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Digital innovation networks at the nexus of new productivity growth

White paper

This paper takes a fresh look at the debate over the relationship between digital technology and productivity. The argument of economic historian Robert J. Gordon is that digital technology will not lead to similar increases in productivity as we saw in the last century, based on his analysis of the five “Great Inventions” in the fields of electricity, urban sanitation, chemicals, the internal combustion engine and communications. In this paper, we argue that the key ingredient in these great inventions is the ability to **diffuse their effects widely** based on the creation of “great networks” in transportation, health, energy and communications. It is this “network effect” that underlies the burst in productivity observed. We then use this essential observation to propose that today’s digital technologies will augment and replace the current static network infrastructure with automated, intelligent Great Digital Innovation Networks (GDINs), which will combine to drive the fourth industrial revolution. By analyzing the effects of the previous great networks, we also develop a model that can be used to predict when this industrial revolution will result in a productivity burst in the US, China and India. Finally, we note a parallel between our framework and the innovation theory explanation of the well-publicized Kondratieff wave of economic cycles, which also predicts an innovation peak roughly in the 2030–2040 timeframe.

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Introduction

Is the link between technology and productivity dead? This is a critical question on the minds of economists, policy-makers and technocrats around the world. The decades-old debate on the productivity paradox — the global slowdown in productivity growth despite a rapid acceleration in technology progress — still rages. Bell Labs has recently examined this paradox and our findings suggest that we need five new digital technologies, deployed at scale and networked together, to spark a new productivity boom (Saniee, 2017). The beginning of this new era is now demonstrably upon us with the impending launch of new massively distributed, cloud-native, dynamically adaptive end-to-end 5G networks. In this paper, we summarize the thesis for the five Great Digital Innovation Networks (GDINs) and the outlook for the future in terms of global productivity.

The five “Great Inventions”

Robert J. Gordon makes a provocative claim in The Rise and Fall of American Growth (Gordon, 2016); he argues that the golden days of technology-driven transformation in the economy and society are behind us. Electrical, sanitary, transportation and communications infrastructure had a dramatic impact during the first and second industrial revolutions. But computers, the internet, and the mobile technologies that define the so-called third industrial revolution have had nowhere near the same impact. And he is not alone in these observations; many techno-pessimists are even more critical, observing that today’s technologies are used to drive e-commerce–based consumerism and the delivery of trivial (if amusing) short-form video content. It is easy to argue that these mobile internet applications effectively distract us rather than increase our productivity (Frankel, 2018). In essence, the underlying technologies have been co-opted to appeal to our baser consumerist and entertainment inclinations and instincts. Although they may increase our sense of well-being, they do not manifestly increase human productivity.

Robert Gordon’s study is based on rigorous analysis of historical macroeconomic data. In his book, he highlights five specific technologies that made a manifest difference: electricity, urban sanitation, chemicals, the internal combustion engine and modern communications. These, he posits, are the “Great Inventions” that powered economic growth from 1870 to 1970, and they formed a unique combination. In other words, according to Gordon, the big productivity boom and rapid economic growth in the US in the first half of the last century was a one-time event, not to be repeated anytime soon.

Gordon’s analysis and arguments intrigued us: on one hand, our lives are increasingly “enabled” by modern technologies like smartphones and the (mobile) internet; on the other hand, we can’t dismiss the data on sluggish productivity growth that is tending toward zero in recent years. Nor can we ignore the prevailing sentiment that people are working longer hours, and the demands on their work and home lives are increasing, with less time available for other activities and pursuits.

The network effect multiplied

There is an emerging counter-opinion that the fourth industrial revolution will change all this; that evolutions or revolutions in technology will, in combination, lead to a renewed growth in productivity driven by the digitization and intelligent control of all “physical” things, such as machines, systems, platforms and infrastructure.

So, we wondered if an alternative framework could be found that explains the previous productivity boom and the current productivity lull, but also allows for a future boom. Reflecting on Gordon's discussions, we had three insights that suggested such an alternative or modified hypothesis.

The **first insight** concerns the "diffusion" of technology innovations — i.e., how fast they spread throughout society. In his book, Gordon devotes significant attention to the diffusion of various innovations, not only technical innovations, but also business model innovations like consumer credit that sped up the diffusion of labor-saving home appliances, such as washers and refrigerators. Why does diffusion matter? In short, because, innovations need to reach a critical level of global adoption to impact a macroeconomic metric like productivity.

