

# The Third Industrial Revolution: Technology, Productivity, and Income Inequality

by Jeremy Greenwood

Jeremy Greenwood is a professor of economics at the University of Rochester. Thanks go to Marvin Kosters for his helpful comments. This article is based on "1974," a paper written in collaboration with Mehmet Yorukoglu, who played a vital role in pursuing this line of research. This article was also published as a monograph, under the title used here, by the American Enterprise Institute (1997).

## Introduction

Did 1974 mark the beginning of a third industrial revolution—an era of rapid technological progress associated with the development of information technologies? Did the quickened pace of technological advance lead to greater income inequality? Is a productivity slowdown related to these phenomena?

The story told here connects the rate of technological progress with the level of income inequality and productivity growth. Imagine that a leap in the state of technology occurs and is embodied in new machines, such as those used in information technologies (IT). Now suppose that adopting these technologies involves a significant cost in terms of learning, and that skilled workers have an advantage at learning. Then the advance in technology will be associated with an increased demand for the skills needed to implement them. Hence, the wages of skilled labor relative to unskilled labor (the skill premium) will rise, and income inequality will increase. In their early phases, new technologies may not operate efficiently due to inexperience. The initial incarnation of ideas into equipment may be far from ideal. Productivity growth may seem to stall as the economy

makes the (unmeasured) investment in knowledge needed if the new technologies are to approach their full potential. The coincidence of rapid technological progress, widening wage inequality, and a slowdown in productivity growth has precedents in economic history.

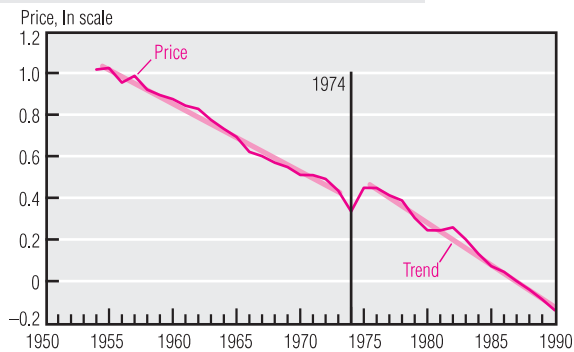
## I. The Information Age

Figure 1 shows the price of a piece of new producer equipment relative to the price of a unit of nondurable consumer goods or services over the period following World War II. The marked drop in the relative price of producer equipment is a reflection of the high rate of technological progress in the producer-durables sector. Specifically, technological progress enables ever-larger quantities of investment goods to be produced with a given amount of labor and capital, a process that drives down the prices of such goods. This type of advance is dubbed *investment-specific* technological progress because it affects the investment-goods sector of the economy.

The price of equipment fell faster after 1974 than before, as the slope of the trend line shows. If the decline in new equipment prices

FIGURE 1

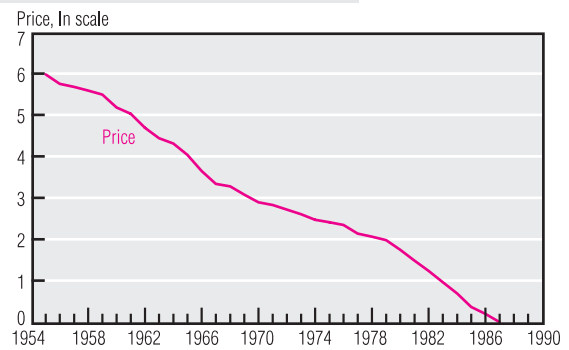
## Price of New Equipment



SOURCE: Greenwood, Hercowitz, and Krusell (1997).

FIGURE 2

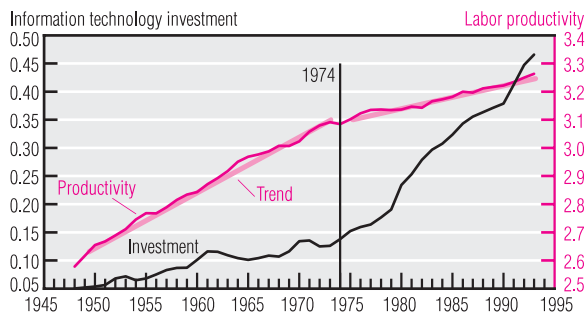
## Price of New Computers



SOURCE: Yorukoglu (1998).

FIGURE 3

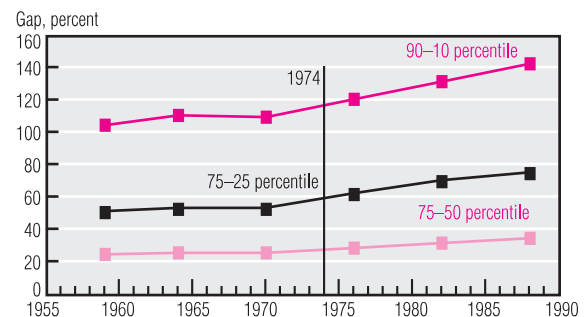
## IT Investment and the Productivity Slowdown



SOURCES: National Income and Product Accounts; and Citibase.

