The Third Industrial Revolution

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Abstract

Was 1974 a watershed? It was dawning of the information age, a period of rapid technological advance associated with the introduction of information technologies. It also was the start of a sharp rise in income inequality and signaled the beginning of the productivity slowdown. Were these phenomena related? Could they have been the result of an Industrial Revolution associated with the introduction of information technologies? The answer offered here is yes, and a simple theory connecting the phenomena will be outlined. Evidence will be presented showing that the coincidence of rapid technological change, widening inequality, and slowdowns in productivity growth are not with out precedence in economic history. Just as the steam engine shook 18th century England, and electricity rattled 19th century America, it will be argued that information technologies are rocking the 20th century economy.

*& Prepared for the American Enterprise Institute. This work is based upon joint research with Mehmet Yorukoglu entitled "1974", which is forthcoming in the *Carnegie-Rochester Conference Series on Public Policy.* The paper contains a computer simulation model incorporating many of the ideas discussed here. It is available as Working Paper No. 429 from the Rochester Center for Economic Research, The W. Allen Wallis Institute for Political Economy, University of Rochester, Rochester, NY 14627-0156 — please contact Mrs. Terry Fisher.

Figure 1: Price of New Equipment

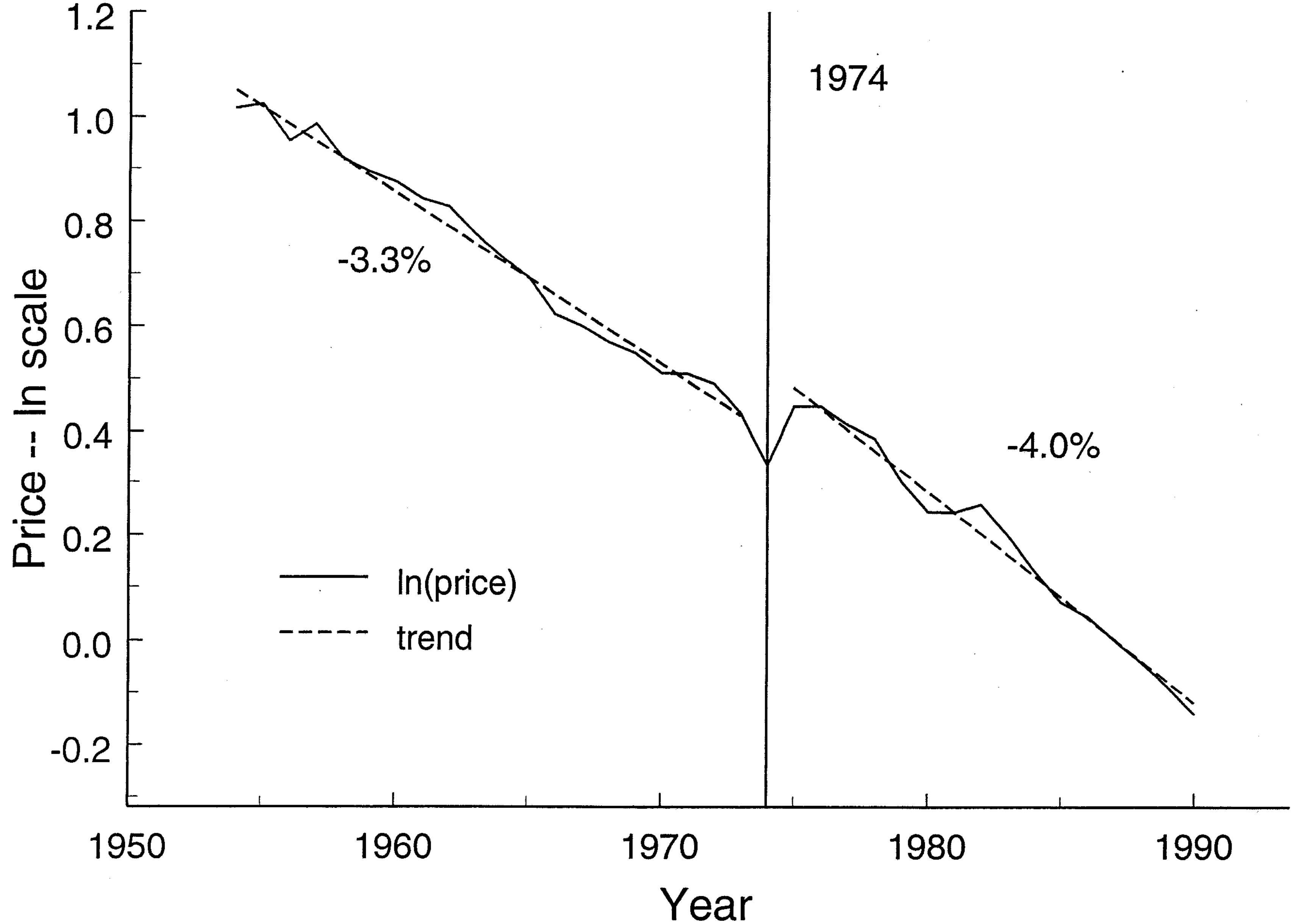


Figure 2: Price of New Computers

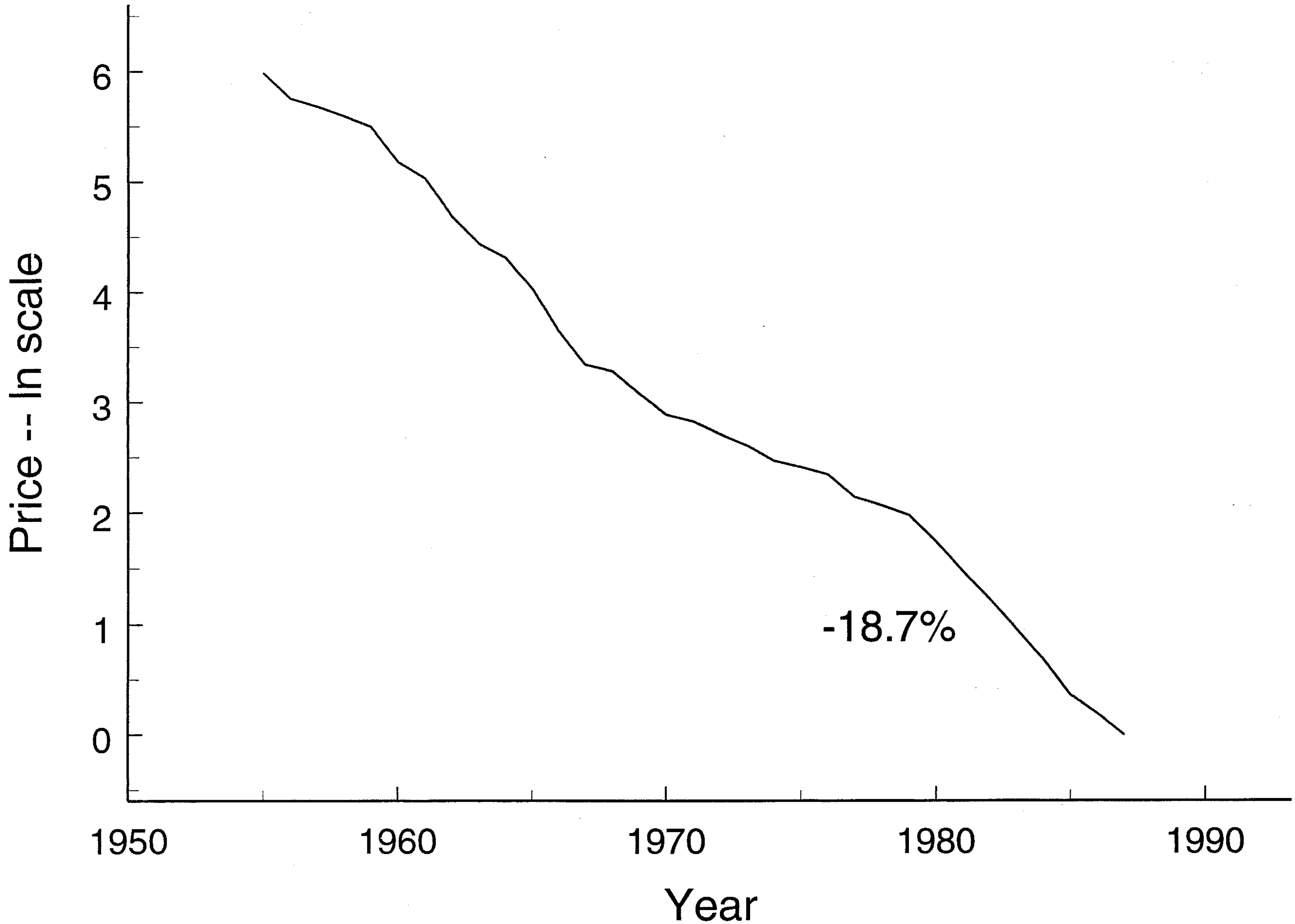


Figure 3: IT Investment and Productivity Slowdown

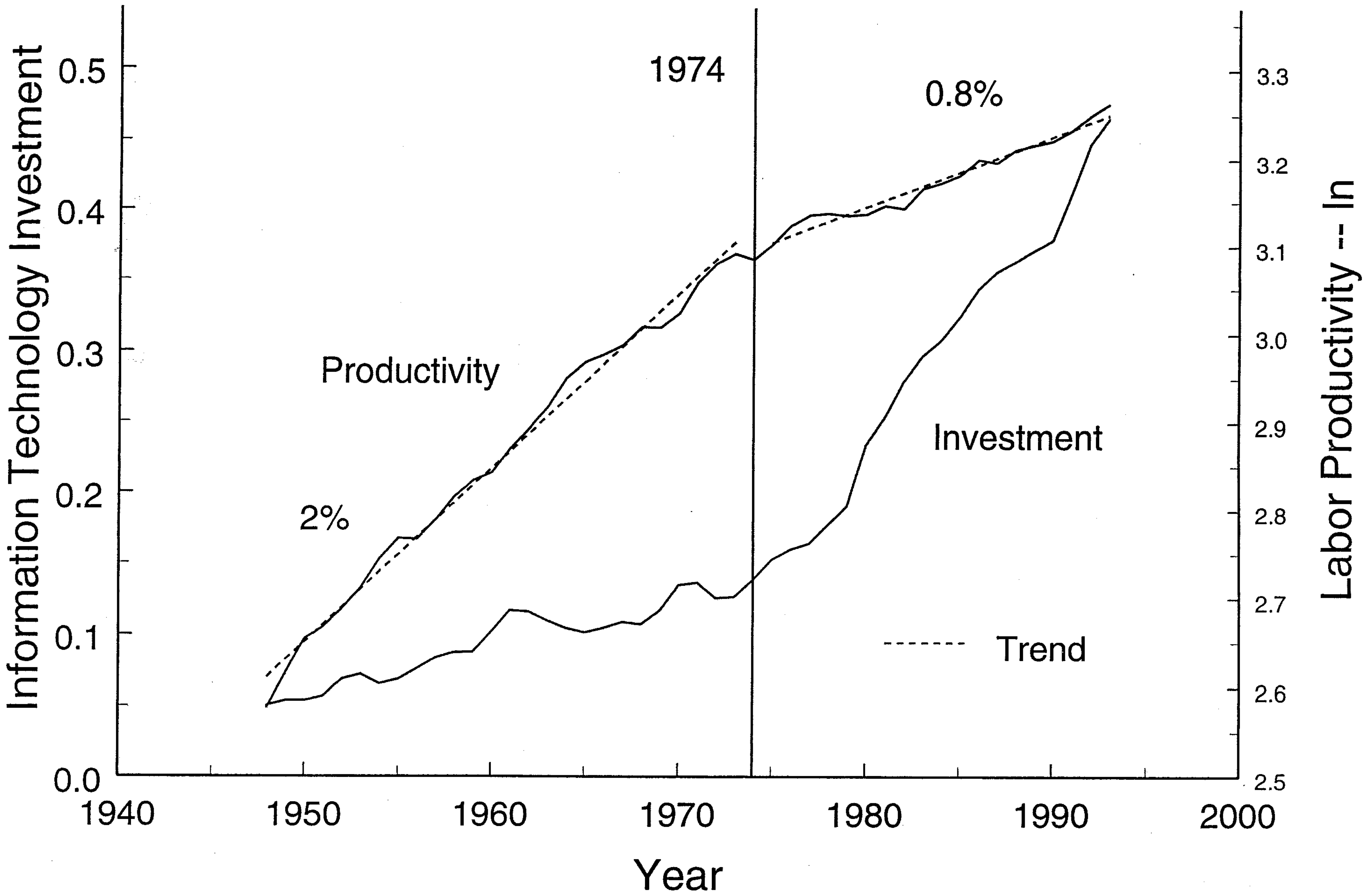
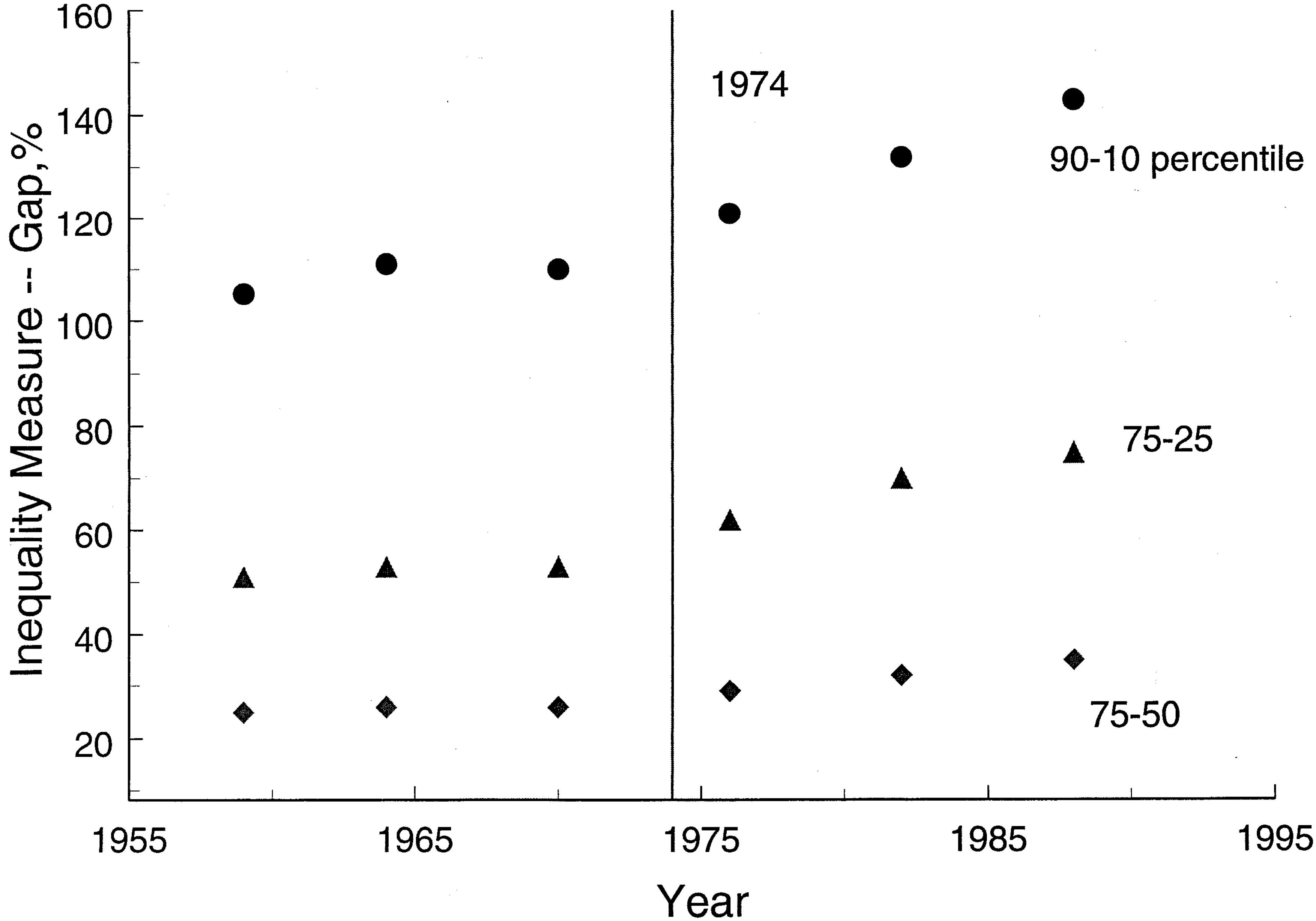


