

Measuring General Purpose Technologies

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Abstract

Electricity and IT are perhaps the two most important GPTs to date. We analyze how the U.S. economy reacted to them. The Electricity and IT eras are similar, but they also different in 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.

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, and information technology (IT) are often classified as GPTs for this reason. They affected the whole economy.

As David (1991) pointed out some years ago, 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 (H-P) filter.¹ Productivity growth was apparently quite rapid during the heyday of steam power (circa. 1870), but fell as electrification arrived in the 1890s, with the defining moment probably being the

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¹Output per man-hour in the business, non-farm sector is from John Kendrick [U.S. Bureau of the Census (1975, Series D684, p. 162)] for 1889-1947, and from the Bureau of Labor Statistics (2002) for 1948-2001. For 1874-1889, we use Kendrick’s decadal averages for 1869-79 and 1879-89, and assume a constant growth rate from 1874-84 and 1885-89.

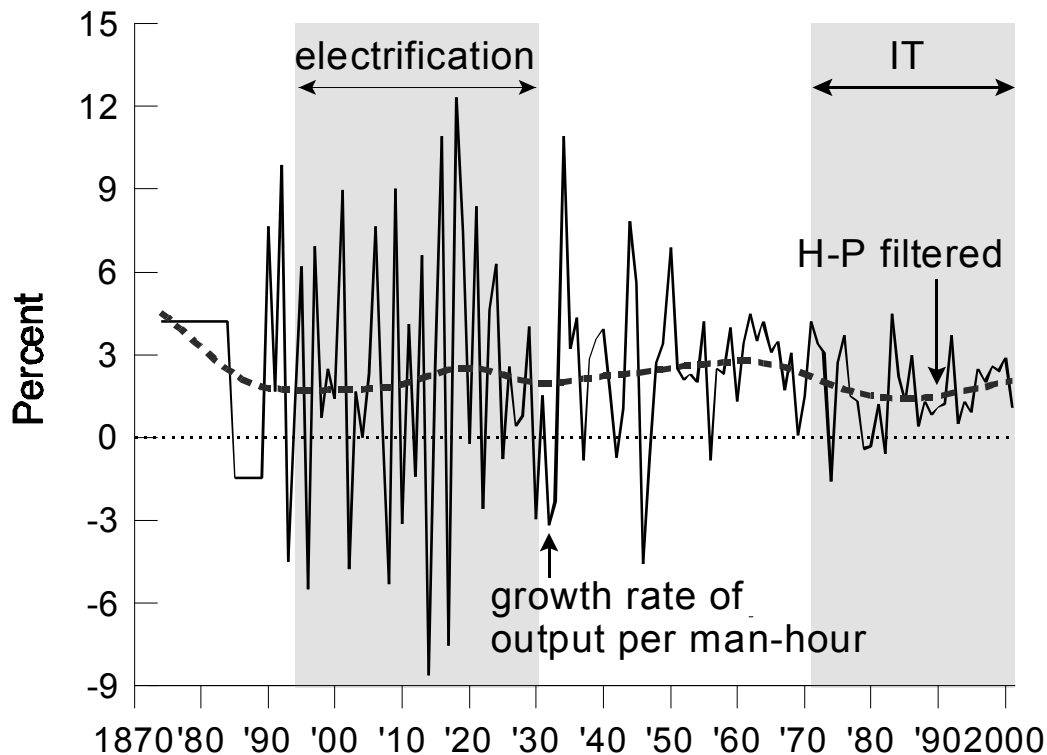


Figure 1: Annual growth in output per man-hour.

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 secondary motors and the widespread establishment of centralized power grids, that electricity finally pervaded businesses and households more generally and the productivity numbers began to rise. Figure 1 also shows that the arrival of IT, which we date with Intel’s invention in 1971 of the “4004 computer chip” (the key component of the personal computer), did not reverse the decline in productivity growth that had begun more than a decade earlier. To some extent it seems that we are still waiting for computers to show up in the productivity figures.

But it is not obvious that the startup of the Niagara Falls dam in 1894 and Intel’s invention of the 4004 chip in 1971 should define the birth of the two GPTs. Indeed, the reader may wonder how we choose the dating for the two GPT eras. In fact, the dates do coincide with periods of adoption: Net adoption of the two GPTs picks up about where the shading begins and, in the case of electrification, adoption reaches a plateau in 1929, whereas new adoption of IT is still rising today so that, on that criterion, the IT era still continues.

1.1 What is a GPT?

Each shaded area in Figure 1 contains a growth slowdown. Will the growth slowdown of the current IT era be followed by a rise in growth 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 will conclude that the two eras are indeed similar.

So, what are these “fundamental” features of the two GPTs that we may attempt to compare? More generally, what criteria can one use to distinguish a GPT from other technologies? Bresnahan and Trajtenberg (1995) 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 therefore a GPT cannot differ qualitatively from these other technologies. Moreover, this is a short list which we shall later broaden. Nevertheless, we shall begin with measures of these three characteristics in the next section. But first, we summarize our 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 of the GPT eras growth is below rates attained in the decades immediately preceding.
2. Measures of reallocation and invention – startups, exits, patents, trademarks, and investment by new firms relative to incumbents – are all higher during the GPT eras.

3. Private consumption rose 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 in the middle 40 years of the 20th century.

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 its net adoption still 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 surely because Europe had to finance a string of wars, whereas the IT era finds the United States in a trade deficit

The differences seem to outnumber the similarities. Yet the overall evidence clearly supports the view that technological progress is uneven, that it does entail the episodic arrival of GPTs, that these GPTs bring on turbulence and lower growth early on and higher growth and prosperity later.

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 provide 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 with the aggregates and then look in more detail at industrial sectors.

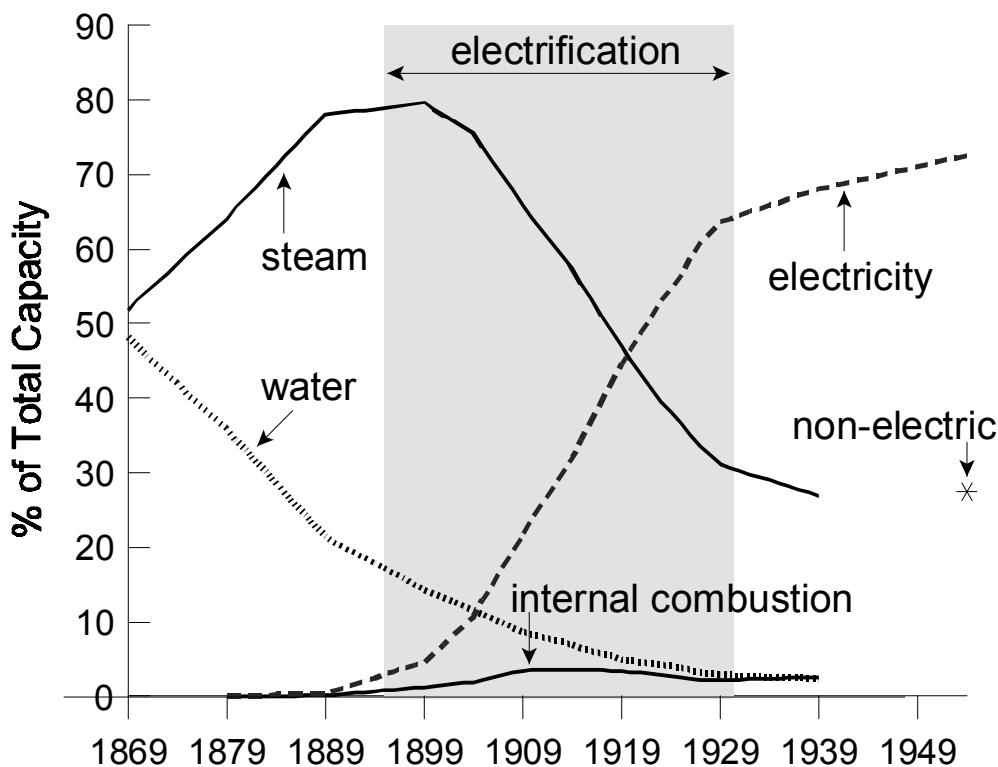


Figure 2: Shares of total horsepower generated by the main sources in U.S. manufacturing, 1869-1954.

