Chapter 18

GENERAL PURPOSE TECHNOLOGIES

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Contents

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Abstract

A general purpose technology or GPT is a term coined to describe a new method of producing and inventing that is important enough to have a protracted aggregate impact. Electricity and information technology (IT) probably are the two most important GPTs so far. We analyze how the U.S. economy reacted to them. We date the Electrification era from 1894 until 1930, and the IT era from 1971 until the present. While we document some differences between the two technologies, we follow David [In: *Technology and Productivity: The Challenge for Economic Policy* (1991) 315–347] and emphasize their similarities. Our main findings are:

1. Productivity growth in the two GPT eras tended to be lower than it was in other periods, with productivity slowdowns taking place at the start of the two eras and the IT era slowdown stronger than that seen during Electrification.
2. Both GPTs were widely adopted, but electricity's adoption was faster and more uniform over sectors.
3. Both improved as they were adopted, but measured by its relative price decline, IT has shown a much faster improvement than Electricity did.
4. Both have spawned innovation, but here, too, IT dominates Electricity in terms of the number of patents and trademarks issued.
5. Both were accompanied by a rise in "creative destruction" and turbulence as measured by the entry and exit of firms, by mergers and takeovers, and by changing valuations on the stock exchange.

In sum, Electrification spread faster than IT has been spreading, and it did so more evenly and broadly over sectors. Also, IT comprises a smaller fraction of the physical capital stock than electrified machinery did at its corresponding stage. On the other hand, IT seems to be technologically more dynamic; the ongoing spread of IT and its continuing precipitous price decline are reasons for optimism about productivity growth in the 21st century.

Keywords

electricity, information technology, IT revolution, productivity slowdowns, technology improvement, creative destruction

JEL classification: O3, N2

1. Introduction

The term "general-purpose technology", or GPT, has seen extensive use in recent treatments of the role of technology in economic growth, and is usually reserved for changes that transform both household life and the ways in which firms conduct business. Steam, electricity, internal combustion, and information technology (IT) are often classified as GPTs for this reason. They affected the whole economy.

As David (1991) has pointed out, however, a GPT does not deliver productivity gains immediately upon arrival. Figure 1 shows the evolution of the growth in output per man-hour in the U.S. economy over the past 130 years, with periods of rapid diffusion of the two major GPTs shaded and the dashed line representing long-term trends as generated with the Hodrick–Prescott (HP) filter.[1] Productivity growth was apparently quite rapid during the heyday of steam power (c. 1870), but fell as Electrification arrived in the 1890s, with the defining moment in the transition probably being the startup of the first hydro-electric facility at Niagara Falls in 1894. It was only in the period after 1915, which saw the diffusion of machines operated by stand-alone secondary motors and the widespread establishment of centralized power grids, that Electricity finally pervaded businesses and households more generally and measures of productivity began to rise.

Figure 1 also shows that the arrival of IT, which we date with Intel's invention in 1971 of the "4004" microprocessor (the key component of the personal computer or "PC"), did not reverse the decline in productivity growth that had begun more than a decade earlier. It seems only now that we are finally seeing computers show up in the productivity figures.

But it is not obvious that the startup of the Niagara Falls dam and the invention of the 4004 chip should define the birth of the two GPTs. After all, Thomas Edison invented the incandescent bulb in 1879 and by 1882 the world's first large central power station had been installed at Pearl Street in New York City, twelve years before we mark Electricity's "arrival". And large mainframe computers predicted the winner of the 1952 U.S. Presidential election, nearly two decades prior to the advent of the microprocessor. An objective measure is needed, though, and we shall define the start of a GPT era as the point in time when the GPT achieves a one-percent diffusion in the median sector. This is another way to arrive at 1894 and 1971 as the starting points where the shading begins in Figure 1. Similarly, we would say that the era is over when the diffusion curve flattens out. For Electrification, it takes until about 1929 for net adoption to reach a plateau, whereas new adoption of IT is still rising today so that, on that criterion, the IT epoch continues.

Each shaded area in Figure 1 contains a productivity-growth slowdown in its initial phases. Will the growth slowdown of the current IT era be followed by a rise in growth

[1] Output per man-hour in the business, non-farm sector is from John Kendrick's series as published in U.S. Bureau of the Census (1975, Series D684, p. 162) for 1889–1947 and from the Bureau of Labor Statistics for 1948–2003. For 1874–1889, we use Kendrick's decadal averages for 1869–1879 and 1879–1889 and interpolate between these benchmarks assuming a constant growth rate from 1874–1884 and 1885–1889.

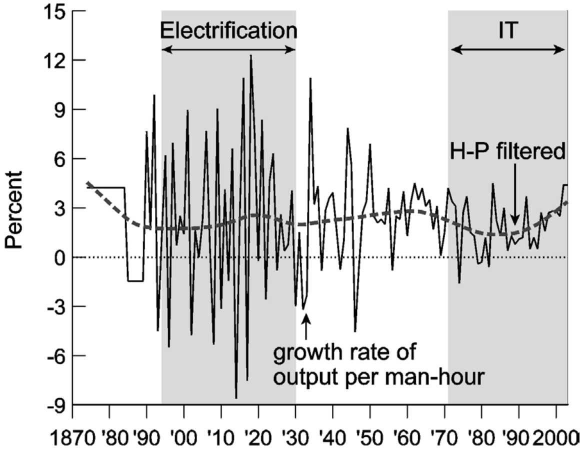

Figure 1. Annual growth in output per man-hour, 1874–2004.

in the first half of the 21st century? If the second shaded area in Figure 1 is in some fundamental respects like the first shaded area, then we can expect growth to pick up over the next several decades. In Jovanovic and Rousseau (2002a) we have argued that the first half of the 21st century will have higher growth than, say, the 1950s and 1960s. Gordon (2000), on the other hand, is pessimistic, arguing that IT does not measure up to Electricity and that it will not have such positive results. This chapter, while documenting key differences between the diffusion paths of the two technologies, will in the end conclude that the two GPT eras are strikingly similar in a number of respects. If anything, our finding that IT is the more "revolutionary" of the two GPTs suggests that its full impact is yet to be seen.

This chapter is organized around the presentation of a collection of facts. The facts are described mainly through graphs and tables which provide evidence on a set of models that we shall mention as we go along. A primarily analytic survey is Greenwood and Jovanovic (2001).

1.1. What is a GPT?

So, what are these "fundamental" features of GPTs that would allow us to compare one to another? And more generally, what criteria can one use to distinguish a GPT from other technologies? Bresnahan and Trajtenberg (1996) argue that a GPT should have the following three characteristics:

1. *Pervasiveness* – The GPT should spread to most sectors.
2. *Improvement* – The GPT should get better over time and, hence, should keep lowering the costs of its users.
3. *Innovation spawning* – The GPT should make it easier to invent and produce new products or processes.

Most technologies possess each of these characteristics to some degree, and thus a GPT cannot differ qualitatively from these other technologies. Note, too, that the third property is, in a sense, a version of the first property if we phrase the latter to say that the GPT should also spread to the innovation sector. Moreover, this list can be expanded to include more subtle features of GPTs, a subject that we consider in Section 3. Yet we find these three basic characteristics to be a useful starting point for evaluating and comparing the impact of various technologies through history. Investigating how Electricity and IT measure up on these three dimensions is the focus of Section 2. But first, we summarize our overall findings.

1.2. Summary of findings

The evidence shows similarities and differences between the Electrification and the IT eras. Electrification was more pervasive (#1), whereas IT has a clear lead in terms of improvement (#2) and innovation spawning (#3). Let us list the similarities and differences in more detail.

1.2.1. Similarities between the Electrification and IT eras

1. In both eras productivity growth rates are below those attained in the decades immediately preceding the GPT's arrival.
2. Measures of reallocation and invention – the entry and exit of firms to the stock market, investment by new firms relative to incumbents, and grants of patents and trademarks – are all higher during the GPT eras.
3. Private consumption rises gradually during each GPT era.
4. Real interest rates are about the same during the two GPT eras, and about three percentage points higher than from 1930 to 1970 – the period between the rapid adoptions of Electricity and IT.

1.2.2. Differences between the Electrification and IT eras

1. Innovation measures are growing much faster for IT than for Electrification – patents and trademarks surge much more strongly during the IT era, and the price of IT is falling 100 times faster, at least, than did the price of electricity.
2. IT is spreading more slowly than did Electrification, and it comprises a smaller part of the capital stock. Its net adoption continues to rise in the United States.
3. The productivity slowdown is stronger in the IT era.
4. No comparable sudden collapse of the stock market occurred early on in the Electrification era.
5. The Electrification era saw a surplus in the U.S. trade balance, in part because Europe had to finance a string of wars, whereas the IT era finds the United States with consistent trade deficits.

The differences seem to be quite important. But overall the evidence clearly supports the view that technological progress is uneven, that it does entail the episodic arrival of GPTs, and that these GPTs bring on turbulence and lower growth early on and higher growth and prosperity later. The bottom line is that with a wider body of data and fifteen more years of it than David (1991) had at his disposal, we confirm his hypothesis that Electrification and IT adoption are manifestations of the same force at work, namely the introduction of a GPT.

2. Measuring the three characteristics of a GPT

As suggested in Figure 1, we shall choose Electricity and IT as our candidate GPTs, and the measures that we construct will pertain mostly to these two technologies. In passing, we shall also touch upon steam and internal combustion. The three subsections below report, in turn, various measures of each characteristic – pervasiveness, improvement, and innovation – for the two GPTs at hand.

2.1. Pervasiveness of the GPT

The first characteristic is the technology's pervasiveness. We begin by looking at aggregates and proceed to consider individual industrial sectors in more detail.

2.1.1. Pervasiveness in the aggregate

Ideally we would like to track the evolution of various candidate GPTs using continuous time series from about 1850 to the present, but we do not have data that consistently cover this entire stretch of time, and thus will need to work with two overlapping segments: 1869–1954 and 1947–2003.

Figure 2 shows the shares of total horsepower in manufacturing by power source from 1869 to 1954.[2] The period covers the decline in usage of water wheels and turbines, the rise and fall of steam engines and turbines, the rise and gradual flattening out of the internal combustion engine's use in industrial applications, and the sharp rise in the use of primary and secondary electric motors. The symmetry of the plot is striking in that, with the exception of internal combustion, power-generating technologies seem to have led for the most part sequential existences. The relative brevity of the entire steam cycle, which rises and falls within a period of 50–60 years, suggests that the technology

[2] We construct the shares of total horsepower in manufacturing as ratios of each power source from DuBoff (1964, table 14, p. 59) to the total (table 13, p. 58). DuBoff estimates these quantities in 1869, 1879, 1889, 1899, 1904, 1909, 1914, 1919, 1923, 1925, 1927, 1929, 1939 and 1954, and we linearly interpolate between these years in Figure 2. This source does not include a breakdown of non-electrical capacity (i.e., water, internal combustion, and steam) after 1939, and so we mark the more broadly-defined "non-electrical" share for 1954 with an asterisk.

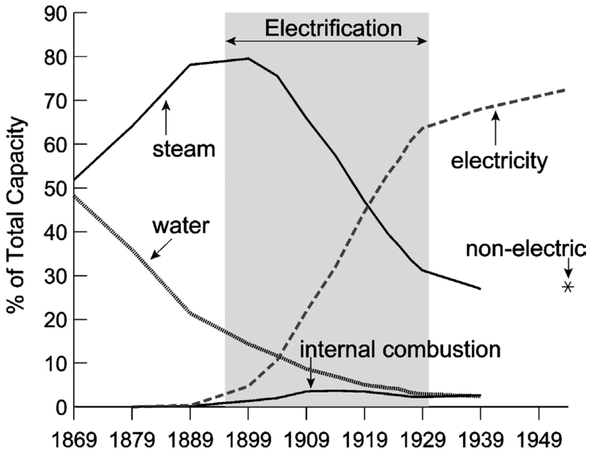

Figure 2. Shares of total horsepower generated by the main sources in U.S. manufacturing, 1869–1954.

which replaced it, Electricity, was important enough to force a rapid transition among manufacturers. In contrast, the decline of water power was more gradual.

