theory of economic growth that helps answer these and many other questions. The theory of economic growth tells us that increases in hours worked can increase the growth of real GDP, but not the growth of real GDP per hour of work. To explain the growth of productivity, we must focus on the two other factors: capital and technology. Capital raises real GDP per hour of work by giving workers more tools and equipment to work with. As we will show in this chapter, however, capital alone is not sufficient to achieve the growth we have seen over the past 200 years. Technology—the knowledge and methods that underlie the production process—also has played a big role.

Understanding the role of capital and technology enables economists to better evaluate the advantages and disadvantages of various economic policies to improve economic growth. For example, should economic policies designed to stimulate economic growth focus more on capital or more on technology? The U.S. economy has benefited from yet another resurgence of productivity growth in the past 10 years. What economic policy will best maintain this high rate of productivity growth?

**Labor and Capital without Technology**

To better understand the important role played by technology in driving economic growth, we begin with a simplified theory in which economic growth depends only on labor and then consider a theory in which it depends on labor and capital.

**Labor Alone**

Suppose real GDP depends only on labor. That is, the amount of output in the economy can be described by the production function \( Y = F(L) \), where \( Y \) is real GDP and \( L \) is labor input. When labor input increases, real GDP increases.

To understand this production function for the whole economy, it helps to consider the production of a single good. Imagine workers on a one-acre vineyard planting, maintaining, and harvesting grapes, and suppose that the only input that can be varied is...
labor. With more workers, the vineyard can produce more grapes, but according to the
simple story that output depends only on labor, the vineyard cannot increase capital
because there is no capital. For example, the vineyard cannot buy wagons or wheel-
barrows to haul fertilizer around. The only way the vineyard can increase output is by
hiring more workers to haul the fertilizer.

Now, suppose all this is true for the economy as a whole. The firms in the economy can
produce more output by hiring more workers, but they cannot increase capital. The situation
is shown for the entire economy in Figure 21-2. On the vertical axis is output. On the horizon-
tal axis is labor input. The curve shows that more labor can produce more output. The curve is
a graphical plot of the aggregate production function \( Y = F(L) \) for the whole economy.

**Diminishing Returns to Labor** The shape of the curve in Figure 21-2 is impor-
tant. The flattening out of the curve shows **diminishing returns** to labor: The greater the
number of workers used in producing output, the less the additional output that comes from
each additional worker. Consider production of a single good again, such as grapes at the
vineyard. Increasing employment at the one-acre vineyard from one to two workers raises
production more than increasing employment from 1,001 to 1,002 workers. A second
worker could take charge of irrigation or inspect the vines for insects while the first worker
harvested grapes. But with 1,001 workers on the vineyard, the 1,002nd worker could find
little to do to raise production. Diminishing returns to labor exist because labor is the only
input to production that we are changing. As more workers are employed on the same

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**Figure 21-2**

**Only Changes in Labor Can Change Output**
The curve shows the production function \( Y = F(L) \), where \( Y \) is
output and \( L \) is labor input (hours of work). In this theory, capital
and technology are out of the picture. With more labor working
on a fixed supply of land, there are diminishing returns, as
shown by the curvature of the production function.
one-acre plot, the contribution that each additional worker makes goes down. Adding one worker when only one worker is employed can increase production by a large amount. But adding one worker when 1,001 already are working on the one-acre plot cannot add as much. For the same reasons, diminishing returns to labor exist for the whole economy.

**Adding Capital**

Now let us add capital to the production function. The total amount of capital in the economy increases each year by the amount of net investment during the year. More precisely,

\[
\text{Capital at the end of this year} = \text{net investment during this year} + \text{capital at the end of last year}
\]

For example, if $10,000 billion is the value of all capital in the economy at the end of last year, then $100 billion of net investment during this year would raise the capital stock to $10,100 billion by the end of this year. This is a 1 percent increase in the capital stock.

With capital as an input to production, the production function becomes \( Y = F(L, K) \), where \( K \) stands for capital. Output can be increased by using more capital, even if the amount of labor is not increased. Consider the vineyard example again. If a wheelbarrow is bought to haul the fertilizer around the vineyard, the vineyard can produce more grapes with the same number of workers. More capital at the vineyard increases output. The same is true for the economy as a whole. By increasing the amount of capital in the economy, more real GDP can be produced with the same number of workers.