2.1.1 Pervasiveness in the aggregate

We would like to track the evolution of GPTs using continuous time series from about 1850 to the present, but we do not have data that consistently cover the entire stretch of time, and thus will need to break this period into two overlapping segments: 1869-1954 and 1947-2001.

Figure 2 shows the shares of total horsepower in manufacturing by power source from 1869 to 1954.² The period covers the fall 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, 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

²We construct the shares of total horsepower capacity in manufacturing as ratios of each power source (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. 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 broader-defined “non-electrical” share for 1954 with an asterisk.

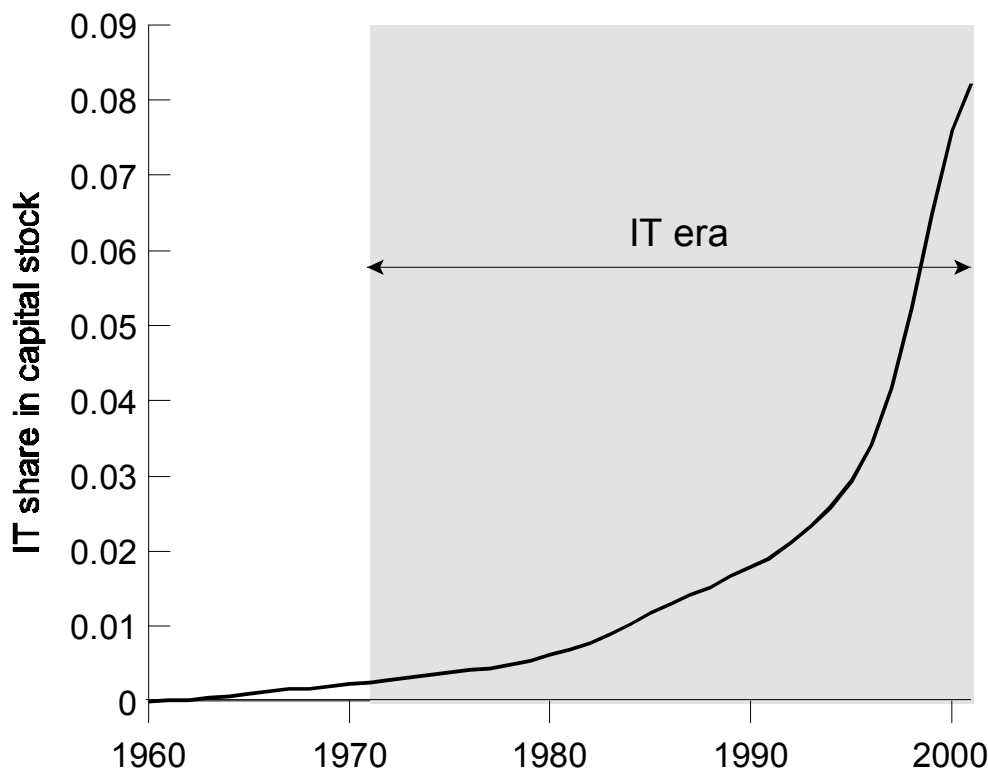


Figure 3: Shares of computer equipment and software in the aggregate capital stock, 1960-2001.

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 that replaced it, Electricity, was important enough to force change quickly among manufacturers. In contrast, the decline of water power was more gradual. Moreover, if we could continue the graph to the present, electricity would surely still command a very high share of manufacturing power as a 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 real share of IT equipment and software in the real aggregate capital stock.³

³We build the ratio plotted in Figure 3 by summing the capital stocks of 62 industrial sectors from the detailed non-residential fixed asset tables in fixed 1996 dollars made available by the Bureau of Economic Analysis (2002). 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.

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 GPT-era, 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," yet computer and software sales continue their rapid rise to this day.

The scaling of the vertical axes in Figure 2 and Figures 3 is different. The vertical axis in Figure 2 measures the shares of total horsepower in manufacturing, whereas the vertical axis in Figures 3 is the real share of IT equipment and software in the real aggregate capital stock. But scaling aside, the diffusion process appears to be much more protracted for IT than for Electrification insofar as a comparison of the shape of the diffusions in the two figures suggests that the IT era will last longer than the 35 years of Electrification. The acceleration in adoption, which was over by about 1905 for Electrification, did not end until about 1997 for IT.

Why did electricity spread faster than IT seems to be doing? We do not know if this is because it was more profitable, or because the rapid price decline of computers and peripherals makes it optimal to wait and adopt later, or still for some other reason.

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 that 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 main message in Figure 4 is that electrical technology affected individual manufacturing sectors with a striking degree of uniformity. Moreover, 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 manufacturing sectors either. This means that the sectors that were the heaviest users of electricity in 1890 remained among the leaders as adoption slowed down in the 1930s. Indeed, the adoption of electricity was sweeping and widespread.

It was not practical 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 turn of the century readily adapted the new technology by using an electric motor rather than steam to drive the shafts which powered looms,

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

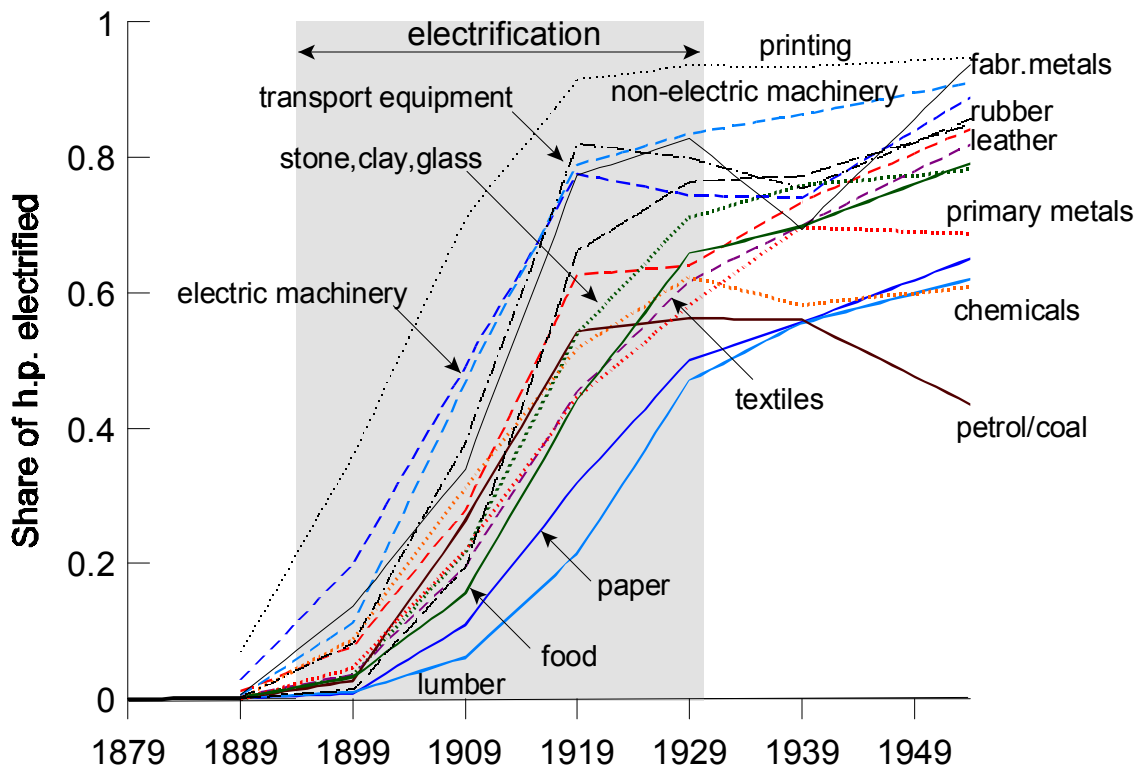


Figure 4: Shares of electrified horsepower by manufacturing sector, 1890-1954.

spinning machines and other equipment [see Devine (1983)]. Further delays in the distribution of electricity made it more costly to electrify a new industrial plant fully.

