Technological Forecasting & Social Change xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

How many singularities are near and how will they disrupt human history?

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ARTICLE INFO

Article history:
Received 7 April 2011
Received in revised form 29 June 2011
Accepted 27 July 2011
Available online xxxx

Keywords:
Technological singularities
Societal transformation
Metrics in technological change

ABSTRACT

This paper reviews a large number of approaches that have been used for considering technologically driven profound societal change. We agree with Vinge's suggestion for naming events that are "capable of rupturing the fabric of human history" (or leading to profound societal changes) as a "singularity". This is a useful terminology especially since a mathematically rigorous singularity seems impossible for technological and related societal change. The overview of previous work is done within the context of a broader look at the role of technological change within human history. The review shows that a wide variety of methods have been used and almost all point to singularities in the present century particularly in the middle of the century. The diversity of the methods is reassuring about the potential robustness of these predictions. However, the subjectivity of labeling events as singularities (even well studied past events) is a concern about all of the methods and thus one must carefully pause when relying in any way on these predictions. The general lack of empirical research in this area is also a concern.
Quantitative considerations (by proponents and opponents) about past singularities or future singularities often confound two types of metrics. The first type is essentially related to diffusion of technologies (or bundles of technologies) where the logistic curve is empirically well established as the proper time dependence. The second type of metric is for technological capability where hyper-exponentials are empirically well established for their time dependence. In this paper, we consider two past singularities (arguably with important enough social change to qualify) in which the basic metric is alternatively of one type or another. *The globalization occurring under Portuguese leadership* of maritime empire building and naval technological progress is characterized by a metric describing diffusion. The *revolution in time keeping*, on the other hand, is characterized by a technological capability metric. For these two cases (and thus robust to the choice of metric type), we find that:

- People undergoing profound technologically-driven societal change do not sense a singularity.
- The societal impacts depend in complicated ways on human needs, institutional variables and other more uncertain factors and thus are particularly hard to project;
- The societal impact is apparently not determined by the rate of progress on either type of metric or by projections to mathematical points with either kind of metric. This finding supports the existing concept that social change due to technology is a more holistic phenomenon than can be characterized by any technical metric.

In the final section, we use these empirical findings as the basis for exploring the possibilities for and nature of future singularities. In this we speculate that the potential for a *future* strong singularity based upon computational capability does not appear particularly probable but that one may already be occurring and is not fully noticed by those (us) going through it. Other possible 21st century singularities (life extension and fossil fuel elimination are two examples considered) may also be already underway rather than waiting for the predicted mid-century changes.

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doi:10.1016/j.techfore.2011.07.013

1. Introduction

Accelerating change is currently a preferred term for describing the unfolding of global-wide transformations that swept the whole planet during the last two centuries and that appear to be continuing and perhaps even accelerating during the first decade of this century. For some authors this portends an approaching global disaster and for others, it points toward a new era of unconceivable wealth and improved human life. The former position is held by those who discuss the proliferation of afflictions swamping mankind and perceive, at least some, as directly coupled with economic growth. There is already a growing planetary consciousness that some extreme measures may have to be undertaken fairly soon if the human race intends to endure as a species. A number of these descriptions of the future make a strong case for a profound change in this century and often utilize the concept of an upcoming singularity. Among these singularity-related theories, one can distinguish at least three major groups: those objectively related to accelerated technological change, another related to prediction horizon analysis and a third one (and the most common) related with artificial intelligence evolution leading to super-intelligence. In all three instances, the singularity is not mathematically defined but instead is a time period, often short, of profound human/societal change.

Our discussion in this paper will focus on the first group described above with significant analysis of the third grouping and minor consideration of the second group, with a threefold objective:

1 – to present a survey on the recent concepts about accelerating change and its potential societal impact,
2 – to attempt to shed some light where misleading concepts such as confounding of capability and diffusion, simple extrapolations, spike-like growth, undefined singularities, etc. have been introduced and
3 – to present an alternative viewpoint about what is needed to consider regarding future major technological transitions and their socioeconomic relevance to the future of humankind.

We hope with this paper to promote a better measurement–evaluation–understanding of the presently observed trends, as well as to provide some tentative guidance for the construction of future scenarios. In Section 1, we discuss some of the extremely long term changes in life and the universe. In Section 2, we begin to address the issue of the role of technological change in the human story while Section 3 focuses entirely on different authors' approaches and conclusions relative to upcoming profound change and singularities. Section 4 covers some related activities that have now emerged in regard to study of singularities. Section 5 examines in some detail two *past examples* that might be labeled singularities while Section 6 is our concluding remarks.