The **second insight** concerns network infrastructure. Gordon focused on physical plumbing infrastructure for the supply of drinking water and sewage, power infrastructure for electricity and gas, communications infrastructure for landline telephony, and transportation infrastructure for cars and trains such as roads and railways. The commonality across all these domains is that they are "networked infrastructures." They are not isolated point infrastructures. The networking enables the "flow" of relevant elements across larger distances, driving greater economic activity by increasing the rate of diffusion. We, therefore, renamed four of the Great Inventions, as "Great Networks": 1) Health Networks (water and sewage); 2) Transportation Networks (roads, rails, cars); 3) Energy Networks (gas and electricity); and 4) Communications Networks (landline telephony). Note that the last of the five Great Inventions identified by Gordon was chemicals — fertilizers and pharmaceuticals. In our construction, these are both inventions that diffuse through, are enabled by, or augment the transportation network and the health network. In other words, although they are technological enablers (of which there are many), they are not primary drivers like the networked infrastructures.

The **third insight** concerns the combinatorial effect of many technologies. It is often the case that multiple innovations need to cross adoption thresholds in the same time period to drive a compounding effect and trigger unprecedented growth. For example, we know that urbanization improved efficiency in per capita consumption of resources. But its rapid growth was not possible without all four of the above Great Networks reaching a critical mass.

The four "Great Networks"

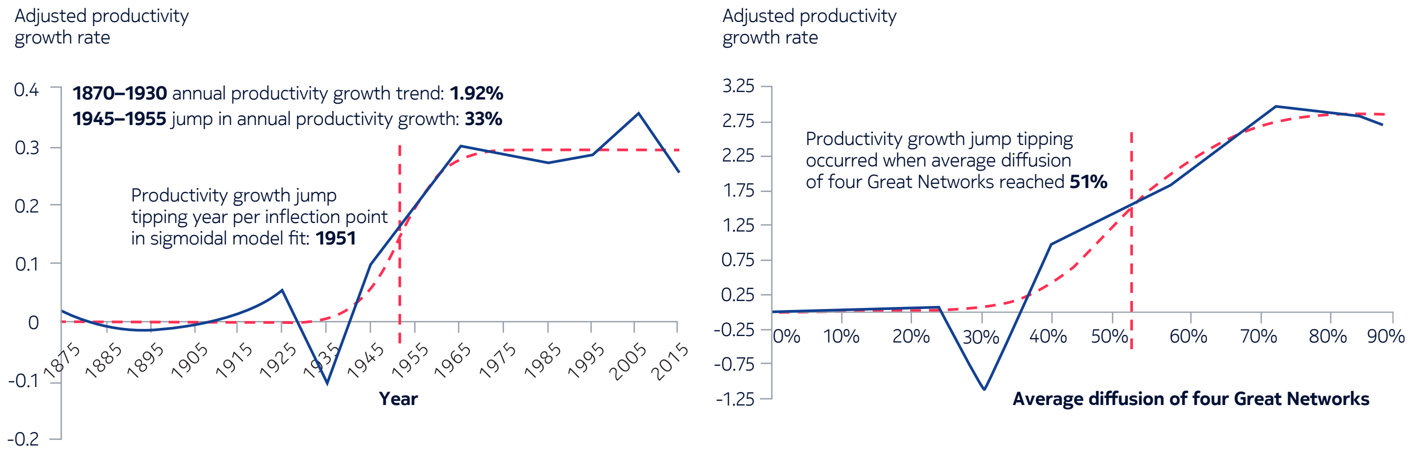
Working from this premise of "combinatorial networked diffusion," we analyzed the diffusion of the four identified Great Networks in the US: drinking water, automobiles, electricity and gas, and landline telephony. We found a very interesting connection; the average adoption of these four networks all reached inflection points during the early 1950s. This was the exact period when the last major productivity growth spurt in the US occurred (Saniee, 2017), as summarized in table 1 and figure 1.

Thus, it seems that combinatorial networked diffusion, or CND for short, can explain the past productivity boom in the US. One could question if the severe economic conditions in the US during the Great Depression, which led to the New Deal and the infrastructure investments made during World War II, might be responsible for the US productivity jump rather than the diffusion of key infrastructure technologies. However, when we extend the analysis using the relevant data for China and India, remarkably, the same connection is observed. The inflection years and average penetrations vary, but the linkage to the respective economic productivity boom periods is clear in all cases (table 1 and figures 2 and 3). Both countries show similar productivity jumps in peacetime and non-emergency economic circumstances.

