Productivity Growth and Capital Deepening in the Fourth Industrial Revolution

Author:
Martin Fleming
The Productivity Institute

Date:
September 2021

The Productivity Institute
Working Paper No. 010

Key words
industrial revolution, productivity, industry 4.0, capital deepening, technological innovation, creative destruction

Authors' contacts:
martin@fleming41com.onmicrosoft.com

Acknowledgements
The comments of Diane Coyle, Bart van Ark, and Tony Venables are appreciated. All comments are welcome. Remaining errors are the responsibility of the author.

Suggested citation

M. Fleming (2021) *Productivity Growth and Capital Deepening in the Fourth Industrial Revolution*. Working Paper No. 010, The Productivity Institute.

The Productivity Institute is an organisation that works across academia, business and policy to better understand, measure and enable productivity across the UK. It is funded by the Economic and Social Research Council (grant number ES/V002740/1).

More information can be found on The Productivity Institute's website. Contact us at theproductivityinstitute@manchester.ac.uk

Publisher

The Productivity Institute, headquartered at Alliance Manchester Business School, The University of Manchester, Booth Street West, Manchester, M15 6PB.

Abstract

The 4th Industrial Revolution has become a means by which political and business leaders frame the global economic transformation anticipated in the decades ahead. However, there has been limited formalization of the concept among economists, resulting in little agreement on causality, public policy efficacy, and the implications for workers and business sector strategy.

Economic historians have identified four such revolutions over 200 years, including the current era, each responding to similar underlying economics characterized by the age of the capital stock, the rate of knowledge diffusion and thus absorptive capacity, and shifting capital and labor income shares. The intersection of tangible and intangible capital investment, technology innovation and "creative destruction" is at the heart of each industrial revolution.

The industrial revolution framework also provides a point in time reference for placing current events in the context of sustained, multi-decade periods of faster or slower GDP and productivity growth. Political, social and economic transformation has accompanied each revolution. Improved economic performance in the decades ahead will depend on the extent to which households, businesses and governments are willing to transform behavior, engage in "creative destruction", and respond to regime switching pressures to bring about a future of more rapid growth and more equal income distribution.

While disappointing outcomes often follow economic shocks, an open issue is whether the 2020-2021 global pandemic will be sufficiently disruptive to deliver fundamental transformation, resulting in improved economic performance and more stable political and social arrangements.

1. Introduction

Small year-to-year differences in economic growth can have large cumulative effects over the long-term. Small improvements in capital deepening and productivity growth over decades and even centuries can potentially result in as much or more impact on economic growth as substantial living standard increases in the near-term.

While economic historians have long focused on industrial revolutions, the economics literature has also provided a detailed development of growth theory.[1] Political and business leaders have also realized the opportunity for long-term growth and have recently begun framing the challenge in terms of the 4th Industrial Revolution. President Biden recently remarked:

> This is a little bit not unlike what happened in 1932. There was a fundamental change, not only taking place here in the United States, but around the world. We're in the middle of the fourth industrial revolution.[2]

Similarly, former Bank of England governor Mark Carney urged a reinvention of the central bank to make it fit for the 4th Industrial Revolution. Carney said: “The Fourth Industrial Revolution is just beginning. And a new economy is emerging.” However, the notion of a 4th Industrial Revolution has received most attention from Klaus Schwab, the founder of the World Economic Forum (WEF). Schwab has written at length of the “profound and systemic change” expected. With a primary focus on leadership and technology, Schwab has encouraged the focus of the many exclusive and well-attended WEF annual sessions on the implications and impact arising from the “speed and breath of this new revolution” (Schwab 2016).

These leaders and others have felt compelled to react to two decades of disappointing growth, limited capital deepening, low inflation, inexpensive credit, and a mysterious slowing in productivity improvement. Productivity growth has decelerated sharply from the rapid pace of the post-war decades of the 1950s, 1960s and 1970s. After a brief revival in the 1990s, productivity growth across the developed world has slowed once again in the decades of the early 21st century. With high investment levels and rapid trade expansion, emerging market economies likewise benefited from the 1990s rapid productivity improvement, only to also fall victim to the slowdown after the 2008 – 2009 global financial crisis. Until 2011, various emerging market economies, especially China and India, pulled the global economy forward, though more as a result of investment-driven labor productivity growth than as a result of total factor productivity (TFP) growth. The past decade’s broad-based and stubbornly persistent slowdown has been seen in both labor productivity as well as TFP (Baldwin 2016 and Van Ark and Venables 2020).

---

[1] Classical economists, such as Smith (1776), Ricardo (1817), Malthus (1798), and in the mid-20th century Schumpeter (1950), and Swan (1956) provided basic ingredients. The work of Solow (1956), Lucas (1988), and Romer (1990) presented the foundation for work of recent decades.

[2] CNN Live Event/Special. Interview with President-Elect Joe Biden and Vice President-Elect Kamala Harris. Aired 9:00 – 10:00 PM ET, 3 December 2020. link

Adding to leadership frustration is the emergence of a new general-purpose technology. The global cloud computing infrastructure, built by a growing array of providers and the increasing application of artificial intelligence (AI) technology, has produced the "new digital economy" on a platform with massive computing power for a broad set of business, government, and personal digital services. The new technology is already providing a rapidly growing collection of services across transportation, healthcare, information and communication (IC), food, and materials, transforming services industries just as automation has transformed manufacturing industries (The Economist 2020a). The recent extremely rapid development of a series of COVID-19 vaccines – reducing development time from years to months – is, in part, attributable to newly available AI tools and deep learning capabilities (Keshavarzi et. al. 2020).

In an era when data science, software development, and related human capital take on a larger role, intangible capital is embodied in AI and IC technology (Corrado, forthcoming). If these investments achieve scale, the technology's promise may be realized. Nevertheless, with success measured over decades and the future uncertain, widespread concern for growth prospects have arisen.

The purpose of this paper is to explore the nature and shape of industrial revolutions and define a useful framework for assessing long-term growth for business strategy and public policy.

Why do industrial revolutions matter? Beyond the potential creation of income and wealth, industrial revolutions provide a frame of reference for understanding sustained, multi-decade periods of faster or slower GDP and productivity growth.[3]

For example, some important questions to be answered:

1. Why were the 30 years between 1945 and 1975 a period of rapid growth in real wages, productivity, tangible and intangible capital investment, income and wealth across the industrialized economies?
2. Conversely, why have the years since 1975 been 45 years of stagnating real wages, slow investment in tangible and intangible capital with limited GDP and productivity growth and labor's income share declining?
3. Will the four-and-a-half decades of sub-par performance give way to a period of renewed robust growth and what will be the nature and extent of the transformation required to realize such gains?

[3] Industrial revolutions provide a broad unifying frame to understand the importance of major technological innovations, such as the steam engine, the microprocessor, and the invention of a new method of invention. Industrial revolutions have resulted in new general-purpose technologies, have embedded the new technology in tangible and intangible capital, and have driven the innovation of new business processes and business models.

Positioning economic activity at any point in time appropriately within its industrial revolution could provide business leaders with strategic guidance, political leaders with policy direction, and workers with career and job role direction.

The outline of the paper is as follows. Section 2.0 defines the emergence of industrial revolutions at the intersection of tangible and intangible capital investment, new technology, and the “creative destruction" driving business model and business process transformation and delivering productivity growth.

Section 3.0 presents an empirical overview, providing the context for the economics of industrial revolutions. Recent advances in natural language processing have allowed Kelly, Papanikolaou, Seru and Taddy (2021) to provide detailed measurement of technology deployment. Surges in technology deployment and follow-on major financial crises are introduced as an element of each era’s transformation. Together, the alignment allows for detailed dating of each industrial era.

Section 4.0 examines the embedded nature of technology in tangible and intangible capital. Recent eras, where data are readily available, are characterized by (1) the nature of capital investment and the aging of the capital stock, (2) the extent of knowledge diffusion and absorptive capacity and (3) shifting labor and capital income share.

Section 5.0 examines the business and economic transformation necessary if growth is to recover in the decades ahead.

Section 6.0 concludes with possible outcomes. Major economic shocks, such as the 2020-2021 global pandemic, can result in hysteresis effects and disappointing outcomes. If a new era fails to emerge, such disappointing outcomes could include a prolonged period of stagflation as the recent experience with more rapid inflation persists with slow growth. Conversely, if economic, social and political disruption is severe effort, “creative destruction”, accompanied by social, political and economic transformation, can ensue resulting in robust growth, increased tangible and intangible capital investment, and improved productivity.

2.0 Industrial Revolutions, Technology and "Creative Destruction"

Economists have long studied industrial revolutions (Kuznets 1955, Kaldor 1961, Kendrick 1961, Denison 1985, Gordon 2016, Crafts 2019). Some focus has been placed on the take-off of industrial activity in the mid-18th century, while other focus has been on periodic technology revolutions and their economic impact (Mokyr 2011). Like much of the developed world, long-run productivity growth in the UK has followed an unstable path in which growth has been slow to accelerate as a result of industrial revolutions, with peaks in the third quarters of the 19th and 20th centuries (See Crafts 2019 and Broadberry, Campbell, Klein, Overton, and van Leeuwen 2015). Four such revolutions have been identified in the literature.

Economic historians have identified four industrial revolutions. See Table 1A. However, four industrial revolutions make for very few data points. Nonetheless, with nearly 100 years of reasonably complete US data covering the better part of two industrial revolutions, some insight can be gleaned. With the benefit of scholarship among economic historians, nearly two centuries and all four industrial revolutions can be examined. There is no expectation that history repeats or that cyclical regularities occur. Rather, the dynamics of growth, innovation, and change, resulting from fundamental economics, which are consistent over extended periods, are of interest.

Table 1A

Era	Industrial Revolution	Years	Technology Innovation
1st	Age of Steam and Railways	1829-1873	"Rocket" Steam Engine (1829)
2nd	Age of Steel, Electricity and Heavy Engineering	1875-1918	Carnegie Bessemer Steel Plan (1875)
3rd	Age of Oil, Automobiles and Mass Production	1908-1974	Model-T Mass Production (1908)
4th	Age of Information and Telecommunications	1971-and Beyond	Intel Microprocessor Announced (1971)

Understanding the nature and progress of industrial revolution begins with an understanding of the economic, political and social forces driving behavior. While a complete grasp of the observed phenomena requires a cross-discipline view, the growth and decline of the tangible and intangible capital stock, and the technology embedded within it, lies at the heart of the behavior of interest. Each revolution proceeds through two periods. The first is the installation period when the next generation of technology is immature and economic activity relies on the capital stock and business practices of the previous era. Second is the deployment period when tangible and intangible capital are renewed, the technology is general-purpose, and economic, social and political institutions are fundamentally transformed. Three phenomena characterize each period: the age of the capital stock, the labor income share, and the rate of knowledge diffusion and thus absorptive capacity. See Table 1B.

Table 1B

	Installation Period	Deployment Period
Age of Capital Stock	From Previous Era Embodying Old Technology	Renewed Embodying New Technology
Knowledge Diffusion	Limited	Abundant
Labor Income Share	Declining	Increasing to Stable

In the economics literature, consideration of technology has evolved substantially. With the early treatment of Solow (1956), technology was assumed to be exogenous. Thirty years later Romer (1986) proposed an endogenous treatment with technology responding to income generating opportunities and delivering increasing returns at the aggregate level. Recent data produced by Kelly, Papanikolaou, Seru and Taddy (2021) suggest lengthy gestation periods, consistent with the work of both Romer (1986) as well as Perez (2002).

The first contribution of this paper is to clearly define periods of industrial revolutions and to focus on the complex dynamics of investment and depreciation. The interrelated dynamics of a broad range of technologies that by their nature are embedded in capital give industrial revolutions a long-life cycle. As is well known, the growth of the capital stock is a function of both the investment in new capital and the depreciation of existing capital. Investment in new tangible and intangible capital receive much attention, leading to expanding product and services choice, increasing productivity, and growing economic activity. However, as the capital stock ages and obsolescence increases, tangible and intangible capital becomes less valuable as technology advances. In endogenous growth theory, technological obsolescence drives heterogeneity in cross-sectional profitability and firm-level productivity.[4] At the aggregate level, capital is reallocated and the economy bears the cost of restructuring obsolete technologies, affecting the overall benefit of innovation (Ma 2021).

In 2019 US private nonresidential tangible and intangible capital had an average age of 16.3 years, up from a low of 13.8 years in 1986. In addition, adjusted for the changing capital stock composition, the average was 18.9 years, nearly equal to its age after the 1930s Great Depression.[5] With the existing capital stock depreciating over an extended period, replacement - embodying new technology - occurs at a measured pace.

The much longer lives of structures (average age of 23.3 years in 2019) likely act as a governor of fundamental business transformation as radical new processes likely require transformed physical space as well as a transformation of equipment (average age of 7.0 years in 2019) and intellectual property

[4] Autor, Dorn, Katz, Patterson, and Van Reenen (2021) points to such heterogeneity as it relates to shifting labor income shares.
[5] Bureau of Economic Analysis, Fixed Asset Account Tables, Table 1.9. Current-Cost Average Age at Yearend of Fixed Assets and Consumer Durable Goods. Last Revised on: 2 September 2020.

(average age of 4.4 years in 2019). Such was the case with the introduction of electric power in the late 19th century with full deployment extending into the early 20th century (David 1990). Likewise, in the late 18th century, as facilities were reconfigured from water power, the steam engine had a long-delayed impact on productivity growth (Crafts 2002).

Technology cycles are also lengthy. Intel was launched in 1971. However, it was not until the mid-1990s before microprocessor technology provided meaningful economic value, as reflected in increased productivity growth (Jorgenson and Stiroh 2000). By 1995, microprocessor innovation resulted in the cost per million computations (CMC) falling by six orders of magnitude over a quarter of a century.[6] An additional 20 years passed, with additional CMC reduction of two further orders of magnitude, before a general-purpose technology was available and the global cloud infrastructure was deployed at scale. The realization of a global technology revolution required mobile device innovation as well as a fundamental redesign of the worldwide computing and communication infrastructure across 40 years. To revolutionize economic value, the stream engine required approximately 80 years, while electric power and mass production each required approximately 40 years (Crafts 2004 and David 1990).

The second contribution of this paper characterizes the periods that make up each industrial revolution. Each era consists of two periods – an installation period and a deployment period with a major financial crisis intervening (See Perez 2002). In each period, state dependence plays a role as perceived market and price effects anticipate future income opportunities.

As the term implies, ***the installation period*** is one in which the new technology is developed or installed. It is a period of experimentation and learning when the new technology finds early, albeit somewhat primitive, applications. While the new technology provides early benefits, innovation in management practices, business models, and new products and services lag. The installation period also carries the legacy of the prior era's long-lived capital, and its embodied technology. With vast wealth having been created in the prior era, the inclination is to defend and grow existing accumulated wealth and resist fundamental transformation (See Gordon 2016 and Mokyr 1998).

Ultimately, the installation period leads to a frenzy of investment in the new technology – e. g. the dot.com bubble and mortgage securitization contribution to the 2008 -2009 financial crisis. However, value creation is not yet sustainable (See Minsky 1975 and Minsky 1986). On the one hand, existing business models and practices cannot support the fundamental change needed to make the new technology fully effective. On the other hand, the value creation capability of the legacy capital and technology of the prior era begins to fade. The frenzy of new investment fails to persist.

The deployment period is one in which the new technology, along with new business models, social acceptance, and political support are sufficiently in place to deploy, or put in place, the new capital, and

[6] Figure 1 in Nordhaus (2021) presents a time trend in the cost per million computations. The data are available here.

its embedded, now general purpose, technology, at a vast scale. State dependence is now such that aggregate demand grows at an increased pace and factor demand grows in a complementary fashion.

Schumpeter (1950) coined the term “creative destruction" which is the continuous process of product and service creation, business process improvement, and business model innovation. Through “creative destruction” new, innovative capabilities replace existing processes that are rendered obsolete over time. The restructuring process runs through major aspects of macroeconomic performance, not only long-run growth but also economic fluctuations, structural adjustment, and the functioning of factor markets. Over the long run, Calballero (2010) estimates the process of “creative destruction” accounts for over 50% of productivity growth.

The intersection of technology innovation and “creative destruction” is at the heart of the distinction between the installation period and the deployment period. The installation period is one in which technological innovation rises in importance as the period progresses. “Creative destruction” creates new firms and new jobs – social media, search, e-commerce, with jobs such as data science – while widespread business model changes are not yet ready to appear. By contrast, in the deployment period, “creative destruction”, or process transformation, becomes more important and intense as the now, inexpensive, general-purpose technology is available to change how businesses, households, and government function and operate while also creating new jobs and new tasks in the context of existing jobs. The nature of “creative destruction” differs in the installation and deployment periods.

