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The Increasing Deflationary Influence of Consumer Digital Access Services

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Consumer digital access services—internet, mobile phone, cable TV, and streaming—accounted for over 2 percent of U.S. household consumption in 2018. We construct prices for these services using direct measures of volume (data transmitted, talk time, and hours of programming). Our price index fell 12 percent per year from 1988 to 2018 while official prices moved up modestly. Using our digital services index, we estimate total personal consumption expenditure (PCE) prices have risen nearly 1/2 percentage point slower than the official index since 2008. Importantly, the spread between alternative and official PCE price inflation has increased noticeably over time.

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Consumer price statistics are prone to distortion from unmeasured quality change and shifting household consumption patterns. For example, does the new iPhone cost more because it has three cameras on the back, or because Apple used its market power to raise prices? Or, when the first commercial mobile phone network arrived in the United States in the early 1980s, was mobile phone service added quickly enough to the basket of goods and services in the consumer price index (CPI) to catch the reduction in the cost of living as the price of the new technology fell rapidly?[1]

Imperfect accounting for new goods is not necessarily problematic for economic policy if it introduces a known and stable bias. If a monetary authority uses an inflation measure that overstates the true pace of price change by 1 percentage point to gauge achievement of its target inflation rate, arguably it may set the target for *measured* inflation 1 percentage point higher than the objective for true inflation to account for the measurement shortcoming.[2] Similarly, a fiscal authority operating in such an environment may treat reported inflation as an overstatement of the true cost of living when creating a formula for indexing program benefits.[3]

However, if the bias embodied in reported price indexes evolves and the change goes undetected, policy-makers may be misled about inflation. We argue

[1] The first commercial mobile cellular phone service was introduced in the United States in 1983 (Farley, 2005). As Hausman (1999, p. 188) rather uncharitably puts it, "The Bureau of Labor Statistics (BLS) did not know that cellular telephones existed, at least in terms of calculating the Consumer Price Index (CPI), until 1998, when they were finally included in the CPI."

[2] Bernanke and Mishkin (1997, p. 110) note, "It seems clear that an inflation target of zero or near zero is not desirable for several reasons. First, much recent research suggests that official CPI inflation rates tend to overstate the true rate of inflation, due to various problems such as substitution bias in the fixed-weight index and failure to account adequately for quality change. Studies for the United States have estimated this overstatement of inflation to be in the range of 0.5 to 2.0 percentage points per year. Thus, as a practical matter, even if the central bank chooses to pursue a zero rate of true inflation, the target for the measured inflation rate should be greater than zero."

[3] Burdick and Fisher (2007, p. 73) discuss Social Security cost-of-living adjustments (COLAs) and note "Others argue that the measure of inflation underlying the COLA is technically biased, causing it to overestimate changes in the cost of living. This argument implies that current COLAs tend to increase, rather than merely maintain, the purchasing power of benefits over time."

the bias in price measures for consumer digital access services, which accounted for over 2 percent of personal consumption expenditures (PCE) in 2018, has risen appreciably over time. Consequently, consumer price inflation used for the calculation of GDP, for thinking about the stance of monetary policy, and for indexing of social welfare programs appears to be increasingly overstated, a fact unremarked upon in previous literature.[4]