2. On the subjectivity of large time-scale perspectives

One characteristic of science throughout the 19th and 20th centuries was its increasing specialization, which naturally led to a disconnected and fragmentary account about the origins of the universe and its coupling to the sweep through time of life on Earth. But in the last quarter of the 20th century, mainly after the birth of the Science of Complexity and perhaps also stimulated by the increasing success of Universal Darwinism as a powerful approach to account for a unified view of the grand scheme of things, we have witnessed the burgeoning of 'Big History', a new method used by some historians (and not restricted to historians of science), in an attempt to offer a unified vision of how things came to be the way they are.

'Big History' consists in an effort to assemble a coherent and accessible account of origins in a broad sense, embracing the past on many different time scales, beginning literally with the origins of the universe and ending in the present day. Such an approach is powerful because it appeals to our deep spiritual, psychic, and social need for a sense of place, as well as a sense of belonging and a sense of orientation amidst the immensity and complexity of the Cosmos.

We perceive a growing sense, across many scholarly disciplines, that it was necessary to move beyond the fragmentary account of reality that has dominated scholarship for more than a century, and scientists moved fast in this direction. Books and courses on 'Big History' proliferated in the 1980s and 1990s, including the precursor work of Gerald Hawkins (*Mindsteps to Cosmos*) in 1983 [1], the success of Stephen Hawking's *A Brief History of Time* [2] in 1988, the introduction of the *Cosmic Calendar* by Carl Sagan in 1989 [3], the publication of a first book on Big History in 1996 by Fred Spier [4], and Coren's *The Evolutionary Trajectory* published in 1998 [5], just to mention a few. For a more recent account of this new broad vision of history we recommend the reading of the excellent book by David Christian (*Maps of Time*) first published in 2004 [6].

As a consequence of this rapid development (alas, also accelerated!) everyone is becoming acquainted with time-line representations in logarithmic scales, where the unfolding of the universe evolution since the Big Bang (galaxies, stars, Sun, Earth,…) started ca. 15 billion years ago, stretching for some billion years, life evolution on Earth started ca. 4 billion years ago, appearance of first humans happened ca. 2 million years ago, first high civilizations appeared some millennia ago, and modern society and its scientific/technological achievements is reckoned in centuries, ending with very modern technological breakthroughs reckoned in some few decades or even years.

The shortening time spans between the succeeding events chosen to mark the different evolutionary steps is striking and mind stretching. The first obvious conclusion of these time-line pictures is that evolution is indeed an ever accelerating process. But what does one gain by noticing this acceleration? Perhaps not so much, with the exception already noted above of a psychological sense of belonging and orientation.

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At this point we can raise some important questions that in our view have not been suitably addressed:

1 – What is the validity of this procedure of placing such distinct phenomena, cosmological, geological, biological, and technological (and in some cases even socio-economical), all in one basket, and arbitrarily choosing the evolutionary events that separate or characterize the different stages of the evolutionary process?
2 – What is indeed accelerating? Which is the suitable parameter to be used in order to calculate the acceleration rate?

Obviously, both questions are closely related. In order to consider all the large spectra of phenomena in the same basket, we need to find a common denominator, or pattern, underlying all the evolutionary steps. Looking at all the published literature on this theme we can't find either a unanimous opinion about what should be this common pattern/denominator or what are the really important evolutionary events to be chosen. Authors have defined such events very differently: mind steps, turning points, evolutionary jumps, critical transitions, paradigm shifts, milestones, etc, and the choice of whatever is to be selected as important events is highly subjective and perhaps arbitrary.

Regarding the second question we find very different approaches leading to completely different results: either an imminent collapse, a kind of countdown to a mathematical singularity, or even the thoroughly opposite side of the coin, a decelerating path of novel evolutionary steps. We believe that the subjectivity of the chosen approach is the main reason for such total incoherence.

The question remains unanswered: what is accelerating? And what is accumulating as the typical exponential curves indicate? Evolution itself, a self-sustaining process with feedback loops, which must be necessarily accelerated? What should we measure to make coherent calculations: the universe's increasing order? Or much on the contrary, its increasing disorder? Or should we measure the universe's increasing complexity? Or the information content attached to the observable universe? Or knowledge accumulated by humans?

