IN THIS CHAPTER, YOU WILL LEARN:

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

In the Solow model of Chapter 8,

- the production technology is held constant.
- income per capita is constant in the steady state.

Neither point is true in the real world:

- 1900–2013: U.S. real GDP per person grew by a factor of 8.3, or 1.9% per year.
- examples of technological progress abound (see next slide).
Examples of technological progress

- U.S. farm sector productivity nearly tripled from 1950 to 2012.
- The real price of computer power has fallen an average of 30% per year over the past three decades.
- 2000: 361 million Internet users, 740 million cell phone users
  2015: 3.1 billion Internet users, 4.9 billion cell phone users
- 2001: iPod capacity = 5gb, 1000 songs. Not capable of playing episodes of *Game of Thrones*.
  2015: iPod touch capacity = 64gb, 16,000 songs. Can play episodes of *Game of Thrones*. 
Technological progress in the Solow model

- A new variable: $E = \text{labor efficiency}$

- 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

- We now write the production function as:

\[ Y = F(K, L \times E) \]

- where \( L \times E \) = the number of effective workers.
  - Increases in labor efficiency have the same effect on output as increases in the labor force.
Technological progress in the Solow model

- Notation:
  \[ y = \frac{Y}{LE} = \text{output per effective worker} \]
  \[ k = \frac{K}{LE} = \text{capital per effective worker} \]

- Production function per effective worker:
  \[ y = f(k) \]

- Saving and investment per effective worker:
  \[ sy = sf(k) \]
Technological progress in the Solow model

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

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
Technological progress in the Solow model

\[ \Delta k = s f(k) - (\delta + n + g)k \]

Investment, break-even investment

Capital per worker, \( k \)
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>$k = K/(L \times E)$</td>
<td>0</td>
</tr>
<tr>
<td>Output per effective worker</td>
<td>$y = Y/(L \times E)$</td>
<td>0</td>
</tr>
<tr>
<td>Output per worker</td>
<td>$(Y/L) = y \times E$</td>
<td>$g$</td>
</tr>
<tr>
<td>Total output</td>
<td>$Y = y \times E \times L$</td>
<td>$n + g$</td>
</tr>
</tbody>
</table>
The Golden Rule with technological progress

To find the Golden Rule capital stock, express $c^*$ in terms of $k^*$:

$$c^* = y^* - i^* = f(k^*) - (\delta + n + g) k^*$$

$c^*$ 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 $\frac{Y}{L}$ and $\frac{K}{L}$ grow at the same rate ($g$), so $\frac{K}{Y}$ should be constant. This is true in the real world.
  - Solow model predicts real wage grows at same rate as $\frac{Y}{L}$, while real rental price is constant. Also true in the real world.
Growth empirics: Convergence

- Solow model predicts that, other things equal, poor countries (with lower \( \frac{Y}{L} \) and \( \frac{K}{L} \)) 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

- Solow model predicts that, other things equal, poor countries (with lower $Y/L$ and $K/L$) should grow faster than rich ones.

- No, because “other things” aren’t equal:
  - In samples of countries with similar savings & pop. growth rates, income gaps shrink about 2% per year.
  - In larger samples, after controlling for differences in saving, pop. growth, and human capital, incomes converge by about 2% per year.
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: Convergence

The Solow growth model suggests that economies with similar rates of population growth and technological progress should exhibit similar levels of per-capita income in the long run, regardless of their initial capital stock. During the adjustment to steady state, countries with a lower capital stock will grow faster than those with higher capital stocks. This is known as the convergence hypothesis. Some recent theories of endogenous growth, by contrast, do not imply convergence. Rather, they suggest that there may be constant or increasing returns to capital and, hence, no tendency for convergence in per-capita income. There is as yet no consensus on whether or not countries do exhibit convergence in per-capita income. Figure 1 shows a scatterplot of growth rates since 1960 against output per worker in 1960. The simple convergence hypothesis suggests that these variables should be negatively related: Countries with higher GDP per person should grow more slowly. Such a relationship is not apparent in Figure 1, casting doubt on the convergence hypothesis. Results on convergence depend in part on the sample of countries examined: There is much stronger evidence of convergence among those countries that are already relatively affluent (as can be seen by looking at the right half of Figure 1), and economists who have looked at this sample have generally concluded in favor of convergence.

