Return of the Solow Paradox? IT, Productivity, and Employment in US Manufacturing[†]

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An increasingly popular "technological-discontinuity" paradigm, powerfully articulated in Brynjolfsson and McAfee (2011), argues that US workplaces have been, and will continue to be, automated and transformed by information technology (IT) capital. Two implications of this transformation are emphasized. First, all sectors—but particularly IT-intensive sectors—are experiencing major increases in productivity. Thus, Solow's paradox is long since resolved: computers are now everywhere in our productivity statistics.[1] Second, IT-powered machines will increasingly replace workers, ultimately

1 Robert Solow's comment on computers appears in his 1987 *New York Times Book Review* article: "… what everyone feels to have been a technological revolution, a drastic change in our productive lives, has been accompanied everywhere, including Japan, by a slowing-down of productivity growth, not by a step up. You can see the computer age everywhere but in the productivity statistics."

leading to a substantially smaller role for labor in the workplace of the future.

Adding urgency to this argument, labor's share of national income has fallen in numerous developed and developing countries over roughly the last three decades, a phenomenon that Karabarbounis and Neiman (2014) attribute to IT-enabled declines in the relative prices of investment goods. And many scholars have pointed to the seeming "decoupling" between robust US productivity growth and sclerotic or negligible growth rates of median US worker compensation (Fleck, Glaser, and Sprague 2011) as evidence that the "race against the machine" has already been run—and that workers have lost.

This paper provides a simple evaluation of this viewpoint using detailed data from the US manufacturing sector. We find, unexpectedly, that earlier "resolutions" of the Solow paradox may have neglected certain paradoxical features of IT-associated productivity increases, at least in US manufacturing. First, focusing on IT-*using* (rather than IT-producing) industries, the evidence for faster productivity growth in more IT-intensive industries is somewhat mixed and depends on the measure of IT intensity used. There is also little evidence of faster productivity growth in IT-intensive industries after the late 1990s. Second and more importantly, to the extent that there is more rapid growth of labor productivity ($\ln(Y/L)$) in IT-intensive industries, this is associated with declining *output* ($\ln Y$) and even more rapidly declining employment ($\ln L$). If IT is indeed increasing productivity and reducing costs, at the very least it should also increase output in IT-intensive industries. As this does not appear to be the case, the current resolution of the Solow paradox does not appear to be what
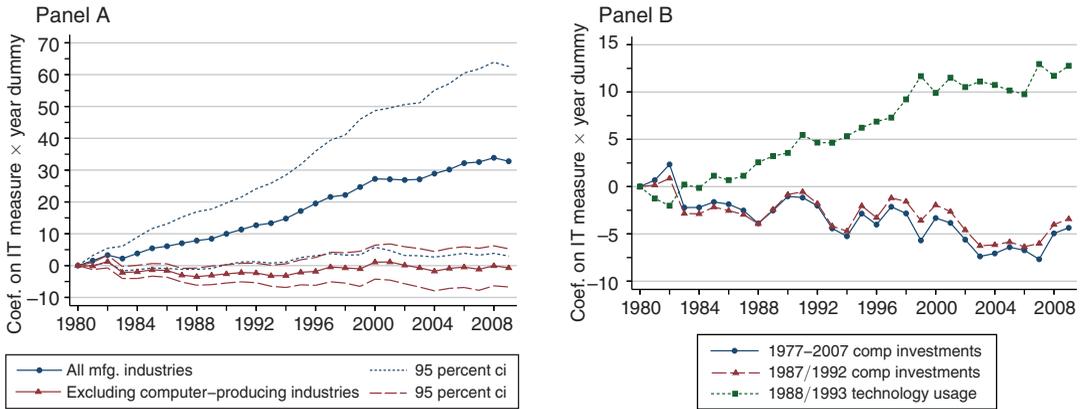
FIGURE 1. IT INTENSITY AND LOG REAL SHIPMENTS PER WORKER, 1980–2009