Among the different approaches to finding a suitable measure for the universe's evolutionary path we find two attempts that deserve some attention: Coren's evolutionary trajectory [5] and Modis' complexity change [7].

In 1998 Richard Coren, Emeritus Professor of Electrical Engineering and Computer Science at Drexel University, published a very interesting book [5] with the suggestive title *The Evolutionary Trajectory: The Growth of Information in the History and Future of Earth*. Coren looked at evolution in terms of information transfer, considering it as the suitable measure of evolutionary change, and is among the first authors proposing a critical event (he did not use the term 'singularity') due to the accelerating rate of change of the evolutionary path. By considering a set of 13 events that he described as 'critical transitions in the evolution on Earth' (beginning with the Big Bang and ending in modern times with digital electronics and computing), and extrapolating a logarithmic plot, he derives a critical time at about 2140 AD, when probably intelligent machines will surpass human intelligence and man–machine merging will be a reality. It is important to note that Coren's date for this event is much more conservative than the date estimated for the same technological achievement by more recent writers as we will see in Section 3.

The physicist and complexity theorist Theodore Modis [7] has undertaken in 2002 a more exhaustive analysis, considering that changes in the evolutionary process are linked to complexity, and used sets of data of some thirteen different sources. His reasoning was that complexity increases both when the rate of change increases and when the amount of things that are changing around us increases. In the spirit of punctuated equilibrium this author then tried to quantify complexity in terms of the spacing of equally different important evolutionary turning points, which he termed milestones. Forecasts for future complexity jumps were obtained on the basis of his calculations of twenty-eight clusters of events, by combining identical, similar, and/or related events from the different lists (totaling 208 events), and by applying exponential and logistic fits on the data. His forecast stipulates that we have already reached the maximum rate of growth for complexity (~1990), and that in the future, complexity's rate of change will be declining.

It is important to note that Modis also used Coren's set of data (with thirteen events) to check his calculations, or in other words, he applied the logistic fit on Coren's data set, concluding that this also leads to the same conclusion of a declining trend, and not an accelerating one as Coren had proposed (through exponential fitting).

The limitation with Modis' approach is once more the consideration of very different evolutionary steps in the same basket. In particular, among the 308 events he used to calculate the clusters, *only ten* occurred in the last 500 years, and are very disparate. This strange choice of events over time may in fact dictate that no exponential can be found. But on the other hand, despite the weaknesses including the same subjectivity within his approach, Modis has shown that in applying a different approach (complexity change and logistic fit), one can find a trend that is not necessarily an accelerating one. Modis also points out that the increasing amount of things changing around us is usually confounded with an accelerated rate of change.

3. Narrowing the focus

Let's now turn to a question introduced in the first paragraph of this paper: what is the role of the (assumed for now) accelerating rate of technology change in the overall story of human existence?

In order to explore possible answers to this question and to begin to fulfill our first objective in the Introduction (survey recent concepts about accelerating change and its societal impact) we narrow our focus of analysis to the shorter time frame of human civilization, or in other words, address a technology macro-history instead of Big History (in the sense used by Spier [4] and Christian [6]).

The probable precursor of today's debate about an *approaching critical transition* of human life was the late British-American astronomer Gerald Hawkins, former chairman for Astronomy at Boston University, who proposed in 1983 his theory of mind steps [1]. Based on the concept of a 'meme pool' that interacting with the human environment shapes the human mind, Hawkins proposed that humanity in its search for a place in the cosmos has made a sequence of five dramatic mind steps toward that goal. Table 1 gives his

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Table 1
Gerald Hawkin's mind steps.

Mind step	Name	Begin	Length (years)
0	Age of Chaos	35,000 BC	32,000
1	Age of Myth and Legend	3000 BC	3150
2	Age of Order	150 AD	1393
3	Age of Revolution	1543 AD	383
4	Age of Space	1926 AD	95
5	–	2021 AD	24
6	–	2045 AD	6
7	–	2051 AD	2
8	–	2053	"Zero!?!"

terminology and dating: mind step 0 (ca. 35,000 years ago, Age of Chaos, with a time span of about 32,000 years), going through mind steps 1 (Age of Myth and Legend, 3150 years long), 2 (Age of Order, 1393 years long), 3 (Age of Revolution, 383 years long), and 4 (Age of Space, which started in 1926, supposed to be 95 years long, finishing then in 2021).

