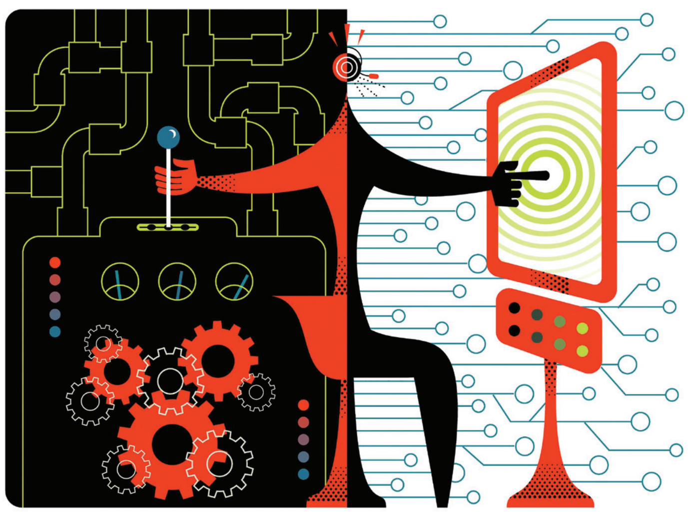
THE COMING PRODUCTIVITY BOOM

Transforming the Physical Economy with Information



Michael Mandel
Bret Swanson

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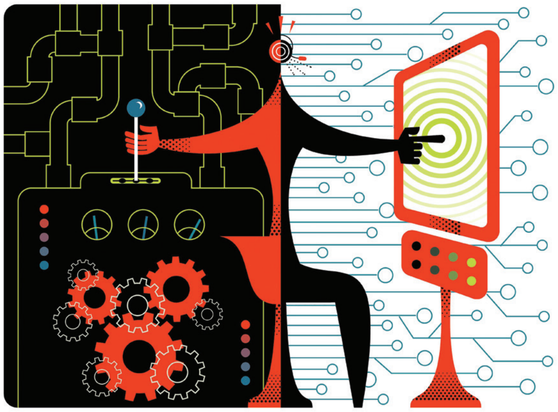

About the Authors

MICHAEL MANDEL, Ph.D., is chief economic strategist at the Progressive Policy Institute. He is also president of South Mountain Economics and a senior fellow at Wharton's Mack Institute for Innovation Management at the University of Pennsylvania. Mandel was previously the chief economist at BusinessWeek.

BRET SWANSON is president of the technology research firm Entropy Economics LLC. He is also a visiting fellow at the American Enterprise Institute's Center for Internet, Communications, and Technology Policy, a scholar at the U.S. Chamber of Commerce Foundation, and vice chairman of the Indiana Public Retirement System (INPRS).

The Technology CEO Council is the public policy advocacy organization comprising Chief Executive Officers from America's leading information technology companies, including Akamai, Dell, IBM, Intel, Micron, Oracle, Qualcomm and Xerox.

techceocouncil.org

Driving a Productivity Boom that Benefits All Americans

It is amazing how many of our nation's biggest challenges can be addressed by a simple formula: faster growth more broadly shared. From infrastructure to healthcare, education to national security, crime to creativity, a bigger pie and a wider winner's circle go far towards solving them.

A simple comparison of potential growth rates tells the story. At the current expected growth rate of 2% annually, the country will struggle to meet its obligations and invest in the future. But if growth accelerates to 2.7% annually, as this paper's analysts project, it will add a cumulative $8.6 trillion in wages and salaries over the next 15 years (measured in 2016 dollars).

And while Americans will have more to spend on meeting their needs, the government will have more funding to help out. Federal revenues will go up by an added $3.9 trillion without any increase in federal taxes as a share of GDP. Some of that will go to cutting the debt, while still leaving additional revenue for other needs, such as infrastructure and security. (These figures are based on projections and analysis developed in this paper.)

Unfortunately, over the past few decades the pace of economic growth around the world has slowed. Whereas U.S. economic growth averaged 3.3% in the 1980s and 3.4% in the 1990s, it fell to just 1.6% in the 2000s and only 2.0% so far this decade. At the same time in more developed economies such as the United States, this more-slowly-rising tide has lifted fewer boats than in the past. The result? Frustration, pessimism, stagnation.

We can do better.

Economic output is the product of two factors: total hours worked times productivity of the workforce. Growth occurs when these factors increase, yet over the past decades both have slowed. To reignite economic growth, we need to accelerate either the size of our workforce or its productivity. And since simple demographics limits the growth of our workforce, the great American economic imperative is to accelerate productivity.

There is good news. With the arrival of powerful new technologies, we stand on the verge of a productivity boom. Just as networking computers accelerated productivity and growth in the 1990s, innovations in mobility, sensors, analytics, and artificial intelligence promise to quicken the pace of growth and create myriad new opportunities for innovators, entrepreneurs, and consumers.

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The Technology CEO Council commissioned this analysis to better understand how new technologies can catalyze growth and what policy makers can do to accelerate these positive trends while making sure their benefits are realized by more Americans. We believe smart public policies will hasten the diffusion of these technologies and enable innovation, entrepreneurship and growth. Policy innovations are likewise critical to maximizing the number of citizens able to reap the rewards of these extraordinary opportunities.

For all the challenges facing our nation and our world, solutions exist. Many will require tough choices and hard work, but the opportunities are there. We are most excited to lead innovative organizations creating many of these emerging solutions, and we are quite eager to assist with policy makers around the world working to bring them to fruition.

The Technology CEO Council

Executive Summary

The Information Age is not over. It has barely begun.

- The diffusion of information technology into the physical industries is poised to revive the economy, create jobs, and boost incomes. Far from nearing its end, the Information Age may give us its most powerful and widespread economic benefits in the years ahead. Aided by improved public policy focused on innovation, we project a significant acceleration of productivity across a wide array of industries, leading to more broad-based economic growth.

- The 10-year productivity drought is almost over. The next waves of the information revolution—where we connect the physical world and infuse it with intelligence—are beginning to emerge. Increased use of mobile technologies, cloud services, artificial intelligence, big data, inexpensive and ubiquitous sensors, computer vision, virtual reality, robotics, 3D additive manufacturing, and a new generation of 5G wireless are on the verge of transforming the traditional physical industries—healthcare, transportation, energy, education, manufacturing, agriculture, retail, and urban travel services.

- At 2.7%, productivity growth in the digital industries over the last 15 years has been strong.

- On the other hand, productivity in the physical industries grew just 0.7% annually, leading to anemic economic growth over the last decade.

- The digital industries, which account for around 25% of U.S. private-sector employment and 30% of private-sector GDP, make 70% of all private-sector investments in information technology. The physical industries, which are 75% of private-sector employment and 70% of private-sector GDP, make just 30% of the investments in information technology.

- This "information gap" is a key source of recent economic stagnation and the productivity paradox, where many workers seem not to have benefited from apparent rapid technological advances. Three-quarters of the private sector—the physical economy—is operating well below its potential, dragging down growth and capping living standards.

- In particular, the crucial manufacturing sector, outside the computer and electronics industry, has barely boosted its capital stock of IT equipment and software over the past 15 years. Not surprisingly, productivity growth in manufacturing has slowed to a crawl in recent years.

- Information technologies make existing processes more efficient. More importantly, however, creative deployment of IT empowers entirely new business models and processes, new products, services, and platforms. It promotes more competitive differentiation. The digital industries have embraced and benefited from scalable platforms, such as the Web and the smartphone, which sparked additional entrepreneurial explosions of variety and experimentation. The physical industries, by and large, have not. They have deployed comparatively little IT, and where they have done so, it has been focused on efficiency, not innovation and new scalable platforms. That's about to change.

- Healthcare, energy, and transportation, for example, are evolving into information industries. Smartphones and wearable devices will make healthcare delivery and data collection more effective and personal, while computational bioscience and customized molecular medicine will radically improve drug discovery and effectiveness. Artificial intelligence will assist doctors, and robots will increasingly be used for surgery and eldercare. The boom in American shale petroleum is largely an information technology phenomenon, and it's just the beginning. Autonomous vehicles and smart traffic systems, meanwhile, will radically improve personal, public, and freight transportation in terms of both efficiency and safety, but they also will create new platforms upon which entirely new economic goods can be created.

- Manufacturing may be on the cusp of transformation—not just by robotics and 3D printing, but by the emergence of smart manufacturing more broadly: a fundamental rethinking of the production and design processes that substantially boost productivity and demand. That, in turn, could create a new set of manufacturing-related jobs and allow American factories to compete more effectively against low-wage rivals.

- Far from a jobless future, a more productive physical economy will make American workers more valuable and employable. It also will free up resources to spend on new types of goods and services. Artificial intelligence and robots will not only perform many unpleasant and super-human tasks but also will complement our most human capabilities and make workers more productive than ever. Humans equipped with boundless information, machine intelligence, and robot strength will create many new types of jobs.

- Employment growth in the digital sector has modestly outpaced employment growth in the physical sector, despite the big edge in productivity growth for digital industries. This suggests that we can both achieve higher living standards *and* create good new jobs. The notion that automation is the key enemy of jobs is wrong. Over the medium and long terms, productivity is good for employment.

- How much could these IT-related investments add to economic growth? **Our assessment, based on an analysis of recent history, suggests this transformation could boost annual economic growth by 0.7 percentage points over the next 15 years. That may not sound like much, but it would add $2.7 trillion to annual U.S. economic output by 2031, in 2016 dollars. Wages and salary payments to workers would increase by a cumulative $8.6 trillion over the next 15 years. Federal revenues over the period would grow by a cumulative $3.9 trillion, helping to pay for Social Security and Medicare. State and local revenues would rise by a cumulative $1.9 trillion, all without increasing the tax share of GDP.**

- Expanding the information revolution to the physical industries will require an entrepreneurial mindset—in industry and in government—to deploy information technology in new ways and reorganize firms and sectors to exploit the power of IT. Some of these technological transformations are already underway. Public policy, however, will either retard or accelerate the diffusion of information into the physical industries. Better or worse policy will, in significant part, determine the rate at which more people enjoy the miraculous benefits of rapid innovation, both as workers and consumers.

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- Better tax policy, for example, can encourage domestic investment and the allocation of capital into more cutting-edge projects and firms. Closing the information gap also will demand the ability of regulators in the physical industries—from the Food and Drug Administration to the Department of Transportation, and every agency in between—to embrace innovation and technological change. Mobilizing information to dramatically improve education and training is imperative if we want our citizens to fully leverage and benefit from these emerging opportunities. Encouraging investment in communications networks, which are the foundation of most of these new capabilities, is also a crucial priority. The free flow of capital, goods, services, and data around the world is as essential as ever to innovation and productivity.

- Launching this new productivity boom thus demands a new, pro-innovation focus of public policy.

Transforming the Physical Economy with Information

In a recent book on the history and future of innovation, a well-known economist argues that information technology is a spent force.[1] Computers and networks just aren't as powerful as previous inventions, he argues, and the United States should expect at least 25 years of relative stagnation. Whereas electrification transformed most every industry and household, the economist argues, information technology is unlikely to improve life outside of the narrow realms of news, finance, and entertainment. "We don't eat computers or wear them or drive to work in them or let them cut our hair," he writes.

He and like-minded pessimists find support for their thesis in the recent slowdown of productivity growth in the United States and around the world (see Figure 1). Despite the increasingly prominent role of smartphones and the Internet in our daily lives, labor productivity growth, averaged over the past 10 years, has plummeted.

What's more, top economists have put the blame for the slowdown squarely on IT. "The slowdown," notes productivity expert John Fernald of the Federal Reserve Bank of San Francisco, "is located in industries that produce information technology (IT) or that use IT intensively, consistent with a return to normal productivity growth after nearly a decade of exceptional IT-fueled gains."[2]

At the same time, job growth has stalled in many industrialized countries. The United States and other industrialized nations, the story goes, appear to be stuck in the worst of all possible worlds, where innovation and the information revolution are disrupting industries and destroying jobs, without giving workers the benefits of higher productivity growth and rising living standards.

Accelerating Atoms With Bits

We are far more optimistic. The problem is not that we have too much innovation and investment in IT. The problem is that we don't have enough in the right places. Far from nearing its end, the Information Age may give us its most powerful and widespread economic benefits in the years ahead.[3]

The surprising fact is that most companies in the U.S. economy are not taking full advantage of the power of information technology. Even today, the bulk of infotech investment—including software—is made in

figure 1. **PRODUCTIVITY GROWTH PLUNGE**

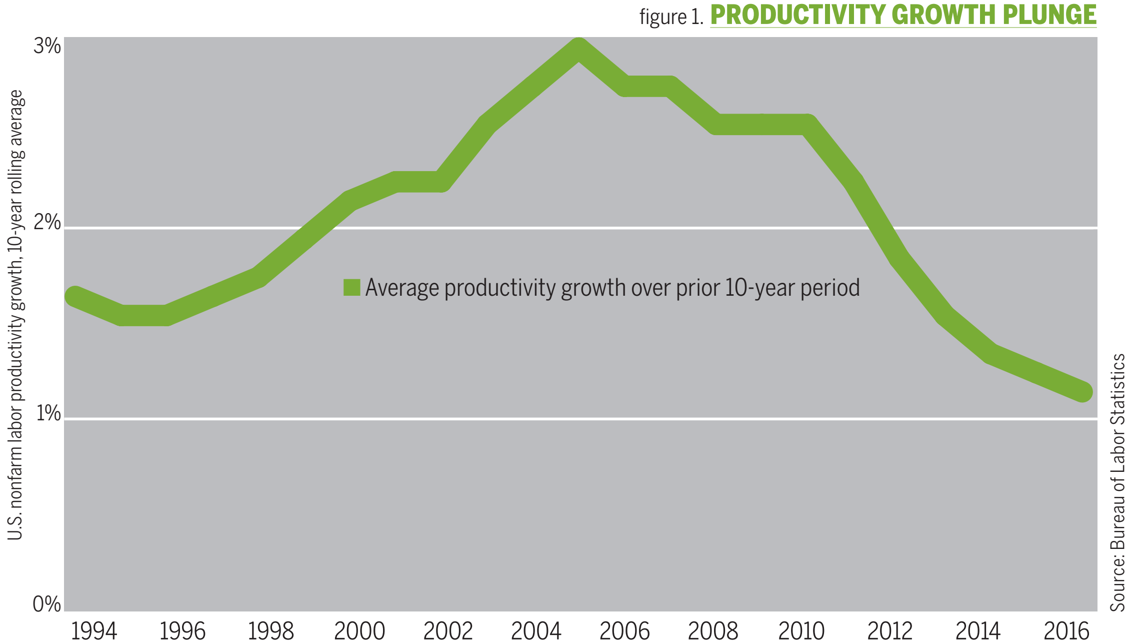
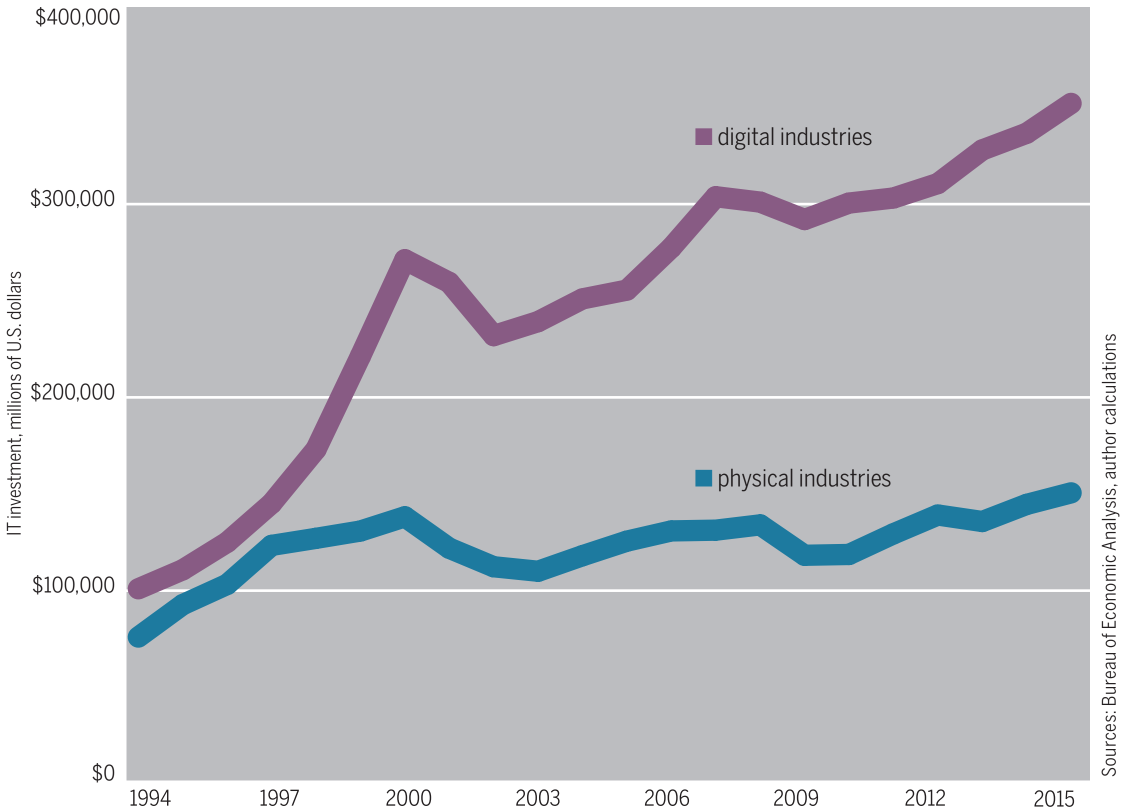