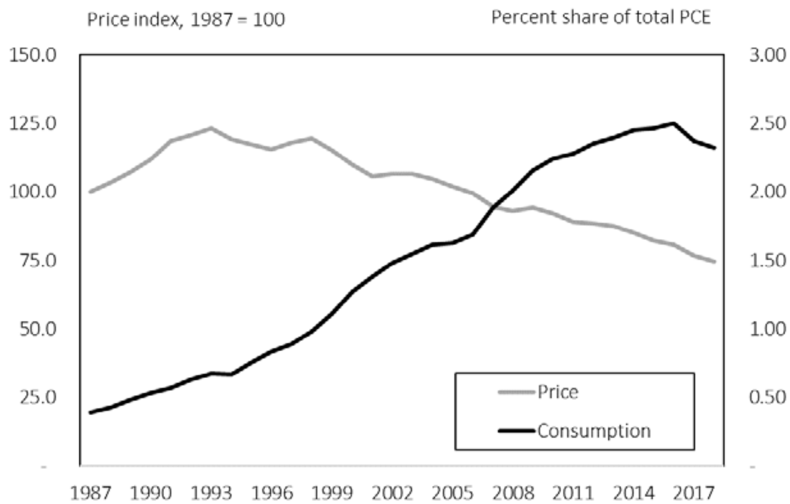
I. Consumer Digital Access Services

Consumer digital access services deliver data, voice, and video programming to households over the internet, mobile cellular networks, and cable television networks. Consumption of digital access services as a share of PCE has risen markedly since the late 1980s (figure 1).[5] As one might expect when households dramatically shift consumption toward a service, digital access prices have declined relative to total PCE prices. Over this roughly 30-year period, the consumer digital access service prices used in the national income and product accounts (NIPAs) rose 1.2 percent per year, on average, 0.9 percentage points slower than the rise in the total PCE price index.

[4] Boskin et al. (1998) estimated that omitted quality adjustment and other sources of bias led the circa 1998 CPI to overstate inflation by 1.1 percentage point. Moulton (2018) estimated a *lower* bias of 0.85 percentage point in the current CPI due to in large part to more effective quality adjustment for consumer durables introduced in 2000 and earlier. Other studies, such as Bils (2009) and Goolsbee and Klenow (2018) have identified noteworthy overstatement of consumer price inflation, but have not pointed to a *worsening* of the issue.

[5] In consumer digital access services, we include the consumption recorded in the following lines of BEA table 2.5.4U. *Personal Consumption Expenditures by Type of Product*: "Cable, satellite, and other live television services" (line 215), "Cellular telephone services" (line 281), "Internet access" (line 285), and a portion of "Video and audio streaming and rental" (line 219) corresponding to our estimate of subscription video on demand spending.

Figure 1. Digital Access Services



Note. Authors' aggregation of BEA prices for consumer digital access services relative to total PCE price index.

The relative price decline is surprisingly modest in the context of capital theory, however. Digital access services are generated by information technology (IT) capital held by telecommunications service providers, internet service providers, cable television companies, and cloud computing companies. Byrne and Corrado (2017a,b) report that investment prices for IT capital fell about 13 percent per year on average from 1986 to 2015. Following Jorgenson (1963), inflation for capital services can be expected roughly to align with investment price growth for the related capital assets, though as Byrne and Corrado (2017a,b) note, these price trends may diverge as utilization rates adapt to changing consumption patterns. In addition, Byrne, Corrado, and Sichel (forthcoming) find that the prices of cloud computing services fell 7 to 17 percent per year, depending on the type of service, from 2010 to 2016.[6]

[6] Although these primarily are services for the business market, they are generated from a similar capital stock, and the large difference between prices for business versus consumer services is implausible. Indeed a primary input to some components of consumer digital access services (e.g., subscription video on demand) is business digital access services from cloud computing providers.

II. Price Index Construction

Because digital access services lend themselves well to the direct observation of volumes, our approach to price index construction is to divide spending by a suitable quantity index for each type of service. Access services are akin to electrical utilities: The natural price for electrical utility services is price paid per kilowatt-hour, suggesting that the price for, say, internet services may be naturally constructed as price per unit of data delivered.[7] Of course, one should not treat intrinsically identical services delivered under different conditions of sale as the same item.[8] For this reason, we construct distinct indexes for data delivered via fixed connection (internet services) and for data delivered to mobile devices (smartphone services). Likewise, we construct distinct indexes for programming delivered with fixed time of broadcast (cable services) and for programming delivered at the time of the user's choosing (streaming services).[9]

The appropriate measure of volume for each these services should account for three margins of use intensity: the number of users, hours spent per user on the service, and the quality of an hour of service. We leverage a wide array of sources including government statistics, company reports and data published by trade groups and consultancies to construct an annual-frequency history from 1987 to 2018 for connected households, users, and time spent per day for each of these services.[10]

[7] Abdirahman et al. (2017) observe implausibly slow price declines for access services in the United Kingdom and propose a similar weighted unit value approach.