Harberger (1998), in his American Economic Association Presidential Address, captures the installation period and the deployment period distinction to some extent. He highlights two types of growth. One, with focused “creative destruction” is characterized as “mushroom” growth with “real cost reduction stemming from 1001 different causes” with a limited number of sectors, industries, or firms experiencing much-improved productivity, as is seen in the installation period. The second type of growth is what Harberger calls “yeasty” growth “with very broad and general externalities, like externalities linked to the growth of the total stock of knowledge or of human capital, or bought about by economies of scale tied to the scale of the economy as a whole”. Once productivity improvement spreads widely across the economy, “yeasty” growth, as is seen in the deployment period, responds to the adoption of a general-purpose technology with substantial “creative destruction” and business process transformation (See van Ark, de Vries, and Erumban 2020).

In the context of the dynamics of industrial revolutions, three characteristics are considered in each period: the age of the capital stock, the rate of knowledge diffusion and thus absorptive capacity, and the labor income share.

The embodiment of innovation, ideas, and technology in the capital stock suggests that as the ***capital stock ages,*** during the installation period, new technology can reduce investment demand and substitute capital for labor, all else equal.[7] Existing capacity requirements can be satisfied, at the margin, with more effective replacement capital. Improved productivity growth can increase the output of existing capital, reducing the need for additional investment. Without an increase in desired capacity growth, improved technology reduces investment needs. In the presence of improved technology, a demand shock is necessary to increase investment spending (Lasky 2003). See Appendix B.

A productivity shock – for example resulting from "creative destruction" with improved management practices or new business models during the deployment period – can work indirectly through the desire for increased capacity as more capital per worker is employed (Lasky 2003). The cost of capital relative to output prices can also fall as a result of lower interest rates and reduced inflation resulting from improved productivity.

With strong total factor productivity (TFP) growth over the 1948 – 1975 period and an aged capital stock of the earlier era, the deployment of the then-mature 3rd Industrial Revolution's mass production technology resulted in strong growth in investment spending. Conversely, in the 1975 – 2010 installation period of the 4th Industrial Revolution, the initially young capital stock, the emergence the new electronics and information technology at the outset of the 4th Industrial Revolution, and slow TFP growth, collectively slowed investment spending from the strong growth of the pre-1975 period (See Figure 3). With the new technology, existing capacity requirements were satisfied, at the margin, with the new technology reducing investment demand. See Appendix B. The new technology also made the old technology obsolete. For example, in the office support function, word processing technology replaced electric typewriters, the internet made fax machines obsolete, and the US office support work force declined from 13% of the US labor force in 1988 to less than 7% in 2020.

Absorptive capacity is the ability of a firm to recognize the value of new, innovative, external information; assimilate such information; and create economic value. Innovative capabilities are, theoretically, a function of prior related knowledge and diversity, making absorptive capacity path dependent with investment in tangible and intangible capital necessary for future success. (See Cohen and Levinthal 1990). Knowledge diffusion is required for knowledge absorption. A decrease in knowledge diffusion from productivity leaders to laggard firms, suggests a decrease in aggregate supply, and all else equal, implies increased markups and profits, a labor share decrease, and a shift to more concentrated sectors where more productive firms pay more to their workers. (See Akcigit and Ates 2021).

Empirically, a decline in knowledge diffusion is observed between productivity leaders and laggard firms in the 1980 to 2010 period – approximately the most recent installation period, with new business formation declining. Conversely, recently assembled data - See Figure 8 - show a substantial increase in

[7] The technology embodiment of capital was an element of the Cambridge capital controversy that raged decades ago between Cambridge UK scholars and those in Cambridge MA. Much was written. See Section One of Cullenberg and Dasgupta (2001) for a summary. Hercowitz, (1998) concludes, as UK scholars asserted, embodiment is the principle "transmission mechanism of technological progress to economic growth".

new business formation in the 1948 to 1980 period – the 3rd Industrial Revolution's deployment period, suggesting that, perhaps, knowledge diffusion and new business formation could both show an increase in the period ahead.

Declining labor income share across the industrialized economies since 1980 is, by now, an established fact. However, causality is very much an unsettled issue. Recent work by Autor, Dorn, Katz, Patterson, and Van Reenen (2020) suggests a steep increase in sales concentration among firms with faster productivity growth. These productivity leaders realize higher markups, enhanced innovation, and larger declines in the labor income share. High-productivity firms with leading-edge capabilities are able to capture the early benefits of the industrial revolution's new technology. Lagging firms wait until the new technology is less expensive, well understood, and the extent and nature of the necessary "creative destruction" is clear. When knowledge diffusion and absorptive capacity becomes wide spread, a broader cross-section of industry firms are able to adopt the new technology, creativity destruct their existing business models and processes, innovate with lessons learned from industry leaders, and profitability invest in new tangible and intangible capital. With such wide spread adoption, macroeconomic benefits are likely with more rapid output and productivity growth and low inflation.[8]

The third contribution of this paper is a focus on the regime switching pressures in the movement from one era or period to another. The move from an installation period to a deployment period as an era progresses and a move from a deployment period to an installation period as one era gives way to the next revolution is a regime switching occurrence.

In the move from the installation period to the deployment period, each of the four industrial revolutions of the past 200 years has been interrupted by a major financial crisis (See Aliber and Kindleberger 2015, Perez 2002 and Reinhart and Rogoff 2009). As the frenzy surrounding a new technology results in dramatic asset price appreciation, values move out of alignment with fundamental value. Thus, a correction is required (See Minsky 1975 and Minsky 1986). Further, in the attempt to maintain income and wealth from the previous deployment era, new and more risky assets are created. However, after passing through the financial crisis and correcting asset values, if the deployment period is to become a reality, sufficient social, economic and political pressure must be present to cause workers, households, businesses, and governments to fundamentally change behavior (See Posen 2021). Growth in the prior installation period created conflict. "Creative destruction" is necessary to destroy the monopoly rents that accumulated. The more rapid growth and improved productivity performance in the anticipated deployment period requires a new economic and social regime. The new regime includes wide deployment of the new general-purpose technology, stepped-up tangible and intangible investment, still further "creative destruction", labor market transformation, and reduced resistance to move from old, accepted practices.

[8] As Autor et. al. (2021) show shifting income shares, growing from firm-level productivity differentials, in the 4th Industrial Revolution's installation period, Allen (2009) shows similar income shifts in the 1st Industrial Revolution.

In the move from the deployment period to the next era's installation period, excess demand for capital investment and the resulting inflation and high interest rates act as governors of continued strong growth. Limitations on available resources, tangible and intangible capital maturity, and an exhaustion of the previous era's technology cause a slowing of activity. While the income and wealth generating benefits of the deployed capital and the embedded technology remain, the focus shifts to a new technology while existing capital depreciates.

Finally, as is well known, the current macroeconomic environment (prior to the 2021 pandemic) is characterized by negative real interest rates, low inflation, and weak productivity growth.[9] Real interest rates have long been recognized as a critical consideration in capital investment decisions. Despite a prolonged period of negative real interest rates, capital investment has continued to lag. Summers (2015), and a series of follow-on papers, has considered in detail the importance of real interest rates in the context of "secular stagnation". Furman and Summers (2020) suggest that reduction in the demand for capital is, at least in part, responsible for driving down real interest rates. Rachel and Summers (2019) find real interest rates would have been 700 basis points lower than those that have been the experience in the absence of fiscal policy of the past two decades. Without the ability of real interest rates to remain substantially negative, capital investment has lagged. If negative real interest rates – substantial or otherwise – have not revived capital investment spending growth, a further explanation is necessary.

[9] While demographics are clearly very important and variable over long time horizons, it is beyond the scope of the current paper to consider the impact in detail. (See Goodhart and Pradhan 2020) The lack of focus is not a statement about the importance of demographic issues over each four industrial revolutions, but only a need for focus. In addition, the current paper does not focus on the dramatically changed role of China in the global economy over the past forty years. Rather, China's role in the global economy is important and will be more important in the years ahead. Its role requires greater treatment in another paper. Similarly, energy technology has played a vital role in each era, migrating from water to steam to electricity to fossil fuels to non-renewables. However, again focus will cause the topic of energy technology to taken up later.

3.0 Growth and Technological Change

In this section, (1) growth is examined in the context of long-term stability and instability that has been observed over 250 years, (2) surges and plunges of innovative activity are identified as are the coincident follow-on of major global financial crises, and (3) four industrial revolutions are defined and important characteristics of each are observed in the volatility of nonresidential tangible and intangible capital net growth, labor productivity, and GDP.

The focus of the post-World War II economics literature on growth, capital deepening, and productivity received its most significant boost from the work of Solow (1956). While others had pointed to a long-time horizon as a topic of interest, it was Solow's 1956 work that created the original framework characterizing the economy's long-run growth path as well as the conditions necessary for an optimal outcome.

In parallel with Solow's work, Schumpeter (1950) expanded the focus beyond the appearance of new technology to the process of "creative destruction" in which

> ….. new innovations continually emerge and render existing technologies obsolete, new firms continually arrive to compete with existing firms, and new jobs and activities arise and replace existing jobs and activities. (See Aghion, Antonin and Bunel (2021), p. 1).

Three decades after Solow's pathbreaking work, Romer (1990) provided the necessary add-ons with a set of knowledge-creating drivers.[10] While Solow assumed an exogenous steady-state path for technology, Romer focused on the development of new technologies in market economies through profit-maximizing research and development. However, Romer's model of innovation-led growth did not include "creative destruction" (See Aghion, Antonin and Bunel 2021).

First, Romer introduced a new view of technology. While Romer recognized that individual firms are subject to diminishing returns, at higher aggregate levels – industry, city, nation - increasing returns are realized as technology is deployed across such geographic and political entities. Romer's insight was that the capital stock consists of both tangible and intangible assets. The focus was on how market economies develop new technologies, endogenously, as profit-maximizing research and development responds to perceived opportunities.

Intangible assets grow out of ideas that Romer famously defined as having properties as non-rivalrous – easily shared – and non-excludable – cannot be owned.[11] Many ideas have such properties and, as ideas

[10] See Royal Swedish Academy of Science (2018) for a summary of the Solow and Romer work.

[11] Romer cites, as a contrary illustration, encoded satellite television broadcasts, a rivalrous, excludable good, that is intellectual property. Pure public goods are both non-rival and non-excludable.

spread, innovation abounds, intangible assets expand, and growth quickens, especially among the most advanced economies.[12, 13]

Second, by the mid-1980s, Romer had the benefit of the Penn World data, a comprehensive cross-country data set, (Summers and Heston 1984) and the Maddison data for countries in the 18th, 19th, and early 20th century (Bolt and Van Zanden 2020). Romer showed that productivity growth across the three leading economies of the 18th and 19th centuries – Netherlands, UK, and US – increased monotonically (Romer 1986 p.1009). For the US, Romer showed per capita GDP growth rates increasing steadily over five sub-periods between 1800 and 1978. The sub-periods approximately coincide with periods of industrial revolution.[14]

Further Romer observed:

> These rates also suggest a positive rather than a negative trend, but measuring growth rates over 40-year intervals hides a substantial amount of year-to-year or even decade-to-decade variation in the rate of growth. (Romer 1986, p. 1009)

3.1 Long-Term Growth and Economic Instability

At the heart of Romer's work was a focus on (1) an endogenous response to income-generating opportunities producing increasing returns to scale in technology deployment, (2) diminishing returns at the firm level, and (3) decade-to-decade variation in national growth rates.[15] With the advantage of nearly 40 years of additional data, a global financial crisis, and the Maddison project data, Figure 1 shows US and UK GDP growth. Over the nearly 200 years, growth varied across the decades in both economies with US growth trending down late in the 20th and early in the 21st century.[16]

Despite Romer's insight, the economics literature has struggled to identify causal factors influencing growth and the policies affecting growth (Banerjee and Duflo 2019, p. 180). Indeed Easterly (2001), a

---

[12] Haskel and Westlake (2018) argue that intangible capital is largely non-excludable.

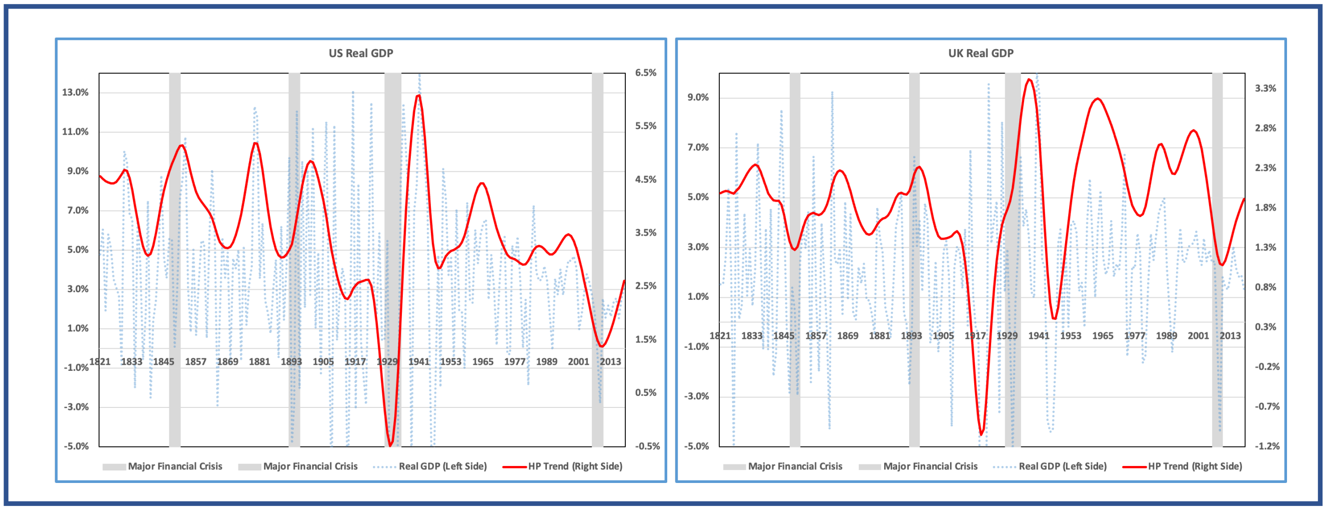
[13] Concurrent with Romer's early work, Lucas (1988) developed a theory of human capital as the driver of growth, along with tangible capital. The endogenous buildup of intangible capital, augmenting labor input in Solow's model, prevents the returns from capital from falling, allowing continued accumulation of tangible capital as well (See Royal Swedish Academy of Sciences 2018).

[14] The intervals Romer identifies are (followed by per capita US GDP annual growth rates): 1800 – 1840, 0.58%; 1840 – 1880, 1.44%; 1880 – 1920, 1.78%; 1920 – 1960, 1.68%; 1960 – 1978, 2.47%. Romer's Figure 1 shows the periods of growth as well as the intervening growth slowdowns.

[15] For a discussion of Romer's views of increasing returns to scale at the aggregate level and diminishing returns at the firm level, see Banerjee and Duflo (2019), pp. 162-165.

[16] For the Hodrick-Prescott (HP) filter see Hodrick and Prescott (1997). Hamilton (2017) presents evidence against using the HP filter, citing spurious dynamic relations. Hodrick (2020) finds the HP filter is better than the Hamilton alternative at extracting the cyclical component of several simulated time series calibrated to approximate US real GDP.

Figure 1



Source: [Maddison Project Database (MPD) 2020](#) with authors calculations. Major Financial Crises from Perez (2002).

noted skeptic of growth theory, asserts national growth rates change significantly from decade to decade with limited sustained impact.[17] (Banerjee and Duflo 2019, p. 181) A significant impediment in understanding growth, especially in advanced economies, has been the difficulty in measuring the technological progress that so concerned Solow and Romer.

To fill the measurement gap, recent work by Kelly, Papanikolaou, Seru and Taddy (2021) apply natural language processing (NLP) methods to data from US patent documents to build indices of breakthrough innovations. Kelly et. al. define breakthrough innovations as distinct improvements in the technological frontier that become the foundation on which subsequent innovations are built.

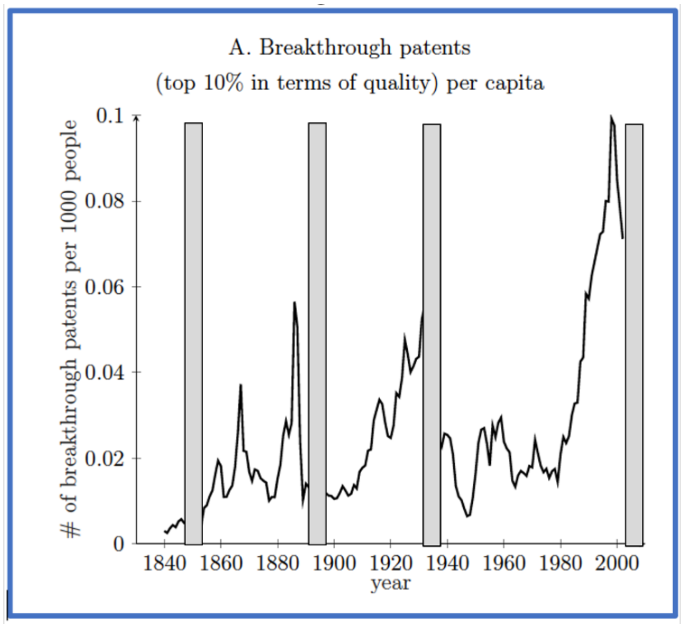
Kelly et. al. develop “measures of textual similarity to quantify commonality in the topical content of each pair of patents.” They identify significant, high quality patents as those whose content is novel and impactful on future patents. As a “ground truth” data set, Kelly et. al. identify major technological breakthroughs across the 19th and 20th centuries. These breakthroughs include watershed inventions such as the telegraph, the elevator, the typewriter, the telephone, electric light, the airplane, frozen foods, television, plastics, electronics, computers and advances in modern genetics. (See Gordon 2016 for a detailed discussion.)