figure 2. **INVESTMENT IN INFORMATION TECHNOLOGY AND SOFTWARE**



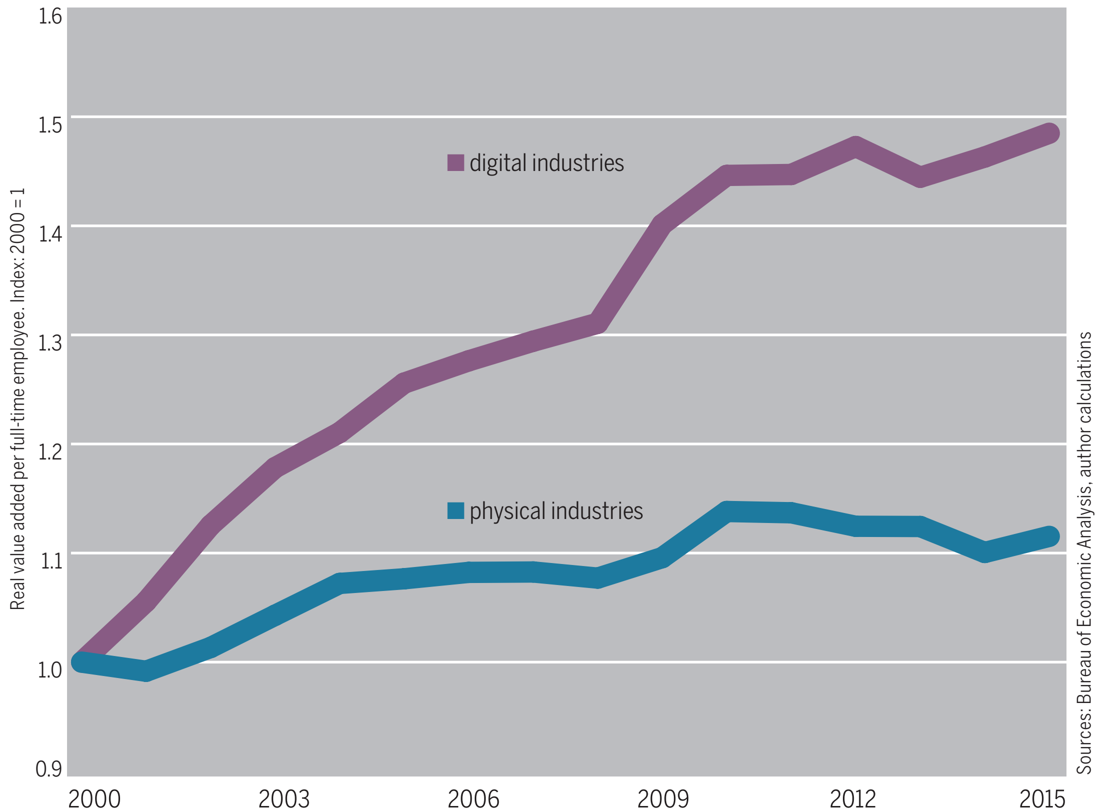
industries where the output is primarily digital: tech, content, finance and insurance, and professional and technical services. By our estimate, these digital industries account for 70% of U.S. private-sector infotech investment (see Figure 2). The rest of the economy—the physical industries—account for only 30% of infotech investment.[4]

These figures—based on official statistics from the Bureau of Economic Analysis—do much to explain our current economic conundrum. The physical industries—such as manufacturing, construction, mining, wholesale and retail trade, utilities, healthcare, hotels, restaurants, transportation—employ roughly 75% of the private-sector workforce, and form the core of our economy. Yet they are lagging in the infotech investment—and the business model innovation that IT often empowers—needed to generate productivity growth. This "information gap" is a key source of recent economic stagnation and the so-called productivity paradox.

Economics tells us that productivity, or output per hour, is the single most important determinant of wages and living standards. The faster productivity grows, the larger the economic pie grows. Higher productivity allows us to create a safety net for the less fortunate; invest in infrastructure and higher environmental standards; pay for retirement and healthcare for the elderly; and generally make life easier for everyone.

Conversely, if we get stuck in a world of slow productivity growth, we face some tough choices. With a fixed or slow-growing economic pie, the only way to make one group better off is to make another group worse off. Politics turns mean and nasty.

Up to now, the digital industries—which make up about 30% of private-sector economic output—have produced far more productivity gains and innovation than the physical industries. From 2000 to 2015, the digital industries generated productivity growth of 2.7% per year, compared to just 0.7% for physical industries (see Figure 3). And according to new data from the National Science Foundation, digital industries were twice as likely to innovate compared to physical industries—15% of companies in figure 3. **PRODUCTIVITY GROWTH: DIGITAL VS. PHYSICAL**



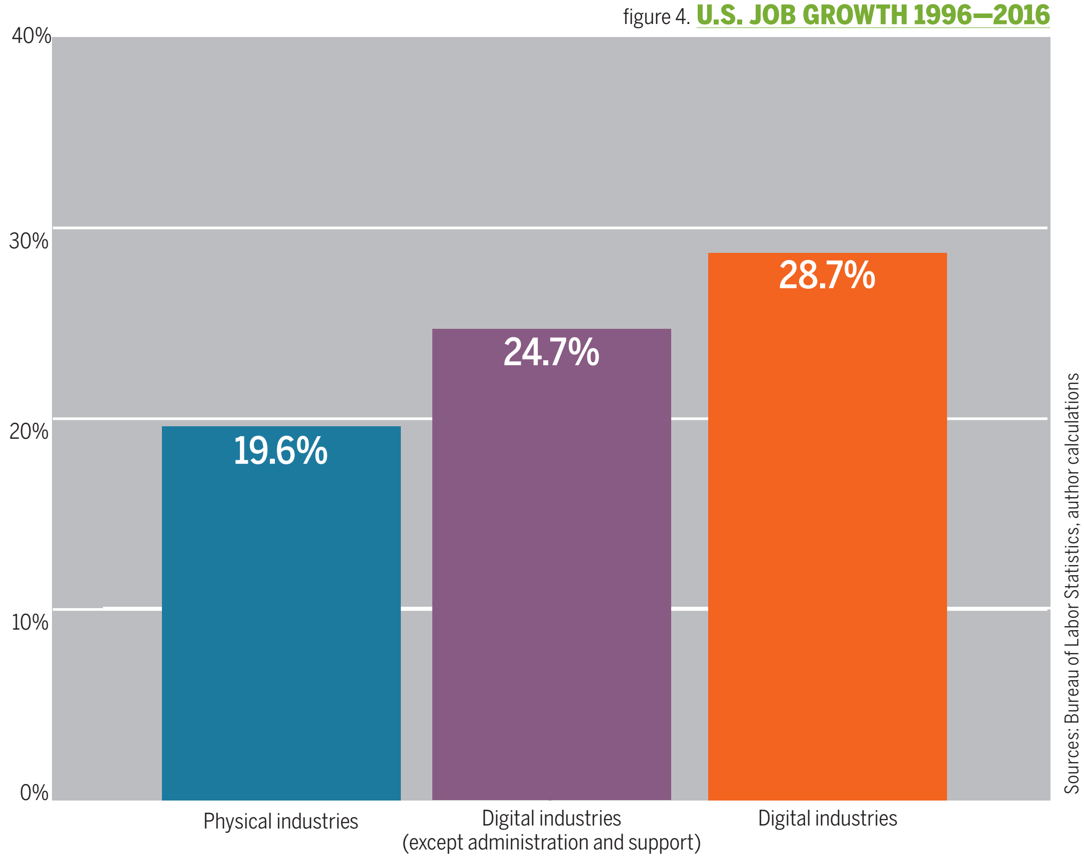
digital industries introduced a new or significantly improved product or service between 2009 and 2011, compared to 8% of companies in physical industries.[5]

In a surprise to many, these productivity gains in the digital sector have not led to job losses. To the contrary: The digital sector as a whole has shown substantial job gains, as falling costs and prices have led to increased demand for the output of the digital sector. From 1996 to 2016, employment in the digital sector grew by 29% (see Figure 4). Even omitting administrative and support service workers (which includes temporary employees), employment in the digital sector still grew by 25%. By contrast, jobs in the physical sector rose by just 20% in that 20-year stretch.

That means there is real potential for big gains in productivity without losing the benefits of job growth: Three-quarters of the private sector is operating well below its potential. That's going to change, as more and more companies in the physical industries adopt digital technologies such as cloud computing, Internet of Things (IoT), artificial intelligence (AI), robotics, 3D printing, and widespread use of machine-to-machine (M2M) mobile communications.

Increasingly we do wear computers—on our wrists and soon on our skin and our corneas. Increasingly we do drive computers—today's cars contain more than 100 silicon chips, and tomorrow's cars will be "the most powerful computers you will ever own."[6] We do eat them—in the form of radically improved agriculture, aided by genetic engineering and satellites, and even in the form of wireless camera pills that we ingest to scope our intestines.[7]

Our pessimistic economist's descriptions of information technology don't capture its true value or its elastic reach. He thinks, for instance, that because bar codes and automatic teller machines are no longer adding to productivity, most of the boost of infotech is behind us. But this ignores the vast future of information-based medicine, customized and lifelong digital education, and the transformation of traditionally physical industries like manufacturing and transportation. Untold new industries will arise and benefit from machine figure 4. **U.S. JOB GROWTH 1996—2016**



learning, 3D printing, cloud-based design, ubiquitous 5G wireless networks, blockchains, and other digital platforms and tools.

An emphasis on building new platforms with these technologies can unleash waves of additional innovation. For example, virtual reality will be a new platform that entrepreneurs can exploit to create new services in education, training, and industrial design. AI-as-a-service will allow entrepreneurs to build products for industries, such as healthcare, that too often are closed to outside innovators. IoT and geolocation platforms will allow tinkerers to leverage data about our physical world to create new personal and commercial services. This will require increased infotech investment in sectors that have historically invested less in technology, but the payoff would be enormous.

- We estimate that these technologies and new business models could accelerate innovation in the physical industries, adding roughly $2.7 trillion (in 2016 dollars) to U.S. GDP annually by 2031 (see Appendix A for methodology).
- This translates into an 11% increase in economic output in 2031, which is equivalent to boosting the average annual growth rate by 0.7 percentage points.[8]
- **Cumulative wage and salary payments to workers would increase by $8.6 trillion, in 2016 dollars.**
- Federal revenue over the 15-year period would grow by a cumulative $3.9 trillion, and state and local revenues would rise by a cumulative $1.9 trillion, without raising the tax share of GDP.

Prevailing Views on Productivity

Economists have offered a variety of explanations for the U.S. productivity slowdown. They've also debated whether there's any slowdown at all.

George Mason University professor **Tyler Cowen** and venture capitalist **Peter Thiel** believe we've suffered a 40-year innovation slump, especially outside of information technology. Northwestern University's **Robert Gordon** thinks the Information Age has come to an end and that, in any case, it wasn't nearly as powerful as previous technological eras, such as electrification. We should thus expect another 25 years of slow growth.

Harvard's **Larry Summers** thinks the problem originates with a persistent and global lack of consumer demand, perhaps the result of deleveraging. Weak demand reduces the need for capital investment, which leads to "secular stagnation."

Others believe that much of the apparent slowdown is an artifact of mismeasurement. The benefits of the digital economy, this theory goes, are especially difficult to grasp using traditional metrics. We may thus be undercounting output and productivity in the information economy, and the entire economy may be doing better than we think. It is pretty clear, for example, that over the last 15 years the official data underestimated the performance improvements of microprocessors and overstated their prices.[a]

Digital goods and services also generate massive consumer surpluses, perhaps worth hundreds of billions of dollars per year.[b] **Jan Hatzius** of Goldman Sachs argues that there is a bias against new goods and services, which by their nature are difficult to compare with the past.[c] **Joel Mokyr** persuasively argues that advances in health substantially boost living standards but often don't show up in the data.

More recently, **Chad Syverson** and the team of **David Byrne, John Fernald,** and **Marshall Reinsdorf** have given us reason to be skeptical of the mismeasurement hypothesis.[d] They show that even if significant mismeasurements exist, and even if we make aggressive assumptions about the true benefits of digital goods and better health, the underestimates are not nearly large enough to account for the productivity slowdown. Most of the productivity slowdown is thus real.

The underlying causes of any productivity slowdown are another fertile area of research. One attractive theory is that weaker business dynamism—the reduced net growth of new firms over the past two decades—has eroded productivity growth.[e] If innovation most often comes from high-growth entrepreneurial firms and start-ups that experiment with new technologies and business methods, then a reduction in firm growth would reduce the possibilities for productivity-driving innovation.[f]

Or perhaps economist **William Baumol** had this all figured out decades ago. In his famous "cost disease" theory, Baumol said that certain high-touch service industries such as healthcare and education are inherently labor-intensive and unproductive. As these industries grow as a portion of the economy, moreover, they exert a downward pull on total productivity.

Why, then, has manufacturing productivity growth also stalled? Maybe it's as simple as "atoms versus bits." Perhaps over-regulation of the physical industries (including healthcare, energy, education, transportation, and manufacturing) has slowed innovation in products built with atoms. Contrast this to the more lightly regulated bits of the digital industries, which have shown remarkable vibrancy.

