The Chinese economy has been growing at an astonishing rate. In 2006, GDP per capita in China grew by 10 percent. In the same year, GDP per capita in the United States grew by just 2.3 percent. In its entire history, the U.S. economy has never grown as fast as the Chinese economy is growing today. If these rates continue, China will be richer than the United States in less than 25 years. How can this make sense? Is there something wrong with the U.S. economy? Do the Chinese have a magical potion for economic growth?

Remember, in the last chapter we explained that among the key institutions promoting economic growth were property rights, honest government, political stability, a dependable legal system, and competitive and open markets. But for each and every one of these institutions, the United States ranks higher than China, despite China’s having made remarkable improvements in recent decades. So why is China growing so much more rapidly than the United States?

To answer this question, we must distinguish between two types of growth, catching up and cutting edge. Countries that are catching up have some enormous advantages. To become rich, a poor country does not have to invent new ideas, technologies, or methods of management. All it has to do is adopt the ideas already developed in the rich countries. As we will see, catch-up countries like China grow primarily through capital accumulation and the adoption of some simple ideas that massively improve productivity.

The United States is the world’s leading economy—it is on the cutting edge. Growth on the cutting edge is primarily about developing new ideas. But developing new ideas is more difficult than adopting ideas already in existence. Calculus isn’t easy but it doesn’t take a genius to understand calculus; it does take a genius to invent calculus. Countries on the cutting edge grow primarily through idea generation.
In this chapter, we will do two things. First, we will develop a model of economic growth based on capital accumulation. The model will help us understand some puzzles such as why China is growing so much faster right now than the United States and why the countries that lost World War II, Germany and Japan, grew much faster in the postwar decades than did the winner, the United States. We will also discuss how poor and rich countries can converge in income over time.

Our model of economic growth based on capital accumulation does a good job of explaining catch-up growth but it doesn’t help much to explain growth on the cutting edge. If we think about growth in the United States, for example, we probably do not think first about more tractors, buildings, and factories—the sorts of things that characterize growth in China. Instead, we think about iPhones, the Internet, and genetic engineering, that is, new products, new processes, and new ideas. Thus, in the second half of the chapter we turn to cutting-edge growth and the economics of ideas. The economics of ideas explains why growth in the United States is slower than in China, but also why growth in China will slow down. It also suggests, however, that U.S. and worldwide economic growth may become faster in the decades ahead than it has been in the past. To put it bluntly (but regretfully for us), many of you will see more progress in your lifetimes than we will have seen in ours.

The Solow Model and Catch-Up Growth

Let’s begin with a model of the wealth of nations and economic growth called the Solow model (after Nobel Prize–winning economist Robert Solow). The Solow model begins with a production function. A production function expresses a relationship between output and the factors of production, namely the exact way in which more inputs will produce more outputs. For simplicity, we assume that there is only one output, $Y$, which we can think of as GDP, and the three factors of production that we discussed in the last chapter: physical capital written $K$; human capital, which we write as $eL$, and can understand as education, $e$, times labor; and ideas that increase the productivity of capital and labor, which we write as $A$. Thus, we can write that output, $Y$, is a function, $F$, of the inputs $A$, $K$, and $eL$:

$$Y = F(A, K, eL)$$

(1)

That looks abstract but it represents a simple economic truth. If we look at a typical production process, say an automobile factory, output depends on capital (the machines, $K$), labor (the workers, $L$, adjusted for their level of skill, so $eL$), and the whole factory is based on ideas ($A$), namely the invention of the auto and all the machines that help make it.

We also can think of the entire economy as relying on capital, labor, and ideas on a larger scale. We will focus on the Solow production function as a description of an entire economy because we are looking at the causes and consequences of overall economic growth.

For our first look at the Solow model, we will temporarily ignore changes in ideas, education, and labor. If we assume that $A$, $e$, and $L$ are constant, then we can simplify our expression for output as $Y = F(K)$. Notice that because $L$ is constant an increase in $K$ always implies an increase in the amount of capital per worker, $K/L$, and an increase in $Y$ is also always an increase in output per worker, $Y/L$. 
Capital, Production and Diminishing Returns

Let’s make a quick sketch of what our production function, \( F(K) \), should look like. More \( K \) should produce more \( Y \) but at a diminishing rate. On a farm, for example, the first tractor is very productive. The second tractor is still useful, but not as much as the first tractor. The third tractor is driven only when one of the other tractors breaks down (remember that the amount of labor is constant). What this means is that increases in capital, \( K \), produce less output, \( Y \), the more \( K \) you already have—so we should have a production function where output increases with more \( K \) but at a decreasing rate. Following this logic, Figure 7.1 graphs output, \( Y \), on the vertical axis against capital, \( K \), on the horizontal axis, holding \( L \) and the other inputs constant.

The Iron Logic of Diminishing Returns

More capital, \( K \), creates more output but at a diminishing rate. The first unit of capital adds one unit to output but the 16th unit of capital adds just 0.13 units to output.

Notice from Figure 7.1 that the first unit of capital increases output by one unit, but as more and more capital is added output increases by less and less—this is the “iron logic” of diminishing returns and it plays a key role in the Solow model. Economists call the increase in output when capital increases by one unit the marginal product of capital. The graph shows that the marginal product of capital is diminishing.

It can sometimes help to look at a specific production function. In Figure 7.1, we used the production function \( Y = F(K) = \sqrt{K} \), which means that output is the square root of the capital input. To see how this works in more detail, plug in some numbers. If \( K = 4 \), then \( Y = \sqrt{4} = 2 \). If \( K \) increases to 16, then \( Y = \sqrt{16} = 4 \) and so forth.
As we said, the reason the marginal product of capital diminishes is that the first unit of capital (the first tractor) is applied where it is most productive, the second unit is applied to slightly less productive tasks because the first unit is already performing the most productive tasks, the third unit is applied to even less productive tasks, and so on.

**Growth in China and the United States**  
The iron logic of diminishing returns explains quite a bit about why China is now growing so much more rapidly than the United States. Imagine, for example, that a country labors under poor institutions—like a lack of competitive and open markets—so that the incentives to invest in capital are low. Now suppose that new institutions are put into place, perhaps new leaders with better ideas replace the old guard. The new institutions increase the incentives to invest and the capital stock grows. But in a country without a lot of capital but good (or much improved) institutions, the marginal product of capital will be very high. In that case, even small investments pay big rewards and economic growth will be rapid.

This process describes what has happened in China. For most of the twentieth century, China labored under very poor economic institutions. China in the 1950s and 1960s was a growth disaster with mass starvation as a common occurrence. Since the death of Chairman Mao in 1976 and the subsequent move away from communism and toward markets, China has been growing very rapidly. Chinese growth has been rapid because China began with very little capital, so the marginal product of capital was very high, and with the new reforms the investment rate increased dramatically. In addition, of course, China has benefited by opening up to trade and investment with the developed world.

China also grew rapidly because improved productivity in agriculture—brought about primarily by better institutions, as we discussed in the last chapter—meant that several hundred million Chinese rural peasants migrated to Chinese cities. Almost overnight these people went from being subsistence farmers, producing perhaps a few hundred dollars worth of output a year, to urban workers, producing perhaps a few thousand dollars worth of output a year in a factory. This is one of the largest economic migrations in human history and for the most part it has been a resounding success.