[8] The 2008 System of National Accounts (European Commission et al., 2009) cautions against using quantity indexes for electricity: "In most cases it is preferable and more practicable to use price indices to deflate current value data. Even for cases like electricity where the volume measure seems to be easily available, a direct volume measure is inappropriate because of the treatment of prices applying in different markets…"

[9] We construct a price index for streaming service based on information for Netflix, Amazon, and Hulu subscription video on demand (SVOD), which we use to deflate "Video and Audio Streaming and Rental" from 2007 forward.

[10] For additional detail on the data sources and assumptions used, see the online technical appendix.

In choosing quality indicators for each service, we distinguish between commodities and differentiated products. Internet and smartphone services are treated as utilities delivering homogeneous bits of data. Much the same as the quality of delivery service for a letter is independent of the content, the data transmitted by these services is put to use for diverse applications.[11] Accordingly, we use bits of internet protocol (IP) data transmitted as a measure of quality for smartphone and internet services, which are commodities.

Cable and streaming services, by contrast, are differentiated by programming and we account for quality using the number of program choices available.[12] In the case of cable television, we use the natural log of the average number of channels available on cable systems. That is, the quality improvement is the same when a system goes from 10 to 20 channels as when the system goes from 100 to 200 channels. In the case of streaming, we use the natural log of the number of films and television shows in the library.[13]

III. Example: Smartphone Service Prices

The approach we employ is illustrated here with smartphone services, the use of which rose from a minor share of the U.S. population prior to the introduction of the Apple iPhone in 2007 to roughly 80 percent in 2018 (figure 2a). Over the same period, hours per day users spent on their smartphones rose five-fold (figure

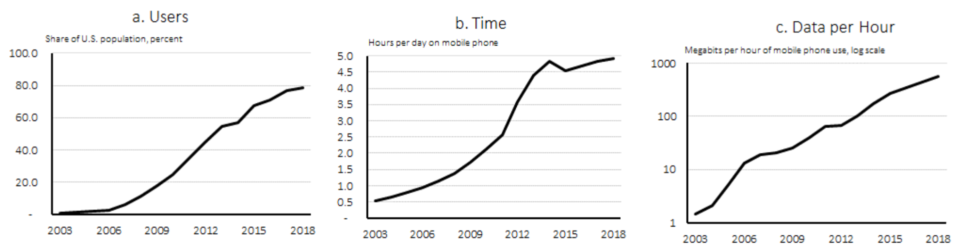
[11] Of course, the data transmission may be regarded as an input into a production process that takes place on the user's device. The consumer IT ecosystem is discussed in greater detail in Byrne and Corrado (2020), including the presentation of alternative prices for consumer IT durables, conditional IT equipment use rates, and estimates of capital services from connected IT devices. See the appendix to this paper for further details.

[12] This approach is based on Corrado and Ukaneva (2016, 2019) who find that number of TV channels (HD and standard) and availability of premium channels and 4K display resolution are important controls in cross-country hedonic regressions of prices for video services bundled with fixed broadband. Admittedly, the number of channels is a coarse indicator; Astine (2001) reports that consumers value some types of channels (e.g. sports and news networks) more than others.

[13] We combine films and series episodes by giving each film the same weight as two series episodes.

2b) and, although hours per day has stabilized since 2013, the amount of data used per hour on the smartphone has continued to soar (figure 2c).

Figure 2. Margins of Smartphone Service Volume



Source. Users, Pew Research Center, extended by the authors; Hours, Consumer Telecommunications Industry Association, reported by Federal Communications Commission, extended by the authors; Data, Cisco (2019), elaborated by the authors.

