Bell Labs Technical Journal

Volume 20 | June 2017

Bell Labs

Will productivity growth return in the new digital era?

An analysis of the potential impact on productivity of the fourth industrial revolution

Bell Labs Technical Journal
Volume 20 | June 2017

Iraj Saniee, Sanjay Kamat, Subra Prakash and Marcus Weldon
Nokia Bell Labs, 600 Mountain Avenue, Murray Hill, NJ 07974

It is increasingly acknowledged that we are on the verge of the next technological revolution and the fourth industrial revolution, driven by the digitization and interconnection of all physical elements and infrastructure under the control of advanced intelligent systems. Therefore, there will be a new era of automation that should result in enhanced productivity. However, such productivity enhancements have been anticipated before, particularly during the third industrial revolution commonly known as the 'information age', and have failed to materialize. Were the productivity increases observed following the first and second industrial revolutions a one-time aberration that will not be repeated in the new digital age? In this paper, we attempt to address this question by a semi-quantitative analysis of the prior productivity jumps and their physical technological origins, and extend this analysis to the latent set of analogous digital technologies. Using this approach, we project that there will indeed be a second productivity jump in the United States that will occur in the 2028–2033 timeframe when the aggregate of the of constituent technologies reaches the tipping point at 51 percent penetration.

Introduction

The lack of significant improvement in economic productivity over the past 30 years, despite the rapid advances and growing investments in information and communication technologies and the digitization and global interconnection and accessibility of whole industries, has been a topic of much concern and debate among economists and policy makers. The concern arises in large part due to the assessment of economic health by measuring increases in gross domestic product, which is linked to productivity. The absence of such growth in the internet (information) age to date suggests that digitization will not produce economic growth but merely economic change, with potentially increased inequality. The prevailing counter-arguments are either that the growth has yet to be realized, or that a new measure of productivity is required that relies less on

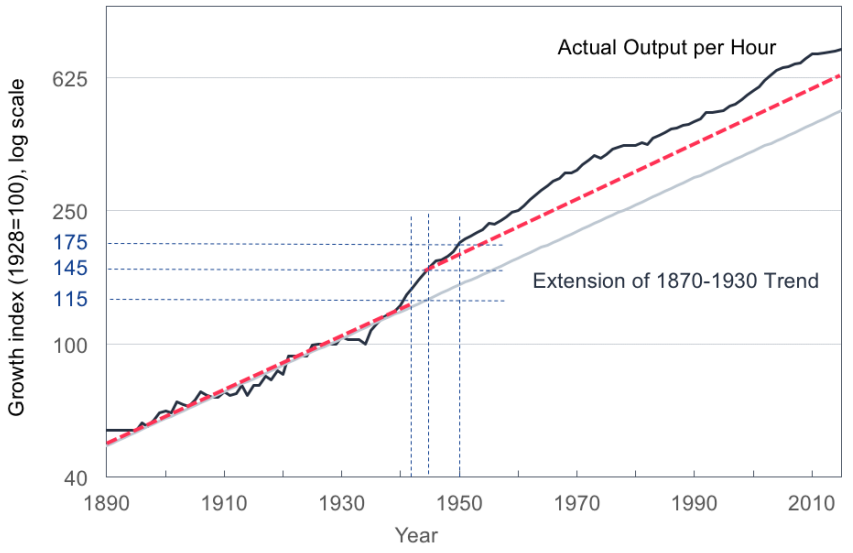

FIGURE 1. Depiction of Gordon's analysis showing a one-time productivity jump of ~30% during 1940–1950 (115 units pre-1942 to 145 units post-1945).

the production of physical goods and services and more on the creation and facile global distribution of digital goods, including soft goods like 'data' and 'knowledge'. In this paper, we attempt to address this question of future productivity as we stand on the precipice of the fourth industrial revolution, which will be driven by the digitization and interconnection of everything, as described in the recent work, The Future X Network: A Bell Labs Perspective (Weldon, 2015).

The origin of the current question on productivity is first raised by the economist Robert J. Gordon in his The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War (Gordon, 2016), which makes a provocative but persuasive argument that the significant jump in productivity during the 1940s was a one-time event (figure 1). Gordon argues that the current advances in information technology, which define the so-called third industrial revolution, pale in social impact compared to the "Great Inventions" of the first and second industrial revolutions, such as electricity, urban sanitation, chemicals and pharmaceuticals, the internal combustion engine and modern communication that powered economic growth in the Golden Century from 1870 to 1970.
Gordon makes a compelling case by linking the qualitative argument of how life in America fundamentally improved from 1870 to 1940, driven by the refinements and wider adoption of the Great Inventions, to his quantitative analysis demonstrating a significant one-time jump in productivity from 1940 to 1950 (figure 1 and figure 2). He attributes the subsequent growth

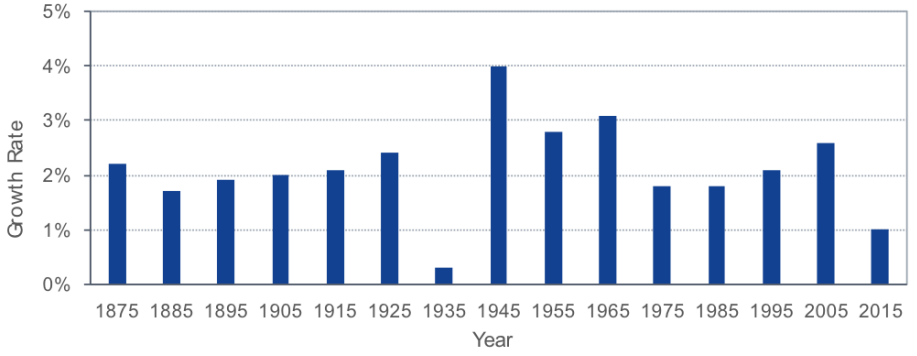

FIGURE 2. US labor productivity growth rates averaged by the decade for the period 1875–2015.

in productivity until 1970 to rising income and spread of the new lifestyle throughout the nation.

