The Rise of Cloud Computing: Minding Your P's and Q's

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1. Introduction

A transformation is underway that is revolutionizing the way computing services are provided to businesses, households, and the government. This new way of accessing computing services—typically referred to as "the cloud" or "cloud computing"—represents the latest transition to a new computing platform in which computing is done on a network of off-site computing resources accessed through the Internet.[1] As this paper shows, the changes are extraordinary and likely will have important consequences for the structure of the economy, productivity growth, and economic measurement. Yet, because the advent of these services is relatively recent, and because they largely are intermediate business inputs rather than final demand, their imprint on the economy is difficult to identify in official statistics.

Byrne and Corrado (2017a) assessed the macroeconomic impact of the shift to cloud computing and concluded that the productivity-enhancing impacts of the shift to cloud computing were not yet particularly evident in macroeconomic data—even after taking major steps to improve the measurement of ICT asset prices (Byrne and Corrado, 2017b) whose prices should be indicative of cloud services prices.[2] This paper builds on their work by developing measures to quantify the prices and quantities relevant for understanding the U.S. cloud services industry —the Ps and Qs of the title.

Our basic finding is that prices for cloud services have fallen rapidly and that the use of the cloud has grown tremendously as has the related infrastructure of IT equipment

[1] The notion of technological change in computing as a platform shift was introduced by Bresnahan and Greenstein (1999), who analyzed the disruptive effects of the introduction of PC/client-server platform on the computer industry.

[2] Other first order macroeconomic impacts of the shift to cloud computing include (1) a weakening in the demand for IT equipment for a given volume of ICT services, (2) a lowering of the cost of supplying a given volume of ICT services (e.g., power consumption costs), and (3) an increase in the productivity of software development.

and software. For our analysis of prices, we assembled a unique data set with quarterly data on prices and characteristics for cloud services offered by three large providers for as long as they have posted prices on the Internet: Amazon Web Services (AWS), Microsoft, and Google. The data for AWS begin in the first quarter of 2009. For each of these providers, the data cover their basic compute, database, and storage products.

For AWS, the price for their compute product fell at an average rate of about 7 percent during 2000-2016. Price declines were slower before 2014 and more rapid starting in the beginning of 2014. Interestingly, 2014 is the year when Microsoft and Google began posting prices for their cloud offerings on the Internet. We suspect that AWS' large price declines were a response to that change in the competitive environment. For AWS' database product, prices fell at an average rate of more than 11 percent during 2009-16. Here too, prices fell relatively modestly until the beginning of 2014, after which they fell at an average rate of more that 22 percent through the end of 2016. AWS' storage product followed a similar pattern, with prices falling at an average annual rate of about 17 percent during 2009-2016 and even faster declines starting in 2014. [The next version of this paper will include results for Microsoft and Google as well.]

We also use a variety of metrics to highlight the extremely rapid growth of the cloud and of capital expenditures by large providers of cloud services. The extremely rapid growth of these capital expenditures raises a puzzle. Why has investment in IT equipment in the NIPAs been so weak if large and important firms are rapidly expanding their capital expenditures for this equipment? In part, this tension could reflect, as noted by Byrne and Corrado, higher utilization of this equipment at cloud providers than at individual businesses that had deployed this equipment previously. That higher utilization would imply less demand for IT equipment for a given demand for computing services. But, there is another possibility: cloud providers appear to be assembling IT equipment on an own-account basis. We believe that this own-account investment should be included in the figures for business investment in IT, and we present some back-of-the-envelope numbers suggesting that this own-account investment is large. Our calculation suggests that, if this own-account investment were included in business IT investment, then the growth rate of real investment in IT equipment and software during 2005-2015 would have averaged a little more than 1 percentage point higher, and real GDP average annual growth would have been about half a tenth higher.[3]

The paper is organized as follows. Section 2 defines cloud computing and provides nomenclature for describing different cloud service products. This section also discusses the key technologies underlying cloud infrastructure. Section 3 describes our new price indexes for cloud computing services, including the data, methodology, and results. Section 4 uses several different metrics to demonstrate the exceptionally rapid growth of cloud computing and the associated infrastructure. We also highlight the puzzle described above concerning IT capital investment. [The next version of this paper will include a discussion of where cloud fits in the NIPAs and how the statistical agencies could improve coverage of the cloud.]

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[3] The level of nominal GDP in 2015 would have been $117 billion higher if our estimate of own-account investment in IT equipment were included.

2. What is cloud computing?

Because cloud computing is so new and has not been studied extensively by economists, we begin with some basic definitions and nomenclature. In particular, we start with the definition developed by the National Institute of Standards (NIST), then discuss the range of cloud services available, and finally turns to a brief review of key technologies underlying the development of cloud computing.

2.1 The NIST Definition of Cloud computing

A definition of cloud computing was created by the National Institute of Standards and Technology (NIST) in November 2009 and, after consultations with many industry and government experts and stakeholders, published in final form in September 2011 (Mell and Grance, 2011). Their definition remains relevant and makes more concrete and complete the brief definition given above. After noting that cloud computing is an evolving paradigm, NIST states:

> 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 of service provider interaction.

NIST describes the following types of clouds:

- *Private cloud* (a cloud infrastructure provisioned for a single organization or specific community of organizations; it may exist on or off premises)[4]
- *Public cloud* (a cloud infrastructure provisioned for open use by the public; it exists on the premises of the cloud provider)
- *Hybrid cloud* (a combination of the above bound together by standardized or proprietary technology that enables data and application portability).

[4] The NIST "community cloud" deployment model is grouped with the "private cloud" model for ease of exposition.

Finally, NIST provides a concise description of the infrastructure that underlies the cloud as:

> the collection of hardware and software that enables the five essential characteristics of cloud computing. The cloud infrastructure can be viewed as containing both a physical layer and an abstraction layer. The physical layer consists of the hardware resources that are necessary to support the cloud services being provided, and typically includes server, storage and network components. *The abstraction layer consists of the software deployed across the physical layer, which manifests the essential cloud characteristics.* Conceptually the abstraction layer sits above the physical layer. [Italics our own, Mell and Grance (2011, page 2.)

2.3 Cloud products

The NIST cloud computing definition also includes a description of service models, or service offerings. In statistical nomenclature, these services correspond to "product types" or product classes. These product classes include:

- Infrastructure as a service (IaaS)
- Platform as a service (PaaS)
- Software as a service (SaaS)

with each described more fully in the box. As discussed below and in the box, we would add Function as a Service (FaaS) to NIST's list.

Definition of Cloud Service Products

IaaS—provides computer processing, storage, networks, and other fundamental computing resources, where the consumer can deploy and run arbitrary software, including operating systems as well as applications. *The consumer neither manages nor controls the underlying cloud infrastructure but has control over operating systems, storage, and deployed applications, and possibly some control of select networking components.*

PaaS—provides ability to deploy consumer-created applications created using programming languages, libraries, services, and tools. *The consumer neither manages nor controls the underlying cloud infrastructure including network, servers, operating systems, or storage but has control over the deployed applications.*

Serverless also known as FaaS or Function as a Service—provides the capability of deploying functions (code) on a cloud infrastructure. *The consumer (who would be a software developer) no longer manages nor controls the underlying cloud infrastructure including network, servers, operating systems, storage, or the computing program.* An Application Program Interface (API) gateway controls all aspects of execution.

SaaS—provides the capability of running providers' applications on a cloud infrastructure. The applications are accessible from various client devices through either a thin-client interface (e.g., web browser) or a program interface. *The consumer neither manages nor controls the underlying cloud infrastructure including network, servers, operating systems, storage, or even individual application capabilities, apart from limited user-specific application configuration settings.*

Sources: Authors' update of NIST service models. See also Cohen (2017) and Avram (2016)

This collection of product types often is referred to as the cloud "stack," and the earlier point about a layer of abstraction lying across the physical layer becomes important for understanding the relationship among these products. As one moves up the stack from IaaS to PaaS and so on, the level of abstraction increases, in the sense that the final user can abstract from (or ignore) more and more of the underlying infrastructure. As highlighted by the italicized sentences in the box, for IaaS, the user still needs to think about operating systems, storage, and other computing resources. For PaaS, the final user needs to think only about the deployed application and can abstract from (or largely ignore) other aspects of the infrastructure.

Since the NIST definition was published, the industry has introduced a new layer of abstraction, called "serverless" or Function as a Service. At this level of abstraction, the final user only needs to think about functions or code that are to be performed and the cloud services provider manages all other aspects of the infrastructure. Serverless can be regarded as sitting above PaaS in the NIST stack, although it may also be regarded as a refined PaaS service, as in the box.

As a final point about nomenclature for cloud service products, we connect this discussion to the state of computing pre-cloud by noting the role of traditional data centers. By using a data center, the final user could abstract from the physical hosting environment, a lower level of abstraction than in any of the cloud services described in the box.

The growth of cloud computing has its roots, at least in part, in the competitive advantage the cloud offers customers in terms of cost, flexibility, and scalability. At the same time, the growth and popularity of the technology also reflects how the layers of abstraction in its products (especially the distinction between PaaS and SaaS) serve distinct classes of customers.

Recent developments in the cloud that facilitate the work of software developers could be particularly significant and could, in time, have important macroeconomic consequences. As cloud vendors adapt technologies that enable them to develop products "higher up the stack" and offer services with greater abstractions, the work of software development is simplified. Thus, although all classes of customers benefit from the move to greater abstraction in the technologies deployed, the benefits enjoyed by software product developers are especially significant. As a specific example, the movement to serverless services with Amazon's 2014 release of the Lambda computing platform has enabled developers to focus only on code and its rapid deployment. This has lowered costs of new software product development among providers of software products for final sale (via SaaS or regular licensing) as well as for applications developed for use within a developer's own firm (or custom-developed for use within a given firm).