Our smartphone service price index is constructed by dividing total spending on smartphone service by aggregate data use, the product of the three series in figure 2. It falls exceedingly fast—an average of 50 percent per year from 2007 to 2018. That is, data used per dollar spent on smartphone service has doubled annually for 16 years. This is perhaps as one would expect given the use of smartphones to deliver an ever-widening array of popular services. Exponential growth in data delivered has been enabled by series of technical innovations in the industry. Over this time period, U.S. mobile phone service providers rolled out two successive generations of wireless technology—3G beginning in 2007 and 4G beginning in 2011, each enabling the transmission of an order of magnitude more data per hour (Hill, 2019).

Our mobile phone service index, which combines the smartphone index just discussed with a distinct index for feature phone service constructed using hours of talk time as a volume indicator, moves down 41 percent per year. Over this same time period, the CPI produced by the Bureau of Labor Statistics (BLS) for mobile phone services, which is used by the Bureau of Economic Analysis (BEA) in the

NIPAs moved down far more slowly, 4 percent per year on average.[14] Interestingly, we found that even an index of the average price paid per user for mobile phone services, which accounts for only the first margin described above, falls faster than the BLS index, at a rate of 8 percent per year.[15]

IV. Aggregate Digital Access Service Price Indexes

Our prices for the four types of consumer digital access services are shown in table 1a. Internet access service prices fell 36 percent per year on average. Price declines for mobile access services—20 percent on average—were somewhat slower than for internet services, but they accelerated as the composition shifted toward data-intensive smartphone service in the most recent period. In contrast, cable access service prices edge up a little under 1 percent per year over time. Streaming services, able to leverage innovations in IT capital more effectively than cable (e.g. by using cloud computing services), fall 23 percent per year on average.

Official prices for both internet and mobile access service also move down over time (table 1b), but at a pace an order of magnitude slower than alternative indexes. Cable access service prices move up somewhat faster than the alternative index, and the official price index for streaming services is essentially flat.

[14] Aizcorbe, Byrne and Sichel (2019) identified spending on equipment included in mobile phone services spending recorded in the national accounts. BEA now incorporates mobile phone prices in their estimate of mobile phone service spending to account for this portion of spending. Our final calculations of an alternative total PCE price index reported in the next section of the paper are an aggregate of our prices for mobile phone service proper and mobile phone equipment as well. Our composite index of equipment and services fell 20 percent per year from 1988 to 2018.

[15] Over this time period, the share of users with smartphones, for which monthly bills are substantially higher, surged from 6 percent to 79 percent; price per user ignoring this composition effect was essentially flat.

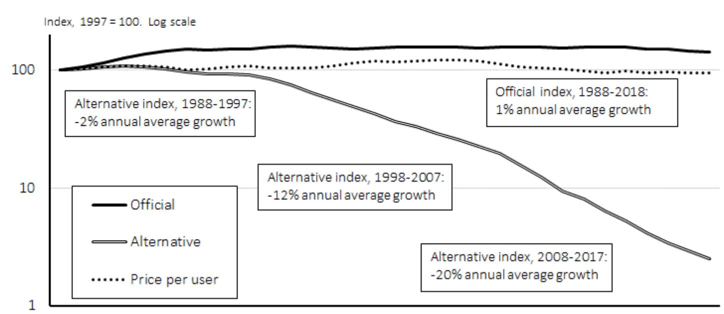
Table 1. Digital Access Service Prices
Average Annual Percent Change

	Internet Access Services	Mobile Access Services	Cable Access Services	Streaming Services	Total Digital Access Services	Memo: Total PCE
			A. Alternative			
1988-2018	-35.7	-20.1	0.6	NA	-11.9	1.9
1988-1997	-43.8	3.3	0.5	NA	-1.7	2.8
1998-2007	-41.3	-20.2	0.2	NA	-13.1	1.9
2008-2018	-23.3	-41.2	1.0	-22.8	-20.0	1.1
			B. Official			
1988-2018	-2.2	-3.7	4.3	NA	1.2	2.1
1988-1997	-4.6	-2.1	6.2	NA	4.5	2.9
1998-2007	-2.7	-4.7	4.3	NA	-0.2	2.0
2008-2018	0.3	-4.2	2.6	1.9	-0.6	1.5

Source: Bureau of Economic Analysis, GDP table 2.5.4U and authors' calculations.
Note: "NA" is "not applicable". "PCE" is "personal consumption expenditures".
Totals for digital access services and PCE include mobile phone expenditures as recorded in NIPAs. Mobile access service price index is solely services.