If we could continue Figure 2 to the present, Electricity would surely still command a very high share of manufacturing power as the next new source (e.g., solar power?) has not yet emerged to replace it. The persistence of Electricity as the primary power source, even though its diffusion throughout the manufacturing sector was complete decades ago, helps to identify it as one of the breakthrough technologies of the modern era.

Figure 3 shows the diffusion of computers in the U.S. industrial sector as measured by the share of IT equipment and software in the aggregate capital stock.[3] Computer and software purchases appear to have reached the first inflection point in their "S-curve" more slowly than Electrification in the early years of its adoption, but it is striking how much faster the IT share has risen over the past few years. Moreover, while the diffusion of Electricity had slowed down by 1930, the year which we mark as the end of the Electrification era, computer and software sales continue their rapid rise to this day.

The vertical axes in Figures 2 and 3 are scaled differently. In Figure 2 the vertical axis measures the share of total horsepower in manufacturing, whereas in Figure 3 it is the share of IT equipment and software in the aggregate capital stock. But scaling aside, a comparison of the shape of the diffusions in the two figures suggests that the

[3] We build the ratio plotted in Figure 3 for 1961–2001 by summing the capital stocks of 62 SIC industrial sectors from the detailed nonresidential fixed asset tables in constant 1996 dollars made available by the U.S. Bureau of Economic Analysis (2002, 2004). IT capital includes mainframe and personal computers, storage devices, printers, terminals, integrated systems, and pre-packaged, custom, and own-account software. The total capital stock is the sum of all fixed asset types.

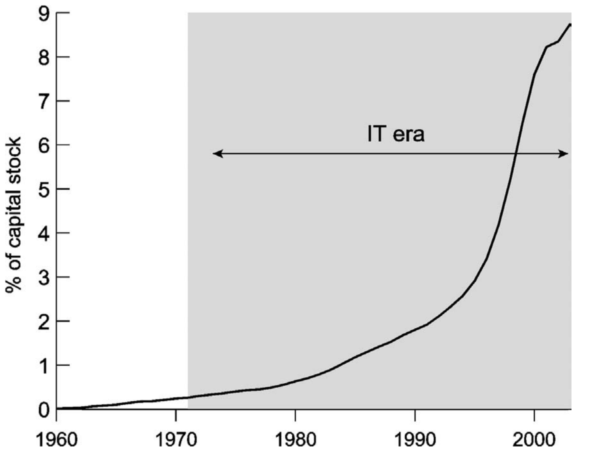

Figure 3. Shares of computer equipment and software in the aggregate capital stock, 1960–2003.

IT-adoption era will last longer than the 35 years of Electrification. Indeed, the acceleration in adoption, which was over by about 1905 for Electrification, did not end until about 1997 for IT. It also appears that IT forms a smaller part of the physical capital stock than did electric-powered machinery at the corresponding stages.

Why did Electricity spread faster than IT seems to be doing? Both technologies are subject to a network externality; Electricity because the connecting of cables and wires to a neighborhood was more profitable when the number of users was larger, and IT especially so after the Internet was invented. Perhaps electrical technologies were more profitable, or perhaps the rapid price decline of computers and peripherals makes it optimal to wait and adopt later as Jovanovic and Rousseau (2002a) emphasize.

2.1.2. *Pervasiveness among sectors*

Cummins and Violante (2002, p. 245) classify a technology as a GPT when the share of new capital associated with it reaches a critical level, and if adoption is widespread across industries. Electrification seems to fit this description. Figure 4 shows the shares of total horsepower electrified in manufacturing sectors at ten-year intervals from 1889 to 1954.[4] Electrical adoption was very rapid between 1899 and 1919 but slowed considerably thereafter, with the dispersion in the adoption rates largest around 1919.

The striking feature of Figure 4 is how *uniformly* electrical technology affected individual manufacturing sectors. Table 1, which shows the rank correlations of Electricity shares across sectors and time, indicates that there was little change in the relative ordering of the sectors. This means that the sectors that were the heaviest users of Electricity

[4] The shares of electrified horsepower include primary and secondary electric motors, and are computed using data from DuBoff (1964, tables E-11 and E-12a–E-12e, pp. 228–235).

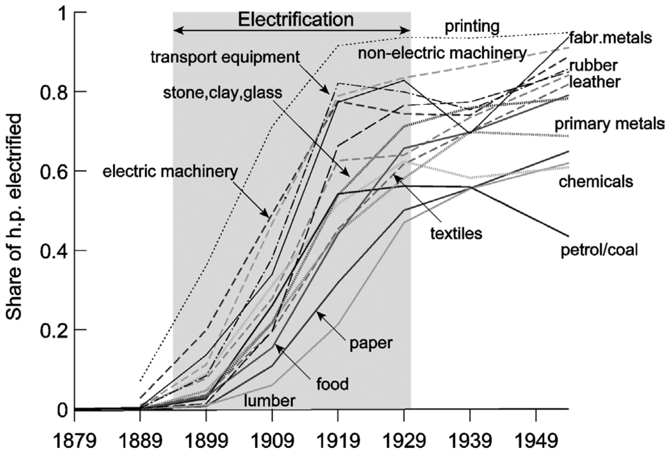

Figure 4. Shares of electrified horsepower by manufacturing sector, 1890–1954.

Table 1
Rank correlations of Electricity shares in total horsepower by manufacturing sector, 1889–1954

	1889	1899	1909	1919	1929	1939	1954
1889	1.000						
1899	0.707	1.000					
1909	0.643	0.918	1.000				
1919	0.686	0.746	0.893	1.000			
1929	0.639	0.718	0.739	0.871	1.000		
1939	0.486	0.507	0.571	0.750	0.807	1.000	
1954	0.804	0.696	0.650	0.789	0.893	0.729	1.000

in 1890 remained among the leaders as adoption slowed down in the 1930s. In sum, the adoption of Electricity was sweeping and widespread.

Why did that adoption take as long as it did? One answer is that it was costly to set up the wiring required to electrify households early on. This is apparent from the peculiar two-stage adoption process that many factories chose in adopting Electricity. Located to a large extent in New England factory towns, textile firms around the start of the 20th century readily adapted the new technology by using an electric motor rather than steam to drive the shafts which powered looms, spinning machines and other equipment [see Devine (1983)]. Moreover, delays in the distribution of electricity made it more costly to electrify a new industrial plant fully.

Figure 5 shows the same data as Figure 4, but now in percentile form. We build it by sorting the Electricity shares in each year and, given that only 15 sectors are represented, plotting the 2nd, 5th, 8th, 11th and 14th largest shares in each year. The percentile diffusion curves will be useful when drawing comparisons with the IT era. They also

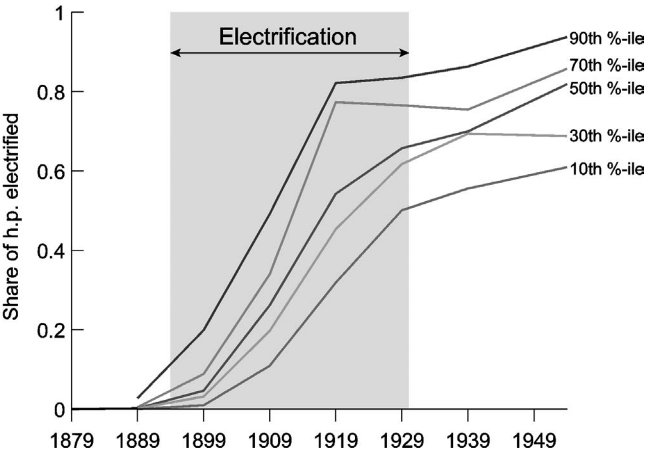

Figure 5. Shares of electrified horsepower by manufacturing sector in percentiles, 1890–1954.

help us in dating Electricity as a GPT. Linear extrapolation between the years 1890 and 1900 suggests that in 1894, about one percent of horsepower in the median industry was provided by Electricity. Whether or not this is actually the "right" percentage for dating the start of the Electrification era, we shall use a one percent share for the median industry to date the beginning of the IT era as well. This provides a common standard for choosing the left-end points of the two shaded areas.

In the century before the Electricity revolution, the technology that primarily drove manufacturing was steam. Figure 6 shows just how slowly steam was replaced between 1899 and 1939.[5] It is natural that industries such as rubber, primary metals, non-electric machinery, and stone, clay, and glass, which saw such rapid increases in electricity use over the same period, would withdraw from steam most rapidly. Indeed, most of the industries that quickly switched over to electricity had been heavy users of steam. This is clear from Figures 4 and 6, taken together, and from the rank correlations of steam shares in total horsepower in Table 2, which decay quickly and suggest a non-uniformity in the destruction of steam technology across the manufacturing sectors.

The spread of IT was also rapid, but does not appear to have been as widespread as Electricity. Figure 7 shows the share of IT equipment and software in the net capital stocks of 62 sectors from 1960 to 2001 plotted as annual percentiles.[6] Some sectors

[5] The sectoral shares of manufacturing horsepower driven by steam were computed from DuBoff (1964, tables E-12a–E-12e, pp. 229–233), and include steam engines and turbines. These shares are available on a decade basis from 1899 until 1939 only, which is why the time coverage in Figure 6 is shorter than that in Figure 4.

[6] The sectoral capital stocks are from the detailed non-residential fixed asset tables in constant 1996 dollars made available by the U.S. Bureau of Economic Analysis (2002). We present the sectoral shares for the IT era in percentile form because the number of sectors covered is much larger than was possible for electrification

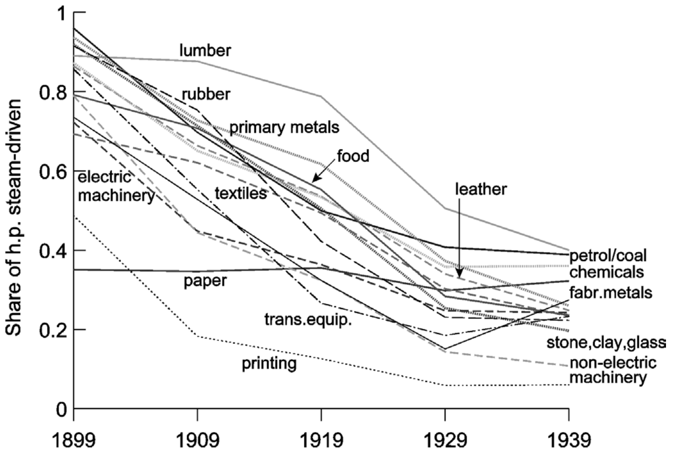

Figure 6. Shares of steam-driven horsepower by manufacturing sector, 1899–1939.

Table 2
Rank correlations of steam shares in total horsepower by manufacturing sector, 1889–1939

	1899	1909	1919	1929	1939
1899	1.000				
1909	0.825	1.000			
1919	0.604	0.800	1.000		
1929	0.525	0.604	0.832	1.000	
1939	0.261	0.282	0.496	0.775	1.000

adopted IT very rapidly, and by 1975 six of them (the 90th percentile) had already achieved IT equipment and software shares of more than 5 percent. Other sectors lagged behind, and some did not adopt IT in a substantive way until after 1985.

On the other hand, the rank correlations of the IT shares across sectors, shown in Table 3, are even higher than those obtained for Electrification. On the face of it then, Electrification would appear to have been the more sweeping GPT-type event because it diffused more rapidly in the U.S. economy and all sectors adopted it pretty much at the same time, whereas IT diffused rapidly in some sectors and not-so-rapidly in others. Nonetheless, the recent gains in IT shares show that the diffusion of this GPT has yet to slow down in the way that Electrification did after 1929.

So far we have discussed adoption by firms, and have used this concept to determine the dating of the two GPT-epochs. We turn to households next.

and steam. Changes in the industrial classifications and the level of detail provided in the BEA's publicly-available fixed asset tables require us to end the series in 2001.

