliability. In economic models, we often use the steady-state value to set an initial guess for $c(0)$, as it provides a realistic starting point close to the model's expected long-term equilibrium.

Exercise: Numerically Solve the Neoclassical Growth Model

Solve the Neoclassical Growth model with the following system of equations:

$$\frac{\dot{c}(t)}{c(t)} = \frac{f'(k(t)) - \rho - \theta g}{\theta} \quad (7)$$

$$\dot{k}(t) = f(k(t)) - c(t) - (n + g)k(t) \quad (8)$$

where the initial condition for capital is $K_0 = 10$, and the intertemporal budget constraint with equality is imposed as the terminal condition.

Capital and Consumption Paths Over Time

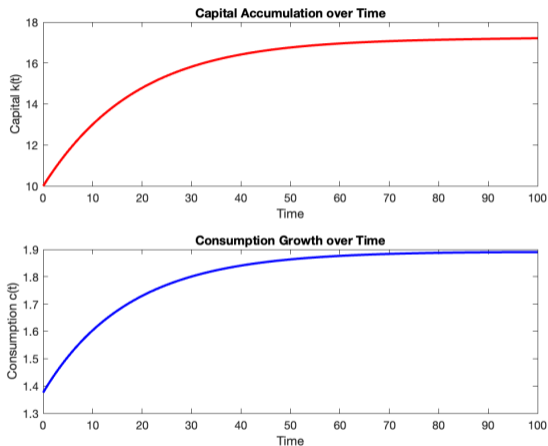


Figure 7: Capital and Consumption Paths Over Time

Saddle Path Dynamics: Initial Capital Below Steady State

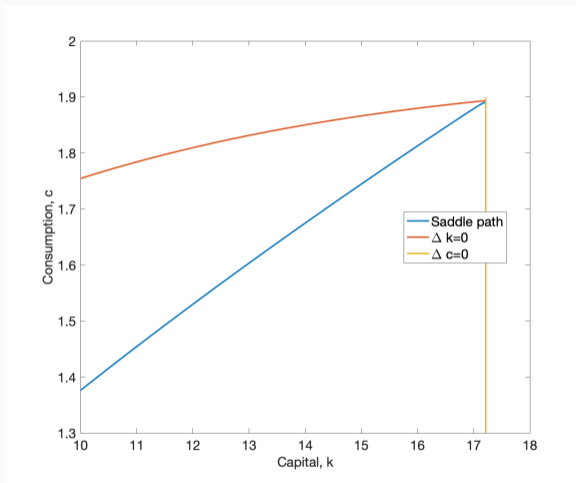


Figure 8: Saddle Path Dynamics: Initial Capital Below Steady State

Section 2-2:

Neoclassical Growth Model in Recursive Representation

Neoclassical Growth Model in Discrete-Time Recursive Formulation

We start with the Ramsey growth model in discrete time, assuming $g = 0$ and $n = 0$:

$$\begin{aligned} V(k_t) &= \max_{c_t, k_{t+1}} \{ U(c_t) + (1 - \rho)V(k_{t+1}) \} \\ \text{s.t. } \quad c_t + k_{t+1} &= f(k_t) + (1 - \delta)k_t \\ f(k_t) &= k_t^\alpha \end{aligned} \tag{9}$$

Discrete to Continuous-Time Transformation

Over a time interval of Δ units, the model can be expressed as:

$$\begin{aligned} V(k_t) &= \max_{c_t, k_{t+\Delta}} \{ \Delta U(c_t) + (1 - \Delta\rho)V(k_{t+\Delta}) \} \\ \text{s.t. } \Delta c_t + k_{t+\Delta} &= \Delta f(k_t) + (1 - \Delta\delta)k_t, \\ f(k_t) &= k_t^\alpha \end{aligned}$$

Discrete to Continuous-Time Transformation

Subtracting $V(k_t)$ from both sides and substituting the constraints into $V(k_{t+\Delta})$, we get:

$$\begin{aligned} 0 &= \max_{c_t} \{ \Delta U(c_t) + (1 - \Delta\rho)V(\Delta k_t^\alpha + (1 - \Delta\delta)k_t - \Delta c_t) - V(k_t) \} \\ &= \max_{c_t} \{ \Delta U(c_t) + V(k_t + \Delta(k_t^\alpha - \delta k_t - c_t)) - V(k_t) - \Delta\rho V(k_t + \Delta(k_t^\alpha - \delta k_t - c_t)) \} \end{aligned}$$

