ICT Services and Their Prices: What Do They Tell Us About Productivity and Technology?

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ABSTRACT

This article reassesses the link between ICT prices, technology, and productivity. To understand how the ICT sector could come to the rescue of a whole economy, a multi-sector model developed by Oulton (2012) is extended to include ICT services and used to calibrate the steady-state contribution of the ICT sector to growth in aggregate U.S. labour productivity. The extended model also has implications for the relationship between prices for ICT services and prices for the ICT assets used to supply them, namely, that, ICT service prices may diverge from ICT asset prices and reflect productivity gains from ICT asset management by the sector. All told, because ICT technologies increasingly diffuse through the economy via purchased services (e.g. cloud services, data analytic services), they are not fully accounted for in the standard narrative of ICT's contribution to economic growth. When this omission is corrected and the price indexes for ICT assets developed in Byrne and Corrado (2017a) are used to indicate the relative productivity of the ICT sector, its contribution to potential labour productivity growth is estimated to be substantially larger than generally thought — 1.4 percentage points per year.

The importance of computers, computer microprocessors, and productivity-enhancing computer software in contributing to the acceleration of productivity growth in the United States in the second half of the 1990s is well established.[2] 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 Jager, 2014) puts these innovations front and center and offers a story in which communi-

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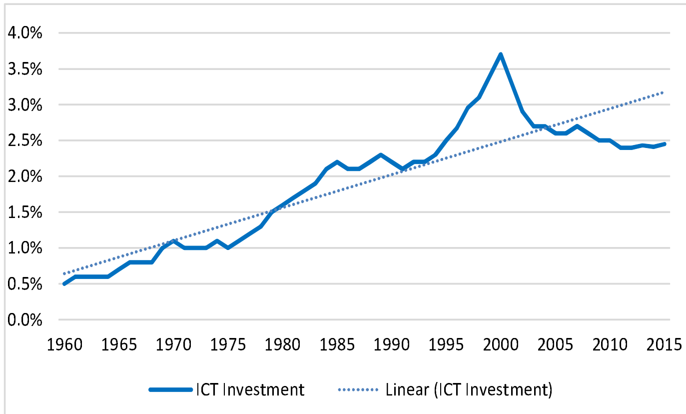
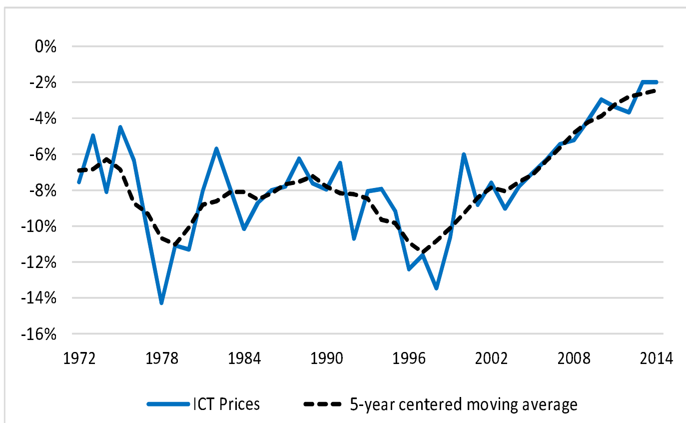
2 See, for example, Jorgenson and Stiroh (2000); Oliner and Sichel (2000) and Brynjolfsson and Hitt (2003).

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

Panel A: Nominal ICT Equipment and Software Investment, 1960-2015, per cent of GDP



Panel B: ICT Real Price Change, 1972-2014, annual rate



Note: Panel A reports private investment only. Nominal ICT investment and ICT price change are measured relative to nominal GDP and the GDP deflator, respectively, and exclude software R&D.
Source: Authors' elaboration of data from U.S. BEA.

cation and communication networks (as much as computing performance) drove productivity developments in the 1990s and early 2000s.

Communication technology has continued to advance since the early 2000s, and rising connection speeds have made possible the cloud and mobile platforms that are transforming how organizations use computing resources and exploit data. But measured productivity growth has slowed dramatically. The deterioration in U.S. labour productivity growth is due in part to historically slow growth in real investment in information and communication technology (ICT) equipment and software, which no longer provides an extra boost to overall output per hour.[3] Indeed, not only has nominal ICT equipment and software (E&S) investment relative to GDP moved sideways since 2010 (Chart 1, Panel A), relative ICT price change has posted *extremely* small declines of late, after having

3 Output per hour for the total U.S. economy grew an estimated 0.5 per cent per year from 2010 to 2015 — the slowest 5-year rate of change in the post WWII era based on The Conference Board's Total Economy Database™ whose output per hour series for the U.S. total economy begins in 1950.

gradually lost force since 2004 (Chart 1, Panel B).

Why is ICT investment so weak? And if digital innovations are so transformative, why are they not having a discernible impact on recent ICT prices (and labour productivity)? Google's Hal Varian offers a view from Silicon Valley, namely, that U.S. productivity is mis-measured (Aeppel, 2015). Another possibility is that the ICT sector is innovating and prospering but is too small to come to the rescue of an economy facing stiff supply-side headwinds that limit its productivity growth (Gordon, 2014a,b). As noted elsewhere (e.g. Brynjolfsson and Saunders, 2010) and by our calculations, the value added share of the U.S. ICT-producing sector (including ICT services production) has remained stable at about 6 per cent of nominal GDP since 2000, showing that it has remained relatively small for an extended period of time.

This article makes, we believe, three contributions that help address this conundrum: First, a multisector growth model developed by Oulton (2012) is extended to include purchased ICT services (e.g. cloud or data analytic services). The amended model shows how ICT can be a driver of growth when ICT investment remains weak and suggests the balanced growth contribution of ICT to U.S. labour productivity growth is very large — 1.4 percentage points per year. About 25 per cent of this total ICT sector contribution owes to the diffusion of ICT technology via purchases of cloud and related ICT services.[4]

Second, the model highlights the channels through which a transition to cloud computing can affect productivity growth and sets out the determinants of ICT services price change during that transition and in balanced growth. The extended model implies, and we further posit via a user cost (Jorgenson, 1963) approach, that price change for marketed ICT services is proportional to price change for the productive assets used to produce them, but that efficiency gains from rising ICT capital utilization may drive an additional wedge between growth rates for ICT services prices and ICT asset prices.

Third, the article puts official ICT product prices under a microscope and reviews the consistency of 14 new ICT research price indexes with the model's implications. The new ICT product price indexes are based on our own earlier work (Byrne and Corrado, 2015a,b) and new work reported in a companion paper to this article (Byrne and Corrado, 2017b) that draws in part on the historical ICT price measurement literature (e.g. Berndt and Rappaport, 2001, 2003). The new price indexes are for cellular and data networking equipment, enterprise software products, high-end computers/servers, PCs, and computer storage systems. Along with high-speed broadband infrastructure, these ICT products have spurred the growth of cloud computing, datacenter design services, and data analytics over the last decade.

The companion paper documents how the new ICT product prices are folded into new estimates of national accounts-style investment price indexes that are then used in this article. The new ICT asset prices suggest that long-term trends in official ICT prices suffer from substantial mismeasurement and that the relative productivity of the ICT sector remains strong and continues to provide an extra kick to labour productivity growth — unlike the implication of Panel B in Chart 1.[5]

4 Note that this article bears most directly on interpreting trends in ICT investment and ICT services use via the take-up of cloud and related technologies by the producing sectors of the economy. Byrne and Corrado (2017a) assess the impact of the take-up of digital technologies by the household sector of the economy.

5 As discussed in Byrne, Fernald, and Reinsdorf (2016), ICT price mismeasurement has been with us for some time, and mismeasurement can only explain a small portion of the recent slowdown in output per hour growth. (Also see Syverson 2016).

We proceed as follows: Section 1 introduces the model, presents its solution, and discusses its implications for ICT services price change. Section 2 first shows how we measure the ICT versus the non-ICT producing sector and reviews selected indicators of ICT technical change, including ICT R&D. The section then describes how the new ICT era involves technologies delivered as services that raise the utilization of ICT capital, and illustrates the take up of these technologies via purchases of ICT services by the non-ICT-producing sector. Section 3 introduces the new ICT research product price indexes and reports and analyzes their implications for assessing ICT services price change and the relative productivity advantage of the ICT sector. This section then uses the implied productivity differential along with Section 2's information on income shares of ICT assets and ICT services to calibrate the model of Section 1. Because the results imply *very weak* productivity in the non-ICT-producing sector, we discuss and then conclude with several hypotheses why this situation is both plausible and likely temporary.

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

Economic growth arises from faster relative growth of TFP in the ICT-producing sector because such growth manifests itself as faster relative ICT price declines, which then enables faster growth of income and consumption. 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 in other countries in the form of improving terms of trade.

To account for the growth of cloud computing, datacenter design services and data analytics, we expand the Oulton model to include intermediate uses of ICT services. The expression for the steady state contribution of ICT to the growth of output per hour 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.

