Enterprise Information and Communications Technology - Software Pricing and Developer Productivity

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Abstract

The 1999 addition of business sector software and services spending was an important National Income and Product Accounts innovation, achieving a novel focus on the measurement of intangible asset investment. Over the intervening years, enterprise information and communication technology (ICT) has fundamentally changed. As a software producing sector, the business sector ICT function now has a much wider array of choices - software-as-a-service; open-source software; computing, storage, and communications; cloud services; and developer services from a range of global resources. Labor and multifactor software development productivity are important sources of value creation, making measurement challenging.

As the software development sector has become increasingly important in providing business sector ICT productivity, software sector developer productivity has become a viable proxy for business sector ICT developer productivity. With the use of a two-sector model and a standard growth accounting framework, a business sector ICT function shadow price is estimated, finding software price declines have been underestimated by 6.5 percentage points (ppt) over 2015 to 2020. The impact on GDP growth is a 0.1 ppt increase. Software spending increased from 19.1% to 25.5% of nonresidential fixed investment and from 48.4% to 64.6% of real intellectual property product spending.

I. Introduction

Since the introduction of business expenditures for computer software as capital formation into the National Income and Product Accounts (NIPAs) 20 years ago, both software development and computing infrastructure have changed dramatically (See Parker and Grimm 2000). Nearly ubiquitous internet access, the widespread use of mobile devices, the advent of cloud computing, the availability of software-as-a service, and more recently productive artificial intelligence (AI) models have fundamentally altered information and communication technology (ICT).

At the dawn of the 21st century, internet use was limited, the iPhone had yet to be launched, cloud computing, as it's known today, was not available and AI models remained nascent. The transformation of ICT away from a focus on basic accounting, finance, human resource, and office tasks to a capability providing digital automation of consumer activities and business processes, near real time information availability, and fast, inexpensive AI models has occurred over a remarkably brief period.

Consequently, over the most recent two decades, a new digital technology has emerged – for consumers, small businesses, and enterprises. The new technology has moved rapidly to include the extensive use of a cloud computing infrastructure that includes computing, storage, massive bandwidth, and low latency user access; the ingestion of vast quantities of structured and unstructured data; the use of machine learning and artificial intelligence to anticipate choice and provide recommended actions; and delivery on mobile, hand-held devices.

With the advent of the new digital technology, business sector software spending occurs in the context of an organizational unit – the ICT business unit. Many firms have multiple units, each consisting of highly skilled software developers, cloud engineers, data scientists, and others, all producing software solutions for the function they support. The resources are acquired at market prices, including software developers, cloud computing services, open-source software, and third-party software from both domestic and non-domestic sources.

As a result, U.S. software spending, as currently reported in the NIPAs, increased from 8.5% of real nonresidential fixed investment in 2002 to 19.1% in 2020 and 21.9% in 2022 with software spending growing from 0.9% of real GDP in 2002 to 2.7% in 2020 and 3.2% in 2022.[1] In real terms, software spending has grown at an annual rate of 9.7% between 2002 and 2020 and 10.5% annually from 2002 to 2022.

The current NIPA methodology focuses on own-account and custom software. Own-account software is defined as software "production by a business for its own use" (See Bureau of Economic Analysis 2019, Chapter 6, page 2). Custom software is software provided by third party developers. The focus here is on the business sector ICT function which incorporates both own-account and custom software.

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[1] See: National Income and Product Accounts, Table 1.1.6. Real Gross Domestic Product and Table 5.3.6. Real Private Fixed Investment by Type, billions of chained (2012) dollars, seasonally adjusted at annual rates. Last Revised on: June 29, 2023.

In addition, the current method of estimating the NIPAs software price index is largely based on prepackaged software prices and the wages rates of computer programmers and systems analysts with an adjustment for productivity changes.

As reported, the NIPA software price index declined at an annual rate of 1.6% over the 20 years from 2002 to 2022.[2] However, recent research finds the current approach underestimates realized price declines. Byrne and Corrado find a 5.5% annual decline in software prices from 1994 to 2004, a 3.5% decline from 2004 to 2008, and a 4.1% decline from 2008 to 2014.[3]

To address this shortcoming, the central focus of this paper is to measure the value created by the portfolio of resources engaged in software production. The method includes the resources necessary, their market prices, and the productivity of development teams in the software production sector to meet the needs of the demand sector as measured in the NIPAs. The approach proposed takes explicit account of a wide range of required inputs with a systematic accounting of productivity changes.

A two-sector model is developed in which a software development sector provides capabilities to the software production sector at market prices. Software production is embedded in the much broader business sector which also acquires resources at market prices. While market competition creates pressure to manage resource cost, the resulting output of ICT units is not sold at a market price. Thus, the development of a software price index is the estimate of a shadow price for an organizational function. The shadow price is the marginal profit contribution of the functional activity, considering alternative capital allocation in capturing the opportunity cost in choosing one alternative over another. The shadow price is the weighted average of the changes in input prices and wage rates adjusted for productivity improvement.

The result finds that the software price index declines have been underestimated by 6.5 percentage points (ppt) over 2015 to 2020 for an average annual decline of 7.6%.[4] The impact on real GDP growth is to increase growth by a 0.1 ppt over the period. The improved price index increases real software spending in 2020 from 19.1% to 25.5% of real nonresidential fixed investment and from 48.4% to 64.6% of real intellectual property product spending.[5] In real terms, software spending growth with the improved price index increases the 2002 to 2020 annual rate from 9.7% to 16.2%.

The outline of this paper is as follows. Section II outlines a conceptual framework for the development and production of software. Section III outlines the influences on software developer productivity and estimates software development sector productivity. Section IV develops a two-sector model, estimates the software production multifactor productivity, and the software price index. Section V concludes.

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[2] See: National Income and Product Accounts, Table 5.3.4. Price Indexes for Private Fixed Investment by Type, Index numbers, 2012=100. Last Revised on: June 29, 2023.

[3] See: Bryne and Corrado (2017a), Appendix A2.

[4] Findings are limited to 2020, the most recent year of the BEA's Integrated Industry Production Account.

[5] Software is also produced in the research and development sector for product development and service delivery, but such software is excluded from this paper.

II. A Conceptual Framework for the Development and Production of Software

Virtually every business organization develops and uses software in some fashion (See Zolas 2020). Nearly all business organizations have ICT functions – most with formal structure and responsibilities but among smaller organizations with responsibilities distributed among business leaders. Such ICT functions acquire a variety of resources and deliver software to business functional areas. Finance, human resources, and operation functions are obvious and well-known illustrations of software applications, but increasingly functions such as customer relationship management, enterprise risk management and compliance, and business security are growth applications.

Figure 1
Technology Resources Required for
Business Sector ICT Software Production

Computer, Communications, and Storage Services	Software Services	Labor Services	Imports of Services
• On-Premise Capital Services • Cloud Services	• License On-Premise Capital Services • Software-as-a-Service • Open Source	• Software Developers • Other Support Roles • All Located Domestically	• Software • Cloud • Other Services

The business sector ICT function is a software producing sector. To produce such software a range of inputs are required. See Figure 1.

- System resources can be acquired either because of an asset purchase with the installation of the asset providing a capital service or as a cloud service which is an intermediate purchase.[6] Each has an associated price. The capital service provided by the asset has a rental rate while the cloud service has a transaction price.
- Software resources are similarly acquired with one notable and important exception. License software is an asset purchase providing a capital service with a rental rate while software-as-a-service is an intermediate purchase at a transaction price. Over the past two decades, open-source software has become increasingly important. Open-source software is available with a license in which the copyright holder grants the right to use, change, and distribute the source code at a zero acquisition price.
- Labor services, located domestically, principally consist of software developers but also include computer and information analysts, support specialists, network administrators, and systems architects.
- Imports of services, providing resources to the business sector ICT function, consist of software, consulting and implementation services, and maintenance and repair services. Imported services principally reflect the labor services provided by software developers and others in non-domestic locations.

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[6] Spending for cloud computing services increased at an annual rate of 38.7% in nominal terms between 2005 and 2021 and 38.0% in real terms over the same period. See: BEA Digital Economy Satellite Account.

To fix ideas, consider customer relationship management (CRM) software which helps business leaders nurture and grow client relationships. See Figure 2. CRM software improves salesforce productivity and with confidential client information builds intangible assets. CRM platforms connect data from sales leads through transaction outcomes; records and analyzes meta data from conference calls, emails, and meetings; and most recently, provides increased analytic insight. With the ability to track and segment client data, artificial intelligence tools assess the probability opportunities will be won or lost, forecast period revenue, and assess the probability of seller retention or attrition.

Most firms, have a CRM capability. Among larger enterprises, CRM usage is virtually universal. Most often the business sector ICT function provides additional tailoring to a third-party tool to address unique organizational needs, key performance metrics, and reporting requirements. Among small business, sellers often subscribe to the service on an individual basis.

CRM software is representative of a broad class of software that is provided either with a license agreement, as-a-service, or with an open-source agreement. Table 1 shows software spending on a worldwide basis. With a zero price, open-source use is not included. Over six-years, software-as-a-service spending grew at an annual rate of almost 19%, accounting for 73% of total software spending.

As suggested by the CRM illustration, a substantial portion of software delivered by the business sector ICT function relies on input from the software development sector. Consequently, software delivered to the business sector requires a two-sector model.[7] A **software development sector**, which is an upstream sector, providing software to the business sector ICT function, which is the **software producing sector**, a downstream sector. The business sector ICT function further develops, tailors, and refines applications for business sector use. Because the software producing sector is an internal business function, the price of such internally produced software does not exist. See Figure 3.

In modeling productivity and prices across two sectors, the software producing sector, produces output in a competitive market and similarly acquires resources in competitive markets.[8] In producing software, the ICT function transacts for resources in competitive markers but provides output to internal users, not in competitive markets. Thus, to describe resource allocation decisions in the ICT functions of business organizations, a two-sector model, consisting of an upstream sector and a downstream sector, is required.

For modelling purposes, the upstream sector consists of firms whose business is to produce new commercial knowledge in the form of computing, storage, and communications equipment; software; and related services. Such firms are in the business of software development, tangible computing asset manufacturing and production, cloud computing service provision, and consulting and integration service delivery. All develop software, as well as provide other services or equipment for the software producing units of the downstream sector.

The downstream sector acquires ICT assets as commercial knowledge inputs. The sector can acquire asset ownership from the upstream sector (license software and purchase tangible capital assets) whose services are available at a known user cost of capital. In addition, the downstream sector can also choose to purchase the functionality of such assets from the upstream sector as-a-service on an as-needed basis

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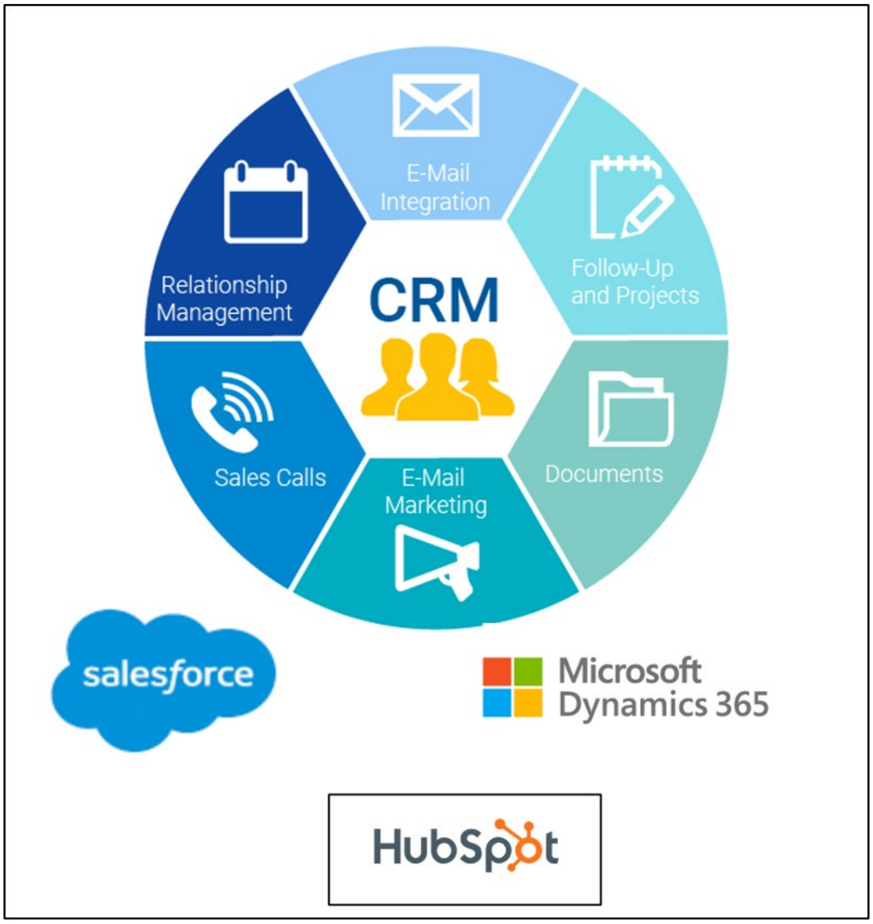
[7] See Corrado, Haskel and Jona-Lasinio (2021) for treatment of a two-sector model.

