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Productivity in the Slow Lane? The Role of Information and CommunicationsTechnology

J. Christina Wang and Alison Pearson

Abstract:
As the current recovery matures in the United States, evidence is mounting that total factor productivity (TFP), the typical measure of technical change, has moved back into the slow lane. This study uses industry data to explore the extent to which the acceleration in TFP in the late 1990s and early 2000s and the subsequent deceleration are attributable to unmeasured investment by firms to take full advantage of the new capabilities made possible by information and communications technology (ICT). We find that this pattern of a TFP speed-up followed by a slowdown has been widespread across industries. Moreover, prior to the mid-2000s, investment in ICT capital grew much faster than investment in non-ICT capital for most industries, and there is little correlation across industries in the growth of these two types of investment. Since then, the relative growth of ICT investment has declined more than its relative price growth has increased. In addition, growth rates of the two types of investment have also become highly correlated across industries. Furthermore, for those industries that use ICT more intensively, the acceleration in TFP in the early 2000s seems to have depended positively on the intensity of ICT investment in the second half of the 1990s. This can be construed as evidence that firms invested simultaneously in tangible ICT capital and intangible organizational capital that diverted resources but enhanced the future efficacy of ICT capital. Taken together, these patterns suggest that firms' growth paths for ICT capital have converged to the steady-state growth path for ICT capital since the mid-2000s. It further implies that TFP has likely reverted back to its long-run, slower, trend rate of growth.

Keywords: productivity, TFP, MFP, information technology, ICT, intangible capital
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Motivation

As the recovery has been maturing in the United States, productivity has performed in a largely lackluster manner over the past couple of years, leading some to revise downward their projections of the U.S. economy's future potential growth rate. This recent development of sluggish productivity prolongs the uncertainty regarding the trend growth of the economy's potential, which was initially heightened because of the outsized volatility experienced during the Great Recession and early stages of the recovery. Having a correct projection of potential growth is important for the conduct of monetary policy. In particular, an accurate estimate of potential growth helps monetary policymakers determine the long-run equilibrium federal funds rate (and other market interest rates) and possibly also the appropriate time path of policy normalization.

To forecast the growth rate of potential aggregate output, a key input is a forecast of the rate of technological change, which in turn determines the rate of capital deepening and hence the growth rate of labor productivity. The objective of this policy brief is to use cross-sectional data to provide a better understanding of the factors that may influence the pace of technological progress. More specifically, we use industry data to explore the extent to which the productivity performance of the U.S. economy since the late 1980s can be explained by the revolutionary developments in information and communication technology (ICT) in the 1990s. We then examine the implications for the trend growth rate of productivity and, in turn, the growth rate of potential output going forward.

Performance of Aggregate Technology over the Past Quarter Century

In classical growth models (see, for example, Solow 1956), an economy's long-run prospects depend entirely on the growth rate of technology, which is typically measured using so-called total (or multi) factor productivity (TFP or MFP, often used interchangeably). In terms of the growth rate of TFP, it is defined as the difference between output growth and revenue-share-weighted input growth:

$$g_{TFP} = g_Y - \sum_{i=1}^{n} s_i g_i \, , \tag{1}$$

where g_X denotes the growth rate of *X*, while s_i denotes the revenue share of input *i*. g_{TFP} is also known as the Solow residual. The factors influencing the growth of TFP are still poorly understood. It is therefore no wonder that Abramovitz's (1956) quip, "it's a measure of our ignorance," endures.

In a number of studies, Basu and Fernald (1997, 2001) have shown that TFP is not an accurate measure of technology at a business cycle frequency or higher (such as quarterly or annual) because of unmeasured fluctuations in inputs (such as labor effort and capital utilization).[1] Since utilization is quite cyclical, the resulting measurement error should more or less average out over a number of years that include both business cycle peaks and troughs. We therefore use the average growth rate of TFP as a proxy for its trend growth and focus mostly on TFP as a measure of technology. Nevertheless, we also examine the behavior of utilization-adjusted TFP, computed according to a method developed by Basu, Fernald, and Kimball (2006), to verify the findings based on the average growth of TFP. Note that the focus of this analysis is to better understand the trend growth of technological change, not the cyclical fluctuations of TFP. As discussed toward the end of this brief, there may be forces that will enable measured TFP to improve further in the near term (such as through better resource allocation), but these are unlikely to affect its trend growth.

Since the goal of this study is to help inform the outlook for trend growth of aggregate technology and, in turn, aggregate output, we start by inspecting the growth performance of aggregate TFP of the private business sector since 1988, using the most timely TFP data, the quarterly TFP series compiled by John Fernald of the San Francisco Fed.[2] The choice of 1988 as

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[1] The standard definition of TFP, as in (1), also does not account for increasing returns to scale or imperfect competition.

[2] These quarterly data are compiled essentially by interpolating the annual data published by the Bureau of Labor Statistics (BLS) using quarterly data on investment from the Bureau of Economic Analysis (BEA). One other difference from the BLS data is that Fernald uses both the expenditure and the income sides of the National Income

the first sample year is dictated by the availability of North American Industry Classification System (NAICS) industry-level productivity data for the analysis below. The basic pattern of average growth rates, however, remains the same using a longer time series of aggregate data.[3]

Figure 1 plots the four-quarter growth rate of TFP (the thick red line), along with the annualized quarterly growth rate (the thin blue line), from 1988:Q1 to 2014:Q2. For comparison, Figure 2 plots the same two measures for the utilization-adjusted measure of TFP, also compiled by John Fernald. Visual inspection, especially of the less volatile four-quarter average growth rate and utilization-adjusted TFP, strongly suggests that the rate of technological change increased in the late 1990s and the early 2000s. To estimate the break dates, we apply the global-minimizer supF trend break test (of the null hypothesis of no break against the alternative hypothesis of a fixed number of breaks) by Bai and Perron (1998, 2003). To reduce the distortion of the test statistics from cyclical fluctuations in utilization, we apply the test to the quarterly growth rate of utilization-adjusted TFP over the full sample from 1950:Q1 to 2014:Q2. The Bai-Perron test identifies four or five breaks in the trend of utilization-adjusted TFP.[4] In either case, 1994:Q1 is one of the two break dates over the relevant sample period (1987 to 2012) for our later analysis using the industry data.[5] The other break in our sample period is identified at 2004:Q1. (See Table 1 for more details of the test statistics and the critical values.) Note that this last break point in adjusted TFP growth is identified as occurring clearly before the financial crisis and the ensuing Great Recession. These test results confirm the finding in Fernald (2014) and suggest that the deep downturn associated with the Great Recession is unlikely to have been the main driver of the subsequent slowdown in TFP growth. These results also confirm findings in previous studies (for example, Fernald 2007) using earlier vintages of data: there

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and Product Accounts (NIPA) data to calculate output. See Fernald (2012) for more details. This modification is adopted in light of findings by Nalewaik (2010) that income data appear to capture cyclical fluctuations better than expenditures data do. This difference, nontrivial for quarter-to-quarter changes, matters little for average growth rates in our analysis.

[3] More specifically, the annualized quarterly growth rate of TFP averages 0.63 percent from 1988 to 1996, as shown in Figure 1, and 0.70 percent if the sample is extended to 1980 to 1996. Excluding years before 1980 avoids mixing up the high growth period of the 1960s with the productivity slowdown typically identified as starting in 1973.

[4] The test statistics are computed using the Matlab programs downloaded from Pierre Perron's website: http://people.bu.edu/perron/code.html.

[5] If we run the Bai-Perron test on bandpass-filtered TFP, the break date is identified at 1997:Q4. Break dates identified using the quarterly growth rate of TFP tend to coincide with recessions.

does appear to be a break in the trend growth of TFP in the mid-1990s. To divide our relevant sample more evenly and make our results more comparable with previous studies, we set 1996:Q4 as the mid-1990s break date.

We therefore divide the sample years into three subperiods: 1) 1988 to 1996, 2) 1997 to 2004, and 3) 2005 to the present. Consistent with results of the trend break tests, we find that the average rate of TFP growth indeed exhibits a noticeable step-up in the 1997 to 2004 subperiod—over 1 percentage point per year faster. (We therefore refer to the middle period as the TFP boom years.) More specifically, TFP grew on average 1.72 percent per year during the boom years, but only 0.63 percent during the period before, and 0.52 percent during the period subsequent to the boom. Note that the growth rates in the most recent quarters are on average slightly higher, but still close to the period average.

It is obvious that TFP experienced unusual fluctuations around the time of the financial crisis and the ensuing Great Recession. It plummeted during the recession and then rebounded strongly early in the recovery. This pattern, however, was almost entirely due to the cyclical fluctuation in utilization. To wit, utilization-adjusted TFP (Figure 2) in fact accelerated during the recession, even as the unadjusted TFP (Figure 1) slowed markedly.[6] This is precisely because the former accounts for the substantial decline in the utilization of inputs during the recession and thus corrects (to a first order) for the downward bias in measured TFP. Consistent with firms optimizing simultaneously along multiple margins of input use, the cutback in utilization coincided with the unprecedented run-up in unemployment. Utilization subsequently returned to more normal levels, boosting measured TFP and partly explaining the forceful rebound in TFP during the early stage of the recovery.

If we are concerned about the enormous variation in utilization around the Great Recession distorting measured TFP, we can compute an alternative average rate using only data since 2011. Over this more recent subperiod, annualized quarterly TFP growth has averaged 0.68 percent, rather similar to the average observed for the pre-TFP-boom subperiod.

[6] See Basu, Fernald, and Kimball (2006) for details about the estimation of utilization-adjusted TFP, and see Fernald (2012) for details about how the method is adapted to quarterly data.

Alternatively, we can use utilization-adjusted TFP, which should be less susceptible to the measurement error in TFP due to cyclically varying utilization. At only 0.43 percent per year, this measure in fact registers an even lower average growth rate over the post-TFP-boom years (see Figure 2 and the last row of Table 2, Panel A).[7]

Combined, these average growth rates strongly suggest that TFP has indeed decelerated since the mid-2000s. In other words, the TFP acceleration in the 1997 to 2004 subperiod was not a permanent increase in trend growth, but rather a permanent increase in the level of TFP that was realized over a few years. Now that this temporary adjustment process is complete, TFP has reverted to its long-run, lower, growth rate. This is an assessment that agrees with the conclusion of Ireland and Schuh (2008) based on a two-sector dynamic general equilibrium model.