The measures of patent significance, developed with the NLP patent citation method, perform substantially better than citation counts in identifying the “ground truth” major technological breakthroughs. Validation shows the relationship of the measures to market value. With novel

---

[17] Easterly’s critique is principally focused on the failure to understand the drivers of growth in less-developed and emerging market economies. While he is explicit that he does not take on a general survey of growth, his broader observation is, implicitly, the gap in understanding the determinants of growth.

Figure 2



Source: Kelly et. al. (2020). Gray bars are major financial crises.

contributions adopted by subsequent technologies, the measures are capturing the scientific value of a patent. (See also Bloom, Hassan, Kalyani, Lerner, and Tahoun 2021).

The resulting Kelly et. al. aggregate innovation index shows three technology surges - mid- to late-19th century, the 1920s and 1930s, and the post–1980 period. Advances in electricity and transportation in the 1880s; agriculture in the 1900s; chemicals and electricity in the 1920s and 1930s; and computers and communication in the post-1960s all contribute to high value innovation. See Figure 2.

The Kelly et. al. innovation index is also a strong predictor of aggregate total factor productivity (TFP) for which a one-standard deviation increase in the index is associated with a 0.5 to two percentage point higher annual productivity growth over the subsequent five to ten years. By mapping technology to industries, sectoral technological breakthroughs indices span the entire sample. Sectors that have breakthrough innovations experience faster growth in productivity than sectors that do not.

The breakthrough innovations are of the nature of the advances that Romer had in mind when suggesting that many such ideas, because they are protected by patents or as trade secrets, are rival and non-excludable. Indeed, the Kelly et. al. innovation index suggests periodic surges of very significant ideas have spread repeatedly, widely, and rapidly over nearly two centuries, suggesting the presence of increasing returns to scale at the industry and national levels.

The periodic technology surges, as identified by Kelly et. al., are further characterized by Perez (2002). The revolutionary technology that drives the surges creates investment in new industries, most often by new, young entrepreneurs, Perez suggests. Funding of such ventures reallocates capital and creates new sources of wealth. New infrastructure is created and existing industries are modernized. The clustering of technological innovation is a further illustration that a broad class of ideas are rival and non-excludable, generating increasing returns to scale.

Perez describes periodic technology revolutions and associated “creative destruction” as:

> ….. strongly interrelated constellation of technical innovations, generally including an important all-persuasive low-cost input, often a source of energy, sometimes a crucial material, plus significant new products and processes and a new infrastructure. The latter usually changes the frontier in speed and reliability of transportation and communications, while drastically reducing their cost. (Perez 2002, p. 8)

3.2 Innovation, Financial Crises and Growth

The periodic technology and innovation surges have been frequently followed by major financial crises. Among the most well-known are the events of the 20th and early 21st century - the Great Depression of the 1930s and the Great Recession and Global Financial Crisis of 2007 – 2009. Scholars, who have carefully tracked such events, agree that both downturns qualify as major financial crises. Aliber and Kindleberger (2015), Reinhart and Rogoff (2009), and Perez (2002), all identify the Great Depression and the Global Financial Crisis as financial crises that are among the historically largest.[18]

Building on the work of Minsky (1975) and Minsky (1986), Aliber and Kindleberger identify crises that follow an exogenous shock that sets off a mania. The mania involves a specific object of speculation, such as commodities, real estate, bonds, and equities, and as well as a source of monetary expansion. Perez builds on the work of Minsky, Aliber and Kindleberger.

Reinhart and Rogoff (2009), famously, develop a quantitative history of financial crisis. Between 1800 and 2009, Reinhart and Rogoff identify 250 external sovereign debt default episodes, 68 domestic debt defaults, and 270 banking crises. Reinhart and Rogoff also highlight inflation and currency crises. However, they label four episodes as global financial crises.[19] In Reinhart and Rogoff’s view, financial crises share three characteristics – a deep and prolonged asset market crash, a banking crisis that is

---

[18] Aliber and Kindleberger (2015) is the seventh edition of the Kindleberger’s classic treatment of the history of financial crises, first published in 1978. Aliber joined Kindleberger after the publication of the fourth edition in 2000.

[19] Reinhart and Rogoff (2009) define global financial crises as having four main elements: (1) a global financial center is involved in a systemic crisis, (2) two or more global regions are involved, (3) the number of countries involved in each region is three or more, and (4) the Reinhart and Rogoff composite GDP-weighted average global financial turbulence index is at least one standard deviation above average. See Box 16.1, pp. 260-261.

Table 2

Era	Industrial Revolution	Years	Technology Innovation	Installation		Major Financial Crisis	Deployment	
				Irruption	Frenzy		Synergy	Maturity
1st	Age of Steam and Railways	1829-1873	"Rocket" Steam Engine (1829)	1830s	1840s	1848-1850	1850-1857	1857-1873
2nd	Age of Steel, Electricity and Heavy Engineering	1875-1918	Carnegie Bessemer Steel Plan (1875)	1875-1884	1884-1893	1893-1895	1895-1907	1908-1918*
3rd	Age of Oil, Automobiles and Mass Production	1908-1974	Model-T Mass Production (1908)	1908-1920*	1920-1929	Europe 1929-1933 US 1929-1943	1943-1959	1960-1974*
4th	Age of Information and Telecommunications	1971-2019	Intel Microprocessor Announced (1971)	1971-1987*	1987-2007	2007-2010	2010-	

Source: Perez (2002) *Phase overlaps between successive surges

followed by profound declines in output and employment, and a vast expansion in the value of government debt.

As measured by Reinhart and Rogoff, financial crises bring declines in real housing prices averaging 35%, a three-and-a-half-year equity price decline averaging 56%, peak to trough output declines averaging 9%, and an increase in the value of government debt rising to 86% of GDP in the major post-World War II episodes.

Table 2 summarizes each of the four revolutions of the industrial era. (See Appendix A for more detail.) Perez (2002) asserts that, initially, the technology is "installed" with an early irruption in which new products and industries experience explosive growth and rapid innovation. However, the technology remains nascent and new applications are limited. Over time the power of the new technology becomes apparent, with applications appearing at an increasing rate. Continuing innovation drives down the cost of the new technology, setting the stage for deployment at scale.

However, soon a frenzy appears. While great wealth is created, as seen recently in social media and search, the broad cross-section of business models and societal institutions remain tied to the prior era. The rush of funding into new ventures results in over-investment and an inability to fully transform household and industrial uses and fully exploit the new technology. To prepare for the period of growth ahead, the ensuing financial crisis is needed to cleanse balance sheets, alter family and household practices, and force complete "creative destruction" and the transformation of busines processes.

The financial crisis provides the preparation for the "deployment" period. The broad economic contraction causes businesses and households to search for new more efficient processes and practices.

The new technology finds new synergy. Business and government practices are transformed and societal norms experience very significant change.

Gordon (2016) provides a rich and masterful overview of the social and economic transformation that reshaped the US during the 2nd and 3rd Industrial Revolutions. Mokyr (1998) details the social and economic transformation of the 1870 – 1914 2nd Industrial Revolution. As new technologies were deployed, social and economic activity transitioned from the installation period through a financial crisis into the deployment period. Gordon provides a detailed description of how technology, growth and institutional change interacted to transform social and economic activity and provide meaningful improvements in living standards, health, and personal comfort. During such periods, economic growth and productivity begin to quicken, the economy and society enter a "golden era". Finally, as the new technology and the transformation resulting in the "creative destruction" matures, rapid growth continues over time. Technology and transformation opportunities become fully exploited. Market saturation creates limits to further growth. Increasing rates of inflation begin to appear.

Table 3A provides a view of growth across the eras. The last column shows the successively slower growth rates across the eras as the US economy has matured. The 19th century eras benefited from continued growth, even during major financial crises and relatively stronger growth in the synergy phase. Conversely, in the 20th century and the early 21st century, financial crises brought significant activity declines while the synergy phases have brought relatively weak growth. The severe financial crises and the weaker expansions in the recent period is suggestive of the transformation challenges delaying the appearance of new opportunities. The weak 1.5% annual growth in the 2010-2019 period is symptomatic of the delay in deploying the current revolution's technology.[20]

Table 3B provides a view of capital deepening. As expected, capital deepening increases more rapidly during the 3rd Industrial Revolution deployment period during which the stock of capital grew at a 2.0% annual rate. Growth slowed in the 4th Industrial Revolution to 1.2% annual rate during the installation period. While the technology irrupts and eventually creates a frenzy, capital deepening slows as the capital stock deployed in the earlier era continues to provide service and generate income. In the current period, capital deepening has failed, thus far, to fully capture the recovery experienced in previous deployment periods. The lag in capital deepening is one manifestation of what has been labeled "secular stagnation". (Summers 2014).

Table 3C shows the well-known productivity slowdown. The robust 2.6% productivity growth in the 3rd Industrial Revolution deployment slowed to 2.0% per year in the installation period in the 4th Industrial Revolution. In the current period, productivity growth has slowed even further to an annual rate of 0.9%. Again, another sign of failure of the deployment period to launch.

---

[20] Section 5.0 of this paper will discuss the delay in detail.

Table 3A

Era	Industrial Revolution	Years	US GDP Growth (Average Annual Growth Rates Major Financial Crises Peak to Trough Change)					
			Irruption	Frenzy	Major Financial Crisis	Synergy	Maturity	Total
1st	Age of Steam and Railways	1829-1873	5.0%	3.4%	+3.3%	5.2%	3.8%	4.2%
2nd	Age of Steel, Electricity and Heavy Engineering	1875-1918	5.1%	2.7%	+8.8%	4.3%	3.2%	3.7%
3rd	Age of Oil, Automobiles and Mass Production	1908-1974	2.6%	3.4%	-30.5%	2.3%	4.0%	3.0%
4th	Age of Information and Telecommunications	1971-2019	3.2%	3.1%	-3.1%	1.5%	-	2.8%
Average			4.0%	3.1%	-5.4%	3.3%	3.7%	3.3%

Source: Maddison Project Database (MPD) 2020 with authors calculations.

Table 3B

	Capital Deeping Capital-Labor Ratios (Thousands of 2012 Dollars per Worker) And Growth Rates							
Industrial Revolution	3rd Era Age of Oil, Automobiles and Mass Production 1945-1974			4th Era Age of Information and Telecommunications 1971-2010			4th Era Age of Information and Telecommunications 2010-2019	
	Deployment Period			Installation Period			Deployment Period	
	1943	1959	1974	1971	1987	2007	2010	2019
Capital-Labor Ratio	141.0	197.5	261.1	273.1	308.0	414.9	424.2	474.1
Annual Growth Rate	--	--	2.0%	--	--	1.2%		1.2%

Source: US Bureau of Economic Analysis. Fixed Assets Accounts Table. Table 1.1 Current-Cost Net Stock of Fixed Assets and Consumer Durable Goods, row 1, US Bureau of Labor Statistics, All Employees: Total Nonfarm Payrolls, Thousands of Persons, Annual, Seasonally Adjusted and Producer Price Index by Commodity: All Commodities.

Table 3C

	Labor Productivity Nonfarm Sector Output per Hour (Base Year 2009 = 100)							
Industrial Revolution	3rd Era Age of Oil, Automobiles and Mass Production 1945-1974			4th Era Age of Information and Telecommunications 1971-2010			4th Era Age of Information and Telecommunications 2010-2019	
	Deployment Period			Installation Period			Deployment Period	
	1947	1959	1974	1971	1987	2007	2010	2019
Index	23.5	32..6	47.4	45.2	58.6	91.6	99.2	107.9
Annual Growth Rate	--	--	2.6%	--	--	2.0%	--	0.9%

Source: US Bureau of Labor Statistics, Nonfarm Labor Productivity, Major Sector Productivity and Costs, Index, 2009 Base Year = 100.

3.3 Capital Investment and the Age of Capital

The surges and plunges of innovation, productivity, and economic growth has capital deepening at its heart. The long-lived nature of capital and capital's technology embodiment, together, suggest change occurs over the long term. With data limited to the most recent hundred years, Figure 3 shows the pace of growth in US private nonresidential net investment, including both tangible and intangible capital, over the period 1925 to the present. Aligned with the 3rd and 4th industrial eras, the Great Depression of the 1930s and the 2008 - 2009 Great Recession and Financial Crisis are clearly reflected as slowdowns in investment growth. The expansion period of 1943 - 1974, as shown in Table 2, is also apparent, as is the slower growth in the early 21st century.

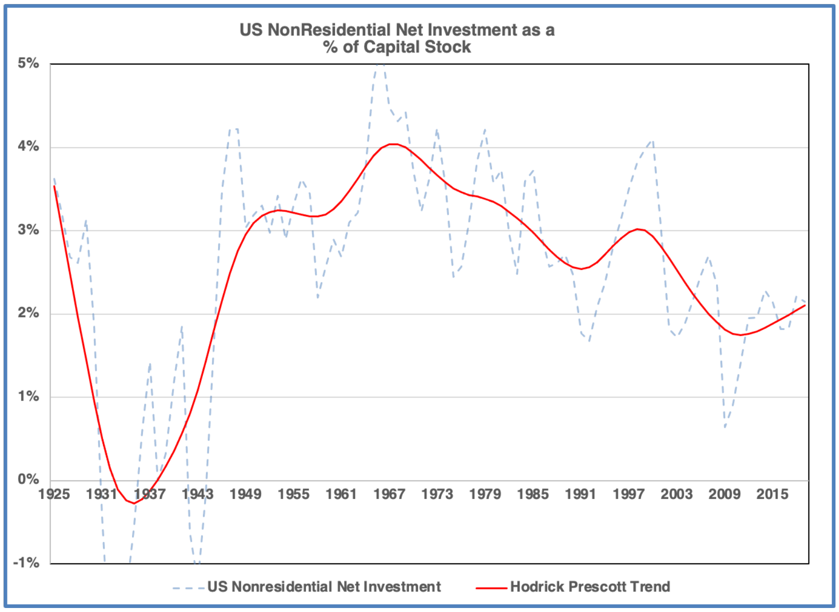
Figure 4 shows nonfarm business sector labor productivity growth over the 1947 - 2019 period. The well-known productivity growth strength is apparent in the 1947 - 1970 period, delivering the fruits of the 3rd industrial era. An extended period of weak growth follows as the existing 3rd industrial era capital stock matured and the 4th era was in its early stages. The growth burst in the 1990s accompanied the frenzy as the early benefits of the microelectronics era emerged. While the trend has turned positive, in the current period, growth remains weak.

Figure 5 shows total factor productivity (TFP) growth over the 1948-2018 period. Like labor productivity, following an episode of strong growth from 1948 to the early 1970s, growth slowed substantially. The late 1990s growth burst coincided with measurable advances in semiconductor technology and the deployment restructured computing systems - initially the client-server computing model appeared and soon inexpensive cloud computing emerged. New software capabilities were also put in place in anticipation of the turn of the century and year 2000. Subsequently, TFP growth has fallen off to record low rates, suggesting full "creative destruction" has yet to appear.

While two industrial eras do not constitute proof, there are some intriguing dynamics revealed in the limited data set. Many capital assets are long-lived asset with replacement occurring infrequently and with legacy technology and innovation embodied in the capital stock for an extended period. Figure 6A shows, as expected, structures have the longest lives while equipment has the shortest, shown in Figure 6B. Interestingly, however, intellectual property products (IPP) – intangible capital – have lives somewhat longer than equipment.