Greg Mankiw, David Romer, and David Weil point out that the Solow model does not literally imply that all countries should converge to the same steady state, however, because of differences in saving rates and population growth rates. After correcting for these differences and also for differences in human capital, Mankiw, Romer, and Weil find that there is much stronger evidence of convergence, as can be seen from Figure 2.


See Supplement 9-1.
ADDITIONAL CASE STUDY

8-2 Convergence of Income Across the United States

The Solow growth model predicts that economies with similar rates of saving, population growth, and technological progress should converge over time. Poor economies should catch up to rich economies and eventually have similar levels of per-capita income. As Figure 1 shows, regional differences in per-capita personal income across the United States have narrowed considerably since the Great Depression. In 1929, the Mideast was the richest region, with income nearly 40 percent above the national average, while the Southeast was the poorest region, with income just above 50 percent of the national average. By 2004, the gap between the richest and poorest regions had narrowed considerably, with New England in the top position at a little over 20 percent above the national average and the Southeast and Southwest tied in the bottom slot at 90 percent of the national average.


See Supplement 9-2.
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.
Policy issues

- Are we saving enough? Too much?
- What policies might change the saving rate?
- How should we allocate our investment between privately owned physical capital, public infrastructure, and human capital?
- 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. economy 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 \(s\).
Policy issues:
Evaluating the rate of saving

To estimate \((MPK − δ)\), use three facts about the U.S. economy:

1. \(k = 2.5 \ y\)
   The capital stock is about 2.5 times one year’s GDP.

2. \(δk = 0.1 \ y\)
   About 10% of GDP is used to replace depreciating capital.

3. \(MPK \times k = 0.3 \ y\)
   Capital income is about 30% of GDP.
Policy issues:
Evaluating the rate of saving

1. \( k = 2.5 \ y \)
2. \( \delta k = 0.1 \ y \)
3. \( MPK \times k = 0.3 \ y \)

To determine \( \delta \), divide 2 by 1:

\[
\frac{\delta k}{k} = \frac{0.1 \ y}{2.5 \ y} \quad \Rightarrow \quad \delta = \frac{0.1}{2.5} = 0.04
\]
Policy issues:
Evaluating the rate of saving

1. \( k = 2.5 \, y \)
2. \( \delta k = 0.1 \, y \)
3. \( MPK \times k = 0.3 \, y \)

To determine \( MPK \), divide 3 by 1:

\[
\frac{MPK \times k}{k} = \frac{0.3 \, y}{2.5 \, y} \quad \Rightarrow \quad MPK = \frac{0.3}{2.5} = 0.12
\]

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:
Allocating the economy’s investment

- In the Solow model, there’s one type of capital.
- In the real world, there are many types, which we can divide into three categories:
  - private capital stock
  - public infrastructure
  - human capital: the knowledge and skills that workers acquire through education
- How should we allocate investment among these types?
Policy issues: Allocating the economy’s investment

Two viewpoints:

1. Equalize tax treatment of all types of capital in all industries, then let the market allocate investment to the type with the highest marginal product.

2. Industrial policy:
   Government should actively encourage investment in capital of certain types or in certain industries, because they may have positive externalities that private investors don’t consider.
Possible problems with industrial policy

- The government may not have the ability to “pick winners” (choose industries with the highest return to capital or biggest externalities).
- Politics (e.g., campaign contributions) rather than economics may influence which industries get preferential treatment.
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.
Establishing the right institutions: North vs. South Korea

After WW2, Korea split into:

- North Korea with institutions based on authoritarian communism
- South Korea with Western-style democratic capitalism

Today, GDP per capita is over 10x higher in S. Korea than N. Korea
Establishing the right institutions: Corruption and Growth

The Solow model does quite a good job of explaining differences in living standards and growth rates among different countries. But it is not perfect, so many economists have sought additional explanations of the varying economic performance of different countries. Paolo Mauro has investigated the link between growth and the incidence of bureaucracy and corruption.

