Revisiting how scientific research drives technological change: The Fifth Industrial Revolution

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Significance:

Moll, Marwala, and Ntlatlapa highlight salient criticisms of terminologies and definitional uncertainties associated with the term 'Fourth Industrial Revolution' (4IR). Scientific research on technological change seems to suggest a need for theoretical synthesis to address a failure of 4IR notions to consider the central role of a *revolution in the scientific/knowledge creation process itself* – that is seemingly a causal driver of current technological and societal changes. The term 'Fifth Industrial Revolution' might helpfully be used to differentiate 4IR debates from those deriving from revolutionary changes in science itself that may underlie our current trajectory of technological change.

Moll[1] argues there has been "no technological revolution, let alone a 'Fourth Industrial Revolution'" (4IR). He refers to Schwab's[2] World Economic Forum discussions of the 4IR:

> *We have yet to grasp fully the speed and breadth of this new revolution. Consider the unlimited possibilities of having billions of people connected by mobile devices, giving rise to unprecedented processing power, storage capabilities and knowledge access. Or think about the staggering confluence of emerging technology breakthroughs, covering wide-ranging fields such as artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3D printing, nanotechnology, biotechnology, materials science, energy storage and quantum computing, to name a few. Many of these innovations are in their infancy, but they are already reaching an inflection point in their development as they build on and amplify each other in a fusion of technologies across the physical, digital and biological worlds.*

For Moll[1]: "What I want to question is the way we use the word 'revolution' to describe and understand our activities. On that score, I argue that we have not witnessed a 'grand', overall technological revolution in recent times. It is important that scientists and technologists understand this." In response, referencing Kuhn, Marwala[3] argues the 4IR represents "a scientific paradigm shift" and that Moll's "argument that the 4IR does not constitute a revolution is thus unfounded". Ntlatlapa[4] also challenges Moll's conclusion that changes associated with the 4IR fail to meet "the criteria for an industrial revolution".

These debates reflect contested definitional understandings of technological change in scientific literature. Scholarly scientific perspectives of contemporary technological change, and its societal implications, abound, typically couched in metaphors such as that of 4IR[2], Industry 4.0[5], the First, Second, and Third Industrial Revolutions[6], and the 'second machine age'[7], amongst others.

Research on the topic has sought to discover core theoretical mechanisms, or fundamental causal drivers of contemporary technological changes. Recent studies of contributions of technological changes in scientific research and biomedicine[8,9] and disaster response[10] suggest some patterns in how roots of societal technological change might derive from innovations in the scientific or knowledge creation process itself. These patterns are relevant to the debates Moll, Marwala, and Ntlatlapa engage with.

These patterns suggest the central role of innovations in the scientific process itself are not sufficiently considered in popular debates about industrial revolutions. Revisiting the key notion of 'productivity', and relating productivity revolutions to some scientific ideas, one might describe the current 'revolution' we are about to fully experience, as a 'Fifth Industrial Revolution' (5IR).[11,12]

In light of Moll's, Marwala's, and Ntlatlapa's discussions, one might criticise the introduction of yet another term for the confluence of technological change we face. Indeed, many technological developments, including ChatGPT, have been associated with a dramatic change in technology use, and, irrespective of terms like 4IR and 5IR, these impacts are tangible and quantifiable. However, the 5IR stream of literature[11,12] seems concerned with a 'revolution' in productivity that becomes evident or measurable at the aggregate level (which is arguably yet to materialise – see Robert Gordon's extensive work on the topic).

It is entirely possible that AI might now 'show up' in the aggregate productivity statistics and drive a global productivity revolution. In that the 5IR literature focuses on the aggregate level and is concerned with identifying a 'revolutionary' increase in global productivity growth, we might therefore expect this to inevitably occur at some time in the future.

The 5IR literature has built on the 4IR literature, and is complementary to previous literature. As such, it does not seek to 'replace' the 4IR in current terminology because 5IR is concerned with extending scientific work on the aggregate relationships between technological change and global productivity growth.

Why is the aggregate level important? Schumpeterian theory predicts that, as new technologies develop, they can disrupt pre-existing products, processes, businesses, and other previous knowledge recipes – making them obsolete.[13] Thus, technological innovation can also create obsolescence, and it is only at the aggregate level that we can see the net results of overall systemic change. Technological change is typically path dependent[14,15] and there is no guarantee that it proceeds in a societally optimal way. An example of this is the QWERTY keyboard, which was built to slow down typing to accommodate limitations of mechanical typewriters. 5IR literature therefore seems interested in overall, or aggregate, productivity growth.

Therefore, 5IR might be a useful term to describe a synthesis of the proliferation of some of the definitions and descriptive popular debates associated with the 4IR, to build a separate literature that extends these debates with a focus on scientific work on global productivity growth. Two rationales summarise some patterns and trends in the scientific literature on technological change.

First, the 5IR concept acknowledges widespread popular use of the term 4IR, *but the new term 5IR* may be necessary to re-anchor debates about productivity revolutions in scientific work often ignored in popular discussions.[11]

The primary industrial revolution has been discussed in terms of its radical productivity enhancements that caused radical societal change.[16] As discussed in the following sections, anchoring debates to scientific work on productivity may offer us a more scientific (historical) definition, as few would disagree that radical societal change has historically occurred due to productivity revolutions.