FIGURE 4

## Measures of Wage Inequality



SOURCE: Juhn, Murphy, and Pierce (1993).

can be taken as a measure of improved efficiency in production, then the pace of technological advance jumped up around 1974. Some economists estimate that 60 percent of postwar U.S. growth may derive from the introduction of new, more efficient equipment.<sup>1</sup> The rapid advance in technology since 1974 is undoubtedly linked to IT development. The price of a new computer has plummeted over the postwar period at an average rate of about 19 percent annually (see figure 2).<sup>2</sup> Hence, a new computer costing \$5,000 in 1987 would have been priced at \$2 million in 1955. Figure 3 illustrates the phenomenal rise of IT investment as a fraction of total equipment investment (less than 7 percent in 1954 compared with 50 percent now).

Growth in labor productivity stalled with the rise in IT investment, as figure 3 also shows. Labor productivity, which gauges the amount of gross domestic product (GDP) created per

hour of work, is often taken as a measure of how efficient labor is in the economy. The more GDP each worker can produce, the better off the economy is. Before 1974, labor productivity grew at about 2 percent annually; after that year, at a paltry 0.8 percent. This change is often termed the “productivity slowdown.” Isn’t it paradoxical that at a time of massive technological advance resulting from the introduction of information technologies and the like, the advance in a worker’s productivity should stall?

By most accounts, wage inequality began to increase around 1974 (figure 4 shows some postwar measures of income inequality).<sup>3</sup> The

■ 1 Greenwood, Hercowitz, and Krusell (1998) break down U.S. postwar growth into its sources in terms of investment-specific and other forms of technological progress.

■ 2 Yorukoglu (1998).

■ 3 The data are from Juhn, Murphy, and Pierce (1993, table 1.B).

percentage gap between the average wage earned by the upper quartile (above the seventy-fifth percentile) and the average wage earned by the lower quartile (the twenty-fifth percentile and below) remained roughly constant between 1959 and 1970. From 1970 to 1988, this gap increased 22 percentage points. That is, the 53 percent gap in wage income that existed between the two groups in 1970 had widened to 75 percent by 1988. The other measures behaved similarly.

## II. The Industrial Revolution

The Industrial Revolution, which began in 1760, epitomizes investment-specific technological progress. This period witnessed the birth of several technological miracles.<sup>4</sup> Crompton's mule revolutionized the spinning of cotton. Next, Watt's energy-efficient engine brought steam power to manufacturing. The main cost of a steam engine was operating it: It was a hungry beast. A Watt steam engine cost £500–800.<sup>5</sup> Operating a steam engine, though, was enormously expensive. Each consumed £3,000 of coal per annum.<sup>6</sup> By comparison, 500 horses, which apparently could produce the same amount of work, cost only £900 in feed. Thus, the pursuit of an energy-efficient steam engine was on. The older Newcomen steam engine of 1769 needed 30 pounds of coal per horsepower hour, while a Watt engine of 1776 required 7.5 pounds. By 1850 or so, this number had been reduced to 2.5. So the cost of steam power fell dramatically over the course of the Industrial Revolution. When the spinning mule was harnessed to steam power, the mechanization of manufacturing was inexorable. By 1841, the real price of spun cotton had fallen by two-thirds.

In 1784, Cort introduced his puddling and rolling technique for making wrought iron, a product vital for the industrialization of Britain. Between 1788 and 1815, wrought iron production increased 500 percent. Its price fell from £22 to £14 per ton from 1801 to 1815, even though the general price level rose 50 percent between 1770 and 1815.

Last, the foundation of the modern machine-tool industry was laid when Wilkinson designed a gun-barreling machine that could make cylinders for Watt's steam engines, and Maudley introduced the heavy-duty lathe.

Skill undoubtedly played an important role in technological innovation and adoption. The Industrial Revolution produced a handful of miracles, but many historians also view it as an

age of continuous and gradual smaller innovations—an age of learning. Implementing and operating brilliant inventions and effecting the subsequent innovations is often demanding, skill-intensive work. It took three months, for instance, for someone brought up in a mill to learn how to operate either a hand mule or a self-acting mule.<sup>7</sup> Learning to maintain the former required three years, while the latter demanded seven. A worker continued to acquire knowledge concerning improvements in the machinery throughout his lifetime. It seems reasonable to conjecture that the demand for skill rose in the Industrial Revolution, since “for the economy *as a whole* to switch from manual techniques to a mechanized production required hundreds of inventors, thousands of innovating entrepreneurs, and tens of thousands of mechanics, technicians, and dexterous rank and file workers.”<sup>8</sup> Mokyr (1994) emphatically rejects the notion that Britain's more advanced science accounted for the development of the Industrial Revolution. He maintains that ideas flowed from the Continent to Britain, and then working technologies flowed back from Britain to the Continent. He quotes an engineer of the day, who observed that “the prevailing talent of English and Scottish people was to apply new ideas to use and to bring such applications to perfection, but they do not imagine as much as foreigners.” Mokyr concludes that “Britain's technological strength during the industrial revolution depended above all on the abundance and quality of its skilled mechanics and practical technicians who could turn great insights into productive applications.”<sup>9</sup> In fact, income inequality rose throughout the Industrial Revolution (see figure 5).<sup>10</sup>

The diffusion of new technologies is often slow because the initial incarnations of the underlying ideas are inefficient. Getting new technologies to operate at their full potential

■ 4 This is chronicled in Mokyr (1994).

■ 5 McPherson (1994, p. 16).

■ 6 The classic source is Landes (1969, pp. 99–103), who quotes a writer's 1778 comment that “the vast consumption of fuel in these engines is an immense drawback on the profits of our mines, for every fire-engine of magnitude consumes £3,000 of coals per annum. This heavy tax amounts almost to a prohibition.”

