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Productivity-Defined 'Fifth Industrial Revolution'

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ABSTRACT

The objective of this conceptual paper is to spur new thinking about how technological change can be harnessed to address existential threats. We suggest current debates about a fourth industrial revolution (4IR) fail to properly consider an ongoing decline in global productivity growth. Robert Solow remarked ‘you can see the computer age everywhere but in the productivity statistics’- the Solow Paradox. Recent work documents an ongoing decline in research productivity, the returns to investments in research. We suggest the definition of an industrial revolution should be one that substantially increases global productivity growth, which is yet to happen. Such a revolution would need to be differentiated from 4IR descriptions of the confluence of technologies and would need to reflect these substantial increases global productivity growth- a fifth industrial revolution (5IR). We describe this productivity revolution as being driven by idea production, following Romer. Whereas Nelson identifies limitations of technology in solving wicked problems- a defining characteristic of current existential threats- we suggest a true productivity revolution (that can solve wicked problems) can be enabled by a 5IR heuristic, if it helps refocus attention on the notion of increasing returns to scale in research, the engine of productivity and growth in Romer’s theory. Finally, we sketch some future dystopian and beneficial consequences of technological change.

Key words: Technological change; industrial revolutions; innovation; productivity; human work obsolescence; post-work; Romer; Solow paradox

1. Introduction

Debates continue about whether it is now already too late to address catastrophic climate change (Farbotko, 2020; Hulme, 2020; Jewell & Cherp, 2020; Moser, 2020; Shultz, Sands, Kossin, & Galea, 2020). Within a global context of rapidly unfolding technological change, we also face looming existential threats, including, but not limited to, global pandemics, climate change, and human geopolitical conflict (Callaghan, 2018). Bostrom (2013: 15) suggests research and practice focused on existential threat reduction is urgently needed:

Existential risks are those that threaten the entire future of humanity. Many theories of value imply that even relatively small reductions in net existential risk have enormous expected value. Despite their importance, issues surrounding human-extinction risks and related hazards remain poorly understood...A moral case can be made that existential risk reduction is strictly more important than any other global public good...Perhaps the most cost-effective way to reduce existential threats today is to fund analysis of a wide range of existential risk and potential mitigation strategies, with a long-term perspective.

If existential risk reduction is ‘strictly more important than any other public good’ then it should attract a lion’s share of resources. Accordingly, mitigating existential risk requires knowledge of how to do so- research that is productive enough to yield this knowledge.

However, theory and evidence in the form of specific calculations suggest societal returns to research are substantial, but as a rule fail to be fully appropriated (B. F. Jones & Summers, 2020), giving rise to a substantial uncaptured positive externality. These calculations, however, fail to consider implications of Bostrom’s argument- that they should include existential risk. Intuitively, it is clear that doing so increases the size of this uncaptured externality exponentially, if not infinitely. If research fails to mitigate existential threats, and if humankind is eliminated, then this could be modelled as an infinitely large externality.

Why is there (possibly) existentially threatening underinvestment in research? We know the current scientific system fails to capture even clearly described social benefits.¹ Given the importance of this shortfall, the objective of the paper is to derive a ‘topology’ of existential threats and to classify them in terms of some arguments that suggests ways to reverse this shortfall. We argue that a failure to address it is increasingly dangerous, and our contributions to literature are as follows.

First, we contribute to a growing literature on existential threats and how to solve them (Bostrom, 2013; Callaghan, 2018; Vinge, 1993), to provoke new thinking. To do so, we extend recent work (Callaghan & Boodhoo, 2023) to link literature on wicked problems (Alford & Head, 2017; Crowley & Head, 2017; Lazarus, 2008; Rittel & Webber, 1973, 1974) to some ideas from literature on economics of innovation (Aghion & Howitt, 1992; Grossman & Helpman, 1991; Romer, 1990), and categorise what we suggest are core, or fundamental, characteristics of existential threats that have to date been unsolvable. Our discussions are inspired by moon versus ghetto observation (Nelson, 1977) that in some respects it was easier to put someone on the moon than to solve problems such as education in resource challenged settings. We therefore contribute to debates about this paradox that in many respects defines the limits of technology to date in solving existential problems. We also argue for certain future scenarios of how technology may ultimately

¹ See B. F. Jones and Summers (2020) for an insightful treatment of this issue, and for a summary of other related work to date.

tackle existential problems. In doing so, we sketch some implications of the theoretical synthesis we derive here.

Second, we contribute to literature on the fourth industrial revolution (4IR) (Schwab, 2017) to extend this literature to incorporate theory and evidence that suggests that despite the confluence of technologies it describes, the 4IR definition of an industrial revolution fails to acknowledge a longstanding and seemingly ongoing global productivity growth slowdown (Cowen, 2011; Gordon, 1992, 2012, 2016), and theoretical models and evidence that research is getting harder (B. F. Jones, 2009; Kortum, 1997; Segerstrom, 1998)- a ‘burden of knowledge’ effect (B. F. Jones, 2009). Declining research productivity extends across many fields, suggesting ideas are becoming ‘harder to find’ (Bloom et al., 2020). Given the extent of public acceptance of the 4IR moniker, following other work (Callaghan, 2019, 2021) we suggest a new term, ‘fifth’ industrial revolution, to bring the definition of industrial revolution back to one of radical increases in productivity. We relate this definition to work on the economics of ideas that offer insights into the trajectory of technological change and its problem-solving capabilities. We transcend notions and debates of technological optimism versus pessimism (Danaher, 2022) to rather focus on relevant theoretical ideas, including those of (Romer, 1990), thereby incorporating them into our overall theoretical synthesis.