The iron logic explains why China is catching up to the United States but also why growth in China will slow down. China now has its first tractor and indeed its second. As it adds a third and beyond, China’s growth rate will fall because the marginal product of capital will fall. Also, China has many problems—from a poor banking system to a lack of experience with the rule of law to a poorly educated population. At the moment, these problems are being swamped by the high productivity of capital. But as capital accumulates and the productivity of capital declines, China’s problems will become more of a drag on Chinese growth.

**Why Bombing a Country Can Raise Its Growth Rate**  
The iron logic also explains why bombing a country can increase its growth rate. Following World War II, for example, Germany and Japan both grew faster than the United States. It may seem odd at first that the losers of a war should grow faster than the winners, but the iron logic of diminishing returns predicts exactly this result. During World War II the capital stock of Germany and Japan—the factories, the roads, and the buildings—was nearly obliterated by Allied bombing. With so little capital remaining, any new capital was highly productive and meant that Germany and Japan had a strong incentive to put new capital into place. In other words, they grew rapidly as they were rebuilding their economies. It’s also the case that Germany and Japan had reasonably good postwar institutions.
But don’t make the mistake of envying Germany and Japan their high growth rates. Germany and Japan grew rapidly because they were catching up. Children who have been malnourished often grow rapidly when they are put on a proper diet but it’s not good to be malnourished. Similarly, countries whose capital stock has been destroyed will grow rapidly, all else being equal, as they catch up but it is not good to have your capital stock destroyed. Note also that growth in Germany and Japan slowed down as their capital stocks grew and approached U.S. levels; by the 1980s they were growing at close to the U.S. rate. The growth rate in Germany and Japan fell not because they did anything wrong but, again, because the marginal product of capital declines the more capital a country has.

Figure 7.1 explains that more capital means more output, albeit at a diminishing rate. But where does capital come from and where does it go? Capital is output that is saved and invested, but capital depreciates over time. In the next section, we show how these two aspects of capital—investment and depreciation—fit together. Understanding investment and depreciation will prove important for isolating the ultimate sources of economic growth.

**Capital Growth Equals Investment Minus Depreciation**

Capital is output that is saved and invested rather than consumed. Imagine, for example, that 10 units of output are produced. Of the 10 units of output, 7 units might be consumed and 3 units invested in new capital. We write the fraction of output that is invested in new capital as gamma (γ), and in the example just given, \( \gamma = \frac{3}{10} = 0.3 \).

Figure 7.2 shows how output is divided between consumption and investment when \( \gamma = 0.3 \). Notice that when \( K = 100 \), 10 units of output are

![Figure 7.2](image-url)
produced and of these 10 units, 7 units are consumed and 3 units are invested in new capital.

Capital also depreciates—roads wear out, harbors become silted, and machines break down. Thus, if there are 100 units of capital in this period, for example, then 2 units might depreciate, leaving just 98 for use in the next period.

We write the fraction of capital that wears out or depreciates as delta (\( \delta \)); in the example just given, \( \delta = \frac{2}{100} = 0.02 \). Figure 7.3 shows how much capital depreciates as a function of the capital stock. When the capital stock is 100, for example, then 2 units of capital will depreciate and when the capital stock is 200, 4 units will depreciate, and so on.

The greater the capital stock, the greater the depreciation, so a country with a lot of roads, harbors, and machines needs to devote a lot of resources to filling potholes, removing silt, and repairing and replacing. In other words, a successful economy must continually replenish its capital stock just to keep going. An economy that does not replenish its capital stock will quickly fall into ruin.

Again, Figure 7.3 shows that capital depreciation increases the greater the capital stock—this will turn out to place another constraint on economic growth.

**Why Capital Alone Cannot Be the Key to Economic Growth**

We now have everything we need to develop a second important insight from the Solow model. Capital depreciation increases, the greater the capital stock so at some point so much capital will be depreciating every period that every unit of investment will be needed just to keep the capital stock constant. When investment just covers capital depreciation, the capital stock stops growing, and
when the capital stock stops growing, output stops growing as well. Thus, the iron logic of diminishing returns tells us that capital alone cannot be the key to economic growth. Let’s explain this in more detail.

Figure 7.4 focuses attention on the two key functions, the investment function from Figure 7.2 and the depreciation function from Figure 7.3.

**FIGURE 7.4**

*Capital Increases or Decreases until Investment Equals Depreciation*

When investment is greater than depreciation, the capital stock grows. When investment is less than depreciation, the capital stock shrinks. When investment equals depreciation, the capital stock stays the same.

Consider first a case where the capital stock grows larger. For instance, when $K = 100$, 3 units of output are invested in new capital and 2 units of capital depreciate. Investment exceeds depreciation so in the next period both the capital stock and output will be larger. Thus, when investment is greater than depreciation ($Investment > Depreciation$) we have economic growth.

Investment increases as the capital stock gets larger, but because of the iron logic, investment increases at a diminishing rate. Depreciation, however, increases with the capital stock at a linear (constant) rate. Thus, at some point investment equals depreciation ($Investment = Depreciation$). At this point, every unit of investment is being used to replace depreciated capital, so the amount of net or new investment (investment after depreciation) is zero. We call this the steady state level of capital. At the steady state level of capital, there is no new (net) investment and economic growth stops. We can summarize as follows:

- **Investment > Depreciation**—the capital stock grows and output next period is bigger
- **Investment < Depreciation**—the capital stock shrinks and output next period is smaller
- **Investment = Depreciation**—the capital stock and output are constant (the steady state)

**Check the Math**

When $K = 100$, $Y = \sqrt{100} = 10$, of these 10 units $0.3 \times 10 = 3$ units are invested in new capital. Depreciation is $0.02 \times 100 = 2$ units so $Investment (3) > Depreciation (2)$ and the capital stock and output grow.

At the steady state the capital stock is neither increasing nor decreasing.

**Check the Math**

As Figure 7.4 is drawn the steady state occurs when $K = 225$ because:

- $Investment = 0.3 \times \sqrt{225} = 4.5$
- $Depreciation = 0.02 \times 225 = 4.5$

thus when $K = 225$

$Investment = Depreciation$
We learn from our “capital only” model that long-run economic growth cannot be due to capital accumulation. The logic of diminishing returns means that eventually capital and output will cease growing. Economic growth, however, does not seem to be slowing. So what else could drive long-run economic growth? Let’s return to the other factors of production that we discussed in Chapter 6—human capital and technological knowledge.

Can increases in human capital drive long-run economic growth? Human capital is an important contributor to the wealth of nations. Figure 7.5 shows that GDP per capita is higher in countries with more human capital, as measured by average years of schooling.

But human capital is just like physical capital in that it has diminishing returns and it depreciates. In other words, an economic principles class is probably the most important economics class that you will take and all the human capital in the world today will be gone in a hundred years. (Why will all the human capital in the world today be gone in a hundred years? Hint: Where will your human capital be in a hundred years?) Thus, within the Solow model, the logic of diminishing returns applies to human capital just as much as to physical capital and neither can drive long-run economic growth.

**Better Ideas Drive Long-Run Economic Growth**

Can better ideas maintain long-run economic growth? Better ideas let us produce more output from the same inputs of physical and human capital. A personal computer today has about the same amount of silicon and labor input as a computer produced 20 years ago but today’s computer is much better—the difference is ideas. Recall our simple production function:

\[ Y = \sqrt{K} \]
We can think of better ideas as a way of getting more output from the same input. So remembering that we let \( A \) stand for ideas that increase productivity, let’s now write our production function as:

\[
Y = A\sqrt{K}
\]

Notice that an increase in better ideas or technological knowledge—as represented by \( A \)—increases output even while holding \( K \) constant, that is, an increase in \( A \) represents an increase in productivity. Figure 7.6 graphs two production functions. The first is when \( A = 1 \), the production function that we have been working with all along. The second is when \( A = 2 \). Notice that when \( K = 16 \), output is 4 when \( A = 1 \), but it’s 8 when \( A = 2 \). Technological knowledge means that we can get more output from the same input.