Combining the four alternative service indexes, our aggregate price index for consumer digital access services fell 12 percent per year from 1988 to 2018. This accords with our expectation, as discussed above, that prices would fall at a similar rate to investment prices for the related IT capital. In contrast, our aggregation of the indexes used in the NIPAs rose just over 1 percent per year. And, the gap between the two growth rates has increased over time, from a difference of 6 percentage points in the 1988 to 1997 period to 13 percentage points in the following ten-year period and to 19 percentage points from 2008 to 2018 (figure 3). In other words, if one takes our measure as the appropriate deflator for this consumption spending, mismeasurement in the PCE price index for digital services has risen substantially over the period studied.

Figure 3. Consumer Digital Access Service Price Indexes



Source. Authors' aggregation of BEA prices and authors' calculations of alternative index and price per user index.

For comparison, we also calculated the average price paid per user for each service type and created an aggregate index (figure 3, dotted line). The secular trend for the price per user index is very similar to the aggregate index based on NIPA prices (figure 3, solid black line). In other words, on average, the official price for digital access services implies there has been little change in the quality of service delivered by the internet, mobile phone networks, and cable systems for 30 years.[16] This is true despite the use of hedonic analysis for the CPI in the case of internet, mobile, and cable services.[17] Thus, it would appear that the solution to the challenge of controlling for quality change in price indexes for digital access services is more nuanced than simply, "use hedonics."

We speculate based on casual observation of the pricing practices of major firms in these markets that the component item prices used in the calculation of the index—i.e. prices for specific service plans—are typically unchanged over time.[18] In such a case, the entirety of quality adjustment in the CPI takes place when an item is replaced either because it is discontinued by a reporter or the BLS refreshes the basket. In the event, the premium or discount paid for the replacement item relative to the exiting item must be apportioned between a difference in quality and pure inflation.[19] If item turnover is infrequent, this approach may not introduce sufficient quality adjustment to produce an accurate index.

In some circumstances, the "flat item price" issue can be addressed with hedonics. Byrne, Oliner and Sichel (2018) do so in constructing a price index for microprocessors, for example. Other studies have provided hedonic price indexes

[16] In real terms, i.e. accounting for the increase in the general price level, quality has increased about 20 percent in total over this time period.

[17] The BLS website indicates hedonic quality adjustments are used for internet and television services and that analysts have estimated the value of wireless high-speed data for use in adjusting the cellular service index. (https://www.bls.gov/cpi/factsheets/telecommunications.htm, accessed February 9, 2020.)

[18] Greenstein (2002) remarked on this issue for internet access services.

[19] Nakamura and Steinsson (2012) identify this phenomenon—unchanging item prices—in the microdata for BLS trade price indexes as contributing to spuriously low "exchange rate pass-through" estimates.

for internet access services with faster declines than official prices, but noticeably slower prices than we find in our study.[20] The alternative we propose for digital access services is to divide aggregate spending by the quantity indexes described above to yield a price index, a solution akin to a hedonic regression with a single quality control variable. To the extent that other characteristics matter, such as latency or reliability of service, and are not correlated with our quantity index, our price index may differ from a true cost of living index. Also, our "hedonic" is constrained to pass through the origin, meaning that the consumer derives no value from a purchased service she does not use. There is surely some value to simply being connected—parents give their children mobile phones for emergencies, for example—but we suspect the distortion from this effect is second-order at the high volumes of service we observe.