For Hawkins mind steps are cumulative — each one overlays the other in the collective mind, and there needs to be some period of time for developing the new meme pool and absorbing the mind step. But the waiting time for a new mind step is getting incredibly shorter, and his geometric series predicts a mathematical "zero time transition" around the year 2053.

Although suffering from the subjective weakness as well as the same lack of empirical proof as the other approaches commented on above, Hawkins' theory has the merit of pointing out that all the mind steps have been associated with inventions to improve the meme transfer: drawing, writing, printing, and nowadays computing. Writing in 1983 Hawkins stated that "…*perhaps we will not be able to move to mind step 5 until another breakthrough in communication technology comes along*…" Remember that in 1983 the Internet was being created and defined as the set of networks using the protocol TCP/IP [8].

Similar to Coren and in despite of finding an acceleration and an approaching critical time, neither author used the concept nor terminology of a Singularity as later writers on the same subjects have tended to do.

In 1980 the physicist Cesare Marchetti, the father of the theory of "*Society as a Learning System*" [9] and former leader of IIASA's Energy Systems Program, a very productive group in the study of logistic technology diffusion during the 1980s and 1990s, has made a very important point about a possible accelerating trend of innovation waves. Marchetti calculated a secular series of logistic fits of inventions and innovations (Figs. 7 through 11 in Ref. 9) that indicate a slight shortening trend in the characteristic time of bursts of inventions and innovations since the onset of the industrial revolution.

In the same vein as the German economist Gerhard Mensch [10] and many other followers of the neo-Schumpeterian school of evolutionary economics, Marchetti believed that inventions and basic innovations appear periodically in the form of swarms in phase with the unfolding of the so-called long economic waves or Kondratieff waves (K-waves). This assumption did not constitute a novelty at that time (1980s), when a number of books, conferences and articles dealing with this subject appeared in the scientific media (for a detailed description of the succeeding Kondratieff waves and their related theories see Devezas's article published in 2001 [11]). The very existence of innovation and invention bursts is still an issue strongly debated and controversial, but the novelty in Marchetti's calculations was the demonstration that the characteristic time (the time span to progress from 10% until 90% of the complete diffusion of a given innovations and/or inventions swarms) was diminishing at a constant geometric rate of roughly 1.42 (see Table 2), which implies a critical event to be reached within about three centuries.

Interestingly, Marchetti has never given much attention to this finding, for he was mainly concerned with the regular pattern and periodicity of the whole socioeconomic behavior. He limited his comments to a brief statement that the bursts of inventions and innovations "show a certain level of acceleration".

In 1979 the Belgian economist Peter Peeters [12] writing about technological progress made the point that "there has evidently been a speeding up of progress", and presented a curious linear graph plotting the time elapsed between the discovery and the general application of nine very important (in his subjective view) inventions/innovations against the year of the introduction of the corresponding invention/innovation. The author defined the elapsed time between introduction and general adoption of the innovation as "*a measure of the resistance to progress or of the strength of tradition*". His graph shows an ever shortening time span between the introduction and general adoption of invention/innovations, which ends up with a time "zero" exactly in the year 2000, which he points to as a signal of "stabilization".

Table 2
Cesare Marchetti's succession of K-waves and their related swarms of inventions/innovations.

K-wave	Midpoint of the K-wave	ΔT (years) Inventions	Inventions center point	ΔT (years) Innovations	Innovations center point
1st	1802	120	1775	47	1828
2nd	1857	85	1883	33	1880
3rd	1921	55	1905	23	1937
4th	1980	38	1968	16	1993
5th(*)	(2035)	(27)		(11)	

(*) — Projection.

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Once again the subjectivity of such approaches choosing arbitrarily a given collection of events and trying to draw conclusions through simple extrapolations is evident. As we have seen this kind of extrapolation leads to very disparate dates, some pointing to some date within the next centuries, some to the end and/or middle of this century, and some even induce us to the conclusion that we seem already overdue (Peeters' conclusion above) for some impending technological transition.

4. Discussion of singularities

As we have already pointed out, the authors mentioned until now, despite the fact that they (at least some of them) find a mathematical discontinuity in their calculations (a "zero" when extrapolating shortening time spans), none has discussed explicitly the concept of a singularity.

