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ICT Prices and ICT Services: What do they tell us about Productivity and Technology?

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Abstract

This paper reassesses the link between ICT prices, technology, and productivity. To understand how the ICT sector could come to the rescue of a whole economy, we introduce a simple model that sets out the steady-state contribution of the sector to the growth in U.S. labor productivity. The model extends Oulton (2012) to include ICT services (e.g., cloud computing) which has implications for the relationship between prices for ICT services and prices for the capital stocks (i.e., ICT assets) used to supply them. ICT asset prices are then put under a microscope, and official prices are found to substantially understate ICT price declines. And because ICT use continues to diffuse through the economy—increasingly via cloud and related services which are not fully accounted for in the standard narrative on ICT's contribution to economic growth—the contribution of ICT to growth in output per hour going forward is calibrated to be substantially larger than thought in the past.

Keywords: Cloud services; Information and Communication Technology (ICT); High-performance computing; Productivity, Technology, Price measurement

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The importance of computers, computer microprocessors, and productivity-enhancing computer software in driving the step up in U.S. productivity growth in the mid-1990s is well established.[1] But the Internet and mobile telephony—two of the 20th century's greatest inventions—have been largely absent in the macroeconomic work on U.S productivity performance until recently. Our research on communications technology and communication equipment price measurement (Byrne and Corrado, 2015a,b) and its implications for interpreting U.S. productivity (Corrado, 2011; Corrado and Jäger, 2014) puts these innovations front and center and offers a story in which communication and communication networks (as much as computing performance) drove productivity developments in the 1990s and the 2000s.

An overarching story of productivity performance for more than 20 years is all to the good, but it begs the question of why U.S. productivity growth has been so dismal since 2004, given that communication technology has made possible the newer cloud and mobile platforms that are transforming how organizations exploit computing resources and data. Indeed, the deterioration in U.S. labor productivity growth is due in part to the fact that investment in information and communication technology (ICT) equipment and software no longer provides an extra boost to overall output per hour.[2] Not only has nominal ICT equipment and software (E&S) investment relative to GDP moved sideways since 2010 (figure 1a), relative ICT price change has posted *extremely* small declines of late, after having gradually lost force since 2004 (figure 1b).

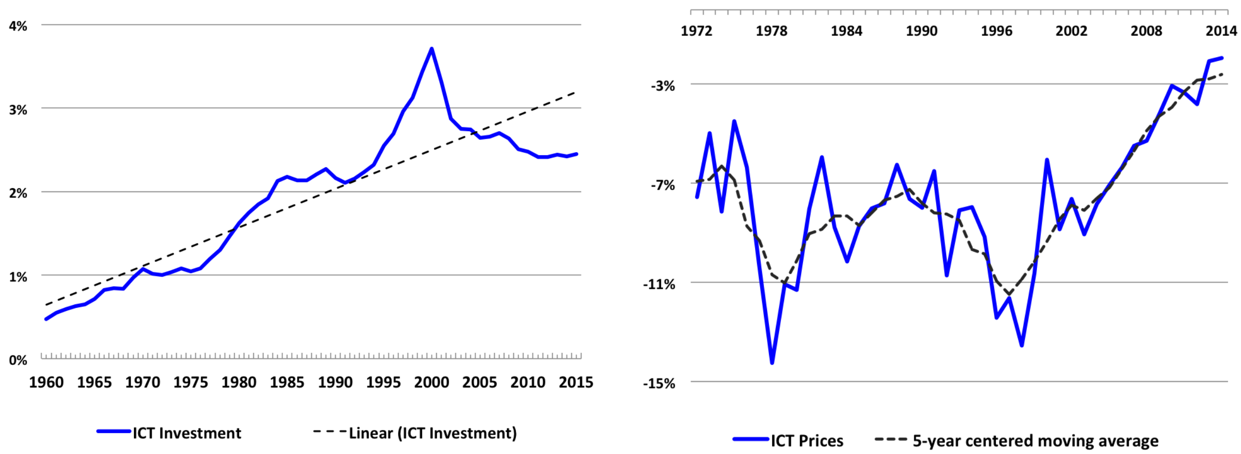
The ongoing digital transformation of the U.S. economy is highly visible in the plentiful supply of new software apps, powerful wireless devices, and widespread access to high-speed broadband, however. Why, then, is ICT investment so weak? And if digital innovations are so transformative, why are they not having a discernible impact on recent ICT prices (and labor productivity)? Google's Hal Varian offers a view from Silicon Valley, namely, that U.S. productivity is mis-measured.[3] It is of course

[1] In e.g., Jorgenson and Stiroh (2000); Oliner and Sichel (2000); Brynjolfsson and Hitt (2003).

[2] Output per hour for the total U.S. economy grew an estimated 1/2 percent per year from 2010 to 2015—the slowest 5-year rate of change in the post WWII era based on The Conference Board's Total Economy Database™ whose output per hour series for the U.S. total economy begins in 1950.

[3] See "Silicon Valley Doesn't Believe U.S. Productivity is Down," *Wall Street Journal*, July 16, 2015, by Timothy Aeppel.

Figure 1: **ICT Equipment and Software Investment and Prices in the United States**



(a) Nominal ICT E&S Investment, percent of GDP (b) ICT Relative Price Change, annual rate

Note: Private investment only.
Source: Authors' elaboration of data from U.S. BEA. The investment ratio for 2015 is based on partial year data. Nominal ICT investment and ICT price change are measured relative to nominal GDP and the GDP deflator, respectively, and exclude software R&D.

possible that the ICT sector—about 6 percent of the economy in value added terms—is innovating and prospering but is simply too small to come to the rescue of the overall economy facing both weak aggregate demand in the aftermath of a global financial crisis (Summers, 2015) and stiff demographic headwinds to its productivity growth (Gordon, 2014a,b). Nevertheless, Varian's comments suggest a conundrum, which this paper addresses.

We proceed as follows: First, to understand how a small sector can be a driver of growth in an economy, we extend a simple two-sector model, originally due to Oulton (2012), to include ICT services, e.g., cloud computing and related services. In the extended model, as in Oulton's original model, the pace of decline in relative ICT prices is an indicator of productivity change in the ICT sector relative to the rest of the economy. The extended model implies, and we further posit via a user cost (Jorgenson, 1963) framework, that price change for marketed ICT services is proportional to price change for the productive assets used to produce them; thus the model implies that purchases of certain ICT services are similar to services provided via direct ownership of ICT capital.

Why might this be important? The new era of mobile and cloud platforms involves technologies (e.g., virtualization, discussed below) whose take up is not fully captured by the standard narrative used to analyze the diffusion of ICT technology in economies; nor are the activities touched most directly by these technologies very evident in official statistics. By incorporating ICT services (i.e., cloud computing and related services) in the modeling and quantification of the contribution of ICT to labor productivity growth, we are able to remedy this situation.[4]

Second, we assess the adequacy of official ICT price measures. We introduce new, quality-adjusted price indexes for communications equipment products based on our own prior work on the measurement of telecommunications and networking equipment (Byrne and Corrado, 2015a) as well as new work set out in a companion paper (Byrne and Corrado, 2016). That paper also introduces new price indexes for enterprise software products, high-end computers and computer storage systems, which, along with high-speed broadband, have spurred the growth of cloud computing, datacenter design services, and data analytics. All told, our findings suggest that ongoing technological change in the ICT sector of the U.S. economy is potentially contributing as much as 1.4 percentage points per year to its overall labor productivity growth.

This rather large estimated contribution of ICT to labor productivity growth stems primarily from two main findings in this paper. The first is that long-term trends in official ICT prices suffer from substantial mismeasurement and do *not* imply that the relative productivity of the ICT sector has ground to a halt and no longer provides an extra kick to productivity growth as suggested by figure 1(b). A second finding is that about 25 percent of the total 1.4 percentage points estimated contribution of ICT to output per hour growth owes to the diffusion of ICT technology via purchases of cloud and related ICT services. These services have grown smartly relative to GDP according to BEA's official input-output tables, and the macro-productivity ICT narrative that focusses on diffusion via ICT investment alone is not sufficient in the new era of mobile and cloud platforms.

1 Framework

ICT plays a central role in modern economies, and quantitative assessments of longer-term economic growth prospects depend heavily on estimates of the contribution of ICT to productivity change for the years ahead. Oulton (2012) proposed an approach to making long-term growth projections based on a two-sector model of an open economy where one sector is an ICT-producing/supplying sector. His

[4]It should be underscored that this paper bears most directly on interpreting recent trends in ICT investment and ICT services use by the producing sectors of the economy. Subsequent work (under way) uses the framework developed in this paper to assess the impact of digitization on the consumer sector, where wireless technologies and especially important issues.

approach is in the spirit of the growth accounting approach to making economic projections (Jorgenson, Ho, and Stiroh, 2004; Jorgenson and Vu, 2010; The Conference Board, 2015; Byrne, Oliner, and Sichel, 2013), in which one of the key drivers of economic growth is growth of total factor productivity (TFP) in the ICT-producing sector *relative* to the rest of the economy.

Benefits to economic growth accrue to faster relative growth of ICT TFP because faster relative ICT TFP growth manifests as faster relative ICT price declines, which then enables faster growth of income and consumption per hour. Oulton's model makes these features of a Jorgenson-style growth projection explicit, along with its corollary that economies with little or no domestic ICT production derive benefits from faster TFP growth in ICT investment goods production elsewhere in the form of improving terms of trade.

To account for the growth and popularity of cloud services enabled by high-speed broadband, this paper expands the Oulton model to include intermediate uses of ICT services. The expression for the steady state contribution of ICT to the growth of OPH in the expanded model is unaffected by assuming a closed economy, as in the original Oulton model. Proceeding with a closed economy assumption for simplicity, the expanded model is set out below.

1.1 Expanded two-sector model

Total final demand Y consists of investment (I) and consumption (C) produced in two sectors of the economy. The two producing sectors are (1) an ICT sector (denoted by the subscript T) and (2) a general business sector excluding ICT producers (denoted by the subscript N). Each sector produces investment and consumer goods and services for final use. Thus we have

$$Y = C + I = Y_T + Y_N \;; \quad Y_T = C_T + I_T \;; \quad Y_N = C_N + I_N \;; \tag{1}$$

and

$$PY = P_T Y_T + P_N Y_N \;; \quad \overline{w}_T = \frac{P_T Y_T}{PY} \;. \tag{2}$$

where P is the price level, P_T and P_N are sector prices, and $\overline{w}_T$ represents the relative size of the ICT sector in final demand in nominal terms.

With regard to intermediates, the ICT sector is assumed to supply services for its own intermediate use, as well as for intermediate use by other producers. The general business sector is assumed to produce intermediates for its own use only; these intermediates are omitted from its production function to keep the exposition simple.[5] With sector N producing for final demand only, and each sector's output (production net of own use) denoted by Q_T and Q_N, respectively, sectoral production may be written in terms of the following outputs and inputs

$$(3) \qquad Q_T \equiv Y_T + S_T^N = A_T F(K_N^T, K_T^T, S_T^T, L^T) \ ; \qquad Q_N \equiv Y_N = A_N F(K_N^N, K_T^N, S_T^N, L^N)$$

where K_i^j denotes sector j's capital input from its stock of investment goods of type i ($i = T, N$) and S_T^j is sector j's intermediate use of ICT services. $L^j = hH^j$ is sector j's labor input, H^j is hours worked in the sector, and h is a labor composition index applicable to the economy as a whole.

The value of each sector's factor payments is given by

$$(4) \qquad P_i Q_i = R_N K_N^i + R_T K_T^i + W H^i + P_T S_T^i \quad , \quad i = T, N \ ,$$

with relevant factor shares given by

$$(5) \qquad \overline{v}_{K_T} = \frac{R_T(K_T^T + K_T^N)}{PY} \quad ; \quad \overline{v}_L = \frac{W(H^N + H^T)}{PY} \quad ; \quad \overline{\zeta}_T^N = \frac{P_T S_T^N}{PY} \ .$$

In equation (4), R_N and R_T are the nominal rental prices of capital and W is the hourly wage, and in (5), $\overline{v}_{K_T}$ and $\overline{v}_L$ are the shares of ICT capital and labor in total income, respectively, and $\overline{\zeta}_T^N$ is ICT business services purchased by sector N relative to total income in the economy.