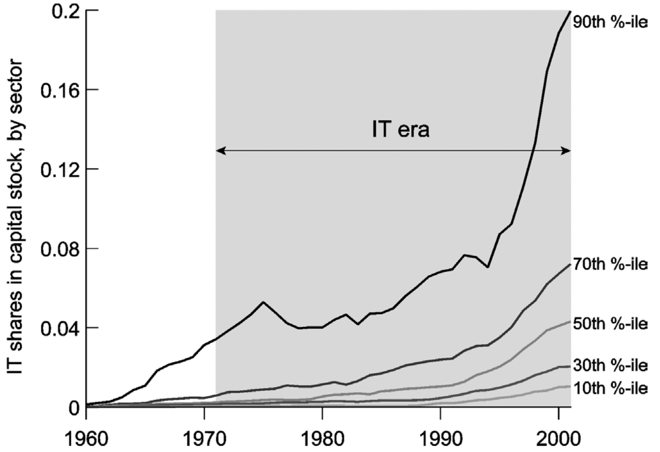

Figure 7. Shares of IT equipment and software in the capital stock by sector in percentiles, 1960–2001.

Table 3
Rank correlations of IT shares in capital stocks by sector, 1961–2001

	1961	1971	1981	1991	2001
1961	1.000				
1971	0.650	1.000			
1981	0.531	0.806	1.000		
1991	0.576	0.746	0.847	1.000	
2001	0.559	0.682	0.734	0.909	1.000

2.1.3. Adoption by households

Households also underwent Electrification and the purchase of PCs for home use during the respective GPT eras. Figure 8 shows the cumulative percentage of households that had obtained electric service and that owned a PC in each year following the arrival of the GPT.[7] If we continue to date Electricity as arriving in 1894 and the PC in 1971, Figure 8 shows that households adopted Electricity about as rapidly as they are adopting the PC. By the time the technology was officially 35 years old (in 1929), nearly 70 percent of households had electrical connections. A comparison with Figure 5 shows that this is just a little higher than the 1929 penetration of electrified horsepower

[7] Data on the spread of electricity use by consumers are approximations derived from U.S. Bureau of the Census (1975) *Historical Statistics of the United States* (series S108 and S120). Statistics on computer ownership for 1975–1998 are from Gates (1999, p. 118), and from the U.S. Bureau of the Census (2000–2004) *Current Population Survey* thereafter.

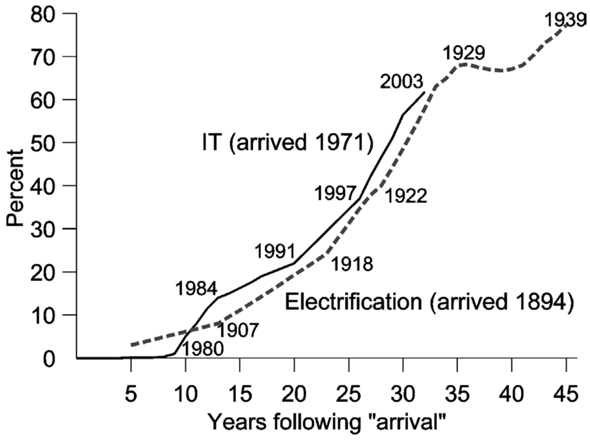

Figure 8. Percent of households with electric service and PCs during the two GPT eras.

as measured by its share in the median manufacturing sector. As in the case of firms, the Electrification of households reaches a plateau in 1929, although it resumed its rise a few years later. On the other hand, there is no sign yet that the diffusion of the computer among either households or firms is slowing down.

With households, as with firms, diffusion lags seem to arise for different reasons for the two technologies. Rural areas were difficult for Electricity to reach, but this is not the case for the PC, where the main barrier is probably the cost of learning how to use it. This barrier seems to have more to do with human capital than was the case with Electricity.

In some ways it is puzzling that the diffusion of the PC has not been much faster than that of Electricity. The price of computing capacity is falling much faster than the price of Electricity did. Affordable PCs came out in the 1980s, when the technology was some 15 years old. On the other hand, households had to wait longer for affordable electrical appliances. Only after 1915, when secondary motors began to diffuse widely and electrical appliances began to be invented, did the benefits of Electrification outweigh the costs for a majority of households. Greenwood, Seshadri and Yorukoglu (2002) document the spread of electrically-powered household appliances and argue that their diffusion helped to raise female labor-force participation by freeing up their time from housework.

2.1.4. On dating the endpoints of a GPT era

Our dating procedure reflects net adoption rates by firms, but the dates would not change much if we had instead used net adoption by households. The shaded areas in our figures are periods when the S-shaped adoption curves are, for the most part, rising. Whether or not they start to fall later should not affect the designated adoption eras. For instance,

Electricity has not yet been replaced in the same way that steam was phased out in the first half of the 20th century, but the Electrification era still ends in 1930 because adoption as measured in Figures 2, 4, and 5 flattens out. Figures 2 and 6 show that the steam era must have ended sometime around 1899 because net adoption had already become negative.

Net adoption is endogenous and should reflect the profitability of the technology at hand compared to that of other technologies. The Niagara Falls dam in 1894 and the development of alternating current made it possible to produce and distribute electricity more cheaply at greater distances. Figures 4 and 5 show that at the outset, some sectors (like printing) raced ahead of others in terms of how quickly they adopted. Later on, as the technology matures, its adoption becomes more universal. Eventually, the lagging sectors tend to catch up a bit, in relative terms, but not completely. Inequality of adoption is highest in the middle of the adoption era. We also see such a temporary rise in inequality among the declining steam shares (Figure 6) at about the same time that inequality was greatest in Electricity adoption.

2.2. Improvement of the GPT

The second characteristic that Bresnahan and Trajtenberg suggested is improvement in the efficiency of the GPT as it ages. Presumably this would show up in a decline in prices, an increase in quality, or both. How much a GPT improves can therefore be measured by how much cheaper a unit of quality gets over time. If technology is embodied in capital, then presumably capital as a whole should be getting cheaper faster during a GPT era, but especially capital that is tied to the new technology.

To investigate these implications, we first look at the price of capital goods generally and then at the prices of capital's components. Figure 9 is a quality-adjusted series

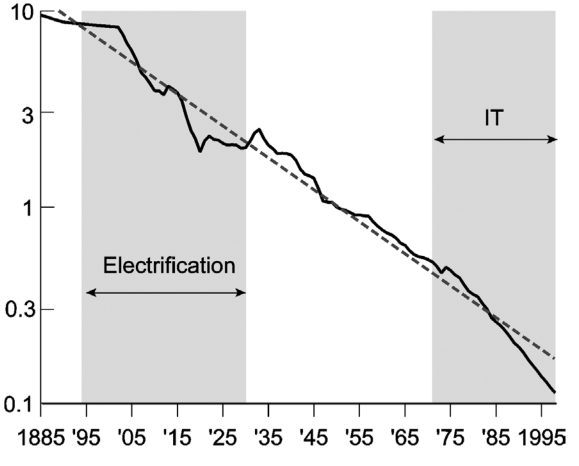

Figure 9. The price of equipment relative to consumption goods.

for the relative price of equipment as a whole, p_k/p_c (i.e., relative to the consumption price index) since 1885, constructed from a number of sources with a linear time trend included.[8] The figure shows that equipment prices declined most sharply between 1905 and 1920, and again after 1975. The 1905–1920 period is also the one that showed the most rapid growth of Electricity in manufacturing (see Figure 4) and in the home (see Figure 8). The post-1975 period follows the introduction of the PC.

Figure 10 considers the prices of components of the capital stock that are tied to our candidate GPTs (as well as to internal combustion), with all prices relative to the aggregate CPI. We use the price of electricity itself because deflators for electrically-powered capital are not available for the first half of the 20th century.[9] Declines in motor vehicle prices should capture the improvement in internal combustion as a possible GPT.[10] The use of the left-hand scale for electricity and motor vehicles and the right-hand scale for computers underscores the extraordinary decline in computer prices since 1960 compared to the earlier technologies.[11] While the relative prices of electricity and motor vehicles fall by a factor of 10, the index of relative computer prices falls by a factor of 10,000.

[8] Krusell et al. (2000) build such a series from 1963 using the consumer price index to deflate quality-adjusted estimates of producer equipment prices from Gordon (1990, table 12.4, col. 2, p. 541). Since Gordon's series ends in 1983, they use VAR forecasts to extend it through 1992. We start with Krusell et al. and work backward, deflating Gordon's remaining estimates (1947–1962) with an index for non-durable consumption goods prices that we derive from the National Income Accounts. Since we are not aware of a quality-adjusted series for equipment prices prior to 1947, we use the average price of electricity as a proxy for 1902–1946, and an average of Brady's (1966) deflators for the main classes of equipment for 1885–1902. We deflate the pre-1947 composite using the Bureau of Labor Statistics (BLS) consumer price index of all items [U.S. Bureau of the Census (1975, series E135)] for 1913–1946 and the Burgess cost of living index [U.S. Bureau of the Census (1975, series E184)] for 1885–1912.

[9] Electricity prices are averages of all electric services in cents per kilowatt hour from U.S. Bureau of the Census (1975, series S119, p. 827) for 1903, 1907, 1917, 1922 and 1926–1970, and from various issues of the *Statistical Abstract of the United States* for 1971–1989. We interpolate under a constant growth assumption between the missing years in the early part of the sample. For 1990–2000, prices are U.S. city averages (June figures) from the Bureau of Labor Statistics (*http://www.bls.gov*). We then set the index to equal 1000 in the first year of the sample (i.e., 1903).

[10] Motor vehicle prices for 1913–1940 are annual averages of monthly wholesale prices of passenger vehicles from the National Bureau of Economic Research (Macrohistory Database, series m04180a for 1913–1927, series m04180b for 1928–1940, *http://www.nber.org*). From 1941–1947, they are wholesale prices of motor vehicles and equipment from U.S. Bureau of the Census (1975, series E38, p. 199), and from 1948–2000 they are producer prices of motor vehicles from the Bureau of Labor Statistics (*http://www.bls.gov*). To approximate prices from 1901–1913, we extrapolate backward assuming constant growth and the average annual growth rate observed from 1913–1924. We then join the various components to form an overall price index and set it to equal 1000 in the first year of the sample (i.e., 1901).

[11] To construct a quality-adjusted price index, we join the "final" price index for computer systems from Gordon (1990, table 6.10, col. 5, p. 226) for 1960–1978 with the pooled index developed for desktop and mobile PCs by Berndt, Dulberger and Rappaport (2000, table 2, col. 1, p. 22) for 1979–1999. Since Gordon's index includes mainframe computers, minicomputers, and PCs while the Berndt et al. index includes only PCs, the two segments used to build our price measure are themselves not directly comparable, but a joining of them should still reflect quality-adjusted price trends in the computer industry reasonably well. We set the index to 1000 in the first year of the sample (i.e., 1960).

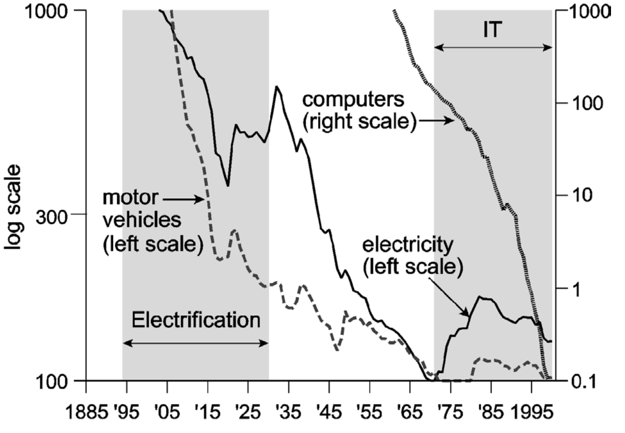

Figure 10. Price indices for products of the two GPT eras.

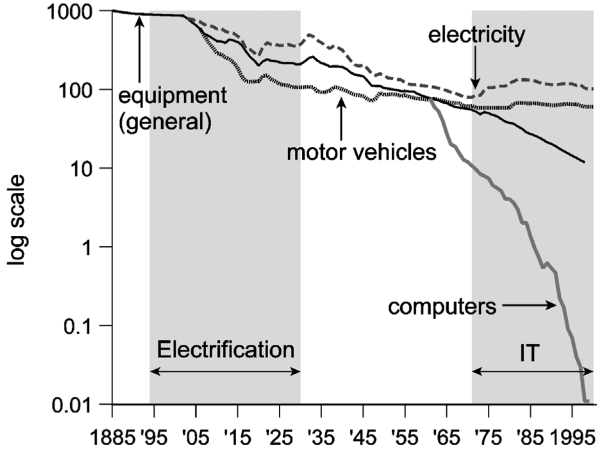

Figure 11. Comparison of the decline in general and GPT-specific equipment prices.

