The Fifth Industrial Revolution. A Provocative Description of a Novel Phenomenon

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Abstract

This paper seeks to highlight the consequences of a threshold limitation associated with what has been described as the burden of knowledge effect. This threshold limitation is seemingly evident in contemporary evidence of a global slowdown in productivity growth, a global decline in research and R&D productivity, and an apparent 'retreat' from globalisation, particularly in the US and across Europe. Longstanding theory that predicts this threshold limitation is revisited, and its consequences are discussed, specifically those related to the dangers of technologically-enabled geopolitical conflict, technological displacement of human labour, and the perils of a failure to focus sufficient attention on mitigating the burden of knowledge effect. Arguments are made explicit through the derivation of theoretical propositions. A mechanism is identified, which we suggest might ultimately mitigate, or even reverse, the burden of knowledge effect. In keeping with literature on productivity revolutions, and particularly the 'fourth industrial revolution,' the productivity effects of which are yet to be seen in factor productivity statistics, we suggest that the potential of this mechanism for productivity enhancement might appropriately be termed the advent of the era of the 'fifth industrial revolution.' The objective of the paper is therefore to provoke novel thinking around certain important issues related to socioeconomic consequences of abdicating the responsibility for societally important research. We suggest that a failure to radically increase our effective global research capabilities immediately might ultimately be catastrophic.

Keywords: Innovation; Management theory development; R&D; global productivity growth slowdown; globalisation; catastrophic societal risk

1. Introduction

Drawing from the perspective of economics, Griliches's (1994:18) words capture succinctly the paradox of innovation and the problems related to its measurement and prediction, suggesting that total factor productivity growth, as an indicator of innovation, is a weak one. Nevertheless, globally, it is declining. Certain evidence suggests that we have been facing a global slowdown in productivity growth (Fabina and Wright, 2013; Haldane, 2017). Certain economic models (see Kortum, 1997; Segerstrom, 1997; Jones, 2009) offer reasons why we are currently experiencing a global slowdown in research and development (R&D) productivity, a phenomenon described as the 'burden of knowledge effect,' associated with increasing difficulty in achieving scientific breakthroughs across fields over time (Jones, 2009). These theoretical models largely explain the evidence that reflects a decline in the productivity of R&D dating from the 1970s onwards (Cowen, 2011; Gordon, 2016). In this paper we link the literature on the global productivity growth slowdown with that related to the R&D productivity slowdown, and question recent claims relating to the effects of certain 'revolutions' promising radically improved productivity.

In light of these global slowdowns in productivity growth and R&D, the influence of transformative innovation associated with the emergence of Google and other Internet innovations has to date largely failed to translate into economic impact (Byrne, Fernald and Reinsdorf, 2016). Technological innovations have therefore yet to challenge the Solow (1987) paradox, whereby the effects of the much heralded technology revolution have yet to manifest in productivity statistics (Acemoglu, Autor, Dorn, Hanson and Price, 2014). Indeed, technological change stands to transform working contexts, with projections of large-scale job losses related to the increasing scale of automation (Brynjolfsson and McAfee, 2014; Chui, Manyika and Miremadi, 2016), it has yet to deliver much needed improvements in productivity growth, or even productivity in the R&D process itself.

Evidence of a slowdown in global productivity growth and productivity in R&D therefore stands in contrast with certain discourse related to the 'fourth industrial revolution'. According to the logics of these discussions, the confluence, or interaction of novel technologies is blurring the boundaries between the physical, digital and biological domains to create cyber-physical systems, promising hitherto unrealised productivity gains (Schwab, 2017). In the absence of a dramatic influence on productivity growth, we suggest that there is another mechanism that is at work across research contexts that might ultimately cause a radical increase in productivity growth. Given current discussions about revolutions, particularly the fourth industrial revolution, for the purposes of this work we couch our descriptions of this novel phenomena in the same terminology, building on its literature to term it a 'fifth industrial revolution.' In doing so, we seek to provoke new and interesting conceptions, and to overturn certain longstanding assumptions about what is really driving technological change.

