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From my perspective

Common errors in reasoning about the future: Three informal fallacies

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ABSTRACT

The continued exponential growth of the price-performance of computing is likely to effectuate technologies that radically transform both the global economy and the human condition over the course of this century. Conventional visions of the next 50 years fail to realistically account for the full implications of accelerating technological change driven by the exponential growth of computing, and as a result are deeply flawed. These flawed visions are, in part, a consequence of three interrelated errors in reasoning: 1) the *linear projection fallacy*, 2) the *ceteris paribus fallacy*, and 3) the *arrival fallacy*. Each of these informal fallacies is likely a manifestation of shortcomings in our intuitions about complex dynamic systems. Recognizing these errors and identifying when and where they affect our own reasoning is an important first step toward thinking more realistically about the future.

1. Introduction

Most professional, academic, and scientific disciplines hold unrealistic views of the future beyond a 15 to 20 year timeframe. The reason why is that these disciplines typically fail to recognize the full implications of accelerating growth of information technology and the technological change it catalyzes. Though definitions of technology vary substantially, the general story of technological progress marks the evolution of our ability to manipulate the material world with ever-greater power and precision using practical knowledge and tools (Drexler, 2013; Li-Hua, 2013). In recent decades computing has played an important role as a general-purpose technology and key enabler that has facilitated the development of a wide array of other technologies, from telecommunications and the Internet to medicine and renewable energy (Lipsey et al., 2005).

Going forward, computing will play a central role in giving rise to machine intelligence and robotics, biotechnology and regenerative medicine, 3D printing and atomically precise manufacturing, fully immersive virtual reality, decentralized clean energy production, and many other socially, economically, politically, and environmentally disruptive technologies. Because improvement in the power, cost, and size of computers is accelerating, many of these technologies that have long been relegated to science fiction are likely to become a reality far sooner than most disciplines imagine.

So while typically anticipated timeframes put many of these technologies so far in the future (on the order of centuries) that their implications may be dismissed as irrelevant to present generations, more thoughtful consideration of the accelerating growth of computing shows that even the more radical of these technologies are likely to arrive within just a few decades. Policymakers, planners, professionals, scientists, and scholars therefore have an obligation to take the implications of radical technological change seriously today.

In this paper I identify three common errors in reasoning about the future: 1) the *linear projection fallacy*, 2) the *ceteris paribus fallacy*, and 3) the *arrival fallacy*. These informal fallacies may help explain why so many observers across a wide range of disciplines remain blind to the tsunami of disruptive technology that is racing toward us, and why conventional visions of how our world will change over the course of the 21st Century are often simplistic, static, and shortsighted. Being aware of these fallacies and making a conscientious effort to safeguard against them can help us think more clearly and realistically about possible futures.

1.1. Acknowledging flaws in past futurist reasoning

Before proceeding to discuss the above fallacies in detail, it is only fair that we first recognize that futurists have a well-documented history of committing serious errors of their own (Carrico, 2013). Two of these errors in particular deserve to be highlighted: 1) subscription to technological determinism, and 2) naïve technological optimism.

Technological determinism is the reductionist assertion that technology plays the dominant role in shaping the organization and content of our global civilization. On this view, technological progress is seen as the primary driver of socioeconomic development and geopolitical structure, and not *vice versa*. Thorstein Veblen is often credited with coining the term itself, but the concept makes a prominent appearance much earlier in the work of Karl Marx on account of

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its direct relation to production and therefore to historical materialism (Smith and Marx, 1994). In *The Poverty of Philosophy*, Marx famously wrote, “the windmill gives you society with a feudal lord; the steam-mill, society with the industrial capitalist” (Marx, 1920, pp. 119). Adherence to the idea generally entails the twin assumptions that the trajectory of technological advancement is fixed and that its effects on society are inevitable. On this view, technology is more like an external force of nature than an internal element of human affairs, and so cultural, economic, and political differences among societies may be ignored or downplayed as a result (Green, 2002).

In recent decades technological determinism has been thoroughly criticized and largely discredited, and today scholars stress instead the causal interdependence among a great number of variables in our global coupled human and natural system – of which technology is only one (see for example Bijker, 2007; Winner, 1993). Nonetheless, technological determinism remains discouragingly widespread not just in futurist circles but in public discourse more broadly as well (Selwyn, 2012).

Naïve technological optimism is the assumption that the net impact of technological progress will always be positive. This assumption follows logically from the belief that progress to date has been, on balance, more beneficial than detrimental to human life. But while technology has indeed vastly improved human quality of life by many measures, the question of whether technology does more good than harm remains open to debate. Recent research, for example, suggests that material prosperity (a central benefit of technology) is not strongly correlated with happiness beyond fairly modest levels of income (see for example Diener and Biswas-Diener, 2008; Easterlin, 2015; Schimmel, 2013; Veenhoven, 2013). Moreover, much of both human suffering and ecological degradation is either directly caused or indirectly enabled by technology. Naïve techno-optimists therefore implicitly presuppose that the solution to any unintended negative side effects of technology is simply better technology.