■ 7 As reported by von Tunzelmann (1994).

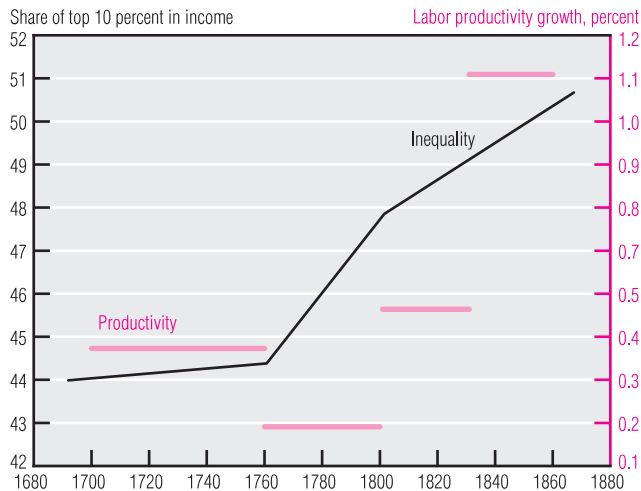
■ 8 Mokyr (1994, p. 29).

■ 9 *Ibid.*, p. 39

■ 10 This is documented in Lindert and Williamson (1983, table 3).

FIGURE 5

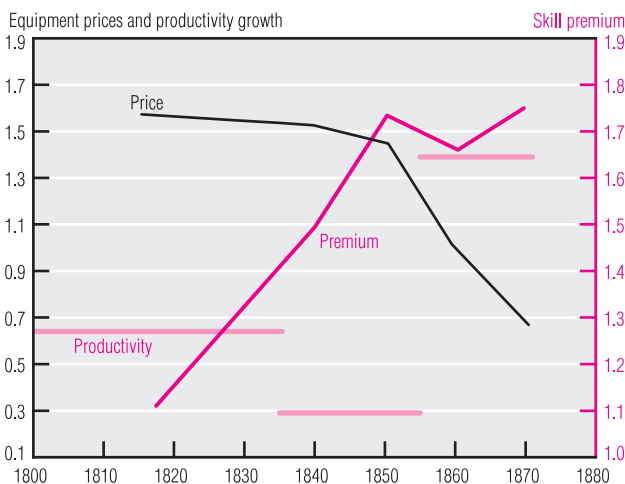
## The Industrial Revolution



SOURCES: Harley (1993) and Lindert and Williamson (1983).

FIGURE 6

## The American Antebellum Period



SOURCES: Abramovitz and David (1973, table 2); Gallman (1992); and Williamson and Lindert (1980, appendix D).

may take considerable time, so their productivity may be low at first. Cort's famous puddling and rolling process had a long incubation period and was commercially unsuccessful at first.<sup>11</sup> Royalties had to be slashed to encourage adoption. Apparently, "both entrepreneurs and workers had to go through a learning period, making many mistakes that often resulted in low outputs of uneven quality."<sup>12</sup> Productivity growth fell in the initial stages of the Industrial

Revolution (see figure 5).<sup>13</sup> Before the coming of the new era, productivity was growing at 0.4 percent a year; once it began, productivity growth fell to an annual rate of 0.2 percent. Was this decline, which lasted 40 years, connected to the teething pains of adopting new technologies? As the revolution spread, productivity growth picked up; 70 years in, it was growing at a much more robust 0.5 percent. Thus, the fruits of the Industrial Revolution took time to ripen.

### III. The American Antebellum Period

The Industrial Revolution spread to the United States around 1840, a time of tremendous investment-specific technological progress. The nation industrialized at a rapid clip. Figure 6 shows the dramatic decline in the price of new equipment relative to all goods.<sup>14</sup> Presumably, this decrease reflects the improved efficiency of new-equipment production, which allowed more of it to be produced for less. One would expect this decline in the price of new equipment to encourage more investment. For the period 1774–1815, the real stock of equipment per capita grew at roughly 0.7 percent annually. Between 1815 and 1860, however, the average annual growth rate was a very robust 2.8 percent, which jumped to a whopping 4.5 percent from 1860 to 1900. Two examples illustrate the extraordinary pace of industrialization. In 1830, there were just 30 miles of railroad tracks in the United States. By 1840, there were 2,808 miles, while in 1860 the number was 30,000.<sup>15</sup> Likewise, the aggregate capacity of U.S. steam engines more than quadrupled between 1840 and 1860 (from 760,000 to 3,470,000 horsepower). That capacity rose another one-and-a-half times (to 5,590,000 horsepower) by 1870. The antebellum period saw a dramatic surge in the skill

■ 11 Again, as related by von Tunzelmann (1994).

■ 12 C.K. Hyde, *Technological Change and the British Iron Industry*, as cited by von Tunzelmann (1994, p. 277).

■ 13 Calculated by Harley (1993, table 3.5).

■ 14 This series is based on calculations using data presented in Gallman (1992).