We base our discussions in theory, contributing to a body of theory that accounts for current declines in productivity, and also suggesting under which conditions alternative theoretical predictions come into their own. The global decline in R&D productivity demonstrates that the theoretical models of Kortum (1997), Segerstrom (1997), and Jones (2009) seem to predict current realities more accurately than alternative models such as those of Romer (1990) and Weitzman (1998). Importantly, the latter models stress the recombinant nature of innovation, and the notion that R&D should ultimately achieve economies of scale and increasing productivity over time. The logic of recombinant innovation suggests that once discoveries are made, these ideas (‘recipes’ for the more efficient combinations of resources) can then be used by others, typically at little cost, allowing a virtuous circle of R&D productivity to develop over time. The paradox of our time seems to relate to the question of why, if the logics of recombinant innovation hold (they provide a strong rationale for the existence of increasing returns to investments in R&D), do we then currently see a long term decline in returns to R&D? Indeed, to what extent is the global decline in productivity growth a function of these declines in R&D productivity? The objective of this paper is to advance an argument that a threshold constraints acts to hold back the operation of recombinant innovation theory, but that there exists a mechanism that might hold the key to overcoming this threshold limitation. We describe the operation of this mechanism in productivity terms, arguing that it holds the potential to radically increase R&D productivity, and, thereby, to radically increase global productivity growth. Thus, unlike the lack of an impact on global productivity growth at this time associated with the effects of the ‘fourth’ industrial revolution, we suggest that the mechanism we discuss here may ultimately impact productivity in a way to earn the moniker the ‘fifth industrial revolution.’

We suggest that diminishing R&D productivity carries with it the threats associated with a lack of research capability, particularly the research insights required in order to be able to manage the complexities an increasingly dangerous global context. Plausibly, a current retreat from globalisation may be exacerbating the twin problems of contemporary global productivity growth and R&D productivity. This effect seems to be exhibited most tellingly in advanced democracies.

Indeed, certain countries at this time seem to be exhibiting such a retreat from globalisation, associated with increasingly nationalistic political agendas, and policies that are at odds with the institutions and principles of free trade and freedom of movement of people (Fidler, 2017; Paletta and Swanson, 2017; Talley, 2017). The 2016 referendum vote in favour of British exit (Brexit) from the European Union (EU) has been interpreted in a similar way (Mulligan, 2017), effectively as a rejection of the current global status quo as it relates to trade agreements (Dhingra, Ottaviano and Sampson, 2017), and the free movement of people. These changes have also been described as the advent of an ‘age of walls’ (Marshall, 2017). Political polarisation within such countries has intensified, as have debates about security threats such as terrorism, cyber-attacks, and the manipulation of democratic processes using social media (Marshall, 2017). Given the complexity of the realities reflected by these different literatures, we suggest that the confluence of these literatures presents us with an important paradox. This paradox may characterise, or even define, our current era.

With a focus on identifying and resolving some aspect of this paradox, this paper seeks to contribute to the literature on the global productivity growth slowdown (see Fabina and Wright, 2013; Haldane, 2017), the literature on the global R&D productivity slowdown (Kortum, 1997; Segerstrom, 1997; Jones, 2009; Cowen, 2011; Gordon, 2016), and the literature that is emerging on the productivity effects of what has been described as the fourth industrial revolution (Schwab, 2017). We seek to contribute to these literatures by linking them. In linking these three bodies of literature, we synthesise certain patterns in theory, and suggest useful insights into how this paradox might ultimately be resolved. We frame our insights in terms of an envisioned ‘fifth industrial revolution,’ and argue that the productivity enhancements that such a revolution in R&D might entail warrants such a description.

In doing so, we seek to answer the following question. If the promised productivity benefits of the fourth industrial revolution (Schwab, 2017) have largely not yet materialised, and the global productivity growth (Haldane, 2017) and R&D productivity (Gordon, 2016) slowdowns have not to date been reversed, then what is it that is holding back the technologies associated Schwab's (2017) predictions from achieving their promised productivity advances?

In answering this question, the core argument of this paper is that while descriptions of certain industrial revolutions have been premised on substantive increases in productivity, there is yet to be such an increase associated with the recent proliferation of technologies mooted to have caused a fourth industrial revolution. Instead, it will be argued here that the next 'industrial revolution' will be one associated with certain innovations *in the knowledge creation process itself*. As stressed previously, in keeping with the literature on 'industrial revolutions', the potential for radical productivity increases in production associated with these innovations is described in terms of theoretical mechanisms that together predicts a 'fifth industrial revolution' of productivity growth.

2. Contributions to the literature

In developing our arguments and ideas related to this construct, of a fifth industrial revolution, we describe our contributions to certain important specific current debates in the literature as follows.

Firstly, we contribute to recent debates about the role of scalability of sustainability (Chatzidakis & Shaw, 2018; Goworek et al., 2018; Nyberg, Wright, & Kirk, 2018; O'Reilly, Allen, & Reedy, 2018; Papazu & Nelund, 2018) by identifying an important channel through which sustainability research might itself experience scale effects that transcend the same threshold limitation that has constrained the use of technology for beneficial human outcomes. We argue that if this threshold limitation is not timeously addressed, then technological proliferation itself (Callaghan, 2018) might outstrip our ability to research how to safely manage it (Bostrom, 2017; Tegmark, 2017), with important implications for sustainability.