Notes: Panel A: $n = 387$ manufacturing industries ($n = 359$ when excluding computer-producing industries). IT intensity is defined as the ratio of computer investments to total investments, averaged over 1977–2007. Panel B: $n = 120$ non-computer-producing industries comprising SIC 34-38. The two computer investment series in panel B define IT intensity as in panel A, using data from the indicated years. The technology usage series defines IT intensity as the employment-weighted share of 17 advanced technologies used by plants within the industry. IT measures are normalized to have zero mean and unit standard deviation. Regressions are employment weighted and include industry and year fixed effects. Confidence intervals are based on standard errors clustered by industry.

adherents of the technological-discontinuity view had in mind.

I. Information Technology and Labor Productivity

We employ the NBER-CES Manufacturing Industry Database, sourced from the Annual Survey of Manufacturers (Becker, Gray, and Marvakov 2013), to estimate and plot a set of simple, descriptive regressions that chart the relationship between IT investment and industry-level outcomes for the time period 1980–2009. Our regression model takes the form

$$(1) \quad \log Y_{jt} = \gamma_j + \delta_t + \sum_{t=81}^{09} \beta_t \times IT_j + e_{jt},$$

where Y is an outcome variable (expressed in log points), γ is a vector of industry fixed effects, δ is a vector of time dummies, IT is a static measure of industry IT-intensity, and e is an error term. This specification normalizes the coefficient on the IT variable to zero in the base year, and hence the series $\{\beta_{81}, \beta_{82}, \ldots, \beta_{09}\}$ may be read as the level of the coefficient on IT in each subsequent year relative to 1980. Following

Berman, Bound, and Griliches (1994) and Autor, Katz, and Krueger (1998), we measure IT intensity as the ratio of industry computer (IT) expenditures to total capital expenditures.[2]

Figure 1, panel A, which plots the over-time relationship between IT-intensity and the log of real shipments per worker (our preferred productivity measure),[3] shows a dramatic differential rise in output per worker in IT-intensive industries throughout the entire 1980–2009 period. But crucially, this pattern is almost entirely driven by the computer-producing sector (North American Industry Classification

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[2] Specifically, we compute this ratio in 1977, 1982, 1987, 1992, 2002, and 2007 (no 1997 measure is available), take the average across these six data points (placing slightly greater weight on the last two periods to compensate for the absence of the 1997 measure), and standardize the result so that the final measure has zero mean and unit standard deviation across employment-weighted industries.

[3] We choose this productivity construct because it is unaffected by the choice of deflators for intermediate inputs: if the productivity of a dollar of IT investment rises over time due to IT quality improvements, this should raise shipments in IT-using industries. By contrast, the effect of rising IT quality on value-added and TFP in IT-using industries is ambiguous. Nevertheless, results using value added measures are very similar and are not shown to conserve space (see Figure A6 of the online Appendix).

System (NAICS) 334).[4] Across the entire manufacturing sector, industries that had a one standard deviation higher rate of IT investment over the sample period saw differential productivity gains averaging a remarkable 10 log points per decade between 1980 and 2009. Excluding computer-producing industries, however, results in a murkier picture. There is some differential productivity growth in IT-intensive industries in the late 1990s, but this effect is very small (on the order of a few percentage points at its peak) and subsides after 2001. By 2009, there is no net relative productivity gain in IT-intensive industries over the full sample period.

This productivity growth pattern is unexpected in light of the earlier resolution of the Solow Paradox (e.g., Oliner and Sichel 2000). One possible explanation is that our focus on manufacturing is misplaced—perhaps the productivity gains from IT investments are taking place elsewhere. While our data do not allow us to exclude this possibility, earlier evidence from Stiroh (2002) suggests that the IT-driven productivity growth in the 1990s was not specific to non-manufacturing and may in fact have been more pronounced in manufacturing. Moreover, productivity growth in US manufacturing has generally exceeded that outside of manufacturing for many decades, and this productivity growth differential rose sharply during the 1990s (Fleck, Glaser, and Sprague 2011).[5]