Table 1. Summary of the last industrial era productivity growth inflections for the US, China and India

	US (Fig 1)	China (Fig 2)	India (Fig 3)
Productivity growth inflection year	1951	2004	2006
Average of diffusion levels of four Great Networks at inflection year	51%	69%	58%

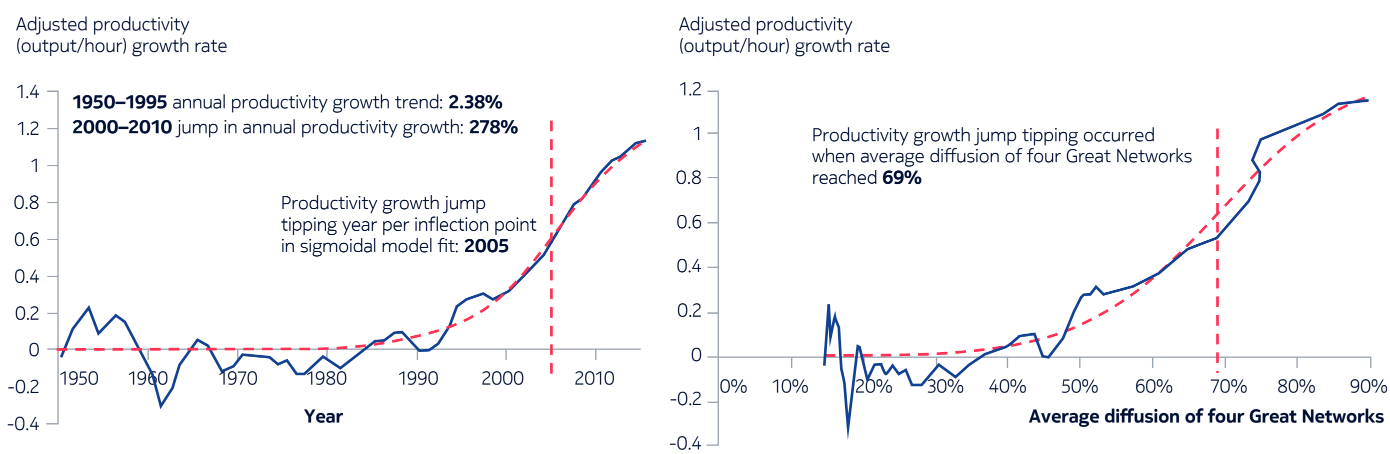
Figure 1a). Productivity growth in the US (in logscale) adjusted by its 1870–1930 trend; 1b) Productivity growth curve in the US mapped to the average diffusion of the four Great Networks



a. US adjusted productivity growth by year

b. US adjusted productivity growth vs. average diffusion of four Great Networks

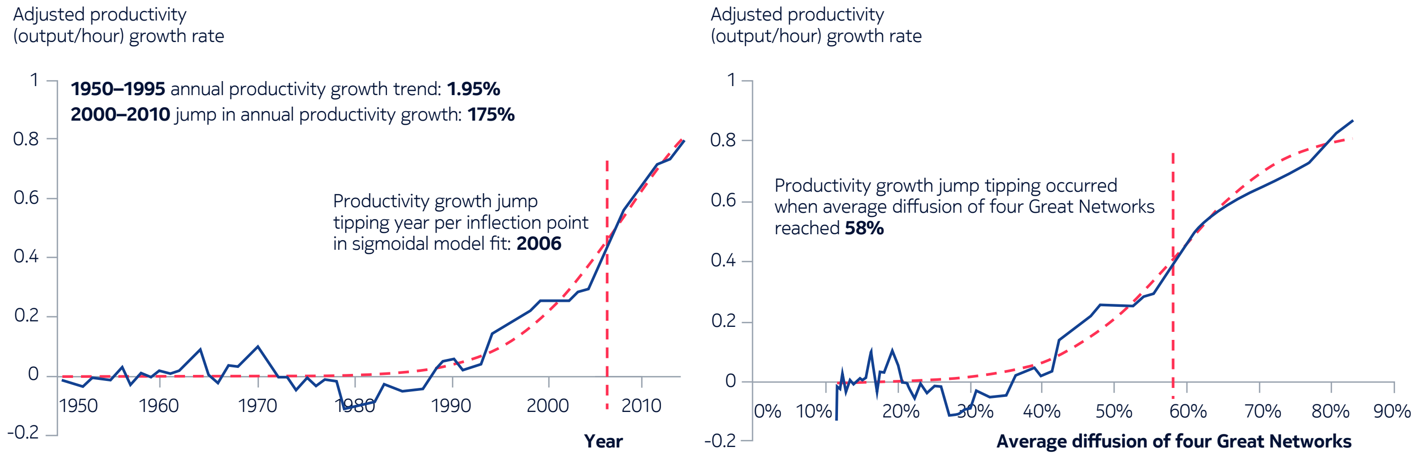
Figure 2a). Productivity growth in China (in logscale) adjusted by its 1950–2010 trend; 2b) Productivity growth curve in China mapped to the average diffusion of the four Great Networks



a. China adjusted productivity growth by year

b. China adjusted productivity growth vs. average diffusion of four Great Networks