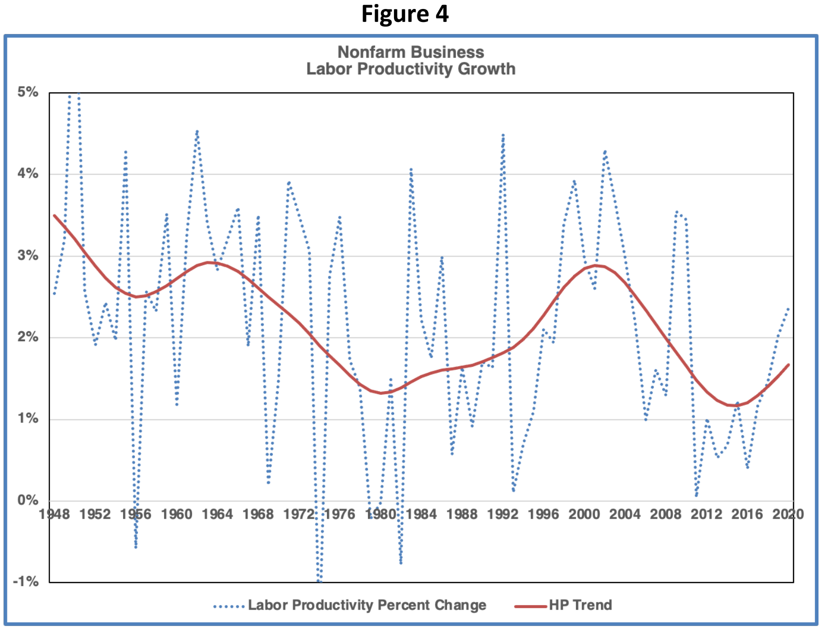
Figures 6A and 6B also shows that as a result of the dramatic slowing of investment spending growth in the 1930s, the capital stock aged, significantly from an average age of 15.3 years in 1925, the stock grew progressively older to 20.6 years in 1945 and 1946. Clearly, some of the aging could have been a result of neglect while production was focused on the 1941-1945 war effort. However, the average age of the capital stock had already reached 19.5 years in 1940 and 1941 with only one added year of age over the ensuing five years.

Figure 3



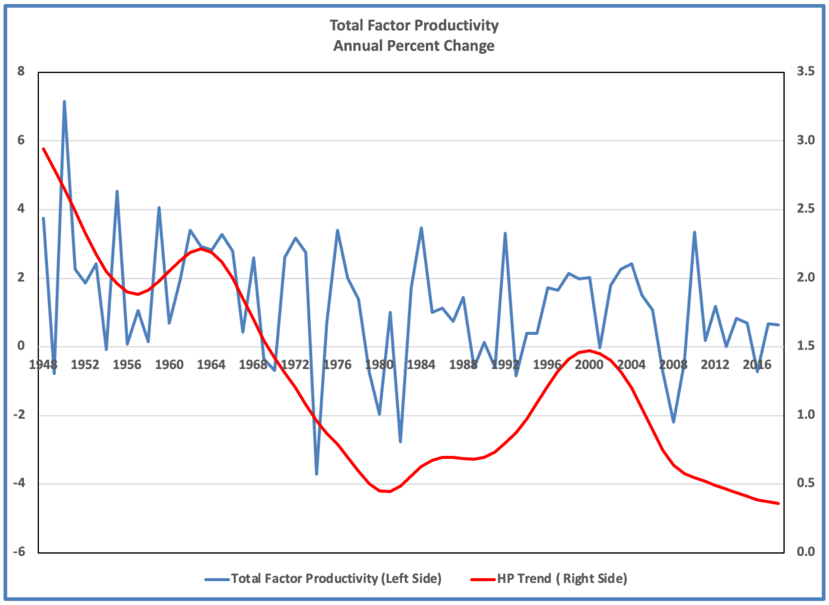
Source: US Bureau of Economic Analysis. Fixed Assets Accounts Table. Table 1.1 Current-Cost Net Stock of Fixed Assets and Consumer Durable Goods, row 4, Table 1.3 Current-Cost Depreciation of Fixed Assets and Consumer Durable Goods, row 4, and Table 1.5 Investment in Fixed Assets and Consumer Durable Goods, row 4.

Figure 4



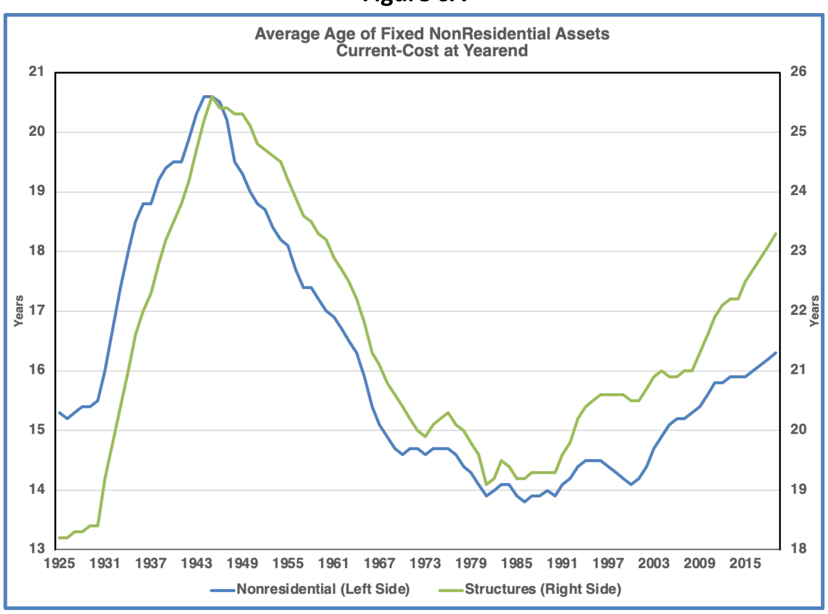
Source: US Bureau of Labor Statistics. Major Sector Productivity and Costs, Series Id: PRS85006093, Nonfarm Business Sector, Index, base year = 100, Base Year 2009. Recession years from NBER Business Cycle Dating.

Figure 5



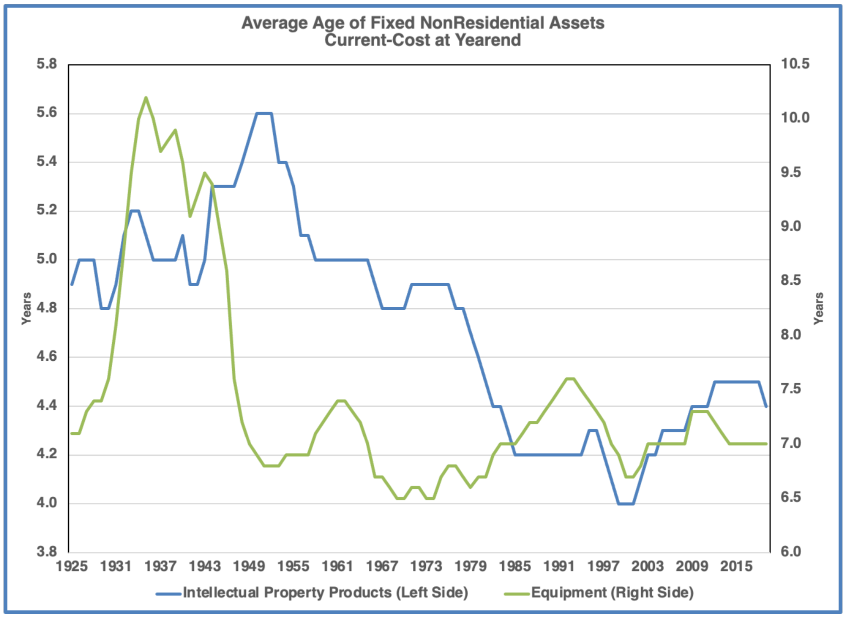
Source: John G. Fernald, "A Quarterly, Utilization-Adjusted Series on Total Factor Productivity." FRBSF Working Paper 2012-19. Produced on March 21, 2019 4:36 PM by John Fernald/Neil Gerstein--fernaldjg@gmail.com (Directory: out\QuarterlyTFP_2019.03.21.1)

Figure 6A



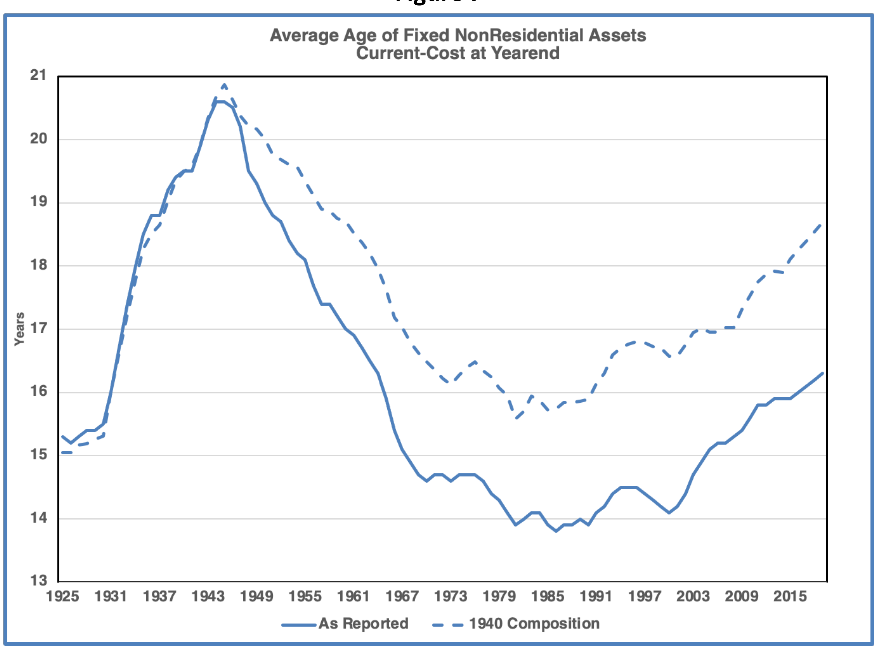
Source: US Bureau of Economic Analysis. Fixed Assets Accounts Table. Table 1.9. Current-Cost Average Age at Yearend of Fixed Assets and Consumer Durable Goods, rows 4, 5, 6, and 7.

Figure 6B



Source: US Bureau of Economic Analysis. Fixed Assets Accounts Table. Table 1.9. Current-Cost Average Age at Yearend of Fixed Assets and Consumer Durable Goods, rows 4, 5, 6, and 7.

Figure 7



Source: US Bureau of Economic Analysis. Fixed Assets Accounts Table. Table 1.9. Current-Cost Average Age at Yearend of Fixed Assets and Consumer Durable Goods, rows 4, 5, 6, and 7 with author's calculations.

As a result of endogenous forces of the 3rd Industrial Revolution's technologies and postwar demand effects, the aged capital stock of the mid-1940s and the consequent pressure for renewal, contributed to the rapid and aggressive investment of the 1950s to the 1970s. The investment surge ultimately drove the age to a low of 13.8 years in 1986. The subsequent three decades of slower investment spending growth, added three years to the stock's age.

Compared with the pre-war capital stock age of 19.5 years in 1940, the 16.2-year age in 2019 is largely accounted for by the shift in the composition of capital investment spending which reflects the increased importance of equipment and IPP in 2019. Figure 7 shows the trend in the age of nonresidential net capital investment with the 1940 weights applied. In the absence of the composition shift, the 2019 average capital age would have been 18.9 years, only slightly below its 1940 value. Controlling for the compositional shift, the capital stock in 2019 is about as aged as it was in 1940.

The US capital infrastructure progressed through a 40-year aging process from the late 1960s to late in the first decade of the 21st century. As the period progressed, the overbuilding of the 1960s, during a period of strong demand, put in place a large physical private and public capital stock. As a consequence of the long period of capital deprecation, the stock became increasingly antiqued and less productive.

The technological capability of legacy capital does not respond swiftly to innovation. Rather, because new technology is only effective when new capital is deployed, the prolonged useful life of tangible and intangible capital slows the rate of adjustment. Capital investment is, in part, governed by the long-lived nature of capital. The increasingly rapid capital deepening in the deployment period - most recently 1943 - 1974 - sets the stage for a slowdown in capital deepening in the subsequent installation period. As the existing capital depreciates, the previous era's technology matures, and the next generation of technology is birthed, unlocked by endogenous generation of new ideas, innovation, and technology creating increased aggregate demand.

4.0 Knowledge Transfer and Labor Income Share

Industrial revolutions are characterized by investment and depreciation of tangible and intangible capital that embodies new and legacy technology whose ability to add value is dependent on "creative destruction" across business organizations, worker cohorts, and governments as new products and services are launched, new business models are created, and existing business processes are transformed.

In this section, two critical features of industrial revolutions are examined – changing capital and labor income shares and knowledge transfers. Each differs fundamentally over the course of each industrial revolution.

Recall that early in the revolution legacy capital embodying the previous era's mature technology is highly income generating but begins to experience increased deprecation, which over time slows its productive capacity and value creation. Simultaneously, a new technology appears that is, initially, expensive and limited in application. As the technology develops, costs decline, applications broaden, and the promise of income generating opportunities expand with "creative destruction" showing the early signs of the transformation to follow. High productivity leading-edge firms find new applications for the new technology. Nonetheless, excessive optimism inflates asset values which are corrected in a protracted global financial crisis.[21]

In the aftermath of the crisis, cleansed balance sheets and available cash are positioned to invest in the now mature and inexpensive new technology with replacement of then-aged tangible and intangible capital. However, even more intense "creative destruction" produces fundamental change, establishing a new order, cutting across labor and product markets with wide spread adoption of new business models, processes, products, and services. Because such deep and profound change is resisted by entrenched interests – wealth holders, business organizations, workers, and governments - often major external events such as wars, depressions, and pandemics are required to cause new social and economic regimes to emerge. However, if "creative destruction" and the ensuing regime transformation is successful, robust output and productivity growth is expected in a low inflation environment.

If such broad-based macroeconomic benefits are to be realized, the move through an industrial revolution requires knowledge transfer. See Coyle (2021). The early technology and business model transformation leaders – for example Facebook, Amazon, Apple, and Google – see their experience and knowledge transferred to newly launched firms and to productivity lagging firms. The rewards that these early leaders and their workers have reaped are shared with those who follow.

[21] In the current era, the IBM 390 mainframe, gave way to the Intel microprocessor which ultimately led to rapid technological innovation that often lacked the needed business model innovation. The resulting dot.com bubble and the Great Financial Crisis prepared the way for the emergence of Facebook, Amazon, Apple, and Google, all users of the then-low-cost technology and creators of fundamentally new business models.

4.1 Knowledge Diffusion and Absorptive Capacity

If organizations are to fully benefit from the renewal of tangible and intangible capital, its ability to absorb knowledge is critical. Industry productivity leaders, by their nature and organizational culture, understand how to learn, transform, and grow. The absorptive capacity of organizations and the rate of knowledge diffusion - "two sides of the same coin" – depend on the nature and extent of capital and labor's interaction. The diffusion of knowledge only creates economic value if organizations have the ability to absorb such knowledge and create productive improvements. Indeed, successful "creative destruction" - launching innovation, creating new firms, and finding new job roles - requires knowledge diffusion and absorptive capacity.

Cohen and Levinthal (1990), in a classic paper, define absorptive capacity as the ability of a firm to recognize the value of new, external information, assimilate such information, and create economic value. Importantly, innovative capabilities are a function of prior related knowledge and diversity, making absorptive capacity path dependent with investment in tangible and intangible capital necessary for future success. (See also Bessen 2015.)

Using cross-sectional survey data on technological opportunities and appropriability conditions, Cohen and Levinthal model firm-level investment in research and development (R&D). The dependent variable is R&D intensity, defined as company-financed business-unit R&D expenditures as a percentage of business unit sales and transfers over the period 1975 through 1977. Technological opportunity is assessed with what are considered two critical sources of such opportunity - the science base of the industry and extra-industry sources of knowledge.[22]

Cohen and Levinthal's findings point to the importance of the interaction between appropriability and the industry four-firm concentration ratio. In addition, the percentage of an industry's tangible capital installed within the preceding five years is positive and significant in the model. Industry leading firms who have recent experience growing their tangible and intangible capital are more likely to invest in new knowledge.

These findings suggest when learning is difficult an increase in the relevance and quantity of knowledge has a more positive effect on R&D intensity. Consistent with the Cohen-Levinthal hypothesis, the estimated coefficients for applied science measures, with the exception of computer science, are lower than that for the basic sciences. In addition, the importance of extra-industry sources of knowledge, reflecting increasingly targeted knowledge, is largely confirmed. The coefficient estimates for the

---

[22] The relevance of eleven basic and applied fields of science and the importance of external sources of knowledge to technological progress in a line of business are included. Intra-industry R&D spillovers are represented with six measures used by firms to capture and protect the competitive advantages. These measures include patents to prevent duplication, patents to secure royalty income, secrecy, lead time, movement down the learning curve, and complementary sales and service efforts. A subset of these measures enter the model appropriately signed and are significantly different from zero.

importance of knowledge originating from universities exceed that for government labs, which, in turn, is greater than that for materials suppliers, which exceeds that for equipment suppliers.

As shown by Cohen and Levinthal, knowledge diffusion is required for knowledge absorption. Akcigit and Ates (2021) explore a theoretical and empirical treatment of a decline in knowledge diffusion between productivity leading and laggard firms in the 1980 to 2010 period. They suggest that a decline in knowledge diffusion among productivity leading firms, consistent with observed facts, implies higher markups and profits as well as a labor income share decrease. The dominant force is the shift to more concentrated sectors – consistent with Cohen-Levinthal findings - where more productive firms thrive with fewer workers. While the Akcigit and Ates (2021) model does not directly speak to the observed decline in the firm entry rate, the increase in market concentration implies that new entrants are likely to compete against dominant market players which would discourage firm creation.

