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# Artificial Intelligence and the Modern Productivity Paradox A Clash of Expectations and Statistics

Erik Brynjolfsson, Daniel Rock, and Chad Syverson

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The discussion around the recent patterns in aggregate productivity growth highlights a seeming contradiction. On the one hand, there are astonishing examples of potentially transformative new technologies that could greatly increase productivity and economic welfare (see Brynjolfsson and McAfee 2014). There are some early concrete signs of these technologies' promise, recent leaps in artificial intelligence (AI) performance being the most prominent example. However, at the same time, measured productivity growth over the past decade has slowed significantly. This deceleration is large, cutting productivity growth by half or more in the decade preceding the slowdown. It is also widespread, having occurred throughout the Organisation for Economic Co-operation and Development (OECD) and, more recently, among many large emerging economies as well (Syverson 2017).<sup>1</sup>

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1. A parallel, yet more pessimistically oriented debate about potential technological progress is the active discussion about robots taking jobs from more and more workers (e.g., Brynjolfsson and McAfee 2011; Acemoglu and Restrepo 2017; Bessen 2017; Autor and Salomons 2017).

We thus appear to be facing a redux of the Solow (1987) paradox: we see transformative new technologies everywhere but in the productivity statistics.

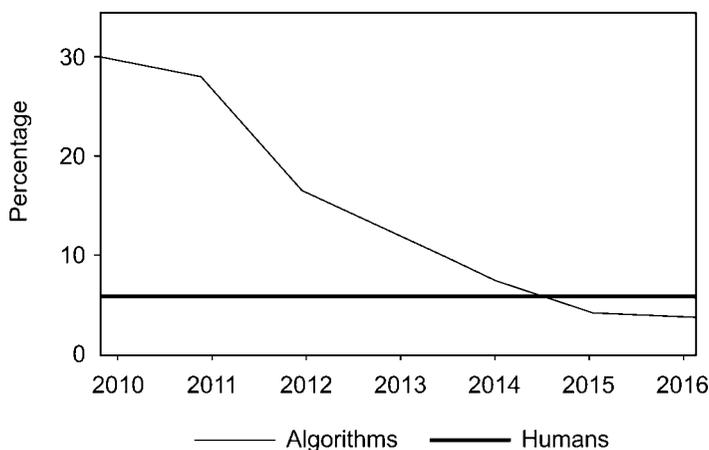
In this chapter, we review the evidence and explanations for the modern productivity paradox and propose a resolution. Namely, there is no inherent inconsistency between forward-looking technological optimism and backward-looking disappointment. Both can simultaneously exist. Indeed, there are good conceptual reasons to *expect* them to simultaneously exist when the economy undergoes the kind of restructuring associated with transformative technologies. In essence, the forecasters of future company wealth and the measurers of historical economic performance show the greatest disagreement during times of technological change. In this chapter, we argue and present some evidence that the economy is in such a period now.

## 1.1 Sources of Technological Optimism

Paul Polman, Unilever’s CEO, recently claimed that “The speed of innovation has never been faster.” Similarly, Bill Gates, Microsoft’s cofounder, observes that “Innovation is moving at a scarily fast pace.” Vinod Khosla of Khosla Ventures sees “the beginnings of . . . [a] rapid acceleration in the next 10, 15, 20 years.” Eric Schmidt of Alphabet Inc., believes “we’re entering . . . the age of abundance [and] during the age of abundance, we’re going to see a new age . . . the age of intelligence.”<sup>2</sup> Assertions like these are especially common among technology leaders and venture capitalists.

In part, these assertions reflect the continuing progress of information technology (IT) in many areas, from core technology advances like further doublings of basic computer power (but from ever larger bases) to successful investment in the essential complementary innovations like cloud infrastructure and new service-based business models. But the bigger source of optimism is the wave of recent improvements in AI, especially machine learning (ML). Machine learning represents a fundamental change from the first wave of computerization. Historically, most computer programs were created by meticulously codifying human knowledge, mapping inputs to outputs as prescribed by the programmers. In contrast, machine-learning systems use categories of general algorithms (e.g., neural networks) to figure out relevant mappings on their own, typically by being fed very large sample data sets. By using these machine-learning methods that leverage the growth in total data and data-processing resources, machines have made impressive gains in perception and cognition, two essential skills for most

2. <http://www.khoslaventures.com/fireside-chat-with-google-co-founders-larry-page-and-sergey-brin>; [https://en.wikipedia.org/wiki/Predictions\\_made\\_by\\_Ray\\_Kurzweil#2045:\\_The\\_Singularity](https://en.wikipedia.org/wiki/Predictions_made_by_Ray_Kurzweil#2045:_The_Singularity); <https://www.theguardian.com/small-business-network/2017/jun/22/alphabets-eric-schmidt-google-artificial-intelligence-viva-technology-mckinsey>.



**Fig. 1.1** AI versus human image recognition error rates

types of human work. For instance, error rates in labeling the content of photos on ImageNet, a data set of over ten million images, have fallen from over 30 percent in 2010 to less than 5 percent in 2016, and most recently as low as 2.2 percent with SE-ResNet152 in the ILSVRC2017 competition (see figure 1.1).<sup>3</sup> Error rates in voice recognition on the Switchboard speech recording corpus, often used to measure progress in speech recognition, have decreased to 5.5 percent from 8.5 percent over the past year (Saon et al. 2017). The 5 percent threshold is important because that is roughly the performance of humans on each of these tasks on the same test data.

Although not at the level of professional human performance yet, Facebook's AI research team recently improved upon the best machine language translation algorithms available using convolutional neural net sequence prediction techniques (Gehring et al. 2017). Deep learning techniques have also been combined with reinforcement learning, a powerful set of techniques used to generate control and action systems whereby autonomous agents are trained to take actions given an environment state to maximize future rewards. Though nascent, advances in this field are impressive. In addition to its victories in the game of Go, Google DeepMind has achieved superhuman performance in many Atari games (Fortunato et al. 2017).

These are notable technological milestones. But they can also change the economic landscape, creating new opportunities for business value creation and cost reduction. For example, a system using deep neural networks was tested against twenty-one board-certified dermatologists and matched their

3. <http://image-net.org/challenges/LSVRC/2017/results>. ImageNet includes labels for each image, originally provided by humans. For instance, there are 339,000 labeled as flowers, 1,001,000 as food, 188,000 as fruit, 137,000 as fungus, and so on.

performance in diagnosing skin cancer (Esteva et al. 2017). Facebook uses neural networks for over 4.5 billion translations each day.<sup>4</sup>

An increasing number of companies have responded to these opportunities. Google now describes its focus as “AI first,” while Microsoft’s CEO Satya Nadella says AI is the “ultimate breakthrough” in technology. Their optimism about AI is not just cheap talk. They are making heavy investments in AI, as are Apple, Facebook, and Amazon. As of September 2017, these companies comprise the five most valuable companies in the world. Meanwhile, the tech-heavy NASDAQ composite index more than doubled between 2012 and 2017. According to CBInsights, global investment in private companies focused on AI has grown even faster, increasing from \$589 million in 2012 to over \$5 billion in 2016.<sup>5</sup>

## 1.2 The Disappointing Recent Reality

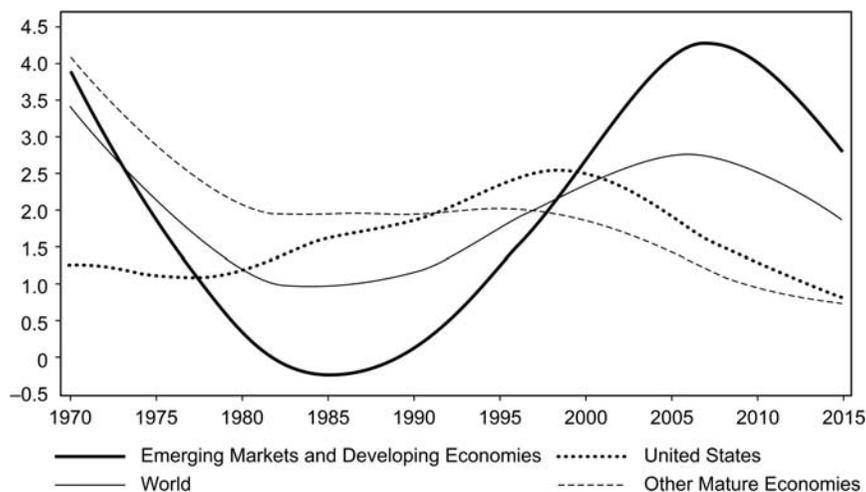
Although the technologies discussed above hold great potential, there is little sign that they have yet affected aggregate productivity statistics. Labor productivity growth rates in a broad swath of developed economies fell in the middle of the first decade of the twenty-first century and have stayed low since then. For example, aggregate labor productivity growth in the United States averaged only 1.3 percent per year from 2005 to 2016, less than half of the 2.8 percent annual growth rate sustained from 1995 to 2004. Fully twenty-eight of the twenty-nine other countries for which the OECD has compiled productivity growth data saw similar decelerations. The unweighted average annual labor productivity growth rate across these countries was 2.3 percent from 1995 to 2004, but only 1.1 percent from 2005 to 2015.<sup>6</sup> What’s more, real median income has stagnated since the late 1990s and noneconomic measures of well-being, like life expectancy, have fallen for some groups (Case and Deaton 2017).