Third, we contribute in practical terms to literature by relating different theoretical ideas to provide a synthesis of theory that we then match with examples of scenarios of existential threats. We intentionally tackle uncomfortable (and therefore potentially unpublishable- ‘unaesthetic’) ideas with the intention of provoking new thinking, a provocation we suggest is urgent, given a growing literature on the doomsday clock and evaluation of existential threats (Farrow et al., 2018).

Fourth, we argue that a dedicated literature and field is needed to focus research- and to lobby for radically increased funding for- on solving existential threats. A problem here is the nature of science as silo-driven by nature (Mode 1 research) and not sufficiently suited to solving real world problems that require multidisciplinary approaches (Mode 2 research) (Gibbons, 2000). This is not to criticise Mode 1 work, or its vital importance, but to rather argue for supplementary efforts to engage in constant cross-discipline theoretical synthesis. Given the nature of wicked problems and the existential threats emerging from them, we suggest the development of a supplementary discipline, ‘research management’, to aid these efforts. The literature on research itself is fragmented, and that a field of ‘research management’ and the professionalisation of such a field that prioritises existential threats as its *raison d’être* could be helpful. Such a field could draw together important insights from disciplines such as economics of ideas, economics of innovation, innovation studies, science and technology studies, innovation management, and other related areas of all stripes.

Why do we suggest ‘management’? We draw from some well established ideas about the production function notion (Lucas Jr, 1996; Romer, 1990; Solow, 1957) to argue that management captures the fundamental function of combining human and physical capital to produce productivity and growth, and the idea-generation underlying the productivity growth process (Aghion & Howitt, 1992; Grossman & Helpman, 1991; Romer, 1990). In so doing, we differentiate and delimit scope of discussions here to those building on assumptions that productivity and growth are ‘good’.

We therefore also acknowledge up front a growing recent literature that contests many of our assumptions and suggest degrowth and other ways forward in addressing climate change and other existential threats (Akbulut et al., 2019; Buch-Hansen & Koch, 2019; Dengler & Seebacher, 2019),

and other longstanding work that takes a less positive view of business and productivity logics that rely on the market as the key mechanism to drive societal problem solving (Marx & Engels, 1967; Marx & Engels, 1975). Nevertheless, we argue that our work here has some value in that it may provoke novel thinking about how to solve existential threats.

Having outlined some contributions of the paper, it proceeds as follows. First, in Section 2 our methodological approach is introduced. Next, the nature of wicked problems is introduced in Section 3, in that the three primary existential threats considered here are considered as wicked problems, namely climate change, geopolitical conflict, and human health threats. After this, in Section 4 we introduce Nelson's work on the moon and the ghetto, and the paradox of why it is possible to put someone on the moon but it is not possible to solve problems such as ensuring quality education for the poor, or other wicked problems. Nelson's work concerns why wicked problems are difficult to solve using technology, and we then argue that technology may ultimately solve wicked problems, but only if the scientific system re-focuses on achieving economies of scale in research productivity. Section 5 considers ideas relating to the speed and direction of technological change and questions whether these can be predicted. In Section 6 We present arguments that 4IR debates and discussions obscure a focus on global productivity growth which has yet to happen. We suggest that an industrial revolution should be defined by its delivery of radical improvements in productivity growth, a state we term 5IR. We also argue that 5IR logics need to derive more clearly to extend theoretical predictions of seminal theory, including that of Solow, Lucas, and Romer. In Section 7 we provide a synthesis of ideas as they relate to the existential threats of climate change, geopolitical conflict, and human health threats. Section 8 concludes.

2. Methodological approach

To derive a theoretical synthesis we use a conceptual review methodology focused by the question of how to solve existential threats before it is too late. We focus on solutions that derive from research, and the economics (and management) of ideas. We suggest this methodological approach is appropriate due to the nested nature of processes of natural and social science- they are embedded within networks of human behaviour, or activities. We will argue that such systems are beset by problems well described by literature on wicked problems. If we rely on these systems to solve existential problems then a starting point would be to understand wicked problems and the constraints they pose to solutions, including of the technological kind. Neo-Schumpeterian perspectives suggest that economic and technological advances are typically beset with challenges posed by the socio-institutional systems they arise within (Castellacci, 2007). Our methodological approach does justice to these forces in that it seeks to categorise them and to relate them to potential solutions. Theoretical ideas of wicked problems are now considered.

3. Wicked problems

As discussed, if social and natural science networks of processes and researchers suffer from similar problems to those of other human systems, a failure to solve existential problems by the research system itself might be classified as a wicked problem. Scientific ideas are not independent of social forces- even natural science practice and its practitioners are embedded in the social systems studies by social science.

History shows that social science research as well as natural science research can sometimes obscure, rather than enlighten (Kuhn, 1962; Lakatos, 1978), and Lakatos describes a failure to

uncover novel facts as pseudoscience. If so, then science can itself create, and deepen entanglement of knowledge creation processes in, wicked problems.