The more interesting question, however, is how the general decline in equipment prices relates to the declines associated more directly with the GPTs of each epoch. Figure 11 makes this comparison by plotting the relative prices of all three GPTs along with the general equipment price index on the same logarithmic scale, with the starting point for each of the GPTs normalized to the level of the general equipment index in that year. By this measure, it is clear that electricity and motor vehicle prices declined at about the same pace as that of equipment generally until the start of the IT price data, though it is also interesting that motor vehicle prices appear to have declined faster than electricity prices. After 1960, declining computer prices and rising shares of computers

in equipment stocks seem to have drawn the general index downward, while computing prices fell thousands of times faster than the general index.

It can be said that the Electricity index, being the price of a kilowatt-hour, understates the accompanying technological change because it does not account for improvements in electrical equipment, and especially improvements in the efficiency of electrical motors. Such improvements may be contained in the price series for capital generally. But based on the price evidence in Figures 10 and 11, electricity, motor vehicles, and computers might all qualify as GPTs. Computers, however, are clearly the most revolutionary of the three.

2.3. Ability of the GPT to spawn innovation

The third characteristic that Bresnahan and Trajtenberg suggested was the technology's ability to generate innovation. Any GPT will affect all sorts of production processes, including those for invention and innovation. Some GPTs will be biased towards helping to produce existing products, others towards inventing and implementing new ones. An example of a more specific technology that was heavily skewed towards future products was hybrid corn. Griliches (1957, p. 502) explains why hybrid corn was not an invention immediately adaptable everywhere, but was rather an invention of a method of inventing, a method of breeding superior corn for specific localities.

Electricity and IT have both helped reduce costs of making existing products, and they both spawn innovation, but IT seems to have more of a skew towards the latter. There is no doubt that the 1920s, especially, also saw a wave a new products powered by electricity, but as the patenting evidence will bear out, the IT era has seen an unprecedented increase in inventive activity. For example, the role of the computer in simulation should be known to many of us writing research papers. Feder (1988) describes how computers play a similar role in the invention of new drugs.

2.3.1. Patenting

Patenting should be more intense after a GPT arrives and while it is spreading due to the introduction of related new products. Figure 12, which shows the numbers of patents issued per capita on inventions annually from 1790 to 2002 and trademarks registered from 1870 to 2002, shows two surges in activity – between 1900 and 1930, and again after 1977.[12] Is it mere chance that patenting activity was most intense during our

[12] We use the total number "utility" (i.e., invention) patents from the U.S. Patent and Trademark Office for 1963–2002, and from the U.S. Bureau of the Census (1975, series W-96, pp. 957–959) for 1790–1962. The number of registered trademarks are from the U.S. Bureau of the Census (1975, series W-107, p. 959) for 1870–1969, and from the *Statistical Abstract of the United States* [U.S. Bureau of the Census (1980, 1992, 2003)] for later years. Population figures, which are for the total resident population and measured at mid-year, are from U.S. Bureau of the Census (1975, series A-7, p. 8) for 1790–1970, and from the Census Bureau's web site thereafter.

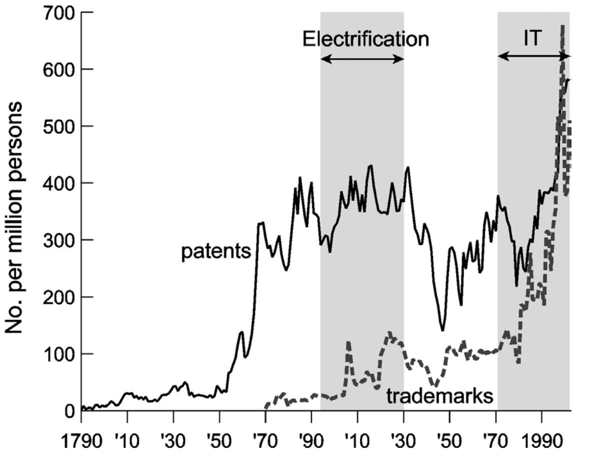

Figure 12. Patents issued on inventions and trademarks registered in the United States per million persons, 1790–2002.

GPT eras? Moreover, it appears that patenting activity picks up after the end of the U.S. Civil War in 1865, and again at the conclusion of World War II in 1945. The slowdown in patenting during the wars and the acceleration immediately thereafter suggest that there may be some degree of intertemporal substitution in the release of new ideas away from times when it might be more difficult to popularize them and towards times better suited for the entry of new products.

Does the surge in patenting reflect a rise in the number of actual inventions, or was the surge prompted by changes in the law that raised the propensity to patent? This question is important because, over longer periods of time, patents may reflect policy rather than invention. Figure 13 analyzes data described in Lerner (2000) and shows that worldwide, changes in patent policy are correlated with the patent series in Figure 12. It is possible, therefore, that the U.S. series reflects the stance of the courts regarding enforcement. Kortum and Lerner (1998) analyze this question and found that the surge of the 1990s was worldwide, but not systematically related to country-specific policy changes. They conclude that technology was the cause for the surge.

Further support for this view comes from the behavior of trademarks per capita, which we also plot in Figure 12. Trademarks behave more or less the same as patents do, except for their more sharply rising trend. Trademarks are easier to obtain than patents and are not governed by legal developments concerning patents. But with trademarks we have a different concern: Do trademarks proxy for the number of products, or do they just measure duplicative activity and the amount of competition? The answer may depend on what market one looks at. In the market for bananas, for example, Wiggins and Raboy (1996) find that brand names are correlated with measures of quality that do explain price variation, suggesting that brand names do signify product differentiation.

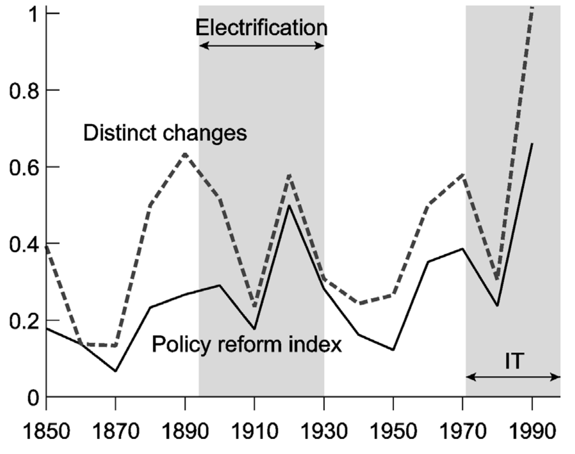

Figure 13. Indices of worldwide changes in patent laws.

2.3.2. Investment by new firms vs. investment by incumbents

New firms do not have costs sunk in old technologies and they are more flexible organizationally than existing firms. One should therefore expect to see job-reallocation waves and waves of entry and exit during the GPT eras. One measure of entry is the extent of new listings on the stock exchange. Figure 14 shows the value of firms entering the New York Stock Exchange (NYSE), the American Stock Exchange (AMEX), and NASDAQ in each year from 1885 through 2003 as percentages of total stock market value.[13] As predicted by Helpman and Trajtenberg (1998a, 1998b), initial public offerings (IPOs) surge between 1895 and 1929, and then after 1977, which again closely matches the dating of our two GPT eras.

The dashed line in Figure 14 is private investment since 1870 as a percent of the net stock of private capital in the U.S. economy as a whole, and as such is the aggregate analog of the solid line that covers only the stock market.[14] The solid line in Figure 15

[13] The data used to construct Figure 14 and others in this chapter that use stock market valuations are from the University of Chicago's Center for Research in Securities Prices (2004) (CRSP) files for 1925–2003. NYSE firms are available in CRSP continuously, AMEX firms after 1961, and NASDAQ firms after 1971. We extended the CRSP stock files backward from their 1925 starting year by collecting year-end observations from 1885 to 1925 for all common stocks traded on the NYSE. Prices and par values are from the *The Commercial and Financial Chronicle* (1885–1925), which is also the source of firm-level data for the price indices reported in the influential study by Cowles and Associates (1939). We obtained firm-level book capitalizations from *Bradstreet's* [Bradstreet Co. (1885–1925)], *The New York Times* and *The Annalist* [The New York Times Co. (1897–1928 and 1913–1925)]. The resulting dataset, which includes 25,319 firms, complements others that have begun to build a more complete view of securities prices for the pre-CRSP period [see, for example, Rousseau (1999) on Boston's 19th century equity market].

[14] To build the investment rate series, we start with gross private domestic investment in current dollars from the U.S. Bureau of Economic Analysis (2004) for 1929–2003 and then join it with the gross capital formation

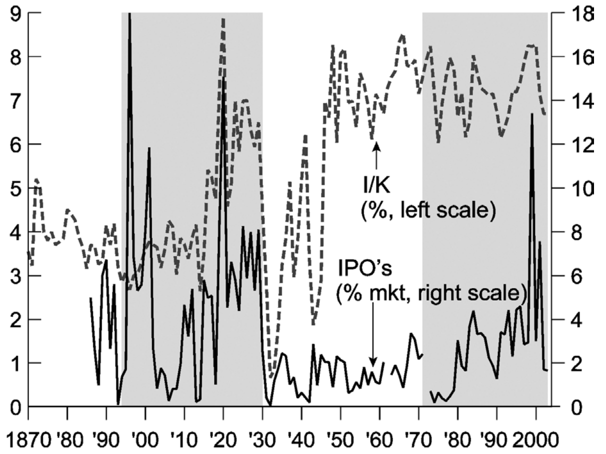

Figure 14. IPOs as a percent of stock market value, and private domestic investment as a percent of the net capital stock, 1870–2003.

shows the ratio of the solid and dashed lines in Figure 14. In both figures it is clear that, during the Electrification epoch, investment by stock market entrants accounted for a larger portion of stock market value than overall new investment in the U.S. economy contributed to the aggregate capital stock. This is consistent with the adoption of Electricity favoring the unencumbered entrant over the incumbent, who may have incurred substantial adjustment costs in using the new technology. We say this because aggregate investment, while indeed including new firms, has an even larger component attributable to incumbents. Moreover, the solid line in Figure 15 was highest in the early years of the Electrification period, which is when these adjustment costs would have been greatest.

Although the solid line in Figure 15 has so far stayed below unity for most of the IT era, it has rapidly risen to a higher level in recent years. This could be because IT adoption involved very large adjustment costs for both incumbents and entrants in the early years until the price of equipment and software fell enough to generate a wave of adoptions by new firms.

series in current dollars, excluding military expenditures, from Kuznets (1961b, Tables T-8 and T-8a) for 1870–1929. We construct the net capital stock using the private fixed assets tables of the U.S. Bureau of Economic Analysis (2004) for 1925–2003. Then, using the estimates of the net stock of nonmilitary capital from Kuznets (1961a, Table 3, pp. 64–65) in 1869, 1879, 1889, 1909, 1919 and 1929 as benchmarks, we use the percent changes in a synthetic series for the capital stock formed by starting with the 1869 Kuznets (1961a) estimate of $27 billion and adding net capital formation in each year through 1929 from Kuznets (1961b) to create an annual series that runs through the benchmark points. Finally, we join the resulting series for 1870–1925 to the later BEA series. The investment rate that appears in Figure 14 is the ratio of our final investment series to the capital stock series, expressed as a percentage.

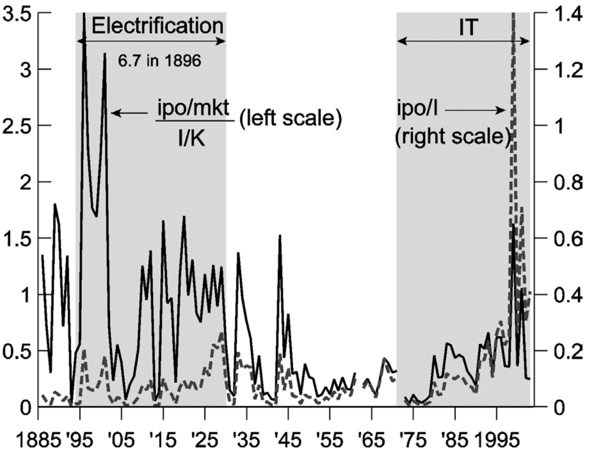

Figure 15. Other investment ratios, 1885–2003.