[8] Consideration of an alternative software investment price index builds on the existing NIPA methodology (See BEA 2019, Chapter 6). In the current approach, business sector software investment consists of prepackaged software purchases, custom software applications provided by third-party developers, and own-account production provided by internal development teams. Each provides new or significantly enhanced applications with maintenance of existing applications excluded.

(cloud computing and software-as-a-service). The upstream providers can be either domestic or non-domestic firms.[9]

Figure 2
Customer Relationship Management Software



Source: https://www.perfectviewcrm.com/what-is-crm/

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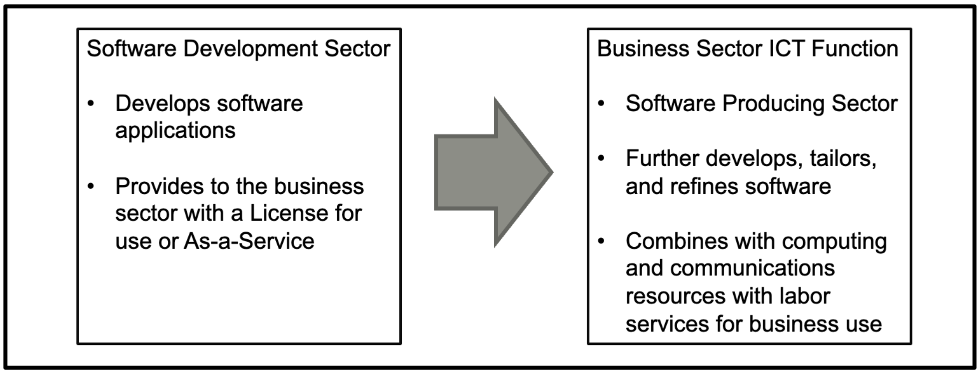
[9] As in Jorgenson (1966), each sector has a production possibility frontier, a flow equation, and due to competition covers cost.

Table 1
Worldwide Software Revenue by Type
Billions of Dollars
2016 - 2022

	2016	2022	2016-2022 CAGR (%)	2016	2022	PPT Change
License or Fee	133.9	125.3	-1.1	52.0%	26.6%	-25.4ppt
SaaS or Subscription	123.5	344.9	+18.7	48.0%	73.4%	+25.4ppt
Total	257.4	470.2	+10.6	100.0%	100.0%	----

Source: IDC

Figure 3
Software Delivered by the Business Sector ICT Function Relies on Input from the Software Development Sector



III. Software Developer Labor Productivity

The change in the business sector ICT function shadow price is the weighted average of the changes in input prices and wage rates, accounting for productivity improvements. However, measuring the productivity of such an internal function is challenging. While in theory one can calculate project level productivity estimates, productivity among software developers and software development teams is highly heterogeneous (See Shrikanth et.al. 2021). If software development productivity in the upstream software development sector includes knowledge that is diffused to the downstream software producing sector, measurement of software development sector productivity can be representative of productivity in the software producing sector as well. Such an assumption is developed in more detail in the sections that follow.

III.1. Software Developer Productivity

Software developer productivity in the business sector is subject to wide variation at the project level. Shrikanth et. al. find substantial heterogeneity among developers and development teams. In a review of the recent computer scientist literature, they write: "…..researchers acknowledge the widely held belief that some good developers are much better (almost 10X) than many poor developers". Further, observing that individual developer performance varies considerably, developers who are productive in one task may not be as productive in another task.

Shrikanth et. al. point to the relationship among quality, on-time delivery, and productivity. With data from thousands of developers doing the same set of tasks, using a wide variety of programming methods and tools, they find that a focus on quality, early in the project life cycle minimizes rework and increases on time delivery. They find "quality entails productivity" and "…on-time delivery is achieved with a quality-driven focus". In achieving quality, on-time delivery, and productivity, there are a number of recent trends that have impacted software development.

II.1.a. Software-as-a-Service

Like many professions and occupations, software developers are finding their ways of working changing as new tasks, tools, and requirements emerge. Table 1 shows with the emergence of software-as-a-service a large proportion of development is occurring in the software development sector. Thus, developers' productivity in the ICT software producing sector is dependent on productivity in the software development sector.

Bout, Hillenbrand, and Soller (2021) find that software-as-a-service has proven capable of meeting as much as 90% of the needs of a given business function. Loukis, Janssen, and Mintchev (2019) in a survey of 102 Dutch firms find that software-as-a-service can enable cost reduction and quality improvement of existing operations and provide rapid and low-cost innovation.

In addition, across both sectors, new development methods have been adopted widely, a deeper set of tools are more broadly available, application performance has become more important than lines of code produced, and developers continue to move across sectors sharing ideas and best practices. While productivity measurement is a challenge, ultimately, software development sector revenue per developer is the only meaningful market-driven result that is based on trustworthy data.

II.1.b. Agile and Devops Methods

With the introduction of agile and devops methods, quality has been the focus in the application of labor services, significantly transforming software development in recent years. Most enterprises use either or both approaches. See Table 2. For both approaches, data are collected, most often with the use of third-party tools, for developer time, task completion, and other productivity metrics. The software development methods shown in Table 2 are deployed by internal development teams – own-account – and external development teams - custom development - in the business sector as well as the software development sector.

Delaet and Lau (2017) found that sound DevOps practices can contribute to a 25% to 30% increase in capacity creation, a 50% to 75% reduction in time to market, and more than a 50% reduction in failure rates. Jadoul et. al. (2021) find evidence that business sector ICT units are adopting agile and devops methods learned from software development sector organizations and other "digital" firms that are delivering increased productivity.

III.1.c. Software Development Tools

While software development tools have been available and used by developers for decades, recent new entrants are most notable. Atlassian and Amazon Web Services (AWS), for example, have expanded both variety and access of such tools, creating more uniformity across both software sectors. These tools optimize software applications, frameworks, and programs by editing, managing, supporting, and debugging code. JIRA, Bugzilla, and Kanboard are popular Agile tools that track projects and effort. Puppet, Chef, TeamCity, and OpenStack are popular DevOps tools. In addition, recent surveys suggest that open-source software platforms provide highly favored development tools. These platforms provide developers with tools to manage and improve projects while accessing software resources. Allowing users to host and share code and other content, with open-source software developers can collaborate by sharing projects, or hosting projects for private use.

In addition, the recent emergence of generative AI offers the possibility of broad-based improvement in developer productivity. Cihon and Demirer (2023) report results from experimental research with GPT-3 and GitHub Copilot.

- Peng et. al. (2023) showed that the completion time of those with access to Copilot was 55.8% lower than those without access, suggesting the possibility of a significant increase in software development productivity. However, there was no significant effect on task success. In terms of heterogeneous effects, less experienced developers, developers facing a heavier workload, and older developers in the age range of 25 to 44 experienced greater benefits from using Copilot.
- Campero et al. (2022) find that GPT-3 significantly enhances performance with programmers achieving a 27% speed improvement and non-programmers, who could not complete the task without GPT-3, achieving performance as high as that of programmers.

Table 2
Software Development Methods

	Customer Software Requirements	Gap	Developer and Tester	Gap	IT Operations and Infrastructure
Agile Methods	Iterative approach focuses on customer collaboration	Agile methods addresses fast changing and evolving requirements	Small teams with members having similar skills	-----	Emphasis on development methods with handoff to operations
DevOps	DevOps takes software ready for release and deploys in a reliable and secure manner	-----	Larger teams across stack holders with skill set between the development and operations	Deliver code to production daily or every few hours to achieve constant operational scale	Manage end-to-end engineering processes with focuses on constant testing and delivery

Source: Hamilton (2023)

- Mozannar et. al. (2022) conducted a user study with 21 programmers solving coding tasks with Copilot, to understand how developers allocate time across these activities. The main finding is that nearly half of the participants' time was spent explicitly interacting with Copilot as developers double-checked and edited Copilot suggestions, suggesting there is a learning curve facing development teams.

III.1.d. Software Performance Engineering

Software development in the post-Moore's law era has generally focused on minimizing the time it takes to **develop an application**, rather than the time it takes to **run the application** once it is deployed. Increasingly, with the emergence of AI, software developers in the ICT function are engaged in performance engineering, collaborating with hardware architects so that new processors present simple and compelling abstractions that make it as easy as possible to exploit hardware (See Leiserson, et. al. 2020).

Leiserson et. al. suggest that as hardware has become increasingly specialized and heterogeneous. High-performing code has become more difficult to write. Consequently, software sector developers - more highly trained and with application specific skills – have taken on more of the development burden. Because faster software has become increasingly important, Leiserson et. al. also suggest various segments of the technology industry have been motivated to develop performance-engineering technologies. Algorithmic advances have already made contributions to performance growth and will continue to do so. A major goal is to solve a given problem with less computational work.

With domain specialized hardware, applications are enabled to run tens to hundreds of times faster. For example, Graphics-Processing Units (GPUs) were originally developed for rendering graphics in gaming applications. However, the use of GPUs has broadened for a variety of nongraphical tasks, such as those that are linear algebra intensive which are at the heart of AI applications. Because they are capable of training large neural networks that general-purpose processors could not train fast enough, GPUs are crucial for linear algebra intensive "deep-learning" models. In addition, Google has developed Tensor-Processing Units (TPUs) specifically for deep learning. Software sector developers, who play a large and growing role in application development, hand off completed solutions to ICT developers in the business sector. See Figure 3.

III.1.e. Developer Movement Across Sectors

With the similarity of skills and requirements in both the upstream software development sector and the downstream ICT software producing sector, there is substantial movement by developers from sector to sector. As is well known, it is difficult to protect the movement of intellectual property. The movement of professionals from company to company and sector to sector is one of means by which intellectual property – best practices, new ideas, and trade secrets - moves.

The clustering of technology companies and the inevitable intellectual property spillovers have long been understood to create important effects (See, e.g., Marshall 1920, Stigler 1951, and Krugman, 1991). More recently, with an annual turnover rate among highly skilled workers of 20% to 25% in the early 1990s, Saxenian (1994) and Almeida and Kogut (1999) show engineers and technical workers in Silicon Valley changing jobs repeatedly contributing to such spillovers.

III.2. Software Sector Productivity

Software developers are more productive as a result of software-as-a-service, the application of agile and devops methods, a broader set of development tools, a focus on performance engineering, and movement across sectors. Multifactor productivity (MFP) measure such benefits.

As with most service providers, software development sector firms have well-established standards for consistent quality. In part, quality standards are achieved in the management of critical functions and the interface between such functions. In the software development sector, research, product development, and production are among the most critical. Setting and achieving quality standards from the development process' beginning and throughout the product life cycle can improve developer productivity. In addition, as software development sector firms compete, market feedback and customer purchases made, or not made, provide important market disciple. As freestanding entities, software development sector firms - some long established and others in early stages of life - have senior corporate leaders providing leadership and guidance. Software development sector firms with delivery and go-to-market teams are well structured to provide consistent quality solutions and service, developing continuously improving developer productivity.[10]

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[10] Insights into the delivery of quality service has grown out of a voluminous literature, both for services sector firms and increasingly manufacturing firms. The seminal references are Haskett, Sasser and Schlesinger (1997) and Teboul (2006), building on work based at Harvard Business School and Insead, respectively.

With the challenges faced by ICT functions, software development sector productivity is increasingly representative of developer productivity in business sector ICT functions generally. The business sector ICT functions are customizing software-as-a-service offerings with the development having been completed by software development sector firms. In addition, new development methods are shared, tools are broadly available, application performance has become more important, and developers continue to move across sectors sharing ideas and best practices. While productivity measurement is a challenge, ultimately, software development sector revenue per developer is the only meaningful market-driven result that is based on trustworthy data.

III.3. Measuring Software Sector Labor Productivity

From the Census Bureau's Quarterly Service Survey, dollar value of output is available. Three sectors are included in the definition of the software development sector – NAICS 5112 Software Publishers; NAICS 5182 Data Processing, Hosting, and Related Services; and NAICS 5415 Computer Systems Design and Related Services. Each is deflated with a price index based on BLS PPI series. The result is chained dollar gross output - a measure of software sector real revenue.