In conclusion, Gordon argues that the great age of dramatic progress is behind us, as the advances over the last 30 years in ICT and digital technologies are not as transformative as the Great Inventions of the prior industrial revolutions. In Chapter 16, he recognizes the recent advances in medical and pharmaceutical technologies, robotics, autonomous vehicles, 3D printing, big data and artificial intelligence, but then dismisses their potential to contribute significantly to social and economic growth, concluding that the current slower growth in productivity is likely to be permanent.

The analysis Gordon presents is coherent and compelling, however, it ultimately rests on the question of the potential of emerging technologies, and whether their full potential has yet been realized or is still latent. Gordon provides numerous historical examples of significant lag between the initial introduction and the subsequent wide-scale deployment of technologies that, in turn, enable further innovative combinations contributing to the eventual surge in productivity. In this paper, we leverage this idea of technology diffusion. We first quantify the diffusion of the four Great Inventions to establish a correlation between the tipping point of the net diffusion and the increase in productivity outlined by Gordon. We then apply the same methodology to what we posit are the equivalent set of digital era great inventions, examine the projected impact on future productivity and whether, and when, a similar tipping point will be realized in the future.

Identification of foundational 'networked' infrastructure technologies during the Golden Century

In this section, we explore the potential link between productivity and penetration of key infrastructural technologies by constructing a simple diffusion model of the Great Inventions and analyzing the tipping point of the net diffusion.

Gordon emphasizes that genuine technology revolutions bring out significant changes in both business practices and lifestyles. This is consistent with the accepted definition of a technological revolution (Perez, 2009), as "the interconnection of new systems or technologies with the ability to profoundly change societies and economies." Examining this definition, it is clear that in addition to the technology itself, there is the explicit requirement of interconnection as well, which suggests that the fundamentally disruptive technologies of any set are those that form new networks. In essence this is a version of the well-known popular law attributed to Bob Metcalfe (Metcalfe, 2013) that "the power of a network is in proportion to the square of the number of compatible connected devices"; which can be simply restated as "massively connected technologies massively disrupt" and are therefore the most likely to drive technological revolutions.

This essential observation is the basis of our extended analysis of the Gordon data and hypothesis. We postulate that the combination of four physical 'networked' infrastructure technologies — communication, energy, transportation, health and sanitation — are the foundational set of technologies that underpin the productivity growth observed by Gordon. We further conjecture that all other inventions discussed by Gordon are in fact dependent on this set, and so are consequential or derivative of this foundational set. In other words they may magnify the productivity gain, but they do not define or drive the jump. For example, the widespread availability of refrigeration is identified by Gordon (Gordon, 2016) as a key technological innovation, and there is no doubt that it changed lifestyles and diets. However, we argue that it is dependent on the availability of networked power and the rapid and inexpensive transportation of perishable

Great inventions of the first and second industrial revolutions - examples from (Gordon, 2016)	Foundational network infrastructure(s)
Car	Transportation
Radio and TV, refrigeration, home appliances	Energy
Telephony	Communication
Public health	Health and Sanitation
Office automation	Energy (Electricity) and Communication
Consumer credit	Energy (Electricity) and Communication
Fashion	Communication and Transportation
Fast Food	Energy (Electricity) and Transportation
Mass agriculture	Transportation
Mass leisure travel	Transportation

TABLE 1. Mapping examples of great inventions of first and second industrial revolutions to the foundational network infrastructures that enabled them.

goods and consumables, and so is derivative of the fundamental technologies, but not a foundational technology itself. We perform a similar mapping of other derivative technologies and the foundational networked infrastructures on which they rely. Referring to table I, we have reduced the analysis to only four foundational networked infrastructures and their defining technologies, which are:

1. Energy networks (gas and electricity technologies)
2. Health and sanitation networks (water and health technologies)
3. Transportation networks (dependent on internal combustion engine technologies)
4. Communication networks (telephony technologies)

In figure 3 we plot the historical diffusion curves of the four foundational technologies, which we model using datasets (see appendix A for relevant data sources) for the growth of registered motor vehicles (a proxy for the transportation infrastructure category), electricity and gas networks (proxy for energy), landline telephones (proxy for communication) and water delivery networks (proxy for health and sanitation). On simple inspection of figure 1 and figure 3, it is apparent that the slow growth in productivity followed by the jump over the 1940–1950 period, then a return to steady state growth shown in figure 1, mirrors the slow initial growth in adoption of these four technologies followed by a phase of rapid growth to an inflection point, after which maturity sets

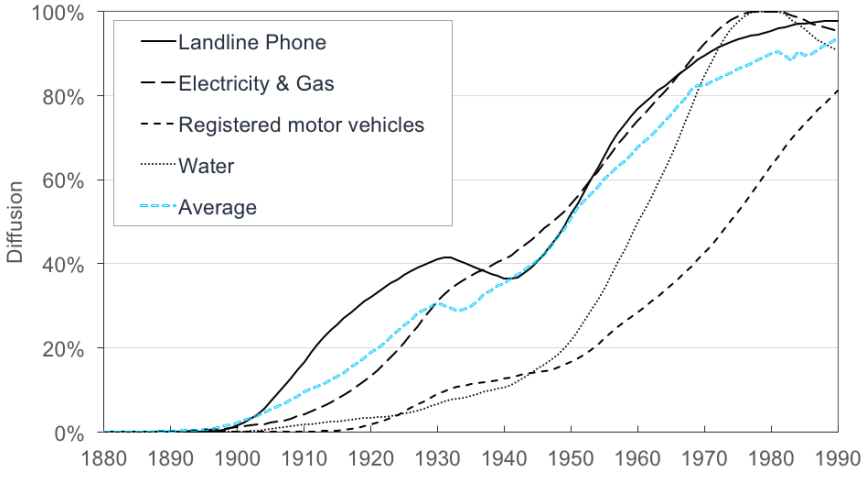

FIGURE 3. Empirical diffusion models of four technologies defined as foundational to the past productivity increase.

