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 and draws conclusions about the relationship between prices for ICT services and prices for the capital stocks (i.e., ICT assets) used to supply them. The currently available information on ICT asset prices and ICT services is put under a microscope, and official prices are found to substantially understate actual ICT price declines. And because ICT capital continues to grow and penetrate the economy—increasingly via cloud services which are not fully accounted for in the standard narrative on ICT's contribution to economic growth—the contribution of the sector to growth in output per hour going forward is calibrated to be substantially larger than it has been 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 (more than computer microprocessors) drove productivity developments in the 1990s and the 2000s. An overarching story of productivity performance for nearly 25 years is all to the good, but it begs the question of why the recent performance of U.S. productivity has been so dismal, given that advances in information and communications technology (ICT) have continued to be strong to this day.

The deterioration in U.S. productivity, as measured in the official statistics, is due in part to the fact that real ICT equipment and software (E&S) investment spurred by rapidly falling relative prices no longer provides an extra boost to the rate of growth in output per hour. Not only has nominal ICT E&S investment relative to GDP moved sideways since 2010 (figure 1a), relative ICT price change has posted historically *very* small declines of late, after having gradually lost force since 2005 (figure 1b). As a result, measured labor productivity growth has been extraordinarily weak: Output per hour for the total 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.[2]

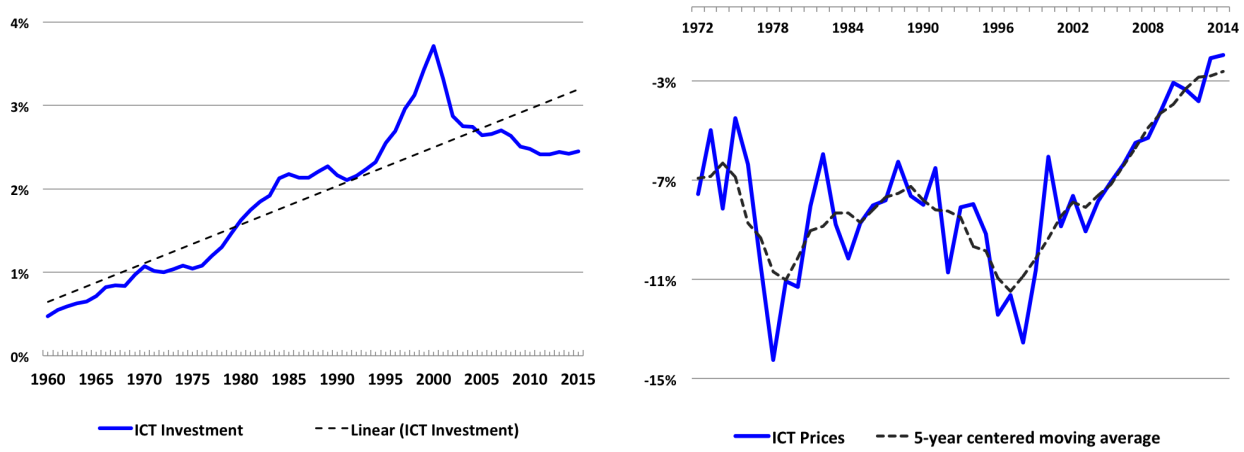
The digital transformation of the U.S. economy is highly visible in the plentiful supply of new software apps, powerful wireless devices, and widespread access to high-speed broadband. Why, then, is ICT investment so weak? And if digital innovations are so transformative, why are they not having a discernible impact on 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 possible that the ICT

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

[2] Based on The Conference Board's Total Economy Database™ whose series for U.S. output per hour 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.

sector—about 6 percent of the economy in value added terms—is innovating and prospering while the overall economy continues to suffer from weak demand in the aftermath of the Great Recession and/or demographic and other headwinds as argued by 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. 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 the user cost 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. Second, the model is used to set out the contribution of ICT technology to total economy labor productivity growth in the medium- to long-term. This involves documenting the growing role of ICT services in the United States, the growing intensity of ICT R&D, and assessing the extent to which official measures of ICT price change are capturing all that is going on.

In our review of ICT price measures, we introduce a new, quality-adjusted price index for commu-

nications equipment investment that draws upon our own prior work on the measurement of telecommunications and networking equipment. We also introduce new price indexes for enterprise software products, high-end computers and computer storage systems, which, along with high-speed broadband, have made the growth of cloud computing and data analytics possible, i.e., they reflect prices of assets used to generate these ICT services. All told, our findings suggest that ongoing ICT technological change potentially contributes as much as 1-1/4 percentage points per year to labor productivity growth in the United States and that trends in official ICT prices suffer from substantial mismeasurement, especially recently, and especially in software, which accounts for more than half of ICT investment.

It should be underscored that the assessment conducted in this paper keeps the scope of GDP as in official statistics and addresses the measurement of technology via ICT prices included in existing national accounts. The paper thus bears most directly on interpreting recent trends in private ICT investment and private ICT services use by the producing sectors of the economy. Subsequent work (under way) uses the framework developed in this paper to address the impact of digitization on the consumer sector, including its measured scope of its activity.

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 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), 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). Thus we have

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

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

Each sector produces investment and consumer goods and services for final use. 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.[4] 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

$$Q_T \equiv Y_T + S_T^N = A_T F(K_N^T, K_T^T, S_T^T, L^T) \ ; \tag{3}$$

$$Q_N \equiv Y_N = A_N F(K_N^N, K_T^N, S_T^N, L^N)$$

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.