The model assumes there is faster technical progress in the ICT sector. Denoting the rate of growth in the Hicksian shifter (A_i) in the sectoral production functions (3) as μ_i, this assumption is expressed as $\mu_T > \mu_N$. A major simplifying assumption is then employed to solve the model, namely, that the sectoral production functions exhibit constant returns and differ only by their A_i terms. This implies factor shares and input quantities are the same in both sectors, in which case log differentiation of the factor payments equations (4) yields the result shown by Oulton that relative ICT price change equals (the negative of) relative ICT TFP growth. Defining the relative ICT price as $p = P_T/P_N$, this result

[5] The complications of chain weighting also are ignored.

is expressed as a steady-state rate of change in relative prices $\dot{p}$ given by

$$\dot{p} = \mu_N - \mu_T < 0 \ . \tag{6}$$

As may be seen, relative ICT price change is negative, reflecting the extent to which the relative growth of productivity in the ICT sector exceeds the growth of productivity elsewhere in an economy.

The expanded model's solution for the contribution of ICT to the growth in GDP per hour ($O\dot{P}H$) is given by

$$\text{Contribution of ICT sector to } O\dot{P}H \ = \ \underbrace{\frac{\overline{v}_{K_T} + \overline{\zeta}_T^N}{\overline{v}_L}(-\dot{p})}_{\text{Investment (use) and productivity (diffusion) effects}} \quad + \quad \underbrace{\overline{w}_T(-\dot{p})}_{\text{Production effect}} \ . \tag{7}$$

For details of this solution, see appendix A1. Equation (7) differs from the solution to the original Oulton model due to the presence of the term $\overline{\zeta}_T^N$ capturing the ICT services-using intensity of the economy. The solution nonetheless aligns with the usual growth accounting approach in which the contribution of ICT capital to growth in output per hour is identified as flowing through two channels: ICT use and ICT production. It is typical to consider the ICT use effect as operating through services provided by producers' own investment in ICT capital, i.e., via services generated by ICT assets that producers' own themselves. In the expanded model, the channel also operates via the contribution of nonICT producers' purchases of ICT services, e.g., purchases of computing, storage, and software services, to total factor productivity.

In steady-state growth, output and output per hour in the N sector grow less rapidly than output and output per hour in the T sector, the sector producing ICT goods and services. In fact, this growth differential is $-\dot{p}$, a result that follows from equality of the marginal product of factors used in the two sectors, which follows from the assumption of perfect competition; see appendix A1 for further details. The model thus implies that, to the extent μ_T really is greater than μ_N, real ICT services prices fall (as they are on par with real ICT asset prices), and real ICT services output growth is faster than growth of real output of the general production sector, evidence for which shall be shown in section 3 below.

1.2 ICT services prices vs. ICT asset prices

The ICT sector's output price is a single price P_T by assumption in a two-sector model. The strictness of this assumption may be readily relaxed, however, yielding the usual multiple sector framework with many relative prices and an aggregate production possibilities frontier that generates multiple types of C and I for final use (e.g., Jorgenson 1966; Jorgenson, Ho, and Stiroh 2005). In what follows, the user cost expression is used to set out the conditions under which a multiple sector framework generates essentially the same implication for ICT services prices as did the simple two-sector model.

Consider the determinants of prices for two types of ICT services in a multiple sector setting. The first is where ICT services production is highly ICT-capital intensive, as in the production of "public" cloud services by the ICT sector for sale to the nonICT-producing sector (e.g., Amazon selling to GM). The second is where ICT services are for designing "private" cloud services facilities within firms in the nonICT producing sector, e.g., services for transitioning from traditional uses of IT datacenter assets to one based on virtualization and grid computing. Virtualization enables server and storage equipment consolidation; grids make more efficient use of computer CPUs.

In each case, the value of the produced ICT services will be denoted as $P^{S_T} S_T^N$, where P^{S_T} is a quality-adjusted price specific to each type of service. P^{I_T} will denote the quality-adjusted price of ICT assets relevant to each case (i.e., it is an investment price index). These prices are expressed below as real prices p^{S_T}, p^{I_T}, relative to, say, the PCE or GDP deflator, below. A steady state required real rate of return on assets ρ is defined consistently (i.e., the price change element is in the same relative terms).

Case 1. Cloud services prices are per period charges for ICT capital services (i.e., an asset rental price) and production of such services is highly ICT-capital intensive. Assume then that the services produced are proportional to the flow of services generated by the ICT assets,

$$p^{S_T} S_T^N = [(\rho + \delta_T)\, p^{I_T} K_T^T]\, \lambda \tag{8}$$

where the expression in brackets on the RHS is the real rental price of ICT capital and λ is the factor of proportionality. (Appendix A1 sets out the four real rental prices in the two-sector model, where, note, δ_T is the depreciation rate of ICT capital). λ and δ_T are constant by assumption, and ρ is constant in steady state growth by definition. Now, if the real price of cloud services p^{S_T} is falling rapidly in constant quality terms, equation (8) suggests that the driver of that change is falling real prices of ICT investment goods p^{I_T}.

Under what conditions might these prices not be in sync? One possibility is when λ is not constant, as would be the case in the presence of increasing returns, e.g., if ICT assets were more or less a large fixed cost that substantially inflated average costs relative to marginal costs (a huge server farm, say). Increased utilization of the relevant assets leads to declines in average costs, and if such declines are passed on to customers, declines in p^{S_T} exceed those for p^{I_T} until steady state growth is achieved.[6] In other words, from (8) we then have

$$\dot{p}^{S_T} \approx \dot{p}^{I_T} + \dot{\lambda}_T \tag{9}$$

where, note, $\dot{p}^{S_T}, \dot{p}^{I_T}$, and $\dot{\lambda}_T$ are all < 0. $\dot{\lambda}_T$ reflects the drop in underutilization, which augments declines in cloud services prices relative to declines in prices of ICT assets used by the vendors of cloud services.[7]

Case 2. System design services are purchased to improve the flow of ICT services produced within firms, and the services price is a fee proportional to the services-induced volume improvement in own-produced ICT services.[8] System design services may then be modeled as an increase in the efficiency of installed ICT asset stocks, an approach relevant to the spread and adoption of cloud technology, i.e., as in designing and installing a "private" cloud with significant server consolidation.

Note first that the real price of ICT capital services r_T^N and ICT capital owned within the nonICT producing sector K_T^N are the subjects of analysis, and that $r_T^N K_T^N = [(\rho + \delta_T)\, p^{I_T} K_T^N]$ is the real income attributed to nonICT producers' deployment of ICT capital. Consider next that producers will pay

[6]Note that equation (8) did not suggest or specify that ρ exhausted observed capital income, which is to say the nominal interest rate in ρ is an ex ante rate. As shown by Berndt and Fuss (1986), the marginal product of capital varies directly with capital utilization and is absorbed in capital income and attributed to capital rental prices only when ex post calculated rates of return are used.

[7] To see this, let λ_T vary with capital utilization, e.g., as in $\lambda_T = 1 - d$ where d is a measure of the underutilization of ICT assets (and can be calculated so as to exhaust capital income). Equation (8) then suggests that improvements in the utilization of ICT capital assets in the public cloud services-producing industry introduce a wedge $\dot{\lambda}_T$ between changes in observed prices for cloud services and prices for ICT assets. Such wedges presumably surface for only periods of time, as changes in utilization usually are a temporary phenomenon.

[8]Note that in the very different case of ICT installation services, the price is simply a margin, i.e., an add-on to the purchase price of ICT assets that has no independent impact on the effectiveness of the investment beyond what is built into a quality-adjusted investment price index.

for system design services up to the point where fees do not exceed the present discounted value of per period benefits provided. Let α denote the proportional fee and $-\dot{\lambda}_N$ the proportional improvement in r_T^N that is provided.[9] Ignoring discounting, the *effective* decline in real ICT asset prices faced by nonICT producers using system design services $\dot{p}^{eI_T}$ is given by

$$\dot{p}^{eI_T} = \dot{p}^{I_T} + \dot{\lambda}_N(1 - \alpha) \tag{10}$$

and industry revenues are expressed as

$$p^{S_T} S_T^N = \alpha\, r_T^N K_T^N \; (-\dot{\lambda}_N) \; . \tag{11}$$

Equation (10) suggests that ICT capital packs an extra punch to nonICT producers' productivity, as the effective growth in real services will exceed real growth in stocks due to increases in utilization of the stocks. Equation (11) suggests that ICT services will grow relative to ICT capital income when substantial improvements are being made by providers (and the improvements they make are long-lived, not shown).

All told, the $\dot{\lambda}$'s represent efficiencies enjoyed by companies that move from a traditional IT datacenter to a cloud computing platform; for new firms, efficiencies represent lower capital required to start a business. Combined, these efficiencies have the potential to be large because cloud computing refers not only to shifts in workload location (from on-premises environments to the public cloud) but also to increased take up of cloud technologies within firms that result in much denser workload-to-ICT capital ratios.

1.3 Quality change or productive externality?

From a macroeconomic point of view, increased demand for cloud computing leads to decreased demand for computing hardware (for a given volume of ICT services) and increased demand for the software developers and software products that enable machine virtualization and application containerization. Over time, the associated extra kick in *effective* ICT price declines implied by equation 10 would lead to greater computerization/digitization of an economy, which would then translate into a restoration of the share of computer hardware in the mix of ICT investment in the longer run. With regard to communication equipment, although high-speed broadband is a fundamental enabler of cloud

[9] Where, as in footnote 7, there is an implicit term d capturing underutilization.

services, virtualization and its associated efficiencies do not have first order impacts on the demand for communication equipment beyond the fundamental need to support datacenter IP traffic.

Before we go further, let us underscore that the server, storage, software product and computing services prices developed and used in section 3 of this paper do *not* treat the application workload of IT capital, or the capability of software products or systems design services to enable cloud computing, as quality change. The macroeconomic impact of the adoption of cloud technology rather is via its contribution to productivity growth, much as is done when analyzing network externalities (or spillovers to ICT capital in general).[10] Cost savings due to virtualization, whether via direct purchases of cloud services or via lower user costs of IT capital in the nonICT-producing sector, thus are viewed as productive externalities, not part of the contribution of ICT capital to growth in output per hour. While this position may have parallels to treating the productivity enhancing impacts of Internet-platform business models as a (network) externality, virtualization as a computing technology is similar to multiplexing in communication where more and more signals are transmitted over physical networks (or spectrum), and where, to the extent possible, increases in capacity are built into quality-adjusted price indexes such as those developed for communications equipment in Byrne and Corrado (2015a,b). Comparable work on prices of servers, storage, software products, and systems design services to consistently account for virtualization and other aspects of cloud technologies is a related challenge, but one well beyond the scope of this paper.

2 ICT sector trends

This section reviews indicators that support the model of the previous section. This requires (a) defining the ICT sector, which is done in in columns 1 and 2 of table 1 below, (b) examining indicators that suggest ICT technology continues to increase at a relatively fast pace, (c) pinning down the relative growth of ICT services (which also bears on the diffusion of cloud technologies), and (d) examining the relative pattern of ICT investment by major component.

The section concludes with an explicit quantification of the model's parameters reflecting the relative size of the ICT sector and the diffusion of its technology in the economy, namely, $\overline{w}_T$, $\overline{v}_{K_T}$, and

[10] In this work, a separate channel is added to decompositions such as equation (7) to account for the contribution of ICT to productivity growth beyond the direct capital contributions captured in growth accounting. For example, Corrado (2011) and Corrado and Jäger (2014) showed that network externalities were a noteworthy contributor to productivity growth in the United States and 8 major European countries during the Internet and wireless network expansion in the first half of the 2000s. Beyond broadband, however, spillovers to ICT have not been found in macro or industry-level data (Stiroh, 2002), despite a large micro-based literature suggesting externalities to IT use by individual firms. See Corrado and van Ark (2016) for further discussion.

Table 1: **ICT-producing Industries**

NAICS 2007 code	Description	Primary Use	BEA industry data code
(1)	(2)	(3)	(4)
Manufacturing:			
3341, 3344	Computers and semiconductors	Final and Intermediate	334 (pt)
3342, 3343, 334511	Communication equipment	Final	334 (pt)
3346	Magnetic and optical recording media	Final	334 (pt)
Services:			
5112	Software publishing	Final	511 (pt)
515	Broadcasting	Final	513 (pt)
517 (pt)	Telecommunications, excluding wireline telephony (but including internet access)	Final and Intermediate	513 (pt)
5182	Data processing, hosting, and related	Intermediate	514 (pt)
51913	Internet publishing and broadcasting and web search portals	Intermediate	514 (pt)
541511	Custom computer programming	Final	5415
541512 (pt)	Computer systems design (integrators)	Final and Intermediate	5415
541512 (pt)	Computer systems design (consultants)	Intermediate	5415
541513,9	Other computer related services	Intermediate	5415

Note: (pt) after an industry codes denotes that not all of the industry consists of ICT production.

$\bar{\zeta}^N_T$. Relative ICT asset price change is presented in section 3, and quantitative implications of the model are drawn there.

