The Past and the Future of Innovation: some lessons from Economic History

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ABSTRACT

In recent years, economists have revived the specter of slow growth and secular stagnation. From the point of view of economic history, what should we make of such doomster prophecies? As economic historians all know, for 97 percent or so of recorded history, the stationary state well-describes the long-run dynamics of the world economy. Growth was slow, intermittent, and reversible. The Industrial Revolution rang in a period of sustained economic growth. Is that growth sustainable? One way to come to grips with that question is to analyze the brakes on economic growth before the Industrial Revolution and examine how they were released. Once these mechanisms are identified, we can look at the economic history of the past few decades and make an assessment of how likely growth is to continue. The answer I give is simple: there is no technological reason for growth in economic welfare to slow down, although institutions may become in some area a serious concern on the sustainability of growth.

Introduction

A concern that economic growth may be coming to an end is not unusual during a severe recession: Alvin Hansen wrote his famous article proposing the concept of secular stagnation at the end of Depression (Hansen, 1939), and Lawrence Summers (2016), inspired by the 2008 recession, has recently revived the concept. The most detailed pessimist prognostications are Cowan (2013) and Gordon (2016). Gordon and Cowan come from the supply side and believe that technological progress has sufficiently exhausted itself to be unable to counteract other "headwinds," whereas Summers focuses on aggregate demand.[1] In what follows I will focus entirely on the supply side, because insufficient aggregate demand and excess savings, insofar as they are a problem at all, can and probably will be offset by growing government deficits, at least in the U.S.

As I will argue below, reports of the demise of technology-driven economic growth in the developed world are premature. It is of course true that *measured* GDP growth and variables derived from it such as TFP growth have performed poorly in the twenty-first century after 2006. Gordon (2018, p. 16) insists on using productivity growth as his "metric of transformation." There is serious doubt whether such measures are a correct reflection of the actual achievements of technological progress. In a seminal article, William Nordhaus has argued that we have failed to measure correctly the true rate of price decline in lighting.[2] More generally, the tenuous link between productivity

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[1] A particularly insightful analysis is Vijg (2011). See Mokyr (2013) for details on his predictions.

[2] Nordhaus (1997). The quality improvement of lighting has experienced a resurgence in the recent decade with the emergence of LED lighting, which is far more energy efficient, involves no fire hazards, has much greater durability (30 to 50 times that of incandescent bulbs) and provides more light than earlier-generation lighbulbs, including halogen lights. Lighting accounts for 15 percent of global electricity consumption and 5 percent of worldwide greenhouse gas emissions. If all lighting switched world-wide to LED lights, we would cut lighting-demand for power back by 85% ("Rise and Shine", 2015). A similar calculation for the decline of the cost of computing power was recently suggested, only half tongue-in-cheek, by Brad De Long (2017) who has calculated that the cost of a new iphone using the technology of 1957 would be 150 trillion dollars and consume 30 times the electricity power of the world today.

growth and welfare-enhancing technological progress seems to have become weaker in the past decades. There are many reasons for this, including the *un*-measurement (as opposed to *mis*measurement) of improvements in digital technology, the rapid improvement in the quality of many existing products, and the hard-to-measure improvements in the service sector, such as the public sector, diagnostic and preventive medicine, and on-line retail commerce. To put it differently, students of contemporary technological progress should wean themselves of TFP-fetishism; aggregate measures such as GDP (the basis for TFP calculations) were designed for a wheat-and-steel economy, not for an information and mass-customization economy in which the service economy accounts for 70-80 percent of value added. While GDP may still be useful for assessing short-term cyclical fluctuations, its value for an age of rapid product innovation is questionable (Coyle, 2014). What matters here is not just that TFP mismeasures the true rate of technological change (which has always been understood), but that the gap is growing over time. The very phenomenon it purports to measure increases the mismeasurement. For that reason, the TFP data that Gordon (2018) employs tell us little about the rate of innovation in the past (much less the future), whereas the narratives in his book (2016) do so in spades.

Many of the issues that Gordon (2018) outlines are real, but none of them demonstrates that the rate of technological progress will slow down. Part of the techno-pessimist predictions seem internally inconsistent. One cannot worry about possible technological unemployment or “layoffs that occur when machines replace labor” (Gordon, 2018, p. 5) and at the same time be concerned about labor productivity not rising. Another problem is that the United States may have become in some ways atypical of the industrialized world: with its welfare state under pressure and growing income inequality, it has shown less willingness or ability to deal effectively with the losers who also accompany technological disruptions. The rise in mortality rates documented by Case and Deaton and cited by Gordon is rather atypical and concentrated among some specific demographic groups. As shown by Alon (2017), some of the growing inequality in the U.S. can be attributed to a deterioration of the education system (specifically high schools) that occurred in the 1970s when vocational education was downgraded and pre-college specialization was phased out, and one that is fairly easily remedied. Most important, however, is the expected impact of digital technology and artificial intelligence on the quality and content of teaching (see below). In contrast to Gordon's dire predictions, then, human capital can expect major improvement in the foreseeable future.

What can the economic historian add to this debate? Very slow economic growth, even "secular stagnation," were of course the rule almost everywhere before the Industrial Revolution. In what follows, I sum up my views on the origins of what Deirdre McCloskey (2016) has felicitously termed the "Great Enrichment."[3] It focuses on the basic fact, known to every economic historian, that before the Industrial Revolution economic growth was slow, intermittent, and reversible. Years of growth were normally offset by years of decline. Even after the Great Enrichment, episodes of economic decline did happen, but the "good years" began to outweigh the bad ones. Economies became more resilient to outside shocks, whether natural or man-made. Asking "why" economic growth was so weak before the Industrial Revolution may seem otiose, since it was the normal, natural state of affairs. Yet the answers points to the many ways in which "modern" economies differ from traditional ones, and thus underline that the Industrial Revolution was in many ways what the physicists call a "phase transition," a major transformation not only of the level and rate of

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[3] The term "Great Enrichment" seems better suited than the term "Great Divergence" popularized by Pomeranz (2001). The latter focuses on the relative gap between West and East, without recognizing that even in the areas that fell behind (and still have not fully caught up), poverty has declined sharply and living standards are far higher than they were in 1750, the alleged date at which "divergence" began.

growth of the system, but rang in an entirely new economic dynamic. It is almost like writing the history of life on earth during the Cenozoic era: mammal species proliferated and evolved, but the entire dynamic of evolution and the environment in which it took place changed in geologically very recent times with the appearance of homo sapiens.

Three Reasons why Economic Growth was so Slow before the Industrial Revolution.

The literature on why and how modern economic growth emerged in the West is vast. In my own writing, as well as that of many others, a large number of theories and arguments have been proposed. I will single out below three fundamental classes of models that have been adduced to explain why there was so little growth before the Industrial Revolution, but no claim is made that they exhaust the issue. The three classes are: Malthusian demographic dynamics; political economy and rent-seeking; and the absence of a foundation of knowledge (epistemic base) of techniques in use.