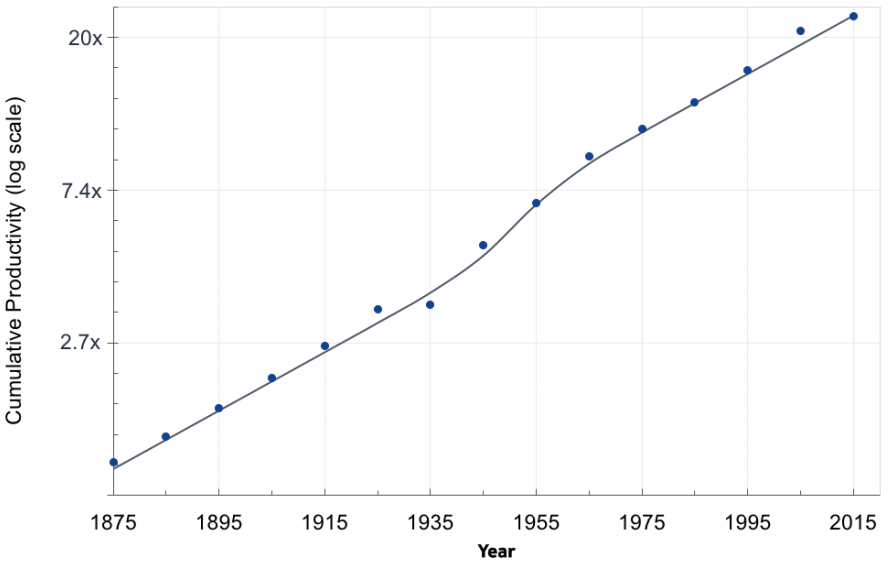

FIGURE 4. The analytical function Ln(P) (solid line) for the productivity data for 1875–1975 (points).

in (see figure 3). However, we seek a more solid quantitative foundation for the comparison and analysis, which we address in the following section.

Quantifying the diffusion of 'networked' infrastructure technologies and the link to productivity during the Golden Century

To validate the connection between technology diffusion and productivity we have analyzed the data presented in figure 1 and figure 2 by a simple sigmoidal function typically used to describe diffusive processes.

Figure 4 shows a sigmoidal curve fit to the productivity data shown in figure 1. The productivity, P, is described by the following equation as a function of time, t:

$$ln(P) = 0.019\ t - 35.637 + \frac{0.294}{1 + 1.022e^{-0.216(t-1951.27)}}$$

The inflection or tipping point of this curve, denoted by t_{tp}, is described by

$$t_{tp} = 1951.27 + \frac{\ln(1.022)}{0.216} = 1951$$

The tipping point is then calculated to occur in 1951, consistent with the time period of the productivity jump identified by Gordon. The utility of this simple curve-fitting analysis will become apparent below, where we establish the connection with the diffusion of the key infrastructure technologies.

In figure 5, we take the productivity data from figure 4 and reference it to 1870–1930 trend line to compute the 'adjusted productivity'. We then map each point to the average diffusion calculated from the four physical infrastructure technologies in each given time interval, as shown in figure 3. We thereby establish the connection between adjusted productivity and technology diffusion, as shown in figure 5 (dotted line). We also plot a smooth sigmoid function (solid line) to fit the data.

We then obtain an analytical expression between the adjusted productivity, P_a, and the average diffusion, d, of the four infrastructure technologies.

$$ln(P_a) = \frac{2.87}{1 + 150.576e^{-0.145(d-16.61)}}$$

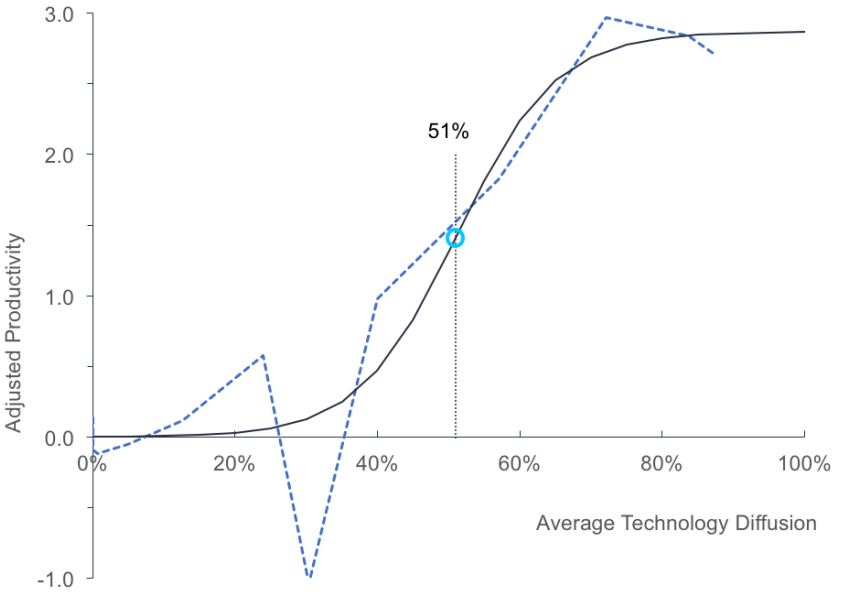

FIGURE 5. Adjusted productivity versus average diffusion of the key physical networked technologies for the period 1890–1930.

Now, if we solve for the inflection point of this adjusted productivity curve in terms of the

$$d_{tp} = 16.61 + \frac{\ln(150.57)}{0.145} = 51\%$$

technology penetration percentage, we find that it occurs at 51 percent of the average adoption level of the key infrastructure technologies. Combining the two tipping point analyses, we find that the tipping point in productivity observed by Gordon occurs when the diffusion of the key networked infrastructure technologies reaches around 51 percent; a rather intuitive result.