Mauro uses data gathered by Business International, a private company that surveys analysts in many different countries about political, bureaucratic, and other factors that might influence the attractiveness of a country to investors. He combines assessments of the degree of red tape, the extent of corruption, and the integrity of the judicial system into a measure that he terms bureaucratic efficiency (BE). Countries such as the United States, Finland, Japan, New Zealand, and Singapore do well in terms of the BE index; countries like Egypt, Haiti, Indonesia, Nigeria, and Thailand do poorly.

Figure 1 is a scatterplot of BE and per-capita income in 67 countries. There is a clear positive association: Countries with high levels of corruption and bureaucracy tend to have lower income. Of course, it might be the case that high-income countries develop better institutions. But Mauro's statistical analyses suggest that the link does indeed run the other way: More corrupt countries tend to be poorer and also tend to grow more slowly.

Policy issues:
Encouraging tech. progress

- Patent laws:
  encourage innovation by granting temporary monopolies to inventors of new products.

- Tax incentives for R&D

- Grants to fund basic research at universities

- Industrial policy:
  encourages specific industries that are key for rapid tech. progress
  *(subject to the preceding concerns).*
CASE STUDY: Is free trade good for economic growth?

- Since Adam Smith, economists have argued that free trade can increase production efficiency and living standards.

- Research by Sachs & Warner:

<table>
<thead>
<tr>
<th>Average annual growth rates, 1970–89</th>
</tr>
</thead>
<tbody>
<tr>
<td>open</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>developed nations</td>
</tr>
<tr>
<td>developing nations</td>
</tr>
</tbody>
</table>
CASE STUDY:
Is free trade good for economic growth?

- 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.
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.
The 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:
  \[ \Delta K = sY - \delta K \]
The 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.
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.
A two-sector model

- Two sectors:
  - **manufacturing** firms produce goods.
  - **research** universities produce knowledge that increases labor efficiency in manufacturing.
- \( u \) = fraction of labor in research
  (\( u \) is exogenous)

- Manufacturing: \( Y = F [K, (1 - u)EL] \)
- Research: \( \Delta E = g(u)E \)
- Capital accumulation: \( \Delta K = sY - \delta K \)
A two-sector model

- In the steady state, manufacturing output per worker and the standard of living grow at rate $\frac{\Delta E}{E} = g(u)$.

- Key variables:
  - $s$: affects the level of income, but not its growth rate (same as in Solow model)
  - $u$: affects level and growth rate of income
Facts about R&D

1. Much research is done by firms seeking profits.

2. Firms profit from research:
   - Patents create a stream of monopoly profits.
   - Extra profit from being first on the market with a new product.

3. Innovation produces externalities that reduce the cost of subsequent innovation.

Much of the new endogenous growth theory attempts to incorporate these facts into models to better understand technological progress.
Is the private sector doing enough R&D?

- The existence of positive externalities in the creation of knowledge suggests that the private sector is not doing enough R&D.

- But, there is much duplication of R&D effort among competing firms.

- Estimates:
  Social return to R&D $\geq 40\%$ per year.

- Thus, many believe govt should encourage R&D.
Economic growth as “creative destruction”

Schumpeter (1942) coined term “creative destruction” to describe displacements resulting from technological progress:

- the introduction of a new product is good for consumers but often bad for incumbent producers, who may be forced out of the market.

Examples:

- Luddites (1811–12) destroyed machines that displaced skilled knitting workers in England.
- Walmart displaces many mom-and-pop stores.