Figure 3a). Productivity growth in India (in logscale) adjusted by its 1950–2010 trend; 3b) Productivity growth curve in India mapped to the average diffusion of the four Great Networks



a. India adjusted productivity growth by year

b. India adjusted productivity growth vs. average diffusion of four Great Networks

The question then becomes, can this logic also explain the current productivity paradox and predict when a future boom might occur? It is reasonable to assume that there will be a new set of networked infrastructures that will underpin the new digital society imagined as the fourth industrial revolution, by analogy to the four Great Networks, that defined the physical society of the past (and present).

The five “Great Digital Innovation Networks”

For the modern economy and the next industrial era, we suggest that digital versions of the four Great Networks are appropriate. For example, the new digital version of the communications network will be characterized by the ubiquity of the plethora of connected devices, tools and systems, etc. The new digital version of the transportation network will include electric and autonomous vehicles, smart transportation infrastructure and traffic management. The new digital version of the energy network will have smart meters, smart grids and highly distributed power generation using renewable energy. Finally, the new digital health network will encompass continuous personal health monitoring using wearables, effective telediagnosis and telemedicine.

In addition, there will be a fifth networked infrastructure that underlies the advances in manufacturing that will arise from the networking of robotic and intelligent control systems. It will include additive manufacturing (3D printing) of locally produced bespoke parts on demand, and the dynamic reconfiguration and reprogramming of AI-enhanced robotics.

Intuitively, we can see how the new digital networks will boost productivity growth in the new industrial era. These digital networks will transform a massive scale of “physical-realm” activities to the “digital realm” where networked computers and control-systems can perform tasks orders of magnitude faster than conventional physical systems. Advances in algorithms and AI-ML allow these systems to be adaptive and save both time and resources by taking proactive measures to prevent undesirable events such as accidents, traffic congestion, illnesses, energy outages, machine failures, etc. In a sense, we will be able to take advantage of activities executed in “digital time” to boost productivity.

Modeling the productivity inflection

We conjecture that the coming era will be defined by five Great Digital Innovation Networks (GDINs) — Health, Transportation, Energy, Communications and Manufacturing. Then we model the future of these digital networks by applying diffusion "S" curves to each, based on the initial trends we identify in the relevant data, and assuming the same inflection points apply as for the prior era (Table 1).

As shown in Table 2 and Figures 4, 5 and 6, this new construction predicts that there will be a new productivity era, with a first tipping point to be in the US (around 2028–2033) followed by similar tipping points in China and India. However, it is important to recognize that this analysis does not take account of exogenous factors such as overt government action that dictates or strongly incentivizes the acceleration of this transformation. Based on recent economic trends, these factors could shift the tipping points in China and India closer to that in the US.

Table 2. Projected future productivity growth jumps in US, China and India

	US (Fig 4)	China (Fig 5)	India (Fig 6)
Next productivity growth inflection period based on projected diffusion of the five Great Digital Networks[1]	2028–2033	2037–2042	2048–2053