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

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

$$P_i Q_i = R_N K_N^i + R_T K_T^i + W H^i + P_T S_T^i \quad , \quad i = T, N \quad , \tag{4}$$

with relevant factor shares given by

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

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

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

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

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

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 $\bar{\zeta}_T^N$ 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, however, the channel also operates via the contribution of producers' purchases of ICT services, e.g., purchases of computing, storage, and software services generated by ICT assets owned by ICT *services producers*, 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.

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. 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.

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.[5] In other words, from (8) we then have

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

[5]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.

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.[6]

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.[7] 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 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.[8] 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).

[6] 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.

[7] 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.

[8] Where, as in footnote 6, there is an implicit term d capturing underutilization reflects the potential for improvement.

All told, the $\dot{\lambda}$'s represent efficiencies enjoyed by companies that move from a traditional IT datacenter to a public or private 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 many IT technologies—server virtualization, containers, and grid computing—all of which result in much denser workload-to-IT 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 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).[9] 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

[9] 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.

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 $\overline{\zeta}_T^N$. 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, by many accounts, such advances stepped down a notch in the first half-decade of the 2000s (Hilbert and López, 2011; Pillai, 2011, 2013). The same cannot be said, however, for advances in communications technology, i.e., internet and wireless technologies (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.[10] 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,

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

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.

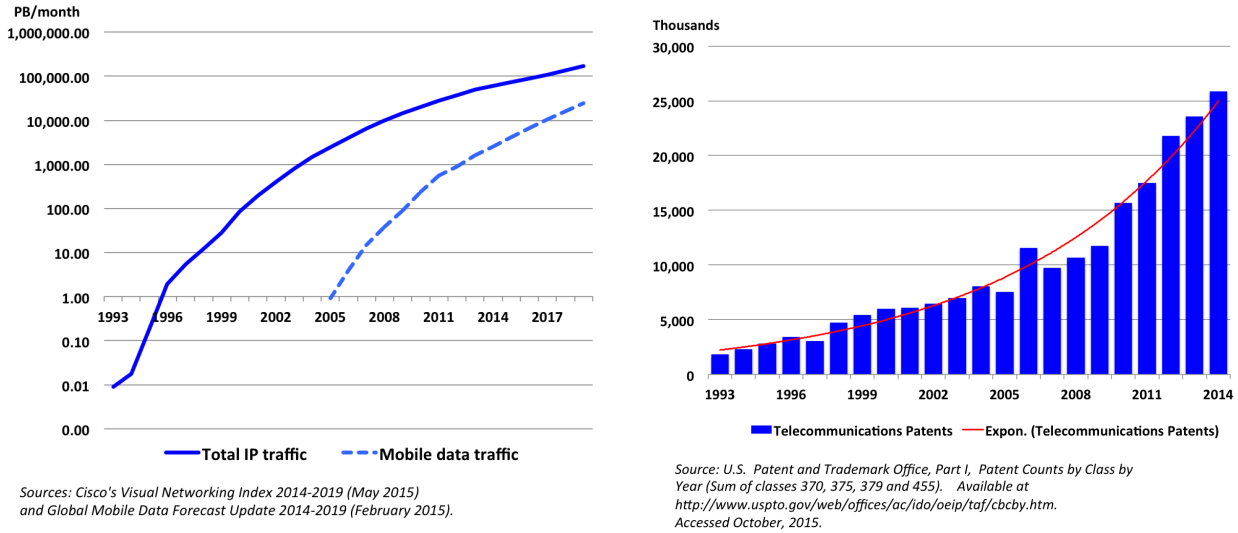
the world could not have achieved the reported 29 percent per year increase in IP traffic and nearly 78 percent per year increase in wireless *data* traffic that it did during this period (figure 2, left panel).[11]

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 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).[12] 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. And the right panel of figure 2 shows that by one measure, the rate at which wireless-related patents are filed in the United States, the current pace of technological change is as brisk as it was in the late 1990s.

[11]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*, the source for the data plotted in the figure.

[12]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 2: **Global IP Traffic and U.S. Telecommunications Patents**



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

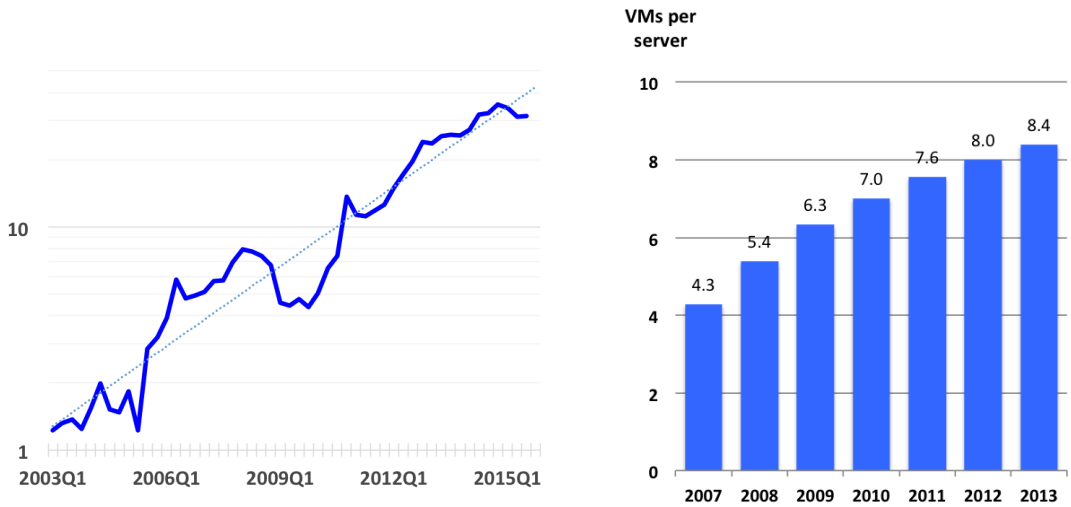
(b) U.S. Telecommunications Patents, 1993 to 2014

Cloud technologies. Virtualization and containerization are relatively obscure topics to economists, but as shown in the previous section, they may be modeled as increases in capital utilization. The basic idea is that applications historically were run on separate servers (i.e., an email server, a database server, a network server, etc.) and, while increasing the workload of servers has been going on for some time, workloads have increased at a much faster pace as cloud technologies have spread.