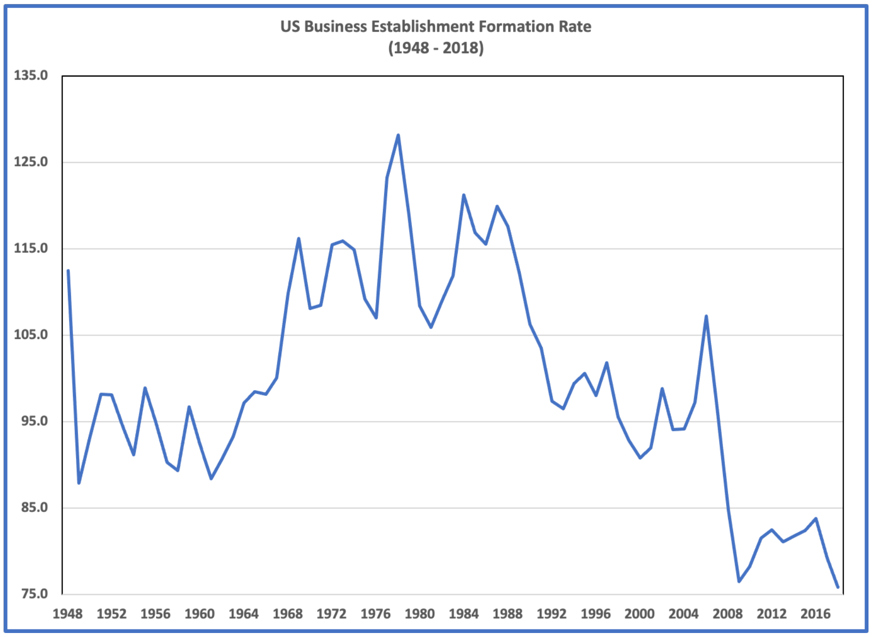
Bessen and Nuvolari (2016) consider knowledge sharing from a historic perspective. They cite the work of Robert Allen as an illustration. Allen (1983) writes that that pig iron industry of Cleveland, UK in 1850 to 1870 – the deployment period of the 1st Industrial Revolution – observed “free exchange of information about new techniques and plant designs”. The knowledge exchange encouraged innovation building on previous advances. Bessen and Nuvolari conclude that knowledge sharing was not rare or marginal. Important technologies at the center of industrialization, such as steam engines, iron and steel production, steamboats, and textile production were developed as a result of a collective effort.

Figure 8 expands the Akcigit and Ates view of business establishment formation from the 1980 to 2010 to 1948 to 2018. After an increasing business formation rate from 1960 to 1978, the figure shows a decline in business formation from 1980 to 2010, similar to the decline shown in Figure 10 in Akcigit and Ates (2021).

The 1948 to 1980 period approximately coincides with the years that have been identified as the deployment period of the 3rd Industrial Revolution. With the fossil-fuel, mass production era having reached maturity and tangible and intangible capital in a period of rapid accumulation, including government sector infrastructure and intellectual capital, business formation began a period of rapid increase. Interestingly, more than a decade was required for the formation rate improvement to begin. By the later portion of the period, business formation accelerated to a very high rate. Once underway the formation rate remained elevated for three decades.

By contrast, the 1980 to 2018 period approximately aligns with the installation period of the 4th Industrial Revolution. With the aging capital of the previous period and the nascent technology of the new electronics and information technology era, business formation slowed. As Akcigit and Ates suggest industry concentration increased. The leadership of IBM in the computer industry and later by Intel, Corp. in the semiconductor industry are examples of concentration in the newly formed, technology industry. Eventually, of course, newly formed, highly innovative industries such as keyword search, social media, and browser software also showed new business formation and high concentration.

Figure 8



Source: Historic Data Colonial Times to Present, Part 2, Business Enterprise, Series V 20-30 Business Formation and Business Failures 1857 to 1970; Statistical Abstract, Various Issues, 1980 – 1990; and US Census Bureau, 2018 Business Dynamics Statistics 1979 – 2018.

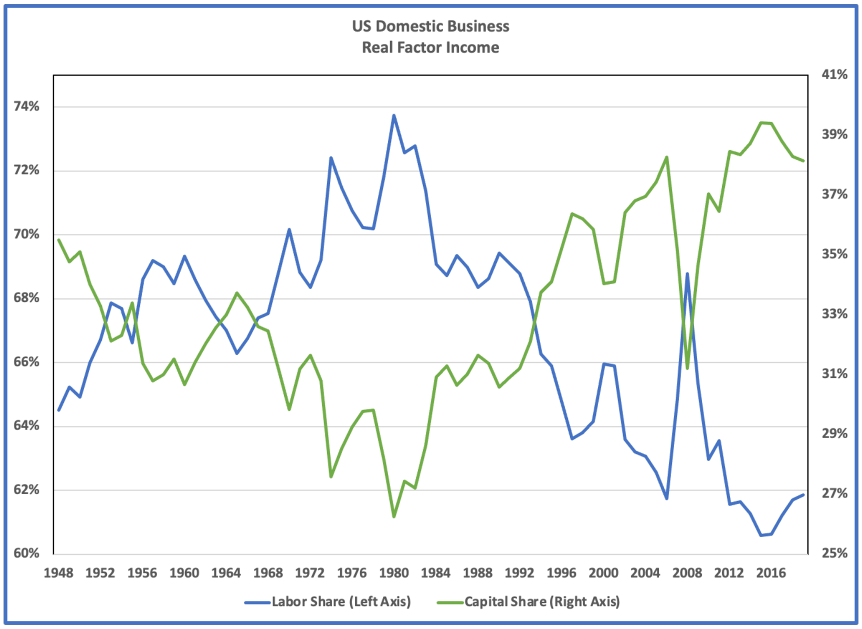
4.2 Labor Income Share

The Akcigit and Ates suggest that declining knowledge diffusion from productivity leading firms results in a labor income share decrease with more productive firms thriving with fewer workers. The labor share decrease implies higher markups and profits along with a shift to more concentrated sectors.

The decline of labor's income share across the industrialized economies is, by now, well-known and well-documented.[23] As is also well-known, it was long understood that labor income as a share of GDP was constant. Kaldor (1961) famously cited the stability of labor's early 20th century income share as a "stylized fact". The post-1980 fall in the US labor income share, shown in Figure 9, has eliminated stable labor income share as a fact. Autor et. al. (2020) find that the fall in labor's income share fall is "real and significant" and not a result of mismeasurement. Autor et. al. also assert that the cause of the share decline is not as a result of "rapid declines in quality-adjusted equipment prices, especially of information and communication technologies", "social norms and labor market institutions, such as unions and the real value of the minimum wage" and "trade and international outsourcing".[24]

[23] See Autor, Dorn, Katz, Patterson and Van Reenen (2020) for an empirical review of labor shares across 12 OECD and a literature review of the fall in labor share.
[24] Autor et. al. do not find manufacturing industries with greater exposure to trade shocks lose labor share relative to other manufacturing industries, but observe employment declines in such industries. They also find a decline in labor's share in nontraded sectors, such as wholesale trade, retail trade, and utilities.

Figure 9



Source: US Bureau of Economic Analysis. National Income and Product Accounts. Table 1.13. National Income by Sector, Legal Form of Organization, and Type of Income Goods, rows 4, 5, 6, and 7 with author's calculations.

Autor et. al. analyze US Economic Census data for six large sectors over three decades; 1982 – 2012.[25] The covered employment makes up approximately 80% of US employment and GDP with data for 676 industries of which 388 are in the manufacturing sector. They also draw on the 2012 release of the EU KLEMS database, to measure international trends in the labor share and augment the measurement of the labor share in the US Economic Census.

Autor et. al. find there has been a "rise in sales concentration within four-digit industries across the vast bulk of the US private sector, reflecting the increased specialization of leading firms on core competencies" (See page 650).[26] The industries that have become more concentrated are those with faster productivity growth and innovation among the industries' productivity leading firms with larger firms getting larger and realizing higher markups. As a result, those industries with increased product market concentration, more rapid productivity growth, and enhanced innovation have experienced

[25] The six sectors are manufacturing, retail trade wholesale trade, services, utilities and transportation, and finance.

[26] Autor et. al. label the industry-leading, high productivity firms as "superstar firms", calling to mind a small set of well-known technology firms. However, their data cover 676 four-digit industries, suggesting the phenomena is wide spread across industry sectors. Firms with the largest sales in a four-digit industry operated in an average of 13 other four-digit industries in 1982, but had presence reduced to fewer than nine industries in 2012. Companies like Amazon, which are becoming increasingly dominant across multiple industries, are the exception.

larger declines in the labor share. Because labor shares tend to be lower in larger firms, reallocation of market share to larger firms tends to depress aggregate labor share.

Importantly, Autor et. al. also show the share declines are largely due to the reallocation of sales and value added between firms rather than a fall in the labor share for the average firm. The reallocation-driven fall in the labor share is most pronounced in the industries exhibiting the largest increase in sales concentration. These same patterns are also present in other OECD countries.

To the extent that the advent of new technology increases automation, lowers marginal costs, and reduces markups, labor's income share rises at the firm level among productivity leading firms. When "market toughness" increases - as defined by lower marginal cost – an aggregate labor income share decline requires between-firm reallocation - the shift of market share to more productive firms.

Finally, Autor et. al. observe that a high level of concentration does not necessarily mean persistent dominance. In the spirit of "creative destruction" one dominant firm could quickly replace another. If incumbents are more likely to innovate than entrants, incumbency could create advantages for high market share firms. Conversely, dominant but complacent firms could be replaced by more eager entrants. Rising industry concentration among productivity-leading firms is more prevalent in industries with quicker technology adoption and more rapid total factor productivity (TFP) growth. The result is a reallocation of output toward high-productivity and low labor share firms.

Shifting capital and labor income shares were a dynamic element in early industrial revolutions. Allen (2009) identifies "Engles' Pause" as the period that aligns with the 1st Industrial Revolution's installation period in which 18th century UK technology innovations revolutionized industries with Britain's income shares remaining relatively constant.

Acemoglu (2002) argues that technological change in the late eighteenth and early nineteenth centuries may have been biased ***toward*** unskilled labor. Increased demand for those unskilled workers in the new factory system was the product of the "invention of a new method of invention". Consequently, there was a large migration of unskilled workers to English cities and a large increase in population.

Both Allen (2009) and Crafts (2021a) simulate counterfactuals that eliminates the population explosion. Both find the population shocks undermined the 1st Industrial Revolution's potential to raise real wages. Because labor's income share is the product of the average wage rate, labor force participation and population, migrating workers add to the available work force, independent of population growth. Increased participation of unskilled labor can hold labor's share constant while the average wage rate is declining.

While industrial revolutions are characterized by investment and depreciation in tangible and intangible capital, it is also characterized by differential knowledge diffusion and changes in labor income share. The high-productivity firms with leading-edge capabilities are able to capture the early benefits of the new technology in the industrial revolution's installation period, resulting in declining labor income share. Lagging firms wait until the new technology is less expensive, well understood and the extent and nature of the necessary "creative destruction" is clear in the deployment period.

As the deployment period progresses and knowledge diffusion is more readily available with increased absorptive capacity on the part of recipients, a broader cross-section of industry firms are able to (1) adopt the new technology, (2) creatively destruct their existing business models and processes, (3) innovate with lessons learned from industry leaders, and (4) profitably invest in new tangible and intangible capital. With such wide spread adoption, macroeconomic benefits are likely with more rapid output and productivity growth and low inflation.

5.0 Business, Political and Social Transformation as Growth Recovers

As the deployment era is set to begin, the gap between the desired and actual capital stock widens, the previous era's embodied but now antiquated technology becomes insufficient, the new general-purpose technology achieves maturity, and low cost. As pressure builds for "creative destruction", a new period of economic, social and political activity can appear.[27] However, robust growth is not guaranteed. If successfully innovated and deployed, new management practices and business models, supported by social and political transformation, will deliver an extended period of rapid income growth and wealth creation. As history has demonstrated, achieving a path of sustained above average growth requires, not only an alignment of current and future financial asset values - delivered by a deep global recession and a major financial crisis - but also sufficient pressure to reduce investor, household, and business resistance. While there are few data points, the US civil war of the 1860s, the global recession of the 1930s, the second world war of the early 1940s, and - perhaps - the 2020-2021 global pandemic might qualify as having massively disrupted social and economic activity at a point in time when the global economy was prepared to enter a new era.

Understanding what the coming deployment period - 2021 and beyond - might look like requires a view of rate and pace of change to information technology, capital investment, labor markets, business strategy, and public policy.

5.1 Information Technology

The semiconductor and electronics technology launched by IBM and later Intel in the early 1970s has given rise to an inexpensive, low cost, general-purpose technology that is now in wide use across virtually every economic and geographic sector. While the digital technology that has emerged from 50 years of innovation has not only automated many previously manual business and personal tasks, it has also resulted in near-instant global communication and ubiquitous digital services, increasing personal and business efficiency. The period ahead is likely to see even more significant gains if digital technology permits the widespread use of artificial intelligence (AI) technology.

In an assessment of the deployment of AI technology, Bresnahan (2019) finds leading applications in early diffusion but on a similar track as other information and communication technology (IC) technology systems of the past 25 years. AI technology applications have been deployed across a range of industries but have gained most traction in consumer-oriented mass-market production, distribution, and marketing systems in search, social media, and retail. User interface capabilities based in natural language processing, cloud computing, statistical prediction, and complementary network technology

[27] See Gordon (2016) and Mokyr (1998) for discussion of social and economic transformation. For a broader discussion of social and economic transformation see: Acemoglu and Robinson (2012) and Acemoglu and Robinson (2019).

remain limited. While early success has been achieved with financial services, human resource systems, and decision support, other industry applications remain nascent.

Acemoglu, Autor, Hazell and Restrepo (2021) find no discernible relationship between AI exposure and employment or wage growth at the occupation or industry level, implying that AI has not yet achieved detectable aggregate labor market consequences.

Brynjolfsson, Rock, and Syverson (2021) find that as firms adopt new technology, productivity growth initially languishes. Intangible capital is necessary for business process, new product, and service development. Later, productivity growth strengthens as capital service flows from the previously applied intangible stocks and measurable output is generated. Measured productivity growth follows a J-curve shape, initially dipping while the investment in intangible capital is larger than the investment in other types of capital, then rising as growing intangible stocks begin to contribute to measured production. In the long run, tangible and intangible investments reach their steady-state growth rates, the return-adjusted value of the intangible capital service flows approaches the value of the initial investment.

As would be expected in the early years of the 4th Industrial Revolution's deployment period, widespread use of the AI technology is in the early stages. In the early years of a possible 30-year journey, applications remain limited, a challenge to deploy, and immature. Capabilities will likely grow, expand, and simplify leading to broad and deep adoption.

5.2 Capital Investment

With the deployment of the new general-purpose technology in an early stage, the turnaround in the long-term trend in nonresidential capital investment spending is also in an early stage (See Figure 3). With growth remaining weak, the decades-long slowdown continues to receive the attention of scholars.

With substantial heterogeneity across sectors, Crouzet and Eberly (2020), who have published the most detailed econometric work, warn statements about the aggregate investment gap may be misleading. However, a redistribution of rewards away from capital owners and to high-wage workers - the providers of intangible capital - could be a contributing factor to weak investment growth. Crouzet and Eberly show "rising rents and rising intangibles cannot be meaningfully analyzed in separation, as their interaction contributes to the gap between investment and returns" (Crouzet and Eberly 2020, p. 2).[28]

[28] While Crouzet and Eberly provide quantitative estimates at the macro level and Autor et. al. provide an empirical model at the firm level, both point to the role of intangible assets. Autor et. al. do not explicitly estimate an investment equation while Crouzet and Eberly model the capital investment implications.

Weak capital investment and the delayed onset of the 4th Industrial Revolution's deployment period has also received attention under the banner of secular stagnation, a notion originally offered by Hansen (1939) and offered again recently by Summers (2014).

Summers suggests:

> it is useful at the outset to consider the possibility that changes in the structure of the economy have led to a significant shift in the natural balance between savings and investment, causing a decline in the equilibrium or normal real rate of interest that is associated with full employment. (Summers 2014 p. 69)

Summers (2014) and Rachel and Summers (2019) argue that the tendency to secular stagnation, but for extraordinary fiscal policy actions, require real interest rates "far below their current slightly negative level". Summers and Rachel estimate that the "private sector neutral real interest rate" might have declined by 700 basis points since the 1970s.