So long as we can develop better ideas that shift the production function upwards then economic growth will continue. In a way, it should be obvious that better ideas are the key to long-run economic growth. How much economic growth would there have been without the discovery of electricity or DNA or the development of the internal combustion engine, the computer chip, or the polymerase chain reaction? It’s just not enough to throw more effort at a problem; we have to actually know what we are doing and that boils down to ideas.

Solow himself tried to estimate how much of U.S. economic prosperity was due to capital and labor and how much was due to ideas. He came up with the figure that better ideas are responsible for about three-fourths of the U.S. standard of living. Many economists have subsequently debated the exact number, but no one contests the central importance of ideas and technological progress for human well-being.
We know that if the capital stock increases and if we are at the steady state level of capital, the level of capital such that the capital stock neither increases nor decreases. It's also true that if then the capital stock and output shrink. Remember that so if we know \( K \) we know \( Y \). And if \( K \) is growing, then \( Y \) is growing. We can see this relationship a little better in Figure 7.8, which plots investment, depreciation, and output in the same graph.

So to understand economic growth we must move from capital accumulation to take a closer look at the economics of ideas. To do that head to the section below titled “Growing on the Cutting Edge: The Economics of Ideas.” Alternatively, more lessons can be learned from a closer inspection of the Solow model. We delve into these further lessons in the next (optional) section.

**The Solow Model—Details and Further Lessons (Optional Section)**

Let’s return to Figure 7.4, which we also reprint here as Figure 7.7.

![Figure 7.7](image)

**Capital Increases or Decreases until Investment Equals Depreciation**

When investment is greater than depreciation the capital stock grows. When investment is less than depreciation, the capital stock shrinks. When investment equals depreciation, the capital stock stays the same.

We know that if \( \text{Investment} > \text{Depreciation} \) the capital stock increases and if \( \text{Investment} = \text{Depreciation} \) we are at the steady state level of capital, the level of capital such that the capital stock neither increases nor decreases. It’s also true that if \( \text{Investment} < \text{Depreciation} \) then the capital stock and output shrink.

Remember that \( Y = \sqrt{K} \), so if we know \( K \) we know \( Y \). And if \( K \) is growing, then \( Y \) is growing. We can see this relationship a little better in Figure 7.8, which plots investment, depreciation, and output in the same graph.

That figure may look complicated, but don’t get thrown off the basic idea, which is simply that the capital stock drives output, \( Y \). For example, if \( K \) is at the steady state level (\( K = 225 \), in this case), then \( Y \) will also be at a steady state level of output, in this case 15. We take the 225 off the horizontal axis and bounce it off the \( Y = \sqrt{K} \) curve to get to \( GDP = 15 \) on the vertical axis. Similarly, since \( K \) drives \( Y \), whenever \( K \) is growing then so is \( Y \). Thus, Figure 7.8
When Capital Is in the Steady State, Output Is in the Steady State

The capital stock drives output. At \( K = 225 \), output is \( \sqrt{225} = 15 \). At \( K = 225 \), investment equals depreciation, so the capital stock is neither growing nor shrinking and thus output is neither growing nor shrinking.

**The Solow Model and an Increase in the Investment Rate**

What happens in the Solow model if \( \gamma \), the fraction of output that is saved and invested, increases? It is simple: a greater investment rate means more capital, which means more output. An increase in the investment rate therefore increases a country’s steady state level of GDP. The result just shows that investment increases the number of “tractors” per worker which raises GDP per worker.

In Figure 7.9 on the next page, we show this intuition in the graph by plotting two investment functions: \( \text{Investment} = 0.3 \sqrt{K} \), which means that 3 units of every 10 units of output are saved and invested \( (\gamma = 0.3) \), as it was in Figure 7.8, and also \( \text{Investment} = 0.4 \sqrt{K} \), which means that 4 units of every 10 units of output are saved and invested \( (\gamma = 0.4) \). Notice that when \( \gamma = 0.4 \), the new steady state capital stock increases to \( K = 400 \) and output increases to 20.

Thus, the Solow model predicts that countries with higher rates of investment will be wealthier. Is this prediction of the Solow model consistent with the evidence? Yes. Figure 7.10, also on the next page, shows that GDP per capita is higher in countries that have higher investment rates.

This makes intuitive sense. More savings mean that more capital goods can be produced and consumers can enjoy a higher standard of living. How wealthy would a country be if it spent all of its resources on partying?

The Solow model says that an increase in the investment rate will increase steady state output. But in the Solow model, the iron logic of diminishing returns cannot be forever avoided. When the investment rate increases we have
Investment is Depreciation so the capital stock increases and the economy grows. But as more capital accumulates, the iron logic sets in and the economy eventually slows until at the new steady state it stops growing once again. So the level of the capital stock determines the output level but not its growth rate, at least not in the very long run.
For further confirmation of this idea, recall the growth miracle of South Korea from the last chapter. In 1950, South Korea was poorer than Nigeria, while today it is richer than some European nations. The evidence on South Korea’s growth is consistent with the Solow model. In the 1950s, the investment rate in South Korea was less than 10 percent of GDP, but the rate more than doubled in the 1970s and increased to over 35 percent by the 1990s. Higher investment rates helped to increase South Korea’s GDP, as the country opened many factories and exported cars and electronics to the rest of the world. As South Korea has caught up to western levels of GDP, however, its growth rate has slowed.

Of course, we should remember that investment rates are themselves caused by other factors such as incentives and institutions. No one wants to invest in an economy, for example, where their investments may be expropriated. One of the reasons the investment rate in South Korea increased is that capitalists believed that their investments would be protected.

In this chapter, we have referred to $\gamma$ as the rate of savings and investment, implicitly assuming that savings equals investment. But savings must be efficiently collected and then transformed into investment. The Soviet Union had a high rate of saving but its savings were not invested well, and thus its effective investment rate was very low. In other words, a country that invests its savings poorly is like a country that doesn’t invest much at all. A country could also have a low rate of saving but a high rate of investment if it imported savings from other countries. The next chapter will discuss in more detail how financial intermediaries efficiently collect savings, often from around the world, and then transform those savings into productive investments.

**The Solow Model and Conditional Convergence**

The Solow model also predicts that a country will grow more rapidly the farther its capital stock is below its steady state value. To understand this result, remember that when the capital stock is below its steady state value, investment will exceed depreciation. In other words, the capital stock will grow. Now look again at Figure 7.1—when the capital stock is low, it has a very high marginal product. Thus, when a country’s capital stock is below its steady state value, the country will grow rapidly as it invests in capital that has a high marginal product. That’s just restating our tractor parable. The tractor is most valuable on the farm that doesn’t already have a tractor, as opposed to the farm that is already working with 13 tractors. (A more detailed explanation of this point can be found in the appendix to this chapter.)