The solid line in Figure 15 shows a downward trend mainly because the stock market became more important as a vehicle for corporate financing among industrial firms in the early part of the 20th century. IPOs are normalized by total stock market value, which was small early on, and has since become larger. The dotted line in Figure 15 shows the ratio of the dollar values of IPOs and aggregate investment. It is upward sloping for the same reason: IPOs were not that important early on because the stock market was small. After 1970, IPOs capture a much larger share of investment by new entrants than they did before World War I, for example, and even a larger fraction than in the 1920s. When we consider both lines together, we do get the impression that new firms invest more during the GPT eras than at other times.

Does the distribution of entries across sectors shed light on the role of technological factors in the entry waves? Perhaps so. Figure 16 is a scatterplot of the share of IPOs in the market capitalizations of 15 manufacturing sectors between 1890 and 1930 vs. their respective shares of horsepower driven by electricity in 1929.[15] In other words, we ask whether sectors with more IPOs ended up adopting the new technology more vigorously than sectors with less entry. The regression line plotted in Figure 16 has a positive slope coefficient, though with only 15 observations it is not statistically significant.

In Figure 17, we regress IPOs over the 1971–2001 period on shares of computers and peripherals in equipment investment in 2000, and once again obtain a sectoral scatter with a positive slope coefficient, though like our result for the Electrification era, it is not statistically significant.

[15] We compute the IPO shares by summing year-end IPO values by sector for 1890–1930, converting the annual totals for each sector into real terms using the implicit price deflator for GDP, and then summing across years. We do the same for all listed firms by sector, and use the ratio of sectoral IPO values to total sector capitalization to compute the shares shown in Figure 16.

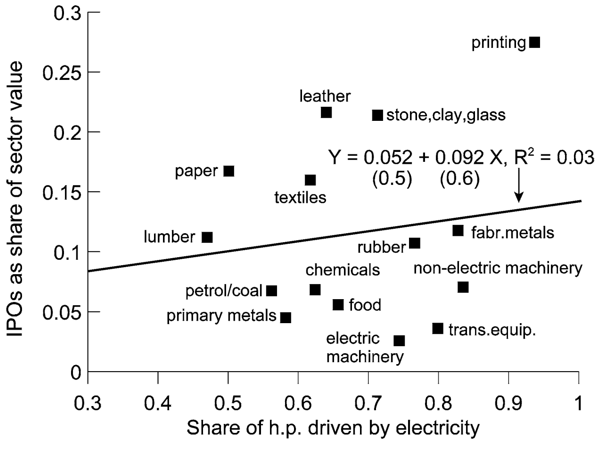

Figure 16. Scatterplot of IPOs as shares of sectoral market values, 1890–1930 vs. shares of horsepower electrified in 1929.

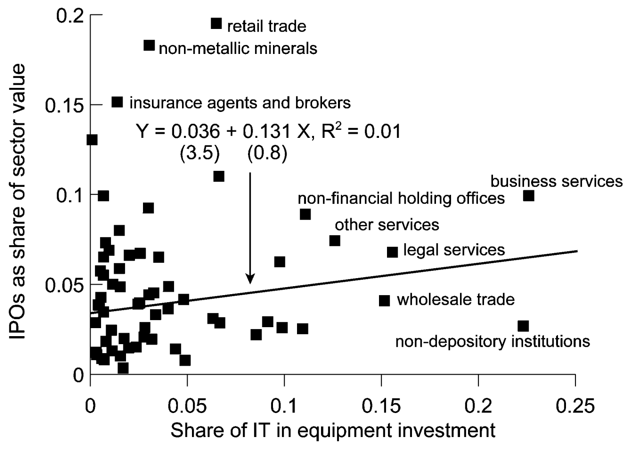

Figure 17. Scatterplot of IPOs as shares of sectoral market values, 1971–2001 vs. shares of IT in equipment investment in 2000.

3. Other symptoms of a GPT

So far we have provided some measures of the three qualities of a GPT – its pervasiveness, its rate of improvement, and its innovation-spawning tendency. Now we turn to less direct measures as suggested by various theoretical models that deal with GPTs. These models predict the following symptoms:

1. *Productivity should slow down* – The new technology may not be user-friendly at first, and output may fall for a while as the economy adjusts.

2. *The skill premium should rise* – If the GPT is not user-friendly at first, skilled people will be in greater demand when the new technology arrives and their earnings should rise compared to those of the unskilled.
3. *Entry, exit and mergers should rise* – These are alternative modes for the reallocation of assets.
4. *Stock prices should initially fall* – The value of old capital should fall. How fast it falls depends on the way that the market learns of the GPT's arrival.
5. *Young and small firms should do better* – The ideas and products associated with the GPT will often be brought to market by new firms. The market share and market value of young firms should therefore rise relative to old firms.
6. *Interest rates and the trade deficit* – The rise in desired consumption relative to output should cause interest rates to rise or the trade balance to worsen.

These, roughly speaking, are the hypotheses that emerge from the theoretical work on GPTs. Now we examine each empirically in turn, and as we go through the facts, we shall mention some of the relevant theories.

3.1. Productivity slowdown

As Bahk and Gort (1993) show, even in routine activities, learning seems to cause delays of several years before plant productivity peaks. It is far from settled, however, whether IT is the reason for the productivity slowdown – Bessen (2002) finds that IT did cause a big part of the slowdown, whereas Comin (2002) argues the opposite. It is also not yet definitely known from the work of Caballero and Hammour (1994) and others whether recessions at business-cycle frequencies are episodes of heightened reallocation. At any rate, the theoretical models of Atkeson and Kehoe (1993), Hornstein and Krusell (1996), Jovanovic and Nyarko (1996), Greenwood and Yorukoglu (1997) and Jovanovic and Rousseau (2002a) emphasize various adjustment costs and learning delays that may cause output to fall at first when a GPT arrives. David (1991) argues that the speed with which a new technology diffuses depends on the pool of investment opportunities that are available when it arrives, and remarks that the quality of this pool in the late 1960s was low because a large backlog from the post-war period had just and finally been eliminated. He also points out that there can often be "slippage" between the technological frontier and implementation due to high input costs and the slow introduction of complementary products.

Figure 1 shows that productivity did not rise quickly in the early phases of the two GPTs, though there is some evidence of greater productivity between 1918 and 1929 and after 1997 or so. Productivity was high in the early years of the Electrification period but fell rapidly as the technology matured. It stayed low through the Depression and 1940s, and then rose rapidly before the IT-age arrived. This pattern is consistent with David's view of exhausted investment opportunities. And while it is interesting to consider the productivity slowdown after 1971, it is also important to recognize that productivity is considerably higher today than it was before IT's arrival.

3.2. The skill premium

As Nelson and Phelps (1966) and Griliches (1969) argued, and Bartel and Lichtenberg (1987) and Krusell et al. (2000) have confirmed, new technology should raise the relative earnings of the skilled. Figure 18 presents a series for the earnings of skilled relative to unskilled labor. We construct the series by combining estimates of the wage ratio for urban skilled and unskilled workers for 1870–1894 from Williamson and Lindert (1980, p. 307) with estimates of the ratio of clerical to manufacturing production wages for 1895–1938 and the returns to 16 versus 12 years of schooling for men for 1939–1995 from Goldin and Katz (1999b).[16]

Although interpreting time series patterns in a continuous series formed from such disparate sources must be done with caution, we note that the series does have a U-shape, with the skill premium high in the early stages of Electrification (i.e., 1890 to 1918) and then rising rapidly during the post-1978 part of the IT epoch. We suspect that the decline in the skill premium from 1918–1924 would have been less deep, and thus the overall U-shape of Figure 18 more apparent, had it not been for the rapid rise of the public higher-education system after the end of World War I [see Goldin and Katz (1999a, p. 10)].

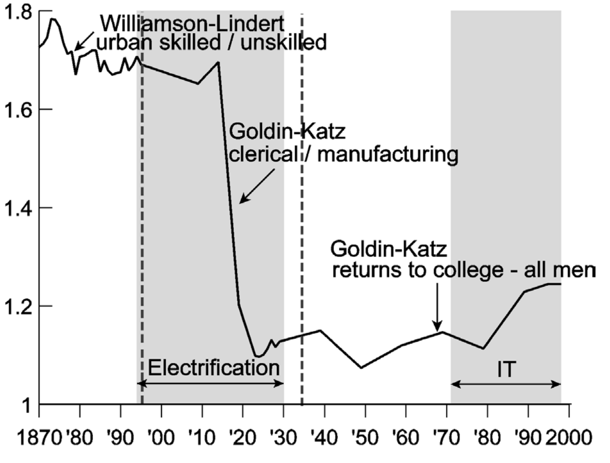

Figure 18. The skill premium.

[16] Combining several very different series into a continuous "skill premium" is necessary due to sectoral shifts in the skilled and unskilled labor forces that render some measures of skill more applicable to certain periods than others. For example, a college education appears to have become a more important determinant of income in the postwar period than it was in earlier years. Since the observations from Goldin and Katz (1999b) are generally decadal, we interpolate between them to obtain an annual series for 1895–1995. The vertical dotted lines in Figure 18 mark the points where we need to change data sources.

3.3. Entry, exit, and mergers should rise

Gort (1969) argued that technological change will generate merger waves. Evidence since then has shown that mergers and takeovers play a re-allocative role for an economy's stock of human and physical capital. Lichtenberg and Siegel (1987), McGuckin and Ngyen (1995) and Schoar (2002) find that the productivity of a target firm rises following a takeover. Jovanovic and Rousseau (2002b, 2002c) study the trade-off between exits and acquisitions at the margin for an economy that needs to update its capital stock. This last pair of papers shows that, at times when the value of organization capital is high, firms are more likely to place themselves on the merger market than to disassemble and sell their assets. Further, reallocation of assets among firms in general (i.e., by merger, consolidation, or purchases of unbundled used capital) is more likely to occur than purchases of new capital when firms need to make large adjustments to their capital stocks because of fixed costs associated with entering the merger market. We believe that both of these conditions are likely to hold during times of sweeping technological change.

The U-shaped top line of Figure 19 is our estimate of the total amount of capital that has been reallocated on the U.S. stock market from 1890 to 2003. Its components are the stock market capitalization of entering and exiting firms divided by two, and the value of merger targets.[17] Entries and exits divided by two, given by the center line, is a rough measure of how much capital exits from the stock market and comes back in under different ownership, or at least under a different name.[18] The lower line is the stock-market value of merger targets. Regardless of whether reallocation occurs through mergers or through entry and exit, it is much more prevalent during the periods that we associate with Electrification and IT.

[17] We identify targets for 1926–2003 using the CRSP stock files and various supplementary sources. CRSP itself identifies 9,758 firms that exited the database by merger between 1926 and 2003. We collected information on all mergers for 1895–1930 in the manufacturing and mining sectors from the original worksheets underlying Nelson (1959), and identified mergers from 1885 to 1894 from the financial news section of weekly issues of *The Commercial and Financial Chronicle* (1885–1925). The resulting target series includes the market values of 10,788 exchange-listed firms in the year prior to their acquisition. Stock market capitalizations are from our extension of CRSP backward to 1885 (see footnote 13). Before assigning a firm that no longer carries a price in our database as an "exit", we check the list of hostile takeovers from Schwert (2000) for 1975–1996 and individual issues of the *Wall Street Journal* [Dow Jones and Company, Inc. (1997–2004)] from 1997–2003 to ensure that we record firms taken private under a hostile tender offers as mergers.

[18] For this to be exactly true, of course, would require that the assets of all firms exiting the stock market be purchased by new firms that ended up listing on one of the major exchanges, and that the capital stocks of these new firms consist of only these used assets, assumptions that we know to be violated in practice. If the quantity of assets that do not return to the stock market through entry is roughly the same as the quantity of assets brought into the stock market by new entrants that are not associated with exiting firms, however, our measure would be roughly correct.