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 |

Figure 5 shows the same data as Figure 4, but now in percentile form. We build them by sorting the electricity shares in each year and, given that only 15 sectors

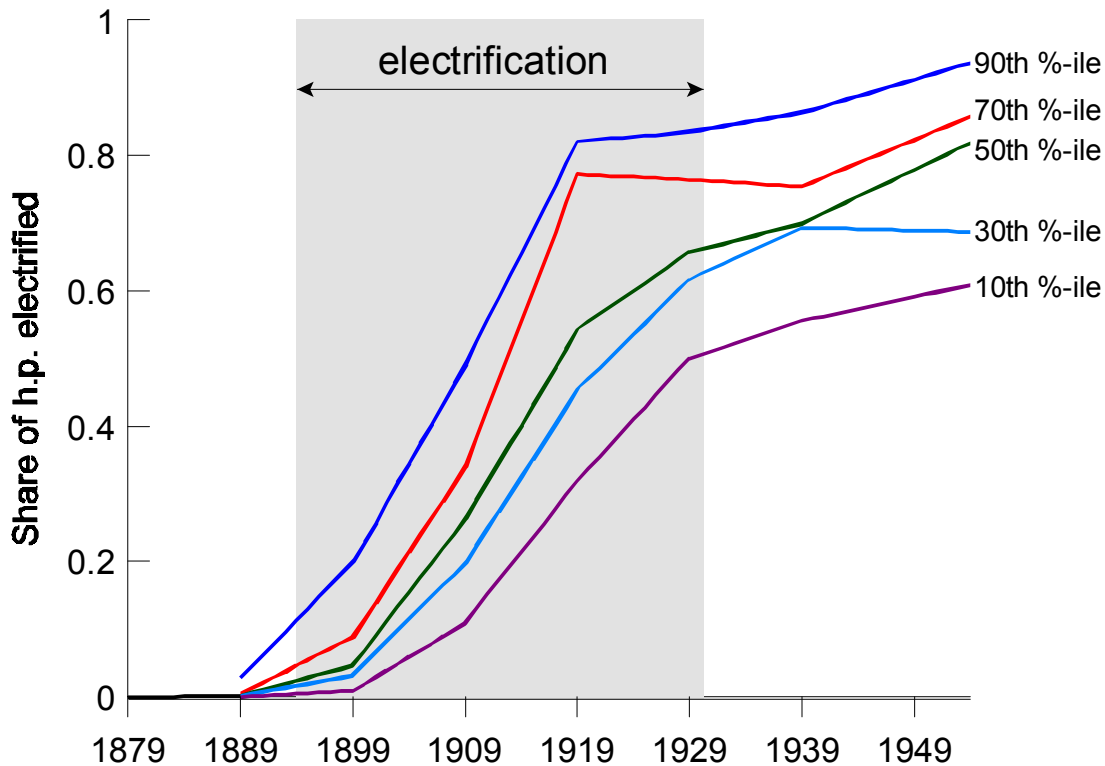


Figure 5: Shares of electrified horsepower by manufacturing sector in percentiles, 1890-1954.

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 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 equivalents in the median industry was provided by electricity. Whether or not this is the right percentage for dating the start of the Electrification era, we shall use the same percentage for the median industry to date the beginning of the IT era, thereby using 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.

⁵The sectoral shares of manufacturing horsepower driven by steam were computed from DuBoff (1964, tables E-12a through 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.

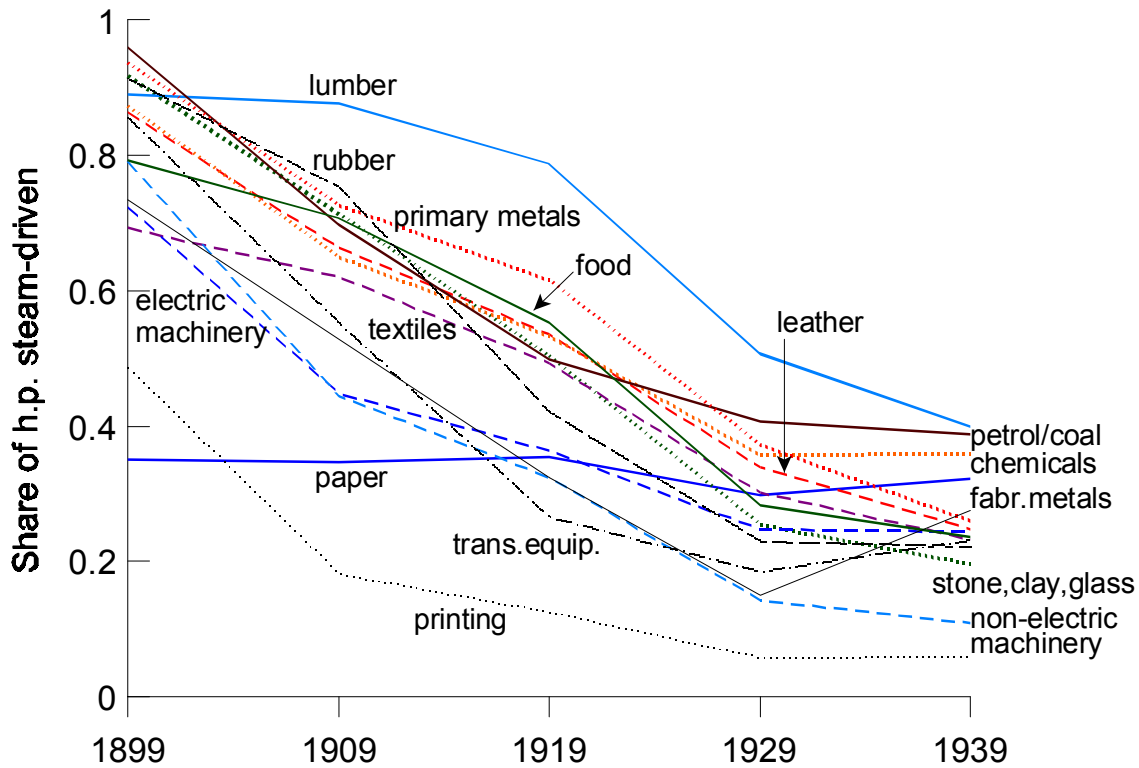


Figure 6: Shares of steam-driven horsepower by manufacturing sector, 1899-1939.

Indeed, most of the industries that quickly switched over to electricity had been heavy users of steam. This is clear from Figure 4 and Figure 6, taken together, and from the rank correlations presented in Table 2 which decay quickly and suggest a non-uniformity in the destruction of steam technology across sectors.