Despite the intuitive appeal, this result should be viewed with a measure of caution; it is a correlation based on plausible logic, but it is not causal in nature. Nonetheless, we will proceed with this analysis in a way that is meaningful within the scope and limitations outlined above. It is important to note that the objective of this analytical exercise is not to predict the precise productivity growth for any specific year, but rather to explore a quantitative linkage between an inflection point in productivity growth and technology penetration or 'diffusion'.

In the next section, we build on this analysis to attempt to find a set of future technologies that are the digital analogs of the physical infrastructure networked technologies discussed above, and then to evaluate whether the diffusion of these technologies can be used to make predictions about future productivity growth.

Quantifying the diffusion of digital 'networked' technologies and the link to productivity in the next industrial era

Paul Krugman notes in his review of Gordon's book (Krugman, 2016) that modern digital technologies must clear the high bar of dramatic transformative impact on the society set by the Golden Inventions from 1870 to 1940 and any claims about current progress need to be compared with that baseline.

It is necessarily true that all new activities and transactions in an economy emerge to satisfy some pressing human need or deficiency. Clearly, the state of the society prior to 1870 called for an economy that addressed the lower-level needs in Maslow's hierarchy of human needs (Maslow, 1984) (figure 6). The emergence of

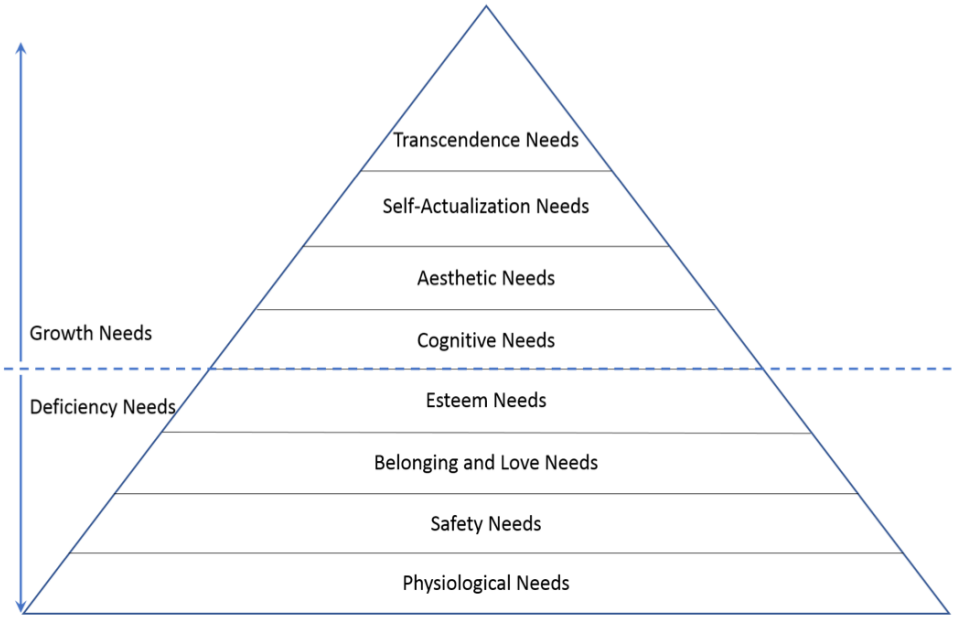

FIGURE 6. Representation of Maslow's hierarchy of human needs.

physical infrastructure, such as networks of gas and electricity, transportation, water/sewage and telephony, facilitated activities and transactions that address these so-called 'deficiency needs'. Indeed, these needs were satisfied to such an extent that we now take the technologies that satisfied them for granted. The fundamental question is whether the information age and the 'fourth industrial revolution' will satisfy higher-level needs (represented by the upper layers in Maslows's hierarchy) and whether, as a result, a new era of enhanced productivity will result.

Erik Brynjolfsson and Andrew McAfee paint a much more optimistic view of the future than Gordon in their 2014 book, The second machine age: work, progress, and prosperity in a time of brilliant technologies (McAfee, 2014). They note the current value and future potential of many emerging digital technologies to address higher-level needs. They go on to highlight the inadequacies of traditional economic metrics, such as gross domestic product (GDP) and total factor productivity (TFP), to fully capturing this value. While acknowledging this issue, Gordon (Gordon, 2016) notes that such measurement index issues were more severe in the past. There is currently significant work in the field of economics to evaluate how to measure many soft productivity elements related to knowledge, cognition and aesthetics. We will not consider alternative measures here, rather we will assume that such a measure exists and that it is close enough to the current measures that the arguments we present below, which are based on an extension of Gordon's logic to the coming era, remain appropriate.

An oft-cited quote on the modern productivity paradox is Robert Solow's quip in 1987 (Solow, 1987) that 'we can see the computer age everywhere but in the productivity statistics'. Gordon notes in his chapter 17 (Gordon, 2016) that the final answer to Solow's paradox is that computers are not everywhere; we don't currently consume computers, or wear them or drive to work in them or let them perform personal functions. In fact, we live in dwelling units that have appliances much like those in the 1950s, and we drive in motor vehicles that perform the same function as in the 1950s, albeit with more fuel efficiency, more functionality and superior safety. However, it is now eminently reasonable to conjecture that we will in the future – and even to some extent currently – 'consume' computers (smart

ingestible medicines and probes), 'wear' computers (smart wearables and clothing), drive in them (autonomous vehicles), live in them (smart homes and cities) and work in them (smart factories and offices).

We assert that we are on the cusp of a new digital era, in which the progress of digitization and connection of everything and everyone, triggered by the 'internet of things' (IoT) and supporting technologies, will approach a critical threshold at which point a confluence of key technologies will automate much of life. The net effect will be to effectively 'create time' by reducing the time taken to perform mundane physical tasks that defined the past era, thus ushering in a new era of productivity, an era marked by increased output per time worked (Productivity, 2017).