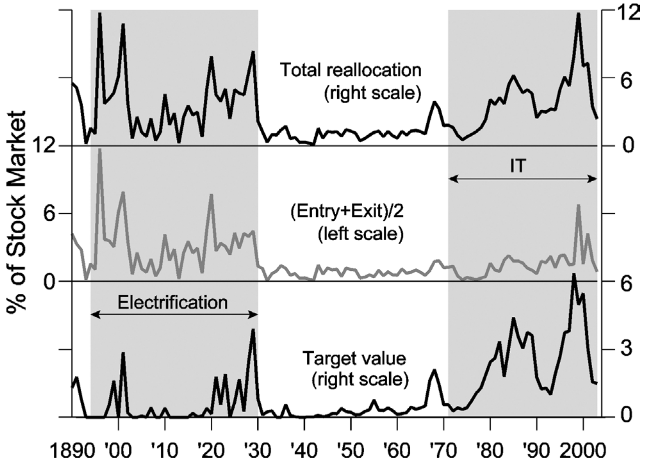

Figure 19. Reallocated capital and its components as percentages of stock market value, 1890–2003.

3.4. Stock prices should fall

The value of old capital should fall suddenly if the arrival of the GPT is a surprise, as in Greenwood and Jovanovic (1999), Hobijn and Jovanovic (2001), Jovanovic and Rousseau (2002a) and Laitner and Stolyarov (2003), or more gradually as in Helpman and Trajtenberg (1998a, 1998b). Figure 20 shows that the stock market declined in 1973–1974.[19] No such sudden drop is visible for stock prices in the early 1890s. Why not? Maybe because the market was thin and unrepresentative in those days, with railway stocks absorbing a large share of market capitalization. More likely, the realization that the new technology would work well was more gradual and not prompted by any single event such as the activation of the Pearl Street power station in 1882 or the completion of the Niagara Falls dam in 1894.

In other words, perhaps a decline in the stock market did not occur early in the Electrification period because the events of the early 1890s were foreseen, as would be the case in Helpman and Trajtenberg (1998a, 1998b). It also could be, as in Boldrin and Levine (2001), that old capital is essential to the production of new capital and that its value may not fall in quite the way that it would when capital can be produced from consumption goods alone, as is the case in many growth models including Jovanovic and Rousseau (2002a).

If stock price declines were caused by the threat of IT to incumbents, this should relate especially to those sectors that later invested heavily in IT. Hobijn and Jovanovic (2001, p. 1218) confirm this using regression analysis.

[19] We obtain the composite stock price index at the end of each year from Wilson and Jones (2002), updating through November 2004 using various issues of the *Wall Street Journal*. We deflate using the CPI.

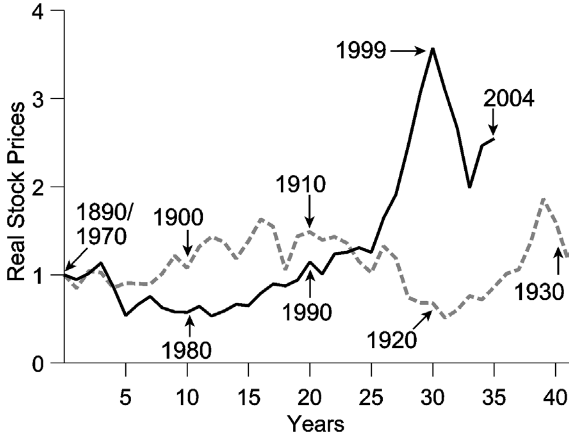

Figure 20. The real Cowles/S&P stock price index across the two GPT eras.

3.5. *Young firms should do better*

If new technologies are brought to market most effectively by new firms, we would expect younger firms in general to perform better than older firms during the eras of GPT adoption. The evidence on this hypothesis turns out to be mixed, but positive overall.

3.5.1. *The age of the leadership*

As a GPT takes hold, we should not only expect to see firms coming to market more quickly, but the market leaders getting younger as well. In other words, every stage in the lifetime of the firm should be shorter. This stands in contrast to Hopenhayn (1992), in which the age distribution of an industry's leadership is invariant when an industry is in a long-run stochastic equilibrium. That is, the average age of, say, the top 5 percent or top 10 percent of firms is fixed. Some leaders hold on to their positions and this tends to make the leading group older, but others are replaced by younger firms, and this has the opposite effect. In equilibrium the two forces offset one another and the age of the leadership stays the same. Keeping the age of the leaders flat requires, in other words, constant replacement.

Figures 21 and 22 plot the value-weighted average age of the largest firms whose market values sum to 5 and 10 percent of GDP, respectively. A firm's "age" is measured as the number of years since incorporation and since being listed on a major stock exchange. We label some important entries and exits from this group in Figure 21 (with exits denoted by "X"). The two figures show that, overall, the age of the leaders is anything *but* flat. It sometimes rises faster than the 45° line, indicating that the age of the leaders is rising faster than the passage of time. At other times it is flat or falling, indicating replacement.

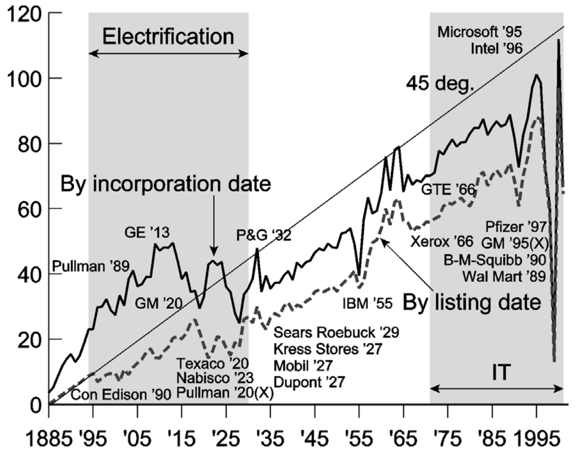

Figure 21. Average age (in years) of the largest firms whose market values sum to 5 percent of GDP, 1885–2001.

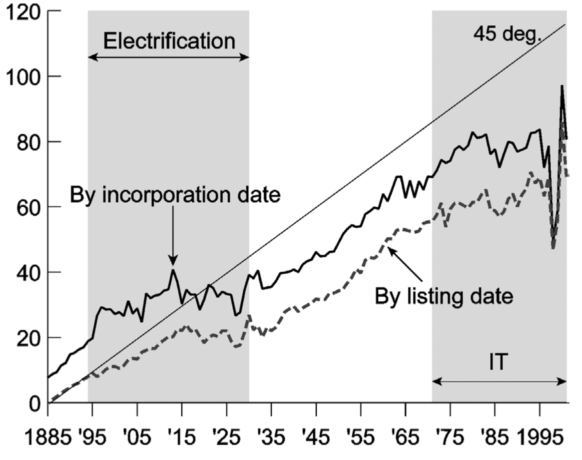

Figure 22. Average age (in years) of the largest firms whose market values sum to 10 percent of GDP, 1885–2001.

Based upon years from incorporation, for example, the leading firms were being replaced by *older* firms over the first 30 years of our sample, because the solid line is then steeper than the 45° line. In the two decades after the Great Depression the leaders held their relative positions as the 45° slopes of the average age lines show. The leaders got younger in the 1990s, and their average ages now lie well below the 45° line.[20]

[20] The volatility in these series derives not from aggregate stock-market volatility, but from the volatility of individual firm valuations. The large dip and subsequent recovery in both series in 1999–2001, for example,

Both figures show, however, that the lines are flat or falling during the Electricity and IT periods, so that replacement at these times was high. This is best seen in Figure 22.

3.5.2. The age of firms at their IPO

According to the third "innovation-spawning" characteristic, when a GPT arrives it gives rise to new projects that are unusually profitable. When such projects arrive, firms will be more impatient to implement them. When it is new firms that come upon such projects (rather than incumbents), they will feel the pressure to list sooner. This argument is developed and tested in Jovanovic and Rousseau (2001). We argue there that the Electricity- and IT-era firms entered the stock market sooner because the technologies that they brought in were too productive to be kept out of the market for very long.

Figure 23 shows HP-filtered average waiting times from founding, first product or process innovation, and incorporation to exchange listing based upon individual company histories and our backward extension of the CRSP database.[21] The vertical distance between the solid and dotted lines shows that firms often have their first innovation soon after founding, but that it then takes years, even decades, to list on a stock exchange.[22] We interpret this delay as a period during which the firm and possibly its lenders learn about what the firm's optimal investment should be. But when the technology is highly innovative, the incentive to wait is reduced and the firm lists earlier, which is what the evidence shows.

Table 4 lists the first product or process innovation for some of the better-known companies, along with their dates of founding, incorporation, and stock exchange listing. It also includes the share of total market capitalization that can be attributed to each firm's common stock at the end of 2003. The firms appearing in the table separate into roughly 3 groups: those based upon electricity and internal combustion, those based upon chemicals and pharmaceuticals, and those based upon the computer and Internet. Let us consider a few of the entries more closely:

comes from Microsoft's enormous price appreciation in 1999, when it was worth more than 5 percent of GDP on its own, and its rapid decline in 2000, which transferred the full 5 percent share to GE. The two firms split the 5 percent share in 2001.

[21] Listing years after 1925 are those for which firms enter CRSP. For 1890–1924, they are years in which prices first appear in the NYSE listings of *The Annalist*, *Bradstreet's*, *The Commercial and Financial Chronicle* or *The New York Times*. The 6,632 incorporation dates used to construct Figure 23 are from *Moody's Industrial Manual* [Moody's Investors Service (1920, 1928, 1955, 1980)], Standard and Poor's *Stock Market Encyclopedia* [Standard and Poor's Corporation (1981, 1988, 2000)] and various editions of Standard and Poor's *Stock Reports* [Standard and Poor's Corporation (1971–2003)]. The 4,221 foundings are from Dun and Bradstreet's *Million Dollar Directory* [Dun and Bradstreet, Inc. (2003)], Moody's, Kelley (1954), and individual company web sites. The 482 first innovations were obtained by reading company histories in *Hoover's Online* [Hoover's, Inc. (2000)] and company web sites. We linearly interpolate the series between missing points before applying the HP-filter to get the time series in Figure 23.

[22] Figure 23 includes several years in the 1970s and early 1980s for which it appears that the average time from first innovation to listing exceeds that from founding to listing. This is a result of differences in the sample sizes used to construct each line.

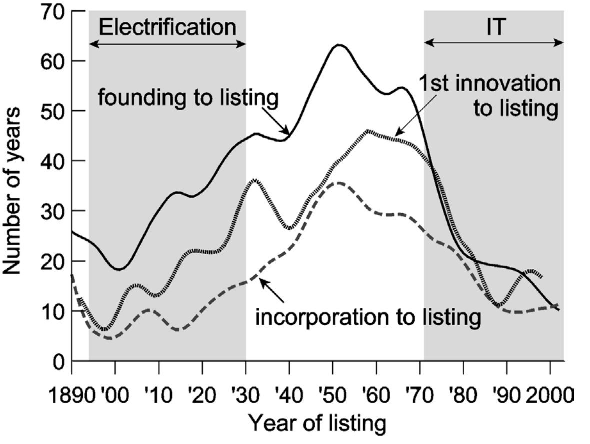

Figure 23. Waiting times to exchange listing, 1890–2003.