Research by **Chad Jones** of Stanford reinforces this view, showing that the quality of institutions is correlated with total factor productivity (TFP) growth.[g] "One of the great insights of the growth literature in the last 15 years," Jones concludes, "is that misallocation [of resources] at the micro level can show up as a reduction in total factor productivity at a more aggregated level."

Defining the Digital versus Physical Economy

Economists have long been concerned with studying the impact of information technology on economic growth.[9] In general, the approach has been to separate the economy into IT-producing industries, IT-using industries, and non-IT-using industries.[10]

This breakdown was appropriate in the early years of the information revolution, where the Internet was relatively new and some industries were much faster in adopting new technologies than others. But today, every industry is using information technology to perform essential functions. Moreover, the set of industries which "produce" information technology and Internet-related services has widened dramatically, to include telecom providers, management consulting firms, and publishers.

In this paper, we draw a distinction between digital industries and physical industries based on the output of those industries. We define digital industries as those private-sector industries where the main output of the industry can be easily provided in digital form and can be readily delivered anywhere in the world via the Internet. This category includes entertainment, publishing, telecom, search, social media, finance and insurance, professional and technical services, and administrative and support services, many of which are IT-based.

We define physical industries as those private-sector industries whose output currently is provided mainly in physical form. This category includes construction, mining, healthcare, most of manufacturing, retailing, food services, education, transportation, and hotels.

Our reason for making this split is that the IT investment of the digital and physical sectors has performed very differently since the late 1990s. Since 1998, investment in computers, communications equipment, and software in the digital sector has more than doubled, from $173 billion to $352 billion.

By contrast, IT investment in the physical industries—where the main output is in physical form—has risen by only 19% over the same period, from $127 billion to $151 billion. In some very real sense, we've been running two economies—one that is taking advantage of the information revolution, and another one that is not.

The sidebar below lists the main digital and physical industries. Digital industries account for roughly 25% of the private-sector workforce and 30% of private-sector GDP.

DIGITAL INDUSTRIES VERSUS PHYSICAL INDUSTRIES

Digital Industries

Where the main output of the industry can be easily provided in digital form

Computer and electronics production; publishing; movies, music, television, and other entertainment; telecom; Internet search and social media; professional and technical services (legal, accounting, computer programming, scientific research, management consulting, design, advertising); finance and insurance; management of companies and enterprises; administrative and support services

Physical Industries

Where the main output of the industry is predominantly provided in physical form

All other industries, including agriculture; mining; construction; manufacturing (except computers and electronics); transportation and warehousing; wholesale and retail trade*; real estate; education; healthcare; accommodations and food services; recreation

** In related research, the digital sector is sometimes defined to include e-commerce.*

Making the Physical Economy Productive Again

Are the physical industries inherently resistant to information technology? Are they impervious to the productivity miracles of Moore's law and the Internet? We don't think so. Remember that soon after Robert Solow's famous quip in the late 1980s that "You can see the computer age everywhere but in the productivity statistics," we in fact got a computer-driven productivity boom.[11] It just took a little time for investments in personal computers and the Internet to show up as a dramatic reorganization of what we now call the digital economy.

There is reason to believe that a number of today's unproductive industries are on the cusp of similarly sweeping technological transitions. We do not suggest that any activity can be made productive merely by "throwing IT at it." We do observe, however, that many of these industries are ripe for change and that creative entrepreneurs are increasingly applying infotech to physical problems in surprising and powerful ways.

The most obvious way the physical industries will apply infotech to the physical world is through the Internet of Things, also known as the Internet of Everything or the Industrial Internet. In addition to connecting the physical world via the Internet, however, they also will infuse the physical world with smarts, supercharging human and physical capital via cognitive computing, artificial intelligence, robotic dexterity, and virtual and augmented reality.

Why has it taken so long? It sounds like a tautology, but industries whose output is information are inherently more amenable to digitization. A daily print newspaper can be easily transformed to a relatively small data set and delivered electronically. Similarly, your annual consumption of financial services can be reduced to a small number of electronic screens. On the business-to-business side, professional services such as engineering and back-end corporate operations such as payroll lose very little when digitized.

But when we examine industries whose output is primarily physical, the game gets far more difficult. To digitize a complex physical object such as a spinning jet engine, an unknown natural environment such as a buried oil field, or a rapidly changing manmade environment such as the traffic and work patterns of a large city, requires a level of sophisticated technology that was not available until fairly recently. Low-cost sensors that can be widely distributed; high-bandwidth wireless networks capable of collecting the information from the sensor; computing systems capable of analyzing terabytes of data in real time; artificial vision that can make sense of images and artificial intelligence that can make decisions—each of these are necessary parts of applying IT to the physical industries. Continued advances and price reductions in sensing, cloud computing, and broadband connectivity, combined with new thinking and new focus about how to apply these technologies to physical problems, are finally about to open up the other four-fifths of the economy to the magical laws of Moore and Metcalfe.[12]

Here are some examples of the coming transformation of physical industries into productivity powerhouses, propelled by information technology.

Personal Transportation

Waze had a fairly simple idea: connect drivers via their smartphones and let them help one another navigate around traffic or construction, or warn fellow drivers to slow down. In a short time, this simple app has made commuting far less grueling and navigating the roads far more enjoyable for millions. Waze shows how information technology can boost our personal productivity by improving a very physical act. But it offers only the smallest hint of the ;coming information revolution in transportation.

Ridesharing services and autonomous vehicles have both received a lot of attention as applications of information technology to the physical business of personal transportation. But if we want to understand how applying IT to the physical sector can both lower costs and boost jobs, we have to think about the creation of a whole new ecosystem of products and services.

Let's start with a number—15.8%. That's the astoundingly large share of household spending going to buying, maintaining, and operating motor vehicles in 2015. The Bureau of Labor Statistics tells us that middle-income households devote 18.2% of their household expenditures to motor vehicles. By comparison, the average household spends 7.2% of its budget on food at home, 2.4% on phone service, and 3.3% on clothing.

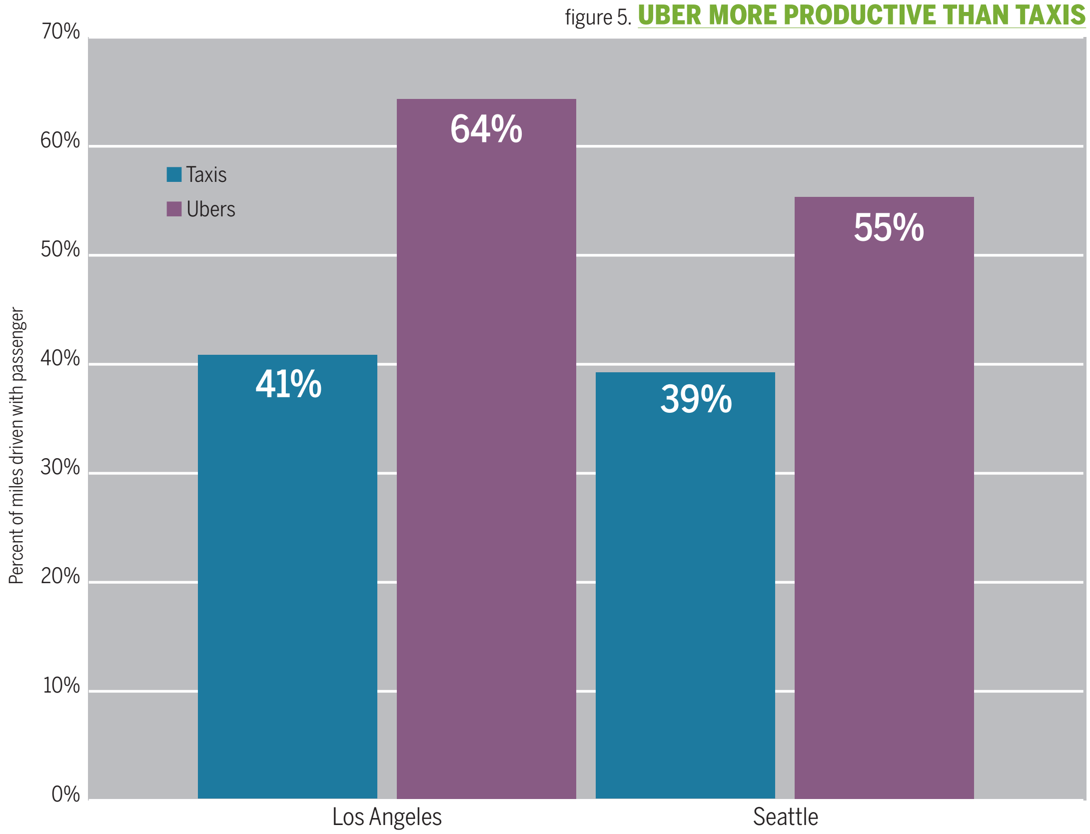
It should thus be obvious that one of the best ways to raise living standards would be to cut the cost of personal transportation. And if we had a way of doing that while creating more jobs, wouldn't that be great?

The cost-saving implications of technology-based ridesharing services such as Uber and Lyft are obvious: Your vehicle sits unused in your driveway or company parking lot most of the day. If it were possible to use vehicles more intensively, that would dramatically cut the cost of personal transportation.

Using mobile apps to seamlessly dispatch ridesharing vehicles accomplishes that. Moreover, the early data on ridesharing services already show the amazing productivity potential of IT in transportation. Economists Judd Cramer and Alan Krueger studied the experiences of Uber and taxi drivers in eight large American cities and found that Uber is far more efficient.[13] Compared to taxis, Uber cars often show utilization rates 40% to 60% higher (see Figure 5). One test of ridesharing's productivity is manifest in the extraordinary growth in total rides. Uber reports that it completed 62 million rides in July 2016, up 15% from its 54 million rides in June. The smaller Lyft reported a record 14 million rides in July 2016.

Beyond ridesharing, connected cars will enable far more efficient traffic management and improve safety through lane warnings and anti-collision technology. Google's self-driving cars have now driven 1.8 million miles, and not once has a Google car been the cause of an accident.[14] In June 2016, a Tesla driver was killed in a now-famous accident. Yet the fact that the event made news demonstrates the power of Tesla's autopilot capabilities. It was the first such event in more than 100 million miles of Tesla autopilot driving.[15] The experimental

figure 5. **UBER MORE PRODUCTIVE THAN TAXIS**



Sources: Judd Cramer and Alan B. Krueger autonomous and autopilot cars of Google and Tesla point to a future in which autonomous vehicles (AVs) are far safer than conventional human-driven cars.

The employment effects are interesting to think about. In the short-term, ridesharing services also create lots of jobs. In just five years, the number of rideshare drivers exploded from zero to more than 500,000.[16] But what about the medium term, as autonomous vehicles become more common?

Here's where we have to think about the whole ecosystem, rather than just one piece of it. As drivers become less important, repair technicians become more important. For one, as vehicles get used more intensively, they will require more regular maintenance, just like taxis do today.

And crucially, vehicles that operate without human control almost certainly will be held to a higher standard of maintenance including regular testing, replacement, and updating of technical systems. As one insurance company notes, referring to AVs, "the operator may still be required to maintain the vehicle, and liability could attach to the operator for a loss arising out of a failure to maintain it properly."[17]

Highly trained repair technicians—those who can figure out whether a stalling car suffers from a software glitch or a faulty fuel pump—will be in high demand. On the other hand, if AVs are safer and there are fewer collisions, some portion of maintenance and repair work may fall. Today, there are roughly 1.1 million auto, bus, and truck repair technicians in the United States, earning on average more than $40,000 per year. We could see their numbers grow, but we could also expect to see entirely new job categories arise as people find creative ways to use autonomous vehicles for new tasks. This is the new middle class, with a mix of digital and mechanical skills and robust employment for the foreseeable future.

Regardless of how the employment effects balance out within the transportation sector, more efficient transportation will free resources for everyone to spend on other goods and services, and to invest in new ventures, creating jobs elsewhere.

Energy Production

Through the 1990s and most of the 2000s, oil and gas mining in the United States was a fading industry. Employment was falling, and domestic production was falling even faster. The low point for oil and gas mining jobs was 2003, while the low point for domestic crude oil production was 2008.

But then information technology started remaking the energy business itself, generating both higher productivity and more jobs. The shale boom of the last decade is the epicenter of IT and energy. Three-dimensional geological computer modeling is making oil and gas drilling a "just-in-time" industry with lag times of weeks and days, rather than months and years. The early returns on the application of information technology to energy are astounding. In just the last half decade, U.S. oil production nearly doubled, from 5 million to 9 million barrels per day.[18] Natural gas production, which had remained remarkably steady since 1970, suddenly rose more than 50% (see Figure 6). The entire increase is due to the revolution in shale technologies, which employ highly sophisticated horizontal drilling and hydraulic fracturing of petroleum-infused rock formations miles under the earth's surface. Finding the shale formations and guiding the drills to precise locations requires high-end 3D computing resources.[19] Feedback from the operations generates massive amounts of data, which will be used to refine the next generation of exploration and drilling.

Geologists had known about the possibilities of shale rock for perhaps 100 years. Yet it was inexpensive computing, often in the cloud, that finally enabled the economical exploration and extraction of this abundant resource.[20] "The speed of improvement has been remarkable," notes energy analyst Mark Mills. "With virtually no increase in capital costs (in some cases, costs are down), the three key measures of drilling—time to drill, wells per rig, and total distance drilled—have improved by 50–150 percent in less than five years."[21] Moreover, the number of jobs in oil and gas mining and related support industries rose by 58% between 2003 and 2015. Use of information technology was a job creator, not a job destroyer.

Shale gas has also been the chief driver of reduced carbon dioxide emissions in the United States. As inexpensive natural gas replaced coal for electricity generation, CO_2 emissions from electricity in 2015 fell to a level not seen since 1988.[22] This, however, was just the first wave of the shale revolution. Exploiting the petabytes of data generated by the new shale fields, big data analysis could enable "Shale 2.0" technologies to produce American oil and gas at prices equal to Saudi Arabia's famously low-cost fields.[23] This is an information revolution in the most physical of industries, and in the industry—energy—that makes every other industry possible.

In a broader sense, each industrial revolution is an energy revolution. Agriculture was vastly more energy-efficient than hunting and gathering. Steam engines and internal combustion engines made horsepower obsolete. The Internet transports data across the globe with a minuscule fraction of the energy of a boat carrying a letter across the oceans. Productivity is producing more output per unit of energy. Energy is at the heart of everything we do, and IT is not only improving energy efficiency, it is now central to energy production.

