Energy, Complexity, and the Singularity[1]

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Summary

This paper explores the relevance of ecological limitations such as climate change and resource exhaustion to the possibility of a technologically-mediated “intelligence explosion” in the near future. The imminent risks of global carbonization and loss of biodiversity, as well as the dependency of technological development on a healthy biosphere, are greatly underestimated by singularity theorists such as Ray Kurzweil. While development of information technology should continue, we cannot rely on hypothetical advances in AI to get us out of our present ecological bottleneck. Rather, we should do everything we can to foster human ingenuity, the one factor that has a record of generating the game-changing innovations that our species has relied upon to overcome survival challenges in our past.

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[1] Published in V. Callaghan, J. Miller, R. Yampolskiy, and S. Armstrong (eds.), *The Technological Singularity: Managing the Journey*. Springer, 2017, pp. 153–165.

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> The technology hype cycle for a paradigm shift—railroads, AI, Internet, telecommunications, possibly now nanotechnology—typically starts with a period of unrealistic expectations based on a lack of understanding of all the enabling factors required.
>
> — Ray Kurzweil, *The Singularity Is Near*, p. 263

1. A Contradiction

There is a striking dissonance between the futuristic optimism of the singularity hypothesizers such as Ray Kurzweil (2005), and the views of a host of other recent authors who warn of the ecological challenges which presently cast a long shadow over the prospects for the human species. Thomas Homer-Dixon, for instance, has stated that "We are on the cusp of a planetary-scale emergency" (2007, p. 308) due to factors that include global warming, resource exhaustion, peak oil, and species extinctions. One cannot help but wonder whether these two disparate groups of thinkers are even talking about the same planet—but, perforce, they are.

This paper will explore the relevance of ecological limitations to the possibility of any sort of information-processing "singularity" or technologically-mediated "intelligence explosion" in humanity's near future. The subtitle of Kurzweil's book (2005) speaks of humans "transcending biology." If we are going to talk about transcending our biological limitations we had better understand them first. We need a clear-eyed awareness of the biophysical imperatives that we will always have to contend with so long as we wish to continue living on this planet, no matter how advanced our technology may become. And we need to grasp the ecological challenges that our species faces today, which are mostly (and ironically) due to our own evolutionary success. At that point we might be able to say whether Kurzweil's information-processing "explosion" can offer us any hope in meeting those urgent challenges.

The seductive attraction of the singularity hypothesis is suggested by the movie *Limitless* (Dixon et al. 2011). A mysterious pharmaceutical has the power to vastly increase its user's creativity, memory, and pattern-recognition ability. The protagonist finds that he can think his way through all problems that come his way so long as he titers his dosage correctly, and by the end of the movie he is fabulously wealthy and well on his way to becoming President of the United States. This is merely a science fiction story, but it seems easy to imagine that as in this movie, if only we or something were dramatically smarter than we are now, all other problems could be solved almost incidentally.

This is essentially the premise of the singularity hypothesis: take care of information processing, and it will take care of everything else. That is why, in Kurzweil's glowing picture of the future, the existential threats presently faced by humanity, such as global warming, ice sheet collapse, resource exhaustion, species extinctions, and nuclear warfare, get only passing mention or are ignored entirely. As an anonymous referee for this paper put it, according to the hypothesis, “in the next century we are going to develop an artificial super-intelligence that will master nanotechnology… If the super-intelligence is friendly it will be able to trivially solve our environmental problems… ”. My aim is to ask if it is reasonable to bet the farm on the premise that we don’t really have to worry about those environmental problems because in only a few decades computer-assisted humanity will simply think its way out of them. And my answer will be—almost certainly not.

2. Challenges

I’ll begin by reviewing some of the ecological reasons why many scientists believe that humanity is now facing what is likely the biggest cluster of survival challenges in its evolutionary history.

2.1. Climate Change

At the top of the list is climate change due to anthropogenic global carbonization. Apart from warming of the troposphere and oceans, the risks attendant upon global carbonization include extreme weather (droughts, storms, wobbles in the polar vortex, flooding, forest fires, and killer heat waves), oceanic acidification, and catastrophic sea level rise (Hansen et al., 2013b; IPCC, 2014). It is fondly hoped that keeping the increase in global surface temperature under 2°C above pre-industrial levels will be sufficient to prevent “tipping points”—that is, critical points at which positive feedbacks cause some deleterious consequence of global carbonization (such as ice sheet collapse or methane release) to accelerate exponentially. However, even if we can hold global temperature increases below the 2°C “guardrail” (which some scientists fear may be already impossible; Anderson & Bowes, 2011), it is by no means clear that dangerous tipping points would not be reached anyway. Sea level rise promises to be the most visible effect of global carbonization in the years to come. There may already be enough heat in the seas to cause the vast but highly vulnerable marine ice domes in the central basin of West Antarctica to crumble (entailing an almost immediate jump of over 3 metres in sea level; Pollard et al., 2015; Alley et al. 2015).