Thus far, we have barely discussed Software as a Service (SaaS). In the usual nomenclature SaaS products sit on the top of the stack. However, we believe that SaaS is best understood as a category of software product services (albeit complex) rather than cloud services per se. SaaS products are usually supplied with transactional metering—that is, not as a collection of elastically provisioned services per the NIST definition. Thus, SaaS products may thus be equally regarded as software products sold via an on-line subscription business model—a business model whose use has grown in the digital economy.[5] [6] Accordingly, the prices and quantities we study as cloud computing in the remainder of this paper exclude SaaS products.

2.3 Cloud technologies

The cloud platform relies on a suite of technologies—mainly virtualization, grid computing, and micro-services architectures—but also everything that makes high-speed

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

[6] As reported by Rackspace, a respected IaaS provider, "In recent years there has been a move by traditional software vendors to market solutions as Cloud Computing which are generally accepted to not fall within the definition of true Cloud Computing." Rackspace goes on to describe SaaS as "software delivered over the web," which is precisely our point. Technically, some SaaS products satisfy the NIST definition of cloud, e.g., the Salesforce Customer Relationship Management (CRM) product, but many others, including other CRM products, do not. See https://support.rackspace.com/white-paper/understanding-the-cloud-computing-stack-saas-paas-iaas/ (accessed February 25, 2017).

broadband possible. Arguably, IT history is at the point where the tagline Sun Microsystems coined in the early 1990s, "The Network is the Computer," is finally right.[7] The network is no longer a mere bridge between autonomous nodes on independent missions and prone to choke points (as in provision of transport). The continuous increase in network capacity, along with a near disappearance of limitations that could choke traffic in an earlier era (hardline security policies, storage performance issues, last-mile WAN hindrances), are the foundation of this latest platform shift in computing.

Behind a virtual machine host on a network of today, computing resources—storage, memory, networking, and CPUs—are physically distributed and managed via processing queues. Long before enterprises began moving onto the cloud, mainframes and servers were virtualized, and an essential element of computing focused on the function of processing queues. With cloud computing, some resource queue end-points are moved offsite, and more than ever, computing resource acquisition and allocation becomes the central task of cloud providers. One can be far more technical about the transformation of computing as it has undergone virtualization and moved to a cloud platform, but it is hard to be more prosaic than the old Sun tagline.

Cloud vendors have made increasing use of virtualization and grid computing to elastically supply information-processing services since the advent of the millennium, with the growth in capacity especially rapid since 2006 when Amazon Web Services opened its doors. The virtualization technology that is the primary enabler of cloud computing has been in commercial use since the 1970s via IBM mainframes. Modern IBM mainframes (circa the System/390 introduced in 1990 and renamed *zSeries* in 2000)

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[7] The Sun Microsystems tagline is attributed to John Gage (Reiss, 1996). The discussion in this paragraph draws from Hubbard (2014). [maybe others once final]

are exceptionally adept at handling large, diverse and varying workloads and remain in use today, though they have lost much force in the large datacenter market with the rise in cloud computing (Byrne and Corrado, 2017b). Grid computing is applying the resources of many computers in a network to a single problem at the same time; the technology was first used in 1989 to link supercomputers and thereafter grew and evolved along with the Internet (De Roure et al., 2003).

"Containers" are another new cloud technology. Containers—a scalable form of virtualization technology—allow users to run and deploy applications without launching a new virtual machine for each application, with the aim to speed software application development, deployment, and scalability, thereby boosting productivity of software developers. In terms of enterprise applications outside of Silicon Valley, it is very early in the application of containers. Indeed, the technology generally was not widely understood outside cloud vendors until the release of open source LINUX formats (Docker 1.0) in March 2013. Docker transformed container technology to a product for enterprise use. The consultancy IDC estimated that in 2014 only 1 percent of enterprise applications are running on containers that can readily be scaled, but reportedly growth in Docker adoption has been very rapid since then.[8]

One final point of history, connecting this discussion to the earlier use of commercial time-sharing services. These services were an important part of the computing environment in its earliest days. There was a period of frantic growth (1955-1965), after which the industry flourished for another 20 years due to a competitive advantage that "arose from the nonlinear relationship between total operating costs and

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[8] See "8 Surprising Facts about real Docker Adoption", originally published October 2015 and last updated June 2016 at https://www.datadoghq.com/docker-adoption/ [accessed February 25, 2017].

performance—the larger the time-sharing system, the lower the per-user cost" (Campbell-Kelly and Garcia-Swartz, 2008, page 27). Commercial time-sharing services underwent a complete industrial boom-to-bust cycle, i.e., like typewriters and punched card machines, after the advent of the PC.[9]

3. Prices of Cloud Computing Services

Outside of sporadic media reports, relatively little is known about the prices of cloud computing services. This paper develops new price indexes for three basic products provided by three of the leading providers of cloud services.

Data

We collected prices on a quarterly basis from Amazon Web Services (AWS), Microsoft Azure, and Google Cloud. [For this version of the paper, we only report prices for AWS products. Results for Microsoft and Google were too preliminary for us to report with confidence at this point.] We collected prices for each provider when they began posting prices on the internet, with the earliest prices from 2009. To collect historical prices, we used the Web Archive (also known as the WayBack Machine) to pull posted prices from web pages as they appeared in prior periods. Table 1 summarizes for each provider the products for which we collected prices and the time period for which prices were available. For each provider, we selected a compute product (renting virtual machines), a selection of database products that offer SQL as well as other database software, and a range of disk storage products.

[9] According to Campbell-Kelly and Garcia-Swartz (2008), the market for time-sharing existed because it was the only means at that time of providing a personal computing experience at a reasonable cost. They also present econometric evidence showing that the growth of time-sharing services in its hey-day had an impact of slowing down the growth of mainframe computer shipments; see their online appendix.

Of course, the services for which we gathered prices are just a subset of the wide array of services available from each provider, and they are at the lower end of the "stack" of cloud products described above. In particular, we place the compute and storage products in the IaaS category, and we place the database products at the boundary between IaaS and PaaS. That said, these compute, database, and storage services are key foundational elements on which many of the services that are higher in the stack are based. Accordingly, we believe that the compute, database, and storage products considered in this paper provide a very useful and broadly representative sample of available cloud services.

AWS has been the market leader and has posted prices on the Internet since 2009. Microsoft began posting prices in early 2014 and Google began posting prices in late 2014.

We note one important limitation of our data. We obtained data on prices and product characteristics but not on quantities because AWS, Microsoft, and Google do not make product-level sales information readily available. We are also unaware of private sources for this information.

Amazon Web Services (AWS)

AWS offers an amazing array of products. One common feature across all products is that customers choose among regions; that is, where the servers are located on which they are running applications and storing data. Currently, AWS offers four regions in the U.S., including Virginia, California, Oregon, and Ohio. (Amazon also offers many regions outside the United States.) For this paper we collected prices for Virginia, California, and Oregon. (The Ohio region was only introduced in October 2016.) For an

AWS customer, choosing a region that is geographically closer reduces latency, and some customers will store data in multiple regions for redundancy. Prices differ across regions, with prices in California generally higher than those in Virginia or Oregon. In general, the differences in prices across regions are in levels, while changes in prices tend to be very similar across regions.

Compute Product (EC2 – Elastic Compute Cloud). Using this product amounts to renting a virtual machine (PC or server) from AWS, and this product is priced in terms of dollars per hour. In AWS nomenclature, the use of a virtual machine is known as an "instance," and AWS offers instances in a wide range of configurations. During the span of our data from 2009 to 2016, AWS offered 55 different configurations of virtual machines. Each configuration has specified characteristics in terms of the power of the processor, the amount of RAM, and the amount of disk space allocated. In addition, customers can choose between Linux and Windows operating systems. For every available configuration, we collected prices as well as characteristics, and we have a total of 4,079 observations for EC2 prices. The characteristics are important, and we will use them to construct hedonic price indexes.

AWS offers several different pricing schemes for instances. For EC2, we collected data for only "on-demand" instances, which can be purchased at any time with no commitment. AWS also offers "reserved" instances, for which a customer pays in advance for a set volume of instances whether or not the instances are used. Prices of reserved instances are lower than those of on-demand instances. In addition, AWS runs a spot market for instances. Customers can bid for instances at a price of the customers' choosing. The customer will receive the instances if they are available, but will not receive them if some other customer offered to pay a higher price for available instances. Prices of spot instances also tend be below those of on-demand instances. Finally, AWS offers quantity discounts to heavier users.

Tracking prices for all of these different types of instances was beyond the scope of this paper. For the purpose of constructing price indexes, a key question is whether the price trends for on-demand instances differ in systematic ways from those of other types of instances. Our sense is that prices within these different pricing schemes tend to move together, but that remains an open question. That said, we suspect that *individual* customers experience price declines that are more rapid for a time than are the trends we estimate. In particular, as customers gain experience with AWS and migrate more applications to the cloud, we suspect that they increasingly shift toward reserved instances and avail themselves of quantity discounts. This shift toward lower-priced instances generates faster price declines during the shift than we estimate from tracking prices of on-demand instances. Of course, once a customer has finished the shift toward lower-priced instance types, the trend in prices experienced by that customer would be in line with the price trends that we estimate.

Our raw data for EC2 prices are plotted in figure 1. This figure plots AWS' posted prices for each instance type for the full time it is in the market, with a different colored line capturing each different instance type. In the figure, we show separate plots for each region and operating system pair with each column of graphs covering a region and each row covering an operating system. The graphs, plotted with a log scale, indicate that prices tend to follow downward step functions, with longish periods of no price change. It also is evident that AWS revamped its offering of instance types around the beginning of 2014, dropping most extant instance types and introducing new ones. Of course the graphs reflect no controls for characteristics or quality of the instances, and as shown below, it turns out that this revamping was associated with a large drop in quality-adjusted prices.