The virtualization technology that is the primary enabler of cloud computing has been in commercial use since the 1970s via IBM mainframes. The foundation of containerization, itself a lightweight virtualization technology, is open source LINUX formats available more recently. In terms of enterprise applications, it is very early on in the application of containerization (the consultancy IDC estimates that only 1 percent of enterprise applications are running on containers) but cloud vendors have been able to make use of virtualization, grid computing, and micro-services architectures such as containerization to enable ever larger workloads to run on a single server and economize on storage since the advent of the millennium. As shown in figure 4(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.

Consider now server virtualization. Although platform transitions are costly for firms, the hardware consolidation offered by transitioning traditional datacenters within firms to "private" clouds is noteworthy. IT consultancies commented in 2008 that server virtualization had become the "killer app" for

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.

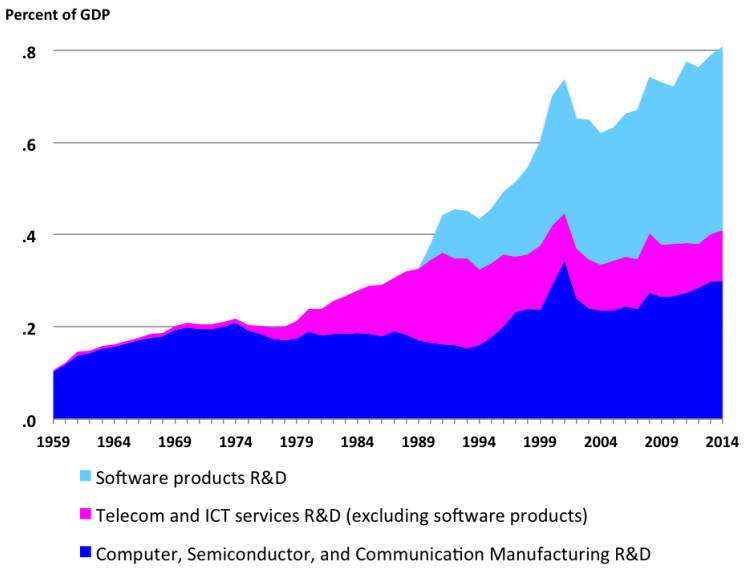
the business datacenter and subsequently IDC estimated that the number of virtual machines (VM) per server in the United States—an indicator of the application workload of a datacenter—advanced nearly 12 percent per year from 2007 to 2013 (figure 4(b)).

R&D investments in ICT. The conduct of ICT R&D in the United States also suggests a brisk pace of change. ICT manufacturing R&D investment relative to GDP—the dark blue shaded area in figure 4 and dominated by R&D focussed on semiconductors and high-speed communication equipment design and related embedded software—has remained robust even though ICT factory output has continued to dwindle and ICT E&S investment is only growing slowly. R&D in telecommunications and ICT services reported in national accounts (the pink shaded area) shows a dwindling share since the mid-1990s, but when software R&D included in software investment—the light blue shaded area of figure 4—is added in, an altogether different picture is presented. The rate of total private R&D investment by ICT-producers in the United States has in fact been very robust in the last decade.

Let us underscore that figure 4's overall trajectory reflects U.S. national accounts' estimates of (1) private R&D investment by ICT-producing industries for the industries listed in table 1 *plus* (2) software products R&D presented as software investment. Software products R&D is thought to be

captured in own-account software investment, and national accountants (in the United States and other countries as well) exclude this category from their headline R&D figures. 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 time series for these estimates reported in table 2 of Crawford, Lee, Jankowski, and Moris (2014).[13]

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



Source: Authors' elaboration of BEA and NSF data.

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. The rate of investment in ICT R&D in recent years continues to increase at its post-Internet pace in this presentation, suggesting that ICT innovation could not have slowed for lack of investment in the development of new technologies and products.

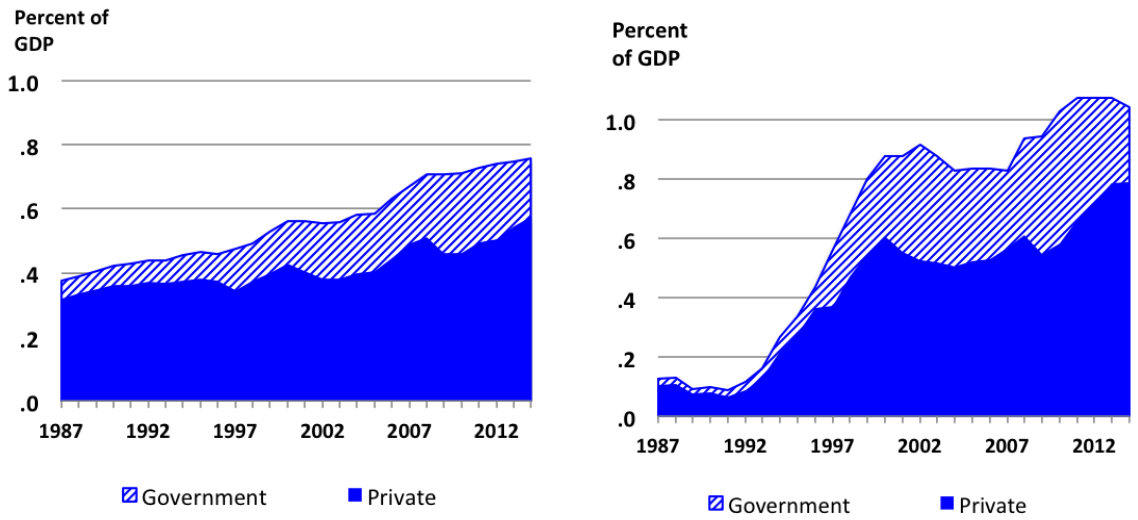
2.2 ICT services and software investment

