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Does the United States have a Productivity Slowdown or a Measurement Problem?

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Abstract

After 2004, measured growth in labor productivity and total-factor productivity (TFP) slowed. We find little evidence that the slowdown arises from growing mismeasurement of the gains from innovation in IT-related goods and services. First, mismeasurement of IT hardware is significant prior to the slowdown. Because the domestic production of these products has fallen, the quantitative effect on productivity was larger in the 1995-2004 period than since, despite mismeasurement worsening for some types of IT—so our adjustments make the slowdown in labor productivity worse. The effect on TFP is more muted. Second, many of the tremendous consumer benefits from smartphones, Google searches, and Facebook are, conceptually, non-market: Consumers are more productive in using their nonmarket time to produce services they value. These benefits do not mean that market-sector production functions are shifting out more rapidly than measured, even if consumer welfare is rising. Still, gains in non-market production appear too small to compensate for the loss in overall wellbeing from slower market-sector productivity growth. Third, other measurement issues we can quantify (such as increasing globalization and fracking) are also quantitatively small relative to the slowdown. Finally, we suggest high-priority areas for future research.

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> "The things at which Google and its peers excel, from Internet search to mobile software, are changing how we work, play and communicate, yet have had little discernible macroeconomic impact.…Transformative innovation really is happening on the Internet. It's just not happening elsewhere."

Greg Ip, *Wall Street Journal*, August 12, 2015

U.S. productivity data highlight the paradox at the heart of the quotation above. The fast pace of innovation related to information technology (IT) seems intuitive and obvious. And yet, productivity growth has been modest at best, since the early 2000s. We explore the hypothesis that the U.S. economy has a measurement problem not a productivity slowdown (e.g., Aeppel, 2015, Feldstein, 2015, and Hatzius and Dawsey, 2015). While we find considerable evidence of mismeasurement, we find no evidence that the biases have gotten worse since the early 2000s.

We focus especially on mismeasurement of IT-related hardware and software, where mismeasurement is sizeable; and we propose a new method to account for "free" digital services such as Facebook and Google. More broadly, we identify potential biases to productivity from intangible investment, globalization, and technical innovations in oil and gas production (i.e., fracking). These are all areas where it is plausible that measurement has changed since the early 2000s. But, quantitatively, our adjustments turn out to make the post-2004 slowdown in labor productivity even larger than measured. Because mismeasurement of investment goods also affects inputs of capital, there is, on balance, only a small reduction in the slowdown of business-sector total factor productivity (TFP) growth.

Figure 1 summarizes our quantitative analysis. The dark portions of the bars show the published data on average growth in U.S. business-sector labor productivity, or output per hour. Growth was exceptional from 1995 through 2004 or so, but the pace then slowed by more than 1-3/4 percent per year. (Section 1 and an appendix discuss data, the timing of the bars in the chart, and the similar pattern in measures of TFP). Suppose productivity growth had continued at its

1995-2004 pace of 3-1/4 percent per year. Then, holding hours growth unchanged, business-sector GDP would need to be \$2.5 trillion (21 percent) larger by 2014 in inflation-adjusted 2009 dollars, and \$3 trillion (24 percent) larger by 2015.[1]

We find no evidence that growing mismeasurement related to IT or other factors can fill this gap. Figure 1 shows our adjustments for various biases. We incorporate consistent measurement of quality-adjusted prices for computers and communications equipment; judgmental corrections to prices of specialized information-processing equipment and software; a broad measure of intangible investment; and ballpark adjustments for other issues--Internet services, globalization, and fracking. These adjustments make true output and labor productivity look better since 2004. But, quantitatively, the adjustments matter even more in the 1995-2004 period. On balance, the labor productivity slowdown is modestly larger.

These findings illustrate the point that mismeasurement concerns are not new. For the areas we can quantify, the downward measurement error in output growth was even larger in the past than it is recently.[2] Hence, measurement error does not explain the downshift in productivity growth. For example, we do find somewhat more mismeasurement of prices in computers and communications equipment in the recent period than previously. But domestic production of those products has plunged, so the mismeasurement has less importance for GDP. The relatively stable (or rising) shares of specialized information-processing equipment or software has not been enough to offset the declining importance of IT in the economy. Moreover, the measurement error must be in final production. For example, biases in semiconductor prices appears large (Byrne et al., 2013). But that bias has a very small effect on GDP because faster true growth of real value added in semiconductors is offset by smaller true

[1] In independent work, Syverson (2016) suggests a similar calculation of the missing growth.
[2] Some sources of upward measurement error in growth, such as globalization, have also have become less important. Still, we will usually take “mismeasured” to mean “causing GDP growth to be understated.”

growth of real value added in products using the semiconductors. Semiconductor bias only matters for GDP because of exports and imports.

The effects on aggregate TFP are even smaller than shown in the figure. Adjustments to equipment, software, and intangibles imply faster GDP growth but also faster input growth (since effective capital services are rising more quickly). After adjusting hardware and software, the aggregate TFP slowdown after 2004 is modestly worse. Adding additional intangibles, as in Corrado et al. (2009), works modestly in the other direction, so in our broadest adjustment for investment goods leaves the 1-1/4 percentage point TFP slowdown little changed.

The "other" adjustment shown in Figure 1 includes effects from globalization and fracking, plus a (very) small adjustment for free digital services such as Google and Facebook. Globalization was most intense in the late 1990s and early 2000s. That caused real import growth to be understated—which artificially boosted measured GDP growth by about 1/10th percentage point. Adjusting for that leads the "other" bar to contribute negatively in 1995-2004 in Figure 1. Fracking and free digital services boost productivity growth by a few basis points in the post-2004 period, leading to a boost of about 1/10th percentage point to growth in the figure.

Even the small adjustment for free digital services requires a novel conceptual framework that builds on a proposal from Nakamura and Soloveichik (2015). Estimates by Brynjolfsson and Oh (2014) suggest that the incremental contribution to well-being is sizeable, albeit still small relative to the $3 trillion hole from reduced market GDP but the benefits included in these estimates are quite properly excluded from the output measured by the national accounts. The reason is that they fall outside the of the market production that GDP is supposed to measure.

Section 3 discusses the conceptual and practical challenges in bringing Google, Facebook, and the like into the accounts. The major "cost" to consumers of Facebook, Google, and the like is not the broadband access, the cell phone service, or the phone or computer; rather, it is the opportunity cost of time. But that time cost does not represent consumption of market sector output. Rather, it is akin to the consumer surplus obtained from television (an old economy invention) or from playing soccer with ones' children. As Becker's (1965) treatment suggests, activities that combine market products (an iPhone, a TV, a soccer ball) with the consumer's own time are properly thought of as nonmarket production. As we discuss, a small amount of market output can, potentially, be included in final consumption, corresponding to online ad spending. That spending is relatively modest and makes little difference for productivity measurement. Thus, while the digital services are valuable, the possible mismeasurement in these areas makes a difference of only a few basis points to market-sector labor-productivity and TFP growth.[3] Of course, even if market productivity growth has been correctly measured, it may have become a somewhat less close proxy for a measure of overall welfare change.

In making these points, we draw on a large body of existing research. Before presuming that the measurement problems have gotten worse, it is worth remembering that in the 1990s and early 2000s, a lot of work looked at missing quality improvement, the problem of new goods, and the fact that consumers had an explosion of new varieties. The biases were frequently estimated to be large. For example, VCRs, cell phones, and other products were added to the consumer price index (CPI) a decade or so after they appeared, and when their prices had already fallen by 80 percent or so. (Gordon, 2015; Hausman, 1999). The explosion in consumer choice, and the possibilities for so-called mass customization, were documented in the 1990s. Around the same time, the Boskin Commission estimated that omitted quality change in new goods was worth at least ½ percent per year (Boskin et al., 1998). (Some academic research found even

[3] Nordhaus (2006) sketches principles of national accounting for non-market as well as market goods and services.

larger effects e.g., Bils and Klenow (2000), while the National Academy of Science Committee on National Statistics panel report (2002) argued for a smaller number.) So again, the issue is not whether there's bias. The question is whether it is larger than it used to be.

The structure of the paper is as follows. Section 1 lays out motivating facts about the productivity slowdown. Section 2 discusses improved deflators for information technology and intangibles, and reworks the growth accounting with alternative capital deflators. We then turn to other issues in Sections 3 through 5 that plausibly changed after 2004. Section 6 concludes.

1. The recent rise and fall of U.S. productivity growth

Three productivity facts frame our subsequent discussion. First, as measured, aggregate business-sector labor productivity and TFP growth rise sharply in the mid-1990s but then slow again after 2004 or so. Second, the slowdown was broadbased across industries, including in relatively well-measured ones, such as wholesale and retail trade, manufacturing, and utilities (Griliches, 1994; Nordhaus, 2002). Third, the TFP slowdown is similar if we hold industry weights fixed—it does not reflect a rising share of slow-growth industries.

Fernald (2014b) interprets the mid-2000s slowdown as a "return to normal"—marking an end (or pause) in a phase of exceptional, broad-based gains from the production and use of information technology. The remaining sections of the paper explore whether rising mismeasurement provides an alternative explanation.[4]

Figure 1 showed business-sector labor productivity. The appendix provides a longer time perspective along with detailed growth-accounting. Of particular interest is the behavior of TFP,

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[4] A separate debate is whether the productivity slowdown of the 1970s was, itself, due to mismeasurement. Griliches (1994) points out that the post-1973 slowdown was concentrated in poorly measured industries. Gordon (2016, for example) argues instead that the post-1973 slowdown reflects the unusual strength of the 1920-1970 period rather than anything specific that happened in the 1970s. Relatedly, Fernald (1999) estimates that building the Interstate Highway System substantially boosted productivity growth in the 1950s and 1960s but then its effects ran their course. Triplett (1999) reviews arguments that the post-1973 slowdown was illusory.

defined as a residual: output growth not "explained" (in a proximate sense) by growth in inputs of capital and labor. In the longer run, TFP growth primarily reflects innovation, broadly construed. The appendix shows that the rapid labor-productivity and TFP growth of the late 1990s and early 2000s came to an end sometime between 2003 and 2006—a slowdown that is statistically significant in formal tests for a change in mean growth.

Figure 2 shows the slowdown in business-sector TFP growth from a Bureau of Labor Statistics dataset, broken into broad industry sources. Because of data availability, the subperiods shown are all between 1987 and 2013. TFP slowed sharply in the 2004-2007 period relative to the late 1990s and early 2000s. So the slowdown in TFP growth predated the Great Recession.

The private business economy is divided into four mutually exclusive pieces: IT producing, wholesale and retail trade, "other well measured," and "poorly measured."[5] Broadly, all sectors show somewhat slower growth after 2004, but especially relatively well measured ones, including wholesale and retail trade. After 2000, IT production adds less and less to TFP growth, a point to which we return in the next section. After 2004, wholesale and retail trade and "poorly measured" contribute little, or even negatively. This is interesting in part because trade was an important area where IT provided a substantial boost after the mid-1990s, in part through reorganizations of the industry. After 2007, other (non-trade) well-measured industries contribute negatively through 2013. Thus, the slowdown is apparent even with more tangible products such as trade and manufacturing where measurement has, traditionally, been considered relatively good. (Of course, even in these industries unmeasured quality improvements and other issues with deflators are occurring.)

[5] "Other well measured" is most of manufacturing (except computers/electronic equipment), agriculture, mining, utilities, transportation, broadcasting, and accommodation. Nordhaus (2002) also considers wholesale and retail trade as well measured, but we have broken that out separately.

Because the slowdown was broadbased, it is not simply an issue that weights have been shifting towards poorly-measured sectors such as services. Services are challenging, not least because the sources, methods, or concepts employed by the BLS and BEA have noteworthy shortcomings (Griliches, 1994; Triplett and Bosworth, 2004).

To see the (non-) effect of changing weights more directly, Figure 3A shows that TFP growth since 1987 would have been essentially unchanged even if weights were held fixed. The light bars show actual average growth in business-sector TFP over the periods shown. Blue bars show a counterfactual where industry weights are held constant at their 1987 values. The weights are industry gross output as a share of aggregate value added, and industry TFP growth is in value-added terms. Over these broad time periods, growth is within a few basis points between the two measures. In other words, shifts in the industry composition of the economy are <u>not</u> a central part of the story.

As Panel B makes this point a different way by showing that the slowdown after the early 2000s is broadbased across industries. The figure shows the change in average annual industry (value-added) TFP growth from 2004-2013 relative to 1995-2004. About two-thirds of industries show a slowdown in measured TFP growth after 2004. We get a similar picture if we look at the change from 1995-2004 to 2004-2007, so it is not simply a matter of the Great Recession affecting many industries. We also get a similar picture using labor productivity (so it is not something about capital measurement).

Our results are consistent with some previous studies that have found that the shrinking size of well-measured sectors was not a first-order explanation for previous swings in productivity (Baily et al., 1988; Sichel, 1997).

In sum, the productivity slowdown is broadbased and is not simply an issue of slow service-sector productivity growth. The economy plausibly received an exceptional boost from

IT in the 1990s and early 2000s. But, by the mid-2000s, the "low-hanging fruit" of a wave of IT-based innovation (including associated reorganizations) had been plucked. For example, industries along the supply chain from factory to retailing were already substantially reorganized to reduce inventory, waste, and headcount; and IT-supported efficiencies in middle management and administrative support had been exploited. So perhaps the gains from further innovation have been more incremental than transformative? Or, it may be the case that we are overlooking nascent IT-based productivity gains in service sectors such as health care and education; perhaps these are in their infancy. We sidestep this more challenging question and turn to an alternative hypothesis that rising mismeasurement might explain the patterns in the data.

2. Growing mismeasurement of information technology?

In this section, we document longstanding challenges in measurement of information technology (information processing equipment and software), particularly with regard to investment.[6] But correcting for this mismeasurement makes the slowdown in labor productivity and TFP growth even worse after 2004. We also note a rise in uncertainty about these effects: Investment has shifted towards special-purpose information processing equipment and intangibles, especially software, categories that have proven especially difficult to measure. With all of our capital adjustments, the TFP slowdown is little affected.

After moving roughly sideways in the post-war period through the late 1970s, official information technology (IT) investment prices moved down as the PC era began, then accelerated sharply to 6 percent per year on average during the "IT boom" and the early 2000s (table 1). Since 2004, price declines have abruptly retreated to a modest rate of 1 percent,

[6] Our focus in this section is on the contribution of IT capital services to productivity and implications for TFP growth. Parallel measurement problems exist for IT consumer durables which we do not discuss explicitly. But, we account for understatement of GDP from mismeasurement of IT through our adjustments to domestic production, whether for the consumer or business market.

coinciding with a decrease in the contribution of IT use and production to labor productivity. This slowdown has led to a revival of interest in measurement of IT sector prices and some recent studies have indicated that official price statistics have understated price declines in recent years.[7] This raises the question of whether price mismeasurement has contributed to a spurious slowdown in measured investment and possibly distorted productivity estimates. Answering that question—whether mismeasurement has *worsened*—requires not just the identification of mismeasurement in the current period, but construction of a fully consistent time series. To that end, we employ price indexes developed by Byrne and Corrado (2016), who review the full post-war history of IT price research and construct alternative price indexes for IT investment and production using not only research for recent years but also work for earlier periods that may not have been incorporated into the NIPAs.