Secondly, and relatedly, this work contributes to longstanding literature related to catastrophic threats to humanity posed by emergent technologies (see Joy, 2000; Cohen and Malankoff, 2012; Baum, 2015; Isai and Knoppers, 2015), and the need for responsible innovation (Osborne and Jackson, 1988; Olsen, Kruke and Hovden, 2007; Grunwald, 2011; Stilgoe, Owen and Macnaghten, 2013; Szerszynski, Kearnes, Macnaghten, Owen and Stilgoe, 2013). It does so by identifying a threshold limitation that has arguably led to the proliferation of information in the absence of a commensurate explosion of knowledge. We will suggest that asymmetry in relationship between information and knowledge, including the knowledge of how to safely manage this explosion in information itself, is a dangerous current threat to human societies. In other words, big data has not sufficiently translated into big knowledge, and has not produced the 'big wisdom' deriving from big knowledge.

Thirdly, we contribute to the debates relating to radical productivity improvements over time, which we describe as the 'revolutions' literature. Certain patterns in the emergence of technology and their contributions to productivity have previously been alternatively described as the first, second and third industrial revolutions (Rifkin, 2011), the fourth industrial revolution (Schwab, 2017), a fourth paradigm of scientific research (Hey, Tansley and Tolle, 2009), or a second machine age (Brynjolfsson & McAfee, 2014). Certain of these trends are also evident in longstanding descriptions of five generations of innovation (Rothwell, 1994). We contribute to this stream of literature in that we suggest that there is a common thread connecting these bodies of literature, and that *it is this connecting logic that holds the key to the coming productivity revolution* that we term the 'fifth industrial revolution.' In contrast to certain of these described revolutions which are not seen to reflected in a dramatic increase in global productivity, we suggest that the fifth revolution predicts, by definition, such a radical change.

Having outlined the objectives of the paper, and having made explicit the contributions it seeks to make to specific literatures, the paper proceeds as follows. First, theory and literature is now reviewed in order to develop the paper's arguments. Next, evidence our suggested threshold limitation is presented, in form of plots of trends in total factor productivity, globalisation growth, and outward foreign direct investment, which we suggest support our arguments in this regard. At this point, theoretical propositions are derived, as we seek to make explicit our arguments. Conclusions are then presented.

In order to justify the importance of our arguments that relate to how to overcome the threshold limitation, it is first necessary to explicitly identify the dangers associated with such a threshold limitation, and discussions to this end now follow.

3. Dangers of the technology threshold limitation

The central argument of this paper is that a threshold limitation currently exists with regard to the ability of technology to radically contribute to productivity across contexts, even if recombinant logics suggest that it must. More specifically, we suggest that the dangers posed by this threshold limitation are primarily threefold.

Firstly, without a way to match the chaos and geopolitical problems created by the information explosion with a commensurate knowledge explosion that radically increases our ability to improve the research process itself (increase our wisdom) to solve (manage) these problems, we may be facing a *geopolitical crisis enabled by technology*. Secondly, given *the impending threats to labour posed by rapid advances in technology*, and other technological threats to human survival, there is little evidence to suggest that knowledge creation will similarly proliferate, such that the rate at which technologically-enabled problems are increasing outstrips the productivity of the problem solving research necessary to solve them. Thirdly, there seems to be little in the way of explicit research *with a focus on addressing the burden of knowledge effect*. This is especially problematic if the current state of declining productivity in R&D continues as a secular trend, as the potential for catastrophic problems may be increasing globally, and a potential solution, in the form of an explicit focus on reversing the burden of knowledge effect, is largely not on the world's research agenda, as a priority.

It bears continually repeating the key argument we make here, that a threshold constraint to knowledge creation that fails to address the asymmetry between exponential increases in information and non-exponential increases in knowledge creation may be increasingly dangerous in the absence of explicit research with a focus on addressing the burden of knowledge effect. Kortum's (1997) theoretical model explains why productivity growth has not risen as research employment has increased, why productivity growth has decreased, and why rates of patenting have failed to increase over time. The model predicts that *technological breakthroughs become progressively harder to find* as a technological frontier increases in size.