Expanded two-sector model

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

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

and

$$PY = P_T Y_T + P_N Y_N; \quad (2)$$

$$\bar{w}_T = \frac{P_T Y_T}{PY}.$$

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

With regard to intermediates, the ICT sector is assumed to supply services for its own intermediate use, as well as for intermediate use by other producers. The general business sector is assumed to produce intermediates for its own use only; these intermediates are omitted from its production function to keep the exposition simple.[6] 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:

$$Q_T \equiv Y_T + S_T^N = A_T F^T(K_N^T, K_T^T, S_T^T, L^T)$$

$$Q_N \equiv Y_N = A_N F^N\left(K_N^N, K_T^N, S_T^N, L^N\right) \quad (3)$$

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 sector *j*'s intermediate use of ICT services. $L^j = hH^j$ is sector *j*'s labour input, H^j is hours worked in the sector, and h is a labour composition index applicable to the economy as a whole.

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

$$P_i Q_i = R_N K_N^i + R_T K_T^i + WH^i + P_T S_T^i,$$

$$i = T, N \quad (4)$$

with relevant factor shares given by

$$\bar{\upsilon}_{K_T} = \frac{R_T\left(K_T^T + K_T^N\right)}{PY};$$

$$\bar{\upsilon}_L = \frac{W(H^N + H^T)}{PY}; \quad (5)$$

$$\zeta_T^N = \frac{P_T S_T^N}{PY}.$$

In equation (4), R_N and R_T are the nominal rental prices of capital and *W* is the hourly wage, and in (5), $\bar{\upsilon}_L$ and $\bar{\upsilon}_{K_T}$ are the shares of labour and ICT capital in total income, respectively, and ζ_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 TFP growth of the ICT-producing sector. 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

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

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 output per hour (*OPH*) is given by

6 The complications of chain weighting also are ignored.

$$\underbrace{\frac{\bar{\upsilon}_{K_T} + \bar{\zeta}_T^N}{\bar{\upsilon}_L}(-\dot{p})}_{\text{Investment (use) and productivity (diffusion) effects}} + \underbrace{\bar{w}_T(-\dot{p})}_{\text{Production effect}} \quad (7)$$

For details of this solution, see Appendix A1.[7] Equation (7) differs from the solution to the original Oulton model due to the presence of the term ζ_T^N capturing the ICT services-using intensity of the economy. The solution nonetheless aligns with the usual growth accounting approach in which the contribution of ICT capital to growth in output per hour is identified as flowing through two channels: ICT use and ICT production. It is typical to consider the ICT use effect as operating through services provided by producers' own investment in ICT capital, i.e. via services generated by ICT assets that producers own themselves. In the expanded model, the channel also operates via non-ICT producers' purchases of ICT capital services, e.g. purchases of cloud services, that provide workers access to ICT technologies in essentially the same way.[8]

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 in turn follows from the assumption of perfect competition. The model thus implies that, to the extent μ_T really is greater than μ_N, real ICT services prices fall (as they are on par with real ICT asset prices), and real ICT services output growth is faster than growth of real output of the general production sector, evidence for which shall be shown in section 3 below.

ICT services prices versus 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 non-ICT-producing sector (e.g. Amazon selling to GM). The second is where ICT services are for designing "private" cloud services facilities within firms in the non-ICT producing sector. In both cases, ICT services facilitate more efficient sharing of datacenter resources across users.

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7 Appendix A1 can be found at http://www.csls.ca/ipm/33/Byrne_Corrado%20Appendix.pdf.

8 The contribution to productivity growth is particularly powerful when ICT services are domestically produced — i.e. the effect shown in equation (7) also includes the industry's contribution to TFP growth via the standard Domar-Hulten channel whereby innovation in upstream industries has impacts on aggregate TFP growth via using industries (Domar, 1961; Hulten, 1978). When purchased ICT services are imported, the technology diffusion channel (i.e their capital deepening-like effect) is still there, but its positive impact is partially offset by the negative effect of ICT services imports on $\bar{w}_T$. Appendix A1 sets out the formula for the Domar-Hulten contribution of the ICT sector to TFP growth in the ICT-services amended model.

$p^{S_T}S^N_T$ is the value of ICT services, 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 as real prices p^{S_T}, p^{I_T}, relative to, say, the PCE or GDP deflator. 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 providers deliver infrastructure, platforms, and software as a service. In this case, ICT services prices are per period charges for resources managed by the cloud provider. Assume that these services are priced as capital services provided to a capital owner and equal to a rental price times the capital stock and a factor of proportionality:

$$p^{S_T}S^N_T = \left[(\rho + \delta_T)p^{I_T}K^T_T\right]\lambda \tag{8}$$

The expression in brackets is the standard expression for capital services and λ is a factor of proportionality representing the efficiency of ICT service provision relative to in-house ICT. As previously indicated, ρ is the real net return to capital investment; and δ_T is the depreciation rate of ICT capital.[9] The term ρ is constant in steady state growth by definition, and δ_T is constant by assumption. Thus, 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 either falling real prices of ICT investment goods p^{I_T} or rising efficiency (falling λ).

Under what conditions might λ fall? One possibility is 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.[10] In other words, from (8) we then have

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

where, note, $\dot{p}^{S_T}$, $\dot{p}^{I_T}$, and $\dot{\lambda}_T$ are all < 0. $\dot{\lambda}_T$ reflects the drop in underutilization, which augments declines in cloud services prices relative to declines in prices of ICT assets according to equation (9).[11] Cloud services prices that fall less than ICT asset prices suggest providers are retaining the efficiency gains for themselves.

9 Appendix A1 (found at http://www.csls.ca/ipm/33/Byrne_Corrado%20Appendix.pdf) sets out the four real rental prices in the two-sector model in a no-tax world where the terms in the nominal interest rate and the relevant relative asset price change are summarized by ρ.

10 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.

11 To see this, let $\dot{\lambda}_T$ vary with capital utilization, e.g. as in $\dot{\lambda}_T$ = 1 - d where d is a measure of the underutilization of ICT assets (and can be calculated so as to exhaust capital income). Equation (9) 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.

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.[12] 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 rental price of ICT capital services r_T^N and ICT capital owned within the non-ICT producing sector K_T^N are the subjects of analysis, and that

$$r_T^N K_T^N = \left[(\rho + \delta_T) p^{I_T} K_T^N\right]$$

is the real income attributed to non-ICT 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.[13] Ignoring discounting, the *effective* decline in real ICT asset prices faced by non-ICT 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 non-ICT 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).

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

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.[14] 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,

12 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.

13 Where, as in footnote 10, there is an implicit term *d* capturing underutilization.

14 These technologies are discussed in the next main section.

although high-speed broadband is a fundamental enabler of cloud services, we have not identified first order impacts of virtualization and its associated efficiencies 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 article 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 is via its contribution to productivity growth, as in network externalities (or spillovers to ICT capital in general). Cost savings due to virtualization, whether they accrue to cloud providers or to non-ICT producers, thus are viewed as productive externalities.[15] While this position is parallel to treating the productivity enhancing impacts of internet platform business models as a (network) externality, virtualization as a computing technology is similar to multiplexing in communication where more and more signals are transmitted over physical networks (or spectrum), and where, to the extent possible, increases in capacity are built into quality-adjusted price indexes such as those developed for communications equipment in Byrne and Corrado (2015a,b). The adjustment of prices of servers, storage, systems software, and systems design services to consistently account for efficiencies due to virtualization and related cloud technologies is a similar challenge, but one well beyond the scope of this article.

ICT Sector Trends

Columns 1 and 2 of Table 1 define the empirical counterpart to sector T of the previous section. Column (1) are the detailed industries that we strive to measure, and column (4) indicates how close we come to achieving that using BEA's annual Input-Output and Final Uses data.

Using data for the T sector so defined, this section contains three subsections which do the following: (a) examine indicators of ICT technologies, including ICT R&D, that suggest that the pace of change in the newer ICT technologies remains very fast; (b) assess the relative growth of ICT services (which also bears on the diffusion of ICT technologies) and relative pattern of ICT investment by major component; and (c) quantify the model's parameters for the relative size of the ICT sector and the diffusion of its technology in the economy, namely, $\overline{w}_T$, $\overline{\upsilon}_{K_T}$, and ζ^N_T. Relative ICT asset price change is presented in section 3, and quantitative implications of the model of section 1 are drawn there.

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 computers (Jorgenson, 2001) — and, according to many accounts, such advances slowed in the first half of the 2000s (Hilbert and Lopez, 2011; Pillai, 2011, 2013). By contrast, advances in communications technology, i.e. internet and wireless technologies, continued at a similar pace (Byrne and Corrado, 2015a,b).

15 This is not to suggest that these effects cannot be isolated and quantified, as they have been in work that adds a separate channel to decompositions such as equation (7) to account for ICT to contributions 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 eight major European countries during the internet and wireless network expansion in the first half of the 2000s. Beyond broadband, however, spillovers to ICT have not been found in macro or industry-level data (Stiroh, 2002), despite a large micro-based literature suggesting externalities to IT use by individual firms. See Corrado and van Ark (2016) for further discussion.

Table 1: ICT-Producing Industries

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

Source: Authors' elaboration of NAICS and data from BEA supply-use tables.