We provide two alternative price indexes. The first—which we call "conservative"—is based solely on research studies using detailed datasets on specific product classes and extrapolation of those results as described in Byrne and Corrado (2016) for communications equipment and for computers and peripherals. For the second—which we call "liberal"—we add plausible assumptions about prices of IT products for which no direct studies are available, namely other information processing equipment and software. The results of our analysis are shown in Figure 6. Overall, our alternative indexes suggest substantially faster price declines for IT than investment prices used in the NIPAs *throughout the post-war period*. For some categories (computers and communications equipment), price measurement appears to have worsened, but the importance of those categories has declined, muting the impact of the rising bias.

[7] See research for communications equipment (Byrne and Corrado, 2015), computers (Byrne and Pinto, 2015), and microprocessors (Byrne, Oliner, and Sichel, 2015).

We discuss the component prices briefly here and compare with the investment prices used in the NIPAs. An appendix provides detailed discussion of the inputs to each price index.

2.1.1. Components of IT Investment

Computers and Peripherals

The official investment price index for computers and peripherals reflects results of internal BEA research (Cole et al., 1986; Dulberger, 1989) which led to the adoption of hedonic regression techniques to account for the rapid technological advances embodied in new models of computers and peripherals. For the post-war period through the early 1980s, BEA prices are consistent with outside studies (Gordon, 1990; Triplett, 1990). Beginning in the 1990s, BLS adopted hedonics for computers (but not peripherals) as well and BEA now relies on BLS prices as inputs for the NIPA investment deflator (Grimm et al., 2005). Despite the commitment to quality-adjustment in the official statistics, outside research indexes indicate somewhat different price trends beginning in the 1980s.

Personal Computers

Our alternative price index for computers and peripherals diverges from official prices beginning in 1984. For PCs, we adopt an aggregate of the indexes developed in a comprehensive study by Berndt and Rappaport (2001, 2003), which exhibits 8 percentage points faster declines through the early 2000s. The documentation for the hedonic models used in the BLS price indexes is not comprehensive enough to allow the source of the difference in results to be identified with confidence.

More recently (since 2004), the BEA index for PCs has slowed dramatically and some aspects of the sources and methods used raise concerns about the accuracy of this development. Figure 5 (top panel) shows the average selling price of PCs sold in the U.S. business market reported by IDC Corp. juxtaposed with the rate of change for the BEA investment price index for PCs. In the late 1990s and early 2000s, the gap between the two series indicates that quality improvements were contributing 15 to 20 percentage points to the fall in constant-quality PC prices. The gap has narrowed since that time and since 2010 the two series are almost identical, implying no improvement in PC quality, holding price constant, for the past five years.

Three measurement problems appear to contribute to this implausible result. First, the BEA investment series is the aggregate of a (domestic) production price index and an import price index calculated independently from one another with different source data (Figure 5). As a result, any discount accruing to a business switching from domestically-sourced to imported equipment is not reflected in the investment price index, a form of "outlet substitution bias" akin to omitting from a consumption price index the price savings associated with switching to shopping at Walmart (Reinsdorf, 1993; Houseman et al., 2011).

Second, the price index for imports falls markedly slower than the index for domestic production over a prolonged period of time: a difference of 14 percent since its introduction in 1995. The implied continual rise in the relative price of imported computers is inconsistent with the increase in import penetration from 50 to 90 percent over the same time period (Byrne and Pinto, 2015). This contradiction strongly suggests the import price trend is inappropriate for use in conjunction with the PPI. Among the possible contributing factors to the relatively flat import price series are the heavy presence of intrafirm (transfer) prices in the index (over 60 percent of the value of the basket in 2013) which may exhibit different behavior than market transaction prices. Also, items that exhibit no price change while in the basket for the index are known to be highly prevalent in BLS import price indexes (Nakamura and Steinsson, 2009), which implies that declines in the index come primarily from judgmental adjustments introduced when new items are added to the basket.

Third, the producer price index itself has drawbacks for use as an investment price index. To begin with, the intention of the PPI program when performing quality adjustment is solely to capture changes in production cost directly connected to specific inputs. As a result, design improvements not clearly tied to a savings in resource costs, do not, by assumption, justify adjusting the producer price of a good entering the index basket, and yet such improvements raise the productivity and user value of the equipment, properly treated as quality change for an investment index (Triplett, 1983). Perhaps as a result of this disconnect between BLS intention and BEA use, the hedonic analysis performed to adjust prices for items newly entering the basket for the PC PPI controls only for technical features, not PC performance as perceived by the user.

Although we are aware of no research directly studying computer prices for this recent period, Byrne, Oliner and Sichel (2015) analyze prices for microprocessors (MPUs), the central analytical component of computers. Their analysis shows the importance of direct measures of performance in hedonic analysis for MPUs: their price index controlling for benchmark scores on a battery of user tasks fell 20 percentage points faster than a hedonic index controlling for technical features from 2000 to 2013. We conclude the BLS hedonic may be understating quality improvement for PCs by 4 percentage points—an amount equal to the bias in the MPU price index weighted by the share of MPU inputs in the final value of PCs (15 percent). In our alternative index, we extend the Berndt-Rappaport index with the bias-adjusted PPI.

Multi-user Computers

The BLS price index for multi-user computers (computers other than PCs) used by BEA is quality-adjusted using a hedonic regression as well. Following the same reasoning used for PCs, we augment the BEA price index beginning in 1993 with an indicator of the average price per computer unit adjusted for MPU performance, which falls markedly faster than the PPI. The performance measure is an average of scores on a suite of benchmark tests developed by

Systems Performance Evaluation Corporation (SPEC), a consortium of industry representatives, to provide reliable comparisons across systems. We blend this price-performance indicator with the PPI, which has the appeal of controlling for computer features not accounted for by the SPEC benchmark. We employ a weighted average of the PPI and the price-performance trend to deflate multi-user computers. This alternative index falls 10 percentage points faster than the official BEA price.

Storage Equipment

For storage equipment as well, the BLS PPI that is the basis for the BEA investment price index appears out of alignment with price-performance trends in the industry. From its introduction in 1993 to 2014, the PPI has fallen 12 percent, in stark contrast to the price per gigabyte for hard disk drives, currently the dominant technology in the industry, which fell 35 percent per year on average (McCallum, 2016). Recent research by Byrne (2015) on employing detailed model-level prices for storage equipment developed prices that fell at nearly the rate of raw price-per-gigabyte series. We use the Byrne (2015) index extended backwards by the price-per-gigabyte series with a 4 percentage point bias adjustment.[8]

All told, our alternative prices for computers and peripherals falls faster than the NIPA index beginning in the early 1980s and the gap between the two increases markedly to 8 percentage points between 1995 and 2004. The difference between the indexes is even larger in recent years, an average of 12 percentage points (Figure 6, top panel). This substantial gap suggests additional work is needed to account well for computer investment in the NIPAs and the rising gap makes the issue increasingly important. But, the percentage point *slowdown* in the

[8] The BEA index for the remaining category, peripherals, falls 5 to 15 percent per year on average for most of its history. In the absence of outside research indicating otherwise, we assume this price index is accurate.

alternative index is still quite large and returns the rate of price declines to the pace seen prior to the IT boom.

Communications Equipment

Investment prices for communications equipment reflect both BLS producer and import price indexes and internal BEA research (Grimm, 1996). Outside work is incorporated to some extent as well, including price indexes published by the Federal Reserve Board, and the investment index does fall faster than the PPI for the industry (Figure 6, bottom panel). However, a substantial amount of research, reviewed in Byrne and Corrado (2015), is not reflected in the NIPAs. This includes work on transmission and switching equipment in the early post-war era by Flamm (1989), as consolidated and augmented by Gordon (1990), and satellite prices constructed by Byrne and Corrado (2015). More recently, the BEA investment price index appears inconsistent with new prices for cellular systems, data networking, and transmission developed in Byrne and Corrado (2015) and Doms (2000). Because sub-indexes are not published for communications equipment investment, it isn't possible to research the difference further. In any event, technological developments in the field that suggest careful attention is needed to account for quality change, such as fourth generation cellular systems now capable of delivering video.

Like the computer investment index, the Byrne and Corrado (2016) communications equipment investment index is carefully constructed to match the scope and weighting of the BEA index. The difference between the BEA investment index and the alternative is noteworthy and the gap is slightly larger in the 2004-2014 period than in the 1995-2004 period. Unlike the index for computers and peripherals, the communications equipment index maintains roughly the same pace of decline as in the IT boom.

Special-Purpose Electronics

The remaining components of the BEA "other information processing" equipment category are a diverse group of special-purpose equipment designed for use in medical, military, aerospace and industrial applications.[9] Examples include magnetic resonance imaging (MRI) machines, electronic warfare countermeasure devices, and a wide variety equipment used for monitoring and controlling industrial processes. Technological advances in recent years have been impressive. One well-known example of is the area of genomic sequencing, where specialized equipment has contributed to dramatic efficiency gains: The cost of sequencing a human genome has dropped from roughly $1,000,000 in 2008 to $1,000 in 2015.[10]

Surprisingly, with the exception of electro-medical equipment, which edges down modestly, BLS producer prices for these products have *risen* on average since the late 1990s. Naturally, differences in market structure, such as the smaller scale of production and the market power of military and medical customer, and the price trends of specialized inputs may cause prices for special-purpose electronics to behave differently than prices for general-purpose electronics like computers (Byrne, 2015). But, these goods have electronic content comparable to computers, so one might expect the equipment prices to reflect the rapidly-falling price of the electronic components used in their production. In our "liberal" alternative scenario, we assume that the prices for other information systems are somewhat more dynamic. In particular, we remove roughly one-third of the difference between the trend price growth of special-purpose and of general-purpose (computer and communications) electronics.[11]

Software

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[9] Navigational equipment and audio-visual equipment are classified as communications equipment in the BEA investment taxonomy.

[10] National Human Genome Research Institute (https://www.genome.gov/sequencingcosts/). While the sequencing of a human genome is not final output, improvements in the tools used to conduct science are the likely foundation of falling prices for health services in the future.

[11] More precisely, we assume total factor productivity in the industry is higher by one-third of the gap with computing and communications equipment.

Investment in software is deflated in the NIPAs by an aggregate of three sub-indexes: prepackaged, custom, and own-account software. BLS producer prices are available for prepackaged software and research has been conducted at BEA and by outside researchers into quality-adjusted price trends (Parker and Grimm, 2000; Copeland and Miller, 2013). To deflate investment in prepackaged software, BEA employs the BLS PPI with an adjustment reflecting the average difference between the PPI and their research results. Because direct observation of prices for custom and own-account software has not been possible, investment in these categories of software are deflated by a blend of an input cost index for the industry and the prepackaged software index. In our "liberal" alternative scenario, we deflate own-account and custom software with an index created with one-third weight on pre-packaged software and two-thirds weight on existing BEA deflators for the respective categories.

IT Investment as a Whole

All told, declines for the official price index for information technology slow dramatically from 6 percent per year for 1995-2004, to 1 percent per year for 2004-2014. Although the alternative index consistently falls faster than the official price, it slows from 9 percent per year for 1995-2004, to 4 percent per year for 2004-2014. The liberal index accelerates as well and provides essentially the same picture. Thus, on first examination, increasing mismeasurement does not appear to explain the slowdown in IT price declines when the available research from all periods is considered.

However, it bears emphasis that the composition of IT investment has shifted appreciably toward components for which measurement is more uncertain. Most notably, software investment has gone from 39 percent of IT investment for 1995-2004 to 48 percent for 2005-2014. Also, special-purpose equipment's share has increased, bringing the share for which measurement is more uncertain to 68 percent. Thus, our confidence in the IT price indexes, even as amended in the alternative indexes, has deteriorated markedly because of compositional shifts, and a role for increasing mismeasurement cannot be ruled out.

2.1.2. Statistical Program Limitations

The contrast between our alternative indexes and the official investment indexes raises the question of agency practice. Statistical agencies face a set of challenges that make addressing the dissonance between official prices and research results difficult. These include data limitations, the need to avoid judgmental adjustments that undermine the reproducibility of indexes, mismatches between economic concepts and feasible price index methods, and limited revision windows. Furthermore, funding limitations for agency measurement programs has hampered innovation.

- Data limitations. For the most part, statistical agencies rely on direct survey collection of data on transaction prices for constructing price statistics. Data from consultancies, trade groups, and advertisements is available but not fully exploited in the official price index programs.[12] In a sector characterized by high market concentration, such as IT, nonresponse or inadequate response from key industry players can seriously undermine these efforts.[13]
- Reproducibility. Statistical agencies face a need to avoid index calculation procedures that depend on subjective judgment and would not be invariant to which analyst processes the data.[14] This argues against, for example, routinely adjusting price indexes by the apparent bias indicated by research results for previous periods.[15]
- Conceptual incompatibility. Because the BLS does not produce buyers' price indexes for investment goods, BEA relies on weighted combinations of producer price indexes and import price indexes to deflate these items. This creates at least two problems. First, there is an "outlet substitution problem" as described above for PCs, wherein the discount associated with shifting from a domestic to a foreign source is omitted from the index, leading to upward bias. In addition, the standard approach to quality adjustment in

[12] For example, Aizcorbe and Pho (2005) use scanner data, which provides high-frequency transaction prices for specific models, Berndt and Rappaport (2003) use advertisements and consultancy data, and Byrne and Corrado (2015) use trade group data, among other sources. Exceptions include BLS use of online price quotes to estimate feature prices for personal computers (Holdway, 2001).
[13] For example, the BLS has resorted to the use of list prices for microprocessors as a substitute for transaction prices due to non-participation (Byrne, Oliner, Sichel, 2015).
[14] For example, price indexes are employed for cost-of-living adjustments, contract escalation clauses, and so forth, making them politically sensitive.
[15] Judgment necessarily plays some role in estimating national accounts, however. For example, BEA uses a bias adjustment in the estimation of prices for investment in prepackaged software (BEA, 2014).

producer prices is the input cost approach, which omits the price change component attributable to the cost of producing the added features.[16]

- Limited window for historical revision: Knowledge gained by research cannot be easily incorporated in the revision window for price indexes at BLS, which does not allow for further revision to the PPIs more than 6 months past initial publication. That being said, BEA has more leeway in the construction of the NIPAs, for which final estimates of GDP, for example, may be released as much as 5 years later.
- Budgetary constraints: Funding limitations for the major economic statistical agencies—BLS, BEA, and Census—have appreciably impaired measurement needed for productivity analysis. For example, the Current Industrial Reports series published by Census, which provided invaluable information on the product composition of domestic manufacturing, was discontinued in 2010. A buyers' price index program for investment goods and intermediate inputs that would have solved the outlet substitution problem referred to above was proposed by BLS but not funded (Alterman, 2015). And despite highly useful pilot studies, BEA has not made regular use of commercially available scanner data (Aizcorbe and Pho (2005), Copeland (2010)).

Consequently, the statistical agencies, despite diligently pursuing the best measurement possible within these constraints, may fall short of fully accounting for the collective wisdom of the measurement community. Yet it would be incorrect to interpret identification of a bias in price statistics as an indictment of the agencies' work. Instead, when an analysis requires consistent historical prices that fully account for technological innovation, the official prices should be adjusted to suit the purpose at hand.