■ 15 In 1840, roughly 30 percent of pig-iron production was devoted to manufacturing tracks, and the railway used 30 percent of the country's steam-power capacity (McPherson [1994, chap. 3]).

premium (see figure 6).<sup>16</sup> Not surprisingly, skilled workers such as engineers, machinists, boilermakers, carpenters, and joiners, saw their wages rise relative to those of common laborers. Last, labor productivity growth slowed in the 1840s just as the American Industrial Revolution was gaining momentum; the annual growth rate of labor productivity is plotted in figure 6.<sup>17</sup>

#### IV. The Hypothesis

The adoption of new technologies involves a significant cost in terms of learning; skill facilitates this learning process. That is, skill is important for adapting to change. There is considerable evidence of learning effects. For example, using a 1973–86 data set consisting of 2,000 firms from 41 industries, Bahk and Gort (1993) find that a plant's productivity increases 15 percent over its first 14 years because of learning effects.

There is also evidence that skill plays an important role in facilitating the adoption of new technologies. Farmers with high education levels adopt agricultural innovations earlier than farmers with low levels. Findings reported in Bartel and Lichtenberg (1987) support the joint hypothesis that 1) educated workers have a comparative advantage in implementing new technologies because they assimilate new ideas more readily; and 2) the demand for educated relative to less-educated workers declines as experience with a technology is gained. For each year equipment ages, skilled labor's share of the wage bill drops 0.78 percentage point. This suggests that less skilled labor is needed as production experience with equipment is gained through time. Using a cross-country data set, Flug and Hercowitz (1996) find that a rise in equipment investment leads to an increase in the skill premium and to higher relative employment for skilled labor. In particular, an increase of 1 percentage point in the ratio of equipment investment to output produces an increase of 1.90 percentage points in the ratio of skilled to unskilled employees. The inference drawn is that when investment in equipment is high, so is the demand for skilled labor, which eases the adoption process.

The hypothesis to be developed here is different from the capital–skill complementarity hypothesis.<sup>18</sup> The latter states that skilled labor is more complementary with capital in production than is unskilled labor or (more or less equivalently) that capital substitutes better for unskilled than for skilled labor. The recent rise

in the skill premium is consistent with capital–skill complementarity and an increase in the rate of investment-specific technological advance.<sup>19</sup> The idea in the current paper, however, is that successful adoption of a new technology requires skilled labor. Moreover, as a technology becomes established, the production process substitutes away from expensive skilled labor toward less costly unskilled labor. Therefore, times of heightened technological progress should see an increase in the demand for skilled labor, which has a comparative advantage in speeding up and easing the process of technological adoption. Such times should therefore be associated with a rise in the skill premium. If this notion is correct, the skill premium should decline once the recent burst of investment-specific technological progress subsides as IT matures.<sup>20</sup>

How large are the costs of technological adoption? Calculations suggest that the costs of adopting new technologies exceed invention costs by a factor of 20 to 1, and that adoption costs may amount to 10 percent of GDP.<sup>21</sup> Surely, the costs of technological adoption must be large. How else to explain the long diffusion lags for new technologies as well as the continual investment in older technologies at the household, firm, and national levels? And, surely, a large part of these adoption costs must be in acquiring or developing the skills needed to implement the new technologies.

#### V. The Learning Curve

As an example of the importance of learning effects, consider the Lawrence Number 2 Mill, an antebellum cotton mill studied by David (1975). The plant, built in 1834 in Lowell, Massachusetts, kept detailed inventories of its equip-

■ 16 These data are reported in Williamson and Lindert (1980, appendix D).

■ 17 The numbers are from Abramovitz and David (1973, table 2).

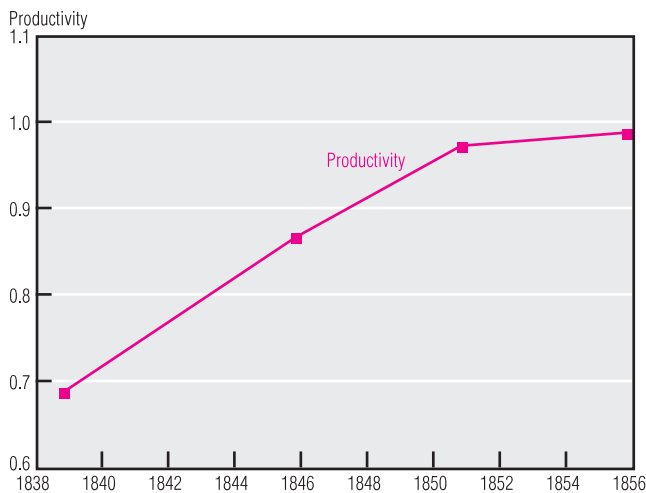
■ 18 The hypothesis was originally advanced by Griliches (1969). A more recent formulation can be found in Krusell et al. (1996).

■ 19 Krusell et al. (1996) make this case.

■ 20 By contrast, this is not an implication of the capital–skill complementarity hypothesis. Suppose that skilled labor is more complementary with equipment than is unskilled labor. Then, other things being equal, the skill premium should rise as long as the stock of equipment increases. That is, there should be a *secular or long-run* rise in the skill premium. For more detail, see Krusell et al. (1996).

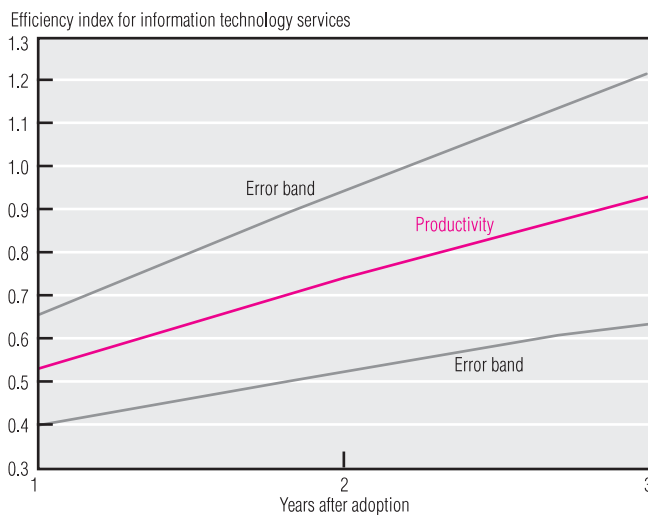
■ 21 See Jovanovic (1997).