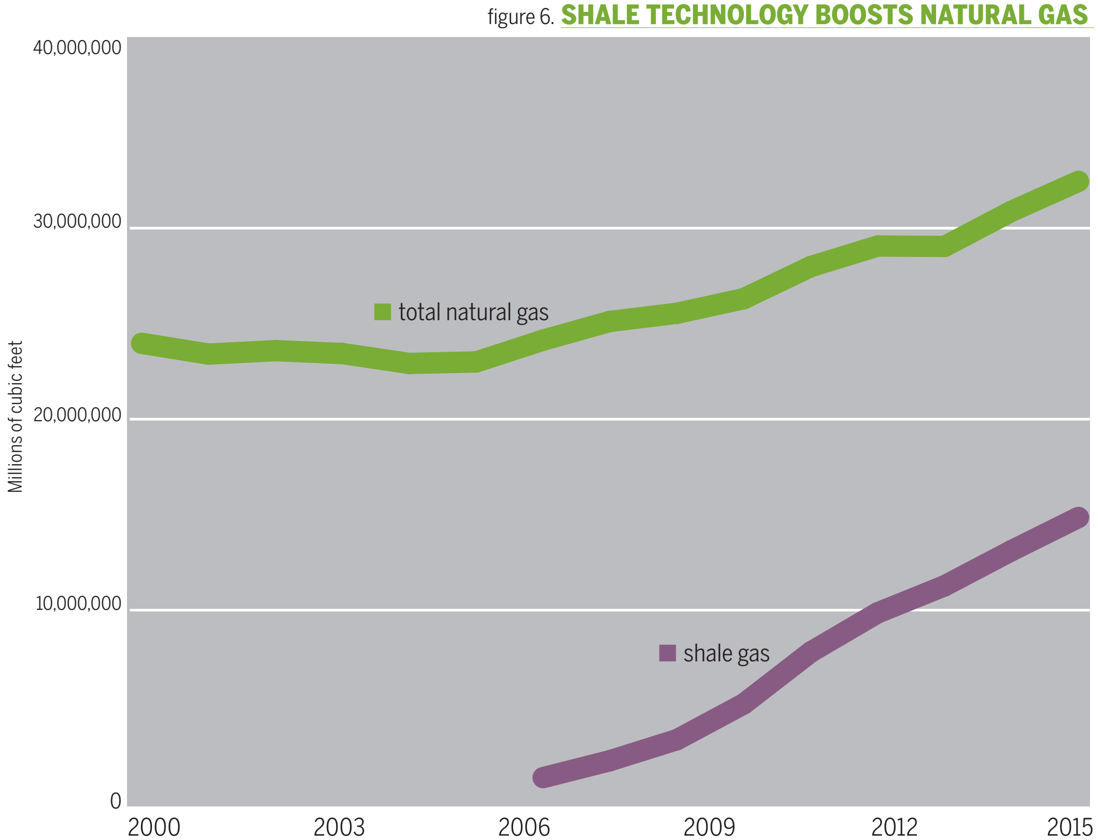
Education and Training

Education and training is a very large industry that has not enjoyed rapid productivity growth. Despite the introduction of MOOCs (massive open online courses) and distance learning, most students are still taught in person with conventional methods that would have looked familiar a century ago. What's more, there's widespread recognition that the quality of education has not kept up with the needs of a rapidly changing economy.

Nevertheless, digital technologies are already beginning to transform primary, secondary, and higher education. The experiments of the last few years with online courses will be refined into truly powerful educational platforms. New analytics will produce customized learning experiences. Education at every level may thus change more in the next decade than in the previous century.

Digital technologies also enable true lifelong learning and training, which is crucial to making workers productive across various economic cycles. Many economists in fact get this point wrong. A key argument by those predicting a continued productivity slump is our inability to keep adding to human capital

figure 6. **SHALE TECHNOLOGY BOOSTS NATURAL GAS**



Source: Energy Information Administration via education. The idea is that making the leap to near-universal elementary and secondary education over the previous 200 years and the more recent rise of a large college-educated population was a big factor in American growth. But we've hit a wall. It's impossible to increase schooling forever. At some point, we all need to go to work. Measured "years of education" will thus by definition level off and will no longer provide a boost to human capital.

Is formal "years of education" the right measure, though? We don't think so. In fact, the universality of knowledge made possible by the Internet opens up vast new opportunities for unconstrained learning across every discipline, from the technical and vocational to the deepest reaches of science. Better information about the skills of workers and the needs of businesses also will allow us to better forecast, produce, and match skills with opportunities. As our overall educational environment improves—both formally and informally—additions to human capital may thus not level off but in fact rise faster than ever.

MOOCs and other online classrooms and tutorials will in fact help revolutionize education. They will radically improve the efficiency of teaching routine tasks and elementary courses; provide far more choice and diversity in content; free students (and teachers) from the constraints of location; and allow people to learn from the very best instructors in most subjects.

Virtual reality and augmented reality, meanwhile, will be important tools in both basic education and job training. Imagine a set of augmented reality glasses that help guide technical students or new hires through a complex procedure, whether with a mechanical device, a construction project, or on a computer. Our ability to guide workers through complicated tasks will jump substantially. Moreover, these workers will be able to interact with the augmented reality system, ask it questions, and get real-time feedback.

These augmented reality systems and other human–machine interfaces may be especially important for low-skilled workers. Many believe the computer age has benefited high-skilled work but devalued low-skilled work. If a worker can't use a computer, he or she is out of luck. As we develop new human–machine systems that are more intuitive and less abstract, however, it will be possible to bring low-skilled workers back into the economic fold and empower them to participate in the overall growth of technological prosperity. Just as the PC and smartphone allowed masses of non-technical people to participate in the computer revolution, which had previously been the province of scientists and engineers, new user-friendly tools that don't look like "computers" will help amplify the important human skills of workers supposedly left behind.

Indeed, increasing the productivity of education and training may be the single most important factor in improving the employability of the American workforce.

Retail, Wholesale, and Distribution

The story of the retail and wholesale industries is a bit different than other industries in the physical sector. In the years before the financial crisis, wholesalers and retailers were among the biggest spenders on information technology, and they were paid off in rising productivity. Better inventory control and ordering helped boost the productivity of the backend of the supply chain. Thus between 1995 and 2005, both wholesale and retail showed annual productivity gains in excess of 4% annually (see Figure 7). Indeed, the American wholesale and retail industries were widely held up as the exemplars of how the United States had leapt ahead of Europe and Japan in terms of applying information technology for growth.

Unfortunately, since then productivity growth has collapsed in both wholesale and retail to the 1% to 2% annual range.

What happened? It turns out that in the end, goods still must be moved physically from the factory or the port, to the warehouse or store, to the ultimate buyer. And it's those physical movements—in particular, the final delivery to the home or office—that have turned out to be the productivity bottleneck. Local freight trucking is an inherently unproductive activity, as delivery drivers navigate congested and potholed streets, search for parking spaces, ring doorbells, and wait for an answer. Indeed, there have been meager productivity gains in local freight trucking in recent years (see Figure 8).

Under the previous model of in-person shopping, consumers absorbed the time and figure 7. **RETAIL AND WHOLESALE: PRODUCTIVITY GROWTH SLOWS**

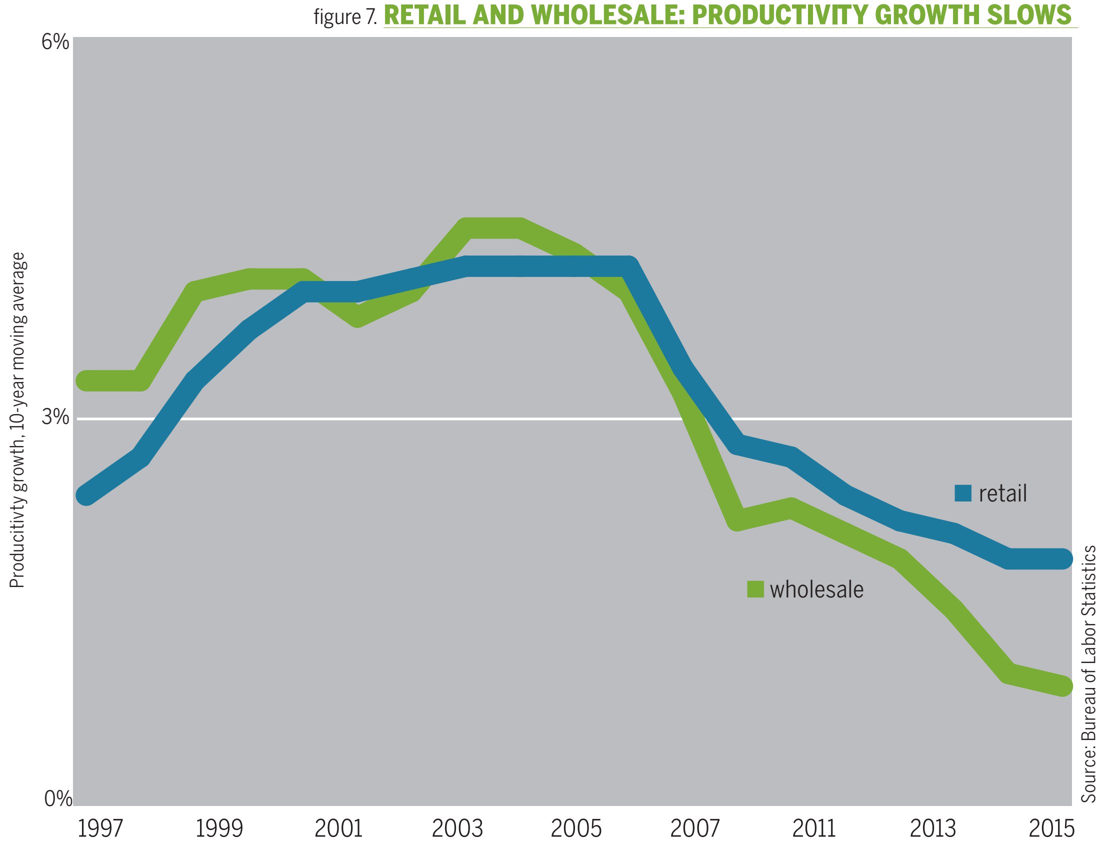
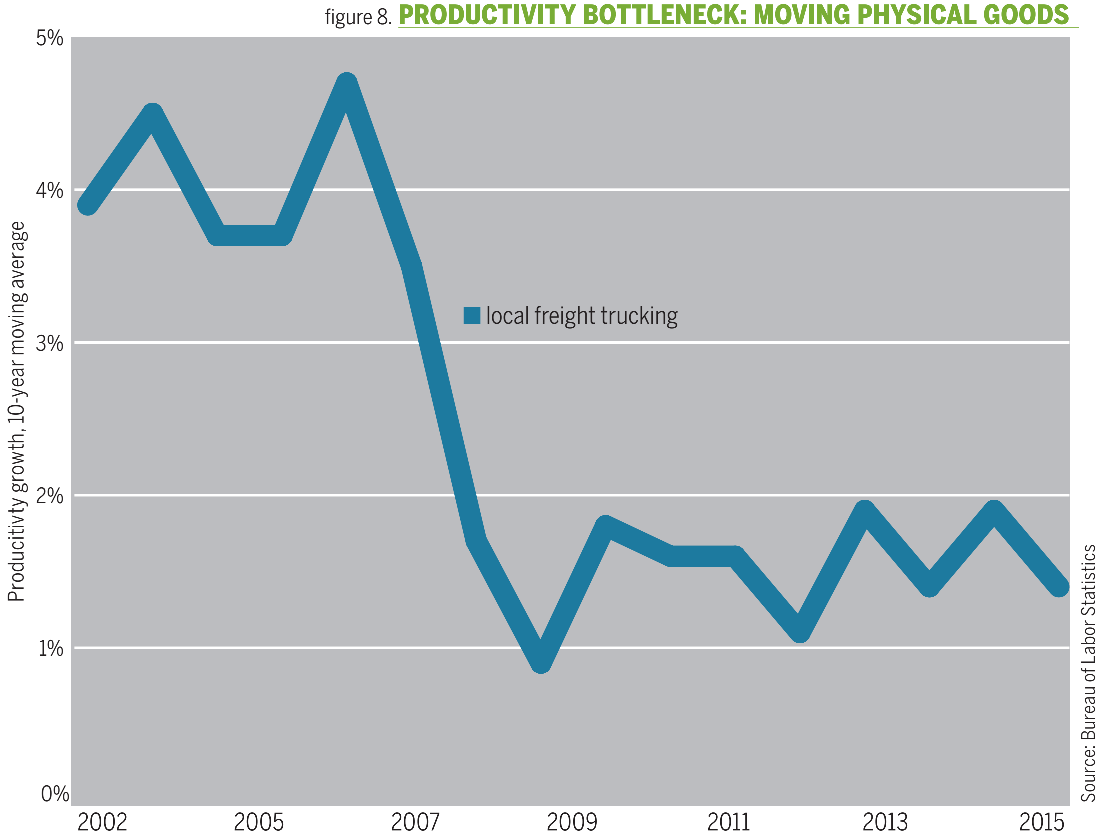


figure 8. **PRODUCTIVITY BOTTLENECK: MOVING PHYSICAL GOODS**



cost of local delivery themselves. The productivity statistics for retail may not take the reduction of consumer driving and shopping time into account, but they do highlight the productivity bottlenecks of delivery. And in the end, productivity depends on the whole supply chain, not just one piece of it.

That's why retailers such as Amazon envision aerial drones as delivery vehicles, bypassing the congested streets.[24] Drones have their own challenges, of course, such as safety. But these challenges are more easily solved by information technology compared to prospect of building new streets. At the same time, applying the Internet of Things to the home may allow automated delivery of food and household supplies direct from warehouses, thus removing one transportation step from the process—or even enable 3D printing of some items at home, thus removing two steps.

Manufacturing and the New IT Revolution

Manufacturing was originally at the vanguard of automation—the application of IT to the factory floor to improve productivity. The first programmable logic controller was designed in 1968 specifically for industrial uses. As more and more domestic factories adopted sophisticated computer-controlled machines, the goods produced by the factories became relatively cheaper for consumers, leading to rising living standards.

Now manufacturing is ready for the next stage of the IT revolution, the application of cloud computing, Internet of Things, artificial intelligence, and related technologies to transform not just production but product design as well. For example, we might see "smart" clothing; furniture with sensors and artificial intelligence built in to adjust to body shapes and create a more comfortable experience; customized and just-in-time products built locally with 3D printing; and "manufactured" artificial organs which have to be "built" close to their eventual users. These new product categories can help reinvigorate domestic manufacturing and potentially create new jobs at home.

Two points: Domestic labor is already a relatively small share of the total costs of manufacturing. So further attempts to increase manufacturing labor productivity for existing products are going to yield diminishing gains. Indeed, over the past 10 years, manufacturing labor productivity growth has slumped to only 2.1% per year, half of its 4.6% annual growth in the 10 years ending in 2006.

However, the sky is the limit when it comes to the design and manufacture of new products with new capabilities. Indeed, that is precisely how millions of jobs were created in the past. Henry Ford designed a new product, called the Model T. But it was mass production that allowed him to make the product cheap enough for ordinary Americans to afford. The result: Booming demand, rising employment, and the creation of the modern automobile industry.

A similar trend today will require a new domestic manufacturing sector, including start-ups that fully embrace the latest changes in IT and create new business models, such as manufacturing-as-a-service (MaaS). So far that hasn't happened: Government data shows that most domestic factories have not added much to their stock of information technology equipment and software over the past 10 years. Between 2004 and 2014, manufacturing IT capital stock increased by just $46 billion, and more than 65% of that gain was in the computer and electronics industry.

Figures 9 and 10 show the challenge. Leaving out the computer and electronics industry, the capital stock of IT equipment in the rest of manufacturing has barely grown since 2000. The capital stock of software in manufacturing is, likewise, barely higher now than in 2000.