Intermediate uses of ICT. ICT R&D historically has been oriented toward producing better and faster computers and more powerful productivity-enhancing computer software 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.

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

[13]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 authors' extrapolation based on total nonresidential own-account software investment.

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.

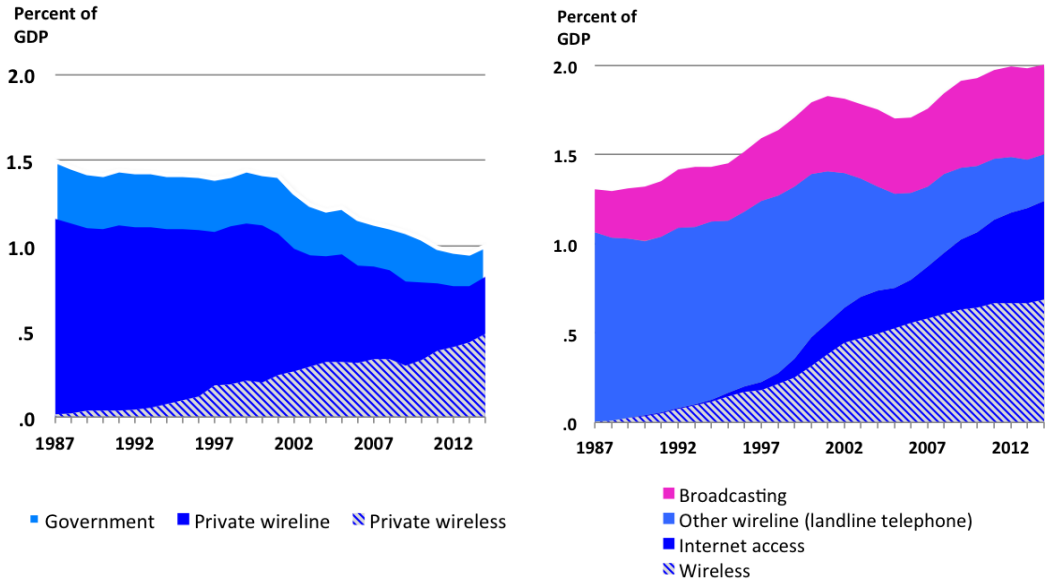
relative to GDP in the United States in recent years (the solid blue shaded areas of the left and right panels of figure 5, respectively). These developments reflect the both the growth of cloud services (which are in NAICS 5182 and has seen steady growth) and a remarkable surge in systems design services 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.[14] 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.[15]

Trends in intermediate and final uses of telecommunications and broadcasting services are shown

[14]To be clear, spending on computer systems design is not counted as investment in national accounts but would be included in expanded frameworks that recognize a portion of professional consulting expenditures as long-lived investment (e.g., as in Corrado, Hulten, and Sichel 2005, 2009). About 35 percent of the intermediate uses of NAICS 5415 are estimated to be long-lived computer design services, but note, this was not a component of the intangible investment estimates developed in Corrado et al. (2005, 2009) and maintained in the INTAN-Invest internationally comparable database covering 22 EU countries and the United States (Corrado, Haskel, Jona-Lasinio, and Iommi, 2012, 2013).

[15]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."

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.

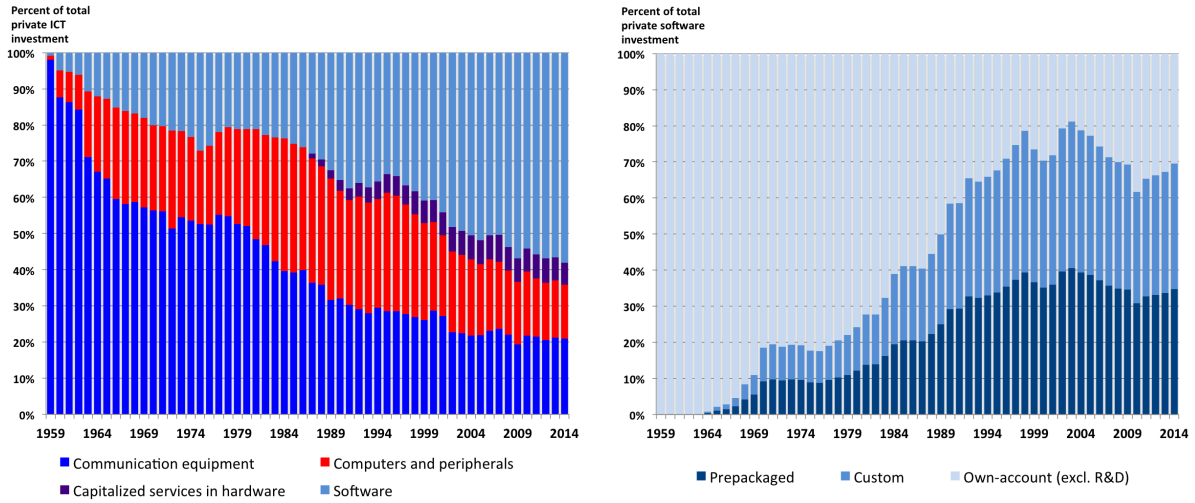
in figure 6. Traditional wireline telephone services ideally would be excluded from this analysis, but a split of traditional vs. IP telephony and internet access services in data on intermediate purchases by industry is not available. As may be seen, business demand for wireless services is robust, especially from 2010 on, whereas total private telecommunications services (which adds in wireline telecom and internet access services) has moved down since peaking in 2000. By contrast, 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.