What is the worst case scenario? Hansen et al. (2013a) show that burning all the fossil fuel there is to burn would eventually lead to a global “moist greenhouse” condition in which icecaps would disappear, sea level would be at least 60 m higher, and the equatorial regions of the planet would be uninhabitable by large mammals (including humans). Other research shows that portions of the seas would eventually go anoxic or possibly even euxinic (a condition in which a body of water becomes dominated by anaerobic bacteria producing toxic hydrogen sulfide; Ward, 2007). I prefer to believe that humanity could not be so foolish as to permit such an extreme outcome, but policy cannot be based on wishful thinking. At present we are not making anything remotely close to a sufficient effort to prevent such scenarios. In the face of the present crisis, Kurzweil's glib remark (p. 249) that we should be careful to not pull *too much* CO_2 out of the atmosphere is, put charitably, not very helpful.

2.2. Biodiversity and Ecosystem Services

For at least thirty years, biologists have been warning that humanity is in the process of engineering one of the major mass extinctions in the history of life on earth (Kaufman, 1986; Wilson, 1992; Brown, 2011; Kolbert, 2014). The problem is not only the loss of irreplaceable species and all the hard-won genetic information they contain. Since 1970 the *number* of non-human animals has been reduced by roughly one half—a process now called *defaunation*—while in the same period the human population has doubled (Dirzo et al., 2014).

These grim facts pose an obvious moral challenge. But the biodiversity crisis is of urgent practical concern as well. The plants and animals of the world provide "ecosystem services" (Costanza et al., 1997) through their production of oxygen, maintenance of soil fertility, purification of water, and contributions to the stabilization of climate—not to mention their provision of the vast biomass that humans consume as food or materials. Unless we want to transition to some sort of totally artificial habitat (which we might have to do on *other* planets) we have to grasp that many of the features that make this planet pleasant and habitable for us are either totally a bioproduct (such as free oxygen), or partially or indirectly bioproducts (such as fertile soils and many aspects of climate). The programmer in his cubicle gleefully coding next generation AI software breathes oxygen generated by the forests and phytoplankton. If he hopes to keep coding he, or someone, is going to have to respect the fact that whatever technological marvels we create, the photosynthesizers must be taken care of. This is something that must be attended to on an on-going basis; we cannot wait for the hypothetical super-intelligence of the future to take care of it for us. It would be suicidal for humanity to assume that the well-being of the myriad organisms we depend upon is "transparent to the user."

2.3. Energy—or, Where's My Jetsons Car?

Popular culture of the 1950s and 1960s exhibited a combination of technological optimism and naïveté that now seems quaint. Recall George Jetson's flying car, which burbled cheerfully as it delivered George and his family to their destinations and then neatly folded up into a briefcase. It was confidently assumed that in the not-too-distant future science would open the door to unlimited supplies of energy that would be "too cheap to meter". At the same time, few thinkers in an era when the transistor had just been invented envisioned how quickly computing would develop. In fact, things have turned out almost exactly the opposite: information technology has exploded while energy technology (apart from some progress in renewables) is stalled.

Compare the automobiles of today with those from the 1960s. Modern autos have enormously more capable electronics, but the engines and transmissions work essentially the same way that they did fifty years ago. At last, all-electric vehicles are beginning to be genuinely competitive with internal combustion cars, enabled by long-awaited advances in battery technology. But for the most part they are still charged by electrical grids energized by the combustion of coal and natural gas—methods that were old in the 1960s. With the recent and very hopeful growth of renewable technologies this may change soon, but as of this writing we are still a long way from weaning ourselves from the old dirty ways; indeed, humanity still derives about 85% of its energy from fossil fuels.