On this view, for example, the solution to air pollution caused by internal combustion engines in automobiles is not to drive less but rather to upgrade to electric vehicles. While this supposition is not necessarily wrong in all cases, neither is it necessarily right. Some

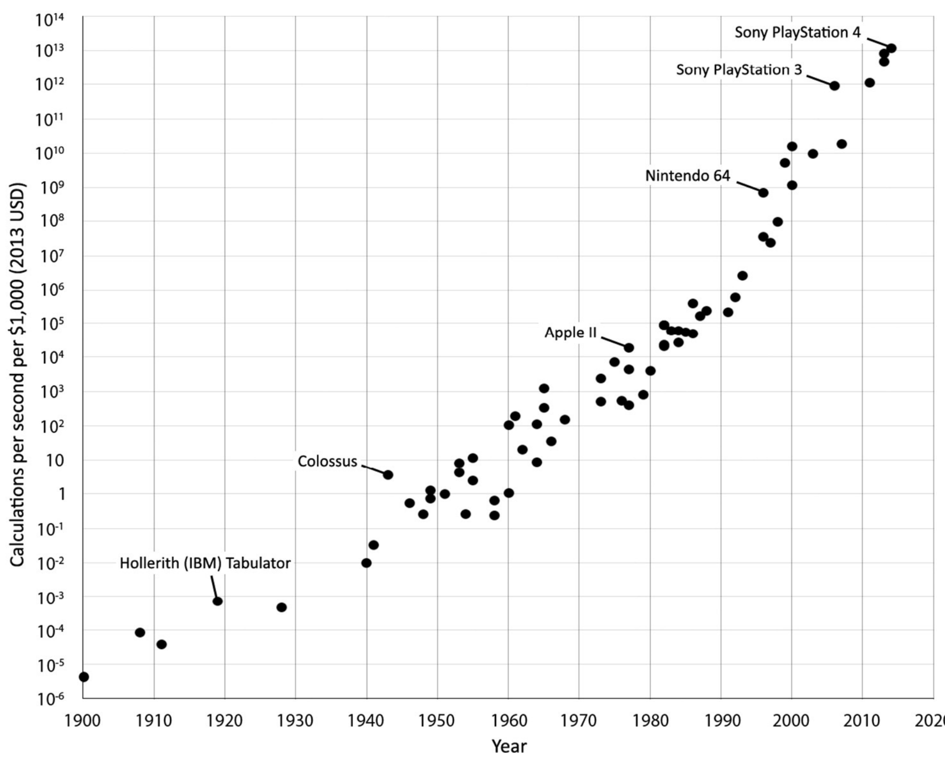

Fig. 1. Exponential growth of the price-performance of computing, 1900–2015.
Data Sources
http://www.singularity.com/charts/page67.html
http://www-03.ibm.com/ibm/history/exhibits/mainframe/mainframe_PP7094.htmlhttps://projects.cs.dal.ca/ddrive/dhb-future.pdf
http://www.cray.com/company/history
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http://www.frc.ri.cmu.edu/users/hpm/book97/ch3/processor.list.txt
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http://gaming.wikia.com/wiki/Instructions_per_second
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http://www.ece.umd.edu/courses/enee759m/papers/Scan001.PDFhttp://www.frc.ri.cmu.edu/~hpm/book97/ch3/processor.list.txt
http://www.forbes.com/free_forbes/2006/0130/076.html
http://www.techpowerup.com/gpudb/1903/wii-u-gpu.html
http://www.anandtech.com/show/6972/xbox-one-hardware-compared-to-playstation-4/2
http://www.techpowerup.com/gpudb/2523/radeon-r9-295x2.html

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technologies are inherently destructive (weapons, for example), and so we should at the very least be cautious and avoid generalizations about technology as a whole in favor of careful case-by-case consideration.

The most ardent among techno-optimists, such as self-described *singularitarians* and *transhumanists*, have been labeled by critics as members of a "sinister cult" who worship technology and await the arrival of godlike machine superintelligence with blind faith and religious fervor – a "rapture of the nerds" (Appleyard, 2014; Sofge, 2014; Stevens, 2011). Though hyperbolic and heavy-handed criticism like this lacks rigor and is easily rebutted, more serious critiques of technological optimism in futurological discourse should not be ignored (see for example Carrico, 2013; Fukuyama, 2003; Habermas, 2003; Kass, 2003; McKibben, 2004; Roache and Clarke, 2009).

1.2. Exponential growth of computation

Exponential change is not readily grasped by human intuition (Meadows, 2008; Sterman, 2002). Fig. 1 shows the exponential progression of the price-performance of computing since 1900 on a semi-logarithmic plot. Over the last 115 years the amount of available computing power per constant dollar has grown by an astonishing *20 orders* of magnitude. To put this scale of change into perspective, consider that a linear plot of these data would require a chart more than 20 *light years* tall – four times the distance to the nearest star.

This trend is not only extraordinarily lengthy and consistent, it is also extremely robust. War and recession, for example, have had little discernible impact. Moreover, the trend spans very different computing architecture paradigms, from mechanical and electromechanical relays, to vacuum tubes, to transistors and integrated circuits. Moore's Law, based on Intel-founder Gordon Moore's observations that transistor density on integrated circuits doubles roughly every two years, is the latest of these paradigms (Kurzweil, 2005; Mack, 2011; Moore, 1965). And while Moore's Law will end in the 2020s because of the physical limits of two-dimensional transistor density in silicon, the larger trend of exponential growth of computing is likely to continue as new paradigms emerge.