Figure 4: Measures of Wage Inequality



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INTRODUCTION

Did 1974 mark the beginning of a new industrial revolution?[1] Was this the start of an era of rapid technological progress associated with the development of information technologies (IT)? Did this increase in the pace of technological advance lead to a rise in income inequality? Is the productivity slowdown related to these phenomena?

A simple story is told here that connects the rate of technological progress to the level of income inequality and productivity growth. The idea is this: Imagine that a leap in the state of technology occurs and that this jump is incarnated in the form of new machines, such as information technologies. Suppose that the adoption of new technologies involves a significant cost in terms of learning and that skilled labor has an advantage at learning. Then the advance in technology will be associated with an increase in the demand for skill needed to implement it. Hence the wages of skilled labor relative to unskilled labor, or the skill premium, will rise and income

[1]Thanks go to Marvin Kosters for helpful comments. This paper based upon joint research with Mehmet Yorukoglu entitled "1974".

inequality will widen. In the early phases the new technologies may not be operated very efficiently due to a dearth of experience. The initial incarnations of ideas into equipment may be far from ideal. Productivity growth may appear to stall as the economy undertakes the (unmeasured) investment in knowledge needed to get the new technologies running closer to their full potential. The coincidence of rapid technological change, widening inequality, and a slowdown in productivity growth is not without precedence in economic history.

THE INFORMATION AGE

Figure 1 illustrates the decline in the price of equipment over the postwar period. It shows the price of a piece of new producer equipment relative to the price of a unit of nondurable consumer goods and services. Clearly over the postwar period producer equipment has become less expensive relative to consumer nondurables and services. This reflects the fact that the rate of technological change in the producer durable sector has exceeded the consumer nondurable sector. Specifically, due to technological progress ever-increasing quantities of investment goods can be produced over time, using a given amount of labor and capital, and this drives their price down. This type of technological advance is dubbed *investment-specific* technological progress, since it affects the investment goods sector of the economy. Observe that the price of equipment fell faster after 1974 than before it, as the slope of trend line shows. If the decline in the price of new equipment can be taken as a measure of improved efficiency in equipment production, then the pace of technological change jumped up around 1974. Some economists estimate that 60% of postwar U.S. growth may derive from the introduction of new, more efficient equipment.[2] The rapid advance in technology

[2]Greenwood, Hercowitz and Krusell (1996) breakdown U.S. postwar growth into it sources in terms of investment-specific and other forms of technological change.

since 1974 is undoubtedly linked to the development of information technologies. The price of computers has plummeted over the postwar period as Figure 2 illustrates. On average the price of a new computer has dropped at around 19% a year. Hence, a new computer costing $5,000 in 1987 would have been priced at $2,000,000 in 1955. Figure 3 shows the phenomenal rise of IT investment (as a fraction of total equipment investment). Observe that in 1954 information technologies accounted for less than 7% of total investment, while they now make up about 50%.

Growth in labor productivity stalled with the rise in IT investment, as Figure 3 also shows. Labor productivity measures the amount of GDP produced per man-hour worked in the economy. It is often taken as measure of how efficient labor is in the economy. The more GDP each worker can produce the better off is the economy. Before 1974 labor productivity grew at about 2% per a year, and after a paltry 0.8%. This is often referred to as the "productivity slowdown". Isn't it somewhat paradoxical that at a time of massive technological advance, due to the introduction of information technologies and the like, the advance in a worker's produce should stall?

By most accounts wage inequality increased around 1974. Some postwar measures of income inequality are shown in Figure 4.[3] As can be seen, the percentage gap between average wage earned by the upper quartile (25th percentile) to the average wage earned by the lower quartile (75th percentile) remained roughly constant between 1959 and 1970. From 1970 to 1988 this gap increased by 22 percentage points. That is, in 1970 there was a 53% gap in wage income between the two groups. In 1988 it was 75%. The other measures behave similarly.

[3]The data is from Juhn, Murphy and Pierce (1993, Table 1.B).

THE INDUSTRIAL REVOLUTION

The Industrial Revolution began in 1760. This period symbolizes the notion of investment-specific technological change. It witnessed the birth of several technological miracles.[4] For example, Crompton's mule revolutionized the spinning of cotton. Watt's energy efficient steam engine brought steam power to manufacturing. The main cost of a steam engine was operating it. They were hungry beasts. A Watts steam engine cost somewhere between £500 and £800.[5] Operating a steam engine, though, was enormously expensive. They consumed £3,000 of coal per annum.[6] By comparison, it cost only £900 to feed 500 horses, which apparently could produce the same amount of work. 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 Watts 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 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 the production of wrought iron increased by 500%. The price of wrought iron fell from £22 to £14 per ton from 1801 and 1815, despite the fact that between 1770 and 1815 the general level of prices rose by 50%. Last, the

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[4] This is chronicled in Mokyr (1994).

[5] Source: McPherson (1994, p. 16).

[6] Source: The classic book by Landes (1969, p. 99-103). Landes (p. 99-101) quotes a writer in 1778 as saying " 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."

foundation of the modern machine-tool industry was constructed. A gun-barreling machine was designed by Wilkinson that could make cylinders for Watt's steam engines. Maudley introduced the heavy-duty lathe. The Industrial Revolution is the quintessential era of investment-specific technological progress.

Skill undoubtedly played an important role in technological innovation and adoption during the Industrial Revolution. While the Industrial Revolution was the age of a handful of miracles, many historians view it also as an age of continuous and gradual smaller innovations — an age of learning. Implementing and operating brilliant inventions and effecting subsequent innovations is often demanding work requiring skill. For instance, it took three months for someone brought up in a mill to learn how to operate either a hand mule or a self-acting mule.[7] The former required three years to learn how to maintain while the latter demanded seven. Knowledge concerning improvements in the machinery continued throughout the worker's lifetime. It seems reasonable to conjecture that the demand for skill rose in the Industrial Revolution as "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."[8] In fact, income inequality rose throughout the Industrial Revolution,

[7]As reported by von Tunzelmann (1994).

[8]Mokyr (1994, p. 29). Interestingly, Mokyr (1994) emphatically states that the notion that Britain's Industrial Revolution was due to its more advanced science is false. Rather, ideas flowed from the Continent to Britain and then working technologies flowed back from Britain to the Continent. He cites (p. 38) an engineer of the day as stating "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 (1994, p. 39) 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."

as is plotted in Figure 5.[9]

The diffusion of new technologies is often slow because the initial incarnations of the underlying ideas are inefficient. Getting new technologies close to their full potential may take a considerable period of time. Thus, new technology's productivity may be low at first. Cort's famous puddling and rolling process went through a long incubation period and was commercially unsuccessful at first.[10] 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."[11] It is interesting to note that growth in productivity fell in the initial stages of Industrial Revolution, as is also shown in Figure 5.[12] Before the Industrial Revolution productivity was growing at 0.4% a year. With the coming of the new era productivity growth fell to annual rate of 0.2%. This lasted for forty years. Was this slump in productivity growth connected to the teething pains of adopting new technologies? As the revolution spread productivity growth picked up. Seventy years into the revolution it was growing at a much more robust 0.5%. Thus, it took time for the fruits of the Industrial Revolution to ripen.