Figure 1.2 replicates the Conference Board’s analysis of its country-level Total Economy Database (Conference Board 2016). It plots highly smoothed annual productivity growth rate series for the United States, other mature economies (which combined match much of the OECD sample cited above), emerging and developing economies, and the world overall. The aforementioned slowdowns in the United States and other mature economies are clear in the figure. The figure also reveals that the productivity growth acceleration in emerging and developing economies during the first decade of the twenty-

4. <https://code.facebook.com/posts/289921871474277/transitioning-entirely-to-neural-machine-translation/>.

5. And the number of deals increased from 160 to 658. See <https://www.cbinsights.com/research/artificial-intelligence-startup-funding/>.

6. These slowdowns are statistically significant. For the United States, where the slowdown is measured using quarterly data, equality of the two periods’ growth rates is rejected with a  $t$ -statistic of 2.9. The OECD numbers come from annual data across the thirty countries. Here, the null hypothesis of equality is rejected with a  $t$ -statistic of 7.2.



**Fig. 1.2 Smoothed average annual labor productivity growth (percent) by region**

Source: The Conference Board Total Economy Database™ (adjusted version), November 2016.

Note: Trend growth rates are obtained using HP filter, assuming a  $\lambda = 100$ .

first century ended around the time of the Great Recession, causing a recent decline in productivity growth rates in these countries too.

These slowdowns do not appear to simply reflect the effects of the Great Recession. In the OECD data, twenty-eight of the thirty countries still exhibit productivity decelerations if 2008–2009 growth rates are excluded from the totals. Cetty, Fernald, and Mojon (2016), using other data, also find substantial evidence that the slowdowns began before the Great Recession.

Both capital deepening and total factor productivity (TFP) growth lead to labor productivity growth, and both seem to be playing a role in the slowdown (Fernald 2014; OECD 2015). Disappointing technological progress can be tied to each of these components. Total factor productivity directly reflects such progress. Capital deepening is indirectly influenced by technological change because firms' investment decisions respond to improvements in capital's current or expected marginal product.

These facts have been read by some as reasons for pessimism about the ability of new technologies like AI to greatly affect productivity and income. Gordon (2014, 2015) argues that productivity growth has been in long-run decline, with the IT-driven acceleration of 1995 to 2004 being a one-off aberration. While not claiming technological progress will be nil in the coming decades, Gordon essentially argues that we have been experiencing the new, low-growth normal and should expect to continue to do so going forward. Cowen (2011) similarly offers multiple reasons why innovation may be slow, at least for the foreseeable future. Bloom et al. (2017) document

that in many fields of technological progress research productivity has been falling, while Nordhaus (2015) finds that the hypothesis of an acceleration of technology-driven growth fails a variety of tests.

This pessimistic view of future technological progress has entered into long-range policy planning. The Congressional Budget Office, for instance, reduced its ten-year forecast for average US annual labor productivity growth from 1.8 percent in 2016 (CBO 2016) to 1.5 percent in 2017 (CBO 2017). Although perhaps modest on its surface, that drop implies US gross domestic product (GDP) will be considerably smaller ten years from now than it would in the more optimistic scenario—a difference equivalent to almost \$600 billion in 2017.

### 1.3 Potential Explanations for the Paradox

There are four principal candidate explanations for the current confluence of technological optimism and poor productivity performance: (a) false hopes, (b) mismeasurement, (c) concentrated distribution and rent dissipation, and (d) implementation and restructuring lags.<sup>7</sup>

#### 1.3.1 False Hopes

The simplest possibility is that the optimism about the potential technologies is misplaced and unfounded. Perhaps these technologies won't be as transformative as many expect, and although they might have modest and noteworthy effects on specific sectors, their aggregate impact might be small. In this case, the paradox will be resolved in the future because realized productivity growth never escapes its current doldrums, which will force the optimists to mark their beliefs to market.

History and some current examples offer a quantum of credence to this possibility. Certainly one can point to many prior exciting technologies that did not live up to initially optimistic expectations. Nuclear power never became too cheap to meter, and fusion energy has been twenty years away for sixty years. Mars may still beckon, but it has been more than forty years since Eugene Cernan was the last person to walk on the moon. Flying cars never got off the ground,<sup>8</sup> and passenger jets no longer fly at supersonic speeds. Even AI, perhaps the most promising technology of our era, is well behind Marvin Minsky's 1967 prediction that "Within a generation the problem of creating 'artificial intelligence' will be substantially solved" (Minsky 1967, 2).

On the other hand, there remains a compelling case for optimism. As we outline below, it is not difficult to construct back-of-the-envelope scenarios

7. To some extent, these explanations parallel the explanations for the Solow paradox (Brynjolfsson 1993).

8. But coming soon? <https://kittyhawk.aero/about/>.

in which even a modest number of currently existing technologies could combine to substantially raise productivity growth and societal welfare. Indeed, knowledgeable investors and researchers are betting their money and time on exactly such outcomes. Thus, while we recognize the potential for overoptimism—and the experience with early predictions for AI makes an especially relevant reminder for us to be somewhat circumspect in this chapter—we judge that it would be highly preliminary to dismiss optimism at this point.

### 1.3.2 Mismeasurement

Another potential explanation for the paradox is mismeasurement of output and productivity. In this case, it is the pessimistic reading of the empirical past, not the optimism about the future, that is mistaken. Indeed, this explanation implies that the productivity benefits of the new wave of technologies are already being enjoyed, but have yet to be accurately measured. Under this explanation, the slowdown of the past decade is illusory. This “mismeasurement hypothesis” has been put forth in several works (e.g., Mokyr 2014; Alloway 2015; Feldstein 2015; Hatzius and Dawsey 2015; Smith 2015).

There is a *prima facie* case for the mismeasurement hypothesis. Many new technologies, like smartphones, online social networks, and downloadable media involve little monetary cost, yet consumers spend large amounts of time with these technologies. Thus, the technologies might deliver substantial utility even if they account for a small share of GDP due to their low relative price. Guvenen et al. (2017) also show how growing offshore profit shifting can be another source of mismeasurement.

However, a set of recent studies provide good reason to think that mismeasurement is not the entire, or even a substantial, explanation for the slowdown. Cardarelli and Lusinyan (2015), Byrne, Fernald, and Reinsdorf (2016), Nakamura and Soloveichik (2015), and Syverson (2017), each using different methodologies and data, present evidence that mismeasurement is not the primary explanation for the productivity slowdown. After all, while there is convincing evidence that many of the benefits of today’s technologies are not reflected in GDP and therefore productivity statistics, the same was undoubtedly true in earlier eras as well.

### 1.3.3 Concentrated Distribution and Rent Dissipation

A third possibility is that the gains of the new technologies are already attainable, but that through a combination of concentrated distribution of those gains and dissipative efforts to attain or preserve them (assuming the technologies are at least partially rivalrous), their effect on average productivity growth is modest overall, and is virtually nil for the median worker. For instance, two of the most profitable uses of AI to date have been for targeting and pricing online ads, and for automated trading of financial instruments, both applications with many zero-sum aspects.

One version of this story asserts that the benefits of the new technologies are being enjoyed by a relatively small fraction of the economy, but the technologies' narrowly scoped and rivalrous nature creates wasteful "gold rush"-type activities. Both those seeking to be one of the few beneficiaries, as well as those who have attained some gains and seek to block access to others, engage in these dissipative efforts, destroying many of the benefits of the new technologies.<sup>9</sup>

Recent research offers some indirect support for elements of this story. Productivity differences between frontier firms and average firms in the same industry have been increasing in recent years (Andrews, Criscuolo, and Gal 2016; Furman and Orszag 2015). Differences in profit margins between the top and bottom performers in most industries have also grown (McAfee and Brynjolfsson 2008). A smaller number of superstar firms are gaining market share (Autor et al. 2017; Brynjolfsson et al. 2008), while workers' earnings are increasingly tied to firm-level productivity differences (Song et al. 2015). There are concerns that industry concentration is leading to substantial aggregate welfare losses due to the distortions of market power (e.g., De Loecker and Eeckhout 2017; Gutiérrez and Philippon 2017). Furthermore, growing inequality can lead to stagnating median incomes and associated socioeconomic costs, even when total income continues to grow.

Although this evidence is important, it is not dispositive. The aggregate effects of industry concentration are still under debate, and the mere fact that a technology's gains are not evenly distributed is no guarantee that resources will be dissipated in trying to capture them—especially that there would be enough waste to erase noticeable aggregate benefits.

#### 1.3.4 Implementation and Restructuring Lags

Each of the first three possibilities, especially the first two, relies on explaining away the discordance between high hopes and disappointing statistical realities. One of the two elements is presumed to be somehow "wrong." In the misplaced optimism scenario, the expectations for technology by technologists and investors are off base. In the mismeasurement explanation, the tools we use to gauge empirical reality are not up to the task of accurately doing so. And in the concentrated distribution stories, the private gains for the few may be very real, but they do not translate into broader gains for the many.