Based on technologies already working in the lab, together with the theoretical limits of computing and the proof-of-concept from biology, many expert observers confidently expect at least another 10 orders of magnitude in price-performance growth – and possibly a great deal more – so long as the existing structures of incentives and investment that have prevailed for the last century continue to place enormous value on information processing power (Bostrom, 2014; Lloyd, 2000, 2006).

The implications of this trajectory are profound. A typical 2016 smartphone is at least 200,000 times faster, 70,000 times cheaper, and 100,000 times smaller than the IBM 7094 supercomputers used by NASA 50 years ago in 1966. If this trend of shrinking size and cost continues, as is many expert observers expect, then in another 50 years devices with the computational power of today's smartphones will be nearly microscopic (*i.e.* comparable in size and sophistication to biological organisms) and cost less than a penny.

As computer power, size, and cost progress toward that extraordinary state, we will pass key tipping points at which qualitatively different technological functionality arises, just as we have over the last five decades. The Internet, search engines, digital music and video, tablets, and smartphones all exploded in popularity once the processing power and bandwidth necessary to support them passed key price-performance thresholds and became affordable to the mass market. These technologies, working both individually and in concert, have in turn revolutionized or obviated a wide range of industries. Some of these technologies required passing the price-performance threshold of hundreds of thousands of calculations per second per dollar. Others required millions. Future technologies will require billions, trillions, and quadrillions.

1.3. Information technology and economic revolution

So far the most profound impact of the exponential growth of computing has been a revolution in our capacity to produce, analyze, and transmit information – and so until now our attention has quite rightly been focused on information technologies. But an equally dramatic revolution in material production technologies likely still lies ahead.

At present our ability to efficiently manipulate matter with great speed and precision is limited largely to factories and laboratories. The situation is directly analogous to the manipulation of information 50 years ago, which could only be performed quickly and accurately by room-sized machines in specialized industrial facilities. But as computers continued to shrink in size and cost, information technology became widely accessible.

Today, sophisticated computers with Internet access reside in the pockets of billions of people worldwide, and a veritable galaxy of applications of these tools has emerged as a result. Over the coming five decades the same pattern we have witnessed with information goods is set to repeat itself with material goods (Drexler, 2013). And just as the desktop electronic calculators of 1965 offered only the faintest glimmer of the kinds of devices that would be available in 2015, today's 3D printers are the crude progenitors of the fabrication devices that are likely to emerge over the next 50 years. The logical culmination of this progression will be a widely decentralized capacity to produce many if not most material products, from toasters to solar panels, with atomic precision at near-zero marginal cost (Drexler, 2013; Rifkin, 2014).

Services are unlikely to be exempt from this transformation. The exponential growth of computing will also continue to drive the development of machine intelligence and robotics. By mid-century robots will be very likely capable of performing many if not most tasks that at present can only be performed by human labor. The technological unemployment that results will not likely be limited to jobs that involve the production of physical products, but will affect knowledge workers as well. A recent University of Oxford study drew a good deal of media attention by suggesting that as much as 47% of jobs in the United States may be susceptible to computerization within just two decades (Frey and Osborne, 2013). Even amidst our current economic recovery, the potential of technological unemployment to affect knowledge-based service industries such as accounting, law, and medicine appears to be a topic of growing public concern (Brynjolfsson and McAfee, 2012, 2013; Francis, 2015; Kalla, 2015; Miller, 2014; Wiseman, 2015).

Over the next several decades the size and cost of computers will continue to shrink, and as important thresholds of speed, size, and cost are passed we are likely to see the emergence and rapid adoption of technologies that disrupt the manufacturing and service sectors in a manner similar to how the publishing and entertainment sectors have been disrupted by personal computing and the Internet. By the 2040s the transition to a world in which goods and services can be produced with little or no human labor at near-zero marginal cost, a period variously described as the "Second Machine Age" (Brynjolfsson and McAfee, 2014) or the "Third Industrial Revolution" (Rifkin, 2011), is likely to be well underway.

Throughout human history the material basis of civilization has being characterized by scarcity. Indeed, scarcity is the *raison d'etre* of economies as we currently understand them (Keynes, 1930; Robbins, 1932). Yet because of the radical technologies now visible on the horizon, we are poised to enter an era characterized not by scarcity but by abundance (Diamandis and Kotler, 2012; Drexler, 2013; Rifkin, 2014). It is therefore almost impossible to overstate the extent to which the technological transition to a post-scarcity world is liable to transform the global economy over the next 30 to 50 years.

1.4. Transcending our ancestral biology

As computing power expands to astronomical levels while at the same time extremely sophisticated devices shrink toward the microscopic scale and approach a negligible marginal cost, we can expect both our understanding of biology as well as our capacity to intervene upon and control it to grow in stride. Machines small enough to enter the bloodstream might be able to run software and perform tasks as complex as those of a tablet or smartphone today. And because these nanobots will be so inexpensive, thousands or even millions could be deployed into the human body (Kurzweil, 2005).

1.4.1. Disease and aging

One obvious application of this technology would be to promote health. A swarm of sophisticated nanobots inside the human body could be used to fight pathogenic organisms, repair damaged tissues, identify and destroy cancers, and perform other health-promoting functions with cellular or even molecular precision. Though this may seem a rather fantastic proposition, researchers are already deploying DNA nanobots to perform targeted therapies with cellular precision (Bachelet, 2006; Douglas et al., 2012). Experimental work today already suggests that these tiny machines will be able to both coordinate with one another and receive instructions remotely as well (Amir et al., 2014; Basulto, 2014).