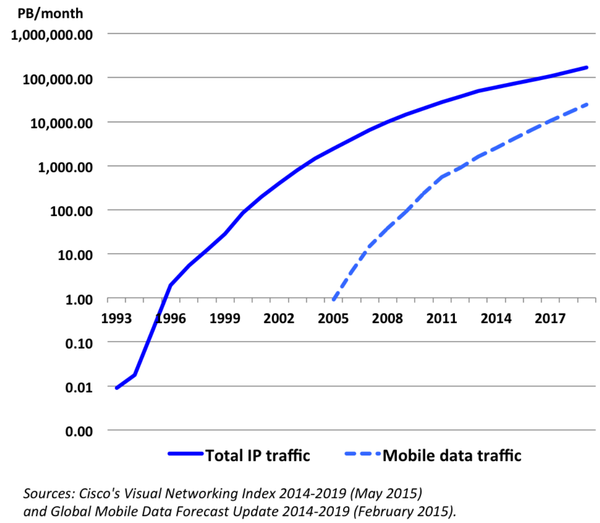
2.1 Technology and R&D

Internet and wireless technologies. Faster relative growth of TFP in ICT production is usually attributed to the relatively rapid pace of advances in computing and semiconductor technology, especially in the speed of microprocessors (MPUs) used in personal computers (Jorgenson, 2001)—and, according to many accounts, such advances stepped down a notch in the first half-decade of the 2000s (Hilbert and López, 2011; Pillai, 2011, 2013). By contrast, advances in communications technology, i.e., internet and wireless technologies, continue at a similar pace (Byrne and Corrado, 2015a,b).

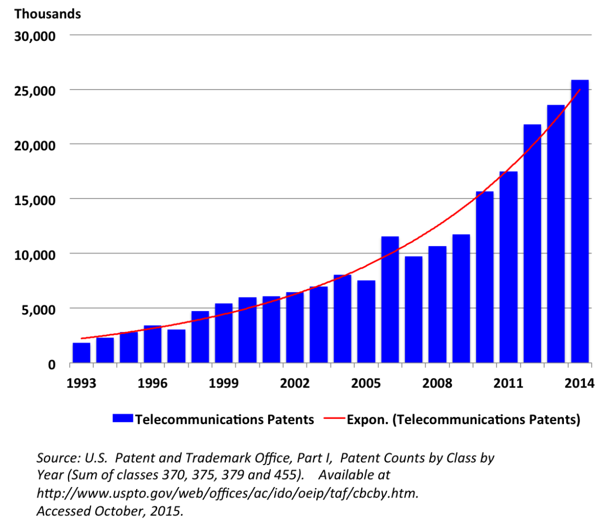
Internet and wireless technologies are not single identifiable inventions, but rather a suite of communications technologies, protocols, and standards for networking computers and mobile devices.[11] Advances in these technologies have been very rapid in the past 25 years and continue at blistering rates to this day. Without continued increases in internet technology and capacity from 2010 to 2015,

[11]This paraphrases (Greenstein, 2000, p. 391), who was describing internet technology.

Figure 2: **Global IP Traffic and U.S. Telecommunications Patents**



(a) Global IP Traffic, 1993 to 2019 (incl. forecast).



(b) U.S. Wireless-related Telecom Patents, 1993 to 2014

the world could not have achieved the reported 29 percent per year increase in IP traffic and nearly 78 percent per year increase in wireless *data* traffic that it did during this period (figure 2, left panel).[12]

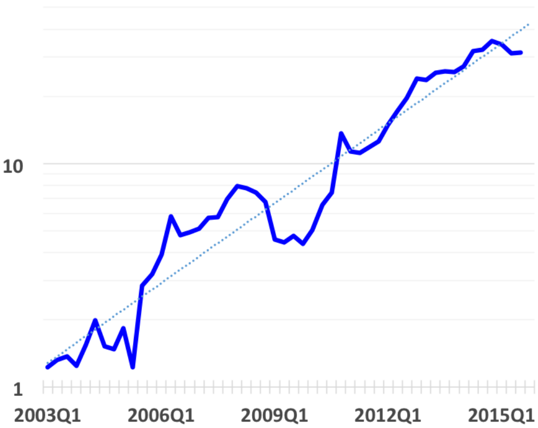
All told, the internet markets of the G-20 are projected to reach $4.2 trillion in 2016—nearly double the size they were in 2010. Three out of four data center workloads are expected to be processed in the cloud by 2018, and Internet of Things (IoT) devices attached to the Internet—most of them wirelessly—are expected to increase more than 25 fold, from nearly 1 billion units in 2010 to 26 billion units by 2020 (IoT devices *exclude* PCs, tablets and smartphones).[13] These estimates plus a continuation of the demand for mobility and hotspots cannot be realized without continued, rapid increases in communications capacity, especially wireless capacity. The panel on the right of figure 2 shows that by one measure (the rate at which wireless-related telecommunications patents are granted in the United States), the current pace of change in communications technology is more rapid than it was in the late 1990s.

Cloud technologies. The virtualization technology that is the primary enabler of cloud computing has been in commercial use since the 1970s via IBM mainframes, but cloud vendors have made increasing

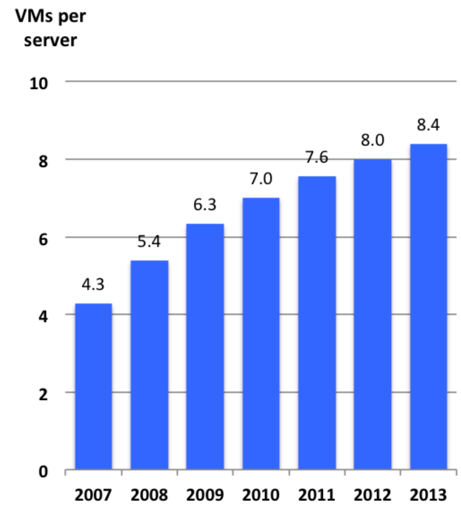
[12]The calculations are based on the historical data and 2015 estimate reported in issues of Cisco's *Visual Networking Index* and *Global Mobile Data Forecast Update*.

[13]The sources for these forecasts are Boston Consulting Group (`http://www.marketwired.com/press-release/g-20s-internet-economy-is-set-reach-42-trillion-2016-up-from-23-trillion-2010-as-nearly-1611718.htm`), Gartner (`http://www.gartner.com/newsroom/id/2636073`), and Cisco's Global Cloud Index (2013-2018) (`http://www.cisco.com/c/en/us/solutions/service-provider/global-cloud-index-gci/index.html`).

Figure 3: **Cloud Providers' Cap Ex and U.S. Server Application Workload**



(a) Cap Ex by Amazon, Microsoft, Google, and Apple



(b) Application workload of U.S. server stock

Sources. Panel (a): Quarterly financial reports. Panel (b): IDC.

use of virtualization to enable servers to run larger workloads and economize on storage since the advent of the millennium. As shown in figure 3(a), the increase in spending for capacity expansion among major cloud vendors has been stunning: Nominal capital expenditures at Amazon (AWS), Microsoft (Azure), Google, and Apple increased 27 percent per year between 2003:Q1 and 2015:Q3.

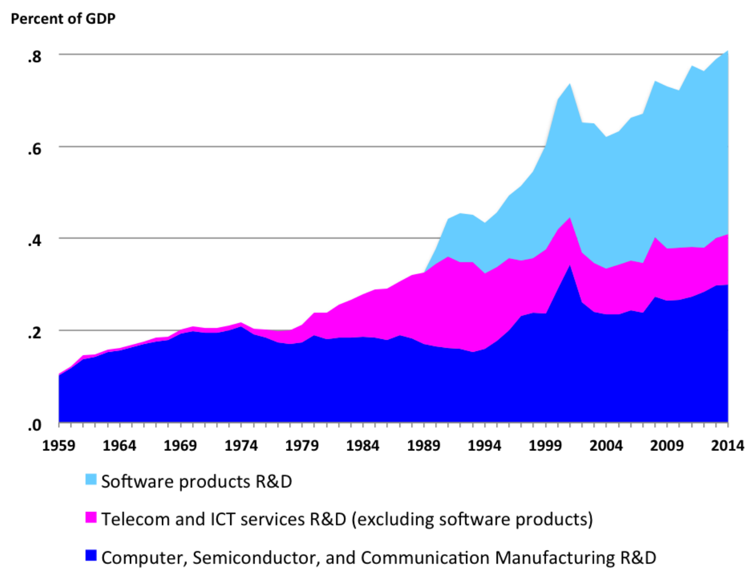
Firms that transition traditional datacenters to a cloud platform (private or public) enjoy substantial hardware consolidation and cost savings. IT consultancies commented in 2008 that server virtualization had become the "killer app" for the business datacenter and subsequently IDC estimated that the number of virtual machines (VM) per server in the United States—an indicator of the application workload of a datacenter server and plotted in figure 3(b)—advanced nearly 12 percent per year from 2007 to 2013. Companies historically ran one application workload per server (and many small and medium size firms still do).

Grid computing is applying the resources of many computers in a network to a single problem at the same time; the technology was first used in 1989 to link supercomputers and thereafter grew and evolved along with the Internet (De Roure, David, et al. 2003). Newer cloud technologies such as containers aim to speed software application development, deployment, and scalability, thereby boosting productivity of software R&D investments, i.e., mainly boosting the productivity of the

ICT-producing sector. In terms of enterprise applications, it is very early on in the application of containerization.[14] The consultancy IDC estimates that only 1 percent of enterprise applications are running on containers that can readily be scaled.

R&D investments in ICT. The conduct of ICT R&D as shown in figure 4 is consistent with a very brisk pace of change, especially in software products. Figure 4's overall trajectory for ICT R&D is not a readily observable component of the U.S. national accounts' headline figure for R&D investment, however, but rather reflects (1) private R&D investment by the industries listed in table 1 as reported in the U.S. national accounts *plus* (2) software products R&D presented as own-account software investment. Because software products R&D is thought to be captured in own-account software investment, national accountants exclude this category from the R&D source data when estimating private R&D investment.

Figure 4: **Private ICT R&D investment in the United States**



Source: Authors' elaboration of BEA and NSF data.

Most software products R&D is carried out in the ICT-producing industries listed in table 1. For the United States, estimates of software products R&D are derived from cross tabulations of the National Science Foundation's R&D survey data by industry of funder and technological focus; figure 4 plots the time series for these estimates reported in table 2 of Crawford, Lee, Jankowski, and Moris (2014).[15]

For the analysis of the ICT sector, indeed for the analysis of R&D in general, including software products R&D with other R&D is a more logical presentation of the available data—and not doing so

[14]Containerization—a scalable form of virtualization technology—generally was not widely understood outside certain cloud vendors until the release of open source LINUX formats (Docker 1.0) in March 2013. Docker transformed container technology to a product for enterprise use.

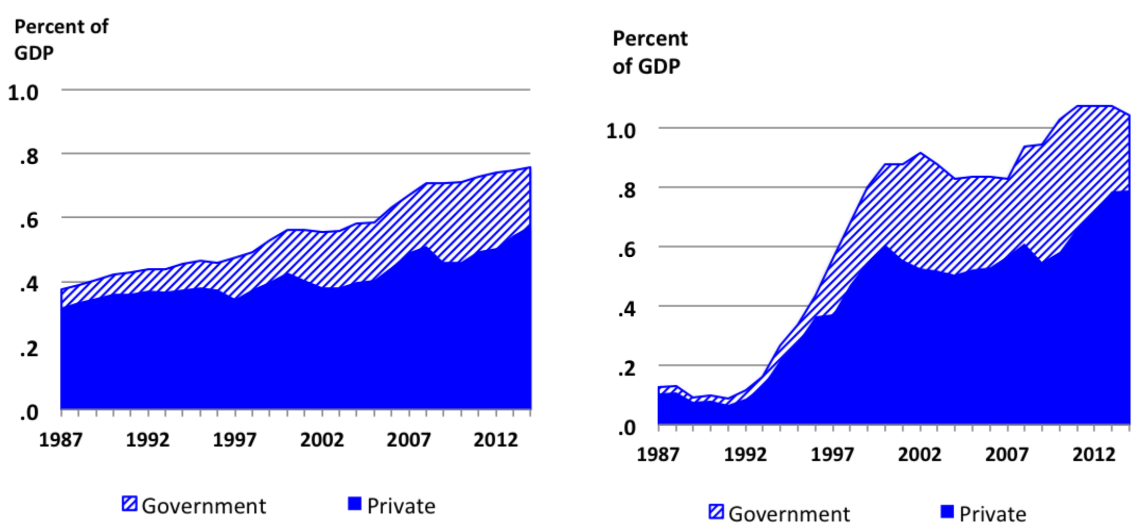
[15]The relevant cross-tabulation of R&D survey data has been published by the National Science Foundation (NSF) for 2012 (NSF, *Business Research and Development and Innovation: 2012*, table 25, October 2015). This recently published figure is consistent with estimates reported in Crawford et al. (2014), which included estimates through 2013. The figure plotted for 2014 is an extrapolation by the authors based on total private own-account software investment.

excludes an area where increases in R&D have been among the most rapid. The rate of investment in ICT R&D in recent years continues unabated in this presentation, suggesting that ICT innovation could not have slowed for lack of investment in the development of new ICT technologies and products.