- *Electricity/Internal Combustion Engine* – Two of largest companies in the United States today are General Electric (GE) and AT&T. Founded in 1878, GE accounted for 2.1 percent of total stock market value at the end of 2003, and had already established a share of over 2 percent by 1910. AT&T, founded in 1885, contributed 4.6 percent to total market value by 1928, and more than 8.5 percent at the time of its forced breakup in 1984. Both were early entrants of the Electricity era. GE's founding was based upon the invention of the incandescent light bulb in 1879, while AT&T established a long-distance telephone line from New York to Chicago in 1892 to make use of Bell's 1876 invention of the telephone. Both technologies represented quantum leaps in the modernization of industry and communications, and both firms brought these technologies to the NYSE about 15 years after founding. General Motors (GM) was an early entrant to the automobile industry, listing on the NYSE in 1917 – nine years after its founding. By 1931 it accounted for more than 4 percent of stock market value, and its share would hover between 4 and 6.5 percent until 1965, when it began to decline gradually to its share in 2003 of only 0.2 percent. These examples suggest that many of the leading entrants at the turn of the 20th century created lasting market value. Further, the ideas that sparked their emergence were brought to market relatively quickly.
- *Chemicals/Pharmaceuticals* – Procter and Gamble (P&G), Bristol–Myers Squibb and Pfizer are both leaders in their respective industries, but took much longer to list on the NYSE than the Electrification-era firms. In fact, P&G and Pfizer were established before 1850, and thus predate all of them. Despite P&G's early start and the creation of the Ivory soap brand in 1879, it was not until 1932 that the company took its place among the largest U.S. firms by exploiting advances in radio transmission to sponsor the first "soap opera". Pfizer's defining moment came when it developed a process for mass-producing the breakthrough drug penicillin

Table 4
Key dates in selected company histories

Company name	Founding date	1st major product or process innovation	Incorporation date	Listing date	% of stock market in 2003
General Electric	1878	1880	1892	1892	2.09
AT&T	1885	1892	1885	1901	0.11
Detroit Edison	1886	1904	1903	1909	0.04
General Motors	1908	1912	1908	1917	0.20
Coca Cola	1886	1893	1919	1919	0.83
Pacific Gas & Electic	1879	1879	1905	1919	0.08
Burroughs/Unisys	1886	1886	1886	1924	0.03
Caterpillar	1869	1904	1925	1929	0.19
Kimberly–Clark	1872	1914	1880	1929	0.20
Procter & Gamble	1837	1879	1890	1929	0.87
Bristol–Myers Squibb	1887	1903	1887	1933	0.37
Boeing	1916	1917	1916	1934	0.23
Pfizer	1849	1944	1900	1944	1.81
Merck	1891	1944	1934	1946	0.69
Disney	1923	1929	1940	1957	0.32
Hewlett–Packard	1938	1938	1947	1961	0.47
McDonalds	1948	1955	1965	1966	0.21
Intel	1968	1971	1969	1972	1.40
Microsoft	1975	1980	1981	1986	1.99
America Online	1985	1988	1985	1992	0.52
Amazon	1994	1995	1994	1997	0.14
E-Bay	1995	1995	1996	1998	0.28

Source: Data from *Hoover's Online*, Kelley (1954), and company web sites.
Note. The first major products or innovations for the firms listed in the table are: GE 1880, Edison patents incandescent light bulb; AT&T 1892, completes phone line from New York to Chicago; DTE 1904, increases Detroit's electric capacity six-fold with new facilities; GM 1912, electric self-starter; Coca Cola 1893, patents soft-drink formula; PG&E 1879, first electric utility; Burroughs/Unisys 1886, first adding machine; CAT 1904, gas driven tractor; Kimberly–Clark 1914, celu-cotton, a cotton substitute used in WWI; P&G 1879, Ivory soap; Bristol–Myers Squibb 1903, Sal Hepatica, a laxative mineral salt; Boeing 1917, designs Model C seaplane; Pfizer 1944, deep tank fermentation to mass produce penicillin; Merck 1944, cortisone (first steroid); Disney 1929, cartoon with soundtrack; HP 1938, audio oscillator; McDonalds 1955, fast food franchising begins; Intel 1971, 4004 microprocessor (8088 microprocessor in 1978); Microsoft 1980, develops DOS; AOL 1988, "PC-Link"; Amazon 1995, first online bookstore; E-Bay 1995, first online auction house.

during World War II, and the good reputation that the firm earned at that time later helped it to become the main producer of the Salk and Sabin polio vaccines. In Pfizer's case, like that of P&G, the company's management and culture had been in place for some time when a new technology (in Pfizer's case antibiotics) presented a great opportunity.

- *Computer/IT* – Firms at the core of the recent IT revolution, such as Intel, Microsoft and Amazon, came to market shortly after founding. Intel listed in 1972, only four years after starting up, and accounted for 1.4 percent of total stock mar-

ket value at the end of 2003. Microsoft took eleven years to go public. Conceived in an Albuquerque hotel room by Bill Gates in 1975, the company, with its new disk operating system (MS-DOS), was perhaps ahead of its time, but later joined the ranks of today's corporate giants with the proliferation of the PC. In 1998, Microsoft accounted for more than 2.5 percent of the stock market, but this share fell to 1.5 percent over the next two years in the midst of antitrust action. By the end of 2003 its share had recovered somewhat to nearly 2 percent of the stock market. Amazon caught the Internet wave from the outset to become the world's first online bookstore, going public in 1997 – only three years after its founding. As the complexities of integrating goods distribution with an Internet front-end came into sharper focus over the ensuing years, however, and as competition among Internet retailers continued to grow, Amazon's market capitalization by 2003 had fallen to 0.14 percent of total stock market value.

These firms, as well as the others listed in Table 4, are ones that brought new technologies into the stock market and accounted for more than 13 percent of its value at the close of 2003. The firms themselves also seem to have entered the stock market sooner during the Electricity and IT eras, at opposite ends of the 20th century, than firms based on mid-century technologies.

When firms gather less information before investing, the investments that they undertake will be riskier. One may conjecture that if new entrants waited less before investing during the GPT eras, then incumbents also undertook projects earlier than they would have normally. In these cases, the resulting investments would be riskier than if more time were allowed to plan them. Moreover, the newness of the GPT would add further risk. On all these grounds, we would expect interest rate differentials on the average investment to be higher in the GPT eras.

Figure 24, which shows the spread between interest rates on riskier and safe investments since 1885, shows that this has been for the most part the case.[23] It is important to note that we formed the series in Figure 24 by joining three different spreads together, and that the "safe" asset is a long-term U.S. government bond before 1920 and a short-term U.S. Treasury bill thereafter, yet the fluctuations in this series should still reflect risk perceptions reasonably well, at least to the extent that term premia rather than riskiness are the main factors that lead to yield differentials among the various government securities.

[23] In Figure 24, we use the spread between the interest rates on Baa-rated corporate bonds (from Moody's Investors Service) and three-month T-bills [from the FRED database of Federal Reserve Bank of St. Louis (2004) for 1934–2003 and the Board of Governors of the Federal Reserve System (1976) for 1920–1934] for the period from 1920 to the present. For 1900–1920, we join the spread between the interest rate on prime commercial paper with 60–90 days until maturity [Homer and Sylla (1991, table 49, p. 358)] and the redemption yields on the U.S. government consol 2s of 1930 [Homer and Sylla (1991, table 46, p. 343)] with the Baa – T-bill spread. Finally, for 1885–1899, we join the spread between the commercial paper rate [Homer and Sylla (1991, table 44, p. 320)] and the redemption yields on U.S. government refunding 4s of 1907 [Homer and Sylla (1991, table 43, p. 316)] with the previous result.

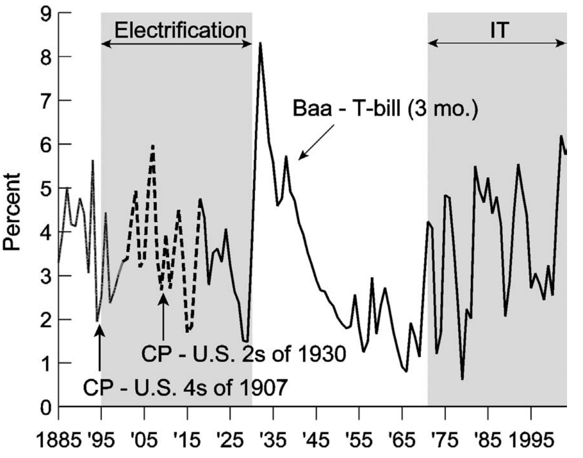

Figure 24. Nominal interest rate spreads between riskier and safer bonds, 1885–2003.

During the Electrification period, spreads rose between 1894 and 1907, which is when uncertainty about the usefulness and possibilities for adoption of the new technology was greatest. Spreads fell after that as the future of Electricity became clearer. In the IT era, spreads have a generally-upward trend throughout, though they did fall for a while in the late 1990s. This may well reflect the lag in the widespread adoption of IT. The spread's sharp rise in 1930 and very slow decline over the next 15 years probably has to do with the macroeconomic instability induced by events prior to and during the Great Depression, and then the heavy borrowing by the U.S. government to finance World War II, which raised rates on T-bills.

Another measure of risk perceptions can be obtained from the distribution of ratings for issues of new corporate bonds. Figure 25 uses data from Hickman (1958, pp. 153–154) and Atkinson (1967, p. 97) for the period from 1908–1965 to show four-year averages, starting at the dates shown on the horizontal axis, of the percent of the total par value of rated new corporate bond issues that received a Moody's rating of single-A or lower and Ba or lower. In other words, the solid line excludes the highest rated bonds (i.e., classes Aaa and Aa), but includes some investment grade bonds (i.e., A and Baa) along with the sub-investment grades (i.e., Ba and lower). The dashed line includes only the sub-investment grades.

The dashed line in Figure 25 indicates that subinvestment grade bonds made up a larger part of the value of total rated new issues during the Electrification era than after the start of the Great Depression, and though these data end in 1965, we note that subinvestment grade issues began to rise again only on the eve of the IT revolution in the mid-1960s. The solid line shows that issues of bonds not receiving the highest Moody's ratings actually rose during the latter part of the Electrification era, peaking in the 1924–1927 period, which was when a host of Electricity-related innovations and appliances were being brought to market. This does not imply an increase in junk-bond

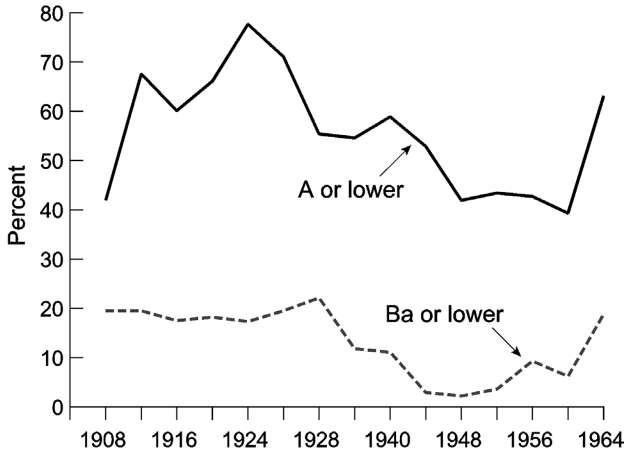

Figure 25. Percent of rated corporate bond offerings with Moody's ratings of A or lower and Ba or lower, four-year averages, 1908–1965.

issuance at this time, but rather is consistent with the view that investors recognized the risks involved with large-scale use of the new technology and were a bit more cautious about overpaying for debt securities associated with it.

3.5.3. *The stock market performance of the young vs. old after entry*

Young firms are smaller. If "creative destruction" does indeed mean that old firms give way to young firms, then we should see signs of it in Figure 26, which depicts the relative appreciation of the *total* market value of small versus large firms since 1885.[24] We define "small" firms as those in the lower quintile of CRSP, and "large" firms as those in the upper quintile. The regression line in Figure 26 (with t-statistics in parentheses) shows small firms outperforming large ones in the long run and an annual growth premium of about 7.5 percent. But the two GPT eras do not show a faster rise in relative appreciations than other times, and this is puzzling. Surprisingly, recessions do not seem to hurt the long-term prospects of small firms: The relative index rises in 10 of the 23 NBER recessions.

The two periods that we wish to focus on are 1929–1931 and the early 1970s. In both periods, the small-capitalization firms lost out relative to the large-capitalization ones. The first period comes at the end of the Electrification era and the relative decline of smaller firms is what one would have expected. But the early 1970s come at the beginning of a new GPT, and small firms should have outperformed the large firms at

24 Being a total value index, this differs from the relative stock price index that is plotted in Figure 8 of Hobijn and Jovanovic (2001). For the post-1925 period, in which they overlap, the qualitative behavior of the two series is essentially the same.