Mutually-reinforcing synergies will clearly arise between nanorobotics and the advancement of our understanding of human biology. So while our knowledge of biology and our capacity to exert control over it remain quite limited today, we have every reason to expect that these will increase enormously alongside the accelerating growth of computing technology. At first this technology is likely to improve the efficacy of disease treatment, aid in preventative care and early diagnosis, and forestall age-related debilitation. But over time, and with accelerating efficacy, the combination of nanotechnology and biotechnology is likely to begin reigning in previously intractable medical challenges.

The logical culmination of our current trajectory, as incredible as it might seem today, is the end of both disease and aging. The precise timeline is of course impossible to know, but given the straightforward technological pathway from present devices to extremely sophisticated machines that are both microscopic and inexpensive, it is clearly not a matter of millennia or centuries, but rather of decades.

1.4.2. Brain-machine interfaces

Another application of nanorobotics technology would be to enable neuronal interfaces, allowing us to connect the human nervous system – including the brain – directly to computers. Such technology would have a number of extraordinary applications, from thought-controlled prostheses to radical expansion of cognitive capacity. Current research into direct neuronal interfaces using titanium and carbon nanotubes already shows promise (Rand and Hanein, 2014; Sorkin et al., 2015; Vitale et al., 2015). Together with advancements in robotics, this technology will pave the way for radical cybernetic enhancement.

1.4.3. Cybernetic enhancement and replacement

One possible culmination of this process would be the complete replacement of all biological functions, including brain function, with synthetic hardware. Beyond visions of "bionic" enhancement of physical capacities, a common view among futurists is that the brain replacement process could be gradual enough so as to be unnoticeable (Chalmers, 2010; Hauskeller, 2012; Pigliucci, 2014). Individual biological neurons in the brain, for example, might be replaced by artificial neurons one by one without any disruption of consciousness or mental function.

One noteworthy implication of such a process would be that once a person's mind is fully synthetic and no longer dependent upon biology, it might be freely transferred across other computational substrates. Although "mind uploading" of this kind certainly still carries the air of science fiction about it, we can nonetheless chart a straightforward path from the present day to that future technology – and once again it is a path measured not in millennia or centuries, but decades.

1.4.4. Obviation of biological needs and related behaviors

Much of human activity today is predicated upon meeting needs that are ultimately rooted in our evolution as social primates. The experiences we seek out and avoid nearly all reflect the nature of our bodies and brains, and this in turn shapes how we interact both with one another and with the Earth itself. Virtually none of the planet's surface is unaffected by human activity, whether it is the atmosphere that has been altered by the emissions of billions of tons of greenhouse gases, the oceans that have been scoured of life and polluted by megatons of plastic, or the transformation of landscapes into cities, suburbs, and farmland (Masco, 2004). We have not imposed this enormous footprint on the biosphere out of malice, but rather as a consequence of striving to meet our needs – needs that are quite narrowly circumscribed by our *Homo sapiens* biology.

Not only can we expect technology to change the ways in which we meet our current needs in profound ways, but – perhaps more importantly – it also stands to change the nature of our needs themselves. For example, the technology of lab-grown beef is nearing market readiness, and promises to offer enormous efficiency, sustainability, and ethical advantages over traditional livestock farming (Post, 2014a, 2014b). But the reason why Americans eat 18 billion pounds of beef every year is because we are omnivorous primates whose brains evolved to enjoy the taste of meat (U.S. Department of Agriculture, 2015). So while the production of beef and other meat is likely to begin shifting from farms to labs in the 2020s, beyond the 2040s both the taste of foods and the need to eat them may begin to be subject to technological control and therefore become optional. The philosophical implications of creating choices of this kind are profound.

Our material needs will not be the only ones affected. For example, many of our most important concerns about morality, ethics, rights, and justice are quite appropriately centered upon physical and mental attributes over which we currently have no control: race, gender, sexual orientation, athletic and cognitive ability, and age. But within a matter of decades – not centuries or millennia – technological advancements are likely to allow us to choose our bodily form as we might choose the style of our clothing or hair today. What will happen to the human condition once we *do* have control over these previously unalterable attributes?

1.4.5. A radically different world within several decades

My purpose here is not to answer these important questions, nor to provide a comprehensive vision of what life will be like at any particular moment in the future. Rather, I simply mean to show as a premise for the arguments to follow below that the trajectory of technological change borne on the back of the exponential growth of computing clearly points to radical technological transformation of both the global economy and the human condition over the next several decades (Bostrom, 2009).

This timescale is: 1) shockingly short to the uniformed observer; 2) within lifetimes of many of this paper's readers; and 3) relevant to planning and policymaking today. The social, economic, political, and environmental changes that such technology portends are therefore staggering.

2. Common errors in reasoning about the future

Most professional and academic disciplines, along with the policy and planning efforts they inform, are almost entirely blind to the tremendous changes that lie just a few decades ahead. They assume that the future will be little different than the present – that technological progress may offer some incremental improvements in efficiency and cost, but that no fundamental changes in the nature of our economy or the human condition are likely to occur. The three informal fallacies discussed below, each of which is a manifestation of inherent shortcomings in human intuitions about complex dynamic systems, may offer at least a partial explanation for this technology blindness.