Figure 3 bridges the quarterly aggregate data and the annual industry data that we use for the analysis below. It plots annual growth rates from 1988 to 2012, the sample period for the industry data, for three series: the official MFP data for the private business sector compiled by the Bureau of Labor Statistics (BLS), the aggregate TFP series for the same sector constructed using the BLS industry data, and, for comparison, utilization-adjusted TFP.[8] The aggregate TFP series constructed using industry data accords well with the official aggregate MFP series, minor differences notwithstanding, as we would expect based on the growth accounting methodology.[9] Figure 4 shows the average growth rate for the three subperiods according to the aggregate TFP constructed using industry data: growth averages 1.72 percent per year over the TFP boom years (1997–2004) and 0.80 percent in the years before and, separately, in the years after. These annual series confirm precisely the same pattern as found above using quarterly

[7] Note that for the utilization-adjusted TFP series, the average growth rate excluding recession years (2008–2009) is actually lower than if the recession years are included precisely because it corrects for the fact that resource utilization, and hence the true quantity of inputs, was lower during the recession.

[8] TFP at the industry level is computed on a gross output basis and then aggregated using Domar weights.

[9] The remaining difference is likely accounted for by the two primary methodological differences between them: 1) labor input is measured by raw hours in the industry data because the BLS has yet to adjust for changes in labor composition at the industry level, and 2) the aggregate MFP series is computed using the value-added concept instead of the gross-output concept, as in the industry data. Domar weighting the industry TFP should eliminate most of the difference to the extent that nonconstant returns to scale and imperfect competition are not important empirically.

data: the TFP growth rate in the middle period is about a full percentage point higher than in the periods before and after, which are similar to each other. (See Table 2 for comparisons without the recession years, which yield a qualitatively similar pattern.) Note that this temporal pattern is in fact stronger in the utilization-adjusted TFP because this measure takes into account the fluctuations in utilization around the 2001 recession, and thus delivers a smoother sequence of TFP growth over the middle years.

One note of caution is in order, however, concerning the TFP data for the more recent years. Like most other aggregate data series for the U.S. economy, it will be subject to revisions that may be nontrivial. The BLS bases its estimates of productivity, TFP included, on data from the National Income and Product Accounts (NIPA) compiled by the Bureau of Economic Analysis (BEA). The NIPA data are revised regularly, and therefore so are the BLS productivity data. More recent data are generally subject to greater revisions because they are often initially estimated based on incomplete data and subsequently revised as more and better data become available. In fact, Fernald (2014) shows that the level of TFP for the mid-2000s was repeatedly revised downward in a sequence of data vintages. Likewise, the depth of the Great Recession was revealed to be more severe by later vintages of data.

Does Information and Communication Technology Explain the TFP Acceleration?

One prominent candidate to explain the TFP acceleration in the late 1990s and early 2000s is the story of ICT as a general purpose technology (GPT). The narrative goes something like this: ICT has greatly enhanced the capability of gathering, processing, and transmitting information, and this represents a new GPT whose benefits can only be fully utilized through complementary investment in both tangible ICT equipment and software and intangible capital (for example, by reorganizing the production process). This story is consistent with the observation that the peak years of the TFP acceleration followed the ICT investment boom with a lag, which is interpreted as evidence that firms needed some time to reoptimize their business processes to fully take advantage of the enhanced capabilities afforded by ICT.

This mechanism of ICT as a GPT that has influenced measured TFP has been explored in a number of previous studies (see, for example, Brynjolfsson and Hitt 2003, Basu et al. 2003, Oliner et al. 2007; Brynjolfsson and Hitt 2000 offer an overview) and has received varying degrees of support. The primary difficulty is that the theory is qualitative, and thus offers little guidance about the length of the lag between restructuring and TFP improvement. Like monetary policy, restructuring is supposed to bear fruit with a long and variable lag. The difficulty for empirical analysis is compounded by the fact that in most cases the intangible investment is unobserved, and hence the resulting intangible capital is also unobserved. Moreover, some more generally applicable best practices that help firms take advantage of the new capabilities afforded by ICT may have spilled over from the sector or sectors that have spent resources to experiment with new production processes to those that have not (or at least have done so to a lesser extent). Such cross-industry spillovers make it more difficult to find a linkage between industry TFP and own ICT investment. On the other hand, to the extent that spillovers within an industry are positively correlated with the amount of ICT investment carried out by the industry, there should be a positive association between industry TFP and own ICT investment.

To the extent that a sufficient degree of complementarity exists between tangible ICT capital and intangible organizational capital, ICT investment and ICT capital can serve as good proxies for unobserved intangible investment and intangible capital, respectively. The ICT-as-GPT story then implies opposing effects of ICT investment and ICT capital on measured TFP. TFP is expected to be negatively correlated with ICT investment, but positively correlated with ICT capital. The reason is that at the time when firms are carrying out the intangible investment, their measured TFP is likely depressed relative to the true TFP because the production of intangible capital is not counted. Once the intangible capital has been formed, however, its contribution to output is also unmeasured, and thus serves to boost observed TFP. These seemingly contradictory effects are two sides of the same coin. Note also that such dynamics apply to any kind of intangible investment and the resulting intangible capital, not only to those related to ICT.

To the extent that the acceleration in measured TFP reflects the contribution of growing unmeasured organizational capital, the economy will converge to the new steady state of a higher level of ICT-related capital, which will then no longer contribute in terms of the growth rate of TFP. Such an episode should thus manifest as a level shift in TFP that appears as higher growth rates over a number of years during the transition to the higher level.

Note that all the discussion and analysis here concerns the possible relationship of ICT capital and investment with TFP, not with labor productivity (LP), of those industries that use ICT. In growth rate terms, LP is the sum of TFP, capital deepening weighted by the share of capital in output, and labor quality:

$$g_{LP} = g_{TFP} + s_K(g_K - g_L) + g_{lq} \, . \tag{2}$$

Thus, the effect of ICT on TFP differs from the effect of ICT on LP in one fundamental aspect: ICT has had a massive effect on LP of the ICT-using industries because of the extraordinary capital deepening brought about by declines in the relative price of ICT capital, owing primarily to the rapid pace of technological change in the ICT-producing industries.[10]

In the standard one-sector Solow-Ramsey growth model, the rate of capital deepening is entirely determined by the growth rate of technology. This result carries through to two-sector growth models (see, for example, Greenwood et al. 2000), with the intuitive modification that capital deepening is determined by the rate of technological change in the sector that produces capital goods, not the average rate of technological change, which includes technological change in the consumption-goods sector. The effect of ICT on capital deepening, and in turn on LP, is well recognized and documented. In contrast, TFP, by definition, is already net of the contribution from measured capital deepening. Were we able to measure the intangible investment in restructuring and the resulting intangible capital and account for them in calculating TFP, this TFP would not be correlated with ICT either. Therefore, it is because of data limitations that we observe a correlation between TFP and ICT investment and capital.

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[10] The extraordinary decline in the relative price of ICT goods in the 1990s, especially the second half, is also partly due to gains in the U.S. terms of trade and tariff reductions, especially for Information Technology (IT) products, as shown in Feenstra et al. (2013).

TFP Growth across Industries

We now turn to industry data to examine whether the contour of TFP growth at the industry level follows a similar time path as aggregate TFP, and whether the cross-industry pattern of TFP growth over the sample years is consistent with the ICT-as-GPT interpretation.

We first inspect the cross-industry dispersion in TFP growth rates. Figure 5 plots the cross-industry distribution of TFP growth rates between 1988 and 2012. Aggregate TFP growth (the red line, equal to Domar-weighted industry growth rates) exceeds the median industry TFP growth (the black line) in most years, especially during the TFP boom years. This means that the boom in aggregate TFP was due to faster growth in industries that account for larger shares in the private economy. The cross-industry dispersion in TFP growth rates, measured by the difference in growth rates between the 90th and the 10th percentile of the growth rate distribution across industries, is wider than usual over two subperiods: 1) the late 1990s to 2000, when ICT investment was booming, and 2) the Great Recession years. Dispersion is low by comparison over both the subperiod before the ICT boom and over the last two sample years (2011–2012). This dynamic of cross-industry dispersion suggests that the middle years were a period when industries (and even firms within the same industry) were investing in and experimenting with the new GPT at different rates. Some industries started earlier or invested more heavily than others. This process led to both the higher growth rate on average and the greater dispersion across industries.

For comparison, Figure 6 shows an analogous range plot of the distribution of ICT investment growth rates across the same set of industries over the sample years. A few salient features emerge. The median rate of ICT investment growth was high during the 1990s, especially the second half, but then retreated in the early 2000s to a much more subdued rate. The dispersion in growth rates across industries is more substantial, especially in terms of industries outside of the middle 50 percent; the upper tail was especially high during the 1990s, while the lower tail was much wider following the dot.com bust and the 2001 recession. This suggests that industries whose production process could most benefit from the new capabilities offered by ICT invested heavily in the new technology in the second half of the 1990s, likely including the complementary restructuring. After having more or less completed a major phase of the technology adoption, they then cut back markedly on the investment.

We next explore whether the speed-up in TFP growth during the middle period and the slowdown afterward were widespread or concentrated among just a few industries. Figures 7 and 8 plot the average TFP growth rate by three-digit 2007 NAICS industries for the three subperiods listed above. Each figure compares two periods, with a 45-degree line facilitating visual comparison. The middle, TFP-boom, subperiod is used as the common reference (depicted on the x-axis). Not surprisingly, the industry producing ICT hardware (334) has the highest TFP growth rate consistently throughout the sample years, and its TFP acceleration during the boom years is essentially the largest among the industries. By comparison, TFP accelerated only slightly in software publishing (511, 519) and computer system design (5415). In and of themselves, however, ICT-producing industries can account for only a small share of the TFP acceleration because of their small weight in aggregate TFP (for example, industry 334 has an average value-added share of only 1.7 percent and a Domar weight of 5 percent over the sample years). It is the industries that use ICT capital more intensively that matter for the aggregate TFP acceleration. The scatterplots also confirm that cross-industry dispersion is somewhat greater for the TFP boom period. Figure 7 visually confirms that TFP grew at a higher rate on average in the TFP boom years—more industries, especially among manufacturing industries (orange circles), are situated below the 45-degree line. By comparison, the slowdown in TFP growth is less salient judging by Figure 8—it appears that as many of the unweighted industry markers are above the 45-degree line as are below it. In particular, a cluster of manufacturing industries exhibit faster TFP growth in the most recent period than in the TFP boom years.