But there is a fourth explanation that allows both halves of the seeming paradox to be correct. It asserts that there really is good reason to be optimistic about the future productivity growth potential of new technologies, while at the same time recognizing that recent productivity growth has been low. The core of this story is that it takes a considerable time—often more than

9. Stiglitz (2014) offers a different mechanism where technological progress with concentrated benefits in the presence of restructuring costs can lead to increased inequality and even, in the short run, economic downturns.

is commonly appreciated—to be able to sufficiently harness new technologies. Ironically, this is especially true for those major new technologies that ultimately have an important effect on aggregate statistics and welfare. That is, those with such broad potential application that they qualify as general purpose technologies (GPTs). Indeed, the more profound and far-reaching the potential restructuring, the longer the time lag between the initial invention of the technology and its full impact on the economy and society.

This explanation implies there will be a period in which the technologies are developed enough that investors, commentators, researchers, and policy-makers can imagine their potentially transformative effects, even though they have had no discernable effect on recent productivity growth. It isn't until a sufficient stock of the new technology is built and the necessary invention of complementary processes and assets occurs that the promise of the technology actually blossoms in aggregate economic data. Investors are forward looking and economic statistics are backward looking. In times of technological stability or steady change (constant velocity), the disjoint measurements will seem to track each other. But in periods of rapid change, the two measurements can become uncorrelated.

There are two main sources of the delay between recognition of a new technology's potential and its measurable effects. One is that it takes time to build the stock of the new technology to a size sufficient enough to have an aggregate effect. The other is that complementary investments are necessary to obtain the full benefit of the new technology, and it takes time to discover and develop these complements and to implement them. While the fundamental importance of the core invention and its potential for society might be clearly recognizable at the outset, the myriad necessary coinventions, obstacles, and adjustments needed along the way await discovery over time, and the required path may be lengthy and arduous. Never mistake a clear view for a short distance.

This explanation resolves the paradox by acknowledging that its two seemingly contradictory parts are not actually in conflict. Rather, both parts are in some sense natural manifestations of the same underlying phenomenon of building and implementing a new technology.

While each of the first three explanations for the paradox might have a role in describing its source, the explanations also face serious questions in their ability to describe key parts of the data. We find the fourth—the implementation and restructuring lags story—to be the most compelling in light of the evidence we discuss below. Thus it is the focus of our explorations in the remainder of this chapter.

#### **1.4 The Argument in Favor of the Implementation and Restructuring Lags Explanation**

Implicit or explicit in the pessimistic view of the future is that the recent slowdown in productivity growth portends slower productivity growth in the future.

We begin by establishing one of the most basic elements of the story: that slow productivity growth today does not rule out faster productivity growth in the future. In fact, the evidence is clear that it is barely predictive at all.

Total factor productivity growth is the component of overall output growth that cannot be explained by accounting for changes in observable labor and capital inputs. It has been called a “measure of our ignorance” (Abramovitz 1956). It is a residual, so an econometrician should not be surprised if it is not very predictable from past levels. Labor productivity is a similar measure, but instead of accounting for capital accumulation, simply divides total output by the labor hours used to produce that output.

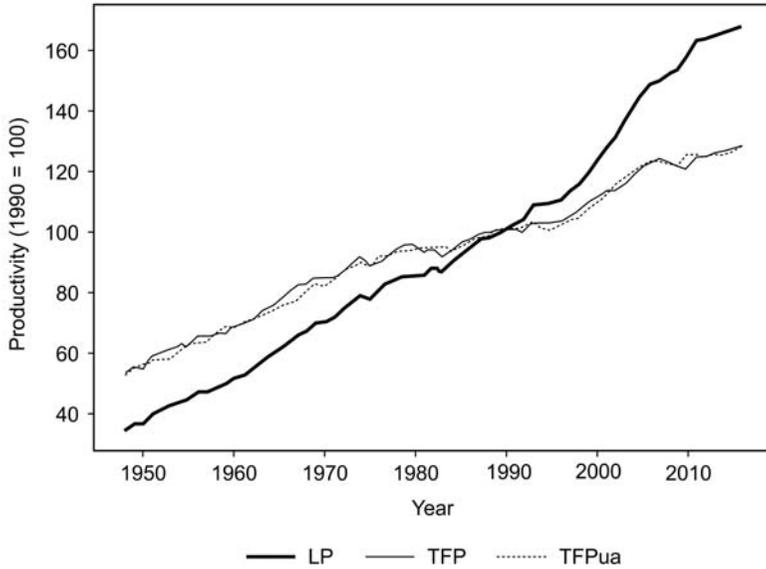
Figures 1.3 and 1.4 plot, respectively, US productivity indices since 1948 and productivity growth by decade. The data include average labor productivity (LP), average total factor productivity (TFP), and Fernald’s (2014) utilization-adjusted TFP (TFPua).<sup>10</sup>

Productivity has consistently grown in the postwar era, albeit at different rates at different times. Despite the consistent growth, however, past productivity growth rates have historically been poor predictors of future productivity growth. In other words, the productivity growth of the past decade tells us little about productivity growth for the coming decade. Looking only at productivity data, it would have been hard to predict the decrease in productivity growth in the early 1970s or foresee the beneficial impact of IT in the 1990s.

As it turns out, while there is some correlation in productivity growth rates over short intervals, the correlation between adjacent ten-year periods is not statistically significant. We present below the results from a regression of different measures of average productivity growth on the previous period’s average productivity growth for ten-year intervals as well as scatterplots of productivity for each ten-year interval against the productivity in the subsequent period. The regressions in table 1.1 allow for autocorrelation in error terms across years (1 lag). Table 1.2 clusters the standard errors by decade. Similar results allowing for autocorrelation at longer time scales are presented in the appendix.

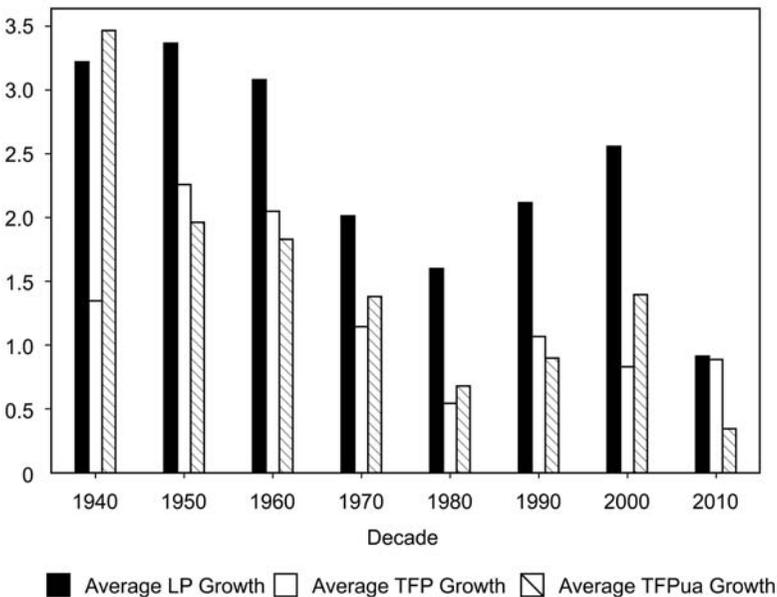
In all cases, the  $R^2$  of these regressions is low, and the previous decade’s productivity growth does not have statistically discernable predictive power over the next decade’s growth. For labor productivity, the  $R^2$  is 0.009. Although the intercept in the regression is significantly different from zero (productivity growth is positive, on average), the coefficient on the previous period’s growth is not statistically significant. The point estimate is economically small, too. Taking the estimate at face value, 1 percent higher annual labor productivity growth in the prior decade (around an unconditional mean of about 2 percent per year) corresponds to less than 0.1 percent

10. Available at <http://www.frbsf.org/economic-research/indicators-data/total-factor-productivity-tfp/>.



**Fig. 1.3 US TFP and labor productivity indices, 1948–2016**

*Note:* 1990 = 100.



**Fig. 1.4 US TFP and labor productivity growth (percent) by decade**

**Table 1.1**                    **Regressions with Newey-West standard errors**

	(1) Labor productivity growth	(2) Total factor productivity growth	(3) Utilization-adjusted productivity growth
Newey-West regressions (1 lag allowed) ten-year average productivity growth			
Previous ten-year average LP growth	0.0857 (0.177)		
Previous ten-year average TFP growth		0.136 (0.158)	
Previous ten-year average TFP <sub>ua</sub> growth			0.158  (0.187)
Constant	1.949*** (0.398)	0.911*** (0.188)	0.910*** (0.259)
Observations	50	50	50
R-squared	0.009	0.023	0.030

*Note:* Standard errors in parentheses.

\*\*\*Significant at the 1 percent level.

\*\*Significant at the 5 percent level.

\*Significant at the 10 percent level.