Table 2
Rank correlations of steam shares in total horsepower
by manufacturing sector, 1889-1954

| | 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 |

The spread of information technology was also rapid, but does not appear to have been as widespread as electricity. Figure 7 shows the share of real IT equipment and software in the real net capital stocks of 62 sectors from 1960 to 2001 plotted as

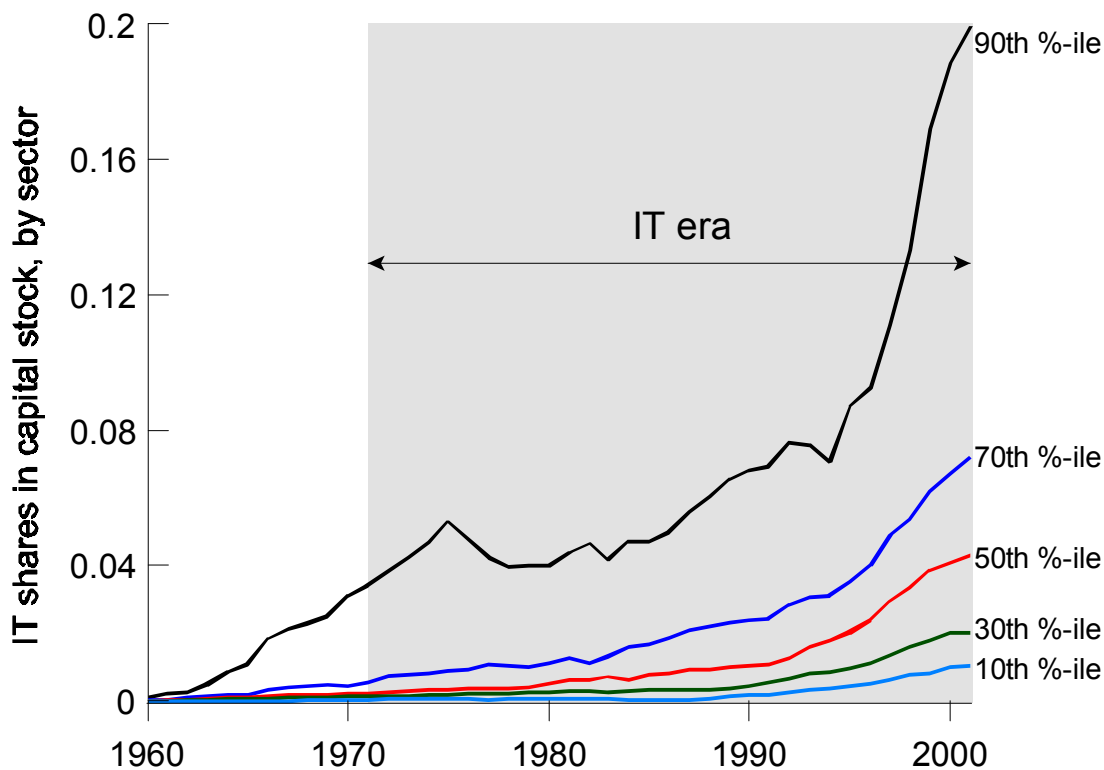


Figure 7: Shares of IT equipment and software in the capital stock by sector in percentiles, 1960-2001.

annual percentiles.⁶ In the case of IT, some sectors adopted 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.

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

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 |

So far we have discussed adoption by firms, and it determines the dating of the two GPT epochs. We turn to households next.

2.1.3 Adoption by households

Households also underwent electrification and the purchase of personal computers for home use during the respective GPT-eras. Figure 8 shows the cumulative percentage of households that obtained electric service and that owned a personal computer in each year following the “arrival” of the GPT.⁷ If we continue to date Electricity as arriving in 1894 and the personal computer in 1971, Figure 8 shows that households adopted electricity about as rapidly as they are adopting the personal computer. By the time the technology is officially 35 years old (in 1929), nearly seventy percent of households had electricity. A comparison with Figure 5 shows that this is just a little higher than the 1929 penetration of electrified horsepower share by 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 to reach for Electricity, but not so for the PC, for which 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 Electrification. The price of computing 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 begin to spread widely,

⁷Data 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 through 1998 are from Gates (1999, p. 118), and from the Census Bureau’s *Current Population Survey* thereafter.

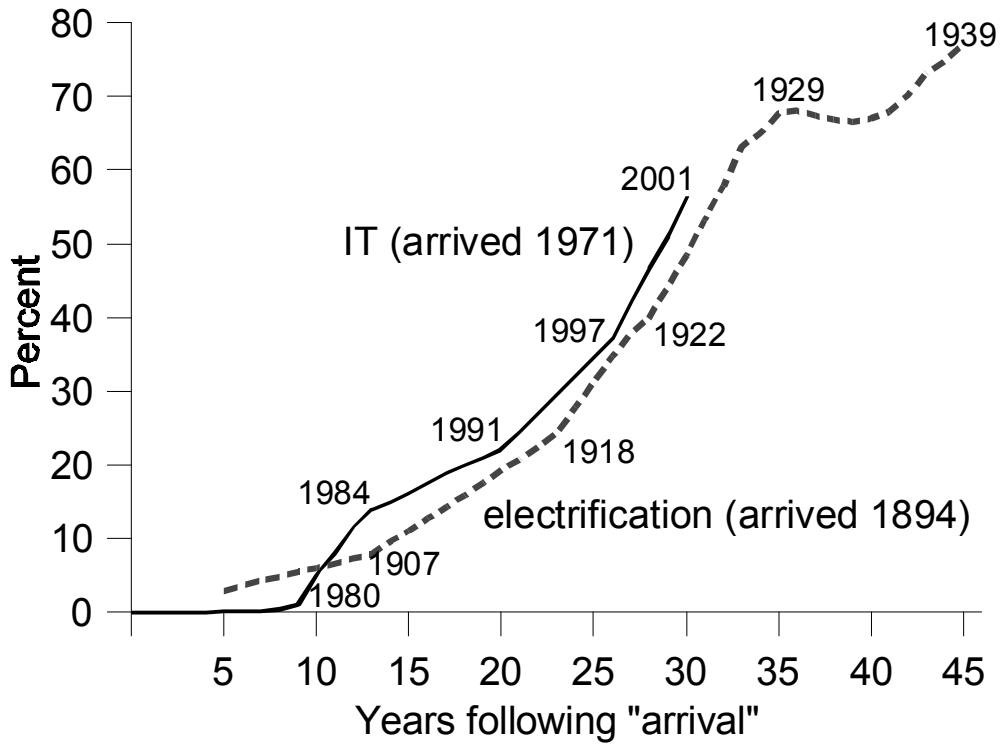


Figure 8: Percent of households with electric service and personal computers during the two technological epochs.

and electrical appliances began to be invented, did the benefits of Electrification outweigh the costs for a majority of households. Greenwood, Shesadri and Yorukoglu (2001) document the spread of electrically powered household appliances and argue that their diffusion helped raise female labor-force participation by freeing up their time from housework.

2.1.4 On dating the endpoints of the era of a GPT

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 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 twentieth 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 is already negative.

Net adoption is endogenous and it 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 in Figure 6 about the same time.

2.2 Improvement of the GPT

The second characteristic that Bresnahan and Trajtenberg suggested is an 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 be therefore 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 answer these questions, we first look at the prices of capital as a whole and then at the prices of its components. Figure 9 is a quality-adjusted series 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 aims to look at the components of the aggregate capital stock; specifically, the components tied to the two GPTs. Because deflators for electrically powered capital are not available in the first half of the twentieth century, Figure 10 compares the declines in relative prices associated with three GPT's – electricity, internal com-

⁸Krusell et al. (2000) build such a series from 1963 using the consumer price index to deflate the 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 (1947-62) 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 1902-46, 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 prices index of all items [U.S. Bureau of the Census (1975, series E135)] for 1913-46 and the Burgess cost of living index [U.S. Bureau of the Census (1975, series E184)], which has greater precision than the BLS series, for 1885-1912.