By far the most popular and widely cited reason why premodern economies did not grow faster is population dynamics. The idea was famously enunciated by Malthus and has since carried its name, although it was perhaps most eloquently expressed by H.G. Wells (1923, p. 68): humanity "spent the great gifts of science as rapidly as it got them in a mere insensate multiplication of the common life." The argument is known to every economist. Under some fairly reasonable assumptions, any rise in income per capita or productivity, whether derived from the "great gifts of science" or any other source, will lead to a decline in deaths and a rise in births, and as population growth sets in, diminishing returns to a fixed factor such as land or more generally the environment will set in, and income will decline (Clark, 2007; Galor, 2011; Ashraf and Galor, 2011).[4]

The disappearance of the Malthusian demographic regime occurred at some time before and during the Industrial Revolution (Kelly and Ó Gráda, 2012, 2014). This disappearance had two components. The first component is that the two key assumptions that made the model work became unrealistic: fertility rises and mortality falls with income per capita, and there is some fixed but important factor ("land") that imposes diminishing returns on labor and hence presses wages down as population increases. The demographic transition consisted of a fall in mortality as incomes rose, and while fertility rates declined as well with rising income, they did not decline enough to offset the effect of falling mortality. As a result, world population has grown enormously since 1750, but its growth is now slowing down everywhere except Africa (and is actually negative in many countries).[5] The Malthusian "positive checks" in which mortality rates rise when income falls below some threshold level that could be regarded as "subsistence," seem to have vanished. The famines of the twentieth century were caused by war and political chaos, not overpopulation (Alfani and Ó Gráda, 2017, p. 5; Naumenko, 2017). Diminishing returns to the fixed amount of land also are no longer realistic. Because of land-augmenting technological progress, agricultural yields have

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[4] Recent thinking about Malthusian models in history has considerably modified our strong commitment to the "iron law of wages" as a powerful constraint on growth in the past. Highly developed regions were more urbanized and experienced higher mortality rates. Through this and other mechanisms, economic growth raised the death rates and thus allowed the Malthusian system to have multiple equilibria: one highly urbanized and mobile, and the other traditional Malthusian describing a population of subsistence farmers (Voigtlaender and Voth, 2012, 2013). In the Netjerlands and England, estimated GDP was no wholly stationary as fundamentalist Malthusians have asserted, and roughly doubled between the late Middle Ages and ca. 1700 (Broadberr, 2015, p. 25).

[5] Alarmist Malthusian predictions in the twentieth century, associated with the writings of Paul R. Ehrlich, have been thoroughly discredited.

increased by orders of magnitude and land no longer constitutes a major factor of production and its share in GDP in the West is minuscule.

The second component is that the rate of growth of output and productivity overwhelmed any negative feedback coming from population growth. The Malthusian model works when there is a one-off shock to income; if income rises continuously, however, the net effect on living standards comes down to a race between growing productivity and diminishing returns to labor. After 1800, rising productivity won. Technological progress has historically more than offset the declining productivity of labor caused by population growth. In short, the Malthusian model simply becomes inapplicable after 1750.

A second class of reasons for the absence of growth in pre-Industrial Revolution economies is driven by the "Smithian" nature of pre-1750 growth, growth based on gains from trade and factor mobility, better-functioning and more integrated markets, and improved allocations due to better institutions. Most of the rise of richer regions and towns in medieval and early modern Europe can be attributed to the widening of local trade and the opening of long-distance commerce. Smithian growth was the source of considerable economic expansion, but it was vulnerable to political shocks and institutional changes (Studer, 2015, pp. 158-161). It was often the unintended victim of dynastic and religious wars, but it could also itself be the cause of more wars; many armed conflicts were about the extraction of wealth, the control of trade routes, and lucrative natural resources. Attempts by predatory nations to plunder and tax richer and more successful economies were common and constituted negative-sum games that reversed previous episodes of expansion. Internally the greatest threat was rent seeking by local rulers and elites, through confiscatory taxes, expropriating wealth, and repudiating debts.[6] In so doing, they were of course killing the geese that laid the golden eggs, but when the future was discounted — as would occur during war — a stationary bandit could behave like a roving one.

In early modern Europe, many successful areas saw their wealth eroded or devastated by war and extraction. Protectionist mercantilism and the use of state-sponsored privateers were additional forms that threats to the prosperity of successful regions took. The southern Netherlands, which in the first half of the sixteenth century had reached new pinnacles of prosperity, were devastated by foreign (mostly Spanish) soldiers and heavy taxes imposed on them by a king in Madrid. Their northern neighbors in the Dutch Republic were spared that fate largely because of good fortune and an easier to defend geography, but their growth came to an end in the eighteenth century because their defense spending had created a huge national debt, mercantilist policies by larger neighbors had hurt its trade and industry, and internal rent-seeking had weakened the Smithian dynamism of the Dutch economy (Prak and Van Zanden, 2013, pp. 152-163). Southern Germany, which experienced considerable growth in the sixteenth century, was devastated by seventeenth-century violence. China, too, enjoyed periods of considerable growth (especially during the Song dynasty), which made the repeated invasion of China tempting for well-armed semi-nomadic people such as the Jurchen, Mongols, and Manchurians. Stability returned in the eighteenth century, but Chinese living standards

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[6] A textbook example was the French merchant and entrepreneur Jacques Coeur (1395-1456), an immensely rich and powerful merchant who basically monopolized France's Mediterranean trade and was wealthy enough to bankroll many of Charles VII's triumphs in the final stages of the Hundred Years wars against England. His wealth and power attracted the greed and envy of many, and eventually the King joined them. He was arrested and tried on charges that have been deemed trumped-up by historians; the result was that his possessions were confiscated and distributed between the King and his cronies. Two centuries later, a similar fate befell Nicolas Fouquet (1615-1680), the fabulously wealthy tax collector, who had enriched himself during the ministry of Mazarin in the years of Louis XIV's minority. He was arrested in 1661 by Louis XIV and imprisoned for the rest of his life; his sumptuous chateau was stripped by the King's servants.

collapsed after 1840, demonstrating again the vulnerability of such growth to political shocks and the ease with which the Smithian gains could be undone.

Even without its vulnerability to political shocks, however, Smithian growth inevitably runs into diminishing returns, and cannot really sustain long-term growth. In the absence of continued technological progress, as allocations become more efficient and gains from trade are realized, a merciless concavity implies that any further gains become increasingly difficult. No wonder then that most classical economists who believed that specialization and the division of labor were the main engines of growth were committed to the idea of a stationary state.

The third factor that explains slow economic growth before the Industrial Revolution is the most obvious and the least discussed one, namely the simple but undeniable fact that people did not know enough about the physical world around them. Of course there were inventions before 1700, some of them revolutionary. But as I have noted elsewhere, the pre-Industrial Revolution world was limited in its ability to exploit technological advances because even though the pre-1750 world produced, and often produced well. Inventions in the pre-1700 era, however, were normally the result of serendipitous strokes of luck, flashes of brilliant intuition, learning by doing, and the slow accumulation of incremental improvements of techniques in use. It was "a world of engineering without mechanics, iron-making without metallurgy, farming without soil science, mining without geology, water-power without hydraulics, dye-making without organic chemistry, and medical practice without microbiology and immunology" (Mokyr, 2005, p. 1119). Technical progress in the eighteenth century came to rely slowly on insights from natural philosophy, on a more useful practical mathematics, and on more careful experimental methods borrowed from scientific practice.[7] Once technological progress began to rely on formal and systematic knowledge, the European advantage rapidly became overwhelming.[8]

The impact of science on technology was highly uneven and nonlinear, which is one of the reasons why many scholars have dismissed its significance for technological development before the twentieth century.[9] Others have equally emphatically seen science as a crucial ingredient.[10] By picking examples, each side can make a convincing case, and the historical reality is that in some industries little science was needed for remarkable progress to be achieved, above all of course in textiles.[11] Indeed, some of the most noted inventors of the Industrial Revolution such as George Stephenson, Henry Cort, Richard Roberts, and Richard Trevithick had little or no formal training and their access to best-practice science was limited. In other industries, *some* knowledge was

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[7] The difference between Europe and Asia was the core of a seminal paper by Justin Lin (1995), who argued that as long as technological progress was "experience-based," large Asian countries held an advantage over Europe and produced many goods of superior artisanal quality such as Chinese ceramics and Indian textiles. Once innovation became more knowledge-based, the center of gravity of innovation shifted to the West.