In the preceding we showed that the diffusion of four key technologies (telephones, motor vehicles, gas and electricity, water) were probable drivers of the 1940's productivity surge corresponding to the four broader categories of networked infrastructures; communications, transportation, energy, and health and sanitation. These four categories all have the attribute of being physical infrastructures, which require significant investments of capital and time to build, and consequently it is natural that there is a significant initial lag between initial construction and large-scale adoption. As highlighted earlier, each one is also a network, resulting in compounding value that arises from the ability to connect or enable significant extended scaling. Each enables a concomitant growth 'jump' after reaching a critical mass, due to the improved economies of scale for the builders and the increasing returns for the users. We also assert that there is an additional factor – what we call 'the combinatorial magic' – that describes the unanticipated set of additional innovations that arise from novel combinations of the constituent technologies and networks to achieve something that resembles exponential growth.

This combinatorial magic lies at the heart of Ray Kurzweil's proposal of a 'singularity' (Kurzweil, 2006) that will arise in future due to the compounding effect of future technologies. However, in Kurzweil's construction, each technology is exponential in adoption and not sigmoidal, which gives rise to his prediction of ever-increasing compounded growth, rather than compounded diffusive growth. The latter ultimately approaches a new steady state asymptote, which forms the basis of our model.

Our approach to analyzing future productivity starts by anticipating a set of new technologies that are the modern-day equivalent of the prior industrial revolution technologies considered by Gordon (Gordon, 2016). In table 2, we postulate five categories of modern digital infrastructure networks that are in early stages of their deployment but have the potential to fundamentally transform economies and societies and, therefore, will constitute a technological revolution (Perez, 2009) once they reach a critical mass of combinatorial magic (compounded adoption).

Importantly, we are not arbitrarily choosing these digital infrastructure networks, they are digital equivalents to the physical infrastructure networks, energy, transportation, health/ sanitation and communications, as indicated in table 2 and described below. However, an additional infrastructure category is warranted that does not have a direct equivalent for the physical era, namely Digital Production. It includes the advent of 3D printing, distributed cloud infrastructure and robotics in increasingly local contexts. Although industrial manufacturing was clearly fundamental in the Gordon era, it was not a first order enabler, rather it was enabled by the four physical infrastructure networks. In contrast, we argue that the technologies identified with this fifth digital category are fundamental to the digital era, and so are directly included in the analysis.

We map these digital infrastructure technologies onto enabling digital technologies, as was done

First and second industrial revolution technologies	Third and fourth industrial revolution technologies
1. Energy networks - Connecting places / systems and moving energy to power them	1. Digital energy networks - Connecting and controlling new power sources, moving them closer to consumption needs and minimizing waste
2. Health and sanitation networks - Connecting human habitats and moving water to and waste away from them	2. Digital health and sanitation networks - Connecting human health systems and moving diagnosis and treatment to the optimum locations
3. Transportation networks - Connecting places and moving people and things to them	3. Digital transportation networks - Connecting and moving people and goods autonomously, improving safety and efficiency
4. Communication networks - Connecting people and moving voice signals to them	4. Digital communication networks - Connecting people and systems and moving data and knowledge among them
	5. Digital production networks - Creating local industrial ecosystems to produce and deliver contextual physical-digital goods and services with optimized cost-performance metrics

TABLE 2. Identification and mapping of physical and digital infrastructure technologies across the past and present/future industrial revolutions

for the preceding Gordon physical era analysis. Due to the incipient nature of these digital infrastructures and uncertainty in forecasting the growth trajectory or degree of impact of any one technology, we choose multiple technological proxies within these categories to analyze the current state of adoption and the likely growth trajectory from multiple dimensions (see appendix B for relevant data sources and analytical approach). We then build composite diffusion curves using projections for the future growth. Finally, we compute the average diffusion curve across the set of five digital infrastructure categories, looking for the 51 percent diffusion tipping point, d_{tp}, analogous to the physical era analysis. This will predict the time when the tipping point will occur.

Each of the five digital infrastructure networks map to what we believe will be the enabling technologies and then we make projections for the diffusion of each technology in the United States (the focus of the Gordon work), as follows:

1. **Digital energy.** We anticipate that using digital technologies to efficiently manage the generation, distribution and consumption of energy from traditional as well as renewable resources will be key in the increasingly digital-physical world. We therefore use the following two technology enablers to project the growth of this digital technology infrastructure:
   a. Smart meter penetration in households. Electric companies had installed smart meters to cover over 50 percent of the households by the end of year 2015. We project the penetration to reach ~100 percent by the year 2031 (appendix B: 1.a). When coupled with smart-grid networks, this will enable the optimal matching of supply and demand for energy networks.
   b. Renewable energy. The penetration of renewable energy was at 19 percent of total electricity production in 2016, with the growth rate often dependent on local and federal policies. We project maximum penetration of about 64 percent by the year 2099 and expect diffusion to cross the 50 percent threshold by the year 2053 (appendix B: 1.b).

2. **Digital health.** Digitization will play a significant role in improving healthcare by enabling comprehensive and continuous monitoring of health status, improved preventive care, better accuracy of diagnosis and efficient delivery of treatment using a combination of novel sensing technologies connected to cloud-based artificial and augmented intelligence systems. Digital health technologies are

currently being adopted by the chronically ill as well as the so-called 'worried-well' segment and we expect the maximum household adoption of health systems to reach around 80 percent by the year 2044 and diffusion to cross the 50 percent diffusion threshold by the year 2030 (appendix B: 2).

3. **Digital transportation.** While transportation network infrastructure (development of highways and ownership of cars) played a key role in the growth of the prior era, the infrastructure is clearly at its limit in terms of traffic that can be carried and the cost to repair and maintain it. Digital technologies are already driving a new reality, with the emergence of autonomous vehicles (AV) that use a multitude of sensors to measure their environs and artificial intelligence (AI) systems to analyze and propose the optimal action. Regulation and policy incentives will play a key role in driving the adoption (for example by mandating dedicated AV lanes, or insurance discounts), but we expect autonomous vehicles' share of total registered vehicles to cross the 50 percent diffusion threshold around the year 2044 and reach the maximum of 100 percent around the year 2087 (appendix B: 3).

