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JEL classification: O4, O3, E0

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Corporate equity market values, profitability, and intangible investment have reached high proportions of income. Are these investments and their outcomes evidence of a well-functioning society? We do not see the rapid growth in aggregate measures of output that would justify these investments and rewards. And why did the yield curve invert as the U.S. federal funds rate reached 2⅜ percent in early 2019, if the inflation rate was near 2 percent? We present the broad case that mismeasurement of growth and prices accelerated in the U.S. during the 21st century and may be responsible for the appearance of secular stagnation in the U.S. We argue that it is possible that productivity growth has accelerated and that prices have been deflating during much of the 21st century. The evidence is very incomplete; large uncertainties surround these estimates. Indeed, the main message of this paper is that uncertainty in economic measurement has risen substantially.

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I. INTRODUCTION

Has economic progress become harder or has progress become harder to measure? This paper seeks to explore the possibility that economic growth in the U.S. is substantially faster in the 21st century than currently measured in U.S. national income accounts data, and that inflation is substantially slower, indeed, that the U.S. has generally been deflating since the Great Recession. We point to evidence across many product areas that rapid progress is occurring. This raises the possibility that not only did U.S. growth and productivity accelerate after 1995, they have possibly continued strongly after 2005 and there has been no secular stagnation. This is a counterpoint to the arguments in Syverson (2017), Byrne et al. (2016), and Groshen et al. (2017) in that we position our arguments relative to the period just before the productivity acceleration from 1995 to 2007 so that the influence of the Internet overall can be viewed clearly.

Our view also challenges the narrative that capitalism is failing by not delivering progress; if anything, we argue progress is too rapid and the incentives to deliver it are extremely strong.

Increasingly, economic progress is taking forms that are not readily measured in the U.S. gross domestic product (GDP) accounts (Hulten and Nakamura, forthcoming). Knowledge and intangible investment are rising rapidly, new products are arriving faster, and the Internet has reduced reproduction costs for many products to zero. All this progress is understated in the U.S. national accounts. This point has been made in several recent papers, including Aguiar et al. (2019), Aghion et al. (2019), Hulten and Nakamura (2018, forthcoming), Brynjolfsson et al. (2019, forthcoming), Byrne and Corrado (forthcoming), Nakamura et al. (2018), Boerma and Karabarbounis (2019), and Neiman and Vavra (2019). The consequence is an appearance that economic progress has slowed rather than accelerated, and that inflation is positive, when in fact the economy is likely deflating. We argue that mismeasurement of real output and inflation could well equal or exceed 2 percent annually, and that acceleration of mismeasurement in the 21st century has been close to 1 percent annually. This is not the fault of U.S. statistical agencies, which arguably remain among the best in the world. The measurement problems discussed here are worldwide and addressing them satisfactorily will require renewed efforts from the entire economics community.

We have argued (Hulten and Nakamura; 2018, forthcoming) that a fully satisfactory view of GDP may require a redefinition of GDP, which we have dubbed EGDP for Expanded GDP. In that work, we address how to formally address the gap between current measures of GDP and welfare measures of output and inflation. We recapitulate this argument as follows:

Real personal consumption expenditure (PCE) is not a welfare measure, as it is measured in the national income accounts, nor is real GDP. However, the underlying economic theory of price and growth is welfare based. For example, the rate of inflation needed to measure the real interest rate is based on the consumption value of an additional dollar in the future relative to today. This is a welfare calculation. Moreover, real growth is, in theory, a money metric utility calculation. Money metric utility is based on the expenditure function: How many nominal dollars today does it cost to buy last year's utility bundle? Real PCE growth is the growth in nominal dollars beyond that measure. This is an average utility calculation, so the calculation is not quite the same as for the theoretical inflation measure, which is a marginal measure. Nonetheless, both are utility calculations. Our claim is that the divergence between the national income measures and welfare has accelerated, and that the national-income measures are becoming less useful for many economic decisions.

A central problem that we face in measuring the economy is the rising economic importance of knowledge and creativity, as the economy focuses on intangible assets, and that these are increasingly digitizable due to the Internet. Once in digital form, reproduction of many products is virtually costless. In a modeled economy in which prices represent marginal resource costs, such goods have zero prices and disappear from GDP. In practice, new business models that accommodate these products make the quantification of consumer welfare and productivity more difficult.

More generally, flows of knowledge and data are very difficult for statisticians to detect and to value. They are nonrival goods, and close to public goods. And, as Hulten and Nakamura (2018, forthcoming) argue, these flows have large impacts on production and consumption technology. A further difficulty is that the value of knowledge and creative products depends on the consumer: The characteristics of the receiver matter as much as what is transmitted. This heterogeneity makes valuation more controversial.

A quantitatively important problem is that we do not quality adjust either health or educational services for advances in medical or curricular knowledge. Much research has been done in the areas of health and education, but their productivity continues to be negative; among other difficulties much of hospital services and education services are provided by nonprofits and governments and are, under national income procedures, deflated using inputs. As these are areas that are increasing in importance, this exacerbates the potential for mismeasurement.

Intangible investment — business investments aimed at creating new products — has become the prime form of U.S. capital investment. Such investment has risen while investment in tangibles has fallen, and such has been the power of this intangible investment that economic profits of corporations have risen very substantially as a proportion of GDP. Unfortunately, how to measure intangible investment remains controversial, and as a result, unlike tangible investment, we deflate intangible investment with inputs. (To this is added an overall productivity correction, but since we mismeasure productivity this correction is incomplete.) Since the falling price of many tangible investments, particularly computers, has been an important source of productivity growth in the past, an economic transition from tangible investment to intangible investment also leads to an acceleration of mismeasurement.

This expansion of intangible investment, and the concomitant decline in the importance of physical quantities of existing products, has led to an increase in the rate of introduction of important new products and faster improvement in the quality and variety of products. One indicator of this is faster turnover of products — more products disappear and are replaced by new ones — as variety increases.

Can we come to an agreement on how to measure these difficult-to-measure phenomena? Or are we doomed to ignore them? Right now we are far from having measures that we can all agree on, and in the absence of such measures, macroeconomics is flying blind, and our policy advice must be far less self-confident than in the past. However, a substantial amount of work is ongoing to create new measures of output growth and inflation, and we will draw on these to illustrate the scope of acceleration of mismeasurement that may be present. Hulten and Nakamura (2018, forthcoming) and Coyle and Nakamura (2019) offer overviews of the path forward. Articles cited herein point to a variety of methods that can be used to capture consumer surplus including capturing the shadow value of time, using revealed preference, direct surveys of consumer value, parametric models, and direct quantity (units). To the extent that such methods arrive at similar answers, we may be able to reestablish a new consensus on how to measure economic activity.

The body of this paper will begin with a discussion of the big four Internet firms, Amazon, Apple, Facebook, and Google. These four firms' highly profitable activities do not appear as growth in PCE that shows through to GDP. That section is followed by a discussion of acceleration of mismeasurement in personal consumption expenditures, followed by a section on the rise of intangible expenditures.

II. THE BIG FOUR INTERNET FIRMS AS EXAMPLES OF MISMEASUREMENT

According to the Bureau of Economic Analysis, U.S. domestic corporations' after-tax economic corporate profits for the period 2007 to 2017 averaged 9 percent of GDP, up from under 6 percent from 1985 to 1995, as shown in Figure 1. To the extent that these profits arise from new products, this producer surplus should be reflected in increases in productivity: Consumers are purchasing products which are superior to existing products, and even if there is no added consumer surplus, the resource cost for these products has fallen with respect to their utility. In addition, the market value of the equity of U.S. domestic corporations has risen relative to GDP. On average, this corporate market value was 70 percent of GDP from 1985 to 1995, while it was 147 percent of GDP from 2007 to 2017, as shown in Figure 2. The changing value of corporate market value is, of course, volatile due in part to market imperfections and lack of perfect foresight and to changing expectations on the expected returns to capital and risk premiums. Nonetheless, in a well-functioning capitalist economy these increases in market value, which indubitably increase the power of corporations to hire workers and to buy assets, should reflect the social value of these corporations' production. Yet we do not see these increases in profitability and market value reflected in gains in productivity and economic growth per capita.

There are three intertwining reasons for understatement of growth: quality, intangibles, and zero prices. First, quality: New goods representing quality improvements are difficult to evaluate quantitatively, and the proportion of new goods is rising. Moreover, what we are good at measuring, increases in quantity, has ceased in many areas where growth has traditionally occurred, such as cars, gasoline, and new housing. Second, intangibles: Expenditures on, profitability of, and the market value of intangible investments have all risen. The real impact of intangible investments has been astonishing in a variety of areas of economic activity. Yet although we can measure the inputs that go into intangible investment, measuring its real quantity has proved difficult. Moreover, the country of residence of intangible assets is difficult to pin down, unlike tangible investments, and this makes the location of its capital services hard to determine. Third, zero prices: New business models are adapting to costless reproduction of knowledge and entertainment by providing consumers products at zero marginal price, posing difficulties for measurement of consumer surplus and output.

Here we examine the big four Internet firms, Apple, Amazon, Facebook and Google, and show that their consumer outputs do not add to economic growth as measured. Are these firms in fact reducing economic output?

At the end of 2017, these four were worth some \$2.6 trillion in market capitalization, and earned some \$80 billion in after-tax profits, up from less than \$400 billion in market cap and \$8 billion in profit in 2007.[1] To put these figures in perspective, total U.S. domestic corporation market cap was \$38 trillion in 2017, up from \$20 trillion,[2] and after-tax economic profits were \$1.8 trillion, up from \$1.4 trillion.[3] Thus the big four accounted for \$2.2 trillion of the \$18 trillion gain in market cap, and \$72 billion of the \$400 billion gain in profits that occurred during this period, more than 10 percent of each. They provide a valuable and economically significant window into the workings of the U.S. economy and our official measures.

Because this paper challenges the validity of inflation measures, for the most part we will lay out these issues in purely nominal terms. For example, one might wish to see to what extent the nominal differences in market cap and profits just discussed translate into real differences. If we were to deflate the above statistics using official inflation rates, the proportions of gain in market cap and profits represented by the big four would be even larger. As it is, if we were deflating during this period, the nominal measures may somewhat overstate the proportion of gains represented by the big four; however, in that case, all the real gains would be even larger relative to the aggregate gains than the nominal proportions.

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[1] Corporate data here and elsewhere is taken from Compustat data. Copyright © 2020, S&P Global Market Intelligence (and its affiliates, as applicable). Obtained via Wharton Research Data Services (WRDS). No further distribution and or reproduction permitted. It is supplemented with data from company annual reports.
[2] U.S. Flow of Funds and Haver Analytics.
[3] U.S. National Income Accounts and Haver Analytics.

All four of these big Internet firms are focused on providing products for consumers, yet their consumer-facing activities do not show up in GDP and probably shrink it.

II.1 Quality: Amazon

A key difficulty in the measurement of quality is that consumers have heterogeneous evaluations of its addition to value and our statistical methodology takes a conservative view of it. Amazon's primary innovation as a retailer is ecommerce, supplying books and other products to consumers and delivering them to their doors. In particular, as of 2018, Amazon had over 100 million subscribers to Amazon Prime, which offers free fast delivery (and there are fewer than 130 million households in the U.S.). Amazon sells most of these goods for less than it would cost to buy them from brick-and-mortar stores (Cavallo, 2017), but as a different outlet, statistically speaking those declines in product prices appear as inferior quality (this is known as *outlet bias*). That is, in the absence of a direct measure of Amazon's retail service quality, the lower prices of its books and other products imply that it is providing an inferior service: If customers are willing to pay higher prices at brick-and-mortar stores, they must be doing so because they receive a superior service. The fact that a great many customers prefer home delivery does not enter into this calculation. At the same time, Amazon's consumers drive less often to stores, which appears as a decline in consumer final expenditures on gasoline. Of course, Amazon spends more on deliveries, which increase its motor fuel purchases, but those are intermediate purchases and do not show up in final GDP, further decreasing measured productivity. The switch from household production of delivery services to Amazon's production appears as an increase in input costs as well as a fall in final output.

A second product that Amazon has introduced that has been highly profitable is Amazon Web Services, Amazon's public cloud product. Public and private cloud services provide very large gains in the efficiency with which computer investments are used. As a result, real investments in computers have not grown as in the past, although the effective amount of computer power in use has swelled. Real investments in information processing equipment has slowed dramatically because we do not measure the computing power that these investments represent (see Byrne et al., forthcoming. An economically important impact of AWS and other cloud services has been to substantially reduce the fixed input cost of an Internet startup, by two or three orders of magnitude, as is discussed later.

II.2. Intangibles: Apple

Apple makes the iPhone, but primarily by generating the intangibles of design and software that are embedded in the iPhone. Production is outsourced to China and other countries. So iPhones do show up in personal consumption expenditures (PCE), but almost all of what appears in GDP is then subtracted out as an import. Apple, in our statistics, appears as if it were an importing wholesaler, rather than a producer of smartphones (Guvenen et al., 2018). One way of viewing this problem is that Apple is supplying an intangible export that is incorporated into the iPhone in China before it returns to the U.S., but this export is not recorded in GDP.

Indeed, Apple reports its intangible assets as residing in Ireland for tax purposes. Unlike tangible assets which must occupy geographical space, intangible assets by their very nature have no fixed location. This makes defining the *domestic* product in gross domestic product more difficult. There is no transaction reported when Apple exports intellectual property from the U.S. to Ireland, whereas there would be an export if Apple exported tangible equipment to Ireland.