FIGURE 7

Lawrence Number 2  
Cotton Textile Mill

SOURCE: David (1975).

FIGURE 8

Learning Curve for  
Information Technologies

SOURCE: Yorukoglu (1998).

ment showing that no new machinery was added between 1836 and 1856. Thus, it seems reasonable to infer that any productivity increases that occurred in these years were due purely to learning effects. In fact, the plant's output per hour of work during this period grew 2.3 percent annually. Figure 7 shows the plant's learning curve. The four observations

pertain to years when the plant was known to be operating at full capacity.

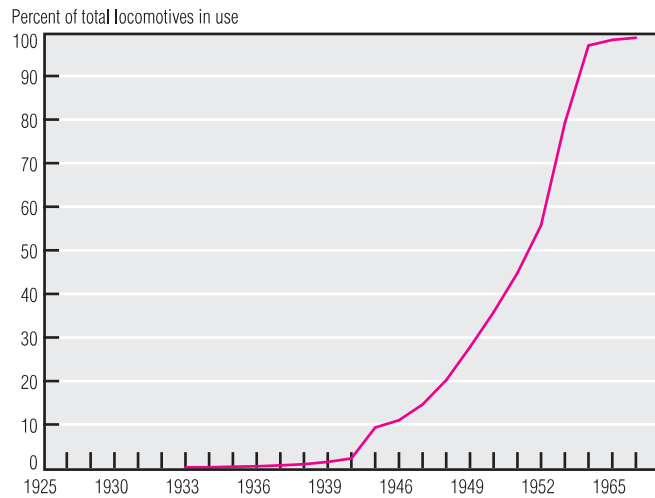
Learning curves from angioplasty surgery, flight-control simulation, munitions manufacturing, and steel finishing are documented in Jovanovic and Nyarko (1995); the literature abounds with additional examples. Yorukoglu (1998) has used data from 297 firms during the 1987–91 period to study the learning curve for information technologies. His results, plotted in figure 8, show strong learning effects. The service flow (analogous to horsepower for a steam engine) captured from new computers increases dramatically over time, growing at approximately 28 percent (compounded) annually. Two words of caution are offered here. First, as the error bands show, the range of estimates is quite wide because the data set permits studying only a small number of firms for a short period of time.<sup>22</sup> Second, a firm uses more than computers to produce output. If computers account for 5 percent of output, then this translates into an output growth rate due to learning alone of about 1.4 percent ( $.28 \times .05 \times 100$  percent) a year.

Often, learning about a technology occurs through use by the final purchaser. For some products, such as software, important operating characteristics are revealed only after intensive use. The manufacturer may then adjust the product in response to feedback from purchasers, a process that may take many iterations (Rosenberg [1982]). The aircraft industry provides an excellent case of such learning by using: As confidence about the operating characteristics of the DC-8 airplane grew through experience, the manufacturer increased the engines' thrust while reducing fuel consumption, and modified the wings to decrease drag. These modifications eventually allowed the airplane to be "stretched," which more than doubled its capacity from 123 seats to 251. The result was a dramatic improvement in operating costs, notably a 50 percent saving in fuel costs per seat-mile. For complicated products, where reliability is a major concern, maintenance experience proves invaluable. In the case of aircraft, maintenance may account for 30 percent of the operating costs associated with labor and materials (this excludes the revenue lost during downtime). The costs of servicing new types of jet engines fall dramatically after their introduction. After a decade of operation, maintenance costs typically have dropped to 30 percent of their initial level.

■ 22 The error bands show the 95 percent confidence intervals.

## FIGURE 9

## Diffusion of Diesel Locomotives



SOURCE: U.S. Department of Commerce, Bureau of the Census, *Historical Statistics of the United States, 1790–1970*.

## VI. The Diffusion Curve

The adoption of new technologies is notoriously slow. The initial incarnations of new ideas are often expensive and bug-infested. The impact of investment-specific technological progress on income and productivity is likely to be regulated by two interrelated factors: the speed of learning and the speed of diffusion. The more costly it is for economic agents to learn about a new technology, the slower the technology's diffusion. But the faster a new technology diffuses through an economy, the easier it may be to learn about it. Thus, there is a feedback loop between the cost of adoption and the extent of adoption. If a new technology represents a radical or discrete departure from past technologies, society's knowledge about it may be quite limited at first. As the technology's use becomes widespread, society's stock of experience with it increases, and the technology's productivity rises.

New technologies are expensive when they are first produced, but prices drop as the manufacturer gains production experience. This encourages adoption, which in turn fuels further price declines when learning and scale effects lower the costs of production. Waves of imitators enter the industry, making pricing more competitive. The odds of imitating a new invention depend on the number of firms that have already succeeded in adopting the new invention. The number of firms increases with

time, making imitation easier. Firms also rush in to produce complementary products, such as software or communication devices for computers. The original product may then have to be modified to incorporate them better. Bringing these complementary products on line may take a lot of time and resources. The availability of such products encourages further adoption, and so on. An invention may take a long time to bear fruit.