2.2. Intangibles beyond the NIPAs

Conceptually, capital investment represents the use of resources that "reduces current consumption in order to increase it in the future" (Corrado et al, 2009). Tangible investments in equipment and structures clearly meet this definition. But a lot of intangible spending by businesses and governments also meets this definition. The U.S. national accounts include some

[16] The BLS *Handbook of Methods* notes, "when changes in physical characteristics of a product *cause product cost differences*, the BLS attempts to make an accurate assessment of real price change by systematically taking account of differences in quality" (emphasis added). The handbook also notes that in the case of some "high-tech" industries, which "frequently develop new products that are technologically superior, yet cost less to produce, than the products they replace," BLS employs hedonic adjustment. However, this is only the case for personal computers and servers in practice.

intangibles—R&D and artistic originals (since 2013) and software (since 1999) — as final fixed capital formation. But businesses undertake considerable other spending that has the same flavor—such as training, reorganizations, and advertising.

Corrado et al (2009) and McGrattan and Prescott (2012) argue that investment spending has increasingly shifted towards intangibles, including those that are not currently counted. Basu, et al (2003) argue that reorganizations associated with IT can explain some of the dynamics of measured U.S. and U.K. aggregate TFP growth.

In the next subsection, we consider the effects of incorporating additional intangibles from Corrado and Jäger (2015). Their (updated) U.S. intangibles data run from 1977-2014. Ordered from largest to smallest estimated values in 2014, their data include investments in organizational capital, branding, training, design, and finance/insurance new products.

Incorporating these intangibles makes relatively little qualitative difference to the slowdown. Other approaches (such as a more model-based approach, as in McGrattan and Prescott, 2012) might yield different results, but these data suggest that the intangibles route is unlikely to explain the productivity slowdown. For example, we experimented with (but do not show) investment adjustment costs along the lines of Basu, Fernald, and Shapiro (BFS, 2001). BFS argued that in the late 1990s, when investment was rising quickly, firms had to divert real resources to adjustment, such as installing the capital. Conceptually, this is a form of intangible investment. With the BFS estimates, adjustment costs held back measured TFP growth by several tenths of a percentage point in the late 1990s—suggesting true technology growth was even faster than measured. However, over broader periods it makes only a modest difference—and, once again, goes in the direction of exacerbating the productivity slowdown. For example, with the BFS parameter values, the weak investment during and since the Great Recession implies that fewer resources have been diverted to adjustment. That, in turn, boosts measured

TFP growth since 2004 by a few points relative to the 1995-2004 period. (We ignore this effect in the remainder of the paper.)

2.3. Capital mismeasurement and TFP

To help interpret the counterfactuals in the next subsection, we highlight here the conceptual reason why it is hard for capital mismeasurement to explain the past slowdown in TFP growth: It affect inputs as well as output in largely offsetting ways.

Consider a stylized example for a closed economy. Suppose that after some date in the past, we miss q percentage points of true investment growth. The miss could reflect an increase in unmeasured quality improvement (relative to whatever we were missing prior to that date) or an increase in the importance of unobserved intangible investment.

The growing mismeasurement implies that true output and true labor productivity grow at a rate $s_I q$ faster than measured, where s_I is the investment share of output and, by assumption, the good is completely produced domestically. But it also implies that true capital input grows more quickly than measured. In steady state, the perpetual inventory formula implies that capital grows at the same rate as investment, so capital input also grows q percent per year faster.

Thus, the change in TFP growth is the extra output growth less the contribution of the additional capital growth. In steady state, the change is $(s_I - s_K)q$, where s_K is capital's share in production. In the data (and a condition for dynamic efficiency), $s_I < s_K$. Hence, in steady state, growing mismeasurement makes true TFP growth *slower*, rather than faster, than measured.[17]

Of course, this is a steady-state comparison. The initial effect is that output responds more quickly than capital, so that TFP initially rises before falling. Also, some domestically

[17] Though not original to them, Basu et al. (2003) make this point in the context of intangible investment. Dale Jorgenson had made this observation to Fernald when software investment was added to U.S. GDP in 1999.

produced capital goods are exported, and some goods used for investment are imported. It is thus an empirical question which effect dominates over particular time frames.

In addition, the slower pace of aggregate TFP growth would be distributed differently. Suppose the mismeasurement reflects faster true TFP growth in domestic equipment and software goods. That implies that TFP growth outside of that production would be even slower than is already measured. Intuitively, this happens because output growth in those areas doesn't change, but growth in capital input is more rapid.

2.4. Simulations: Mismeasurement of durables worsens the slowdown

We now assess the quantitative importance of mismeasurement of durable goods. To the extent we can quantify it, mismeasurement has become *less* important for output and labor productivity. That is, after adjusting for consistent measurement, the labor productivity slowdown after 2004 becomes even larger than in the official data. As discussed above, the mismeasurement was large in the past as well—and domestic production was more important. The adjustment to TFP growth is modest, but most adjustments also tend to make the TFP slowdown a touch larger than in the official data.

We begin narrowly, with areas that are most grounded in a consistent methodology over time. This first "conservative" simulation considers alternative deflators for two categories of equipment for which considerable recent research has been done: Computers and peripherals; and communications equipment. (See the discussion in Section 2.1.1) We also consider alternative deflators for semiconductors. Those are primarily an intermediate input into other electronic goods but, because of exports and imports, revised deflators modestly affect final output growth. We then add more speculative adjustments for specialized equipment (NAICS 3345) and software. Finally, we add estimates of intangibles from Corrado and Jäger (2015).

Given alternative deflators or measures of intangibles, we adjust both input (capital services) and output. An appendix describes the details. The revised capital input measure grows more quickly because of the faster implied growth in computers and other information-processing equipment. For the purpose of capital input, it doesn't matter whether the investment goods are produced domestically or imported. Business-sector output also grows more quickly because of faster growth in domestic computers and other info-processing equipment.

Importantly, some of the domestic production of these products are sold to consumers. Hence, the output adjustment also captures the effect on real GDP of consumer purchases of computers and communications equipment (such as mobile devices).

For semiconductors, the adjustment to output only involves net exports. In a closed economy, an adjustment that raises the true output of semiconductors is exactly offset by higher true intermediate input usage of semiconductors—leaving GDP unchanged. However, in an open economy, semiconductors are exported and imported. Since we do not have separate adjusted prices for imported versus domestically produced semiconductors, we assume that any adjustments are proportional and weight them by the share of net exports in business output.

Column (0) of table 1 shows our baseline starting point from the published data. As discussed Measured labor productivity growth (the top panel), capital deepening (the middle panel), and TFP growth (the bottom panel) both sped up in the 1995-2004 period but slowed thereafter. The slowdown in labor productivity growth was about 1-3/4 pp per year. Some of that slowdown is explained by a reduced pace of capital deepening, leading to a slowdown in TFP growth of about 1-1/4 pp per year. The slowdown in labor productivity has been particularly pronounced since 2010, though the growth-accounting says it is "explained" by the lack of capital growth relative to labor. Hence, TFP growth was about equally weak from 2004-2010 as from 2010-2014.

Column (1) then shows how results change relative to this baseline from adjusting computers, communications equipment, and semiconductors. As the top panel shows, these adjustments do affect labor productivity in a noticeable way. But the increase in labor productivity is most pronounced for the 1995-2004 period, at just under 0.3 pp per year. After 2004, the alternative deflators add only a little over 0.1 pp per year to growth. The reduced effect reflects not only the slightly smaller magnitude of the price adjustments, but also the declining importance of domestic IT production relative to imports. Domestic production of computer and communications equipment amounted to 2.9 percent of nominal business-sector GDP in the late 1990s, but only 0.5 percent by 2014. So mismeasurement of computers and communications equipment had a much larger effect in the 1990s than it does today.

The middle panel shows that the adjustments make substantial difference to capital services growth as well. Again, the major adjustment is in the 1995-2004 period when prices, by any measure, were falling rapidly. The bottom panel shows that the effect on TFP growth is relatively small—a matter of a few basis points. But they go in the direction of exacerbating the post-2004 TFP slowdown. Adjusted TFP is a little stronger than measured in the 1995-2004 period, but a little weaker after 2004.

Column (2) adds somewhat more speculative adjustments for specialized equipment and software. The upward boost to output and labor productivity is, not surprisingly, a bit larger in each time period than in column (1). But again, the upward boost is larger in the 1995-2004 period than in the post-2004 period, this time by almost exactly 2/10ths percentage point. Adjusting capital goods, once again, turns out to exacerbate the slowdown in labor productivity growth. For TFP in the bottom panel, the adjustments also modestly exacerbate the TFP slowdown.

Column (3) adds intangibles from Corrado and Jäger (2015). With intangibles, the adjustments to labor productivity are even larger—but, again, effects are largest in the 1995-2004. Together, the adjustments in column (3) add about ½ percentage point to labor productivity relative to the published data in 1995-2004. From 2004-2014, the adjustments add only 2/10ths percentage point. Thus, the slowdown in labor productivity growth with the adjustments in column (3) is about 3/10ths percentage point *larger* than what is already measured. For labor productivity, then, the adjustments taken together make the labor productivity slowdown markedly worse.

Of course, the slowdown in capital growth, in the middle panel, is also much larger. As a result, in the bottom panel, the slowdown of TFP growth is virtually unaffected relative to the measured baseline. In particular, the adjustment subtracts 12 to 13 basis points from TFP growth in the 1995-2004 period and the 2004-14 period.[18] The important takeaway is that correcting for capital mismeasurement does not resolve the post-2004 slowdown.

Not shown, we also experimented with arbitrarily doing an aggressive adjustment to software deflators after 2004. True software prices are assumed to fall 5 percent per year faster than measured. Since the adjustment is entirely made after 2004, it captures the hypothesis that measurement has gotten worse—all of the effects are concentrated in the post-2004 period. Even that aggressive adjustment has relatively modest effects. The adjustment would add around

[18] The careful reader will note that output growth 1995-2004 is 1/10th higher in column (3) than column (2), whereas capital growth is less than 1/10th higher. So why does TFP growth fall, even though the output effect looks larger than the adjusted contribution of capital (capital's share times capital growth)? The reason is that, with intangibles, capital's share is also adjusted upwards, and so the effect on TFP involves not just the adjustment to capital growth, but also the adjustment to capital's share multiplied by (the new) capital growth rate. This effect can be a few tenths.

1/10th pp to labor productivity growth after 2004. But capital growth is also higher in this simulation, and TFP is affected by only a couple basis points.

Of course, since the alternative deflators imply a different time pattern for investment-producing TFP, a question is whether these changes affect the apparently broadbased nature of the TFP slowdown. The answer appears to be no. A quick answer comes from using relative prices to decompose aggregate TFP into "investment" TFP and "other" TFP. Suppose the two "sectors" have the same production functions (other than a multiplicative constant) and face the same factor prices. These are strong assumptions, but the literature on investment-specific technical change shows that it yields a sharp result: $\Delta TFP_I - \Delta TFP_O = \Delta P_O - \Delta P_I$. This equation captures the intuition that the main reason why prices of consumption and "other" goods has been rising relative to the price of investment has been fast technical progress in computers and other capital goods.

Not shown, this decomposition shows that, even though the effect on overall TFP is muted, there are larger effects on implied sectoral TFP growth rates from the adjustments in column (1) as well as from software. Still, with the modified deflators, the major effects of the alternative deflators on the *changes* after 2004 are for investment TFP growth. The slowdown in "other" TFP after 2004 appears little affected by these modifications).[19]

In sum, there is clear evidence that important capital goods prices are mismeasured and that the mismeasurement varies over time. However, the effects of measurement have been less important, rather than more important, since 2004. So the adjusted labor productivity slowdown is even larger. With the inclusion of intangibles, our adjustments leave the TFP slowdown largely unchanged.

[19] I don't know if this is clear. We could show it in a table if we want, or even (more ambitiously) recalculate capital input measures by industry to redo the industry table. That's harder with intangibles.

Thus, the important takeaway is that, if the productivity slowdown after the early 2000s reflects mismeasurement, it needs to be somewhere other than in durable goods. In the remainder of the paper, we find that growing mismeasurement of internet services, fracking, and globalization (shown as "other" in Figure 1) can only partially fill that gap.

3. "Free" online services

The benefits from online information, entertainment, social connection, and the like have been found to be large (Goolsbee and Klenow, 2006, Varian, 2011, and Brynjolfsson and Oh, 2012 and 2014). But despite their far-reaching implications for consumer welfare, these benefits do not change the fact that market-sector TFP growth slowed broadly. Under long-standing national accounting conventions, the benefits are largely outside the scope of the market economy; as we discuss, given the small monetary size of the sector, it is very hard to bring many of those benefits inside the market boundary. Indeed, the largest estimates of the gains are based on models of the time cost of using the internet as input into home production of non-market services. We will argue that the gains from non-market production using the consumer's time are not comparable to gains in market sector output and that money value of time used in the estimates may be too high. And, regardless of how they are treated, the non-market gains are not big enough to offset a significant fraction of the "missing" $3 trillion per year in business output from the productivity slowdown.

We also consider whether the market output of online service providers whose revenue comes from selling ads has been properly captured in our output measures. In the standard approach used in national accounts, the output of these online service providers is entirely consumed by the advertisers. Drawing on an earlier literature on the treatment of free broadcast TV, Soloveichik (2015) and Nakamura and Soloveichik (2015) argue for inclusion of entertainment and information services supported by advertising in household final consumption, noting that this would avoid artificial changes in GDP when consumers switch between free and subscription based media services.

An estimate of the value of the free entertainment and information services cannot just be added to household consumption, however, because consumption and production have to balance. In Nakamura and Soloveichik (2015) the newly recognized household consumption is accompanied by newly recognized ad watching services of households. Yet taken together, this pair of new transactions does not affect the measure of TFP.

To modify the standard approach in a way that would change TFP requires a special treatment of the advertising revenue, so that some of the output that is currently shown as consumed by the ad buyers can instead be shown as consumed by the households who are the direct users of the online services. This means that part of the cost of running an ad must be viewed as a rent paid to access to the users of the free online services rather than as a payment for advertising services. For example, royalties paid to access the oil underneath a landowner's property do not represent a purchase of services by the petroleum company.

3.1. The Time Cost Approach to Gains from Free Online Services

The standard approach to measuring gains from new goods considers the difference between the amount of money that consumers would have been willing to pay and the amount that they actually had to pay. Yet the main "cost" to a user of, say, Facebook or YouTube or TripAdvisor, is the opportunity cost of the user's time. Starting with Goolsbee and Klenow, (2006) studies of the gains from free online services have, therefore, considered the time costs of using these services, and not only the money costs associated with accessing them.

Time costs can be modeled in the framework of Becker's (1965) model of the allocation of time. To be more concrete, suppose the representative consumer has the following utility function:

$$U(Z_I, Z_{TV}, Z_1, Z_2 \ldots)$$

Households benefit from the consumption of (possibly unpriced) services from the **I**nternet, Z_I, from television, Z_{TV}, and from other activities, $Z_i, i \subset \{1{,}2 \ldots\}$. The elements of Z_i include meals at home, meals in restaurants, having a clean house, playing soccer, skiing, and so forth.

In the Becker model, the Z_i are not, in general, the direct purchases of market goods and services. Rather, households combine purchased market goods and services with their own time to generate the actual service they value. They buy a soccer ball (which is part of GDP), and combine that market purchase with their (leisure) time, and their children's time, to obtain "soccer services." They combine a market purchase of a restaurant meal with several hours of their time. They combine gasoline and a car (both purchased in the market) with their time in order to go on a vacation that they enjoy. They combine a hotel room with their time to get a refreshing night of sleep during that vacation. Broadly, the services take the form:

$$Z_i = g_i(C_i, T_i, Q_i) \subset \{I, TV, 1{,}2 \ldots\}$$

Playing soccer generates services from the market consumption of a soccer ball, C_i; the time spent playing soccer, T_i; and, possibly, technical change Q_i in the household's production function for combining the market purchase with time.