A second category of explanation for these unexpected results is that our measure of IT investment, constructed by averaging computer investment data from 1977–2007, misses the mark. Plausibly, an IT investment measure that focused on the most recent years of IT investments—rather than averaging over

three decades—might prove more predictive of recent industry-level productivity growth since such a measure would better reflect the current locus of the IT frontier. We explore this possibility in Figure A1 of the online Appendix by plotting the over-time relationship between labor productivity and IT investment in non-computer-producing industries using three different vintages of IT investment measures, corresponding to averages of 1977 and 1982, 1987 and 1992, and 2002 and 2007 investments, as well as our preferred measure from panel A, which is simply the weighted average of all six years of investment data. This analysis does not lend support to the hypothesis that our primary IT measure is "out of date." Indeed, the strongest predictor of industry relative productivity growth during the 1990s is the 1977/1982 investment measure, whereas the most recent measure (from 2002/2007) is the weakest predictor. Moreover, none of these measures predicts relative productivity growth in IT-intensive industries during the 2000s.

A further concern with our simple IT investment measure is that it may fail to capture recent innovations in IT that are embodied in newer manufacturing technologies, such as computer numerically controlled machinery, pick and place robots, automated guided vehicle systems, material working lasers, etc. To explore this possibility, we exploit data from the Census Bureau's Survey of Manufacturing Technology (SMT) conducted in 1988 and 1993, and previously used by Doms, Dunne, and Troske (1997), which surveyed plants about their use of 17 advanced manufacturing technologies. Specifically, we reestimate equation (1) while replacing the computer investment measure with a SMT-based measure of the employment-weighted mean fraction of the 17 technologies in use across plants in the 120 four-digit industries for which they are available (averaging over 1988 and 1993). We exclude computer-producing industries from this analysis (and all subsequent analyses), since our focus is on *induced* productivity gains in IT-using industries. Figure 1, panel B, which plots these estimates, documents that labor productivity rose relatively rapidly in SMT-intensive manufacturing industries during the 1980s and 1990s. As with the computer investment measure, however, the relationship between SMT technology adoption and industry-level labor productivity plateaus in the late

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[4] Our focus on NAICS 334 follows Houseman, Bartik and Sturgeon (2013), who underscore that the relatively robust growth of productivity and value-added in US manufacturing over the last two decades is substantially driven by IT-producing industries. What Figure 1, panel A contributes to this discussion is the finding that outside of the IT-producing industries, there is little relationship between IT investments and productivity growth.

[5] Table 2 of Stiroh (2002) shows somewhat slower differential productivity growth of IT-intensive industries relative to 1987–1995 when durable goods manufacturing is excluded from the sample (compare columns 4 and 5 in the upper panel), though the pattern is reversed when the comparison is to 1977–1995 in the second panel.

1990s, and shows little further relative gain in labor productivity after 1999.

The SMT survey was only administered to plants in five major high-tech sectors (SICs 34–38)—presumably those sectors where the 17 manufacturing technologies studied were most applicable.[6] To check whether our main results for computer investment carry over to this restricted set of sectors, we reestimate our prior (Figure 1, panel A) model using only these five high-tech sectors (excluding computer-producing industries), applying two vintages of the computer investment measure: our main measure using data from 1977–2007; and a measure that uses only investment data from 1987 and 1992, chosen to parallel the SMT's survey years of 1988 and 1993. These estimates, also plotted in Figure 1, panel B, indicate that the computer investment measure is a weaker predictor of productivity growth in these five high-tech sectors than is the SMT-based measure. However, neither the SMT nor the computer investment measure predicts a differential rise in productivity in IT-intensive industries after the late 1990s.

In sum, our evidence so far suggests very limited IT-driven productivity growth in computer-intensive manufacturing industries, with the contrasting result of more rapid productivity growth in industries using advanced manufacturing technologies more intensively. Different measures of IT intensity thus appear to give different results. Our result based on advanced technologies may suggest that adoption of high-tech, IT-related capital has contributed to rapid productivity growth in manufacturing, but our subsequent results cast doubt on this interpretation.