We are living in an age in which U.S. investments in intangibles — investments to create new products and processes — are very large and rising and exceed U.S. investments in tangible goods (Corrado et al., 2005, Nakamura, 2003). Although some of this expenditure is now recognized in U.S. GDP as investment, most of it remains unrecorded. In particular, when a corporate intangible investment is successful, a corporation must spend additional resources to market and support it; roughly half of corporate "Sales, General, and Administrative" expenditures appear to function as capital investments, although they are not considered such in the national income accounts. These expenditures are a reliable marker of the ex post value of intangible investment and are very useful in measuring the market value of a firm's intangible investment. Yet it is precisely these corporate investments that are omitted from GDP. Figure 3 shows U.S. nominal investments in tangibles and intangibles, including official measures of intangibles from U.S. GDP measures, and intangibles as measured using the methodology in Nakamura (2003).

Moreover, what we mean by *real* investment in intangibles is unresolved; we do not have a satisfactory means for deflating the nominal investments we record. What we do in general is to measure real intangibles by deflating with input prices and adding back in a measure of overall productivity growth. As we shall see, we do not do a good job of measuring input price changes, implying that the productivity gains of these intermediate producers are also lost. Since tangible investments have been an above average source of productivity gain, a switch from tangibles to intangibles results in a measured slowdown in productivity. Aside from measuring input costs better, we can also use the rate of obsolescence of intangibles as a measure of the rate of qualitative output growth.

We can see the payoff to these investments in intangibles in quality improvements and cost decreases in a multitude of products, not just in the Internet. These provide further evidence of the acceleration of the U.S. economy.

II.3. Zero price goods: Facebook and Google

Facebook and Google provide their main products to consumers for free, and they gain almost all of their revenues from advertising. So the consumer benefits of Facebook and Google do not show up in PCE (Nakamura et al., 2018). Rather, they appear as increased costs of marketing in the products that are advertised. And since some of their products replace products that consumers used to pay for, such as snail mail, film processing, or music CDs, they also tend to reduce GDP. As we discuss in more detail below, consumers are spending a large proportion of their leisure time using free services. The advertising model is far from new; radio and TV are also supplied for free subsidized by advertising. But the Internet makes the model far more powerful and broad-based.

Nominal GDP measures inputs and outputs and equates the two. To the extent that Facebook and Google pay workers and make investments, their inputs and outputs must appear in GDP. Facebook and Google earn almost all their revenues from advertising and so their production within the GDP framework is seen solely as an intermediate input into the advertised products. To the extent, say, that they earn advertising revenue from soap manufacturers, they are an intermediate input into soap revenues. If this is all they do, then they contribute to the costs of GDP without directly contributing to final output. Their value to consumers is not measured.

From the logic of the fundamental welfare theorems of competitive economics, the price of a good should reflect its resource cost. The paradox of air (or water) versus diamonds is that air has great utility and diamonds do not, but air has zero price and diamonds have a large price. This paradox is invoked to dismiss the value of goods with zero marginal price. But a proliferation of such goods increases the wedge between welfare- and transaction-based measures.

Why is the "free" model so powerful as to make Google and Facebook two of the globe's most valuable companies? A key consequence of the Internet is the very low cost of reproduction of digitized goods. Entertainment and knowledge and information of all kinds have become available at zero marginal resource cost, and providing them at zero marginal price is therefore optimal. The advertising model is one way to achieve this optimum.

Zero marginal prices can also be sustained by bundling into a subscription. Many products, like movies and music, increasingly come bundled in subscriptions where the marginal price of a viewing, a listen, or a read is zero. This bundling extracts greater value from the customer, but it does so by providing greater utility — the customer has greater access to the full catalog of movies, TV, and music. When these goods were sold or rented as physical CDs or DVDs, a consumer's choice at a given time was limited by the inventory in hand either on his or her shelves or at the retailer. Now the consumer has on hand the bundler's entire catalog. This improvement in access is hard to evaluate. Moreover, on the Internet, customers can sample freely, and because entertainments are experience goods whose utility is hard to predict in advance, this sampling itself has substantial informational value for the consumer. This dynamism makes it even harder to infer the value of the good to the consumer.

Our industrial era statistical methods do not properly interpret these business models — ecommerce, outsourcing, advertising support, and subscriptions — and make it appear as if we are reaping far fewer benefits from intangible investment and enjoying less consumption than we are. In addition, old problems, like the measurement of quality change and new products, have become more important and challenging.

Of course, just because a good has zero resource cost does not mean it must have zero price; shifting from a world of the welfare theorems to a world of creative destruction, we often do pay positive prices for goods with zero marginal resource cost as a consequence of market power created by intellectual property rights. These positive prices represent a return to intangible investments and are pure producer surplus once the intangible investment is sunk. In addition, the increased proportion of such products reduces the connection between transactions and resource costs.

III. DIRECT MEASURES OF CONSUMER WELL-BEING

In this section, we summarize work on two problems of measures of consumer well-being, the first being measures of variety and new products and the second the Internet and zero priced goods. We shall argue that it is conceivable that personal consumption expenditures inflation has been overstated by 2 percent, and that the acceleration of inflation may be 1 percent.

III.1 Statistical procedures

Before we go further, it is useful to discuss how real expenditures are constructed. For the most part, nominal transactions are estimated from consumer expenditures, generally retail sales estimates less purchases by businesses that are considered intermediate products. Box office receipts at movie theaters are one example. These are then typically deflated with consumer price indexes, which are calculated month to month by taking the prices of precisely defined products (brand, product, size) that are identical over time (including being purchased from the same establishment). In the case of movie theaters, this will be the price of a movie ticket. Periodically, the products being priced are refreshed with a new sample; each new item and the outlet at which it is to be measured are chosen randomly to match consumer expenditure patterns.

The economic theory that underlies price measurement relies upon the expenditure function: how much money do we need to pay to buy the same utility that we received previously. If all consumer products are available in the present and past periods, and assuming rationality and unchanged tastes, then we can bound the expenditure function with Paasche and Laspeyres price indexes and closely approximate the theoretical measure by measuring the price change for each item from period to period. In other words, if products and their utilities are unchanged from period to period, then our procedures approximate a true cost-of-living index. The proportional increment in nominal income, beyond what is needed to maintain constant utility, is considered to be the rate of increase in real income. This procedure defines a money-metric utility function, in the sense defined by Samuelson (1974) and as justified by Diewert (1976, 1978).

However, this justification no longer holds true if (1) a new product appears, (2) a new sales outlet appears, (3) a product price falls to zero, (4) an old product disappears, (5) the quality of a product changes, (6) the information that consumers possess about a product changes, or (7) a consumer uses an existing product for a new purpose. When rapid changes occur in consumer behavior, in the business models by which products are sold, and in the knowledge that consumers and experts possess, our standard methods of accounting falter. It is worth noting that in the movie theater example, there is no attempt to measure the average quality of the movies shown, and that is true for many service sector products, such as education and medical services. That is, what our statistics call an identical product from period to period may not, in fact, have the same utility.

III.1.1 Treatment of product disappearance. A practical difficulty in the consumer price program is that quite often the products chosen for measurement disappear permanently. This means that the observation for that period is lost. An added wrinkle is that just before it disappears, a product is often being sold at a discounted price (they may be placed on a deeply discounted final sale rack, for example). This means that if the next item is simply spliced in, the discount price will be permanently embedded in the price series, and we would observe deflation over time (Moulton and Moses, 1997). This problem can be solved if the Bureau of Labor Statistics (BLS) price collector can find a comparable item that is not on sale and has the price that the original item would have had were it not on the sale rack. If the price collector cannot find such a comparable item, a procedure called class-mean imputation is used. In class-mean imputation, the average price increase when comparable items *can* be found is used to impute the missing price change when comparable items cannot be found. This class-mean imputation expunges final sale effects, if it can be assumed that the comparable items and the noncomparable ones are similar in their pricing.

One idea that supports this approach is that measured price declines should reflect only changes in cost of production.[4] The temporary fall in price just before a product disappears is not due to a change in cost, but rather due to the discontinuance of the product.

[4] The BLS treatment of new cars in an example of this approach. When items that were formerly options become standard and are included in the base model, the BLS asks the manufacturer how much the item cost to produce, not what the option cost previously.

When goods enter the production bundle and others leave, this raises the difficult question of whether the entering goods are superior to the goods lost, and, if so, by how much. Perhaps the final sale of a disappearing item reflects its obsolescence. If so, removing the final sale effect prevents us from measuring this obsolescence. Using the expenditure function measurement principle just outlined, the increase in price inflation from one period to the next is in principle the relative increase in the cost of maintaining the same utility in the new period as in the old. Ideally, we need to find the utility-price ratios of new goods vs. old goods. In practice, measuring such ratios is very difficult. Shapiro and Wilcox (1996) labeled the problem the "house-to-house combat of price measurement." New varieties that are of substantial value to consumers may also appear, but the procedures just described will not measure the value of new varieties.

Now in some cases, prices of goods do fall due to obsolescence. For example, for many years Intel would rapidly and steadily mark down the prices of its microprocessors, and the personal computers that were built with them showed a similar steady decrease. Other consumer durables show a similar pattern as prices of components have fallen steadily. Yet even in this case not all quality improvement is captured. Bils and Klenow (2001) argue that quality change in durable consumer goods was 3.7 percent annually, of which 1.5 percentage points were captured in the CPI and 2.2 percentage points were not (see also Bils, 2009).

When items permanently disappear from the economy and are replaced by new ones, this can be described as a change in variety, in new goods, or as quality improvements. We discuss these in the following section.

III.2 Turnover, variety, and new products

Here we consider measures of acceleration in product turnover and calibrate its impact by using two recent studies, one focusing on outlets (Aghion et al., 2019) and the other on variety (Neiman and Vavra, 2019).

III.2.1 Faster turnover. Variety growth and product turnover has been rapid over the past decades. One important indicator is the rate at which products disappear from outlets. A source for this statistic is the BLS consumer price measurement program. How often do the products chosen to be prices in the CPI permanently disappear so that their monthly price change cannot be found? The answer is relatively frequently, and there is some indication that the rate has accelerated. In Moulton and Moses (1997), the average rate of product replacement across all products in the CPI was 3.85 percent in 1983, 3.95 percent in 1984, and 3.90 percent in 1995, representing overall stasis in this statistic over that period. In Groshen et al. (2017) this rate has risen to 5 percent as measured in 2014. This represents a 25 percent increase in the rate of product disappearance: The average product is available to be priced for 20 months rather than 25 months.

Interpreting this faster rate of product disappearance is not easy. Product disappearances may be trivial, such as a change in model number, in which case a direct substitution may be made for a comparable item. Both in 1995 and in 2014, in 40 percent of the cases, no comparable item can be found, suggesting a nontrivial disappearance.[5, 6] This suggests the possibility that new products are entering at a faster rate and displacing existing products faster.

For this to be occurring at a 25 percent faster rate suggests accelerated mismeasurement from this source over the period 1995 to 2014. It would be useful for the BLS to publish annual time series of the rate of product disappearance (including the rate for each major product category as was done in Moulton and Moses).

III.2.2 Outlets. One source of this faster rate of product disappearance could be turnover in outlets. As noted for Amazon, when a new outlet sells goods at lower prices, its products will be deflated using the price index for existing outlets. Since the prices are lower at Amazon, it will appear as if it is selling fewer quantities; this is the “outlet” bias of Reinsdorf (1993).

Faster turnover in outlets has been studied by Aghion et al. (2019) who attribute a roughly 0.5 percentage point rate of overestimation of inflation to this source for all nonfarm business. Their data show an acceleration in this mismeasurement bias, from 0.52 percentage point in 1983–1995, to 0.48 in 1996–2005, to 0.65 in 2006–2014. This represents a 25 percent increase in the rate of mismeasurement from 1983–1995 to 2006–2014, which fits with the

[5] For clothing items, which disappear with high frequency, comparable items can sometimes be found with differences in the type of fabric. In these cases, the BLS uses hedonic methods to infer the implied change in price. A switch from cotton to rayon in socks will be evaluated depending on the proportions and the coefficients on the hedonic equation.

[6] The proportion of comparable items was lower in 1983 to 1984, but in the interim the BLS had changed central features of its product replacement program as Moulton and Moses discuss, pp. 335–6.

acceleration in the rate of product disappearance. We can get a 0.13 percent rate of acceleration of mismeasurement from this source. While this study looks at nonfarm businesses as a whole, much of the impacts are concentrated in hotels and restaurants, so these effects are in important consumer sectors. This is line 1 on Table 1, which shows impacts on the PCE deflator, and line 1 on Table 4, which shows impacts on the GDP deflator.

III.2.3 Variety. Another form of mismeasurement is variety increase; while products disappear, even more new products appear. New products — such as Greek yogurt, heirloom apples, and Tostito taco scoops — may offer different characteristics that some customers value highly while others do not. The presumption is that these new products and varieties require additional costs in their creation and adoption, including research and development and marketing costs. And to justify these costs, the new products must offer opportunities for additional profits.

Are consumers substantially better off when there are differences in the shape, taste, or density of products? Niemann and Vavra (2019) study this question using Nielsen Homescan data, which primarily examines nondurable goods of the kind found at grocery and drug stores.

Current statistical methodologies do not capture consumers' valuation of greater variety, although the production and distribution of greater variety evidently add to production costs, such as by increasing the storage and display costs of the greater number of products.

If consumers didn't care much about new varieties, then given product price fluctuations, we ought to see these new varieties being purchased fairly randomly across different households as prices varied. This would be reflected in the household's basket containing a wider variety. However, instead what we see is that when a household adopts a new variety, it tends to value it very highly. So much so that while the overall variety of products has increased substantially, each individual household shopping basket has actually fewer varieties. This suggests that when households choose the new varieties, they strongly prefer them to the old choices that they have replaced.