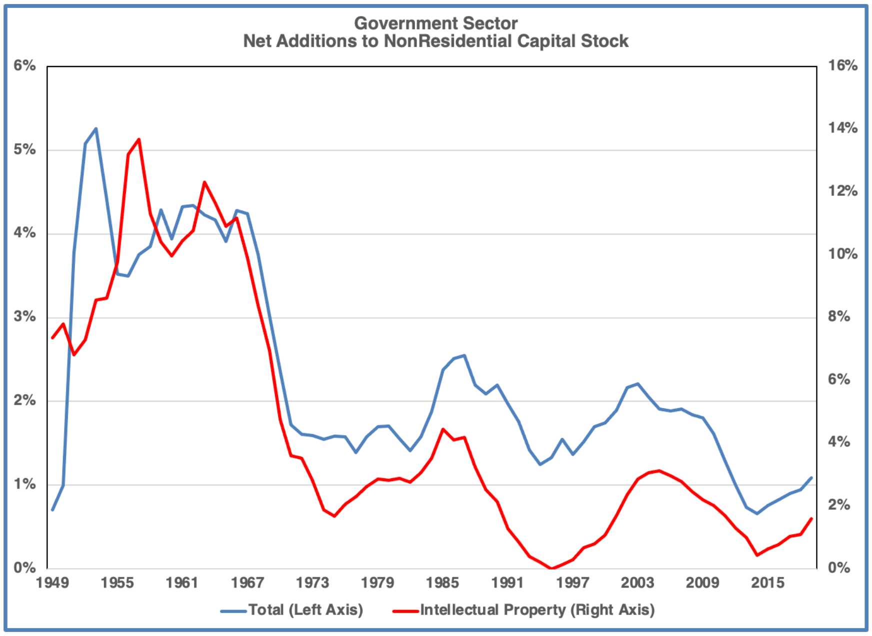
5.3 Global Social, Economic and Political Transformation

Similar slow, early and lagging transformation is underway in other domains. Among many scholars, Summers (2014) and Rachel and Summers (2019) advocate the need for more aggressive federal government investment. Mazzucato (2021) "looks at the grand challenges facing us in a radically new way, arguing that we must rethink the capacities and role of government within the economy and society, and above all recover a sense of public purpose".

The recent weakness in US government sector investment is shown in Figures 10 and 11. Conversely, it is of interest to see in the deployment period of the 3rd Industrial Revolution the strength of federal government investment spending, preceded the rapid and robust expansion of private nonresidential capital. In particular, federal spending expanded rapidly, building the stock of intellectual property. While US federal investment in intellectual property was encouraged by US-Soviet strategic competition, boosting military expenditures and creating the desire to explore space, private benefits emerged. The rival and nonexclusive nature of public sector intangible asset investment provided private sector organizations with opportunities for growth and innovation. Similarly, the significant investment in structures – roads, bridges, etc. – also encouraged private sector expansion. More than 60 years later, the infrastructure provided by such investment has depreciated significantly and lacks the electronic capability that the internet-of-things now provides.

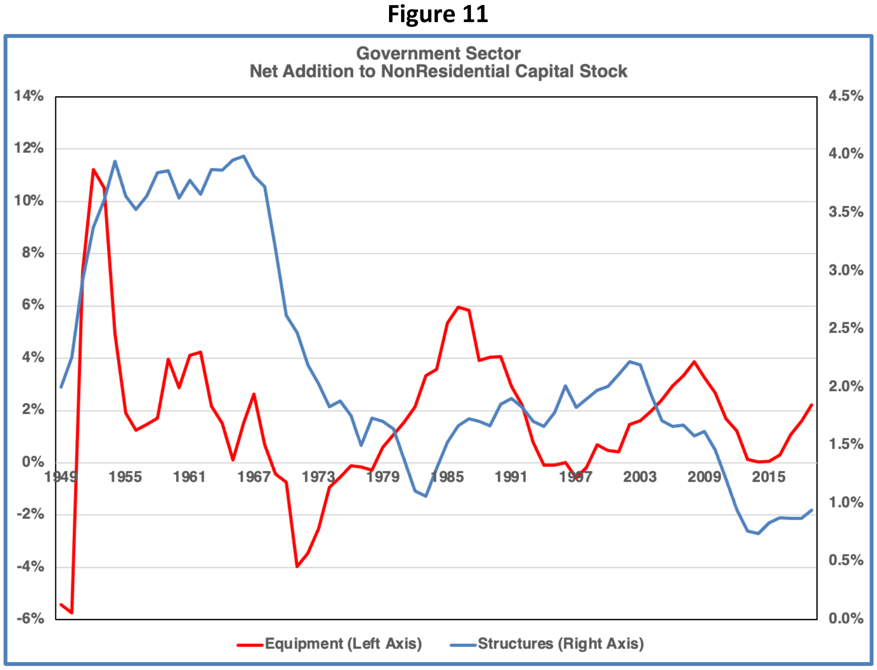
Beyond the need of a shift in the drivers of tangible and intangible capital investment, the social contract among government, business leaders and workers is in need of fundamental reexamination. Both the wage structure and the nature of employer-employee relationships are among the issues at the heart of the transformation. Employer-employee relationships contribute to productivity differences across manufacturers and service providers (See Fleming 2021).

Figure 10



Source: US Bureau of Economic Analysis. Fixed Assets Accounts Table. Table 1.1 Current-Cost Net Stock of Fixed Assets and Consumer Durable Goods, row 16 and 19, Table 1.3 Current-Cost Depreciation of Fixed Assets and Consumer Durable Goods, row 16 and 19, and Table 1.5 Investment in Fixed Assets and Consumer Durable Goods, row 16 and 19.

Figure 11



Source: US Bureau of Economic Analysis. Fixed Assets Accounts Table. Table 1.1 Current-Cost Net Stock of Fixed Assets and Consumer Durable Goods, row 17 and 18, Table 1.3 Current-Cost Depreciation of Fixed Assets and Consumer Durable Goods, row 17 and 18, and Table 1.5 Investment in Fixed Assets and Consumer Durable Goods, row 17 and 18.

Employee engagement - worker's involvement, satisfaction and enthusiasm for a job role - has been recognized at points in the past as important for productivity growth, business success, and improved living standards. Perhaps the most radical restructuring – early in the deployment period of the 3rd Industrial Revolution - was the 1950 Treaty of Detroit. At a time when manufacturing employment was nearly a third of US payroll employment – it is currently less than 10% - automobile industry leaders, United Auto Worker (UAW) leaders, and President Harry Truman codified and extended institutions for labor relations that had begun in the 1930s and had been enlarged in the very different environment of the second world war (Levy and Temin 2007). Importantly, the successful auto industry agreements soon scaled to other industries.

Beyond issues related to the *wage* structure, one might also expect changes in *work* structure, such as outsourcing or off-shoring, to impact employer-employee relationships. In the US, recent work by Stansbury and Summers (2020) cites declining worker power as a unified explanation for rising profitability and market valuations of US businesses, sluggish wage growth, and reduced unemployment and inflation, especially in the recovery from the 2008 – 2009 financial crisis.

Wages, compensation, skill development, career advancement, work environment, management relationships all contribute to worker engagement and, thus, productivity. Further, the issue is to understand the extent to which improvements in worker engagement can scale to provide broader economy-wide benefit. The improvement of income and social welfare benefits along with an improved management and decision-making framework, captured in the Treaty of Detroit and subsequently scaled across the US economy, appear to have been correlated with subsequent productivity improvement at the macroeconomic level.

Finally, business strategy undoubtedly also faces the need to transform in fundamental ways. The 4th Industrial Revolution's installation period – like those preceding it – focused on invention and innovation at the level of basic systems and electronics. In the deployment period, invention and innovation will be at the system level. The installation period is a time of experimentation for business models as well as for the technology. As the technology matures, as engineering successfully embeds the technology in the capital investment, and as successful business models are discovered, the installation period can begin to give way to the deployment period. After the assets that funded poor investments are washed out in the major financial markets crash, new, often revolutionary business models begin to appear. As Bresnahan observes, Amazon would be exhibit A of a radical new business models and processes, building on revolutionary new technology, with a fundamentally new business model.

6.0 Conclusion

Clearly, the future is uncertain. There is no guarantee that the deployment era of the 4th Industrial Revolution will deliver robust and rapid growth, capital deepening, productivity growth increases, and improved living standards that earlier periods have delivered. The concern is well-founded. Hysteresis is the persistence of negative effects after the initial cause is removed. Blanchard, Cerutti, and Summers (2015) examine 122 recessions over 50 years in 23 countries, finding a high proportion have been followed by lower output or slow growth. Blanchard and Summers (1986) argue economic shocks have a persistent effect on unemployment. Citing 15 years of steadily rising European unemployment, they distinguish between insiders and outsiders in wage bargaining. If wages are largely set by bargaining between insiders and firms, outsiders are disenfranchised and wages are set with a view to insuring the jobs of insiders. Membership considerations, and lack of fundamental transformation, can explain the tendency of the equilibrium unemployment rate to follow the actual unemployment rate.

Consequently, if robust and rapid growth is forthcoming, it is likely that economic, social, and political transformation is required. Public investment in both tangible and intangible capital is certainly a requirement. Policy actions that encourage the deployment of the new technology along with policy actions that support and promote both the engagement of workers and the development of skills for newly required tasks is also necessary. More fundamentally, it is the resistance to change that must be overcome if workers, business leaders, elected public officials, and capital owners are to risk setting aside old, comfortable ways to adopt new and different ways. The hope of improved and more equal living standards as income and wealth accumulation call for new ways of working, leading, and investing. Posen (2021) writes, "the United States needs to embrace economic change rather that nostalgia".

The 2020 - 2021 global pandemic has clearly disrupted businesses, households and governments. With many families experiencing devastating consequences and many businesses destroyed, the open issue is whether the shock has been of such size as to create sufficient pressure to drive fundamental change – overcoming the hysteresis effect.[29] Increased use of e-commerce and work-from-home are changes of the nature that were in train well before the pandemic. It's possible that the pandemic's disruption and devastation has been severe enough that governments, businesses, and households will not return to old pre-pandemic ways, but will transform to new ways. As Aghion, Antonin, and Bunel (2021) write, such is the power of "creative destruction".

Such radical transformations have been experienced in the past. The military build-up for World War II resulted a large number of young men – there were also a number of brave young women – gaining new skills, military disciple, and experience that, at the conclusion of the conflict, were applied to business and government with new education opportunities. Workers, often women, on the home front similarly gained new labor market experience. The manufacturing sector converted almost completely to war-

[29] A recent survey by PWC (2021) found that 65% of employees are looking for a new job and 88% of executives are seeing higher turnover than normal.

time production. At the conclusion of the war, the manufacturing sector, largely, did not return late 19th century technology, but deployed the then-mature 20th century technology. While the 2020 - 2021 pandemic will perhaps inflict disease and death on the scale of a world war, it remains to be seen how businesses, households, and governments transform in the aftermath.

In the years ahead, the outcome will, ultimately, depend on the nature of the social contract that emerges among workers, business and political leaders, and owners of capital. Economic shocks do not, by their nature, deliver negative outcomes. The direction of the sign depends on the response of the social and economic system. With sufficient leadership, flexibility, and foresight transformation can deliver a positive future.

References

Acemoglu, Daron (2002), "Directed Technical Change", *Review of Economic Studies*, 69, 781-809.

Acemoglu, Daron, David Autor, Jonathon Hazell, and Pascual Restrepo (2021), *AI and Jobs: Evidence from Online Vacancies*, Paper presented at the American Economic Association 2021 Annual Meeting, January 3rd, link.

Aghion, Philippe, Celine Antonin, and Simon Bunel (2021), *The Power of Creative Destruction, Economic Upheaval and the Wealth of Nations*, (The Belknap Press, Cambridge).

Akcigit, Ufuk and Sina T. Ates (2021), "Ten Facts on Declining Business Dynamics and Lesson from Endogenous Growth Theory", *American Economic Journal: Macroeconomics*, 13 (1), 257 - 298.

Aliber, Robert Z. and Charles P. Kindleberger (2015); *Manias, Panics and Crashes, A History of Financial Crises*, Seventh Edition; (Palgrave Macmillan, New York, NY).

Allen, Robert C. (1983), "Collective Invention", *Journal of Economic Behavior and Organization*, 4 (1), 1-24.

Allen, Robert C. (2009), "Engels' Pause: Technical Change, Capital Accumulation, and Inequality in the British Industrial Revolution", *Explorations in Economic History*, 46(4): 418–435.

Allen, Robert C. (2017), "Class Structure and Inequality during the Industrial Revolution: Lessons from England's Social Tables, 1688-1867", Working Paper # 0002 May.

Autor, David, David Dorn, Lawrence F. Katz, Christina Patterson, and John Van Reenen (2020), "The Fall of The Labor Share and The Rise of Superstar Firms," *The Quarterly Journal of Economics*, 645–709.

Banerjee, Abhijit V. and Duflo, Esther (2019), *Good Economics for Hard Times* (Hachette Book Group, Inc, New York, NY).

Basu, Susanto, John G. Fernald, and Zheng Liu (2012) "Technology Shocks in A Two-Sector DSGE Model" Manuscript, Federal Reserve Bank of San Francisco, June.

Bessen, James (2003), "Technology and Learning by Factory Workers: The Stretch-out at Lowell, 1842", *The Journal of Economic History*, 63(1): 33-64.

Bessen, James (2015), *Learning by Doing; The Real Connection between Innovation Wages, and Wealth*, (Yale. University Press, New Haven).

Bessen, James and Alessandro Nuvolari (2016), "Knowledge Sharing Among Inventors: Some Historical Perspectives", in Dietmer Harhoff and Karim R. Lakhani, *Revolutionizing Innovation: Users, Communities, and Open Innovation*, (The MIT Press, Cambridge, MA).

Blanchard, Olivier J. and Lawrence H. Summers (1986), *Hysteresis and the European Unemployment Problem*, National Bureau of Economic Research, Working Paper No. 1950. June.

Blanchard, Olivier J., Eugenio Cerutti, and Lawrence H. Summers (2015), *Inflation and Activity – Two Explorations and their Monetary Policy Implications*, IMF Working Paper, Research Department, November.

Bloom, Nicholas and John Van Reenen (2007), "Measuring and Explaining Management Practices Across Firms and Countries," *The Quarterly Journal of Economics*, 122(4)4: 1351–1408.

Bloom, Nicholas, Raffaella Sadun, and John Van Reenen (2012), "Americans Do IT Better: US Multinationals and the Productivity Miracle," *American Economic Review*, 102(1): 167-2011.

Bloom, Nicholas, Tarek Alexander Hassan, Aakash Kalyani, Josh Lerner, Ahmed Tahoun (2021), "The Diffusion of Disruptive Technologies", National Bureau of Economic Research, Working Paper 28999, July.

Bolt, Jutta and Jan Luiten van Zanden (2020), *Maddison Style Estimates of the Evolution of the World Economy, a New 2020 Update*, (October) link.

Bresnahan, Timothy (2019), *Artificial Intelligence Technologies and Aggregate Growth Prospects*, Version IV, May link.

Broadberry, Stephen, Bruce M. S. Campbell, Alexander Klein, Mark Overton, Bas van Leeuwen (2015), *British Economic Growth, 1270-1870*, (Cambridge University Press, Cambridge, UK).

Brynjolfsson, Erik, Daniel Rock, and Chad Syverson (2021), "The Productivity J-Curve: How Intangibles Complement General Purpose Technologies", *American Economic Journal: Macroeconomics*, 13(1): 333–372.

Caballero, Ricardo (2010), "Creative Destruction", in Steven N. Durlauf and Lawrence E. Blume, *Economic Growth*, (SpringerLink, Berlin/Heidelberg, Germany), pp. 24 – 29.

Cohen, Wesley M. and Daniel A. Levinthal (1990), "Absorptive Capacity: A New Perspective on Learning and Innovation", *Administrative Sciences Quarterly*, 35, pp 128-152.

Corrado, Carol (forthcoming), "Intangible Capital", in *Productivity Measurement Initiative*, The Brookings Institution Hutchins Center on Fiscal and Monetary Policy.

Coyle, Diane (2021), “The idea of Productivity”, The Productivity Institute Working Paper 003, June.

Crafts, Nicholas (2002), *The Solow Productivity Paradox in Historical Perspective*, Center for Economic Policy Research, Discussion Paper No. 3142, January.

Crafts, Nicholas (2004), “Steam as a General-Purpose Technology: A Growth Accounting Perspective,” *Economic Journal* 114 (495): 338–51.

Crafts, Nicholas (2019), "The Sources of British Economic Growth since the Industrial Revolution: Not the Same Old Story," The Warwick Economics Research Paper Series (TWERPS) 1216, University of Warwick, Department of Economics.

Crafts, Nicholas (2021a), “Understanding Productivity Growth in the Industrial Revolution”, *Economic History Review*, 74(20: 309-338.

Crafts, Nicholas (2021b), “Artificial Intelligence as General-Purpose Technology: an Historical Perspective”, Working Paper, February.

Crafts, Nicholas and Charles K. Harley (1992), "Output Growth and the British Industrial Revolution: A Restatement of the Crafts-Harley View", *Economic History Review*, 45 (4):703.

Crafts, N. and Mills, T. C. (2020a), ‘Sooner Than You Think; the Pre-1914 UK Productivity Slowdown Was Victorian Not Edwardian’, *European Review of Economic History*, 24(4): 736–748.

Crafts, N. and Mills, T. C. (2020b), ‘The Race Between Population and Technology: Real Wages in the First Industrial Revolution’, *Centre for Economic Policy Research* Discussion Paper No. 15174.