THE AMERICAN ANTEBELLUM PERIOD

The Industrial Revolution spread to the U.S. in the nineteenth century, approximately around 1840. This was an era of tremendous investment-specific technological change. The nation industrialized at a rapid clip over this period. Figure 6 shows the

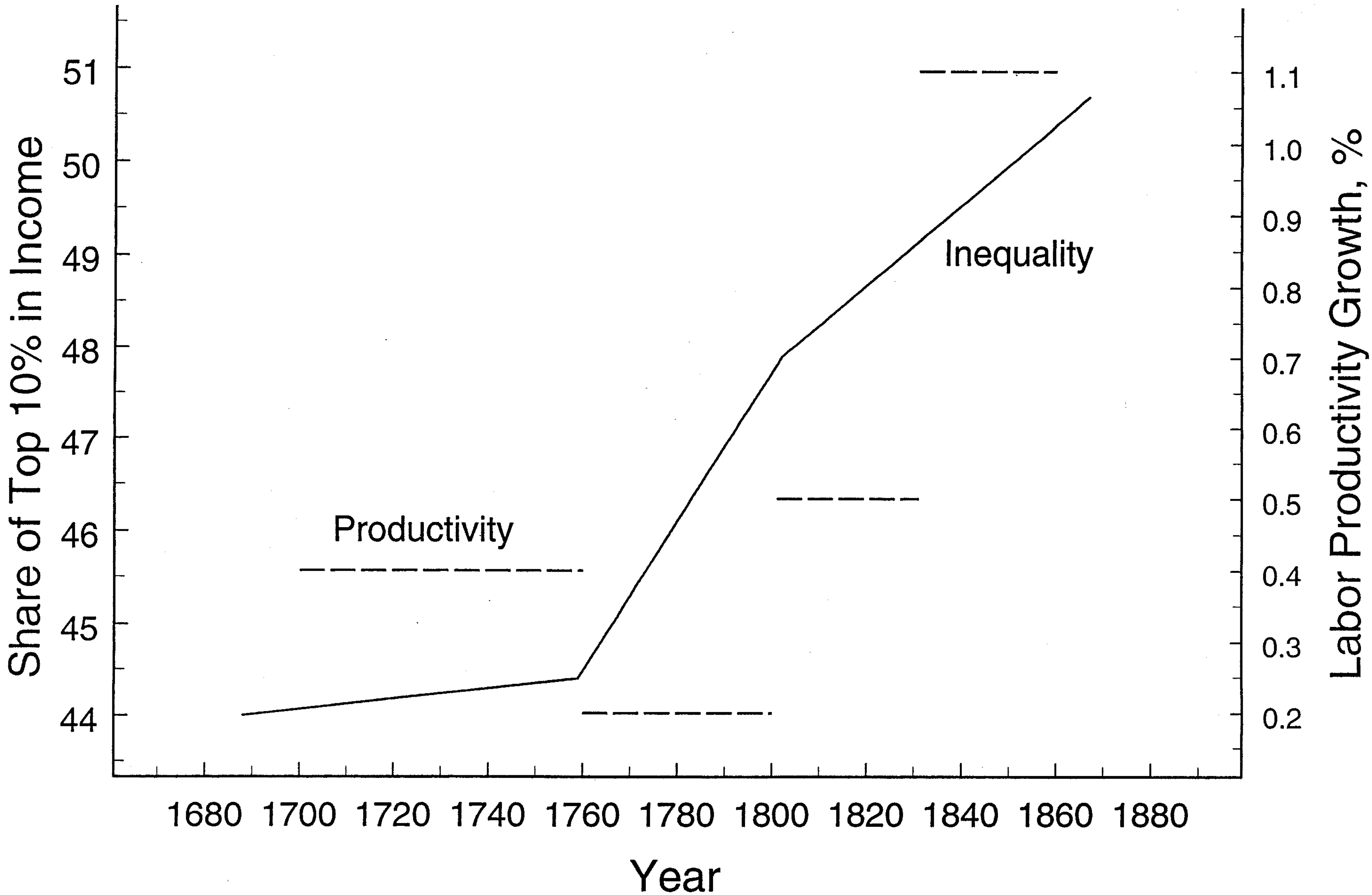
[9] This is documented in Lindert and Williamson (1983, Table 3).

[10] Again, as related by von Tunzelmann (1994).

[11] The quote is by C.K. Hyde (1977), *Technological Change and the British Iron Industry*, as cited by von Tunzelmann (1994, p. 277).

[12] As calculated by Harley (1993, Table 3.5).

Figure 5: Industrial Revolution



dramatic decline in the price of new equipment (relative to all goods) that occurred.[13] Presumably, this reflects improved efficiency in the production of new equipment. More equipment could now be produced for less. One would expect that this decline in the price of new equipment should have encouraged more investment. For the period 1774 to1815 the real stock of equipment per capita grew at roughly 0.7% per year. Between 1815 and 1860, however, the average annual growth was a very robust 2.8%. This jumped up to a whopping 4.5% over the interval from 1860 to 1900. Two examples might help to illustrate this incredible pace of industrialization. In 1830 there were just 30 miles of railroad tracks in the U.S. By 1840 this had risen to 2,808 miles, while in 1860 the number was 30,000.[14] Likewise the aggregate capacity of U.S. steam engines more than quadrupled between 1840 to 1860 from 760,000 to 3,470,000 horsepower. It rose another one and a half times by 1870 to 5,590,000. The antebellum period saw a dramatic surge in the skill premium as Figure 6 illustrates.[15] Not surprisingly skilled workers, such as engineers, machinists, boilermakers, carpenters, and joiners, all saw their wages rise relative to the common laborer. Last, it is interesting to note that there was a slowdown in labor productivity growth for the 1840's just as the American Industrial Revolution was gaining steam; the annual growth rate of labor productivity is plotted in Figure 6.[16]

THE HYPOTHESIS

The idea developed here is that the adoption of new technologies involves a significant cost in terms of learning and that skill facilitates this learning process. That is,