In addition, the Occupational Employment and Wage Statistics (OEWS) program of the Bureau of Labor Statistics (BLS) produces employment and wage estimates annually for nearly 800 occupations. At the national level, occupational estimates for specific industries are available.[11] For the three NAICS industries of interest, consistent occupation data are available from 2002 to 2020. Two occupations are of interest. Computer and mathematics occupations in the software development sector, as defined, is the most comprehensive measure of employment, consisting of software developers, programmers, testers, information analysts, research scientists, support specialists, administrators, architects, data scientists and mathematicians. The second occupation of interest is software and web developers, programmers, and testers. Table 3 provides a view of computer and mathematics employment for the software sector. Figure D.1 summarized data sources.

Figure 4 shows chained dollar gross output across NAICS 5112, 5182, and 5415 grows faster than developer population after 2015. The preceding five years from 2010 to 2015 output growth matched developer population growth.

Software developer productivity, shown in Figure 5, generally improved across recent decades. Improvement stagnated after 2008 – 2010 Great Recession - when the developer population declined at a 2.2% annual rate while real software sector output rose at a 4.5% annual rate. Following the recession from 2011 to 2016 developer population increased at a 6.3% annual rate while real software sector output rose at a 6.0% annual rate.[12]

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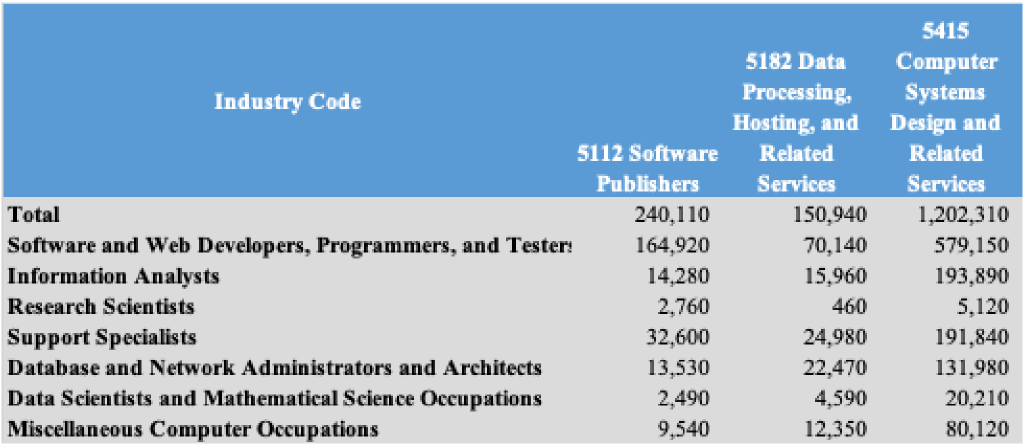
[11] See: https://www.bls.gov/oes/oes_emp.htm#scope

[12] See Gordon and Sayed (2022) for a view of hiring, separations, and productivity over the business cycle.

Figure 6 shows developer productivity growth rates for both computer and mathematics occupations and software developers, programmers, and testers. Across the broadest developer population, computer and mathematics occupations realized an annual average productivity growth of 2.5% from 2002 to 2020. Across the narrower developer population – 51% of total - software developers, programmers, and testers realized an annual average of 3.1% productivity growth from 2002 to 2020. See Table 4.

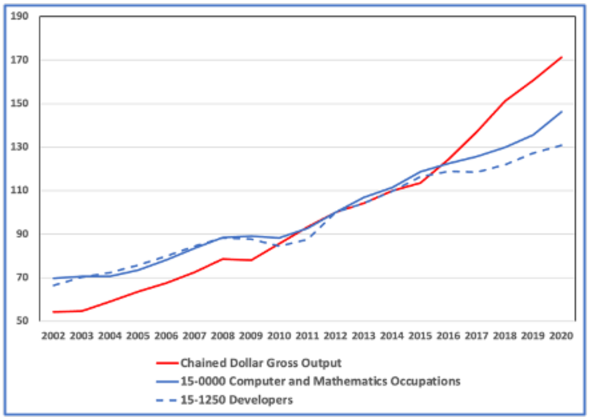
Table 3
Software Development Sector Employment
By Four-Digit Industry
Computer and Mathematical Occupations
2020



Industry Code	5112 Software Publishers	5182 Data Processing, Hosting, and Related Services	5415 Computer Systems Design and Related Services
Total	240,110	150,940	1,202,310
Software and Web Developers, Programmers, and Tester	164,920	70,140	579,150
Information Analysts	14,280	15,960	193,890
Research Scientists	2,760	460	5,120
Support Specialists	32,600	24,980	191,840
Database and Network Administrators and Architects	13,530	22,470	131,980
Data Scientists and Mathematical Science Occupations	2,490	4,590	20,210
Miscellaneous Computer Occupations	9,540	12,350	80,120

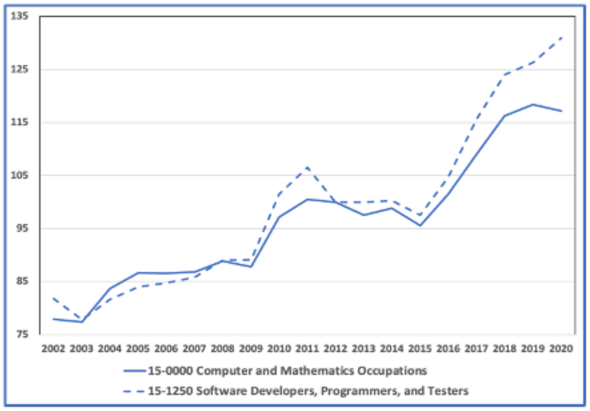
Source: BLS Occupational Employment and Wage Statistics.

Figure 4
Software Development Sector Sum of NAISC 5112, 5182 and 5415 Output and Employment (Index 2012 = 100)



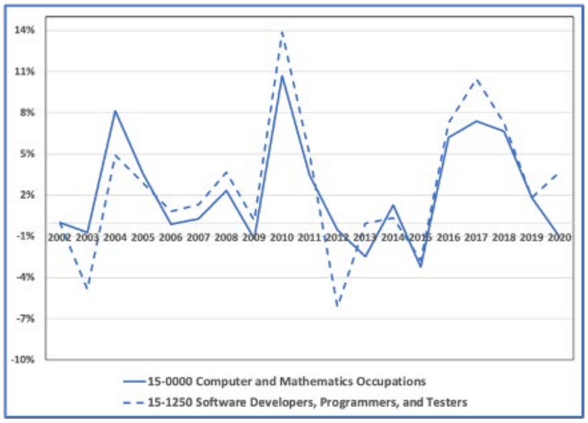
Source: Author's Calculations; BEA Current and Chained Dollar Gross Output and Price Index NAICS 5112, 5182, and 5415; and BLS Occupational Employment and Wage Statistics.

Figure 5
Software Developer Labor Productivity Weighted by NAISC 5112, 5182 and 5415 Sector (Index 2012 = 100)



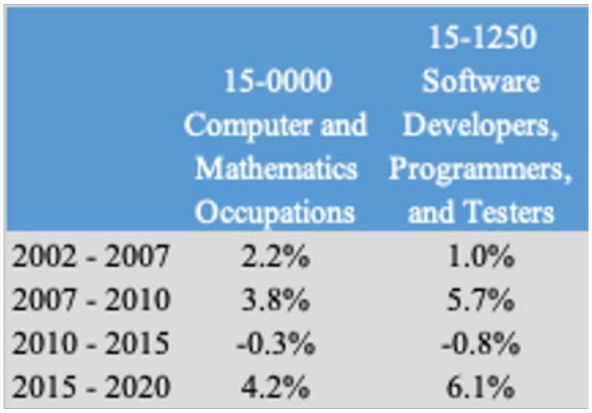
Source: Author's Calculations; BEA Current and Chained Dollar Gross Output and Price Index NAICS 5112, 5182, and 5415; and BLS Occupational Employment and Wage Statistics.

Figure 6
Software Developer Productivity Weighted by 5112, 5182 and 5415 Sector (% Change)



Source: Author's Calculations; BEA Current and Chained Dollar Gross Output and Price Index NAICS 5112, 5182, and 5415; and BLS Occupational Employment and Wage Statistics.

Table 4
Software Sector Developer Productivity Index Weighted by Sector Index 2012 = 100



	15-0000 Computer and Mathematics Occupations	15-1250 Software Developers, Programmers, and Testers
2002 - 2007	2.2%	1.0%
2007 - 2010	3.8%	5.7%
2010 - 2015	-0.3%	-0.8%
2015 - 2020	4.2%	6.1%

Source: Author's Calculations

IV. A Two-Sector Model, Labor Productivity, and Software Price Index

As developed in Section II, the Software Price Index model consists of an upstream sector and a downstream sector. Both sectors employ labor with software developers as the occupation of principle interest. The downstream sector is a price taker, like many innovation models (See Corrado, Haskel and Jona-Lasinio 2021). Both the upstream sector and the downstream sector acquires assets (K_t) at a price (P_t^K), purchases services (I_t) at a market price (P_t^I), and labor (L_t) is employed at wage rate (W_t). Multifactor productivity (Z_t) is realized. The change in the net stock of ICT assets is $\Delta ICT_t = N_t - \delta_K ICT_{t-1}$ where N_t is new investment and δ_K is depreciation. The upstream sector flow of payments is $P_t^K K_t + P_t^I I_t$.

IV.1. Two Sector Model

Since markets for software services are generally not well developed inside business organizations, it is useful to work with a price-like concept that captures the marginal value contribution of the services provided.[13] Because most business organizations have alternative capital allocation choices, the marginal profit contribution of such choices, whether recognized explicitly or implicitly, is a primary decision factor. Thus, the cost per unit of software is referred to as a shadow price. In the business sector ICT function, software units (Q_t^{ICT}) are produced at a shadow price (P_t^{ICT}).

The functional form of the production function and other equations will be identical for both the upstream and downstream sectors with notation simplified for ease of exposition.

$$Q_t = F(L_t, K_t, I_t, Z_t) \qquad (1)$$

The capital services price (P_t^K) associated with the quantity of capital services is often referred to as the rental price or the user cost of capital (See Jorgenson, Ho, and Stiroh 2005, pp. 154-155 for more detail). In equilibrium, ignoring uncertainty and adjustment costs, investors – e.g. corporate parents or venture capital providers – are indifferent between earning a nominal rate of return from an investment or buying a unit of capital – in this case computing equipment or software – collecting a rental price, and then selling the depreciated asset in the next period. Such a decision criteria implies the following:

$$(1 + i_{t+1})P_{ac,t}^K = c_{k,t+1} + (1 - \delta_k)P_{ac,t+1}^K$$

where i_{t+1} is the nominal interest rate, $P_{ac,t}^K$is the acquisition price of capital, $c_{k,t}$ is the rental fee or user cost of capital, and δ_k is the economic depreciation rate.
If $c_{k,t} = P_t^K$, $\pi_{ac,t} = \frac{P_{ac,t}^K}{P_{ac,t-1}^K} - 1$, the inflation rate, and $(i_t - \pi_t)$ is the real return for each asset, then

$$P_t^K = (i_t - \pi_t)P_{ac,t-1}^K + \delta_k P_{ac,t}^K \qquad (2)$$

In the results that following, capital service prices – equation (2) – play an important role. For capital assets, existing published price indices are asset acquisition prices. In contrast, the capital services price index is the weighted average of the asset's acquisition price, accounting for period lags with the real rate of return and the depreciation rate as the weights. Jorgenson et. al. define the real rate of return as

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[13] While transaction prices are, in some instances, assigned to such internal services, they are not arrived at in a competitive marketplace. Such prices are typically administrative.

a weighted average of the interest cost of debt and the industry-specific return on equity which includes the debt/capital ratio and the dividend/payout ratio.