Figure 4. Projected diffusion of the five Great Digital Networks in the US

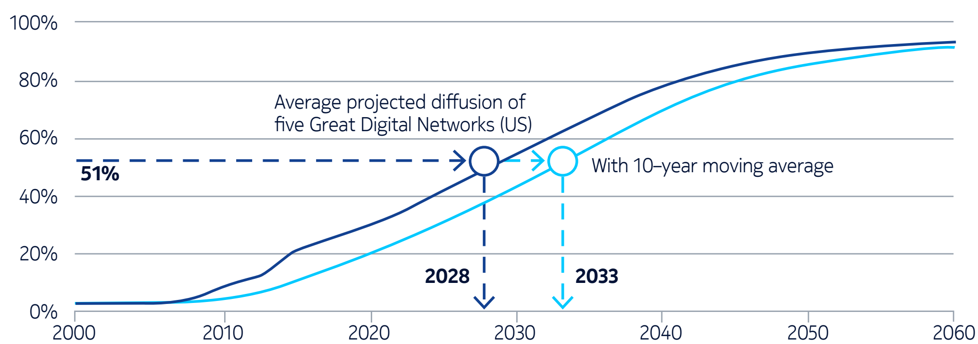
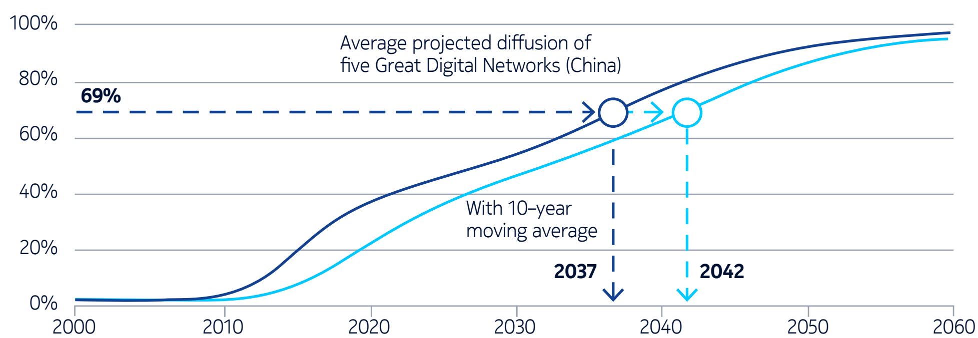
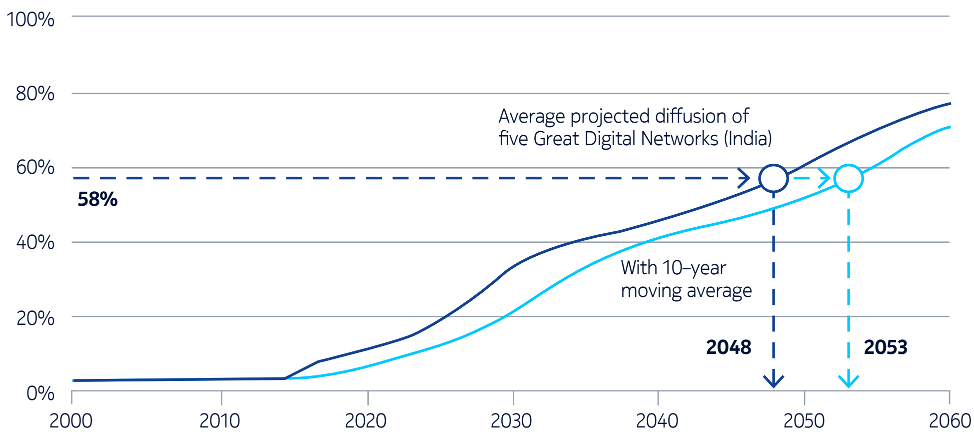


Figure 5. Projected diffusion of the five Great Digital Networks in China



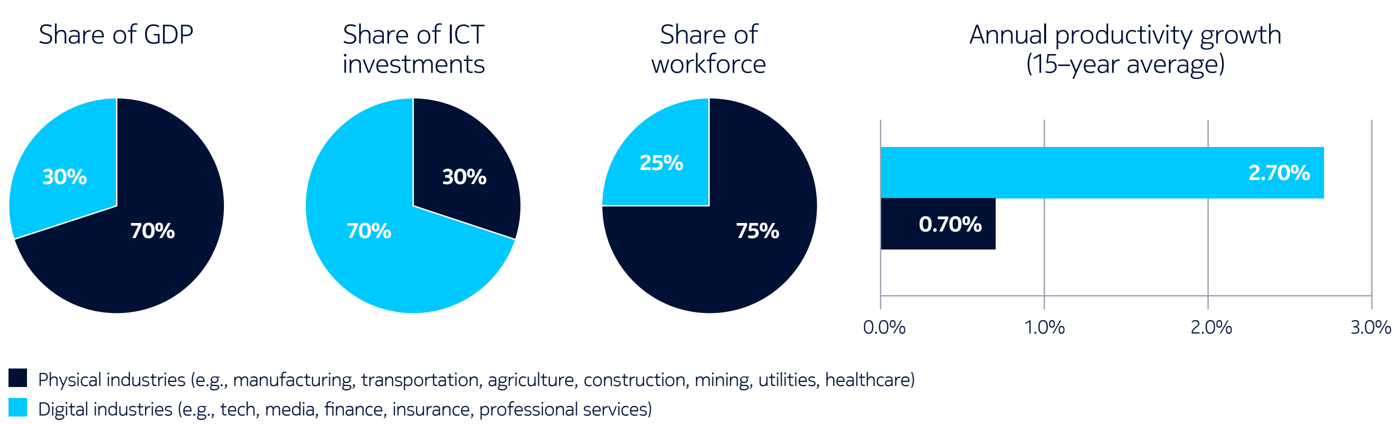
1 Our projections are based on analysis of current trends, including diffusion modeling of established trends where data is available, and assumptions based on government policies and targets for adoption of relevant nascent technologies. Technologies considered are: smartphones, e-commerce and AI/ML (Digital Networks); renewable energy and smart meters (Digital Energy); electric and autonomous vehicles (Digital Transportation); remote patient monitoring (Digital Health) and industrial 3D printing (Digital Manufacturing). Projections are subject to revision as more trends get established and more data becomes available