**Table 1.2**                    **Regressions with standard errors clustered by decade**

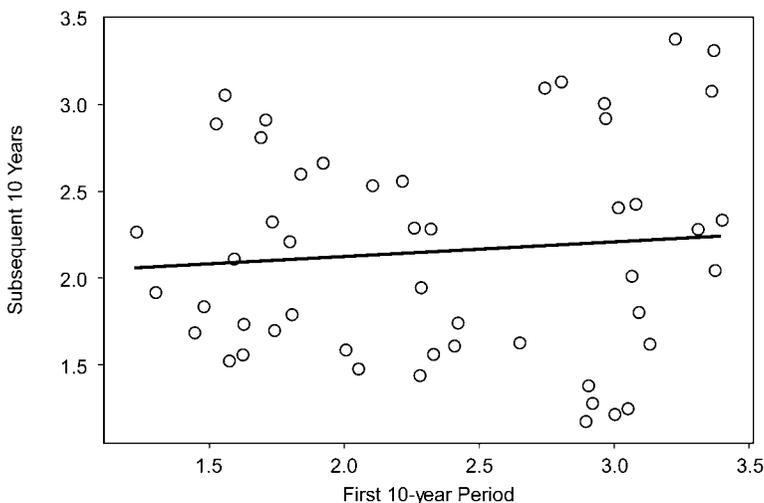
	(1) Labor productivity growth	(2) Total factor productivity growth	(3) Utilization-adjusted productivity growth
Ten-year average productivity growth (SEs clustered by decade)			
Previous ten-year average LP growth	0.0857 (0.284)		
Previous ten-year average TFP growth		0.136 (0.241)	
Previous ten-year average TFP <sub>ua</sub> growth			0.158  (0.362)
Constant	1.949** (0.682)	0.911** (0.310)	0.910 (0.524)
Observations	50	50	50
R-squared	0.009	0.023	0.030

*Note:* Robust standard errors in parentheses.

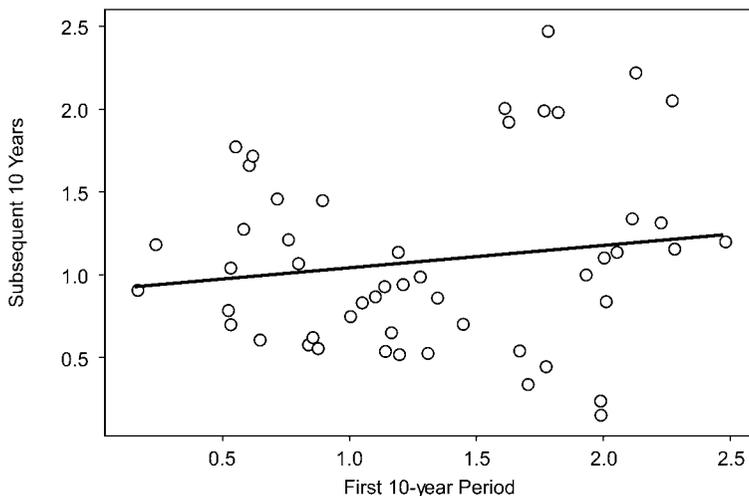
\*\*\*Significant at the 1 percent level.

\*\*Significant at the 5 percent level.

\*Significant at the 10 percent level.



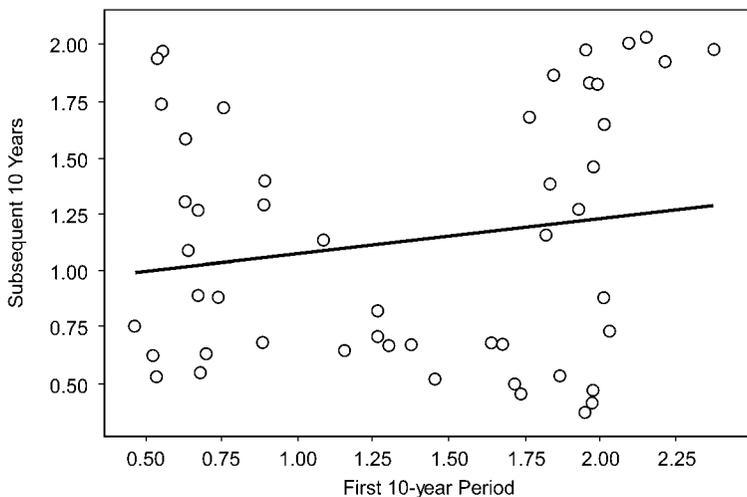
**Fig 1.5 Labor productivity growth scatterplot**



**Fig. 1.6 Total factor productivity growth scatterplot**

faster growth in the following decade. In the TFP growth regression, the  $R^2$  is 0.023, and again the coefficient on the previous period’s growth is insignificant. Similar patterns hold in the utilization-adjusted TFP regression ( $R^2$  of 0.03). The lack of explanatory power of past productivity growth is also apparent in the scatterplots (see figures 1.5, 1.6, and 1.7).

The old adage that “past performance is not predictive of future results” applies well to trying to predict productivity growth in the years to come,



**Fig. 1.7 Utilization-adjusted total factor productivity growth scatterplot**

especially in periods of a decade or longer. Historical stagnation does not justify forward-looking pessimism.

### 1.5 A Technology-Driven Case for Productivity Optimism

Simply extrapolating recent productivity growth rates forward is not a good way to estimate the next decade’s productivity growth. Does that imply we have no hope at all of predicting productivity growth? We don’t think so.

Instead of relying only on past productivity statistics, we can consider the technological and innovation environment we expect to see in the near future. In particular, we need to study and understand the specific technologies that actually exist and make an assessment of their potential.

One does not have to dig too deeply into the pool of existing technologies or assume incredibly large benefits from any one of them to make a case that existing but still nascent technologies can potentially combine to create noticeable accelerations in aggregate productivity growth. We begin by looking at a few specific examples. We will then make the case that AI is a GPT, with broader implications.

First, let’s consider the productivity potential of autonomous vehicles. According to the US Bureau of Labor Statistics (BLS), in 2016 there were 3.5 million people working in private industry as “motor vehicle operators” of one sort or another (this includes truck drivers, taxi drivers, bus drivers, and other similar occupations). Suppose autonomous vehicles were to reduce, over some period, the number of drivers necessary to do the current workload to 1.5 million. We do not think this is a far-fetched scenario given the potential of the technology. Total nonfarm private employment in mid-

2016 was 122 million. Therefore, autonomous vehicles would reduce the number of workers necessary to achieve the same output to 120 million. This would result in aggregate labor productivity (calculated using the standard BLS nonfarm private series) increasing by 1.7 percent ( $122/120 = 1.017$ ). Supposing this transition occurred over ten years, this single technology would provide a direct boost of 0.17 percent to annual productivity growth over that decade.

This gain is significant, and it does not include many potential productivity gains from complementary changes that could accompany the diffusion of autonomous vehicles. For instance, self-driving cars are a natural complement to transportation-as-a-service rather than individual car ownership. The typical car is currently parked 95 percent of the time, making it readily available for its owner or primary user (Morris 2016). However, in locations with sufficient density, a self-driving car could be summoned on demand. This would make it possible for cars to provide useful transportation services for a larger fraction of the time, reducing capital costs per passenger-mile, even after accounting for increased wear and tear. Thus, in addition to the obvious improvements in labor productivity from replacing drivers, capital productivity would also be significantly improved. Of course, the speed of adoption is important for estimation of the impact of these technologies. Levy (2018) is more pessimistic, suggesting in the near term that long distance truck driver jobs will grow about 2 percent between 2014 and 2024. This is 3 percent less (about 55,000 jobs in that category) than they would have grown without autonomous vehicle technology and about 3 percent of total employment of long distance truck drivers. A second example is call centers. As of 2015, there were about 2.2 million people working in more than 6,800 call centers in the United States, and hundreds of thousands more work as home-based call center agents or in smaller sites.<sup>11</sup> Improved voice-recognition systems coupled with intelligence question-answering tools like IBM's Watson might plausibly be able to handle 60–70 percent or more of the calls, especially since, in accordance with the Pareto principle, a large fraction of call volume is due to variants on a small number of basic queries. If AI reduced the number of workers by 60 percent, it would increase US labor productivity by 1 percent, perhaps again spread over ten years. Again, this would likely spur complementary innovations, from shopping recommendation and travel services to legal advice, consulting, and real-time personal coaching. Relatedly, citing advances in AI-assisted customer service, Levy (2018) projects zero growth in customer service representatives from 2014 to 2024 (a difference of 260,000 jobs from BLS projections).