Figure 21-3 illustrates how more capital raises output. The axes are the same as those in Figure 21-2, and the curve again shows that more output can be produced by

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**Figure 21-3**

**Capital Is Also a Factor of Production**

The axes in this figure are just like those in Figure 21-2, but now if more capital is added to production, more output can be produced with the same labor input. For example, when labor input is at Point A, more output can be produced with more capital.
more labor. But, in addition, Figure 21-3 shows that if we add capital to the economy—by investing a certain amount each year—the relationship between output and labor shifts up: More capital provides more output at any level of labor input. To see this, pick a point on the horizontal axis, say, Point A, to designate a certain amount of labor input. Then draw a vertical line up from this point, such as the dashed line shown in Figure 21-3. The vertical distance between the curve marked “Less capital” and the curve marked “More capital” shows that additional capital raises production.

**Diminishing Returns to Capital**  Figure 21-4 also shows *diminishing returns to capital*. Each additional amount of capital—another wheelbarrow or another hoe—results in a smaller addition to output. Hence, the gaps between the several production functions in Figure 21-4 get smaller and smaller as more capital is added. As more capital is added, the ability to increase output per worker reduces. Compare adding one wheelbarrow to the vineyard without any wheelbarrows with adding one wheelbarrow to the vineyard that already has 50 wheelbarrows. Clearly, the 51st wheelbarrow would increase farm output by only a minuscule amount, certainly much less than the first wheelbarrow. A one-acre vineyard would not even have much room for the 51st wheelbarrow.

Diminishing returns to capital also occur for the economy as a whole. Thus, adding more capital per worker cannot raise real GDP per worker above some limit, and even getting close to that limit will require an enormous amount of capital. Eventually, growth in output per hour of work will stop.

Thus, labor and capital alone cannot explain the phenomenal growth in real GDP during the last 200 years.

*Figure 21-4*

**Capital Has Diminishing Returns Also**
As capital per worker increases, each additional unit of capital produces less output. Thus, there is a limit to how much growth per worker additional capital per worker can bring.
Technology: The Engine of Growth

We have seen that growth driven by increases in capital and labor, although important, is not sustainable. Diminishing returns imply that the additional output obtained by increasing these inputs becomes smaller and smaller, eventually leading to no further economic growth. For output to grow over the very long run, we need not just to increase inputs, but also to get more output from existing inputs. Technology is what enables us to get more output from a given quantity of inputs.

What Is Technology?

Technology is difficult to define, envision, and measure. A broad definition of technology is that it is anything that raises the amount of output that can be produced with a given amount of labor and capital. (Ch. 17)

The Role of Technology in Economic Growth

In the twenty-first century’s highly automated world, the image (left) of women in long skirts packing fruit delicacies into glass jars in the mid- to late 1800s seems quaint beside the image (right) of robotic arms in an assembly line at this modern-day car plant. Yet both represent huge leaps in industrial productivity at different periods of history. Capital and technology played critical roles in the development of each of these increasingly more efficient methods of production.
amount of inputs (labor and capital). In essence, technology is the stock of knowledge or ideas that exist in an economy: the ideas that help produce goods and services such as baby clothes, wine, and television shows; the ideas that help save lives, such as penicillin, vaccines, and heart transplants; and the ideas that help us communicate around the world, such as cell phones and the Internet.

When we add technology to capital and labor, we have the modern theory of economic growth. The theory can be summarized by the now familiar aggregate production function

\[ Y = F(L, K, T) \]

where \( T \) stands for technology. Increases in technology therefore will increase output. Such increases in technology are termed technological progress. We sometimes use the term technological change instead of technological progress.

**Invention, Innovation, and Diffusion** Technological change occurs when new ideas are developed into new products that increase production, such as the steel plow, the harvester, the combine, the automobile, radar, the telephone, the computer, the airplane, lasers, and fiber-optic cable. Economists distinguish between an invention, which is the
discovery of new knowledge or a new principle, such as electricity, and innovation, in which the new knowledge is brought into application with a new product, such as the electric light-bulb. Economists also distinguish between the innovation itself and the diffusion of the innovation throughout the economy, a process that involves advertising, marketing, and spreading the innovation to new uses, such as the use of the electric lightbulb to create night shifts in factories.