With a parameterized model, Neiman and Vavra find that over the 12-year period from 2004 to 2016, variety increased welfare by 9.5 log percent, or about 0.8 percent annually. They do not have data from 1983 to 1995. If variety growth were 25 percent greater in this period compared to 1983–1995, using the BLS CPI product disappearance measures discussed earlier, then it is possible that there was a 0.16 percent acceleration in mismeasurement due to variety improvement. This study applies directly only to a relatively small amount of the household budget; nondurables are roughly one-fifth of PCE, reducing the overall acceleration within PCE to 0.03 percentage point (line 2 on Tables 1 and 4). This part of consumption, nondurable goods, is generally considered to be much better measured than the services sector, in many areas of which quality measurement is not attempted. So to be conservative we limit the impact to only the sectors under study, but we should keep in mind that it would not be surprising to find it applies to all of personal consumption expenditures.

To underscore the possible increase in variety across additional products, it is worthwhile to look at new products in pharmaceuticals, hospitals, and electric lightbulbs.

III.2.4 Pharmaceuticals. In 2016, manufacturers of pharmaceuticals and medicinals spent some $99 billion on research and development, accounting for more than 20 percent of all U.S. R&D. Moreover, the U.S. government also invested roughly $30 billion in FY 2016 through the National Institutes of Health. At the same time, the level of productivity of drug manufacturers, according to the BLS's industry productivity studies division, fell by 25 percent from 2007 to 2018, or about 2.5 percent annually. The inflationary counterpart of this fall is a sharply rising real price of prescription drugs of 21 percent over this period (as measured in the personal consumption expenditures deflator). Prescription drugs expenditures were roughly $400 billion in 2016, or 3.1 percent of PCE; by comparison, in 1995 they were 1.3 percent of PCE. Pharmaceutical company profits, according the Census's Quarterly Financial Reports, were $63 billion in 2016. Is it true that the patents being produced by pharmaceutical companies are without value and do not increase the productivity of drug manufacturing? If price inflation in drugs is overmeasured by 5 percent annually, this would result in a 25 percent increase in the productivity of drug manufacturers, rather than a 25 percent decline. With drug consumption accounting for 1.3 percent of PCE in 1995, a 5 percent mismeasurement adds 0.065 percentage point to PCE growth, while with 3.1 percent of PCE in 2016, the mismeasurement implies that drugs add 0.155 percentage point to PCE growth, an acceleration of 0.09 percent (line 3 on Table 1 and Table 4).

The difficulty of measuring prices correctly is illustrated by age-related macular degeneration (AMD), a disease which strikes 12 percent of those over 80 and can result in blindness. Currently over 2 million in the U.S. suffer from this disease.[7] Two drugs are now used to treat AMD: Avastin and Lucentis. Lucentis was the first drug approved for treatment, in 2006. In 2012, it was shown that Avastin and Lucentis were equally effective in treating this disease; this matters because Lucentis costs $2,023 per dose and Avastin $55—dosage is monthly and can be indefinite (National Institutes of Health, 2012; Hutton et al., 2014). Using either drug, two-thirds of patients retained driving vision (20/40 or better) compared to 15 percent for previously available treatments. In 2010, total expenditures were $2 billion, with two-thirds of the patients receiving Avastin (as an off-label use) and one-third receiving Lucentis. 200 thousand new patients get this disease annually.

The main point to make is that Lucentis can cost as much as $25 thousand annually, but if it prevents blindness that is a tradeoff many would make. By contrast. Avastin would cost less than $1 thousand annually. This suggests some $24 thousand in consumer surplus for Avastin, or about $5 billion annually relative to expenditures of $2 billion.[8] This calculation does not take into consideration the producer surplus in producing either product.

Another interesting pharmaceutical case is Gilead Sciences' sofosbuvir, that offers a successful cure for hepatitis C in some 90 to 95 percent of cases and costs some $50 thousand per regimen (Wapner, 2014). Gilead sold $19 billion of its sofosbuvir products in 2015, the year sales peaked, of which $12.5 billion was sold in the U.S., representing about 3 percent of all pharmaceutical sales. (In 2016 sales of sofosbuvir products fell to $15 billion, $8.4 billion in the U.S.) The manufacturing cost of sofosbuvir is said to be below $200 per regimen, and a nonprofit has committed to selling its version for $300, although the clinical trials for its variant

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[7] I am lumping together age-related macular degeneration and diabetic macular edema, which are treated similarly.
[8] An interesting sidelight is that Avastin was approved for cancer treatment; it targets the blood vessels that support tumor growth. Chemotherapy doses of Avastin are 150 times the dosage for AMD therapy; Avastin costs several thousand dollars per dose and it is reprocessed in formularies for use in AMD. Both drugs were developed by Genentech (since 2008 owned by Roche, a Swiss pharmaceutical company), but Genentech did clinical trials for AMD for Lucentis only, not Avastin. The two drugs have a similar mechanism of action: suppressing blood vessel growth in the eye that causes macular degeneration. In 2017, Roche's worldwide sales of Lucentis were $1.4 billion while sales of Avastin were $6.7 billion. Britain's National Health Service did not approve Avastin for off-label use until 2018 (Campbell, 2018).

have not been completed (cure rates so far appear to equal or exceed those of Gilead's.). This would imply that in 2015 some $12 billion worth of U.S. purchases of sofosbuvir products was producer surplus and should be measured as an increase in productivity. This represents about 0.08 percent of PCE. Between sofosbuvir's introduction in 2013 and 2015, this represents a 0.04 percentage point annual gain for PCE from this set of products over a two-year period.

Sofosbuvir is manufactured in Foster City, CA, and so in this case the product is produced in the U.S. Gilead Sciences did not discover sofosbuvir, but purchased Pharmasset, the U.S. drug company started by two Emory University scientists and based in Princeton that did, for $11 billion. Thus the intellectual property was created in the U.S. as well. However, many pharmaceuticals are created and/or produced in foreign countries, with generic production often taking place abroad. All these issues further complicate the attribution of productivity in pharmaceuticals manufacturing.

III.2.5 Nonprofit and government hospitals. Subtracting 5 percent from the rate of inflation of prescription drugs is, of course, quite arbitrary, but it results in a reasonable rate of productivity gain for an industry with substantial investments in research and development. The health care sector as a whole is very difficult to deflate, as can be attested by the hundreds of articles written in this area. Hospital services in 2017 accounted for $1 trillion of the $2.8 trillion health care goods and services. Of this, $0.9 trillion is either nonprofit or government; for these national income rules require that their output be deflated by inputs. Nonprofit and government hospital services have risen from 5.7 percent of personal consumption expenditures to 6.9 percent. If we were to deflate these by an additional 2 percentage points annually, that would reduce inflation by 0.138 percentage point in 2017 and by 0.114 percentage point in 1995, an acceleration of 0.024 percentage point (line 4, Table 1 and Table 4).

Hospital health care improves based upon the skill of the practitioners and the cures and palliatives they can deploy: the drugs they can administer, the medical equipment that they can bring to bear, the operations that can be performed. Numerous papers, including Murphy and Topel, 2006, Chernew et al., 2016, and Dauda et al., 2018, attest to the continuing value of improvements in medical care and make the view that productivity has been negligible in hospitals hard to maintain.

III.2.6 Residential lightbulbs. Lighting has been shown by Nordhaus (1996) to be subject to tectonic changes, that is, changes in technology that are hard to capture in price indexes because they are so large. One example is the switch from candles to kerosene lamps, another was the switch from kerosene to electric lights. In recent years, inexpensive LED lamps have been introduced, thanks to the longtime workings of Heitz's law, by which the cost of lumens from LEDs falls by a factor of 10 every decade.

This generation of LED lightbulbs produce light using a seventh as much energy: a 100-watt equivalent bulb uses 14 watts to produce 1,400 lumens, lasts 10 times as long (10 thousand hours) and costs between $1 and $3 (standard incandescent bulb used to cost about $0.50). If a bulb is used three hours a day, its annual electricity use costs $2 instead of $13. For the last few years, electricity for home lighting has fallen by $2 billion a year, according to the Department of Energy,[9] and LED bulb spending, which now dominates the market, was likely $1 billion annually (buying 300 million LED bulbs a year, being used on average 2 hours a day, will save roughly $2 billion.)

If the purchase of $1 billion allows a saving of $2 billion, then for real PCE to remain constant (assuming no change in lighting usage) the real value of the purchase must be $3 billion. So the correct implicit deflation rate is 67 percent annually during this transition period. The value of the real gain, $2 billion annually, is 0.01 percentage point added to real PCE and to real GDP (line 5 on Table 1 and Table 4).

This large contribution from a single small product illustrates the difficulty that national accountants face in measuring real PCE in rapidly changing markets, and the large value that new products can represent.

III.3 Internet Impacts, Intangibles, and Advertising-Supported Zero-Price Products

The Internet giants have earned their enormous profits and market values in a period in which time spent on the Internet has soared for U.S. consumers and around the world. On its face, this would suggest that the Internet might be an important source of utility for consumers.

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[9] As reported in the National Electrical Manufacturing Association blog in 2019. https://blog.nema.org/2019/08/27/lighting-leads-21st-century-reduction-in-use-of-electricity-in-residential-and-commercial-buildings/.

Although estimates of consumer time spent on the Internet vary from source to source, Nielsen's Total Audience Report found that in 2017 Q3, consumer viewing from smartphones, desktops, laptops, tablets, and other Internet-connected devices averaged four hours per day, up from about one hour in 2010. Of this, smartphones and tablets — products not available before 2007 — accounted for three hours. From 2010 to 2017, time spent on the Internet rose 22 percent annually.

III.3.1 Goolsbee and Klenow (2006) parametric measure of Internet usage. One way to calculate the value of free products is to use a parametric model to estimate the amount of consumer surplus by utilizing the shadow value of the leisure time that is spent in consumption of the product. Such a calculation was first performed on the value of the Internet in Goolsbee and Klenow (2006). They include in their model paid costs of Internet access and hours spent on the Internet and parameterize the elasticity of substitution by regressing income on time spent on the Internet. We can update the Goolsbee and Klenow (2006) calculation using the 2017 average weekly usage of adults of 28 hours instead of the 2005 value that Goolsbee and Klenow used of 4.9 hours per adult.[10] We also update Internet access expenditures to include cellular access as well as Internet providers. When we do so, we get an estimate of welfare that rises from 2.9 percent of Internet users' full income to 12.7 percent of full income for all adults, or a gain of about 0.8 percent per year over the period from 2005 to 2017.

III.3.2 Byrne and Corrado's nonparametric measure of Internet. Alternatively, Byrne and Corrado (forthcoming) take the view that the Internet usage consists of use of two sets of services, one supplied by the household to itself (home services), and the other supplied by businesses to the household (business services). Home services use stocks of IT capital in the home — network access equipment such as computers, cellphones, and TVs. Business services include subscriptions to Internet, streaming, and telecommunications services. Both of these are subject to changing intensities of utilization, how much time consumers spend on each. Here the idea, for example, is that if you pay for a subscription and spend more time using it, or if you buy a computer and spend more time on it, then the quantity of services received rises. This is

[10] In 2005, they estimated that Internet users spent 7.7 hours per week and that 63 percent of adults used the Internet.

nonparametric in that the value of a capital service is considered proportional to the time spent utilizing it.

Byrne and Corrado estimate real output by combining measures of household time expenditure with measures of quality, such as measures of household investment and the declining cost of network equipment. They estimate that in the period 2007 to 2017, real annual GDP growth from this source would have been 0.55 percentage point higher, and that real annual PCE growth would be about 0.80 percentage point higher. From this, they subtract an estimate of the gains already included in GDP and PCE growth, but these estimates do not appear to take into account all the other substitutions within the accounts, as discussed in section III.3.5.

III.3.3 Bytes as a measure of quantity. Another possibility is to use quantities. In the other studies noted here, minutes of time were used as the basis for telecommunications measures. Arguably, bytes might be the appropriate measure for the Internet and for smartphone usage, from an engineering perspective. Internet data transmission in North America, according to Cisco's Visual Networking Index, grew from 1,279 petabytes (PB) per month to 25 thousand PB per month from 2008 to 2017. This 19-fold increase represents a 39 percent annual rate of growth (Cisco, 2009; Cisco, 2019). Mobile traffic rose from 6 PB per month to 1.3 thousand PB per month, a 200-fold increase, for a 59 percent annual rate of growth. Cellular telephone and Internet access services account for an average of 1.4 percent of PCE during the period 2008 to 2017, 0.96 percent for cellular and 0.46 percent for Internet access.[11] Data are available in Table 1. If we deflate these using their 59 percent and 39 percent annual rates of growth, the contribution to the PCE growth rate would be to add 0.8 percentage point annually to real PCE growth and subtract 0.8 percentage point from the PCE deflator. Similar estimates can be produced for other countries with data in Abdirahman et al. (2017) for non-U.S. countries, particularly the U.K.

III.3.4 Nakamura et al. (2018) barter measure of free products. The estimate based on bytes does not include a measure of the cost of the free goods that firms like Facebook and Google provide to consumers. That is, as a business model, advertising media make expenditures on entertainment, software, and transmission to provide utility for consumers, in exchange for

[11] In 2017, these were 0.92 percent for cellular service and 0.54 percent for Internet services.

being able to insert advertisements in their media. One way of adding these back in is to estimate the expenses of firms like Facebook and Google and marketing costs of other firms, and then deflate using input costs. In this method, a barter transaction is imputed in which households trade their data and their willingness to see or hear marketing in exchange for the content they enjoy. This calculation is carried out in Nakamura et al. (2018). Adding these imputed free goods to PCE raises the PCE growth rate by a further 0.1 percentage point. Nakamura et al. use only input deflators to measure the value of free goods.

We can use three different methodologies (Goolsbee and Klenow, Byrne and Corrado, and Abdirahman et al.) to assess the consumer value of the mobile Internet revolution, and each suggest that real PCE growth should be 0.8 percentage point higher and PCE inflation about 0.8 percentage point lower. (Arguably, the expenditures pointed to by Nakamura et al. are additional to the three calculations made above, but we will not add these to our estimate.) This use of multiple approaches to achieve an approximate answer illustrates a way to achieve consensus on controversial measurements, as suggested by Coyle and Nakamura (2018).