Beyond labor savings, advances in AI have the potential to boost total factor productivity. In particular, energy efficiency and materials usage could be improved in many large-scale industrial plants. For instance, a

11. <https://info.siteselectiongroup.com/blog/how-big-is-the-us-call-center-industry-compared-to-india-and-philippines>.

team from Google DeepMind recently trained an ensemble of neural networks to optimize power consumption in a data center. By carefully tracking the data already collected from thousands of sensors tracking temperatures, electricity usage, and pump speeds, the system learned how to make adjustments in the operating parameters. As a result, the AI was able to reduce the amount of energy used for cooling by 40 percent compared to the levels achieved by human experts. The algorithm was a general-purpose framework designed to account complex dynamics, so it is easy to see how such a system could be applied to other data centers at Google, or indeed, around the world. Overall, data center electricity costs in the United States are about \$6 billion per year, including about \$2 billion just for cooling.<sup>12</sup>

What's more, similar applications of machine learning could be implemented in a variety of commercial and industrial activities. For instance, manufacturing accounts for about \$2.2 trillion of value added each year. Manufacturing companies like GE are already using AI to forecast product demand, future customer maintenance needs, and analyze performance data coming from sensors on their capital equipment. Recent work on training deep neural network models to perceive objects and achieve sensorimotor control have at the same time yielded robots that can perform a variety of hand-eye coordination tasks (e.g., unscrewing bottle caps and hanging coat hangers; Levine et al., [2016]). Liu et al. (2017) trained robots to perform a number of household chores, like sweeping and pouring almonds into a pan, using a technique called imitation learning.<sup>13</sup> In this approach, the robot learns to perform a task using a raw video demonstration of what it needs to do. These techniques will surely be important for automating manufacturing processes in the future. The results suggest that artificial intelligence may soon improve productivity in household production tasks as well, which in 2010 were worth as much as \$2.5 trillion in nonmarket value added (Bridgman et al. 2012).<sup>14</sup>

Although these examples are each suggestive of nontrivial productivity gains, they are only a fraction of the set of applications for AI and machine learning that have been identified so far. James Manyika et al. (2017) analyzed 2,000 tasks and estimated that about 45 percent of the activities that people are paid to perform in the US economy could be automated using existing levels of AI and other technologies. They stress that the pace of

12. According to personal communication, August 24, 2017, with Jon Koomey, Arman Shehabi, and Sarah Smith of Lawrence Berkeley Lab.

13. Videos of these efforts available here: <https://sites.google.com/site/imitationfromobservation/>.

14. One factor that might temper the aggregate impact of AI-driven productivity gains is if product demand for the sectors with the largest productivity AI gains is sufficiently inelastic. In this case, these sectors' shares of total expenditure will shrink, shifting activity toward slower-growing sectors and muting aggregate productivity growth à la Baumol and Bowen (1966). It is unclear what the elasticities of demand are for the product classes most likely to be affected by AI.

automation will depend on factors other than technical feasibility, including the costs of automation, regulatory barriers, and social acceptance.

### 1.6 Artificial Intelligence Is a General Purpose Technology

As important as specific applications of AI may be, we argue that the more important economic effects of AI, machine learning, and associated new technologies stem from the fact that they embody the characteristics of general purpose technologies (GPTs). Bresnahan and Trajtenberg (1996) argue that a GPT should be pervasive, able to be improved upon over time, and be able to spawn complementary innovations.

The steam engine, electricity, the internal combustion engine, and computers are each examples of important general purpose technologies. Each of them increased productivity not only directly, but also by spurring important complementary innovations. For instance, the steam engine not only helped to pump water from coal mines, its most important initial application, but also spurred the invention of more effective factory machinery and new forms of transportation like steamships and railroads. In turn, these coinventions helped give rise to innovations in supply chains and mass marketing, to new organizations with hundreds of thousands of employees, and even to seemingly unrelated innovations like standard time, which was needed to manage railroad schedules.

Artificial intelligence, and in particular machine learning, certainly has the potential to be pervasive, to be improved upon over time, and to spawn complementary innovations, making it a candidate for an important GPT.

As noted by Agrawal, Gans, and Goldfarb (2017), the current generation of machine-learning systems is particularly suited for augmenting or automating tasks that involve at least some prediction aspect, broadly defined. These cover a wide range of tasks, occupations, and industries, from driving a car (predicting the correct direction to turn the steering wheel) and diagnosing a disease (predicting its cause) to recommending a product (predicting what the customer will like) and writing a song (predicting which note sequence will be most popular). The core capabilities of perception and cognition addressed by current systems are pervasive, if not indispensable, for many tasks done by humans.

Machine-learning systems are also designed to improve over time. Indeed, what sets them apart from earlier technologies is that they are designed to improve *themselves* over time. Instead of requiring an inventor or developer to codify, or code, each step of a process to be automated, a machine-learning algorithm can discover on its own a function that connects a set of inputs  $X$  to a set of outputs  $Y$  as long as it is given a sufficiently large set of labeled examples mapping some of the inputs to outputs (Brynjolfsson and Mitchell 2017). The improvements reflect not only the discovery of new algorithms and techniques, particularly for deep neural networks, but

also their complementarities with vastly more powerful computer hardware and the availability of much larger digital data sets that can be used to train the systems (Brynjolfsson and McAfee 2017). More and more digital data is collected as a byproduct of digitizing operations, customer interactions, communications, and other aspects of our lives, providing fodder for more and better machine-learning applications.<sup>15</sup>

Most important, machine-learning systems can spur a variety of complementary innovations. For instance, machine learning has transformed the abilities of machines to perform a number of basic types of perception that enable a broader set of applications. Consider machine vision—the ability to see and recognize objects, to label them in photos, and to interpret video streams. As error rates in identifying pedestrians improve from one per 30 frames to about one per 30 million frames, self-driving cars become increasingly feasible (Brynjolfsson and McAfee 2017).

Improved machine vision also makes practical a variety of factory automation tasks and medical diagnoses. Gill Pratt has made an analogy to the development of vision in animals 500 million years ago, which helped ignite the Cambrian explosion and a burst of new species on earth (Pratt 2015). He also noted that machines have a new capability that no biological species has: the ability to share knowledge and skills almost instantaneously with others. Specifically, the rise of cloud computing has made it significantly easier to scale up new ideas at much lower cost than before. This is an especially important development for advancing the economic impact of machine learning because it enables cloud robotics: the sharing of knowledge among robots. Once a new skill is learned by a machine in one location, it can be replicated to other machines via digital networks. Data as well as skills can be shared, increasing the amount of data that any given machine learner can use.

This in turn increases the rate of improvement. For instance, self-driving cars that encounter an unusual situation can upload that information with a shared platform where enough examples can be aggregated to infer a pattern. Only one self-driving vehicle needs to experience an anomaly for many vehicles to learn from it. Waymo, a subsidiary of Google, has cars driving 25,000 “real” autonomous and about 19 million simulated miles each week.<sup>16</sup> All of the Waymo cars learn from the joint experience of the others. Similarly, a robot struggling with a task can benefit from sharing data and learnings with other robots that use a compatible knowledge-representation framework.<sup>17</sup>

When one thinks of AI as a GPT, the implications for output and welfare gains are much larger than in our earlier analysis. For example, self-driving cars could substantially transform many nontransport industries.

15. For example, through enterprise resource planning systems in factories, internet commerce, mobile phones, and the “Internet of Things.”

16. <http://ben-evans.com/benedictevans/2017/8/20/winner-takes-all>.

17. Rethink Robotics is developing exactly such a platform.

Retail could shift much further toward home delivery on demand, creating consumer welfare gains and further freeing up valuable high-density land now used for parking. Traffic and safety could be optimized, and insurance risks could fall. With over 30,000 deaths due to automobile crashes in the United States each year, and nearly a million worldwide, there is an opportunity to save many lives.<sup>18</sup>

### 1.7 Why Future Technological Progress Is Consistent with Low Current Productivity Growth

Having made a case for technological optimism, we now turn to explaining why it is not inconsistent with—and in fact may even be naturally related to—low current productivity growth.

Like other GPTs, AI has the potential to be an important driver of productivity. However, as Jovanovic and Rousseau (2005) point out (with additional reference to David's [1991] historical example), "a GPT does not deliver productivity gains immediately upon arrival" (1184). The technology can be present and developed enough to allow some notion of its transformative effects even though it is not affecting current productivity levels in any noticeable way. This is precisely the state that we argue the economy may be in now.

We discussed earlier that a GPT can at one moment both be present and yet not affect current productivity growth if there is a need to build a sufficiently large stock of the new capital, or if complementary types of capital, both tangible and intangible, need to be identified, produced, and put in place to fully harness the GPT's productivity benefits.

The time necessary to build a sufficient capital stock can be extensive. For example, it was not until the late 1980s, more than twenty-five years after the invention of the integrated circuit, that the computer capital stock reached its long-run plateau at about 5 percent (at historical cost) of total nonresidential equipment capital. It was at only half that level ten years prior. Thus, when Solow pointed out his now eponymous paradox, the computers were *finally just then* getting to the point where they really could be seen everywhere.

David (1991) notes a similar phenomenon in the diffusion of electrification. At least half of US manufacturing establishments remained unelectrified until 1919, about thirty years after the shift to polyphase alternating current began. Initially, adoption was driven by simple cost savings in pro-

18. These latter two consequences of autonomous vehicles, while certainly reflecting welfare improvements, would need to be capitalized in prices of goods or services to be measured in standard GDP and productivity measures. We will discuss AI-related measurement issues in greater depth later. Of course, it is worth remembering that autonomous vehicles also hold the potential to create new economic costs if, say, the congestion from lower marginal costs of operating a vehicle is not counteracted by sufficiently large improvements in traffic management technology or certain infrastructure investments.

viding motive power. The biggest benefits came later, when complementary innovations were made. Managers began to fundamentally reorganize work by replacing factories' centralized power source and giving every individual machine its own electric motor. This enabled much more flexibility in the location of equipment and made possible effective assembly lines of materials flow.