Crouzet, Nicolas and Janice Eberly (2020), *Rents and Intangible Capital: AQ+ Framework*, link, March.

Cullenberg, Stephen E. and Indraneel Dasgupta (2001), “From Myth to Metaphor: A Semiological Analysis of the Cambridge Capital Controversy”, in Jack Amariglio, Stephen E Cullenberg, and David F Ruccio editors, *Postmodernism, Economics and Knowledge* 1st Edition, Routledge, Chapter 16, pp. 337 – 353.

David, Paul A. (1990), “The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox”, *American Economic Review, Papers and Proceedings*, 80(2), 355-361.

Denison, Edward (1985), *Trends in American Economic Growth* (Brookings Institution Press, Washington, DC).

Easterly, William (2001), *The Elusive Quest for Growth* (MIT Press, Cambridge, MA).

Fernald, John G. (2019), "A Quarterly, Utilization-Adjusted Series on Total Factor Productivity." *FRBSF Working Paper* 2012-19.

Fleming, Martin (2021), *Leadership, Transformation and Worker Engagement Impact on Productivity*, (Unpublished), February.

Furman, Jason and Lawrence Summers (2020), *A Reconsideration of Fiscal Policy in the Era of Low Interest Rates*, paper prepared for presentation to the Hutchins Center on Fiscal & Monetary Policy and Peterson Institute for International Economics, December.

Gilchrist, Simon and John C. Williams (2002), *Investment, Capacity, and Uncertainty: A Putty-Clay Approach*, Federal Reserve Bank of San Francisco Working Paper 2002-3, San Francisco CA, May.

Goodhart, Charles and Manoj Pradhan (2020), *The Great Demographic Reversal*, (Palgrave Macmillan, London).

Gordon, Robert J. (2016), *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War,* (Princeton University Press, Princeton, NJ).

Hamilton, James D. (2017), "Why You Should Never Use the Hodrick-Prescott Filter" Working Paper.

Hansen, Alvin, H. (1939), "Economic Progress and Declining Population Growth", *American Economic Review* 29 (1) March pp. 1-15.

Harberger, Arnold, C. (1998), "A Vision of the Growth Process", *American Economic Review*, 88(1): 1 – 31.

Haskel, Jonathan and Stian Westlake (2018), *Capitalism Without Capital*, (Princeton University Press, Princeton).

Hercowitz, Zvi (1998), "The 'Embodiment' Controversy: A Review Essay", *Journal of Monetary Economics* 41, 217 – 224.

Hodrick, Robert J. (2020). "An Exploration of Trend-Cycle Decomposition Methodologies in Simulated Data" Working Paper.

Hodrick, Robert; Prescott, Edward C. (1997). "Postwar U.S. Business Cycles: An Empirical Investigation". *Journal of Money, Credit, and Banking*. 29 (1): 1–16. JSTOR 2953682.

Johansen, Leif (1959). "Substitution Versus Fixed Production Coefficients in the Theory of Economic Growth: A Synthesis." *Econometrica*, Vol. 27, No. 2: 157-176. JSTOR 1909440.

Jorgenson, Dale, and KJ Stiroh (2000), "Raising the Speed Limit: U.S. Economic Growth in the Information Age" *Brookings Papers on Economic Activity* 1: 125-212.

Kaldor, Nicholas (1961), "Capital Accumulation and Economic Growth," in *The Theory of Capital*, ed. F. A. Lutz and D. C. Hague, (St. Martin's Press, New York), pp. 177–222.

Kelly, Bryan, Dimitris Papanikolaou, Amit Seru, and Matt Taddy (2021), "Measuring Technological Innovation over the Long Run", *American Economic Review: Insights*, 3(3): 303-20.

Keshavarzi Arshadi Arash, Webb Julia, Salem Milad, Cruz Emmual, Calad-Thomson Stacie, Ghadirian Niloofar, Collins Jennifer, Diez-Cecilia Elena, Kelly Brendan, Goodarzi Hani and Yuan Jiann Shiun; (2020) Artificial Intelligence for COVID-19 Drug Discovery and Vaccine Development, *Frontiers in Artificial Intelligence,* 3:65. https://doi.org/10.3389/frai.2020.00065

Kendrick, John W. (1961), *Productivity Trends in the United States*, (National Bureau of Economic Research, Cambridge, Ma).

Kuznets, Simon (1955), "Economic Growth and Income Inequality", *American Economic Review*, 45(1), 1-28.

Lasky, Mark (2003), *A Putty-Clay Model of Business Fixed Investment*, Congressional Budget Office Working Paper 2003-9, Washington, DC, September.

Lewis, William Arthur, (1954), "Economic Development with Unlimited Supplies of Labour", *Manchester School of Economics and Social Studies* 22(May): 139–191.

Levy, Frank and Peter Temin (2007), Inequality and Institutions in 20th Century America, Industrial Performance Center, Massachusetts Institute of Technology, MIT-IPC-07-002.

Lucas, R. (1988), "On the Mechanics of Economic Development", *Journal of Monetary Economics*, 22(1), 3-42.

Ma, Song (2021), "Technology Obsolescence", Yale University School of Management, link.

Malthus, Thomas (1798), *An Essay on the Principle of Population*, (W. Pickering, London, 1986).

Mazzucato, Mariana (2021), *Mission Economy, A Moonshot Guide to Changing Capitalism* (Alen Lane, London).

Minsky, Hyman P. (1975), *John Maynard Keynes*, (Columbia University Press, New York, NY).

Minsky, Hyman P. (1986), *Stabilizing an Unstable Economy*, Twentieth Century Fund Report, (Yale University Press, New Haven CT).

Mokyr, Joel (1990), *The Levers of Riches: Technical Creativity and Economic Progress*, (Oxford University Press, New York, NY).

Mokyr, Joel (1998), *The Second Industrial Revolution, 1870 – 1914*, Northwestern University, link.

Mokyr, Joel (2011), *The Economics of the Industrial Revolution*, (Routledge, London).

Nordhaus, William D. (2021), "Are We Approaching and Economic Singularity? Information Technology and the Future of Economic Growth", *American Economic Journal: Macroeconomics*, 13(10), 299-332.

Perez, Carlota (2002), *Technological Revolutions and Financial Capital*, (Edward Elgar, Cheltenham, UK).

Posen, Adam S. (2021), "The Price of Nostalgia; America's Self-Defeating Economic Retreat", *Foreign Affairs*, May/June pp. 28-43.

PWC (2021), *PwC US Pulse Survey: Next in Work; At a Pivotal Monet for the Future of Work, Companies Can Help Their Businesses and Employees Thrive*, link.

Rachel, Lukasz, and Lawrence H. Summers (2019), "On Secular Stagnation in the Industrialized World," *Brookings Papers on Economic Activity*, Spring, pp.1-76.

Reinhart, Carmen M. and Rogoff Kenneth S. (2009); *This Time is Different, Eight Centuries of Financial Folly*; (Princeton University Press, Princeton, NJ).

Ricardo, David (1817), *On the Principles of Political Economy and Taxation*, (Cambridge University Press, Cambridge, UK, 1951).

Romer, P.M. (1986), "Increasing Returns and Long-Run Growth", *Journal of Political Economy*, 94(5), 1002-1037.

Romer, P.M. (1987a), "Growth Based on Increasing Returns Due to Specialization", *American Economic Review, Papers and Proceedings*, 77(2), 56-62.

Romer, P.M. (1987b), "Crazy Explanations for the Productivity Slowdown", in Fischer, S. (ed.) *NBER Macroeconomics Annual*, 2, 163-210.

Romer, P.M. (1990), "Endogenous Technological Change", *Journal of Political Economy*, 98(5), S71-S102.

Romer, P.M. (1993), "Two Strategies for Economic Development: Using Ideas and Producing Ideas," in *Proceedings of the World Bank Annual Conference of Development Economics 1992*, Washington, DC: World Bank.

Royal Swedish Academy of Sciences, (2018), *Economic Growth, Technology Change and Climate Change*; (Scientific Background on the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel).

Schumpeter, Joseph A. (1950), *Capitalism, Socialism and Democracy*, (Harper Collins, New York, 3rd edition 2008).

Schwab, Klaus (2106), *The Fourth Industrial Revolution*, (World Economic Forum, Geneva).

Solow, Robert M. (1956), "A Contribution to the Theory of Economic Growth," *Quarterly Journal of Economics*, 70(1), 65-94.

Smith, Adam (1776), *An Inquiry into the Nature and Causes of the Wealth of Nations*, (Random House, New York, 1937).

Stansbury, Anna and Lawrence H. Summers (2020), "Declining Worker Power and American Economic Performance", *Brookings Papers on Economic Activity* forthcoming.

Summers, Lawrence H. (2014). "U.S. Economic Prospects: Secular Stagnation, Hysteresis, and the Zero Lower Bound." *Business Economics* 49(2): 65-73.

Summers, R. and A. Heston (1984), "Improved International Comparisons of Real Product and its Composition: 1950–1980", *Review of Income and Wealth*. June, 207-262.

Swan, Trevor (1956), "Economic Growth and Capital Accumulation", *Economic Record*, 32:December, pages 334-361.

The Economist (2020), "Reasons to be Cheerful", 12 December, pp. 69-71.

Van Ark, Bart and Anthony Venables (2020), "A Concerted Effort to Tackle the UK Productivity Puzzle", *International Productivity Monitor*, Centre for the Study of Living Standards, vol. 39, pages 3-15, Fall link.

Van Ark, Bart, Klaas de Vries, and Abdul Erumban (2020), *How to Not Miss a Productivity Revival Once Again?* National Institute of Economic and Social Research Discussion Paper No. 518, November.

Appendix A: Dating Major Global Financial Crises

Both of the most recent major global financial crises - 1930s and 2000s - followed close behind the peaks in the Kelly et. al. innovation index. Perez cites the mass production process that permitted the building of the Ford Motor Company's Model-T in 1908 as the signature innovation of the early 20th century, ultimately providing rapid growth of the 1920s and the mania that ensued (See Gordon 2016, pp. 149-168). Later in the century, it was Intel's microprocessor that made computing and communications at scale possible and that gave rise the current era.

While both of these technological innovations have gone on to demonstrate long-run success, in the excitement following their creation, the frenzy and mania – the roaring 20's and the dot.com bubble - eventually resulted in a separation of current period pricing and long-run fundamentals. The ensuing asset price correction and write down of debt, which financed such asset purchases, resulted in painful balance sheet adjustments that required deep recessions to correct.

While the 1929 – 1933 global depression and the 2008 – 2010 global financial crisis are well known, the 19th century's major financial crises are less well known. Further, available data describing the period are relatively sparce and are very limited for the early decades of the century.[30]

The 1890 peak in the Kelly et. al. innovation index is followed by a financial crisis aligning with the 1893-1894 recession as dated in the NBER chronology. See Table A.1. Both Perez and Aliber-Kindleberger designate the recession as a major global financial crisis. Aliber-Kindleberger and Reinhart-Rogoff designate the 1907- 1908 recession as a follow-on major global financial crisis as balance sheets were cleansed for the explosive growth ahead.

Perez points to the 1875 opening of the Carnegie Bessemer Pittsburgh steel plant as the instantiation of the innovation that drove the surge. Perez describes the era at the turn of the century as one in which distributed electrical power for industrial production was introduced.[31] Perez writes that economies of scale were created with massive steel structures for vertically integrated plants. Universal standardization and cost accounting were introduced for control and efficiency. Science became a productive force.

While data for the early decades of the 19th century are very limited, there is consensus that the building of the rail networks across continental Europe, Britain and the US resulted a mania at mid-century. Aliber-Kindleberger and Perez detail the 1848 – 1850 panic that followed the railroad mania. Aliber-

[30] The Kelly et. al. innovation index is limited by the lack of available patent data prior to 1840. Portions of the Reinhart-Rogoff financial crisis data extend back to 1800. Aliber, Kindleberger and Perez are economic historians and provide qualitative descriptions for earlier centuries.
[31] David (1990) and earlier papers describe the process of industrial electrification in detail. See also Gordon 2016, pp. 114-122. After the very significant technology deployment of the 1870s, Gordon (2016, p. 61) concludes: "The Second Industrial Revolution was on its way to changing the world beyond recognition."

Table A.1

Peak	Trough	Contraction	Expansion	Cycle			Major Financial Crisis		
Quarterly dates are in parentheses		*Peak to Trough*	*Previous Trough to This Peak*	*Trough from Previous Trough*	*Peak from Previous Peak*	*Kelly et. al. Innovation Peak*	*Perez*	*Aliber-Kindleberger*	*Reinhart - Rogoff*
Pre-NBER Chronology	*1793-1794*						Crisis	Crisis	
	1825-1826							Crisis	Crisis
	1848-1850						Crisis	Crisis	
	December 1854 (IV)	--	--	--	--				
June 1857 (II)	December 1858 (IV)	18	30	48	--				
October 1860(III)	June 1861 (III)	8	22	30	40				
April 1865(I)	December 1867 (I)	32	46	78	54				
June 1869(II)	December 1870 (IV)	18	18	36	50	Peak			
October 1873(III)	March 1879 (I)	65	34	99	52				
March 1882(I)	May 1885 (II)	38	36	74	101				
March 1887(II)	April 1888 (I)	13	22	35	60				
July 1890(III)	May 1891 (II)	10	27	37	40	Peak			
January 1893(I)	June 1894 (II)	17	20	37	30		Crisis	Crisis	
December 1895(IV)	June 1897 (II)	18	18	36	35				
June 1899(III)	December 1900 (IV)	18	24	42	42				
September 1902(IV)	August 1904 (III)	23	21	44	39				
May 1907(II)	June 1908 (II)	13	33	46	56			Crisis	Crisis
January 1910(I)	January 1912 (IV)	24	19	43	32				
January 1913(I)	December 1914 (IV)	23	12	35	36				
August 1918(III)	March 1919 (I)	7	44	51	67				
January 1920(I)	July 1921 (III)	18	10	28	17				
May 1923(II)	July 1924 (III)	14	22	36	40				
October 1926(III)	November 1927 (IV)	13	27	40	41				
August 1929(III)	March 1933 (I)	43	21	64	34	Peak	Crisis	Crisis	Crisis
May 1937(II)	June 1938 (II)	13	50	63	93				
February 1945(I)	October 1945 (IV)	8	80	88	93				
November 1948(IV)	October 1949 (IV)	11	37	48	45				
July 1953(II)	May 1954 (II)	10	45	55	56				
August 1957(III)	April 1958 (II)	8	39	47	49				
April 1960(II)	February 1961 (I)	10	24	34	32				
December 1969(IV)	November 1970 (IV)	11	106	117	116				
November 1973(IV)	March 1975 (I)	16	36	52	47				
January 1980(I)	July 1980 (III)	6	58	64	74				
July 1981(III)	November 1982 (IV)	16	12	28	18				
July 1990(III)	March 1991(I)	8	92	100	108				
March 2001(I)	November 2001 (IV)	8	120	128	128	Peak			
December 2007 (IV)	June 2009 (II)	18	73	91	81		Crisis	Crisis	Crisis

Source: NBER US Business Cycle Expansions and Contractions, Kelly et al. (2020), Perez (2002), Aliber and Kindelberger (2015), Reinhart and Rogoff (2009)

Kindleberger (2015, p. 192) write: "In January 1847 distress developed in London in response to railroad calls and the crisis came late in the summer".

Perez suggests that the 1829 test of the "rocket" steam engine for the Liverpool-Manchester railway began a series of innovations that resulted in economies of agglomeration and the creation of industrial cities, scale from standard parts and machine-made machines, and steam as an energy source. Crafts (2004) finds "steam contributed little to growth before 1830 …... Only with the advent of high-pressure steam after 1850 did the technology realise its potential."

Mokyr cites important innovations in the late 18th and early 19th centuries resulting from unskilled-bias technology: "First in firearms, then in clocks, pumps, locks, mechanical reapers, typewriters, sewing machines, and eventually in engines and bicycles, interchangeable parts technology proved superior and replaced the skilled artisans working with chisel and file" (See Mokyr 1990, p. 137. Cited in Acemoglu 2020).

Appendix B: Long-Lived Capital with Embedded Tangible and Intangible Capital

The embodiment of innovation, ideas, and technology in capital investment – both tangible and intangible – has been among the most notable features of the four industrial revolutions. The nature of technological embodiment has been a source of periodic controversy in the economics literature. Putty-clay capital was studied in the 1960s, and received renewed attention in the 1990s and 2000s. See Gilchrist and Williams (2003).

With putty-clay capital, the ex-ante production technology allows substitution between capital and labor. Ex post, however, productivity is determined by the embodied vintage technology and the fixed choice of capital intensity. In a putty-clay model, capital is replaced with capital that has greater capacity than the depreciated capital.[32] The purchase of new capital only affects the productivity of the workers using the new capital. It leaves the productivity of workers using legacy capital unaffected. The new capital does not impact the productivity of existing capital.[33]

To understand the influences of growth, productivity, technology and depreciation on investment spending, Lasky (2013) builds a model of investment spending in which the desired change in output capacity is a function of net additions to capacity, the growth in capacity from existing capital, and the difference in output from replacement capital and the capital replaced. The implication, by simple arithmetic, is that net additions to capacity - represented by an investment equation - equals the desired change in capacity minus both the increase in capacity from replacing depreciating capital with new capital and the gains in productive capacity from existing capital.