To see the connection between industry-level TFP and aggregate TFP growth, we plot in Figures 9 and 10 the Domar-weighted TFP growth rates by industry group. That is, we compute the sub-aggregate TFP for each industry group by summing up the Domar-weighted TFP growth for industries within that group.[11] Industries that contribute more to aggregate TFP thus are given greater weights in these calculations. The size of each circle is proportional to that industry group's Domar weight. These Domar-weighted plots make it clear that those industry groups accounting for larger shares of aggregate TFP, chiefly other service industries (that is, apart from financial and information services) and manufacturing, indeed grew faster during the middle years. The deceleration in the trade sector's TFP since 2005 relative to the previous two subperiods seems particularly noteworthy. The fact that TFP growth in wholesale and retail trade industries was as rapid before the TFP boom years as during the boom years is consistent with anecdotal evidence in previous studies (see, for example, Foster, Haltiwanger, and Krizan 2006, and Basker 2007) that big-box retailers such as Wal-Mart became more productive by adopting ICT to build an efficient supply chain.[12] It is somewhat curious that even with the tremendous growth of online retailers such as Amazon, this sector's TFP has decelerated noticeably.[13]

Figure 11 helps to visualize more directly the cross-industry distribution of TFP acceleration in the middle period. The acceleration vis-à-vis the later period (that is, the difference in TFP growth between the boom period and the post-boom period) is measured on the x-axis, while the acceleration vis-à-vis the earlier period is shown on the y-axis. So if an industry is situated in the positive section of the 45-degree line, it means the industry experienced a TFP acceleration in the boom years and later reverted to exactly the same average growth rate as in the pre-boom years. This plot shows that, except for a cluster of manufacturing industries, most industries line up pretty well along the 45-degree line, meaning they have fairly similar average TFP growth rates before and after the boom years; the correlation coefficient is 0.60. This is especially true of service industries other than information and financial services (yellow circles), which account for close to half of the total economy. In

[11] Note that we simply use each industry's Domar weight in aggregate TFP and sum the resulting weighted TFP growth within each sector. We do not use each industry's Domar weight defined based on that sector's output.

[12] Because we include the early 2000s in our TFP boom subperiod, we find that the TFP of the retail trade sector (NAICS = 44, 45) did not accelerate during this boom period relative to the earlier period. By comparison, previous studies (for example, Basu et al. 2003) found that the TFP of retail trade accelerated in the second half of the 1990s relative to the first half.

[13] NAICS 454111, included in industry 44,45 in our sample, includes "E-tailers" and "Web retailers."

contrast, a small cluster of industries, especially manufacturing of transportation equipment (336) and machinery (333), exhibit better TFP performance in the most recent subperiod than in the middle period. Overall, the cross-industry pattern suggests that the TFP acceleration in the middle years was temporary for a reasonably large number of industries. Among the rest, more industries show better TFP performance in the post-boom years than in the pre-boom years. This seems a promising note for TFP growth going forward.

ICT Investment Growth across Industries

We next carry out a similar comparison of the growth rates of ICT investment over the three subperiods as a basic check on the plausibility of the ICT-based explanation of the TFP boom. We count as ICT capital computers (along with peripheral equipment), software and communication equipment. As depicted in Figure 12, it is clear that investment in ICT capital decelerated in most industries, especially service industries, in the most recent subperiod relative to the TFP boom years. But arguably the more salient feature is that ICT investment growth in recent years slowed relative to the pre-boom years for almost all the industries. This suggests that at least one phase of the ICT revolution has drawn to a close: industries invested heavily in ICT capital to reach a steady-state (trend) level and their pace of investment eventually slowed as they converged to the steady state.

Corroborating evidence also emerges when we compare average investment growth rates in ICT capital (x-axis) versus non-ICT equipment (y-axis) for the three subperiods, depicted in Figures 13 through 15. The relationship between ICT and non-ICT investment is clearly different between the last subperiod and the previous two. Before 2005, investment grew substantially faster in ICT than in non-ICT capital for the vast majority of industries, and the dispersion across industries in the pace of ICT investment was greather than in non-ICT investment. There is at most a weak relationship between the two kinds of investment at the industry level. A markedly different pattern has emerged since 2005. First, ICT investment has slowed sufficiently so that on average its growth is only slightly faster than the growth of non-

ICT investment. Second, ICT and non-ICT investment are highly correlated across industries—if an industry invested more heavily in ICT capital, it also did so in non-ICT equipment. This is consistent with the hypothesis that industries have more or less reached their steady-state ICT capital level since the second half of the 2000s.

There is, however, an alternative interpretation that is potentially more plausible for the last subperiod because of the outsized aggregate nontechnology shocks brought about by the financial crisis and the ensuing deep recession. These common shocks may have been large enough to induce common movements in investment across all industries. In principle, firms invest until at the margin the benefit (equal to the marginal product of capital, MP_K) equals the cost (equal to the user cost of capital):

$$MP_K = (r + \delta)P_I - \dot{P}_I \,, \tag{3}$$

where r is the effective interest rate for funding a project (which typically equals a weighted average rate for debt and equity), r is the capital depreciation rate, P_I is the (relative) price of investment goods, and $\dot{P}_I$ is the change (that is, the time derivative) of P_I.[14] The marginal benefit, MP_K, depends, among other things, on expected demand, while the marginal cost depends on the cost of financing (r). The financial crisis likely constituted a significant adverse common shock to the marginal cost (through a much higher effective r, possibly because of credit constraints), while the deep recession produced a massive negative shock to the marginal benefit. To the extent that these aggregate shocks are sufficiently large, they can induce greater correlation in growth across types of capital and across industries.

To explore this possibility, we further divide the last subperiod into three segments: 1) pre-crisis, from 2005 to 2007, 2) crisis and recession, from 2008 to 2010, and 3) post-recession, from 2011 to 2012. We use simple OLS regressions to summarize the correlation and relative average growth rates between these two types of investment over the three subperiods and compare them with the pattern over the entire period from 2005 to 2012. The coefficient estimates for the three subperiods are reported in the first three columns of Table 3, and, for

[14] More generally, it should be Tobin's q in place of P_I, which coincides with q if there is no capital adjustment cost.

comparison, the coefficients for the period as a whole are reported in the last column. One common feature that emerges from comparisons using these shorter subsamples is that ICT investment and non-ICT investment are highly correlated across industries before, during, and after the crisis and during the recession. The average growth rate is obviously much lower during the downturn, as would be expected. The relative average growth also varies over these years: the rate for ICT investment exceeded that for non-ICT investment in 2005 through 2010, but the relationship was reversed after the downturn. The reason for this is likely that non-ICT investment plummeted more during the recession and thus required some catch-up afterward. In sum, it is unlikely that the high correlation between ICT and non-ICT equipment investment since 2005 was driven by the aggregate shocks experienced during the financial crisis and the Great Recession.

There is yet another plausible explanation for both the more similar growth rates and the much greater cross-industry correlation between ICT and non-ICT equipment investment since 2005: it is at least partially because some non-ICT equipment contains an ever increasing amount of ICT components. In other words, the line between ICT and some non-ICT capital is now rather blurred. This hypothesis warrants further analysis in future studies.

TFP's Relationship with ICT Investment: Cross-Industry Patterns

Last, we conduct regression analysis to estimate how significant a relationship exists between TFP and intangible investment associated with ICT. Arguably, the primary difficulty with a quantitative assessment of the effect of ICT-related intangible capital on TFP is that the relevant theory provides little guidance on either the length of the lag between TFP improvement and the earlier ICT-related intangible investment, or what firm or industry characteristics might affect this lag. An additional difficulty with industry data is that they represent the (weighted) average of activities of firms within an industry. Therefore, a lead-lag relationship such as that hypothesized for ICT investment and TFP growth can be obscured at the industry level if firms in an industry stagger the timing of when they carry out the activity concerned. If some fraction of the firms in an industry are always carrying out ICT investment at a given point in time, and the investment starts boosting TFP approximately the same amount of time afterward, then it becomes much harder to detect a relationship in which ICT investment leads an improvement in TFP. Such staggering of investment in ICT equipment along with restructuring is quite likely, as suggested by studies using firm-level data, such as Brynjolfsson and Hitt (2003).

This may explain why the strongest evidence of TFP acceleration following lagged ICT investment is found for the early 2000s versus the second half of the 1990s. As shown in Figure 16, investment in ICT capital evidently accelerated over the years from 1995 to 2000. This coincided with a period of the most pronounced decline in the price of ICT capital, especially computers and peripheral equipment. The pace of ICT investment then decelerated precipitously around the 2001 recession, after which it settled at a much more subdued rate compared with the period prior to the recession. In fact, nominal spending on ICT capital decelerated, meaning the slowdown in real investment exceeded the slowdown in the relative price decline. This suggests that the relative demand for ICT capital is elastic. The timing of these developments suggests that, over the second half of the 1990s, there was likely more concerted investment across firms in ICT equipment and software, along with spending on training and process reengineering that enhanced the efficacy of newly installed ICT capital. The recession that followed probably gave firms an incentive to deploy the productivity-enhancing techniques they had built up, thus making the TFP improvement manifest in a more synchronized manner than it would otherwise have been.[15]

We indeed find that the acceleration in TFP in the early 2000s (specifically 2000 to 2004) over the period from 1995 to 1999 is positively correlated with the intensity and pace of ICT investment during the earlier period. Specifically, we estimate the following equation:

$$g_{TFP,00-04} - g_{TFP,95-99} = \alpha_0 + (\alpha_1 + \beta_1 g_{ITinv,95-99}) D_{ITprod} + (\alpha_2 + \beta_2 g_{ITinv,95-99}) D_{ITuse} + \varepsilon, \quad (4)$$

[15] The findings in Oliner et al. (2007) can be interpreted in this light. They find that labor productivity accelerated the most after 2000 (until 2004) in industries that had the lowest gross profit share during the late 1990s. These industries' low profitability reflects at least in part their heavier spending on labor, which may well have been devoted to restructuring activities.

where $g_{ITinv,95-99}$ denotes the average growth rate of ICT investment over 1995 to 1999, in some cases weighted, as discussed below. D_{ITprod} denotes the dummy variable for ICT-producing industries (2007 NAICS codes 334, 511, and 5411), while D_{ITuse} denotes industries that are typically classified as intensive users of ICT capital.[16]

Within the nonfarm private sector, this correlation is significant for the ICT-producing industries, as can be seen from the coefficient (β_1) on the interaction term between the dummy variable for these industries and the growth of ICT investment in 1995 to 1999, reported in Table 4.[17] But more importantly, it is significant for intensive ICT users, as evidenced by the coefficient (β_2) on its interaction term with the earlier ICT investment (also see Table 4).[18] And the pattern of the coefficients also indicates that the intensity of the earlier ICT investment matters: the interacted coefficients are significant when ICT investment growth is weighted by either its share in equipment and software investment or in all types of investment.