No culture that hopes to maintain anything like our present level of population and social complexity, let alone undertake dramatic leaps in technological sophistication, has a future if it must derive the larger part of its energy from the combustion of a rapidly-dwindling, one-time-only stock of toxic sludge accumulated in ancient anaerobic basins (Deffeyes, 2005). Hydrofracturing ("fracking") only slightly extends the lifetime of this resource, at significant environmental cost; fracking is the equivalent of sucking out the last dregs of a milkshake with a straw, and cannot be expected to provide energy security for more than a very few decades (Hughes, 2014; Inman, 2014). And let's not forget about climate change. Quantitative studies (e.g., McGlade & Ekins, 2015) show that we cannot burn the larger part of the remaining fossil fuels if we want to have the slightest hope of preventing the disastrous effects of global carbonization. Our technological society (with its present level of complexity and population) has no long-term future if it must depend upon fossil carbon.

Despite this, it remains importantly unclear whether renewables (solar, biomass, wind, and geothermal energy), or nuclear energy as it is presently implemented, can provide enough net energy, quickly enough, to maintain our global civilization at its present level of complexity. Kurzweil himself believes that this challenge will be obviated as we move to renewables. He points out, correctly, that Earth is bathed with thousands of times more solar energy than we need to power our culture. However, it still remains a matter of debate whether solar-powered technology has to potential to replace oil. Ecologist Charles Hall is blunt:

> I do not see…anything that implies a 'business as usual' (i.e., growth) as the most likely scenario… Even our most promising new technologies appear to represent at best minor, even trivial, replacements for our main fossil fuels at least within anything like the present investment and technological environment… depletion seems to be effectively trumping technological progress again and again. (Hall 2011, p. 2497)

On the other hand, Mark Jacobson and co-authors have carried out a painstaking analysis of possible alternative energies, and they argue, in contrast to Hall, that wind, water, and solar power are in principle capable of supplying all of the world's current energy needs; barriers to this result, they claim, "are primarily social and political, not technical or economic" (Jacobson & Delucchi, 2011).

Fully replacing fossil fuels with renewable technology will require a huge investment in new infrastructure, and a great deal of fossil fuel is going to have to be burned in order to get that infrastructure up and running. Renewables also face intense opposition from entrenched interests who wish to continue to profit from the present ways of generating and distributing energy. Despite these difficulties, recent advances in solar and wind energy tend to support Jacobson's optimism, and I agree with Kurzweil that renewables show great promise. But as with many of his technological speculations, Kurzweil is too willing to treat an unsecured promissory note as money in the bank. ("[N]anotechology…in the 2020s will be capable of creating almost any physical product from inexpensive raw materials and information"; p. 13.) We are emphatically not yet out of the woods. Solving the challenge indicated by Hall—finding ecologically sustainable ways of producing and using energy that can do *at least* as much work for humanity as fossil fuels—is a necessary condition for the possibility of a "singularity" or indeed any further dramatic and lasting development in the technological sophistication of human culture.

2.4. The Troubles with Science

Kurzweil says that "we're doubling the rate of progress every decade" (p. 11) and it is clear from the context of this quote that he is not talking only about information technology. However, in many respects that are highly relevant to human flourishing, it is simply not the case that the rate of advancement is even linear.

One important department of knowledge that is not growing exponentially is our fundamental understanding of physics. In his controversial *Trouble With Physics* (2006; see also Woit, 2006), the distinguished theorist Lee Smolin suggests that the story of modern physics since about 1975 could be called a "tragedy":

> For more than two centuries, until the present period, our understanding of the laws of nature expanded rapidly. But today, despite our best efforts, what we know for certain about these laws is no more than what we knew back in the 1970s (Smolin 2006, p. viii).

But what about lasers? Magnetic resonance imaging? The increase in the speed and miniaturization of microelectronics (one of the few positive trends that *has* been quasi-exponential)? The Internet? Flat-screen TVs? GPS positioning? The near-total obsolescence of chemical photography due to CCDs? Smart phones and tablets? Photovoltaics? LEDs? Quantum computing (still largely theoretical but quite promising)?

All of these marvels are based on *applications* of physical principles, mostly in the province of quantum mechanics, which were discovered before 1930 (Peacock, 2008). The one really new thing that has appeared in physical science in the past thirty years is dark energy (Kirshner, 2002) and this was not so much an increase in understanding as a stark reminder of how limited our understanding of the physical universe still is. Most important, argues Smolin, we are presently stuck not merely because the problems faced in current theoretical physics are so technically difficult, but because of a complex of cultural, philosophical, and socio-economic blinders that actively discourage the intellectual risk-taking that is essential for innovation.