Now consider a stylized problem that captures the key issues in valuing the Internet. Households seek to maximize well-being subject to cash and time budget constraints:

$$Max\ U(Z_I(C_I, Q_I(1-\tau_I)T_I), Z_{TV}(C_{TV}, (1-\tau_{TV})T_I), Z_3(C_3, T_3), Z_4(C_4, T_4) \ldots) \qquad (1.1)$$

$$s.t. \sum_i P_i C_i + F_I + F_{TV} = WT_{Work}, \tag{1.2}$$

$$T_{Work} + T_I + T_{TV} + \sum_i T_i = 1 \tag{1.3}$$

To simplify, this formulation ignores durable goods, such as computers and cell phones and TVs and beds (though these durables are, in practice, important) as well as non-wage assets. In the cash budget constraint, income is the wage, W, multiplied by time spent working, T_{Work}. In the time budget constraint, total time is normalized to one. In other words, time spent working is time *not* spent doing other activities.

Households purchase broadband access C_I, via cable or mobile phone or other means by paying a fixed or flat cost each period of, F_I. The Internet services that they actually value then depends on the time they spend online, T_I. They may also pay a flow “time tax” τ_I which is proportional to their use of the Internet. For example, they get “free” access to Youtube videos in exchange for spending a proportion of their time watching ads.

As in Brynjolfsson and Oh (2012), the Internet may get better over time, as captured in quality Q_I. Most naturally, this captures the growing number of web sites you can visit or the number of videos available on YouTube or whether your friends are on Facebook. These are not, per se, direct aspects of the “quality” of your Internet service provider (ISP), such as download speed, which conceptually represents a larger quantity of market services, C_I. (Brynjolfsson and Oh, 2012, point out that download speed does not, in fact, get factored into the quality-adjusted “price” of Internet access as measured in the statistics.)

Television is, conceptually, similar to the Internet. You also may pay a fixed cost for watching TV, F_{TV}, as well as paying a time tax, τ_{TV}, again in the form of watching ads. Historically in the United States, prior to cable TV, $F_{TV} = 0$, and the entire service provision was paid for through watching ads. We return to this point below. For other goods, the price is P_i. In the budget constraint, the value of market purchases (on the left-hand-side) equals labor income, which is the wage W multiplied by the time that is not used for other activities.

Conceptually, it is useful to rewrite the budget constraint (1.3) as

$$\left(\sum_i P_i C_i + F_I + F_{TV}\right) + W\left(T_I + T_{TV} + \sum_i T_i\right) = W \qquad (1.4)$$

"Full expenditure" in this setup is the sum of market expenditures (the first term in brackets) and the monetary value of non-market expenditures of time (the second term). Some non-market expenditures could be on home production of goods and services that are a close substitute for market goods and services, such as cooking and cleaning and so forth. Others are for leisure (surfing the Internet for personal reasons, watching TV, playing soccer, and so forth). Some are in the middle, such as Wikipedia, where unpaid content writers create and edit entries for the personal enjoyment of it, but it substitutes for market encyclopedia services.[20]

The national accounts are concerned with market activities, i.e., the prices and quantities that appear in the first term in brackets. However, the importance of non-market activities (the The American Time Use Survey indicates that, in 2014, only 24 percent of non-sleeping time for those 15 and over was spent working) has not gone unrecognized.[21] Mackie et al. (2005) and Nordhaus (2006) discuss the advantanges of developing satellite accounts on nonmarket activities and the practical challenges that this would involve

Brynjolfsson and Oh (2014) find that the incremental gains over 2002-2011 implied by the money constraint in equation (1.4)—which **would** be appropriate to add to market sector

[20] In the GNU Manifesto, Stallman (1987) describes his vision that "In the long run…no one will have to work very hard just to make a living. People will be free to devote themselves to activities that are fun, such as programming." (We thank Hank Farber for pointing us to this quotation.)

[21] The American Time Use Survey indicates that, in 2014, only 15 percent of total time for those 15 and over was spent working, and 24 percent of non-sleeping time. See http://www.bls.gov/tus/tables/a1_all_years.xlsx.

output—are tiny, averaging only $2.7 billion per year. The estimates of the incremental consumer surplus implied by the growth of time spent on online are much more sizeable, averaging $25.2 billion for 2002-2011, with larger effects in the years after 2005. [22]

If we added these incremental gains to the output of the business sector, productivity growth would accelerate by around 0.3 percent per year. Doing so is not strictly appropriate, however, if the question is the productivity of the economy in producing market goods and services. The gains implied by changes in the allocation of consumers' time are linked to home production of non-market services, not the market output that is the object of measures of growth in business sector productivity.

It is also worth considering the assumptions required to use the wage rate as an exchange rate for converting a time price to a money price. As specified above, the model of the allocation of time assumes that time spent in market work involves no disutility. If the psychic costs of market work are high, the amount of wage income that an individual would be willing to forego to spend an extra hour of time online may be greater than the amount that that individual would pay out of pocket to spend time online. At the margin, time spent working probably involves disutility, so adjusting the wage rate for the disutility of market work would yield a lower shadow value of time spent in home production activities.

3.2.Market Production of New Goods

In thinking about the gains from free digital services, it is important to remember that real household consumption and real GDP are measures of the change at the margin, not total amounts of consumer surplus. In measuring output growth over a given time interval, what is

[22] As a nonprofit institution serving households, Wikipedia's output is counted in GDP and in PCE (though not in the business sector for which productivity is calculated). Thus, its output, almost $0.2 billion in 2011, should be removed from the $25.2 billion and $2.7 billion figures if they are used to adjust GDP or PCE.

relevant is the incremental consumer surplus implied by the change in the consumption of the digital services. Thus, a large consumer surplus from free online services would not necessarily imply a large underestimation of the recent growth rate even if these services belonged in GDP. In fact, under normal circumstances, a chained Fisher index (which is the formula used by BEA to measure real personal consumption expenditures) will capture the change in consumer surplus from changing consumption of existing goods.[23]

In the case of a rise in the consumption of an existing free good, the change in quantity will have a weight of zero. This is gives the correct measure of consumer surplus: consumers adjust the quantity consumed of each good (excluding those for which consumption is at a corner solution of zero) so that value of the marginal unit consumed is proportional to the price. On the other hand, an adjustment for unmeasured changes in consumer surplus is needed when new goods appear and existing goods exit. A number of widely used free digital services (including Facebook, YouTube, and Google Maps) appeared after the start of the productivity slowdown.

When a new good appears, we can suppose that, in the prior period, it was offered for sale at the "virtual price" that just drove demand to zero. The area under the demand curve from the virtual price down to the actual price of the good after it entered is the consumer surplus that measures the gains from the new good. Even in the case of a free new good, the consumer surplus implied by the fall from the virtual price to the actual price of zero might be substantial.

Furthermore, the costs of the broadband or wireless connection and the device needed to access the digital services means that these services are not entirely free. Greenstein and McDevitt (2009), for example, use data on the growth of broadband access services, and estimate

[23] The online appendix shows that the Laspeyres and Paasche quantity indexes that are averaged to obtain the Fisher index are upper and lower bound measures of the relative change in consumer surplus.

that the uptake of broadband generated an average of $0.3 billion per year in unmeasured consumer surplus in 1999 and 2003, and an annual average of just over $1 billion in 2004-2006.

3.3. Alternative Treatments of Advertiser-Supported Digital Services

Although a strict application of the principle that the marginal value of a service is proportional to its price would imply that free online services have no effect on the change in real consumption except when they are newly available, the infra-marginal value of these services is not zero. In addition, many of these services did, in fact, become available near or after the start of the productivity slowdown. We therefore consider the effects of including a measure of these services in household consumption.

The national accounts do include the free information services provided by Wikipedia in final consumption because it is a nonprofit institution serving households. Yet most free digital services are supported by advertising. In the national accounts, a business whose revenue comes entirely from advertisers is treated as providing all of its services to the ad buyers. Broadcast TV services have, for example, long been counted in the national accounts as an intermediate input: Companies buy advertising, so major broadcasting networks such as ABC or NBC are like an ad agency. Many internet services have that same treatment: Facebook and Google are counted as providing advertising services to businesses, not services consumed by households.

Building on an earlier literature that debated the treatment of broadcast television in national accounts, Nakamura and Soloveichik (2015) propose a framework for counting the entertainment and information services that are supported by advertising revenue in households' consumption, with the services valued at their cost of production. The framework is based on the observation that consumers implicitly pay for the entertainment and information by watching ads (or, in some cases, providing valuable personal information). The "time taxes" τ_I and τ_{TV} were not included in the cash budget constraint (1.4) because they do not have an explicit price. But, conceptually, they can be viewed as part of a barter transaction that can be imputed between households and firms. In this barter transaction, the time that consumers spend viewing ads is a service purchased from households by providing them with entertainment or information services. Recording consumption of advertiser-supported services by households in the national accounts would, for example, prevent a distortion when programming moves from free TV to a format that consumers pay for explicitly.

When the "free" entertainment/information services are added to households' consumption, GDP goes up by the value of the extra household consumption. But the national accounts need to balance—someone has to produce the extra value added. The TV networks or the providers of the online services have the same capital and labor; their value added does not change. Rather, on the production side, the rise in GDP can be traced to households' production of "ad-watching services." With no change in the output consumed by the advertisers, recording output sold to households requires us to impute an equivalent amount of purchases of services from consumers who view the ads.

This approach is reasonable: it monetizes an implicit barter transaction that consumers undertake with Google and Facebook and other advertising-supported service providers and it recognizes that consumers value the services they receive. Nevertheless, treating consumers as supplying ad-watching services would not change business-sector productivity because the ad-watching services are outside the boundary of the business sector! The intermediate inputs of the ad-watching services used by the business sector would have to be added to the input side of the productivity calculation, and this would exactly offset the effect of adding the extra output.[24]

[24] Another concern with this treatment of ad-watching services is that a more explicit agreement for consumers to watch the ads to receive the services would be required for the ad watching to be viewed as part of a barter transaction under international national accounting guidelines (United Nations, *et al.*, 2009, para. 3.51 and 3.53).

Productivity measurement **will** be affected if some of the output that the national accounts currently include in intermediate consumption of the ad buyers is instead treated as consumed by those who directly benefit from the entertainment and information services. In the international guidelines for national accounts, payments for permission to access nonproduced assets are a type of income transfer that does not purchase any services called a rent (United Nations *et al.*, 7.153). If part of the price of an ad is a rent paid to the broadcaster or digital service provider for access to the viewer base or user base, then that part of the ad price does not, in fact, represent a purchase of services. Treating a component of ad prices as a rent would therefore raise the measure of the value added of the ad buying industries.

Let A be the size of the user community for a free digital service, which serves as the audience for the ads. Also, let P be the price per view that the digital service provider receives, and let N be the number of times each user sees an ad during a single time period. Ad revenue in period t therefore equals $N_t P_t A_t$. Assuming the direct cost of displaying an ad to the audience A is DA, and that the cost of providing services to the community of users is $C(S)$, cash flow in period t equals $N_t P_t A_t - N_t D_t A_t - C(S_t) = N_t \hat{P}_t A_t - C(S_t)$, where $\hat{P}_t = P_t - D_t$.

Users of the free services are “sticky” enough so that the user community is akin to an intangible capital stock, albeit one that does not arise from an investment process. Let the rate of decay of A equal δ and the interest rate equal r. Then the digital service provider’s problem in period t is one of choosing N_t and S_t to maximize the present value of the cash flow stream:

$$N_t \hat{P}_t A_t - C(S_t) + \frac{N_{t+1} \hat{P}_{t+1} A_{t+1} - C(S_{t+1})}{1+r} + \cdots$$

In the online technical appendix we show that setting the derivative to zero implies that the marginal cost of producing digital services equals the present value of the marginal net revenues from the resulting increase in A:

$$N_t \hat{P}_t \frac{\partial A_t / \partial S_t}{r + \delta} = C'(S_t)$$

The marginal cost of digital services is proportional to the marginal willingness to pay of the advertisers. This price could be smaller than the willingness to pay of the users.[25] It is, however, appropriate to use the price that the producer cares about when measuring output from the producers' perspective (but in measuring the associated real consumption a deflator for the cost of producing the online services should be used).

Note that $C'(S_t)/(\partial A_t/\partial S_t)$ is the marginal cost of adding to A, so we can define u_t as an audience access rent that is analogous to a user cost price of the "services" of the intangible asset, $u_t = (r + \delta)C'(S_t)/(\partial A_t/\partial S_t)$. The ad price can then be partitioned into services component and an access rent component:

$$P_t = (1/N_t)[D_t + u_t]$$

Under the approach that treats ad watching as a payment for the digital services the cost of producing the digital services serves as the measure of their value. Let the "markup" μ be the ratio of the rent collected from selling access to the audience to advertisers to the cost of producing the digital services needed to attract the audience. The standard treatment and the two alternative treatments can then be summarized as shown in the table below.

	Standard treatment	**Ad viewing as barter**	**Part of ad price as rent**
Services to advertisers	$NDA + NuA$	$NDA + NuA$	NDA
Services to consumers	0	NuA/μ	NuA
Services from consumers	0	$-NuA/\mu$	0
Total value added (excluding other inputs)	$NDA + NuA$	$NDA + NuA$	$NDA + NuA$

[25] For example, the cost of producing the show *Longmire* was higher than the advertising revenue that it generated, but lower than the willingness to pay of *Netflix* viewers.

1.4 Significance of free digital services for our productivity measures

The effect of allocating the part of output of the providers of free entertainment and information services to household final consumption is noticeable in the case of the GDP level. When services to households from traditional print and broadcast media are included along with digital services, the level of U.S. GDP shifts up by about 0.5 percent (Soloveichik, 2015b). On the other hand, the effect on the growth rate of real GDP is small. In Nakamura and Soloveichik (2015, Table 3) real advertising services have an average growth rate of 2 percent from 2004 to 2013, while the real output of the business sector used in productivity measurement grows at just over 1.5 percent per year. Assuming that the real growth rate of the advertising-supported services was the same as the real growth rate of the advertising and using a share weight of 1.3 percent of business sector implies an upward revision of 0.0065 percentage points to productivity growth in the slowdown period when the advertising-supported services are added to consumption. A similar adjustment in the pre-slowdown period would, however, be larger, so this adjustment does not reduce the size of the productivity slowdown.

On the other hand, the appearance of online advertising may have led to a kind of new goods bias in the deflator for advertising. Soloveichik's (2015b) estimate of the 2012 cost per viewer-hour of an online advertisement is 11 cents, compared wth 54 cents for broadcast TV. The lower cost of attracting ad viewers by providing free digital services suggests that for purposes of ad delivery, the replacement of other forms of advertising by online advertising may represent a large productivity gain. For example, in the business model of Facebook, consumers create the content for free, making the cost of attracting users to the website quite low.

Suppose, for example, that the quality-adjusted cost of online advertising is half of the cost of advertising via traditional media. A unit value price index that would capture this substitution can be calculated as the change in a share-weighted harmonic mean, so the rise in the market share of online advertising from 7 percent in 2004 to 27 percent in 2013 reported by Nakamura and Soloveichik implies a unit value price index for advertising of 84.25 and an average annual growth rate adjustment of –1.9 percent per year. With a 1.3 percent weight of advertising in the output of business, the implied adjustment to productivity growth would then be about 0.025 percent per year.