Note that here ICT investment is used as a proxy for the related restructuring. It is logical to expect firms to conduct more such intangible investment the more important ICT is in their overall investment activity. In fact, the nominal value share may well understate the relative importance of real ICT investment, since its price was falling rapidly over that period. The logic of weighting ICT investment is analogous to the finding in Basu et al. (2003) regarding the contribution of ICT-related intangible capital to TFP: it is likely greater the more intensively an industry uses ICT capital. Between ICT capital over the same period (2000 to 2004 in this case) and ICT investment earlier, it is plausible that the intensity of ICT investment in the earlier period is a better proxy for the amount of reorganization carried out if the intangible capital so formed depreciates much more slowly than the tangible ICT capital. Little is known, however, about the depreciation process of such organizational capital.

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[16] See, for example, Fernald (2014) Appendix Figure 1 for a list. These are primarily business and scientific service industries and equipment and machinery manufacturing.

[17] Note that TFP in fact decelerated substantially after 2000 for these industries on average, evidenced by the large negative intercept for the sector. We already observed this visually in Figures 7 and 8 above.

[18] Note that we omit the outlier industry 518,9 (data processing and other information services). Otherwise, the coefficients on the interaction term with the dummy variable denoting ICT-using industries would be much larger and more significant.

Other specifications that we have experimented with that are similar to those examined in Basu et al. (2003) do not yield coefficient estimates that consistently support the ICT-as-GPT theory. For example, regressing TFP acceleration in the TFP boom years over the first subperiod on ICT investment growth in the first subperiod produces coefficients with the right sign but that are statistically insignificant. These results make it clear that quantitative evidence for ICT as the culprit for the TFP deceleration in recent years is far from overwhelming. This assessment is partly an inference from reversing a process that had previously been shown to boost TFP a decade ago, especially at the firm level (see, for example, Brynjolfsson and Hitt 2003).

Part of the slowdown in TFP growth in the most recent years may be the unfortunate consequence of firms curtailing all investment, perhaps especially intangible investment, drastically during the recession. As uncertainty continues to subside and financial conditions continue to normalize, investment, especially intangible investment broadly defined, will likely recover further. This should help the performance of TFP going forward.

Concluding Remarks

This policy brief uses industry data to analyze the dynamics of technological progress since the late 1980s in order to help inform the outlook for the trend growth of potential output. We find evidence that suggests that the TFP acceleration in the late 1990s and early 2000s is not a permanent increase in trend growth, but just an upward level shift in the path of TFP, realized over a number of years.

This level increase was quite likely induced by new information and communication technology and augmented by rapid declines in the relative price of ICT equipment and software in the 1990s, especially the second half of the 1990s. While investing heavily in tangible ICT capital, firms likely also engaged in activities such as reorganizing operational processes that enabled them to take greater advantage of the new capabilities afforded by ICT. Contributions from the unmeasured intangible organizational capital provided a temporary boost to measured TFP growth after the ICT investment subsided. Indeed, for those industries that either produce ICT capital or are classified as intensive users of ICT capital, their TFP acceleration in the early 2000s relative to the late 1990s is positively correlated with the intensity of ICT investment in the earlier period.

Now that this phase of the ICT revolution has largely come to an end, trend productivity growth has likely reverted to the long-run, lower, rate. Still, a tremendous amount of uncertainty remains surrounding any such assessment. TFP has continually eluded researchers' attempts to forecast it successfully. Factors that would be deemed relevant by intuition, such as R&D, have not consistently predicted TFP growth. Nevertheless, one could imagine that "the next big thing" of innovation might come along over the next few years and bring about another TFP resurgence. It might be mobile technology and further reorganization of production, especially in terms of the delivery of services. People also talk about 3-D printing, bio-tech, etc. To the extent that it is another GPT, however, it would be reasonable to expect TFP not to rise much initially because some productive resources would be diverted to making intangible investments in the new technology.

Instead, the more likely near-term boost to aggregate TFP will probably come from better allocation of resources through greater worker turnover and improved availability of capital to small and young firms that may have been constrained in their ability to invest, especially in intangible capital (such as R&D). The magnitude of the boost from better allocation, however, may be limited, especially since the recovery has already been underway for five years. On the other hand, there may be independent boosts to capital deepening, and in turn to labor productivity, if the general perception of uncertainty recedes further and expectations of the economy's prospects continue to improve.

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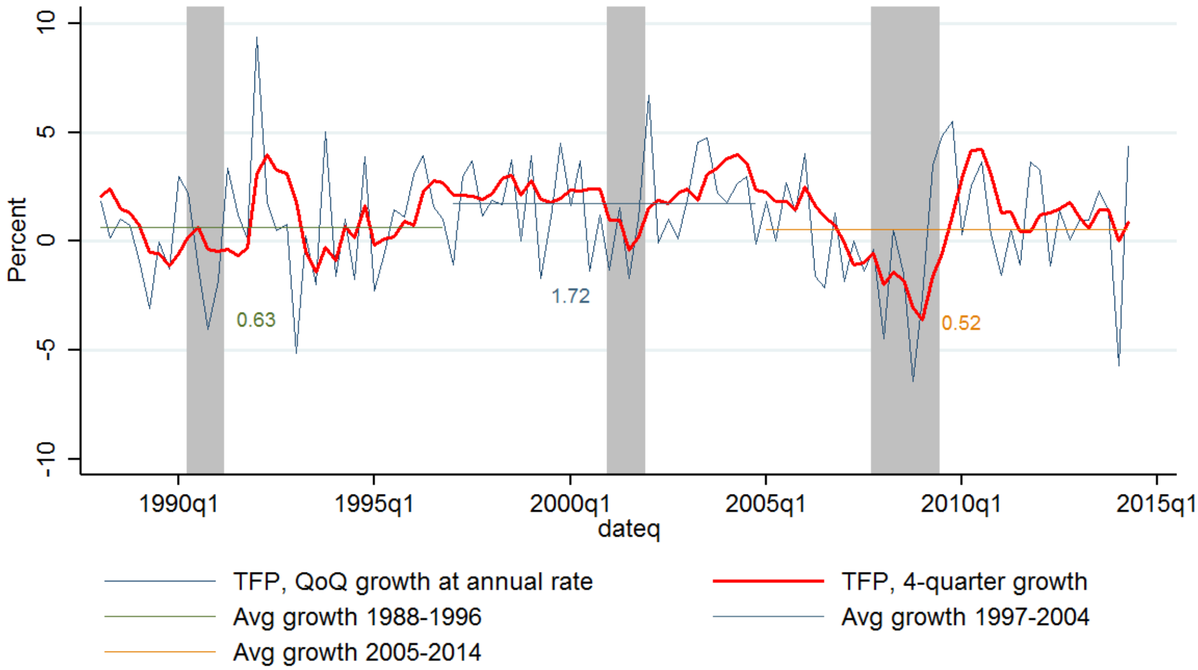
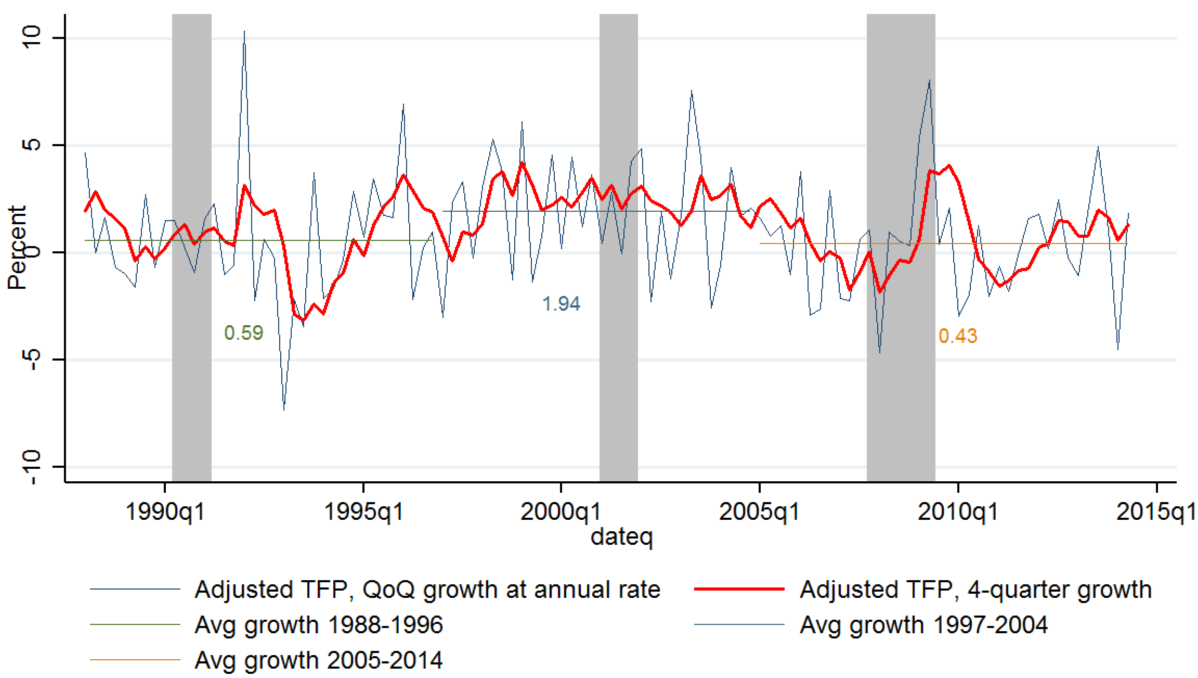
Figure 1. Quarterly TFP for the private business sector, 1988:Q1 to 2014:Q2