We already used this result to explain why China is growing rapidly and why Germany and Japan grew rapidly after World War II. More generally, the Solow model predicts that if two countries have the same steady state level of output, the country that is poorer today will catch up because it will grow faster. We don’t know for certain which countries have the same steady state level of output but we might guess, for example, that countries with similar institutions and history have similar steady states. Figure 7.11 on the next page tests this prediction using data from 18 of the 20 founding members of the OECD (Organisation for Economic Co-operation and Development). The average annual growth rate between 1960 and 2000 is on the vertical axis, and real per capita GDP in 1960 is on the horizontal axis. The data clearly show that among the OECD countries the poorer countries grew faster. You can see that lower income in 1960 is associated with higher growth between 1960 and 2000.
Since the poorer countries grow faster, they eventually catch up to the richer countries. Thus, over time the OECD countries have converged to a similar level of GDP per capita. We say that the model and the data exhibit conditional convergence because we only see convergence among countries that plausibly have similar steady state levels of output. As we know from Chapter 6, we do not observe convergence among all countries—the existence of growth disasters such as Nigeria means that some countries are diverging from the rest of the world rather than catching up.

From Catching Up to Cutting Edge
Several predictions of the simple Solow model are consistent with the evidence—countries with higher investment rates have higher GDP per capita, and countries grow faster the farther their capital stock is from its steady state level. One prediction of the simplest form of the Solow model, however, is inconsistent with the evidence. The simplest form of the Solow model predicts zero economic growth in the long run. Remember, in the long run, the capital stock stops growing because Investment = Depreciation and if the capital stock isn’t growing then neither is output. The United States, however, has been growing for over two hundred years, so we will need to look at a better developed version of the Solow model. In particular, is there any way to escape the iron logic? Yes, better ideas can keep the economy growing even in the long run.

Solow and the Economics of Ideas in One Diagram
Let’s revisit the Solow model one last time and show how better ideas fit within that model. It’s simple: better ideas let us produce more output from the same inputs of capital. But when we produce more output, it makes sense to increase consumption and investment. So better ideas also increase capital accumulation.
Figure 7.12 shows the process in a diagram. Okay, the diagram is not so simple. Let’s take it in steps. Remember that $A$ denotes ideas and a bigger $A$ means that we are working with better ideas that increase output for the same level as capital. So imagine that we begin with $A = \text{ideas} = 1$. The economy is in the steady state and output = 15 (at point $a'$). Now suppose that $A$ increases to $A = 1.5$. Better ideas produce more output from the same capital stock, so output immediately increases from 15 at point $a'$ to 22.5 at point $b'$. But with greater output, investment also increases, moving from point $a$ to point $b$. Since investment is now greater than depreciation, capital begins to accumulate. Capital accumulates and the economy grows until investment is once again equal to depreciation at point $c$ at which point output is now 33.75 (at point $c'$).

**FIGURE 7.12**

**Better Ideas Generate More Output and More Capital Accumulation** When $A = 1$, output = 15 (at point $a'$). Having better ideas ($A = 1.5$) means that more output is produced from the same capital stock so output immediately increases from $a'$ to $b'$. Since investment $= 0.3 \times \text{Output}$, more output also means more investment so investment increases from $a$ to $b$. Since investment is now greater than depreciation, the economy begins to accumulate more capital and thus to grow. The economy grows until a new steady state is reached at point $c$ with capital stock of 506 and output = 33.75 at point $c'$. Notice that better ideas increase output directly because of higher productivity and indirectly due to more capital accumulation.

Thus, Figure 7.12 shows how the Solow model and the economics of ideas fit together. Better ideas increase output directly and by so doing they increase capital accumulation indirectly. Of course, before we ever reach the new level of output, ideas may have gotten even better! And, thus, the process
of economic growth is a continuous two-step process of better ideas and more capital accumulation.

**Growing on the Cutting Edge:**
**The Economics of Ideas**

We have learned from the Solow model that better ideas are the key to economic growth in the long run. Capital accumulation alone will not create much growth in the United States or the other developed economies such as Japan and Western Europe because these economies already have so much capital that investment is subject to a lot of depreciation. Instead, these countries are on the cutting edge; they must develop new ideas to increase the productivity of capital and labor. Thus, to better understand economic growth on the cutting edge we must turn to the economics of ideas.

We will emphasize the following:

1. Ideas for increasing output are primarily researched, developed, and implemented by profit-seeking firms.
2. Spillovers mean that ideas are underprovided.
3. Government has a role in improving the production of ideas.
4. The larger the market, the greater the incentive to research and develop new ideas.

**Research and Development Is Investment for Profit**

In Chapter 6, we emphasized that economic growth was not automatic, and we said that the factors of production do not fall from the sky like manna from heaven. In order to increase output, the factors of production must be produced and organized efficiently. All of this applies to ideas or technological knowledge just as much as to physical and human capital. Once again, incentives are the key. Economic growth requires institutions that encourage investment in physical capital, human capital, and technological knowledge (ideas).

In the United States, there are about 1.3 million scientists who research and develop new products, more than in any other country in the world, and most of these scientists and engineers, about 70 percent, work for private firms. (The ratios are broadly similar in other developed countries.)

Private firms invest in research and development when they expect to profit from their endeavors. Thus, the institutions we discussed in the last chapter—property rights, honest government, political stability, a dependable legal system, and competitive and open markets—also drive the generation of technological knowledge. When it comes to knowledge, other institutions are especially important. These institutions include a commercial setting that helps innovators to connect with capitalists, intellectual property rights such as copyright and patents, and a high-quality educational system (we will turn to these issues shortly).

It’s not just the number of scientists and engineers that matters for economic growth, as many other people come up with new ideas on their jobs, at school, or at home in their garages. Mark Zuckerberg, for example, wrote the software for Facebook as a Harvard student. Just as important, the business culture and institutions of the United States are good at connecting innovators with business people and venture capitalists looking to fund or otherwise take a chance
on new ideas. Ideas without backers are sterile. In the United States, potential innovators know that if they come up with a good idea, that idea has a good chance of making it to the market. The incentive to discover new ideas is correspondingly strong.

American culture also supports entrepreneurs. People like Apple CEO Steve Jobs, for example, are lauded in the popular media. Historically, however, entrepreneurs were often attacked as job destroyers, as the sidebar on eighteenth-century British entrepreneur John Kay illustrates.

Compared to most other countries, the United States has a very good cultural and commercial infrastructure for supporting new ideas and their conversion into usable commercial products.

Artistic innovation also requires many individuals with a diversity of viewpoints, many sources of support and employment, and businesspeople looking to profit from and support innovations. It’s not surprising, therefore, that the United States is also a leader in artistic innovation. American movies, popular music, and dance have spread around the world. But the United States is not just good at popular culture: It is also a leader in abstract art, contemporary classical composition, avant-garde fiction and poetry, and modern dance, to name just a few fields. The lesson is that artistic, economic, and scientific innovations spring from similar sources.

A further significant part of the infrastructure for creativity is property rights. We now turn to one form of intellectual property rights, patents.

**Patents** Many ideas have peculiar properties that can make it difficult for private firms to recoup their investments in those ideas. In particular, new processes, products, and methods can be copied by competitors. The world’s first MP3 player was the Eiger Labs’ MPMan introduced in 1998. Ever heard of it? Probably not. Other firms quickly copied the idea and Eiger Labs lost out in the race to innovate. Imitators get the benefit of new ideas without having to pay the costs of development. Imitators, therefore, have lower costs so they tend to drive innovators out of the market unless some barrier prevents quick imitation.

Imitation often takes time and this does give innovators a chance to recoup their investments. The Apple iPhone design, for example, is already being copied by other firms, but until that happens, Apple can exploit monopoly power to sell millions of iPhones for high profits. That is what makes Apple willing to invest in research and development in the first place and that is why the iPhone exists. Firms often compete not by offering the same product at a lower price but by offering substantially new and better products.