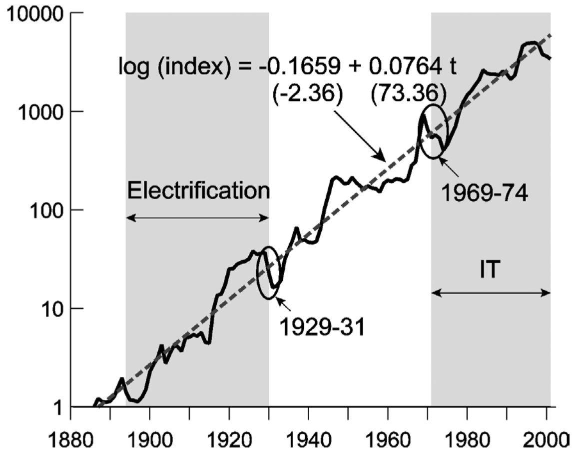

Figure 26. The relative capital appreciations of small vs. large firms, 1885–2001.

that time. Yet the opposite happened. It is only after 1974 that the small-capitalization firms start to perform better.

Regression evidence on age and stock market performance. If the GPT is brought in by young firms, then the capital loss imposed by the GPT's arrival should fall more heavily on old firms. To test this using data on individual firms, let

A_i = age since listing of firm i in 1970;

S_i = share (in firm i's sector) of IT capital in the capital stock in 2001.

This measures a firm's exposure to the impact of the new technology within its sector. We use the change in a firm's stock price over intervals that start in 1971 and end in 1975, 1980, 1985, 1990 and 1995 as measures of expected performance. These should reflect the market's assessment of how well the firm will handle the consequences of the GPT. The regressions take the form

$$\ln\left(\frac{P_{i,1975}}{P_{i,1970}}\right) = c_0 + c_1 A_i + c_2 S_i - c_3 A_i S_i.$$

We summarize the firm-level results in Table 5.

The interaction between the firm's age (A) and its exposure to the new technology (S) is negative and significant only when the period during which we measure price appreciation extends to 1990 and 1995. We would have expected this coefficient to be negative always, since older firms in sectors where IT would become important would be less able to adjust to the new technology than newer firms. The interaction term has a positive coefficient for the 1971–1975, 1971–1980 and 1971–1985 periods, but it is

Table 5
Age and stock market performance

	Dependent variable: $\ln(P_{t+i}/P_t)$				
	1971–1975	1971–1980	1971–1985	1971–1990	1971–1995
constant	−0.737	−0.143	0.152	−0.057	0.577
	(−24.3)	(−2.96)	(2.58)	(−0.59)	(6.06)
A	0.007	−0.001	−0.001	0.003	−0.002
	(6.40)	(−0.46)	(−0.55)	(0.97)	(−0.51)
S	−3.497	−2.266	−1.035	−0.602	2.719
	(−7.60)	(−3.37)	(−1.20)	(−0.46)	(1.88)
$A * S$	0.047	0.043	−0.016	−0.122	−0.106
	(2.22)	(1.14)	(−0.39)	(−2.09)	(−1.76)
R^2	0.089	0.009	0.003	0.006	0.012
N	2218	1814	1367	981	843

Note. The table presents coefficient estimates for the subperiods included in the column headings with t-statistics in parentheses. The R^2 and number of observations (N) for each regression appear in the final two rows.

statistically significant only for the 1971–1975 period. It thus seems that IT firms took a long time to realize gains in the market after the technology's arrival. There are not very many firms with continuous price data prior to 1900, but we have enough observations to attempt the same regression for the Electrification era. In this case, we got

$$\ln\left(\frac{P_{i,1899}}{P_{i,1894}}\right) = \underset{(1.09)}{2.111} - \underset{(-0.46)}{0.129}\, A_i - \underset{(-0.88)}{2.307}\, S_i + \underset{(0.55)}{0.213}\, A_i S_i,$$

with t-statistics in parentheses and $R^2 = 0.015$, $N = 56$. In this very small sample, we do not see a direct effect of age on capital depreciation as Electrification got underway, and the interaction term is not statistically significant.

3.6. Consumption, interest rates, and the trade deficit

If it is unanticipated, the arrival of a GPT is good news for the consumer because it brings about an increase in wealth. How quickly wealth is perceived to rise depends on how quickly the public realizes the GPT's potential for raising output. The rise in wealth would raise desired consumption. But to implement the GPT firms would also need to increase their investment. Therefore aggregate demand would rise, and in a small open economy this would lead to a trade deficit. In a closed economy, on the other hand, since income does not immediately rise, the rise in aggregate demand would cause the rate of interest to rise so that the rise in aggregate demand would be postponed.

How much consumption rises depends on two factors. The first is the GPT's pervasiveness worldwide – if the entire world is equally affected then consumption could not

rise right away and the main effects would be transmitted though the rate of interest. The second is the openness of the U.S. economy. Even if, say, the United States were the only country affected by the GPT, the rise in consumption would be related to how easily capital could flow in.

In these respects, the IT episode differs from the Electrification episode in several important respects. Capital inflows into the United States simply were not in the cards during a large part of the Electrification episode. World War I exhausted the European nations and the United States could not borrow from the rest of the world to finance its electrification-led expansion – it was instead a creditor during this period. Moreover, even if the war had not taken place, it is not clear whether the United States could have borrowed much from the rest of the world because Britain, Germany, France, and several other countries were undergoing the same process – Electrification was more synchronized across the developed world than IT has so far been.

In sum, we would expect the United States to have behaved more like a closed economy during the Electrification era and more like a small open economy during the IT era. Specifically, we would expect to see

(1) a larger rise in the trade deficit during the IT era than during the Electrification era,
(2) a smaller rise in consumption during the Electrification era then during the IT era,
(3) a larger rise in the rate of interest during the Electrification era.

3.6.1. *The trade deficit*

Figure 27, which plots the trade deficit as a percentage of GNP since 1790 along with an HP trend, shows sharply-rising trade deficits at the start of the IT revolution, though not in the early years of Electrification.[25] The trade deficit indeed opens up fairly dramatically during the IT era, whereas during the Electrification era we see a surplus. As we mentioned, this surplus was driven by the various Colonial wars that took place at the turn of the century and, of course, by World War I.

3.6.2. *The consumption–income ratio*

We expected to see a smaller rise in consumption during the Electrification era than during the IT era, and after we adjust for the downward long-run trend, this is indeed what has happened. Private consumption rises gradually during each GPT era, and this is set against a long-run secular trend for private consumption that is negative. Figure 28 shows the ratio of consumption to GDP since 1790.[26] As our GPT hypotheses would

[25] GDP and total imports and exports of goods and services are from the U.S. Bureau of Economic Analysis (2004) for 1929–2003. For 1790–1920, imports and exports are from U.S. Bureau of the Census (1975, series U-8 and U-1, p. 864, respectively), and the GDP series are from Kendrick (1961) and Berry (1988).

[26] The series for consumption and GDP are from the U.S. Bureau of Economic Analysis (2004) for 1929–2003, Kendrick (1961, table A-IIb, cols. 4 and 11, pp. 296–297) for 1889–1929, and Berry (1988,

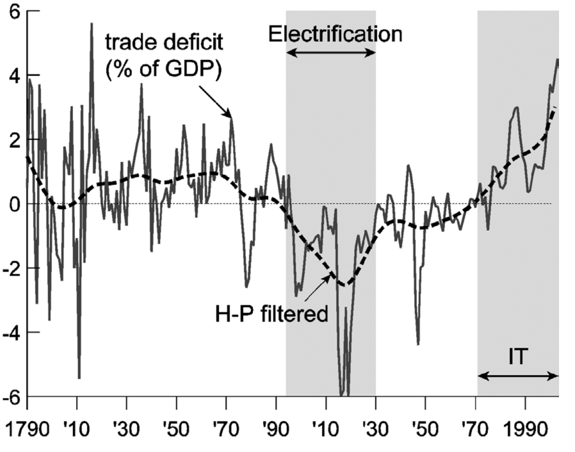

Figure 27. The trade deficit as a percent of GDP, 1790–2003.

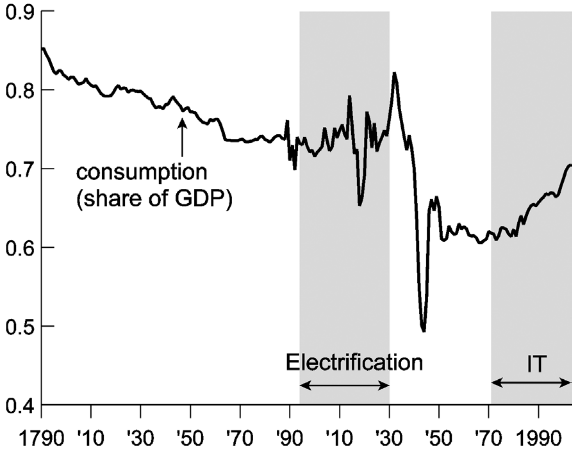

Figure 28. The ratio of consumption to income, 1790–2003.

suggest, the arrival of Electricity in 1890 seems to mark the end of a long-term decline in the ratio that been underway for a century. And though the level of the series falls during the Great Depression and World War II, never to return to its pre-1930 levels, consumption takes another sharp upward turn near the start of the IT revolution and continues to rise.

table 9, pp. 25–26) for 1790–1889. The BEA figures are for personal consumption, but the Kendrick and Berry figures include the government sector as well. Since consumption in the government sector was much smaller prior to World War I, we suspect that the downward trend in the 19th century is a result of changing private consumption patterns rather than a reduction in the government sector's consumption.

3.6.3. Interest rates

We expected a larger rise in the rate of interest during the Electrification era than during the IT era. Relative to HP trends, the evidence is not favorable. Figure 29 shows that ex-post real interest rates were about the same during the two GPT eras, and much lower in the middle 40 unshaded years of the 20th century.[27] The dashed line is the HP detrended series. The averages are presented in Table 6. We note that the ex-post rate is quite high in the first era, before 1894. If the arrival of electricity and its impact was foreseen prior to 1894, interest rates would have risen earlier, but this probably does not explain why they were so high then. More likely, the pre-1894 era reflects a lack of financial development: The stock market was small then, and the financial market not as deep. This may have given rise to an overall negative trend in interest rates over the 134-year period as a whole.

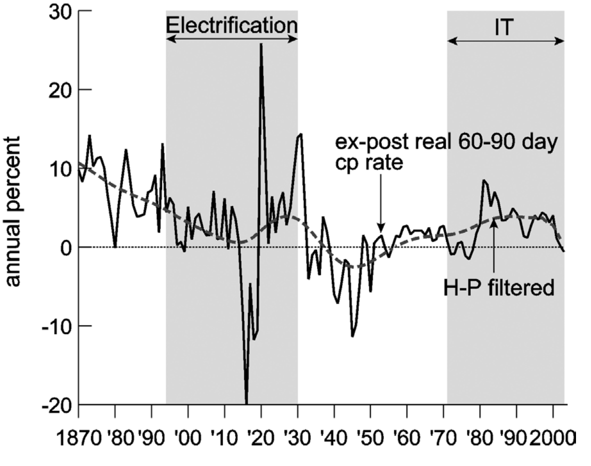

Figure 29. The ex-post real interest rate on commercial paper, 1870–2003.

Table 6

Era	Ex-post real interest rate
1870–1893	7.78
1894–1930	2.61
1931–1970	−0.16
1971–2003	2.75

[27] Commercial paper rates are annual averages from the FRED database for 1934–2003 and from Homer and Sylla (1991) for earlier years. We compute the ex-post return by subtracting inflation as computed by the growth of the implicit price deflator for GNP from the U.S. Bureau of Economic Analysis (2004) for 1929–2003 and Berry (1988) for earlier years.

4. Conclusion

Technological invention is uneven, and comes in bursts; that much has for a long time been clear to students of growth. Electricity and IT are, to most observers, the two most important GPTs to date, or at least they seem so according to the three criteria that Bresnahan and Trajtenberg proposed. In this chapter we have analyzed how the U.S. economy reacted to the creation of these two GPTs. Having discussed in detail GPTs with reference to the Electrification and IT eras, we believe that we have shown that the concept is a good way to organize how we think of technological change and its effects.

The Electricity and IT eras differ in some important ways. Electrification was more broadly adopted, whereas IT seems to be technologically more revolutionary. The productivity slowdown is stronger in the IT era but the ongoing spread of IT and its continuing precipitous price decline are reasons for optimism about growth in the coming decades relative to what happened in the middle of the 20th century following the spread of Electricity. But it is the similarities between the two epochs that are the most instructive and that will guide our expectations about how the next GPT will affect economic life when it comes along.

Acknowledgements

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