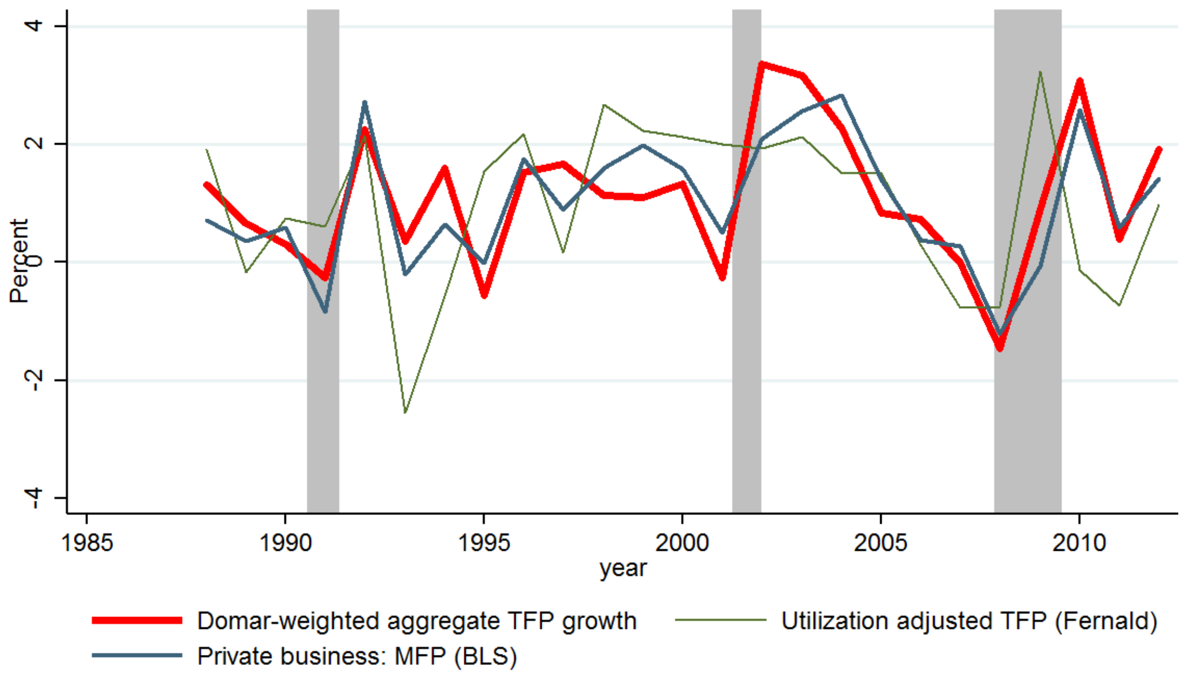
Source: Authors' calculations based on Federal Reserve Bank of San Francisco (FRBSF) data.

Figure 2. Quarterly utilization-adjusted TFP for the private business sector, 1988:Q1 to 2014:Q2



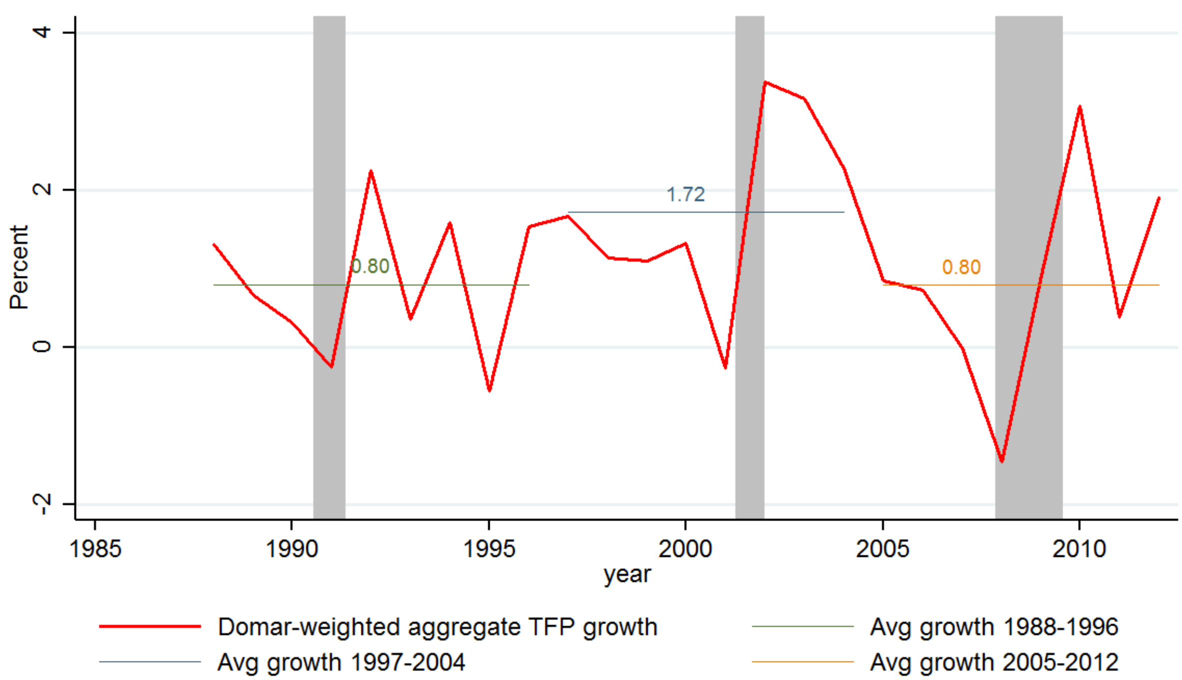
Source: Authors' calculations based on FRBSF data.

Figure 3. Annual TFP growth for the private business sector: Comparison of aggregate (TFP) constructed using industry data and aggregate (MFP) published by the BLS



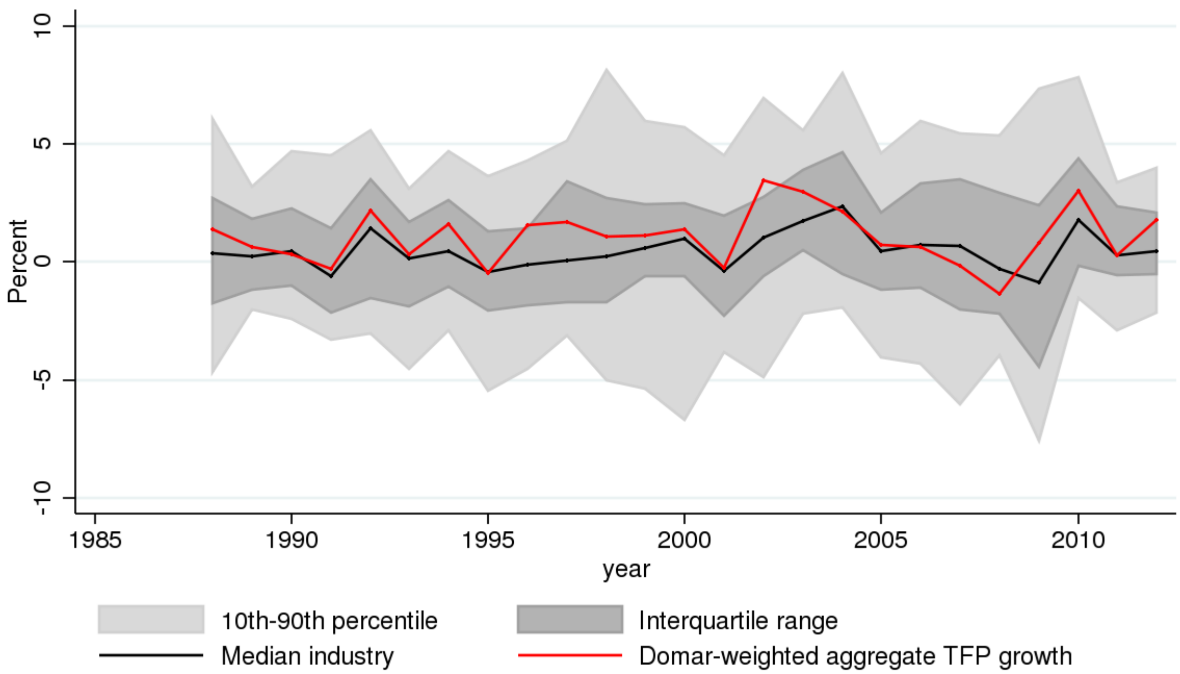
Source: Authors' calculations based on Bureau of Labor Statistics (BLS)and FRBSF data.

Figure 4. Average TFP growth for the private business sector, 1988–2012: aggregate (TFP) constructed using industry data



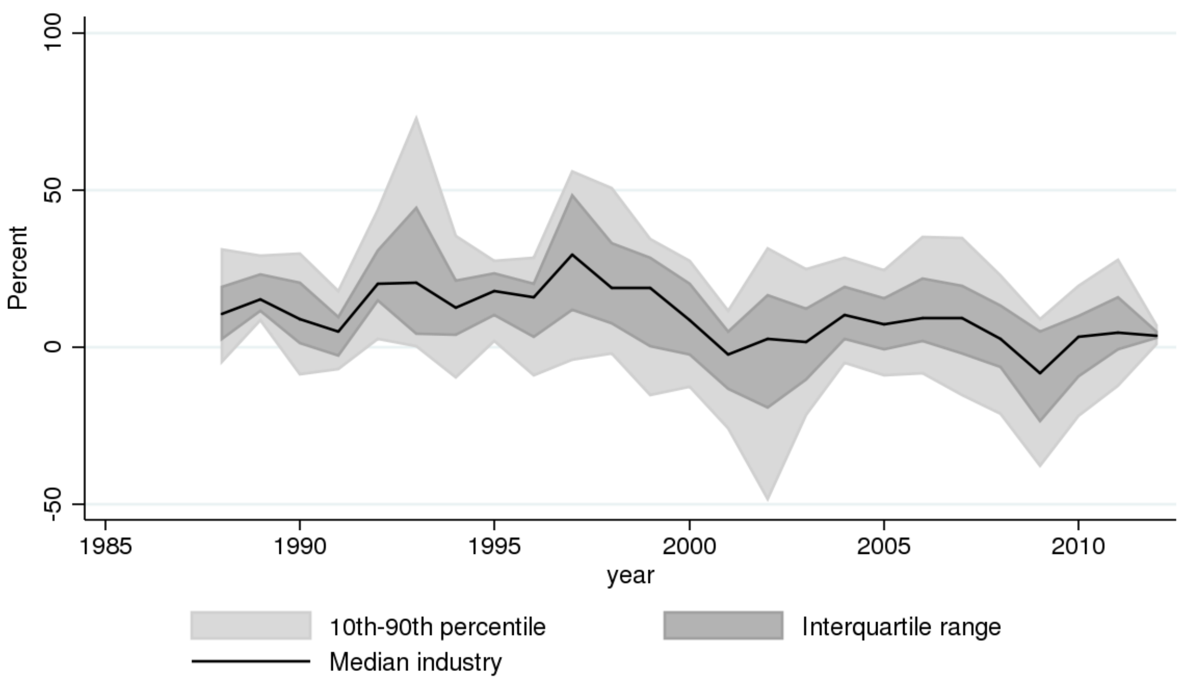
Source: Authors' calculations based on BLS data.