2.2 ICT services and software investment

Intermediate uses of ICT. ICT R&D historically has been oriented toward producing better and faster computers and more powerful productivity-enhancing computer software (installed locally) for businesses and other organizations (i.e., investment goods). But with the locus of ICT R&D having shifted toward software apps and services enabled by high-speed communication and high performance computing systems, one should not be surprised to see an associated shift in ICT spending, too.

Figure 5: **Intermediate Uses of Information and Computer Services, percent of GDP**

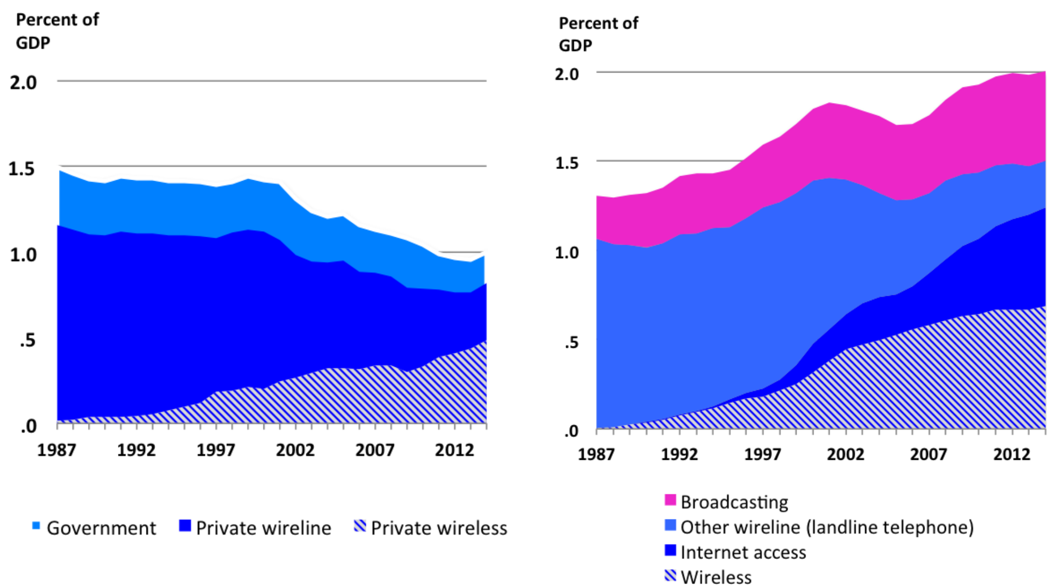


(a) Data processing and related services (b) Computer systems design

Note. Estimates are net of own sector, i.e, ICT-producing sector, use; see table 1 for industries comprising the ICT-producing sector. Figures are through 2014.
Source: Authors' elaboration of data from U.S. BEA.

Private demand for data processing, hosting, and related information services (NAICS 5182, 51913) and for computer systems design services and related computer services (NAICS 54152,3,9) rose sharply relative to GDP in the United States in recent years (the solid blue shaded areas of the left and right panels of figure 5, respectively). These developments reflect the both the growth of cloud services (which are in NAICS 5182 and has seen steady growth) and a remarkable surge in systems design services that likely also owes to the demand for cloud-based IT systems to the extent that systems design services are co-investments with the demand for cloud computing.[16] All told, the analysis in section 1 suggested that the relative growth of ICT services industries would be strong if there were real gains to reconfiguring IT departments to capture cost savings due to cloud technologies. The prospective cost savings, along with a growing demand for data analytics and revenue momentum of the "subscription" business model that has been widely used to deliver ICT services, all underscore that the relative growth of ICT services since 2000 is unsurprising.[17]

Figure 6: **Intermediate and Final Uses (PCE) of Telecommunications and Broadcasting Services, percent of GDP**



(a) Intermediate Telecom Use (b) Final Telecom and Broadcasting Use (PCE)

Note. Estimates are net of own sector, i.e., ICT-producing sector, use; see table 1 for industries comprising the ICT-producing sector. Broadcasting is in the right panel only because intermediate uses of the output of this industry are essentially nil. Figures are through 2014.
Source: Authors' elaboration of data from U.S. BEA.

Trends in intermediate and final uses of telecommunications and broadcasting services are shown in figure 6. Traditional wireline telephone services ideally would be excluded from this analysis, but a split of traditional vs. IP telephony and internet access services in data on intermediate purchases by industry is not available. As may be seen in panel (a), business demand for wireless services is robust, especially from 2010 on, whereas total private telecommunications services (which adds in wireline

[16] To be clear, spending on computer systems design is not counted as investment in national accounts even though in principle it would be included in expanded frameworks that recognize a portion of consulting services as long-lived investment in new business process design (e.g., as in Corrado, Hulten, and Sichel 2005, 2009).

[17] For further discussion of the role of business models in ICT services provision, see OECD (2014), chapter 4, "The Digital Economy, New Business Models and Key Features."

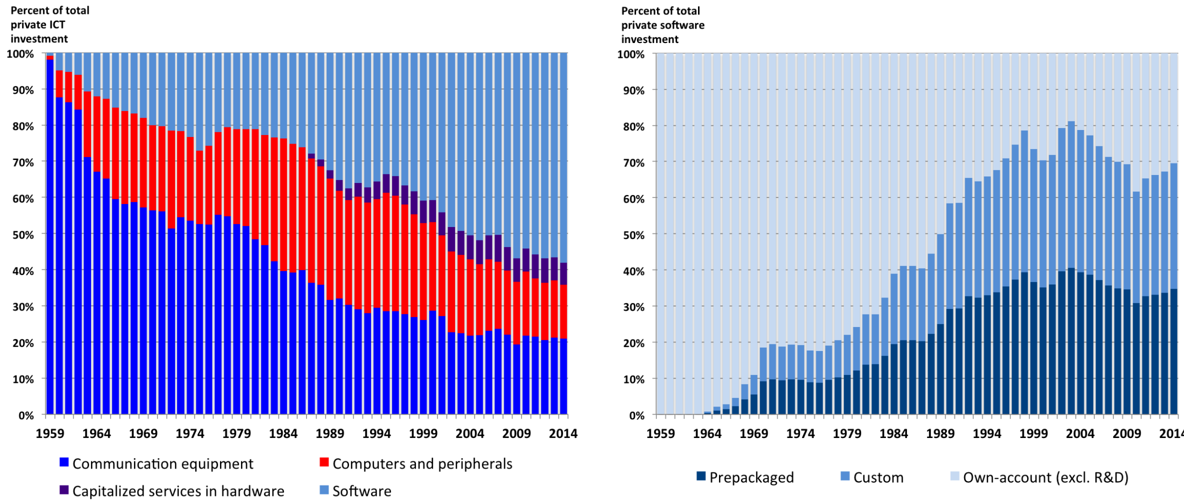
telecom and internet access services) has moved down since peaking in 2000. By contrast as shown in panel (b), consumer total telecom demand has not declined since 2000 but the relative pattern of consumer total telecom versus consumer wireless demand is similar to private industry. A breakdown of landline telephone and internet access services is available for consumers, and the detail shows, as expected, that wireline telephone services are a sharply declining component of total consumer NAICS 515,7 services spending whereas internet access is a growing component.

All told, information, computer, and wireless communication services supplied to private industries net of the ICT-producing sector's own use has increased .06 percentage points per year relative to nominal GDP during the past 19 years, i.e., the ratio of such services to GDP rose from .7 percent in 1995 to 1.9 percent in 2014. To put this in perspective, consider again figure 1(a). This increase ICT business services use by other private producers is in fact a tad larger than the long-term increase in private spending on ICT investment goods (relative to GDP), i.e., the coefficient on time in the regression trend line plotted in figure 1(a) is .05.

Final investment in software assets. Nearly 60 percent of total ICT investment in 2015 was for acquisition of new software assets, a dramatic turnabout from 1995 when 65 percent of total ICT investment was for equipment and equipment-related capitalized services (figure 7, left panel). Between 1995 and 2005, the pure equipment share of total ICT investment dropped dramatically (20 percentage points). The computing equipment spending share has continued to trend down since 2005—it was only 14 percent in 2014—whereas the communication equipment share stopped dropping in the early 2000s has fluctuated between 21 and 22 percent since then.

Within new software assets, purchases of marketed, standardized (prepackaged) software products are about 1/3 of total software, as illustrated by the dark blue shaded area in the right panel of figure 7. The lion's share of software is custom produced, whether as purchased services or performed on own account. Price measures for these custom components do not exist (i.e., BLS does not produce prices indexes for NAICS 541511, or any part of 5415 for that matter); the BEA estimates them based in part on its price index for prepackaged software products. The paper reviews these prices in a subsequent section, but suffice it to say BEA's price indexes for software investment fall 2 percent per year, not the 15 to 20 percent that high-tech equipment prices do. All told, the dramatic shift in overall ICT investment from computing equipment toward software illustrated in figure 7 suggests that the rate of overall ICT investment price change *should* have slowed over time.

Figure 7: **ICT and Software Investment Shares, 1959 to 2014**



(a) ICT investment component shares

(b) Software investment component shares

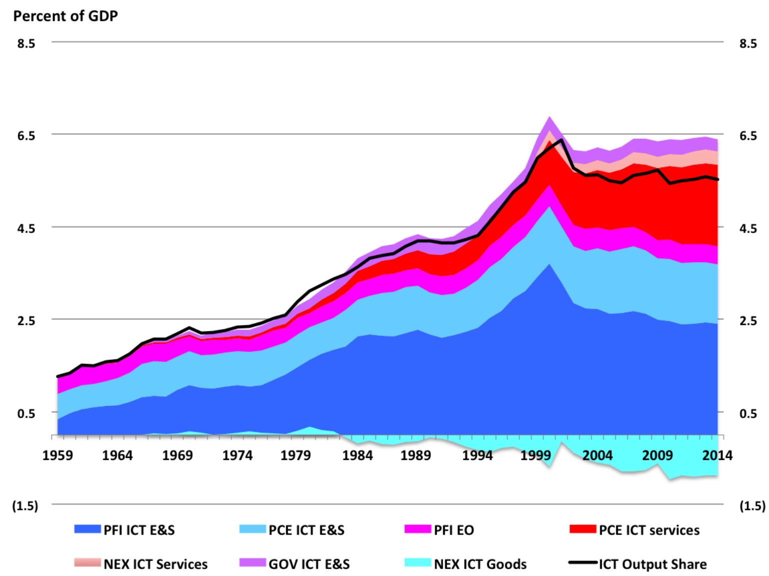
Note. Excludes software products R&D.
Source: Authors' elaboration of data from U.S. BEA.

2.3 Sector final output and capital income

ICT final output share. Consider first the ICT sector final output share $\overline{w}_T$, which captures what the domestic tech sector supplies to final investment and consumption. A substantial share of ICT investment and consumption goods are produced abroad and do not add much to the sector's final output share. Note, too, that even though the overwhelming share of ICT intermediate services are domestically produced in the United States, services only enter $\overline{w}_T$ via final consumption and net exports. Final consumption includes digitally-provided entertainment services as well as telecommunication services sold to consumers.

The inclusion of digital entertainment services in ICT final output raises the question of whether investments in digital entertainment originals (EO) should also be considered part of ICT final output—and correspondingly, how to treat R&D investments in ICT. Our thinking is that EO assets are more akin to software assets than to the software original used to produce software assets. In other words, software originals are used to generate produced capital assets (software products) that in turn yield services (over a period of years) to the owner/purchaser of the asset whereas entertainment originals are assets whose owners generate digital services for current consumption. EO investments are therefore included in ICT final output but R&D investments that produce new blueprints or original code for manufacturing/reproducing ICT equipment and software products are not.

