In this chapter, you will learn...

- how to incorporate technological progress in the Solow model
- about growth empirics: confronting the theory with facts
- about policies to promote growth
- a simple model in which the rate of technological progress is endogenous

Introduction

In the Solow model of Chapter 7,
- the production technology is held constant.
- income per capita is constant in the steady state.

Neither point is true in the real world:
- 1904-2004: U.S. real GDP per person grew by a factor of 7.6, or 2% per year.
- examples of technological progress abound (see next slide).

Examples of technological progress

- From 1950 to 2000, U.S. farm sector productivity nearly tripled.
- The real price of computer power has fallen an average of 30% per year over the past three decades.
- Percentage of U.S. households with ≥1 computers:
  - 8% in 1984, 62% in 2003
- 1981: 213 computers connected to the Internet
  2000: 60 million computers connected to the Internet

Technological progress in the Solow model

- A new variable: \( E \) = labor efficiency
- Assume:
  - Technological progress is labor-augmenting: it increases labor efficiency at the exogenous rate \( g \):
    \[
    g = \frac{\Delta E}{E}
    \]
### Technological progress in the Solow model

- **Notation:**
  - \( y = \frac{Y}{L \cdot E} \) = output per effective worker
  - \( k = \frac{K}{L \cdot E} \) = capital per effective worker
- **Production function per effective worker:**
  - \( y = f(k) \)
- **Saving and investment per effective worker:**
  - \( sy = sf(k) \)

\[ (\delta + n + g)k = \text{break-even investment: the amount of investment necessary to keep } k \text{ constant.} \]

Consists of:
- \( \delta k \) to replace depreciating capital
- \( nk \) to provide capital for new workers
- \( gk \) to provide capital for the new “effective” workers created by technological progress

### Steady-state growth rates in the Solow model with tech. progress

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Steady-state growth rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital per effective worker</td>
<td>( k = \frac{K}{L \cdot E} )</td>
<td>0</td>
</tr>
<tr>
<td>Output per effective worker</td>
<td>( y = \frac{Y}{L \cdot E} )</td>
<td>0</td>
</tr>
<tr>
<td>Output per worker</td>
<td>( \frac{Y}{L} = \frac{y \cdot E}{L} )</td>
<td>( g )</td>
</tr>
<tr>
<td>Total output</td>
<td>( Y = y \cdot E \cdot L )</td>
<td>( n + g )</td>
</tr>
</tbody>
</table>

### The Golden Rule

To find the Golden Rule capital stock, express \( c' \) in terms of \( k' \):

\[
\begin{align*}
  c' &= y' - i' \\
  &= f(k') - (\delta + n + g)k'
\end{align*}
\]

\( c' \) is maximized when \( MPK = \delta + n + g \)

or equivalently, \( MPK - \delta = n + g \)

In the Golden Rule steady state, the marginal product of capital net of depreciation equals the pop. growth rate plus the rate of tech progress.

### Growth empirics: Balanced growth

- Solow model’s steady state exhibits **balanced growth** - many variables grow at the same rate.
- Solow model predicts \( Y/L \) and \( K/L \) grow at the same rate (\( g \)), so \( K/Y \) should be constant.
- This is true in the real world.
- Solow model predicts real wage grows at same rate as \( Y/L \), while real rental price is constant.
- This is also true in the real world.
Growth empirics: Convergence

- Solow model predicts that, other things equal, “poor” countries (with lower $Y/L$ and $K/L$) should grow faster than “rich” ones.
- If true, then the income gap between rich & poor countries would shrink over time, causing living standards to “converge.”
- In real world, many poor countries do NOT grow faster than rich ones. Does this mean the Solow model fails?

Growth empirics: Convergence

- What the Solow model really predicts is conditional convergence - countries converge to their own steady states, which are determined by saving, population growth, and education.
- This prediction comes true in the real world.