Database Product (RDS – Relational Database Service). Using this product amounts to renting database software along with a virtual machine (called an instance class) to run the software. It is priced in terms of dollars per hour. AWS offers several different database engines, including MySQL, SQL, SQL Standard, SQL Express, SQL Web, SQL Enterprise, PostgreSQL, Oracle, Aurora, and MariaDB. Some of these are open source while others are proprietary and require a license. For those requiring a license, AWS offers instances for which customers use their own license as well as instances for which AWS provides the license (for a higher price). AWS also offers several different instance classes with differences in the CPU power of the virtual machine, the amount of RAM, network performance, and whether the instance class is optimized for input-output to storage. For every available configuration, we collected prices as well as characteristics for on-demand instances. (AWS also offers reserved instances for its database product.) In total, we have 5,340 observations on RDS prices.

Our raw data for a selection of RDS prices are plotted in figure 2. This figure plots AWS' posted prices for each RDS instance type for the MySQL database software for the Virginia, California, and Oregon regions. Because of the multiplicity of types of database software, it is not feasible to plot all our data in a single figure. That said, the data in this figure are broadly representative of those for other regions and database software. The graphs are plotted with a log scale and show the same overall pattern as the EC2 price plots. Prices tend to follow downward step functions, with longish periods of no price change. As with EC2, AWS revamped its offerings around the beginning of 2014, dropping most extant instance types and introducing new ones.

Storage Product (S3 – Simple Storage Solution). Using this product amounts to renting hard disk space. It is priced in terms of $ per terabyte (TB).[10] The pricing scheme for S3 builds in volume discounts directly with pricing tiers. For example, customers pay one price for the first TB used, a lower price for the next 49 TB used, a still lower price for the next 50 TB used, and so on.[11] AWS also offers three different types of storage: “standard” allows immediate access to stored data; “infrequent” access is for longer-term storage and data can be retrieved only with a delay; and “glacier” storage has an even longer delay for retrieval. As with other AWS products, customers can choose among regions. We collected prices for all pricing tiers, all three types of storage, and the Virginia, California, and Oregon regions. In total, we have 445 observations on S3 prices.

Our raw data for S3 prices are plotted in figure 3. This figure plots AWS’ posted prices for each price tier for the full time it is in the market for each region and type of storage pair. (Each different price tier is represented by a different colored line.) In the figure, each column is for a region, and each row is for a different type of storage (standard, infrequent, and glacier).

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[10] A Terabyte of data is 1,014 Gigabytes. The prefix “tera” is from the Greek work for monster.
[11] The pricing tiers have changed over time. For example, early on price dropped after the first TB of data, while now pricing does not drop until after the first 50 TB of data. This change reflects the on-going decline in the price of storage.

Results

The new quality-adjusted price indexes presented here for EC2 (compute) and RDS (database) control for quality change are based on adjacent-quarter regressions. For S3 (storage), quality does not change appreciably because the product is just a TB of storage so we rely on matched-model indexes.

To explain our rationale for using adjacent-quarter regressions, we first describe a dummy-variable hedonic specification:[12]

$$\ln(P_{i,t}) = \alpha + \sum_k \beta_k X_{k,i,t} + \delta_t D_{i,t} + \varepsilon_{i,t} \qquad (1)$$

where $P_{i,t}$ is the price of a product in period t, $X_{k,i,t}$ is the value of characteristic k for that product in period t (measured in logs or levels, as appropriate), $D_{i,t}$ is a time dummy variable (fixed effect) that equals 1 if the price i is observed in period t and zero otherwise, and $\varepsilon_{i,t}$ is an error term.

A potential shortcoming of equation 1, highlighted by Pakes (2003) and Erickson and Pakes (2011), is that the coefficients on the characteristic are constrained to remain constant over the full sample period. Byrne, Oliner, and Sichel's (forthcoming) study on microprocessors used adjacent-year regression; here, we follow their setup but use adjacent-quarter regressions. [In the next version of the paper, we will estimate Fisher price indexes that are based on a sequence of quarterly cross-section regressions that allow the coefficients to change every quarter rather than every two quarters.]

To make things precise, we describe our adjacent-quarter procedure for EC2; the procedure for RDS is parallel. For EC2, we estimate the following regression for each two-quarter overlapping period:

[12] The language used here to describe adjacent-quarter regressions draws heavily from Byrne, Oliner, and Sichel (forthcoming).

$$\ln(P_{i,t}) = \alpha + \sum_k \beta_k X_{k,i,t} + \delta D_{2t} + \varepsilon_{i,t} \quad (2)$$

where $P_{i,t}$ is the price of EC2 instance of type i in quarter t and $X_{k,i,t}$ is k^{th} characteristic of instance i in quarter t. The dummy variable D_{2t} equals 1 if the price observation is for the second quarter of the two-quarter overlapping period and 0 otherwise.

To construct a price index from these sequences of regressions, we spliced together the percent changes implied by the estimated coefficients on the D_{2t} variables. All of the reported results are bias-adjusted to account for the transformation from log prices to a non-log price index.[13]

Because we do not have quantity data, the adjacent-quarter regressions are unweighted so that each observation receives an equal weight in the regression. This approach is an unfortunate limitation of not having quantity data.

EC2. For the adjacent-quarter regressions for EC2, the following characteristics entered as natural logs: *ECU* (AWS' designation of the power of the processor), *Mem* (the amount of memory in GB), and *Storage* (the amount of disk storage in GB).[14] The regressions also include the following fixed effects: *storSSD* (=1 if the disk storage is solid state), *pltfrm* (=1 if the processor is 64 bit, =0 if the processor is 32 bit), *System* (=1 if the system is Linux, =0 for Windows), *inO* (=1 if the price is for the Oregon region), and *inC* (=1 if the price is for the California region).

Results of these regressions are summarized in Table 2. Because of the number of adjacent-quarter regressions, the table summarizes the regression results, showing the minimum, maximum and median values of coefficient estimates across the regressions.

[13] Because the exponential function is nonlinear, the translation from the natural log of prices to price levels requires an adjustment in order to be unbiased. We apply the standard adjustment based on the estimated variance of the coefficient δ, as described in van Dalen and Bode (2004).
[14] In later periods, AWS began charging separately for disk storage for some instances. For these observations, *Storage* is set equal to zero.

In addition, of the 31 adjacent-quarter regressions, the table shows the fraction of the estimates for each coefficient that are significant at the 5 and 10 percent significance levels.

The coefficient on the dummy variable capturing quality-adjusted price change, *D2,* has a median value of zero, reflecting that prices are not changing in most quarters. The coefficient for the variable for processor power, *ECU* generally is positive and highly significant, as prices are higher for instances providing more processor power. The same pattern holds for the memory variable, *Mem.* The variable for disk storage is almost always significant though its sign often is negative. Among the fixed effects, solid-state disk storage, *StorSSD,* has relatively little effect on prices, while instances running with Linux, the *System* variable, are priced at a hefty discount to instances running with Windows (for which AWS would be paying a license fee). The coefficient on the fixed effect distinguishing between 32 and 64 bit processors (*pltfrm*) is quite variable across regressions and significant in about a third of the regressions. Prices in the Oregon region, captured by the *inO* variable, are little different from those in Virginia, while prices in the California region, the *inC* variable typically are more than 10 percent higher than prices in Virginia.

Table 3 reports the price indexes generated by these regressions, as well as the number of observations and adjusted-R^2 for each adjacent-quarter regression.[15] The adjusted-R^2s are quite high, indicating that the right-hand-side variables are capturing most of the sources of variation in prices. The price index is shown in the first column and percent changes at quarterly rates are reported in the second column. These figures highlight that prices do not change in most quarters. Price declines are large in some

[15] The price trends for EC2 are similar to those reported by Zhang (2016).

quarters, with the biggest drop in the first quarter of 2014, when AWS revamped its offerings of EC2 instances. Although not evident in the plots of posted prices in figure 1, the newly offered instances provided much higher quality at prices that were, on their face, roughly comparable to the posted prices of the old offerings of instances. Accordingly, the hedonic regressions identify a very large quality-adjusted price decline in that period.

All told, quality-adjusted prices for EC2 instances fall at an average *annual* rate of about 7 percent over the full sample. Interestingly, prices fell at an annual average rate of about 5 percent from the beginning of 2009 to the end of 2013. Then, in early 2014, just as Microsoft had entered the market to sufficient degree that they were posting their cloud prices on the Internet, AWS began cutting prices more rapidly. That started with the big price drop in early 2014, and over the period from the start of 2014 to the end of 2016, EC2 prices fell at an average annual rate of 10.5 percent.

RDS. For the adjacent-quarter regressions for RDS, the following characteristics entered as natural logs: *Vcpu* (AWS' designation of the power of the processor) and *Memory* (the amount of memory in GB. The regressions also include the variable *IOPerformance* which is a qualitative variable indicating whether the network performance is low, moderate, high, or very high. In addition, the regressions include the following fixed effects: *Provisioned IOPS optimized* (=1 if instance is optimized for input to and output from storage), *inO* (=1 if the price is for the Oregon region), *inC* (=1 if the price is for the California region), a set of fixed effects for each type of database software offered (the omitted category is SQL standard).

Results of these regressions are summarized in Table 4. As for the EC2 results, the table summarizes the regression results, showing the minimum, maximum and median values of coefficient estimates across the regressions. In addition, of the 25 adjacent-quarter regressions, the table shows the fraction of the estimates for each coefficient that are significant at the 5 and 10 percent significance levels.

The coefficient on the dummy variable capturing quality-adjusted price change, *D2,* has a median value of zero, reflecting that prices are not changing in most quarters. The coefficient for the variable for processor power, *Vcpu* generally is positive and relatively significant, as prices are higher for instances providing more processor power. The same pattern holds for the memory variable, *Memory.* The variable for IOPerformance also is always positive and almost always significant. Among the fixed effects, the variable *Provisioned IOPS optimized* (indicating optimization of storage input/output) is always positive and significant. Just as for EC2, prices in the Oregon region, captured by the *inO* variable, are little different from those in Virginia, while prices in the California region, the *inC* variable typically are more than 10 percent higher than prices in Virginia. Among the fixed effects for different database software, most are priced at significant discounts relative to SQL standard. Oracle is the big exception; if AWS provides the license, Oracle is priced significantly above SQL standard.