Rittel and Webber (1973:136) define wicked problems as requiring “elusive political judgement for resolution”- but that they are typically social “problems are never solved”, but rather at “best they are only re-solved- over and over again.” They are “complex, intractable, open-ended, unpredictable” (Alford & Head, 2017: 397). Accordingly, discussions of wicked problems recall Nelson’s paradox that we are able to visit the moon- a technologically advanced achievement- but cannot seem to solve problems like ensuring education for the poor (in the ghetto), and mitigating increasing healthcare costs, pollution, or drug abuse, and global warming, to name a few. Given the potential for misunderstandings, we use blocked text to ensure unambiguous and transparent insights into the ideas here about wicked problems. According to Rittel and Webber (1973:135):

A great many barriers keep us from perfecting [an idealized] planning/governing system: theory is inadequate for decent forecasting; our intelligence is insufficient to our tasks; plurality of objectives held by pluralities of politics makes it impossible to pursue unitary aims; and so on. The difficulties attached to rationality are tenacious, and we have so far been unable to get untangled from their web. This is partly because the classical paradigm of science and engineering- the paradigm that has underlain modern professionalism- is not applicable to the problems of open societal systems. One reason the publics have been attacking the social professions, we believe, is that the cognitive and occupational styles of the professions- mimicking the cognitive style of science and the occupational style of engineering- have just not worked on a wide array of social problems...We shall want to suggest that the social professions were misled somewhere along the line into assuming they could be applied scientists- that they could solve problems in the ways scientists can solve their sorts of problems. The error has been a serious one.

Here we have a diagnosis of the problem- that the approaches of natural science and an engineering approach to problem solving are fundamentally unsuited to untangling the complexities of wicked problems. Part of the problem, however, may lie in subjective understandings of wicked problems. Alford and Head (2017: 410/411) consider this further:

...the public participation approach may also add something to the process of defining ‘success’ [in solving wicked problems], in that those involved can exercise great control over the definition of success, and are therefore in a better position to trade off different costs and benefits in a way which makes progress in the face of intractability. The term ‘wicked problems’ has been bandied about indiscriminately by some public officials and scholars. Some of them use it to describe situations which they effectively over-estimate: problems which might be somewhat complicated in conventional terms, but not in fact wicked, as exemplified by large engineering projects like the Channel Tunnel. Others use it to describe problems that are in fact wicked, but from varying perspectives about policy implications. Of these, the more pessimistic overestimate the difficulty, seeing these problems as insuperable and therefore in the ‘far-too-hard’ basket. Others acknowledge the intractabilities, but nevertheless err on the side of optimism, assuming these problems are susceptible to the usual mix of rational understandings, organisational routines, coordination systems and databases.

Alford and Heads’ understanding stresses the need to define the type of wicked problems we are concerned with and we do so here as ‘intractable human behaviours that create entanglements that defy problem solving due to their inherent complexity.’ Levin, Cashore, Bernstein and Auld (2012:127) offer more nuanced insights relevant to our argument that time is running out to solve existential problems:

The notion that time is running out separates many environmental concerns from social challenges. In the latter case, much of which is considered appropriate policy is mediated by the political system.

Stakeholders with various interests interact and attempt to influence each other's policy preferences. The political system then responds, or fails to respond, with some kind of policy intervention. Losing coalitions tend to regroup, build more support for their ideas, and then attempt once again to influence the policy agenda...Those wishing to address super wicked problems such as climate change, however, do not have the luxury of 'coming back' to the political system for a retry, exacerbating the 'one shot' problem noted by Rittel and Weber. The time dimension will, at some point, be too acute, have too much impact, or be too late to stop or reverse...Climate change is arguably the most illustrative case of time running out. Significant impacts will occur; with each passing year, they become more acute; and if we do not act soon, the risk of harm to human communities and ecosystems, as well as non-linear change and catastrophic events, increases.

Any effective solutions of climate change and other looming existential threats therefore seem to require the ability to solve wicked problems. If we cannot urgently solve wicked problems caused by human behaviour it may soon be too late. Are there any realistic solutions?

We suggest, however, that any realistic solutions will, by definition, start as ideas. Hence, insights from theory that predicts how ideas can solve problems may offer some direction in this regard. According to probabilistic innovation theory, from a probabilistic perspective, chances of solving problems increase in proportion to the volume of problem solving effort (Callaghan, 2015, 2016). Accordingly, technological advances are particularly important because they can increase exposure of problems to problem solving inputs (such as through crowdsourced problem solving- crowdsourced R&D, or through data collection, or even research fundraising- crowdfunding.) But to what extent is technology the only viable solution/enabler we have to solving existential problems? At this point we turn to Nelson's work which explicitly delineates the limitations of technology to date in solving wicked problems.

4. Technology as the solution, or primary enabler, for solving wicked problems

Nelson (2011) defines technologies as the systematized professional know-how related to the performance of tasks. Technology has developed unequally, in a way that is largely unrelated to effective demand. If we pin our hopes on technological progress to solve existential threats then we need to have confidence that technological progress will proceed in the direction of solving our existential threats. Nelson (2011:683) outlines how technological progress typically unfolds:

So what do we know about how technological progress proceeds? Over the past half-century a large interdisciplinary body of scholarship has developed concerned with this question. For the most part that research has focused on the advance of product designs and production processes in fields like electronics, aircraft, agriculture, chemical products. Recently there has been a surge of study of advances in various areas of medical practice. In contrast, there has been much less research and writing on the evolution of teaching practices, or modes of business management, or knowledge of the effectiveness of different forms of economic organisation.

Management practices, to the extent that they are fundamentally responsible for the combination of human and physical capital to produce goods and services, may therefore have contributed greatly to increased human standards of living over time. Perhaps a dedicated field of research management could provide the meta theoretical and practical synthesis across disciplines needed to improve our responses to existential threats. This would include a need to manage technologies and technological capabilities.