There is considerable evidence that the diffusion of innovations is slow. In a classic study, Gort and Klepper (1982) examined 46 product innovations, beginning with phonograph records in 1887 and ending with lasers in 1960. They traced diffusion by examining the number of firms producing the new product over time. Only two or three firms on average were producing each new product for the first 14 years after its commercial development; then the number of firms increased sharply (by an average of six firms per year over the next 10 years). Prices fell rapidly after a product's inception (down 13 percent annually for the first 24 years). Using a 21-product subset of the Gort and Klepper data, Jovanovic and Lach (1996) find that the output of a new product took approximately 15 years to rise from the 10 percent to the 90 percent diffusion level. They also cite evidence from a study of 265 innovations that it took 41 years on average to move from 10 percent to 90 percent diffusion. Finally, it took the steam locomotive 54 years to move from the 10 percent to the 90 percent diffusion level in the U.S. and the diesel (a lesser innovation) 12 years. The diffusion curve for diesels (figure 9) shows that it took about 25 years after their introduction in 1925 for diesels to account for half of the locomotives in use.

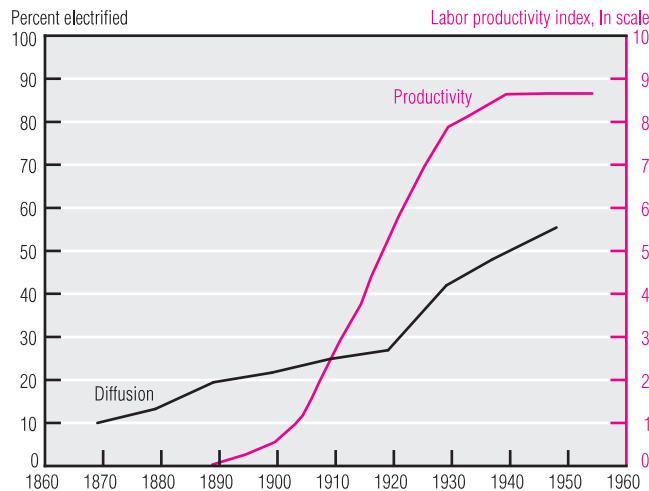
## VII. The Computer and the Dynamo

The metamorphosis of a novel idea into a productive technology can take a long time.<sup>23</sup> Because a technology's development is uncharted at its infancy, a lot of time and resources can go into exploring the various paths that may be taken. Electricity and computers are two interesting examples of this uncertain process. Ironically, one of the Industrial Revolution's least productive inventions formed the foundation of the current Information Age. Sometime between 1823 and 1832,

■ 23 The section title is borrowed from David (1991).

FIGURE 10

## The Electrification of America



SOURCE: David (1991, tables 2 and 3).

Charles Babbage created his “Difference Engine,” a mechanical computer. The insight for this device came partly from a binary-coded loom, invented in 1801 by Jean-Marie Jacquard, which used punch cards to control fabric patterns. But as recently as 50 years ago, the coming of the Information Age was still not obvious. Just after World War II, *Popular Mechanics* (March 1949) wrote, “Where a calculator on the ENIAC is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may only have 1,000 vacuum tubes and weigh only 1½ tons.”

### The Electrification of America

The electrification of America, masterfully chronicled and analyzed by David (1991), illustrates the delays in successfully exploiting new technologies. The era of electricity dawned around 1900, in the midst of the Second Industrial Revolution, which typically is considered to have started in the 1860s and ended in the 1930s. It saw the birth of the modern chemical industry and the internal combustion engine, in addition to electricity. Electricity was obviously useful as a source of lighting in homes and businesses, but it had to supplant water and steam as a source of power in manufacturing.<sup>24</sup> This process was complicated by the large stocks of equipment and structures, already in place, that were geared to these power sources.

Thus, in the early stages, electricity tended to be overlaid onto existing systems. In particular, the mechanics of steam- and waterpower favored having a single power unit drive a group of machines, and early electric motors retained the group-drive system of belts and shafting that had been used by steam- and waterpower. Hence, early electric motors were also used to drive a group of machines. The benefits of electricity derived from the savings in power requirements and the greater control over machine speed. Not surprisingly, electric power tended to be used mostly by industries that were expanding rapidly, since new plants could be designed to accommodate this power source better.

By around 1910, it was apparent that machines could be driven with individual electric motors. This realization had a great impact on workplace productivity. The apparatus used in the group-drive system could be abandoned, so factory construction no longer had to allow for the heavy shafting and belt housing required for power transmission. The labor demands of maintaining that system were also eliminated. Furthermore, the production process became more flexible for several reasons: It was no longer necessary to shut down the entire power system for maintenance or parts replacement. Because each machine could be controlled more accurately, the quantity and quality of output increased. Machines could now be located and moved about more freely to accommodate the production process. Last, the workplace became considerably safer. Figure 10 shows the diffusion of electric motors in manufacturing.<sup>25</sup> Horsepower from electric motors, as a fraction of the total mechanical drive in manufacturing establishments, followed a typical S-shaped diffusion pattern. Labor productivity growth in manufacturing slowed down at the time of electricity’s introduction.<sup>26</sup>

In 1890, an astute observer might have understood the importance of electricity for lighting homes and powering factories. He would not, however, have been able to predict how it would transform lives through the other inventions it would spawn: radio, television, and computers.