Table 5 reports the price indexes generated by these regressions. The adjusted-R^2s are quite high, indicating again that the right-hand-side variables are capturing most of the sources of variation in prices. The price index is shown in the first column and percent changes at quarterly rates are reported in the second column. As for EC2, these figures highlight that prices do not change in most quarters. Price declines are large in some quarters, with the biggest drop at the beginning of 2014, when AWS revamped its offerings.

All told, quality-adjusted prices for RDS instances fall at an average *annual* rate of more than 11 percent over the full sample. Over sub-periods, the pattern is that same as that for EC2 prices. Prices fell at an annual average rate of about 3 percent from the beginning of 2009 to the end of 2013. Then, in early 2014, just as Microsoft had entered the market to sufficient degree that they were posting their cloud prices on the Internet, AWS began cutting prices more rapidly. That started with the big price drop in early 2014, and over the period from the start of 2014 to the end of 2016, RDS prices fell at an average annual rate of more than 22 percent.

S3. As noted, quality does not change appreciably over time for S3, the AWS storage product. Accordingly, we essentially construct matched-model indexes by tracking price changes over time for each price tier. Table 6 reports the resulting price indexes for each price tier. As for EC2 and RDS, these figures indicate that prices do not change in most quarters. Price declines are large in some quarters, with the biggest drop at the beginning of 2014, as AWS appeared to be responding to a competitive threat from Microsoft (and Google later in the year).

The bottom three lines of the table provide summary figures that are an unweighted average of price change across all of the price tiers. All told, prices for S3 storage fall at an average *annual* rate of more than 17 percent over the full sample. Over sub-periods, the pattern is that same as that for EC2 prices. Prices fell at an annual average rate of about 12 percent from the beginning of 2009 to the end of 2013. Then, in early 2014, just as Microsoft had entered the market to sufficient degree that they were posting their cloud prices on the Internet, AWS began cutting prices more rapidly. That started with the big price drop in early 2014, and over the period from the start of 2014 to the end of 2016, S3 prices fell at an average annual rate of about 25 percent.

4. How Big is the Cloud?

Official revenue data for the cloud services industry and its main products according to nomenclature used in this paper are not available. The NAICS industry 518210 (Data Processing, Hosting, and Related Services) subsumes the relevant core activity but also includes traditional data centers.[16] That said, BEA's data on intermediate uses of these services (along with internet publishing) suggests the intensity of business use has been rising steadily (figure 4).

According to more detailed metrics, cloud activity itself has exploded upward. Since emerging in the mid-2000s the cloud model has rapidly dominated the data center market. Cloud providers currently account for 90 percent of data center traffic and have accounted for essentially all growth since 2010 (figure 5). Indeed, data center traffic at cloud providers rose at 62 percent average annual rate between 2010 and 2016.

Concurrently, capital expenditures at large cloud service—called "hyperscale" data center operators—have surged to roughly $50 billion per year (figure 6).[17] From 2010 to 2015, these expenditures rose at an annual average rate of 17 percent. Fixed investment by these firms is now on par with the massive investments by first-tier

[16] The structure of NAPCS, introduced in 2017, usefully distinguishes between web site hosting, data storage services, and so forth, but does not distinguish between services provided by traditional data centers and cloud vendors. See the industry description at https://www.census.gov/eos/www/naics/index.html and the NAPCS structure at https://www.census.gov/eos/www/napcs/ (accessed March 5, 2017).

[17] Cisco classifies a data center operator as hyperscale if they have revenue of $1B in Iaas/Paas or $2B in SaaS or $4B from internet/search/social networking or $8B from e-commerce/payment processing.

telecommunications service providers (figure 7).[18] (The firms whose products are studied further in this paper—Amazon, Microsoft, and Google—have played a prominent role in this trend and now account for nearly half of capital investment at the world's hyperscale cloud operators.)

Figure 8 shows the importance and rapid growth of the cloud from a different perspective: the share of the world's most powerful computers operated by IT service firms leapt from under 10 percent in 2006 to more than 40 percent in 2009 and has persisted at that level since.[19]

And, tying back to the discussion of virtualization, IT consultancies commented in 2008 that server virtualization had become the "killer app" for the business datacenter. Subsequently, IDC estimated that the number of virtual machines (VM) per server in the United States—an indicator of the application workload of an enterprise server—advanced nearly 12 percent per year from 2007 to 2013 (Byrne and Corrado, 2017a).

Where has all this Investment Gone?

In light of this wave of investment, the shift away from IT equipment in business fixed investment in equipment and intangibles may be seen as puzzling (figure 9). However, as we noted, the higher utilization that follows as firms outsource IT functions to the cloud may translate into weaker investment in the short run. Indeed, IDC Inc. reports that the nominal value of sales of servers to U.S. firms fell at an annual average rate of 11 percent from 2004 to 2016 and the decline accelerated since 2008.

[18] The third type of capital stock needed for effective cloud services has expanded as well. 40 percent of U.S. adults now own tablets and 60 percent own smart phones. Byrne and Corrado (2017b) estimate the stock of ICT consumer durables has risen markedly in recent years as well.

[19] The IT services category is necessarily broader than cloud services because the descriptions of individual supercomputing sites vary in specificity. That being said, some sites are identified as Microsoft Azure and AWS.

That being said, we also consider another possibility: that cloud services firms have been building their own IT equipment, at least in part. If so, then a portion of the capital expenditures reported above may be for components that have gone into IT equipment built on an own-account basis rather than for already assembled IT equipment. Google, Facebook, and Twitter, for example, are reported to have built both computing and network equipment from purchased components.[20] Consistent with this possibility, the "use tables" published by the U.S. Bureau of Economic Analysis indicate that the output of the Computer and Electronics Manufacturing sector (NAICS 334) used by IT services sectors is substantial—$58.6 billion in 2015.[21] At the same time, the "make tables" indicate that these electronic intermediates are not made into final electronics sold by the IT services sector. This suggests that these components are used for own-account production of IT equipment used within the firms.

If this story is correct, this own-account investment should be (but we believe likely is not) counted in the NIPAs as business investment in IT equipment, albeit own-account investment. How much might this own-account investment add up to? For the sake of argument, we assume that the value of the own-account production of final electronics is equal to twice the value of the electronic intermediates used.[22] With this valuation, story for business investment in IT equipment changes markedly. As seen in figure 10, nominal IT equipment and software investment including our estimate of own-account would be $117 billion higher in 2015 than in the official estimates, amounting to

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[20] See "Like Google and Facebook, Twitter designs its own servers," Wired Magazine, July 9, 2015. (https://www.wired.com/2015/07/like-google-facebook-twitter-designs-computer-servers/)

[21] We treat BEA categories 511, 512, 514 and 5415 as IT services. This group includes industry 518210 mentioned above (in category 514) as well as software publishing, telecom services, and computer design services.

[22] We believe this assumption is conservative; although the details of data center server inputs are not available, Gartner, Inc. reports that the market value of personal computers is roughly four times the value of electronic inputs.

0.65 percent of GDP. For real investment in IT equipment and software, adding this own-account investment would boost the average annual growth rate during 2005-2015 by a little over 1 percentage point compared with official estimates. For real GDP growth, including this own-account investment would add half a tenth a year to the growth rate during this period.[23]

5. Conclusion

We find that cloud computing has exploded. By available measures, the quantity of cloud activity has grown extremely rapidly as has associated capital investment. At the same time, prices of basic cloud services have fallen rapidly since 2009, based on a unique dataset we assembled. However, because cloud is so new and so much of it is intermediate input, it is challenging to track in the statistical system, and the available data do not distinguish between cloud-based and traditional services. We highlight one area where real GDP may be understated by a noticeable amount as a result of changes in the economy related to the rise of cloud computing.

[23] Using the alternative prices in Byrne and Corrado (2017a), the additional own-account investment would add nearly a tenth of percentage point a year to real GDP growth during 2005-2015.

References

Avram, Abel (2016), "FaaS, PaaS, and the Benefits of the Serverless Architecture," *InfoQ,* posted on June 25, 2016 and available at: https://www.infoq.com/news/2016/06/faas-serverless-architecture

Bresnahan, Timothy F. and Shane Greenstein (1999). "Technological Competition and the Structure of the Computer Industry." *Journal of Industrial Economics* 47 (1), pp. 1-40.

Byrne, David M. and Carol A. Corrado (2017a). "ICT Prices and ICT Services: What do they tell us about Productivity and Technology?" FEDS paper source (update of Conference Board working paper EPWP-1605).

Byrne, David M. and Carol A. Corrado (2017b). "Accounting for Innovation in Consumer Digital Services," posted on March 7 and available at: http://conference.nber.org/confer/2017/CRIWs17/program.html.

Byrne, David M., Stephen D. Oliner, and Daniel E. Sichel, "How Fast Are Semiconductor Prices Falling?" *Review of income and Wealth*, forthcoming, also available as NBER working paper #21074, April 2015.

Campbell-Kelly, Martin and Daniel D. Garcia-Swartz (2008). "Economic Perspectives on the History of the Computer Time-Sharing Industry, 1965-1985." *IEEE Annals of the History of Computing*, pp. 16-36.

Cohen, Robert B. (2017) "Understanding the Next Production Revolution and its Relationship to Software Innovations." Mimeo, Economic Strategy Institute (January 22).

De Roure, David, Mark A. Baker, Nicholas R. Jennings, and Nigel R. Shadbolt (2003). "The Evolution of the Grid." In F. Berman, G. C. Fox, and T. Hey (Eds.), *Grid Computing: Making the Global Infrastructure a Reality*, Wiley Series in Communications Networking and Distributed Systems, Chapter 3, pp. 65–100. Chichester, England: John Wiley & Sons, Ltd.