Researchers are considered to sample from probability distributions of production techniques. Previous research forms a technological frontier of the most effective techniques required to produce all the goods in an economy. Researchers are taken to sample according to Pareto distributions, and productivity growth is then proportional to growth in the research stock (Kortum, 1997). With the advance of this frontier, technological breakthroughs become increasingly harder to find. This explanation accords with evidence that shows that rates of patenting have remained relatively constant, notwithstanding a steep rise in research employment since the 1950s. Kortum's (1997) model effectively predicts a 'fishing out' effect, in that technological breakthroughs will simply become increasingly harder to find.

Similarly, Jones's (2009:310) model predicts that if "a rising burden of knowledge is an inevitable by-product of technological progress, then ever increasing effort may be needed to sustain long-run growth." This burden of knowledge effect is making it more and more difficult for individuals to accumulate knowledge sufficient to reach the technological frontier, this reflected in increasing ages of Nobel Prize winners and periods of study. This burden of knowledge effect is taken to represent a fundamental threshold limitation to achieving research breakthroughs, across almost all fields of scientific endeavour.

Segerstrom's (1997) model also suggests that R&D difficulty is increasing over time, but, whereas Kortum's (1997) model suggests a fishing out process, Segerstrom (1997) highlights the increasing difficulty of the R&D process itself. In a more hopeful vein, Jones (2009:310) points to the potential for a new scientific paradigm to emerge, in that "even if the stock of knowledge accumulates over long periods, some future revolution in science may simply the knowledge space, causing a fall in the burden of knowledge." We suggest here that the failure of scholarly research to take such suggestions seriously may become increasingly dangerous over time.

At this point, in order to advance our arguments, it is necessary to first provide further evidence that the burden of knowledge effect is not the only manifestation of a fundamental threshold effect that is constraining human progress. In the coming section, we will argue that this threshold constraint is manifesting in the form of a decline in global productivity growth, in a decline in the growth of globalisation, and in perverse geopolitical occurrences.

4. Evidence of a threshold limitation

The measurement of productivity is inherently problematic. Indeed, the use of the total factor productivity residual as a measure of productivity has been termed "a measure of our ignorance" (Abramovitz, 1956:11). Hence, as a measure technical change, for many scholars it sits uncomfortably amidst other potential measures. From an economic perspective, the fundamental sources of productivity growth derive from improvements in the "quality of labour and capital and from other, not otherwise measured, sources of efficiency and technical change, the latter being in turn the product of formal and informal R&D investments by individuals, firms, and governments, and the largely unmeasured contributions of science and other spillovers" (Griliches, 1994:1). According to Griliches (1994:1/2):

> This general view of the sources of growth was put into doubt by the events of the 1970s and 1980s. Beginning in 1974 (or perhaps already in 1968) productivity growth slowed down significantly in the Unites States and abroad, and it has not fully recovered yet, at least as far as national aggregates are concerned. The many explanations that were offered for these events were not very convincing…Even more ominously, the slowdown was blamed on diminishing returns to science and technology in general and the onset of widespread socio-economic

> sclerosis…What is it about our data and data acquisition structure, and possibly also our intellectual framework, that prevents us from making more progress on this topic?

Evidence of the slowdown in growth in total factor productivity growth, a measure of technical progress, in developed country contexts, can be seen in Figures 1 and 2. Figure 1 plots the growth in total factor productivity over time for Western Europe, and Figure 2 for the United States (US). It might be argued that countries like China provide new hope for technical progress, but as Figure 3 shows, there seems to be no increasing trend in this data.

To what extent is this global productivity slowdown related to globalisation? The golden age of globalisation, of 1990-2010, has ended, and has been followed by a reversal in the pattern of globalisation, as today's "trade tensions are compounding a shift" that has been underway since 2008, as cross-border "investment, trade, bank loans and supply chains have all been shrinking or stagnating relative to world GDP" (Economist, 2019:9).

Figure 4 shows that the pattern of a steady increase in economic globalisation peaked a few years prior to 2010, and has since declined. Further evidence of this decline is seen in the trend in foreign direct investment (outflows, as a percentage of GDP), with a longstanding upward trend that is first reversed in 2001, then demonstrates a recovery until the mid-2000s.