Let $N_{e,t}$ be the units of expansion capital of each type put in place at time t. Let $R_{m,t,i}$ be the units of capital of type m and age i depreciating at time t. Let y_t be the average output during period t of workers using only capital existing before time t. Let $y^h_{m,t,i}$ be the hypothetical output of a worker using a unit of capital of type m aged i years at time t had it not depreciated at time t.[34]

[32] Originally introduced by Johansen (1959), putty-clay technology, breaks the tight restriction on short-run production possibilities imposed by Cobb-Douglas technology and provides a natural framework for examining issues related to irreversible investment. However, an impediment to the adoption of the putty-clay framework has been the analytic difficulty associated with a model in which all existing vintages of capital are tracked.

[33] In the neoclassical production function, output is a function of labor hours, and the capital stock. Any investment affects the marginal productivity of all labor and existing capital. Empirical investment behavior supports the assumption of ex post fixed proportions (clay) over the assumption of ex post variable proportions (putty). See Lasky (2003).

[34] Lasky (2013) presents $N_{e,t}$ and $R_{m,t,i}$ as the number of machines for expansion and replacement. Also, $k_{m,t}$ is the size of machine type m used by worker n at time t. The assumption is that every worker uses a similar, although not identical, mix of different type of plant and equipment. Lasky's exclusion of intangible capital limits the model for current purposes. In this paper, the assumption is that there is both tangible and intangible capital. $N_{e,t}$ and $R_{m,t,i}$ are units of capital for expansion and replacement and $k_{m,t}$ is the size of capital of type m in constant dollars used by worker n at time t.

Let $y_{m,t+i,i}$ denote the output at time $t+i$ of a worker using capital of type m aged i periods at time $t+i$.

$$y_{m,t+i,i} = A_{t+i}U_{t+i}G_{m,t+i}(k_{m,t})^{\alpha} \qquad (1)$$

where A_{t+i} is economy-wide technology, U_{t+i} is the effect of economy-wide intensity of usage, or effort, on productivity, $G_t(\,)$ is the function aggregating different types of capital, $k_{m,t}$ is the size of capital of type m in constant dollars used by worker n at time t, and α is capital's coefficient in the production function. There are M types of capital.

Let y_t be period t output of workers using only capital existing before time t. If new capital was the same size as existing capital, expansion capacity would be $N_{e,t}y_t$. However, if new capital differs in size from existing capital, output will differ from that of existing capital. The output of expansion capital can be expressed as

$$N_{e,t}y_t\left[1+\sum_{m=1}^{M}\left(\frac{y_{m,t,0}}{y_t}-1\right)\right] \qquad (2)$$

In a putty-clay world, the output of replacement capital is generally larger than the output of a worker using depreciated capital. Let $R_{m,t,i}$ be units of capital of type m and age i depreciating at time t and let L_m be the service life of capital of type m. The total replacement capital of type m:

$$R_{m,t} = \int_0^{L_m} R_{m,t,i}\,di \qquad (3)$$

At time t, the increase in capacity obtained by replacing depreciated capital of all types with new capital is:

$$\sum_{m=1}^{M} R_{m,t}y_{m,t,0} - \sum_{m=1}^{M}\int_{i=0}^{L_m} R_{m,t,i}y^{h}_{m,t,i}di \qquad (4)$$

Let $\dot{A}_t$ be annualized growth of technology at time t. Then the rate of increase of capacity due to technology growth at time t is:

$$\left({\dot{A}_t}/{A_t}\right)N_t y_t \qquad (5)$$

where N_t is the total capital of each type at time t. Let $Y\dot{E}_t$ be the desired change in output at time t. Output per worker from new investment is:

$$N_{e,t}y_t\left[1+\sum_{m=1}^{M}\left(\frac{y_{m,t,0}}{y_t}-1\right)\right]$$
$$= \dot{Y}E_t - \sum_{m=1}^{M} R_{m,t}y_{m,t,0} + \sum_{m=1}^{M}\int_{i=0}^{L_m} R_{m,t,i}y^{h}_{m,t,i}di - \left({\dot{A}_t}/{A_t}\right)N_t y_t \qquad (6)$$

Adding $R_{m,t}y_{m,t,0}$, output of type m replacement capital, to both sides of equation (6), yields the output of new capital of type M:

$$
\begin{aligned}
&(N_{e,t} + R_{M,t})y_{M,t,0} \\
&= \dot{Y}E_t + R_{M,t}y_t - \left(\dot{A}_t / A_t\right) N_t y_t \\
&-N_{e,t} \sum_{m=1}^{M} (y_{m,t,0} - y_t) + R_{M,t}(y_{m,t,0} - y_t) \\
&- \textstyle\sum_{m=1}^{M} R_{m,t}y_{m,t,0} + \sum_{m=1}^{M} \int_{i=0}^{L_m} R_{m,t,i}y_{m,t,i}^{h}di \qquad (7)
\end{aligned}
$$

The first line of equation (7) to the right of the equal sign indicates the capacity of workers using new capital as the desired change in capacity plus the capacity of depreciated capital less the change in capacity from using improved technology with existing capital. The second line adjusts for the net output of new machines. The third line adjusts for the net output of existing machines.

To specify the investment equation, output per worker $y_{M,t,o}$ in equation (7) is replaced with the size of new capital of type M. Businesses choose the units of capital that maximize expected profits. The optimal units of capital depend on output per worker and the cost of capital.

The present discounted value of profits associated with a new unit of capital of type m purchased and put into service at time t is:

$$\pi_{m,t}^{*} = \int_0^{L_m} (p_{t+i}y_{m,t+i,i}, F_{t,i})di - q_{m,t}k_{m,t} \quad (8)$$

where p_t is the price of output y_t, F is the discount factor:

$$F_{t,i} = e^{-\int_0^i r_{t+j}dj}$$

For the nominal rate of return r_{t+j} at time t, $q_{m,t}$ is the purchase price of new capital of type m. Setting the derivative of the expected profit function (8) to zero and solving for $q_{m,t}$ yields:

$$q_{m,t} = \int_0^{L_m} \left(\hat{p}_{t+i} \frac{\delta \hat{y}_{m,t+i,i}}{\delta k_{m,t}} \hat{F}_{t,i}\right) di \qquad (9)$$

where a circumflex over a variable indicates an expected value.

If $\frac{\delta y}{\delta k}$ is replaced with the elasticity of the capital aggregator, G, with respect to the change in the size of the i-year-old type m capital at time $t+i$

$$s_{m,t+i,i} = \frac{\delta lnG_{m,t+i(k_{m,t})}}{\delta lnk_{m,t}}$$

then, the first order condition is:

$$q_{m,t} = \int_0^{L_m} \left(\hat{p}_{t+i} \alpha_t s_{m,t+i,i} \frac{\hat{y}_{m,t+i,i}}{k_{m,t}} \hat{F}_{t,i} \right) di \quad (10)$$

where $\alpha_t s_{m,t+i,i}$ is the share of the present discounted value of the expected output to be produced by the work using the new capital that equates with the cost of new capital. If $s_{m,t+i,i}$ is constant over time:

$$q_{m,t} k_{m,t} = \alpha s_{m,t,0} p_t y_{m,t,o} \int_0^{L_m} e^{(\dot{p}_t + \dot{y}_m - r)} di \quad (11)$$

Evaluating the integral and solving for $k_{m,t}$ yields the optimal size of capital units:

$$k_{m,t} = \alpha s_{m,t,0} \frac{p_t}{v_{m,t}} y_{m,t,o} \quad (12)$$

where $v_{m,t}$ is the cost of capital:

$$v_{m,t} = q_{m,t} \frac{r - \dot{p}_t - \dot{y}_m}{1 - e^{[-(r - \dot{p}_t - \dot{y}_m) L_m]}} \quad (13)$$

For simplification, rewriting equation (7):

$$(N_{e,t} + R_{M,t}) y_t = \dot{Y}E_t + R_{M,t} y_t - \left(\dot{A}_t / A_t \right) N_t y_t + NONC + NOEC \quad (14)$$

where $NONC$ is net output of new capital and $NOEC$ is net output of existing capital. Investment in capital of type m at time t:

$$I_{m,t} = (N_{e,t} + R_{M,t}) k_{m,t} \quad (15)$$

Substituting for $k_{m,t}$ from equation (12), dividing by y_t, and substituting for $(N_{e,t} + R_{M,t})$ yields:

$$I_{m,t} = \alpha s_{m,t,0} \frac{p_t}{v_{m,t}} \frac{y_{m,t,0}}{y_t} \left[\dot{Y}E_t + R_{M,t} y_t - \left(\dot{A}_t / A_t \right) N_t y_t + NONC + NOEC \right] \quad (16)$$

Investment in capital of type m is a function of (1) the elasticity of output with respect to capital of type m, (2) the ratio of the output price to the cost of capital, (3) the increment of desired capacity growth from capital type m, (4) desired capacity growth, (5) replacement demand, (6) growth in technology and (7) the net gain from net new and existing capital.

With (16), the impact of demand and productivity shocks on investment spending can be considered. Somewhat surprisingly, the model is explicit about the impact of technology on investment but treats the impact of changes in total factor productivity (TFP) indirectly. Technology, A, alters the output delivered per unit of capital. Similarly, improved technology can also reduce $q_{m,t}$, the purchase price of capital. TFP, as is the standard definition, alters output as resources are collectively utilized in alternative configurations. Changes in technology and TFP do not, in principle, need to be associated or causally related. [35]

In (16), an increase in TFP could cause a proportionate rise in output and thus in investment. TFP could also affect the cost of capital relative to the output price. For example, if higher productivity leads to lower inflation and interest rates, real interest rates and the real cost of capital could decline. Similarly, improved TFP could increase the output of existing capital, reducing the need for investment. Conversely, if output falls sufficiently or the cost of capital increases, or both, a TFP decrease could reduce investment, possibility even in the face improving technology.

A demand shock is defined as a change in $\dot{YE}$ independent of other terms in (16) with an increase in demand resulting in an increase in capacity. Of course, in a dynamic context, the persistence of the demand-induced investment increase will depend on the response of prices, interest rates, and the cost of capital.

Applying the investment equation to the industrial revolution periods, the installation period, most recently 1975 – 2010, is characterized by (1) ageing capital following substantial capital investment spending in the preceding deployment period, (2) a new technology, nascent at the outset of the period reaching maturity later in the period, and (3) focused business model innovation. Such conditions could suggest slower investment spending growth. One consequence is increased obsolescence of tangible and intangible capital as technology advances, driving heterogeneity in cross-sectional profitability and firm-level productivity. At the aggregate level, capital is reallocated with restructuring costs affecting the overall benefit of innovation.

Conversely, the deployment period, for example 1945 – 1975, is characterized by (1) a mature, low-cost technology, and (2) rapid business model innovation. The combination of a demand shock and a productivity shock would result in substantial capital investment and, eventually, resulting in a younger capital stock.

---

[35] If TFP captures, for example, improved management practices or business model innovation, improved capital technology - for example increased computing power or advances in software technology - may or may not result in output and investment increases depending on how resources are combined. The distinction between the success of management practices and information technology investment has been the focus of Bloom, Van Reenen and collaborators across a substantial body of work. See Bloom, Sadun, and Van Reenen (2012). Bloom and Van Reenen (2007) find measures of managerial practice are strongly associated with firm-level productivity, profitability, Tobin's Q, sales growth, and survival rates. They calculate that product market competition and family firms account for about half of the half of the gap in management practices between the US and France and one-third of the gap between the US and the UK.

Other evidence of the periodic de-linkage of technological innovation and increased TFP growth can be found in the economics literature. The influence of innovation on TFP – capturing for example improved management practices, business model innovation and new product and service offerings – manifest over long periods. Over a five- to ten-year horizon, the Kelly et. al. innovation index is a strong predictor of TFP, for which a one-standard deviation increase in the index is associated with a 0.5 to two percentage point higher annual productivity growth.

In addition, Basu, Fernald and Liu (2014) find that output, consumption, investment, and labor hours rise in response to improvements in consumer-goods technology but all decline following similar improvement in investment-goods technology. Basu, Fernald and Liu show the effects are consistent with the predictions of a two-sector dynamic stochastic general equilibrium (DSGE) model with sticky prices in each sector. The assumption that investment goods prices are costly to adjust helps fit the evidence that the relative price of investment goods adjusts slowly to shocks.

Appendix C: Shifting Labor Income Shares in the 1st Industrial Revolution

Shifting capital and labor income shares were a dynamic element in early industrial revolutions. Allen (2009) identifies "Engles' Pause" as the period that aligns with the 1st Industrial Revolution's installation period.[36] Allen shows the UK economy passed through a two stages evolution – remarkably similar to the installation and deployment periods – characterized by fluctuations in profitability, real wages, productivity and capital investment.

Allen asserts the prime movers of the 1st Industrial Revolution were 18th century UK technology innovations, including mechanical spinning, coke smelting, iron puddling, and the steam engine. After 1800, the revolutionized industries were large enough to affect the national economy.[37] The macroeconomic impact was strengthened by rising agriculture sector productivity and inventions like the power loom, the railroad, and the application of steam power generally (Crafts, 2004). The adoption of the new technology led to increased capital investment – for cities, housing, and infrastructure as well as for plant and equipment.[38]

However, Britain's income shares during the 1st Industrial Revolution's as estimated by Crafts (2021a) and Allen (2009) are relatively constant during the installation period, in contrast to the decline in labor income shares during the 4th Industrial Revolution.

Acemoglu (2002) argues that technological change in the late eighteenth and early nineteenth centuries may have been biased ***toward*** unskilled labor. There was (1) a large migration of unskilled workers from English villages and Ireland to English cities and (2) a large increase in population. The emergence of the most "skill-replacing" technology, the factory system, coincided with a substantial change in the relative supply of workers and increased demand for those unskilled workers in the new factory system, the product of the "invention of a new method of invention". These innovations – the factory system and new methods of inventions – constitution significant innovation much like innovations surrounding social media, e-commence, and search in the current period.

Crafts (2021a) also focuses on increased population growth and labor supply. Crafts and Mills find that fertility and mortality shocks between the 1760s and the 1820s raised the crude birth rate and lowered the crude death rate both by about 6 percentage points. In the circumstances of other periods, such increases would have led to real wage declines. In the context of the industrial revolution, the

---

[36] Crafts and Harley (1992) address measurement associates with UK economic growth in the 18th and 19th centuries.

[37] During Britain's 1st Industrial Revolution, Crafts (2021a) shows output growth increasing only marginally. However, capital deepening, human capital, and TFP growth are sources of growth. As expected, larger increases occur in the deployment period. The experience of the 1st Industrial Revolution is seen by Crafts as an exception to revolutions that followed. The essence of the 1st Industrial Revolution was not rapid productivity growth in the short run but the "invention of a new method of invention" which increased technological progress in the long run.

[38] Bessen (2003) traces a similar path of US 19th century technology development.

implication was that the population increase severely inhibited the scope for productivity growth to raise real wages.

The workforce increase created profit opportunities for firms introducing technologies that could be used with unskilled workers – often women and children. The advent of steam power and the expansion of freight and passenger rail travel across Britain and the continent expanded the scope and scale of available markets. To meet the unprecedented increase in demand and market opportunity, the incentive to replace skilled artisans with unskilled laborers was a major objective of technological improvements over the period.

Acemoglu's framework is consistent with the notion that the incentives for skill-replacing technologies were shaped by the large increase in the supply of unskilled workers. With such an increase, Acemoglu's model suggests short-run real wage declines were followed, as markets expanded over the long run, by wage increases. Thus, the constancy of labor's income share.

Allen (2009) also points to the significance of increased relative supply. Allen simulates the counterfactual that eliminates the population explosion that accompanied industrial revolution. Both output per worker and the real wage from 1770 to 1860 trend upward, with little lag of wages behind output after the increase in productivity growth in 1801. "Engel's pause" in real wage growth is eliminated with simulated shares changing very little.

Crafts (2021a) also advances a counterfactual and finds that:

> ….in the absence of both these shocks [fertility and mortality], the model estimates that average real earnings growth would have been increased by 1 percentage point per year [more] between 1780 and 1840, by which time real earnings would have been more than double the 1780 level.

The counterfactuals suggest that demographic shocks which raised population growth to a new high during Britain's 1st Industrial Revolution undermined its potential to raise real wages. The constancy of British labor's income share in the early 19th century highlights the point that labor's income share is the product of the average wage rate, labor force participation and population. Migration of workers from the agricultural sector to the industrial sector adds to the available work force independent of population growth. Increased participation of unskilled labor can hold labor's share constant while the average wage rate is declining.