[8] The great prophet of human progress, Condorcet, fully realized this transition by the end of the eighteenth century. In his famous 1795 essay on human progress argued that although "isolated nations long influenced by despotism and superstition" (he means in all likelihood Asia) had been the origin of many important new technologies in textiles, ceramics, and metal, it was being surpassed by Europe in his age because there is nothing there that "announces the presence of genius — all improvements there appear as the slow and painstaking work of a long routine" (Condorcet, 1796, p. 51).

[9] For arguments in this vein, see Hall (1974), Mathias (1979), and Landes (1969). The most recent powerful statement is by McCloskey (2010). Even more extreme is John R. Harris (1998, pp. 219–21) who has argued that at least for a while France's scientists gave its steelmakers misleading and useless advice and that Britain was better off by relying on tinkerers. From a somewhat different point of view, the same argument is made by the late Larry Epstein who has argued that "the acceleration of technical innovation in the eighteenth century is more likely to have been caused by increasingly mobile and better informed technicians...than by an intellectually driven 'industrial enlightenment'" and expresses skepticism about the significance of eighteenth century natural philosophy for contemporary technological progress (Epstein, 2013, p. 67).

[10] The opus classicus arguing for a key role for science in the Industrial Revolution remains Musson and Robinson (1969). For more recent statement arguing for the importance of science see Jacob (1997, 1998, 2014) and Jacob and Stewart (2004). Most explicit is David Wootton (2015), who sees the Scientific Revolution of the seventeenth century as critical to the Industrial Revolution.

[11] As D.S.L. Cardwell noted regarding the textile machinery in the Industrial Revolution "one thing that all these textile machines have in common is that they satisfy Bacon's criterion for a certain kind of invention: they incorporated no principles, materials or processes that would have puzzled Archimedes" (Cardwell 1994, pp. 185-86). The exception here was the chlorine bleaching process, a classic case of science and technology interaction. See Musson and Robinson (1969), ch. VIII.

prerequisite, but this was a long shot from anything we would call a full understanding of the physical and biological underpinnings of techniques in use. How much knowledge was needed depended again on the production process under discussion.[12]

In some areas, however, new scientific insights and mathematical techniques proved important for progress early on. One of these was hydraulics. Water power was invented in the West in the first century BC and over almost two millennia improved slowly (though its applications expanded considerably in medieval times). A sudden acceleration took place in the eighteenth century, when a host of improvements were introduced. Its accelerated improvement was due to a combination of better experimental techniques and the systematic use of mathematics and formal science in its analysis (Reynolds, 1983, pp. 204-65; Wootton,2015, pp. 486–89). An equally striking example is gas lighting, one of the most under-researched topics of the Industrial Revolution until Leslie Tomory's (2012) pathbreaking book. The scientific basis for the controlled burning of gases was *pneumatic chemistry*, a branch of experimental science that went back to Jan-Baptist van Helmont in the early seventeenth century. It was taken further by giants of Enlightenment science such as Joseph Black, Antoine Lavoisier, and especially Alessandro Volta. New scientific instruments and a growing need for lighting public areas and factories produced a major multinational effort in the use of gas lighting in the closing decades of the eighteenth century. As

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[12] Newcomen's atmospheric engine required notions that had been developed by seventeenth-century experimental philosophers, above all the realization of atmospheric pressure and that a vacuum was possible and could be exploited (Wootton, 2015, pp. 500–8). It is undeniable that without the work of a long line of well-trained natural philosophers beginning with that of the Neapolitan Giambattista della Porta via the discovery of the atmosphere by Torricelli in 1643 and all the way to the experimental physicist Denis Papin, who built the first workable model of an atmospheric engine in the 1690s, it is hard to see Newcomen's device succeeding (Kerker, 1961; Cohen 2012, pp. 476–78, 729; Wootton, 2015, pp. 490–95). That said, the physics of steam engine were not properly understood until the work on thermodynamics by Clausius, Joule, and others in the middle of the nineteenth century — almost 150 years after the Dudley Castle engine of 1712.

Tomory notes, however, the actual industrial process developed turned out to be an accidental by-product of distillation of hydrocarbons. Science and tinkering worked hand in hand.

Separating the effect of science from that of improving artisanal skills and trying to somehow do a mental accounting exercise as to which of the two contributed more to the Industrial Revolution thus loses sight of the powerful complementarity between the two.[13] It is not always easy to know what contribution science made to invention, but as Pasteur said, Fortune favored the prepared mind. Moreover, inventors shared with natural philosophers a scientific method of careful experimentation, accurate measurement, and systematic searches for regularities (Jacob, 1997).[14] The idea that industry had something to learn from science was slowly taking root in the more progressive corners of Enlightenment Europe. Progressive industrialists studied science, adopted its experimental methods, were in contact with academic scientists, and routinely hired scientists and mathematicians as consultants (Mokyr, 2009, pp. 58-59).

There was something inherently different in the way the western world went about improving technology during and after the Industrial Revolution. The Industrial Revolution did not invent invention, but as Alfred North Whitehead famously wrote, it invented the *method* of invention by realizing not just the potential of science as a "storehouse of ideas" but also coming up with the

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[13] Many of the great minds of the scientific enlightenment were also important inventors, beginning with the brilliant Dutch mathematician Christiaan Huygens, credited with the invention of the pendulum clock in 1656, all the way to the physicist Joseph Priestley, who invented carbonated water in 1767 and erasers in 1770. Engineers such as John Smeaton and scientists such as René Réaumur straddled the worlds of formal science and technology, full well realizing that it was the interaction of these types of knowledge that held the key to further economic progress.

[14] An example of such an approach is what is known as "Humboldtian Science" named in honor of Alexander von Humboldt, an inductive methodology that was based on observations with the best instruments possible and tried through the search for empirical regularities to connect them with universal mathematical laws (Olesko, 2003, p. 384). Of particular interest here is the idea of "parameter variation," a systematic method used by engineers to evaluate improvements when a single component is altered while all others are held constant. Cardwell (1994, p. 195) attributes this insight to John Smeaton. In practice, this was often difficult to carry out but there are recorded cases of its successful application, e.g. the construction of the tubular Britannia bridge by William Fairbairn (Byrom, 2017, p. 228).

“imaginative designs” needed to bridge the gap between a scientific idea and production (Whitehead [1925], 1953, p. 96). It was no longer enough to establish that a technique worked; people were curious to know how and why it did, and once they made progress on that front, techniques could be improved further. The oft-repeated gag that science owed more to the steam engine than the other way around remains a half truth. But it does underline that the interaction between the two was what counted, and that the two forms of knowledge coevolved as it were like two symbiotic species, mutually enforcing and abetting one another.

Technology stimulated and abetted science and not just the other way around. It did so through two main channels.[15] First, inventions, even when made without much of a scientific understanding, focused the attention of scientists on a particular area, wondering how it worked and thus helping to set the research agenda. Interesting enough, a rough division of labor between Britain and the Continent emerged, in which British practical people discovered things that worked, and French theoreticians and German chemists uncovered the underlying science. The most famous example is the essay by Sadi Carnot ([1824], 1986) on steam power which pioneered thermodynamics, by his own admission inspired by watching a steam engine of a type pioneered by Arthur Woolf at work.[16] Less well-known but equally illustrative is the work of physicists inspired by the Wright brothers’s Kitty Hawk flight in 1903, which once and for all showed that heavier than air

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[15] The connection from technology to science was formulated in an especially compelling fashion by the late Nathan Rosenberg (1982).