With per capita personal consumption expenditures averaging $36 thousand from 2007 to 2017, this 0.8 percentage point represents a decade gain of $3,200 per person. Is this plausible? This question has been studied in consumer surveys by Brynjolfsson et al. (2019) and others.

Brynjolfsson et al. ask how much Internet users would have to be paid to not access various pieces of the Internet. Users' median response, reflecting willingness-to-pay for the items included in their surveys (search engines, email, maps, video, e-commerce, social media, messaging, and music) was $32,232 in 2017. This is 10 times the $3,200 gain in per person value that was just calculated for the 2007–2017 period.

Corrigan et al. (2018) focus on experiments in which users were paid to stop using Facebook and estimate that the average user would have to be paid more than $1,000 to deactivate their Facebook account for a year. Dolfen et al. (2019) estimate that ecommerce benefits to consumers from 2007 to 2017 were more than $1,000 per consumer. Given these very partial estimates of the value of the Internet, the $3,200 gain if anything appears to be conservative as a measure of the total value of the Internet over this period.

III.3.5 Comparison with existing national income account measures. How much should we adjust the above measure of the value of the Internet to account for its existing contribution in the national accounts? Just as the example of LED lamps illustrates how a decline in complementary requirements ought to be reflected in the real value of the lamps, so too the replacement of wired telephone service by broadband and cellular service should be reflected in the real value of these communication services.

Varian (2016) has pointed out the many ways that the iPhone substitutes for other products; it is a Swiss army knife whose utility is constantly being increased by new apps. For example, Brynjolfsson et al. (2020) estimate that just the photo capabilities are worth some £800 annually for the median user. Internet goods and services substitute for many other products.

Table 2 shows the proportion of various Internet-related products in personal consumption expenditure for selected dates from 1959 to 2017. Information processing equipment and telephone and related communications equipment are defined to be Internet goods; cable and satellite television and radio, video and audio streaming and rental, cellular telephone, and Internet access are defined to be Internet services. All six of these Internet products have risen as a proportion of total personal consumption expenditures. Defining these as Internet products is somewhat arbitrary, since information processing equipment, telephones, and cable TV were all in operation before the Internet age; however, these were then relatively smaller proportions of consumption.

The non-Internet goods are video and audio equipment, recording media, photographic equipment, and film and photographic supplies. The non-Internet services are photo processing and studios; repair and rental of audiovisual, photo, and information processing equipment; telecom landlines; and postal and delivery services.[12] All the non-Internet products have fallen as a proportion of expenditures.

As depicted in Figure 1, during the 21st century, consumer telecom expenditures fell substantially as a proportion of all consumer spending, from just under 1.9 percent to just over 1.1 percent. Although cellular phone spending rose from just over zero in 1987 to 0.9 percent in

[12] It can be noted that in the early years of the Internet, landlines were used for dialup modems, and that repair of information processing equipment is being put into non-Internet as well.

2018, landline expenditures have fallen from 1.7 percent to 0.2 percent. As a proportion of consumer expenditures, savings from landlines overwhelmed the total cost of cellular phone service, and savings continued straight through the mobile Internet revolution. Similarly, audio and video entertainment is now available both as streamed services (including radio) and as discs, tapes, vinyl, and permanent downloads. This category comprised 0.56 percent of personal consumption expenditures in 1997 but has since fallen to 0.3 percent, as the durable goods component fell from 0.4 percent in 1997 to 0.1 percent in 2017, and the streaming services rose from 0.15 percent to 0.18 percent. Streaming with Spotify and Netflix and other services have effectively replaced a large proportion of the permanent purchases. At the same time, the availability of songs and videos for listening and viewing as well as the time spent on these services has increased dramatically (Aguiar and Waldfogel, 2018).

Table 3 summarizes the overall development of expenditures. Total Internet expenditures rose from 3.0 percent of PCE in 2017 to 3.7 percent in 2017, a gain of 0.7 percentage point. At the same time, non-Internet expenditures fell by 1 percentage point, so that combined expenditures fell by over 0.3 percentage point. This is in sharp contrast to the period from 1959 to 1997, when the total rose from 3.2 percent to 5.0 percent, a gain of nearly 0.5 percentage point per decade. These entertainment and communications products are, in toto, luxury goods, and relative to trend, consumption has fallen 0.8 percentage point.

Table 4 shows the contributions of these products to the real growth of personal consumption expenditures in various decades. Despite the sharply increased connection time on the Internet, these real contributions are measured to have slowed as the Internet grew more important, falling from 0.5 percentage point from 1998 to 2007 to 0.3 percentage point from 2007 to 2017.

Thus across the spectrum of these goods and services, what we see in the existing data is a slowing of contributions to real GDP, where we ought to see a sharp acceleration.

In view of all these savings, we have chosen not to include a deduction from our Internet estimates for what is already included in PCE and GDP. A more conservative reading would be to subtract 0.3 percentage point from our estimates for PCE and 0.2 percentage point for GDP.

In Table 1, we have drawn together the estimates of inflation mismeasurement for personal consumption expenditures that include outlet bias, variety bias in nondurable goods, pharmaceuticals, government and nonprofit hospitals, LED lightbulbs, and the Internet and its zero price products. All told, we see overmeasurement of consumer inflation of 0.8 percentage point in the period roughly from 1983 to 1995, and of 1.9 percentage points from 2007 to 2017, an acceleration of mismeasurement of 1.1 percentage points. These numbers have very wide error bounds. However, we argue that they are plausible sources of mismeasurement, that they are collectively large, and that a major effort is required if we are to reduce the uncertainty surrounding our estimates of inflation and consumption growth.

IV. EXAMPLES OF THE RISE OF INTANGIBLES AND RAPID GROWTH

Intangible investment, investment in the private development of new products, whether measured as Nakamura (2003) or Corrado et al. (2005, 2009) do, or measured as in the U.S. national accounts, has risen throughout the postwar period, some 70 years. In the U.S. accounts, intangible investments were, as of 2017, 4.4 percent of GDP. In contrast, the methodologies of Nakamura and Corrado et al. capture a larger proportion of the expenditures necessitated by developing and selling new products and estimate intangibles investments to be over 12 percent of measured GDP (11 percent of GDP augmented with these additional gross investments). For example, corporate expenditures on administration and marketing are as important in the realization of the value of new products as the inputs of scientists, software engineers, and designers. Peters and Taylor (2017) show that adding half of "administrative, sales, and general" expenditures of public corporations to the stock of capital expenditures substantially improves the predictive power of "q" measures on future investment expenditures. Gourio and Rudanko (2014) offer additional support for the importance of customer capital in a parameterized model.

Before the 1980s, the 10-year average intangible to GDP ratio never rises above 4 percent, whereas now it is about 12 percent. Figure 1 shows estimates based on Nakamura as well as the official estimates, as a proportion of GDP. Just as the 21st century begins, the rate of intangible investment shoots up and continues to rise above that high level after the bursting of the Internet bubble.

Kahle and Stulz (2017) study public corporations in Compustat data and find that in 2015, the average public corporation invested in R&D at a 7.5 percent rate relative to total corporate assets, while the investment rate in capital expenditures (that is, tangibles) was 4.2 percent; by contrast in 1995 the same numbers were 5.7 percent for R&D and 9.6 percent for capital expenditures. In short, the U.S. corporation has now solidly centered its investments in intangibles rather than tangibles, on new product development rather than production per se. Indeed, as we saw with Apple, many firms have outsourced the production of products.

As economies shift from tangible to intangible investment, there are several measurement issues in addition to that of nominal quantities. One is deflation: The standard methodology of measuring a product of unchanged quality from one month to the next is difficult to apply to innovation, where activities are inherently different from one period to the next. A solution is to use either a general price deflator, such as the PCE or GDP deflator, which captures the opportunity cost of the resources that go into intangible investment, or input price deflators (which posits zero productivity growth) and add back in a measure of productivity. Here we critique the latter method, which is the one used in practice in the U.S., in two ways.

First, input price deflators may not fall rapidly enough. We will present a number of instances in which input prices into innovation fall dramatically. These rapid price declines are generally not captured by price indexes.

One perspective is to look to the rate of obsolescence of intangibles to measure the rate of technological progress. To the extent that intangibles are depreciating, they do not do so because of physical deterioration, but because they are becoming obsolete or their intellectual property rights are time limited. With patents extending for 20 years and copyright far longer, the rate of depreciation may be driven largely by obsolescence. An exception is pharmaceuticals, where patent life is more binding since the patent lives are shortened by the periods needed to test for safety and efficacy.

IV.1 Measurement difficulties with nominal intangible investment

Measuring intangible investments is usually harder than measuring tangible investments, because a large proportion of intangible investments are made in-house, while most tangible investments are purchased at arm's length. The contracts and transactions surrounding the purchase of tangibles — whether the construction of an office building or the purchase of an airplane or a smartphone for business use — provide a clear paper trail that creates a reasonably bright line between these investments with a long-term payoff versus other corporate expenditures that are consumed in creating goods and services (think food purchases by a restaurant or a grocery store, or employee wages at a nail salon.) Even this bright line is actually a bit fuzzy. For example, when firms like Google and Amazon build cloud computing centers, they construct the servers in-house, buying the computer housing, circuit boards, and processors and putting them together without buying a server, per se. Thus even tangible investments may cease to appear arm's length. For a period of time, these own-account investments went unrecognized in the U.S. national accounts — arm's length server *purchases* declined so that nominal investments in computing equipment appeared to be falling, until these problems were recognized by Byrne et al. (forthcoming).

The definition of intangible investment becomes even murkier with the investment model known as URL: ubiquity now, revenues later. This model is based on the notion that for many network businesses of the kind that are facilitated by the mobile Internet, economies of scale are extremely important. An Internet platform benefits from having more suppliers and more buyers on the same platform: the more buyers, the more suppliers are likely to sign up, and the more suppliers, the more buyers are likely to sign up. Thus rapid growth is highly incentivized, and this will be facilitated by providing free or discounted access to the service and products in its growth phase. This implies that the business may have to fund losses during this period. All of these losses must be (at least in expectation) paid for in the long run by future revenues, and, therefore, all of these expenditures can be seen as intangible investment. In the period before an Internet startup begins drawing in revenue, all its expenditures are intangible investments. Thus all the losses that Uber and Lyft are experiencing, or that Facebook experienced in its early years, were intangible investments. In the early years of ebooks, Amazon sometimes charged less for ebooks than it was paying to the publishers; those losses too could be considered intangible investments in its Kindle platform because they helped to induce readers to buy Kindles, and once the Kindle was established, that in turn gave Amazon tremendous leverage within the ebook market; by 2014–2015 Amazon had two-thirds of the ebook market (Smith and Telang, 2016). It also can happen that creating a network can be relatively inexpensive compared to its value; Apple's App Store, Google Search, and Facebook were networks that required relatively small investments relative to their value.

The methodologies of Corrado et al. and Nakamura multiply the size of intangibles by including advertising and marketing, a substantial amount of corporate expenditures that support the scientists, hardware and software engineers, designers, and other creators and also the cost of organizational capital: the dynamic changes to firms required as new ideas and products course through them.

In accounting terms, to the extent a firm is making long-term investments, it should capitalize and amortize these expenses over time. Only the amortized part of the investments is countable as expenses. However, firms under Generally Accepted Accounting Principles expense intangible investments; as a consequence, current expenses appear greater than they should be and profits smaller than they are truly. (This confers a substantial tax benefit on investment in intangibles beyond the R&D tax credit). In the national accounts, corporate economic profits do have this accounting done properly to the extent that intangible investments are recognized. However, as intangible investments are undercounted in the national accounts, corporate profits are understated even there. These difficulties with the measurement of intangible assets further underscore the mismeasurement of output in the 21st century U.S. economy. Nevertheless, I wish to focus here on the deflation of intangible investments, and will use the NIPA nominal measures of intellectual property investment in what ensues.

IV.2 Real Intangible Investments

Intangible investments are difficult to deflate. Since intangible investments are creative processes, what is being done in one period is necessarily different from what is done in the next. There is no "constant quality" product whose price can be traced from period to period and efforts to use hedonic measures to capture, say, the number of lines of code and their quality have not been very successful. Instead, standard practice is to use input prices to deflate outputs, which would omit any productivity gain, and a measure of aggregate productivity growth is added to avoid distortions. A further difficulty is often that input prices are difficult to measure accurately when rapid changes are occurring, which we document below.

Alternatively, one could use the rate of obsolescence of intangibles as a method of deflation, arguing that the rate of obsolescence must approximate the rate of technological progress. Or one can directly measure improvements in quantifiable dimensions of a group of intangible inputs or outputs and attempt to extrapolate to the total.

IV.2.1 Software. Arguably, one way to measure the rate of quality improvement in software can be surmised from its rate of depreciation, since software does not deteriorate as machinery does, but only becomes obsolete. If obsolescence is due to technological progress, then the rate of depreciation is the inverse of the rate of progress. The BEA applies a five-year service life, for a 33 percent annual rate of depreciation. With software accounting for 2.4 percent of GDP in 2016, a 33 percent rate of technological progress would add 0.8 percentage point to GDP growth. To include other corporate expenditures in support of software, we would double or triple that to 1.6 or 2.4 percentage points. To be very conservative, we instead cut this in half, to 0.4 percentage point. Software was just 1.2 percent of GDP in 1996, so 0.2 percentage point is acceleration since then. This uses a rate of obsolescence of about 16 percent annually.[13] This correction is shown on line 6 on Table 4, together with the personal consumption expenditures estimates of inflation mismeasurement, rescaled to reflect contributions as a percentage of GDP.

In 2018, BEA moved software expenditures in R&D from software investment to R&D investment. For the purposes of this calculation, we have restored the software expenditures in R&D to software investments. Otherwise software would be 1.7 percent of GDP.