Figure 6. Projected diffusion of the five Great Digital Networks in India



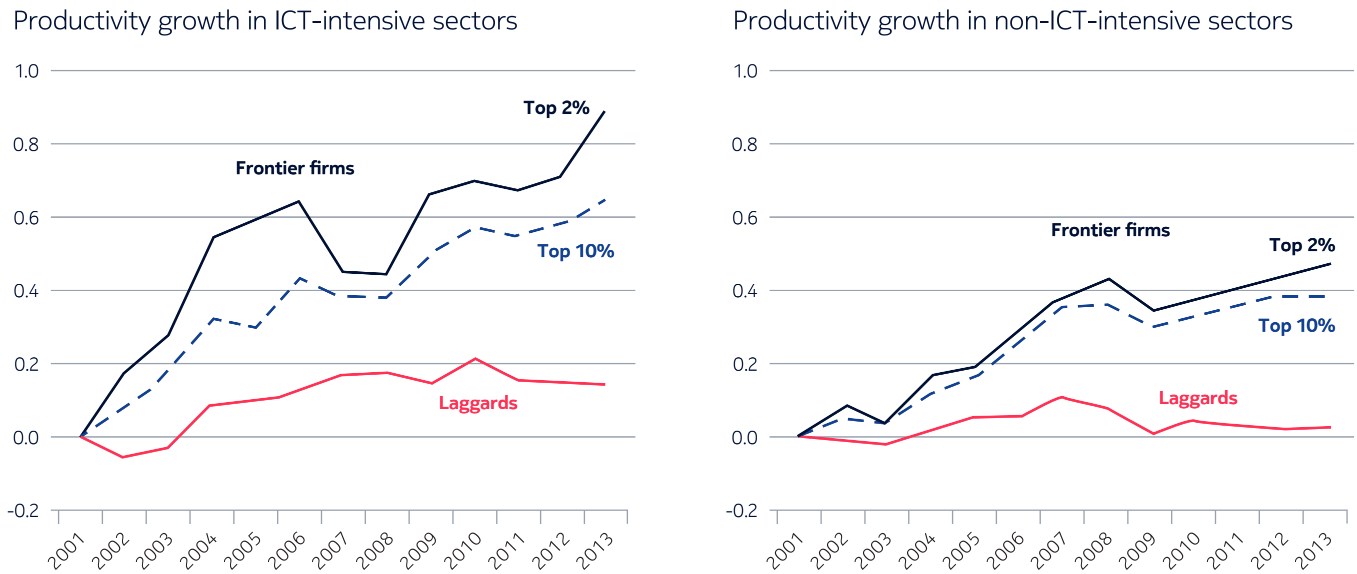
This forecasted future is encouraging, but it is worth exploring why the current era — the mobile internet age that essentially represents the first digital era — has not already resulted in such a productivity boom. The simple answer is that, even in the most developed countries, we have two very different economies today — an efficient but relatively smaller digital economy, and an inefficient but much larger physical economy. As illustrated in figure 7, the US digital economy only represents 30% of the total economy, employing only 25% of the workforce, but it represents 70% of the ICT investment and exhibits high productivity growth of ~2.7% per year. However, the clear majority of the US economy (70%) is still "physical," employs 75% of the workforce but shows only 0.7% productivity growth, consistent with the fact that these industries represent only 30% of the total ICT investment (Mandel, 2017).

Figure 7. Tale of two economies, the physical vs. digital industries



Moreover, the benefits of adopting productivity-enhancing technologies are cumulative. As shown in figure 8, the gap between the companies with leading productivity growth compared to the rest increases with time, and those physical industries that have been digitized and automated have experienced commensurately higher increases in productivity (Andrews, 2016).