Growth empirics: Factor accumulation vs. production efficiency

- Differences in income per capita among countries can be due to differences in:
  1. capital – physical or human – per worker
  2. the efficiency of production (the height of the production function)
- Studies:
  - both factors are important.
  - the two factors are correlated: countries with higher physical or human capital per worker also tend to have higher production efficiency.

Growth empirics: Factor accumulation vs. production efficiency

- Possible explanations for the correlation between capital per worker and production efficiency:
  - Production efficiency encourages capital accumulation.
  - Capital accumulation has externalities that raise efficiency.
  - A third, unknown variable causes capital accumulation and efficiency to be higher in some countries than others.

Growth empirics: Production efficiency and free trade

- Since Adam Smith, economists have argued that free trade can increase production efficiency and living standards.
- Research by Sachs & Warner:

<table>
<thead>
<tr>
<th></th>
<th>open</th>
<th>closed</th>
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<tbody>
<tr>
<td>developed nations</td>
<td>2.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>developing nations</td>
<td>4.5%</td>
<td>0.7%</td>
</tr>
</tbody>
</table>
Growth empirics:
Production efficiency and free trade
- To determine causation, Frankel and Romer exploit geographic differences among countries:
  - Some nations trade less because they are farther from other nations, or landlocked.
  - Such geographical differences are correlated with trade but not with other determinants of income.
  - Hence, they can be used to isolate the impact of trade on income.
- Findings: increasing trade/GDP by 2% causes GDP per capita to rise 1%, other things equal.

Policy issues
- Are we saving enough? Too much?
- What policies might change the saving rate?
- How do a country’s institutions affect production efficiency and capital accumulation?
- What policies might encourage faster technological progress?

Policy issues:
Evaluating the rate of saving
- Use the Golden Rule to determine whether the U.S. saving rate and capital stock are too high, too low, or about right.
  - If \((MPK - \delta) > (n + g)\),
    - U.S. is below the Golden Rule steady state and should increase \(s\).
  - If \((MPK - \delta) < (n + g)\),
    - U.S. economy is above the Golden Rule steady state and should reduce \(s\).

To estimate \((MPK - \delta)\), use three facts about the U.S. economy:
1. \(k = 2.5y\)
2. \(\delta_k = 0.1y\)
3. \(MPK \times k = 0.3y\)

To determine \(\delta\), divide 2 by 1:
\[
\frac{\delta_k}{k} = \frac{0.1y}{2.5y} \Rightarrow \delta = \frac{0.1}{2.5} = 0.04
\]

To determine \(MPK\), divide 3 by 1:
\[
\frac{MPK \times k}{k} = \frac{0.3y}{2.5y} \Rightarrow MPK = \frac{0.3}{2.5} = 0.12
\]
Hence, \(MPK - \delta = 0.12 - 0.04 = 0.08\)
Policy issues: Evaluating the rate of saving

- From the last slide: $MPK - \delta = 0.08$
- U.S. real GDP grows an average of 3% per year, so $n + g = 0.03$
- Thus, $MPK - \delta = 0.08 > 0.03 = n + g$

Conclusion:
The U.S. is below the Golden Rule steady state: Increasing the U.S. saving rate would increase consumption per capita in the long run.

Policy issues: How to increase the saving rate

- Reduce the government budget deficit (or increase the budget surplus).
- Increase incentives for private saving:
  - reduce capital gains tax, corporate income tax, estate tax as they discourage saving.
  - replace federal income tax with a consumption tax.
  - expand tax incentives for IRAs (individual retirement accounts) and other retirement savings accounts.

Policy issues: Establishing the right institutions

- Creating the right institutions is important for ensuring that resources are allocated to their best use. Examples:
  - Legal institutions, to protect property rights.
  - Capital markets, to help financial capital flow to the best investment projects.
  - A corruption-free government, to promote competition, enforce contracts, etc.