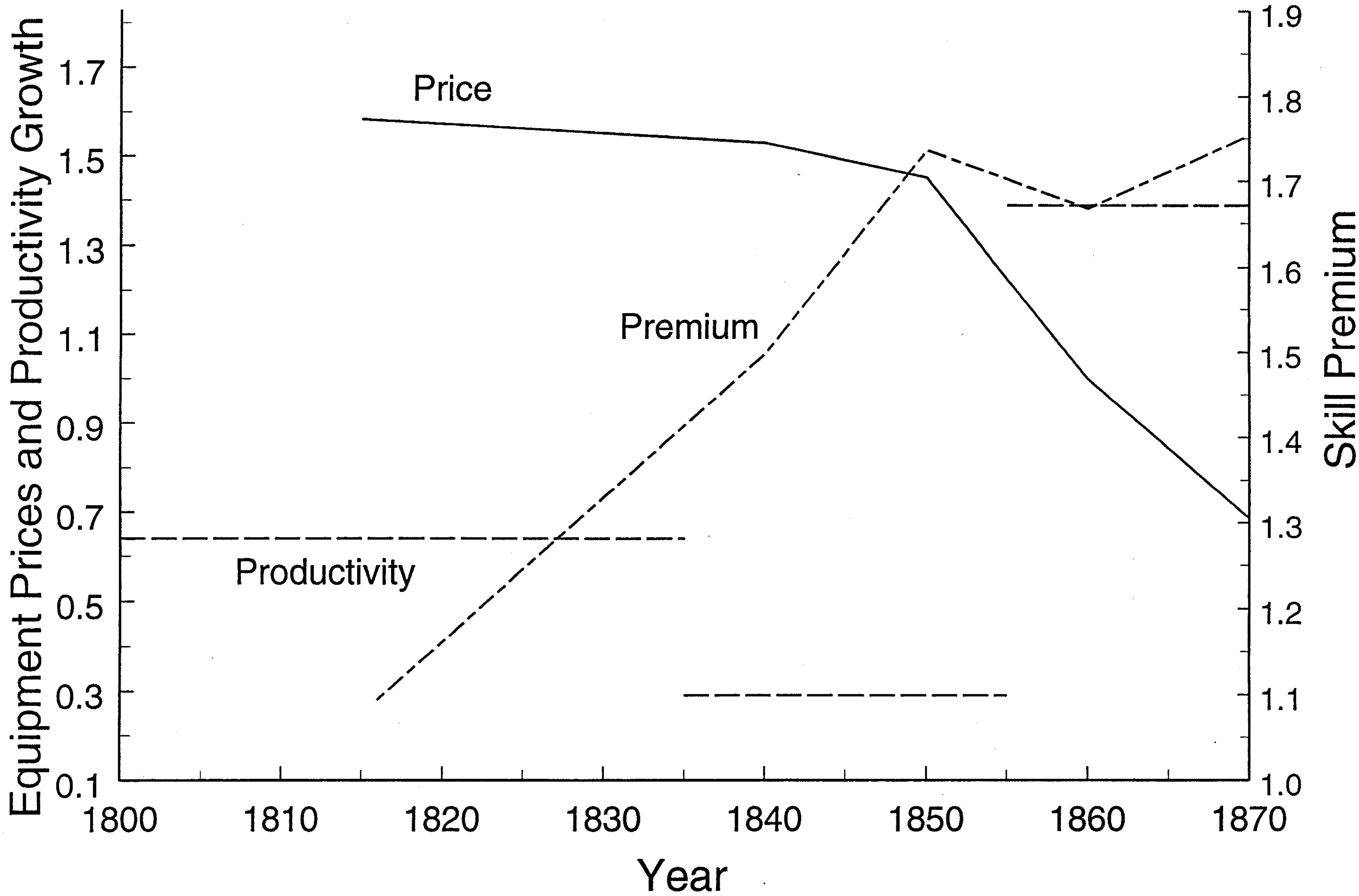
[13]This series is based upon some calculations using data presented in Gallman (1992).

[14]In 1840 roughly 30 percent of pig iron production was devoted to producing railway tracks, and the railway was using 30 percent of the country's steampower capacity (McPherson, 1994, Chap 3).

[15]The data used is reported in Williamson and Lindert (1980, Appendix D).

[16]The numbers are taken from Abramovitz and David (1973, Table 2).

Figure 6: U.S. Antebellum Period



skill is important for adapting to change. There is considerable evidence for learning effects. For example, using a data set from 1973 to 1986 consisting of 2,000 firms from 41 industries, Bahk and Gort (1993) find that a plant's productivity increases by 15% over the first fourteen years of its life due to learning effects.

There is also evidence that skill plays an important role in facilitating the adoption of new technologies. It is known that farmers with high levels of education adopt agricultural innovations earlier than farmers with low levels. Findings reported in Bartel and Lichtenberg (1987) support the joint hypothesis that (i) educated workers have a comparative advantage in implementing new technologies because they are better at assimilating new ideas and (ii), the demand for educated versus less-educated workers declines as experience is gained with a technology. Apparently for each year equipment ages there is a drop of 0.78 percentage points in skilled labor's share of the wage bill. This suggests that less skilled labor is needed as production experience with equipment is gained through time. Flug and Hercowitz (1996) find, using a cross-country data set, that a rise in equipment investment leads to an increase in the skill premium, and higher relative employment for skilled labor. In particular, a one percentage point increase in the equipment investment-to-output ratio leads to a 1.90 percentage point increase in the skilled-to-unskilled employment ratio. The inference drawn is that when investment in equipment is high so is the demand for skilled labor, which is used to ease process of adoption.

It is important to note that the hypothesis to be developed here is different from the capital-skill complementarity hypothesis.[17] This hypothesis 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 labor than skilled labor.

[17]The hypothesis was orginially advanced by Griliches (1969). A modern reincarnation can be found in Krusell et al (1996).

The recent rise in the skill premium is consistent with capital-skill complementarity and an increase in the rate of investment-specific technological change.[18] The idea in the current paper, however, is that a 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 more economical unskilled labor. Therefore, in times of heightened technological progress the demand for skill should rise, since this type of labor 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, once the recent burst of investment-specific technological change subsides, as IT matures, the skill premium should decline.[19]

How large are the costs of technological adoption? Calculations suggest that the costs of adopting new technologies exceed inventions cost by a factor of 20 to 1, and that adoption costs may amount to 10% of GDP.[20] Surely, the costs of technological adoption must be large. How else can the long diffusion lags for new technologies be explained, as well as the continual investment in old dominated technologies at the level of households, firms and countries. And surely a large part of these adoption costs must be in acquiring or developing the skills needed to implement the new technologies.

[18]Krusell et al (1996) make this case.

[19]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 equal, the skill premium should rise so long as the stock of equipment increases. That is, there should be a *secular or long-run* rise in the skill premium. See Krusell et al (1996) for more detail.

[20]The calculations are presented in Jovanovic (1996).

THE LEARNING CURVE

As a case in point for the importance of learning effects consider the Lawrence #2 mill, a cotton mill in the antebellum period studied by David (1975). This mill was built in 1834 in Lowell, Massachusetts. Detailed inventories of the equipment at this plant show that no new machinery was added between 1836 and 1856. Thus, it seems reasonable to infer that any increases in productivity over this period arose purely due to learning effects. In fact, output-per-manhour in this plant grew on average at 2.3% per year over this period. Figure 7 shows the plant's learning curve. The four observations pertain to years when it is known that the plant was operating at full capacity. Learning curves from angioplasty surgery, flight control simulation, munitions manufacturing, and steel finishing are documented in Jovanovic and Nyarko (1995); there are a plethora of other examples in the literature. Yorukogolu (1996) has studied the learning curve for information technologies using data from 297 firms over the time period 1987-1991. His learning curve for information technologies is plotted in Figure 8. It shows strong learning effects. The service flow (similar to horsepower for a steam engine) captured from new computers increases dramatically over time. This flow grows at approximately 28% (compounded) per year. Two words of caution are offered here. First, as the error bands show the range of estimates is quite high — this is because the data set permitted studying only a small number of firms for a short period of time.[21] Second, computers aren't the only thing that a firm uses to produce output. If computers account for 5% of output then this translates into an output growth rate due to learning alone of about 1.4% (.28x.05x100%) a year.

Often learning about a technology comes through use by the final purchaser. Im-

[21] The error bands show the 95% percent confidence intervals.