Erickson, Tim and Ariel Pakes, "An Experimental Component Index for the CPI: From Annual Computer Data to Monthly Data on Other Goods," *American Economic Review* 101 (August), 1707-1738, 2011.

Gort, M and S. Klepper (1982), ''Time Paths in the Diffusion of Product Innovations,'' *Economic Journal*, 92, pp. 630-653.

Hubbard, Patrick (2014). "The Network in the Computer, Again" *Network Computing* (May 6), available at http://www.networkcomputing.com/cloud-infrastructure/network-computer-again/1827958867

Mell, Peter and Timothy Grance (2011). *The NIST Definition of Cloud Computing*. NIST Special Publication 800-145. Doi: http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-145.pdf

OECD (2014). *Addressing the Tax Challenges of the Digital Economy*. OECD/G20 Base Erosion and Profit Shifting Project. Paris: OECD Publishing.

Pakes, Ariel, "A Reconsideration of Hedonic Price Indexes with an Application to PC's," *American Economic Review*, 93(5), 1578–96, 2003.

Reiss, Spencer (1996) "Power to the People", Wired Magazine (December 1), available at
https://www.wired.com/1996/12/esgage/

van Dalen, Jan and Ben Bode, "Estimation Bias in Quality-Adjusted Hedonic Price Indexes," mimeo, Rotterdam School of Management, 2004. http://www.ipeer.ca/papers/vanDalenBodeOct.1,2004,SSHRC%20Paper17.pdf

Zhang, Liang, "Price Trends for Computing Services," Senior Thesis, Wellesley College, May 2016.

Table 1
Cloud Providers and Products for which Prices Collected

	Amazon Web Services 2009:Q1-2016:Q4	**Microsoft Azure** 2014:Q1-2016:Q4	**Google Cloud** 2014:Q4-2016:Q4
Compute	EC2 (Elastic Compute Cloud)	Virtual machines	Compute engine
Database	RDS (Relational Database Service)	SQL database	Cloud SQL
Storage	S3 (Simple Storage Service)	Disk stoarge	Cloud storage

Table 2
Amazon EC2 Adjacent-Quarter Regressions, 2009:Q2-2016:Q4
(summary of coefficient estimates across all adjacent-quarter regressions)

	Minimum	Maximum	Median	Fraction significant at 5%	Fraction significant at 10%
D2	-.329	.031	.0	2/31	2/31
ECU	-.114	.604	.212	28/31	29/31
Mem	-.739	.85	.630	31/31	31/31
Storage	-.66	.199	-.067	30/31	31/31
StorSSD	-.049	.017	.0	0/31	10/31
System	-.444	0	-.341	29/31	29/31
pltfrm	-.477	2.103	.0	10/31	10/31
inO	-.025	.038	.0	0/31	0/31
inC	.0	.146	.127	23/31	24/31
Constant	-5.939	-.926	-4.616	31/31	31/31

Note: *D2* is the dummy varieable for the second quarter of the adjacent-quarter regression. *ECU*, *Mem, and Storage* are in natural logs. *ECU* measures processor power, *Mem* is the amount of RAM, and *Storage* is the amount of disk storage. Other variables enter as fixed effects. *StorSSD* =1 if solid state storage, *System* =1 if operating system is Linux, *pltfrm* =1 if the processor is 64 bit, *inO* = 1 if the region is Oregon, and *inC* = 1 if the region is California. The omitted categories are the Windows operating system in the Virginia region with magnetic hard drive disk storage and a 32-bit processor.

Table 3
Amazon EC2 (Compute Product) Price Index

	Price Index	Percent Change (qtrly rate)	Number of observations	Adjusted R^2
2009: 1	100.00			
2009: 2	100.00	.0	20	0.996
2009: 3	100.00	.0	20	0.996
2009: 4	95.29	-4.7	38	0.91
2010: 1	95.29	.0	56	0.927
2010: 2	95.29	.0	60	0.926
2010: 3	91.27	-4.2	69	0.955
2010: 4	91.77	.5	75	0.968
2011: 1	91.77	.0	76	0.969
2011: 2	91.77	.0	76	0.969
2011: 3	91.77	.0	76	0.969
2011: 4	84.92	-7.5	98	0.967
2012: 1	87.71	3.3	126	0.961
2012: 2	88.68	1.1	132	0.96
2012: 3	88.68	.0	132	0.963
2012: 4	88.68	.0	132	0.963
2013: 1	82.37	-7.1	156	0.953
2013: 2	77.98	-5.3	182	0.949
2013: 3	77.98	.0	184	0.974
2013: 4	77.95	.0	242	0.974
2014: 1	56.15	-28.0	370	0.944
2014: 2	56.15	.0	440	0.956
2014: 3	56.15	.0	440	0.956
2014: 4	56.15	.0	440	0.956
2015: 1	56.15	.0	440	0.956
2015: 2	56.15	.0	440	0.956
2015: 3	56.15	.0	440	0.956
2015: 4	56.15	.0	440	0.956
2016: 1	48.84	-13.0	518	0.938
2016: 2	48.84	.0	596	0.936
2016: 3	48.72	-.2	596	0.936
2016: 4	48.72	.0	298	0.936
Memo: Avg at annual rate				
2009:1-2016:4		-6.9		
2009:1-2013:4		-5.1		
2014:1-2016:4		-10.5		

Note: Based on adjacent-quarter hedonic regression as described in the text. All estimates are bias adjusted to account for the translation from log price to a price index. The last two columns show the number of observations and adjusted R^2s from each of the adjacent-quarter regressions.

Table 4
Amazon RDS Adjacent-Quarter Regressions, 2010:Q3-2016:Q4
(summary of coefficient estimates across all adjacent-quarter regressions)

	Minimum	**Maximum**	**Median**	**Fraction significant at 5%**	**Fraction significant at 10%**
D2	-0.53	0.01	0.00	5/25	5/25
Vcpu	-0.15	0.22	.03	16/25	16/25
Memory	0.57	.74	.69	25/25	25/25
IOPerformance	0.04	0.35	0.25	24/25	24/25
Provisioned IOPS optimized	0.07	0.22	0.13	25/25	25/25
inC	0.09	0.12	0.11	25/25	25/25
inO	-0.01	0.01	0.00	0/25	0/25
Aurora	-1.31	0.00	0.00	5/25	5/25
MySQL	-1.44	0.00	-1.00	18/25	18/25
Oracle (own license)	-1.43	0.00	-1.00	17/25	17/25
Oracle	0.00	0.76	0.37	21/25	21/25
PostgreSQL	-1.38	0.00	0.00	12/25	12/25
SQL (own license)	-1.02	0.00	-0.67	18/25	18/25
SQL express	-1.37	0.00	-0.96	18/25	18/25
SQL web	-0.66	0.00	-0.60	18/25	18/25
MariaDB	-1.44	0.00	0.00	4/25	4/25
Constant	-3.10	-1.99	-2.87	25/25	25/25

Note: No observations for 2015:Q4 were available in the web archive.

Table 5
Amazon RDS (Database Product) Price Index, 2010:Q2-2016:Q4

	Price Index	Percent Change (qtrly rate)	Number of observations	Adjusted R^2
2010: 2	100.00			
2010: 3	100.00	0.0%	22	0.999
2010: 4	93.73	-6.3%	24	0.997
2011: 1	93.73	0.0%	24	1
2011: 2	93.73	0.0%	44	0.999
2011: 3	93.73	0.0%	64	0.999
2011: 4	93.73	0.0%	64	0.999
2012: 1	93.73	0.0%	64	0.999
2012: 2	93.73	0.0%	133	0.971
2012: 3	93.73	0.0%	202	0.967
2012: 4	93.73	0.0%	202	0.967
2013: 1	87.25	-6.9%	242	0.971
2013: 2	87.19	-0.1%	282	0.976
2013: 3	87.19	0.0%	282	0.976
2013: 4	87.19	0.0%	308	0.978
2014: 1	82.29	-5.6%	420	0.977
2014: 2	48.30	-41.3%	601	0.975
2014: 3	48.30	0.0%	696	0.981
2014: 4	48.30	0.0%	696	0.981
2015: 1	48.30	0.0%	696	0.981
2015: 2	48.30	0.0%	696	0.981
2015: 3	48.55	0.5%	712	0.981
2015: 4	48.55	0.0%		
2016: 1	38.38	-20.9%	1183	0.983
2016: 2	38.20	-0.5%	1218	0.985
2016: 3	38.20	0.0%	702	0.984
2016: 4	38.20	0.0%	606	0.983
Memo: Avg ch, annual rate				
2010:2-2016:4		-11.6		
2010:2-2013:4		-3.3		
2014:1-2016:4		-22.6		

Note: Based on adjacent-quarter hedonic regression as described in the text. All estimates are bias adjusted to account for the translation from log price to a price index. The last two columns show the number of observations and adjusted R^2s from the adjacent-quarter regressions. No observations available for 2015:Q4; we assumed no price change in that quarter.