Is it realistic, however, to hope that technology will evolve specifically in a problem-solving way, to address these threats? There will necessarily be winners and losers in the wake of technological evolution that happens through competitive selection processes, and R&D (Nelson, 2011). Technologies can have strong cores, such as those of advanced engineering; others have weaker

cores, such as those used in teaching which are typically labour intensive and at the mercy of individual endowments of motivation and skills. According to Nelson (2011:685):

I propose that teaching is a canonical example of human goal-oriented activities where we have not yet identified or achieved a controllable replicable set of procedures- a core, to use the language I established earlier- that is broadly effective across the range of relevant contexts. Performance in meeting the needs these activities aim to address tends to be highly uneven. There can be some instances of great effectiveness, but also many (as contrasted with unusual) instances of frustrating failure. I note that the activities tend to be labor-intensive, reflecting both as cause and effect the lack of standardization.

Nelson (2011:685) provides further insightful examples from the field of education to make his point.

The principal reason why it has been so difficult to make cumulative significant advances in educational practice, I would argue, is that it has proved very difficult to discover or develop a body of educational practice that can be controlled tightly, and replicated easily, that at the same time is effective in the variety of contexts where education must proceed. Practices that are effective seem to depend on the backgrounds, knowledge, and motivations of the student body, and also on the skills and personality of the teacher...to date no artifact has been developed for educational purposes that has the power of an antibiotic for dealing with infection. Related to that, it has proved nearly impossible to identify the key elements that lie behind effective practice when that occurs, other than very broadly.

Nelson's (2011:687) prognosis is not good- although findings can occur unexpectedly, he likens research programmes into such problems as searching in an area where 'the light is dim':

Solving problems by developing better ways of doing things generally is to be preferred to dealing with problems by trying to do the best one can with the practices in hand and allocating more resources to the effort. However, unfortunately, where there is no effective core, and there is no clear vision regarding where one might be found or developed, a solution through innovation is not likely in the cards. This is not to argue that research in the field should be abandoned. Important findings and inventions can occur unexpectedly. But a research-support program should be understood as a search for useful knowledge, in an arena where the light is dim. In such a context, one should not expect too much, or bet too much. And if this is the case, it is important to recognize it.

Nelson (2011:689) sums up his predictions of technology's potential to solve global warming:

There is good reason to believe that, without major breakthroughs in the technologies employed to produce and use energy, the costs of dealing effectively with the global-warming problem will prove to be so high that there will be political stalemate. And, unlike the case of education, or homelessness, where it is hard to see efforts to create and develop significantly superior know-how as having a high chance of success, there is a real promise in this area.

5. Is technological change really problem-solving in nature?

Mokyr (2010:14) stresses that technological change is often uncertain and even often 'wrong headed':

Technology moves at a certain speed and in certain directions, and the study of innovation helps us understand these laws of motion. Moreover, to come to grips with why technology changes the way it does, we need to be clearer about the way in which prescriptive knowledge (technology) and propositional knowledge (science and general knowledge about nature) affect one another. Knowledge about the physical environment creates an epistemic base for techniques in use. Technology, in turn, sets the agenda for scientists, creating a feedback mechanism...Technological change, like all evolutionary processes, was often wasteful, inefficient, and frequently wrong-headed. It was inevitably so, because by definition the outcome of the project was unknown, and so mistakes were made, duplicatory efforts took place, blind alleys were entered. Moreover, a great deal of what seems to use successful innovation was not adopted, for reasons that ex post seem hard to fathom and at times frivolous. But the degree of inefficiency of the innovative process was not constant over time.

Technological change can be path dependent and can result in sub-optimal outcomes (Arthur, 2013). Two ideas emerge from this literature- the notion of speed and direction of evolutionary technological change. The recent Covid pandemic illustrates the need for speed. Callaghan (2015) stresses the need to ultimately achieve real time research productivity- in the case of antibiotic development or a pandemic, research learning needs to be faster than that of the bugs. Evidence suggests, however, that academic research is often slow to incorporate novel or emerging technologies (Rubin and Callaghan, 2019). The definition of required timeliness of research interventions to stave off existential threats depends on the existential threat itself. It has been argued that it is now already too late to address catastrophic consequences of climate change (Farbotko, 2020; Hulme, 2020; Jewell & Cherp, 2020; Moser, 2020; Shultz, Sands, Kossin, & Galea, 2020).

What of the direction of technological change? Arthur (2013: 1186/7) references Kay's (2013) work on typewriter standards as follows:

...QWERTY, as a standard—or better as an example of what the market has served us up in the long evolution of one particular technology- has become in economics a focal point, a rallying point for a larger issue: whether the market can lock us into an inferior standard. And this itself is part of a still larger issue: whether the free markets of capitalist economies can drive us into inferior outcomes....and once again, the debate very obviously is not about keyboards. It is about an ideology, in this case the libertarian one that markets steer us to the correct outcome...Markets do lock in, and frequently. Optimality is a much trickier issue...Most often, a standard taken up at the outset is optimal for the people choosing. Later the criterion shifts and the now difficult-to-budge outcome looks non-optimal...Saying an outcome depends on historical accident is also tricky. What appears to be accidental at a coarse level may turn out to look inevitable at a more detailed level, then again to be largely accidental at a still more detailed level.

Much analysis of technological change relies on equilibrium analysis. Schumpeter (1937:158) also suggests it is difficult to predict systemic effects based on equilibrium analysis.

I felt very strongly that...there was a source of energy within the economic system which would of itself disrupt any equilibrium that might be attained. If this is so, then there must be a purely economic theory of economic change which does not merely rely on external factors propelling the economic system from one equilibrium to another. It is such a theory that I have tried to build.

The innovative process itself has “has dynamic and hysteresis-like properties means that the static economic modeling will be of limited use for analysis” according to Rosenberg and Hall (2010:5). The overriding implication of literature considered in this section is that where wicked problems are concerned innovation/research progress will typically be very slow. Similarly, the direction of technological change cannot be assured, and it is very difficult to model.