The fundamental concept of singularity implies that a given measure reaches infinity in a finite time, which is the case (mathematically speaking) of hyperbolic growth, and that is different from a simple exponential growth when the measure approaches asymptotically infinity in an infinite time. The concept of a singularity is a pure mathematical abstraction, which finds usage mainly among mathematicians and astrophysicists. But this has changed in the last few years as we discuss in the following paragraphs.

Recently, many authors writing about a technological singularity opens his/her line of thought quoting a statement of the legendary mathematician and information theorist John von Neumann, who in the late 1950s said that "*the ever-accelerating progress of technology…gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue*". This statement has the same standing in the Singularity school as Richard Feynman's well known statement "*There is a plenty of room at the bottom*" today for any author writing about Nanotechnology.

The acceleration of publications and theories about an upcoming singularity started perhaps after 1993 when Vernor Vinge, a mathematician and computer scientist at San Diego State University (and also a successful science fiction writer) presented the concept in his famous talk "The Coming Technological Singularity" [13] at the VISION-21 Symposium sponsored by NASA Lewis Research Center. Vinge had already used the concept previously, perhaps in an unnoted fashion, in two instances: an article in Omni Magazine from January 1983 [14] and in the science fiction novel "*Marooned in Real-time*" published in 1986 [15]. Since then the word Singularity (often written with a capital letter), has gained a non-mathematical meaning — *that of an event capable of rupturing the fabric of human history*. Some who foresee a large scale societal transition do not attempt to specify its nature.

Vinge brought to the scientific community the audacious hypothesis that human (computational) technology will give rise in the fairly near future to entities with greater than human intelligence, a phenomenon to happen before 2030. This could happen through some combination of these:

1 – There may be developed computers that are "awake" and superhumanly intelligent, which he coined as the AI (artificial intelligent) scenario;
2 – Computer/human interfaces may become so intimate that users may reasonably be considered superhumanly intelligent, which he coined as the IA (intelligence amplification) scenario;
3 – Large computer networks (and their users) may "wake up" as a superhumanly intelligent entity, which he coined as the Internet Scenario; and finally
4 – Biological science may provide means to improve natural human intellect, which he coined as the Biomedical Scenario.

As in many other instances in history, Vinge's idea was a product of the times (the 1980s), or what historians use to coin as the "*historical opportunity*", for by this time some other authors have advanced this superhuman perspective, but perhaps in a more cautious fashion. That is the case for instance of the 1988 best seller *Mind Children* [16] authored by the Carnegie Mellon roboticist Hans Moravec, in which he outlines predictions about the future of artificial life. Moravec, based on extrapolation of Moore's Law, presents a timeline and a scenario in which robots will evolve into a new series of artificial super intelligent species, starting around 2030–2040.

The Singularity meme has then evolved and the concept has gained special relevance after the series of publications of the inventor and futurist Ray Kurzweil, namely *The Age of Intelligent Machines* (1990) [17], *The Age of Spiritual Machines* (1999) [18] and particularly *The Singularity is Near* (2005) [19], a triad of books extending the ideas of Moravec and Vinge. In each of these books Kurzweil presented some bold forecasts about the future of computation and the economy in general. Today, looking backwards to the whole set of forecasts placed by Kurzweil in his books, we can even recognize the accuracy of some of his forecasts, but considering the actual unfolding of 'computer intelligence' developments (different from computer capability) and the world economy as a whole it is not yet possible to see clear signs of the technological nirvana he presented, as will be discussed in the next section.

In the introduction of his seminal last publication (*The Singularity is Near*) Kurzweil says "*this book is the story of the destiny of the human–machine civilization, a destiny that we have come to refer to as the Singularity, …an impending Singularity that is increasingly transforming every institution and aspect of human life, from sexuality to spirituality*". Defining more concretely the concept he states that "*it is a future period during which the pace of technological change will be so rapid, its impact so deep, that human life will be irreversibly transformed*". For him "*the Singularity will allow us to transcend our biological bodies and brains. We will gain power over our fates. Our immortality will be in our own hands*". The critical date calculated by Kurzweil for the Singularity is 2045. Undoubtedly the works of Vinge and Kurzweil have sparked in some a fervent attitude regarding the 'near future' of humankind, which has been coined as the 'Transhumanistic school'. A possible drawback is that the utopian visions may simply add to the inertia relative to the solving problems myopia that seems apparent for most decision makers around the world.