2.1. The linear projection fallacy

The linear projection fallacy is the error of presuming that future change will be a simple and steady extension of past trends. I am so far unable to find any detailed discussion of this fallacy in the academic literature, but the term is used by Michael Kruse in a 2007 essay about economic forecasting (Kruse, 2007). The linear projection fallacy presumes both that 1) the present rate of change will continue into the indefinite future, and 2) the trend going forward will be characterized by a smooth succession of increments without disruption or discontinuity. Projections of this kind are therefore *linear*, hence the name of the fallacy.

This fallacy is pervasive, and in practical terms it means that most disciplines envision futures in which our world experiences only minor changes at the margins – a few fancier gadgets here, some efficiency gains there. At first glance, it may seem as though linear projections are a conservative and therefore responsible way to forecast future change. But more thoughtful consideration shows that indulging our linear intuitions and simplifying the complex dynamic phenomenon of technological change in this way is reckless and deeply problematic.

2.1.1. Reinforcing feedback

One key nonlinear aspect of technological progress is that it is characterized by a reinforcing feedback loop, or what is commonly referred to in the futurism discourse as *accelerating returns* (Kurzweil, 2000). The exponential growth of computing is perhaps the clearest example of this phenomenon, as discussed above, but the same reinforcing feedback loop applies to technological progress more broadly: each new tool that is developed produces synergies with existing tools and is then used to create still newer and more powerful tools (Drexler, 2013).

2.1.2. Tipping points

Tipping points are a second nonlinear aspect of technological progress. Technologies such as the Internet and smartphones emerge and are adopted only once specific thresholds of computing speed, size, and cost are exceeded. As the term suggests, passing a tipping point results in rapid transformation. Today, for example, it is difficult to imagine life without the Internet and smartphones, but that time was only 20 years ago. Two decades from now it will be just as difficult to imagine life without self-driving vehicles and natural language user interfaces. And in the decades beyond, life without swarms of nanobots that safeguard human health and repair ecological damage might be as unimaginable as life without vaccines and electricity is for many of us today.

2.1.3. Examples and consequences of the linear projection fallacy

If we are to make reasonable projections of possible futures, it is essential that we recognize the nonlinear nature of technological progress. Unfortunately, even disciplines whose subject matters mandate long-term forecasts fall prey to the linear projection fallacy and seldom acknowledge or attempt to account for the transformative changes that lie ahead.

For example, there has been virtually no mention of self-driving cars or autonomous vehicles (AVs) in the urban planning literature in the last five years. This is despairingly shortsighted given that AVs represent the most radical development in personal mobility in the last century, and will in turn create a cascade of social, economic, and environmental transformations in urban areas. Concerns that are central to urban planning such as traffic congestion, parking, suburban sprawl, commuting, public transit systems, and air quality will all be profoundly impacted by widespread adoption of AVs which is expected to begin in the mid-2020s (Anderson et al., 2014; Eno Center for Transportation, 2013; Gao et al., 2014; LeBeau, 2015; Naughton, 2015; Ramsey, 2015). Any discussion of cities in the literature beyond a 10-year timeframe that ignores AVs is therefore naïve and thoroughly unrealistic.

Similar shortcomings can be found in the disciplines of law, medicine, accounting, and tax preparation – to name just a few professions that stand to be profoundly disrupted by machine intelligence (Brynjolfsson and McAfee, 2014). Professional work that once took encyclopedic domain knowledge or small armies of personnel can now be performed instantly by technology such as IBM's Watson, which can search for, identify, read, and analyze documents millions of times faster than any human (Friedman, 2014). For its part, IBM is promoting Watson as a supporting tool for highly skilled knowledge workers rather than a replacement for them (IBM, 2015), but concerns about technological unemployment are widespread nonetheless (Miller, 2014).

Linear thinking is seductive in its simplicity. But given the inherently nonlinear nature of technological change, professional and academic disciplines that inform planning and policymaking with long-term forecasts, scenarios, and models should take great care to avoid the linear projection fallacy.

2.2. The ceteris paribus fallacy

The *ceteris paribus* fallacy is the error of attempting to reason about the future by considering a single aspect of change while holding "all else equal". The earliest use of this term I am able to find is by Lord Stamp who discusses the concept as an extension of the fallacy of composition (Stamp, 1941). Lord Stamp's analysis does not focus on the anticipation of possible futures *per se*, but the reasoning he outlines applies just the same: "[n]o doubt it is indispensable to isolate some characteristic under consideration, and to ignore the surrounding conditions, for the purpose of that examination … [but] it is a truncation of reality, and only to be justified if it is succeeded by a corresponding examination of the factors ignored in the first process … and finally by a reconciliation of the results" (Stamp, 1941, pp. 168). We should take care, in other words, not to lose sight of the forest for the trees.

2.2.1. Vulnerability of scientific analysis to the ceteris paribus fallacy

We scientists are particularly vulnerable to the *ceteris paribus* fallacy because our training emphasizes the importance of isolating variables in order to examine their relation to observations in a controlled fashion. After all, reasoning in the form of *analysis* means to gain an understanding of something complex by breaking it into its component parts. Ideally, analysis of a complex system, object, or substance is then followed by *synthesis* – the "reconciliation of the results" to which Lord Stamp referred. But it is important to recognize that analytic reasoning can only be meaningfully applied to the present state of a complex system, object, or substance; predicting future states requires synthetic reasoning.