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.[16] 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, the world could not have achieved the reported 29 per cent per year increase in IP traffic and nearly 78 per cent per year increase in wireless *data* traffic that it did during this period (Chart 2, Panel A).[17]

All told, the internet markets of the G-20 were projected to reach $4.2 trillion in 2016 — nearly double their size in 2010. Three out of four datacenter workloads are expected to be processed in the cloud by 2018, and Internet of Things (IoT) devices attached to the internet — most of them wirelessly — are expected to increase more than 25 fold, from nearly 1 billion units in 2010 to 26 billion units by 2020 (IoT devices *exclude* PCs, tablets and smartphones).[18] 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. Panel B of Chart 2 shows that by one measure (the rate at which wireless-related telecommunications patents are granted in the United States), the current pace of change in communications technology is more rapid than it was in the late 1990s.

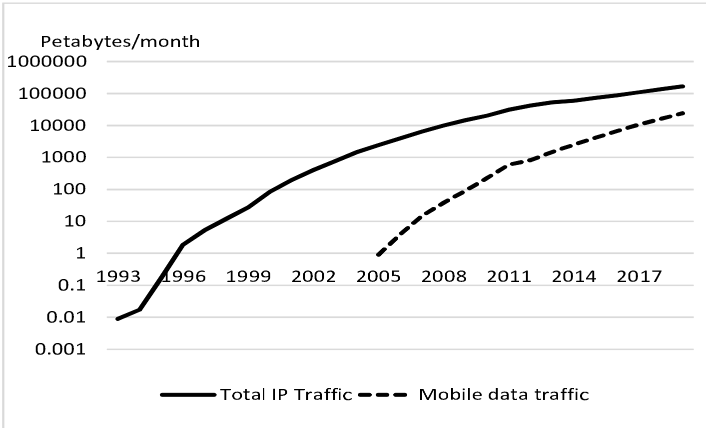
16 This paraphrases Greenstein (2000: 391), who was describing internet technology.

17 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.

18 The sources for these forecasts are Boston Consulting Group (2012), Gartner (2013), and Cisco's Global Cloud Index (Cisco, 2013).

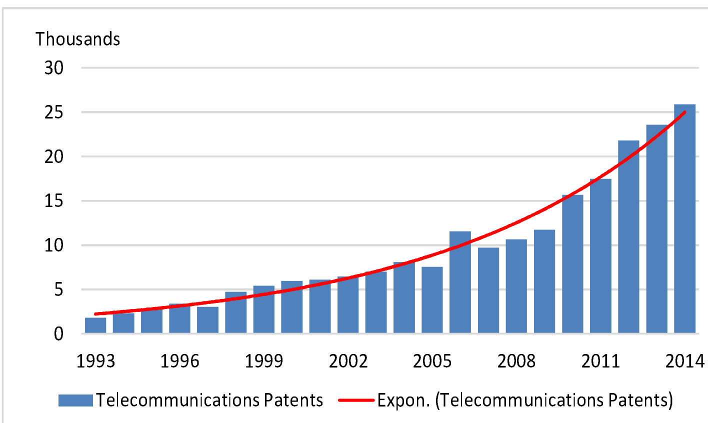
Chart 2: Global IP Traffic and U.S Telecommunications Patents

Panel A: Global IP Traffic, 1993-2019 (incl. forecast)



Source: Cisco's Visual Networking Index 2014-2019 (May 2015) and earlier editions.

Panel B: U.S Wireless-related Telecommunications Patents, 1993-2014



Source: U.S. Patent and Trademark office, Part 1, Patent Counts by Class by Year (sum of classes 370, 375, 379, and 455). Available at http://www.uspto.gov/web/offices/ac/ido/oeip/taf/cbcby.htm. Accessed October, 2015.

Cloud technologies

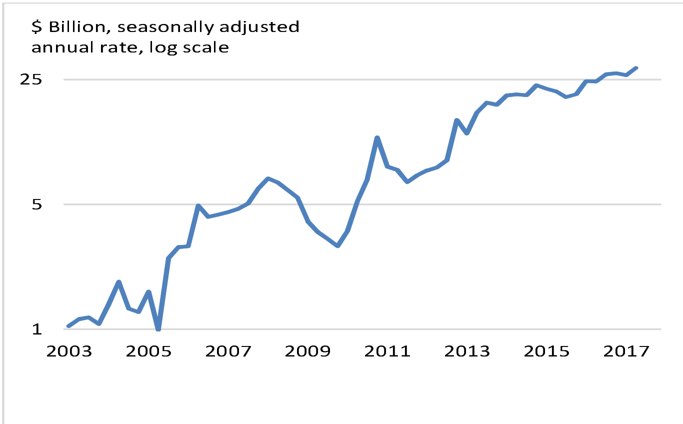
Cloud service providers supply ICT resources over the internet.[19] Services range from simple data storage to full provision of software for "business intelligence" applications. Access is as ubiquitous as wireless and wireline networks. The feasibility and affordability of cloud services is the capstone of an ongoing series of networking innovations that have raised access speeds, lowered storage costs, and perhaps most importantly, enabled seamless and invisible sharing of computing resources across users.

Cloud computing involves three major technologies that raise the utilization of computer resources and speed software development: virtualization, grid computing and containerization. "Virtualization" provides each user with a distinct virtual machine with its own operating

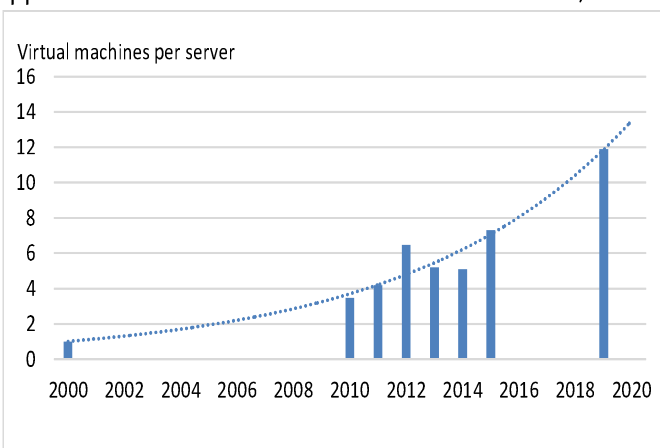
19 According to the National Institute of Standards and Technology, "cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction" (Mell and Grance, 2011).

Chart 3: Capital Expenditure by Cloud Providers and Server Application Workload in the United States

Panel A: Global Capital Expenditure by Amazon, Microsoft, and Google, 2003Q1-2017Q2



Panel B: Average Application Workload of Global Cloud Datacenters, 2000-2020



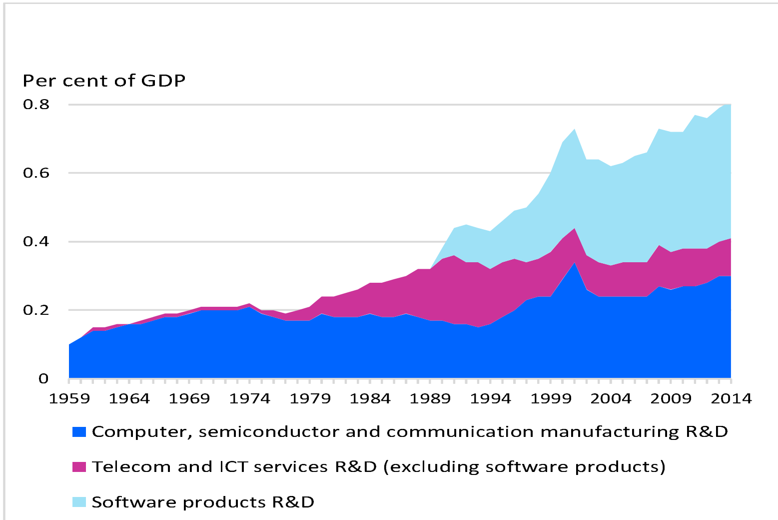
Sources: Panel A: Quarterly financial reports, seasonally adjusted by authors. Panel B: 2010-2015 observations and 2019 forecast: Cisco Global Cloud Index: Forecast and Methodology 2015-2019; 2000 observation: International Data Corporation.

system kernel but allocates resources from actual individual machines to multiple users, enabling higher resource utilization in the datacenter. A complete history is beyond the scope of this article, but virtualization and time sharing (simultaneous use of the same computer by multiple jobs) have their roots in the early history of IBM mainframes, and grid computing (applying the resources of many computers in a network to a single job) developed along with the internet.[20] More recently "containerization" technology has allowed multiple platform environments to operate on the same virtual machine, increasing the speed of application development, deployment, and scalability.

As shown in Chart 3, Panel A, the increase in spending for capacity expansion among major cloud vendors has been stunning: nominal capital expenditures at Amazon, Microsoft, and Google increased 23 per cent per year between

20 Grid computing was first used in 1989 to link supercomputers and thereafter grew and evolved along with the internet (De Roure *et al.* 2003).

Chart 4: Private ICT R&D investment in the United States, 1959-2014



Source: Authors' elaboration of Bureau of Economic Analysis and National Science Foundation data.

2003:Q1 and 2017:Q2.[21] Firms that transition from traditional datacenters to a cloud platform (private or public) enjoy substantial hardware consolidation and cost savings. IT consultancies commented in 2009 that server virtualization had become the "killer app" for the business datacenter (Bailey, 2009). Cisco has estimated that the average application workload of global cloud datacenters, indicated by the number of virtual machines per server plotted in Chart 3, Panel B, more than doubled from 2010 to 2015. Companies historically ran one application workload per server (and many small and medium size firms still do).