One could make similar harsh observations about medicine: we still do not have a cure for the common cold let alone most types of cancer, and the development of new antibiotics and vaccines has slowed to a crawl because there presently is no model for funding the necessary research and development. Stem cell technology holds the promise of transforming the central focus of medicine from repair-and-support to regeneration, but (like quantum computing) it is in its early exploratory phase. Obviously, there have been significant improvements in medical treatment in the past thirty to forty years, but like most other recent technological advances they are for the most part incremental, refinements of principles that were understood decades ago.

A Ptolemaic astronomer circa 1500 CE could have exclaimed, "Look, our models are getting better and better at explaining the increasingly fine observations that our naked-eye astronomers are making! The number of epicycles is increasing exponentially!" What he would have been missing was the fact that the proliferation of ad hoc epicycles was a sign that the vein of geocentric astronomy was played out. At critical times new, disruptive insights are needed. Just as a declining society can only be saved by what Tainter (1988, p. 215) calls a new "subsidy" of energy, at a certain point a stagnant knowledge paradigm can only be revived by a new subsidy of creative insight (Kuhn, 1970).

The lack of progress in fundamental physics is probably one of the main reasons for our lack of progress in energy. At the end of this paper I will have more to say about why our ability to generate new insights is failing us precisely at the time when we need it the most.

3. Energy and Complexity

It is crucial to realize how important the energy question is for any discussion of possible technological advances. The need for energy is a matter of simple (non-equilibrium) physics. Any complex society is a physical system (technically, a dissipative structure; Schneider & Sagan, 2005) that can maintain its coherence and complexity only if it is provided with a generous flow of usable energy. The greater the complexity to be maintained, the greater the energy flow required. If the energy flow falters, the society must simplify itself proportionally or suffer collapse (Tainter, 1988). A generous energy flow is a necessary condition for our present global society to keep functioning at anything close to its present level of complexity. The energy a society needs in order to maintain its complexity comes in one way or another from its "EROI", its "energy return on energy invested in producing energy" (Murphy & Hall, 2010). No improvements in the efficiency with which net energy is used can by themselves save a society whose EROI is continually diminishing, as is the world EROI today (Inman, 2013). Efficiency can buy time, but beyond a point efficiency measures can themselves be a drain since they also demand resource-consuming complexity. In principle we could recycle every bent paperclip, but at what cost?

Kurzweil states that he is a "patternist, someone who views patterns of information as the fundamental reality" (p. 5). This suggests a deep misunderstanding of physics. Recall Rolf Landauer's famous dictum (1991) that "information is physical." While the same bits of information can be encoded in many different physical substrates, they must always be encoded on *some* physical substrate; there is no such thing as pure information except as a mathematical abstraction. Landauer's rule therefore demands that we consider the *physical requisites* for an advanced society to develop and maintain a high level of informational complexity. Perhaps it is Kurzweil's fanciful metaphysics that has led him to underestimate the biophysical requirements for his "information explosion."

Given the ecological trends cited above, it is very unclear that the complexity of modern society can be sustained for much longer at its present level, let alone expanded enough to allow for a dramatic increase in information-processing capacity. This is certainly the case even given the great increases in efficiencies due to the hypothetical advances in nanotechnology and miniaturization that Kurzweil cites in his discussion of energy needs (2005). Kurzweil is right that in principle much of our technology could be miniaturized, thereby (again, in principle) enabling higher complexity for a given energy flow. However, miniaturization needs a lot of supporting infrastructure. Gigaflop computer chips presently require multi-billion dollar factories for their production; materials must be mined, shipped, and fabricated, and the energy and material requirements for these activities are huge. When we estimate the ecological limits to complexity we must consider not only the requirements of our end-product technology but also the requirements of the complex infrastructure required to produce and support those marvellous end-result devices. Some of those requirements (such as mining, agriculture, and forestry) cannot be miniaturized, because they involve the interaction of human technology with parts of the global ecosystem (such as its geology or forests) that cannot be miniaturized. We can't nano-size the ecological impact of cutting down a tree. Like humanity itself, the technological ecology we create cannot exist independently of the biophysical ecology of the planetary system, and ultimately it must scale with *it* and interface with *it* on *its* terms.

A defender of the singularity hypothesis might say that I have simply failed to grasp the magical power of exponential expansion. I address this point below.