The sewing machine is a good illustration of invention, innovation, and diffusion. By 1847, inventors had built 17 different machines capable of mechanically forming a stitch. But only one of these, Elias Howe’s sewing machine, developed into a commercially successful innovation. As Howe tried to sell his invention to consumers, he discovered how to modify it to make it more useful and attractive. Soon the invention turned into a popular innovation that was used widely. Wide diffusion of the innovation occurred as others produced household versions of the sewing machine, like the one marketed by the Singer Company. This example also illustrates that innovation and diffusion require the work of an entrepreneur who recognizes the potential of the invention.

Technology depends in part on scientific knowledge, and many people feel that science will become more and more important in driving future technological change. But technology is much more than scientific knowledge. The discovery of DNA did not improve technology until it was applied to genetic engineering. The knowledge of mathematics made the invention and development of computers possible, a technology that obviously has improved productivity.

**Organization and Specialization** Technology also includes the way firms are organized. Better organization schemes can mean a smaller bureaucracy and more output per hour of work without the addition of capital. More efficient organization can improve the flow of information within a firm and thereby affect labor productivity. Better incentive programs that encourage workers to communicate their ideas to management, for example, increase productivity.

Henry Ford’s idea of the assembly line greatly increased the productivity of workers. The assembly line enabled the car to come to the worker rather than having the worker go to the car. Thus, each worker could specialize in a certain type of activity; through specialization, productivity increased. The assembly line alone is estimated to have reduced the time it took a group of workers to produce a car from 12.5 hours to 0.5 hours. Productivity increased, and so too did wages.

New technology can affect how labor and capital are used at a firm. Economists distinguish between labor-saving and capital-saving technological change. Labor-saving technological change means that fewer workers are needed to produce the same amount of output; capital-saving technological change means that fewer machines are needed to produce the same amount of output. An example of a labor-saving technological change would be a steam-powered tractor replacing a horse-drawn plow, and later gasoline power replacing steam power, enabling the same worker to plow many more acres. An example of a capital-saving technological change is the night shift. Adding two crews of workers—one working in a steel mill from 4 P.M. to midnight and another working from midnight to 8 A.M.—makes the same steel-making furnaces three times as productive as when the working hours are only from 8 A.M. to 4 P.M.

Specialization of workers at a firm adds to productivity. Adam Smith emphasized the importance of specialization in his Wealth of Nations; his term division of labor refers to the way a manufacturing task could be divided among a group of workers, each of whom would specialize in a part of the job.

Because specialization permits workers to repeat the same task many times, their productivity increases, as in the old adage “practice makes perfect.” Each time the task is repeated, the worker becomes more proficient—a phenomenon that economists call
**learning by doing**

The commonsense principle of learning by doing is that the more one does something, the more one learns about how to do it. For example, as the number of airplanes produced of a particular type—say, a Boeing 777—increases, the workers become more and more skilled at producing that type of airplane. Careful studies of aircraft production have shown that productivity increases by 20 percent for each 100 percent increase in output of a particular type of plane. This relationship between learning and the amount of production is commonly called the “learning curve.” Learning is a type of technological progress.

**Human Capital**

Many firms provide training courses for workers to increase their skills and their productivity. *On-the-job training* is a catchall term for any education, training, or skills a worker receives while at work.

Most workers receive much of their education and training before they begin working, whether in grade school, high school, college, or professional schools. Because increases in education and training can raise workers’ productivity, such increases are considered another source of technological change.

The education and training of workers, called **human capital** by economists, is similar to physical capital—factories and equipment. To accumulate human capital—to become more educated or better trained—people must devote time and resources, much as a firm must devote resources to investment if physical capital is to increase.

The decision to invest in human capital is influenced by considerations similar to those that motivate a firm to invest in physical capital: the cost of the investment versus the expected return. For example, investing in a college education may require that one borrow the money for tuition; if the interest rate on the loan rises, then people will be less likely to invest in a college education. Thus, investment in education may be negatively related to the interest rate, much as physical investment is. Thus, to encourage more education and thereby increase economic growth and productivity, the U.S. government provides low-interest loans to college students, making an investment in college more attractive. We will return to the government’s role in education as part of its broader policy to increase economic growth later in the chapter.

**The Production of Technology: The Invention Factory**

Technology sometimes is discovered by chance by a lone inventor and sometimes by trial and error by an individual worker. A secretary who experiments with several different filing systems to reduce search time or with different locations for the computer, the printer, the telephone, and the photocopier is engaged in improving technology around the office. Frequently, technological progress is a continuous process in which a small adjustment here and a small adjustment there add up to major improvements over time.