Table 6
Amazon S3 (Storage Product) Price Indexes, Standard Storage, Virginia
(percent change, quarterly rate)

	Terabyte (TB) Range						
	s≤ 1	**1<s≤50**	**50<s≤100**	**100<s≤500**	**500<s≤1K**	**1K<x≤5K**	**≤5K**
2009: 2	.0	.0	.0	.0			
2009: 3	.0	.0	.0	.0			
2009: 4	.0	.0	.0	.0			
2010: 1	.0	.0	.0	.0	.0	.0	.0
2010: 2	.0	.0	.0	.0	.0	.0	.0
2010: 3	.0	.0	.0	.0	.0	.0	.0
2010: 4	-6.7	.0	-21.4	-15.4	-9.5	.0	.0
2011: 1	.0	.0	.0	.0	.0	.0	.0
2011: 2	.0	-16.7	.0	.0	.0	.0	.0
2011: 3	.0	.0	.0	.0	.0	.0	.0
2011: 4	.0	.0	.0	.0	.0	.0	.0
2012: 1	-10.7	-12.0	-13.6	-13.6	-5.3	.0	.0
2012: 2	.0	.0	.0	.0	.0	.0	.0
2012: 3	.0	.0	.0	.0	.0	.0	.0
2012: 4	.0	.0	.0	.0	.0	.0	.0
2013: 1	-24.0	-27.3	-26.3	-26.3	-27.8	-25.0	.0
2013: 2	.0	.0	.0	.0	.0	.0	.0
2013: 3	.0	.0	.0	.0	.0	.0	.0
2013: 4	-10.5	-6.2	-14.3	-14.3	-15.4	-15.0	-21.8
2014: 1	-64.7	-6 .7	-51.7	-51.7	-48.2	-45.1	-36.0
2014: 2	.0	.0	.0	.0	.0	.0	.0
2014: 3	.0	.0	.0	.0	.0	.0	.0
2014: 4	.0	.0	.0	.0	.0	.0	.0
2015: 1	.0	.0	.0	.0	.0	.0	.0
2015: 2	.0	.0	.0	.0	.0	.0	.0
2015: 3	.0	.0	.0	.0	.0	.0	.0
2015: 4	.0	.0	.0	.0	.0	.0	.0
2016: 1	-23.3	-22.0	-24.1	-24.1	-26.3	-25.0	-23.6
2016: 2	.0	.0	.0	.0	.0	.0	.0
2016: 3	.0	.0	.0	.0	.0	.0	.0
2016: 4	.0	.0	.0	.0	.0	.0	.0
Memo: Avg ch, AR							
2009:1-2016:4	-18.1	-18.7	-19.5	-18.8	-18.9	-15.7	-11.6
2009:1-2013:4							
2014:1-2016:4							
2009:1-2016:4	**Average across all price tiers**	**-17.3**					
2009:1-2013:4	**Average across all price tiers**	**-12.1**					
2014:1-2016:4	**Average across all price tiers**	**-25.1**					

Note: Based on matched-model indexes for each price tier. AWS offered different sets of price tiers in different periods so not all tiers have entries for every period.

Figure 1
Amazon EC2 Posted Prices by Instance, for Each Region and for Linux and Windows

Figure 2
Amazon RDS Posted Prices by Instance, for MySQL in the Virginia, California, and Oregon Regions