[16] Carnot’s now famous book was at first ignored in France and found its way second-hand and through translation into England, where there was considerably more interest in his work by the builders of gigantic steam engines such as William Fairbairn in Manchester and Robert Napier in Glasgow (Smith, 1990, p. 329).

flight was possible and stimulated more theoretical work that eventually crystallized in modern formal aerodynamics.[17]

Second, the way technology affected science was through more powerful instrumentation. Human senses limit our ability to make very accurate measurements, to observe extremely small items, to overcome optical and other sensory illusions, and the mind has limited computational ability. Technology consists in part in helping us overcome the limitations that evolution has placed on us and learn of natural phenomena we were not meant to see or hear—what Derek Price (1984) has called "artificial revelation." Much of the seventeenth-century scientific revolution was made possible by better instruments and tools, above all the great trio of the telescope, the microscope, and the barometer. In the eighteenth century new equipment, such as Laplace's calorimeter and Volta's eudiometer enabled the advances that created modern post-Lavoisier chemistry. A combination of improved microscopy and better lab techniques made the discovery of the germ theory possible, arguably one of the greatest advances in medicine of all time (Bracegirdle, 1993, pp. 112-114). In the twentieth century, the number of examples that demonstrate the impact of better instruments and scientific techniques multiplies. One of the greatest heroes of modern science is x-ray crystallography. The technique has been instrumental in discovering the structure and function of many biological molecules, including vitamins, drugs, and proteins. Its most famous application was no doubt the discovery of the structure of the DNA molecule, but its use has been instrumental in twenty-nine other Nobel-prize winning projects (International Union of Crystallography, 2017).

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[17] Fifteen years after Kitty Hawk, the German theoretical physicist Ludwig Prandtl published his great work on how wings could be scientifically rather than empirically designed and the lift and drag precisely calculated (Constant, 1980, p. 105; Vincenti, 1990, pp. 120–25). Prandtl's work led among others to improvements in the design of wings and much improved airplane streamlining (Lienhard, 2008).

Needless to say, scientific progress was not the result of instruments alone: what was needed was a complex system of positive and negative incentives to overcome the appropriability issues in knowledge-creation. How and why that system came about in early modern Europe is discussed at length in Mokyr (2016). But that technological progress in a world of artisanal tinkering and learning-by-doing alone, without any insights from the sphere of formal codified knowledge (theoretical or experimental), would eventually run into diminishing returns and the economy would settle in a stationary state.

The harnessing of formal knowledge and its application to designs and techniques were the difference between the secular stagnation that could have been and what actually happened. Most telling is the fact that the political disasters that followed 1914, while devastating in the short run, did not set long-run global growth rates back in any significant fashion, in a way comparable to what happened to Germany after the thirty-years war or for that matter to the Roman Empire after 200 AD. Growth based on the expansion of useful knowledge is not easy to arrest, much less reverse. It is hard and perhaps impossible for a society to "unlearn" what has been learned, especially if the knowledge is distributed over a large population and made widely accessible through printing, to say nothing of electronic media.

Institutions and the Prospects for Economic Growth

Will institutional setbacks put an end to economic growth as they have done so often in the past? The idea surely has considerable currency today, and for good reason. It is not without justification that economic historians speak of "technological *progress*" but "institutional *change.*" The notion that western liberal demography triumphed in 1989 and that we have reached "the end of history" has been sadly refuted. But unlike much of the past, it seems unlikely today that small wealthy nations have much to fear from predatory neighbors. The international order, through formal multinational institutions such as NATO and the UN as well as informal institutions such as US-led coalitions, will not tolerate such predatory attacks, and potential predators know this full-well.[18] Rather than full-scale roving-bandit raids, however, there is a danger that medium-sized but poor nations could engage in the future in nuclear blackmail of their richer neighbors.

A larger concern is that in many countries corruption at an unprecedented level can seriously hamper economic growth. It is important to stress that the rise of autocracies and the decline in civil rights and freedom of expression are not *ipso facto* tantamount to a kleptocracy, in which a small elite plunders the resources of the country. Lee Kuan Yew is a classic example of an incorruptible autocrat, and there seems no easy model to predict whether such autocrats will turn out to be like Lee or venal dictators such as Nicolae Ceauceşcu or Viktor Yanukovych. That said, at some level corruption becomes so powerful that it seriously reduces the quality of governance, threatens the rule of law and weakens entrepreneurship. Russia today stands as an example: as Guriev (2014) has noted, Russian corruption has undermined property rights and the enforcement of contracts, and incentives for investment have vanished. As a result, Russian growth has significantly slowed down. Other large countries, such as Venezuela and Nigeria, suffer from similar afflictions, each in their own way.

What is interesting for the economic historian is how some countries in the West and western offshoots in the past were able to minimize corruption and keep internal rent-seeking at manageable

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[18] Singapore is at first glance uncomfortably hemmed in between two larger and poorer neighbors, Indonesia and Malaysia. Its income per capita exceeds that of Malaysia by a factor of 3.2 and that of Indonesia by a factor of 7.4, yet its population is tiny compared to either. All the same, the likelihood of a predatory war against it is very low. Indeed, the last time that such a predatory war can be seen to have taken place was Saddam Hussein's invasion of Kuwait in August 1990, which ended disastrously for him.

levels. Mercantilism, as Ekelund and Tollison (1981) have pointed out, was a system of rent-seeking, in which resources were redistributed from some groups to others. Mercantilism came under attack from Enlightenment philosophers, and after 1815 it went into a tailspin, replaced by liberalism and a political economy that regarded free trade, open access markets, and a professional and honest civil service as desirable and just. As a consequence, rent-seeking declined in the western countries that experienced industrialization. After 1750 "old corruption" in Britain started to wane, and by 1850 or so, much of western Europe had in one form or another embraced the basic notions of political economy and adopted a culture that condemned rent-seeking in most of its forms.[19] The rise of nationalist and socialist ideologies in the second half of the nineteenth century brought some forms of rent-seeking back, especially protectionism and farm subsidies. A hardy weed, rent-seeking could not quite be extirpated in developed economies but it could be kept within limits so that it did not endanger efficiency and growth. But will it in the future? Even in economies that are regarded as having relatively "good" institutions, there is a concern that rent-seeking will jeopardize and slow down the dynamic and innovative forces.[20]

A cursory glance at *Transparency International*'s corruption index or the WB's "governance indicators" confirms what everyone knows: rent seeking is still rampant in today's world and clearly can and does seriously impede growth and development in large segments of the world. But will it

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[19] The canonical text on Britain is Harling (1996). Linda Colley has defined Britain's civil service that emerged at this time as a service elite, who brought to government a new approach that consisted of professionalism, hard work, and uncompromising private virtue which proved remarkably effective (1992, p. 192). In Prussia, as Walter Dorn (1931, p. 404) observed, an incorruptible civil service was established in the first half of the eighteenth century and then adapted to modern life during the Stein-Hardenberg reforms. "It managed to support the army of a first-rate power on the resources of a third-rate state and at the same time accumulated a large reserve in the public treasury."

[20] Bessen (2015) points to a number of threats to innovation in the United States, including litigiousness and patent trolls, legislation that restricts labor mobility through "non-compete" contracts, and the political influence of large defense contractors on Pentagon procurement.

impede long-term global growth? Autocratic regimes that plunder the wealth of their entrepreneurial class, weaken the rule of law, and suppress dissent make the environment in their countries hostile to investors, especially foreign ones, and are inimical to "out of the box" thinking and academic freedom. While such institutions can limit intellectual innovation in some countries, it may have little effect on global trends. Top scientists and engineers will continue to move to those countries where they can best do their work. Countries with bad institutions will lose some of their best and brightest citizens. As long as there is adequate mobility of both ideas and the people generating them, it will be impossible to stop innovation from occurring. Moreover, much faster than in the seventeenth century, in the twenty-first century if an idea is generated *somewhere*, it becomes available *everywhere.*

Regimes that suppress pluralism and intellectual dissent encounter a global competitive world that will help to make any kind of ideological heavy-handedness costly in the long run — which is not to say that such policies are not viable. Historical examples of autocratic rulers from Louis XIV's revocation of the edict of Nantes to Nazi Germany's expulsion of Jewish scientists to Iran's post-1979 theocracy demonstrated that off-the-equilibrium-path behavior by autocrats is all too common.[21] Enlightenment writers in the eighteenth century realized this full well and thought — naively it turns out — that in a competitive world system the ability of bad rulers to ruin their economies was constrained.[22] The same holds true today: in Venezuela, an almost classical case of

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[21] For recent work on the expulsion of Huguenots, see Hornung (2014). For the costs to Germany in terms of science, of Hitler's policies, see especially Waldinger (2016).