Dividing both sides by Δ :

$$0 = \max_{c_t} \left\{ U(c_t) + \frac{V(k_t + \Delta(f(k_t) - \delta k_t - c_t)) - V(k_t)}{\Delta} - \rho V(k_t + \Delta(k_t^\alpha - \delta k_t - c_t)) \right\}$$

Taking the limit as $\Delta \rightarrow 0$, we obtain:

$$0 = \max_{c_t} \{ U(c_t) + V'(k_t)(f(k_t) - \delta k_t - c_t) - \rho V(k_t) \}$$

Hamilton-Jacobi-Bellman (HJB) Equation

Rearranging terms and dropping time notation leads to the HJB equation:

$$\rho V(k) = \max_c \{U(c) + V'(k) \cdot (f(k) - \delta k - c)\} \quad (10)$$

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The optimal consumption, $c = c(k)$, is derived from the first-order condition:

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Denote $s(k) = f(k) - \delta k - c = k^\alpha - \delta k - c$, which represents optimal savings (investment).

Section 2-3:
Numerical Solution:
Finite Difference Method

The finite difference approximations to HJB equation (10), associated with the FOC (11) is:

$$\begin{aligned}\rho V_i &= U(c_i) + V'_i \cdot (k_i^\alpha - \delta k_i - c_i) \\ \text{with } c_i &= (U')^{-1}(V'_i)\end{aligned}\tag{12}$$

where $i = 1, \dots, I$, $V_i = V(k_i)$ with a uniform step size $\Delta k = k_{i+1} - k_i$.

Key Challenges

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 - **Upwind Scheme** (Next section)
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 - Explicit Method
 - **Implicit Method**

Algorithm Sketch

1. Construct I discrete grid points for k , denoted as k_i where $i = 1, \dots, I$, and let $V_i = V(k_i)$.
2. For each k_i on the grid, guess for a value of $\mathbf{V}^0 = (V_1^0, V_2^0 \dots V_I^0)$.

For iterations $n = 0, 1, 2, \dots$,

3. Compute $(V_i^n)'$ using a mixed method or upwind scheme.
4. Compute \mathbf{c}^n from $c_i^n = (U')^{-1}[(V_i^n)']$.
5. Find V_i^{n+1} using the update rule of an explicit or implicit method.
6. If \mathbf{V}^{n+1} is close enough to \mathbf{V}^n : stop. Otherwise, go to step 3.

Finite Difference Approximation

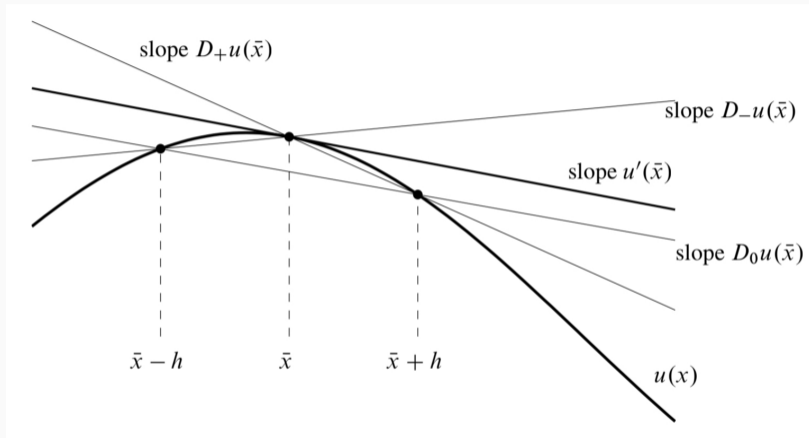


Figure 9: Various approximations to $u'(\bar{x})$ interpreted as the slope of secant lines.

Finite Difference Approximations

Suppose we have values $V_i = V(k_i)$ on a uniformly spaced grid of k , denoted as $K = \{k_1, \dots, k_I\}$, with step size $\Delta k = k_{i+1} - k_i$.