This approach to organizing factories is obvious in retrospect, yet it took as many as thirty years for it to become widely adopted. Why? As noted by Henderson (1993, 2006), it is exactly *because* incumbents are designed around the current ways of doing things and so proficient at them that they are blind to or unable to absorb the new approaches and get trapped in the status quo—they suffer the “curse of knowledge.”<sup>19</sup>

The factory electrification example demonstrates the other contributor to the time gap between a technology's emergence and its measured productivity effects: the need for installation (and often invention) of complementary capital. This includes both tangible and intangible investments. The timeline necessary to invent, acquire, and install these complements is typically more extensive than the time-to-build considerations just discussed. Consider the measured lag between large investments in IT and productivity benefits within firms. Brynjolfsson and Hitt (2003) found that while small productivity benefits were associated with firms' IT investments when one-year differences were considered, the benefits grew substantially as longer differences were examined, peaking after about seven years. They attributed this pattern to the need for complementary changes in business processes. For instance, when implementing large enterprise-planning systems, firms almost always spend several times more money on business process redesign and training than on the direct costs of hardware and software. Hiring and other human-resources practices often need considerable adjustment to match the firm's human capital to the new structure of production. In fact, Bresnahan, Brynjolfsson, and Hitt (2002) find evidence of three-way complementarities between IT, human capital, and organizational changes in the investment decisions and productivity levels. Furthermore, Brynjolfsson, Hitt, and Yang (2002) show each dollar of IT capital stock is correlated with about \$10 of market value. They interpret this as evidence of substantial IT-related intangible assets and show that firms that combine IT investments with a specific set of organizational practices are not just more productive, they also have disproportionately higher market values than firms that invest in only one or the other. This pattern in the data is consistent with a long stream of research on the importance of organizational and even

19. Atkeson and Kehoe (2007) note manufacturers' reluctance to abandon their large knowledge stock at the beginning of the transition to electric power to adopt what was, initially, only a marginally superior technology. David and Wright (2006) are more specific, focusing on “the need for organizational and above all for *conceptual* changes in the ways tasks and products are defined and structured” (147, emphasis in original).

cultural change when making IT investments and technology investments more generally (e.g., Aral, Brynjolfsson, and Wu 2012; Brynjolfsson and Hitt 2000; Orlikowski 1996; Henderson 2006).

But such changes take substantial time and resources, contributing to organizational inertia. Firms are complex systems that require an extensive web of complementary assets to allow the GPT to fully transform the system. Firms that are attempting transformation often must reevaluate and reconfigure not only their internal processes but often their supply and distribution chains as well. These changes can take time, but managers and entrepreneurs will direct invention in ways that economize on the most expensive inputs (Acemoglu and Restrepo 2017). According to LeChatelier's principle (Milgrom and Roberts 1996), elasticities will therefore tend to be greater in the long run than in the short run as quasi-fixed factors adjust.

There is no assurance that the adjustments will be successful. Indeed, there is evidence that the modal transformation of GPT-level magnitude fails. Alon et al. (2017) find that cohorts of firms over five years old contribute little to aggregate productivity growth on net—that is, among established firms, productivity improvements in one firm are offset by productivity declines in other firms. It is hard to teach the proverbial old dog new tricks. Moreover, the old dogs (companies) often have internal incentives to not learn them (Arrow 1962; Holmes, Levine, and Schmitz 2012). In some ways, technology advances in industry one company death at a time.

Transforming industries and sectors requires still more adjustment and reconfiguration. Retail offers a vivid example. Despite being one of the biggest innovations to come out of the 1990s dot-com boom, the largest change in retail in the two decades that followed was not e-commerce, but instead the expansion of warehouse stores and supercenters (Hortaçsu and Syverson 2015). Only very recently did e-commerce become a force for general retailers to reckon with. Why did it take so long? Brynjolfsson and Smith (2000) document the difficulties incumbent retailers had in adapting their business processes to take full advantage of the internet and electronic commerce. Many complementary investments were required. The sector as a whole required the build out of an entire distribution infrastructure. Customers had to be “retrained.” None of this could happen quickly. The potential of e-commerce to revolutionize retailing was widely recognized, and even hyped in the late 1990s, but its actual share of retail commerce was miniscule, 0.2 percent of all retail sales in 1999. Only after two decades of widely predicted yet time-consuming change in the industry, is e-commerce starting to approach 10 percent of total retail sales and companies like Amazon are having a first-order effect on more traditional retailers' sales and stock market valuations.

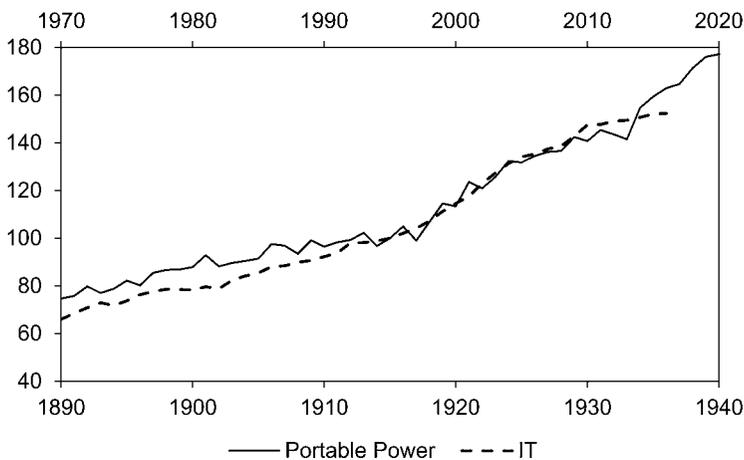
The case of self-driving cars discussed earlier provides a more prospective example of how productivity might lag technology. Consider what happens to the current pools of vehicle production and vehicle operation workers

when autonomous vehicles are introduced. Employment on production side will initially increase to handle research and development (R&D), AI development, and new vehicle engineering. Furthermore, learning curve issues could well imply lower productivity in manufacturing these vehicles during the early years (Levitt, List, and Syverson 2013). Thus labor input in the short run can actually increase, rather than decrease, for the same amount of vehicle production. In the early years of autonomous vehicle development and production, the marginal labor added by producers exceeds the marginal labor displaced among the motor vehicle operators. It is only later when the fleet of deployed autonomous vehicles gets closer to a steady state that measured productivity reflects the full benefits of the technology.

### 1.8 Viewing Today's Paradox through the Lens of Previous General Purpose Technologies

We have indicated in the previous discussion that we see parallels between the current paradox and those that have happened in the past. It is closely related to the Solow paradox era circa 1990, certainly, but it is also tied closely to the experience during the diffusion of portable power (combining the contemporaneous growth and transformative effects of electrification and the internal combustion engine).

Comparing the productivity growth patterns of the two eras is instructive. Figure 1.8 is an updated version of an analysis from Syverson (2013). It overlays US labor productivity since 1970 with that from 1890 to 1940, the period after portable power technologies had been invented and were starting to be placed into production. (The historical series values are from Kendrick [1961].) The modern series timeline is indexed to a value of 100 in 1995 and



**Fig. 1.8** Labor productivity growth in the portable power and IT eras

is labeled on the upper horizontal axis. The portable power era index has a value of 100 in 1915, and its years are shown on the lower horizontal axis.

Labor productivity during the portable power era shared remarkably similar patterns with the current series. In both eras, there was an initial period of roughly a quarter century of relatively slow productivity growth. Then both eras saw decade-long accelerations in productivity growth, spanning 1915 to 1924 in the portable power era and 1995 to 2004 more recently.

The late-1990s acceleration was the (at least partial) resolution of the Solow paradox. We imagine that the late 1910s acceleration could have similarly answered some economist's query in 1910 as to why one sees electric motors and internal combustion engines everywhere but in the productivity statistics.<sup>20</sup>

Very interesting, and quite relevant to the current situation, the productivity growth slowdown we have experienced after 2004 also has a parallel in the historical data, a slowdown from 1924 to 1932. As can be seen in the figure, and instructive to the point of whether a new wave of AI and associated technologies (or if one prefers, a second wave of IT-based technology) could reaccelerate productivity growth, labor productivity growth at the end of the portable power era rose again, averaging 2.7 percent per year between 1933 and 1940.

Of course this past breakout growth is no guarantee that productivity must speed up again today. However, it does raise two relevant points. First, it is another example of a period of sluggish productivity growth followed by an acceleration. Second, it demonstrates that productivity growth driven by a core GPT can arrive in multiple waves.

## 1.9 Expected Productivity Effects of an AI-Driven Acceleration

To understand the likely productivity effects of AI, it is useful to think of AI as a type of capital, specifically a type of intangible capital. It can be accumulated through investment, it is a durable factor of production, and its value can depreciate. Treating AI as a type of capital clarifies how its development and installation as a productive factor will affect productivity.

As with any capital deepening, increasing AI will raise labor productivity. This would be true regardless of how well AI capital is measured (which we might expect it won't be for several reasons discussed below) though there may be lags.