IV.2.2 Cloud computing. Byrne et al. (forthcoming) argue that cloud computing has had a major impact on the U.S. economy. This has not been taken into account thus far in the analysis of software, where it has been assumed that deflation has been steady throughout. Yet as we argue below, cloud computing has reduced the cost of intangible investment quite dramatically. Despite large increases in the intensity of computer use, measured investment in tangible computer investment has slowed real GDP growth by 0.1 percentage point, as discussed in

[13] It might be noted that the BEA deflator for consumer prepackaged software, an area where a careful study of Microsoft Windows and Office was performed, showed a 17 percent rate of decline in the period from 1985 to 2000 (Abel et al., 2017), so such a deflation rate is not outside past experience. By contrast, the investment deflator for own-account software has been flat since 1985.

Section IV.3.2. It therefore seems reasonable to add back in 0.1 percentage point in acceleration of software and other intangible investment costs. This is line 8 on Table 4.

IV.2.3 R&D excluding software. Removing software investments from R&D, we see that R&D excluding software has grown much slower than software as a proportion of GDP, from 1.4 percent in 1996 to 1.5 percent in 2016. Including other corporate support and marketing, we estimate that full costs of R&D were more like 3 to 4 percent in each period. To account for the rapid acceleration of input cost declines, we estimate that the deflator for R&D fell at a 1 percent annual rate from 1985 to 1995 and at a 3 percent annual rate from 2007 to 2017. This implies a 0.09 percentage point additional contribution from R&D in the earlier period and a 0.15 percentage point additional contribution in the later period. These are shown on line 9 of Table 4.

IV.2.4 Rapid cost declines to research and development and marketing. One reason that a productivity slowdown could have occurred is that cost reduction may become itself more costly. Bloom et al. (2019) argue that "ideas are getting harder to find," pointing out that the famous rate of doubling of computer capacity called Moore's Law required 18 times more researchers in 2014 than it did in 1971. They find similar reductions in productivity in agriculture and medicine, and in all firms. For all firms, a main measure of productivity is revenue generated.

We have already discussed the rapid increase in data flowing over the Internet and telecommunications. This acceleration in output was not accompanied by large increases in revenue of the sort that Bloom et al. use as a sign of returns to innovation, as the firms we discussed were simultaneously losing customers in other streams.

And we can find numerous other examples of very large cost declines and very large gains in productivity that are not in the data. We have already discussed a few of these. We will be discussing these below, but they are assembled in Table 5.

IV.3 Examples of acceleration in intangible inputs

Here we review important cases of improvement in intangible productivity where the improvements are tectonic: Cost changes are so fast they are hard to capture in our indexes.

IV.3.1 DNA sequencing and manipulation. Let us consider the firm Illumina, which pioneered second-generation genome sequencing. By developing a technique that made sequencing more orderly and efficient relative to the first generation shotgun technique, Illumina was able to reduce the cost of sequencing a single human genome from around $1 million in 2007 to $1,000 in 2018,[14] and it has announced that its next generation will reduce the cost of such sequencing to $100 (Regalado, 2020). This rate of progress (1,000 times in 10 years) represents a 100 percent annual rate of growth in productivity, compared to a 41 percent rate of growth for Moore's Law. In the process, Illumina's stock market cap rose to $25 billion by 2017. From its startup through 2017, it spent less than $10 billion in intangible investment. Illumina dominates the market for genome sequencing, reports 2018 net profit of $800 million, and currently invests about $1 billion annually for R&D, marketing, and other intangibles. Illumina — which earns income from manufacturing machines and providing the consumables needed to use them — has made possible big data research on genomics, with over 1 million human genomes now sequenced. At the 2007 price of $1 million each, that amount of data would have cost $1 trillion. Now it appears that all the earth's nearly 8 billion human genomes could be sequenced for less than $1 trillion.

The speed with which the coronavirus was sequenced is testimony to this decline in costs. So too is the cancer genome project, in which the DNA of thousands of cancerous tissues were sequenced alongside comparison DNA from noncancerous tissues from the same patients (Campbell et al., 2020). These projects both will suggest new cures, and customization of cures to a patient's cancer DNA may also be possible. Broadly speaking, the speed with which biological and medical research can be done has been greatly accelerated.

As the cost of gene sequencing has plummeted, the incomplete reads of DNA performed by Illumina's silicon array chips have gotten better and cheaper. These are used by 23andme and Ancestry to offer both ancestry and health information. 23andme's price for a standard customer DNA analysis fell from $1,000 in 2007 to $100 to 2013.[15] And the quality of the health and ancestry information provided with these services keeps improving as science advances and the size of the data pool increases: The two firms have acquired information on more than 20 million individuals. In addition, the databases of these firms are being actively used in cooperation with

[14] Data taken from National Human Genome Research Institute. https://www.genome.gov/about-genomics/fact-sheets/DNA-Sequencing-Costs-Data.
[15] Taken from 23and me media center timeline. https://mediacenter.23andme.com/assets/timeline/index.html.

pharmaceutical companies in the pursuit of genomic understanding and possible future gene therapies, and with forensic criminologists in the investigation of violent crimes.

The proliferation of DNA data is complemented by inexpensive genetic manipulation via the CRISPR-Cas9 family of techniques, invented in 2012 by 2020 Nobel Laureates Jennifer Doudna and Emmanuelle Charpentier and their labs as a precise means to repair or modify individual DNA sequences (Doudna and Steinberg, 2017). Editing a genome has fallen in price from "tens of thousands of dollars" to $65 since 2012, about the same rate of decline as DNA sequencing. Setting up a basic laboratory with this technology for genetic manipulation can cost as little as $10,000, so we are embarked on a new and both exciting and perilous age of genetic therapy and manipulation. The Food and Drug Administration has approved at least four gene therapy treatments, with over a hundred treatments in trial.[16] Although manipulation of the heritable human genome has been declared off-limits for the time being by the scientific community, a Chinese scientist has illegally violated that sanction and two children were born with modified genomes.

The nominal economic magnitudes of these outcomes are relatively small. Illumina's revenue is under $3 billion in 2018, Ancestry.com reported $1 billion in customer revenue in 2017, and 23andme had consumer revenues estimated at $475 million in 2018 (Carson and Chaykowski, 2019) and is not making a profit. The industry thus far appears to be perhaps 0.02 percent of GDP. Nevertheless, at a 100 percent rate of growth, that would add 0.02 percent to real growth, nearly half of the acceleration we find for R&D. At the same time, 23andme lays claim to the world's largest genomic database available for research, with over 1 million samples available for testing; 80 percent of their clients have volunteered their DNA for research. A revolution has occurred in the data available for genetic research, with almost no impact on GDP. The value of the data may well be very large and is not accounted for in our measures of intangibles. Finally, these advances widely impact public and private medical, pharmaceutical, and biotech research and development, expenditures that exceed $100 billion.

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[16] See FDA news releases at https://www.fda.gov/news-events/press-announcements/fda-continues-strong-support-innovation-development-gene-therapy-products and https://www.fda.gov/news-events/press-announcements/fda-approves-first-cell-based-gene-therapy-adult-patients-relapsed-or-refractory-mcl.

IV.3.2 Cloud computing. Another key innovation is cloud computing. Cloud computing, which has been made practical by the ability to move data quickly over the Internet, uses farms of computer servers to provide computer services. This permits much more efficient utilization of computer processing capacity, since a lot of the server capacity at any one firm is idle much of the time. The declines in price from cloud computing from 2010 to 2016 reduced the prices of cloud computing by one-third (Byrne et al., forthcoming) –. At the same time, it also conserves on IT resources by concentrating the best researchers to solve the problem of creating powerful virtual machines and running them in a highly efficient manner. In all, this has had the impact of greatly reducing the costs of Internet startups, as noted by Ewens et al. (2018). They quote venture capitalist Mark Andreesen, "In the '90s, if you wanted to build an Internet company, you needed to buy Sun servers, Cisco networking gear, Oracle databases, and EMC storage systems ... and those companies would charge you a ton of money even just to get up and running. The new startups today, they don't buy any of that stuff. ... They're paying somewhere between 100x and 1000x [less] per unit of compute, per unit of storage, per unit of networking." Ewens et al. show that these reductions in cost are so large that the business model of early-stage venture capital for Internet startups has changed dramatically: So many startups are being created that venture capitalists now tend to play a minor role in governance and mentorship, a role increasingly taken over by accelerators like YCombinator.

As already mentioned, cloud computing has been pioneered by Amazon, whose cloud service has provided the bulk of its profits for the last several years. Amazon Web Services was relaunched in 2006 to take its current form, and it was with this announcement that cloud computing costs became a game changer. Microsoft has grown its cloud services, which now generate 20 percent of revenues and one-third of profits.

Amazon's 2018 AWS revenues were $26 billion, having doubled since 2016, with net revenues of $7 billion. Microsoft's Azure commercial cloud services have been, to date, AWS's most successful competitor, with 2018 revenues of $23 billion, having more than doubled since 2016. However, these revenues do not show up directly in GDP, since they are intermediate services. Since this is a more efficient use of computational services, the main effect is a slowing in reported business investments in servers, reducing the growth rate of GDP. From 1985 to 1995, real growth in investment in computers and peripherals was 22 percent annually, from

1995 to 2005, 23 percent, and from 2005 to 2015, 7 percent. The net contributions to real GDP growth were 0.14 percent, 0.18 percent, and 0.04 percent. Since computer usage growth has been rapid, it appears probable that at least 0.1 percentage point accelerated undermeasurement has occurred, as estimated in Section IV.2.2.

IV.3.3 Artificial intelligence. Another example that has gotten many recent headlines is artificial intelligence (AI). A widely quoted blog post by Amodei and Hernandez (2018) shows that between early 2012 and late 2017, the rate at which AI training runs were increasing doubled every 3.4 months (10x annually), resulting in a 300 thousand-fold increase in the number of petaflops/sday[17] of training behind the latest AI advance, the latest being the 2,000 petaflops/sday used by AlphaGoZero, which trained itself to play the ancient game Go without reliance on knowledge of the human history of game play (Silver et al., 2018). After this training, AlphaGoZero was widely considered a superhuman Go player. Advances appear to be taking advantage of the falling cost of more and more training. An update to the blog post including data going back to 1959 showed that until 2012, training time increases approximated Moore's Law. Thus many of the astonishing advances in AI since 2012 appear to take advantage of a combination of cheaper computing and greater expenditures available from intangible investment in AI.

Advances in software often take the form of insightful simplification. An AI team at Carnegie Mellon recently completed two huge challenges in game play. Their programs aimed to achieve superhuman performance at what is widely considered to be the most challenging game of poker, Texas Hold 'Em. Poker is more difficult than Go in that players have imperfect information — they don't see the cards the other players have — and so there is scope for bluffing and other strategies that are not available in perfect information games such as chess or Go. But at least in one-to-one matches the game is zero-sum, which assures the existence of a solution. The team's first effort was called Libratus, published in 2017, and the program succeeded in beating four of the world's best poker players one on one. The team's second effort, Pluribus, was to see if they could build a program for multiplayer Texas Hold 'Em. In the end, Pluribus beat top players in two formats: playing multiple human players simultaneously, and with single human players playing against multiple versions of Pluribus (Brown and Sandholm,

[17] A petaflops/sday is 10^{15} neural net operations per second for one day, or about 10^{20} operations.

2019). Most remarkably, the algorithms that the Carnegie Mellon team used in Pluribus required much less training time than Libratus: While Libratus required $1 million in compute time to train, Pluribus required only $150 in compute time (Simonite, 2019). This was done using a new counterfactual routine. Thus a more complicated problem was solved with a 6,000-fold reduction in computer requirements in less than two years. The much lower training time means that anyone can afford to build a superhuman poker player for use in online poker playing.

The potential for these large advances in software, both from decreasing costs of hardware runs and from inspired improvements, suggests that a 33 percent average rate of obsolescence and a 33 percent annual rate of price decline may not be absurd, although we have used an estimated rate of obsolescence that is far lower.

IV.3.4 Transportation, sensors, and batteries. Consider the self-driving car. Tesla has developed electric cars with some self-driving capability and sold some 378 thousand in 2019. Google's self-driving car group, Waymo, has been testing self-driving cars as taxis in relatively easy-to-navigate suburbs of Phoenix, Arizona; taxi rides include a human minder who doesn't touch pedals or steering wheel except in an emergency. Fully self-driving cars able to operate in difficult driving conditions are likely to be years away. Yet both these firms — and many others — are accumulating data and also driving down the cost of key components. When self-driving cars become available, they will save a tremendous amount of driving attention time: U.S. adults drive an hour a day, according to the American Time Use Survey 2018.

Lidar systems — systems that use light as radar uses radio waves — are capable of much more accurate sensing of the environment than radar and also can operate under a wider range of weather conditions. The device can see in 3D, not just 2D. In 2005–2007, lidar systems from Velodyne cost $75,000 each, much too expensive for mass production. By 2014, that had fallen to $8,000 for a system from Luminar. Waymo is selling its lidar system, but not to car competitors, for $7,500. Luminar has announced that by 2022 systems will cost from $500 to $1,000 (Ohnsman, 2019; Lambert, 2020). Those prices are low enough to become valuable options on practically every car and greatly reduce the cost of experimenting with self-driving cars using lidar.

Electric cars, like Tesla's, can also be a big help in reducing carbon use. But electric cars require batteries. For example, the Tesla Mark 3 requires 75 kwh of battery storage capacity.

According to the government-sponsored BNEF, the price of battery storage has fallen from $1,160 to $156 per kwh, from 2010 to 2019, a seven-fold improvement, for a 25 percent annual rate of productivity growth.[18] Recent announcements by Volkswagen suggest a further reduction to $100 per kwh (Ewing, 2019). To scale this 11-fold decline, the cost of 75 kwh falls from over $80,000 per car to $7,500.