4. **Digital communication.** The most fundamental role of networks is to allow one entity to communicate with another. The future of such communications networks is in flux, with phenomena such as 'cord cutting' (of wired phone services) and replacement with increasingly sophisticated wirelessly connected smartphones well under way. In addition, the increase in proportion of transactions that occur electronically through e-commerce web services and electronic payment methods is a significant trend that is already apparent. Last, the rise of AI systems, in the form of image and voice recognition and chatbots has an undeniable future trajectory that will transform communication between people, things, systems and platforms. We therefore use the following digital technologies to project the diffusion of this digital infrastructure network:
   a. Smartphone penetration. We select the minimum speed of 4G as cut-off as it provides enough speed to be useful beyond basic digital communication services such as voice, text messages and web browsing. 4G smartphone penetration crossed the 50 percent diffusion threshold in the year 2015 in the United States, with 100 percent penetration of the population above age 10 expected to occur around the year 2030 (appendix B: 4.a).
   b. Cognitive assistants (AI). Consumer AI systems in the form of chatbots and natural language processing assistants, such as Siri, Alexa and Google Assistant, are becoming increasingly prevalent for simple query processing and response. While this will continue unabated as new forms of neural networking technologies are developed and utilized that learn and predict outcomes, in the fourth industrial revolution, we expect significant impact from AI and augmented intelligence (AugI) systems in industrial and civil infrastructure and systems control. However, we anticipate that the adoption in the industrial domains will soon align with the consumer adoption as the two are linked (since most industrial systems will be automated to improve customer experience in some dimension), so we project consumer and industrial AI and AugI systems to perform around 50 percent of mundane functions by the year 2035 and close to 100 percent by the year 2050 (appendix B: 4.b).
   c. E-Commerce. While e-commerce has clearly disrupted many sectors of the economy, its full impact is yet to be achieved. In 2015, about 12 percent of overall retail US trade value was via e-commerce. We project a maximum penetration of about 75 percent around the year 2070, and expect diffusion to cross the 50 percent diffusion threshold in the year 2031 (appendix B: 4.c).

5. **Digital production.** The final category in the digital infrastructure networks is, as discussed above, one that is an analog of prior mass-scale manufacturing seen in the first and second industrial revolutions. However, in the digital era, it is elevated from being an outcome to being a key enabler. As discussed in The Future X Network (Weldon, 2015), two key enablers are the movement of digital processing and services creation from centralized cloud infrastructures to highly distributed edge clouds, due to the need for ultralow latency (~1ms) and ultrahigh bandwidth (10 Gbps); and the concomitant movement of physical good re-creation to be similarly close to the end user to allow on-demand, bespoke manufacturing with minimal tooling or transportation delays. We therefore select the following two digital technologies to predict the diffusion of this infrastructure:
   a. 3D printing. Additive manufacturing or 3D printing enables products to be manufactured or "printed" close to where and when they are needed. 3D printing will have a profound impact not only on manufacturing but also on the supply chain, logistics and retail industry. Indeed, delivery companies are conducting trials of 3D printers on their trucks, recognizing that this could represent a significant part of their value proposition in future (McCormick, 2015). With the cost of 3D printers falling rapidly and with advances in raw materials and printing technology itself, we expect local 3D printing infrastructures to experience a surge in the coming decades, reaching a maximum penetration of around 45 percent of total US manufactured goods around the year 2060 and diffusion to cross the 50 percent threshold around the year 2024 (appendix B: 5.a).
   b. Edge cloud systems. Many digital control applications require latencies on the order of 1ms or less, in order to maintain system performance, user experience or the precision of an operation. Much has been written on these requirements, but the critical observation is that such latencies require the service or application to be instantiated no more than 100km from the user, due to the finite speed of light. To approximate this shift to local cloud infrastructures we use the conversion of a fraction of service provider central offices to data centers. This shift is currently nascent but accelerating driven by the ETSI Multi-access Edge Computing (MEC) specification (Multi-Access Edge Computing, 2017) and open source initiatives such as Open CORD (Central Office Re-architected as a Data center) (CORD, 2017). We anticipate a maximum of CORD penetration of 100 percent in the year 2055 and expect diffusion to cross the 50 percent threshold before year 2030 (appendix B: 5.b).

By analyzing current technology and market trends, trends for cost reductions of component technologies and a variety of forecasts by industry analysts, as well as accounting for intellectual property and regulatory and policy factors (appendix B), we have built diffusion models for the representative sub-technologies described above. Figure 7 shows the projected diffusion curves and figure 8 provides the diffusion curve of the combined index, computed by a simple arithmetic average of the curves in figure 7.

It is clear from these diffusion curves that although some technologies may take longer to reach an inflection point and full adoption, the majority are anticipated to show vigorous growth in the late 2020s. The net effect is that the 51 percent inflection point occurs in 2028, based on a simple average. It is clear that a simple averaging of the diffusion curves is subject to significant error, although this approach worked surprisingly well in the earlier analysis of the Gordon data. However, the analysis of the prior physical era was well established as the diffusion had already past the tipping point, so the form of the sigmoid curves was well-defined. Clearly that

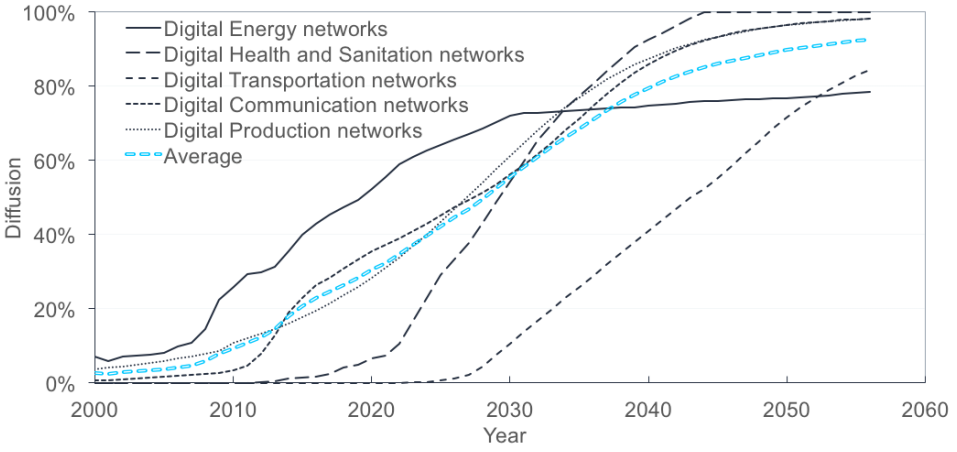

FIGURE 7. Projected diffusion of key enabling digital infrastructure network technologies