Apple also relies on patents to protect its innovations. A patent is a government grant of temporary monopoly rights, typically 20 years from the date of filing. Patents delay imitation, thus allowing innovative firms a greater period of monopoly power. Apple, for example, has patented one of the most distinctive features of the iPhone, the multipoint touchscreen. Apple’s patent, filed in 2004, gives Apple the right to prevent other firms from copying its technology until 2024. Still, we may well see other similar devices in the near future if Apple licenses its technology to other firms. Furthermore, competitors are finding ways to produce the same effect using different methods—a majority of patented innovations are imitated within five years.

Nevertheless, Apple’s patent gives it some monopoly power, and as you know if you studied micro first, firms with monopoly power raise prices above competitive levels. Thus, patents increase the incentive to research and develop new...
products, but also increase monopoly power once the products are created. The trade-off between creating incentives to research and develop new products while avoiding too much monopoly power is one of the trickiest in economic policy.²

Spillovers, and Why There Aren’t Enough Good Ideas

Even when a firm has a patent on its technological innovation and other firms cannot imitate in a direct way, ideas tend to spill over and benefit other firms and consumers. A new pharmaceutical will be patented, for example, but the mechanism of action—how the pharmaceutical works—can be examined and broadly copied by other firms to develop their own pharmaceuticals.

Spillovers have good and bad aspects. The good aspect of imitation or spillovers is that ideas are non-rivalrous. If you consume an apple, then I cannot consume the same apple. When it comes to eating an apple, it’s either you or me—we can’t share what we each consume so economists say that apples are rivalrous. But ideas can be shared. You can use the Pythagorean theorem and I can use the very same theorem at the very same time. The Pythagorean theorem can be shared by all of humanity, which is why economists say that ideas are non-rivalrous.

Since many ideas can be shared at low cost, they should be shared—that’s the way to maximize the benefit from an idea. The spillover or diffusion of ideas throughout the world is thus a good thing. For instance, the idea of breeding and growing corn originated in ancient Mexico but now people grow corn all over the world. Spillovers, however, mean that the originator of an idea doesn’t get all the benefits. And if the originator doesn’t get enough of the benefits, ideas will be underprovided. For this reason, while economists know that idea spillovers are good, they also know that spillovers mean that too few good ideas are produced in the first place.

To understand why spillovers mean that ideas will be underprovided, think about why firms explore for oil. Answer: to make money. So what would happen to the amount of exploration if whenever a firm struck oil, other firms jumped in and drilled wells right next door? Clearly, the incentive to explore would decline if firms didn’t have property rights to oil fields. Firms explore for ideas just like they explore for oil and if other firms can set up right next door to exploit the same field of ideas, the incentive to explore will decline.

Figure 7.13 illustrates the argument in a diagram. A profit-maximizing firm invests in research and development (R&D) so long as the private marginal benefit is larger than the marginal cost. As a result private investment occurs until point a in Figure 7.13. Spillovers, however, mean that the social benefit of R&D exceeds the private benefit so the optimal social investment is found where the marginal social benefit just equals the marginal cost at point b. Since the private benefit to R&D is less than the social benefit, private investment in R&D is less than ideal.

Government’s Role in the Production of New Ideas

Can anything be done to increase the production of new ideas? We have already mentioned one important government policy that affects the production of new ideas, namely patents. Patents reduce spillovers and thus increase the incentive to produce new ideas, but they can also slow down the spread of new ideas.
The government could also subsidize the production of new ideas. Returning to Figure 7.13, a subsidy or tax break to R&D expenditures, for example, will shift the (private) marginal cost of R&D curve down, thus increasing private investment.

The argument for government subsidies is strongest when the spillovers are largest. The modern world is founded on mathematics, physics, and molecular biology—basic ideas in these fields have many applications so spillovers can be large. But even if the social benefits to basic science are large, the private returns can be small. It’s probably easier to make a million dollars producing pizza than it is to make a million dollars producing mathematical theorems. In fact, Thomas S. Monaghan made a billion dollars producing pizza (he’s the founder of Domino’s) while mathematicians Ron Rivest, Adi Shamir, and Leonard Adleman didn’t make nearly so much on their RSA algorithm even though their algorithm is used to encrypt data sent over the Internet and thus forms the backbone for all Internet commerce.

The large spillovers to basic science suggest a role for government subsidies to universities, especially the parts of universities that produce innovations and the basic science behind innovations. Perhaps most importantly universities produce scientists. Most of the 1.3 million scientists who research and develop new products in the United States were trained in government-subsidized universities. Thus, subsidies to the hard sciences support the private development of new ideas and those initial subsidies are likely to pay for themselves many times over.

**Market Size and Research and Development**

Imagine that there are two diseases that if left untreated are equally deadly. One of the diseases is rare, the other one is common. If you had to choose, would
you rather be afflicted with the rare disease or the common disease? Take a mo-
moment to think about this question because there is a right answer.

If you don’t want to die, it’s much better to have the common disease. The
reason? The costs of developing drugs for rare and common diseases are about
the same, but the revenues are greater, the more common the disease. Pharma-
ceutical companies concentrate on drugs for common diseases because larger
markets mean more profits.

As a result, there are more drugs to treat common diseases than to treat rare
diseases, and more drugs means greater life expectancy. Patients diagnosed with
rare diseases—those ranked at the bottom quarter in terms of how frequently
they are diagnosed—are 45 percent more likely to die before age 55 than are
patients diagnosed with more common diseases.3

Larger markets mean increased incentives to invest in research and develop-
ment, more new drugs, and greater life expectancy. So imagine this, if China
and India were as wealthy as the United States, the market for cancer drugs
would be eight times larger than it is today.

China and India are not yet wealthy countries but what this thought exper-
iment tells us is that people in the United States benefit tremendously when other
countries grow rich.

Like pharmaceuticals, new computer chips, software, and chemicals also re-
quire large R&D expenditures. As India, China, and other countries including
the United States become wealthier, companies will increase their worldwide
R&D investments.

The Future of Economic Growth

Over the last 10,000 years, growth in per capita world GDP has been increas-
ing. Growth in per capita GDP was approximately zero from the dawn of civi-
lization to about 1500, increased to 0.08 percent a year between 1500 and
1760, doubled during the next hundred years, and increased even further during
the nineteenth and twentieth centuries. Today, worldwide per capita GDP
is growing at around 2.2 percent a year.

Could economic growth become even faster? Yes. Let’s take a look again at
our measure of technological progress, \( A \). We can summarize what we have said
about the factors causing \( A \) to increase in a simple equation:

\[
A(\text{ideas}) = \text{Population} \times \text{Incentives} \times \text{Ideas per Hour}
\]

In words, the number of new ideas is a function of the number of people,
the incentives to innovate, and the number of ideas per hour that each person
has. Of course, this equation is not meant to be exact—it’s just a way of think-
ing about some of the key factors driving technological growth. So let’s go
through each of the factors and think about what they imply for the future of
economic growth.

The number of people is increasing, which is good for idea generation.
More important, the number of people whose job it is to produce new ideas
is increasing. In all the world today, there are perhaps 6 million scientists and en-
gineers of which 1.3 million come from the United States. These 1.3 million
represent about one-half of one percent of the U.S. population, a surprisingly
small percentage. Yet for the world as a whole, the ratio of scientists and engineers to population is much lower.