IV.3.5 Energy/climate change. Two energy sources to reduce the amount of carbon use are solar and wind power. But the weather cannot be relied upon to deliver power at precisely the times it is demanded. That implies a role for electrical storage to time-shift electricity supply to meet demand. The reductions in battery costs just discussed has been such that studies show that in Germany, where time of day plays an important role in electricity pricing, itself relatively expensive, the most recent technology already has a high payoff for homeowner adoption (Comello and Reichelstein, 2019). In the U.S., the same is not so true at the homeowner end, but large electric storage facilities are being cost effective for the wholesale electrical grid.

IV.3.6 Space commercialization. Elon Musk's SpaceX developed the Falcon 9 rocket that is now being used to resupply the Space Station. The Falcon 9 and its precursor, the Falcon 1, cost respectively $300 million and $90 million to develop. NASA has estimated that using its normal procurement model, it would have paid $4 billion to develop the Falcon 9, and that might have been subject to cost overruns (NASA, 2011, Zapata, 2017). Thus development costs were 10 times lower. And the price per flight fell by roughly three times. The Atlas 5 rocket that is the Falcon 9's main U.S. competitor costs $110 million to $230 million per launch, whereas the Falcon 9 costs $61 million for a roughly comparable payload (Federal Aviation Agency, 2018).

SpaceX and other new rocket and space startups are also working to substantially further lower the cost of flights by ensuring that the hardware is reusable, so that the primary cost of an additional flight becomes the fuel cost. Musk has speculated that his newest rocket, the Starship, when fully reusable would be capable of putting 100 passengers in Mars orbit with out-of-pocket costs of as little as $2 million per launch, with fuel costs under $1 million.

[18] https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/

U.S. rocket flights support an industry whose total value is very large — $50 billion to $100 billion annually (FAA, 2018). These expenditures are a combination of civilian and military uses, with some part of them related to science and technological development.

The remarkable declines in space exploration costs have triggered an era in which many for-profit companies are developing plans to commercially exploit space and countries including India, China, and Japan have joined a new race to the moon.

IV.4 Summary

Very large declines in prices or increases in productivity arise from innovative expenditures. These declines in prices are often difficult to measure. In addition, when the price declines take the form of new products, the implicit price improvements and productivity gains are not captured in standard measurement procedures. Nordhaus (1996) has argued that large price changes — which he describes as tectonic — are inherently very difficult if not impossible for statistical agencies to capture. In the current period of rapid and broad scientific and technological advance, such tectonic changes have become ubiquitous.

I have argued here that real intangible investment growth causes GDP to be undermeasured by more than 0.6 percentage point, of which 0.35 percentage point represents acceleration. Adding together the measures of consumer spending already discussed, and we find that GDP growth is undermeasured by 2 percentage points, with acceleration accounting for half of this undermeasurement. The statistics are summarized in Table 4.

V. FINAL REMARKS

It has been suggested that capitalism is in crisis if it is delivering increasing inequality and profitability without also delivering long-term growth. U.S. official economic statistics suggest that growth is unusually slow, and that as inequality has risen, none of this growth has flowed through to the average household. This has occurred at a time when the rewards to U.S. corporations are unusually high and stock market valuations even higher. This outcome is the end result of a period of time in which, acting on the advice of economists, policymakers have lowered taxes, reduced regulations, decreased tariffs, and strengthened intellectual property protections domestically and globally. And economists and policymakers continue to call for structural improvements to allow greater productivity growth, despite the fact that past efforts have been futile.

The data reviewed herein suggest a very different picture of the dynamism of the U.S. economy. We have attempted to review very broadly how mismeasurement might have accelerated. As can be seen, the evidence is very fragmentary, and our estimates are in places very arbitrary, but perhaps no less arbitrary than the official measures. As we noted in the beginning, from an economic perspective, it is welfare that matters for many economic decisions.

One place where we can observe the problems caused by economic mismeasurement is in monetary policy. The rate of inflation as measured in the 12-month core PCE deflator in December 2018 was 2 percent. At that time, the U.S. Federal Reserve's Federal Open Market Committee raised the fed funds to an effective rate of 2.4 percent, and the yield curve inverted. This should have been less than a half percent real rate, a rate that should have still been supportive of economic growth. But it was not, and the FOMC began taking back the hikes in the summer. But if the true rate of inflation was roughly zero, this market reaction is not so surprising.

Figure 5 shows the real long-term rate of interest, as measured by the 10-year Treasury note, deflated by the *Survey of Professional Forecasters*' 10-year CPI inflation expectation. By this measure, the long-term real rate of interest has fallen from 3.2 percent to 0.2 percent. But if inflation is undermeasured by 2 percent, the long-term real rate is not this low. The extremely low nominal interest rates around the world — with some of them negative — make much more sense if we are experiencing a worldwide deflation, as our argument suggests.

Figure 6 shows that per capita annual real GDP growth in the period from 2005 to 2017 was 0.8 percent, starkly lower than any other 12-year period (the previous low was 1.6 percent) and well below the 2.2 percent average growth rate from 1947 to 2005. As a consequence, it appears that, as shown in Figure 7, the average household gained no benefit during this period when corporations were earning outsize profits and shareholders were benefiting from unusual capital gains. But as we have shown, the median household gained many benefits during this period, particularly using the Internet much more of the time and for many new purposes, but also benefiting from cures for macular degeneration and hepatitis C and an increasing variety of new products and outlets that they have found very valuable.

Finally, technological advances at very fast rates can be found throughout the economy. These very rapid growth rates are collected in Table 5. It may be that in a few areas progress has become harder, but in many areas it has become much faster.

It is undoubtedly true that a portion of the population is unhappy and suffering, with high rates of drug addiction and suicidality, and experiencing shorter lifespans (Case and Deaton, 2015). This part of the population is less educated, and it is the portion of the population which is most vulnerable to experiencing rapid technological and scientific advances as a cost. In a world in which higher education is increasingly needed to maintain an understanding of the working of our society, this population suffers the most from human capital inequality.

Rapid economic progress is confronting us with a wide variety of ethical and social issues. As space commercialization becomes cheaper, how do we determine national and private property rights in the cosmos? With the rise of two-way mass communication, who censors speech and weeds out bots? How shall we limit genetic therapy and the genetic manipulation of fauna and flora? With so much intellectual property creating monopoly powers, how do we prevent abuse of those powers? What are the limits to privacy invasion? How do we control artificial intelligence, drones, self-driving cars, and robots to ensure ethical behavior? How do we prevent rising human capital inequality? Our ability to adapt and to control these new human capabilities is being outrun by their rapid advances.

Arguably, the problem that capitalism presents is not that it is working poorly and delivering no progress, but that is delivering progress at a rate that is making life harder. It could be that, as happened in the early days of the industrial revolution, much of the population is inevitably worse off despite the rise in progress. But not knowing whether we are growing too slow or too fast does not help us to understand or solve our problems.

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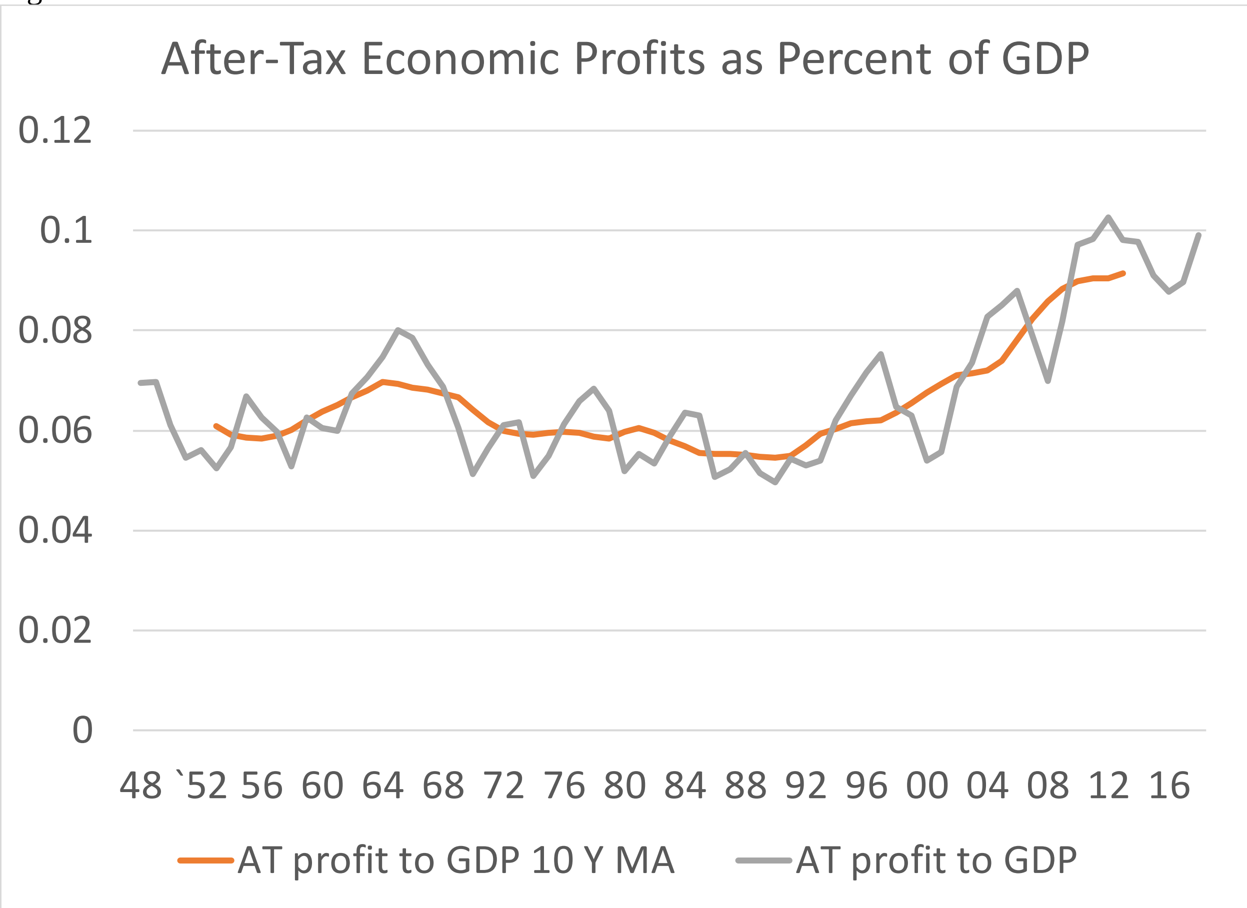
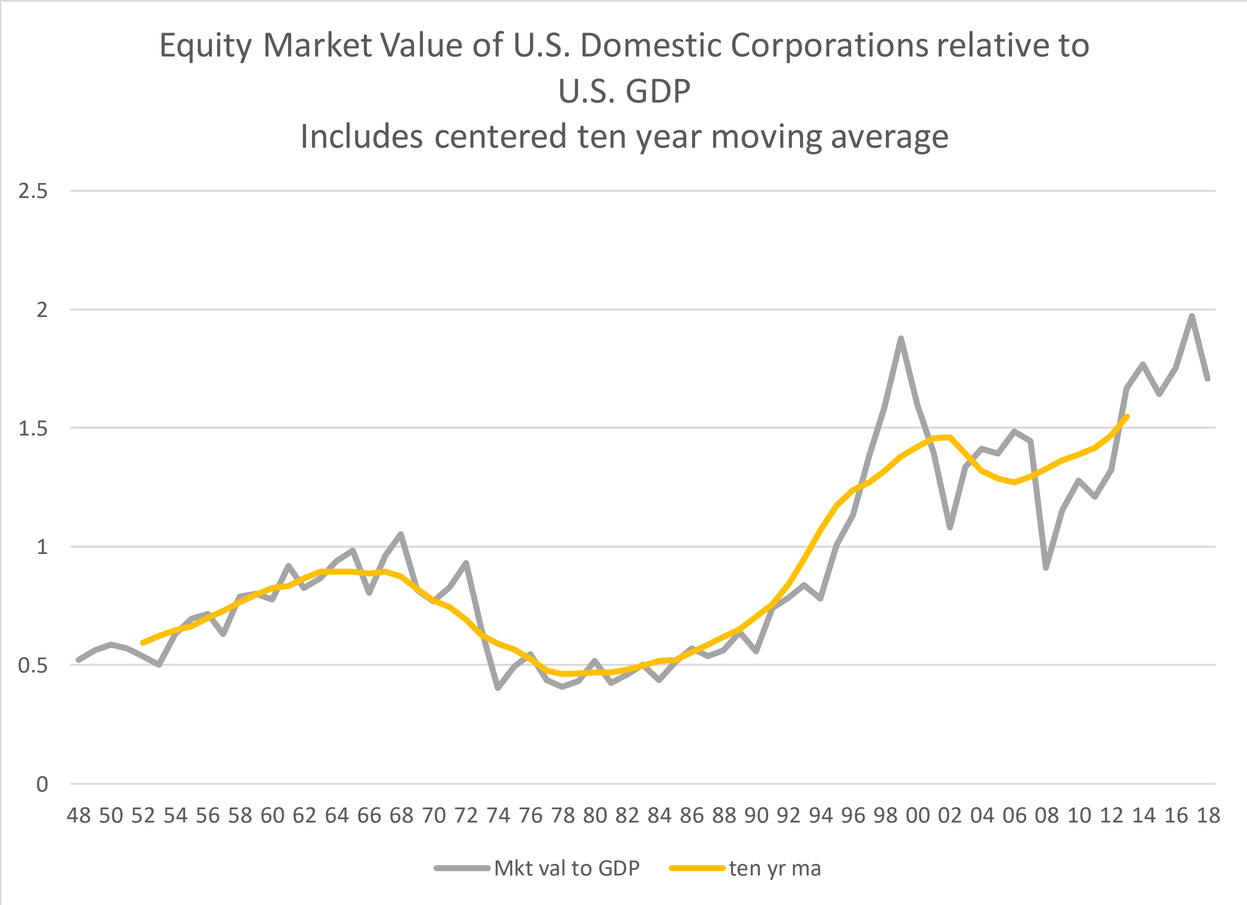
Figure 1.