It's an article of faith for many economists that manufacturing has seen enormous productivity gains. Over the last 20 years, U.S. manufacturing output grew by 40% in real terms, even as millions of manufacturing jobs were shed. This is seemingly the definition of productivity. But these effects are highly dependent on the specific manufacturing industries in question. Manufacturing productivity gains have been concentrated in the computer- and tech-producing industries. And in more recent years, the economic data show that overall manufacturing productivity growth has been slowing. The latest report from the Bureau of Labor Statistics estimated that figure 9. **MOST MANUFACTURING LAGS IT INVESTMENT**

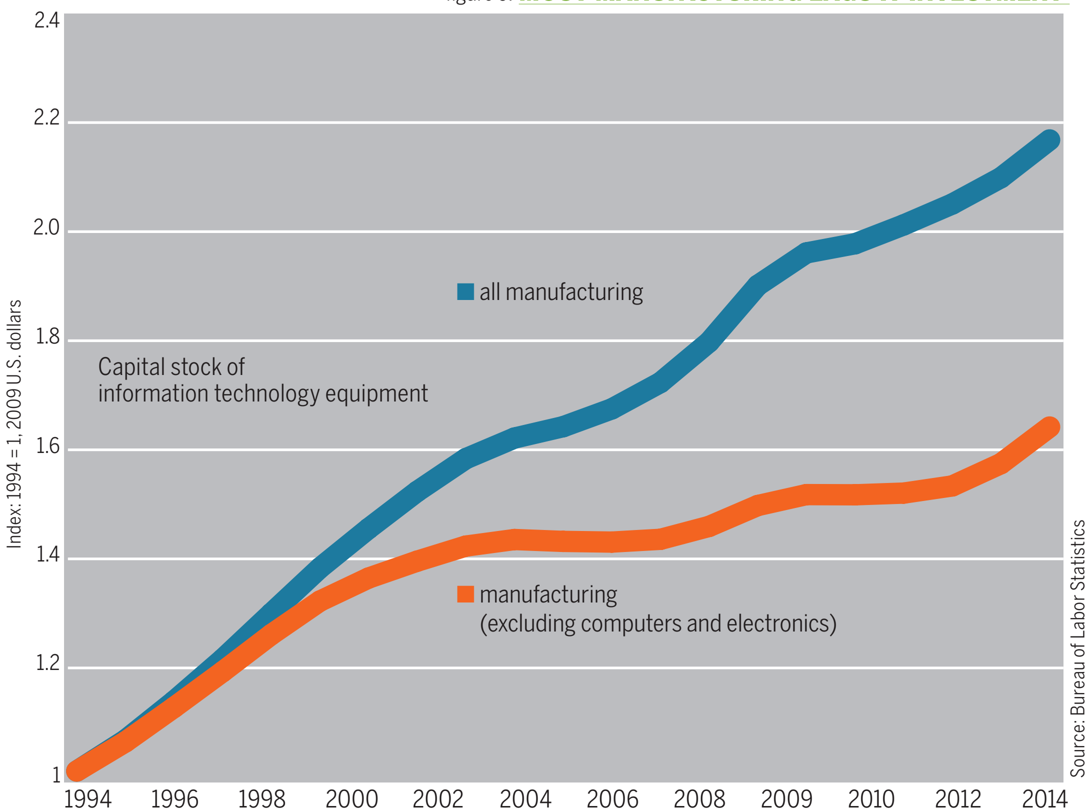
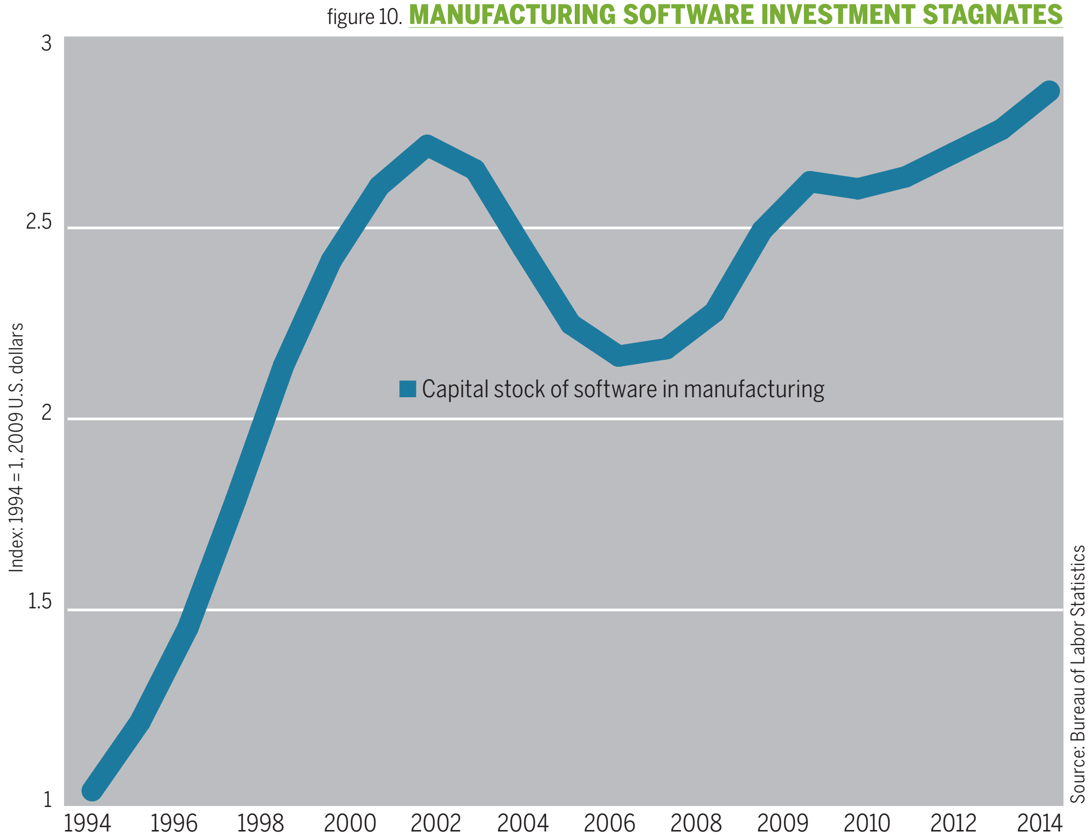


figure 10. **MANUFACTURING SOFTWARE INVESTMENT STAGNATES**



productivity growth in manufacturing was only 0.2% and 0.3% in 2015 and 2016, respectively, barely big enough to see.

Most manufacturing industries actually have experienced falling or stagnant multifactor productivity growth since the early 1990s. ("Multifactor productivity growth (MFP), also known as total factor productivity (TFP), is a measure of economic performance that compares the amount of goods and services produced (output) to the amount of combined inputs used to produce those goods and services," according to the Bureau of Labor Statistics. "Inputs can include labor, capital, energy, materials, and purchased services."[25]) There's no way that domestic factories can compete against low-wage foreign rivals without big gains in multifactor productivity, which has been absent. The notion that manufacturing jobs are lost (or gained) either due to technology or trade, one or the other, is too simplistic. More often, it is a complex interplay of the two. Some of the least productive manufacturing activities were the first to be moved offshore, to China for example, while activities that were relatively more IT-intensive and more productive often remained. In many manufacturing sectors, it is thus the lack of automation that has been a crucial cause of falling employment.[26]

Technology and trade are indispensable forces for economic growth and rising living standards. Manufacturing jobs have been in a secular decline as a portion of U.S. employment since World War II.[27] Technologies of course always make some jobs obsolete. The rise of China over the last 30 years, meanwhile, caused sharp employment dislocations in certain industries over a relatively short period of time. We should not conclude, however, that either technology or trade is a villain. Quite the opposite. We cannot have job and wage growth without technology and trade. The key is achieving economic growth that is fast enough to provide new opportunities to replace the old ones, acting as a cushion in a dynamic economy.

If we take a broader look, we can see that highly productive industries have experienced big job gains. Productivity growth in the digital industries has been far higher than in the physical industries. Yet employment in the digital industries has grown faster over the past 20 years than employment in the physical industries. Productivity growth does not equal job losses.

What about robots? According to trade association data, 31,000 robots valued at $1.8 billion were shipped to North American customers in 2016. The spending on robots pales next to the $300 billion in industrial equipment and manufacturing buildings that corporations spent in the United States in 2016.

In many cases, robots help the United States retain jobs. Consider a modern semiconductor fab, which has installed a proprietary network of wafer-handling robots. This system probably reduced the number of wafer-handling jobs by several dozen. Yet the robots allowed the new fab to be built in the United States, instead of in a low-cost overseas location, thus saving or creating some 1,200 high-paying American jobs.

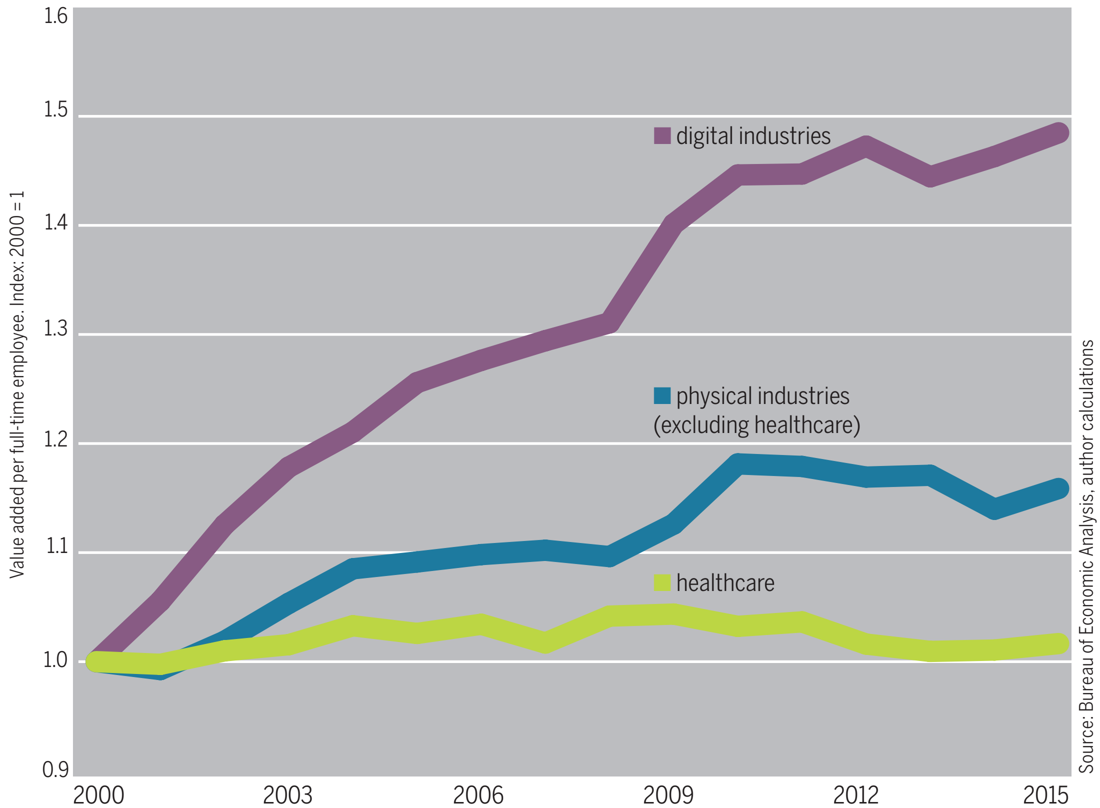
The upside of robots in manufacturing spreading out into new industries is thus enormous. That's crucial for increasing the productivity of existing manufacturing processes and creating new processes altogether.

In many ways manufacturing is the classic case where atoms will be boosted by bits. The process is already underway—but the diffusion of the Industrial Internet across the manufacturing sectors will take place over the next two decades. New, IT-enabled product categories, combined with design and customization that increasingly treats manufacturing as a service, will not necessarily bring back "old jobs" but instead create new and better ones.

Healthcare

Healthcare is among the largest industries, which makes its very weak productivity growth in recent years all the more problematic. Measured by Bureau of Economic Analysis data, total productivity growth in healthcare over the last 15 years was less than a tenth of growth in the stagnant physical industries and a mere thirtieth of the growth in digital industries (see Figure 11).

This weakness in productivity growth shows up as the need for an ever-increasing number of expensive healthcare workers, including an explosion in health administration. For example, in 2016 the U.S. population increased by 0.7%. Meanwhile, the number of figure 11. **BOOSTING HEALTHCARE PRODUCTIVITY CRUCIAL FOR GROWTH**



healthcare workers, including administrators, grew by 2.5%. While there are huge problems measuring the quality of healthcare, it's clear that lagging productivity in hospitals and physician offices is a chief driver of today's high medical bills and tomorrow's gigantic imbalances in federal and state budgets.

According to the Centers for Medicare and Medicaid Services (CMS), today's health expenditures in the United States (around $3 trillion) will grow to more than $5.4 trillion by 2024.[28] Healthcare's portion of the national economy is thus expected to grow to nearly 20% from an already-high 17%. This dead weight isn't just breaking our finances; it threatens to deaden our innovative capacity.

Fortunately, no sector of the economy is poised for a larger productivity surge. We envision a four-faceted information revolution in health.[29] It will be, as we have described elsewhere, a broad transformation of the sprawling industry, consisting of:

1. **Smartphones and Personal Technology.** Supercomputers in billions of individuals' pockets (and on their wrists and in their brains and intestines) all connected via broadband networks, will enable cheap, anywhere, all-the-time diagnostic tools and communication and data collection capabilities. Smartphones will be used not only for direct communication with physicians and nurses, substantially reducing the ubiquitous office visit. They also will be used as tools to diagnose ear infections, monitor heart rhythms, remind us to take medication, and detect emergent maladies by sensing chemicals in our breath and noticing changes in our retinas. They will connect to a host of sensors and drug dispensers that will meander through our bodies.
2. **Big Data, Social Data.** With the collection, coordination, sharing, and analysis of unimaginably large troves of specific data about patients, treatments, physicians, environments, and facilities, researchers and patients themselves will dig deeper and make more connections than ever before. IBM's Watson Health is already successfully analyzing libraries of medical images, patient histories, research papers, and genetic data to assist doctors by identifying evidence-based, personalized treatment options for cancer patients.

Some of the algorithms at the heart of today's deep learning technologies were developed 30 years ago. But we didn't enough computing power or sufficiently large data sets to make them useful. Now, with millions of times the computing power and data sets trillions of times bigger, that is changing. The accumulation of data and speed of discovery will produce a virtuous circle that will make today look like a dark age of medicine.

One surprising development is that individuals with no medical background are using the Internet, which has democratized medical knowledge and expertise, to make significant breakthroughs in their own health and that of others in their networks.

3. **New Cures.** The truly radical new understanding of biological information networks, including genomics and proteomics, will yield personalized molecular medicine. Cracking this "code of life" is the most fundamental application of information technology at the heart of the health information revolution … and it is happening. In 2001, the cost to sequence one genome was $100 million. Today, the cost is just $5,000—and the cost is dropping rapidly toward $1,000.[30] "The vital core of medicine," writes Peter Huber in *The Cure in the Code,* "is now on the same plummeting-cost trajectory as chips and software."

   Computational bioscience will combine our knowledge of this biocode with exploding empirical data to clear the way for scientists to design new therapies in the cloud. This should dramatically reduce the cost of pharmaceutical development and greatly expand the number of therapies that can be created and tested by moving medical research away from a hit-and-hope world of trial-and-error guesswork. Immuno-oncology is just one promising field in which scientists are already designing anti-cancer drugs using knowledge of specific cellular mechanisms and bio-information networks to, in effect, reprogram the body's own defense systems. But it is still early days. Understanding the code of life will also enable us, within just the next few years, to begin manufacturing artificial human organs on a large scale.