Figure 8: **ICT Final Output Share**



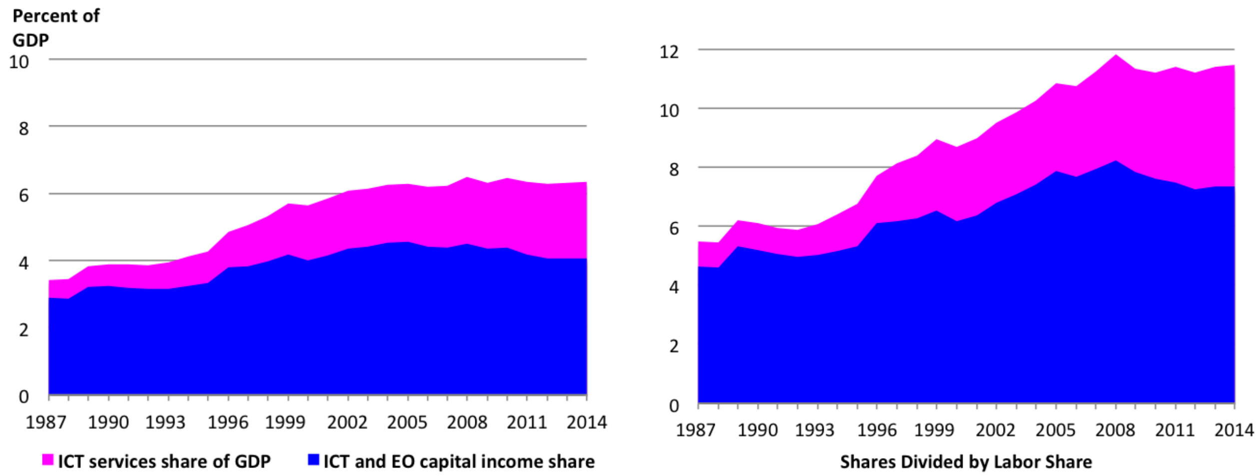
Note: E&S is equipment and software. PFI = private fixed investment. PFI ICT E&S excludes software R&D. PCE ICT components include video and cellular equipment and exclude landline telecommunications.
Source: Authors' elaboration of BEA's NIPA data.

The ICT final output share $\overline{w}_T$ and its major components are shown in figure 8. As may be seen, the share trended down in the early 2000s, but has been about flat at 5.6 percent of GDP for the past ten years (2004 to 2014). The ICT goods net exports component has been stable of late, while ICT final services (PCE and net exports) has expanded to offset the downward drift in ICT final goods (PCE and PFI E&S, the dark and light blue shaded areas). Note that if ICT final PCE services and EO capital were not included in the analysis, the ICT final output share would average 2.6 percent per year from 2004 to 2014—just a tad higher than the final output share of software over the same period (2.4 percent per year according to NIPA table 9.3U).

ICT income and services shares Consider now the shares defined in equation (5): ICT and EO capital's share of total income ($\overline{v}_{K_T}$), labor' share ($\overline{v}_L$), and ICT services share net of sector own use ($\overline{\zeta}_T^N$). Consistent with the pattern shown by the ICT investment rate, the share of capital income earned by ICT (and EO) capital has edged down since the mid-2000s, after having climbed steadily over the 1990s (the blue shaded area in the right panel of figure 9).

Capital income is the nominal value of the flow of services provided by capital assets owned and used in production, and it is typical to regard $\overline{v}_{K_T}$ as a basic indicator of the extent to which ICT has diffused via use in production in an economy. ICT business services also are inputs to production but may be marketed versions of the same services provided via direct ownership of ICT capital. As may be seen, the trajectory of the total income generated by the use of ICT capital assets in the U.S. economy changes rather dramatically with the inclusion of marketed services, suggesting that $\overline{v}_{K_T}$, alone, is an

Figure 9: **ICT capital income and services shares**



Source: Authors' elaboration of capital and labor income data from U.S. BLS productivity major sector and total economy systems and U.S. BEA input-output data. BLS capital income for software was adjusted to exclude software products R&D.

insufficient indicator of ICT use in production. The left panel plots the capital income share relative to the labor share (a ratio of the compensations for ICT capital and labor). This combination of parameters is applied to the ICT productivity differential captured by the steady state rate of decline in real ICT asset prices (or effective asset prices) to determine the contribution of the ICT "use and diffusion" effect to OPH growth. The parameter combination averages 11.3 percent for the past 10 years, considerably higher than the 7.7 percent share implied by ICT capital ownership alone.

3 ICT investment prices

Accurate ICT asset prices are required for the quantitative evaluation of equation (7). The strategy in this section is to present newly developed ICT product price measures, confirm their alignment with the trends in technology and R&D discussed in the previous section, and contrast them where relevant to official statistics. Then we examine new ICT investment research price indexes built from the new product price indexes.

The new product price indexes reflect work that either (a) was conducted by the authors as part of writing this paper or (b) appears in the literature but has not been incorporated into BEA's official ICT price statistics, e.g., Berndt and Rappaport (2003); Abel, Berndt, and White (2007); Copeland (2013); Byrne and Corrado (2015a). Further information on the sources and methods used to construct the new ICT product and investment price indexes are in a companion paper (Byrne and Corrado, 2016), available *here*.

3.1 New ICT product prices

Table 2 (page 23) reports prices for selected ICT products. More than a dozen new research price indexes are shown. Four are price indexes for the telecom products newly developed and analyzed in Byrne and Corrado (2015a,b); the computer storage device index was introduced in Byrne (2015). The remainder are price indexes newly developed for this paper and whose construction is discussed in the companion paper. Of these, the indexes for servers, enterprise software, enterprise wireline telecom services, along with telecom products, are particularly relevant for understanding developments in the last decade.

The following observations emerge from table 2: First, prices for telecom equipment products (lines 1 to 4) fall relatively rapidly—between 12 and about 18 percent per year during the last decade (column 2). Although these are noteworthy rates of decline—especially for cellular networking equipment, the red circled item in column 2—they are slower than price declines estimated for computing equipment (lines 5 to 7). Second, computer price declines have slowed in the past decade and the gap between rates of decline for computers and communications equipment has dwindled from about 20 to 10 percentage points. Third, the greatest computer declines, and the greatest gap, occurs in the 1994 to 2000 period, when MPU prices were falling especially fast (line 23). The post-2004 slowddown in MPU prices is not evident in servers (line 5) and PCs (line 7) until the 2008-2014 period, however. Prices for storage equipment—a product based on a magnetic density, not semiconductors—also slow during the same period. Finally, and by contrast, prices for enterprise and other software products (which includes systems software as well as application software) maintain relatively strong declines through the most recent period (the red circled items in line 10).

More broadly, when we think of digitization and connectivity of the economy, and specifically of enablers of growth in cloud computing and other online services, computing capacity and data/content storage capacity emerge as important factors (along with broadband capacity, discussed previously). Declines in the research price indexes for servers and storage shown in the table 2 (the red circled items in column 2, lines 5 and 6) are fairly close to the rate of decline in cloud computing and storage prices implied in press reports—about 30 percent per year.[18] From equation (9), prices for cloud computing

[18] Silicon Valley's Mark Andreessen, wrote in the *Wall Street Journal* in 2011, "... the cost to a customer running a basic internet application [at the first cloud computing company Loudcloud] was approximately $150,000 per month [in 2000]. Running that same application today in Amazon's cloud costs about $1,500 per month." Andreessen's figures imply a price drop of more than 30 percent per year for cloud services during the first decade of the 2000s, a pace of

and storage services cannot plausibly be falling so rapidly unless prices of the large-scale equipment and software assets that enable the provision of these services—load-balancing routers, multiple servers, and storage systems for handling data for multiple sessions across servers, etc.—are falling rapidly too, as we find. By contrast, official ICT price measures (lines 15 and 16, column 2) suggest a gap of 20 to 25 percentage points between price change for ICT equipment and prices for ICT cloud computing and storage services (based on press reports).

Consider further prices of telecom and internet access services in light of the analysis in section 1. Imperfect competition and large fixed costs (in the form of nonICT assets) clearly create potential for these prices to deviate from the prediction that changes in ICT services prices should align with changes in prices for the underlying ICT assets used to produce them. Services of nonICT capital assets (including land) are a substantial fraction (51 percent) of total capital income in the telecom and internet access services industry, whereas such assets play a less material role (16 percent) in the capital of the information processing services industry, which includes cloud computing and storage services, suggesting the potential for substantial deviation.[19]

We focus on the enterprise segment of wireline telecom services using data from *Telegeography*, who report prices of individual service offerings for four groups of enterprise business services (virtual private network; dedicated internet access; IP private line, domestic; and IP private line, international) from 2006 on. The results of computing a matched model price index for enterprise wireline telecom services yields a price index that falls 8.2 percent per year from 2006 to 2014 (line 12 in the table)—a pace of change on par with the results of the new price index for enterprise software (line 10) but below that for the relevant telecom equipment (lines 1 and 2). Although the enterprise wireline segment of telecom and internet access services is not necessarily representative of the total industry (see again figure 6), the fact that enterprise wireline telecom prices fall about as fast as software assets (i,e., an ICT asset) but not less than 1/2 the declines seen for telecom equipment is very relevant to the arguments put forth in this paper.[20]

change that has apparently continued. In March 2014 Google announced price cuts for its cloud computing services and storage by 30 percent, only to be followed in May 2915 by further cuts in the 20 to 30 percent range. (See this 2014 *Tech Crunch* article and this 2015 *InfoWorld* article for reports on these changes.)

[19]NonICT capital income asset shares are derived from the detailed capital measures for the NAICS 515,7 and NAICS 518,9 industries from 2004 to 2014 as reflected in the BLS MFP database excluding (accessed July 1, 2016).

[20]Note further that when the new enterprise services index is folded into an overall nonresidential price index for wireline services, the result falls substantially faster (7.3 percentage points) than its counterpart in official data (line 19, column 2). The construction of this index is detailed in the companion Byrne and Corrado (2016) paper.

Table 2: **Price Change for Selected High-tech Products, 1994 to 2014 (annual rate)**

		1994 to 2004	2004 to 2014	1994 to 2000	2000 to 2004	2004 to 2008	2008 to 2014
		(1)	(2)	(3)	(4)	(5)	(6)
Research indexes:							
1.	Data networking[a]	-13.5	-12.1	-13.6	-13.0	-9.7	-13.6
2.	Local loop transmission	-18.4	-14.2	-13.8	-24.7	-14.4	-14.1
3.	Cell networking	-17.5	-18.4	-18.6	-15.8	-13.5	-21.5
4.	Cell phones	-19.4	-15.9	-17.7	-21.9	-15.3	-16.3
5.	Computer servers	-29.4	-26.1	-28.4	-30.7	-30.8	-22.8
6.	Computer storage	-49.2	-26.1	-54.5	-40.1	-30.1	-23.4
7.	Personal computers	-30.3	-23.7	-36.8	-19.3	-30.2	-19.1
8.	Prepackaged software	-9.6	-7.0	-10.3	-8.4	-6.8	-7.1
9.	Desktop	-5.8	-4.0	-5.3	-6.5	-3.9	-4.0
10.	Enterprise and related	-11.4	-8.4	-12.6	-9.4	-8.2	-8.5
11.	Telecom services, wireline[b]	-1.5	-5.8	-2.2	-3.4	-5.6	-5.9
12.	Enterprise only[c]	–	-8.2	–	–	-8.4	-8.1
13.	A/V equipment	-9.0	-16.3	-7.1	-11.8	-15.8	-16.7
Memo:							
14.	Computer mfg. industry[d]	-25.2	-19.8	-30.7	-22.7	-26.3	-15.1
Official indexes:							
15.	Computer servers	-22.2	-10.7	-24.8	-18.1	-17.9	-5.6
16.	Computer storage	-13.3	-4.7	-14.8	-11.1	-5.6	-4.0
17.	Personal computers	-25.1	-9.6	-29.0	-18.9	-16.9	-4.4
18.	Prepackaged software	-5.2	-2.5	-5.0	-5.4	-2.3	-2.7
19.	Telecom services, wireline[e]	-1.8	1.5	-2.2	-1.3	1.8	1.3
20.	A/V equipment[f]	-7.8	-13.2	-6.2	-10.3	-13.0	-13.3
Memo:							
21.	Computer mfg. industry[d]	-17.4	-11.8	-23.8	-17.4	-19.6	-6.1
Performance measures (annual percent change):							
22.	MPUs[g]	-59.9	-38.9	-64.2	-52.4	-36.9	-40.2
23.	Smartphone storage[h]	23.9	–	16.5	49.5	90.9	–
24.	Top500 computers (median)[i]	88.4	69.1	81.8	98.7	92.4	55.2

SOURCES: Byrne and Corrado (2015a,b, lines 1 to 4); this paper, lines 5 to 15, 23, 24 and 26, using McCallum (2002) and Byrne (2015) to inform line 6; Berndt and Rappaport (2001, 2003) to inform line 7; Abel et al. (2007) and Copeland (2013) to inform line 9; Gordon (1990) to inform line 14; and Grimm (1998), Byrne, Oliner, and Sichel (2015), Federal Reserve and Bank of Japan estimates to inform lines 23 and 24. The source for lines 16 to 22 is BEA. The source for line 25 is Hilbert and López (2011).