Second, and relatedly, building on Moll's[1] criticism of "fanciful, rhetorical, science-fiction like evocations", setting aside popular (or populist) notions of these phenomena, and other descriptions of the 4IR that are largely descriptive and atheoretical, one might ask, *what does scientific study of technological change tell us*? Is there a pattern that is grounded in scientific work that can unite popular debates?

Many popular debates seemingly do not sufficiently draw from seminal scientific notions of technological change[17] and the evolution of this literature that explicitly models it theoretically[13,18,19]. Similarly, these debates do not seem to engage sufficiently with current ongoing scientific conversations on the topic.[20-22]

What seemingly unites the scientific literature is a simple notion – that many historical advances, or revolutionary improvements in quality of life, in human history were *driven by the same phenomenon*: a step change in the way we generated knowledge – the effectiveness of our scientific system itself[23]. In Nielsen's[23] words:

> *Revolutions are sometimes marked by a single, spectacular event…But often the most important revolutions aren't announced with the blare of trumpets…We are in the midst of a great change in how knowledge is constructed…A change of similar magnitude is going on today: we are reinventing discovery…To historians looking back a hundred years from now, there will be two eras of science: pre-network science, and networked science. We are living in the time of transition to the second era of science.*

Nielsen gives examples of very large-scale projects, such as the Polymath Project (solving difficult mathematical problems using crowdsourcing), GenBank (collecting global genetic information), Wikipedia (the online encyclopaedia), and Galaxy Zoo (mapping the galaxy using global participants), that seem to demonstrate revolutionary productivity in scientific knowledge production.

Nielsen's examples seem to highlight the workings of some causal mechanisms underlying these radical productivity improvements, and some of the 'why' of current technological change. Building on Nielsen's work, the term 5IR might therefore usefully provide a synthesis and a clear logic (differentiated from fragmented 4IR thinking) to argue that a productivity revolution is currently underway due to the causal influence of *radical innovations in the scientific research or knowledge creation system itself*.

Thus, instead of a 4IR focus largely on the outputs of this revolution, or its 'contents', 5IR thinking should focus more precisely on the fundamental cause of this change. This change seems to be caused by a revolution in how we generate knowledge – not simply regarding (big) data and information – but in the scientific/knowledge creation process itself[9] and a coming paradigm change in scientific research itself[24].

Nielsen's[23] explanations of the causal mechanisms underlying this revolution also seem to reconcile an important paradox in the science/technology literature – of the failed predictions of Romer's[25] and other endogenous growth models, as well as recombinant growth theory[26], to reflect in evidence of constant or increasing returns to scale of idea creation. Romer's Nobel Prize winning work suggests that productivity results from non-rivalrous 'knowledge recipes' that, once created, can often be used by others at little cost. In short, this should ultimately improve productivity over time, with increasing returns to scale in knowledge creation. This body of work is based on rigorous theoretical modelling, and this failure seems to be at the crux of debates about the failure of technological change to deliver radical aggregate productivity enhancements. It recalls the longstanding Solow Paradox, whereby, according to Solow himself in the late 1980s, you "can see the computer age everywhere but in the productivity statistics".[20,27]

This failure seems well documented[28-33], and also seems to be related to what Jones[28] describes as a 'burden of knowledge' effect, analogous to Romer's own description of a 'fishing out' effect in research. The argument here is that science – *the research process itself*, and theoretical models featured in discussions deemed worthy enough to earn their theorists Nobel awards – seem to underlie predictions of the fundamental trajectory of technological change.

In short, Romer's work seemingly has a radical implication – that returns to the creation of ideas could possibly be exponential, demonstrating increasing returns over time. Nielsen's work may offer evidence of how these returns can be achieved, and reasons for why social structures of science are slowing these shifts. As suggested by Neo-Schumpeterian theory, economic and technological advances are typically held back by socio-institutional forces of human societies.[34]

Moll, Marwala, and Ntlatlapa's insightful discussions provide a useful reference point to highlight the broad and fragmented nature of broader 4IR debates. These 4IR debates could be supplemented to include reference to an extensive body of theoretical and empirical work on how changes in the knowledge creation/scientific process itself may also explain the current trajectory of technological change. The term 5IR might helpfully differentiate 4IR work to include a primary focus on science itself and a revolution within science. This revolution in the processes of science may fundamentally be driving a mode transition, from declining returns to idea creation to increasing returns. As Nielsen[23] predicts, there will ultimately be no doubt that we are in the midst of a revolution, if the revolution entails the reinvention of discovery itself.

In conclusion, some implications derive from discussions above that extend previous work on predicting outcomes of technological change.[35]

First, Amara's Law, that 'we tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run'[36] implies that if the radical changes predicted by Romer and Nielsen do arise from idea proliferation then they will be profound. Although some have argued that the most impactful technological changes have largely been limited to Internet and communication technologies and entertainment[7] – which seemingly supports some of Moll's observations that large-scale change is yet to be experienced – 5IR logics suggest that large-scale societal change will now accelerate.

Second, and finally, probabilistic innovation theory[10] predicts (perhaps fancifully) not only increasing returns to scale in research, but ultimately that real-time research productivity will be possible, and that research will ultimately be able to solve all 'solvable' problems – problems that are inherently solvable. We might all agree that not even 'fanciful, rhetorical, or science-fiction-like evocations' can describe what such a future would look like. More critical engagement in these conversations is urgently needed.

Competing interests

There are no competing interests to declare.

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