4. Exponentials and Feedbacks

Kurzweil's *Singularity is Near* is a paean to the power of the exponential function. For example, never mind that solar power presently provides only a tiny fraction of our energy; it is expanding exponentially and therefore will soon take over the world's energy production. We need a more balanced picture of how exponential expansions work and then cease to work.

An exponentially growing quantity *if unchecked* will grow from background noise to an impressive signal rather quickly; this is elementary. However, the mere fact that some process is growing exponentially does not by itself guarantee that it will keep growing; there will, with certainty, be feedbacks and tipping points that will slow or halt the growth.

A simple example of an exponentially growing system that hits a limiting threshold is a population of yeast in a carboy of grape juice and sugar. In this ideal environment the yeast organisms multiply exponentially. But their metabolism has a waste product, ethanol, which is toxic to the yeast at a certain concentration (although desirable to the person who makes the wine). When that concentration is reached the population of yeast sterilizes itself out of existence almost instantaneously. One can think of many similar examples. No exponential expansion can go on forever; something always has to give.

Exponential growth can be illustrated by a pond with water plants on its surface which double their coverage every day. We are supposed to be amazed by the fact that if the surface of the pond is half covered on a certain day, it will be totally covered the next day. The interesting question is what happens the day after. In some cases symbiotic negative feedbacks will kick in and the growth rate will slow down to a steady state; in other cases a predator will feast on the bloom, keeping it in check; and sometimes the plant growth will choke the pond by using up too much oxygen or a vital nutrient.

Realistic systems in nature, such as ecosystems containing predators and prey, undergo complex cycles due to their mutual interactions and the phase relations between them; even economic systems can be modelled in such terms (Motesharrei et al., 2014). Negative feedbacks always damp out exponential growth sooner or later, and these feedbacks may act gradually or drastically.

Kurzweil understands that no exponential process can go on forever, but he dismisses the problems I describe here ("The Criticism from Malthus," pp. 433–434) because, he argues, the energy requirements of advanced computers will be so minimal that they will achieve the singularity *before* limiting factors can catch up with their exponential growth in computing capacity, like a driver gunning his car to beat a yellow light. Again, Kurzweil fails to grasp the dependency of computing technology on the continued healthy functioning of its supporting ecological context. We can't wait for however many decades it takes for the super-intelligence to appear, and then hope to go back and repair what is left of the planet.

For all his talk of the power of exponentials, Kurzweil is a remarkably linear thinker. (After all, an exponential growth function is linear when expressed logarithmically.) He sees one trend and extrapolates it, while failing to grasp that there are other powerful trends and countervailing forces (many themselves growing nonlinearly) which must be expected to interact in complex and unpredictable ways. The growth of information processing technology, while certainly important, is hardly the only major trend in our time, and supposing that it will allow us to "transcend biology" is not even good science fiction. The continued existence of the complex technological infrastructure that allows us to build our computers and networks is utterly dependent upon the continuing health of a global ecosystem (the "earth system") whose complex, interdependent operations we are now in the process of thoughtlessly dismantling.

5. Ingenuity, not Data Processing

Kurzweil speaks of his "veneration for human creativity" (p. 2), but at times he exhibits a certain frustration with human limitations:

> While human intelligence is sometimes capable of soaring in its creativity and expressiveness, much human thought is derivative, petty, and circumscribed (p. 9).

So painfully true. However, we should do a better job of understanding the potentials of the human brain before declaring it obsolete.

The most important capacity of the human mind does not lie in its abilities to remember or calculate; these are modest compared to digital computers. The great survival trick that the human animal has evolved and brought to a level unprecedented in evolutionary history is ingenuity, the capacity for creative problem solving. A nice demonstration of ingenuity is the sewing needle, which is not found in the fossil record before about 30,000 years ago. As Brian Fagan (2012) observes, the unspectacular sewing needle allowed early humans in sub-arctic conditions to craft *tailored* clothing, and thus was likely one of many innovations that got our ancestors through that harsh period. The possibility of the sewing needle is implicit in the physics of materials and therefore it could have been deduced by brute force by some sufficiently powerful digital computer, like a winning chess strategy. But that is not how it actually came about.

Ingenuity is that poorly understood neurological capacity by which human beings can occasionally introduce something new that expands the sheaf of survival options. It is not a freakish phenomenon exhibited only by a few rare geniuses, but a natural human capacity like athletic or musical ability. Like such abilities, it is present in unequal amounts in different people and it may be suppressed by a variety of social, political, economic, and cultural factors; however, it can be promoted by other factors (including education and opportunity).