Figure 5. Cross-industry distribution of TFP growth rates



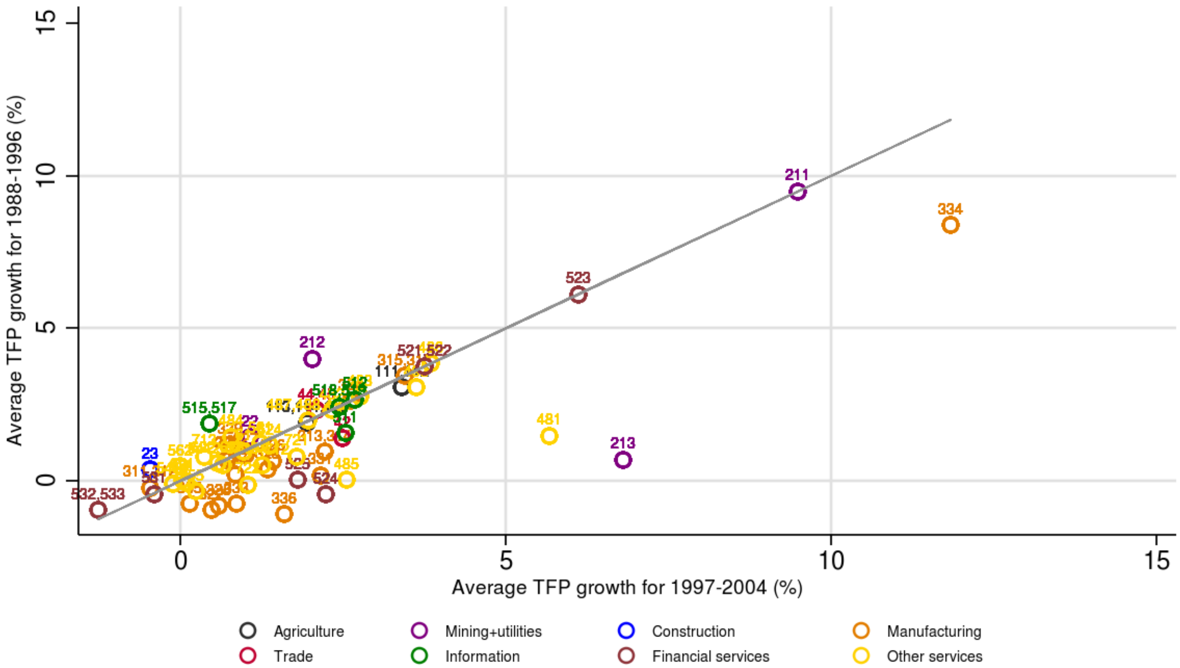
Source: Authors' calculations based on BLS data.

Figure 6. Cross-industry distribution of ICT investment growth rates



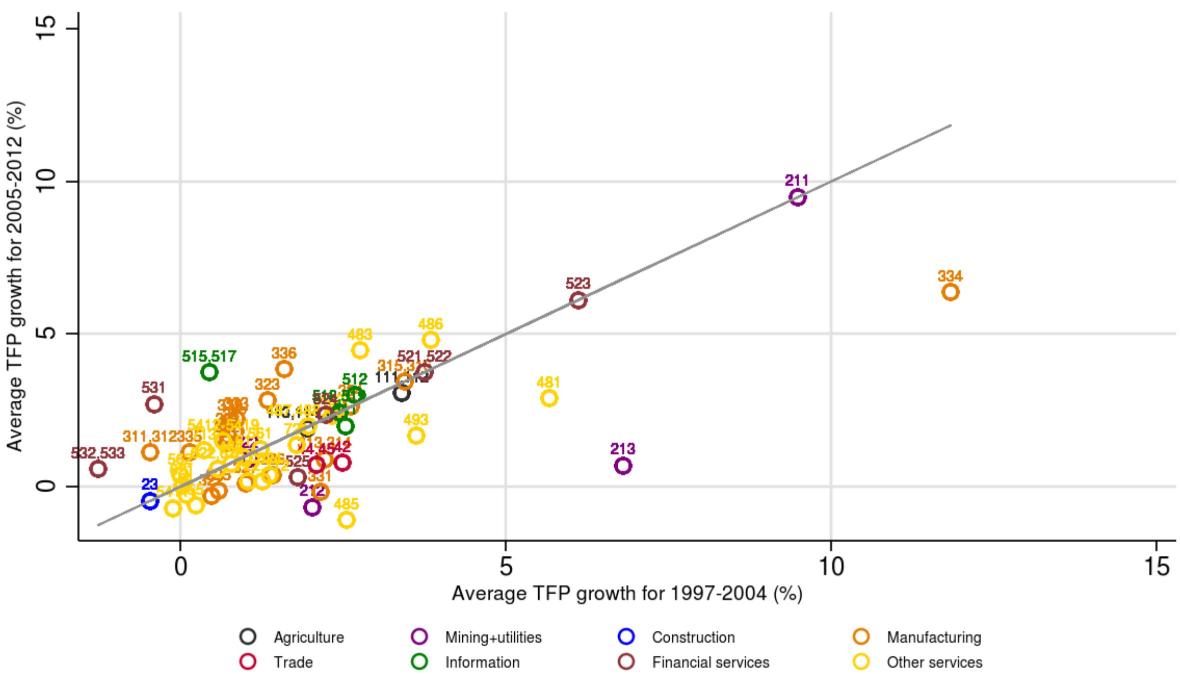
Source: Authors' calculations based on BLS data.

Figure 7. Average TFP growth by 3-digit NAICS industries: 1997–2004 versus 1988–1996



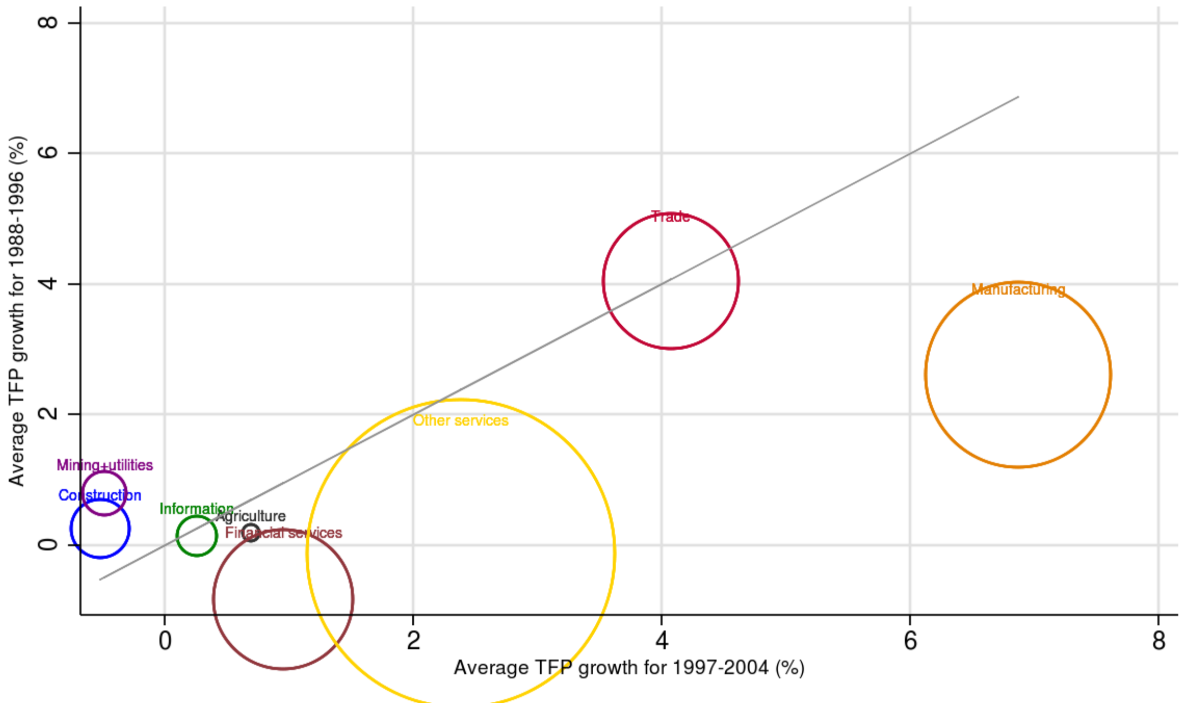
Source: Authors' calculations based on BLS data.

Figure 8. Average TFP growth by 3-digit NAICS industries:1997–2004 versus 2005–2012



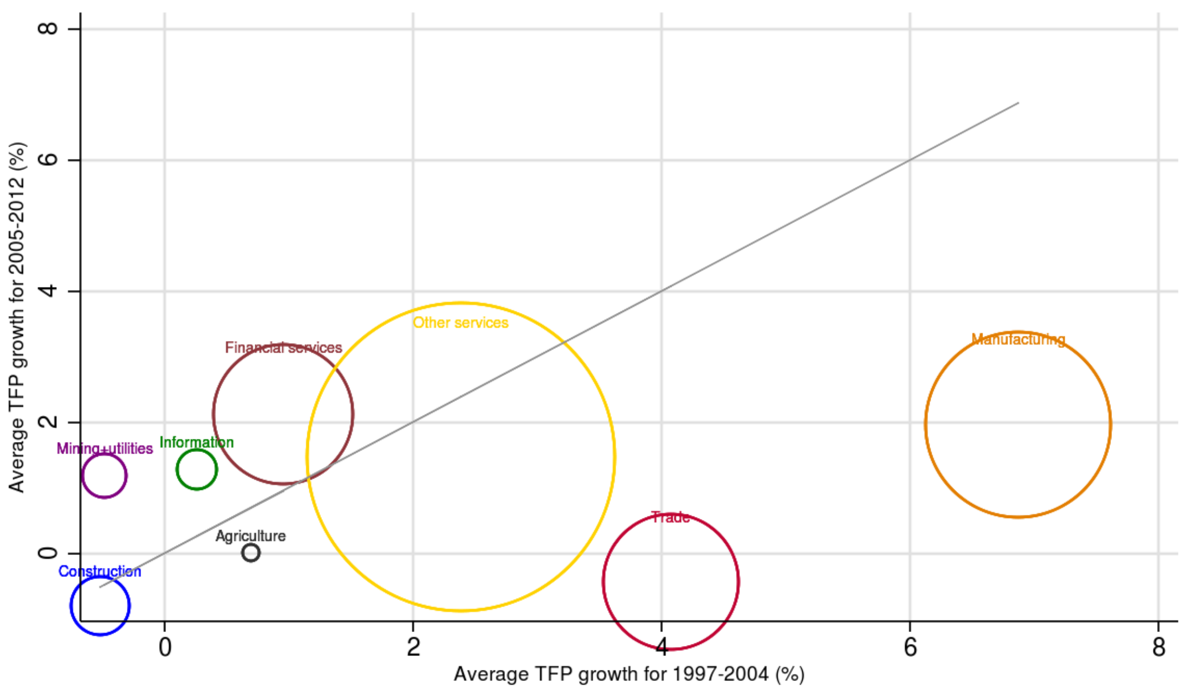
Source: Authors' calculations based on BLS data.