Following Oliner and Sichel (2002) Appendix A, assume perfect competition, constant returns to scale, profit maximization and no adjustment costs, the prices for the associated services are:

$$P_t^I = P_t^Q\left(\frac{\partial F_t}{\partial I_t}\right) \Rightarrow \frac{P_t^I}{P_t^Q} = \left(\frac{\partial F_t}{\partial I_t}\right) \qquad (3)$$

$$P_t^K = P_t^Q\left(\frac{\partial F_t}{\partial K_t}\right) \Rightarrow \frac{P_t^K}{P_t^Q} = \left(\frac{\partial F_t}{\partial K_t}\right) \qquad (4)$$

$$W_t = P_t^Q\left(\frac{\partial F_t}{\partial L_t}\right) \Rightarrow \frac{W_t}{P_t^Q} = \left(\frac{\partial F_t}{\partial L_t}\right) \qquad (5)$$

Totally differentiate (1), divide by ∂t and Q_t and substitute (3), (4), and (5). Define rate of change:

$$\dot{K_t} = \frac{\partial K_t}{\partial t}\frac{1}{K_t}, \ \dot{I_t} = \frac{\partial I_t}{\partial t}\frac{1}{I_t}, \dot{L_t} = \frac{\partial L_t}{\partial t}\frac{1}{L_t}, and\ M\dot{F}P_t = \frac{\partial Z_t}{\partial t}\frac{1}{Z_t}$$

$$\dot{Q_t} = \beta_t^K\dot{K_t} + \beta_t^I\dot{I_t} + \beta_t^L\dot{L_t} + M\dot{F}P_t \qquad (6)$$

β_t^x is the cost share. The output change is the weighted average of the change in resources consumed and gains from multifactor productivity (MFP). Subtracting $\dot{L_t}$ from both sides yields labor productivity (LP)

$$L\dot{P_t} = \dot{Q_t} - \dot{L_t} = \beta_t^K\dot{K_t} + \beta_t^I\dot{I_t} + (\beta_t^L - 1)\dot{L_t} + M\dot{F}P_t \qquad (7)$$

Solve for $M\dot{F}P_t$

$$M\dot{F}P_t = L\dot{P}_t - [\beta_t^K\dot{K_t} + \beta_t^I\dot{I_t} + (\beta_t^L - 1)\dot{L_t}] \quad (8)$$

For the software development sector, labor productivity is:

$$LP_{S\dot{S},t} = \beta^K_{SS,t}K_{S\dot{S},t} + \beta^I_{SS,t}I_{S\dot{S},t} + (\beta^L_{SS,t} - 1)L_{S\dot{S},t} + MF\dot{P}_{SS,t} \qquad (9a)$$

For the business sector ICT function, labor productivity is:

$$LP_{IC\dot{T},t} = \beta^K_{ICT,t}K_{IC\dot{T},t} + \beta^I_{ICT,t}I_{IC\dot{T},t} + (\beta^L_{ICT,t} - 1)L_{IC\dot{T},t} + MF\dot{P}_{ICT,t} \qquad (9b)$$

For the software development sector, multifactor productivity is:

$$MF\dot{P}_{SS,t} = LP_{s\dot{s},t} - [\beta^K_{SS,t}K_{S\dot{S},t} + \beta^I_{SS,t}I_{S\dot{S},t} + (\beta^L_{SS,t} - 1)L_{S\dot{S},t}] \quad (10a)$$

For the business sector ICT function, multifactor productivity is:

$$MF\dot{P}_{ICT,t} = LP_{IC\dot{T},t} - [\beta^K_{ICT,t}K_{IC\dot{T},t} + \beta^I_{ICT,t}I_{IC\dot{T},t} + (\beta^L_{ICT,t} - 1)L_{IC\dot{T},t}] \quad (10b)$$

With estimates of MFP available from equations (10a) and (10b), the dual approach is used to estimate software shadow price changes. The dual of profit maximization is cost minimization. The dual approach provides a shadow price and imputes value to the utilization of scarce resources with no accounting loss. The dual yields equation (11). Appendix A provides the details.

$$P_t^{IC\dot{T}} = \dot{p}_t^K\beta^K_{ICT,t} + \dot{p}_t^I\beta^I_{ICT,t} + \dot{p}_t^L\beta^L_{ICT,t} - MFP_{ICT,t} \qquad (11)$$

IV.2. Labor Productivity

The very significant transformation of ICT over the past two decades has increased the focus of both scholars and practitioners on improved measurement and work methods.[14] Based on the premise that software development sector developer productivity is a reasonable measure of business sector ICT function developer productivity, assume from equations 9a and 9b,

$$\dot{LP}_{ICT,t} = \dot{LP}_{ss,t}$$[15]

From equation 10b, with labor productivity from the software development sector's software developers, programmers, and testers ICT function multifactor productivity (MFP) is calculated. Equation 11 provides the estimate of the ICT function shadow price index. The implementation of equations 10b and 11 requires data for resource usage and prices.[16]

To implement the estimate of the software price index, the BEA Integrated Industry-Level Production Account (IILPA) data are employed.[17] These data provide both capital services quantities and rental price deflators for computing, communications, software and other capital that deliver the services acquired by the business sector (See Garner, Harper, Russell, and Samuels 2021). Data for cloud computing and open-source software services are necessary. Employment and wage data are also required. And, data for imported services are required. In all cases both quantities and prices are necessary.

The IILPA provides sector level capital services data for communication and computing equipment, software, and other capital. For each capital service, a price is associated with the quantity of capital services. In recent decades, intermediate services, such as cloud computing and software-as-a-service are also available. A transaction price is associated with such services. These intermediate services are provided by the software development sector to the business sector ICT function.[18]

The business sector ICT function is a business service most often internal to business and government organizations that employ a wide range of ICT resources. (See Figure 1.) As inputs, the function requires both the acquisition of capital – e.g. computing, storage, and software – and the purchase of intermediate services – e.g. cloud computing, software-as-a-service, open-source software, and labor. The ICT function is a software producing sector and delivers its output as software, as reported in the NIPA accounts. The end user in a business or government organization benefits from new or improved software tools and capabilities with a portfolio of technology resources required for the

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[14] In a series of papers, Byrne, Corrado and collaborators have reviewed current methods and proposed, where possible, improvements. See: Byrne and Corrado (2017a) and (2017b).

[15] The equality of $\dot{LP}_{ICT,t}$ and $\dot{LP}_{ss,t}$ implies a relationship between $\dot{P}_{ICT,t}$ and $\dot{P}_{SS,t}$. See Appendix C for details.

[16] Figure D.2 shows the data sources used for the MFP and price equation calculations.

[17] Data are available through 2020. https://www.bea.gov/data/special-topics/integrated-industry-level-production-account-klems

[18] For modelling purposes, the software development sector includes firms that provide software, cloud computing, and other resources. These firms include pure software firms and others such as Amazon Web Service, Microsoft Azure, and Google Cloud.

production of the resulting software, as specified in equation (1).[19] Appendix E provides a detailed view of data for the right side of equation 11.

IV.3. Results: Software Price Index

With the factor shares, price changes, and growth rates along with the assumed labor productivity growth, equation 10b is used to calculate the multifactor productivity level and rate of change. Figure 7 shows the results of the MFP calculation. The MFP level increased 1.0% per year over the 2007 to 2020 period. However, over the 14 years, there were three distinct periods. As aggregate growth declined in the 2007 to 2010 period, developer employment was little changed with real software sector growth remaining strong and developer productivity increasing 5.7% annually. As aggregate growth recovered from the Great Financial Crisis, developer employment recovered, and labor productivity growth slowed. (See Gordon and Sayed 2022.) Over the most recent five years, software output grew rapidly, and productivity increased.

Figure 8 shows the business sector software price index and its rate of change. The index trended down throughout the period, interrupted from 2010 to 2015 when MFP growth turned negative as development teams scaled up. Without more rapid growth in resource use, in the absence of productivity declines, the software price index was virtually flat. However, in the last half of the decade, developer productivity gains resumed, and the software price index renewed its decline.

Table 5 shows the components of MFP growth and software price percent change. In the top panel of the table, MFP growth reflects the variability of labor productivity growth as business conditions change as well as the more limited variability of compensation changes. As hiring resumed in the 2010 to 2015 period, compensation increases accelerated over the prior and following period. The growth of capital services and intermediate purchases accelerated throughout the period, as technology resources were applied at increasing rates.

On the bottom panel of Table 5, the software price index fell continuously over the period. The price declines reflect MFP improvement and accelerating price declines across the weighted combination of labor service, capital services, and intermediate purchases.

With all the elements required for the software price calculation, Table 6, Figure 9, and Figure 10 compare the change in the software price index with the currently published NIPA price index.

As has been shown, there are a number of elements that determine the software index. For ease of exposition, Table 6 shows the incremental impact on the index as resources are added to the index calculation. The rows of Table 6 are as follows:

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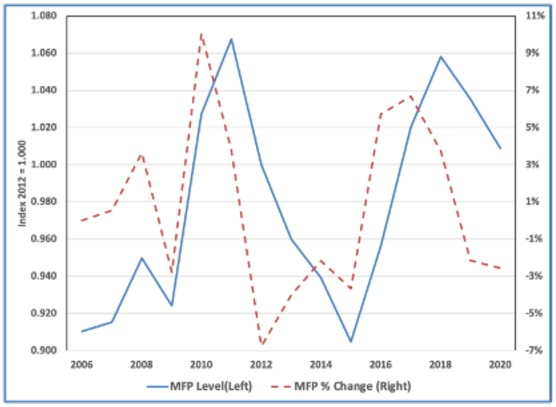
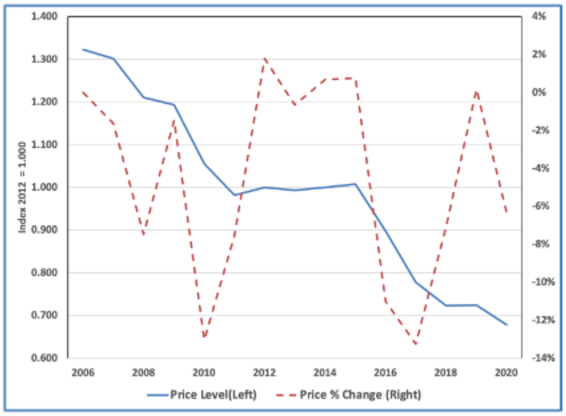
[19] The model and empirical estimates include all U.S. economic sectors - farm, business, and government. For ease of exposition, references will be to the business sector.

Figure 7
Multifactor Productivity Business Sector ICT Function
Index 2012 = 1.00



Source: Author’s Calculations.

Figure 8
Business Sector ICT Function
Price Index 2012 = 1.00



Source: Author’s Calculations.

Table 5
ICT Software Price, Labor Productivity, MFP, and Capital Services and Intermediate Purchases
Annual Percent Change

	2007 to 2010	2010 to 2015	2015 to 2020
MFP % Change	4.1%	-2.1%	2.4%
Labor Productivity % Change	5.7%	-0.8%	6.1%
Labor Services % Change	3.7% *	5.1% **	4.0% ***
Weighted Capital Services and Intermediate Purchases% Change	5.5%	6.6%	8.3%
ICT Software Price % Change	-6.8%	-1.1%	-7.7%
MFP % Change	4.1%	-2.1%	2.4%
Weighted Price Changes Labor Services, Capital Services and Intermediate Purchases	-2.7%	-3.2%	-5.3%

Source: Author’s Calculations. From equation 10b, MFP % change is Labor Productivity % change minus Labor Service % change minus Capital Services and Intermediate Purchases % change. Labor Services % change is percent change in developer wages times the share of labor services minus one. Because labor share is less than one, Labor Services % change is negative. * 2007 to 2010 labor share is 14.8% and percent change in compensation is 4.4%. ** 2010 to 2015 labor share is 13.6% and percent change in compensation is 5.9%. **** 2015 to 2020 labor share is 12.0% and percent change in compensation is 4.4%. From equation 11, ICT Function % change is the weighted price % change for Labor Services plus Capital Services and Intermediate Purchases which is negative in all cases minus MFP % change. All quantity changes are in real terms.

$$
\begin{aligned}
\%\ \Delta\ \text{Software Price Index} = {} & \%\ \Delta\ \text{Capital Services Prices} - \%\ \Delta\ \text{MFP (Row 2)} + \\
& \%\ \Delta\ \text{Labor Wages (Row 3)} + \%\ \Delta\ \text{Imported Services Prices (Row 4)} + \\
& \%\ \Delta\ \text{Cloud Computing Prices (Row 5)} + \%\ \Delta\ \text{Open-Source Software (Row 6)}
\end{aligned}
$$

The largest contributor to the software index price decline is from the bundle of capital services. In the bundle, communications equipment is 27%, computing equipment is 14%, software is 53%, and other capital is 6%. See Figure 9. The introduction of the MFP estimates in equation 11 and capital services with the use of the IILPA data resulted in a 6.5 ppt addition price index decline over the 2015 to 2020 period. The methodological change from the use of traditional use BLS software price indices to the introduction of capital services and their associated rental prices has the largest impact on the price index differential. Table 6 shows that the price of software delivered to business organizations is heavily influenced by less expensive communications and computing equipment (See Kaushik, Soni, and Soni 2012).