The effects of AI on TFP are more complex and the impact *will* depend on its measurement. If AI (and its output elasticity) were to be measured perfectly and included in both the input bundle in the denominator of TFP

20. We are not aware of anyone who actually said this, and of course today's system of national economic statistics did not exist at that time, but we find the scenario amusing, instructive, and in some ways plausible.

and the output bundle in the numerator, then measured TFP will accurately reflect true TFP. In this case, AI could be treated just like any other measurable capital input. Its effect on output could be properly accounted for and “removed” by the TFP input measure, leading to no change in TFP. This isn’t to say that there would not be productive benefits from diffusion of AI; it is just that it could be valued like other types of capital input.

There are reasons why economists and national statistical agencies might face measurement problems when dealing with AI. Some are instances of more general capital measurement issues, but others are likely to be idiosyncratic to AI. We discuss this next.

### 1.10 Measuring AI Capital

Regardless of the effects of AI and AI-related technologies on actual output and productivity, it is clear from the productivity outlook that the ways AI’s effects will be *measured* are dependent on how well countries’ statistics programs measure AI capital.

The primary difficulty in AI capital measurement is, as mentioned earlier, that many of its outputs will be intangible. This issue is exacerbated by the extensive use of AI as an input in making other capital, including new types of software, as well as human and organizational capital, rather than final consumption goods. Much of this other capital, including human capital, will, like AI itself, be mostly intangible (Jones and Romer 2010).

To be more specific, effective use of AI requires developing data sets, building firm-specific human capital, and implementing new business processes. These all require substantial capital outlays and maintenance. The tangible counterparts to these intangible expenditures, including purchases of computing resources, servers, and real estate, are easily measured in the standard neoclassical growth accounting model (Solow 1957). On the other hand, the value of capital goods production for complementary intangible investments is difficult to quantify. Both tangible and intangible capital stocks generate a capital service flow yield that accrues over time. Realizing these yields requires more than simply renting capital stock. After purchasing capital assets, firms incur additional adjustment costs (e.g., business process redesigns and installation costs). These adjustment costs make capital less flexible than frictionless rental markets would imply. Much of the market value of AI capital specifically, and IT capital more generally, may be derived from the capitalized short-term quasi-rents earned by firms that have already reorganized to extract service flows from new investment.

Yet while the stock of tangible assets is booked on corporate balance sheets, expenditures on the intangible complements and adjustment costs to AI investment commonly are not. Without including the production and use of intangible AI capital, the usual growth accounting decompositions of changes in value added can misattribute AI intangible capital deepening

to changes in TFP. As discussed in Hall (2000) and Yang and Brynjolfsson (2001), this constitutes an omission of a potentially important component of capital goods production in the calculation of final output. Estimates of TFP will therefore be inaccurate, though possibly in either direction. In the case where the intangible AI capital stock is growing faster than output, then TFP growth will be underestimated, while TFP will be overestimated if capital stock is growing more slowly than output.

The intuition for this effect is that in any given period  $t$ , the output of (unmeasured) AI capital stock in period  $t + 1$  is a function the input (unmeasured) existing AI capital stock in period  $t$ . When AI stock is growing rapidly, the unmeasured outputs (AI capital stock created) will be greater than the unmeasured inputs (AI capital stock used).

Furthermore, suppose the relevant costs in terms of labor and other resources needed to create intangible assets are measured, but the resulting increases in intangible assets are not measured as contributions to output. In this case, not only will total GDP be undercounted but so will productivity, which uses GDP as its numerator. Thus periods of rapid intangible capital accumulation may be associated with *lower* measured productivity growth, even if true productivity is increasing.

With missing capital goods production, measured productivity will only reflect the fact that more capital and labor inputs are used up in producing measured output. The inputs used to produce unmeasured capital goods will instead resemble lost potential output. For example, a recent report from the Brookings Institution estimates that investments in autonomous vehicles have topped \$80 billion from 2014 to 2017 with little consumer adoption of the technology so far.<sup>21</sup> This is roughly 0.44 percent of 2016 GDP (spread over three years). If all of the capital formation in autonomous vehicles was generated by equally costly labor inputs, this would lower estimated labor productivity by 0.1 percent per year over the last three years since autonomous vehicles have not yet led to any significant increase in measured final output. Similarly, according to the AI Index, enrollment in AI and ML courses at leading universities has roughly tripled over the past ten years, and the number of venture-back AI-related start-ups has more than quadrupled. To the extent that they create intangible assets beyond the costs of production, GDP will be underestimated.

Eventually the mismeasured intangible capital goods investments are expected to yield a return (i.e., output) by their investors. If and when measurable output is produced by these hidden assets, another mismeasurement effect leading to overestimation of productivity will kick in. When the output share and stock of mismeasured or omitted capital grows, the measured output increases produced by that capital will be incorrectly attributed to total factor productivity improvements. As the growth rate of investment in unmeasured capital goods decreases, the capital service flow from

21. <https://www.brookings.edu/research/gauging-investment-in-self-driving-cars/>.

unmeasured goods effect on TFP can exceed the underestimation error from unmeasured capital goods.

Combining these two effects produces a “J-curve” wherein early production of intangible capital leads to underestimation of productivity growth, but later returns from the stock of unmeasured capital creates measured output growth that might be incorrectly attributed to TFP.

Formally:

$$(1) \quad Y + zI_2 = f(A, K_1, K_2, L)$$

$$(2) \quad dY + z dI_2 = F_A dA + F_{K_1} dK_1 + F_L dL + F_{K_2} dK_2.$$

Output  $Y$  and unmeasured capital goods with price  $z(zI_2)$  are produced with production function  $f$ . The inputs of  $f(\cdot)$  are the total factor productivity  $A$ , ordinary capital  $K_1$ , unmeasured capital  $K_2$ , and labor  $L$ . Equation (2) describes the total differential of output as a function of the inputs to the production function. If the rental price of ordinary capital is  $r_1$ , the rental price of unmeasured capital is  $r_2$ , and the wage rate is  $w$ , we have

$$(3) \quad \hat{S} = \frac{dY}{Y} - \left( \frac{r_1 K_1}{Y} \right) \left( \frac{dK_1}{K_1} \right) - \left( \frac{wL}{Y} \right) \left( \frac{dL}{L} \right)$$

and

$$(4) \quad S^* = \frac{dY}{Y} - \left( \frac{r_1 K_1}{Y} \right) \left( \frac{dK_1}{K_1} \right) - \left( \frac{wL}{Y} \right) \left( \frac{dL}{L} \right) - \left( \frac{r_2 K_2}{Y} \right) \left( \frac{dK_2}{K_2} \right) + \left( \frac{zI_2}{Y} \right) \left( \frac{dI_2}{I_2} \right),$$

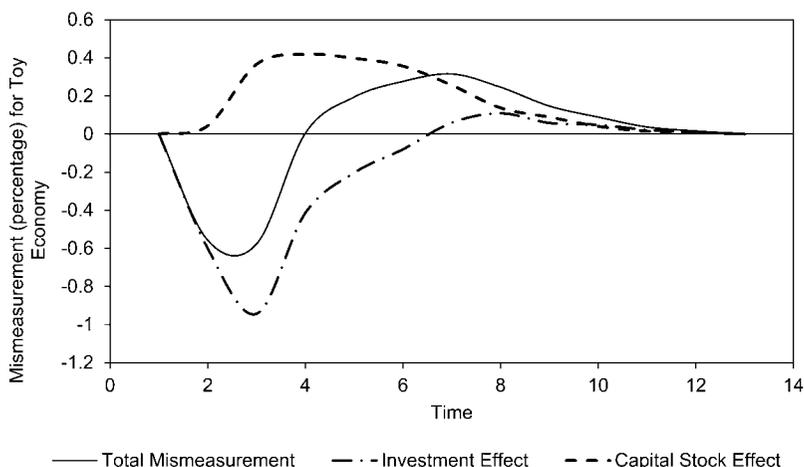
where  $\hat{S}$  is the familiar Solow residual as measured and  $S^*$  is the correct Solow residual accounting for mismeasured capital investments and stock.

The mismeasurement is then

$$(5) \quad \hat{S} - S^* = \left( \frac{r_2 K_2}{Y} \right) \left( \frac{dK_2}{K_2} \right) - \left( \frac{zI_2}{Y} \right) \left( \frac{dI_2}{I_2} \right) = \left( \frac{r_2 K_2}{Y} \right) g_{K_2} - \left( \frac{zI_2}{Y} \right) g_{I_2}$$

The right side of the equation describes a hidden capital effect and a hidden investment effect. When the growth rate of new investment in unmeasured capital multiplied by its share of output is larger (smaller) than the growth rate of the stock of unmeasured capital multiplied by its share of output, the estimated Solow residual will underestimate (overestimate) the rate of productivity growth. Initially, new types of capital will have a high marginal product. Firms will accumulate that capital until its marginal rate of return is equal to the rate of return of other capital. As capital accumulates, the growth rate of net investment in the unmeasured capital will turn negative, causing a greater overestimate TFP. In steady state, neither net investment's share of output nor the net stock of unmeasured capital grows and the productivity mismeasurement is zero. Figure 1.9 provides an illustration.<sup>22</sup>

22. The price of new investment ( $z$ ) and rental price of capital ( $r$ ) are 0.3 and 0.12, respectively, in this toy economy. Other values used to create the figure are included in the appendix.