■ 24 While only 3 percent of households used electric lighting in 1899, almost 70 percent did by 1929 (David [1991, table 3]).

■ 25 The data source is David (1991, table 3).

■ 26 *Ibid.*, table 2.



## The Computerization of America

As with electrification, the harvest of the IT revolution has not been immediate. When the era of computers began in the 1950s, they were used primarily in academic and industrial research to perform calculations that were impractical or impossible to do manually (Jonscher [1994]). Number-crunching costs declined rapidly over this period. Between 1950 and 1980, the cost per MIP (million instructions per second) fell 27–50 percent annually, spurring the use of computers as calculating devices. In a feedback loop, widespread adoption led to further price reductions as computer manufacturers rode up their learning curves. In the 1960s, computers became file-keeping devices used by businesses to sort, store, process, and retrieve large volumes of data, thus saving on the labor involved in information-processing activities. The cost of storage probably fell at an annual rate of 25–30 percent from 1960 to 1985. More recently, computers have evolved into communication devices, beginning with the advent of remote accessing and networking in the 1970s. This allowed a partial liberation of the computer from the “clean room,” but that umbilical cord was not completely cut until the 1980s, with the introduction of the personal computer and the spread of networking.

IT is likely to streamline corporate structures significantly by economizing on the number of workers employed in information collection and processing. The goal of any firm is simple: Maximize profits. To achieve it, the firm’s organizational structure must be capable of detecting profit opportunities, directing actions to harvest them, and monitoring and evaluating returns on its activities. These activities largely involve handling and processing information. By 1980, there were 1.13 times as many information workers as production workers, compared to just 0.22 in 1900. IT can do much of this information collection and processing more efficiently than workers can, eliminating the need for battalions of clerks, pools of secretaries, scores of purchasing and sales agents, and layers of supervisors and administrators. Through IT, headquarters, design centers, plants, and purchasing and sales offices can be linked directly to one another. Over time, such major changes in business structure will inevitably raise labor productivity as it becomes possible to create more output with less labor. Studies such as Brynjolfsson and Hitt (1993) indicate that this is happening already.

How realistic is the hypothesis just presented? To judge this, Greenwood and Yorukoglu (1997) have developed an economic model of the Information Age, which they simulate on a computer. The model incorporates two ingredients. First, firms face a learning curve when they adopt a new technology. Second, firms can travel up this curve faster by hiring skilled labor. With the dawning of the Information Age, the growth rate of labor productivity slumps in the model economy, and income inequality widens. The effects of the Information Age gradually work their way through the system over time. In the model, productivity growth does not surpass its old level for about 20 years, and the level of productivity does not cross its old trend line—the path it would have traveled had it continued at its former growth rate—for 40 years. Unskilled wages fall in the initial stages of the Information Age. Twenty years elapse before this loss in unskilled wages is recovered, and about 50 go by before unskilled wages cross their old growth path. Interestingly, during the early stages of the Information Age, the stock market booms as it capitalizes the higher rates of return offered by new investment opportunities. For many in the economy, waiting for the benefits of technological miracles will be like watching the grass grow—but it will grow.

## VIII. Conclusion

Plunging prices for new technologies, a surge in wage inequality, and a slowdown in the advance of labor productivity—could these herald the dawn of another industrial revolution? Just as the steam engine shook eighteenth-century England, and electricity rattled nineteenth-century America, are information technologies now rocking the twentieth-century economy?

The story told here is simple. Technological innovation is embodied in the form of new producer durables or services, whose prices decline rapidly in periods of high innovation. Adopting new technologies is costly. Setting up and operating new technologies often involves acquiring and processing new information. Because skill facilitates this adoption process, times of rapid technological advance should be associated with a rise in the return to skill. At the dawn of an industrial revolution, the long-run advance in labor productivity pauses temporarily as economic agents undertake the (unmeasured) investment in information required to get new technologies operating closer to their full potential.

How will this affect people's lives? In the long run, everybody will gain. Technological progress, which implies that a unit of labor can eventually produce more output, makes a unit of labor more valuable. Given time, this translates into higher wages and standards of living for all. Clearly, everybody today is better off because of Britain's Industrial Revolution, but this was not true in 1760. So what about the short run? Skilled workers will fare better than unskilled ones, but this disparity will shrink over time for two reasons. First, as information technologies mature, the level of skill needed to work them will decline. Firms will substitute away from expensive skilled labor toward more economical unskilled labor. As this happens, the skill premium will decline. Second, young workers will tend to migrate away from low-paying unskilled jobs toward high-paying skilled ones. This tendency will increase the supply of skilled labor and reduce the amount of unskilled labor, easing pressure on the skill premium. Moreover, the wealthy will do better than the poor in the short run because the introduction of new technologies leads to exciting profit opportunities for those with the wherewithal to invest in them. These profit opportunities will shrink over time as the pool of unexploited ideas dries up. On average, the old have more capital to invest than the young. Thus, young, unskilled agents will fare worst in the short run. But in the long run, the rising tide of technological advance will lift everybody's boat.