Finally, it is worth noting that some of the welfare effects of free digital services involve better choices of where and what to buy made possible by reductions in information costs attributable to online services. Information from TripAdvisor or Yelp may improve restaurant selection (and even have dynamic spillover effects by making bad restaurants improve or exit.) In addition, online information and online shopping have brought about a large expansion in the set of available varieties. A cost of living index that measured the gains from improved matching of products and product varieties to consumers' preferences and circumstances would undoubtedly show that they are substantial.

Divergences between welfare change and real GDP when activities shift between market production (that is, production that generates money income) and non-market production made possible by the Internet arise in other contexts, as well. A large fraction of the travel agent business has, for example, been replaced by consumers doing online searches and then making their own reservations. Yet it is worth remembering that welfare changes from substitution between non-market activity and the market activity are not a new phenomenon. In the early 20th century, for example, paid domestic workers did many tasks that by mid-century had been taken over by the homeowners themselves. Conversely, home appliances such as washing machines served as "engines of liberation" (Greenwood, Sheshadri, and Yorokolglu, 2002) that led to a dramatic increase in labor-force participation by women. Furthermore, despite the undoubted substitutability of non-market for market production in generating consumer welfare, many of the applications of the main measure of productivity require a concept that is cleanly defined as a measure of the relation between output and inputs in the market sector. Incorporating many imputations for non-market output would also make the productivity measure more subjective and model-driven, as opposed to data-driven. Gains in non-market output and their contribution to welfare, though relevant, are best treated as a separate concept from productivity change.

4. E-commerce and Gains in Variety and Match Quality

E-commerce has continued to grow rapidly in importance both in business-to-business transactions and business-to-consumer transactions ever since the mid-1990s. Although business-to-business e-commerce has had effects that make the measurement of aggregate productivity more difficult, such as contributing to outsourcing and to reorganization of production into global supply chains, it is the unmeasured benefits to consumers from e-commerce that are allegedly an important source of overlooked productivity gains.

Retail sales are a reasonable proxy for sales to households that would count as final consumption. According to the Census of Retail Trade, the share of e-commerce in retail sales was 0.9 percent in 2000, 1.8 percent in 2003, 2.9 percent in 2006, 4.0 percent in 2009, 5.3 percent in 2012 and 6.8 percent in 2015.[26] These relatively large shifts in purchasing patterns suggest that consumers have enjoyed substantial gains from e-commerce. These gains include

[26] Note that these percentages are held down by the inclusion in overall retail sales of some items that are not well-suited for ordering online, such as gasoline and building supplies. The Census Bureau defines e-commerce as covering purchases made over the internet or other electronic network or via email.

savings of time and transportation costs, and the ability to search over broad and deep sets of varieties that are available for purchase.

Brynjolfsson, Hu and Smith (2003) estimate the gains from increases in variety related to the large number of books in print that are easily found and ordered from Amazon and other online booksellers. The compensating variation from the appearance of a new good with a constant price elasticity of $\alpha < -1$ may be approximated by dividing its post-entry sales $1+\alpha$. In 2000, out of $24.59 billion in total book sales, the authors estimate than $578 million were from online purchases of obscure titles that would have been hard to find at brick-and-mortar stores. The range of the price elasticity estimates imply a range of compensating variation estimates of $731 million to $1.03 billion, or around 3 to 4 percent of total book sales that year.

The assumption of a constant demand elasticity all the way back to y-axis may lead to overestimation of the area under the demand curve used to measure the compensating variation, and there are also losses in consumer surplus from the disappearance of brick-and-mortar book stores. Feenstra (1994) develops a formula that tends to give more conservative estimates of the unmeasured gains from growth of variety based on a CES model with the elasticity of substitution $\sigma > 1$. Let λ_t equal 1 minus the share of expenditures in period t going to new varieties, and let λ_0 be the 1 minus the share of expenditures in period 0 going to varieties that disappear in period 1. Then the welfare change from differences in the availability of varieties can be accounted for by multiplying the CES price index calculated from just the continuing varieties by a factor of $(\lambda_t / \lambda_0)^{1/(\sigma-1)}$. The elasticity of substitution between different varieties of the same good is usually high; a σ of 4 would be typical. With this assumption for σ and assuming no variety disappearances, the 2.35 percent market share garnered by obscure book titles made newly accessible by the internet would imply a correction to the price index of

–0.8 percent, while with a relatively low assumption for σ of 3 the bias would be –1.2 percent. These gains accumulated over a period of several years, so on an annual basis they would be smaller.

Books, of course, are not the only type of good with increased availability of varieties on the internet. The variety of recorded music has, for example, expanded even more. One approach to estimating the gains from e-commerce in general is to view e-commerce itself as a sort of new variety. Using a value of 4 for σ then implies a correction in 2012-2015 of –0.17 percent per year to the price index for goods bought through retail channels based on the average gains of 0.5 percent per year in the market share of e-commerce. In 2000-2003 the correction for gains from e-commerce is just –.11 percent per year, and in the late 1990s it was smaller still. Personal consumption expenditures on goods amount to about 25 percent of the gross value added of business excluding housing. Using this as a weight on the bias in the retail sales price index, implies an upward correction of just over 0.04 percent per year in business sector productivity after 2012 and under 0.03 percent per year in the period preceding the productivity slowdown. Introducing a correction for gains from e-commerce would therefore shave around than 0.01 percent per year off of the productivity slowdown.

Lower search costs and more variety at online outlets mean that better matches are possible between product characteristics and consumers’ individual tastes and circumstances. Yet the benefits of free (or low cost) online information for improving match quality extend beyond e-commerce. Many consumers routinely read online reviews written by fellow consumers before choosing a restaurant, vacation spot or consumer product. The Internet has also brought about new markets for used goods through webites such as eBay and Craig’s List. Making more efficient use of what we have raises welfare, but does not represent an outward shift in market output or even the production possibility frontier that is achievable with a given factor endowment.

A well-known example the need to distinguish between increases in welfare and productivity gains occurs with changes in terms of trade. Favorable shifts in export and import increases the opportunity to gain from trade, allowing real consumption to rise as the economy moves to a different point on the production possibility frontier. Although these gains in potential real consumption imply an increase in real gross domestic income, such an increase in income cannot be attributed to a productivity gain. Similarly, welfare gains from better utilization of a given level of output ought to go in different category from a productivity improvement.

5. Other Measurement Problems that Made the Productivity Slowdown Seem Worse

We now consider two other measurement issues that do, to a small degree, contribute to the slowdown in measured productivity growth. The first is fracking, where the technological innovations that allow access to lower "quality" natural resources is imperfectly measured. A back-of-the-envelope calculation suggests that true aggregate labor and TFP growth might be 5 basis points faster since 2004. The second is globalization, where the import-prices declines from offshoring are largely missed. This led to an understatement of true import growth in the late 1990s and early 2000s (around the time of China's WTO accession), and a corresponding overstatement of perhaps 10 bp in growth in output, labor productivity, and TFP. These effects were included in the "other" category in Figure 1.

5.1. Technological Innovation in Oil and Gas Extraction: the Fracking Revolution

In the industry TFP data discussed in Section 1, oil and gas extraction had strong TFP performance in the 2007-2013 period. And yet, mining is always difficult for productivity analysis because of unobserved variation in the "quality" of the natural resources. Technological innovations in the 2000s made it possible to extract oil and gas from previously uneconomic geologic formations. This technological change means that oil and gas structures almost surely improved more rapidly than in the statistics, so true growth in mining structures was almost surely faster than measured. Because of this innovation, a key input (land quality) effectively fell in quality. As we discuss, our benchmark estimate is fracking technologies imply that true labor productivity and TFP growth were about 5 bp faster in the post-2004 period.

In the 2000s, a cost-effective way to extract natural gas from shale using horizontal drilling and hydraulic fracturing discovered in the late 1990s was improved upon and extended to the extraction of oil from shale and other low permeability formations. As a result, the last half of the 2000s saw a remarkable resurgence in US oil and gas production (Figure 7). Among its impacts have been a hasty repurposing of import facilities being built for liquefied natural gas (LNG) as export facilities, and a change in OPEC's pricing strategy.

Wells that embody a novel technology that makes it economical to extract deposits that were previously impossible to exploit have many of the characteristics of a new good whose appearance would be missed by conventional measures of TFP. Conventional TFP would not capture all of the gains from a new technology that allows extraction of an oil or gas deposit with unfavorable physical characteristics that would previously have been left in the ground.

Nordhaus and Kokkelenberg (1999, 63-64) observe that deposits of an exhaustible natural resource vary in their costs of extraction. Above some cutoff level of rent (the difference between extraction cost and the market price of output) extraction does not occur. Suppose, for example, that technological progress reduces the unit cost of extraction for all deposits. Now, $\pi > 1$ units can be extracted from any given deposit in period 1 with the same inputs of labor and capital that produced 1 unit in period 0. The market price of output is set on world markets and does not change, and neither does the cutoff level of rent for extraction to be undertaken. Deposits that were previously uneconomic now begin to be extracted. The level of productivity at the least productive establishment remains constant, while that of the most productive establishment rises from λ_0^{max} to $\lambda_1^{max} = \pi\lambda_0^{max}$. Assuming productivity levels are uniformly distributied across establishments from 1 to λ_0^{max} and that all establishments are identical in size as measured by inputs, measured productivity growth for the industry, denoted by $\hat{\pi} - 1$, equals:

$$\hat{\pi} - 1 = \frac{1 + \pi\lambda_0^{max}}{1 + \lambda_0^{max}} - 1 = \frac{\lambda_0^{max}}{1 + \lambda_0^{max}}(\pi - 1)$$

For example, if $\lambda_0^{max} = 2$, only two-thirds of true productivity gains would be measured.

In cases where inputs of labor and capital are being substituted for inputs of land, properly accounting for land as a factor of production is likely to result in a lower measure of aggregate inputs growth, and a higher measure of TFP growth, than official methods yield.[27] Careful measurement of land services in mining, and elsewhere, is challenging. In the BLS productivity data, oil and gas extraction apparently uses almost no land, because subsoil mining rights are included with the structure. Based on work by Zheng and Block (2014), roughly half of the value of structures investment in oil and gas actually represents subsoil natural resources.

[27] An alternative approach to measuring multifactor productivity for mining that includes services of natural resource assets is discussed in Schreyer, Brandt and Zipperer (2015). The Australian Bureau of Statistics (ABS) publishes an experimental measure of MFP for mining that includes services of subsoil natural resource assets in inputs. In the tables released in December 2015, this raises the estimated growth rate of mining MFP over 2000-01 to 2014-15 from –4 percent per year to –1 percent per year. Similarly, Zheng and Bloch (2014) find that adjusting for inputs of natural resources, declining returns to scale and capacity utilization raises MFP growth for the mining industry of Australia between 1974-75 and 2007-08 from –0.2 percent per year to 2 percent per year.

Accounting properly for technological progress in oil and gas industries requires an assessment not only of land quality changes, but also quality-adjusting the fixed assets that embody the technological improvements. These consist primarily of oil and gas wells drilled for exploration or development purposes. The quality adjustment would reflect the cost reduction made possible by better technology while holding constant the mix of deposits being exploited.

As a back-of-the-envelope calculation, accounting for technology change in the oil and gas structures (which in the NIPAs include intangible mineral exploration assets) plausibly raises aggregate labor productivity and TFP growth about 5 basis points per year in the late 2000s. Specifically, in the post-2004 period the average share of investment in oil and gas structures in value added of business is about 0.9 percent. But, plausibly about half of that is the structure itself (which is improving), or about 0.5 percent of business value added; the remainder is actually the subsoil asset (where the quality is getting worse). In terms of output (i.e., final investment), suppose there is a fairly large true quality adjustment to the price index for oil and gas extraction structures of 10 percent per year after 2004. Multiplying that by the assumed 0.5 percent share of business value added implies that true investment is about 5 bp faster. That goes directly into the "other" portion shown in Figure 1, boosting labor productivity in the post-2004 period. For TFP, the question is how much capital is improving and land is deteriorating. As a rough first pass, we assume the two effects offset—leaving measured capital growth about right. In that case, the 5 bp increment to labor productivity also passes through to aggregate TFP.

5.2. Globalization

As mentioned above, standard techniques for constructing price indexes do not capture the change in the average price paid by the buyers of a product when they alter their purchasing patterns to buy from a different seller. Furthermore, the import price indexes (MPI) used to construct deflators for imports in the NIPAs do not capture changes in the price paid by buyers when they switch from a domestic source to an offshore producer.

The failure to measure the price change when the sourcing for an item moves offshore or moves to a different import supplying country results in bias in the deflators for imports and in the estimated growth rate of real imports.[28] This bias was particularly significant in the late 1990s and early 2000s, when the location of many kinds of manufacturing was shifting rapidly from the US and other countries with high labor costs to emerging market economies. One impetus for this was China's 2001 accession to the World Trade Organization (WTO), which coincided with the start of a large shift in the sourcing for many manufactured goods used in the US to China. Another was a multilateral free trade agreement that reduced tarrifs for IT products to zero over an interval of four years ending in 2000, which accelerated international sourcing changes for IT products (Feentra, Mandel, Reinsdorf and Slaughter, 2013).

Reinsdorf and Yuskavage (2015) use two approaches to estimate the sourcing bias for imported consumer goods in 1997-2007 and find a bias in range of 0.8 to 1 percent per year for durable goods including computers, and around 0.6 percent per year for imported apparel and footwear. However, even if we assume that the bias estimate of 1 percent per year for durable goods can be generalized to similar kinds of imported capital goods and that the bias in in the apparel index can be generalized to all textile products, the upward bias in business TFP is only 0.1 percent per year because the affected kinds of imports have a relatively small weight in GDP.

Another aspect of globalization made possible by reductions in the cost of telecommunications is international trade in services over a wire. The number of American jobs that could potentially be offshored to a country with lower wages has been estimated to be very

[28] This problem is examined in Houseman, Kurz, Lengermann, and Mandel, 2010 and 2011, and in a news story by Mandel, 2009.

large (Blinder, 2009), and the offshoring of services could lead to the same sort of upward bias in measures of productivity that is caused by offshoring of goods. Thus far, however, the effects have been modest.

5.3. The "Sharing" Economy

In principle, nominal GDP already includes transactions from the sharing economy, such as rides on Uber and Lyft. Whether this is true in practice is unclear: the Quarterly Census of Services indicates slowing nominal growth of the local transportation measure that includes taxis, which is where one would expect to find the new kinds of local transportation services. Even if included, it is unlikely that the deflator used to compare the new services to previously existing ones correctly measures the decline in quality-adjusted price experienced by many consumers. Thus, there is probably some (at this point very, very small, but likely growing) downward bias in the growth rate of real GDP from the emergence of the sharing economy.

It would be useful to have official statistics on the nominal output of the various types of services included in the sharing economy. Research indexes of price change could then be developed to try to calibrate the size of the bias.