Today, because much of the world is poor, thousands of potentially great scientists will spend most of their lives doing backbreaking work on a farm. If the world as a whole were as wealthy as the United States and could devote the same share of population to research and development as does the U.S. today, there would be more than five times as many scientists and engineers. Thus, as the world gets richer more people will be producing ideas and because of spillovers, these ideas will benefit everyone.

The incentives to innovate also appear to be increasing. Consumers are richer and the world is becoming one giant integrated market due to trade; each of these factors boosts the incentives to innovate.

The incentives to innovate also increase when innovators can profit from their investments without fear of expropriation. The worldwide improvement in institutions—that is the movement toward property rights, honest government, political stability, and a dependable legal system—has been very positive for both innovation and economic growth.

It could be that someday we will run out of new ideas, or new ideas will experience diminishing returns so the number of ideas per hour falls. When the law of diminishing returns applies to ideas as well as to capital, then economic growth will end. There are at least two reasons, however, for thinking that this day of reckoning lies far in the future.

First, many ideas make creating other ideas easier. Sadly, the authors of this book can remember the day when answering even simple questions like who won the 1969 World Series could not be answered without going to a library, consulting a card catalog (don’t ask), looking for the appropriate book in the stacks, and then (if the book hadn’t been checked out) finding the answer. Today, you can probably find the answer using Google on your cell phone faster than you can read this paragraph. (By the way, it was the New York Mets in one of the greatest upsets of baseball history.) Since we still have many new ideas about creating even more ideas, it does not seem that ideas production has come close to diminishing returns.

The second reason to think that the number of ideas per hour is not yet strongly diminishing comes from one of the pioneers of the economics of ideas, Paul Romer. (Romer is not only a distinguished theorist of ideas, he is a first-class idea entrepreneur; he started Aplia, the online economics test bank and tutorial system that many of you use and which is a good example of an idea that makes learning new ideas easier.) Romer points out that ideas for production are like recipes and the number of potential recipes in the universe is unimaginably vast.

The periodic table contains about a hundred different types of atoms, which means that the number of combinations made up of four different elements is about $100 \times 99 \times 98 \times 97 = 94,000,000$. A list of numbers like 6, 2, 1, 7 can represent the proportions for using the four elements in a recipe. To keep things simple, assume that the numbers in the list must lie between 1 and 10, that no fractions are allowed, and that the smallest number must always be 1. Then there are about 3,500 different sets of proportions for each choice of four elements, and $3,500 \times 94,000,000$ (or 330 billion) different recipes in total. If laboratories around the world evaluated 1,000 recipes each day, it would take nearly a million years to go through them all.\(^5\)
True, many of the recipes are going to be like chicken liver ice cream (not that good), but the field of ideas that we can explore is so large that diminishing returns may not set in for a very long time.

Putting all this together, economic growth might be even faster in the future than it has been in the past. There are more scientists and engineers in the world today than ever before and their numbers are increasing both in absolute terms and as a percentage of the population. The incentives to invest in R&D are also increasing because markets are getting larger due to globalization and increased wealth in developing countries such as China and India. Better institutions and more secure property rights are spreading throughout the world.

We have reason to be optimistic about the future of economic growth but, of course, nothing is guaranteed. In the twentieth century, two world wars diverted the energy of two generations from production to destruction. When the wars ended, an iron curtain isolated billions of people from the rest of the world, reducing trade in goods and ideas—to everyone’s detriment. World poverty meant that the United States and a few other countries shouldered the burden of advancing knowledge nearly alone. We must hope that this does not happen again.

**Takeaway**

The Solow model is governed by the iron logic of diminishing returns. When the capital stock is low, the marginal product of capital is high and capital accumulates, leading to economic growth. But as capital accumulates, its marginal product declines until per period investment is just equal to depreciation, and growth stops.

Despite the simplicity of the Solow model, it tells us three important things about economic growth. First, countries that devote a larger share of output to investment will be wealthier. The Solow model doesn’t tell us why some countries might devote a larger share of output to investment, but we know from Chapter 6 that wealthy countries have institutions that promote investment in physical capital, human capital, and technological knowledge. We will also say more about how financial intermediaries channel saving into investment in Chapter 8.

Second, growth will be faster the farther away a country’s capital stock is from its steady state value. This explains why the German and Japanese economies were able to catch up to other advanced economies after World War II, why countries that reform their institutions often grow very rapidly (growth miracles), and why poor countries grow faster than rich countries with similar levels of steady state output.

Third, the Solow model tells us that capital accumulation cannot explain long-run economic growth. Holding other things constant, the marginal product of physical and human capital will eventually diminish, thereby leaving the economy in a zero-growth steady state. If we want to explain long-run economic growth, we must explain why other things are not held constant.

New ideas are the driving force behind long-run economic growth. Ideas, however, aren’t like other goods: ideas can be easily copied and ideas are non-rivalrous. The fact that ideas can be easily copied means that the originator of a new idea won’t receive all the benefits of that idea so the incentive to produce ideas will be too low. Governments can play a role in supporting the production of new ideas...
by protecting intellectual property and subsidizing the production of new ideas when spillovers are most likely to be present.

The non-rivalry of ideas, however, means that once an idea is created we want it to be shared, which is a nice way of saying copied, as much as possible. There is thus a trade-off between providing appropriate incentives to produce new ideas and providing appropriate incentives to share new ideas.

An important lesson from the economics of ideas is that the larger the market, whether in terms of people or wealth, the greater the incentive to invest in research and development. Similarly, having more people and wealthier countries increases the number of people devoted to the production of new ideas. Thus, the increased wealth of many developing nations, the move to freer trade in global markets, and the spread of better institutions throughout the world are all encouraging for the future of economic growth.

**CHAPTER REVIEW**

**KEY CONCEPTS**
- Marginal product of capital, p. 117
- Steady state, p. 121
- Conditional convergence, p. 128
- Non-rivalrous, p. 132

**FACTS AND TOOLS**

1. Which countries are likely to grow faster: Countries doing “cutting-edge” growth or those doing “catch-up” growth?
2. When will people work harder to invent new ideas: When they can sell them to a market of 10,000 people or when they can sell them to a market of 1 billion? Does your answer tell us anything about whether it’s good or bad from the U.S. point of view for China and India to become rich countries?
3. Many people say that if people save too much, the economy will be hurt. They often refer to the fact that consumer spending is two-thirds of GDP to make this point. This is sometimes called the “paradox of thrift.”
   a. In the Solow model, is there a paradox of thrift? In other words, is a high savings rate good or bad for a country’s long-run economic performance?
   b. What about in the real world? According to the data in Figure 7.10, is there a paradox of thrift?
4. Many people say that “the rich grow richer and the poor grow poorer.” Is this what Figure 7.11 says about the countries in that graph? Did the rich countries grow faster or slower than the poor countries?
5. Compared to its fast growth today, is China’s economy likely to grow faster or slower in the future?
6. What is more important for explaining the standard of living in the rich countries: Capital or ideas?
7. According to Thomas Jefferson, how are ideas like flames?
8. What is a patent?
9. When will people work harder to invent new ideas: When they can patent those ideas for one year or when they can patent them for 10 years?
10. Which three countries on the list are good examples of “conditional convergence?”
    - China
    - Ireland
    - Argentina
    - North Korea
    - Greece
11. Let’s keep track of a nation’s capital stock for five years. Mordor starts off with 1,000 machines, and every year, 5 percent of the machines depreciate or wear out. Fortunately, the people in this land produce 75 machines per year,
every year. The key equation for keeping track of capital is quite simple:

Next year’s capital = This year’s capital + Investment – Depreciation

Fill in the table.