Figure 9. Domar-weighted TFP growth by industry group: 1997–2004 versus 1988–1996



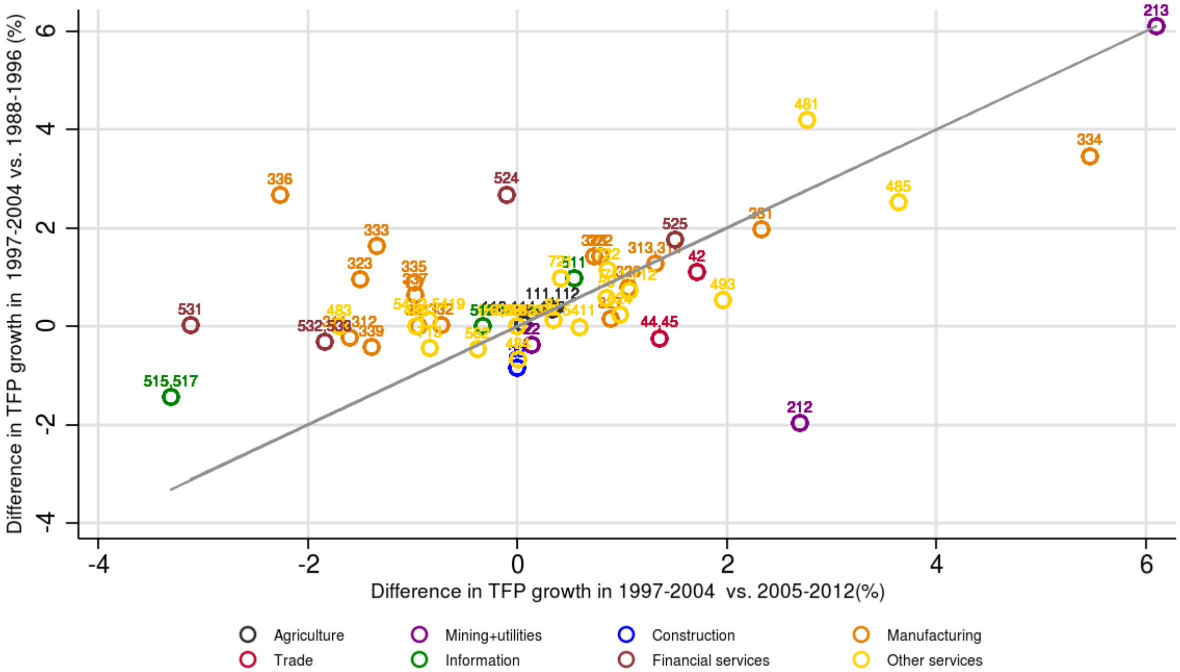
Source: Authors' calculations based on BLS dat.a
Notes: The size of each circle is proportional to that industry group's Domar weights in aggregate TFP.

Figure 10. Domar-weighted TFP growth by industry group: 1997–2004 versus 2005–2012



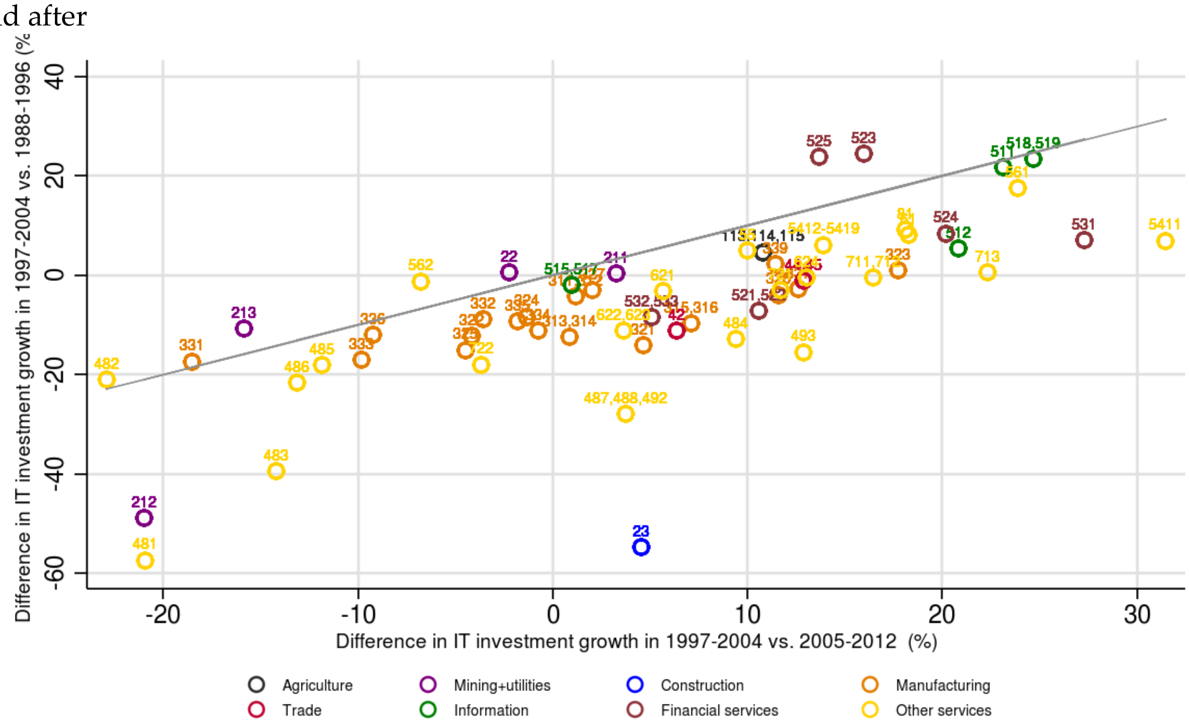
Source: Authors' calculations based on BLS data.
Notes: The size of each circle is proportional to that industry group's Domar weights in aggregate TFP.

Figure 11. TFP acceleration by industry in 1997–2004 relative to the periods before and after



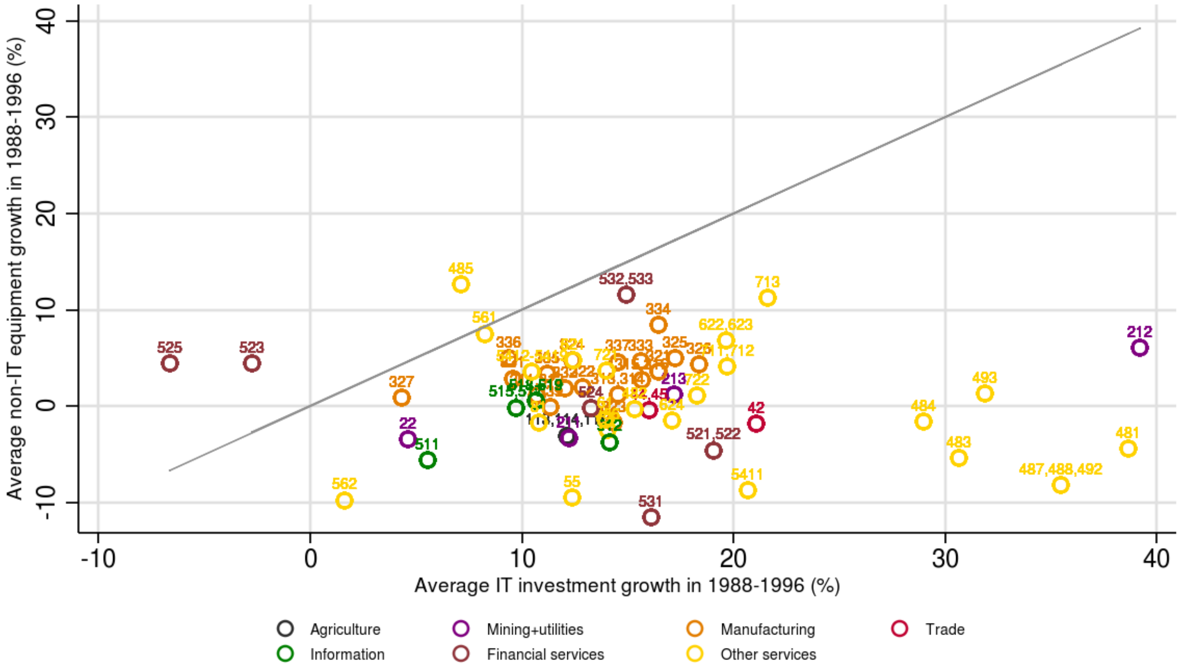
Source: Authors' calculations based on BLS data.

Figure 12. ICT investment acceleration by industry in 1997–2004 relative to the periods before and after



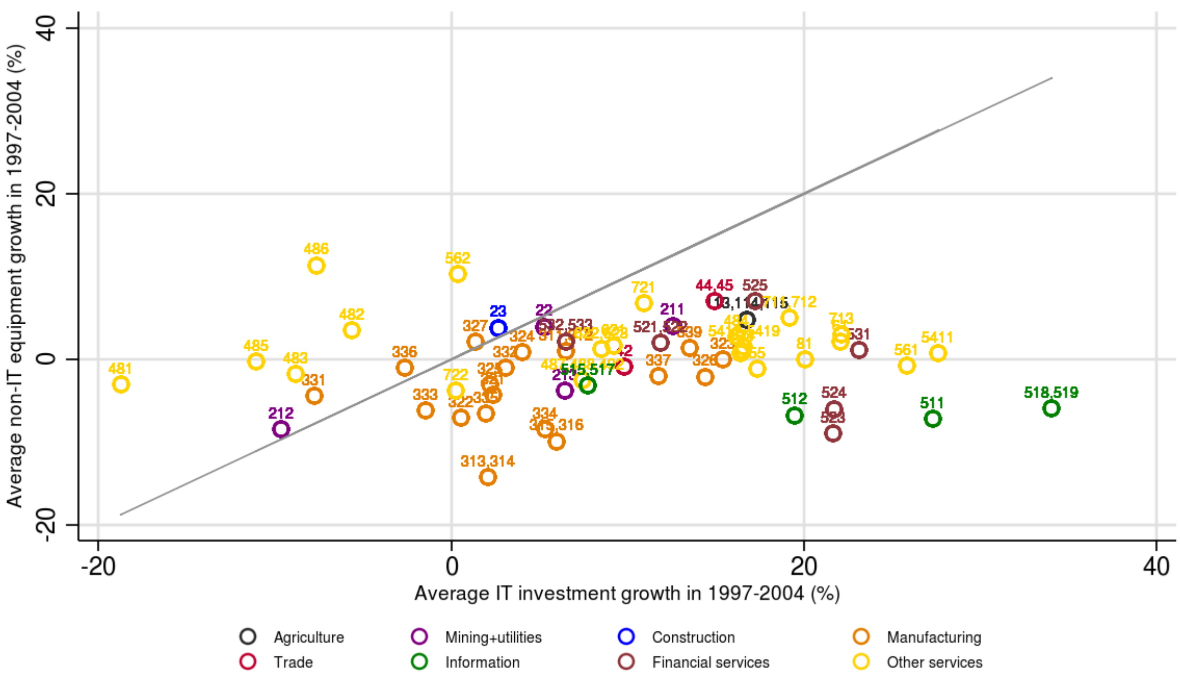
Source: Authors' calculations based on BLS data.