Finding a creative innovation is like winning more "lives" in a video game. Historically, human ingenuity in this sense is a proven commodity, but we also know that it can be prevented from acting by powerful social forces such as dogmatic religion, ideology, vested interests (financial, political, intellectual, or corporate), or the sheer lack of room to operate due to poverty or scarcity of resources. These anti-creative forces can be dominant in times of ecological stress (Peacock, 1999). Authoritarianism of all stripes (whether acting from naked self-interest or misguided social concern) tends to see innovation as threatening (Whatmough, 1996). Arguably, many episodes of societal collapse in the past occurred because human ingenuity either failed or was not permitted to operate. There is a real danger now that as scarcity and other ecological challenges increase in our time, those who benefit from our present unsustainable system may well "double down" and block the innovations that are needed.

The need to protect and foster our capacity for ingenuity is, I submit, is the greatest challenge facing humanity right now, rising seas notwithstanding. Certainly it is of interest (although obviously also risky) to try to construct computers that might be capable of creativity. However, when we are faced with urgent, time-constraining challenges such as global carbonization we should invest far more resources than we are now into the one factor—human ingenuity—that has a proven track record in solving apparently intractable problems. That is what is going to get us through our present ecological bottleneck if anything can. There is no question that information technology can assist and supplement human ingenuity; this is already well-demonstrated. One may also speculate that computers will someday exceed the creative problem-solving ability of humans but that day has not yet come, and we cannot bank on it any more than I can do my household budget on the assumption that I will win a major lottery.

6. In Summary

Kurzweil seems to be virtually oblivious to the magnitude and urgency of current ecological challenges such as global carbonization. Humanity's immediate ecological problem is this: the methods by which we presently garner the resources of energy and materials that we need cannot go on because they are biophysically unsustainable. We are running a complex, globalized, industrialized society almost entirely on a source of energy (fossil fuels) that can be extracted in economically significant quantities for only a few more decades (one to two) at most. Pollution from the exploitation of this resource is well on its way to dangerously destabilizing the planet's climate (through global warming) and the viability of the ocean's food chain (through acidification). Other deleterious human impacts on the earth system—through such factors as habitat encroachment and fragmentation, soil erosion, deforestation, and over-fishing—are by now on a geological scale.

The notion that a highly speculative increase in computing power could enable us to leapfrog all of these ecological difficulties is at best a long shot. The way past our ecological bottleneck is not to bet that we can transcend biology but to integrate our technology and its supporting infrastructure symbiotically with the Earth system (Peacock, 2011). Regardless of what marvels of efficiency may eventually be realized in microelectronics and nanotechnology, our elaborate technological ecosystems of the future will be as dependent upon a flourishing planetary biota as we are now. And a key component of moving to that quasi-symbiotic state will be to engender the flourishing of those human capacities that are most likely to contribute to the innovations that are required. The ability of the human mind to generate novelty, such as the not-so-humble sewing needle and of course computers themselves, is well demonstrated; the possibility that machine intelligence could do the same thing remains, at this writing, purely speculative. As discussed elsewhere in this volume, machine intelligence also carries unknown risks (see also Barrat, 2013; Gaudin, 2014): even if the singularity does occur before the servers are swamped by rising seas, how can we be sure that we would not simply have created a vast computer virus run amok? AI researchers may have to take precautions similar to those taken by medical researchers who study Ebola.

I hope it is clear that I do not claim that there is a dichotomous choice between environmental remediation and AI research. The development of info- and nano-tech can and should continue, with suitable precautions. What I claim is that we can neither *rely* on nor *wait for* miraculous hypothetical developments in AI to get us out of our present ecological jam.

In summary: *necessary* conditions for any dramatic technological advance (such as the “singularity”) include the following: the continued healthy functioning of the earth system, and abundant and sustainable sources of non-fossil energy. And our best chance of satisfying these necessary conditions is not gambling on a technological long-shot but doing everything we can to foster human ingenuity, the one factor that has a proven capacity to generate game-changing innovation.

Acknowledgments

I thank Maxime Chambers-Dumont for assistance and anonymous referees for helpful and stimulating comments. I am grateful to the University of Lethbridge for supporting my work in many ways. Any errors, omissions, or misinterpretations remaining in this paper are entirely my responsibility.

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