Visions of the future that suffer from the *ceteris paribus* fallacy make the mistake of considering only one technological, social, economic, political, or ecological change – one variable – at a time.

2.2.2. Examples of the ceteris paribus fallacy

Consider the following examples: 1) Climate science predicts changes in sea level by 2050 or 2100 given specific quantities of greenhouse gas emissions scenarios, *ceteris paribus* (IPCC, 2014); 2) Energy forecasts predict fossil fuel trends through 2040, *ceteris paribus* (OECD, 2014); and 3) Transportation plans predict vehicles miles traveled and transit revenues for 2040, *ceteris paribus* (San Francisco County Transportation Authority, 2013).

The assumption of *ceteris paribus* does not hold in these examples because all else is *not* equal.

For example 1 we must recognize that by 2050 radical new technologies will be available not only to mitigate greenhouse gas emissions, but to restore and control atmospheric composition as well – to say nothing of the all but unimaginable technologies that will arise by 2100. For example 2 we must recognize that by 2040 the energy sector will have been dramatically altered both on the supply side by renewable and next-generation nuclear energy as well as on the demand side by technologies like electric vehicles and decentralized manufacturing. And for example 3, we must recognize that by 2040 personal mobility will have been profoundly affected by AVs.

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2.2.3. Specific forms of the ceteris paribus fallacy

With respect to technological change, the *ceteris paribus* fallacy most commonly takes one of three forms.

First, visions of the future often fail to synthesize *all* of the implications of a new technology. For example, we may anticipate that AVs will reduce traffic congestion and lower vehicle emissions per vehicle mile travelled (Anderson et al., 2014; Eno Center for Transportation, 2013). But to leap from the claim that "AVs will reduce congestion and pollution" to "cities in 2040 will have lower congestion and pollution because of AVs" is to commit the *ceteris paribus* fallacy. The reason why is that we may *also* anticipate that AVs will increase total vehicle miles traveled *per capita* by dramatically increasing the available drive time for any individual automobile, and thus in turn also *elevate* congestion and pollution as a result. AVs may therefore have both positive and negative impacts on congestion and pollution, and so any realistic vision of cities in 2040 requires a "reconciliation of the results" – a synthesis of all individual analyses.

Second, visions of the future often fail to anticipate how multiple new technologies will interact to produce cumulative effects. Just as leaping to a conclusion about the future of cities based on only one impact of AVs is an example of the *ceteris paribus* fallacy, so too is making a claim based on the impacts of just a single technology. AVs are not the only new technology that will impact traffic and air quality by 2040. Others include advances in telepresence that reduce the need to travel (Borggren et al., 2013; Coroama et al., 2012; Verdantix, 2010), increased prevalence of electric vehicles (Brady and O'Mahony, 2011; Soret et al., 2014; U.S. Department of Energy, 2015), and adoption of renewable and next-generation nuclear power (Schwartz et al., 2014), to name just a few.

Third, and closely related, is that visions of the future often fail to recognize the full implications of the *enabling technologies* that underlie new functionality. AVs, for example, can rightly be considered a single technology in a functional sense: they are cars that can pilot themselves, which is a novel and unprecedented capability. But the underlying machine intelligence that enables this singular functionality is achieved *via* synergistic aggregations of other technologies, including computer hardware and software, laser and radar sensors, sonar and stereo imaging, robotics, wireless telecommunications, and GPS-assisted three-dimensional positioning. And some of these component technologies that enable AVs will also enable the telepresence, electric vehicles, and clean energy technologies mentioned above.

2.2.4. Science fiction and the ceteris paribus fallacy

The *ceteris paribus* fallacy arises when we envision the future based on new functionality alone without considering the full implications of the enabling technologies that underlie it. Such visions amount to imagining how the world *as it is today* would be transformed by a single new functional capacity. How would the world as it is today be different if cars could drive themselves (*ceteris paribus*)? How would the world as it is today be different if intelligent androids existed (*ceteris paribus*)? How would the world as it is today be different if we possessed teleportation technology (*ceteris paribus*)?

Consider the science fiction example of Star Trek. The existence of artificial general intelligence (AGI) and teleportation are central storytelling conceits in the Star Trek universe. But these technological capacities (if they do indeed arise) will not spring forth fully formed; they will emerge as products of many underlying technological advancements, each of which will have had a wide range of other world-changing implications of their own.

A moment's consideration shows that AGI and teleportation would have to be built atop fantastic levels of computing power and control over matter at the atomic level. Yet because these enabling technologies are ignored, *Star Trek* stories are brimming over with incongruities such as humans piloting vehicles, phasers and photon torpedoes missing their targets, colonies awaiting deliveries of medical supplies, traders exchanging material goods, and patients dying of injuries and old age – none of which make the slightest sense in a universe where machines are as intelligent as humans and where objects as complex as the human body can be reconstructed instantly atom by atom.

The first priority of science fiction is, of course, to tell coherent stories. But it is discouraging how much credence visions of the future such as the one portrayed in *Star Trek* are given in both public and academic discourse.

2.2.5. Timescales and the ceteris paribus fallacy

Building theoretical explanations with which to make predictions is of course as much a part of the scientific process as empirical observation. Such predictions are, however, usually limited to a narrow level or unit of analysis. Predictions of how a disease will react to treatment, how a market will react to a new tax policy, or how an ecosystem will react to pollution require us to assume *ceteris paribus* by necessity.