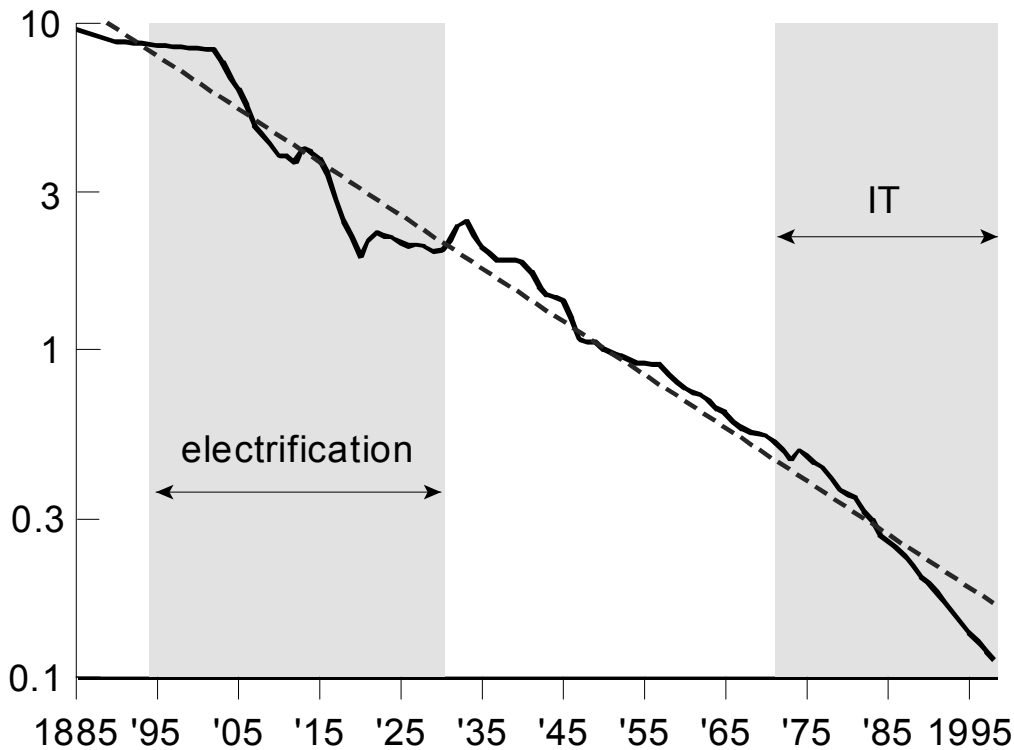


Figure 9: The relative price of equipment.

bustion, and computers – once again relative to the consumption price index.⁹ The

⁹To 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 1960-78 with the pooled index developed for desktop and mobile personal computers by Berndt, Dulberger, and Rappaport (2000, table 2, col. 1, p. 22) for 1979-99. 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 prices trends in the computer industry reasonably well. We set the index to 1000 in the first year of the sample (i.e., 1960).

Electricity prices are averages of all electric energy services in cents per kilowatt hour from the *Historical Statistics of the United States* (U.S. Bureau of the Census, 1975, series S119, p. 827) for 1903, 1907, 1917, 1922, and 1926-70, and from the *Statistical Abstract of the United States* for 1971-89. 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).

Motor vehicle prices for 1913-40 are annual averages of monthly wholesale prices of passenger vehicles from the National Bureau of Economic Research (Macrohistory Database, series m04180a for 1913-27, series m04180b for 1928-40, <http://www.nber.org>). From 1941-47, they are wholesale prices of motor vehicles and equipment from *Historical Statistics* (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>).

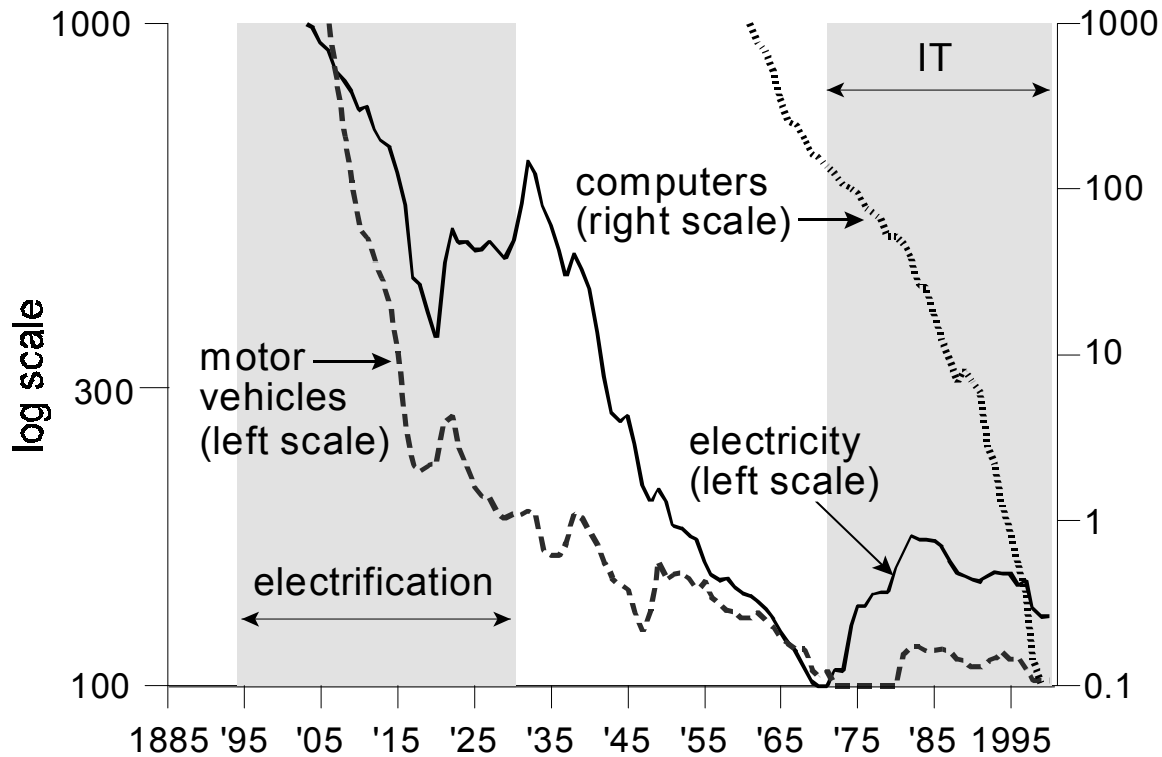


Figure 10: Price indexes for products of two technological revolutions.

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. While the electricity and the automobile indexes fall by a factor of 10, the computer index falls by a factor of 10,000.

The more important question, however, is how the general decline in equipment prices compares 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 GPT's along with the general equipment index on the same logarithmic scale, with the starting point for each of the GPTs normalized to the level of the general equipment price 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

To approximate prices from 1901-1913, we extrapolate assuming constant growth and the average annual growth rate observed from 1913-24. 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).