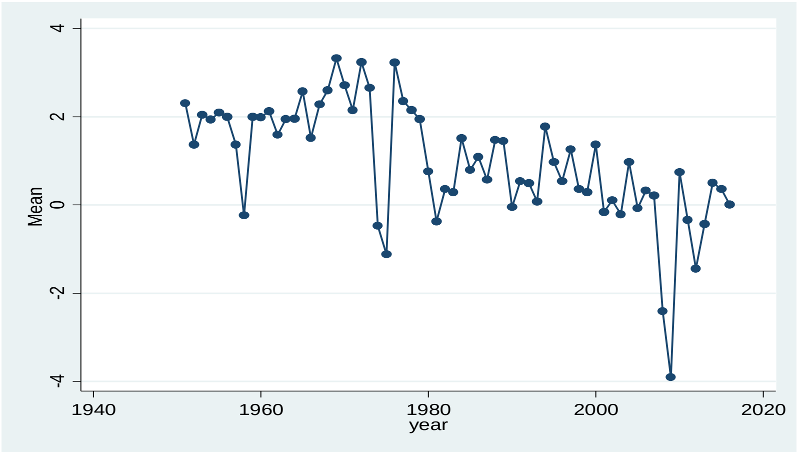

Figure 1. Plots of total factor productivity growth per year for Western Europe (Total Economy Database, 2017)

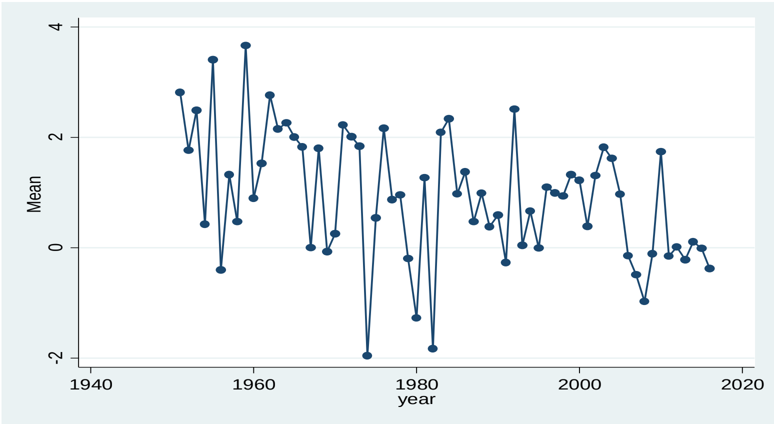

Figure 2. Total factor productivity growth per year for the United States (Total Economy Database, 2017)

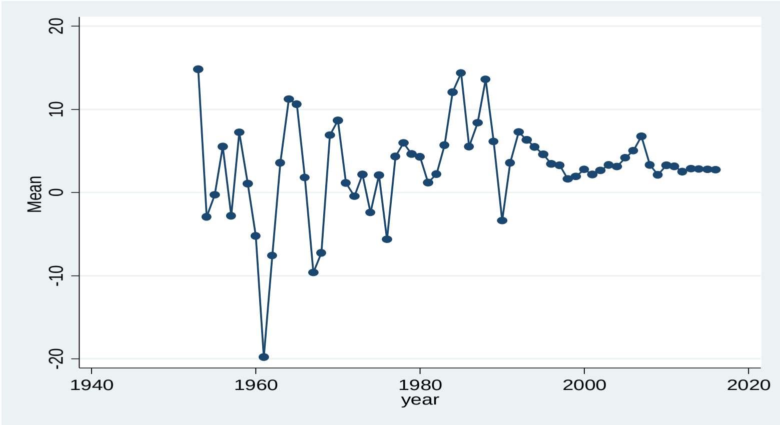

Figure 3. Total factor productivity growth per year for China (Total Economy Database, 2017)

Thus, a decline in R&D productivity contributes to a decline in total factor productivity. Other research findings give us an idea of the extent to which R&D contributes to productivity growth. As an example, previous research in the OECD context suggests that an increase of 1% in business R&D generates an increase of 0.13% in productivity growth, in foreign R&D generates 0.44%, and 1% in public R&D generates 0.17%, with these effects larger in countries with a greater share of universities and where business R&D activities are more intensive (Guellec and van Pottelsberghe de la Potterie, 2001).

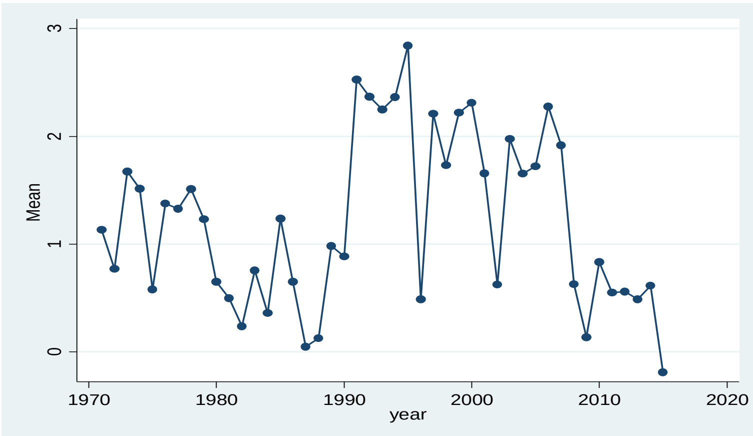

Figure 4. Trends in annual growth of globalisation (KOF, 2018)