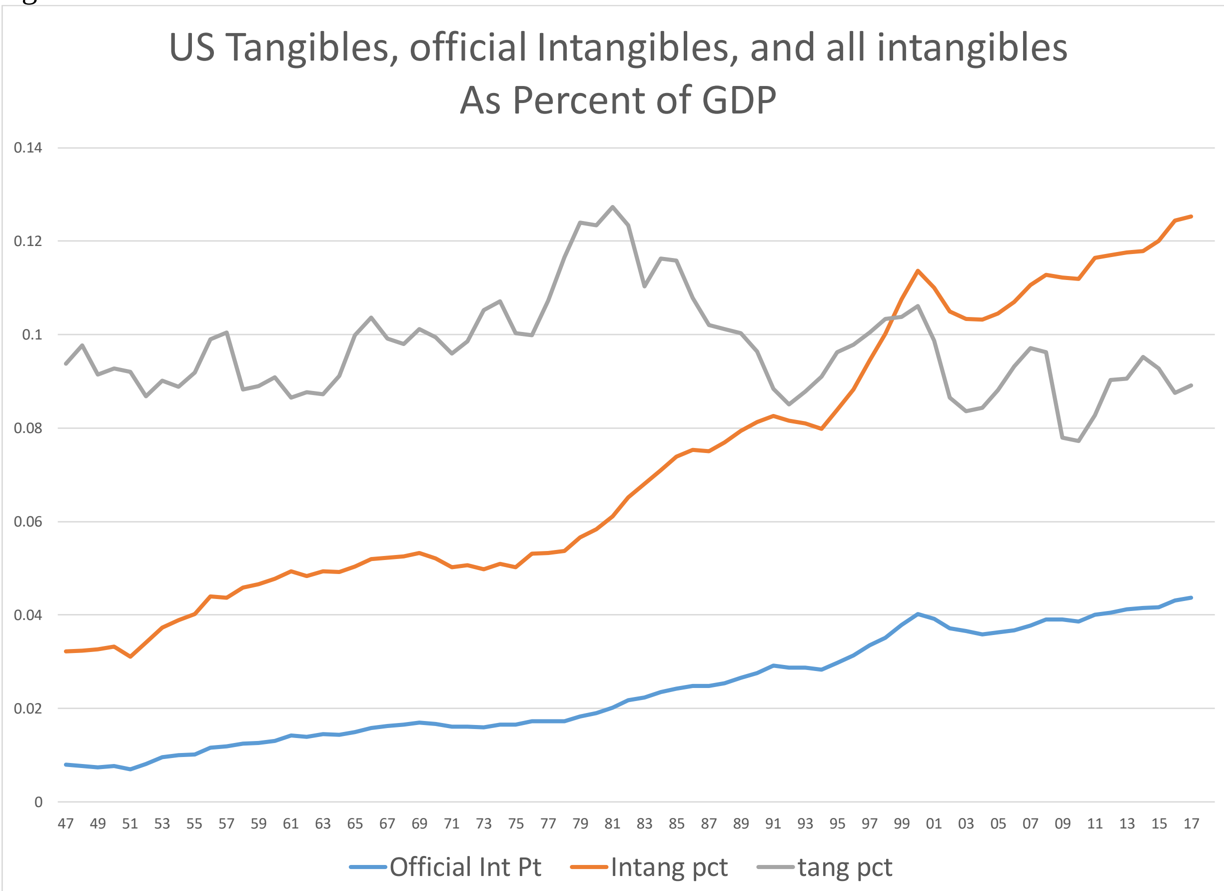
Sources: BEA data, Haver Analytics

Figure 2.



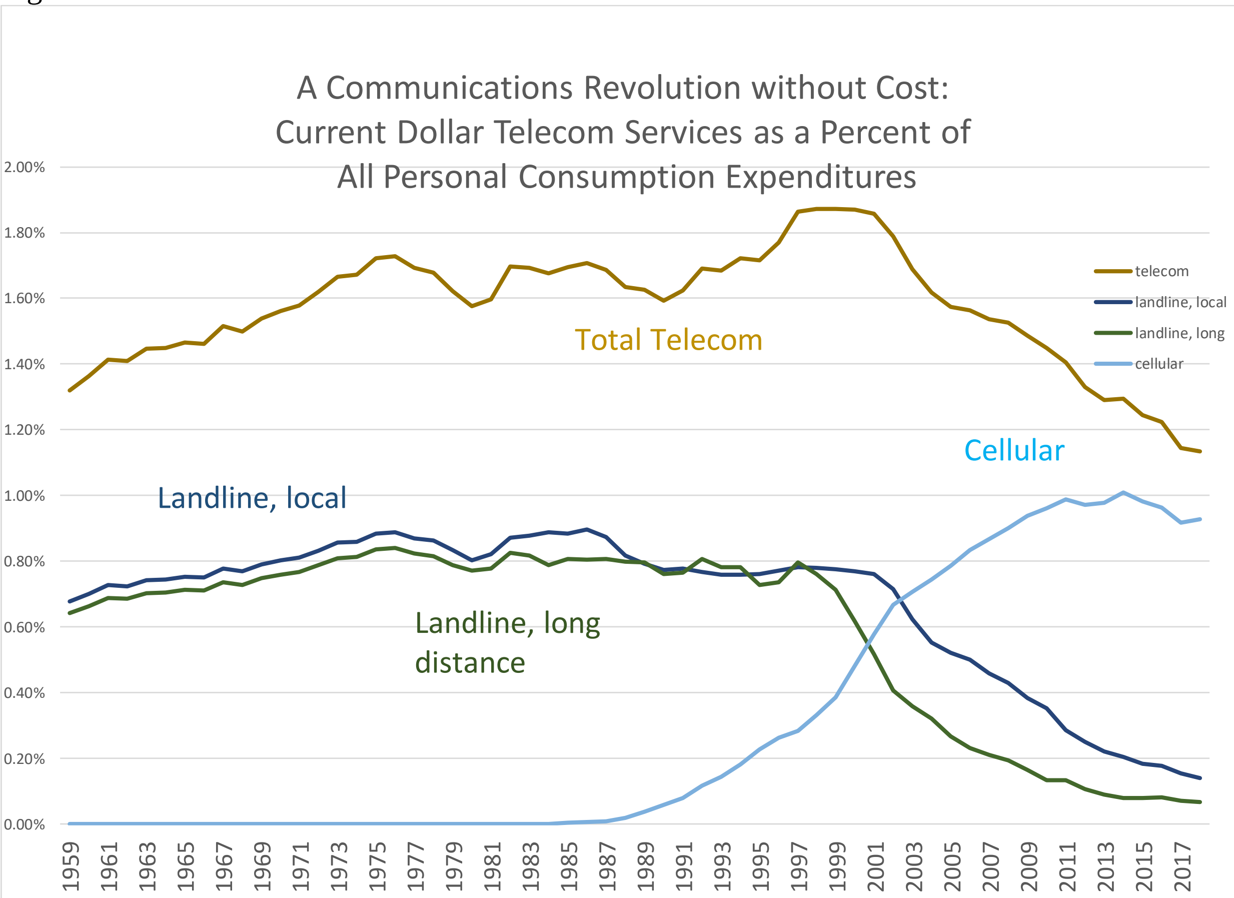
Sources: Flow of Funds, Haver Analytics

Figure 3.



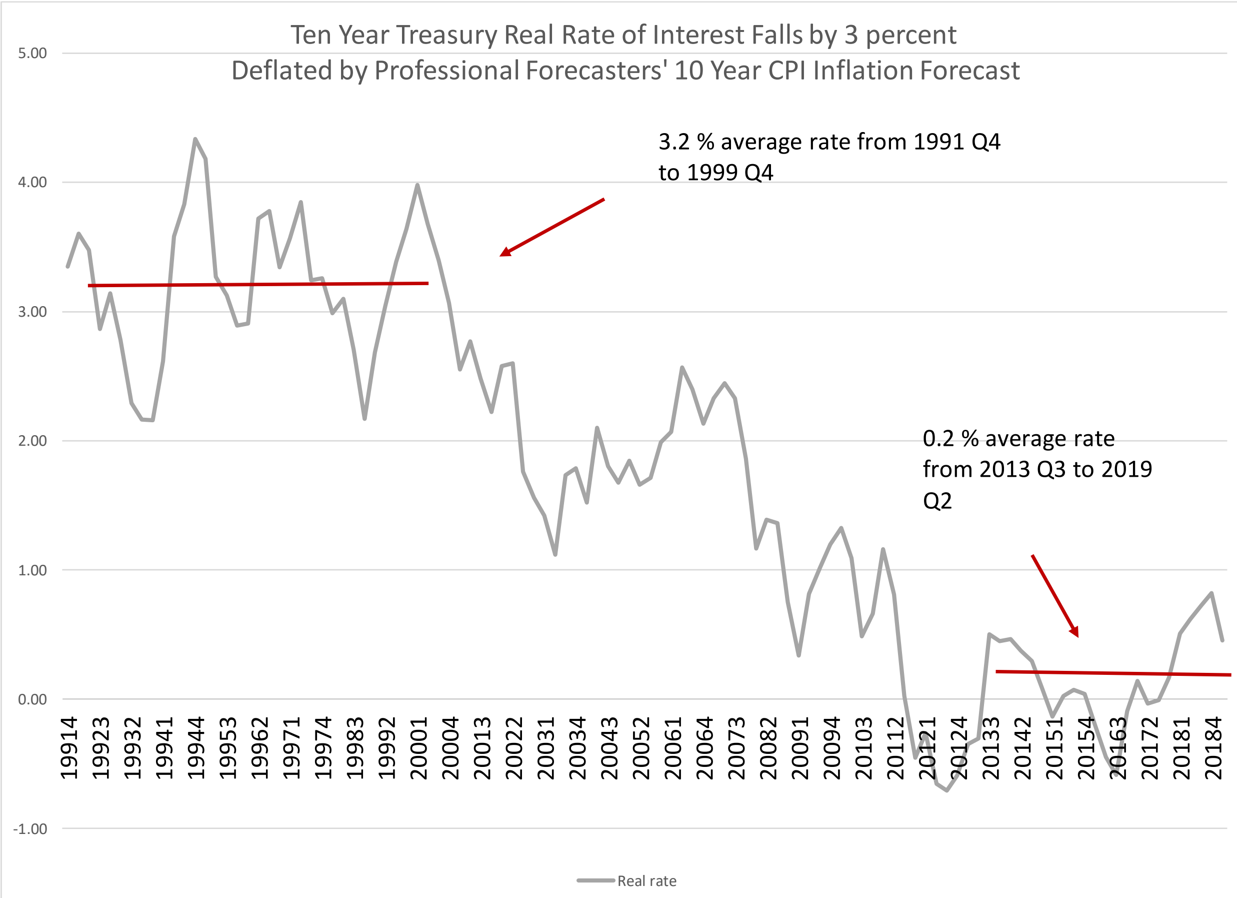
Sources: BEA, Haver Analytics, author’s calculations

Figure 4.