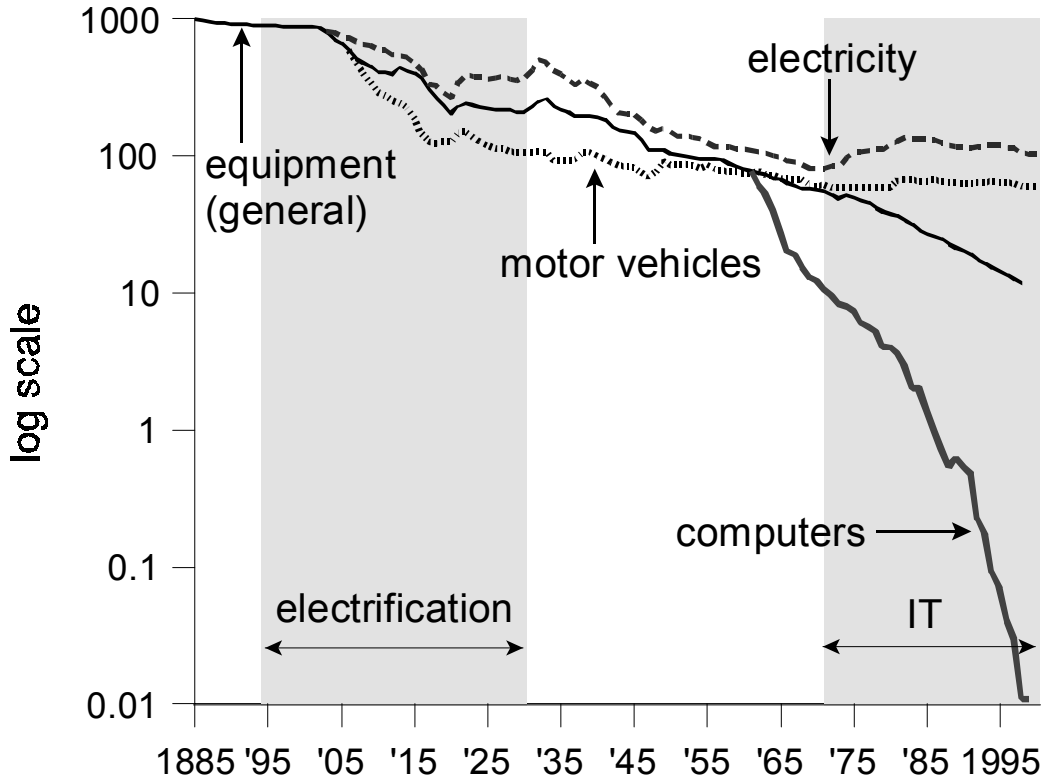


Figure 11: Comparison of the decline in general and GPT-specific equipment prices.

equipment 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. Yet based on the price evidence in figures 10 and 11, electricity, motor vehicles, and computers might all qualify as GPTs, but computers 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 hy-

brid corn was not an invention immediately adaptable everywhere, but, rather, that it was the 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 is more skewed towards the latter. The 1920s especially saw a wave a new products powered by electricity, and the computer is now embodied in many new products as well. But as the patenting evidence will bear out, IT seems to have more of a skew towards contributing to further innovation – 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 per capita numbers of patents issued on inventions annually from 1790 to 2000 and trademarks registered from 1870 to 2000, shows two surges in activity – between 1900 and 1930, and again after 1977.¹⁰ Is it mere chance that patenting activity was most intense during our technological revolutions? 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 acceleration immediately thereafter suggest that there is 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 detail in Lerner (2002) and shows that worldwide, changes in patent policy changes are correlated with the patent series in Figure 12. It is possible, therefore, that the U.S. series reflects court-enforcement attitudes. 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, and they conclude that technology was the cause for the surge.

¹⁰We use the total number “utility” (i.e., invention) patents from the U.S. Patent and Trademark Office for 1963-2000, 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 various issues of the *Statistical Abstract of the United States* 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 Bureau of Economic Analysis thereafter.

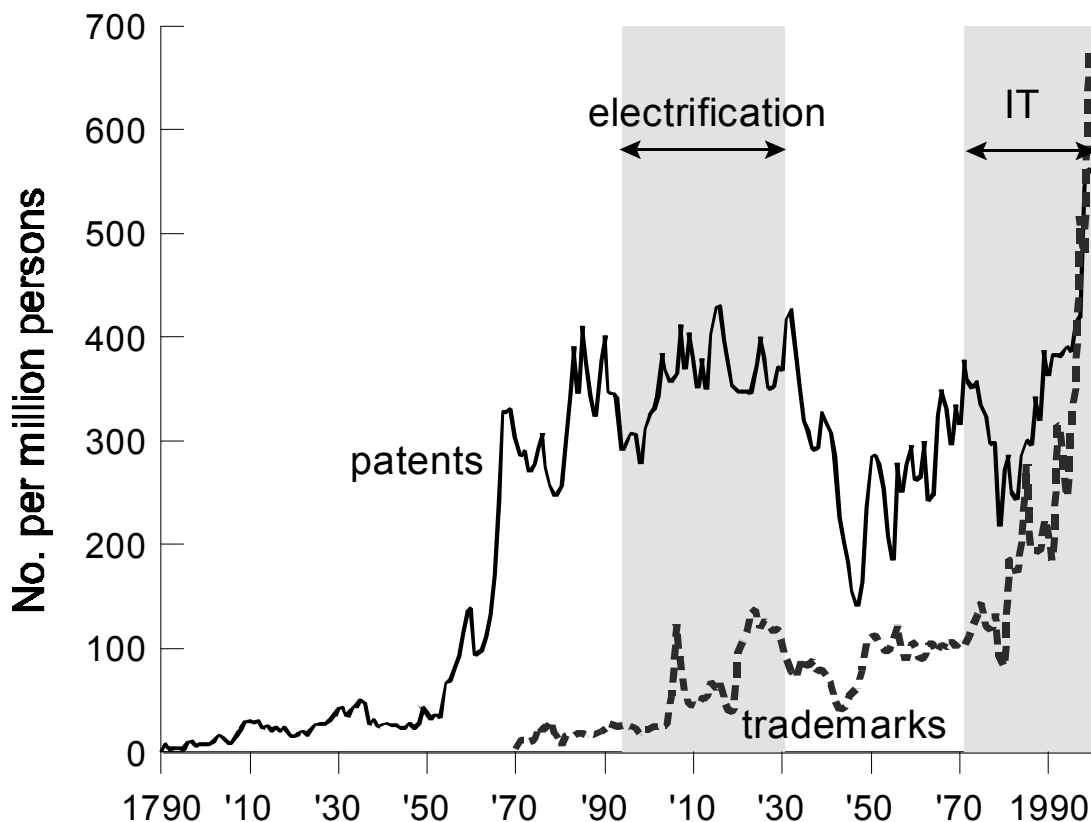


Figure 12: Patents issued on inventions and trademarks registered in the United States per million persons, 1790-2000.

Further support for this view comes from the behavior of trademarks per head, which we also plot in figure 12. Trademarks behave more or less the same as patents do, except for their higher 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, therefore, that brand names do signify product differentiation.

2.3.2 Investment in new firms vs. investment by incumbents

If new technologies are more easily embraced by new firms that do not bear the burden of costs sunk in old technologies and the rigid and firm-specific organization capital required to operate them, we should expect to see waves of new listings on