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.

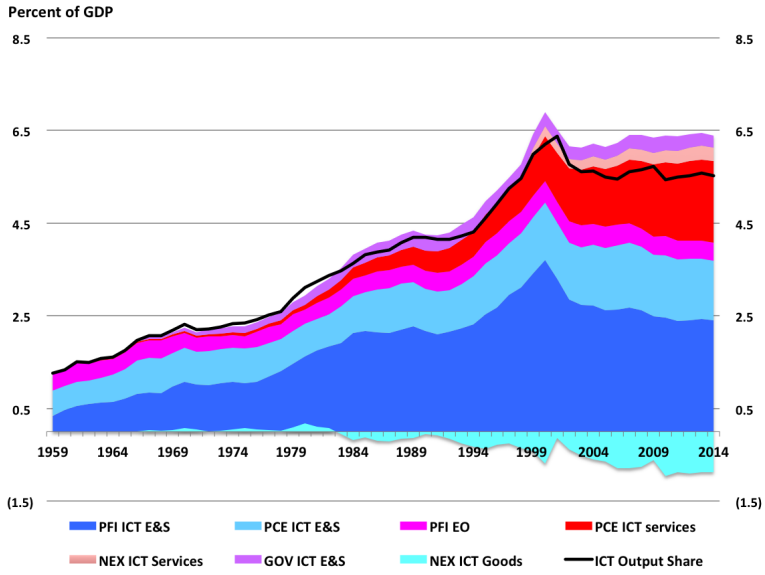
Within new software assets, purchases of marketed, standardized software products are about 1/3 of total software, as illustrated by the dark blue shaded area in the right panel of figure 7. The lion's share of software is custom produced, whether as purchased services or performed on own account. Price measures for these 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 on part on the 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 do not fall 20 (or even 15) percent per year as

high-tech equipment prices often do. All told, the dramatic shift in ICT investment from computing equipment toward software illustrated in figure 7 suggests that the rate of ICT price change *should* have slowed over time.

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.

Figure 8: **ICT Final Output Share**



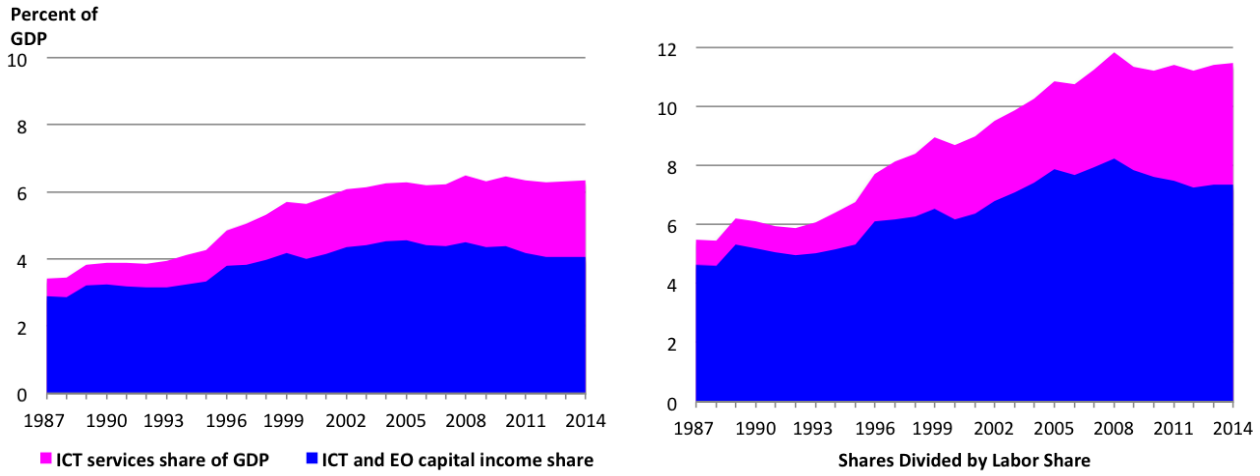
Note: E&S is equipment and software. PFI = private fixed investment. PFI ICT E&S excludes software R&D. PCE ICT components include video and cellular equipment and exclude landline telecommunications.
Source: Authors' elaboration of BEA's NIPA data.

The 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. The 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 services for sale in the service marketplace. Accordingly to this reasoning, EO investments should be included in ICT final output but R&D investments that produce new blueprints or original code for manufacturing/reproducing ICT equipment and software products should not.

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). Its 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).

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.

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 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.[16]

3 ICT investment prices

Relative ICT investment prices are used to evaluate the model's implication for ICT's contribution to productivity growth. In this section, we first examine price change for selected ICT products, in part to confirm the basic trends in technology and R&D discussed in the previous section, but also to examine nuances and developments revealed by the newly developed price statistics themselves. The strategy is to present results of new price research and contrast those results with official statistics. Second, the new ICT product price indexes are used to build a new research price index for ICT assets. This index is then used to ascertain (a) the most likely contribution of ICT to growth in output per hour in balanced growth and (b) the impact of ICT investment price mismeasurement on recent macro-productivity growth statistics for the United States.