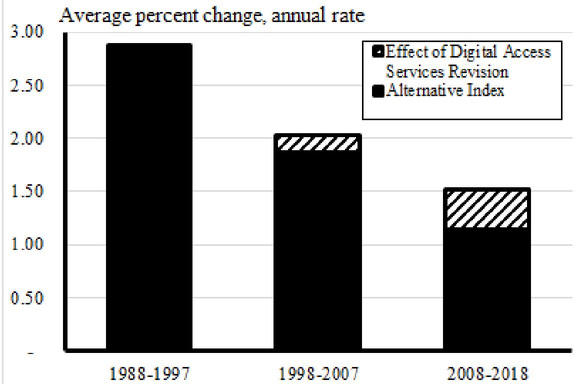
V. Total PCE Prices

Aggregating our alternative measure of digital service prices with official prices for the remainder of the index basket, total PCE prices increase ¼ percentage point more slowly on average than the NIPA PCE deflator over the 30-year period. The alternative index rises at an average rate of 1.9 percent while the official index rises at rate of 2.1 percent (table 1). Importantly, the difference between the official and alternative index growth rates increases over time. That is, the sharp declines we find in digital service prices, augmented by the rising share of these services in the overall basket, magnify the marked reported slowdown in the PCE inflation rate since 1987 by nearly ½ percentage point (figure 4).[21]

[20] Stranger and Greenstein (2007) and Yu and Prud'homme (2010) find price declines on the order of 15 percent per year for the 1990s in the United States and Canada, respectively. Greenstein and McDevitt (2011) and Flamm and Herrera (2017) report more modest declines for the 2000s. On prices for mobile phone services, see Yun et al. (2019).

[21] To be precise, our estimate is 39 basis points, a "weak ½." In Byrne and Corrado (forthcoming), we propose a set of alternative price indexes for consumer IT durables as well, which point to additional understatement of consumer IT price declines. Adding our estimates for IT durables to our estimates for IT services raises the effect to 47 basis points.

Figure 4. PCE Inflation



Source. Bureau of Economic Analysis; authors' calculations.
Note. Alternative index is aggregate of authors' index for digital access services and official prices for other items.

VI. Implications

The most basic implication of our finding that PCE prices have risen more slowly than reported in recent years is that real incomes and real expenditures have grown faster than indicated in official measures, perhaps indicating greater average welfare gains.

The policy implications of the apparent increasing divergence between the true cost of living and official consumption prices depend on future efforts by national statistical agencies to address this measurement issue.

If the method proposed here for digital access service prices were employed in the NIPAs, our work suggests this would result in a noticeably lower path for the PCE price index, the primary indicator of inflation employed by the Federal Open Market Committee (FOMC) to measure success achieving its statutory mandate of promoting stable price inflation. Assuming the FOMC's numerical goal for inflation remains unchanged, monetary policy would need to remain accommodative for longer to ensure the economy reaches the 2 percent inflation target.

With regard to fiscal policy, both government receipts and expenditures would be impacted automatically if the BLS were to adopt the approach proposed here in the CPI. For example, cost-of-living adjustments for social welfare program benefits indexed to the CPI would increase more slowly. At the same time, increases to (nominal) tax revenues from "bracket creep" would be more modest.

More subtly, the results presented here provide support for claims of the importance of the digital activity households conduct outside the boundary of national accounts.[22] Using the "free" services available on the internet—social networking, search engines, etc.—requires digital access services to transport data as a complementary input. The torrent of data consumed by households is in part the result of derived demand driven by the value of these "free" activities.[23] We discuss this issue in depth in Byrne and Corrado (forthcoming), including the additional measurement improvements needed to fully capture the value of free consumer digital activities in national accounts.

All told, we estimate that the consumer surplus associated with consumer digital goods and services amounted to about $30,000 per user from 2004 to 2017 (2017 dollars) and conclude that existing GDP misses consequential growth in output and income associated with content delivered to consumers via their use of digital platforms. The additional moves required to capture digital services

[22] See discussions in Brynjolfsson, Collis, Diewert, Eggers, and Fox (2019), Coyle (2019), and Nakamura, Samuels, and Soloveichik (2017).