In terms of enterprise applications, it is very early on in the application of containerization.[22] International Data Corporation (IDC) estimates that in 2016 only 1 per cent of enterprise applications were running on containers that could readily be scaled. Within the ICT-producing sector, however, containerization and related microservices have been central to boosting the productivity of new software development, i.e. boosting the productivity of software R&D investments.

R&D investments in ICT

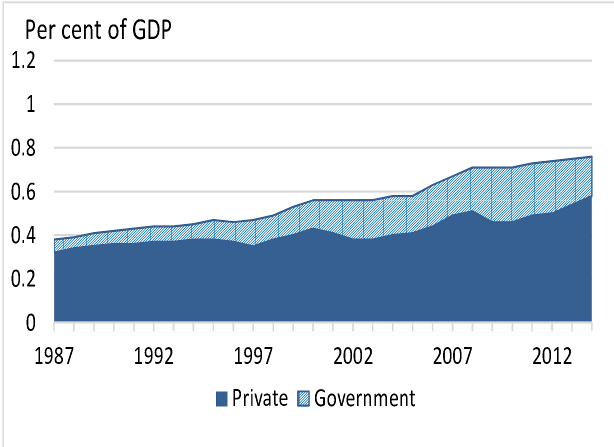
The trend of ICT R&D investment, as shown in Chart 4, is consistent with a very brisk pace of change. The overall trajectory for ICT R&D depicted in Chart 4 is not a readily observable component of the U.S. national accounts' estimate for R&D investment. The estimates in Chart 4 were developed by the authors and reflect (1) private R&D investment by the industries listed in Table 1 as reported in the U.S. national accounts *plus* (2) software products R&D presented as own account software investment. National accountants regard software products R&D as captured in own-account software investment. Consequently, they exclude

21 Amazon, Microsoft and Google accounted for 40 per cent of global capital expenditures by large cloud computing firms in 2015. (Firms classified as "hyperscale" by Cisco Systems Inc.)

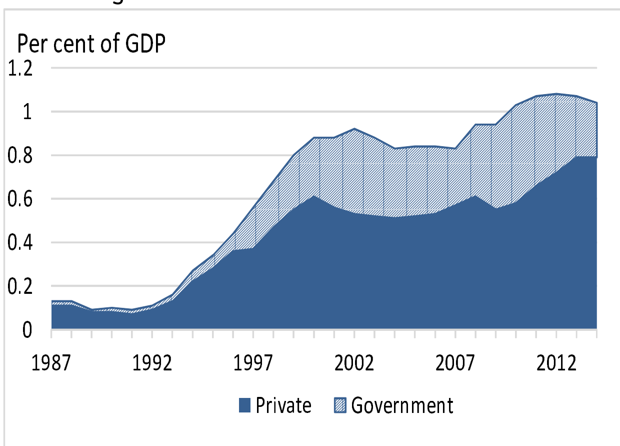
22 Containerization — a scalable form of virtualization technology — generally was not widely understood in the business world outside cloud vendors until the release of open source LINUX formats (Docker 1.0) in March 2013. Docker transformed container technology into a product for enterprise use.

Chart 5: Intermediate Uses of Information and Computer Servicesin the United States, 1987-2014, per cent of GDP

Panel A: Data processing and related services



Panel 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.

Source: Authors' elaboration of data from U.S. BEA

software products R&D from the R&D source data when estimating private R&D investment.

Most software products R&D is carried out in the ICT-producing industries listed in Table 1. For the United States, estimates of software products R&D are derived from cross tabulations of the National Science Foundation's R&D survey data by industry of funder and technological focus; Chart 4 plots the time series for these estimates reported in Crawford, Lee, Jankowski, and Moris (2014: Table 2).[23]

For the analysis of the ICT sector, indeed for the analysis of R&D in general, including software products R&D with other R&D is a more logical presentation of the available data — and not doing so excludes an area where increases in R&D have been among the most rapid. The rate of investment in ICT R&D in recent years con-

23 The relevant cross-tabulation of R&D survey data has been published by the National Science Foundation (NSF) for 2012. This recently published statistics are consistent with estimates reported in Crawford *et al.* (2014), which included figures through 2013. The figure for 2014 in Chart 4 is an extrapolation by the authors based on total private own-account software investment.

tinues unabated in this presentation. This suggests that ICT innovation could not have slowed for lack of investment in the development of new ICT technologies and products.

ICT services and software investment

Intermediate uses of ICT

ICT R&D historically has been oriented toward producing better and faster computers and more powerful productivity-enhancing computer software (installed locally) for businesses and other organizations. 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 also see an associated shift in ICT spending.

Private demand for data processing, hosting, and related information services (NAICS 5182, 51913) and for computer systems design services and related computer services (NAICS 54152,54153,54159) rose sharply relative to GDP in the United States in recent years (the solid dark shaded areas of Panels A and B of Chart 5, respectively). These developments reflect both the growth of cloud services (which is in NAICS 5182 and has seen steady growth) and a remarkable surge in systems design services. This latter development is likely to be related to the demand for cloud-based IT systems to the extent that systems design services are co-investments with the demand for cloud computing.[24] All told, the analysis in section 1 suggested that the relative growth of ICT services industries would be strong if there were real productivity 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.[25]

Trends in intermediate and final uses of telecommunications and broadcasting services are shown in Chart 6. Traditional wireline telephone services ideally would be excluded from this analysis, but a split of traditional versus IP telephony and internet access services in data on intermediate purchases by industry is not available. As may be seen in Panel A, business demand for wireless services is robust, especially from 2010 on, whereas total private telecommunications services (which adds in wireline telecom and internet access services) has moved down since peaking in 2000. By contrast as shown in Panel B, consumer total telecom demand has not declined since 2000 but the relative pattern of consumer total telecom versus consumer wireless demand is similar to private industry. A breakdown of wireline 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 and 517 services spending whereas internet access is a growing component.

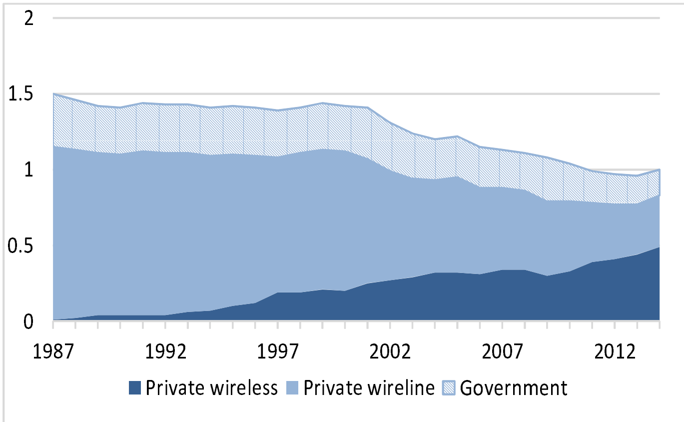
All told, information, computer, and wireless communication services supplied to private industries net of the ICT-producing sector's own use has increased .06 percentage points per year relative to nominal GDP during the past 19 years, i.e. the ratio of such services to GDP rose from 0.7 per cent in 1995 to 1.9 per cent in 2014.

24 To be clear, spending on computer systems design is not counted in the national account definition of investment even though in principle it would be included in expanded frameworks that recognize a portion of consulting services as investment in new business process improvement (Corrado, Hulten, and Sichel, 2005 and 2009).

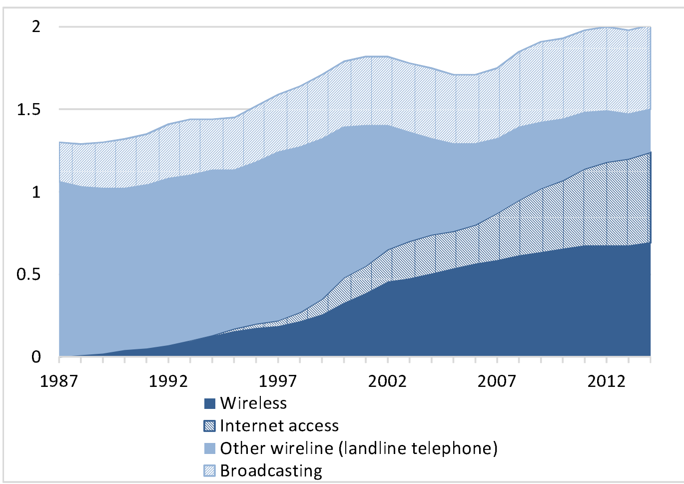
25 For further discussion of the role of business models in ICT services provision, see OECD (2014, chapter 4).

Chart 6: Intermediate and Final Uses (PCE) of Telecommunications and Broadcasting Services in the United States, 1987-2014, per cent of Nominal GDP

Panel A: Intermediate Telecom Use



Panel 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 Panel B only because intermediate uses of the output of this industry are essentially nil.