With the cost of labor services and imported service rising over the period, even with reduced consumption both detract from software price index declines. Over the entire 2007 to 2020 period, real spending for domestic labor service rose at a CAGR of 5.1% with software developer wage rates rising at an annual rate of 2.6% over the period. Real spending in imported services rose at a CAGR of 4.0% with prices averaging unchanged over the period.

As currently measured, cloud computing prices have little impact on the software price index from 2015 to 2020. The move to cloud computing services slowed the price decline by 0.4 ppts. The rental price of on-premise computing capital services declined at an annual rate of 1.6% over the period while the transaction price of cloud computing rose 0.3% on average over the period.[20] However, because the rental price of on-premise computing capital services is typically calculated based on the time period of maximum usage while cloud computing prices are based on resources consumed, migration to cloud computing typically results in cost reduction (See Armbrust et. al. 2009).

By contrast, the increased use of open-source software further contributes to price declines. The increased penetration and usage of open-source software resulted in a further 0.8 ppt decline in the price index, almost offsetting the effect of cloud computing prices.

As Figure 10 shows, the published NIPA index declined at an average annual rate of 1.1% over the 2015 to 2020 period. The software price index declined – on the right side of the figure - at an average annual rate of 7.6% over the same period for a net increase in the price decline of 6.5 ppts.

The finding that the software price index has been declining more rapidly than the NIPA estimates implies investment spending, productivity growth, and real GDP growth have been underestimated. The model follows closely the work of Byrne, Oliner and Sichel (2013) and Greenstein

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[20] Cloud services output (NAICS 5182) is deflated by BEA with Producer Price Index software prices (NAICS 5182). In the upcoming 2023 Comprehensive Update of the NIPAs, cloud service specific prices will be introduced to deflate cloud services.

and Nagle (2014) who measure productivity and growth improvement from the broader application and adoption of ICT.[21] Table 7 shows comparative investment and growth calculations which assumes a 6.5 ppt average annual underestimate of the ICT function price decline between 2015 and 2020 as shown above in Figure 10. As the table shows investment spending estimates increase meaningfully with a smaller impact on the overall real GDP growth rate.

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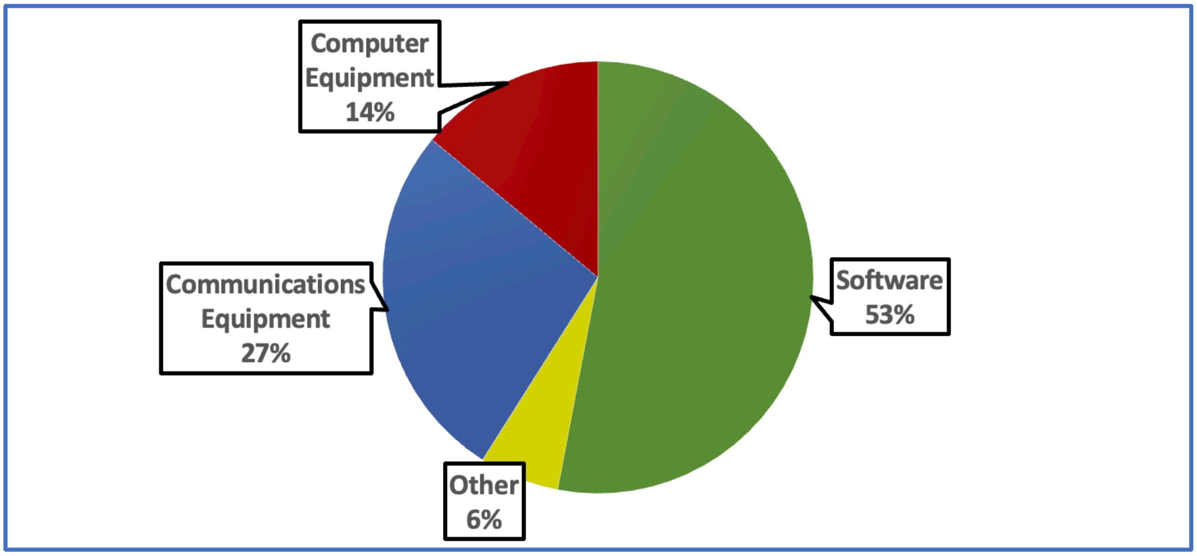
[21] Like the two-sector model, Byrne, Oliner and Sichel consider the use and deployment of a broad portfolio of ICT resources. Greenstein and Nagle focus on the introduction of Apache open-source software.

Table 6
Business Sector ICT Price Index
2015 to 2019 % CAGR

	2007 to 2010	2010 to 2015	2015 to 2020	2007 to 2020
NIPA Index	-1.7%	-1.3%	-1.1%	-1.3%
With Capital Services (KLEMS Data)	-7.2%	-1.0%	-8.2%	-5.4%
With Labor Services	-6.2%	+0.2%	-7.2%	-4.2%
With Imported Services	-5.9%	+0.4%	-7.2%	-4.0%
With Addition of Cloud Computing	-5.7%	+1.1%	-6.8%	-3.6%
With Addition of Open-Source Software	-6.7%	-0.9%	-7.6%	-4.9%
Net Increase in Price Decline	5.1 ppts	-0.2 ppts	6.6 ppts	3.7 ppts

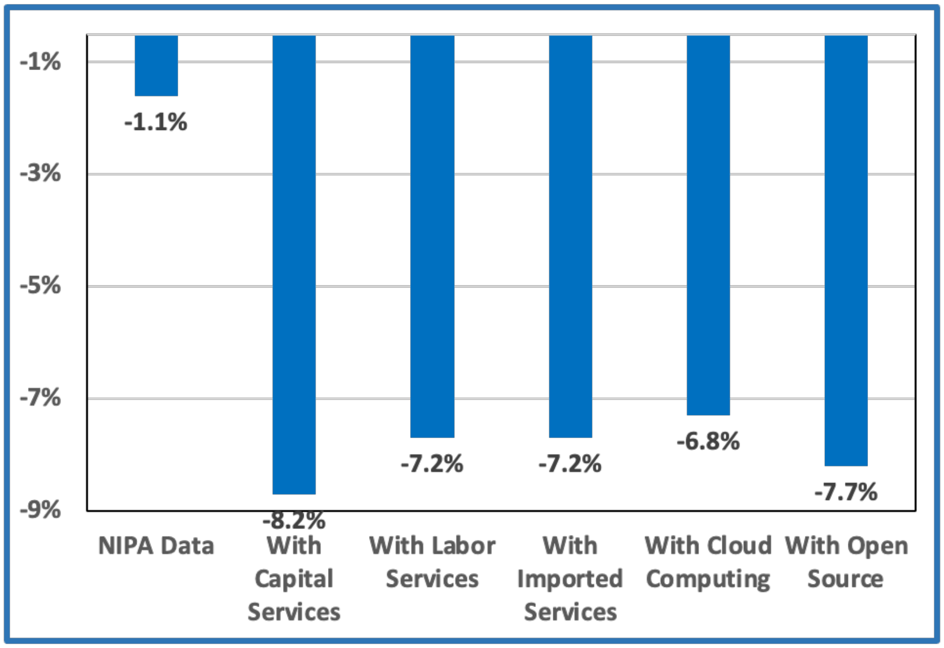
Source: Author's Calculations.

Figure 9
Capital Services Distribution



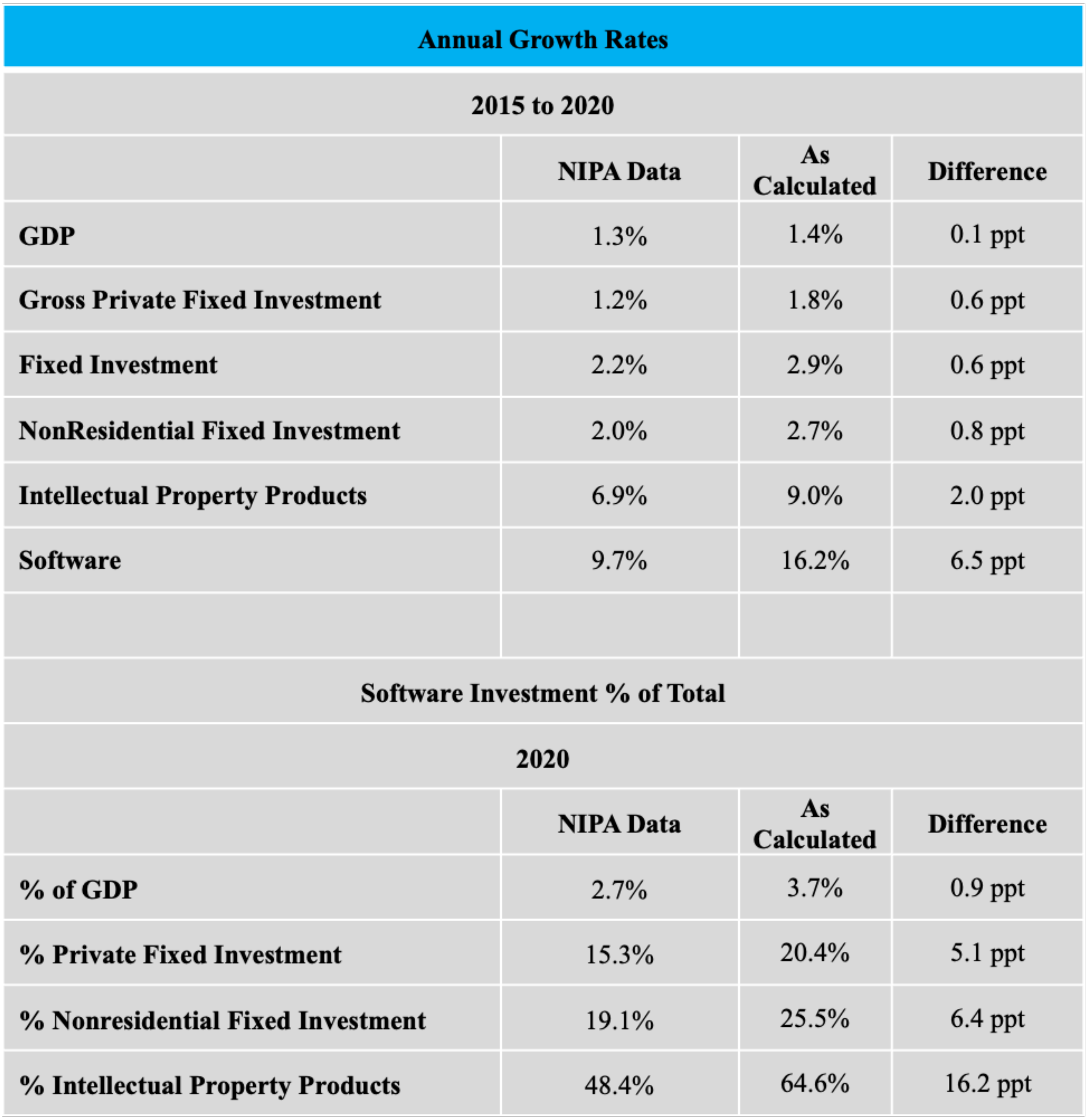
Source: Author's Calculation

Figure 10
Business Sector ICT Function Price Index
2015 to 2020 % CAGR



Source: Author's Calculations.

Table 7
Revised Business Sector ICT
Real Spending Estimates
Billions of 2012 Dollars



Annual Growth Rates			
2015 to 2020			
	NIPA Data	**As Calculated**	**Difference**
GDP	1.3%	1.4%	0.1 ppt
Gross Private Fixed Investment	1.2%	1.8%	0.6 ppt
Fixed Investment	2.2%	2.9%	0.6 ppt
NonResidential Fixed Investment	2.0%	2.7%	0.8 ppt
Intellectual Property Products	6.9%	9.0%	2.0 ppt
Software	9.7%	16.2%	6.5 ppt
Software Investment % of Total			
2020			
	NIPA Data	**As Calculated**	**Difference**
% of GDP	2.7%	3.7%	0.9 ppt
% Private Fixed Investment	15.3%	20.4%	5.1 ppt
% Nonresidential Fixed Investment	19.1%	25.5%	6.4 ppt
% Intellectual Property Products	48.4%	64.6%	16.2 ppt

Source: Author's Calculations. Assumes 6.5% underestimate of constant dollar software spending growth.

V. Conclusion

The introduction of enterprise software spending in the National Income and Product Accounts, more than 20 years ago, represented one of the first successful measures of intangible asset investment. The innovation was a recognition that the global technology sector made a meaningful contribution to productivity improvement over the second half of the 1990s. However, over more recent decades much has changed. The nature and manner in which information and communication technology is produced, deployed, and used has change markedly. As a result, current estimates of price changes in enterprise software appears to underestimate the declines realized in the current century. The consequence is an underestimate of real private fixed investment spending, real GDP growth, and productivity improvement.