<table>
<thead>
<tr>
<th>Year</th>
<th>Capital</th>
<th>Depreciation</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,000</td>
<td>0.05 × 1,000</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>1,025</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>75</td>
<td></td>
</tr>
</tbody>
</table>

THINKING AND PROBLEM SOLVING

1. Consider the following three countries that produce GDP this way:

   \[ Y = 5 \sqrt{K} \]

   Ilia: \( K = 100 \) machines
   Caplania: \( K = 10,000 \) machines
   Hansonia: \( K = 1,000,000 \) machines

   What will GDP (\( Y \)) be in these three countries? Hansonia has 10,000 times more machines than Ilia, so why isn’t it 10,000 times more productive?

2. Consider the data in the previous question: If 10 percent of all machines become worthless every year (they depreciate, in other words), then how many machines will become worthless in these three countries this year? Are there any countries where the amount of depreciation is actually greater than GDP? (This question reminds you that “More machines mean more machines wearing out.”)

3. Of course, no country makes only investment goods like machines, equipment, and computers. They also make consumer goods. Let’s consider a case where the countries in question 1 devote 25 percent of GDP to making investment goods (so \( \gamma, \text{ gamma,} = 0.25 \)). What is the amount of savings in these three countries? In which countries is Investment < Depreciation? When is Investment > Depreciation?

4. A drug company has $1 billion to spend on research and development. It has to decide on one of two projects:

   a. Spend the money on a project to fight deadly forms of influenza including bird flu.
   b. Spend the money on a project to fight a condition of red, itchy skin known as eczema.

   The company expects both projects to be equally profitable, all things considered: Yes, project A is riskier (since the rare flu may never come along), but if the disease hits, there will be a worldwide market willing to pay a lot of money to cure the flu.

   Then one day, before deciding between A and B, the drug company’s CEO reads in the newspaper that the European Union and the United States will not honor patents in the event of a major flu outbreak. Instead, these governments will “break the patent” and just make the drug available everywhere for $1 per pill. The company will only get $1 per pill instead of the $100 or $200 per pill they had expected.

   Given this new information about the possibility that governments will “break the patent,” which project is the company likely to spend its research and development money on? (Note: In the wake of the deadly anthrax attacks of 2001, the U.S. government threatened to do just this with the patent for Cipro, the one antibiotic proven to cure the symptoms of anthrax infection.)

5. After World War II, a lot of France’s capital stock was destroyed, but it had educated workers and a market-oriented economy. Do you think the war’s destruction increased or decreased the marginal product of capital?

6. In the Solow model, you’ve seen that as the total stock of capital equipment gets larger, the number of machines wearing out grows as well. Often, most investment ends up just replacing worn-out machines. This is actually true in the United States and other rich countries. According to the U.S. National Income and Product Accounts (the official U.S. GDP measures), about 12 percent of total GDP just goes toward replacing worn-out machines and computers and construction equipment.

   a. In the Solow model, if the depreciation rate increases, what happens to the steady state capital level and output level? Answer in words and by using a diagram such as Figure 7.4. (Bonus: if the depreciation rate
increases from 0.02 to 0.03 what is the new steady state level of capital and output?)

b. If the Solow model explains an important part of the real world, should countries hope for high depreciation rates or low depreciation rates? How does this square with the observation that when machines wear out, that “creates jobs” in the manufacturing industries?

7. The Solow model isn’t useful for only thinking about entire countries: As long as the production function runs into diminishing returns and your total stock of inputs constantly wears out, then the Solow model applies. Consider a professor’s knowledge of economics. The more she learns about economics, the more she will forget (depreciation), but the more she knows, the more knowledge she can create (production). So eventually in steady state, she will know only a fixed amount about economics, but what she knows might change over time; some decades she might know a lot about the Federal Reserve while other decades she might know a lot about the electricity market. In any case, knowledge fades away.

a. Apply the Solow model to a chef’s skill at cooking.

b. Apply the Solow model to the size of a navy’s fleet of ships.

c. Apply the Solow model to the speed of a cheetah, where the input is calories.

8. Many inventors decide that patents are a bad way to protect their intellectual property. Instead, they keep their ideas a secret. Trade secrets are actually quite common: The formula for Coca-Cola is a trade secret, as is Colonel Sanders’ secret recipe. What is one major strength of keeping a trade secret rather than applying for a patent? What is a major weakness inherent in going down the trade secret route?

9. Since ideas can sometimes be copied quite easily, many people think that we should put more effort into creating new ideas. Let’s see if there are trade-offs to having more people creating new ideas. To keep things simple, let’s assume that the growth rate of the economy depends on how many people search for ideas, whether in laboratories, or huddled over laptops in coffee shops, or while listening to “Stairway to Heaven” at three in the morning. People either produce stuff or produce ideas. Here’s how this economy works:

\[
Y_t = (1 - R) \times A_t L_t \quad \text{(GDP production function)}
\]

\[
A_{t+1} = (1 + R) \times A_t \quad \text{(Technology production function)}
\]

There are a total of \(L\) people in the society, a fraction \((1 - R)\) of them work in factories and offices making stuff (remember, people working in offices help create output too!), while the remaining fraction \(R\) try to come up with good ideas all day long. To keep the story simple, there are no diminishing returns.

a. What’s the trade-off here? If 100 percent of the people work to make new ideas \((R = 1)\), won’t that create a prosperous world?

b. In this society, if people are willing to wait a long time for a reward, should they choose a large \(R\) or a small \(R\)?

c. Plot out GDP in this society for 5 years if \(A\) starts off at 100, \(L\) starts off at 100, and \(R\) is 10 percent.

<table>
<thead>
<tr>
<th>Year</th>
<th>(A)</th>
<th>(Y)</th>
<th>(Y/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>9,000</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
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<td></td>
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<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
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</tbody>
</table>

d. Plot out GDP in this society if the society instead chose \(R = 20\) percent.

10. In Facts and Tools question 2, we saw that big markets create a big demand for inventions. This is an example of what Adam Smith meant when he said that “the division of labor is limited by the extent of the market.” Now let’s look at how big markets impact the supply side of inventions. The big idea is quite simple: More people means more ideas.

a. In order to create new ideas, you need to have people trying to come up with new ideas. In 1800, there were approximately 300 million humans on the planet—roughly equal to today’s U.S. population. If good ideas are “one in a million,” that is, if one person per year out of a million comes up with a world-shaking idea like contact lenses
or James Brown’s song “The Payback” or the video game Grand Theft Auto, how many great new ideas will occur in the world of 1800? How many will occur in a world of 6 billion people?

b. More realistically, people in the rich countries are most likely to invent earth-shaking ideas and share them with others. There’s nothing special about people in rich countries but they have the education and the laboratories and the Internet connections that will make it practical to invent and spread ideas. If only the top 20 percent of the earth’s population is really in the running to create new ideas, how many new big ideas will come along each year in 1800 and today?

c. If half of the population of India and China become rich enough to create new ideas (to simplify assume populations of 1 billion each), and start coming up with big ideas at the same rate as the top 20 percent, how many big ideas will India and China alone create for the planet every year?

d. Many people think there are too many people on the planet. (As P. J. O’Rourke once wrote, many people’s attitude toward global population is “Just enough of me, way too much of you.”) Look at your answer from part b. If the world’s population now gets cut in half from the current 6 billion, how many big ideas will come along each year?