Figure 7: Lawrence Number 2 Cotton Textile Mill

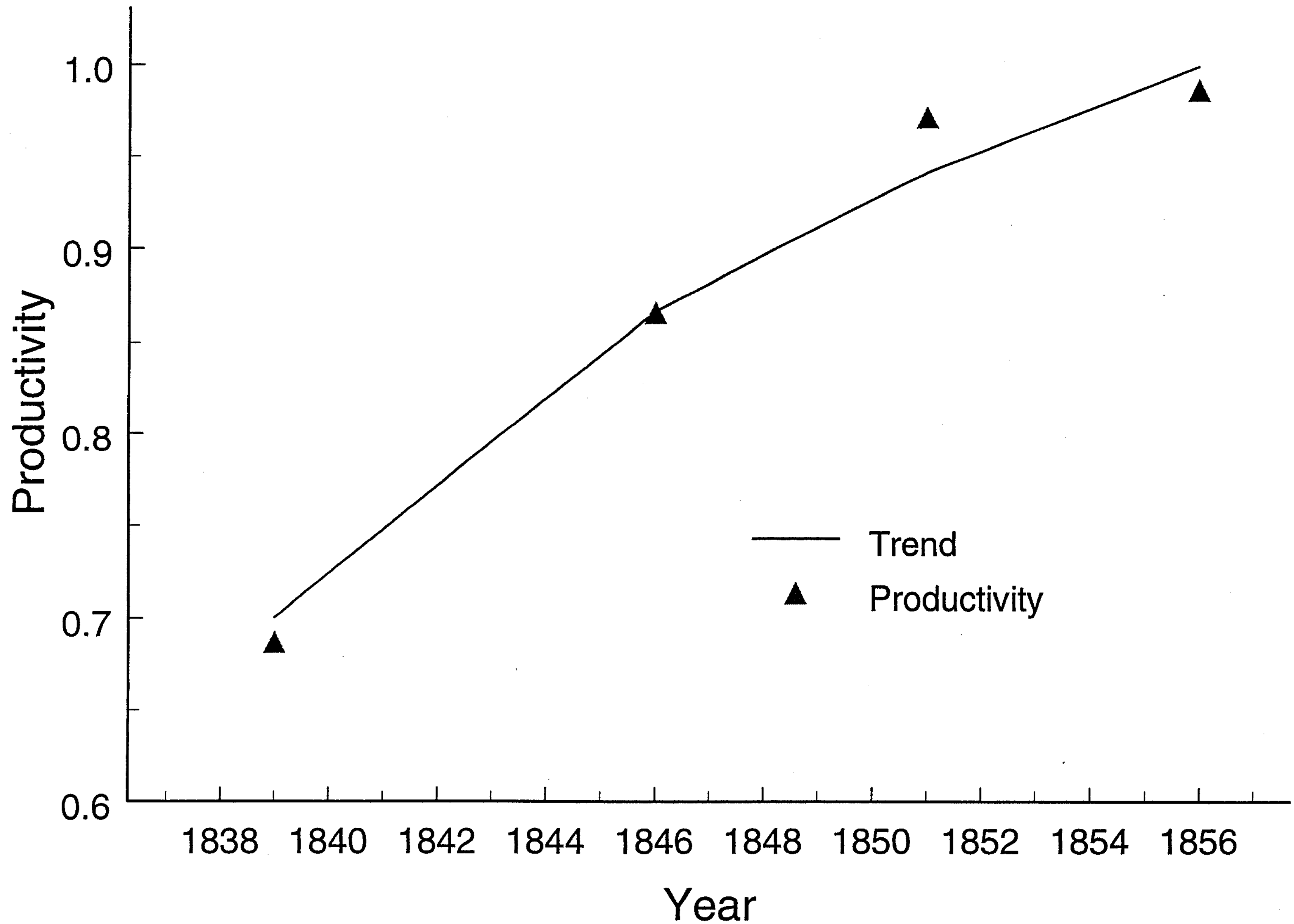
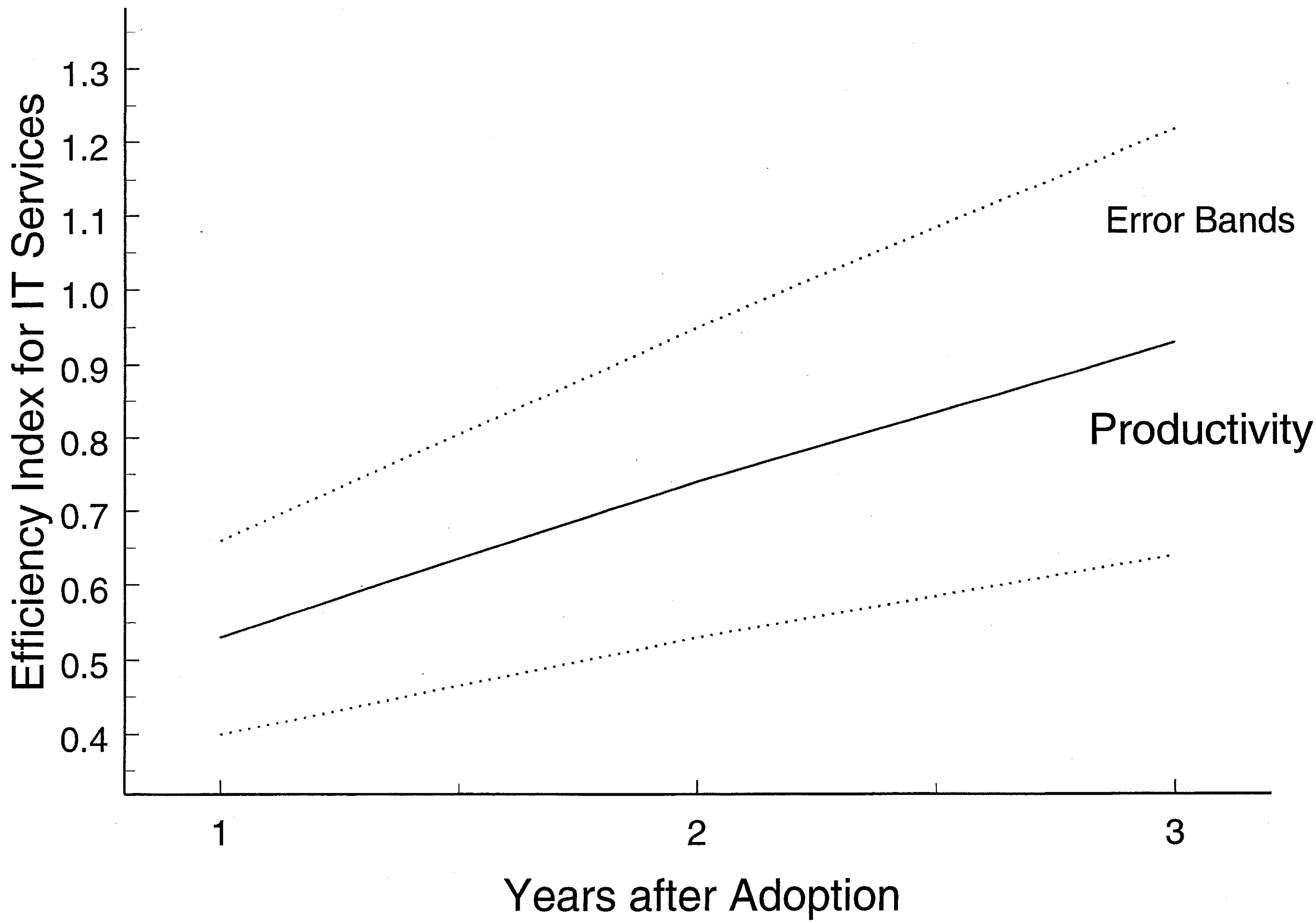


Figure 8: Learning Curve for Information Technologies



portant operating characteristics about some products — such as software — are only revealed after intensive use. Manufacturers may then adjust the product on the basis of the feedback they receive from purchasers. The process may take many iterations. The aircraft industry provides an excellent example of such learning by using. As confidence about the operating characteristics of the DC-8 airplane was gained by experience, the manufacturer increased the thrust of the engines while reducing fuel consumption, and modified the wings to lower drag. This eventually allowed the airplane to be stretched to increase its capacity from 123 to 251 seats. The result was a dramatic improvement in operating costs, such as a 50% savings in the fuel costs per seat mile. For complicated products reliability is a major concern. Here maintenance experience proves invaluable. For aircraft maintenance may account for 30% of the operating costs associated with labor and materials. This excludes the lost revenue associated with down-time. It is interesting to note that the costs of servicing new types of jet engines fall dramatically subsequent to their introduction. After a decade of operation maintenance costs have typically dropped to 30% of their initial level.

THE DIFFUSION CURVE

The adoption of new technologies is notoriously slow. The initial incarnations of new ideas are often expensive and plagued with bugs. The impact that investment-specific technological change has 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 will be its speed of 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 use of the technology becomes widespread, society's stock of experience with it increases and the technology's productivity rises.