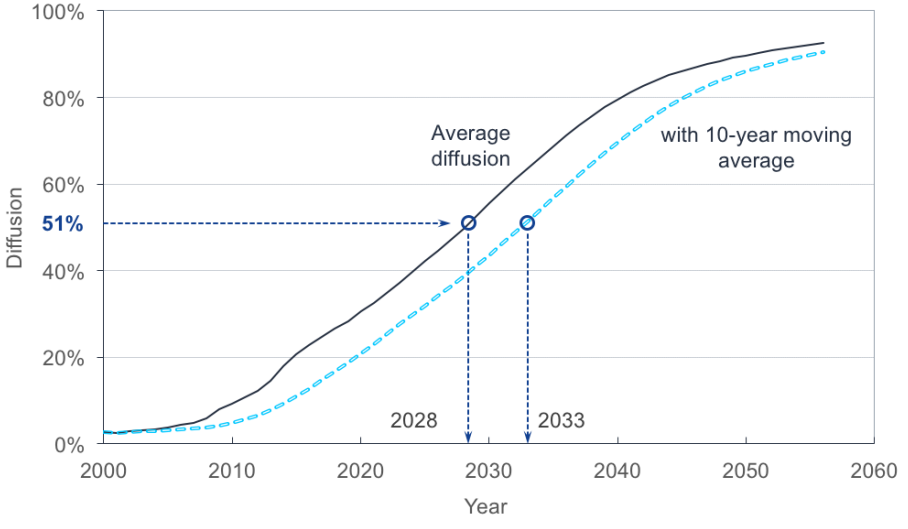

FIGURE 8. Projected average diffusion of key digital infrastructure technologies, raw data average (solid line); 10-year moving average (dashed line).

cannot be the case for future technology adoption projections, especially those based on nascent trends, which therefore requires a significant degree of informed speculation. In order to partially address this uncertainty, we also compute a 10-year moving average, thus the 51 percent tipping point is projected to occur around the year 2033.

Conclusions and concerns

In this work we have undertaken to put the Gordon productivity analysis on a more quantitative footing, rooted in the diffusion of fundamental enabling technologies. This we have achieved to an acceptable extent, based on the coincidence between the productivity jump and the set of key technologies reaching a 51 percent tipping point. We have then endeavored to extend the analysis to answer the question 'Will a similar jump in productivity occur in the future?' by identifying an analogous set of digital technologies and estimating the diffusion of these technologies, based on data and views from multiple sources. Then by applying

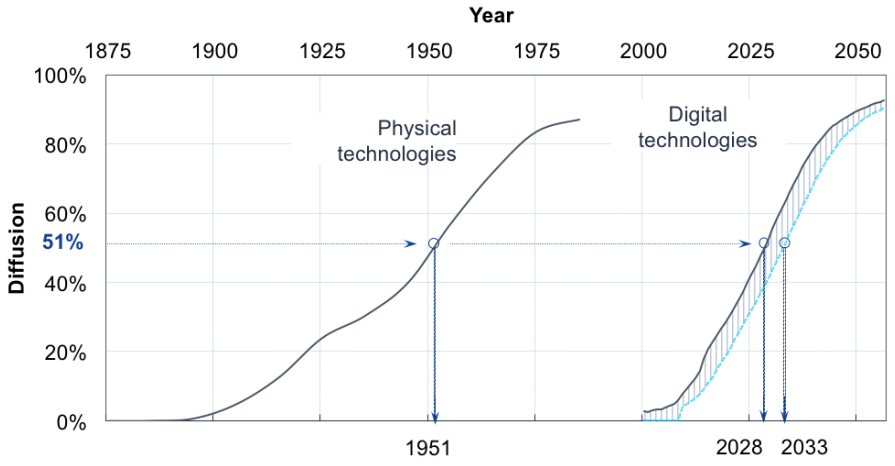

FIGURE 9. Average diffusions of key physical and digital infrastructure technologies due to the prior and future industrial revolutions.

the same 51 percent tipping-point logic, we predict that a similar jump in productivity should occur in the 2028–2033 timeframe (figure 9). Despite the simple appeal of such an analysis, it is important to recognize that in many ways it is no more than a coherent technological prophecy. We assume that, as with all future predictions, we will be proven incorrect in multiple ways, and surprisingly correct in some.

However, we believe the primary importance of this work is that it advances the debate about the origin of the past productivity jump — and the potential for future productivity increases — in a meaningful way, and provides a basis for further analysis and a methodology for evaluation of key technology adoptions and their relative impact on future productivity. We look forward to seeing more quantitative treatises that validate or extend the analysis in the coming years, as trends come to pass (or not) and more defining data is generated. In particular, we invite analyses of markets other than the US, to see if similar arguments and technology diffusions can be applied more generally, which would in itself further validate the applicability of the approach and allow comparison of the relative adoption and productivity growth of different markets in the new global-local digital era.

Acknowledgements

We would like to acknowledge Gina Shih for her valuable contributions to this work and a multitude of conversations with people too numerous to mention that stimulated this work.

References

Arthur, B. (2009). The Nature of Technology. Free Press (Simon & Schuster).

CORD. (2017). Retrieved from Open CORD: http://opencord.org/

Gordon, R. J. (2016). Rise and Fall of American Growth — The U.S. Standard of Living Since the Civil War. Princeton University Press.