II. What Drives Rising Y/L: The Numerator or the Denominator?

Since our measure of labor productivity equals the log ratio of gross output to payroll employment, the positive relationship we detect in Figure 1 between industry IT and output per worker during the 1990s implies that industry output is rising proportionately faster than employment in IT-intensive industries. But it does not reveal whether either output is rising faster or employment is falling faster relative to non-IT-intensive industries.

We thus explore these two outcomes (output and employment) separately in the remaining figures. Under the assumption that IT-intensive industries are seeing improvements in technology and automation and reductions in production costs, we would expect them to experience a relative expansion in output. The implications for employment are of course ambiguous—and this could make the labor productivity measure somewhat more difficult to interpret—because these industries may be shedding labor as they automate, but may also increase employment as they expand.

Figure 2, panel A examines the numerator of this ratio, the logarithm of shipments, measured either as real or nominal shipments, using our 1977–2007 measure of computer investments. The relationship between IT-intensity and industry shipments is almost precisely the opposite of expectations: both real and nominal shipments rise at best modestly in IT-intensive industries (relative to non-IT-intensive industries) during the 1980s and then commence a relative decline in the 1990s that accelerates in the 2000s. Thus, relative output growth in IT-intensive industries begins to fall exactly when the IT-productivity payoff is thought to have materialized. While it could be that demand for the output of IT-intensive industries is price inelastic, this would not explain why *real* shipments decline. If, on the other hand, IT-intensive industries have upgraded their quality relative to other industries and this is not fully captured by the industry price deflators, this mismeasurement could explain the decline in real shipments but not the decline in nominal shipments. The two sets of results together defy a simple explanation.

We repeat this exercise in Figure 2, panel B using the embodied IT capital measures from the SMT database. Though we detected above a more robustly positive relationship between use of advanced manufacturing technologies and growth in output per worker, Figure 2, panel B makes clear that this pattern is not driven by rising relative output in SMT-intensive industries. Instead, real (and nominal) shipments in industries that heavily adopted these technologies also exhibit a sharp relative decline between 1992 and 1996, with no rebound thereafter.

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[6] These SICs are fabricated metal products, non-electrical machinery, electrical and electronic equipment, transportation equipment, and instruments and related products industries.
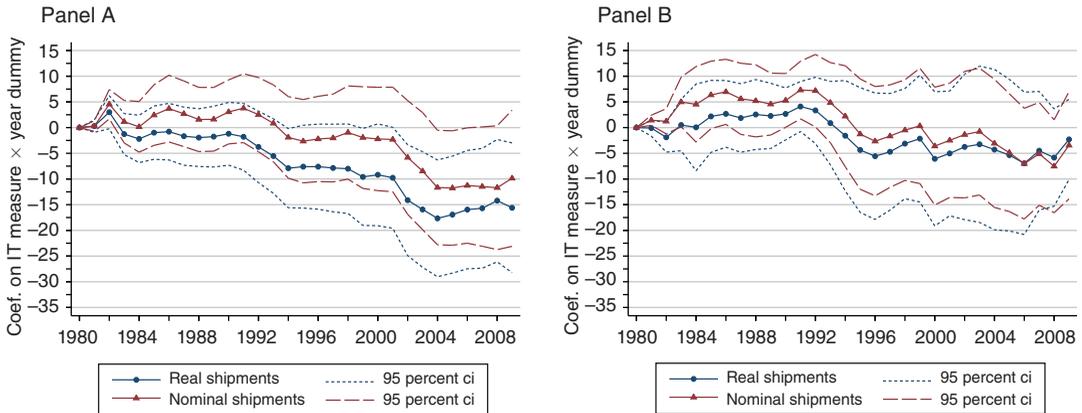
FIGURE 2. IT INTENSITY AND LOG REAL AND NOMINAL SHIPMENTS, 1980–2009