CASE STUDY: The productivity slowdown

<table>
<thead>
<tr>
<th></th>
<th>Growth in output per person (percent per year)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1948-72</td>
</tr>
<tr>
<td>Canada</td>
<td>2.9</td>
</tr>
<tr>
<td>France</td>
<td>4.3</td>
</tr>
<tr>
<td>Germany</td>
<td>5.7</td>
</tr>
<tr>
<td>Italy</td>
<td>4.9</td>
</tr>
<tr>
<td>Japan</td>
<td>8.2</td>
</tr>
<tr>
<td>U.K.</td>
<td>2.4</td>
</tr>
<tr>
<td>U.S.</td>
<td>2.2</td>
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Possible explanations for the productivity slowdown

- Measurement problems: Productivity increases not fully measured.
  - But: Why would measurement problems be worse after 1972 than before?
- Oil prices: Oil shocks occurred about when productivity slowdown began.
  - But: Then why didn’t productivity speed up when oil prices fell in the mid-1980s?

Worker quality: 1970s - large influx of new entrants into labor force (baby boomers, women). New workers tend to be less productive than experienced workers.

The depletion of ideas: Perhaps the slow growth of 1972-1995 is normal, and the rapid growth during 1948-1972 is the anomaly.
CASE STUDY: I.T. and the “New Economy”

Growth in output per person (percent per year)

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<tbody>
<tr>
<td>Canada</td>
<td>2.9</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>France</td>
<td>4.3</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Germany</td>
<td>5.7</td>
<td>2.0</td>
<td>1.2</td>
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Apparently, the computer revolution did not affect aggregate productivity until the mid-1990s.

Two reasons:
1. Computer industry’s share of GDP much bigger in late 1990s than earlier.
2. Takes time for firms to determine how to utilize new technology most effectively.

The big, open question:
- How long will I.T. remain an engine of growth?

Endogenous growth theory

- Solow model:
  - sustained growth in living standards is due to tech progress.
  - the rate of tech progress is exogenous.
- Endogenous growth theory:
  - a set of models in which the growth rate of productivity and living standards is endogenous.

A basic model

\[ \Delta K = sY - \delta K \]

- Divide through by \( K \) and use \( Y = AK \) to get:
  \[ \frac{\Delta Y}{Y} = \frac{\Delta K}{K} = sA - \delta \]
- If \( sA > \delta \), then income will grow forever, and investment is the “engine of growth.”
- Here, the permanent growth rate depends on \( s \). In Solow model, it does not.

A basic model

- Production function: \( Y = AK \) where \( A \) is the amount of output for each unit of capital (\( A \) is exogenous & constant)
- Key difference between this model & Solow: \( MPK \) is constant here, diminishes in Solow
- Investment: \( sY \)
- Depreciation: \( \delta K \)
- Equation of motion for total capital:
  \[ \Delta K = sY - \delta K \]

Does capital have diminishing returns or not?

- Depends on definition of “capital.”
- If “capital” is narrowly defined (only plant & equipment), then yes.
- Advocates of endogenous growth theory argue that knowledge is a type of capital.
- If so, then constant returns to capital is more plausible, and this model may be a good description of economic growth.
1. Key results from Solow model with tech progress
   - steady state growth rate of income per person
c   - depends solely on the exogenous rate of tech progress
   - the U.S. has much less capital than the Golden Rule steady state

2. Ways to increase the saving rate
   - increase public saving (reduce budget deficit)
   - tax incentives for private saving

3. Productivity slowdown & “new economy”
   - Early 1970s: productivity growth fell in the U.S. and other countries.
   - Mid 1990s: productivity growth increased, probably because of advances in I.T.

4. Empirical studies
   - Solow model explains balanced growth, conditional convergence
   - Cross-country variation in living standards is due to differences in cap. accumulation and in production efficiency

5. Endogenous growth theory: Models that
   - examine the determinants of the rate of tech. progress, which Solow takes as given.