6. Conclusions

The "productivity paradox 2.0" remains alive: Despite ongoing IT-related innovation, aggregate U.S. productivity growth slowed markedly after 2004 or so. We propose several adjustments to IT-related hardware, software, and services. The good news is that the adjustments make recent growth in GDP and investment look modestly better than recorded. The bad news is that it makes the paradox even worse—the slowdown in labor productivity is even larger after our durable-goods adjustments, while the slowdown in TFP is not much affected. The reason is that mismeasurement was substantial in the 1995-2004 period as well as more recently, and rising import penetration for computers and communications equipment means that domestic production (which matters for GDP) has fallen over time. Moreover, that the slowdown was broadbased suggests that ongoing innovation in IT is not substantially spilling over into other areas. Other measurement challenges, such as globalization, factoryless manufacturing, and fracking, only modestly explain the slowdown: Correcting for these factors can perhaps explain 2/10ths percentage point of the TFP slowdown.

Other evidence also suggests that true underlying growth is relatively modest. First, the U.S. productivity slowdown has been mirrored in many parts of the world (Eichengreen et al., 2015; Cette, et al, 2016). This suggests underlying macroeconomic factors may be driving the slow pace of growth, given the varied sources and methods used across national statistical systems. Syverson (2015) finds that the slowdown across countries is not correlated with IT production or use, again suggesting that the problem is not mismeasurement related to IT goods or services. Second, the decline in economic dynamism—both in the form of fewer startups and slower reallocation of labor resources in response to productivity shocks—supports the idea that productivity-enhancing innovations are diffusing through the economy more slowly (Decker et al., 2015; Haltiwanger et al., 2015). Relatedly, Mandel (2015) looks at labor market metrics such as occupational employment and help-wanted ads, and finds evidence consistent with tremendous occupational change in narrow segments of the economy (such as IT and oil/gas extraction), but little evidence suggesting widespread, rapid innovation.

If not mismeasurement, why did productivity growth slow? The slowdown predated the Great Recession, which suggests that event was not the story—or, at least, not the whole story. Given that growth was similar in the 1970s and 1980s as it has been since 2004, a plausible story is that it was the fast-growth 1995-2004 period that was the anomaly. With the Internet, the reorganization of distribution sectors, and the like, a lot of things came together in a short period of time. With hindsight, that looks like a one-time upward shift in the level of productivity rather than a permanent increase in its growth rate. Looking forward, we could get another wave of the IT revolution. Indeed, it is difficult to say with certainty what gains may yet come from cloud computing, the internet of things and the radical increase in mobility represented by smartphones. But, since the early 1970s, modest and incremental productivity growth has more often been the norm.

Changes in overall welfare are somewhat harder to assess. Transformative gains related to mobile technologies and the Internet clearly raise welfare. We argued that most of those gains properly belong outside the purview of market-sector GDP—and proposals to incorporate them into GDP raise concerns. But that does not mean these innovations are not valued by households—they are. Still, the available estimates of the welfare gains (based on the value of leisure time) suggests that "free" digital services add the equivalent of perhaps 3/10ths percent of GDP per year to wellbeing. That is small relative to the 1-3/4 percent slowdown in labor productivity growth in the business sector from 2004-2014.

Nevertheless, much is unknown. Shapiro and Wilcox (1997) described the field of quality adjustment as "house to house" combat in the area of national accounting. The analysis needs to be done product by product. And so, statistical agencies are always forced to play catch up.[29] Digital services are a particularly challenging area, where satellite accounts could help shed light on a measure of economic activity that extends beyond the market. And in general, increased discussion and incorporation of research on quality change would improve the light shed by the published accounts.

[29] Wasshausen and Moulton (2006) discuss how statistical agencies incorporate quality adjustments into the accounts.

Finally, we conclude with implications for policymakers. Slow productivity growth, if it persists, implies slow potential growth going forward. Benefits in the nonmarket sector can offset that somewhat for well-being, but it does not help with taxes or the budget.

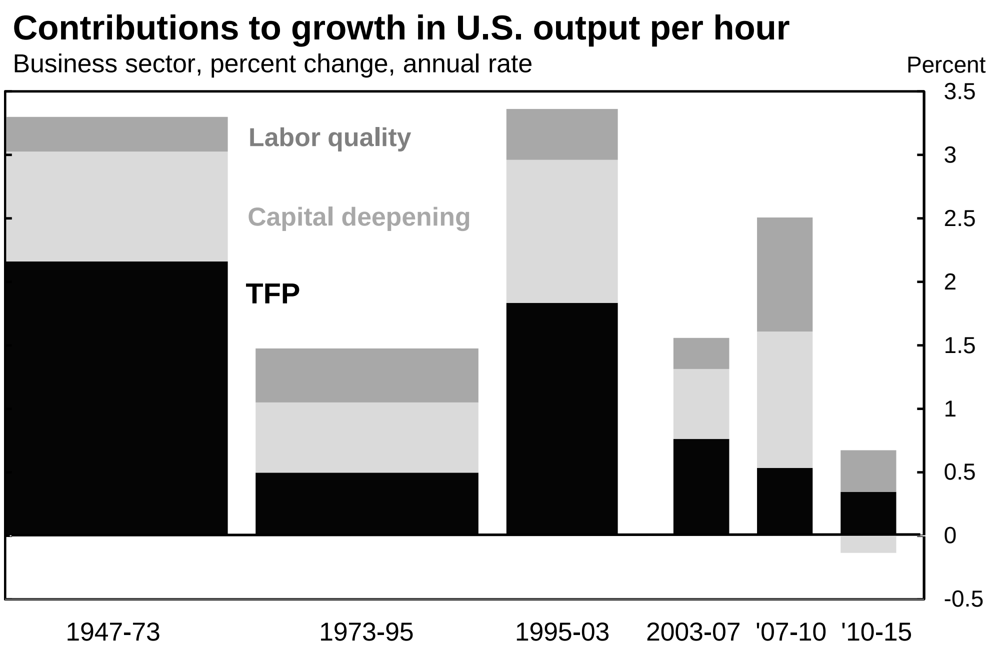
Appendices

6.1.Appendix A: Data

Fernald (2014) Quarterly Growth-Accounting Data. Data run 1947:Q2-2015:Q4, although all data are converted to annual for the paper. The vintage used for this paper was mainly from February 4, 2016. Current vintage data are available at http://www.frbsf.org/economics/economists/jfernald/quarterly_tfp.xls. The dataset includes quarterly growth-accounting measures for the business-sector, including output, hours worked, labor quality (or composition), capital input, and total factor productivity.

Output is a geometric average from the income and expenditures sides. Hence, labor-productivity growth in Figure 1 will differ very slightly from the BLS Productivity and Cost dataset, which uses the expenditure-side measure of output. Capital input is a user-cost-weighted aggregate of capital input growth of disaggregated types of equipment, software, intellectual property, and inventories that are available quarterly, as well as land (which is interpolated from annual BLS estimates).

The figure below shows a bar chart of business-sector labor productivity with its growth-accounting components since 1947.



Source: Fernald (2014a). Quarterly; samples end in Q4 of years shown except 1973 (ends Q1). Capital deepening is contribution of capital relative to quality-adjusted hours. Total factor productivity measured as a residual.

“Normal” growth has varied substantially over the post-war period. Before 1973 and from 1995-2003, labor productivity rose at above 3 percent per year. In between, its growth rate averaged only about 1-1/2 percent per year. The rapid growth in the late 1990s and early 2000s came to an end sometime between 2003 and 2006—a slowdown that is statistically significant in break tests.[30]

In the four years prior to the Great Recession (2003-2007), labor productivity rose at only about a 1-1/2 percent pace. Its growth rate then rebounded modestly during and (especially) immediately after the Great Recession (2007-2010). Yet, during the five years from the end of 2010 to the end of 2015, growth has been markedly lower. According to annual data back to the 19th century from Gordon (2016), this period is the lowest five-year growth rate recorded.

The shaded regions of each bar show the contribution of standard growth-accounting components: labor "quality" (or composition), capturing changes in the educational attainment and experience of workers; capital deepening, or capital per quality-adjusted hour; and TFP, measured as a residual. The contributions of labor quality and capital deepening have varied somewhat over time, but the broad patterns in labor productivity largely track TFP growth.[31]

According to the growth accounting, the weak performance in the final bar reflects capital "shallowing"—automation was, in effect, running in reverse. Mechanically, hiring has been extremely fast, with hours worked rising at about a 2 percent annual pace. In contrast, capital services have accelerated more slowly than hiring. To some extent, this reflects an unwinding of the strong pace of capital deepening during and immediately after the Great Recession: Employment fell in the recession, leaving firms with plentiful capacity. In addition, labor quality added less than during the recession, when low-skilled workers lost jobs.

For alternative capital simulations discussed in the paper, we adjust deflators and real investment quantities for information processing and software. The simulations use published nominal values of nonresidential gross private domestic investment for computers and peripheral equipment, communications, and software (NIPA Table 1.5.5). The alternative deflators are then used to calculate alternative real investment series, which are then accumulated via perpetual inventory methods into real capital stock measures by assets. They are then aggregated with user costs into an alternative Tornquist index of real capital input.

BLS Industry Data.

Industry multifactor productivity (MFP) data were downloaded from http://www.bls.gov/mfp/mprdload.htm (accessed August 11, 2015). "Well measured" industries follow Griliches (1994) and Nordhaus (2002). IT-producing industries and wholesale/retail trade are broken out separately. "Other well measured" comprises manufacturing (excluding IT producing), agriculture, mining transportation, utilities, broadcasting, and accommodations. Everything else is in poorly measured. See Fernald (2014b) for further details.

Intangibles: Data are from Corrado and Jäger (2015), which in turn updates U.S. estimates from Corrado et al. (2009) and Corrado et al (2012). Carol Corrado provided these unpublished data on nominal intangible investments from 1977-2014 (via email on February 12, 2016). To convert the data to real values, we deflate with the business-sector deflator. For initial capital stock values, we calculate investment growth rates (g) for the first 10 years and then use the "steady state" formula that $K_0 = I_0/(\delta + g)$, where I_0 is the initial real investment value and δ is

[30] Formal break tests justify the dates shown by the first three bars (see Fernald, 2014b). Exact break dates in the early- to mid-2000s vary with productivity series used, but fall in the range of 2003:Q4-2006:Q1.

[31] This standard measure of TFP does not adjust for cyclical effects on factor utilization. The Fernald (2014a) dataset does includes a model-based measure of factor utilization. Utilization adjustments turn out to make little difference in the subperiods shown here. Utilization had largely (though perhaps not entirely) reversed its sharp recessionary declines by the end of 2010. Of course, specific industries shown later could be different.

the depreciation rate. The depreciation rates are taken from Corrado et al (2009). For non-national-account intangibles, we aggregate the intangible capital stocks into a Tornquist index of capital input using estimated user costs. The user costs assume a constant real interest rate of 5 percent per year.

To aggregate intangible output with the Fernald quarterly TFP dataset, we use a Tornquist index. The weights are nominal business-sector output and nominal intangible spending. Similarly, we aggregate capital input with national-accounting measures with the new intangibles as a Tornquist index.

We also recalculate factor shares. Capital's share rises and labor's share falls. Intuitively, payments to labor don't change but nominal output is larger. Algebraically, the adjustment is $(1-\alpha_{New}) = (1-\alpha)\, PY/(PY + Intan)$, where PY is measured business-sector factor costs and *Intan* is nominal intangible spending. The numerator on the right-hand side gives payments to labor.

Appendix B: Adjusting output

For the simulations in Section 2.4, we adjust output (business-sector real GDP) for the assumed mismeasurement. (For capital, this is mainly described in the earlier appendix describing the Fernald TFP data.) This appendix shows that the main adjustment involves adding the Domar-weighted (i.e., industry nominal gross-output relative to aggregate value added) adjustment to domestic gross output growth.

We start with the Tornquist approximation to the chained Fisher index of value added. From the national accounting identity, the change in aggregate value added growth is:

$$dv = \sum_i w_i dv_i$$

dj is the log change in variable *J*. w_i is the value-added share of industry *i*. Industry value-added growth, using the Tornquist (Divisia) formula, is:

$$dv_i = \left(dy_i - s_{M1,i}dn_{1,i} - s_{M2,i}dn_{2,i}\right) \Big/ \left(1 - s_{N1,i} - s_{N2,i}\right) .$$

In this expression, dy_i is growth (log change) in gross output. $dn_{1,i}$ is growth in an intermediate input (such as semiconductors) where we might want to adjust the price/quantity. $dn_{2,i}$ is the growth of intermediate inputs that are not affected by our adjustments. $s_{N,j}$ are the respective intermediate-input shares of the two types of intermediates.

Adjusting deflators implies new measures of output and of the first intermediate. The new growth rate is

$$dv_i^{New} = \left(dy_i^{New} - s_{N1,i}dn_{1,i}^{New} - s_{N2,i}dn_{2,i}\right) \Big/ \left(1 - s_{N1,i} - s_{N2,i}\right) .$$

Thus, the adjustment to industry value added is:

$$dv_i^{New} - dv_i = \frac{dy_i^{New} - dy_i}{\left(1 - s_{N1,i} - s_{N2,i}\right)} - \frac{s_{N1,i}\left(dn_{1,i}^{New} - dn_{1,i}\right)}{\left(1 - s_{N1,i} - s_{N2,i}\right)}$$

Thus, if there are no changes in input prices/quantities, the change in value-added is a "grossed up" version of change in gross output. Otherwise, it is necessary to adjust off the appropriately share-weighted change in intermediate-input prices/quantities as well.

Of course, if the adjusted intermediate input (which we'll take to be semiconductors) is domestically produced, we get a positive output adjustment for that industry, but then an offsetting adjustment for using industries.

To see this effect, first note that $w_i / (1 - s_{N1,i} - s_{N2,i}) = P_i Y_i / PV$, i.e., the Domar weight (nominal gross output relative to nominal aggregate value added). So the weight on the "output adjustment" is just the Domar weight. It follows that the second weight, on the intermediate input adjustment, is $s_{N1,i} P_i Y_i / PV = P_{N,i} N_i / PV$.

Second, consider what happens when we adjust semiconductor prices. We need to add aggregate value added growth in (domestic) semiconductors, but subtract the effect of domestic and foreign semiconductors for their use as intermediate inputs. Straightforward but somewhat tedious algebra shows:

$$\begin{aligned}\sum_i w_i dv_i &= \frac{P_S^D Y}{PV}\left(dy_S^{D,New} - dy_S^D\right) - \sum_i \frac{P_S^D N_{S,i}^D}{PV}\left(dy_S^{D,New} - dy_S^D\right) - \sum_i \frac{P_S^F N_{S,i}^F}{PV}\left(dy_S^{F,New} - dy_S^F\right) \\ &= \left(dy_S^{D,New} - dy_S^D\right)\left(\frac{P_S^D Y - \sum_i P_S^D N_{S,i}^D}{PV}\right) - \left(dy_S^{F,New} - dy_S^F\right)\sum_i \frac{P_S^F N_{S,i}^F}{PV} \\ &= \left(dy_S^{D,New} - dy_S^D\right)\left(\frac{P_S^D X_S}{PV}\right) - \left(dy_S^{F,New} - dy_S^F\right)\frac{P_S^F N_S^F}{PV}\end{aligned}$$

The first term is the adjustment from domestic output multiplied by the nominal value of semiconductor exports relative to value added. The second effect is the adjustment to imported output, multiplied by the value of semiconductor imports to value added. In a closed economy, where exports and imports are zero, this effect disappears.

In sum, for final products, we weight the adjustment to prices/quantities by the so-called Domar-weight—i.e., the ratio of nominal industry gross output to aggregate value added. For semiconductors, we use an export weight for domestic production, then subtract off an import-weighted "foreign" adjustment.