Notes: Panel A: $n = 359$ non-computer-producing manufacturing industries, and IT intensity is based on 1977–2007 computer investments. Panel B: $n = 120$ non-computer-producing industries in SIC 34-38, and IT intensity is based on 1988/1993 technology usage. Real shipments are computed using industry-specific price deflators.
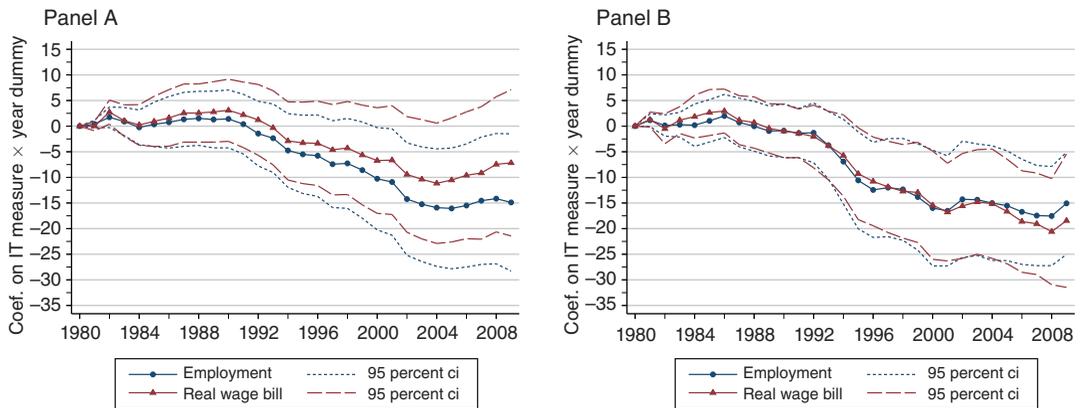

FIGURE 3. IT INTENSITY AND LOG EMPLOYMENT AND REAL WAGE BILL, 1980–2009

Notes: Panel A: $n = 359$ non-computer-producing manufacturing industries, and IT intensity is based on 1977–2007 computer investments. Panel B: $n = 120$ non-computer-producing industries in SIC 34-38, and IT intensity is based on 1988/1993 technology usage.

The combination of rising log output per worker and falling log output in IT-intensive industries implies that log employment must have fallen even more rapidly than output in these industries, a reality confirmed by Figure 3. Whether measured by total employment or by the real wage bill, labor input in technology intensive industries declined sharply from the early 1990s through the early 2000s (in relative terms), and then roughly held steady during the 2000s. Thus, the flattening relationship between IT investments—measured

either as computer investments (panel A) or usage of advanced manufacturing technologies (panel B)—and labor productivity in the 2000s is proximately explained by the cessation of relative employment declines in these industries. Though one can read this evidence as corroborating the "worker-less workplace" narrative of recent technological change, the timing appears wrong: relative employment declines in technology-intensive industries halted or modestly reversed from 2000 forward, which is inconsistent with the premise that IT has

contributed to the slackening of labor demand in the new millennium.

III. Conclusion

This paper documents a pattern of growth among IT-using manufacturing industries that stands in contrast to the powerful and intuitively appealing view that IT is making workers redundant through outsized productivity gains. While we find some evidence of differential productivity growth in IT-intensive manufacturing industries, this depends on the measure of IT intensity and is never visible after the late 1990s. More importantly, when present, it is driven by declining relative output accompanied by even more rapid declines in employment. It is difficult to square these output declines with the notion that computerization and IT embodied in new equipment are driving a productivity revolution, at least in US manufacturing. It may well be that IT-induced technological changes are transforming non-manufacturing, or that they are so widespread as to be taking place rapidly even in non-IT-intensive industries. But at the very least, our evidence suggests that the previously-proposed resolutions of the Solow Paradox need to be critically examined, and that proponents of the technological-discontinuity view need to provide more direct evidence of the IT-induced transformation in the US economy. Prior declarations of the death of the Solow Paradox may have been premature.

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