Accordingly, we conclude that technological change needs to be driven toward solving existential problems. This may require research effort, and success in this regard may depend on the ability to make research productivity scalable- to achieve economies of scale in research productivity. To do this, it is first necessary to focus attention on research productivity itself. We suggest discussions and debates regarding the 4IR have obscured a focus on research productivity itself- that it has largely failed to align these debates with theory that predicts how ideas generate productivity and growth. We suggest that an inflection point will ultimately be reached in research productivity and that if research productivity is able to ‘scale’ then even wicked problems will ultimately be solvable. A 5IR describes a revolution in global productivity growth, which has yet to happen. We suggest that a revolution in research productivity that results in exponential returns to investments in research will be a game changer, and that this revolution holds the promise to solving our existential threats.

6. Technological advances implied by 5IR logics

Following previous use of the term 5IR (Callaghan, 2019, 2021), it is defined here as a revolution in productivity of the knowledge creation process itself. What differentiates this definition from that of the 4IR (Schwab, 2017) is that the confluence of technologies described in many discussions of the 4IR do not reconcile these developments with the failure of these technologies radically improve global productivity growth- a condition required for an accurate description of the term ‘industrial revolution.’ We use the term to build on 4IR literature, and are not concerned with the second or third industrial revolution terminology in popular usage.

Recent technological advances have largely occurred in information and communication technologies (ICT) and entertainment sectors (Brynjolfsson & McAfee, 2014). Accordingly, a large literature evidences a failure of technological advances to dramatically increase productivity growth. This failure recalls the Solow paradox, that ‘you can see the computer age everywhere but in the productivity statistics’ (Acemoglu et al., 2014; Solow, 1987) as well as literature on a global productivity growth slowdown (Allen, 1997; Byrne et al., 2013; Callaghan, 2021; Gordon, 2013; Murray, 2018).

What underlies this failure? Although its causes are complex, an important reference point for discussions of industrial revolutions *defined as productivity growth revolutions* (and, hence, the 5IR) would be the Nobel recognised work of Solow, Lucas, and Romer. Solow’s work (1956) highlighted the exogenous role of technology in growth using models based on productivity function logics. Lucas (1988) subsequently stressed the role of human capital, and Romer (1990) ‘endogenized’ technical/technological change by modelling it- treating it as caused within the model- rather than exogenous.

Romer’s model can be taken to suggest that stocks of knowledge- recipes for combining human and capital resources- will create greater productivity over time. This might be termed a standing on shoulders effect, similar to how Newton’s laws of physics built on previous work to produce knowledge recipes the whole world could use. Many idea recipes are non-rivalrous- once ‘out there’, others can use the idea to increase productivity at little or no cost- when one uses an idea it does not stop others using it too.

However, the global productivity growth slowdown over the past decades (Cowen, 2011; Gordon, 2016) does not reflect Romer’s prediction of a standing on shoulders effect, and its implication for productivity growth. As discussed, 4IR discussions are often unrelated to the criteria of an industrial revolutions- that they need to reflect in a sustained substantial increase in productivity growth. 5IR discussions should focus on extensions of Romer’s models to incorporate specific technological effects. Such models could predict causal mechanisms underlying a coming potential radical increase in productivity- a coming revolution in research productivity that could be *commensurate with the scale of the existential threats we face*. This idea can be used to derive some implications for how a radical productivity revolution might happen, and its consequences.²

How dystopian can a 5IR be? We will suggest that a 5IR may result in the elimination of scarcity of goods and services, and radically increased productivity and growth (think AI enabled robots working 24/7). But at the extreme, the dystopian potential for human labour obsolescence has to be considered. As a thought experiment, by supplementing Romer’s (1990) model to modify the human capital term in the production function to incorporate the complementary and substitution effects of AI (operationalised by advances in robotics), it is possible to derive some interesting predictions regarding the implications of a 5IR. Of course, production functions of the Cobb-

² For a more detailed and user-friendly explanation of Romer’s (1990) model, and its assumptions, see C. I. Jones (1998).

Douglas type model these effects as complementary (Griliches, 1979) and even full substitution of human labour can simply be modelled as a high degree of complementarity.

In this model, human labour can be completely replaced by AI. Because AI can be used at lower marginal costs than human labour it can have unmatched productivity advantages. Examples illustrate this modelled effect: AI and fully automated factories can run 24/7 as can driverless trucks. In a world largely devoid of large supply chains disrupted by inexpensive production facilities, on-site production and part replacement can also be performed 24/7 using 3D manufacturing and robots. Although this thought experiment relates primarily to intermediate goods and manufacturing, it can be extended to service operations. Incorporation of such modifications then demonstrate an *exponential standing on shoulders effect*, and radical productivity growth, but at the same time also the potential for full human displacement by AI.

This essentially realises Rifkin's envisioned 'end of work' scenario (Rifkin, 1996), as well as the shift of economic relationships from a bricks and mortar world with high marginal costs to one based on electronic economics- where marginal cost intersects marginal revenue with high fixed cost and extremely low marginal costs (Rifkin, 2014)- for example, one more electronic copy of a product costs almost nothing to ship online.

This minor modification of Romer's model predicts a 5IR, a full productivity revolution, whereby production of goods and services can increase exponentially. An implication of this is that many problems of resource scarcity faced by humans can be solved. If the tax system is anchored to this increase in productivity, or production of goods and services, then tax can be used to cater for the needs of a post-work population. This population may not need to work, but psychological consequences of this would require attention, as would other issues relating to surviving a technological future (Callaghan, 2018). Service jobs, for instance, might be reserved for humans.