— The forward difference approximation of V' at k_i is:

$$V'_i \approx \frac{V_{i+1} - V_i}{\Delta k} \equiv V'_{i,F}$$

— The backward difference approximation of V' at k_i is:

$$V'_i \approx \frac{V_i - V_{i-1}}{\Delta k} \equiv V'_{i,B}$$

— The central difference approximation of V' at k_i is:

$$V'_i \approx \frac{V_{i+1} - V_{i-1}}{2\Delta k} \equiv V'_{i,C}$$

The mixed method approximation for V'_i is defined as:

$$V'_i \simeq \begin{cases} V'_{i,F} = \frac{V_{i+1} - V_i}{\Delta k}, & i = 1 \\ V'_{i,C} = \frac{V_{i+1} - V_{i-1}}{2\Delta k}, & i \in \{2, 3, \dots, l-1\} \\ V'_{i,B} = \frac{V_i - V_{i-1}}{\Delta k}, & i = l \end{cases} \quad (13)$$

Implementation in MATLAB

- Use MATLAB's `gradient` function to compute the numerical derivative:

$$\mathbf{V}'(k) = \text{gradient}(\mathbf{V})/dk$$

Algorithms

`gradient` calculates the *central difference* for interior data points. For example, consider a matrix with unit-spaced data, A , that has horizontal gradient $G = \text{gradient}(A)$. The interior gradient values, $G(:,j)$, are

$$G(:,j) = 0.5*(A(:,j+1) - A(:,j-1)));$$

The subscript j varies between 2 and $N-1$, with $N = \text{size}(A,2)$.

`gradient` calculates values along the edges of the matrix with *single-sided differences*:

$$G(:,1) = A(:,2) - A(:,1);$$

$$G(:,N) = A(:,N) - A(:,N-1);$$

Implementation in MATLAB

- Use MATLAB's `gradient` function to compute the numerical derivative:

$$\mathbf{V}'(k) = \text{gradient}(\mathbf{V})/dk$$

- Construct the $I \times I$ matrix \mathbf{D} (finite-difference operator), so that the derivative $\mathbf{V}'(k)$ can be approximated by:

$$\mathbf{V}'(k) \simeq \mathbf{D} \times \mathbf{V}(k)$$

The matrix \mathbf{D} is defined as:

$$\mathbf{D} = \begin{pmatrix} -1/dk & 1/dk & 0 & \dots & 0 \\ -0.5/dk & 0 & 0.5/dk & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \vdots & -0.5/dk & 0 & 0.5/dk \\ 0 & 0 & 0 & -1/dk & 1/dk \end{pmatrix} \quad (14)$$

The value function is updated iteratively for $n = 1, \dots$, according to:

$$\rho V_i^{n+1} = U(c_i^n) + (V_i^n)' \cdot (k_i^\alpha - \delta k_i - c_i^n)$$

with $c_i^n = (U')^{-1}[(V_i^n)']$

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While the explicit method is straightforward to implement, it can be less reliable in numerical implementations.

To improve convergence, the value function is updated iteratively for $n = 1, \dots$, according to:

$$\frac{V_i^{n+1} - V_i^n}{\Delta} + \rho V_i^n = U(c_i^n) + (V_i^n)' \cdot (k_i^\alpha - \delta k_i - c_i^n) \quad (15)$$

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with $c_i^n = (U')^{-1}[(V_i^n)']$

The parameter Δ is the step size of the explicit method. It can be shown that the explicit method only converges if Δ is sufficiently (prohibitively) small. (Candler, 1999)

Explicit Method Algorithm

1. Construct I discrete grid points for k , denoted as k_i where $i = 1, \dots, I$, and let $V_i = V(k_i)$.
2. For each k_i on the grid, guess for a value of $\mathbf{V}^0 = (V_1^0, V_2^0 \dots V_I^0)$.

For iterations $n = 0, 1, 2, \dots$,

3. Compute $(V_i^n)'$ using (13).
4. Compute \mathbf{c}^n from $c_i^n = (U')^{-1}[(V_i^n)']$.
5. Find V_i^{n+1} from (15).
6. If \mathbf{V}^{n+1} is close enough to \mathbf{V}^n : stop. Otherwise, go to step 3.