Figure 13. Investment growth in ICT capital versus non-ICT equipment: 1988–1996



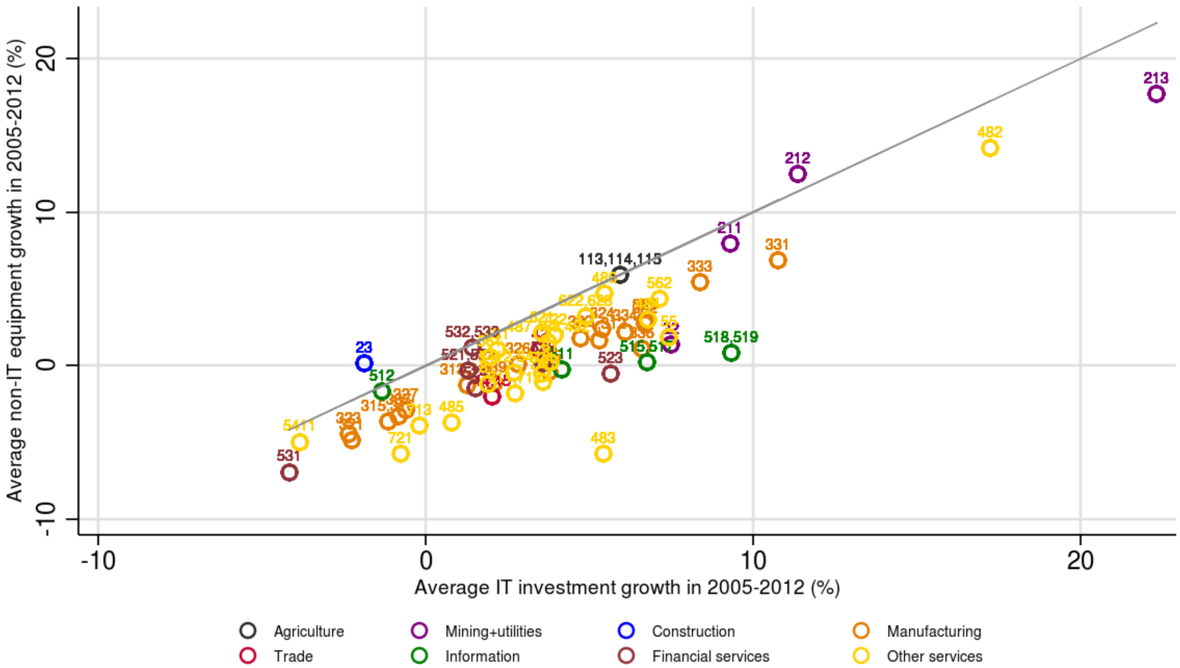
Source: Authors' calculations based on BLS data.
Notes: Construction (NAICS=23) is an outlier in ICT investment growth (57.5%) because of extremely small initial ICT capital stock and is omitted to achieve the same scale as the figure below for the next period.

Figure 14. Investment growth in ICT capital versus non-ICT equipment: 1997–2004



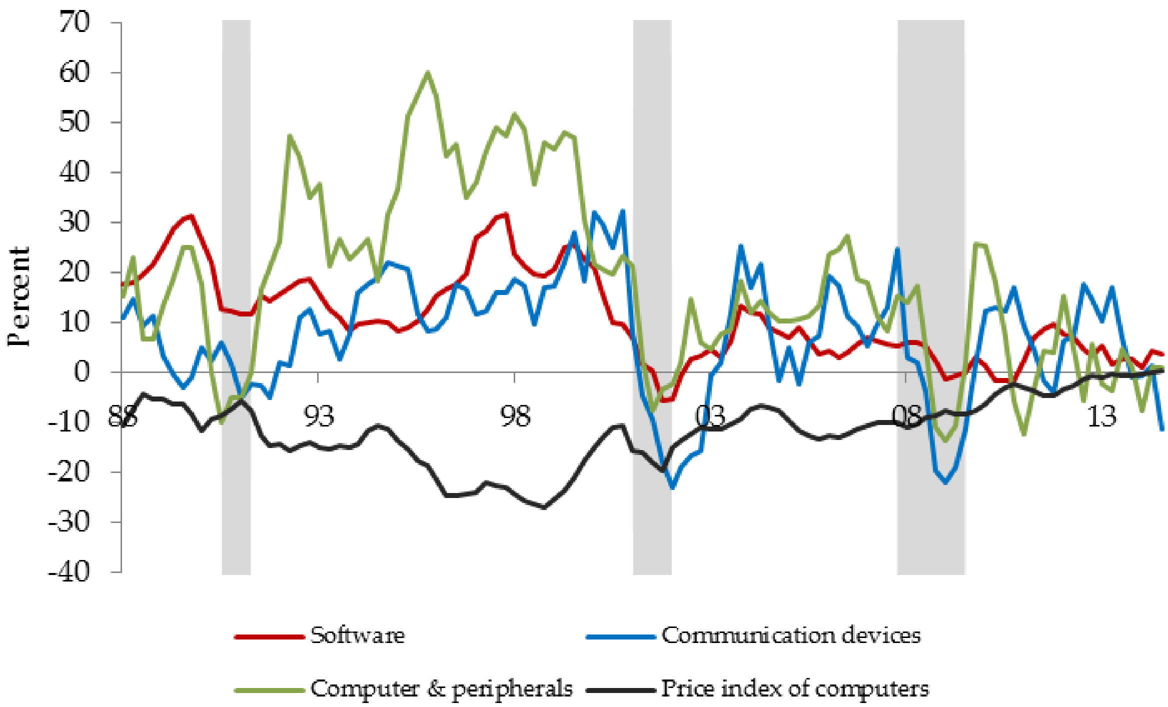
Source: Authors' calculations based on BLS data.

Figure 15. Investment growth in ICT capital versus non-ICT equipment: 2005–2012



Source: Authors' calculations based on BLS data.

Figure 16. Real investment and price index of ICT equipment and software
(Four-quarter growth rate)



Source: Bureau of Economic Analysis.

Table 1. Trend breaks in utilization-adjusted TFP: Bai-Perron supF break test statistics

The supF test statistic for 0 versus 4 breaks:	45.762				
Break dates within sample period 1987–2008:	1994:Q1				
The supF test statistic for 0 versus 5 breaks:	38.913				
Break dates within sample period 1987–2008:	1994:Q1	2004:Q1			
Critical values at the 1% level are (for k=1 to 5):	15.37	12.15	10.27	8.65	7

Notes: These tests are conducted using the Matlab programs, the main file of which is brcode.m, downloaded from Pierre Perron's website: http://people.bu.edu/perron/code.html.

Table 2. Average TFP growth rates for the private business sector (in percent)

Panel A. All years of data

	Industry total TFP	BLS MFP	Utilization-adjusted TFP
1988–1996	0.799	0.635	0.648
1997–2004	1.721	1.755	1.845
2005–2012	0.795	0.670	0.449
2005Q1–2014Q2	--	--	0.428

Panel B. Excluding recession years

	Industry total TFP	BLS MFP	Utilization-adjusted TFP
1988–1996	0.931	0.820	0.653
1997–2004	2.004	1.933	1.821
2005–2012	1.152	1.108	0.185
2005Q1–2014Q2	--	--	0.146

Notes: The first two columns of data are aggregates constructed using industry data, while the last two columns are aggregates reported directly by the Bureau of Labor Statistics.

Table 3. Relationship between ICT and non-ICT investment over 2005 to 2012: before, during, and after the financial crisis and Great Recession

	Average Non-ICT equipment growth, 2005–2007	**Average Non-ICT equipment growth, 2008–2010**	**Average Non-ICT equipment growth, 2010–2012**	**Average Non-ICT equipment growth, 2005–2012**
Average ICT investment growth 2005–2007	0.894***			
	(0.0518)			
Average ICT investment growth 2008–2010		0.844***		
		(0.0479)		
Average ICT investment growth 2010–2012			1.000***	
			(0.0716)	
Average ICT investment growth 2005–2012				0.875***
				(0.0590)
Constant	-4.160***	-5.326***	2.486***	-2.673***
	(0.697)	(0.434)	(0.794)	(0.362)
Observations	58	58	58	58
R-squared	0.842	0.847	0.777	0.797

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 4. Relationship between TFP acceleration in 2000–2004 over 1995–1999 and ICT investment in 1995–1999 (excluding outliers)

	ICT inv. growth, weighted by share in equipment+software investment	ICT inv. growth, weighted by share in all investment	ICT investment growth, unweighted
Investment growth (1995–1999 Average)	-0.0925	0.217	-0.0403
	(0.0692)	(0.340)	(0.0402)
Investment growth * ICT-using industries	0.207*	1.045**	0.117
	(0.118)	(0.459)	(0.0738)
Investment growth * ICT-producing industries	0.304**	3.519***	0.405**
	(0.120)	(0.615)	(0.185)
Dummy variable of ICT-using industries	-0.867	-0.453	-1.462
	(1.125)	(0.788)	(1.603)
Dummy variable of ICT-producing industries	-7.323***	-7.320***	-13.95***
	(1.938)	(1.270)	(4.819)
Constant	1.208**	0.636*	1.469
	(0.539)	(0.357)	(0.960)
Observations	58	58	58
R-squared	0.169	0.249	0.156
Adj. R-squared	0.0893	0.177	0.0750

Notes:

1. The dependent variable in all the regressions is the change in the TFP growth rate in 2000–2004 relative to 1995–1999.
2. The main regressor is either the simple average growth rate of ICT investment in the earlier period, or this ICT growth rate weighted by a measure of the intensity of an industry's ICT investment— either relative to equipment and software investment or relative to all types of investment, as specified in the column heading.
3. We omit the outlier industry 518,9 (data processing and other information services). Otherwise the coefficients on the interaction term with the dummy variable denoting ICT-using industries would be much more significant.
4. Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.