The point of this section is to highlight the argument that a relatively simple extension can be made to the series of models predicting productivity growth- the Nobel recognised work of Solow, Lucas, and Romer, and the role of technology in producing productivity growth- to demonstrate the potential of AI to fully replace human labour while at the same time increasing productivity to eliminate many resources needs of humans.

7. Synthesis and recommendations

On the basis of the discussions above, we are able to sketch some scenarios for how to address existential threats. Our core argument is that there is insufficient focus on what really matters to do this- that popular and scholarly discussions of the 4IR need to be supplemented with a focus on 5IR dynamics- addressing the reasons why Romer's exponential returns to investments in knowledge creation are not yet visible in the productivity statistics. Resolving this Romer/Solow paradox may hold the answer to addressing existential threats, if any real-world problem involving human behaviour can in essence be solved by an exponential increase in knowledge creation- our core assumption here. This assumption derives from probabilistic innovation theory (Callaghan, 2015, 2016). Probabilistic innovation theory is concerned with the probabilistic mechanisms that underlie novel methodologies like crowdsourcing, crowdfunding, and large scale knowledge creation projects such as Galaxy Zoo and GenBank (Nielsen, 2012), where participants across the globe name astronomical bodies and submit genetic samples, respectively. Probabilistic innovation theory predicts that by radically increasing the chances of a research discovery (by exposing problems to tens of thousand of people for instance), a threshold will be reached where the mode of discovery in a particular area itself changes from uncertainty to risk. Think an area of pharmaceutical innovation that provides a probable payoff to investments in a new drug.

Essentially, probabilistic innovation theory might be considered cynical in its predictions. It predicts that brute force- only very large numbers and only research that can attain economies of

scale- can the mode of science be changed from the present one to transcend a fundamental threshold limitation of our current scientific system. Callaghan is sceptical of the scientific system and its potential to address existential threats, suggesting that the scientific system itself should re-focus to, where appropriate, deliverable scalable research productivity. What are the implications of our synthesis of ideas here for existential problem solving, and what recommendations derive from it? The discussion below is delimited to three existential problems that capture the essence of our arguments here, namely climate change, geopolitical conflict, and human health. Table 1 summarises some key tensions associated with coming technological change.

Overall, categories in Table 1 suggest two overarching themes. First, that the effects of technological change will depend on the extent to which the wicked problem of human power is either strengthened or weakened. If technology empowers elites at the expense of their populations in countries across the world this could be problematic. Ideas sketched in Table 1 suggest power of elites may become an existential threat to us all. The other theme is the benefits to human populations, which seems to be vulnerable to the actions of powerful groups- benefits to human populations may also create categories of winners and losers.

Table 1. Wicked existential threat characteristics and solutions from exponential research productivity: Key tensions

Climate Change			Geopolitical Conflict			Human Health		
Sub-problem components	5IR solutions	Societal implications of success	Sub-problem components	5IR solutions	Societal implications of success	Sub-problem components	5IR solutions	Societal implications of success
Lack of cross-country consensus	Values change through improved education and knowledge exchange. Social science knowledge increases to solve through better education, reduced resource scarcity and conflict	More sharing of universal values regarding climate change and its priority or empowerment of elites with other priorities?	Resource scarcity	Technology can facilitate shifts to renewables and should eliminate scarcity if power over technology is inclusive.	A more equitable world, or a world that is increasingly insular- made up of 'fortresses' and greater global inequality.	Pandemics	Real time research productivity can address problems inclusively as they arise, as long as elites are not able to interfere. A pandemic threat of one country is a threat to all.	Technological advances like augmented reality and electronic work
Global geopolitical conflict	Social science knowledge increases to solve through better education, reduced resource scarcity and conflict	Democratisation of education or empowerment of elites?	Power dynamics	Technology may empower elites who are then no longer incentivised to look after their populations.	Technology may increase or decrease power of elites- elites may pose an existential threat to human life under conditions of rapid technological change.	Biological warfare	5IR defined by research productivity can contribute both to risk and to countermeasures. Key problem is power relationships of humans.	New weapons that make nuclear threats obsolete can also make the world more dangerous. Unclear if elites and the power they wield will be an existential threat.
Developmental priorities over climate priorities	Education and values change from more equitable educational opportunities. This should enable values change over time.	If control is maintained over technological change, then resource scarcity might be eliminated through exponentially productive goods and services creation. Human behaviour may still dictate applications, however, and elites may become more entrenched.	Supply chain conflicts	Ultimate elimination of supply chains may reduce geopolitical conflict	Production fully localised- potential for further deglobalisation?	Costs of aging populations- crises of funding healthcare for those living decades longer than they used to.	Technology can spur exponential increases in idea generation according to some of the models discussed above. Organ printing and other opportunities should allow older people to be much more healthy and productive.	Global values change and improved education at all ages. Human life span extension that adds to overall productivity and quality of life.

Climate Change			Geopolitical Conflict			Human Health		
Sub-problem components	5IR solutions	Societal implications of success	Sub-problem components	5IR solutions	Societal implications of success	Sub-problem components	5IR solutions	Societal implications of success
Industry emissions	5IR changes may produce technologically enabled alternatives, and a transformation to renewable energy.	Lobbies and countries with natural resources are incentivised to influence democracies and hold back innovation. Technology will spread, however, if cost and other benefits to stakeholders are clear.	Conflicts and wars	5IR can spur technological arms race between blocks of countries with different values. This may spur innovation but at the cost of ethical and careful management of technological change.	It is unclear if the potential for malevolence increases with global technological capabilities. Nuclear capability enables war and conflict.	Diseases of the poor	Technological progress can eliminate diseases of the poor, and equalise opportunity.	Developmental challenges are addressed and populations are able to benefit from greater productivity and a higher standard of life.
Resource conflict	'Revolving door' of resource conflict- now lithium and rare earths- but ultimately innovation can replace these sources to become fully renewable	Elites in resource dominated economies mitigate threats to power	Roles of elites	Elites in countries may control technology, creating dystopian conditions for their populations	Will AI be or enable the next atom bomb? Will elites become an existential threat for all of us?	All diseases	Gene editing and other techniques should eradicate all disease. However, benefits of these technologies need to be accessible to all or this will simply differentiate elites. This might make elites invulnerable to the passage of time, at the cost of their populations.	Aging may be reduced, with humans essentially living forever. Unclear implications. There may be a need to seriously consider expansion into space to accommodate growth in human populations.