New technologies have high prices when they are first produced. Prices drop as the manufacturer gains experience in production. This encourages adoption, which in turn fuels further price declines as production costs fall due to learning and scale effects. Waves of imitators enter the industry leading to more competitive pricing. The odds of imitating a new invention depends on the number of firms who have already successfully adopted the new invention. The number of firms increases through 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 better such products. To bring these complementary products on line may take a lot of time and resources. The availability of such products encourages further adoption, and so on. It may take a long time an invention to bear fruit.

There is considerable evidence that the diffusion of new 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 that were producing the new product over time. On average there were only 2 or 3 firms producing each new product for the first 14 years after its commercial development, upon which there was a sharp increase in the number of firms (on average 6 firms per year over the next 10 years). It is interesting to note that prices fell rapidly following the inception of a new product (13% a year for the first 24 years). Using a 21 product subset of the Gort and Klepper data, Jovanovic and Lach (1996) report that it took approximately 15 years for the output of a new product to rise from the 10 to 90% diffusion level. They also cite evidence from a study of 265 innovations that found that it took a new innovation

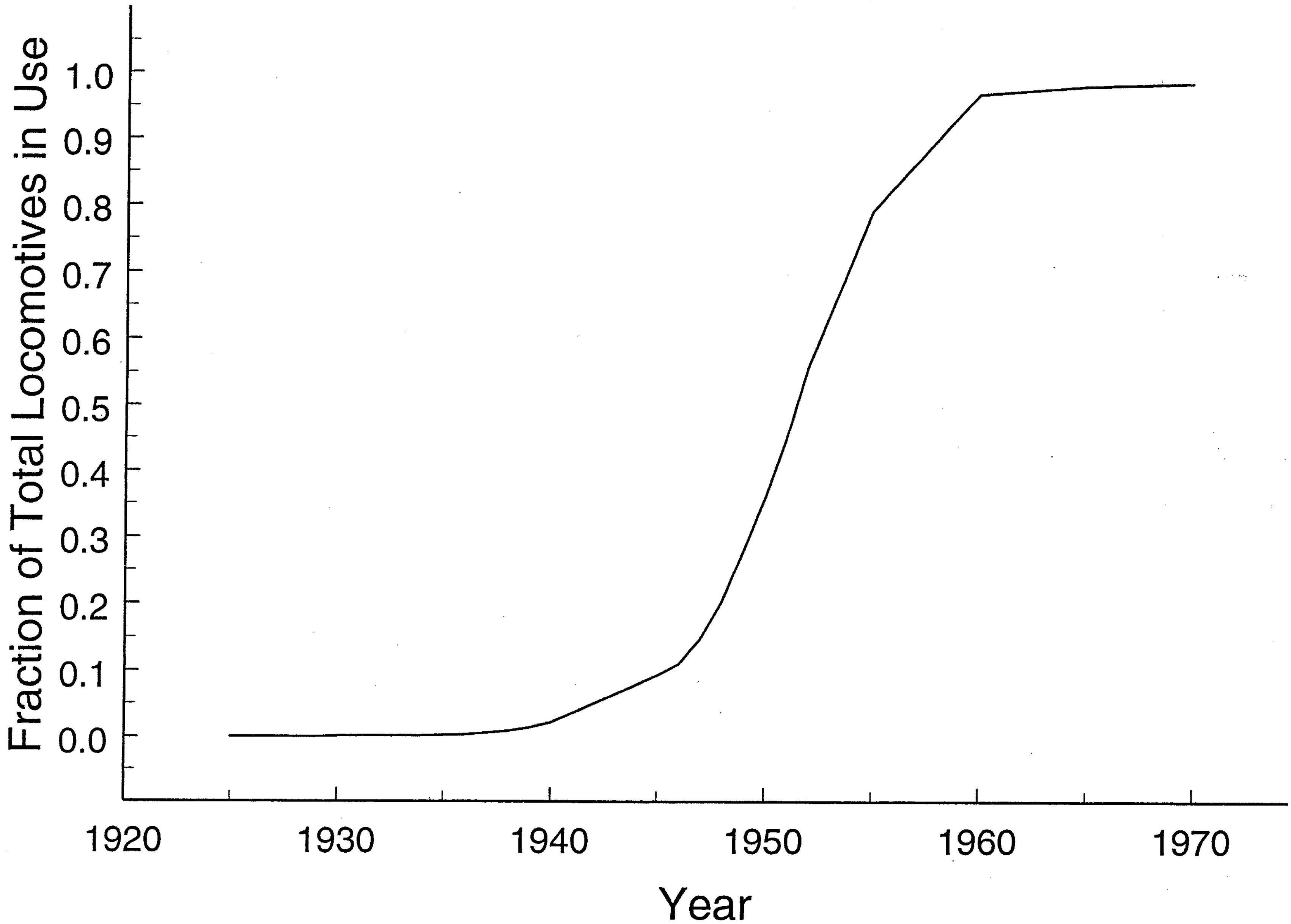
41 years on average to move from the 10 to 90% diffusion level. Finally, in the U.S. it took the steam locomotive 54 years to move from the 10 to 90% diffusion level and the diesel (a smaller innovation) 12 years. The diffusion curve for diesels is plotted in Figure 9. As can be seen, it took approximately 25 years from the time the first diesel locomotive was introduced in 1925 to the time they accounted for half of the locomotives in use, which occurred somewhere between 1951 and 1952.

THE COMPUTER AND THE DYNAMO

The metamorphosis of a novel idea into a productive technology can take a long time.[22] The course of a technology's development is often uncharted at its infancy. A lot of time and resources can go into exploring the various paths that may be taken. The evolution of electricity and of computers are two interesting examples of this uncertain process. It's ironic that one of the least productive inventions of the Industrial Revolution is the foundation of the current Information Age. Some where between1823 and 1832 Charles Babbage created his "Difference Engine", which was a mechanical computer. Part of the insight for this invention came from a binary coded loom invented in 1801 by Jean-Marie Jacquard that used punchcards to control fabric patterns. But less than fifty years ago it still wasn't obvious that there would be an information age. 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 1 1/2 tons."

[22]The section title is borrowed from David (1991).

Figure 9: Diffusion of Diesel Locomotives



The Electrification of America

The electrification of America, as masterfully chronicled and analyzed by David (1991), illustrates the delays in the successful exploitation of new technologies. The era of electricity dawned around 1900. Electricity was obviously useful as a source of lighting in homes and businesses, but it had to supplant water and steam as source of power in manufacturing.[23] This was made difficult by the fact that there were large stocks of equipment and structures already in place geared to these sources of power. Thus, in the early stages, electricity tended to be overlaid onto existing systems. In particular, the mechanics of steam and water power favored one power unit driving a group of machines. 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. The group drive system of belts and shafting used by steam and water power were retained. Not surprisingly, electric power tended to be used mostly in those industries that were rapidly expanding, since new plants could be designed to better accommodate this power source.

By around 1910 it was apparent that machines could be driven with individual electric motors. This had a large impact on productivity in the workplace. The belt-drive apparatus used in the group drive system could now be abandoned. Factory construction no longer needed to allow for the heavy shafting and belt-housing required for the group drive power transmission. Additionally, the labor needed to maintain this system was eliminated. Furthermore, flexibility in the production process rose for several reasons. The entire power system no longer needed to be shut down for maintenance or replacement purposes. Also, since each machine could be more accurately controlled, increases in the quantity and quality of output obtained.

[23]While only 3% of households used electric lighting in 1899, almost 70% did by 1929 (David 1991, Table 3).

Machines could now be located and moved more freely to accommodate better the production process. Last, the workplace was made considerably safer. Figure 10 shows the diffusion of electric motors in manufacturing.[24] Electric motor horsepower, as a fraction of the horsepower of the total mechanical drive in manufacturing establishments, follows a typical S-shaped diffusion pattern. It is interesting to note that labor productivity growth in manufacturing slows down at the time of electricity's introduction.[25]

In 1890 an astute observer might have understood the importance of electricity for lighting homes and powering factories. He wouldn't have predicted how it would transform future lives through the other inventions it would spawn: radio, television, and computers.