For computers, communications equipment, specialized equipment, and A/V equipment, we obtained annual values of domestic production from Board of Governors databases. For software, we assume domestic production is equal to final sales of software for private investment (NIPA Table 1.5.5) or consumption (NIPA Table 2.4.5U).[32]

[32] This ignores government purchases of prepackaged or custom software (as well as net exports). From Table 5.9.5B, all government software investment (which includes own-account software that is not in the business sector) would add about 10 percent to production of software. That would affect the calculations by perhaps 1 or 2 basis points.

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Figure 1: Published and adjusted U.S. labor productivity

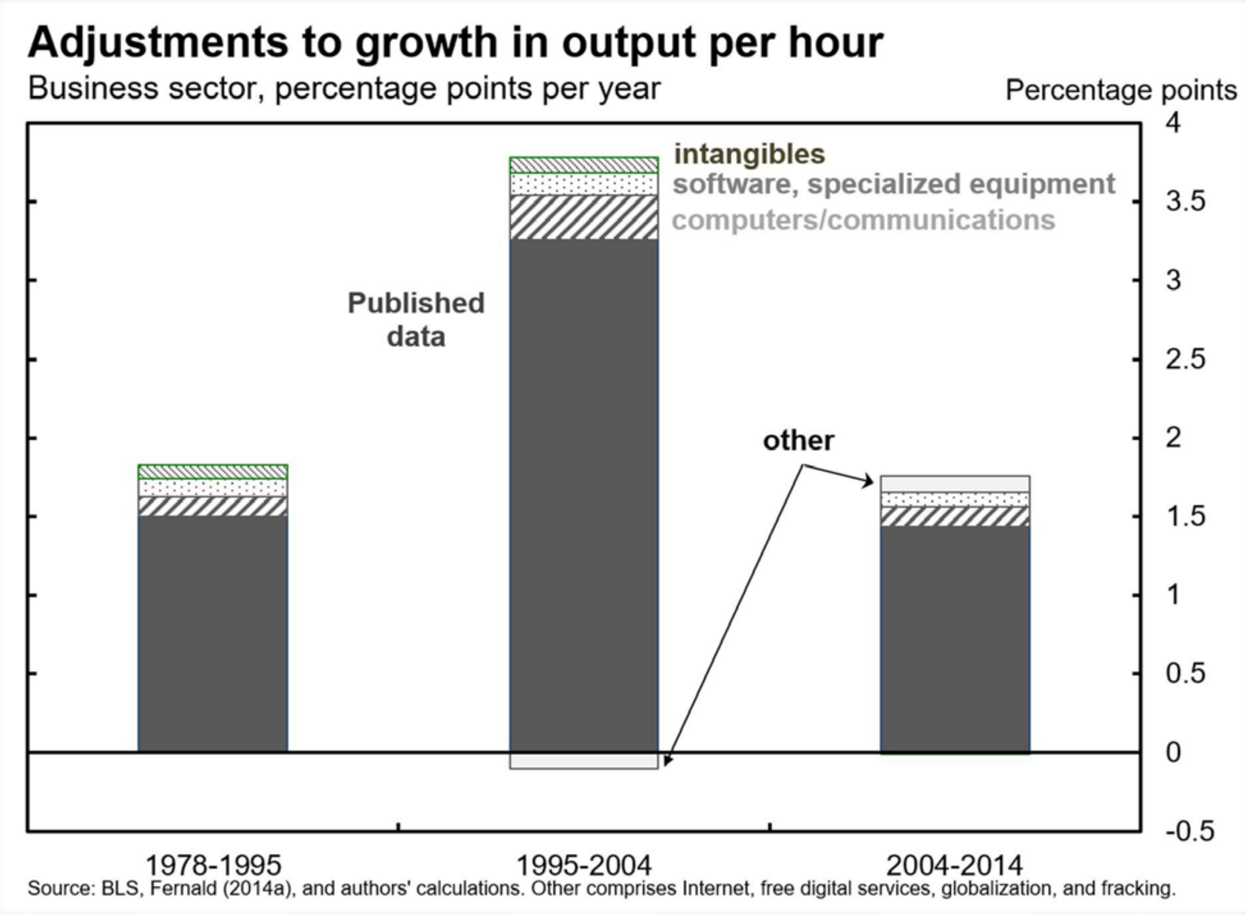
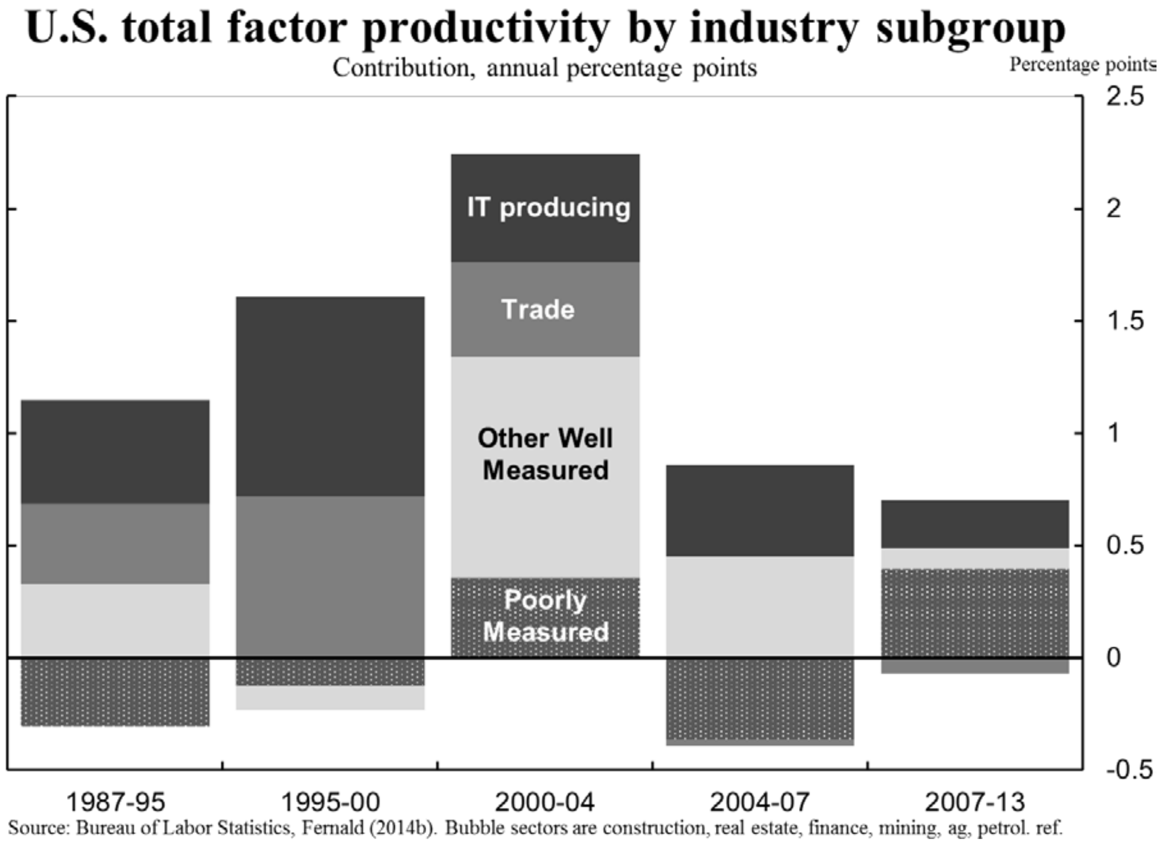
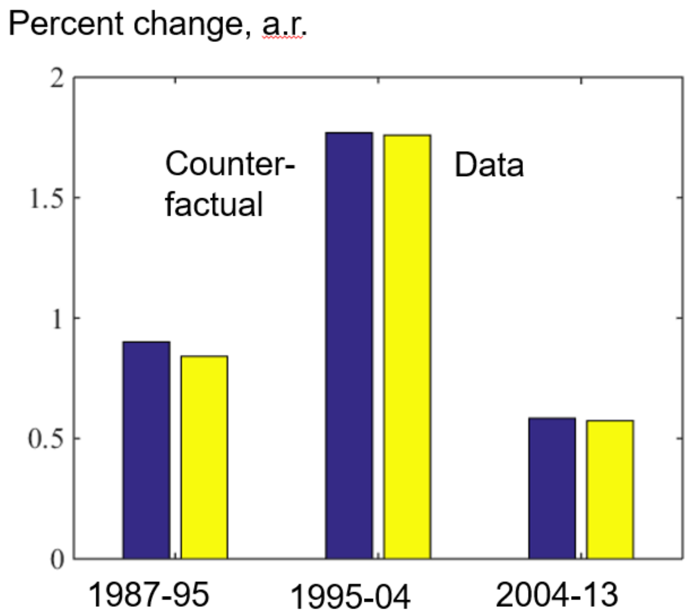


Figure 2: Contribution to U.S. TFP growth by industry subgroup



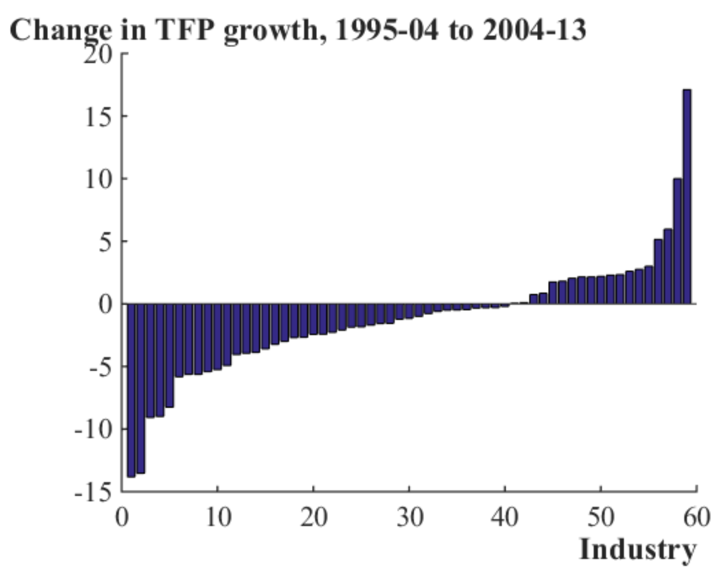
Notes: Aggregate TFP growth based on BLS industry data is decomposed into four mutually exclusive categories as shown. IT production is computer and electronic product manufacturing; publishing (including software); and computer systems design. Trade is wholesale and retail trade. “Other well measured” follows Nordhaus (2002), and comprises manufacturing (excluding IT producing), agriculture, mining, transportation, utilities, broadcasting, and accommodations. Remaining industries are in “poorly measured.” See Fernald (2014b) for further details. Source: BLS and authors’ calculations.

Figure 3A: Aggregate TFP growth holding industry weights fixed



Note: Yellow bars show actual average growth in business-sector TFP over period shown. Blue bars show counterfactual where industry weights are held constant at their 1987 values. Weights are industry gross output as a share of aggregate value added. Source: BLS and authors' calculation.

Panel B: Broadbased deceleration in TFP growth



Notes: Horizontal axes ranks business-sector industries by the change in value-added TFP growth after 2004, i.e., average growth 2004-13 less average growth 1995-04. Growth rates calculated as 100 times log change. The three industries with the largest (positive) acceleration in TFP growth are (i) funds and trusts, (ii) water transport, and (iii) oil and gas mining.

Figure 4: Prices for Information Technology

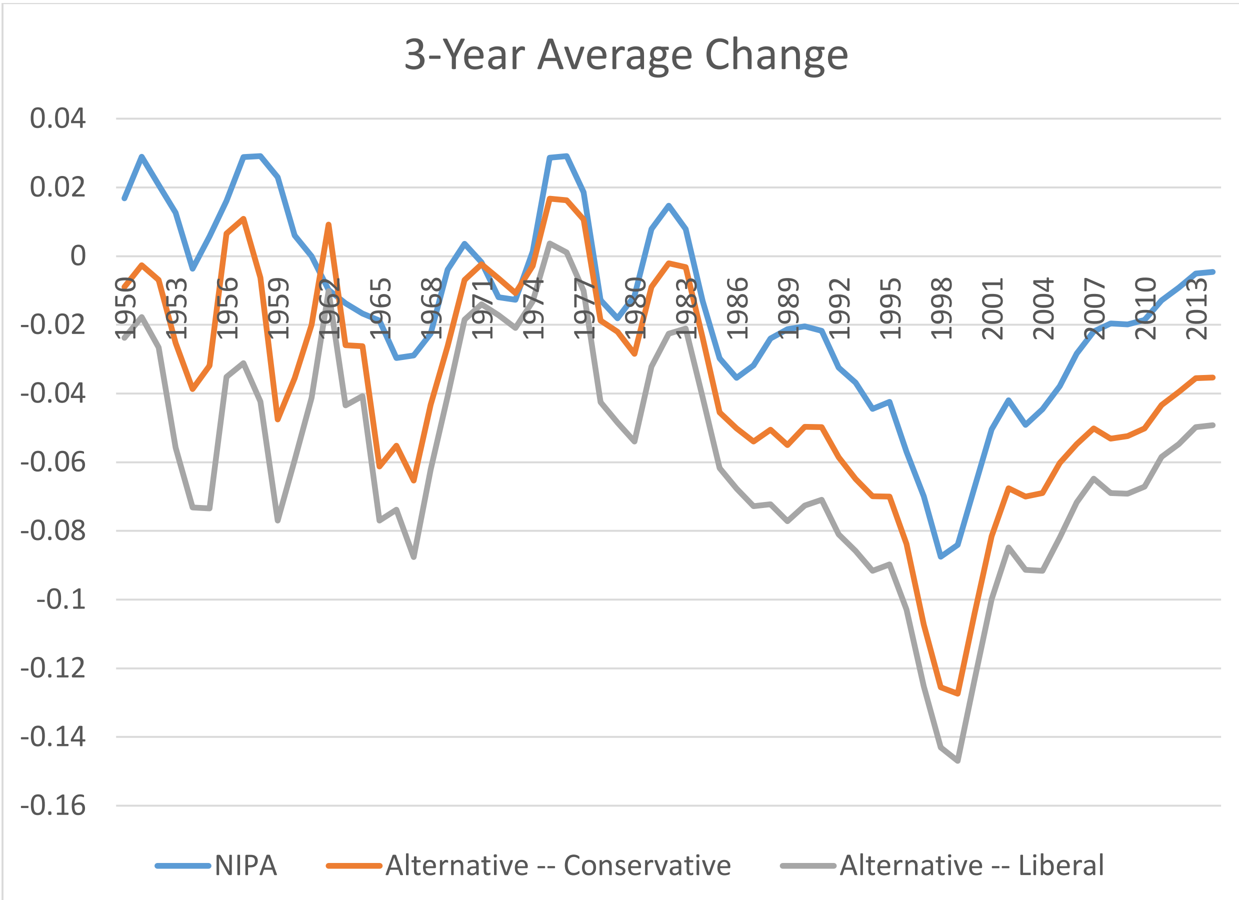
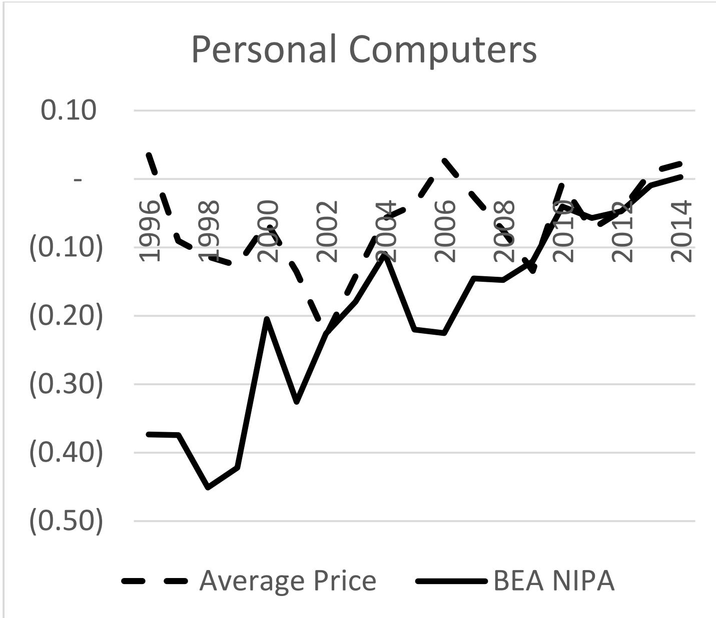