Existential threats are now considered in relation to ideas in Table 1. They are also considered in light of the categories shown in Table 2. In Figure 1, four scenarios are sketched on the basis of two overarching themes in the literature, namely the power of elites and the extent to which socio-institutional systems resist technological change. The four include extinction, dystopia, asymmetry, and transcendence.

7.1. Climate change

Climate change is the quintessential example of an existential threat of our time. As a wicked problem, what are the wicked sub-problems that comprise it? To achieve climate change objectives, multilateral cooperation is needed. It will not help if a few countries reduce emissions and others offset these gains by continuing to pollute. But what of many countries whose primary source of revenue is fossil fuel exports? It is not in their interests to disrupt their primary source of income. Because the industry structure of such countries is based on natural resources, elites will often have taken control of it. Climate change might pit countries against each other, exacerbating global conflict.

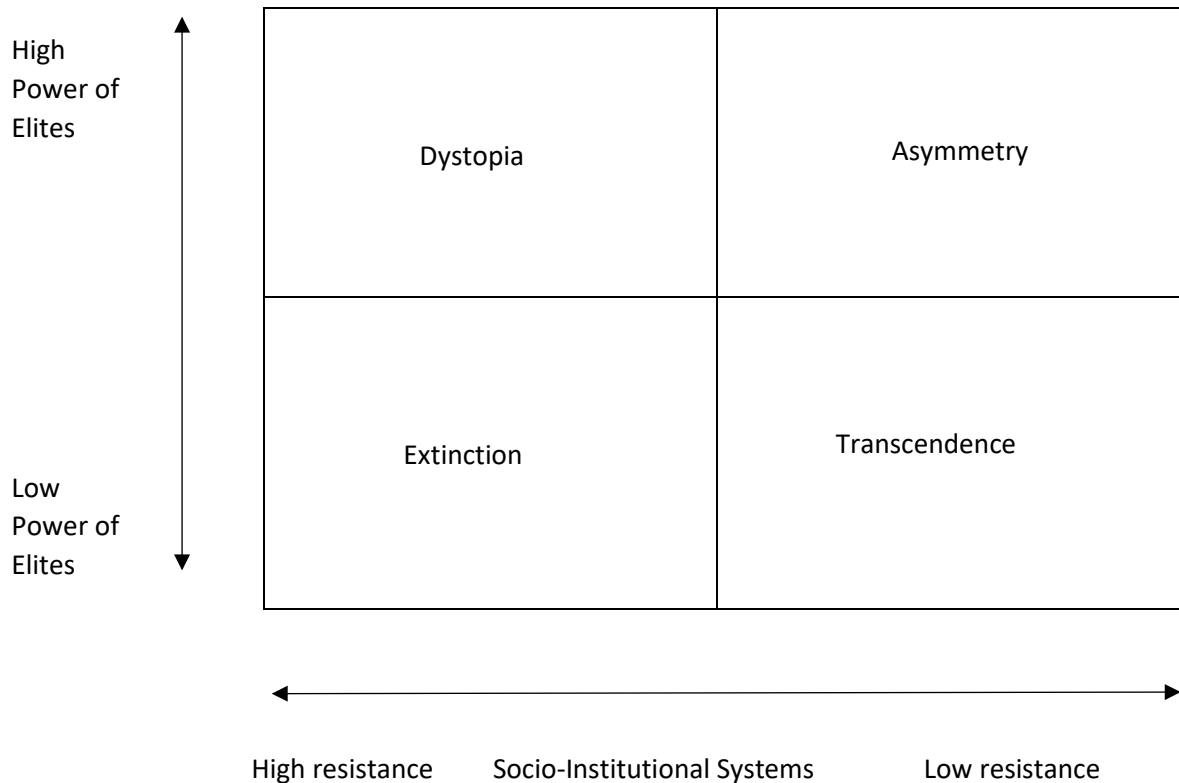


Figure 1. Scenarios of power of elites and resistance of social-institutional systems to technological change

Perhaps only technological change can force the necessary global shift to renewables. But elites are incentivised to intervene in other countries to strengthen resistance of socio-institutional systems, perhaps through lobbying or other active measures. Elites are defined here as powerful ruling classes that are entrenched politically in countries. Examples include authoritarian regimes.

If elites have low power, and there is high socio-institutional resistance to technological change, then we remain at the mercy of the first existential threat to befall us. The threat of climate change is well documented.

If elites get the upper hand amidst strong socio-institutional resistance to technological change then we might face extinction but with dystopian characteristics. Blocks of countries dependent on natural resources may exert force to protect their interests. With insufficient technological change to enable a mode transition to renewables, these elites retain their power in geopolitical relationships and can keep building alliances to strengthen their block. For elites, what is the attraction of democracy if they lose everything after an election every few years. Elites are incentivised to preserve the impression of democracy while subverting it. Hence, we refer to elites instead of democracy here.