However, the longer the timeframe of any prediction about our global coupled human and natural system, the less plausible the assumption of *ceteris paribus* becomes. And because the pace of technological progress is accelerating, any projection beyond 20 years or so that assumes *ceteris paribus* is very nearly meaningless given the radical changes that technologies such as machine intelligence, robotics, decentralized solar power, and 3D printing – to mention just a few – will bring to society, the economy, and the environment starting in the 2030s.

Perhaps more insidiously, even though forecasts such as those mentioned above by the IPCC, OECD, and SFCTA that commit the *ceteris paribus* fallacy do not depict actual future states of our world any more accurately than an episode of *Star Trek* or an uninformed layman's wild guess, they are credited with undue legitimacy because they originate from respected academic and professional authorities.

2.3. The arrival fallacy

The arrival fallacy is the category error of envisioning possible futures as static objects (a destination or goal) instead of as snapshots of an inherently dynamic process. I am so far unable to find any formal discussion of this concept in the academic literature, but the term itself is used by Tal Ben-Shahar in *Happier* to describe the mistaken belief that happiness is a destination one can reach after achieving personal goals (Ben-Shahar, 2007). Although the content differs, the structure of the arrival fallacy as I use the term here is the same: "the future", like happiness, is not a point of culmination but rather an ongoing procession of changes.

2.3.1. Examples of the arrival fallacy in science fiction

Science fiction is, perhaps of necessity, widely plagued by the arrival fallacy. Technology in the imagined future of *Star Trek*, to continue the previous example, is more advanced than today but remains essentially static – frozen at a fixed point of development. In the case of *Star Trek*, of course, this is in part a consequence of decidedly terrestrial considerations such as the need to reuse sets and adhere to the storytelling conventions of episodic television. But even in "hard" science fiction that aspires to be scientifically plausible such as Larry Niven's *Ringworld* universe, to take a prominent example, technology is often depicted as changing either very slowly or not at all.

2.3.2. Examples of the arrival fallacy in visions of space exploration

Consider the widespread and seemingly "futuristic" prediction that within several decades we will have the technology necessary to begin colonizing Mars (Andersen, 2014; Weise, 2015). That may be perfectly true, but the visions of Martian colonies that typically follow – of intrepid pioneers in space suits who learn to grow crops and slowly begin to terraform the planet over many decades or even centuries – are hopelessly misguided as a result of the arrival fallacy.

We might well have the technology to establish a human colony on Mars by the 2040s, but how sensible will farms on Mars be in the 2060s when 3D printers can manufacture any physical object with atomic

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precision, including food? How sensible will trudging around in space suits and living in domed habitats be in the 2080s when humans can upload their minds into non-biological bodies? How sensible will it be in the 2100s and beyond for humanity to explore the vastness of space as *Homo sapiens* instead of as, say, sentient starships or clouds of nanobots?

2.3.3. Even accurate predictions have short lifespans

If a prognosticator from 1949 had precisely described the world of 1989, how long would that description of "the future" have remained accurate? Until 1994? Until 1999? Even if we focus solely on technological progress and ignore social and geopolitical changes, the world of 1989 was – for all practical purposes – one without the Internet or search engines, without digital cameras or video or music, and without mobile phones. Within 20 years those technologies had radically transformed the global economy.

As it happens, several stark examples of the arrival fallacy come to us from 1989. *The End of History?* is an influential essay by Francis Fukuyama whose titular phrase reflects the idea that humanity may be destined to arrive at a final sociopolitical structure: "What we may be witnessing is not just the end of the Cold War, or the passing of a particular period of post-war history, but the end of history as such: that is, the end point of mankind's ideological evolution and the universalization of Western liberal democracy as the final form of human government" (Fukuyama, 1989). Several years later Fukuyama provided a longer treatment of the same idea in his book *The End of History and the Last Man* (Fukuyama, 1992), which according to Google Scholar has been cited more than 13,000 times.

Meanwhile, the title of Bill McKibben's international bestseller *The End of Nature* (McKibben, 1989), which introduced the issue of climate change to the general public, highlights the fact that no part of the Earth's surface is uninfluenced by human activity. Although McKibben's work is apocalyptic where Fukuyama's is triumphant, both of these widely read and extraordinarily influential authors commit the arrival fallacy by assuming that our civilization has somehow reached a state of affairs that can no longer change.

2.3.4. An accelerating target

Not only is it wrong to think that change will slow or cease in the future, but the very opposite is true: the pace of change is accelerating. The threat of the arrival fallacy itself is therefore escalating over time because the absolute duration for which even a perfect prediction remains accurate is shrinking exponentially.

Technology changed far less over the course of the 10th Century than it did over the course of the 20th Century, for example. Although the impacts of disruptive technology are difficult to quantify, we can clearly expect more technological change per unit time going forward. How long will it take for the world of 2050 to experience as much technological change as occurred in the two decades between 1990 and 2010? Ten years? Five years? Two years? And how long for the world of 2060, or 2070, or 2080? Days, hours, or perhaps even minutes?

The future is not just a moving target but an accelerating one. The lesson of the arrival fallacy is that we must clearly and explicitly account for the inherent dynamism of our global coupled human and natural system whenever we envision possible futures, and the further forward we look the greater care and consideration we must take.