Source: Authors' elaboration of data from U.S. BEA

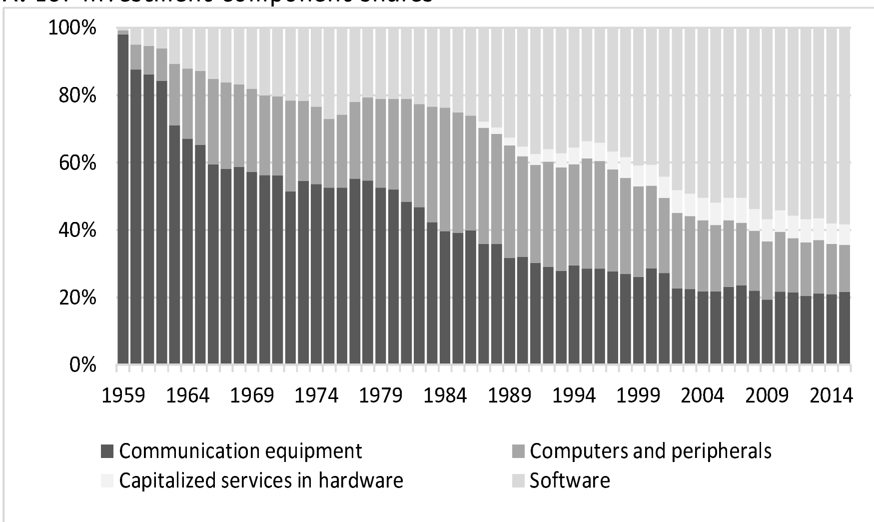
To put this in perspective, consider again Panel A of Chart 1. This increase in ICT business services use by other private producers is in fact a tad larger than the long-term increase in private spending on ICT investment goods (relative to GDP), i.e. the coefficient on time in the regression trend line plotted in Chart 1 (Panel A) is .05.

Final investment in software assets

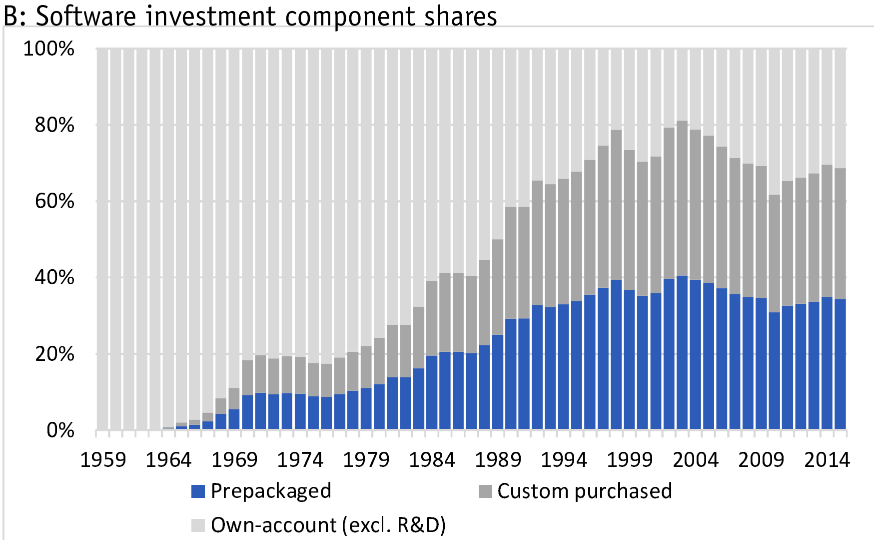
Nearly 60 per cent of total ICT investment in 2015 was for acquisition of new software assets, a dramatic turnabout from 1995 when 65 per cent of total ICT investment was for equipment and equipment-related capitalized services (Chart 7, Panel A). Between 1995 and 2005, the pure equipment share of total ICT investment dropped dramatically (20 percentage points). The computing equipment spending share has continued to trend down since 2005 — it was only 14 per cent in 2014 — whereas the communication equipment share stopped dropping in

Chart 7: Private ICT and Software Investment Shares in the United States, 1959-2014

Panel A: ICT investment component shares



Panel B: Software investment component shares



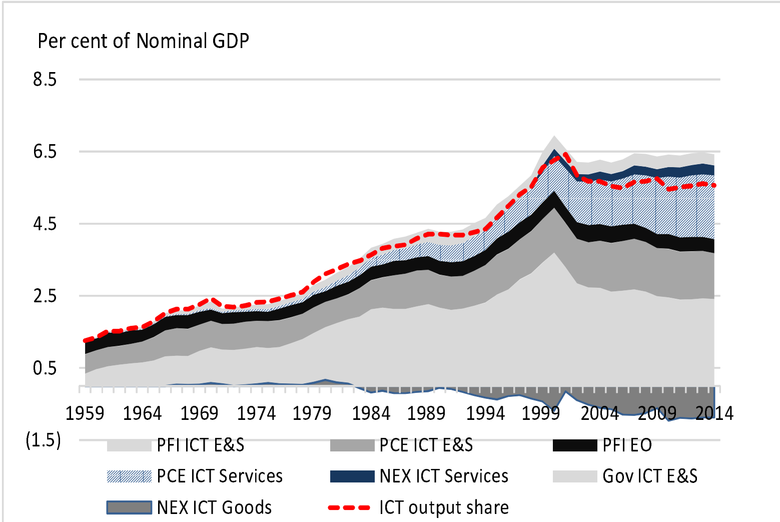
Note. Excludes software products R&D.
Source: Authors' elaboration of data from U.S. BEA.

the early 2000s and has fluctuated between 21 and 22 per cent since then.[26]

Within new software assets, purchases of marketed, standardized (prepackaged) software products are about one third of total software, as illustrated by the dark shaded area in Panel B of Chart 7. The lion's share of software is custom produced, whether as purchased services or performed on own account. Price measures for these custom components do not exist. BLS does not produce prices indexes for NAICS 541511, or any part of 5415 for that matter. The BEA estimates these price indexes based in part on its price index for prepackaged software products.

26 Note that the emergence of the cloud business model may have led ICT equipment investment to be underestimated. Byrne, Corrado, and Sichel (2017a) calculate that if electronic components purchased by the ICT services sector are used to build server farms, total ICT equipment investment may be understated by as much as 25 per cent in 2015. This does not change the picture of weakness in the non-ICT sector investment.

Chart 8: ICT Final Output Share in the United States, 1959-2014



Note: E&S is equipment and software. PFI = private fixed investment. PCE = personal consumption expenditure. NEX= net exports. EO = entertainment originals. PFI ICT E&S excludes software R&D. PCE ICT components include video and cellular equipment and exclude wireline telecommunications.
Source: Authors' elaboration of BEA's NIPA data.

The companion paper (Byrne and Corrado, 2017b) reviews these prices, but suffice it to say BEA's price indexes for software investment fall 2 per cent per year, not the 15 to 20 per cent that high-tech equipment prices do. All told, the dramatic shift in overall ICT investment from computing equipment toward software illustrated in Chart 7 suggests that the rate of overall ICT investment price change *should* have slowed over time.

Sector final output and capital income

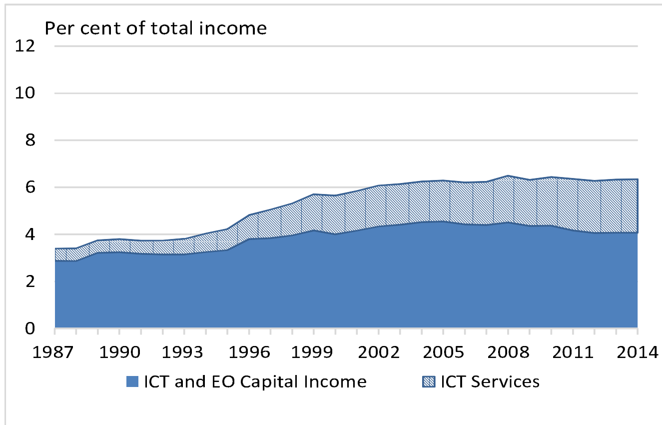
ICT final output share

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

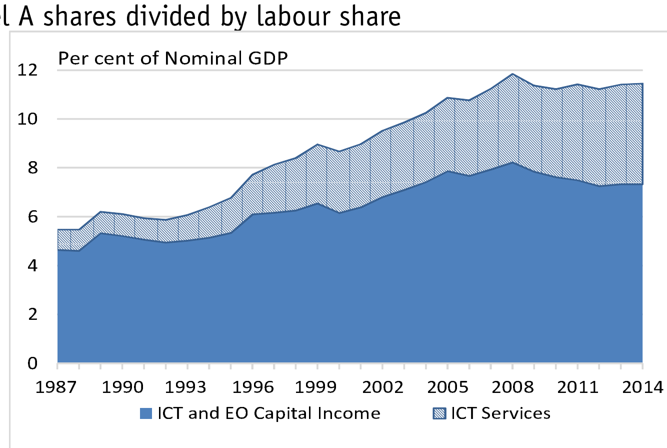
The inclusion of digital entertainment services in ICT final output raises the question of whether investments in digital entertainment originals (EO) should also be considered part of ICT final output — and correspondingly, how to treat R&D investments in ICT. Our thinking is that EO assets are more akin to software assets than to the software original that is used to produce the software assets. The purchasers of software assets (software products) use the assets to generate (ICT) services for a period of time, just as the owners of entertainment originals use their assets to generate (entertainment) services for a period of years. EO investments are therefore included in ICT final output but R&D investments that produce new blueprints or original code for manufacturing/reproducing ICT equipment and software products are not.