NOTES: a. Column 1 is from start date of series (1986). b. Nonresidential. c. Columns 2 and 5 are from start date of series (2006). d. NAICS 334111. e. Nonresidential, calculated by authors. f. PCE index excluding recording media, calculated by authors. g. Quality-adjusted price index using performance measures from 2000 on. h. Capacity in MB. i. MFLOPS per second.

3.2 New Software Prices

Table 3: **New Software Price Index**

Structure of the new index	
1.	Software products
2.	Software products, except games
3.	**Desktop and portable device software**[a]
4.	**Enterprise, networking, database, tools/languages, and other software**
5.	Application software
6.	System software
7.	Game software products

a. Covers both application and system software products.

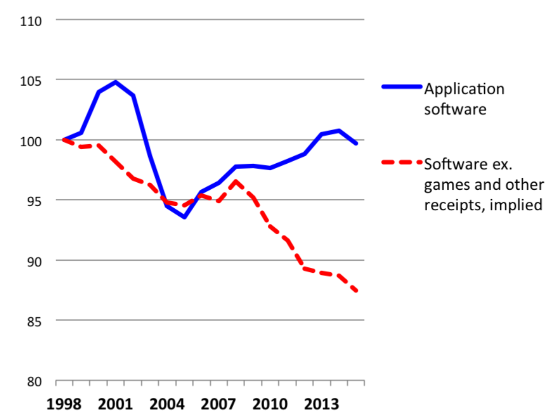
As suggested by table 2 and illustrated on the right (table 3), our new software products price index has two major "end-use" components, desktop and portable device software (line 3), and enterprise and related (i.e., networking, database, mainframe tools/languages, and other) software (line 4). Both components of the new index include application and systems types of software. The subcomponents of desktop software by type are implicit, whereas the subcomponents of enterprise and related software (lines 5 and 6) are separately estimated.

New research on software asset prices by type of use—internet platform apps, customer relations database software, data analytics/business intelligence software, systems for management of cloud services or of e-commerce transactions, etc.—is badly needed to better flesh out this structure (especially its enterprise component), but we were able to make sufficient headway to inform the analysis of recent software investment price change for this paper. The most important new source of information that has been incorporated is our own inference of recent trends in prices for system software based on the PPI for overall software publishing relative to certain of its components. Without going into details, what has been done can be understood from the following facts: (1) prices for system software are collected by the BLS, but a PPI component for systems software is unpublished because estimates do not meet standards for disclosure; (2) the PPI for application software is the primary source data for U.S. national accounts estimates of software investment prices, and (3) recent trends in BLS prices for application software (a published index) and systems software (our inference) diverge substantially, imparting a notable bias in the BEA's software investment price index.

The divergence is illustrated using published and implied BLS software price indexes in the figure to the right. The structure of the BLS PPI is shown in the table below the figure; this plus a few facts tell the story. The PPI for software excluding games (line 1 of the table below figure 10) has fallen since 2006 whereas the PPI for application software (line 3) has risen; the PPI for other software receipts (line 7) and also a component of line 1 climbs 1 percent a year. When an index representing all software products (excluding games) is estimated by subtracting the contribution of other receipts from software excluding games, that implied index falls (line 2 and shown in the figure) falls. Its implied systems component falls even more sharply (line 6 and not shown in the figure).

In short the BEA has been using the dark blue line shown in figure 10 to drive its software investment price index from 1998 on, whereas this paper uses the dashed red line. There are numerous other features of the software products and software investment price indexes developed for this paper, including the folding in of research available in the literature but not reflected in BEA's current methodology and an effort to align our new work to BEA's history so that figures are comparable over time. (The companion paper includes these details.)

Figure 10: **BLS software price indexes, published and implied, 1998=100**



Structure of BLS Software PPI	
1.	Software publishing, except games
2.	Software, except games and other receipts
3.	Application software publishing
4.	Desktop and portable device apps
5.	Enterprise and other apps
6.	Systems software publishing
7.	Other receipts
8.	Game software publishing

Note: Indexes for items in red are not disclosed.

It is important to underscore that most existing research on software prices, and essentially all of the work that informed BEA's software price methodology reported in Parker and Grimm (2000), pertains to PC desktop application software.[21] Greenstein and Nagle (2014) looked at the economic benefits of Apache, a widely-used open source software system used to manage e-commerce transactions in the 1990s, and found substantial benefits even after accounting for substitution with priced products. This suggests there could be large price declines in the systems software in wide use today, but we cannot really know without additional research. The implied systems software component in the PPI in fact drops relatively rapidly, and while its incorporation in an ICT asset price index is a major step forward (sales of systems software accounted for about 47 percent of all domestically-produced software product sales in the United States in 2013 and 2014, according to the Census Bureau's 2014 Services Annual Survey), its impact on the new price index for enterprise software is partially offset by the rising PPI for enterprise and network application

[21]One study available to Parker and Grimm (Harhoff and Moch, 1997) covered a PC database platform for business applications, but prices for PC desktop operating systems were not studied until much later (Abel et al., 2007; Copeland, 2013). As discussed in the supplemental paper, systems software includes enterprise databases as well as operating systems.

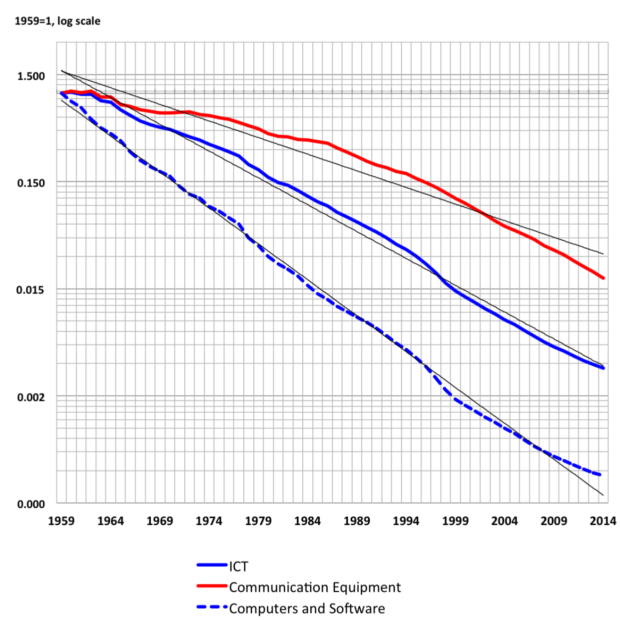
software (a component of the applications software PPI shown in figure 10). Many new products in the data analytics/business intelligence and marketing/management of customer relationships space have been introduced in recent years—consistent with the strong software products R&D shown in the previous section. All told, much additional research is needed to further improve the price measures for enterprise application and systems software reported in this paper.

3.3 New ICT Investment Prices

To assess the macroeconomic implications of the ICT goods and services prices just discussed, the indexes must be folded into national accounts-style investment price indexes. Detailed components of the investment price indexes are reported in the appendix to this paper (table A1, page 40), where it may be seen that the results are largely presaged by the results presented in table 2.

Figure 11 and table 4 report key results in terms used to assess the course of the relative productivity differential of the ICT sector ($\dot{p}$) and its current and historical misstatement. The real price of communication equipment (the red line in figure 11) falls below its simple long-term trend after 2000 and has remained there since then. The combined real price for computers and software (the dotted blue line) has not shown large deviations from trend, but note it did fall below trend beginning in the mid-1990s but returned to it by about 2004 and flattened further after that. The aggregate real ICT price index (the solid blue line) is spot on its long-term trend in 2014—11.5 percent per year (in log changes).

Figure 11: **Real ICT Investment Prices, 1959=1**



SOURCE— Nominal price change reported in appendix table A1 (page 40), whose construction is described in Byrne and Corrado (2016) available *here*. Real prices are relative to BEA's GDP deflator.

Table 4 shows that while real ICT price declines have gradually slowed over the past 10 years, at 9.9 percent per year from 2004 to 2014 (line 1, column 3), the recent experience is not all that far from the long-term trend shown in figure 11. From 2004 to 2014, the estimate of real ICT price change is 5.8 percentage points per year lower than suggested by official data (line 8, column 3). In

Table 4: **Real ICT Investment Price Change (annual rate)**

		1963 to 1987 (1)	1987 to 2004 (2)	2004 to 2014 (3)	1994 to 2004 (4)	2004 to 2008 (5)	2008 to 2014 (6)
1.	**ICT investment**	-9.5	-12.7	-9.9	-14.1	-11.3	-8.9
2.	Communications equipment	-4.5	-9.4	-10.5	-10.7	-9.9	-11.0
3.	Computers and peripherals	-21.2	-23.0	-19.0	-25.4	-23.9	-15.6
4.	Software	-5.8	-6.6	-5.7	-7.3	-6.1	-5.5
	Contributions to line 1:						
5.	Communications equipment	-2.4	-3.1	-2.7	-3.4	-2.7	-2.7
6.	Computers and peripherals	-5.8	-7.0	-4.0	-7.6	-5.4	-3.0
7.	Software	-1.3	-2.6	-3.2	-3.1	-3.2	-3.2
Memos:							
	Line 1 less BEA:						
8.	**ICT investment**	-2.1	-4.2	-5.8	-4.8	-5.5	-5.9
	Contributions to line 8:						
9.	Communications equipment	-1.7	-1.4	-1.6	-1.3	-1.2	-1.8
10.	Computers and peripherals	-.1	-1.9	-2.2	-1.8	-2.3	-2.1
11.	Software	-.3	-.9	-2.0	-1.7	-2.0	-2.1

Note—Contributions are in percentage points.
Source—For nominal prices, onllne supplement available *here*. Real prices are relative to BEA's GDP deflator.

terms of component contributions to real ICT price change (lines 5 to 7), the contribution of software from 1994 on is particularly noteworthy and owes, in part, to its growing share. But all told, in terms of differences relative to BEA (lines 9 to 11), all three components make similar contributions to the estimated nearly 6 percentage point per year understatement of overall ICT price declines in recent years (column 6).

3.4 Implications

The solution of the two-sector model set out by equation (7) in section 1, implies that the contribution of ICT to output per hour growth could be as large as 1.4 percentage points per year if the trends established during the most recent ten-year period (2004 to 2014) continue to hold in the medium-term and conditions approximate balanced growth. This is a substantial contribution.

The balanced growth contribution is based on two components. The first reflects the ICT use and diffusion effects that together sum to 1.1 percentage points per year. This large component stems from (1) a productivity differential for ICT assets that is nearly 10 percentage points per year, in combination with (2) the large relative income share for ICT assets and ICT services revenues that was shown in figure 9. The second component of the balanced growth contribution is a relatively small production effect—0.3 percentage points per year. This reflects a productivity differential for

ICT production in the United States (software products, EO originals, and consumer ICT services) of 5-3/4 percentage points per year and a rather small final output share; factory production of ICT equipment in the United States had all but dried up during the past decade.[22]

The estimates of ICT price change shown in table 4 further imply that the growth rate of output per hour would be higher by .22 percentage points per year from 2004 to 2014 if official measures were adjusted to reflect the research reported in this paper.[23] The conventionally calculated contribution of ICT to labor productivity growth (i.e., via capital spending per worker) also would be higher—by .4 to .6 percentage points per year depending on whether EO capital is included (the high estimate) or excluded (the low estimate) from the analysis.[24] All told, these impacts imply that growth in total factor productivity has been even more dismal than recorded in official estimates.[25]

Finally, figure 12 updates the picture of real ICT prices introduced at the start of this paper. As previously noted, real ICT price change is still estimated to have gradually lost force in recent years, but to a point that leaves the current pace of change in strongly negative territory. From a macroeconomic perspective, as highlighted by the two-sector model, this is *the* crucial result for continuing to regard ICT—either via investment, purchased services, or production—as a driver of economic growth in the future. From a historical perspective, figure 12 further shows that, according to the new price indexes assembled in this paper, the pace of real ICT price change during the late 1990s was extraordinary. The ten-year trends used to calibrate and draw implications from the two-sector model do not incorporate the experience of the late 1990s.