The new price research presented reflects work that (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 (2001, 2003); Abel, Berndt, and White (2007); Copeland (2013); Byrne and Corrado (2015a). Details on the new work and new price indexes are in a supplement to this paper ("Byrne-Corrado Supplementary Material"), available as a separate document.

[16]Consider further that national accounts do not capitalize consumer investments in durable goods and that capitalization requires that the implicit services provided by consumers' ownership of ICT assets be included in GDP and total income. An extension of the national accounts (not the model) is thus required to analyze the consumer sector in the same fashion used here to analyze the producer sector; moreover, the model has the same implications for consumer ICT services prices as it does for intermediate ICT services. Note further that the outstanding consumer-owned stocks are rather consequential (or at least as consequential as producer stocks, as suggested by the relative size of the light blue PCE E&S share in figure 8), suggesting that imputed PCE ICT services likewise are consequential. The calibration of the contribution of consumer ICT services to augmented GDP growth and productivity is is reported in a follow on, forthcoming paper.

3.1 New ICT product prices

Table 2 reports prices for selected ICT products and services. 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 remainder are price indexes newly developed for this paper. Of these, the indexes for servers, enterprise software, enterprise wireline telecom services, along with telecom products, are notable in that their results are particularly relevant to understanding developments in the last decade.

Regarding table 2, the following observations emerge: 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 8 and line 12). This is especially the case during the period of very rapid declines in MPU prices (1995 to 2000, column 3, line 23).

Second, price declines for telecom equipment products have been rather steady over time, especially when compared with price declines for computers and semiconductors. While telecom equipment prices fell historically somewhat faster during the late 1990s (column 3), they have not been materially slower since 2004 (column 2 vs column 1). This general pattern also holds when the post–1995 period is broken into sub-periods (see especially column 6 compared with column 5). The post-2000 slowdown in MPU prices noted previously is evident in both servers (line 5) and PCs (line 7) but not in the new price index for servers until very recently (see column 6). In general, the ICT product prices shown in the table reflect a mix of stability and slowdown—computer storage slows down steadily (and by a lot), whereas software remains stable after 2004. Enterprise and other software (which includes systems software as well as application software) maintains relatively strong price declines through the most recent period (the red circled items in line 10).

Third, 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). 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

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.

close to the rate of decline in cloud services prices implied in press reports—about 30 percent per year.[17] From equation (9) it is hard to see how prices for cloud computing and storage services can 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 software and storage systems for managing multiple sessions and data for multiple sessions across servers, etc.—are falling rapidly too. Put differently, given a competitive cloud services landscape and the two-sector model's implication for the relationship between ICT services prices and ICT asset prices, it is hard to see how press reports of declines in cloud services prices of 30 percent could be so far from changes in official ICT price measures—indeed, lines 15 and 16 (column 2) on the table suggest a gap of 20 to 25 percentage points.

Finally, the analysis in section 1 suggested that relative prices for ICT services are proportional to relative ICT capital assets prices and examined the case of cloud services in some depth to consider how prices for ICT services can deviate from ICT asset prices. Consider now wireline telecom services, where imperfect competition (and/or fixed costs) clearly create potential for ICT services prices to deviate from the two-sector model's prediction that ICT services price change should align with changes in prices for the underlying ICT assets used to produce them.

To focus on the enterprise segment, data from *Telegeography* are used. *Telegeography* reports 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 each of the four groups of service offerings and taking a geometric mean 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 but below that for the relevant telecom equipment (lines 1 and 2). Considering that nonICT assets are involved in providing wireline services, the fact that prices in this segment fall about as fast as software assets is very relevant to the arguments put forth in this paper. Needless to say, when the new enterprise services index is folded into an overall nonresidential price index for wireline service,

[17] 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 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.)

the result falls substantially faster (7.3 percentage points) than its counterpart in official data (cf. line 19, column 2).

3.2 New Software Prices

As suggested by table 2 and illustrated in table 3 shown on the right, the 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 include application and systems types of software. In the new software price index developed for this paper, the subcomponents of desktop software by type are implicit, whereas the subcomponents of enterprise and related software (lines 5 and 6) are separately estimated.

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.

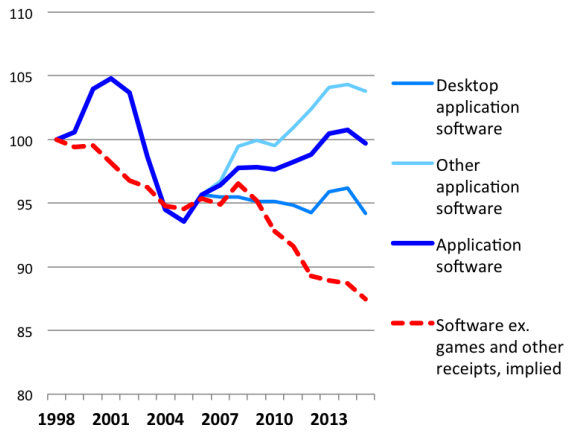
New research on software asset prices by type of use—internet platform apps, customer relations database software, data analytics/business intelligence software, systems for management of cloud services or of e-commerce transactions, etc.—is badly needed to better flesh out this structure (especially its enterprise component), but we were able to make sufficient headway to inform the measurement and analysis of recent price change for software investment 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: (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 index (implied, line 2 and shown in the figure) falls. Its systems component (also implied, line 6) falls even more sharply.