Chart 9: ICT Services and Capital Income in the United States

Panel A: ICT services and ICT and EO capital income shares



Panel B: Panel A shares divided by labour share



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 is adjusted to exclude software products R&D.

The ICT final output share $\overline{w}_T$ and its major components are shown in Chart 8. As may be seen, the share trended down in the early 2000s, but has been about flat at 5.6 per cent of GDP for the past ten years (2004 to 2014). The ICT goods net exports component has been stable of late, while ICT final services (PCE and net exports) has expanded to offset the downward drift in ICT final goods (PCE and PFI E&S, the dark and lightblue 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 per cent per year from 2004 to 2014 — just a tad higher than the final output share of software over the same period (2.4 per cent 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 ($\overline{\upsilon}_{K_T}$), labour' share ($\overline{\upsilon}_L$), and ICT services share net of sector own use (ζ_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 dark shaded area in Panel A of Chart 9).

Capital income is the nominal value of the flow of services provided by capital assets owned and used in production. It is typical to regard $\overline{\upsilon}_{K_T}$ 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 $\overline{\upsilon}_{K_T}$, alone, is an insufficient indicator of ICT use in production. Panel B in Chart 9 plots the capital income share relative to the labour share (a ratio of the compensations for ICT capital and labour). 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 labour productivity growth. The parameter combination averages 11.3 per cent for the past 10 years, considerably higher than the 7.7 per cent share implied by ICT capital ownership alone.

ICT Investment Prices

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

The new product price indexes reflect work that either (a) was conducted by the authors as part of the work for this study or (b) appears in the literature but has not yet been fully incorporated into BEA's official ICT price statistics, e.g. Berndt and Rappaport (2003); Abel, Berndt, and White (2007); Copeland (2013); Byrne and Corrado (2015a). Further information on the sources and methods used to construct the new ICT product and investment price indexes are in our companion paper (Byrne and Corrado, 2017b).

New ICT product prices and implications for ICT services prices

Table 2 reports prices for selected ICT products. More than a dozen new research price indexes are shown. Four are price indexes for the telecom products newly developed and analyzed in Byrne and Corrado (2015a,b); the computer storage device index was introduced in Byrne (2015). The remainder are price indexes newly developed for this study and whose construction is discussed in the companion paper (Byrne and Corrado, 2017b). Of these, the indexes for servers, enterprise software, enterprise wireline telecom services, along with telecom products, are particularly relevant for understanding developments over the last decade.

The following observations emerge from Table 2. First, prices for telecom equipment products (lines 1 to 4) fall relatively rapidly — between 12 and 18 per cent per year over the 2004-2014 period (column 2). Although these are noteworthy rates of decline — especially for cellular networking equipment, the item circled in column 2 — they are slower than price declines estimated for computing equipment (lines 5 to 7).

Second, computer price declines have slowed in the past decade and the gap between rates of decline for computers and communications equipment has dwindled from about 20 to 10 percentage points.

Third, the greatest computer declines, and the greatest gap, occurs in the 1994 to 2000 period, when MPU prices were falling especially fast

Table 2: Price Change for Selected High-tech Products in the United States, 1994-2014 (average annual rate of change)

	1994-2004	2004-2014	1994-2000	2000-2004	2004-2008	2008-2014
	(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 per cent change):						
22. Microprocessor Units (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: Lines 1-4 Byrne and Corrado (2015a,b); Lines 5-14 Byrne and Corrado (2017b), 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 13, and Grimm (1998) and Byrne, Oliner and Sichel (2015) to inform line 22. The source for lines 15 to 21 is BEA. The source for line 23 in Hilbert and Lopez (2011). The source for line 24 is authors' estimates using data from http://www.top500.com.

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.

(line 23). The post-2004 slowdown in microprocessing units (MPU) prices is not evident in servers (line 5) or PCs (line 7) until the 2008-2014 period however. Price declines for storage equipment also slowed in the post-2004 period as technical challenges emerged for advancing both the magnetic density of hard disk drives and the feature density of flash memory used in solid state drives (Byrne, 2015). Finally, and by contrast, prices for enterprise and other software products (which includes systems software as well as application software) maintained relatively strong declines through the most recent period (the items circled in line 10).[27]

From equation (9), prices for cloud computing and storage services are closely tied to the asset prices just discussed. However, imperfect competition and other fixed costs (in the form of non-ICT assets) create potential for these prices to deviate from the prices of the underlying ICT assets. Services of non-ICT capital assets (including land) are not an appreciable fraction of total capital income in the information processing services industry (16 per cent), which includes cloud computing and storage services, but they are more material (33 per cent) for the broadcasting, telecom and internet access services industry.[28]

What direct evidence is available for ICT service prices? Press reports have highlighted declines of 20 to 30 per cent per year at major cloud service providers.[29] Silicon Valley's Mark Andreessen, co-founder of Loudcloud, the first cloud computing company, wrote in the Wall Street Journal in 2011, "... the cost to a customer running a basic internet application [at 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, 2011). Andreessen's figures imply a price drop of more than 40 per cent per year during the first decade of the 2000s. Byrne, Corrado, and Sichel (2017b) construct price indexes for storage, computing, and database services offered by Amazon, Microsoft and Google from 2009 forward and find average prices declines on the order of 10 to 15 per cent per year, with notable acceleration when Google and Microsoft achieved significant scale in the commercial market.

We also examined prices for the enterprise segment of wireline telecom service using data from a telecommunications consultancy, Telegeography, who 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 onwards. The results of computing a matched model price index for enterprise wireline telecom services yields a price index that falls 8.2 per cent per year from 2006 to 2014.

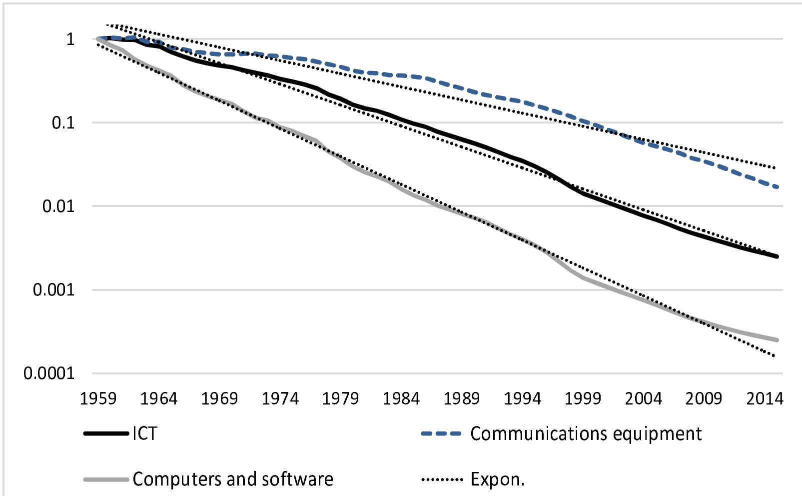
The results summarized in the previous paragraph are on par or slightly faster than the results of the price index for enterprise software (line 10); the results are also similar to the price indexes for the relevant telecom equipment (lines 1 and 2) and somewhat below the relevant computing equipment prices (lines 5 and 6). These comparative results suggest that the aggregate ICT asset price index might be a reasonable proxy for ICT services price change, consistent with the model and analysis in section 1.

27 The software products price measures were developed for use in this study, and the new indexes are documented in our companion article (Byrne and Corrado, 2017b). The inclusion of system software, whose prices are falling relatively rapidly, and the construction of an explicit component for enterprise software are the major innovations; the enterprise software price measure is an important anchor in our analysis of ICT services prices.

28 Non-ICT capital income asset shares are derived from the detailed capital measures for the NAICS 515 and 517 and NAICS 518 and 519 industries from 2004 and 2014 as reflected in the BLS MFP database (accessed July 1, 2016).

29 In March, 2014, Google announced price cuts for "virtually all" its cloud computing and storage services of 30 per cent, only to be followed in May, 2015, by further cuts in the 20 to 30 per cent range (Lardinois, 2014; Yegulalp, 2015).

Chart 10: Real ICT Investment Prices in the United States, 1959-2014,1959=1



Source: Nominal price change reported in Appendix Table A2 available at http://www.csls.ca/ipm/33/Byrne_Corrado%20Appendix.pdf, whose construction is described in Byrne and Corrado (2017b). Real prices are relative to BEA's GDP deflator.

New ICT Investment Prices Indexes

To assess the macroeconomic implications of the ICT goods and services prices just discussed, the indexes must be folded into national accounts-style investment price indexes. Detailed components of the investment price indexes are reported in the Appendix, where it may be seen that the results are largely presaged by the results presented in Table 2.[30]

Chart 10 and Table 3 report key results in terms used to assess the course of the relative productivity differential of the ICT sector ($\dot{p}$) and its current and historical misstatement. The real price of communication equipment falls below its simple long-term trend after 2000 and has remained there since then. The combined real price 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 is spot on its long-term trend in 2014 — 11.5 per cent per year (in log changes).