That said, a balanced growth calculation does not incorporate temporary factors that might disturb productivity outcomes, and the last ten years experienced a global financial crisis. Although a thorough review of influences on productivity growth during this period is beyond the scope of this paper, we

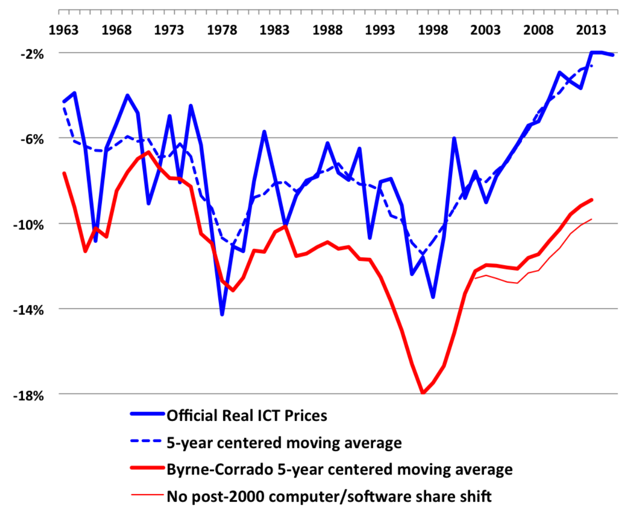
[22]The precise calculation leading to 1.4 percentage points per year is as follows: multiply the 2004 to 2014 relative income share shown in figure 9 (.113) times 9.9 percentage points (implied by line 1 on table 4) and add the 2004 to 2014 ICT final output share $\overline{w}_T$ shown in figure 8 (.056) times 5.7 percentage points (implied by line 4 on table 4). Line 4 is the software productivity differential, which is conservatively extended to other domestically-produced components of final demand following the logic of the two-sector model.

[23]The precise calculation is the 2004 to 2014 ICT final output share $\overline{w}_T$ shown in figure 8 (.056) times 3.9 percentage points, which is this paper's estimate of software asset price change from 2004 to 2014 (sign reversed, i.e., -3.8 percent per year less the change in BEA's official index of .1 percent per year). This result is in the same ballpark as the findings reported in Byrne, Fernald, and Reinsdorf (2016).

[24]The precise calculation is the relevant share from figure 9 times 5.9 percentage points, where 5.9 is the difference between the ICT asset price measures reported in this paper and the official estimates of change from 2004 to 2014.

[25]According to BLS figures for "output per unit of combined inputs" in their *Total Economy Production Account Tables* dated March 24, 2016, TFP for the total U.S. economy grew 0.4 percent per year from 2004 to 2014, compared with 1.3 percent per year from 1994 to 2004. The ICT price measures reported in this paper, given existing GDP in all other regards, imply that TFP for the total U.S. economy likely edged up only .2 percentage points per year from 2004 to 2014.

Figure 12: **Real ICT Price Change, Redux**



can close the loop on the macroeconomic implications of the paper's two-sector model discussed in section 1.3. Consider (a) that computer demand is unlikely to remain as weak in the medium term as it has been during a period of adjusting to a cloud platform, and (b) that weak demand and slow income growth have obscured nonICT producers' gains from increased ICT capital utilization due to the adoption of cloud technologies.

With regard to (a), the thin red line in figure 12 shows a counterfactual for real ICT price change in which the computer and software shares did not shift after 2000. The counterfactual closes the gap between the end point of the centered moving average of real ICT price change (about 9 percent) and the long-term trend used to determine the contribution of ICT to growth in output per hour (about 10 percent). This then mitigates the concern that ICT price change continued to slow over the 10 year period used to calibrate the model, i.e., that the calibrations are based on an adjustment phase during which growth in unit computer demand has been substantially diminished by the spread of cloud technologies suggests the last 10 years of actual ICT price declines were unusually slow.

With regard to (b), figure 13 uses industry-level changes in total factor productivity growth before and after the Great Recession and relates them to the increase in intensity of ICT services use. The figure suggests that nonICT producers have not reaped the gains in productivity that should have

Figure 13: **TFP Acceleration and ICT Services Use**

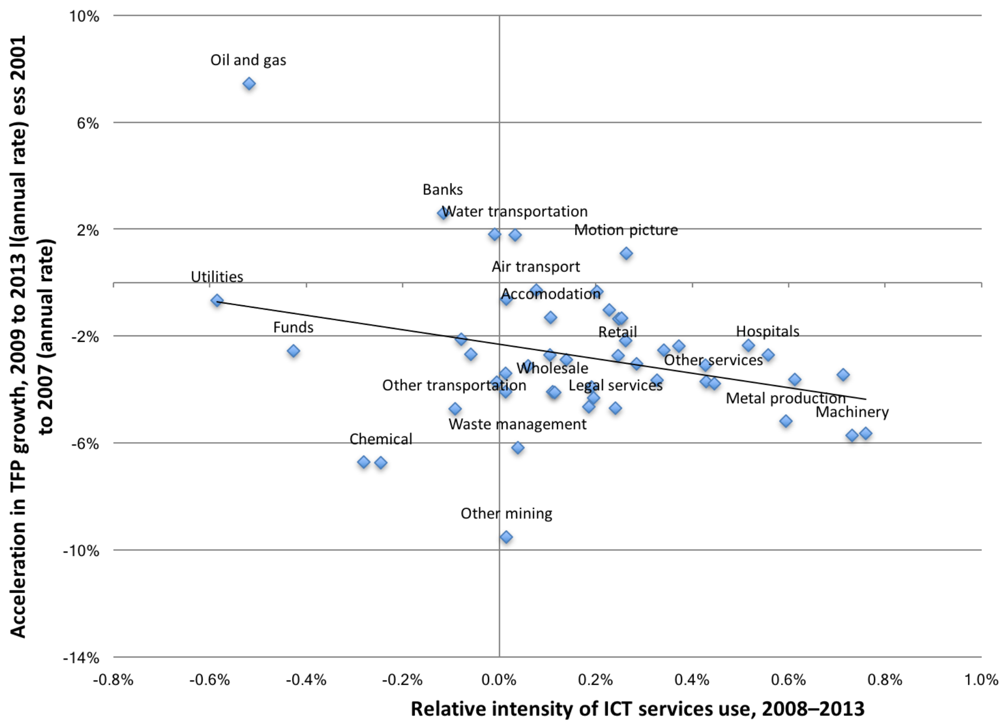
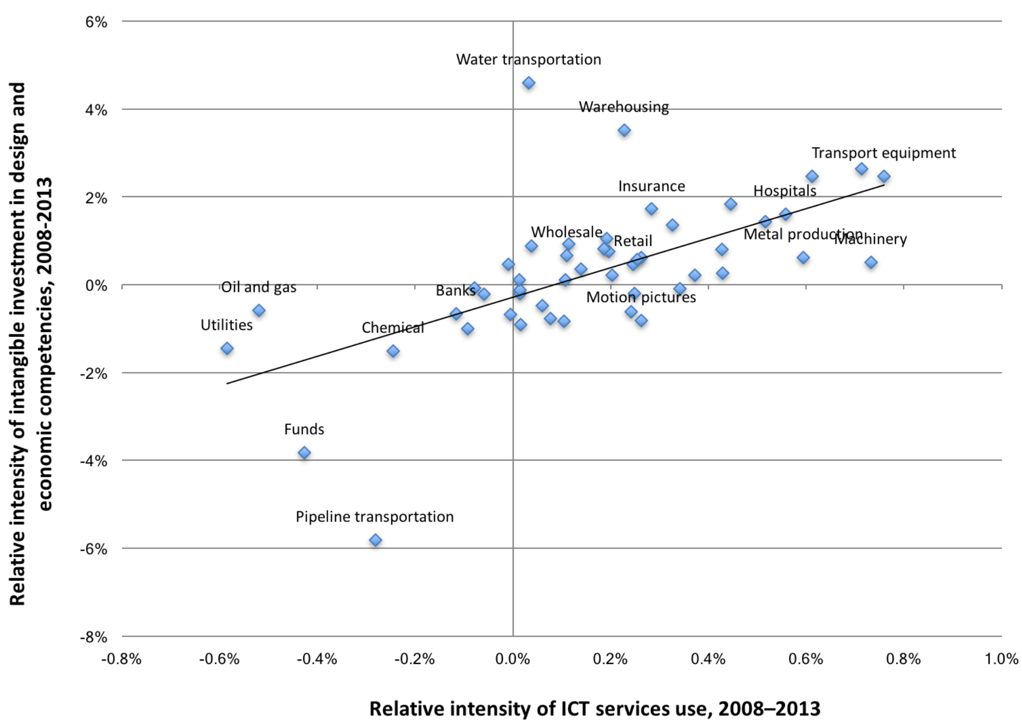


Figure 14: **Intangible Investment and ICT Services Use**



Notes to figures 13 and 14: NonICT producing industries only. Relative intensity is the use or investment rate averaged over period indicated relative to its trend over the previous decade. The rates are calculated relative to the sum of value added plus purchased ICT services. Chart outliers are suppressed.

been enjoyed by the adoption of cloud platforms.[26] And figure 14 suggests that the failure of nonICT producers to reap productivity gains did not owe to a lack of co-investments in the intangible assets that are especially crucial during the installation phase of new ICT platforms, e.g., investments in business process change and employer-specific training (Brynjolfsson, Hitt, and Yang, 2002).

It is unclear why industries whose usage of ICT services increased the most after 2007 had weaker (or no greater) rates of change in productivity from 2010 to 2013 relative to prior performance despite their co-investments in ICT-related intangibles, but several possibilities are likely. First, the very swift pace of change in the ICT sector may have created adjustment costs that temporarily offset gains from adapting to the rapid pace of digital innovation.[27] Second, it is possible some ICT spending may be defensive, e.g., in cyber security. Third, the Great Recession may have induced firms to "pull forward" their plans to adopt cloud-based ICT systems, and the savings from doing so may have only staunched losses that were particularly severe among adopters. All told, the "diffusion" portion of the model's "use and diffusion" effect of 1.1 percentage points per year contribution of ICT to labor productivity growth seems to have not only shut down, but may even be temporarily generating negative productivity spillovers. Nearly 1/3 of the "use and diffusion" effect is due to diffusion via intermediate use. It is of course common to regard innovation in upstream sectors as diffusing to downstream sectors through intermediate use (Domar, 1961), and there is no reason to believe that this channel will not return in full force in the years ahead.

4 Summary and conclusion

This paper set out a two-sector model that illustrated how the ICT sector can have an out-sized influence on economic growth via its relative productivity growth; the model, originally due to Oulton (2012), was expanded to include ICT services for improved relevancy. A central feature of the model is that relative ICT asset prices reflect the relative productivity of the sector. Official measures of ICT prices suggest that the relative productivity of ICT capital has been gradually eroding for 10 years and that its current advantage is close to nil. This paper found no evidence in support of this central implication of the current official ICT price measures.

[26] Although this paper has shown a disturbing degree of price mismeasurement that would feed directly into the TFP estimates plotted in this figure, these concerns are somewhat ameliorated because the figure uses *changes* in the rate of productivity growth (i.e., double differences) and examines nonICT-producing industries only.

[27] Adjustment costs were used to analyze the Solow paradox (e.g., Greenwood and Yorukoglu, 1997) and productivity growth in the 1990s (e.g., Basu, Fernald, and Shapiro, 2001; Hall, 2001; Kiley, 2001).

The paper first found that ICT R&D has not only been well-maintained, but that software products R&D has enjoying a stunning rise. If technical change in the ICT sector has ground to a halt, then the return to software R&D must have fallen dramatically, which seems unlikely in the face of more than a decade of relative growth in investments in this area and the advent of cloud technologies that should have boosted the productivity of the conduct of software R&D.

Second, the model developed in this paper predicted strong growth in ICT services use and strong relative growth of ICT design services to the extent that cloud technologies has taken hold. The overt, first order macroeconomic effects of the transition to cloud technologies—weak computer hardware demand and increase in ICT capital utilization—are not easy to detect in macrodata. But strong relative growth in cloud services and systems design services (i.e., relative to GDP) is a key feature of the current ICT landscape and one sign that innovation is still driving the sector. All told, via the user cost relationship as well as the paper's two-sector model, we also found that ICT services price change is driven by ICT asset price change; the alternative ICT asset price change measures reported in this paper—especially the 26 percent annual decline in real prices for servers and storage equipment (15 and 21 percentage points faster, respectively, than drops in official prices for these assets; see again table 2)—are consistent with press reports that suggest prices for cloud services are dropping rapidly.

More broadly, the paper introduced new measures for ICT asset price change that incorporated available research as well as new work conducted expressly for this paper. The ICT asset price measures were based on more than a dozen new ICT product price indexes, and the new ICT investment price indexes for communication equipment, computers, and software were developed to be as coherent as possible with national accounts practices. The new results feature substantial innovations for total telecom equipment, computer servers, software products, and enterprise telecom services (wireline). Although much new evidence on ICT asset prices and ICT services prices was marshaled for the analysis reported in this paper, large gaps in evidence remain—enterprise software products and differentiated computer design services are notable examples of these holes.