Figure 8. Difference between most productive firms versus the rest, for ICT-intensive and non-ICT-intensive sectors

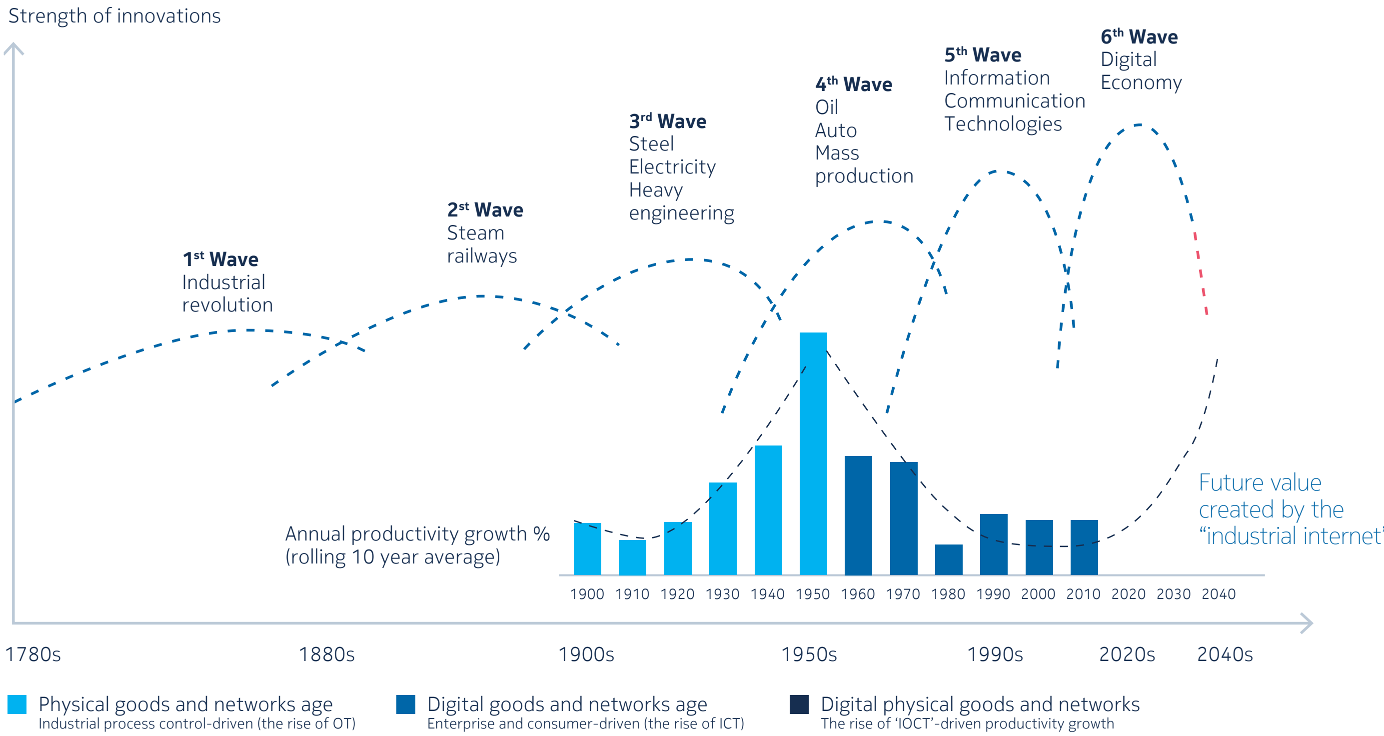


Therefore, the apparent paradox is resolved; the mobile internet technologies have simply not transformed most physical processes and systems. Consequently, it is imperative that we now focus on improving the productivity of the physical sector by digitizing and automating sectors such as manufacturing, construction, mining, utilities, healthcare, transportation, logistics, and wholesale and retail trade.

It is worth noting that there is an interesting connection between the productivity jumps we predict and the completion of long-wave macro-business cycles known as Kondratieff waves. Although there is much discussion around the cause of these long-timescale economic waves, the innovation theory explanation is that so-called “K-waves” result from the “bunching of basic innovations that launch technological revolutions that in turn create leading industrial or commercial sectors” (“Kondratieff Wave”). This perspective, known as the Schumpeter-Freeman-Perez paradigm (Perez, 2009), identifies five such completed cycles in modern history: (1) the Industrial Revolution of the 1770s; [2](2) the Age of Steam and Railways of the 1830s; (3) the Age of Steel, Electricity and Heavy Engineering of the 1870s; (4) the Age of Oil, the Automobile and Mass Production of the 1900s; and (5) the Age of Information and Telecommunications of the 1970s – as depicted schematically in figure 9, overlaid on Robert Gordon’s data. We observe that the completion of the projected sixth wave, that of the Digital Economy, matches our projected productivity jump in the 2030–2040 timeframe. A more detailed study is required to explore this connection, but it is logically consistent with the arguments we make in this paper.