Asymmetry occurs when socio-institutional forces are insufficient to hold back technological change. Outcomes in this scenario are unclear. Elites may use increasingly available technology to entrench their inequalities, or to control their populations. Ultimately, the fate of global populations may depend on the outcome of a technological arms race, defined by a striving for asymmetry- and dominance of elites over non-elites. Unfortunately, elites have an advantage, in that in elite-dominated societies technological progress may proceed unencumbered by ethical, moral, or human welfare concerns. Elites may continue to suppress human rights and labour rights to artificially attract manufacturing activity, further perpetuating deindustrialisation. If elites dominate, then the chances of extinction increase. Elites are therefore potentially a threat to humankind in this scenario.

Table 2. Optimistic versus pessimistic scenarios of elite power and resistance to technological change

Scenario	Optimistic societal outcomes	Pessimistic societal outcomes
Extinction	Continue as present- at mercy of first existential threat- extinction of humankind, or survival of some.	Extinction of humankind
Dystopia	Elites control countries in stand-offs, with a cost to populations in their countries.	Elites act malevolently- elites as existential threat to human populations
Asymmetry	Technology expands rapidly, increasing inequality- technological leadership dictates fate of human populations. Outcome ultimately depends on whether countries with lower elite power are able to advance technologically more quickly.	Conflict spurred by rapid technological change, with elites having fewer regulatory or ethical controls. Elites take the lead technologically due to rejection of moral standards, ethics, and welfare concerns. Elites control electoral processes of other countries and elites gain world dominance.
Transcendence	Power of elites limited and technology advances with ethical, moral, and welfare concerns that allow socio-institutional forces to co-evolve with technological change. Human quality of life is radically improved, and the existential threat of elites is mitigated.	Problems inherent in technological change may themselves pose an existential threat. Scale of risk is increased overall, but may be unavoidable.

If elites are not able to dominate, and technological advances spread relatively equitably through human populations then the fruits of technological progress may be realised most fully. This does not, however, guarantee that human populations are free of the inherent threats of technological advancement itself. Coevolution of socio-institutional systems is required that ensures ethical, moral and welfare concerns are addressed, in a way that includes checks and balances. In this

scenario, the existential threat posed by elites is successfully mitigated and analysis reduces to purely the consequences and benefits of technological change itself.

7.2. Geopolitical conflict

Geopolitical conflict can rise from the incentives countries have to pursue their interests. Elites might be incentivised to create conflict to unite their populations. World Wars illustrate the dangers of militarist elite-dominated power. Countries with elites that survive because of natural resources may also resist technological change.

Extinction as a scenario captures a world in which the current status quo prevails. Under these conditions we face the threat of nuclear war and populations continue to be at the mercy of their elites, but this is limited to the block of countries ruled by elites. Although perhaps unlikely, mistakes can happen due to geopolitical conflicts, with catastrophic consequences. But again, we are at the mercy of the realisation of the first existential threat to 'reach' us. Under dystopia, elites of countries wage war and global conflict, without the power of technology to disrupt their power, but also with the consequences of new forms of warfare that transcend nuclear, as might occur under the asymmetry scenario. Under transcendence, technology reduces power of elites and technological benefits are dispersed.

7.3. Human health

Under the extinction scenario, pandemics threaten human populations, and the current scientific system is unable to transition to one based on economies of scale (Callaghan, 2016). Similarly, many countries become fiscally deadlocked as the average age of their populations rises inexorably. Disease and illness perpetuate, with all humans destined to a one-sided and almost never-ending struggle against health issues. Under dystopia, elites dominate, and enjoy inequitable health care or perpetuate current conditions, endangering global health through lack of transparency and other consequences of their incentives to retain power of information and other powers over their populations. Under asymmetry, there is competition between elite-dominated countries and other countries of the world. Elites may have a profound advantage, in that they may be free of ethical, moral, or welfare-related constraints to their pursuit of biomedical and biological advantage. Under transcendence, health benefits of technological change are spread across human populations more equitably.

8. Conclusion

The objective of the paper was to provoke novel thinking about existential threats, and to do this by sketching some scenarios. Although not exhaustive, our discussions suggest some conclusions.

First, many existential problems seem to be wicked in nature, in that they are caused or exacerbated by complex human behaviour, and stand in contrast to other problems that can be solved by technology using an engineering mentality.

Second, although much work has been done on the limitations of technology in solving existential problems, it seems that the speed and direction of such change may be inherently unpredictable, and it might be useful to re-focus discussions of technological change to those related to how to increase or improve research productivity.

Third, it is possible that a focus on attaining economies of scale in the knowledge creation process itself is confounded by discussions of a 4IR that is not explicitly defined as a productivity growth revolution. By refocusing on productivity growth, and seminal theories of productivity growth, a revolution in knowledge creation itself- a 5IR-may be better monitored and tracked as it occurs and rolls out. A 5IR returns to the definition of an industrial revolution as a productivity revolution, that is yet to fully unfold.

Fourth, given logics of how technological change happens (as a revolution in research productivity), two overriding forces seem to shape the consequences of technological change for human populations- the extent to which elites take advantage of technological forces and the extent to which socio-institutional forces resist technological change. Some scenarios are considered together with their implications.

Although not exhaustive, scenarios here may be useful in understanding the evolution of technological change and how to ensure it happens to improve ethical, moral, and welfare conditions of human populations.

Our overarching contribution is perhaps to provoke thinking about what an industrial revolution should be, and to consider its implications for how we engage with it. By reconceptualising its nature we might better be able to understand its driving forces and mitigate them for our benefit, in that an industrial revolution as described here can act as a heuristic to guide action to address existential threats, before it is too late.

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