[22] Thus Immanuel Kant wrote a few years before the French Revolution that "Now the States are already involved in the present day in such close relations with each other, that none of them can pause or slacken in its internal civilisation without losing power and influence in relation to the rest; and, hence the maintenance, if not the progress, of this end of Nature is, in a manner, secured even by the ambitious designs of the States themselves. Further, Civil Liberty cannot now be easily assailed without inflicting such damage as will be felt in all trades and industries, and especially in commerce; and this would entail a diminution of the powers of the State in external relations" (Kant [1784], 2010, pp. 30–31).

rapid institutional deterioration, there has been a massive exodus of young, educated professionals with no plans to return; Venezuela's loss is the gain of the destination countries, although the massive flight is still a negative-sum game (Newkirk and Crooks, 2017).

Measuring Technology and Innovation

Can the technological tsunami that started with the first Industrial Revolution be sustained? Techno-pessimism comes in two flavors. One is Gordon's technological slow-down hypothesis, that maintains that future innovation will have a much more limited effect on living standards (and will be too weak to forestall the other headwinds he foresees). The other is the apocalyptic view that foresees a world in which people, in some way or another, have been replaced and displaced by machines, mostly some combination of robots, artificial intelligence, and more sinister ways in which intelligent non-humans of our own creation will create some hazy form of dystopia.[23] A closely-related dystopian view is that technology will in some way or another become more powerful than people (as for example in Bostrom's (2014) "superintelligence" or Kurzweil's "singularity") and that there is an inherent contradiction between ever-advancing science and free will and that humans will become powerless against machines more intelligent than themselves (Harari, 2017, p. 284). The good news is that those pessimistic predictions cannot *both* be right. The even better news is that they can both be wrong. Leaving aside the more speculative predictions of various machines-

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[23] The dystopian view of a world in which nobody works was already foreseen by David Ricardo in an 1821 letter to J.R. McCulloch when he wrote that "if machinery could do all the work that labour now does, there would be no demand for labour and nobody would be entitled to consume anything who was not a capitalist and who could not hire or buy a machine" (Ricardo [1821] 1952, pp. 399-400). In such a dystopian world life is vapid and devoid of meaning, as originally imagined in Vonnegut (1974) and described by Rifkin (1995). Among twentieth-century economists, the best-known of the dystopians is Leontief (1983). Most apocalyptic and one-sided is Harari (2017, p. 330) who predicts "the creation of a massive new unworking class... a "useless class" [who] will not merely be unemployed — it will be unemployable." More sophisticated analysis equally concerned with labor-saving technological progress run amok can be found in Brynjolfsson and Macafee, 2014.

eat-men dystopias, I will discuss briefly the concern that future technological progress will be slower and less significant than in the past.

The argument that the low-hanging fruits that affect economic welfare have mostly been picked at first glance carries some conviction. Gordon (2016, pp. 638, 641-42) writes that "the century 1870-1970 was unique. Many of these inventions could happen only once and others reached natural limits ... the innovation slowdown and four headwinds — inequality, education, demography, and debt — [imply] a bleak future in which median real disposable income will barely grow at all." Many of the twentieth century inventions he describes have indeed revolutionized daily life and created enormous consumer surpluses: he points to air conditioning, antibiotics, high definition music and television, running hot and cold water, household appliances, and communication devices that made life more comfortable and reduced frictions and transactions costs. Have we reached some kind of saturation in that new innovations will add smaller and smaller gains on the margin?

It is not clear whether the past decade has seen a slow-down of innovation. Economists have different measures of innovation such as TFP growth and patent counts, all of them flawed.[24] TFP can grow (or not) regardless of technological progress, and considerable technological progress can take place without TFP growth.[25] Gordon's figures imply a TFP growth rate of 0.4 percent annually

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[24] In contrast with the TFP data, the number of patents granted in the US between 1997 and 2015 increased by an average annual rate of over 5 percent, more than five times the rate of TFP growth in that period and shows no sign of slowing down. A different approach pioneered by Alexopoulos and Cohen (2017) focuses on the content of publications and shows how it correlates with technological progress and productivity growth. They conclude (p. 3) that "a massive new wave of information and computer-related technologies in fields such as cybersecurity, robotics, artificial intelligence, and data mining/analytics, seems to be building, carrying with it the usual promise of new jobs and rising productivity."

[25] There has been a rapidly-growing literature that points to reduced competition and a loss of dynamism that can explain the slow-down of TFP growth in the U.S. in recent years (e.g., Decker et al., 2014, 2015). An influential paper by Hsieh and Klenow (2009) has shown the sheer magnitude that resource allocation can have on TFP. Most recent research has confirmed that fundamentals in the U.S. have changed since 2000 with lower competition and reduced anti-trust enforcement (Döttling, Gutiérres and Philippon, 2017). While some of that work deals with investment rather than TFP, it is plausible that they are subject to similar forces

for 2004-2014, which he contrasts with the 1.03 percent growth in the 1994-2004. These numbers are derived from GDP growth, less the weighted growth of inputs. Rather than come up with examples in which relatively few breakthroughs have happened (the kitchen and laundry room) as against areas in which in the past decade major breakthroughs have taken place (solar panels, LED lighting, diagnostic medicine, fracking, and the miniaturization of computing), I will propose a somewhat different approach to technological progress in the future, based on historical experience.

Is mis-measurement the culprit? Gordon (2018, pp. 19-21) cites a number of studies that seem to indicate that the degree of mismeasurement has not increased and so it would be rash to attribute the slow-down in productivity growth to worse measurement. As Brynjolfsson, Rock, and Syverson (2017) note, "After all, while there is convincing evidence that many of the benefits of today's technologies are not reflected in GDP and therefore productivity statistics, the same was undoubtedly true in earlier eras as well." Yet it is yet to be convincingly demonstrated that the *rate of understatement* has not become worse. To be sure, the fact that the services and products made possible by new digital technology are often distributed freely or at very low cost is by itself insufficiently large to explain the productivity slowdown, but once the introduction of new goods and services, plus quality improvements across a wide spectrum are added to these computations, it becomes significant (Feldstein, 2017).[26] It is therefore crucial to estimate whether product innovation has become more important relative to process innovation, because the former is

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[26] If the sectors for which mismeasurement is particularly important were increasing in their share in GDP, mismeasurement would indeed have become worse as is the case for the services sector (Feldstein, 2017, p. 17). A specific example is the health care industry in which quality improvements and new goods remain largely unrecorded. The share of health care in the US's GDP increased from 13.1 percent to 17.1 percent between 1995 and 2014 (https://data.worldbank.org/indicator/SH.XPD.TOTL.ZS) and 17.9 percent in 2016 (https://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/NationalHealthExpendData/NationalHealthAccountsHistorical.html). Even if the rate of improvement of medical services did not accelerate, the growing weight of medical spending indicates that the bias is getting worse.

excluded from the CPI (until it becomes a significant part of expenditures) whereas the latter will immediately be registered as a decline in prices and thus as real income growth).