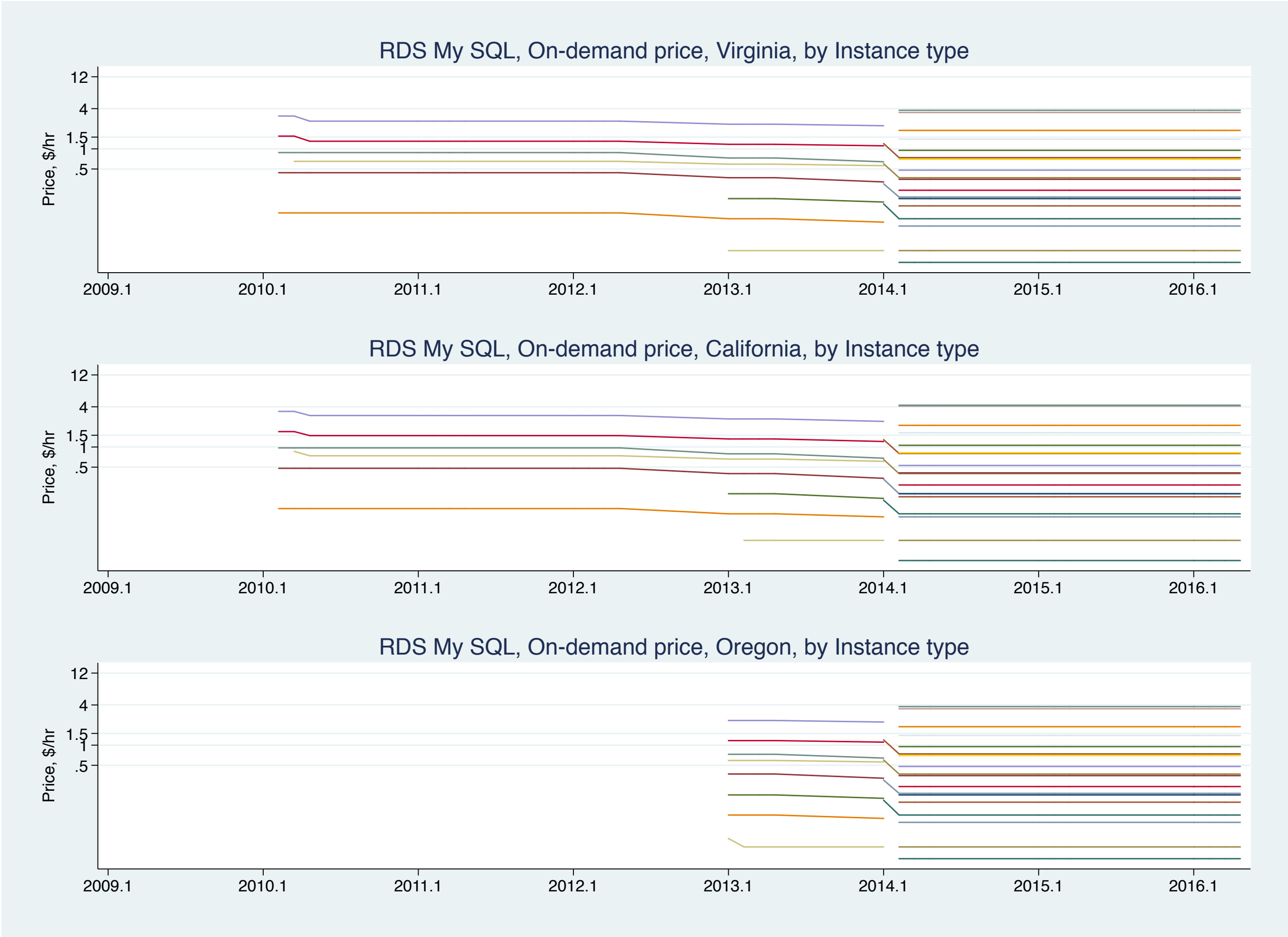


Figure 3
Amazon S3 Posted Prices by Price Tier, for Each Region and Storage Type

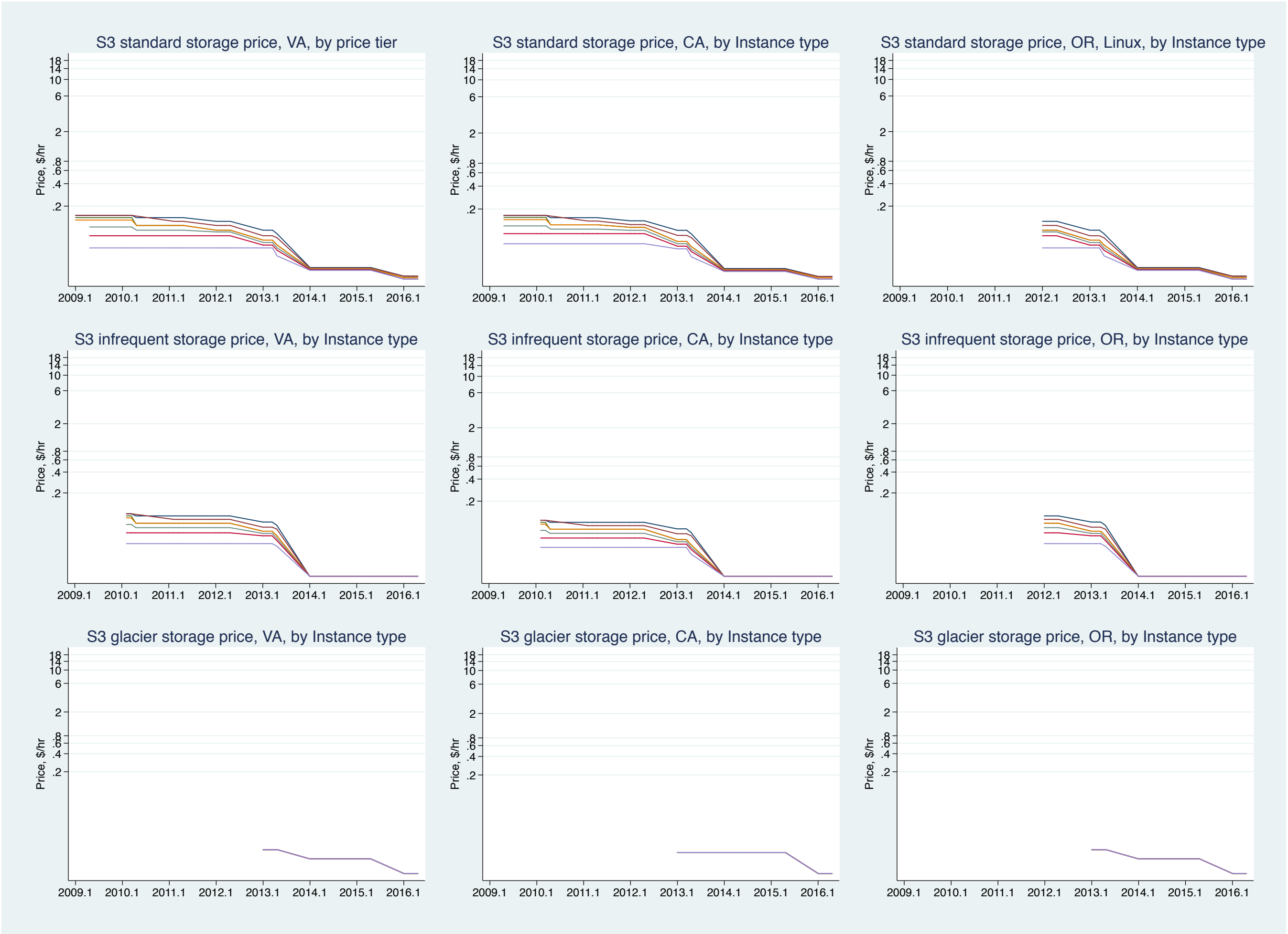
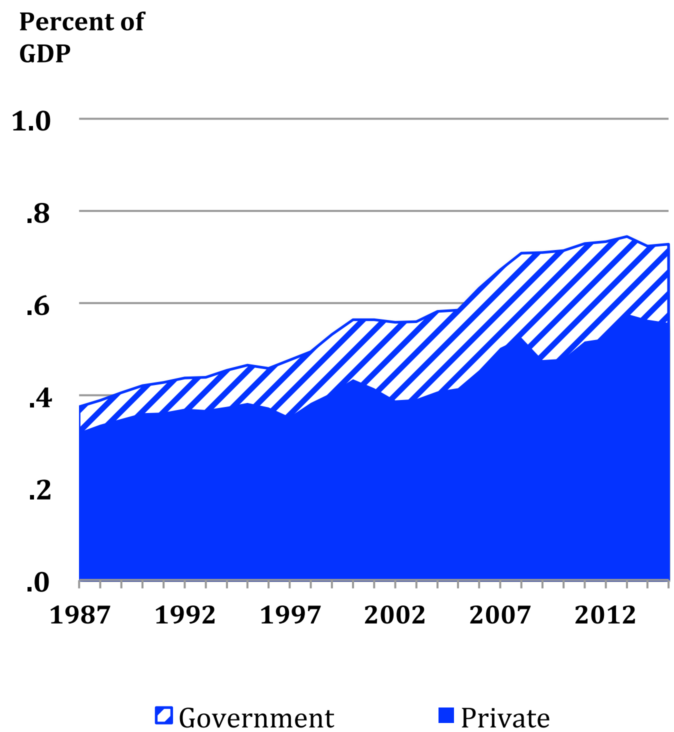
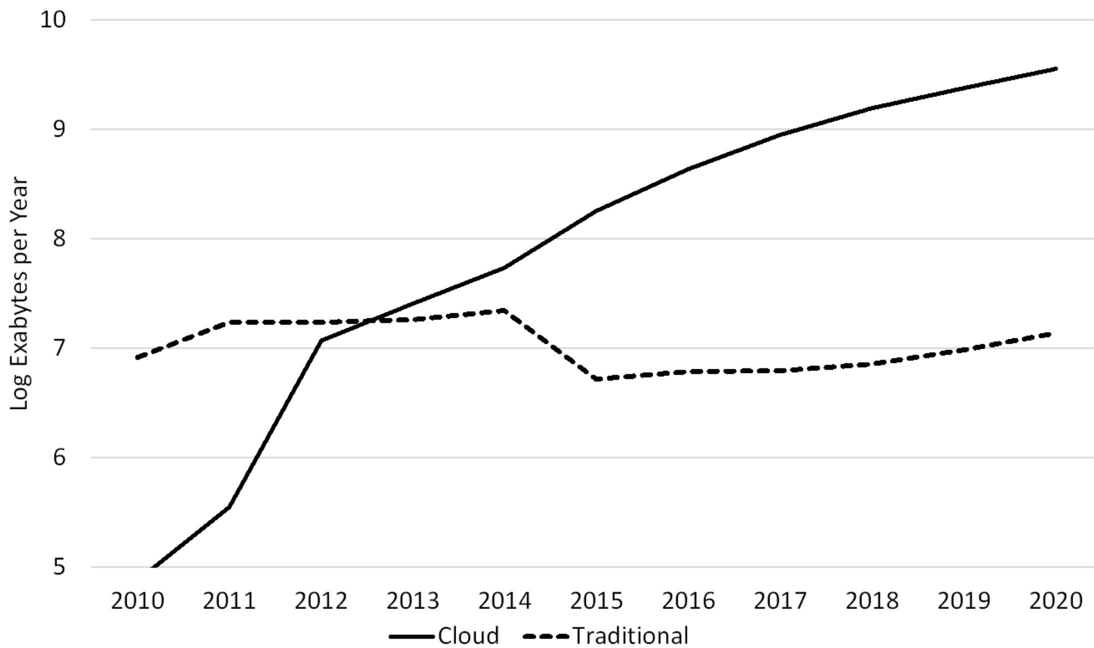


Figure 4. Intermediate uses of information services, 1987 to 2015



Note: Data processing, hosting, and other information services products, wherever produced (BEA IO product code 514, covering 2002 NAICS 5182, 51913)

Figure 5. Global Data Traffic by Datacenter Type
Historical and Projected, Ratio Scale



Source. Cisco Global Cloud Index, Forecast and Methodology, 2015-2020 and earlier editions.

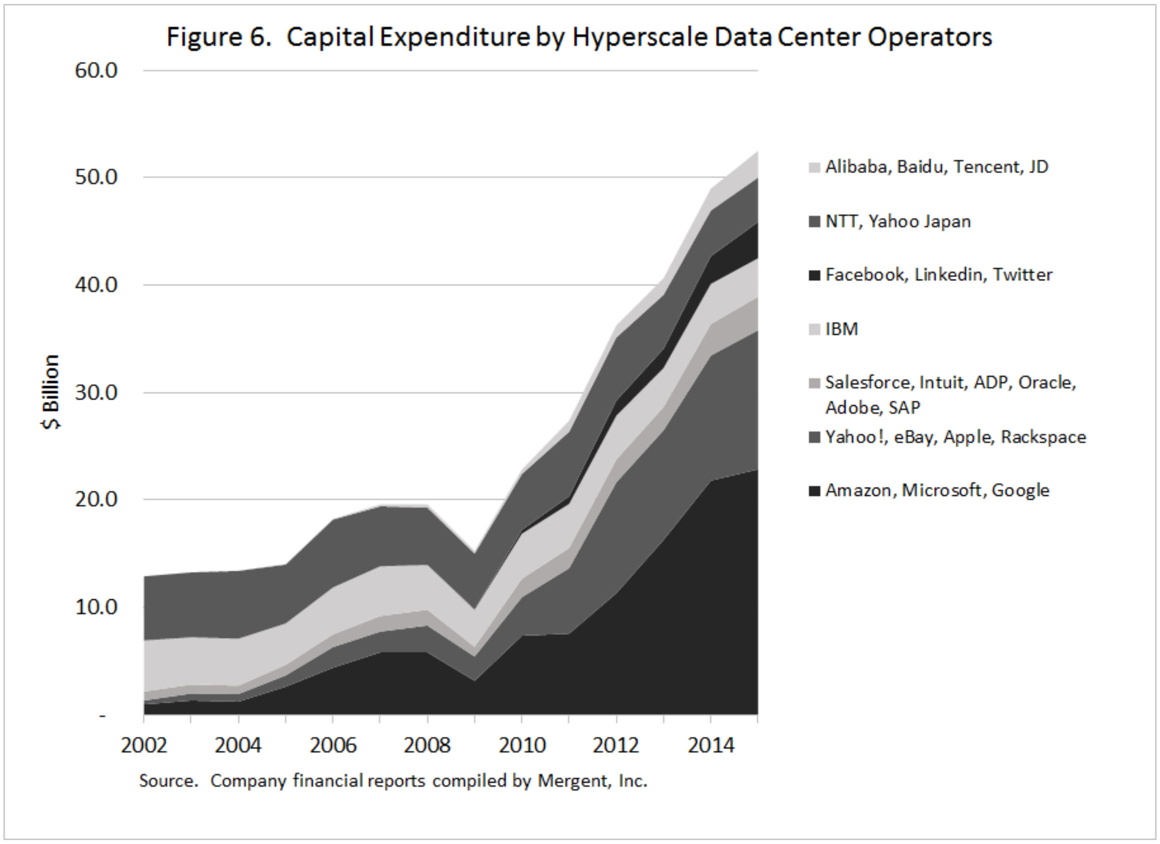
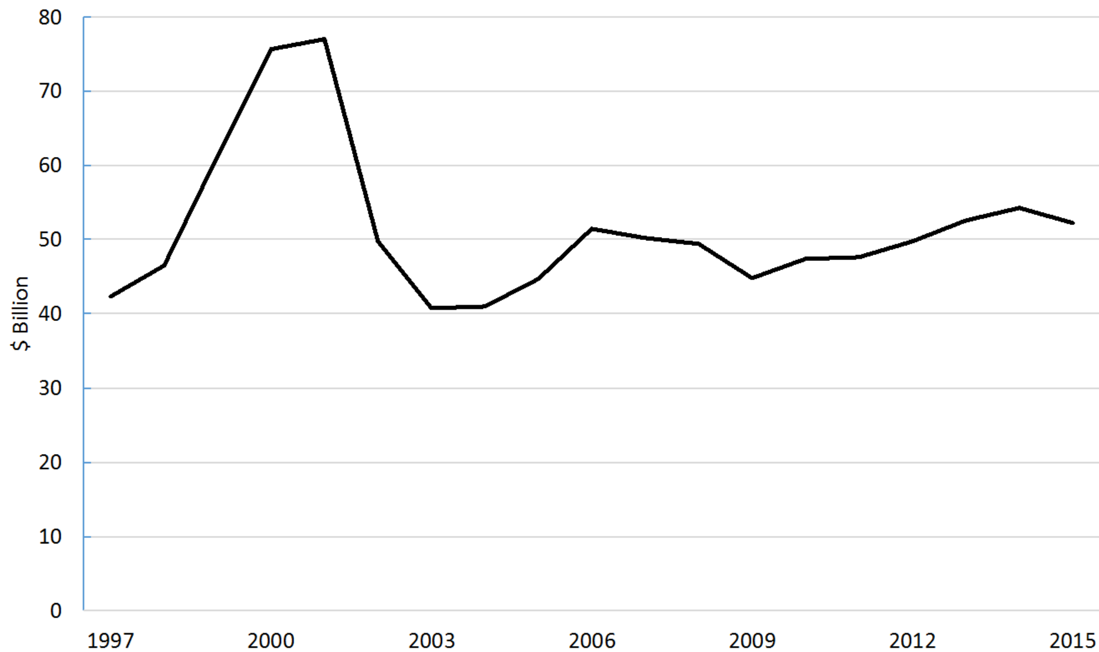