The paper's primary conclusion that real ICT price declines remain squarely in negative territory suggests that the sector will continue to deliver an out-sized contribution to growth in output per hour—1.4 percentage points per year in balanced growth. This figure is substantial in light of historical average OPH growth of 2 percent, but it emerges from two sources documented in this paper: first, an ICT income share that has continued to expand along with the relative growth of ICT services, and second, a rate of real ICT price change that has declined more than 10 percent per year since 1959 and currently is understated by nearly 6 percentage points. Although the current weakness in output per hour growth owes at least in part to headwinds unrelated to ICT, correlations in the available industry-level data show that total factor productivity in nonICT producing industries has not been improving along with increased ICT services use. Additional research is needed to deepen our understanding of the linkages between measured productivity, firm performance and firm spending on ICT assets and ICT services.

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Appendix

A1 The steady-state solution of the two-sector model

Model. Lower case variables are per hour versions of inputs and outputs introduced in the text, i.e., $x_i^j = X_i^j / H^j$ is the per hour form of variable X where $i = T, N$ denotes type of good or service where relevant (i.e., ICT or other types), and $j = T, N$ denotes sector of use (ICT-producers or other producers). As in the Oulton model, the sector production functions i are Cobb-Douglas and written here in per hour form as :

$$q_N = A_N (k_T^N)^{\alpha} (k_N^N)^{\beta} (s_T^N)^{\gamma} (h_N)^{1-\alpha-\beta-\gamma} \tag{A1}$$

and

$$q_T = A_T (k_T^T)^{\alpha} (k_N^T)^{\beta} (s_T^T)^{\gamma} (h_T)^{1-\alpha-\beta-\gamma} \tag{A2}$$

The functions for the two sectors are identical except for TFP (the Hicksian shifter) whose growth rates μ_T and μ_N are exogenous.

The supply-use equations for the open economy version of the model are

$$\begin{gathered} Y = C + I + X - M \ ; \ Y = Y_T + Y_N \quad \text{where} \\ Y_T = C_T + I_T - M_C - M_I \ ; \quad Y_N = C_N + I_N + X_C + X_I \ . \end{gathered} \tag{A3}$$

Imports $M = M_C + M_I$ are imports of ICT goods, and exports $X = X_C + X_I$ are exports of all other goods, i.e, the economy is an (net) importer of ICT and a (net) exporter of all other types of output. Next, we assume input supplies must equal demands, so that $H = H_N + H_T$ and $K_i = \sum_j K_i^j$, $j = T, N; i = T, N$. Accumulation equations are given by

$$\dot{K}_N = I_N - \delta_N K_N \tag{A4}$$

$$\dot{K}_T = I_T - \delta_T K_T \tag{A5}$$

Recalling that $p = P_T / P_N$, a steady state in this model is when trade is balanced $X = pM$ and when the real interest rate r and proportions of total hours allocated to each sector H_i/H $(i = T, N)$ are constant. With sectoral hours shares constant in steady state growth, for sectoral and overall output per hour to grow at a constant rate it follows that the services share of ICT production must also be constant. This follows from the definitions:

$$Q_T \equiv Y_T + S_T^N \ \text{ and } \ Q_N \equiv Y_N \tag{A6}$$

where in the steady state, the growth rate Q_N and Y_N (and thus q_n and y_n) are identical by definition. The growth rate of Q_T is a (constant) share-weighted average of the growth rates of Y_T and S_T^N, which grow at the same rate, and thus imply $\dot{q}_T = \dot{y}_T$ in steady growth.

Note also that with sectoral hours shares constant in steady state growth, OPH growth in the total economy is a share-weighted average of the growth rates of OPH growth in each of the sectors, i.e., accounting for "labor reallocation" due to shifts in hours shares is not needed.

Growth rate of relative ICT prices ($\dot{p}$). Given the model's assumption that production functions are the same up to a scalar multiple, it is easy to see that the rate of change in relative ICT prices $\dot{p}$ (where recall $p = \frac{P_T}{P_N}$) is given by

$$\dot{p} = \mu_N - \mu_T < 0 \tag{A7}$$

Equation A7 is proved by total differentiation of the payments equations, text equation (4), with respect to time. With μ_N and μ_T constant by assumption, so too is $\dot{p}$.

Growth rate of output per hour. To obtain the steady state growth rates of labor productivity, first differentiate equation (A1) and (A2) with respect to time, which gives

$$\dot{q}_N = \mu_N + \alpha \dot{k}_N^N + \beta \dot{k}_T^N + \gamma \dot{s}_T^N + (1 - \alpha - \beta - \gamma)\dot{h} \tag{A8}$$

$$\dot{q}_T = \mu_T + \alpha \dot{k}_N^T + \beta \dot{k}_T^T + \gamma \dot{s}_T^T + (1 - \alpha - \beta - \gamma)\dot{h} \tag{A9}$$

where from (A6) we have

$$\dot{q}_N = \dot{y}_N \quad \text{and} \quad \dot{q}_T = \dot{y}_T \quad . \tag{A10}$$

Consider first the N sector. Profit maximization requires that the real user cost equals the real marginal product of capital, which for nonICT and ICT capital are given by

$$(i + \delta_N) = \alpha \frac{q_N}{k_N^N} \quad \text{and} \quad (i + \delta_T - \dot{p})p = \beta \frac{q_N}{k_T^N} \quad . \tag{A11}$$

where i is the nominal rate of interest and the real interest rate is the nominal rate minus the growth rate of the N sector price P_N, expressed in terms of the relative price p in (A11).

In steady state where the real interest rate is constant and factors are paid their marginal products, the solutions for sector N are then

$$\dot{q}_N^* = \dot{y}_N^* = \dot{k}_N^{N*} \tag{A12}$$

$$\dot{q}_N^* = \dot{y}_N^* = \dot{k}_T^{N*} + \dot{p} \tag{A13}$$

where * denotes a steady state solution (recall $\dot{p}$ is constant by assumption).

Consider now the T sector. Equality of the real marginal product of ICT capital in T sector production with real user cost implies

$$(i + \delta_T - \dot{p}) = \beta \frac{q_T}{k_T^T} \tag{A14}$$

Because the left hand side of (A14) is constant, it follows that $\dot{q}_T = \dot{k}_T^T$ from which it follows:

$$\dot{q}_T^* = \dot{y}_N^* - \dot{p} \quad . \tag{A15}$$

In steady state growth, output per hour in sector T grows faster than output per hour in sector N.

Finally, equality of the real marginal product of ICT intermediate services across the two sectors implies that

$$\frac{\partial q_N}{\partial s_T^N} = \gamma \frac{q_N}{s_T^N} = \gamma \frac{Y_N}{S_T^N} \tag{A16}$$

must be identical to

$$\frac{\partial q_T}{\partial s_T^T} = \gamma \frac{q_T}{s_T^T} = \gamma \frac{Y_T + S_T^N}{S_T^T} \tag{A17}$$

Equation (A16) implies that $\dot{s}_T^N$ is equal to $\dot{y}_N$ in steady state growth but from (A15), we know that q_T, of which s_T^N is a component, grows at a faster rate than $\dot{y}_N$. It is readily seen that the condition $\dot{q}_T = \dot{y}_T$ solves this dilemna and implies

$$\dot{s}_T^N = \dot{y_N} - \dot{p} \tag{A18}$$

$$\dot{y}_T = \dot{y}_N^* - \dot{p} \ . \tag{A19}$$

Now substitute equations (A12), (A13), and (A18) into (A8), the expression for growth in output per hour in sector N:

$$\dot{y}_N = \mu_N + \alpha \dot{y}_N + \beta(\dot{y}_N - \dot{p}) + \gamma(\dot{y}_N - \dot{p}) + (1 - \alpha - \beta - \gamma)\dot{h}$$

which after rearranging terms yields

$$\dot{y}_N = \frac{\mu_N - (\beta + \gamma)\dot{p}}{(1 - \alpha - \beta - \gamma)} + \dot{h} \ . \tag{A20}$$

Define the steady state output share of the T sector as

$$\omega_T^* = \frac{pY_T}{Y_N + pY_T} \tag{A21}$$

in which case the steady state OPH growth rate for the total economy may be written as

$$\begin{aligned} \dot{y}^* &= (1 - \omega_T^*)\dot{y}_N^* + \omega_T \dot{y}_T^* \\ &= \dot{y}_N^* + \omega_T^*(\dot{y}_T^* - \dot{y}_N^*) \ . \end{aligned} \tag{A22}$$

Substituting (A19) into (A22) yields

$$\dot{y}^* = \dot{y}_N^* - \omega_T^* \dot{p}$$

and subsitituting (A20) into this expression and combining terms yields our final result, an expression for the contribution of the ICT sector to total OPH growth:

$$\begin{aligned} \dot{y}^* &= \frac{\mu_N - (\beta + \gamma)\dot{p}}{(1 - \alpha - \beta - \gamma)} + \dot{h} - \omega_T^* \dot{p} \\ &= \frac{\mu_N}{(1 - \alpha - \beta - \gamma)} + \dot{h} \ + \underbrace{\frac{(\beta + \gamma)(-\dot{p})}{(1 - \alpha - \beta - \gamma)} + \omega_T^*(-\dot{p})}_{\textit{Contribution of ICT to total OPH growth}} \end{aligned} \tag{A23}$$

The final term in equation (A23) appears as text equation (7) where $\beta, \gamma, (1 - \alpha - \beta - \gamma)$, and ω_T are replaced by their empirical counterparts $\overline{v}_{K_T}, \overline{\zeta}_T^N, \overline{v}_L$, and $\overline{w}_T$.

Contribution of ICT to growth in TFP The amended model's solution for aggregate TFP μ also is different than that implied by the original Oulton model. Under the usual neoclassical growth accounting assumptions in the presence of intermediates (e.g., Hulten 1978), the growth of aggregate

TFP is the sum of the growth of each sector's TFP growth times its Domar-Hulten weight, which is the ratio of each sector's sectoral production (gross output net of own use) to aggregate value added, $P_i Q_i / PY$. From (2) and (5), these weights are expressed as:

$$\frac{P_T Q_T}{PY} = \overline{w}_T + \overline{\zeta}_T^N \quad ; \quad \frac{P_N Q_N}{PY} = 1 - \overline{w}_T$$

whose sum is greater than one by the relative size of ICT services supplied to nonICT producers.

The growth of aggregate TFP μ is then given by

$$\mu = \underbrace{(\overline{w}_T + \overline{\zeta}_T^N)\mu_T}_{\text{Contribution of ICT sector}} + (1 - \overline{w}_T)\mu_N \qquad \text{(A24)}$$

The contribution of the ICT sector to overall TFP growth is larger than the sector's share in final demand $\overline{w}_T$ to account for the diffusion of the sectorn's innovation via use of ICT services (intermediate inputs) by other producers in the economy.

A2 Nominal ICT investment deflators

The table below shows detailed components of the nominal national accounts-style price deflators calculated for the analysis in this paper. The methods used to construct these deflators are described in detail in a supplemental document available *here*.

Table A1: **Nominal ICT Investment Price Change (annual rate)**

		1963 to 1987 (1)	1987 to 2004 (2)	2004 to 2015 (3)	1994 to 2004 (4)	2004 to 2008 (5)	2008 to 2015 (6)
1.	**ICT investment**	-4.9	-10.6	-8.0	-12.4	-8.9	-7.5
2.	Communication equipment	.4	-7.3	-8.7	-9.1	-7.4	-9.5
3.	Telecom	-.3	-11.7	-12.4	-14.3	-10.1	-13.7
4.	Other equipment	.4	-8.3	-9.3	-10.3	-8.1	-10.0
5.	Capitalized services	–	1.1	-3.7	-.1	-2.5	-4.3
6.	Computers and peripherals	-17.1	-21.2	-17.0	-24.0	-21.8	-14.1
7.	Servers and storage	-18.1	-25.2	-25.7	-31.0	-30.6	-22.7
8.	PCs	–	-27.9	-23.4	-30.3	-30.2	-19.2
9.	Other equipment	-9.0	-9.3	-3.3	-8.8	-5.4	-2.0
10.	Capitalized services	–	-2.0	-2.2	-3.1	-1.5	-2.6
11.	Software	-1.0	-4.4	-3.9	-5.5	-3.5	-4.1
12.	Prepackaged	-9.8	-9.0	-7.0	-9.6	-6.8	-7.2
13.	Custom and own-account	.0	-2.0	-2.2	-3.1	-1.5	-2.6
Memos:							
14.	ICT excluding PCs	-4.5	-8.4	-6.5	-9.9	-6.6	-6.4
15.	Computers excluding PCs	-16.6	-17.1	-11.6	-19.8	-14.5	-9.9
16.	BEA ICT	-2.7	-6.4	-2.1	-7.5	-3.3	-1.4
17.	BEA ICT excluding PCs	-2.6	-4.5	-1.4	-5.2	-1.9	-1.2
18.	Computers excluding PCs	-16.6	-11.0	-3.6	-12.7	-6.6	-1.8

NOTE: Figures reported as "BEA" are authors' calculations based on BEA data.