Price changes in business sector ICT software – the shadow price change – is the cost-share weighted average of the changes in resource prices minus the change in MFP. While some, but not all, prices paid for enterprise ICT resources and services have declined, the productivity of software developers has advanced substantially over the period. Estimates indicate a 5.7% developer productivity CAGR over 2007 to 2010 and a 6.1% CAGR over the more recent 2015 to 2020 period. Multifactor productivity improvement has been somewhat less consistent with a 1.0% CAGR over 2007 to 2020 but a 2.4% CAGR over the more recent 2015 to 2020 period.

In improving the software price index, the largest contribution results from a methodological shift from traditional price indices which measure software acquisition prices to a bundle of capital services prices. The business sector ICT function employ a range of tangible capital assets, including communications, computing, and storage equipment, software, and other capital, such as facilities and buildings. Collectively, these capital assets contribute to less expensive software produced for business sector use.

In addition to substantial labor productivity advances, the advent of open-source software represents an important source of downward price pressure. While software available at a zero price continues to require labor services, the increased use of open-source software lowers the weighted cost of the largest resource in the enterprise ICT services mix. Software spending is 49.2% of total ICT spending in 2020.

The view of the business sector ICT function that emerges is one in which the growth in technology resources has accelerated over the most recent decade-and-a-half. The development, deployment, and use of software, including open-source software, is at the heart of the functions' activity and its shadow price. Second, the attractiveness and convenience of cloud computing have, apparently, limited transaction price declines for the first decade of its life and slowed software price declines. Third, the use of imported services, which accelerated broadly in the first decade of the century, has slowed recently. Finally, employment and productivity improvement have been sensitive and responsive to aggregate economic conditions.

Taken together, the model and resulting estimates find, between 2015 and 2020, the software price index declined at a 7.6% annual rate, 6.5 percent points more than published NIPA estimates. Tangential to the ICT software price index, it's of interest to note that domestic labor and imported services decline in a complementary fashion, as the increased use of technology inputs substitute for reduced labor and imported services.

The business sector ICT function can substantially influence aggregate investment, productivity, trade, and growth. The effectiveness, quality, and the implicit price of software delivered to the business organizations in which they live is an important contributor to business success and, ultimately, living standards.

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Appendix A

Cost Minimization in Dual Production Theory

From Samuelson (1947) the problem is to minimize cost:

$$C = A + \sum_1^n w_i v_i \qquad (\text{A.1})$$

where $v_i$are production inputs and $w_i$are input prices, subject to constrained output:

$$\varphi(v_i \dots\dots\dots. v_n) = \bar{x} = constant \qquad (\text{A.2})$$

where φ is a production function and x is output.

The constrained minimization problem is:

$$G = A + \sum_1^n w_i v_i - \lambda[\varphi(v_i \dots\dots\dots. v_n) - \bar{x}] \qquad (\text{A.3})$$

To achieve a minimum:

$$\frac{\partial G}{\partial v_i} = 0 = w_i - \lambda\varphi_i \; (i = 1 \dots\dots\dots. n) \qquad (\text{A.4})$$

which may be written:

$$\frac{1}{\lambda} = \frac{\varphi_1}{w_1} = \frac{\varphi_2}{w_2} = \cdots \dots\dots. = \frac{\varphi_n}{w_n} \qquad (\text{A.5})$$

$$\lambda = \frac{w_1}{\varphi_1} = \frac{w_2}{\varphi_2} = \cdots \dots\dots. = \frac{w_n}{\varphi_n}$$

For total cost to be at a minimum for any given output, the marginal productivity of the last dollar ($1/\lambda$) must be equal in every case or the marginal physical productivity of any factor must be proportional to the price at which it can be hired, λ is the factor of proportionality.

$$\varphi_i = \lambda w_i$$

Write the total differential of (A.4) and (A.2):

From (A.4)

$$\sum_1^n \varphi_{ij} dv_j + \frac{\varphi_i}{\lambda} d\lambda = \frac{dw_i}{\lambda} \; (i = 1 \dots\dots\dots. n) \qquad (\text{A.6})$$

From (A.2)

$$\sum_1^n \varphi_j dv_j = dx \; (\text{A.7})$$

Assume each firm is small relative to the market for each input so that unlimited amounts of each input can be brought at their respective prices ($w_1 \ldots\ldots\ldots. w_n$). There are ($n+1$) linear equations in ($n+1$) unknows ($dv_1 \ldots\ldots\ldots. dv_n, d\lambda$) to be solved.

Samuelson solves for $d\lambda$:

$$d\lambda = \frac{\sum_1^n \frac{dw_i}{\lambda} \Delta_{i,n+1} + dx\Delta_{n+1,n+1}}{\Delta} \qquad (A.8)$$

Two special cases:

$$\frac{\partial \lambda}{\partial w_k} = \frac{\Delta_{k,n+1}}{\Delta} \qquad (A.9)$$

$$\frac{\partial \lambda}{\partial x} = \frac{\Delta_{n+1,n+1}}{\Delta} \qquad (A.10)$$

Where Δ is the matrix in determinant notion for the left side of the system of equations in (A.6) and (A.7) and Δ_{rc} is the cofactor of the element of the rth row and the cth column.

Consider as an illustration a cost equation with three inputs.

$$\varphi_{11} dv_1 + \varphi_{12} dv_2 + \varphi_{13} dv_3 + \frac{\varphi_1}{\lambda} d\lambda = \frac{dw_1}{\lambda}$$

$$\varphi_{21} dv_1 + \varphi_{22} dv_2 + \varphi_{23} dv_3 + \frac{\varphi_2}{\lambda} d\lambda = \frac{dw_2}{\lambda}$$

$$\varphi_{31} dv_1 + \varphi_{32} dv_2 + \varphi_{33} dv_3 + \frac{\varphi_3}{\lambda} d\lambda = \frac{dw_3}{\lambda}$$

$$\varphi_1 dv_1 + \varphi_2 dv_2 + \varphi_3 dv_3 + 0 = dx$$

Restate in matrix form:

$$\begin{bmatrix} \varphi_{11} & \varphi_{12} & \varphi_{13} & \frac{\varphi_1}{\lambda} \\ \varphi_{21} & \varphi_{22} & \varphi_{23} & \frac{\varphi_2}{\lambda} \\ \varphi_{31} & \varphi_{32} & \varphi_{33} & \frac{\varphi_3}{\lambda} \\ \varphi_1 & \varphi_2 & \varphi_3 & 0 \end{bmatrix} \begin{bmatrix} dv_1 \\ dv_2 \\ dv_3 \\ d\lambda \end{bmatrix} = \begin{bmatrix} \frac{dw_1}{\lambda} \\ \frac{dw_2}{\lambda} \\ \frac{dw_3}{\lambda} \\ dx \end{bmatrix}$$

Solve for $d\lambda$

$$d\lambda = \frac{1}{\lambda}\left[dw_1 \frac{\Delta_{1,4}}{\Delta} + dw_1 \frac{\Delta_{2,4}}{\Delta} + dw_1 \frac{\Delta_{3,4}}{\Delta}\right] + dx \frac{\Delta_{4,4}}{\Delta}$$

Samuelson provides special cases shown in (A.9) and (A.10).

$$d\lambda = dw_1 \frac{\partial\lambda}{\partial w_1} + dw_2 \frac{\partial\lambda}{\partial w_2} + dw_3 \frac{\partial\lambda}{\partial w_3} + dx \frac{\partial\lambda}{\partial x} \qquad \text{(A.11)}$$

A change in w_i, changes λ by the share of $w_i v_i$ in total production value (px) where p is the market price of x. Assume $\partial\lambda/\partial x = 0$.

As demand is generated for an additional output (x), the existing constraint ($\bar{x}$) prevents additional production with existing resources $(v_i \ldots \ldots \ldots . v_n)$. To minimize cost and maintain profitability, λ must rise as adjustment occurs until production returns to the fixed rate. The increase reflects systems working at greater than capacity incurring incremental wear and tear on equipment and structures, worker's exhaustion and stress, and forgone future opportunities while meeting current demand. Conversely, a falloff in demand requires a decrease in λ until output returns to the fixed rate.

λ is the "shadow price" which provides a measure of value in opportunities foregone as resource allocation decisions are made, reflecting the willingness to pay in terms of market goods.

Appendix B

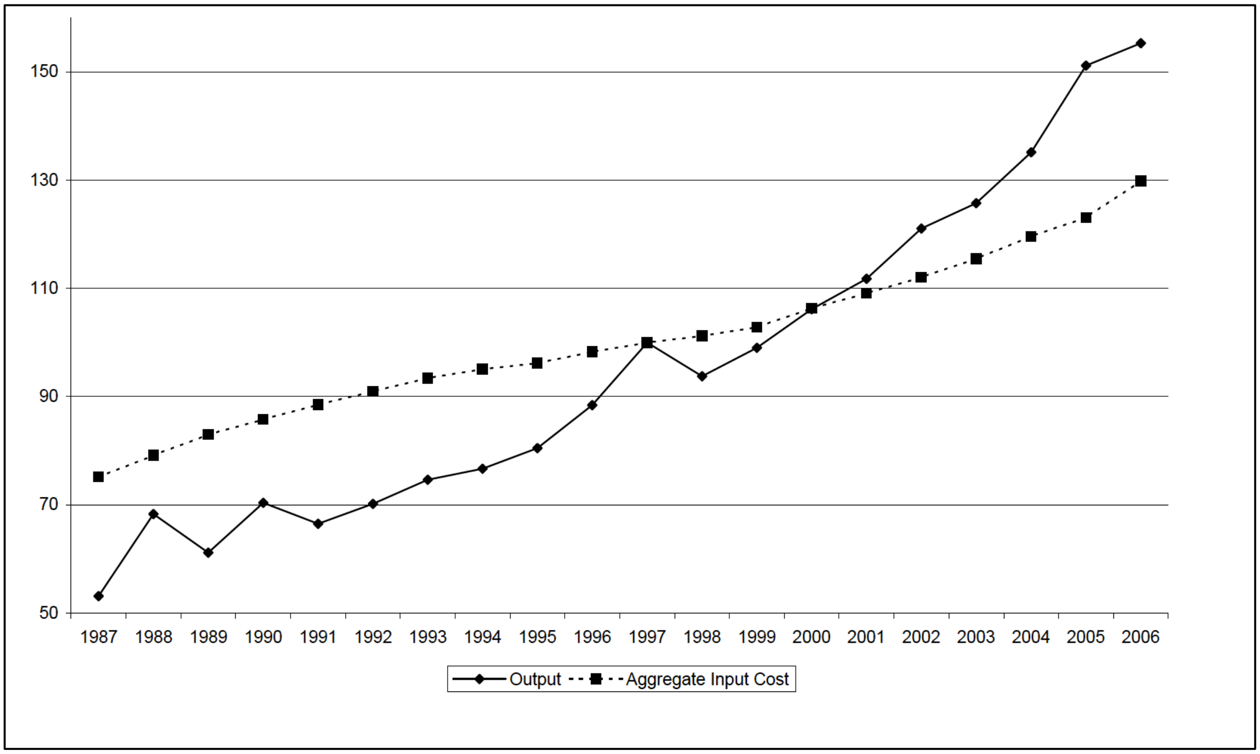
The Scientific R&D Services Sector

Analogous to the interaction between the software development sector and the software producing sector, Copeland and Fixler (2009) develop a framework for a view that the scientific R&D services sector provides for internally provided R&D activity. It is the use of a market facing sector to develop an understanding of how an internal organizational function is likely influenced by an external sector. Not only is the scientific R&D sector market facing, but knowledge is defused, and then absorbed, and skilled workers move from sector to sector. Much like the software development sector, the scientific R&D services sector provides innovation to the broader business sector, providing a means to discover both R&D services productivity and prices. Copeland and Fixler suggest that unlike industries such as pharmaceutical or semiconductor manufacturing, where R&D is undertaken largely internally, scientific R&D services "provide a clean look at the production of innovation" (Page 1). Over the period 1987 to 2006, Copeland and Fixler estimate labor productivity in the scientific R&D services sector increased at an average annual rate of 1.5%.

Based on a model of innovation, Copeland and Fixler (2009) develop a framework for constructing an R&D output price index. They assert that the price of innovation is equal to the expected discounted profit stream attributable to the adoption of the innovation. The estimates show R&D output prices increased at an annual average rate of 5.8% from 1987 to 2006. Using the R&D service firm's output price index, nominal scientific R&D services revenues are deflated and find that real revenues grew at an average rate of 2.6%. By contrast, the traditional input-price approach - largely R&D worker wage rate growth - shows a price increase of 2.9%. See Figure B.1. Price increases based on R&D worker wage rate growth fails to capture productivity gains and incremental R&D services firm's value creation.