But more and more technological change is the result of huge expenditures of research and development funds by industry and government. Thomas Edison’s “invention factory” in Menlo Park, New Jersey, was one of the first examples of a large industrial laboratory devoted to the production of technology. It in turn influenced the development of many other labs, such as the David Sarnoff research lab of RCA. Merck & Co., a drug company, spends nearly $1 billion per year on research and development for the production of new technology.

Edison’s Menlo Park laboratory had about 25 technicians working in three or four different buildings. In the six years from 1876 to 1882, the laboratory invented the lightbulb, the phonograph, the telephone transmitter, and electrical generators. Each of these inventions turned out to be a successful innovation that was diffused widely.
For each innovation, the Federal government granted a **patent**. A patent indicates that the invention is original and gives the inventor the exclusive right to use it until the patent expires. To obtain a patent on the rights to an invention, an inventor must apply to the Patent and Trademark Office of the Federal government. Patents give inventors an inducement to invent. The number of patents granted is an indicator of how much technological progress is going on. Edison obtained patents at a pace of about 67 a year at his lab.

Edison’s invention factory required both labor and capital input, much like factories producing other commodities. The workers in such laboratories are highly skilled, with knowledge obtained through formal schooling or on-the-job training—human capital. A highly trained workforce is an important prerequisite to the production of technology.

The supply of technology—the output of Edison’s invention factory, for example—depends on the cost of producing the new technology, which must include the great risk that little or nothing will be invented, and the benefits from the new technology: how much Edison can charge for the rights to use his techniques for making lightbulbs. Inventive activity often has changed as a result of shifts in the economy that change the costs and benefits. For example, increases in textile workers’ wages stimulated the invention of textile machines, because such machines yielded greater profits by enabling the production of more output with fewer workers.
Special Features of Technology

Technology has two special qualities. The first is nonrivalry. This means that one person’s use of the technology does not reduce the amount that another person can use. If one university uses the same student registration system as another university, that does not reduce the quality of the first university’s system. In contrast, most goods are rivals in consumption: If you drink a bottle of Coke, one fewer bottle of Coke is available for other people to drink.

The second feature of technology is nonexcludability. This occurs when the inventor or the owner of the technology cannot exclude other people from using it (see the Economics in Action box on p. 553). For example, the system software for Apple computers shows a series of logos and pull-down menus that can be moved around the screen with a mouse. The idea easily could be adapted for use in other software programs by other companies. In fact, the Windows program of Microsoft has features similar to those of the Apple software, but according to the court that ruled on Apple’s complaint that Microsoft was illegally copying, the features were not so similar that Microsoft could not use them. If the court had ruled in favor of Apple, then Apple could have excluded Microsoft from using the Apple features.

As the example of Apple and Microsoft shows, the legal system determines in part the degree of nonexcludability. Trademarks, copyrights, and patents help inventors exclude others from using their inventions without compensation. But it is impossible to exclude others from using much technology.

Thus, technology may spill over from one activity to another. If your economics teacher invents a new way to teach economics on a computer, it might spill over to your chemistry teacher, who sees how the technology can be applied to a different subject. Spillovers sometimes occur because research personnel move from one firm to another. Henry Ford knew Thomas Edison and was motivated to experiment on internal-combustion engines by Edison. Hence, Edison’s research spilled over to another industry, but Edison would have found it difficult to receive compensation from Henry Ford even if he had wanted to.

Because inventors cannot be fully compensated for the benefits their ideas provide to others, they may produce too little technology. The private incentives to invent are less than the gain to society from the inventions. If the incentives were higher—say, through government subsidies to research and development—more inventions might be produced. Thus, the government has a potential role to play in providing funds for research and development, both in industry and at universities.

**REVIEW**

- Technological change has a broad definition. It is anything that increases production for a given level of labor and capital. Technological change has been an essential ingredient in the increase in the growth of real GDP per hour of work in the last 200 years.
- Technology can be improved by the education and training of workers—investment in human capital. Technology also can be improved through inventions produced in industrial research laboratories, as well as by trial and error. In any case, the level of technology is determined by market forces.
- But technology exhibits nonrivalry in consumption and a high degree of nonexcludability. These are precisely the conditions in which an underproduction of technology will occur.