   In addition, 3D bioprinting of human tissue and organs are envisioned for use in clinical trials of new drugs, instead of human trials, which could improve patient safety, reduce costs, and accelerate time to market. Likewise, 3D printing already is improving customization and reducing the time and cost of making artificial limbs.

4. **The App-ification of Healthcare.** Healthcare is too often a closed and stagnant system. For all of the new health information technologies to truly flourish, the economic model of healthcare must change. Instead of a centralized, opaque, top-down system of big hospitals, big insurance, and big government, we need an entrepreneurial model of numerous firms and technologies (healthcare "apps") delivering better care at lower prices to patient-consumers. Healthcare should be more like the smartphone ecosystem—a platform that empowers millions of diverse apps, products, and services created by other people and firms, targeting the needs of individual consumers.

   This new model will include Uber-like "doctor on demand" platforms. It will include a multitude of personalized, affordable insurance products. It will promote real and knowable prices. It will encourage far more participation by technologists and entrepreneurs to deliver new therapies and health services to consumers who are far more interested in value. It will mean a far greater focus by healthcare providers on innovation, efficiency, and cost reductions. It will reduce unnecessary tests and office visits. But at the same time, this new model will entail more preemptive diagnostics, preventive care, and health maintenance, rather than post-symptom acute care. (For example, some believe that with better early detection tools, we could cure 80% of cancers with today's therapies.[31]) The potential is enormous, but a successful reorganization of healthcare delivery will be limited mostly by the extent of improvements in tax and regulatory policy.

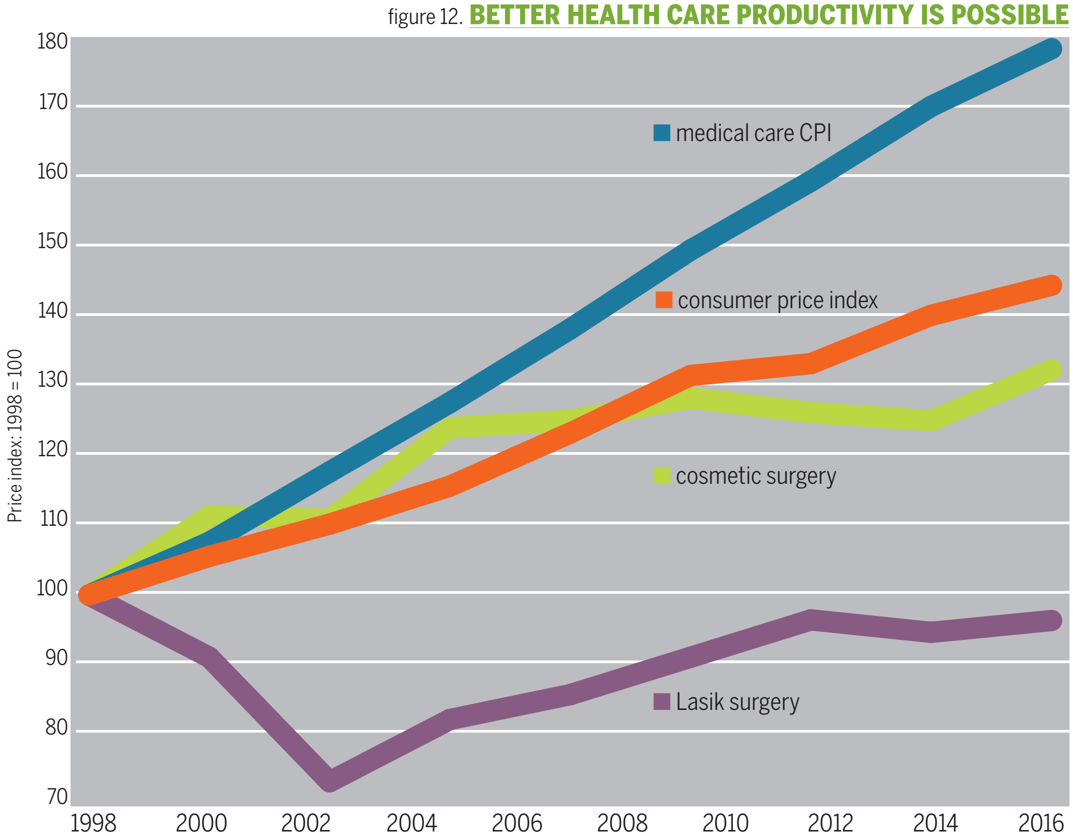
Many believe William Baumol's dictum, which has indeed held for decades, that healthcare productivity is unlikely to improve in the future. But we already have a number of examples that show healthcare innovation is possible. Consider the cases of Lasik eye surgery and cosmetic surgery. Over the last 20 years, healthcare prices have grown at around twice the rate of inflation. Cosmetic surgery prices, meanwhile, have grown more slowly than the general price index. Lasik surgery prices have actually fallen over this period, and the quality has radically improved (see Figure 12).[32] These medical services exist mostly outside of the bureaucratic third-party payer system, and are instead competitive out-of-pocket consumer services. Providers of these services are thus compelled to invest in technologies and organizational efficiencies to compete for customers. Another example of a competitive, market-based, technologically innovative health service is orthodontia. Lasik surgery, cosmetic surgery, and orthodontia show that with rational incentives in a healthy marketplace, the medical field will deploy technology aggressively to achieve high-quality, low-cost results.

Healthcare is not inherently inflationary or unproductive. Yes, particular health needs, like eldercare, may be especially labor intensive for now. But we likely will find ways to improve even these necessarily human-to-human interactions. And the embrace of information technologies across the full range of health and medicine will more than make up for the few remaining stubborn tasks that resist the productivity pull of information.

Imagine the productivity boost we would enjoy simply by reducing the number of cardiac office visits by two-thirds, as one Stanford cardiologist assumes we will. Imagine walking into a pharmacy, getting your blood analyzed on the spot, and walking out the door with a 3D-printed pill customized to your needs. Or what if you could do all that in your home? Now imagine the productivity boost we would enjoy by doing something really big, like curing Alzheimer's disease.

Achieving these benefits will require a new mindset across the breadth of health and medicine, one that prioritizes innovation through information intensity. With better policies that encourage innovation, doctors, nurses, hospitals, scientists, entrepreneurs, and patients themselves will deploy information solutions in new and creative ways, improving the efficiency of existing services and transforming the entire health ecosystem, from the delivery of care on the front lines to the deepest reaches of biological research. Boosting productivity in healthcare alone will go a long way to reviving overall long-term economic growth.

figure 12. **BETTER HEALTH CARE PRODUCTIVITY IS POSSIBLE**



Sources: First Trust Advisors, Bureau of Labor Statatistics, The American Society for Aesthetic Plastic Surgery, allaboutvision.com

Optimistic Signs in the Cloud

While IT investment by the physical industries has been sluggish, spending on information technology services in recent years has increased rapidly. Starting after the Great Recession, spending on technology services and goods, not including investment, by the physical industries grew nearly 50% in just four years, from a baseline of around $225 billion between 2000 and 2010 to a much higher level of more than $330 billion in 2015 (see Figure 13). This shift likely represents the transition away from investment in internal IT departments and into "the cloud"—toward outsourced computing, data storage, and software-as-a-service (SaaS) offerings.

Cloud computing is a fundamental force in our economic transformation. It's only about 10 years old, however, and it will continue to grow for decades. Before 2008, most Internet traffic was peer-to-peer file sharing between PCs.[33] But now the cloud dominates. The clustering of computer servers and storage systems in large data centers created a powerful new economic model—what some call "warehouse-scale computing."[34] The radical price drops in computing and storage, accessible by anyone with a broadband Internet connection, gave birth to a new business model that was soon dubbed "cloud computing." And today, the vast amount of Internet traffic is generated in or passes through the cloud.

Cloud computing has been a chief input to the mobile app revolution, enabling entrepreneurs to develop massively complex software and services with little capital investment. It also powers the revolution in Web video, exemplified by YouTube and Netflix; enables consumer PC backup services; and supercharges our smartphones by remotely doing much of the heavy lifting of the apps we enjoy. Most data-heavy firms have spent the last decade migrating their computing and storage needs from in-house IT systems to private data centers and now to the cloud. From a standing start in 2006, cloud computing will, according to Cisco's Global Cloud Index, generate 4

figure 13. **THE CLOUD COMPUTING EFFECT**

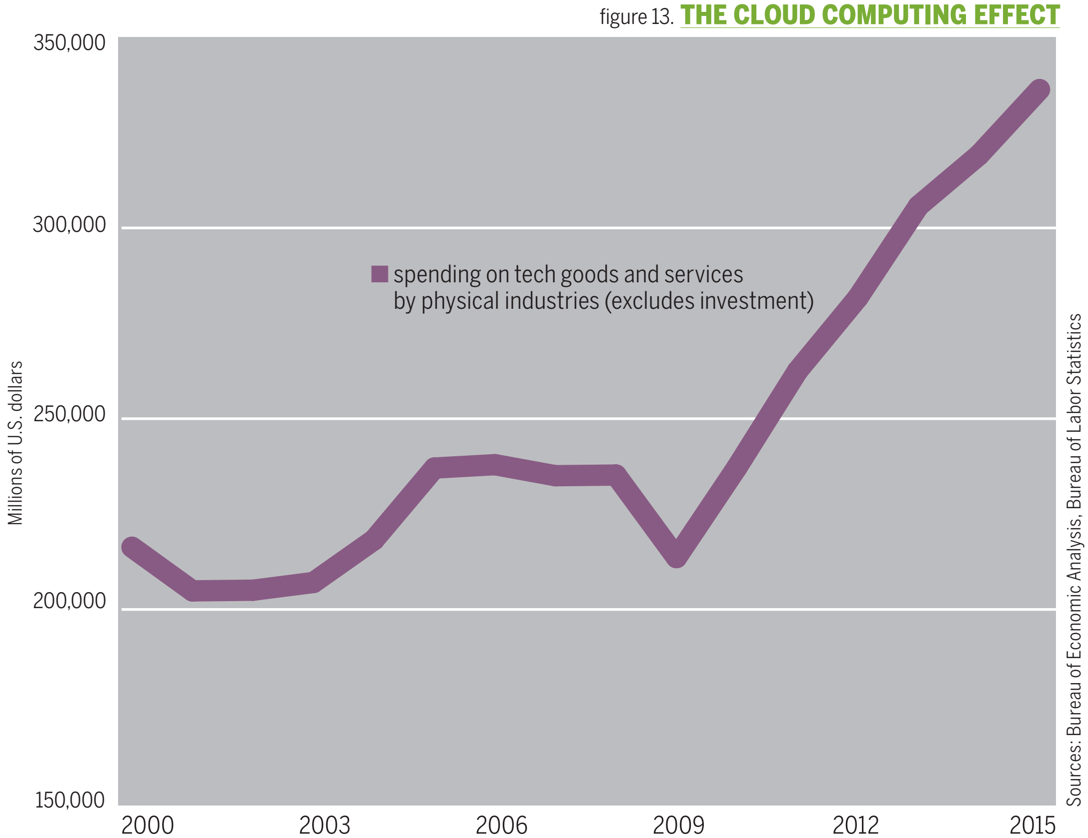


table 1. **SOME PHYSICAL INDUSTRIES BOOST SPENDING ON TECH GOODS AND SERVICES**

Increase in spending on tech goods and services, 2010–2015*

	Percent change	Billions of dollars
Transit and ground passenger transportation	326%	0.6
Petroleum products	163%	0.9
Other transportation equipment	118%	18.4
Farms	117%	0.7
Motor vehicles	86%	10.9
Food and drink services	68%	4.1
Accommodation	59%	1.1
Retail	34%	7.5
Mining	31%	0.6
Healthcare	27%	8.8
Wholesale	21%	4.7
All other physical industries		44
	TOTAL	102

** Does not include IT investment*

Sources: Bureau of Economic Analysis, author calculations

zettabytes of traffic in 2016 (a zettabyte is a billion trillion bytes).[35] By 2019, cloud traffic is projected to grow to 8.6 zettabytes.

The recent spending rise on infotech services highlights the possibilities for the physical economy, and it is likely just the beginning of a much larger wave.

Gartner, the market research firm, estimates that what it calls the "cloud shift"—the transition from spending on traditional IT offerings to cloud services—will be $111 billion in 2016, growing to more than $216 billion in 2020.[36]

The recent uptick in physical industry spending on IT cloud services is especially notable in two sectors, transportation and petroleum manufacturing. This likely reflects (1) the rise of Uber and Lyft ridesharing services and (2) the shale oil and gas boom. Taxis and petroleum drilling are among the most physical of industries. But the application of inexpensive and abundant cloud computing power has jolted these once-tired industries back to life in just the last several years.

The recent spending rise on infotech services highlights the possibilities for the physical economy, and it is likely just the beginning of a much larger wave. So far, the increases in spending have been relatively concentrated in a few industries (see Table 1).[37] Technology goods and services still represent just 3.7% of all spending on inputs by physical industry firms, meaning these firms still have lots of room to boost infotech intensity.

Projecting the Economic Impacts

As enterprises in the physical industries learn how to better use IT-related investments to transform their operations, as described in previous sections, what kind of gain in productivity and growth can we expect? To analyze this question, we use a new dataset from the Bureau of Economic Analysis and the Bureau of Labor Statistics. This new dataset, called the "integrated industry-level production accounts" and described in Appendix A, is specifically designed to help answer questions about sources of growth in the economy.

We use the integrated industry-level production accounts to analyze the slowdown in productivity growth in the physical sector. In particular, we examine the "New Economy" high-productivity-growth period, when physical industries such as retail and wholesale trade showed rapid productivity growth, driven by IT-related investments (see Appendix A for details). By comparison, over the decade from 2004 to 2014, the IT-related slowdown in growth in the physical industries helped slice 0.7 percentage points off overall productivity.

The industry-by-industry analysis in this paper suggests that the whole range of physical industries—from personal transportation and energy to education, retailing, manufacturing, and healthcare—is ready for an IT-driven transformation that could reverse this negativetrend. How big? If the physical sector merely regains the dynamism it had in the late 1990s and early 2000s, that could add 0.7 percentage points to annual GDP growth.

That may not seem like much. But if the baseline growth rate is only 2%, as most economists now think, a jump to 2.7% annually makes a big difference. By 2031, the higher growth rate pushes up GDP by 11% compared to its previous path, or $2.7 trillion (in 2016 dollars). That's enough to significantly lift incomes and living standards, as wage and salary payments would rise by a cumulative $8.6 trillion over the next 15 years, in 2016 dollars. In addition, the larger economy would yield around $3.9 trillion in cumulative federal revenues and $1.9 trillion in additional state and local revenues over the 15-year period, all without increasing the tax share of GDP.

One important insight is that the physical industries make up 75% of private-sector employment, while the digital industries are only 25%. As a result, an acceleration of productivity growth in the physical sector has three times the overall impact as the same acceleration in the digital sector.[38]

The industry-by-industry analysis in this paper suggests that the whole range of physical industries—from personal transportation and energy to education, retailing, manufacturing, and healthcare—is ready for an IT-driven transformation.