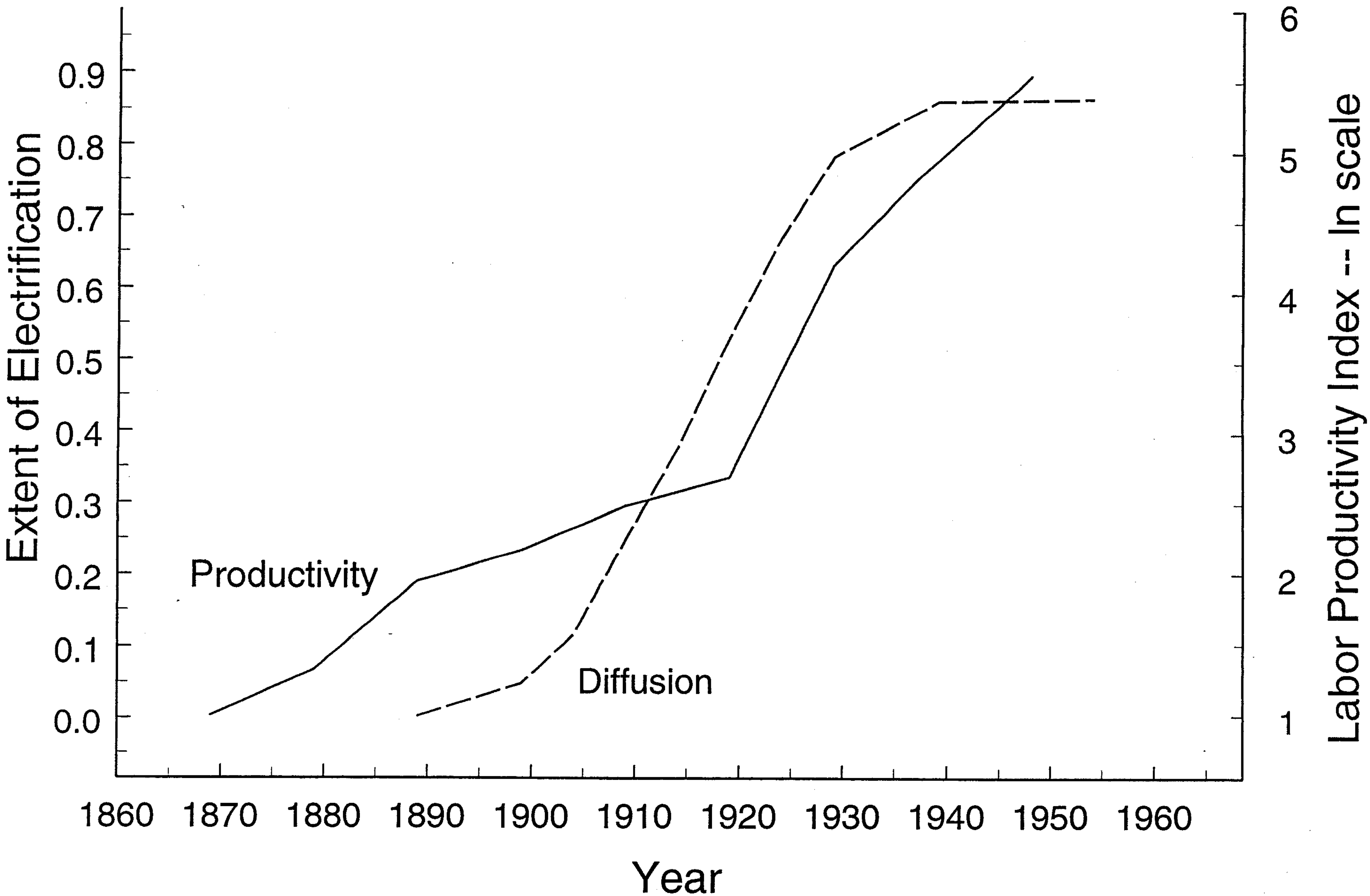
The Computerization of America

As it did with the electrification of America, it is taking time for the world economy to reap the harvest from the information technology revolution. The era of computers saw daybreak in the 1950's. Early computers were essentially calculating devices. They were used primarily in academic and industrial research and performed calculations that were impractical or impossible to do manually. There was a rapid decline in the cost of number crunching over this period. Between 1950 and 1980 the cost of a MIPs (million instructions per second) fell by somewhere between 27 to 50% per year. This spurred on the use of computers as calculating devices. The adoption of computers led in turn to further price reductions as computer manufacturers rode up their learning curves, a feedback loop. The 1960's saw computers become file keeping devices. There were used by businesses to store, sort and process, and retrieve large

[24]The data source is David (1991, Table 3).

[25]Again, the data is based on David (1991, Table 2).

Figure 10: The Electrification of America



volumes of data. They saved on labor involved in information processing activities. The cost of storage probably fell at annual rate of 25 to 30% from 1960 to 1985. More recently computers have evolved into communication devices. This started in the 1970's with the advent of remote accessing and networking. This allowed a partial liberation of the computer from the "clean room". The umbilical cord to the "clean room" was finally cut in the 1980's with the introduction of the p.c. and the spread of networking.

IT is likely to lead to much more streamlined corporate structures by economizing on the number of employees involved in activities associated with information collection and processing. The goal of any firm is simply put: maximize profits. To do this the firm must have an organizational structure in place capable of detecting profit opportunities, directing actions to harvest them, and of monitoring and evaluating the 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, as opposed to just 0.22 in 1900. IT can do much of this information collection and processing activity more efficiently than labor, eliminating the need for battalions of clerks, pools of secretaries, scores of purchasing agents, and layers of supervisors and administrators. Headquarters, design centers, plants, and purchasing and sales offices can now be directly linked to one another via information technologies. The effects of such major changes in business structure may take some time to transpire, but they will inevitably lead to an increase in labor productivity as more output can be produced with less labor. Studies, such as Brynjolfsson and Hitt (1993), indicate that this is now happening.

So how realistic is the hypothesis presented above? To judge this Greenwood and Yorukoglu (1996) have developed an economic model of the Information Age, which they simulate on computer. The model incorporates two ingredients. First, it is assumed that firms face a learning curve when they adopt a new technology. Second, it is presumed that firms can travel up this learning curve faster by hiring skilled labor. With the dawning of the Information Age, the growth rate in labor productivity slumps in the model economy and income inequality widens. It takes time for the effects of the Information Age to work their way through the system. In the model, it takes about 20 years before productivity growth surpasses its old level and 40 years for the level of productivity to cross its old trend line — the path that productivity would have travelled along if it had continued at its old growth rate. Unskilled wages fall during initial stages of the Information Age. Twenty years elapse before this loss in unskilled wages is made up and about 50 go by before they 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 the new investment opportunities. For many in the economy, though, waiting for the benefits of technological miracles will be like watching grass grow; but grow it will.

CONCLUSION

Plunging prices for new technologies, a surge in wage inequality, and a slump in the advance of labor productivity — could this be the hallmark of the dawn of an industrial revolution? Just as the steam engine shook 18th century England, and electricity rattled 19th century America, are information technologies now rocking the 20th century economy?

The story told here is simple. Technological innovation is embodied in the form of new producer durables or services. The prices of these goods 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. Skill facilitates this adoption process. Therefore, times of rapid technological advancement 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 temporarily pauses 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 change implies that eventually more output can be produced by a unit of labor. Hence a unit of labor becomes more valuable. Given time this translates into higher wages and standards of living for everyone. Clearly, everybody today is better off due to the British industrial revolution. This wasn't true, however, in 1760. So what about the short run? In the story told, skilled workers will fare better than unskilled ones. 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 will increase the supply of skilled agents, and reduce the amount of unskilled labor, easing the pressure on the skill premium. Additionally, in the short run the wealthy will do better than the poor. 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, in the short run young, unskilled agents fare the worst. In the long run the rising tide of technological change will lift everybody's boats.

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