2 The five dates shown here are the putative beginning dates of each cycle.

Figure 9. Schematic of the Kondratieff-Schumpeter-Freeman-Perez innovation long waves[3] and the next projected productivity growth jump



The critical importance of the Digital Communications Innovation Network

We posit that the first catalytic step for this industrial revolution must be to create the necessary digital network fabric, as was the case for the great physical infrastructure networks of the past. In the digital age, the Digital Communications Innovation Network must be the forebearer, in order to lay the foundation for the remaining four GDINs and allow the optimized (low latency, highly reliable) transport of the data and control messages that, in turn, enable the requisite sensing, analysis, optimization and automated outcomes and actions that drive new levels of productivity.

To understand the critical importance of the new Digital Communications Innovation Network and the limitations of the current mobile internet, it is instructive to consider the performance requirements of the physical systems we need to digitize. The majority of these systems depend on "operations technology" (OT) systems that control the constituent processes. These OT systems are typically proprietary and relatively antiquated as they have "worked well" for decades, and meet very high-performance requirements, as shown in table 3.

3 Hargroves and Smith (2005).

Table 3. Performance requirements for automation and optimization of industrial systems and the enabling Digital Communications Network

Use case		Availability	Cycle time (milliseconds)	Payload size (bytes)	# of devices	Service area
Motion control	Printing machine	>6x9's	<2	20	>100	100m
	Machine tool	>6x9's	<0.5	50	~20	3m
	Packaging machine	>6x9's	<1	40	~50	3m
Mobile robots	Cooperative motion control	>6x9's	1	40-250	100	<1km^2
	Video-operated remote control	>6x9's	10-100	15-150	100	<1km^2
Mobile control panels with safety functions	Assembly robots or milling machines	>6x9's	4-8	40-250	4	10m
	Mobile cranes	>6x9's	12	40-250	2	50m
Process monitoring		>4x9's	>50	Variable	10,000 devices per km^2	

Source: 5G-ACIA, 2019.

In particular, these OT closed-loop control processes require very low latency and very high reliability, as well as the ability to support a high density of devices, with mission-critical security. Today, these OT systems are wired together with physical (Ethernet) cabling, but with a significant amount of logic resident locally on each device or machine, as there was, until now, insufficient computing power and coordination between systems to drive larger scale coordination or adaption. However, it is this inherently isolated and limited control paradigm that is the origin of the inefficiency; systems cannot be rearranged, reconfigured, repurposed or remotely operated fast enough to meet rapidly changing demands in today's digital world. They are, for all practical purposes, fixed in time and space.

However, with the emergence of 5G wireless networking technologies and low-cost, high-performance computing infrastructure that can be distributed close to these systems, the necessary performance requirements can now be met **with the flexibility needed to drive the target productivity improvements**. Importantly, technologies such as artificial or augmented intelligence will be critical to achieving this performance, as many of the optimizations are not well described by conventional mathematical or engineering approaches, nor can they be computed by a human operator.

Summary

In summary, imagine a world where every human has optimized physiological, physical and even psychological performance via a new Digital Health Innovation Network, where every vehicle and container follows an optimized route via a new Digital Transportation Innovation Network, where every power source is optimally utilized with maximum efficiency via a new Digital Energy Innovation Network, and where every good is optimally produced via a new Digital Manufacturing Innovation Network. These four Great Digital Networks are all underpinned by the all-important new Digital Communications Innovation Network.

This is the basis of the fourth industrial revolution, and it is, once again, a networked and networking revolution that will drive unprecedented levels of and new value creation, and a new Kondratieff wave of economic prosperity in the 2030–2040 timeframe.

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Abbreviations

5G	5th generation, the latest generation of cellular mobile communications
AI	artificial or augmented intelligence
AR	artificial or augmented reality
CND	combinatorial networked diffusion
GDP	gross domestic product
ICT	information and communications technology
IoT	internet of things
ML	machine learning
MR	mixed reality
OT	operations technology
VR	virtual reality

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