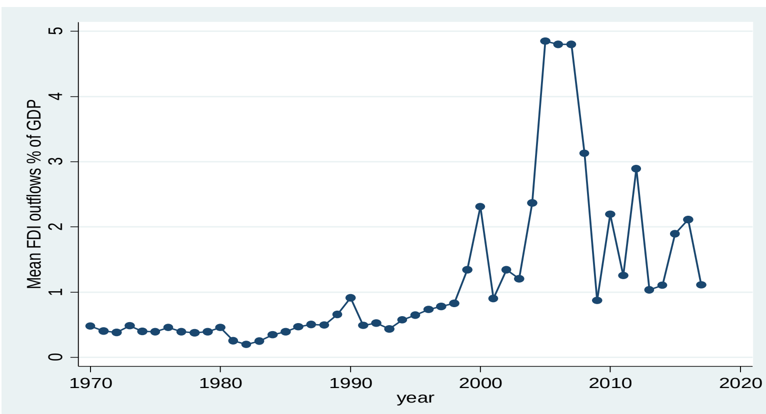

Figure 5. Annual global averaged foreign direct investment outflows as percentage of gross domestic product (World Bank, 2019)

Off a three-year peak it then declines, exhibiting some degree of instability across the years since. Whatever the trend here, it is clear that there is more uncertainty of late in this trend.

What seems to be evident across these plots is that some kind of threshold effect is present, a levelling off from past increases, or even decreases. Declines in total factor productivity include, as a component, declines in R&D productivity.

Another example of such research is found to suggest that large United Kingdom (UK) production firms that have substantial R&D activities have total factor (revenue) productivity on average about 14% higher than those that do not (Bond and Guceri, 2017). Although there is much evidence of the contributions of R&D to productivity (see Broström and Karlsson, 2017), what is seemingly lacking from this literature is research that explicitly seeks to understand how to develop economies of scale in the scientific research process itself, and particularly that *which takes a management perspective, related to the proactive management of the research process itself*.

5. The fifth industrial revolution hypothesis

Whereas steam power enabled more efficient energy applications on a global scale (the first revolution), oil and electricity (the second) took this further, and the computer era provided productivity enhancements that changed the nature of work itself (the third) (Rifkin, 2011), the emergence of novel technologies (the fourth)(Schwab, 2017) does not fundamentally alter the problem of asymmetry between the exponential growth in informational capacity, and the lack of a commensurate exponential growth in knowledge. Indeed, the radical productivity increases predicted by discussions of the fourth industrial revolution have largely not materialised (see again Figures 1-3).

Whereas exponential growth in information generation and transmission may have been underpinned by Moore's law, no comparable law seems to exist currently for the translation of information into knowledge. It is only through knowledge increases that we may gain the wisdom necessary to be able to manage the proliferation of information, and dangerous technologies (Callaghan, 2018). Key to our arguments that we are about to experience a productivity revolution is a body of literature that has demonstrated proof of concept with regard to the potential for economies of scale to be realised in the research process. Nielsen (2012) offers a useful summary of the mechanics of how these economies of scale can be achieved. We limit ourselves here to the theoretical arguments that predict that a productivity revolution is possible.

The research process itself is reconceptualised, so as to be able to develop novel methodological insights that can complement those associated with the current scientific discovery system. This reconceptualization overturns certain longstanding assumptions about the discovery process. Although the real life examples offered by Nielsen (2012) provide proof of concept, what we contribute to his work is a theoretical rationale for the phenomenon he describes. Without detracting from our purpose here, it is useful to give an example of the novel thinking that is associated with the body of literature that we suggest describes thinking associated with this fifth industrial revolution.