**Fig. 1.9** The mismeasurement J-curve for an economy accumulating a new kind of capital

Looking forward, these problems may be particularly stark for AI capital, because its accumulation will almost surely outstrip the pace of ordinary capital accumulation in the short run. AI capital is a new category of capital—new in economic statistics, certainly, but we would argue practically so as well.

This also means that capital quantity indexes that are computed from within-type capital growth might have problems benchmarking size and effect of AI early on. National statistics agencies do not really focus on measuring capital types that are not already ubiquitous. New capital categories will tend to either be rolled into existing types, possibly with lower inferred marginal products (leading to an understatement of the productive effect of the new capital), or missed altogether. This problem is akin to the new goods problem in price indexes.

A related issue—once AI is measured separately—is how closely its units of measurement will capture AI’s marginal product relative to other capital stock. That is, if a dollar of AI stock has a marginal product that is twice as high as the modal unit of non-AI capital in the economy, will the quantity indexes of AI reflect this? This requires measured relative prices of AI and non-AI capital to capture differences in marginal product. Measuring levels correctly is less important than measuring accurate proportional differences (whether intertemporally or in the cross section) correctly. What is needed in the end is that a unit of AI capital twice as productive as another should be twice as large in the capital stock.

It is worth noting that these are all classic problems in capital measurement and not new to AI. Perhaps these problems will be systematically worse for AI, but this is not obvious *ex ante*. What it does mean is that econo-

mists and national statistical agencies at least have experience in, if not quite a full solution for, dealing with these sorts of limitations. That said, some measurement issues are likely to be especially prevalent for AI. For instance, a substantial part of the value of AI output may be firm-specific. Imagine a program that figures out individual consumers' product preferences or price elasticities and matches products and pricing to predictions. This has different value to different companies depending on their customer bases and product selection, and knowledge may not be transferrable across firms. The value also depends on companies' abilities to implement price discrimination. Such limits could come from characteristics of a company's market, like resale opportunities, which are not always under firms' control, or from the existence in the firm of complementary implementation assets and/or abilities. Likewise, each firm will likely have a different skill mix that it seeks in its employees, unique needs in its production process, and a particular set of supply constraints. In such cases, firm-specific data sets and applications of those data will differentiate the machine-learning capabilities of one firm from another (Brynjolfsson and McAfee 2017).

### 1.11 Conclusion

There are plenty of both optimists and pessimists about technology and growth. The optimists tend to be technologists and venture capitalists, and many are clustered in technology hubs. The pessimists tend to be economists, sociologists, statisticians, and government officials. Many of them are clustered in major state and national capitals. There is much less interaction between the two groups than within them, and it often seems as though they are talking past each other. In this chapter, we argue that in an important sense, they are.

When we talk with the optimists, we are convinced that the recent breakthroughs in AI and machine learning are real and significant. We also would argue that they form the core of a new, economically important potential GPT. When we speak with the pessimists, we are convinced that productivity growth has slowed down recently and what gains there have been are unevenly distributed, leaving many people with stagnating incomes, declining metrics of health and well-being, and good cause for concern. People are uncertain about the future, and many of the industrial titans that once dominated the employment and market value leaderboard have fallen on harder times.

These two stories are not contradictory. In fact, in many ways they are consistent and symptomatic of an economy in transition. Our analysis suggests that while the recent past has been difficult, it is not destiny. Although it is always dangerous to make predictions, and we are humble about our ability to foretell the future, our reading of the evidence does provide some cause for optimism. The breakthroughs of AI technologies already demon-

strated are not yet affecting much of the economy, but they portend bigger effects as they diffuse. More important, they enable complementary innovations that could multiply their impact. Both the AI investments and the complementary changes are costly, hard to measure, and take time to implement, and this can, at least initially, depress productivity as it is currently measured. Entrepreneurs, managers, and end-users will find powerful new applications for machines that can now learn how to recognize objects, understand human language, speak, make accurate predictions, solve problems, and interact with the world with increasing dexterity and mobility.

Further advances in the core technologies of machine learning would likely yield substantial benefits. However, our perspective suggests that an underrated area of research involves the complements to the new AI technologies, not only in areas of human capital and skills, but also new processes and business models. The intangible assets associated with the last wave of computerization were about ten times as large as the direct investments in computer hardware itself. We think it is plausible that AI-associated intangibles could be of a comparable or greater magnitude. Given the big changes in coordination and production possibilities made possible by AI, the ways that we organized work and education in the past are unlikely to remain optimal in the future.

Relatedly, we need to update our economic measurement tool kits. As AI and its complements more rapidly add to our (intangible) capital stock, traditional metrics like GDP and productivity can become more difficult to measure and interpret. Successful companies do not need large investments in factories or even computer hardware, but they do have intangible assets that are costly to replicate. The large market values associated with companies developing and/or implementing AI suggest that investors believe there is real value in those companies. In the case that claims on the assets of the firm are publicly traded and markets are efficient, the financial market will properly value the firm as the present value of its risk-adjusted discounted cash flows. This can provide an estimate of the value of both the tangible and intangible assets owned by the firm. What's more, the effects on living standards may be even larger than the benefits that investors hope to capture. It is also possible, even likely, that many people will not share in those benefits. Economists are well positioned to contribute to a research agenda of documenting and understanding the often intangible changes associated with AI and its broader economic implications.

Realizing the benefits of AI is far from automatic. It will require effort and entrepreneurship to develop the needed complements, and adaptability at the individual, organizational, and societal levels to undertake the associated restructuring. Theory predicts that the winners will be those with the lowest adjustment costs and that put as many of the right complements in place as possible. This is partly a matter of good fortune, but with the right road map, it is also something for which they, and all of us, can prepare.

## Appendix

Table 1A.1 Regressions with Newey-West standard errors with longer time dependence

	(1) 1 lag allowed	(2) 2 lags allowed	(3) 3 lags allowed	(4) 4 lags allowed	(5) 10 lags allowed
Newey-West regressions, ten-year average, labor productivity growth					
Previous ten-year average productivity growth	0.0857 (0.177)	0.0857 (0.207)	0.0857 (0.227)	0.0857 (0.242)	0.0857 (0.278)
Constant	1.949*** (0.398)	1.949*** (0.465)	1.949*** (0.511)	1.949*** (0.545)	1.949*** (0.624)
Observations	50	50	50	50	50
R-squared	0.009	0.009	0.009	0.009	0.009
Newey-West regressions, ten-year average, TFP growth					
Previous ten-year average TFP growth	0.136 (0.158)	0.136 (0.181)	0.136 (0.197)	0.136 (0.208)	0.136 (0.233)
Constant	0.911*** (0.188)	0.911*** (0.216)	0.911*** (0.233)	0.911*** (0.244)	0.911*** (0.257)
Observations	50	50	50	50	50
R-squared	0.023	0.023	0.023	0.023	0.023
Newey-West regressions, ten-year average, TFP (util. adj.) growth					
Previous ten-year average TFPua growth	0.158 (0.187)	0.158 (0.221)	0.158 (0.246)	0.158 (0.266)	0.158 (0.311)
Constant	0.910*** (0.259)	0.910*** (0.306)	0.910*** (0.341)	0.910*** (0.368)	0.910*** (0.412)
Observations	50	50	50	50	50
R-squared	0.030	0.030	0.030	0.030	0.030

Note: Standard errors in parentheses.  
 \*\*\*Significant at the 1 percent level.  
 \*\*Significant at the 5 percent level.  
 \*Significant at the 10 percent level.

**Table 1A.2** Parameters for the toy economy J-curve

Time	Net investment	Net capital stock	Investment growth rate	Capital stock growth rate	Output
0.0	1.0	10.0			10,000.0
1.0	15.0	25.0	14.0	1.5	10,500.0
2.0	80.0	105.0	4.3	3.2	11,025.0
3.0	160.0	265.0	1.0	1.5	11,576.3
4.0	220.0	485.0	0.4	0.8	12,155.1
5.0	250.0	735.0	0.1	0.5	12,762.8
6.0	220.0	955.0	-0.1	0.3	13,401.0
7.0	140.0	1,095.0	-0.4	0.1	14,071.0
8.0	100.0	1,195.0	-0.3	0.1	14,774.6
9.0	50.0	1,245.0	-0.5	0.0	15,513.3
10.0	20.0	1,265.0	-0.6	0.0	16,288.9
11.0	10.0	1,275.0	-0.5	0.0	17,103.4
12.0	0.0	1,275.0	-1.0	0.0	17,958.6

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## Comment Rebecca Henderson

“Artificial Intelligence and the Modern Productivity Paradox” is a fabulous chapter. It is beautifully written, extremely interesting, and goes right to the heart of a centrally important question, namely, what effects will AI have on economic growth? The authors make two central claims. The first is that AI

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