By comparison, deflating total R&D nominal expenditures with two price indexes; the output-based price index for the portion of total R&D expenditures from scientific R&D services (25%) and an aggregate input-cost price index for the remainder of R&D expenditures (75%), Copeland and Fixler find that real total R&D expenditures grew at an average annual rate of 1.4% compared with 2.6% in published data. Using an aggregate input-cost price index understates R&D price growth for scientific R&D services and, thus, over states real growth. If the scientific R&D sector performance is representative of the functioning of the broader business R&D function, the 1.2 percentage point growth rate differential leads to substantial mismeasurement of R&D growth which would be weaker in real terms that reported. Such a finding is the reverse of the hypothesized issue in the software development space.

Figure B.1
Research and Development Price Indexes
1997 = 100



Source: Copeland and Fixler (2009)

Appendix C

Business Sector ICT Shadow Price and Software Developer Productivity

The assumed equality of software developer productivity in both the software developer sector and the software producing sector suggests a relationship between the business sector ICT function shadow price and the software developer sector price. By definition, the change in labor productivity (LP) equals the change output quantity minus the change in labor quantity while the change in output quantity equals the change in output value minus the change in the price.

$$\dot{LP}_{ICT,t} = \dot{Q}_{ICT,t} - \dot{L}_{ICT,t} = \dot{V}_{ICT,t} - \dot{P}_{ICT,t} - \dot{L}_{ICT,t}$$

$$\dot{LP}_{SS,t} = \dot{Q}_{SS,t} - \dot{L}_{SS,t} = \dot{V}_{SS,t} - \dot{P}_{SS,t} - \dot{L}_{SS,t}$$

where

$\dot{LP}_{ICT,t}$ and $\dot{LP}_{SS,t}$	Change in labor productivity (LP) in the business sector ICT function and the change in labor productivity in the software developer sector, respectively
$\dot{Q}_{ICT,t}$ and $\dot{Q}_{SS,t}$	Change in the quantity of output in the business sector ICT function and the change in the quantity of output in the software developer sector, respectively
$\dot{V}_{ICT,t}$ and $\dot{V}_{SS,t}$	Change in the nominal value of output in the business sector ICT function and the change in the nominal value of output in the software developer sector, respectively
$\dot{P}_{ICT,t}$ and $\dot{P}_{SS,t}$	Change in the shadow price of the business sector ICT function output and the change in the output price in the software developer sector, respectively
$\dot{L}_{ICT,t}$ and $\dot{L}_{SS,t}$	Change in labor services in the business sector ICT function and the change in labor services in the software developer sector, respectively

If $\dot{LP}_{ICT,t} = \dot{LP}_{SS,t}$, then

$$\dot{P}_{ICT,t} = \dot{P}_{ss,t} + (\dot{V}_{ICT,t} - \dot{V}_{SS,t}) + (\dot{L}_{SS,t} - \dot{L}_{ICT,t}) \qquad (\text{C.1})$$

In equation (C.1), it's obvious that if the change in the nominal value of output in both sectors is equal and if the change in labor services in both sectors is also equal, the change in the shadow price of the business sector ICT function output equals the change in the output price in the software developer sector. Further, if data for the right-side variables are available, estimating the business sector ICT function shadow price would be the change in the software development sector output price, as adjusted for differences in changes in the nominal value of output and labor services in each sector.

However, because of the unique requirements that the business sector ICT function faces, there is no external market for the software delivered by the ICT function and $\dot{V}_{ICT,t}$ is unknown. To be sure there are consulting and implementation services as well as a range of other external service offering, but except for a limited set of circumstances, the software delivered by the ICT function cannot generally be purchased and readied for deployment as a result of a competitive market transaction. Thus, value of $\dot{V}_{ICT,t}$ cannot be determined.

Appendix D

Data Sources and Assumptions

Figure D.1
Developer Productivity Data Sources

Concept	Data Element	Components	Source
Output	Chained Dollar Gross Output (Millions of 2012 Dollars)	5112 Software Publishers 5182 Data Processing, Hosting, and Related Services 5415 Computer Systems Design and Related Services	BEA
Employment	Number of Employees	15-0000 Computer and Mathematics Occupations 15-1250 Software Developers, Programmers, and Testers 15-1256 Software Systems and Application Developers	BLS OEWS

Figure D.2
Multifactor Productivity and Price Equation Data Sources

Concept	Data Items	Source	Years
Communications Equipment Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Computer Equipment Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Cloud Computing Services	Real Cloud Services Gross Output	BEA Digital Economy Satellite Account	2005-2021
Cloud Computing Services	Cloud Services Price Index	Sichel (2019)	2003-2021
Software Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Open-Source Software Services	Open-Source Software % of Total	Murciano-Goroff, Zhuo and Greenstein (2021)	2000-2020
Other Capital Services	Real Compensation Rental Price	BEA Integrated Industry Production Account	1999 - 2021
Labor Services	Software Developer and Computer Operations Employment and Wages	BLS Occupation Employment and Wage Survey	2002-2021
Imports of Services	U.S. Trade in Services, by Type of Service Telecommunications, Computer, and Information (Millions of Dollars)	BEA Digital Economy Satellite Account	1999-2021
Imports of Services	PPI Telecommunications (PCU517) PPI Computer Services (PCU5112) PPI Data Procession (PCU5182)	BLS Producer Price Index	2007-2021

Figure D.3
Price Indexes

Data Element	Components	Index Type
Computing Services Prices	Computing Equipment Implicit Price Deflator Cloud Services Price Index	Tornqvist Index
Software Services Prices	Software Services Implicit Price Deflator * (1 – Open-Source %)	Weighted Index
Imports of Services Prices	PPI Telecommunications (PCU517) PPI Computer Services (PCU5112) PPI Data Procession (PCU5182)	Tornqvist Index

Figure D.4
Table of Assumptions

Concept	Assumption	Source
% of Developer Time for Maintenance	50%	BEA Chapter 6 (2019)
% of Other Capital Services to Support Business Sector ICT Function	1%	Author's Assumption
% of Software Applications Available for Open-Source Software Requirements	50%	Author's Assumption
% of Benefits in Total Compensation	31%	BLS Employment Cost Index

Appendix E

Resources and Prices

E.1. Computing and Communications Usage and Prices

Capital services and the associated rental prices are available from the BEA's Integrated Industry-Level Production Account. Nominal and real compensation by type of capital are reported and rental price deflators, which is the user cost of capital, are calculated. Capital rental rates are the prices that users incur to acquire services from the capital stock.

Figure 11 shows the rental price deflator and the share of total ICT spending for communications equipment capital services. The rental price fell 8.3% CAGR from 2007 to 2020 while the share of communication equipment services in total ICT spending rose by 4.4 percent points (ppts) from 14.0% to 18.4%.

Business sector ICT organizations have the option of acquiring computing and storage services from on-premise equipment or, as a substitute, from a cloud service provided by a third-party vendor. For on-premise computing and storage, the on-premise capital equipment provides a service and a rental rate provides a price.

By contrast, cloud computing is a service sold at a market price. A third party – for example Amazon, Google, Microsoft - has acquired, deployed, and maintains the computing and storage equipment capital stock and incurs a rental rate as the cost of doing so. The user – in this case the ICT function – consumes the service and pays a market price. The contrasting computing and storage models provides similar services at competing prices. The center of computing activity is the hyperscale cloud data center. Housing the most mission critical network equipment and systems, cloud data centers specialize in collecting, processing, storing, and sharing data.[22]

Figure 12 shows, with data from the BEA's Digital Economy Satellite Account, cloud usage increased from one percent of total computing and storage services in 2005 to 40% in 2020.[23] The increased usage of cloud services has not only altered the business sector computing and storage model, but it has also impacted the trend in the prices. As is well known, improvements in semiconductor technology over six decades have resulted in a continued decline in computing costs. The challenge has been, and will likely

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[22] Cloud computing capability is also supplemented with edge computing. New technologies, such as autonomous vehicles, generate massive data volumes, require low latency, and must provide near-real time response. Edge servers can be considered within the boundaries of the cloud data center segment.

[23] Amazon Web Services was launched in March 2006 and Microsoft Azure was launched in February 2010. Prior to the launch of these services, "cloud computing" was provided by traditional mainframe computer service. https://www.bea.gov/data/special-topics/digital-economy

remain, quality improvements and the needed price adjustments capturing improvements.[24] However, Figure 13 suggests that with the introduction of cloud services in 2006, the rental price of on-premise computing declined at an annual rate of 7.5% between 2006 and 2012 with little change in cloud computing transaction prices.[25] Over the period, 2016 to 2020, the rental price of on-premise computing declined at an annual rate of 10.7% while the transaction price of cloud computing and storage services declined at an annual rate of 5.4%.

Figure 14 shows that share of ICT spending for computing and storage rose from 11.3% in 2006 to 15.7% in 2012 but increased to only 16.0% in 2020. The increased use of cloud services over the period, apparently, slowed computing and storage spending relative to spending for other ICT resources. The figure also shows the computing price index, including the prices of both computing equipment capital services and cloud computing, fell at an annual rate of 6.6% between 2006 and 2012 but slowed to a decline of 1.4% over the subsequent eight years.[26] The adoption of cloud services for a wider set of applications between 2012 and 2020 resulted in much slower price declines.[27]

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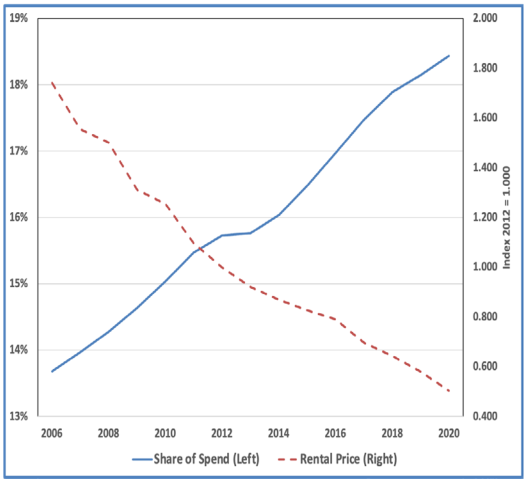
[24] See: Cole, R., Y. C. Chen, J. A. Barquin-Stolleman, E. Dulberger, N. Helvacian, and J. H. Hodge (1986). "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment", *Survey of Current Business*, 66, pp. 41-50.

[25] Cloud services output (NAICS 5182) is deflated by BEA with Producer Price Index software prices (NAICS 5182). In the upcoming 2023 Comprehensive Update of the NIPAs, cloud service specific prices will be introduced to deflate cloud services. Wu et. al. (2021) estimate a hedonic pricing model for Amazon Web Services, estimating an average annual cloud services price decline of 20.0% between 2008 and 2017.

[26] Tornqvist indexes are used for compute capital services and cloud service price indexes. See Figure 14.

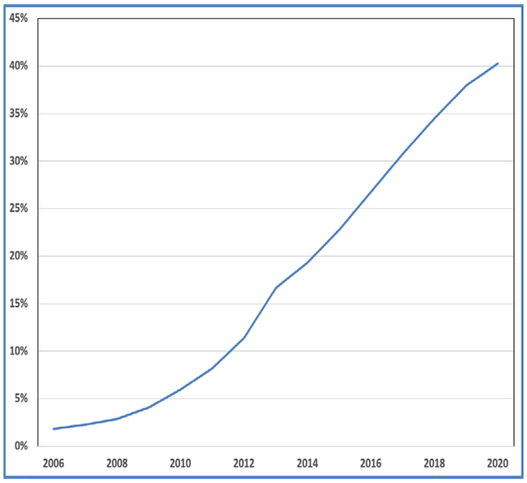
[27] The rental price index for other capital e.g. office and computing facilities, rose 2.2% CAGR from 2006 to 2019 and fell by 6.8% in 2020. Not surprisingly, the share of other capital services fell by 4.4 ppts from 8.1% to 3.7% over the 2006 to 2020 period. From the BEA Integrated Industry-Level Production Account, 1% of other capital services are assumed to support, the ICT function.