A useful example in this regard, is Taleb's (2010) notion that research discoveries are akin to black swan events, or unpredictable occurrences. Taleb (2010:xxv) explains further:

> Black Swans being unpredictable, we need to adjust to their existence (rather than try to naively predict them). There are so many things we can do if we focus on antiknowledge, or what we do not know. Among many other benefits, you can set yourself up to collect serendipitous Black Swans (of the positive kind) by maximizing your exposure to them. Indeed, in some domains- such as scientific discovery and venture capital

> investments- there is a disproportionate payoff from the unknown, since you typically have little to lose and plenty to gain from a rare event. We will see that, contrary to social science wisdom, almost no discovery, no technologies of note, came from design and planning- they were just Black Swans. The strategy for the discoverers or entrepreneurs is to rely less on top-down planning and focus on maximum tinkering and recognizing opportunities when they present themselves. So I disagree with the followers of Marx and those of Adam Smith: the reason free markets work is because they allow people to be lucky, thanks to aggressive trial and error, not by giving rewards or "incentives" for skill. The strategy is, then, to tinker as much as possible and try to collect as many Black Swan opportunities as you can.

The example of Linux is another example of a novel method of knowledge creation. Raymond (2000) explains the open source success of Linux in terms of a contrast between how most of the commercial world develops its products (the cathedral model) versus the open source approach (the bazaar model). With reference to software engineering, he argues that "given enough eyeballs, all bugs are shallow" (Raymond, 2000:1). How can this principle be applied to theory development relating to the scientific research process?

Probabilistic innovation theory (Callaghan, 2015) falls back on reductionist logics, with the assumption that it is only when inputs into a problem solving process are radically increased, that a threshold is reached whereupon there begins to exist a probabilistic relationship between these inputs and breakthrough innovations. It is by 'unfolding' the problem space, or making it amenable to the large scale problem solving efforts of large numbers of problem solvers, that breakthroughs can be achieved probabilistically. Even so, it is not possible to know up front what specific form these breakthroughs will take.

Whereas the information era's principle of exponential information creation derives from Moore's law, the dynamics of the fifth industrial revolution may be described in terms of the principle of probabilistic innovation, whereby it is only extremely high volumes of problem solving inputs are able to overcome the threshold limitation of the burden of knowledge effect. A probabilistic relationship therefore needs to exist between levels of problem solving effort and breakthrough research outputs. For this relationship to become probabilistic, it is necessary to radically increase the input side of the equation up and until the point at which the uncertainty related to obtaining some breakthrough is reduced sufficiently to make the achievement of breakthroughs probable. In other words, the radical increase in inputs at some point changes the relationship between inputs to outputs from one of uncertainty to one of probability, where the risk of not obtaining breakthroughs (of a kind unknown at the outset) becomes measurable for the first time. The following proposition is therefore derived from this discussion.

Proposition 1: *It is possible to create a constant stream of breakthroughs in a research area, and the only constraint to this is the breakthrough density (richness) of the problem scape and the minimum level of problem solving inputs required to escape the uncertainty threshold limitation.*

Probabilistic innovation theory predicts, therefore, that it is possible to move the innovation process from a state of uncertainty to a state in which the probability of producing breakthroughs can be a measurable function. Probabilistic innovation theory is in no way revolutionary, but is rather a simple extrapolation of logics that already exist. What is offers, however, is a useful heuristic notion around which literature and theory development might be usefully related. As an anchoring logic, it provides useful insights for the study of the research, or discovery system itself.

As long as a certain level of input is attained, a critical mass of engagement is enabled, so as to enable the probabilistic relationship between inputs and outputs.

According to probabilistic innovation theory, the problem of the threshold limitation posed by the burden of knowledge effect *is a methodological one*. The answer to the problem of a system that cannot develop knowledge to keep pace with the exponential creation of knowledge is perhaps to develop methodologies that enable economies of scale in the research process itself.

The notion of economies of scale in the research process itself is also a useful heuristic that might guide further theory development and testing. The logic is that if the development of economies of scale in the research process is the focus of a concerted research effort, then over time, increasing economies of scale in research might overtake the burden of knowledge effect. Proposition 2 is therefore derived:

Proposition 2: *A continual increase in the economies of scale attainable in the research process will ultimately allow researchers to overtake the burden of knowledge effect.*

Economies of scale are already being achieved in certain areas. For example, the innovation platform InnoCentive (https://www.innocentive.com/) has demonstrated proof of concept, as scientific problems are put out to a global problem solving community, in the form of open calls. Problems are typically solved more cheaply and more quickly than they are able to be solved by in-house R&D departments. Although nascent, it is the phenomena of probabilistic innovation and the rise of economies of scale in the research process that best describe the potential for exponential knowledge creation that may ultimately match the exponential information generation mechanics driven by the effects predicted by Moore's Law.

The term 'fifth industrial revolution' therefore relates to the envisioned productivity increases that we suggest might accompany successful attempts to mitigate the influence of the burden of knowledge effect. In so doing, it may be possible to surmount the threshold constraint that has manifested in the global productivity slowdown, as well as to address a failure to produce sufficient research focused on successfully managing the threats that have arisen from a proliferation of technologies.