If the *variety* of products and services is introduced on top of the quality improvement, it seems intuitively plausible that mismeasurement has worsened in the past two decades.[27] Gordon (2018, p. 20) dismisses the impact of smartphones and tablets as primarily for consumers and having little impact on productivity. But there is more that just consumer surplus to digital gadgets: they materially reduce the costs of daily activities, including shopping, communication, contact with authorities, medical care, and commuting. While such costs are normally not subtracted from calculating GDP, they are properly speaking inputs, and so their decline in recent years should be another reason why recent growth rates are understated. As Gordon notes, there is nothing to innovations generating consumer surpluses vastly larger that their contribution to output, but the impressive list of such innovations he provides (2018, p. 21) took place during a full century; the impact of smartphones — a general purpose consumer good — has taken less than a decade and is still ongoing. To that we should add a host of other innovations in medical services and diagnostics, lighting, automotive engineering, and entertainment, all of them in the span of a decade or two.

It also seems likely that the twenty-first century productivity slow-down described by Gordon is temporary, until new General Purpose Technologies such artificial intelligence (AI) and genetic editing have fully been incorporated into production lines (Brynjolfsson, Rock and Syverson, 2017; Alexopoulos and Cohen, 2017). As was the case in the past, GPT's — steam and electricity immediately come to mind — took many decades to be fully applied in all their potential uses. Any

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[27] Between 1975 and 2008, the number of products in the average supermarket swelled from an average of 8,948 to almost 47,000, according to the Food Marketing Institute, a trade group (*Consumer Reports*, 2014). This estimate seriously underestimates the growth of variety in the past decade, because online retailing effectively makes a far larger set of goods available than any individual store could.

observer looking at steam power in Britain in 1775 would have used Gordon's terminology (2018, p. 18) which is that it is "nothing new" and that "so far" the effect has been minimal.

Moreover, the productivity gains from technological progress in the past two centuries may have been overstated because of inputs that were used and never paid for, in large part because there were no property rights and markets for those inputs. Of those, the physical environment was clearly by far the largest. In computing the historical productivity gains brought about by the sharp rise in the use of fossil fuels and various forms of combustion engines, their impact on the global climate was not taken into account. The same is true for air quality: Chinese and Indian economic growth does not subtract a term reflecting the cost of using up air quality in Delhi and Beijing (and scores of other mega cities, mostly in the developing world), that have become profoundly unhealthy spaces. In nineteenth-century Britain, the growing use of coal in industrial cities had severe health costs that have recently been quantified (Hanlon, 2015). Agricultural productivity growth is measured gross of the negative impact that the use of antibiotics in livestock production has through the growth of multi-drug resistance, and the effect of fertilizer runoff that has drained into the lakes and oceans creating disastrous algae blooms. Especially striking are the effects of growth in the world's oceans, with rising water temperatures, massive pollution and acidification ("global warming's evil twin") particularly threatening.[28] Past productivity growth estimates in the fisheries does not account for the reduction in future stocks that high-productivity techniques entail. Due to

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[28] Acidification of seawater means that more calcium carbonate dissolves in the water creating bicarbonates that use carbonate ions needed to form calcium carbonate , and that hurts shellfish and other creatures at the bottom of the food chain whose shells depend on it leading to potentially cascading and catastrophic effects on the entire ocean life chain. It is also another cause of the destruction of coral reefs because it kills the symbiont algae who cover it (these algae can photosynthesize, providing the corals with energy). Since 1885, the pH of the world's oceans has declined from 8.2 to 8.1 and is predicted to reach 7.8 by 2094 (Climate Interpreter, 2012).

the improvement of fishing techniques, much of the ocean's resources are over-exploited and fishing stocks are seriously threatened with depletion and are likely to follow the sad trajectory of Newfoundland's vanished cod. The threat to a resource that supplies more proteins to the world population than beef and provides close to a tenth of humanity with its livelihood is almost entirely due to the vastly superior technologies used by fishermen paired to the difficulty of regulating the industry (*The Economist*, 2017b). Environmental regulations that supposedly reduce productivity today should be seen as paying the environmental pipers of the past two centuries.

The very nature of technological progress implies that most new techniques have unanticipated and unintended consequences. In an important book, Edward Tenner (1997) wrote about what he called technological "bite-back," in which new inventions, often many years later, turn out to have far higher costs that was imagined at the time of their inception.[29] Chlorofluorocarbons, once used almost universally as perfectly safe refrigerant gases, were found to destroy a scarce resource nobody before had paid any attention to: the atmosphere's ozone layer. Meanwhile, DDT, a wondrously effective insecticide discovered on the eve of World War II, proved as dangerous to two- and four-legged creatures as it was to six-legged ones. Thomas Midgley's famous 1921 invention of lead additives to gasoline to stop engine knock has turned out to be one of the most

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[29] Pollution, of course, is the most widely discussed forms of bite back. Air and water pollution are by far the most widely discussed, but it may well be that soil pollution is the most insidious, in part because it is the hardest to notice: green pastoral fields may well hide toxic heavy metals and pesticides for countless centuries. Soil pollution is also the hardest to clean up. It has been estimated that to remove pollutants from the soil in the huge areas in China (between 10 and 19 percent of all farmlands according to different estimates) that have been contaminated with such poisons at a quality comparable to the cleanup of a London industrial site before the Olympic stadium could be built there (admittedly a high bar), could cost $1,000 trillion or more than the entire wealth of the world (The Economist, 2017c). Soil pollutants find their way, often unnoticed, into the food supply, with unknown but certainly negative effects on consumers' health. Such social costs — never accounted for in any National Income Accounts — should be kept in mind when we compute the past growth of GDP and its derivatives such as TFP.

costly innovations of the twentieth century, though in this case the dangers of lead poisoning were known at the time (Nriagu, 1990).[30]

Could such environmental concerns revive the Malthusian concerns that growth may slow down because of assumption of a "fixed factor ?" The concept of a finite planet earth that can carry only a limited number of people can be extended by the notion that it can only support a finite level of consumption. Even in the absence of population growth, rising income levels may place limits on consumption through congestion, pollution, and the exhaustion of irreproducible resources. Hence a modern version of the writings associated with a now-forgotten doomster economist of the 1960s still needs to be addressed.[31] The main logical issue here is that economic growth can be resource-saving as much as resource-using, and that the very negative effects that congestion and pollution engender will set into motion searches for techniques that will abate them. Such responses may be more effective in democratic than in autocratic regimes because concerned public opinion can map better into public policy, but in the end the need for humans to breath clean air is about as universal a value as one can find. Investment in soil reclamation, desalination, recycling, and renewable energy count just as much as economic growth as economic activities that use up resources. Whether or not wise policies will help steer technological progress in that direction, the basic notion that per capita income growth *has to* stop because the planet is finite is palpable nonsense.

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[30] Indeed Midgley himself suffered from lead poisoning, all the while arguing against all evidence that "The exhaust does not contain enough lead to worry about, but no one knows what legislation might come into existence fostered by competition and fanatical health cranks" (cited by Kovarik, 1994). For an imaginative assessment of the bite-back effects of the tetraethyl lead additive, see Aizer et al., 2017. It has also been argued that lead poisoning was responsible for the rise in crime in the United States and that the removal of lead from gasoline and other sources was the prime factor in reducing crime in the 1990s (Reyes, 2007).

[31] See Mishan (1967) who argued against economic growth on both environmental and moral grounds. On a more persuasive level, Fred Hirsch (1977) argued that economic growth was self-defeating because many goods were "positional" (that is, reflective of a relative position in society) and thus zero sum. Against them, see the powerful arguments made in favor of growth by Benjamin Friedman (2005).