Table 3 shows that while real ICT price declines have gradually slowed at 9.9 per cent per year in the 2004-2014 period compared to 12.7 per cent in the 1987-2004 period (line 1, column 3), the recent experience is not all that far from the long-term trend shown in Chart 10. From 2004 to 2014, the estimate of real ICT price change is 5.8 percentage points per year lower than suggested by official data (line 8, columns 3 and 2). In terms of component contributions to real ICT price change (lines 5 to 7), the contribution of software from 1994 on is particularly noteworthy and owes, in part, to its growing share. But all told, in terms of differences relative to BEA (lines 9 to 11), all three components make similar contributions to the estimated nearly 6 percentage point per year understatement of overall ICT price declines in recent years (column 6).

Implications

Chart 11 updates the picture of real ICT price change in Panel B of Chart 1 to include the new

30 The Appendix can be found at www.csls.ca/ipm/33/Byrne_Corrado%20Appendix.pdf

Table 3: Real ICT Investment Price Change in the United States, 1963-2014 (average annual rate of change)

	1963-1987	1987-2004	2004-2014	1994-2004	2004-2008	2008-2014
	(1)	(2)	(3)	(4)	(5)	(6)
1. ICT investment	-9.5	-12.7	-9.9	-14.1	-11.3	-8.9
2. Communications equipment	-4.5	-9.4	-10.5	-10.7	-9.9	-11.0
3. Computers and peripherals	-21.2	-23.0	-19.0	-25.4	-23.9	-15.6
4. Software	-5.8	-6.6	-5.7	-7.3	-6.1	-5.5
Contributions to line 1:						
5. Communications equipment	-2.4	-3.1	-2.7	-3.4	-2.7	-2.7
6. Computers and peripherals	-5.8	-7.0	-4.0	-7.6	-5.4	-3.0
7. Software	-1.3	-2.6	-3.2	-3.1	-3.2	-3.2
Memos:						
Line 1 less BEA estimates:						
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	-0.1	-1.9	-2.2	-1.8	-2.3	-2.1
11. Software	-0.3	-0.9	-2.0	-1.7	-2.0	-2.1

Note: Contributions are in percentage points. Real prices are relative to BEA's GDP deflator as of May 2016.
Source: Authors' estimates. The corresponding nominal prices are shown in Appendix A2 found at http://www.csls.ca/ipm/33/Byrne_Corrado%20Appendix.pdf. Their derivation is set out in Byrne and Corrado (2017b).

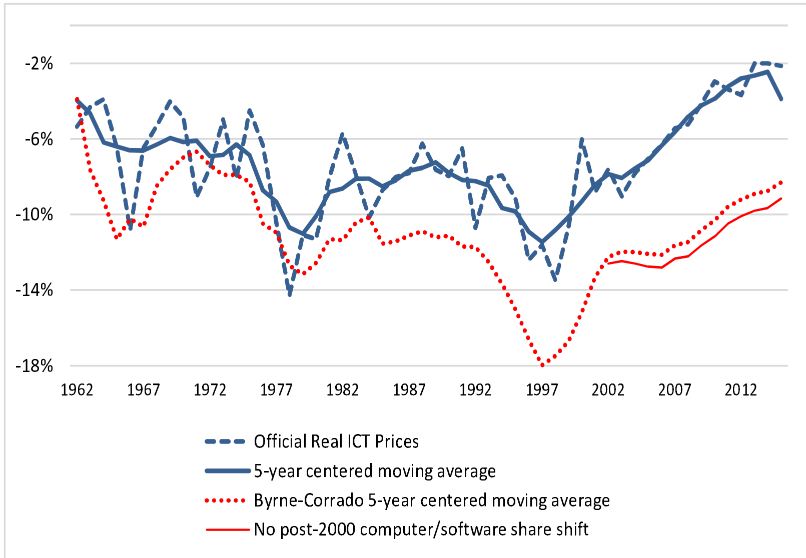
estimate reported on line 1 of Table 3. According to the new estimate real ICT price change is still estimated to have gradually lost force in recent years, but the current pace of change remains in strongly negative territory. From a macroeconomic perspective as highlighted by the two-sector model, 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. Chart 11 further suggests that the newly estimated pace of real ICT price change from the mid-1990s through the early 2000s was extraordinary, and the experience likely is a poor indicator of relative ICT productivity going forward.

A calibration of the solution to the two-sector model set out in equation (7) based on parameters drawn from the most recent ten-year period for which data are available implies a still large contribution of ICT to output per hour growth — 1.4 percentage points per year. This of course assumes that these parameters are reasonable, which we shall detail in a moment. Regarding the assumption of balanced growth, empirics will be sensitive to the actual over-the-period changes in factor utilization and/or the cost of capital from 2004 to 2014, and these changed little on balance.[31] The balanced growth assumption is in this sense not unreasonable, and we use calculations for the 2004 to 2014 period as indicative of what we might expect ICT to contribute to growth in total economy labour productivity growth going forward.

Column 2 of Table 4 shows the components of this estimated ICT contribution. (Column 1 shows calculations for the prior ten-year period

31 See updated figures for the utilization adjustment in Fernald (2012) at http://www.frbsf.org/economic-research/indicators-data/total-factor-productivity-tfp/ and updated figures of stock market returns in Shiller (2000) at http://www.econ.yale.edu/~shiller/data.htm, respectively (accessed September 2017).

Chart 11: Real ICT Price Change in the United States, 1963-2014, Redux



Source: Authors'calculations.

for reference only.) The first component of the contribution is the sum of the ICT use and diffusion effects, which is 1.1 percentage points per year (line 2, column 2). As shown on lines 2(a) and 2(b), this reflects the large income share for ICT assets and ICT services revenues (also shown in Chart 9) multiplied by a productivity differential for ICT assets that is nearly 10 percentage points per year (taken from Table 3, line 1, column 3). The second component is the 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 5.75 percentage points per year and a rather small final output share. Factory production of ICT equipment in the United States all but dried up since 2004, and the software productivity differential is applied to other domestically-produced ICT components of final demand following the logic of the two-sector model.

The memo items in Table 4 shed light on why our calculation of the ICT contribution is so high. There are three reasons. First, the conventionally calculated contribution of ICT to labour productivity growth (i.e. via the rate of growth of ICT capital per worker) does not factor in business use of cloud computing; nor does it factor in purchases of ICT consulting services that capture design services for private clouds, and possibly data analytics and related Artificial Intelligence services. Collectively, we call this the "ICT diffusion effect." The channel is estimated to be 0.4 percentage points per year, line 2 less line 4b, (after rounding) and is measured by an appropriate weight times the relative ICT productivity differential. A second reason why our calculation of the ICT contribution is high is our inclusion of EO capital, which is worth 0.2 percentage points per year, line 2 less line 4b, (after rounding). Together these sum to a tidy 0.5 percentage points per year.

The third reason for our large estimated ICT contribution is the new estimates of ICT price change that imply that the growth rate of output per hour would be higher by 0.22 percentage points per year from 2004 to 2014 if official measures were adjusted to reflect the research

Table 4: ICT Contributions to Growth in Output Per Hour in the United States(percentage points, average annual rate)

	1994 to 2004	2004 to 2014
	(1)	(2)
1. Total ICT	1.8	1.4
of which:		
2. ICT use and diffusion effect	1.2	1.1
(a) Weight (ratio): $\frac{\bar{\upsilon}_{K_T}+\bar{\zeta}_T^N}{\bar{\upsilon}L}$	0.085	0.113
(b) Productivity differential: $-\dot{p}$	14.0	9.9
3. ICT production effect	0.6	0.3
(a) Weight (ratio): $\bar{w}_{\mathrm{T}}$	0.055	0.056
(b) Productivity differential: $-\dot{p}$	10.6	5.8
Memos:		
4. Line 2 excluding:		
(a) Diffusion effect	0.9	0.8
(b) EO capital	1.0	0.9
(c) Both diffusion and EO	0.7	0.6
5. Effect of ICT price misstatement on:		
(a) Growth in output per hour	0.27	0.22
(b) Use effect	0.30	0.44

Notes: Contributions are based on equation (7) where the diffusion effect is the contribution of ICT business services to productivity growth. Line 2 (a) is ratio to labour share of total domestic income, and line 3 (a) is ratio to total nominal GDP. Lines 2 (b) and 3 (b) are estimates of productivity differentials in annual percentage changes. Line 2 (b) is the differential for all ICT assets whereas line 3 (b) is an estimate for final ICT goods and services.