Figure 5: Prices for Personal Computers

Panel A: Implicit Quality Adjustment



Panel B: Domestic (PPI) and Imported Prices for PCs

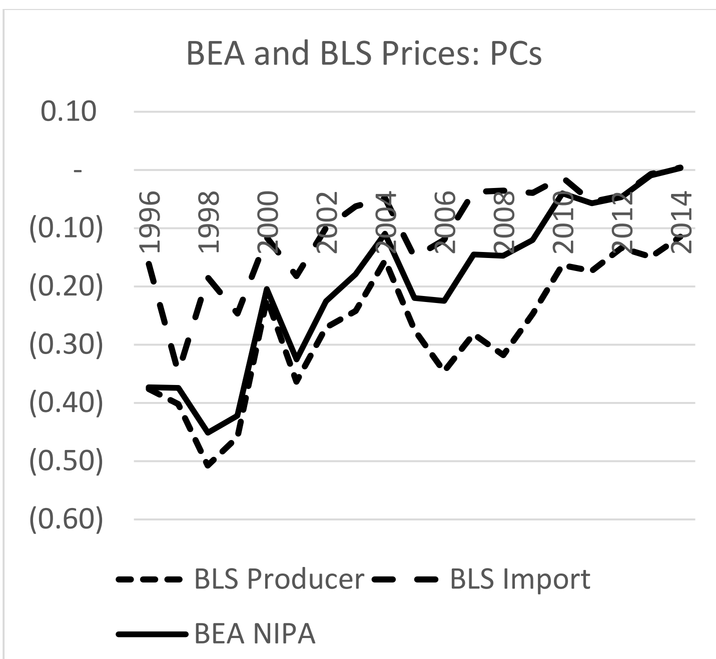
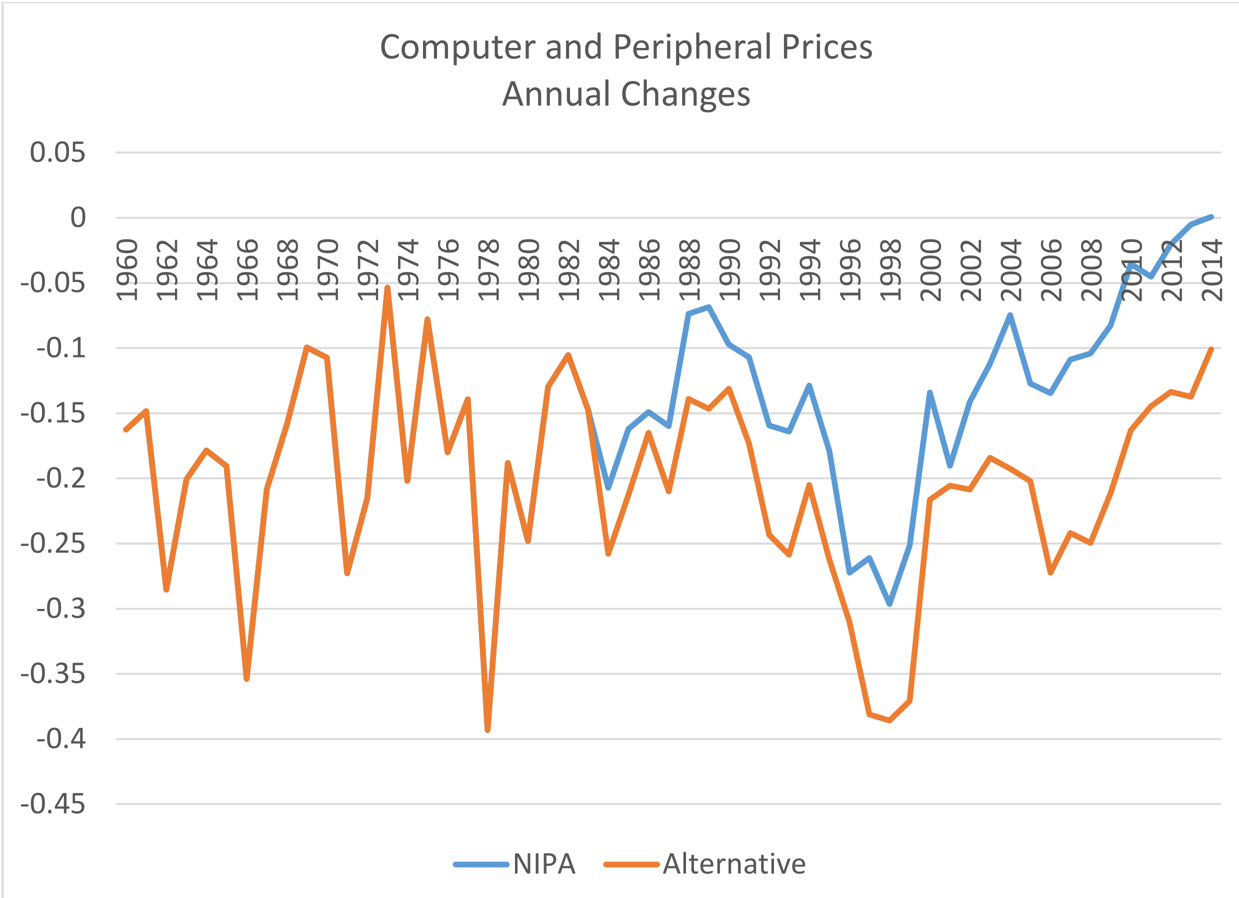


Figure 6: Official and alternative prices for computers and communications



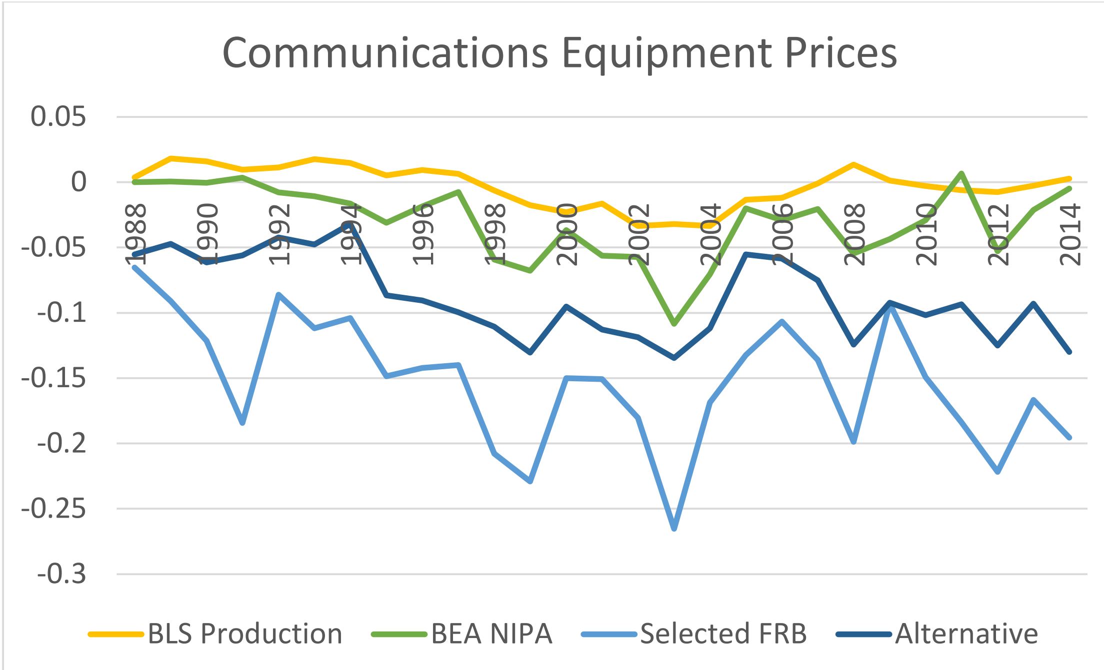

Communications Equipment Prices
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
BLS Production
BEA NIPA
Selected FRB
Alternative

Figure 7: U.S. production of oil and gas

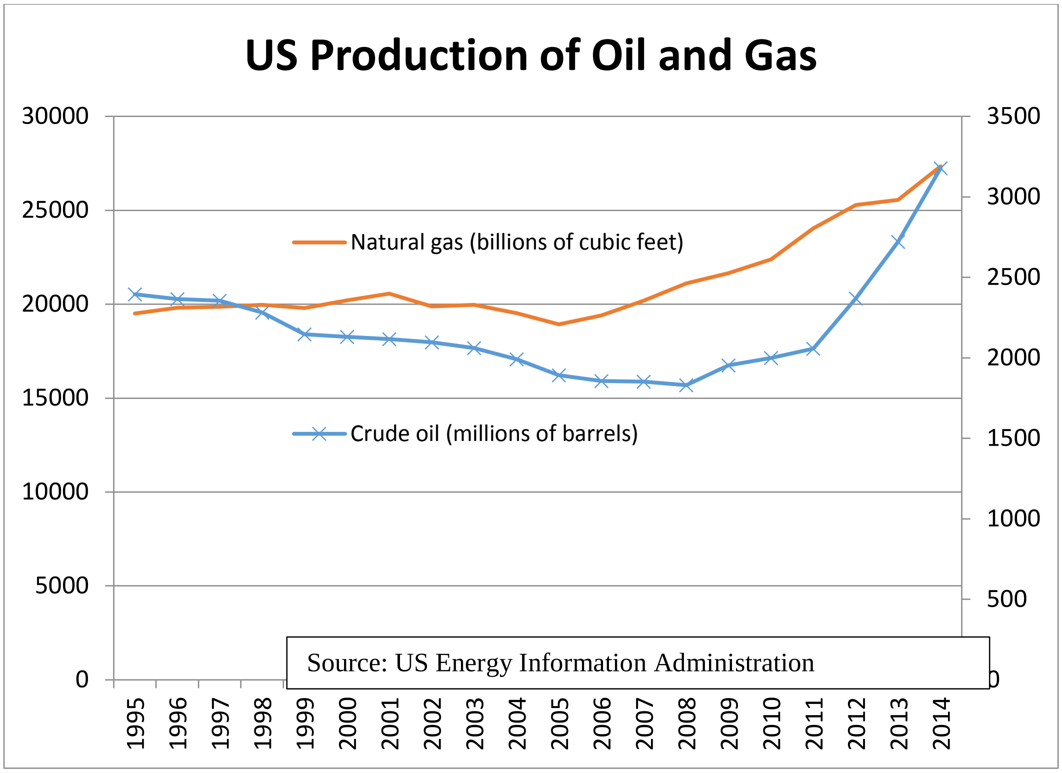


Table 1: Prices and weights for IT investment

	Average			
	1947-1978	1978-1995	1995-2004	2004-2014
IT Investment Share of BFI	12%	24%	31%	29%
IT Investment Price Indexes				
BEA NIPA	0.2%	-2.2%	-6.1%	-1.4%
Alternative -- Conservative	-1.8%	-4.4%	-9.2%	-4.4%
Alternative -- Liberal	-3.9%	-6.5%	-11.2%	-5.9%
Share of IT Investment				
Computers and Peripherals	13.1%	22.8%	20.8%	14.5%
Communications Equipment	36.9%	26.6%	22.6%	17.0%
Other Info. Systems Equipment	38.3%	26.7%	17.3%	20.4%
Software	11.7%	23.9%	39.3%	48.2%
Price Deflators				
Computers and Peripherals*				
BEA NIPA	-18.1%	-14.6%	-19.3%	-6.6%
Alternative	-18.1%	-19.0%	-27.3%	-18.6%
Communications Equipment				
BEA NIPA	1.9%	1.4%	-5.4%	-2.7%
Alternative	-3.0%	-2.7%	-11.2%	-10.3%
Other Info. Systems Equipment				
BEA NIPA	2.3%	2.9%	-0.6%	0.5%
Alternative	-1.7%	-2.2%	-8.9%	-4.9%
Software*				
BEA NIPA	-0.7%	-1.2%	-1.1%	0.1%
Alternative	-4.8%	-4.4%	-2.5%	-0.8%

Note. "Conservative" alternative incorporates alternative computer and communications prices. "Liberal" alternative adds alternative software and special-purpose prices. Computers and software price indexes begin in 1958.

Table 2: Adjustments to business-sector growth-accounting

(percentage points per year relative to baseline)

			annual pp. change relative to baseline		
		(0)	(1)	(2)	(3)
		Published baseline (% change, a.r.)	Conservative	Liberal	Liberal + Intangibles
Labor productivity	1978-1995	*1.50*	0.12	0.24	0.32
	1995-2004	*3.26*	0.28	0.42	0.52
	2004-2014	*1.44*	0.13	0.22	0.21
	2004-2010	*1.92*	*0.17*	*0.27*	*0.27*
	2010-2014	*0.71*	*0.06*	*0.13*	*0.12*
Capital-hours ratio	1978-1995	*2.20*	0.31	0.60	0.73
	1995-2004	*3.68*	0.77	1.16	1.22
	2004-2014	*1.80*	0.50	0.80	0.63
	2004-2010	*3.14*	*0.55*	*0.87*	*0.64*
	2010-2014	*-0.22*	*0.44*	*0.69*	*0.62*
TFP	1978-1995	*0.53*	0.02	0.05	-0.01
	1995-2004	*1.82*	0.03	0.04	-0.12
	2004-2014	*0.49*	-0.06	-0.08	-0.13
	2004-2010	*0.44*	*-0.03*	*-0.04*	*-0.14*
	2010-2014	*0.58*	*-0.10*	*-0.14*	*-0.12*

(0) = Baseline, business sector, from Fernald (2014a)
(1) = Alt. deflators for computers and communications ("conservative")
(2) = (1) + alt. deflators for specialized equipment and software ("liberal")
(3) = (2) + intangibles from Corrado et al (2012, updated)
Note: Averages start 1978 because of availability of intangibles data

Notes: Each column involves a separate, experimental adjustment to selected components of capital investment. The entries show the percentage-point adjustment to business-sector growth accounting components, relative to the unadjusted estimates in column (0). Column (1) uses our preferred alternative indices of computers, communications, and semiconductors back to 1969 (with official deflators before then). Column (2) adds intangibles from Corrado et al (2012). Column (3) adds to that experiment an extra surge in real spending on software after 2004:Q4 by assuming the true software deflator falls 5 percentage-points faster each year than measured. Column (4) is any other thought experiment that seems informative. Perhaps a highly aggressive adjustment.