3. Conclusion

Technological growth follows an exponential trajectory because advancements in practical knowledge are compounding. Each new tool and technique we invent synergizes with previous ones, and in turn facilitates the creation of still newer and better tools and techniques (Drexler, 2013; Kurzweil, 2005). Moreover, technological progress in general has now become inextricably linked to the exponential growth of computing because the latter enables new functionality of many kinds (Lipsey et al., 2005).

Dynamic nonlinear phenomena are deeply unintuitive, and even otherwise well-informed and highly-educated observers may succumb to errors in reasoning about exponential growth (Meadows, 2008; Sterman, 2002; Sweeney & Sterman, 2000). Three common forms that these errors take with respect to visions of possible futures are: 1) the linear projection fallacy, which is the error of presuming that future change will be a simple and steady extension of past trends; 2) the *ceteris paribus* fallacy, which is the error of attempting to reason about the future by considering a single aspect of change while holding "all else equal"; and 3) the arrival fallacy, which is the category error of envisioning possible futures as static objects instead of as snapshots of an inherently dynamic process. The prevalence of these fallacies even in ostensibly futuristic forecasts contributes to widespread misconceptions about the magnitude of change we are likely to witness over the course of this century.

3.1. Caveats

As with any broad assertions about the future, forecasting, and the nature of technological and social change, several caveats are in order here.

First, technological growth is not inevitable. As robust as its progress has been since the industrial revolution and thanks to the rise of capitalism globally, it is not completely inconceivable that socioeconomic, geopolitical, or ecological forces could derail technological growth either temporarily or permanently.

Second, while the exponential growth of the price-performance of computing has been ongoing for many decades, and there are clear indications from existing lines of research that the trend will continue for several decades more, there can of course be no guarantee of this. Though perhaps unlikely, the exponential trajectory we have seen so far might begin slowing to a logistic (s-shaped) curve in the next decade or two rather than much later in the century as we approach the physical limits of computation.

And third, it is possible that recursively self-improving artificial general intelligence (AGI) whose advent would demarcate an "event horizon" or "singularity" (Kurzweil, 2005; Vinge, 1993) beyond which we cannot hope to make meaningful predictions about the future of any kind, will be invented sooner (in one or two decades) rather than later (in five or six decades).

These possibilities do not substantively affect the arguments I have presented here. We have very good theoretical and empirical reasons for expecting that the growth of technology in general (*i.e.* our capacity to understand and manipulate the material world), and of computing in particular, will continue to accelerate for long enough to deliver staggering advancements on a timescale that to any observer who succumbs to the aforementioned fallacies must seem impossibly short – decades, rather than centuries or millennia. If AGI appears earlier than expected then the discussion of the future I have presented here is moot – but then, so too are all other conceivable discussions.

The task before us therefore remains the same: we must think as soberly and rationally as possible about the time that remains prior to the arrival of that technological singularity, regardless of whether or not such a day does indeed ever come (Bostrom, 2014; Kurzweil, 2005; Modis, 2013; Vance, 2010).

3.2. Thinking realistically about possible, probable, and preferable futures

Observers sometimes deride the more thoughtful and accurate visions of the future that take full account of exponential growth as "science fiction", "utopian", or – ironically – "unrealistic". Nevertheless, truly fantastic technological capacities are likely to arise abruptly over the course of this century – particularly as computers pass key thresholds of performance, size, and cost.

Examples include: 1) microbots and nanobots that rival insects and microorganisms in size and sophistication, which can then be put to use restoring and safeguarding human and ecological health; 2) the

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rapid and precise manipulation of matter at the microscopic level, which will allow for widespread decentralization and dramatic cost reduction of the manufacture of material goods and the processing of wastes; and 3) narrow machine intelligence, which among other things will allow for the ongoing transfer of economic tasks that are currently performed by human labor to capital in the form of machines.

By the 2040s these advancements are likely begin to upend two seemingly immutable conditions around which we have organized our lives throughout human history: 1) material scarcity, and 2) our biological heritage. It is difficult to overstate how profound the social, economic, political, and ecological impacts on our civilization will be as a result.

Disciplines that make forecasts and projections on the order of decades already face the prospect of embarrassment for their technology blindness and temporal imprecision. Well-regarded declarations of the "end of history" (Fukuyama, 1989) and the "end of nature" (McKibben, 1989) were made just before the Internet revolution began to transform socioeconomics, geopolitics, and political ecologies worldwide. Energy sector analysts in the 1990s and early 2000s failed to anticipate how dramatically hydraulic fracturing would expand global oil and gas reserves, nor how quickly it would increase domestic production in the United States (U.S. EIA, 1999). And both academic and professional urban planners have so far failed to anticipate the radical changes that self-driving or autonomous vehicles will have upon cities beginning in the 2020s (Dorr, 2016; Guerra, 2015). These examples are just a handful among a multitude of cautionary tales that warn against relying on crude intuitions and naïve assumptions about the nature and pace of technological change.

Scientists, scholars, and experts across the full range of academic and professional disciplines can begin to reason more clearly about the future by recognizing and avoiding the linear projection, *ceteris paribus*, and arrival fallacies. This may in turn lead to more realistic foresight, more accurate projections, and more useful scenario forecasts that acknowledge the radically transformative technological advances that await our civilization over the course of this century.

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