11. According to economists Robert Barro and Xavier Sala-i-Martin, convergence isn’t just for entire nations: It’s also true for states and regions as well. They looked at state-level GDP per capita in the United States in 1880, and then calculated how fast each state grew over the next 120 years. They found that convergence held almost exactly.

a. With this in mind, draw arrows to connect the GDP per capita data on the left with the long-term growth rates on the right.

<table>
<thead>
<tr>
<th>GDP per capita in 1880</th>
<th>Annual growth rate, 1880–2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>West: $8,500</td>
<td>1.6%</td>
</tr>
<tr>
<td>East: $6,300</td>
<td>1.7%</td>
</tr>
<tr>
<td>Midwest: $4,700</td>
<td>2.2%</td>
</tr>
<tr>
<td>South: $2,800</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

b. Graph the data from part a in the figure below. Does this look like Figure 7.11’s story about the OECD countries, or is it quite different?

![Graph](image)

Note: Barro and Sala-i-Martin also found that convergence also held almost exactly for regions of Japan: The areas that were poorest in 1930 grew fastest over the next 70 years. Thus, it is difficult to find major evidence in favor of the commonsense idea that “the poor areas grow poorer.”

12. Are we running out of ideas? Economist Paul Romer thinks not. To make things concrete, he notes that if we keep trying out different molecules to search for interesting compounds like new drugs, new plastics, etc., the universe may end from heat death before we finish our search. For example, if we try out 100 different atoms out of the 117+ (and rising!) elements in the periodic table, and only look at the 6-atom molecules, this is 100^6 different molecules. And, of course, many common molecules in our bodies consist of hundreds of atoms, so this only scratches the surface of interesting compounds.

a. If it takes a machine 1 minute to test out and fully analyze a new 6-atom molecule, how many years will it take for this one machine to test out all 100^6 molecules? (Note: Modern biochemists create computer simulations of molecules to analyze whether potential drugs are likely to work in the molecules that make up the human body, but this is only one narrow form of analysis.)

b. How many machines would it take to test out all of these molecules within 100 years?
c. What about all 10-atom molecules: How many years would it take for one machine to test all of these compounds at one per minute? If your computer can handle it, what about all 100-atom molecules, molecules vastly simpler than many proteins in your body?

**Challenges**

1. Which country would you expect to have a higher rate of investment: A catch-up country or a cutting-edge country?

2. If the government of a poor catch-up country is trying to decide whether to encourage investment or encourage research and development, which of the two should it favor? (Note: in a world of trade-offs, you can't just say "Both are important!")

3. The Solow model makes it quite easy to figure out how rich a country will be in its steady state. We already know that you're in a steady state when investment equals depreciation. In math, that's:

\[ \gamma Y = \delta K \]

Since \( Y = \sqrt{K} \) in our simplest model, that means that \( K = Y^2 \):

\[ \gamma Y = \delta Y^2 \]

There are a lot of ways to solve this for \( Y \)—the easiest might just be to divide both sides by \( Y \), and then put everything else on the other side. When you do this, you can learn how steady state GDP depends on the savings rate \( \gamma \) and the depreciation rate \( \delta \). Here are a few questions:

a. Many people say that if people save more, that's bad for the economy: They say that spending money on consumer goods keeps the money moving through the economy. Does this model say that?

b. Many people say that when machines and equipment get destroyed by bad weather or war, that makes the economy better off by encouraging businesses and families to spend money on new capital goods. Does this model say that?

4. Let's think about two countries, Frugal and Smart. In Frugal, people devote 50 percent of GDP to making new investment goods, so \( \gamma = 0.5 \), and their production function is \( Y = \sqrt{K} \). In Smart, people devote 25 percent of GDP to making new investment goods, so \( \gamma = 0.25 \), and their production function is \( Y = 2\sqrt{K} \). Both countries start off with \( K = 100 \).

a. What is the amount of investment in each country this year?

b. What is the amount of consumption (GDP – Investment, or \( Y – I \)) in each country this year?

c. Where would you rather be a citizen: Frugal or Smart?

5. Which of the following goods are non-rivalrous?

- Sunshine
- An apple
- A national park
- A Mozart symphony
- The idea of penicillin
- A dose of penicillin

6. According to economist Michael Kremer, as human populations have grown over the last million years, so has the human population growth rate. This was true until the 1800s. How does Thinking and Problem Solving question 10 help explain why human populations grew faster despite the fact that there were more mouths to feed?
CHAPTER APPENDIX

Excellent Growth

Using a spreadsheet, you can easily explore the Solow model and duplicate all
the graphs in this chapter. First, label column A, “Capital, K” and put a 1 in cell
A2. Second, you can create an increasing series by inputting the formula
“=A2+1” in cell A3 and copying and pasting that formula into cells A4 to say
A500. Your spreadsheet should look like Figure A7.1.

In column B, create a series for Output. Remember that Y = \sqrt{K}, so in cell
B2 input the formula “=SQRT(A2)” and then copy and paste that formula into
B3 to B500, as in Figure A7.2.

Now create the headings Investment, Depreciation, Investment Share, and
Depreciation Rate in columns C to F—like in Figure A7.3.

In cell E2, put the investment share, 0.3, used in the text and in cell F2 put
the rate of depreciation that we used, 0.02.

In cell C2, which is highlighted, we want to input the formula for invest-
ment, which is \gamma Y, where \gamma is the investment share. We could input “=0.3*B2”
into C2 but we would like to be able to easily adjust the investment share and
see what happens, so we will input “=$E$2*B2”. The $E$2 says take the invest-
ment share from cell E2 and when we copy and paste this formula it always uses
cell E2 (not E3, E4, etc.). Copy and paste cell C2 into C3 to C500.
### Figure A7.2

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### Figure A7.3

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\[ \text{C2} = \$\text{E2} \times \text{B2} \]
Depreciation is just $\delta K$, where $\delta$ is the depreciation rate. As with investment, we might want to alter this parameter so into cell D2 we will input “=$F$2*A2”.

That’s it! To duplicate the graph in Figure 7.4, for example, just highlight columns A, B, C, and D, click the Chart icon (you can also click Chart in the Insert menu), choose XY (Scatter) and the highlighted sub-type, and then click on finish. (In Excel 2007 click Insert and then Scatter in the Chart submenu to do the same thing.) See Figure A7.4.

The result is as in Figure A7.5.

If you want to see what happens if the investment share increases to 0.4, as in Figure 7.9 in the chapter, just change cell E2 to 0.4 and the graph will change automatically. You can make other adjustments as well. One thing to watch for is that with parameters too different than the ones we have given, the equilibrium capital stock may be greater than 500. So if you want to see the full picture, you will need to extend the rows even further.
CHAPTER EXCEL APPENDIX QUESTION

1. Use the instructions in the appendix to set up the Solow model in Excel with the Investment Share, $\gamma$, equal to 0.3 and with the Depreciation Rate, $\delta$, equal to 0.02. Both numbers are just what we used in the chapter. Now increase the Investment Share to 0.36.

   a. What is the new level of steady state capital? (Remember, the level of steady state capital is where Investment = Depreciation.)

   b. At the new steady level of capital what is the level of output, $Y$?

Now change the Investment Share back to 0.3 and this time increase the Depreciation Rate to 0.025.

   c. What is the new level of steady state capital?

   d. At the steady state level of capital what is the level of output, $Y$?

   e. Fill in the blanks with your conclusions:
      An increase in the investment share _____ the steady state level of capital and output.
      An increase in the depreciation rate _____ the steady state level of capital and output.