[23] According to Sandvine, an internet consultancy, video streaming, including free video (e.g. YouTube) as well as purchased video and advertising, accounted for 61 percent of global downstream IP traffic in 2019, excluding China and India. Web browsing and social networking accounted for an additional 19 percent of traffic. *The Global Internet Phenomena Report, September 2019*.

consumer surplus in GDP are discussed in the appendix to this paper; note these moves do not affect measured output per hour in the business sector even though they are driven by correlates of the factors driving growth in paid-for, business-produced digital access services previously discussed.

Owing to the misstatement of real paid-for digital access services (alone), labor productivity growth appears to have been somewhat faster than official statistics indicate. Fernald (2015) identifies 2004 as a structural break in U.S. productivity growth, with a markedly slower rate since then: The most recent data indicates productivity has risen 1.1 percent per year on average from 2005 forward, down from 2.3 percent for 1995-2004. Employing our price series for consumer digital services, labor productivity has risen 1.3 percent per year since 2005 and 2.4 percent in the previous period. In short, the productivity slowdown has been on the order of 1 percentage point, rather than 1-¼ percentage point.[24]

Long run implications of our findings depend on whether rapid price declines for consumer digital access services persist. These plunging prices point to ongoing rapid innovations in the hardware and software employed by service providers which have enabled profitable delivery of the high volume of data required by digital household activity. It seems the "IT Revolution" is not over. Whether forthcoming waves of innovation, such as the 5G technology now being deployed for mobile services, will embody similar deflationary influence remains to be seen.

[24] Again, to be precise, our digital access service prices reduce the stepdown in productivity by 14 basis points. Folding in our prices for consumer IT durables spending, discussed in Byrne and Corrado (forthcoming), together with the alternative digital access service prices, the stepdown in productivity is reduced by 19 basis points.

Appendix. Data Sources and Methods

As shown in the table below, we leverage a large number of sources and make myriad judgements to estimate consumer digital access services. The central data source for smartphone and internet services is internet protocol (IP) traffic reported by Cisco, Inc. in their annual *Visual Networking Index* report. For cable television viewing hours from Nielsen Corp. are multiplied by the log of the number of channels available per system on average as reported by the Federal Communications Commission (FCC). For streaming, we draw on company statements, Nielsen data, and FCC reports. Complete accounting of the calculations is provided in the spreadsheet available from the authors on request.