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 supplement to this 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: Price 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 the BEA's software price methodology as reported in Parker and Grimm (2000), pertains to PC desktop application software.[18] 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

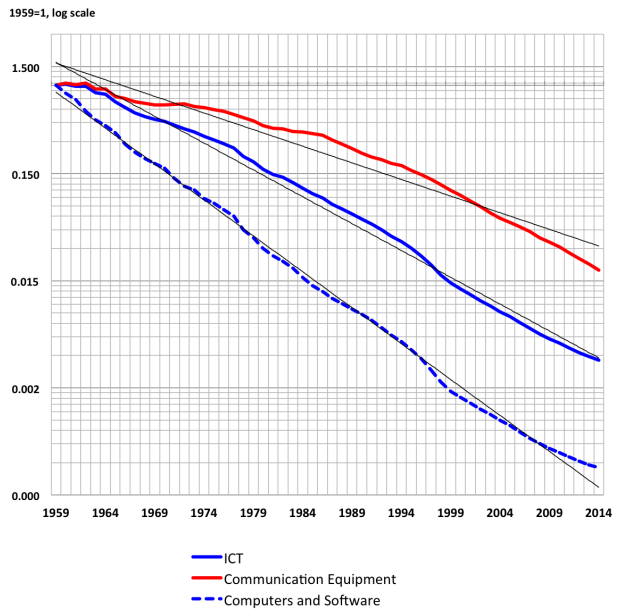
[18] At least one study available to Parker and Grimm (Harhoff and Moch, 1997) covered PC database platforms used for implementing business applications, but prices for PC desktop operating systems were not studied until much later (Abel et al., 2007; Copeland, 2013).

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 software ("other application software" in figure 10). Many new products in the data analytics/business intelligence and marketing/management of customer relationships spaces have been introduced in recent years—consistent with the strong software products R&D reported in the previous section. All told, additional research is badly needed to assess/further improve the price measures for enterprise software (apps and systems/infrastructure) reported in this paper.

3.3 New ICT Investment Prices

To assess the macroeconomic implications of the ICT product prices introduced in table 2, the indexes must be folded into national accounts-style investment price indexes. Although not especially obvious, BEA's investment price indexes for communications equipment and computers and peripheral equipment include a small but growing capitalized services components where we are able to make use of new services price indexes. The procedures used for constructing the new equipment and software investment price indexes are described in the supplement to this paper.

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



Source: Product prices shown in table 2 and supplement to this paper.

Figure 11 and tables 4 and 5 report our main results. The relative price of communication equipment (the red line on the left) falls below its simple long-term trend after 2000 and remains there since then. The combined price index for computers and software 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. (That trend is 11.5 percent, in log changes).

While real ICT price declines have slowed over the past 10 years, at 9.9 percent per year from 2004 to 2014, the recent experience is not all that far from the long-term trend. From 2004 to 2014, the

Table 4: **Real 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**	-9.5	-12.7	-9.7	-14.1	-11.3	-8.8
2.	Communications equipment	-4.5	-9.4	-10.4	-10.9	-9.9	-10.8
3.	Computers and peripherals	-21.2	-23.0	-18.5	-25.5	-23.9	-15.3
4.	Software	-5.8	-6.6	-5.7	-7.4	-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	-3.8	-7.6	-5.4	-2.9
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	-2.1	-1.8	-2.3	-2.1
11.	Software	-.3	-.9	-2.0	-1.7	-2.0	-2.0

NOTE: Real prices are relative to the GDP price deflator. Contributions are in percentage points.

estimate of real ICT price change is 5.9 percentage points per year lower than suggested by official data. In terms of component contributions to real ICT price change, the contribution of software (line 7) from 1994 on is notable, especially in recent years (column 6). But all told, in terms of differences relative to BEA (lines 9 to 11), all three components contribute very similar amounts (in percentage points) in recent years (column 6). Revisions to communications equipment are particularly notable in earlier years (row 9, column 1).

Table 5 shows some of the underlying components of the ICT investment price index built for this paper. The results are largely presaged by the product prices introduced in table 2 although the price index for custom and own-account software, which is also used as the price index for the capitalized services component of computer investment, has not been previously discussed. The dynamic in this index is driven in large part by the price index for prepackaged software, however, and details of its construction (which build upon but further modify BEA's index) may be found in the supplement to this paper.

3.4 Implications

The two-sector model employed in this paper, specifically equation (7), 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

Table 5: **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

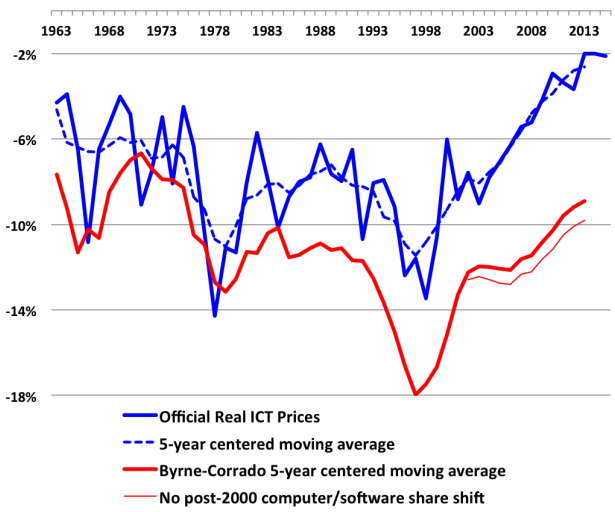
NOTE: Figures reported as "BEA" are authors' calculations based on BEA data.

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 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 was all but dried up in the United States during the past decade.[19]

[19]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.

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



The estimates of ICT price change shown in tables 4 and 5 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.[20] 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.[21] All told, these impacts imply that growth in total factor productivity has been even more dismal than recorded in official estimates.[22]

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

[20] 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 (3.8 percent per year, sign reversed) less the change in BEA's official index (.1 percent per year, sign reversed).