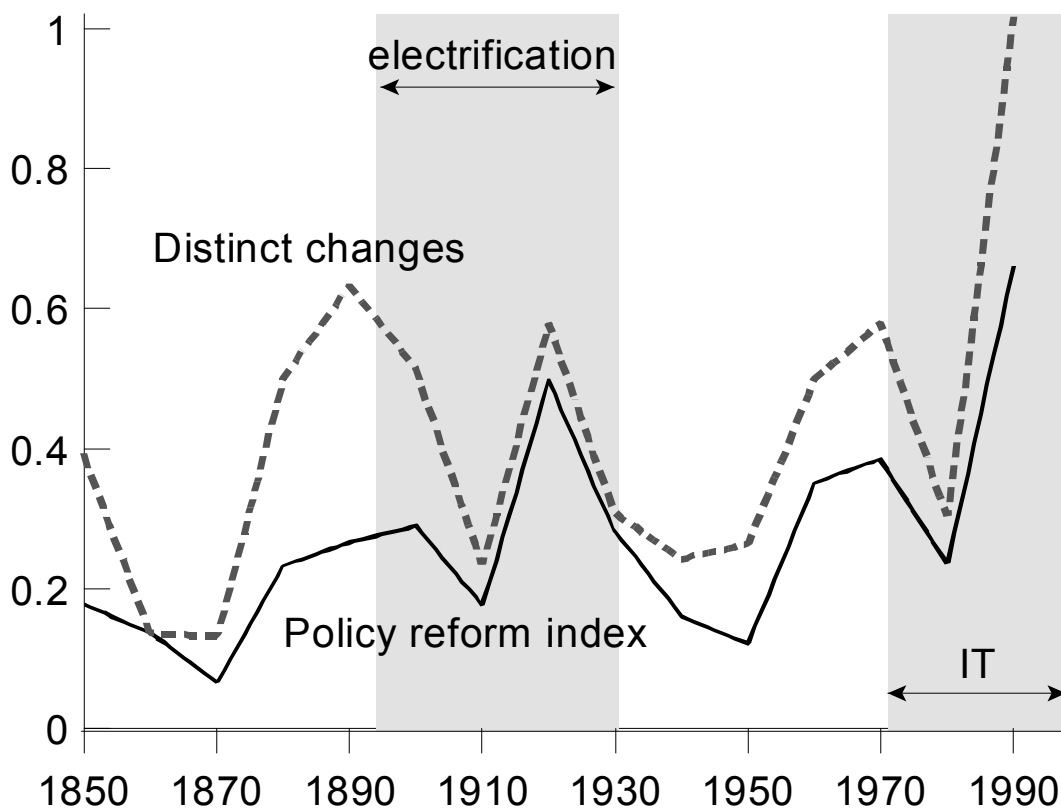


Figure 13: Indexes of worldwide changes in patent laws.

the stock exchange during GPT eras. 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 2001 as percentages of total stock market value.¹¹ As predicted by Trajtenberg and Helpman, IPOs surge between 1895 and 1929, and then after 1977, which again closely matches the dating of our two technological revolutions.

¹¹The data used to construct Fig. 14 and others in this chapter that use stock market valuations are from the University of Chicago's Center for Research in Securities Prices (CRSP) files for 1925-2001. 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*, which is also the source of firm-level data for the price indexes reported in the well-known study by Cowles et al. (1939). We obtained firm book capitalizations from *Bradstreet's*, *The New York Times*, and *The Annalist*. The resulting dataset, which includes 24,475 firms, though limited to annual observations, actually includes more common stocks than the CRSP files in 1925. As such, the dataset complements others that have begun to build a more complete view of securities prices in other markets for the pre-CRSP period [see, for example, Rousseau (1999) on Boston's 19th century equity market.

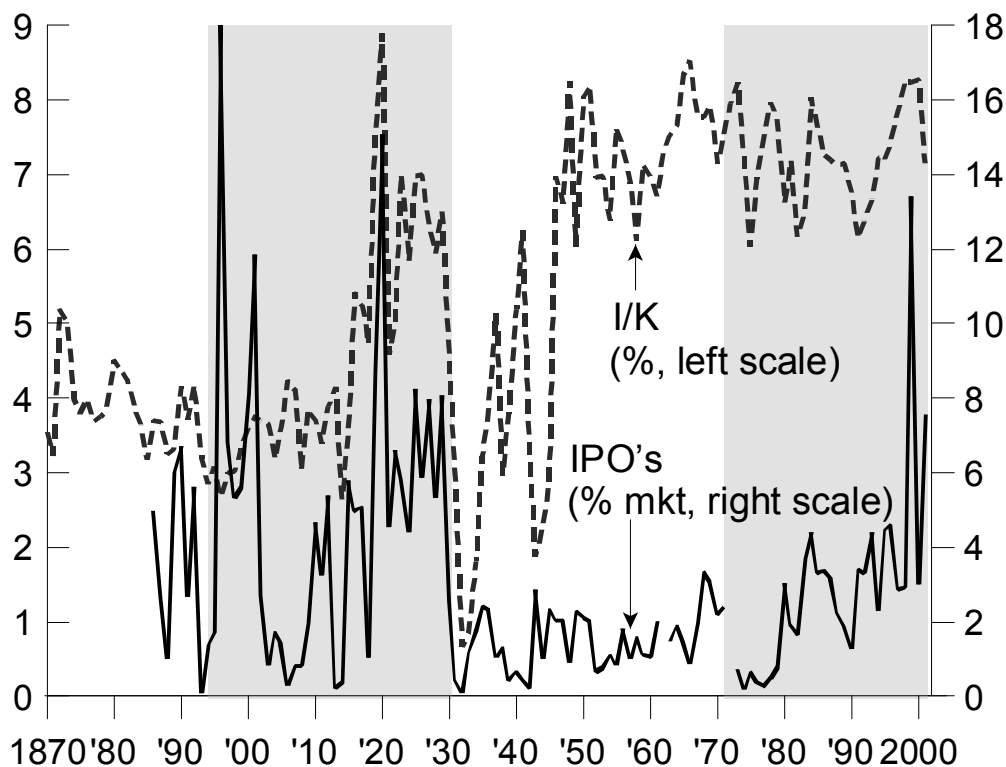


Figure 14: Annual IPOs as a percent of stock market value, and investment as a percent of the net capital stock, 1870-2001.

The dashed line in Figure 14 is private investment since 1870 as a percent of the net stock of private capital for the U.S. economy as a whole, and as such is the aggregate analog of the solid line that covers only the stock market.¹² The solid line in Figure 15 shows the ratio of the solid and dashed lines in Figure 14. In both figures it is clear that, during Electrification, investment by stock market entrants accounted for a larger portion of stock market value than overall new investment in

¹²To build the investment rate series, we start with gross private domestic investment in current dollars from the Bureau of Economic Analysis (2002, Table 1, pp. 123-4) for 1929-2001 and then ratio splice the gross capital formation 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 Bureau of Economic Analysis (2002) for 1925-2001. Then, using the estimates of the net stock of non-military capital from Kuznets (1961a, Table 3, pp. 64-5) 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 ratio-splice 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 to the capital stock series, expressed as a percentage.

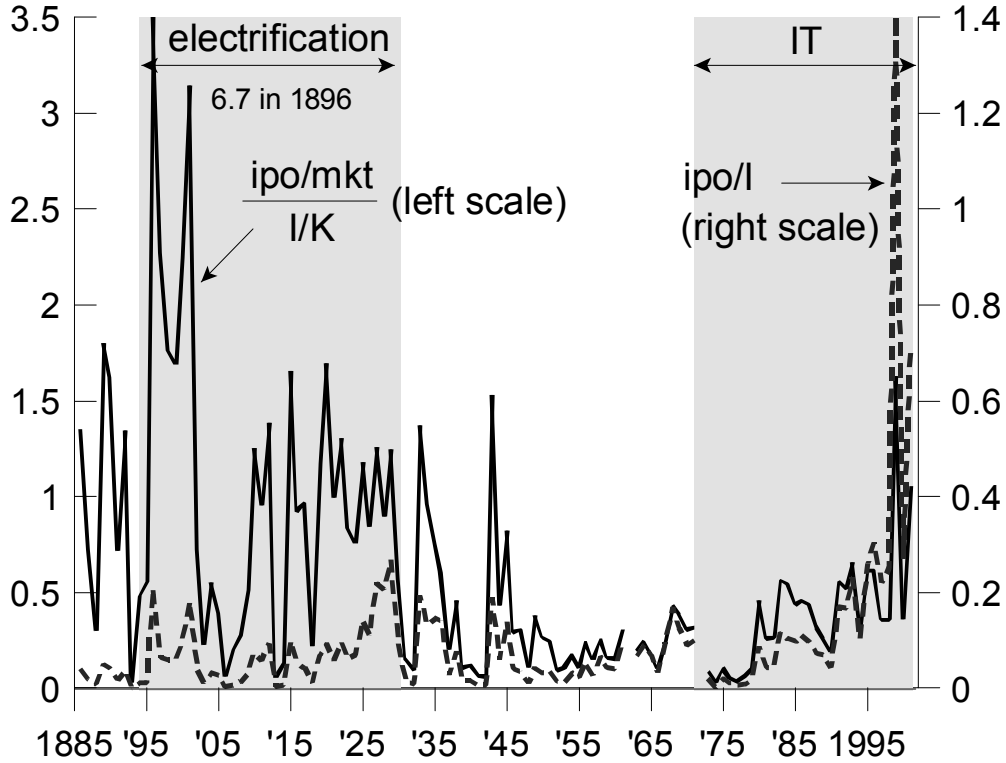


Figure 15: Ratio of IPOs as a percent of the stock market to investment as a percent of the net capital stock, 1885-2001.