V^{n+1} is now *implicitly* defined by:

$$\frac{V_i^{n+1} - V_i^n}{\Delta} + \rho V_i^{n+1} = U(c_i^n) + (V_i^{n+1})' \cdot (k_i^\alpha - \delta k_i - c_i^n) \quad (16)$$

with $c_i^n = (U')^{-1}[(V_i^n)']$

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with $c_i^n = (U')^{-1}[(V_i^n)']$

The step size Δ can be arbitrarily large. (Achdou et al., 2022)

Implicit Method Algorithm

1. Construct I discrete grid points for k , denoted as k_i where $i = 1, \dots, I$, and let $V_i = V(k_i)$.
2. For each k_i on the grid, guess for a value of $\mathbf{V}^0 = (V_1^0, V_2^0 \dots V_I^0)$.

For iterations $n = 0, 1, 2, \dots$,

3. Compute $(V_i^n)'$ using (13).
4. Compute \mathbf{c}^n from $c_i^n = (U')^{-1}[(V_i^n)']$.
5. Find V_i^{n+1} from (17).
6. If \mathbf{V}^{n+1} is close enough to \mathbf{V}^n : stop. Otherwise, go to step 3.

Implicit Method: Matrix Representation

1. Define I discrete grid points for k , denoted as k_i for $i = 1, \dots, I$, and form an $I \times 1$ vector $\mathbf{k} = [k_1, k_2, \dots, k_I]'$.
2. Let $V_i = V(k_i)$. For each k_i on the grid, make an initial guess for the value function as an $I \times 1$ vector $\mathbf{V}^0 = [V_1^0, V_2^0, \dots, V_I^0]'$.

For iterations $n = 0, 1, 2, \dots$

3. Compute the derivative of the value function as an $I \times 1$ vector $(\mathbf{V}^n)'$ using an $I \times I$ finite-difference operator \mathbf{D} such that $\mathbf{D}\mathbf{V}^n \simeq (\mathbf{V}^n)'$.
4. Compute the optimal consumption as an $I \times 1$ vector \mathbf{c}^n from $\mathbf{c}^n = (U')^{-1}(\mathbf{D}\mathbf{V}^n)$.
5. Compute the optimal savings as an $I \times 1$ vector \mathbf{s}^n from $\mathbf{s}^n = f(\mathbf{k}) - \delta\mathbf{k} - \mathbf{c}^n$.
6. Find \mathbf{V}^{n+1} from:

$$\frac{1}{\Delta}(\mathbf{V}^{n+1} - \mathbf{V}^n) + \rho\mathbf{V}^{n+1} = U(\mathbf{c}^n) + (\mathbf{D}\mathbf{V}^{n+1}) \cdot \mathbf{s}^n$$

where the dot indicates element-wise multiplication.

7. If \mathbf{V}^{n+1} is close enough to \mathbf{V}^n : stop. Otherwise, go to step 3.

Alternative matrix formulation:

$$\frac{1}{\Delta}(\mathbf{V}^{n+1} - \mathbf{V}^n) + \rho \mathbf{V}^{n+1} = U(\mathbf{c}^n) + \mathbf{S}^n \mathbf{D} \mathbf{V}^{n+1}$$

where $\mathbf{S}^n = \text{diag}(\mathbf{s}^n)$ is an $I \times I$ diagonal matrix with diagonals $\mathbf{s}^n = \{s_1^n, \dots, s_I^n\}$.

Equivalently, solve the linear system:

$$\mathbf{V}^{n+1} = \left(\left(\rho + \frac{1}{\Delta} \right) \mathbf{I} - \mathbf{S}^n \mathbf{D} \right)^{-1} \left[U(\mathbf{c}^n) + \frac{1}{\Delta} \mathbf{V}^n \right] \quad (18)$$

Steady-State Conditions and Capital Grid Setup

To capture dynamics near the steady state accurately, set the grid for the state variable k within a range that includes the steady-state level k_{ss} .

Steady-State Conditions and Capital Grid Setup

To capture dynamics near the steady state accurately, set the grid for the state variable k within a range that includes the steady-state level k_{ss} .