Some portion of technological change and economic growth in the near future, then, is likely to take the form of fixing the unpaid costs and damages of past economic growth by redesigning and replacing existing systems that had social costs much beyond what was originally realized. Will technological solutions work to solve problems caused by technology? Some eminent historians of technology have written dismissively about "technological fixes" (e.g. Hughes, 2004), but it is often the only alternative to severe cases of biteback, and in some documentable cases it has succeeded brilliantly.[32] That more and better technology can fix the mistakes and negative spillovers of previous advances seems confirmed by the record, although there is of course no certainty that they can do so in all cases. The need for tetraethyl lead in gasoline was eliminated by technical advances in automotive engineering and petroleum chemistry. In recent years the sharp decline in the price of solar panels has made solar-generated electricity an economic reality.[33] The technological solution that will keep the world eating fish will have to be aquaculture, which still needs considerable research to optimize feed and habitat.

In many areas, technological progress should thus be seen as a *constantly self-correcting* process, in which new techniques have unforeseen negative consequences, which require further tweaking, but those fixes in turn will cause more bite-back effects and so on. What negative bite-

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[32] An example of a technological fix to a bite-back effect is what occurred after improvements in sugar production and refinement in the nineteenth century, which brought down the price of candy and other sugar products and led to a veritable epidemic of tooth decay (no pun intended) in the industrialized world. The technological fix was the addition of fluorides to drinking water, which dramatically reduced dental decay. At the same time, the other deleterious health effects of high sugar consumption are still awaiting further medical advances (though progress in sugar-substitutes research is on-going). Another technological fix is fresh water contamination and salination. Desalination techniques have improved a remarkably in the past decades and in recent years revolutionary techniques to produce clean water have been developed, such as forward osmosis (requiring less energy than traditional reverse osmosis) and the use as carbon dioxide to filter out undesirable particles in water at three orders of magnitude (1000-fold) more efficiently than conventional microfiltration processes (*Filtration and Separation News,* May 17, 2017). The newly-discovered material graphene has considerable promise in solving the threat of fresh water scarcity (see below).

[33] In the past, technological adaptations in energy use have worked more often than not. Burning coal for home heating, electricity generation and manufacturing (made possible by continuous cost declines in the production and transportation of coal since 1800) led to massive urban air pollution (Hanlon, 2015). The problem was largely solved by switching to low-sulfur coal, cleaning up smokestacks, and switching to natural gas.

back effects mean is that the true social costs of many innovations have been understated and the bill for some inputs will be paid by a future generation. If output is generated at time t while the inputs are paid for in t+1, any comparison of TFP between t and t+1 will be confounded. TFP growth in the past has been overstated and so its decline may be exaggerated as well, although it is not known by how much. Some portion of innovative effort in the coming decades, rather than aimed at directly raising living standards, may be directed toward maintaining what we already have and correcting the eventual costs incurred as belated bite-back effects kick in.

Such innovations will contribute to economic output and will thus contribute to measured economic growth. But they may not show up necessarily as TFP growth. To see this, consider the following: suppose we have a fossil-burning power plant that produces electricity at, say, 15 ¢ per KwH (which is about the US average). Now suppose that we scrap that plant for environmental reasons and replace it with a windmill farm that, with fixed capital amortized in the same way as the fossil plan, can produce electricity at 15.5 ¢ per KwH. Using standard calculations (and relying on the dual of TFP computation), this would imply a decline in TFP as conventionally measured of about 3 percent. But if the windfarm has zero impact on global temperatures, it will have saved on a social cost that is not counted in the standard national accounts.

Can Technological Progress be Sustained?

Is it reasonable to expect technological progress to continue at a fast pace? It is perhaps fair to extend the arboreal metaphor by noting that science allows us to build taller and taller ladders to reach higher-hanging fruits. Based on rapidly improving scientific insights, technological breakthroughs have the potential to change life in the foreseeable future as much as it did so in the century and a half since the Civil War. Without making specific predictions on what areas of human life are most likely to be changed dramatically, at least some of the leading candidates are known: driverless cars, decarbonization of all energy consumption, additive manufacturing a.k.a. three-dimensional printing, new artificial materials designed *in silico*, virtual reality and transcranial stimulators, artificial intelligence (enhanced by deep learning), robotics, and medical advances in diagnostic technology as well as in degenerative and neurological conditions that may significantly slow down the ageing process and increase QALY's if not extend life expectancy itself.[34]

Ecclesiastes notwithstanding, there is much under the sun that is entirely new. If the history of the Industrial Revolution was dominated by energy, the future may well witness more radical progress in the evolution of new materials. Naming an economic epoch after its dominant raw material ("the bronze age") is an age-honored habit among historians. Many technological ideas in the past could not be realized because the materials that inventors had available were simply not adequate to make the design a reality. But modern technology allows scientists to design new synthetics and new materials that Nature never had in mind. Such artificial materials, developed at the nano-technological level, promise the development of materials nature never dreamed of and that deliver custom-ordered properties in terms of hardness, resilience, elasticity, and so on. New resins, advanced ceramics, new solids, carbon nanotubes — are all in the process of development or

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[34] A novel area that has received notice recently is the development of "nanorobotics," the injection of extremely tiny devices into live bodies. Dubbed "nanomedicine," it is the process of diagnosing, treating, and preventing disease and traumatic injury, of relieving pain, and of preserving and improving human health, using molecular tools and molecular knowledge of the human body (Thangavel et al., 2014).

perfection, and an air of excitement permeates sites such as materialstoday.com and events such as Composites and Advanced Materials Expo (CAMX).[35]

AI and genetic engineering seem to qualify as General Purpose Technologies (GPT's). It seems widely agreed that GPT's take a long time to fully affect the economy, because by definition they require complementary innovations and investments. Artificial intelligence has been receiving enormous attention in recent years because of the breakthroughs in pattern recognition and machine learning and neural networks. How they will affect the economy remains to be seen. One area in which AI seems best at appears to be customization and personalization of services that previously had been of a one-size-fits-all nature, especially in education and medicine. By characterizing what individual students need, machine-learning can suggest to teachers the individually-optimized materials and protocols that maximize the student's potential (US department of education, 2017). Coupled to the breakthroughs in machine-learning, AI may produce the most revolutionary breakthrough in education methods since Pestalozzi. Personalized ("precision") medicine, in which treatment is decided by algorithms and made conditional on a vast amount of genetic and other information about each patients is also on the horizon, although its full potential is still in dispute.

As Dyson has remarked, if the twentieth century was the century of physics, the twenty-first century will be the century of biology.[36] Recent developments in molecular biology imply

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[35] Perhaps the best-known of these new materials is graphene (a single layer of carbon atom, and often described as the world's first 2-dimensional material), discovered in 2004 by two researchers at Manchester. As often is the case, the discovery was in part the result of intuition and improvisation, but clearly carried out by two prepared minds who proceeded to win the Nobel Prize in 2010. The full potential of graphene may not be realized for a while, but its properties (flexibility, toughness, and high conductivity) are such as to create an enormous enthusiasm among specialists. A recent development is the use of graphene for desalinating seawater and recycling contaminated water into drinking water at much greater efficiency (Cohen-Tanugi et al, 2014; Abraham et al., 2017).

[36] Dyson (2015, pp. 2-3) suggests a future in which the tools of genetic engineering becomes available to individual breeders: "there will be do-it-yourself kits for gardeners ... also kits for lovers of pigeons and parrots...breeders of dogs and cats will have their kits too...domesticated biotechnology ... will give us an explosion of diversity of new living creatures ... new lineages will proliferate to replace those that monoculture farming and deforestation have destroyed."

revolutionary changes in humans' ability to manipulate other living beings. Of those, the ones that stand out are the decline in the cost of sequencing genomes at a rate that makes Moore's Law look sluggish by comparison.[37] Especially promising is the technique to *edit* a base pair in a genetic sequence thanks to recent improvements in CRISPR Cas9 techniques (Belluz and Irfan, 2017). The other is synthetic biology, which allows for the manufacturing of organic products without the intermediation of living organisms. The idea of cell-free production of proteins has been around for about a decade (Zhang, 2009), but has only recently has its full potential become known to the public even if it is still years away (*The Economist,* 2017a).