At the heart of our arguments that a coming productivity revolution is possible is our identification of a mechanism that might underlie this productivity increase. A 'societal R&D ratio,' or the ratio of how many researchers are working on the front line of a problem to how many are directly affected by it is a useful anchoring heuristic, in that it provides a realistic assessment of the fundamental problem created by the burden of knowledge effect.

Our key argument is therefore that a concerted focus on the problem of how to enable economies of scale in the research process is an urgent imperative. As discussed, there exists a growing body of literature, such as probabilistic innovation theory, that suggests how to achieve these economies of scale in the research process, whether by unfolding the problem space or populating it with very large numbers of problem solvers (Callaghan, 2018), or through the re-design of the discovery process itself (see Nielsen, 2012). These mechanisms are beyond the scope of this work, however, which is delimited to the identification of a threat to knowledge creation, in the form of a threshold limitation, and to seeking to offer useful insights into a potential remedy for the problem. Proposition 3 is therefore derived:

Proposition 3: *A continual increase in the economies of scale attainable in the research process will ultimately result in radically increased productivity across contexts of human endeavour.*

Whereas discussions of the fourth industrial revolution (Schwab, 2017) occur in the absence of an increase in total factor productivity, the first, second and third revolutions described by Rifkin (2011) were associated with novel forms of radical productivity enhancement. We therefore suggest a fifth, relating to the power of knowledge creation that can be delivered by research at the front edge of a new frontier of research *into the research process itself, that seeks to apply technology to enable economies of scale* in the research process.

Although we still await the technological capabilities that can enable real time research capability, we suggest that the theory already exists that predicts that this is possible (see Callaghan, 2018), and proof of concept already exists as to the conditions under which it is possible (see Nielsen, 2012). We suggest that these ideas are important, and that a rigorous engagement with these ideas might be useful, in that a focus on the problem of the threshold limitation from all angles is increasingly important.

The core implication of our arguments is that if research effort can be focused toward understanding how economies of scale can be enabled in the research process this will cut out much of the redundancies that exist in iterative research that is not brought together with this common focus. Similarly, another important implication of the fifth industrial revolution is that it represents a new way of thinking about research, akin to Taleb's (2018) notion that research breakthroughs are Black Swans, or unexpected and uncertain events, and that our current research system is simply not geared up to populate research spaces with the very large numbers of problem solvers required to change the dynamics of infinitesimally small societal R&D ratios.

We therefore suggest that the research system therefore needs to be supplemented with a methodology that explicitly takes into account the fact that breakthroughs are uncertain and unpredictable, but that a reconfigured research landscape that applies probabilistic principles can break through the uncertainty threshold that derives from the burden of knowledge effect. Finally, we suggest that breaking through this threshold and successfully transcending the burden of knowledge effect will set in motion the productivity revolution that will reverse the current global decline in productivity growth.

6. Conclusions and Recommendations

There are two conclusions that can be derived from the discussions here. First, it may be necessary to increase research into how to enable economies of scale in the R&D process. As stressed previously, a growing body of theory already exists on how to do this. Applying the logics of the societal R&D ratio, if all of us stand to be affected by the burden of knowledge effect, then more of us as researchers should be seeking to mitigate its effects.

Second, in a context in which liberal democracies seem to be abdicating much research activity to the forces of the market, others are increasing their state support for research. Probabilistic innovation theory would predict that it is the scale of research activities that enable peace and stability in a world that perhaps increasingly uncertain in its global trends.

In order to address the asymmetries between the information revolution and the (much hoped for) knowledge revolution that might currently be held in check by the burden of knowledge effect, governments may need to *radically increase investments in research activities*.

Only through a radical increase in the scale of research activity, on a worldwide basis, might the burden of knowledge effect be mitigated, as long as a sufficient portion of this work focuses on how to mitigate the burden of knowledge effect itself.

In conclusion, we point to the importance of the societal R&D ratio, and the problem that to date we have largely left the fate of our planet, our societies, and our children, to the mercy of the dynamics associated with infinitesimally small ratios, where there are simply too few focused on researching the solutions of societally important problems. Another problem is that, if they are, they might be vulnerable to the problem of limited research funding, as the abdication of much funding responsibility is left to commercial or market interests, which may be less interested in such problems. The objective of this paper was therefore to provoke new thinking, in light of the argument that sufficient research engagement needs to occur with the burden of knowledge effect, before it is too late.

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