Krugman, P. (2016, January 25). Paul Krugman Reviews 'The Rise and Fall of American Growth' by Robert J. Gordon. The New York Times.

Kurzweil, R. (2006). The Singularity is Near. Viking.

Maslow, A. (1984). Motivation and Personality. Addison & Wesley.

McAfee, E. B. (2014). The second machine age: work, progress, and prosperity in a time of brilliant technologies. New York: W.W. Norton & Company.

McCormick, R. (2015, February). "Amazon wants to fit trucks with 3D printers to speed up deliveries." Retrieved from The Verge: https://www.theverge.com/2015/2/27/8119443/amazon-3d-printing-trucks-patent

Metcalfe, B. (2013). "Metcalfe's law after 40 years of Ethernet." IEEE Computer.

Multi-Access Edge Computing. (2017). Retrieved from ETSI: http://www.etsi.org/technologies-clusters/technologies/multi-access-edge-computing

Perez, C. (2009). "Technological revolutions and techno-economic paradigms., in Working Papers in Technology Governance and Economic Dynamics," Working Paper No. 20. Talinn: (Norway and Tallinn University of Technology, Tallinn).

Productivity. (2017). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Productivity

Solow, R. (1987, July 12). "We'd better watch out." New York Times Book Review. The New York Times.

Weldon, M. K. (2015). The Future X Network: A Bell Labs Perspective. CRC Press.

Appendix A

Data sources for physical technologies

1. Electricity and landline telephone: Federal Reserve Bank of Dallas, adapted from Fortune, June 8, 1998, http://www.physics.udel.edu/~watson/scen103/appliances.html

2. US natural gas Marketed Production: Energy Information Administration, https://www.eia.gov/dnav/ng/hist/n9050us2a.htm

3. US population served by public drinking water: American Society of Civil Engineers, Failure to Act - The Economic Impact of Current Investment Trends in Water and Wastewater Treatment Infrastructure, 2011, http://www.asce.org/uploadedFiles/Issues_and_Advocacy/Our_Initiatives/Infrastructure/Content_Pieces/failure-to-act-water-wastewater-report.pdf

4. US registered motor vehicles: http://www.railsandtrails.com/AutoFacts/ http://www.allcountries.org/uscensus/1027_motor_vehicle_registrations.html https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_11.html

Appendix B

Data sources and forecasting methodology for digital technologies

1. Digital energy
   a. Smart meter forecast is based on Bell Labs Consulting analysis and actual deployment data between 2007 and 2015, and projection data to 2020, from IEI Report, Oct 2016.
   URL: http://www.edisonfoundation.net/iei/publications/Documents/Final%20Electric%20Company%20Smart%20Meter%20Deployments-%20Foundation%20for%20A%20Smart%20Energy%20Grid.pdf
   b. Renewable energy as percentage of total electricity forecast is based on Bell Labs Consulting analysis and Table 9 Electricity Generating Capacity of the Annual Energy Outlook 2017 by US. Energy Information and Administration. URL: https://www.eia.gov/outlooks/aeo/

2. Digital health
   a. Total penetration of households with digital health systems is based on Bell Labs Consulting analysis and "Smart Home Market Opportunities Model by Strategy Analytics," Feb 2017.

3. Digital transportation
   a. Autonomous vehicles forecast is based on Bell Labs Consulting analysis of various data sources including adjusted adoption rate of motor vehicles in the twentieth century and Advanced Driver Assistance Systems (ADAS), Dec 2016, ABI Research. Our autonomous vehicles forecast includes SAE levels 3 to 6.

4. Digital communication
   a. The smartphones with a high-speed connection forecast is based on Bell Labs Consulting analysis of GSMA Intelligence database. We exclude the population of 10 years and younger from the total addressable market.
   b. We define AI systems to be systems that have significant cognitive and decision making capabilities. Examples of today's systems include Watson, Aribo, AlphaGo. AI systems household penetration forecasts are based on projections of when mass adoption is likely to start, by reference to conventional computing where adoption accelerated when the unit price of computers went below the $1,000 threshold. With concurrent advances in machine learning algorithms and reduction in cost of computing, Bell Labs Consulting projects that unit cost of AI systems will decline at twice the rate of the unit cost of computing.

      Cost of computing projections and AI derived from Sandberg, A. and Bostrom, N. (2008), "Whole Brain Emulation: A Roadmap, Technical Report #2008-3," Future of Humanity Institute, Oxford University.
      URL: www.fhi.ox.ac.uk/reports/2008-3.pdf
      Vandegrift, D (2016): Costs of AI: An Update
      URL: http://www.davidvandegrift.com/blog?id=41
      Aslett, M (2016): Arimo combines TensorFlow and Spark for predictive behavioral analytics, 451 Research
      URL: https://451research.com/report-short?entityId=90394

   c. E-Commerce (total retail, excluding automobiles, fuel and restaurant) forecast is based on Bell Labs Consulting analysis of data from "Estimated Annual U.S. Retail Trade Sales - Total and E-commerce1: 1998-2015"
      URL: http://www.census.gov/retail

5. Digital production
    a. 3D printing is based on Bell Labs Consulting analysis of data sources including the following,
        i. “Disruptive manufacturing - The effects of 3D printing,” Deloitte, 2013
        ii. “3D printing and the new shape of industrial manufacturing,” PwC, 2014
        iii. “3D Printing: Second Edition” by Christopher Barnatt
        iv. “If 3D printing has changed the industries of tomorrow, how can your organization get ready today?” EY, 2016 http://www.ey.com/Publication/vwLUAssets/Accelerate_your_3D_technology_journey_in_oil_and_gas/$FILE/ey-3dprinting-journey-oil-and-gas.pdf

    b. Central Office Re-architected As a Datacenter (CORD) forecast is based on Bell Labs Consulting analysis of public announcements.

Nokia Oyj
Karaportti 3
FI-02610 Espoo
Finland
Tel. +358 (0) 10 44 88 000

Product code: SR1706012095EN (June)