Exercise: Solve for the Steady-State Level of Capital

Solve for the steady-state level of capital in the following equation:

$$\rho V(k) = \max_c \{U(c) + V'(k) \cdot (f(k) - \delta k - c)\}$$

with $U'(c) = V'(k)$

Steady-State Conditions and Capital Grid Setup

Steady-State Level of Capital

In the steady state:

$$\dot{k} = f(k) - \delta k - c = 0$$

Therefore, the following conditions hold:

$$\rho V'(k) = U'(c) \cdot (f'(k) - \delta)$$

Applying the FOC, $V'(k) = U'(c)$:

$$f'(k_{ss}) = \rho + \delta$$

$$\therefore k_{ss} = \left(\frac{\rho + \delta}{\alpha A} \right)^{\frac{1}{\alpha-1}}$$

Initial Guess for the Value Function

We use the following initial guess for the value function:

$$V_i^0 = \frac{U(f(k_i))}{\rho}, \quad i = 1, \dots, I.$$

Saddle Path Dynamics

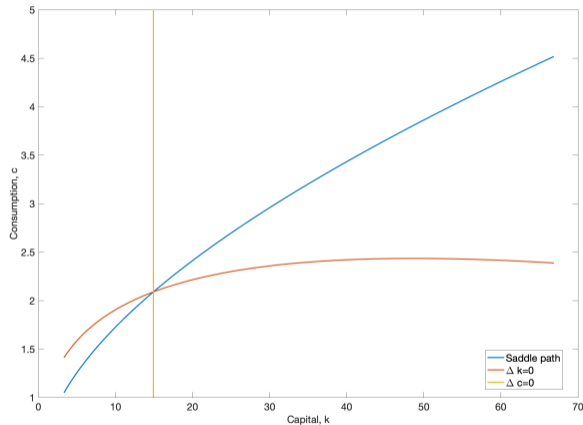


Figure 10: Saddle Path Dynamics

Saddle Path Dynamics with Low θ

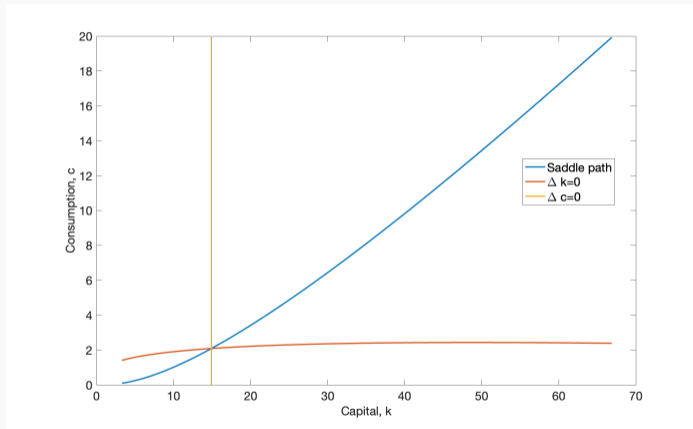


Figure 11: Saddle Path Dynamics with Low θ

Saddle Path with Different θ

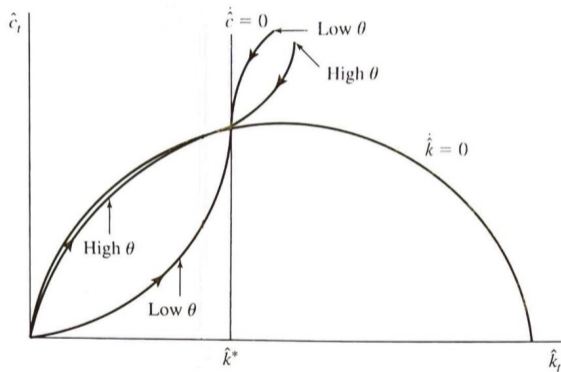


Figure 2.2

Source: Barro and Sala-i-Martin (2004)

Figure 12: Saddle Path with Different θ

Shape of the Saddle Path

- The saddle path gives $c(k)$ (called the policy function)
- What is the shape of this path?
- Consider different values of θ
- Recall that $1/\theta$ is the intertemporal elasticity of substitution
- High θ (low $1/\theta$) implies strong desire to smooth consumption
Household will try to shift consumption from the future
Saddle path will be close to $\dot{k}(t) = 0$ locus

Figure 13: Shape of the Saddle Path (Steinsson 2024)

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