On the consumer level, digital goods and services amount to only 15% of personal consumption spending. So it's important to realize productivity gains in the physical industries to improve consumer welfare. A recent analysis by one of the authors showed that consumer prices in the physical sector have been accelerating, while consumer prices in the digital sector have been falling.[39] But because the share of physical goods and services are so much larger, any acceleration of productivity in the physical sector will have a disproportionate benefit for consumers.

The Future of Job Growth

Specialization and efficiency create wealth and drive demand. New products and efficiencies in one arena may displace some current products and workers, but they unlock new pathways for higher-value products, firms, and jobs. In other words, innovation creates new products and services that didn't exist before.

New technologies boost job growth in at least three distinct ways: **directly,** for workers who build the new tools and products; **indirectly,** for workers who leverage the new tools to create unrelated businesses and services; and through **economic growth,** as rising productivity unlocks scarce resources to invest in new projects and spend on other consumer goods.

Think back to a hundred years ago, when 40% of U.S. employment was in farming and another 30% in manufacturing. If someone had told you then that 100 years hence these two sectors would combine into just 14% of the economy, the outlook would have seemed cataclysmic. It's relatively easy for people to see which jobs might be made obsolete by technology but far more difficult to imagine the new ones.

For example, the discovery of antibiotics and invention of x-rays were not only great for public health, they also created the modern healthcare industries. Hospitals, which had been charitable institutions where poor people went to die, became respected institutions where people came to be healed—and not so incidentally, where many new jobs were created.

Today, the needs and demands of modern society are creating new occupations at a rapid clip. As of March 2017 for example, there are roughly 50,000 job postings for social media managers, digital marketing specialists, and the like. The number of job openings in 3D printing and additive manufacturing is rising fast.

Who would have predicted even 15 years ago that, beginning with the introduction of the first popular smartphone in 2007, a new software industry would emerge? Yet in just a few short years, entrepreneurs and firms created more than 1.5 million new apps, and the cumulative number of mobile apps downloaded by iOS and Android users exploded from essentially zero to nearly 400 billion.[40] This "app economy" now supports an astounding 1.66 million jobs in the United States.[41]

The app economy is a good example of why it's so important that public policy promote innovation and plan for surprises. Heavily regulated and taxed economies tend to discourage start-ups and the growth of small firms. They do this in part by directly prohibiting innovation or indirectly discouraging investment and experimentation. They also make competing against incumbents more difficult by imposing costs that large, established firms can more easily bear.

Many modern economies attempt to guarantee employment by subsidizing existing firms and making job turnover difficult. This approach may be comforting in the short term but usually isn't effective in the long term. By discouraging new hires at existing firms and blocking new firm formation, these efforts often backfire, resulting in higher unemployment and lower incomes. This is one reason the U.S. economy and labor market for the last several decades were generally healthier than much of Western Europe.[42]

New calls for tariffs and other protectionist measures are another form of this static, zero-sum view. Closed economies may be able to protect some existing jobs for a short time. Protectionism, however, usually comes at the cost of higher input prices, higher consumer prices, retaliatory obstacles to exports or market access, and an overall reduction in dynamism and thus long-term job growth. In today's highly integrated world, importers are exporters, and vice versa.[43] In an increasingly knowledge-based, data-driven world, moreover, the very concept of imports and exports is losing relevance. On the other hand, an open economy full of enterprise and entrepreneurship offers a tradeoff: in return for an apparently higher degree of uncertainty, an open economy almost always delivers a more prosperous future. This has been one of America's chief advantages for several centuries.

Public Policy

In this paper we have argued that productivity growth can be significantly accelerated by the application of information technology to the physical industries. This is an important point in the wide-ranging policy debates now taking place in the United States, Europe, and the rest of the industrialized world. If policymakers and voters begin to feel like slow growth is inevitable, then economic policy inevitably tilts towards dividing up a fixed pie. That means less willingness to entertain the benefits of international trade and immigration, and more willingness to regulate business, including technology. Why support disruptive innovation if it doesn't lead to growth and rising living standards?

Conversely, if productivity growth begins to accelerate, public support for "growth" industries will rise. There will be more tangible benefits from cross-border flows of goods, services, people, and data, and more willingness to support innovation and trade.

To fully exploit the power of information technology, however, will require public policy changes that encourage investment and innovation in lagging non-digital sectors, as shown in Table 2. In today's economy, the most important factor in any business is human capital. Productivity-enhancing policies must therefore focus on empowering people. Expanding information technology to the physical economy also will require the very best innovation infrastructure. Finally, the United States should embrace in all its industries the entrepreneurial climate that has produced so much wealth and opportunity in the digital industries.

Empowered People

A new, fully digital economy will require a workforce with the skills to thrive in connected, data-driven firms and industries. If existing digital industries are struggling to find enough technical talent, how can we expect the other 70% of the private economy to fully staff the information-intensive future?[44] We therefore need to upgrade our education and workforce development systems to dramatically expand the number of Americans who can help create, and thrive in, the digitally-enabled economy.

table 2. **PUBLIC POLICY CHANGES TO ENCOURAGE INNOVATION AND INVESTMENT**

EMPOWERED PEOPLE	INNOVATION INFRASTRUCTURE	ENTREPRENEURIAL BUSINESS CLIMATE
EFFECTIVE EDUCATION Transform how and what U.S. students learn to match the accelerated, digital and global economy.	**UBIQUITOUS CONNECTIVITY** Expand spectrum available for commercial use, broadband investment through deregulation and Internet of Things readiness.	**PRO-GROWTH TAX POLICY** Lower the rate for employers, shift to a territorial system and improve innovation incentives.
LEGAL IMMIGRATION Ensure legal pathways for the world's best and brightest.	**ROBUST R&D FUNDING** Robustly fund federal labs and universities.	**TRADE POLICY** Expand U.S. workers' access to global markets and work to reduce trade barriers.
MEANINGFUL HELP Offer more effective adjustment assistance, lifelong learning incentives, help for entrepreneurs, and apprenticeships.	**SECURE NETWORKS** Secure government networks, help private networks defend themselves, and drive global agreement on norms.	**SMART REGULATION** Make government more efficient with fewer old barriers to new technologies.

Employers do not believe our secondary and higher educational systems are satisfactorily equipping students and future employees to succeed on the job. One industry study, "Pursuit of Relevance," found that half of college students graduate without essential workforce skills, including both technical know-how and soft skills, such as communication, teamwork, and problem solving.[45] Boosting collaboration between higher education and industry leaders and improving the relevance of curricula are thus two important steps.

One industry study, "Pursuit of Relevance," found that half of college students graduate without essential workforce skills, including both technical knowhow and soft skills, such as communication, teamwork, and problem solving.

Reducing the cost of education is an important goal as well. More students and parents are finally scrutinizing the "value proposition" of higher education, but so far only a small minority of colleges and universities have stepped up to successfully meet the challenge. Overconsumption of a product with a questionable payoff cannot go on forever. We should therefore reform subsidies that tend to encourage educational price inflation and instead promote innovative solutions that can help families invest in education and training that is likely to pay off in the real world.[46]

The information explosion means the fundamental nature of education is changing. Skills and certifications earned outside of traditional tracks will become more common. Public policy should be open to experimentation with new credentialing arrangements. Competition from nontraditional educational sources, which often leverage new technologies, will play an important role in encouraging traditional institutions to improve their value propositions and should thus be encouraged. Remodeling our educational systems can both improve the quality and boost the quantity of education, all while making it far more cost-effective.

Solving the immigration impasse is an important component of this human capital equation. U.S. leadership in innovation has long depended on big contributions from immigrant technologists and entrepreneurs. Encouraging the world's smartest, most ambitious, most creative people to join the American experiment will be crucial to a productivity revival and also will help mitigate the demographic challenges of an aging society.

As the nature of work changes, we also should adapt our policies to support a labor market that is more dynamic and jobs that are more flexible. Benefit policies conceived when many people worked at one company for a lifetime should evolve so that health insurance and retirement savings plans can move seamlessly among employers or self-employed workers.

Innovation Infrastructure

Because communications networks are the foundation of all information technology, they are centrally important tools for all the industrial transformations we discuss. The digital industries succeeded in large part because over the last 20 years, U.S. firms, encouraged by a bipartisan light-touch regulatory framework, invested $1.5 trillion in broadband communications networks, both wired and wireless.[47]

Similar investments—in 5G wireless, fiber optics, cloud computing, software, and IoT sensor networks—will have to be made over the next 20 years to consummate the transition of the physical industries to IT. If they are to act as the central nervous system for complex systems, such as autonomous vehicles, next-generation networks will need to be even faster and more ubiquitous, robust, and secure than today's networks.[48] Policies governing these networks, and the services running over them, are thus a crucial lever that can either encourage, or deter, investment on such a massive scale.

Baking cyber-preparedness into all levels of the digitally-enabled economy (from network design to worker training to corporate governance) will be critical to effective defenses, which will encourage investment in infrastructure, ensuring the physical industries can depend on networks and data that are even more reliable and secure than the first-generation Internet.

Elevating cybersecurity as a national priority is key. The founders of the Internet built an ingenious experimental system, but they did not emphasize security from the beginning. As the Internet spreads to more mission-critical operations—in transportation or health, for example—security is taking on new importance. Baking cyber-preparedness into all levels of the digitally-enabled economy (from network design to worker training to corporate governance) will be critical to effective defenses, which will encourage investment in infrastructure, ensuring the physical industries can depend on networks and data that are even more reliable and secure than the first-generation Internet.

Another crucial component of the nation's innovation infrastructure is its research and development capacity. From Bell Labs to Xerox PARC, at universities and national labs, from high-tech incubators to tinkerers' garages, basic research has been a foundation of progress. Because the United States operates at the innovation frontier, it must continue to generate new ideas to grow. Funding and incentivizing R&D should thus remain a top priority.

Entrepreneurial Business Climate

If the physical industries are to enjoy the experimentation and breakthrough business models that characterize the digital industries, they will have to adopt a similar entrepreneurial ethos. But many of these industries simply cannot do so under existing policy. Improving tax, trade, and regulatory policies is thus essential to unlocking the next waves of innovation.

The physical industries will have to dramatically step up their investment not only in information technology, but also in other advanced equipment, to take advantage of new opportunities. The U.S., however, has fallen further behind other countries that have modernized their tax policies to enable their global corporations to better compete and to encourage foreign direct investment and job creation. Fundamental tax reform is thus an imperative. Unfortunately, high corporate and individual tax rates in the current U.S. tax code discourage domestic investment and risk-taking. This disincentive has been amplified by recent changes in the global tax system—the so-called base erosion and profit shifting (BEPS) rules—which encourage U.S. companies that want to take advantage of low overseas tax rates to actually move jobs to those countries.[49]

In effect, the U.S. corporate tax system is now on a collision course with reality. A simpler corporate tax code, with a significantly lower rate, and a change to territorial treatment of profits, would substantially boost investment and economic growth. The Tax Foundation, for example, estimates that a new 20% rate would raise long-term GDP by 3.3% and help create 641,000 additional jobs over the next 10 years.[50] Because the current code is so inefficient and economically destructive, a lower, more competitive tax rate probably could collect nearly as much tax revenue as today's code, but with far fewer distortions and disincentives.[51] Other changes, such as immediate expensing of capital expenditures, also would help boost overall investment, including in the types of IT infrastructure needed to transform the physical industries.

Because the United States operates at the innovation frontier, it must continue to generate new ideas to grow. Funding and incentivizing R&D should thus remain a top priority.

Trade policy is another tool that, with a modernized tax code, can provide the best platform for American entrepreneurs to build technologies and products for the world. With 95% of the world's consumers outside the United States, access to markets will always be an important consideration. Knocking down non-tariff trade barriers (NTTBs) should continue to be a priority, especially where other nations attempt to restrict data flows or compel local storage of information. And because the United States creates so much of the world's intellectual property (IP), protecting IP and enforcing agreements is crucial. Because technology, data, IP, and knowledge work are so global in nature, maintaining a free flow of business inputs is not optional. With the other policy enhancements mentioned here, the United States should prosper in an open world economy.

Regulation is essential for a well-functioning economy. No one doubts that consumer protection is an essential function of government. However, regulatory paradigms conceived prior to the emergence of the digital age (in healthcare, medicine, transportation, education, infrastructure, and government services) are obstacles to the diffusion of information technology into the physical industries. Clearing away outmoded webs of regulation and replacing them with smart, modern systems is one of our biggest challenges—and most exciting opportunities.

It is difficult to pinpoint the exact costs of regulation, but we know they are extraordinarily large. The federal government itself estimates that major new regulations issued since 2009 cost $112 billion per year. Excluding environmental rules, the remaining regulations still cost $58 billion per year.[52] Compliance costs are burdensome, but the biggest downside of regulation is the gigantic opportunity cost of lost innovation. These dynamic costs of regulation, accumulating over decades, could mean trillions of dollars of lost GDP, even excluding the impact of environmental rules.[53]

Carefully addressing the heavy burden of innovation-stifling regulations, without hurting consumers, could pay off big. One mechanism might be a Regulatory Improvement Commission, which would be charged with identifying and selectively improving or eliminating outdated regulation.[54] The goal would be to encourage experimentation with information technology tools and promote entrepreneurial ventures that can provide healthcare more efficiently, discover new medicines more quickly, deliver energy to the market more inexpensively and cleanly, and manufacture millions of old and new products more productively. And because it is so central to all of these possible advances, the way we choose to govern the Internet is especially important.

Conclusion

The information gap—the divergence of infotech intensity and productivity between the digital and physical industries—helps to answer many of today's big economic questions, such as the source of our decade-long "stagnation" and the "productivity paradox." It also helps to explain why so many citizens in certain regions and industries feel left out of America's relative prosperity.

The physical industries have invested relatively less in information technology, and they generally have not exploited IT's role as an enabler of breakthrough business models. The digital industries built new platforms—the PC, the Web, the smartphone, cloud computing, electronic financial markets—which empowered further explosions of entrepreneurial activity. The physical industries, on the other hand, have not built or leveraged information platforms to nearly the same degree.

If 70% of the private sector has yet to fully embrace the power of information technology, many of the industries and workers that have not yet fully shared in the fruits of the information revolution can hope for faster income and job growth in the years ahead.

The information gap, however, points to a hopeful path forward. If we have not met a fundamental technological wall, and if we haven't run out of new ideas, it means a return to robust economic growth is still possible. Meanwhile, if 70% of the private sector has yet to fully embrace the power of information technology, many of the industries and workers that have not yet fully shared in the fruits of the information revolution can hope for faster income and job growth in the years ahead. Consumers, meanwhile, who have enjoyed unprecedented abundance in digital content and communications services, will be encouraged that relatively expensive products and services in healthcare, education, energy, transportation and other physical industries might now follow a similarly innovative path of more choice and value for the dollar. An economy where more Americans participate and benefit will lift up them and their families, and it will help us work through several big political challenges—such as entitlements—that are more difficult to resolve in a bifurcated, slow-growth economy.

Many of the technological transformations highlighted in this paper are underway already. Public policy, however, will either retard or accelerate the diffusion of information into the physical industries. Unleashing these industries and technologies could substantially boost economic growth—delivering an economy that's $2.7 trillion larger by 2031. Better or worse policy will thus, in significant measure, determine the rate at which more people enjoy the miraculous benefits of rapid innovation, both as workers and consumers.