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 large 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 ratio of IPO to aggregate investment activity was highest in the early years of Electrification, which is when these adjustment costs would have been greatest. Although the ratio given by the solid line in Figure 15 has so far stayed below unity for most of the IT-era, it has been rising rapidly 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 promote adoption among new firms.

The solid line in Figure 15 shows a downward trend mainly because the stock market gained importance as a model of financing in the early part of the 20th century. IPOs are normalized by the stock market which was small early on, and has since become larger. The dotted line in Figure 15 shows the ratio of the unnormalized series of IPOs and aggregate investment. This has a positive trend for

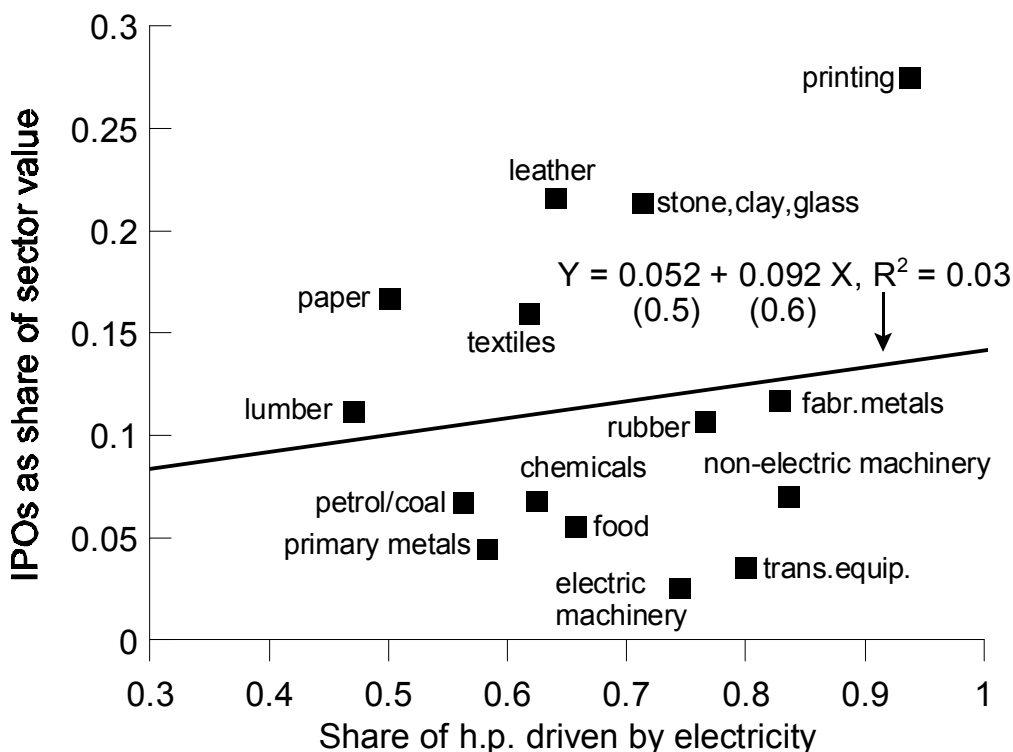


Figure 16: IPOs as shares of sector value 1890-1930 vs. shares of electricity-driven horsepower in 1929.

the same reason that the previous figure showed a negative one: IPOs were not that important early on because the stock market was small. After 1970, IPOs capture a much larger share of the investment by new entrants than they did before the first World War, 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 capitalization of 15 manufacturing sectors between 1890 and 1930 vs. their respective shares of horsepower driven by electricity in 1929.¹³ In other words, we ask whether sectors with more IPOs ended up embracing the new technology more vigorously than sectors with less entry. The regression line plotted in Fig. 16

¹³We compute the IPO shares by sector by summing year-end IPO values by sector for 1890 through 1930, converting each year's total into real terms using the implicit price deflator for gross domestic product, and then summing across years. We do the same for all listed firms by sector, and use the quotient of sector IPO values and total sector values to compute the shares shown in Fig. 16.

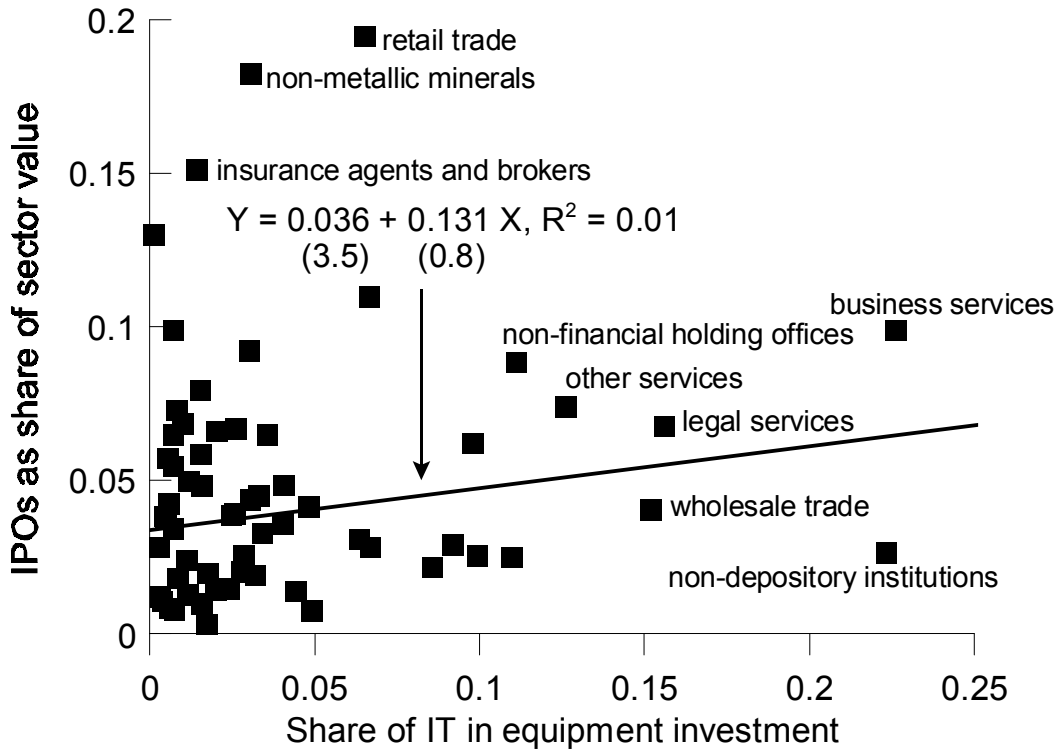


Figure 17: IPOs as shares of sector value 1971-2001 vs. shares of IT in equipment investment in 2000.

indicates that this relationship is indeed positive, though with only 15 observations the slope coefficient is not statistically significant at conventional levels.

In Figure 17, we consider IPOs over the 1971-2001 IT-epoch against shares of computers and peripherals in equipment investment in 2000, we once again obtain a sectoral scatter with a positive slope, though like Electrification, the slope coefficient is not statistically significant.

3 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, 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 Electricity and IT eras, we believe 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 are similar, but they also differ in 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.

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