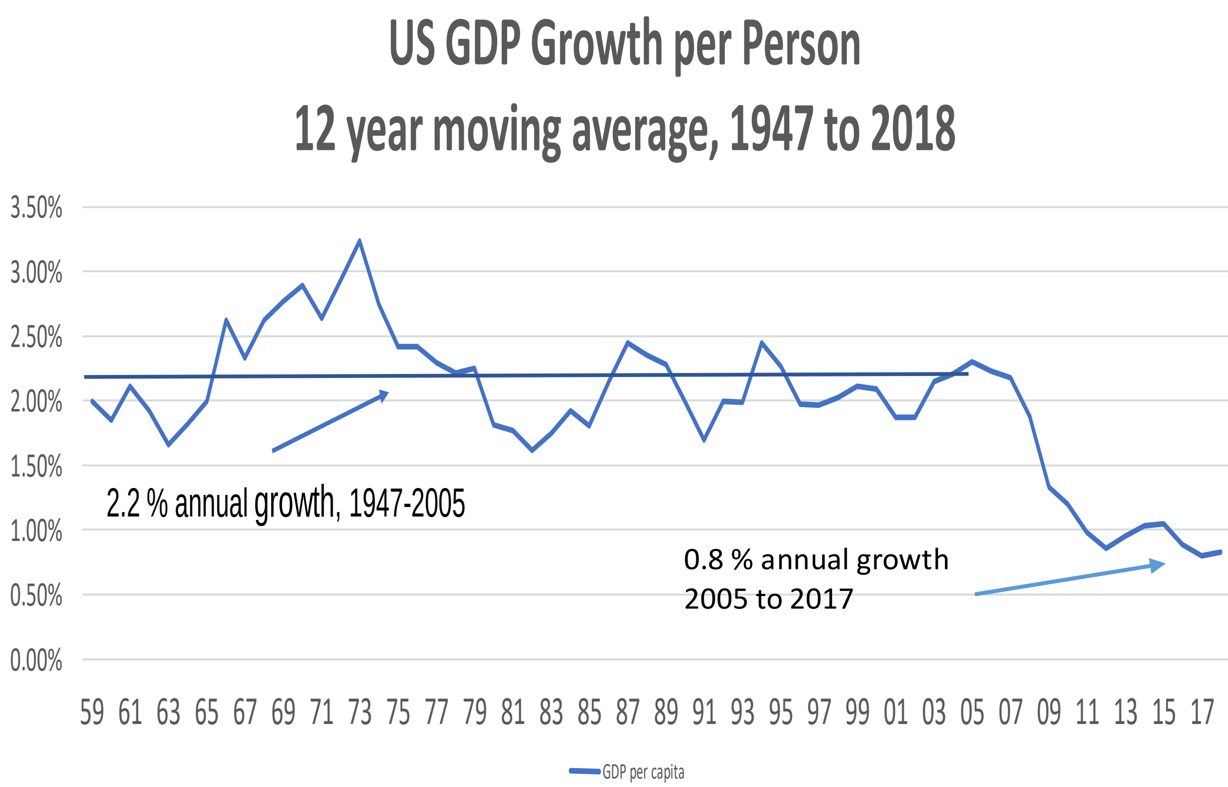
Sources: BEA, Haver Analytics

Figure 5



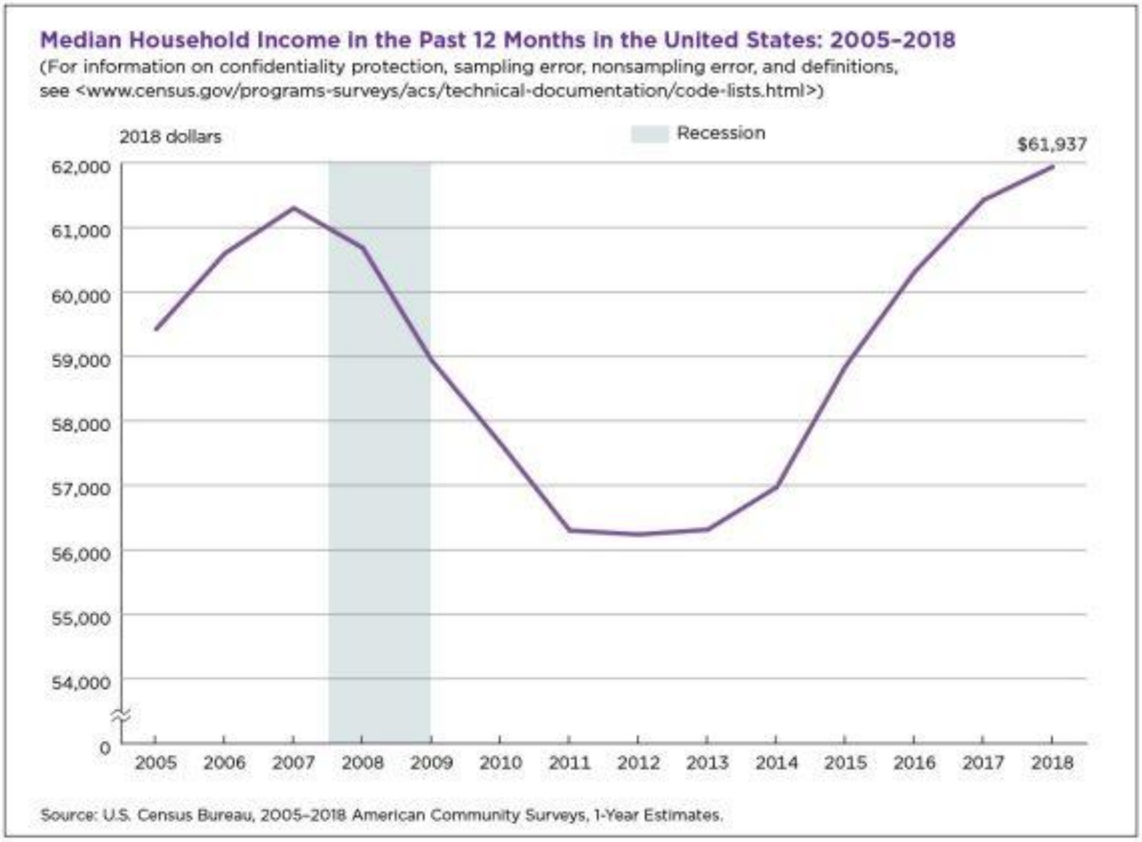
Sources: Federal Reserve Bank of Philadelphia, Federal Reserve Board of Governors, Haver Analytics.

Figure 6.



Sources: Bureau of Economic Analysis, Census Bureau, Haver Analytics.

Figure 7.



Median Household Income in the Past 12 Months in the United States: 2005–2018
(For information on confidentiality protection, sampling error, nonsampling error, and definitions,
see <www.census.gov/programs-surveys/acs/technical-documentation/code-lists.html>)
2018 dollars
Recession
$61,937
62,000
61,000
60,000
59,000
58,000
57,000
56,000
55,000
54,000
0
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Source: U.S. Census Bureau, 2005–2018 American Community Surveys, 1-Year Estimates.

Table 1. Acceleration of Inflation Mismeasurement, Personal Consumption Expenditures (PCE), 21st Century					
Mismeasurement Issue	Period	Impact on PCE, 20th century	Impact on PCE, 21st century	Acceleration	Source
1. Outlet Bias	1983–95 relative to 2008–14	0.52	0.65	0.13	Aghion et al. (2019)
2. Variety bias	1983–95 relative to 2004–16	0.13	0.16	0.03	Nieman and Vavra (2018) and author's estimate
3. Pharmaceuticals	1983–95 relative to 2006–16	0.07	0.16	0.09	Author's estimate
4. Hospitals, government and nonprofit	1985–95 relative to 2007–17	0.11	0.14	0.02	Author's estimate
5. LED lightbulbs	1983–95 relative to 2008–19	0.00	0.01	0.01	Author's estimate
6. Internet and zero price products	1983–95 relative to 2007–17	0.0	0.80	0.80	Goolsbee and Klenow (2006), Byrne and Corrado (forthcoming), author's estimate
7. Total Mismeasurement		0.83	1.92	1.09	

Table 2. Consumption of Internet Goods and Services, and Communications and Entertainment Products Displaced
(Proportion of Nominal Personal Consumption Expenditures, 1959–2017, percentage points)

	1959	1967	1977	1987	1997	2007	2017
Total	3.16	3.89	4.01	4.57	4.96	5.09	4.72
Internet	0.06	0.09	0.18	0.76	1.73	2.93	3.61
Non-Internet	3.11	3.79	3.83	3.80	3.23	2.16	1.11
Goods	1.15	1.59	1.48	1.78	1.85	2.20	1.89
Internet Goods	0.04	0.05	0.05	0.26	0.69	1.04	1.23
Non-Internet Goods	1.11	1.54	1.43	1.51	1.17	1.16	0.66
Services	2.01	2.30	2.54	2.79	3.10	2.88	2.82
Internet Services	0.02	0.05	0.13	0.50	1.04	1.88	2.37
Non-Internet Services	1.99	2.25	2.41	2.29	2.06	1.00	0.45

Sources: BEA, Haver Analytics

Table 3. Contributions to Real PCE Growth Rate from Internet Goods and Services, and Displaced Entertainment and Communications Goods and Services
Percentage points

	1968–77	1978–87	1988–97	1998–2007	2008–17
Total	0.30	0.32	0.37	0.53	0.30
Internet	0.01	0.09	0.22	0.40	0.29
Non-Internet	0.28	0.24	0.15	0.13	0.01
Goods	0.12	0.18	0.22	0.39	0.21
Internet good	0.00	0.04	0.15	0.22	0.15
Non-Internet goods	0.12	0.14	0.08	0.16	0.06
Services	0.17	0.15	0.15	0.14	0.09
Internet services	0.01	0.05	0.07	0.17	0.14
Non-Internet services	0.16	0.10	0.08	-0.03	-0.05

Sources: BEA, Haver Analytics, author's calculations

Table 4. Acceleration of Inflation Mismeasurement, Gross Domestic Product, 21st Century

Mismeasurement Issue	Period	Impact on GDP, 20th century	Impact on GDP, 21st century	Acceleration	Source
1. Outlet Bias	1983–95 relative to 2008–14	0.52	0.65	0.13	Aghion et al. (2019)
2. Variety bias	1983–95 relative to 2004–16	0.09	0.11	0.02	Nieman and Vavra (2018) and author's estimate
3. Pharmaceuticals	1983–95 relative to 2007–17	0.04	0.10	0.06	Author's estimate
4. Hospitals, government and nonprofit	1983–95 relative to 2007–17	0.08	0.10	0.02	Author's estimate
5. LED lightbulbs	1983–95 relative to 2008–19	0.00	0.01	0.01	Author's estimate
6. Internet and zero price products	1983–95 relative to 2007–17	0.00	0.55	0.55	Various
7. Software	1983–95 to 2007–17	0.20	0.40	0.20	Author's calculation
8. Cloud computing	1983–1995 relative to 2006–16	0.0	0.10	0.10	Byrne et al. (forthcoming)
9. Research and development cost decreases	1985–95 relative to 2007–17	0.09	0.15	0.06	Author's estimate
10. Total mismeasurement		1.02	2.17	1.15	

Table 5.

Rates of Improvement of Selected R&D and Data Inputs			
Type	Time period	Improvement	Annual Rate of Change
Moore's Law	1958 to 2014	Doubles every two years	41 %
Consumer Internet Bytes	2008 to 2017	19 X	39 %
Cellular Bytes	2008 to 2017	200 X	59 %
DNA Sequencing	2007 to 2017	1000 X	100 %
DNA manipulation	2012 to 2018	150 X	130 %
Startup Cloud computing	2006 to 2007	100 X to 1000 X	10000 % +
Cloud computing, price declines	2010 to 2016	2 X to 3X	10-20 %
Rocket development	2007 to 2015	10 X	33 %
Rockets, cost per flight	2007 to 2015	3 X	14 %
AI, Libratus to Pluribus training	2017 to 2019	6000X	7600 %
Sensor, Lidar	2007 to 2016	9 X	27 %
LEDs, cost per lumen	1975 to 2017	16000 X	23 %

Source: see text

Appendix Table 1. Home entertainment, information and communications expenditures decline as a proportion of total personal consumption expenditures since 1997 after rising nearly half a percentage point a decade							
Red type indicates Internet goods and services							
	1959	1967	1977	1987	1997	2007	2017
Goods and Services, total	3.160	3.884	4.008	4.523	4.892	4.951	4.488
Goods inclusive total	1.146	1.583	1.472	1.733	1.787	2.070	1.664
Durables subtotal	1.032	1.446	1.335	1.609	1.737	2.051	1.652
Video and Audio Equipment	0.894	1.289	1.164	1.286	1.061	1.092	0.606
Televisions	0.497	0.770	0.423	0.399	0.211	0.380	0.231
Other Video Equipment	0.143	0.179	0.231	0.245	0.193	0.192	0.111
Audio Equipment	0.197	0.247	0.309	0.257	0.250	0.218	0.140
Recording Media	0.057	0.092	0.202	0.384	0.407	0.303	0.124
Photographic Equipment	0.105	0.114	0.125	0.105	0.058	0.050	0.040
Information Processing Equipment	*0.033*	*0.044*	*0.046*	*0.219*	*0.618*	*0.908*	*1.006*
Telephone and Related Communication Equipment	*0.003*	*0.003*	*0.004*	*0.043*	*0.068*	*0.135*	*0.228*
Nondurables:							
Film and Photographic Supplies	0.114	0.136	0.137	0.123	0.050	0.019	0.012
Services total	2.014	2.301	2.536	2.790	3.105	2.881	2.824
Audio-Video, Photographic/Info Processing Svc, subtotal	0.492	0.553	0.632	0.883	1.003	0.925	1.050
Cable & Satellite Television & Radio Services	*0.020*	*0.047*	*0.129*	*0.384*	*0.544*	*0.631*	*0.737*
Photo Processing	0.063	0.106	0.147	0.144	0.118	0.030	0.015
Photo Studios	0.096	0.112	0.127	0.121	0.110	0.075	0.055
Repr/Rent of Aud-Vis/Photo/Info Process Equip	0.313	0.289	0.230	0.126	0.083	0.082	0.062
Video & Audio Streaming & Rental	*0.000*	*0.000*	*0.000*	*0.108*	*0.148*	*0.108*	*0.181*
Communication, subtotal	1.522	1.748	1.904	1.908	2.102	1.957	1.774
Telecommunication Services	1.320	1.515	1.693	1.686	1.863	1.536	1.144
Landline Telephone Services, Local Charges	0.678	0.778	0.870	0.873	0.782	0.459	0.155
Landline Telephone Svc/Long-Distance Charges	0.642	0.736	0.823	0.806	0.797	0.211	0.071
Cellular Telephone Services	*0.000*	*0.000*	*0.000*	*0.008*	*0.284*	*0.866*	*0.918*
Postal and Delivery Services	0.202	0.233	0.212	0.221	0.174	0.141	0.095
Internet Access	*0.000*	*0.000*	*0.000*	*0.000*	*0.065*	*0.280*	*0.536*

Sources: BEA, Haver Analytics

Appendix Table 2. BEA rates of depreciation Type of Asset	Rate of depreciation
Private intellectual property products	
Software /23/	
Prepackaged	0.5500
Custom	0.3300
Own-account	0.3300
Research and development /24/	
Pharmaceutical and medicine manufacturing	0.1000
Chemical manufacturing, excluding pharmaceutical and medicine	0.1600
Semiconductor and other electronic component manufacturing	0.2500
Other computer and electronic product manufacturing	
Other computer and electronic product manufacturing, nec	0.4000
Computers and peripheral equipment manufacturing	0.4000
Communications equipment manufacturing	0.2700
Navigational, measuring, electromedical, and control instrument manufacturing	0.2900
Motor vehicles, bodies and trailers, and parts manufacturing	0.3100
Aerospace products and parts manufacturing	0.2200
Other manufacturing	0.1600
Scientific research and development services	0.1600
All other nonmanufacturing	
Software publishers	0.2200
Financial and real estate services	0.1600
Computer systems design and related services	0.3600
All other nonmanufacturing, nec	0.1600
Universities and colleges	0.1600
Other nonprofit institutions	0.1600
Entertainment, literary, and artistic originals /25/	
Theatrical movies	0.0930
Long-lived television programs	0.1680
Books	0.1210
Music	0.2670
Other	0.1090

Source: Bureau of Economic Analysis, BEA Depreciation Rate