Figure E.1
Communications Equipment Capital Services
Rental Price Deflator and Share of Spend



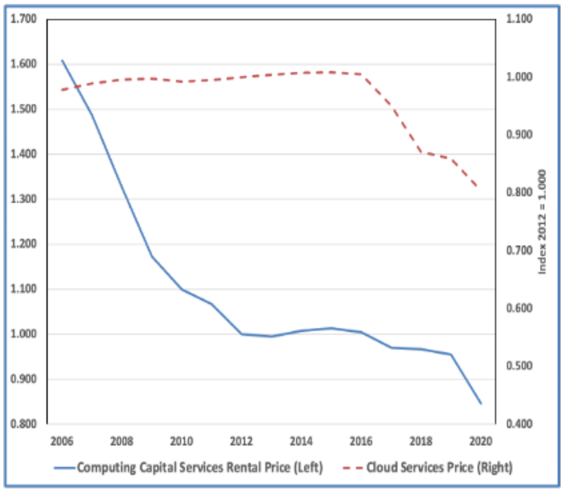
Source: Author's Calculations and BEA Integrated Industry-Level Production Account

Figure E.2
Cloud Computing and Storage Percent of Computing Services



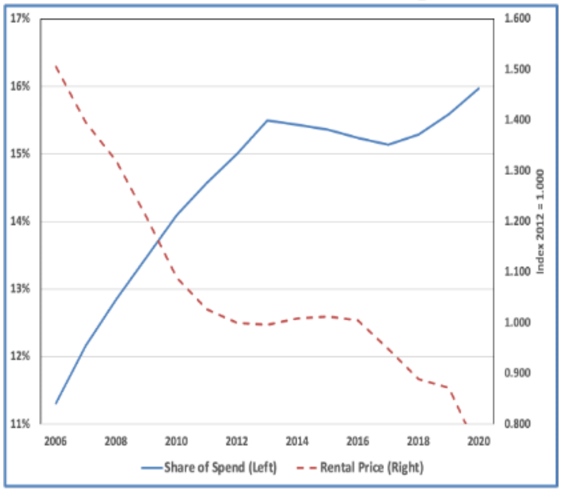
Source: Author's Calculations and BEA Digital Economy Satellite Account

Figure E.3
Computing and Storage Services
Price Index 2012 = 1.00



Source: Author's Calculations and BEA Digital Economy Satellite Account

Figure E.4
Computer and Storage Equipment Capital and Cloud Services
Price Index and Share of Spend



Source: Author's Calculations and BEA Integrated Industry-Level Production Account.

E.2. Software Usage and Prices

Like the transformation of computing and storage, the means by which software is acquired, deployed, and used has also experienced two decades of transformation. Not only has software-as-a-service taken on increased importance, but open-source software has taken on an expanded role as well. The critical nuance in the economics of open-source software is that while there is no price attached to an open-source license, its increased usage reduces the usage of software licensed for a fee and software-as-a-service. The result is a reduction in the weighted average software price. A larger proportion of the required functionality is available at a zero price. Further, despite its zero price, developer services are still required in the software deployment process.

Figure 15 shows the change in the quality adjusted capital stock of web server software, a representative category of open-source software. Murciano-Goroff, Zhuo, and Greenstein (MZG 2021) have built an extensive database of U.S. web server use between 2001 and 2018.

MZG find that the omission of economic value created by open-source web server software is over $4.5B of mismeasured server software across organizations in the U.S. MZG calculate the quality adjusted capital stock of web server software. For value calculation, capital services are assumed proportional to the stock and Microsoft price reflects market value. Figure 16 shows open-source web-server software grows to nearly 75% of usage among applications with open-source options. For shadow price calculation, 50% of software applications are assumed to be possible candidates for open-source substitution and web-server software is assumed to be representative of the broad class of open source software.

Bringing together software capital services spending and open-source software, Figure 17 shows software spending increased from 48.7% of total sending in 2006 to 49.2% in 2019 – a 0.5 ppt increase – with the imputed value of the open-source applications offsetting the proportionate decline in license and as-a-service software. Software remains the largest factor input in the business sector ICT production function. Over the 2006 to 2020 period, the weighted average software price fell by 5.5% CAGR.[28]

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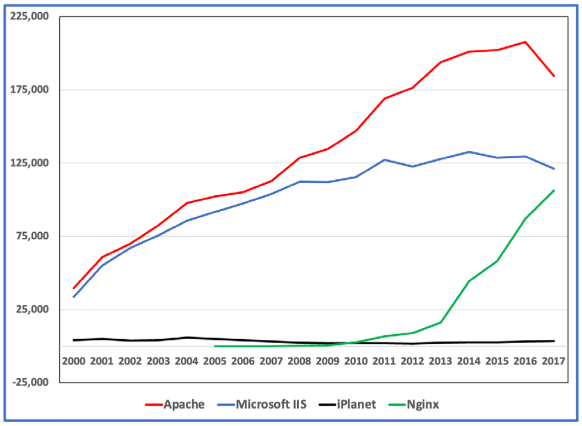
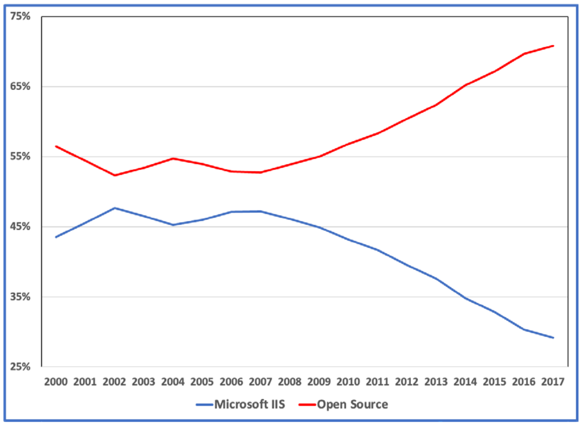
[28] BEA data sources do not yet provide separate spending estimates for software-as-a-service and software licensing for capital services. With a zero price, the price of open-source software does not enter the software price index shown in Figure 17. The Tornqvist index is not used because it would require taking the log of zero. See Freeman Inklaar, and Diewert (2021, p. 2.) The Figure 17 index is weighted by one minus the percent of open-source software.

Figure E.5
Web Server Software
Quality Adjusted Capital Stock



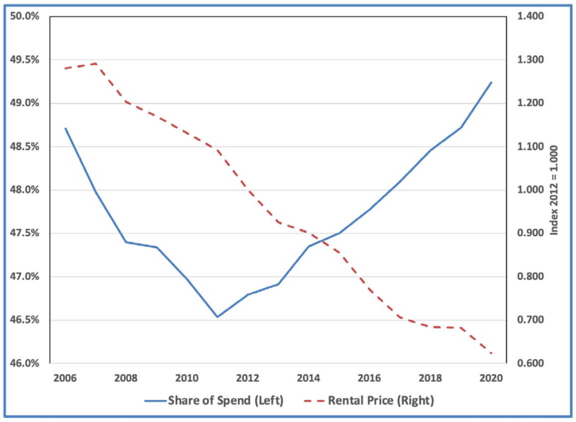
Source: Author's Calculations and Murciano-Goroff, Ran and Greenstein (2021).

Figure E.6
Web Server Software
License and Open Source % of Total



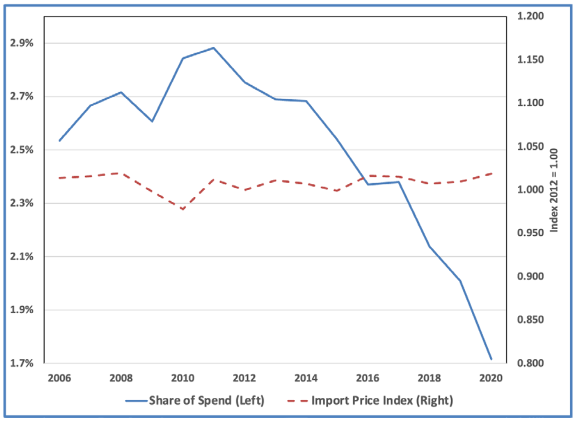
Source: Author's Calculations and Murciano-Goroff, Ran and Greenstein (2021).

Figure E.7
Software Capital and Open-Source Services
Rental Price Deflator



Source: Author's Calculations and BEA Integrated Industry-Level Production Account

Figure E.8
Imported ICT Services % of Total Spend
And Imported Services Price Index



Source: Author's Calculations and BLS Occupational Employment and Wage Survey

E.3. Imports of Services

The third transformation experienced by the ICT function is the increased of non-U.S. labor, often located in eastern Europe, India, and other Asian nations. Outsourcing tasks, and consequently importing services, appears to be widespread. ICT function activities are the most typically outsourced with 92% of North American firms engaged in outsourcing to some extent in 2019 (See Boskamp 2023).[29] The high proportion of outsourcing firms suggests such activity is not limited to multi-national enterprises or large U.S. enterprises. Di Gregorio, Musteen and Thomas (2009) find that offshore outsourcing of administrative and technical services by small and medium enterprises is associated with greater extent and scope of international sales. Asatiani, Penttinen and Kumar (2019) survey Finish small and medium enterprises finding cost reduction, a focus on core competence, and business process improvements are all associated with a higher degree of outsourcing.

With data from BEA's international services estimates, trade in ICT services, rose marginally between 2006 and 2011. See Figure 18. However, the share of imported services fell after 2011. In real terms, imported telecommunications, computer, and data processing services grew at a CAGR of 9.8% between 2006 and 2011. However, after 2011 growth slowed to a CAGR of 4.3% to 2020. As shown in Figure 19, computer services - end-user licenses and customization of software; cloud computing and data storage services; consulting and implementation services; and facilities management services; and data recovery services – constitute the bulk of imported services with growth slowing substantially over the past decade. As shown in Figure 18, there has been little change in import prices over the 2006 to 2020 period.

E.4. Labor Services and Wages

Figure 20 shows domestic labor services with hourly wages and benefits rising from $43 in 2006 to nearly $60 in 2020 while the share of spending for domestic labor services fell from 15.2% in 2006 to 10.9% in 2020. Over the entire 2006 to 2020 period, real spending for domestic labor service rose at a CAGR of 5.1% while real spending in imported services rose at a CAGR of 4.7%.

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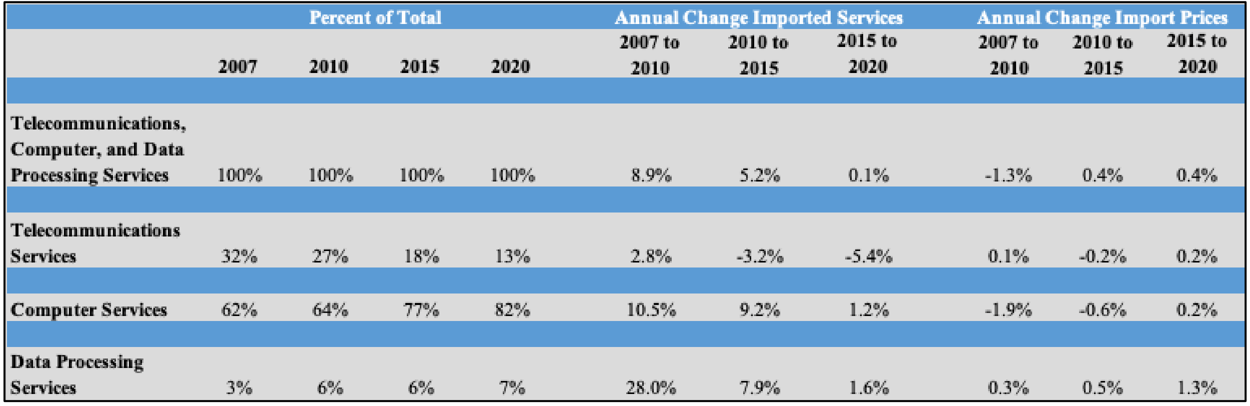
[29] In the first quarter of 2022, there were 5.4 million U.S. firms with fewer than 100 employees and 128,000 firms with more than 100 or more employees. https://www.bls.gov/cew/classifications/size/size-data-info.htm

Figure E.9
Telecommunications, Computer, and Data Processing Imported Services
(Billions of 2012 Dollars)



	Percent of Total				Annual Change Imported Services			Annual Change Import Prices		
	2007	2010	2015	2020	2007 to 2010	2010 to 2015	2015 to 2020	2007 to 2010	2010 to 2015	2015 to 2020
Telecommunications, Computer, and Data Processing Services	100%	100%	100%	100%	8.9%	5.2%	0.1%	-1.3%	0.4%	0.4%
Telecommunications Services	32%	27%	18%	13%	2.8%	-3.2%	-5.4%	0.1%	-0.2%	0.2%
Computer Services	62%	64%	77%	82%	10.5%	9.2%	1.2%	-1.9%	-0.6%	0.2%
Data Processing Services	3%	6%	6%	7%	28.0%	7.9%	1.6%	0.3%	0.5%	1.3%

Source: Author's Calculations and BES Imports of Services and BLS PPI.