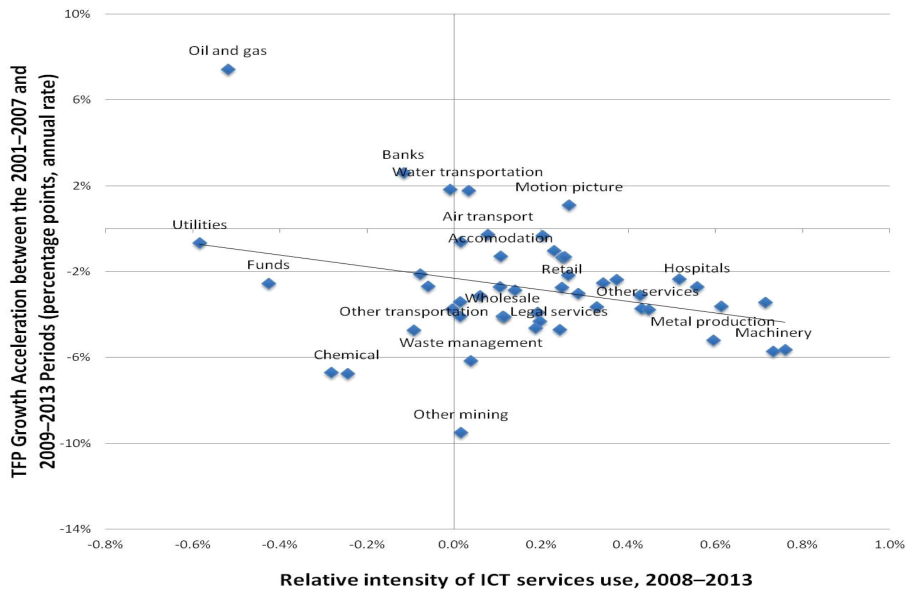
Source: Calculations use estimates reported in Table 4 and Chart 9.

reported in this article (Table 4, line 5(a), column 2).[32] But as shown on line 5(b), the conventional use effect (or ICT capital deepening) would be 0.44 percentage points higher — and this in turn implies that growth in total factor productivity (the difference between the adjustment to growth in output per hour and the adjustment to capital deepening) has been 0.2 percentage points more dismal than recorded in official estimates.[33] Moreover, the implied contribution of the non-ICT-producing sector to total factor productivity growth is unbelievably dismal after accounting for the ICT asset price misstatement and excluding the expected ICT diffusion effect via purchased services, -0.18 percentage points per year. In the prior ten-year

32 The precise calculation is the 2004 to 2014 ICT final output share $\bar{w}_{\mathrm{T}}$ reported on line 3 (a) (and shown in Chart 8) times 3.9 percentage points, which is this study's estimate of software asset price change from 2004 to 2014 (sign reversed, i.e. -3.8 per cent per year less the change in BEA's official index of 0.1 per cent per year). This result is in the same ballpark as the findings reported in Byrne *et al.* (2016).

33 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 per cent per year from 2004 to 2014, compared with 1.3 per cent per year from 1994 to 2004. Thus, the ICT price measures reported in this article, given existing GDP in all other regards, imply that TFP for the total U.S. economy likely edged up only 0.2 percentage points per year from 2004 to 2014.

Chart 12: TFP Growth Acceleration in the United States Between the 2001-2007 and 2009-2013 Periods and ICT Services Use, 2008-2013



Notes: Relative intensity is the use or investment rate averaged over the period indicated relative to its trend over the previous decade. ICT-producing industries and outlier industries are excluded. The outlier industries are: apparel, leather and allied product manufacturing; securities, commodity contracts, and investments; rental and leasing services and lessors of intangible assets; and management of companies.

Sources: Authors' elaboration of data from the US Bureau of Labor Statistics and US Bureau of Economic Analysis.

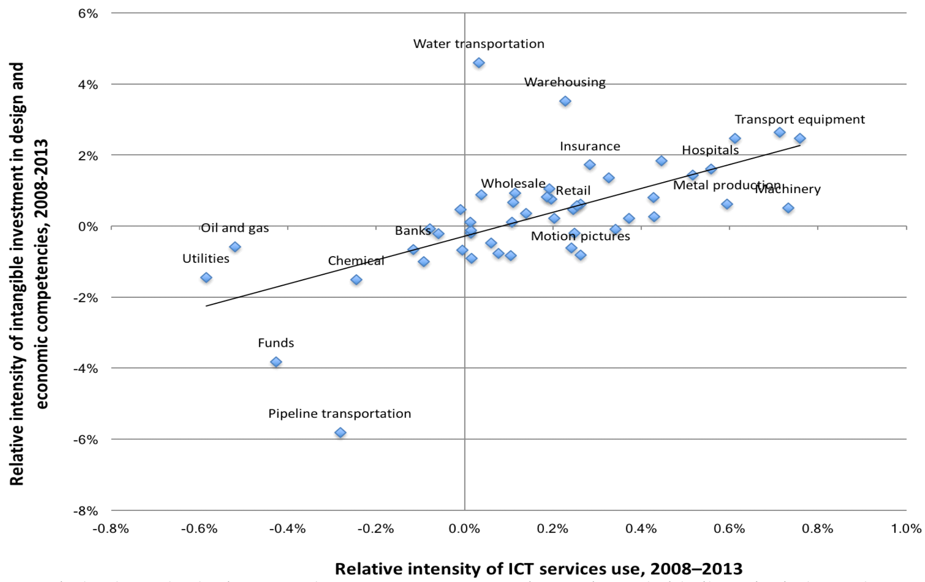
period, the comparably calculated contribution was 0.95 percentage points per year.

Having suggested that comparing the 2004-2014 period with the preceding 10 years period was problematic, consider now temporary factors that may have disturbed productivity outcomes during recent years. In particular, from the discussion of macroeconomic implications in section 1 consider that:

- computer demand is unlikely to remain as weak looking ahead as it has been during a period when firms have been adjusting to a cloud platform;
- weak demand and slow income growth during the Great Recession obscured non-ICT producers' cost savings from increased ICT capital utilization owing to adoption of cloud technologies.

With regard to the first point, the bottom line in Chart 11 shows a counterfactual for the post-2000 period for real ICT price change in which the computer and software investment 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 per cent) and the long-term trend used to determine the contribution of ICT to growth in output per hour (about 10 per cent). We believe this mitigates the concern that ICT price change continued to slow over the 10 year period used to calibrate the model, i.e. that the calibrations are based on an adjustment phase during which growth in unit computer demand has been substantially diminished by the spread of cloud technologies, leading actual ICT price declines to have been unusually slow (per the

Chart 13: Intangible Investment and ICT Services Use in the United States, 2008-2013



Notes: Relative intensity is the use or investment rate averaged over the period indicated relative to its trend over the previous decade. ICT-producing industries and outlier industries are excluded. The outlier industries are: apparel, leather and allied product manufacturing; securities, commodity contracts, and investments; rental and leasing services and lessors of intangible assets; and management of companies. Business competencies refer to design and economic competencies suchas brand, organizational structure, and firm-specific employee training.

Sources: SPINTAN (EU FP7 project under grant agreement No. 612774); INTAN-Invest per Corrado et al (2016); and elaboration of data from the US Bureau of Economic Analysis.

discussion of the impact of declines in underutilization on effective prices in section 1).

With regard to the second point, Chart 12 uses industry-level changes in total factor productivity growth before and after the Great Recession and relates them to the increase in intensity of ICT services use. The chart suggests that non-ICT producers have not reaped the gains in productivity that should have been enjoyed by the adoption of cloud platforms.[34] And Chart 13 suggests that the failure of non-ICT producers to reap productivity gains was not due to a lack of co-investments in the intangible assets that are especially crucial during the installation phase of new ICT platforms, e.g. investments in business process change and employer-specific training (Brynjolfsson, Hitt, and Yang, 2002).

It is unclear why industries whose usage of ICT services increased the most after 2007 had weaker (or no greater) rates of change in productivity from 2009 to 2013 relative to prior performance despite their co-investments in ICT-related intangibles, but several possibilities are likely. First, the very swift pace of change in the ICT sector may have created adjustment costs that temporarily offset gains from adapting to the rapid pace of digital innovation.[35] Second, it is possible some ICT spending may be defensive, for example in cyber security. Third, the Great Recession may have induced firms to "pull forward" their plans to adopt cloud-based ICT

34 Although this study has shown a disturbing degree of price mismeasurement that would feed directly into the TFP estimates plotted in Chart 11, these concerns are somewhat ameliorated because the chart uses changes in the rate of productivity growth and examines non-ICT-producing industries only.

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

systems, and the savings from doing so may have only staunched losses that were particularly severe among adopters. All told, the "diffusion" portion of the model's "use and diffusion" effect of 1.1 percentage points per year contribution of ICT to labour productivity growth seems to have not only shut down, but may even be temporarily generating negative productivity spillovers. Because it is common, even fundamental, to regard innovation in upstream sectors as diffusing to downstream sectors through intermediates use, there is no reason to believe that this channel will not return in full force in the years ahead.[36]

Summary and Conclusion

This article set out a two-sector model that illustrated how the ICT sector can have an outsized influence on economic growth via its relative productivity growth; the model, originally developed by 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 since 2004 and that its current advantage is close to nil. We found no evidence in support of this central implication of the current official ICT price measures.

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

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

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

36 Byrne, Oliner and Sichel (2017) also discuss the dismal pace of TFP growth in the non-ICT sector. Braenstedder and Sichel (2017) point to several emerging technologies as potential sources of improving TFP.

ware products and differentiated computer design services are notable examples of these holes.

The article's primary conclusion that real ICT price declines remain squarely in negative territory suggests that the sector will continue to deliver an out-sized contribution to growth in output per hour — 1.4 percentage points per year in balanced growth. This figure is substantial in light of historical average output per hour growth of 2 per cent and compared to the extraordinarily weak productivity growth in recent years.

The figure emerges from two sources documented in this study: 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 per cent 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 non-ICT producing industries has not been improving along with increased ICT services use. Additional research is needed to deepen our understanding of the linkages between measured productivity, firm performance and firm spending on ICT assets and ICT services.

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