The pessimism about growth ignores the fact that information has revolutionized only 30% of the private-sector economy. Applying the power of information to the remaining 70% will replicate the gains of digital industries, but on a much larger scale. In the process, many physical industries, firms, and jobs will become digital industries, firms, and jobs. Even this optimistic view, however, understates the vast potential. For there is no endpoint, no fundamental limit to innovation. The digital world itself will continue to evolve and grow, and the digital–physical distinction will become less salient. As information technology propagates, entirely new industries, firms, and jobs will emerge in a never-ending cycle, propelling the economy forward and making the next chapters of our technology journey even more exciting, widespread, and uplifting.

Appendix

Projecting the Potential Productivity Gains from the New IT Revolution

In this Appendix we develop our projection for future productivity gains from use of information technology. Our analysis is based on a newly developed dataset from the Bureau of Economic Analysis (BEA) and the Bureau of Labor Statistics (BLS).[55] This dataset, the "integrated industry-level production accounts," was published for the first time in 2014. The latest release came in June 2016, covering economic growth from 1998 to 2014.

Data

Because of their newness, the integrated industry-level production accounts are not well known, so it is worth describing them. The conventional national accounts used to calculate GDP divide the economy into functional categories such as consumption and investment. BEA also publishes tables that report production by industry.

The integrated industry level production accounts go a step further. They are specifically designed to report the sources of economic growth for all goods-producing and all service-producing industries, including the public sector. For each of 63 industries, the dataset reports the contribution to value-added growth for each of eight factors of production:

1. IT capital
2. R&D capital
3. Software capital
4. Entertainment originals capital
5. Other capital
6. College labor
7. Non-college labor
8. Integrated multifactor production growth

This data allows us to ask and answer all sorts of interesting questions about the sources of economic growth, on both the industry and aggregate level. For example, in which industry did software investment contribute the most to overall GDP growth between 2000 and 2014? The answer: The insurance industry. Or try this one: In which industry did employment of college-educated workers contribute the most to overall GDP growth between 2000 and 2014? State and local government, followed by ambulatory healthcare services.

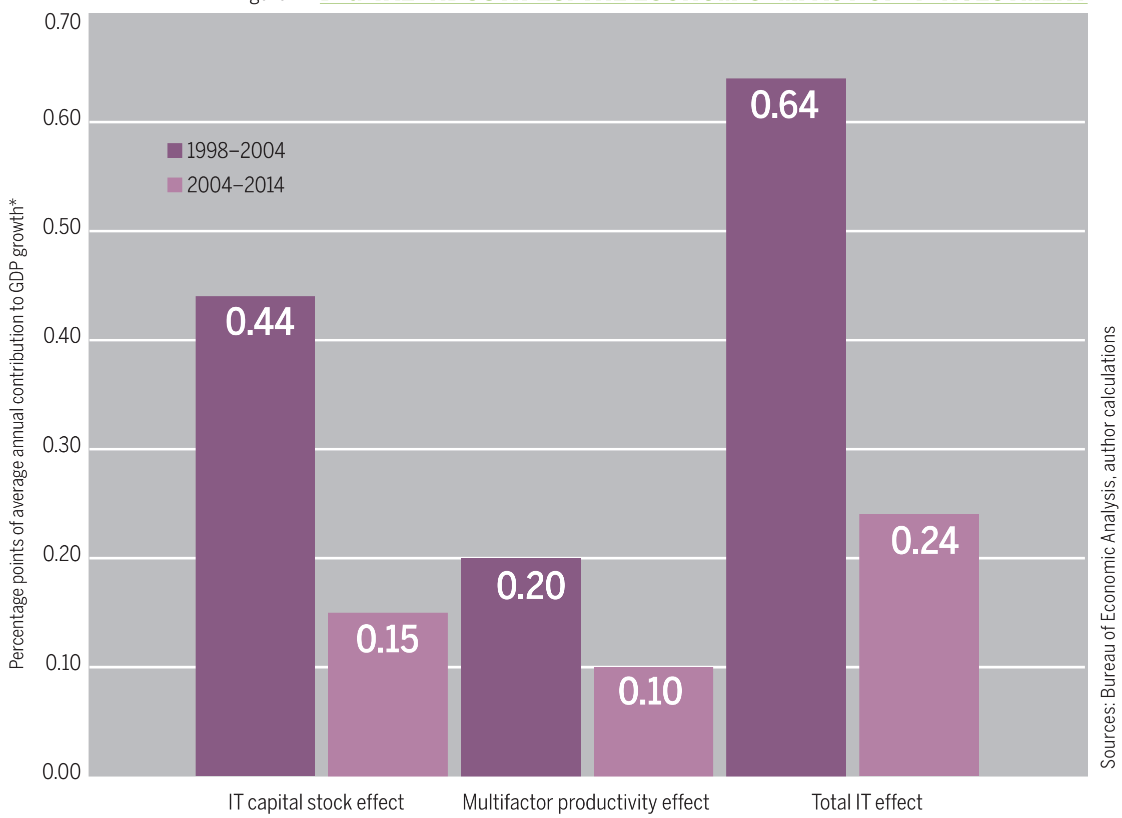
This new dataset allows us to drill down and analyze the effects of information technology equipment and software on growth. Specifically, we look at two types of impact. First, investment in information technology equipment and software increases the stock of productive capital, which makes workers more productive at whatever task they were already doing. We call this the IT **"capital stock effect."**

But investment in information technology also enables companies to transform production and create new products and services which would not have been possible before. This is the **"multifactor productivity effect,"** which are the gains over and above the direct benefits of new equipment. For example, investment in mobile networks enables the creation of smart phones, which in turn enables the creation of mobile apps, which in turn can be used for a very wide variety of purposes, including shopping and navigation. All these new activities boost growth and productivity.

Analysis

We divide the economy into digital and physical industries, as per our analysis in this paper. The one difference is that we estimate the effect on growth of all of GDP, not just the private sector. In particular, we can compare the high productivity growth in the "New Economy" period of 1998–2004 with the slow-productivity growth decade of 2004–2014. The first period includes both the IT boom of the late 1990s, and the early 2000 years when use of IT helped boost productivity in a wide range of industries. The second period includes the financial and housing bubble leading up to the Great Recession, the Great Recession itself, and the years of stagnant growth afterwards.

Figure 14 shows the IT capital stock effect and multifactor productivity effect for the digital sector across these two periods. We can see that both the IT capital stock and the multifactor productivity effects dropped sharply from the first decade to the next. In the figure 14. **DIGITAL INDUSTRIES: THE ECONOMIC IMPACT OF IT INVESTMENT**



* Excludes computer and electronic manufacturing

New Economy period, the IT capital stock and multifactor productivity contributed an average of 0.64 percentage points annually to GDP growth. By comparison, in the second period, which includes the Great Recession, there was a sharp drop in the total contribution to GDP growth of the total IT effect coming from the digital sector, to 0.24 percentage points per year.

Figure 15 shows the IT capital stock effect and the multifactor productivity effect for the physical sector across these two decades. In the first period, the IT-related contribution of the physical sector to GDP growth was roughly comparable to the digital sector, at 0.61 percentage points annually. This represents large IT-related gains in physical industries such as wholesale and retail trade. But in the second period, the IT-related contribution to growth actually turns negative, to -0.10 percentage points per year, as multifactor productivity goes in reverse.

Table 3 summarizes the comparison between the digital and physical sectors. The deceleration of IT-related growth affects both the digital and physical sectors, but the impact on the physical sector is much bigger.

Projection

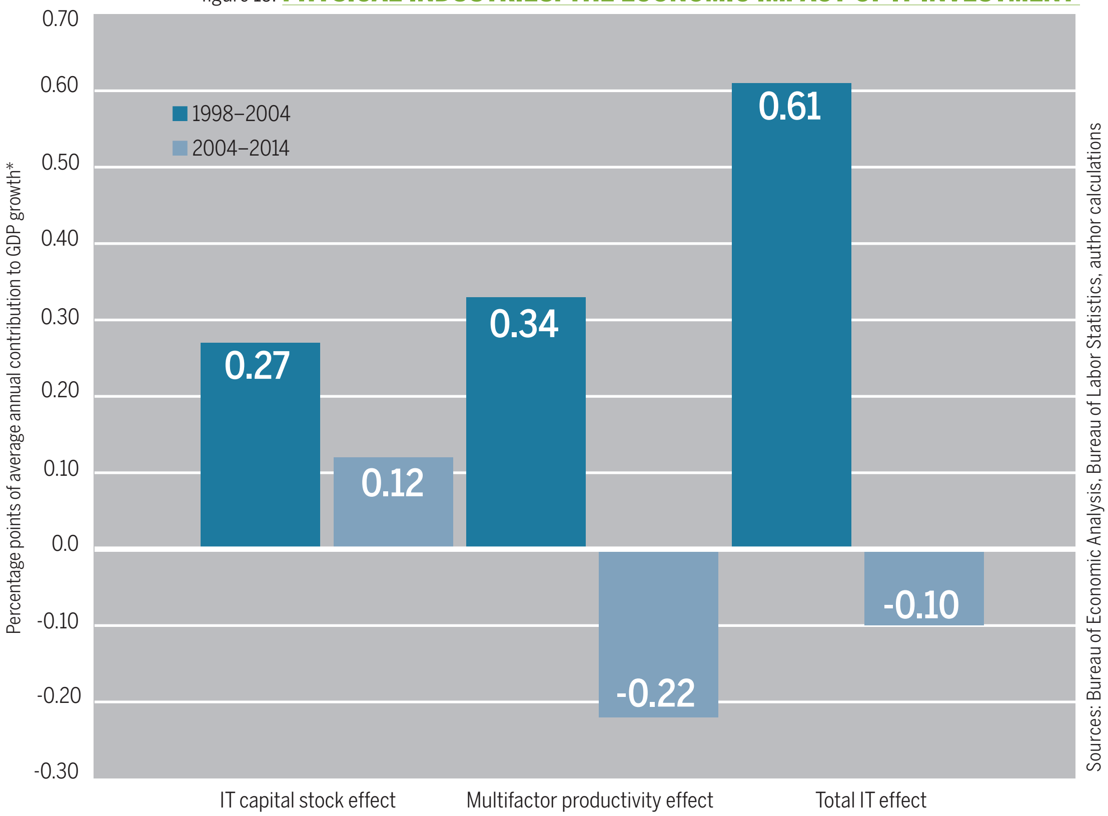
So how can we use the recent historical evidence to project the future impact of information technology on growth? The slowdown of IT-related growth in the digital sector may simply be the result of the initial introduction of the Internet falling back to a more sustainable pace. Instead, we regard the slowdown of IT-related growth in the physical sector as a much bigger problem for the economy, because it has resulted in slowing overall growth and rising prices.

From that perspective, the key questions are:

1. Can physical sector enterprises utilize IT to transform their operations in such a way to boost productivity and growth?
2. How much gain it is possible to achieve?

We believe the answer to the first question is yes, especially as the Internet of Things spreads more widely.

figure 15. **PHYSICAL INDUSTRIES: THE ECONOMIC IMPACT OF IT INVESTMENT**



* Excludes real estate and includes government sector

To answer the second question, we assume that the physical sector can regain the level of IT capital stock and multifactor productivity effects seen in the New Economy period. In other words, based on recent historical evidence, we assume that IT investment and multifactor productivity growth in the physical sector could accelerate enough to add 0.7 percentage points to the economy-wide growth rate.

That may not seem like much. But if the baseline growth rate is only 2%, as most economists now think, boosting that to 2.7% annually makes a big difference. By 2031, the higher growth rate pushes up GDP by 11% compared to its previous path, or $2.7 trillion (in 2016 dollars). That's enough to significantly lift incomes and living standards. In addition, the larger economy would yield around $3.9 trillion

table 3. **THE PRODUCTIVITY SLOWDOWN: 2004–2014 VS. 1998–2004**

	IT CAPITAL EFFECT*	MULTIFACTOR EFFECT	TOTAL DIFFERENCE
Digital industries**	-0.29	-0.1	-0.4
Physical industries***	-0.15	-0.56	-0.71

The change in contribution to GDP growth, measured in percentage points, of the 2004–2014 period compared to the 1998–2004 period

* IT capital stock includes computers, related peripheral equipment, communications gear, and software.

** Digital Industries omits computer and electronics manufacturing.

*** Physical Industries omits real estate, which is mainly household ownership of residential housing, and includes government sector.

Sources: Bureau of Economic Analysis, Bureau of Labor Statistics, author calculations in cumulative federal revenues and $1.9 trillion in additional state and local revenues over the 15-year period, all without increasing the tax share of GDP.

Timing

Judging the timing of productivity shifts is very difficult, except in retrospect. However, the historical evidence suggests that the shift from low-productivity growth regimes to high-productivity growth regimes can happen relatively quickly. The productivity acceleration of the 1990s happened within the space of two or three years, as the Internet came into prominence.

However, because of revisions to economic statistics, productivity accelerations and decelerations are often only apparent in retrospect. That's because contemporaneous estimates of GDP growth are typically based, in part, on extrapolation from recent trends. So the shift to faster productivity growth may not appear clearly in the data until several years later. For example, the 1996 increase in non-farm business labor productivity was originally reported as 0.7%.[56] Today that number has been revised up to 2.7%, signaling the beginning of the productivity boom of the 1990s.

Such large revisions in productivity statistics are not uncommon. In fact, it's possible that the productivity upshift may already be underway. For the purposes of our projection, we assume that the next productivity boom starts in 2017.

Notes for "Prevailing Views on Productivity" on page 8

a See David M. Byrne, Stephen D. Oliner, and Daniel E. Sichel. "How Fast Are Semiconductor Prices Falling?" Working Paper 21074, National Bureau of Economic Research, April 2015. http://www.nber.org/papers/w21074. See also Bret Swanson. "Moore's Law at 50: The Performance and Prospects of the Exponential Economy." American Enterprise Institute, November 2015. http://www.aei.org/wp-content/uploads/2015/11/Moores-law-at-50.pdf.

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c Jan Hatzius. "Productivity Paradox 2.0." Goldman Sachs, *Top of Mind* 39 (October 2015): 6. http://www.goldmansachs.com/our-thinking/pages/macroeconomic-insights-folder/the-productivity-paradox/report.pdf.

d Chad Syverson. "Challenges to Mismeasurement Explanations of the U.S. Productivity Slowdown." National Bureau of Economic Research, Working Paper 21974, January 2016. http://www.nber.org/papers/w21974; and David M. Byrne, John G. Fernald, and Marshall B. Reinsdorf. "Does the United States Have a Productivity Slowdown or a Measurement Problem?" Brookings Institute, March 1, 2016. https://www.brookings.edu/wp-content/uploads/2016/03/ByrneEtAl_ProductivityMeasurement_ConferenceDraft.pdf.

e See, for example, Robert W. Fairlie, E.J. Ready, Amobio Morelix and Joshua Russell. "2016: The Kauffman Index on Startup Activity: National Trends." Ewing Marion Kauffman Foundation, August 4, 2016. http://www.kauffman.org/~/media/kauffman_org/microsites/kauffman_index/startup_activity_2016/kauffman_index_startup_activity_national_trends_2016.pdf.

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[2] John Fernald. "Productivity and Potential Output Before, During, and After the Great Recession." Working Paper 20248, National Bureau of Economic Research, June 2014. National Bureau of Economic Research. http://www.nber.org/papers/w20248.

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