[21] 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.

[22] 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 showed no change or only edged up a tad from 2004 to 2014.

assembled in this paper, the pace of real ICT price change during the late 1990s was extraordinary. Robert Gordon argues that this period of productivity growth should be ignored when gauging long-term trends in productivity, and the results in this paper bolster his argument. 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 witnessed a major financial crisis. Although a thorough review of influences on productivity growth during this period is beyond the scope of this paper, it is possible to close the loop on the central 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 (or costs of adjusting to a new ICT platform) 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 its long-term trend by nearly 1 percentage point and suggests that the contribution of ICT to growth in output per hour could be larger—1.5 percentage points per year—than calibrations based on an adjustment phase during which growth in unit computer demand has been substantially diminished by the spread of cloud technologies.

With regard to (b) figure 13, which uses industry-level changes in total factor productivity growth before and after the Great Recession, suggests that nonICT producers did not in fact reap gains in productivity that should have been enjoyed by the adoption of cloud platforms.[23] And figure 14 suggests it was not for lack of co-investments in the intangible assets that are crucial during the installation phase of ICT, e.g., investments in employer-specific training and business process change.

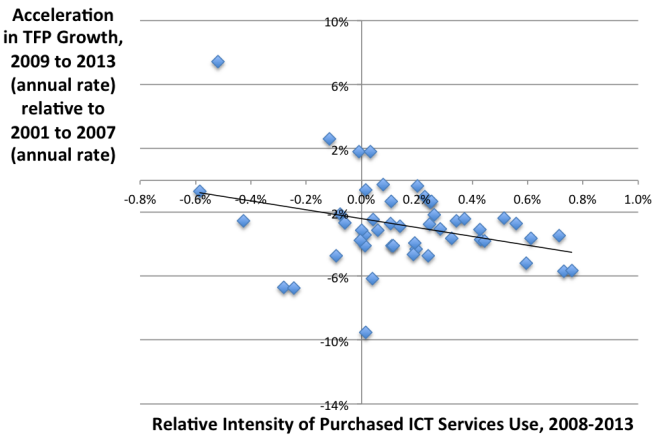
[23] Although this paper has shown a disturbing degree of price mismeasurement that would feed directly into the TFP estimates plotted in this figure, these concerns are somewhat ameliorated because the figure uses *changes* in the rate of productivity growth (i.e., double differences) and examines nonICT-producing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

As may be seen on the right, industries whose usage of ICT services increased the most after 2007 had weaker rates of change in productivity from 2010 to 2013 relative to prior performance. It is unclear why we see this pattern in the industry-level data, but several possibilities are likely.

On the one hand, 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.[24] On the other, 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.

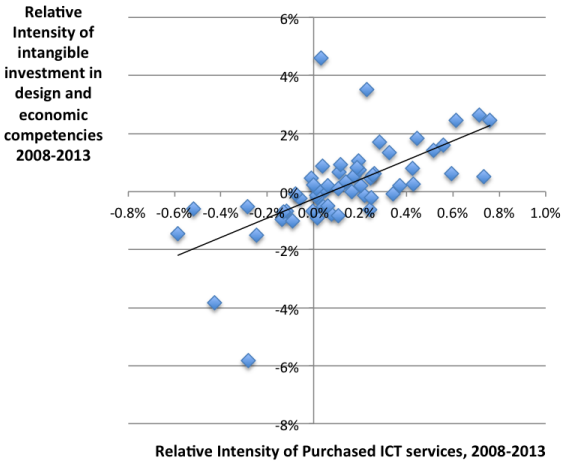
All told, the model's "diffusion" effect portion of its calibrated "use and diffusion" effect of 1.1 percentage points per year contribution of ICT to labor productivity growth seems to have not only shut down, but may even be temporarily generating a negative productivity spillovers. Note that nearly 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.

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



Note: NonICT-producing industries only.
Source: Elaboration of data from the U.S. BLS and BEA.

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



Note: NonICT-producing industries only.
Source: Elaboration of data from the U.S. BEA.

In figures 13 and 14, 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.

[24] 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).

4 Summary and conclusion

This paper set out a two-sector model that illuminated 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.

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 technology area. 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 had 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 is a key feature of the current ICT landscape and one of the most relevant signs that innovation is still driving the sector. All told, via the user cost relationship as well as the paper's two-sector model, ICT services price change is driven by ICT asset price change, and while cloud services providers enjoy scale and perhaps unique abilities to harness advanced technologies, it seems unlikely that cloud services prices which reportedly are dropping about 30 percent per year, could be dropping so much faster (20 to 25 percentage points!) than prices for the high-end computing and storage equipment deployed in the delivery of cloud services.

Finally, the paper introduced new measures of relative ICT price change that incorporated available research as well as new work conducted expressly for this paper. More than a dozen new ICT product price indexes were introduced, and new ICT investment price indexes for communication equipment, computers, and software were developed. 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 is that real ICT price declines remain squarely in negative territory and suggest that the sector will continue to deliver an out-sized contribution to growth in output per hour in balanced growth—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 and ICT services.

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Appendixes

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 :

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

and

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

The functions for the two sectors are identical except for TFP, 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:

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

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 is given by

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

which as stated in the text is proved by total differentiation of the payments equations (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 equal 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 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). 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 of the (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

$$\frac{\partial q_N}{\partial s_N^T} = \gamma\frac{q_N}{s_N^T} = \gamma\frac{Y_N}{S_N^T} \tag{A16}$$

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 $\dot{s}_N^T$ 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 simplifying yields our 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

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

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.