Sources and Methods for Digital Access Service Prices

	Revenue	Households	Users	Time Units	Quality Units
Cable	BEA NIPA table 2.4.5U., line 215: "Cable, satellite, and other live television services"	1987-1988: Statistical Abstracts of the United States (citing Census of Housing) 1989-2015: FCC reports, "Status of Competition in Markets for the Delivery of Video Programming," (citing SNL Kagan reports) various years. 2016-2017: Extrapolated based on reports from available companies (AT&T, Verizon, Chartered, Comcast, DIRECTV, DISH)	1987-present: Number of subscribing households times number of residents at least two years old per TV household reported by Nielsen.	Average hours by age group (2-11, 12-17, 18+) reported by Nielsen, weighted by population age distribution from U.S. Census.	1987-present: hours weighted scaled by (natural log of) number of channels per system reported by FCC.
Internet	BEA NIPA table 2.4.5U., line 285: "Internet access"	Broadband: 1999-2017: FCC report, "Internet Access Services," various years. Dial-up: 1987-2000: company financial reports & press reports, extrapolated. 2001-2009: FCC report, "Internet Access Servics," various years. 2010-2017: AOL reports through 2014, extrapolated to 2017.	1987-1997: extrapolated using 1998-2008 growth rate 1998-present: prevalence of home internet use for adults and for population younger than 18 times population by age from U.S. Census.	1987-1991: judgemental extrapolation using 50% growth rate. 1992-2008: hours per user from Statistical Abstract of the United States (reporting data from VSS Consulting) 2009-2010: log-linear interpolation 2011-2018: hours per user reported by Nielsen	1987-1989: extrapolation using 1990-1993 growth rate. 1990-1993: Volume extrapolated using global fixed internet traffic. 1994-2004: Volume extrapolated using overall fixed internet data traffic (North America) from Cisco. 2005-2018: Volume of consumer fixed internet data traffic (North America) from Cisco.
Mobile: Feature Phone	BEA NIPA table 2.4.5U., line 281: "Cellular telephone services", less estimate of mobile phone (equipment) spending included, allocated according to weighted feature/smartphone user mix (Assume smartphone contracts are 4 times as expensive as feature phone contracts.)	U.S. households times individual feature phone penetration share.	1987-2004: Statistical Abstracts of the United States (citing Consumer Telecom Industry Association) 2005-2018: share of adults who own cell phone less share who own smartphone (Pew Research Center) times population greater than 15 years old (U.S. Census)	1987-1992: extrapolated using 1993-1998 growth rate. 1993-2014: talk time per subscriber from FCC reports, various years (citing CTIA), smoothed. 2015-2018: average talk time, 2010-2014.	Hours of talk time (no quality change).
Mobile: Smartphone	BEA NIPA table 2.4.5U., line 281: "Cellular telephone services"less estimate of mobile phone (equipment) spending included, allocated according to weighted	U.S. households times individual smartphone penetration share.	2005-2018: share of adults who own smartphone (Pew Research Center) times population greater than 15 years old (U.S. Census)	2005-2010: extrapolated 5% growth 2011-2017: average time spent on smartphone from press reports (citing eMarketer), smoothed.	Cisco-reported mobile IP traffic
Streaming	2007-2011: revenue per member extrapolated backward using 2012-2013 growth rate times reported paying members (members reported for 2009-2011, extrapolated for 2007-2008) 2012-2018: company annual reports	Company reports supplemented by press reports and extrapolated.	Number of households times average household size reported in population Census.	Data use divided by data rate per time unit using North American fixed internet protocol traffic reported in Cisco VNI Forecast, various years times share of traffic for each provider reported by Sandvine, times average data rate based on HD/SD shares derived from Cisco VNI forecast.	Raw viewing hours multiplied by high-definition video share, scaled by (natural log of) number of titles available by service scaled as one movie = two TV episodes, one TV season = 15 TV episodes. (FCC reports, news sources)

Notes:
For additional detail, consult the notes below columns in the service calculation tables.
Streaming price index is based on spending and quality units for Netflix. The resulting index aligns, on average, with more volatile indexes constructed for Amazon and Hulu streaming based on more limited information.

Appendix. Consumer Digital Capital Services

The body of the paper presents prices for consumer digital *access* services. Here we review how "free" services can be measured as consumer digital *capital* services, which has two major implications. First, as discussed in the main body of the paper, it suggests that the implied price change for "free" services is related to prices for the digital gizmos that enable generation of such services. Second, it implies that capitalizing consumer "connected" IT capital preserves the scope of digital services consumption that can be captured in national accounts. When consumers watch a Netflix movie on their home TV or tablet computer instead going to a movie theatre, the home-based consumption is captured via services of their IT capital. Without accounting for consumers' use of connected IT capital, final demand would be lower because theatre tickets would not be purchased.

Importantly and as discussed in depth in Byrne and Corrado (2020), the choice of whether to buy or rent IT capital varies over time, much the same as happens for residential housing. In the case of housing, the imputed services of owner-occupied housing and payments for rental properties are both counted in PCE. As with housing, inclusion of connected IT capital services affects PCE in two major ways. (1) The imputed capital services are counted as consumption and income, raising nominal PCE. (2) The additional services are deflated by the price of IT capital, which raises real PCE because IT prices fall faster than PCE prices on average. In addition, the use intensity of equipment augments the stream of capital services.[25]

The estimate of the increase in consumer surplus reported in the text is built from the price and quantity dynamics of three separately estimated components of

[25] This impact should not be confused with the full impact of capitalizing consumer IT durables (or even all durables), in part because of the impetus from increased use of smartphones and computers for accessing content delivery services but also because some digital IT goods, e.g., cameras, are not only standalone capital but have experienced a sharp fall off in demand.

PCE as set out in table 3 of Byrne and Corrado (2020): digital IT goods investment, digital IT capital services, and digital access services.

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