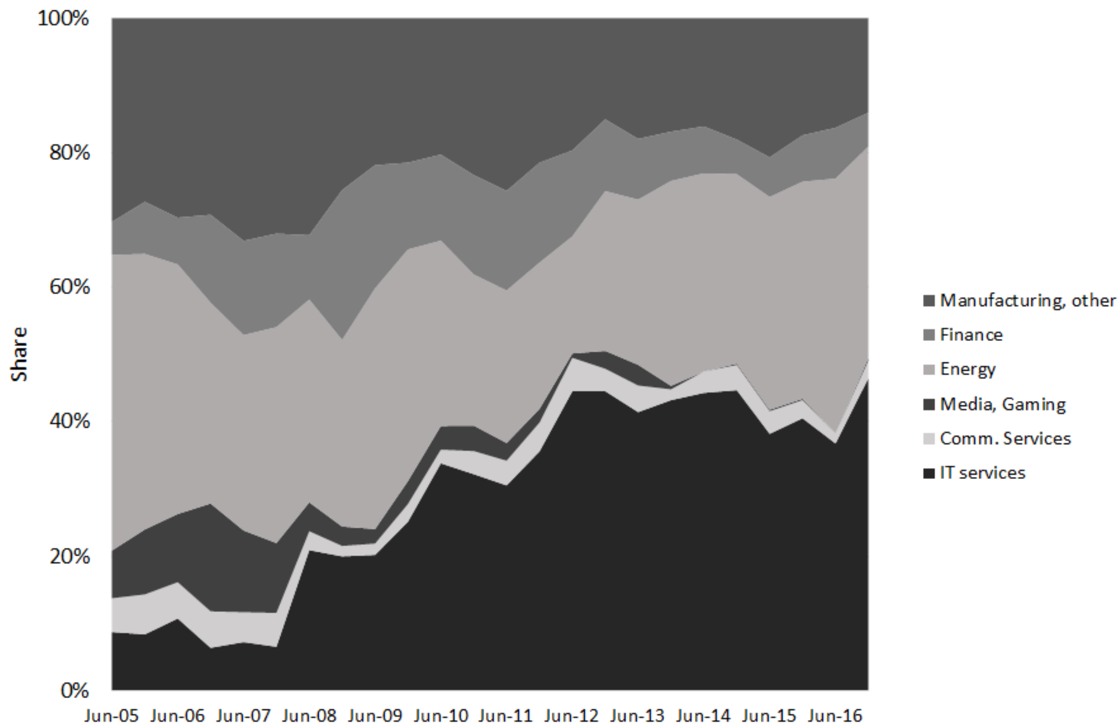
Figure 6. Capital Expenditure by Hyperscale Data Center Operators
60.0
50.0
40.0
30.0
20.0
10.0
-
$ Billion
2002
2004
2006
2008
2010
2012
2014
Alibaba, Baidu, Tencent, JD
NTT, Yahoo Japan
Facebook, Linkedin, Twitter
IBM
Salesforce, Intuit, ADP, Oracle, Adobe, SAP
Yahoo!, eBay, Apple, Rackspace
Amazon, Microsoft, Google
Source. Company financial reports compiled by Mergent, Inc.

Figure 7. U.S. Telecom Service Provider Capital Expenditures



Source. Company financial filings.
Note. Includes AT&T, Verizon, Sprint Nextel, T-Mobile, Century Link, and related companies.

Figure 8. Industrial Supercomputer Capacity by Sector



Source. top500.com, authors' calculations.

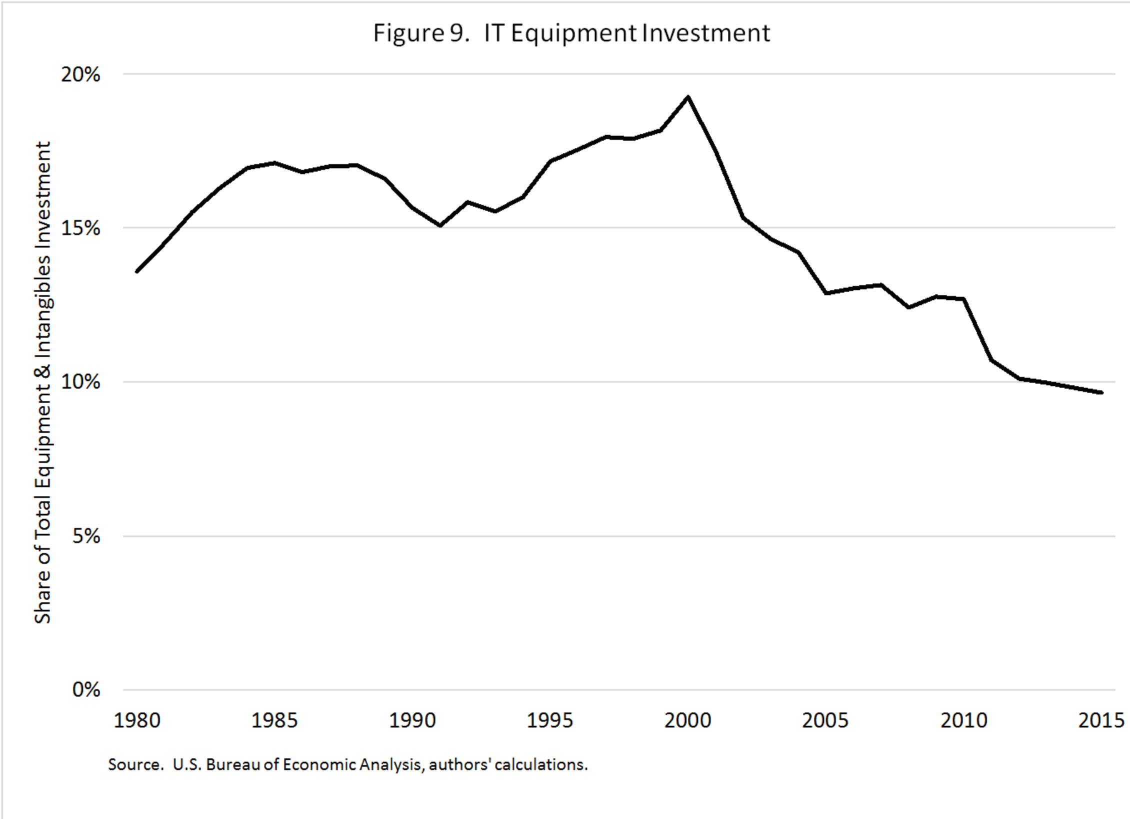
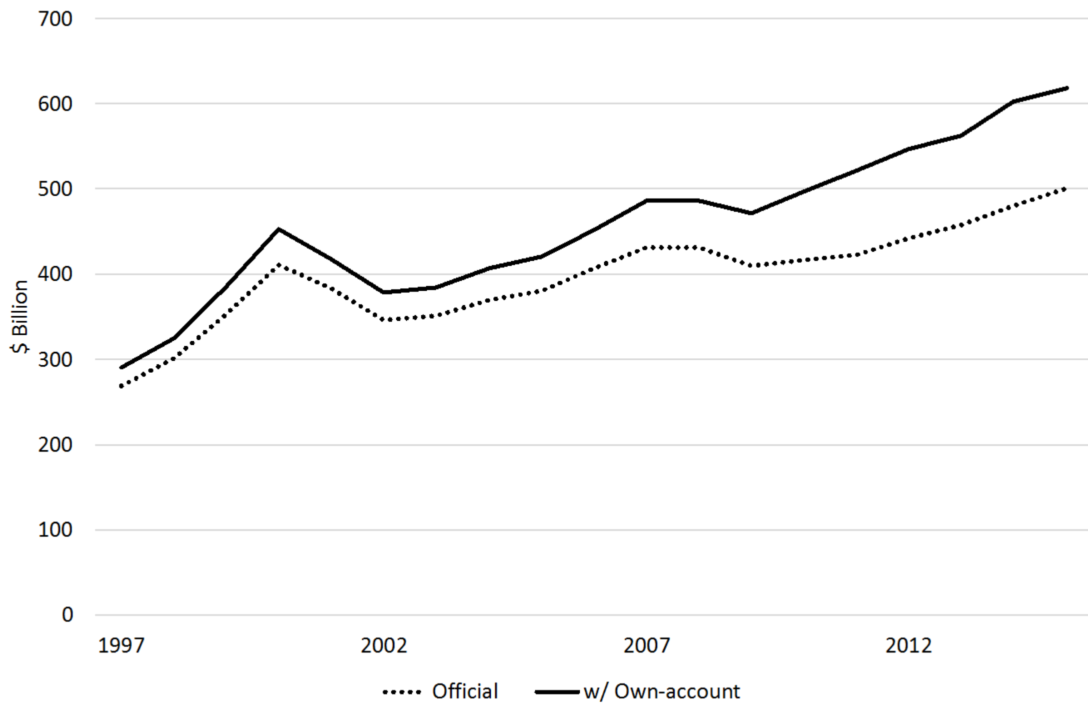


Figure 9. IT Equipment Investment
Share of Total Equipment & Intangibles Investment
20%
15%
10%
5%
0%
1980
1985
1990
1995
2000
2005
2010
2015
Source. U.S. Bureau of Economic Analysis, authors' calculations.

Figure 10. IT Equipment & Software Investment



Source. U.S. Bureau of Economic Analysis, authors' calculations.