## References

- Abramovitz, Moses, and Paul A. David.** "Reinterpreting Economic Growth: Parables and Realities," *American Economic Review*, vol. 63, no. 2 (May 1973), pp. 428–39.
- Bahk, Byong-Hong, and Michael Gort.** "Decomposing Learning by Doing in New Plants," *Journal of Political Economy*, vol. 101, no. 4 (August 1993), pp. 561–83.
- Bartel, Ann P., and Frank R. Lichtenberg.** "The Comparative Advantage of Educated Workers in Implementing New Technology," *Review of Economics and Statistics*, vol. 69, no. 1 (February 1987), pp. 1–11.
- Brynjolfsson, Erik, and Lorin Hitt.** "Computers and Growth: Firm-Level Evidence," Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Working Paper No. 3714–94, August 1994.
- David, Paul A.** "The 'Horndal Effect' in Lowell, 1834–56: A Short-Run Learning Curve for Integrated Cotton Textile Mills," in Paul A. David, ed., *Technical Choice, Innovation, and Economic Growth: Essays on American and British Experience in the Nineteenth Century*. London: Cambridge University Press, 1975, pp. 174–91.
- . "Computer and Dynamo: The Modern Productivity Paradox in a Not-Too-Distant Mirror," in *Technology and Productivity: The Challenge for Economic Policy*. Paris: Organisation for Economic Co-operation and Development, 1991, pp. 315–47.
- Flug, Karnit, and Zvi Hercowitz.** "Some International Evidence on Equipment–Skill Complementarity," *Review of Economic Dynamics*, forthcoming.
- Gallman, Robert E.** "American Economic Growth and Standards of Living before the Civil War" in Robert E. Gallman and John Joseph Wallis, eds., *American Growth and Standards of Living before the Civil War*, National Bureau of Economic Research Conference Report. Chicago: University of Chicago Press, 1992, pp. 1–18.
- Gort, Michael, and Steven Klepper.** "Time Paths in the Diffusion of Product Innovations," *Economic Journal*, vol. 92, no. 367 (September 1982), pp. 630–53.
- Greenwood, Jeremy, Zvi Hercowitz, and Per Krusell.** "Long-Run Implications of Investment-Specific Technological Change," *American Economic Review*, vol. 87, no. 3 (June 1997), pp. 342–62.
- , and Mehmet Yorukoglu. "1974," *Carnegie–Rochester Conference Series on Public Policy*, vol. 46 (June 1997), pp. 49–95.
- Griliches, Zvi.** "Capital–Skill Complementarity," *Review of Economics and Statistics*, vol. 51, no. 4 (November 1969), pp. 465–68.

- Harley, C. Knick.** "Reassessing the Industrial Revolution: A Macro View," in Joel Mokyr, ed., *The British Industrial Revolution: An Economic Perspective*. Boulder, Colo.: Westview Press, pp. 171–226.
- Jonscher, Charles.** "An Economic Study of the Information Technology Revolution," in Thomas J. Allen and Michael S. Scott-Morton, *Information Technology and the Corporation of the 1990s*. Oxford: Oxford University Press, 1994, pp. 5–42.
- Jovanovic, Boyan.** "Learning and Growth," in David Kreps and Kenneth F. Wallis, eds., *Advances in Economics and Econometrics*, vol. 2. New York: Cambridge University Press, 1997, pp. 318–39.
- , and **Saul Lach.** "Product Innovation and the Business Cycle," *International Economic Review*, vol. 38, no. 1 (February 1997), pp. 3–22.
- , and **Yaw Nyarko.** "A Bayesian Learning Model Fitted to a Variety of Empirical Learning Curves," *Brookings Papers on Economic Activity*, Microeconomics Issue, 1995, pp. 247–99.
- Juhn, Chinhui, Kevin M. Murphy, and Brooks Pierce.** "Wage Inequality and the Rise in Returns to Skill," *Journal of Political Economy*, vol. 101, no. 3 (June 1993), pp. 410–42.
- Krusell, Per, Lee E. Ohanian, José-Victor Ríos-Rull, and Giovanni L. Violante.** "Capital–Skill Complementarity and Inequality," Federal Reserve Bank of Minneapolis, Staff Report No. 239, September 1997.
- Landes, David S.** *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*. London: Cambridge University Press, 1969.
- Lindert, Peter. H., and Jeffrey G. Williamson.** "Reinterpreting Britain's Social Tables, 1688–1913," *Explorations in Economic History*, vol. 20, no. 1 (January 1983), pp. 94–109.
- McPherson, Natalie.** *Machines and Growth: The Implications for Growth Theory of the History of the Industrial Revolution*. Westport, Conn.: Greenwood Press, 1994.
- Mokyr, Joel.** "Technological Change, 1700–1830," in Roderick Floud and Donald McCloskey, eds., *The Economic History of Britain since 1700*, 2d ed. New York: Cambridge University Press, 1994, pp. 12–43.
- Rosenberg, Nathan.** "Learning by Using," in Nathan Rosenberg, ed., *Inside the Black Box: Technology and Economics*. New York: Cambridge University Press, 1982.
- von Tunzelman, Nick.** "Technology in the Early Nineteenth Century," in Roderick Floud and Donald McCloskey, eds., *The Economic History of Britain since 1700*, 2d ed. New York: Cambridge University Press, 1994, pp. 217–99.
- Williamson, Jeffrey G., and Peter H. Lindert.** *American Inequality: A Macroeconomic History*. New York: Academic Press, 1980.
- Yorukoglu, Mehmet.** "The Information Technology Productivity Paradox," *Review of Economic Dynamics*, vol. 1, no 2 (April 1998), pp. 551–92.