None of those technological predictions can be made with any certainty, and it is inevitable that some advances will be made that no one is forecasting, while other promising advances may disappoint. But the case that technological progress will not slow down does not depend on one area of technology or another. It is based on the observation that technology pulls itself up by the bootstraps by giving scientific researchers vastly more powerful tools to work with. Some of those tools have been known in more primitive form for centuries; others are radical innovations that have no clear-cut precursors. Of the traditional tools, the microscope is the most prominent one, as it is of course basic to the ubiquitous tendency toward miniaturization: to operate at smaller and smaller (nanoscopic levels). The Betzig-Hell super-resolved fluorescent microscope, whose developers were awarded the Nobel prize for chemistry, is to Leeuwenhoek's microscope as a thermonuclear device is to a fourteenth-century fire bomb. More or less the same can be said for telescopy, where the revolutionary Hubble telescope is soon to be replaced by the much more advanced James Webb space telescope.

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[37] The sequencing cost per genome has declined from $95 million per genome in 2001 to about $1250 in 2015 (NIH, 2015).

The two most powerful scientific tools that only have become available in the past decades and that represent complete breaks with the past are fast computing (including unlimited data storage and search techniques) and laser technology. Both, of course, have found innumerable direct applications in production, in both capital and consumer goods. But their full long-run impact on productivity is underestimated by by concentrating on annual TFP growth, because those figures fail to account for the indirect effect of those techniques on research that may lead to technological advances in an entirely different area in the future.

The impact of computers on science has gone much beyond large-scale calculations and standard statistical analysis: a new era of data-science has arrived, in which models are replaced by powerful mega-data-crunching machines, that detect patterns that human minds could not have dreamed up and cannot fathom. Such deep learning models engage in data-mining using artificial neural networks. Rather than dealing with models, regularities and correlations are detected by powerful computers even if they are "so twisty that the human brain can neither recall nor predict them" (Weinberger, 2017, p. 12). Here the slogan might well be: who needs causation as long as we have correlation? In a philosophical sense, there is nothing new here: there was always an inductive method in science, in which scientists collected data on plants, shells, and rocks and looked for regularities without fully understanding the underlying laws. The difference is just in scale, but in these matters scale is everything. Much as the James Webb is to Galileo's first telescope, the huge data banks of mega crunchers are to Carl Linnaeus's notebooks.[38]

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[38] Ernest Rutherford's possibly apocryphal quip that "all science is either physics or stamp collecting" has been interpreted as a put-down of inductive science, but in fact the accumulation of facts and the search for patterns and regularities has always been an integral part of any serious investigation of nature.

But computers can do more than crunch data: they also simulate, and by so doing, they can approximate the solution of fiendishly complex equations that allow scientists to study hitherto poorly-understood physiological and physical processes, design new materials *in silico,* and simulate mathematical models of natural processes that so far have defied attempts at closed form solution. Such simulations have spawned entirely new "computational" fields of research, in which simulation and large data processing are strongly complementary in areas of high complexity. Historically some scientists may have dreamed about such a tool, but it is only the most recent decade that will have the capability to do this at a level that will inevitably affect our technological capabilities. With the advent of quantum computing, computational power in many of these areas will increase by a substantial factor.[39] By the same token artificial intelligence, the source of much concern that it will replace educated knowledge workers and not just routinized jobs, could become the world's most effective research assistant, even if it will never become the world's best researcher *(The Economist,* 2016, p. 14).

Laser technology is an equally revolutionary scientific tool; when the first lasers were developed, it was said, its inventors thought it was a technique "in search of an application." But in the 1980s, lasers were already used for cooling micro samples to extraordinarily low temperatures, leading to significant advances in physics. Nowadays, the deployment of lasers in science has a dazzling range. Among its many applications, one of the most important is LIBS (Laser Induced Breakdown Spectroscopy), an astonishingly versatile tool. It is used in a wide range of fields that

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[39] The idea of quantum computing was proposed by Richard Feynman more than thirty years ago, but algorithms for it turned out to be very difficult to write and for decades it remained, much like nuclear fusion, a technique that was always "a few decades away." Recent advances, mostly in software writing, have raised hopes for a myriad of applications (e.g. Gibney, 2014).

require a quick chemical analysis at the atomic level, without sample preparation.[40] LIDAR (light radar) is a laser-based surveying technique which creates highly detailed three-dimensional images used in geology, seismology, remote sensing, and atmospheric physics. But lasers are also a mechanical tool that can ablate (remove) materials for analysis. For laser ablation, any type of solid sample can be ablated for analysis; there are no sample-size requirements and no sample preparation procedures. Chemical analysis using laser ablation requires smaller amounts of sample material and a focused laser beam permits spatial characterization of heterogeneity in solid samples. Another area, laser microdissection combines powerful microscopes and lasers to isolate and procure subpopulations of tissue and single cells. Among its many other uses, laser interferometers have been used to detect the gravitational waves Einstein postulated, one of the holiest grails in modern physics.

Much like the new instruments and tools of the seventeenth century rang in the scientific revolution and the age of steam, high-powered computers and lasers will lead to technological advances that cannot be imagined more than Galileo could foresee the locomotive.

Conclusion

If the recent economic history of technology teaches us *anything*, it is that the past is a poor guide to the future. After millennia of very slow and reversible growth, the world has taken off in the past two centuries on a path of unprecedented economic expansion, driven primarily by useful knowledge and human ingenuity. As our ability to understand natural phenomena expands so will our ability to harness nature to our needs. To criticize the cliché that "everything that can be invented

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[40] LIBS is applied in remote material assessment in nuclear power stations; geological analysis in space exploration; diagnostics of archaeological objects; metal diffusion in solar cells; in biomedical applications to analyze biological samples like bones, tissues and fluids, and to detect excess or deficiency of minerals and toxic elements in bodies.

has been invented already" is now itself a cliché; but the question whether the positive feedback mechanism driving technological progress will eventually run into diminishing returns and slow down is and will probably remain unresolved. In the case of Smithian Growth such diminishing returns are a priori obvious; in the case of the growth of useful knowledge theory is of little help and the best we can do is to observe that thus far the evidence for it is not persuasive.

Equipped with increasingly powerful tools, our understanding of natural processes will continue to grow at a rapid pace, and new applications, some imaginable and some not, will continue to appear. They will lead to continued improvement in economic welfare, even if these are not always reflected in our National Income Accounts. In terms of other economic variables, the nature of work and the meaning of a "job" may well change radically as work becomes less and less confined in time and space and the "factory system" may continue its slow decline (Mokyr, 2002, ch. 4; Mokyr, Vickers, and Ziebarth, 2015). The already increasingly fuzzy boundary between work and leisure may become even fuzzier as grunt work that involves serious disutility is increasingly relegated to machines and robotic devices. In the (extreme) limit only those who want to work will do so. The dazzling technological improvements in leisure technologies in the past decades would make such a development less than frightening. Keynes's famous prediction of a leisurely society that had shed its "Adamite curse" in his Economic Possibilities for our Grandchildren may still come true.[41]

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[41] Keynes's view was seconded by Leontief, who noted in his essay on technological unemployment that "Those who ask what the average working man and woman could do with so much free time forget that in Victorian England the 'upper classes' did not seem to have been demoralized by their idleness. Some went hunting, others engaged in politics, and still others created some of the greatest poetry, literature, and science the world has known" (Leontief, 1983). The same was of course true for the leisure classes of earlier periods.

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