We do not intend in this chapter to perform an in depth analysis about the dubious and/or positive points of Kurzweil's future world view, for this was already done by four different authors in a special issue of Technological Forecasting and Social Change

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published in 2006 [20]. But considering that a half decade has already passed since the publication of Kurzweil's book, as well as of the publication of the critics in TFSC, we will briefly review in the next section the main points that are of interest for the purposes of the present article.

There have been different approaches to the concept of singularities and for our purposes it will be useful to consider briefly the recent publications of some authors involved in this dialog. For the sake of simplicity of the presentation and not intending to discuss the details of each of the different approaches published in previous years, we present below a listing and summary of the most relevant works related to this issue, with the main objective of understanding the rationale or methodology used for both anticipating a critical technological transition and for how the technological transition affects the socioeconomic realm. In the final part of this section we present a table that summarizes all approaches discussed/presented in Sections 1–3, in which we find a convergence of the dates for some impending transition and/or singularity, beyond which it is impossible to construct any reliable future scenario. Acceleration is the underlying driver of almost all of these approaches, and the predicted transition dates appear to converge to some date within the present century or the beginning of the next.

Listed below are selected works of key authors, each followed by the date of publication and a short summary of the main points of the respective approach:

1 – Laurent Nottale et al., 2000 [21] – Utilizing the fractal mathematics due to Mandlebrot [22] these authors develop a model based upon a fractal tree of the time sequences of major evolutionary leaps at various scales (log-periodic law of acceleration–deceleration). The application of the model to the evolution of western civilization shows evidence of an acceleration in the succession (pattern) of economic crisis/non-crisis, which point to a next crisis in the period 2015–2020, with a critical point $T_c = 2080$. The meaning of T_c in this approach is the limit of the evolutionary capacity of the analyzed group and is biologically analogous with the end of a species and emergence of a new species. While the mathematics and the application to biological evolution have apparently solid grounding, the events and the analogy to civilization are not at all developed in this interesting paper.

2 – Francis Heylighen, 2004–2005 [23,24] – This author speculates that accelerating change will lead to a metasystem transition when a global superorganism will emerge – the "Global Brain" – a system that would integrate the whole of humanity together with all its supporting technologies and most of its surrounding ecosystems, and that would function at a level of intelligence, awareness and complexity that we at present simply cannot imagine. Heylighen should not be thought of as a typical 'singularitarian',[1] for he does not put emphasis either on a sudden transition nor on an exact date for the transition, but rather his emphasis is on the qualitative diffusion-like transition. But he agrees with most 'singularitarians' that such a transition is quite imminent and is likely to happen in the very short term, still in his own lifetime. For him 2040 is a good date, give or take a decade or two.

3 – Jürgen Schmidhuber, 2006 [25] – The time intervals between the most notable events in over 40,000 years or 2^9 lifetimes (80 years to this author) of human history have sped up exponentially, apparently converging to a historic singularity (the Omega point, term coined by Teilhard de Cardin in 1916) to happen about 2040. The author also speculates that such shortening time between past important events may reflect the human capacity to allocate memory space to past events. For instance, events that happened between 2 and 4 lifetimes ago get as much memory space as events in the previous interval of twice the size. In conclusion the author states that "*maybe that's why there has never been a shortage of prophets predicting that the end is near — the important events according to one's view of the past seem to accelerate exponentially*".

4 – William Halal, 2008 [26] – Halal recently conducted the TechCast Project based at George Washington University and at his own company TechCast LCC, using a sophisticated website (www.TechCast.org) that scanned the published technical literature and surveyed 100 high-tech executives, scientists and engineers, academics, consultants and other experts around the world to forecast breakthroughs in all fields. The results were published recently in a short book titled "*Technology's Promise*" [26] showing forecasts for 61 leading technologies organized into seven fields (Energy & Environment, Information Technology, E-Commerce, Manufacturing & Robotics, Medicine & Biogenetics, Transportation and Space). These results and framework constitute probably the most complete forecasting system actually available covering the entire span of technological innovation. Halal is not a 'singularity discusser', and the label may also not apply to any of the 100 experts participating in his survey, for the concept of superhuman intelligence did not come to the fore in the book. In the discussion devoted to the evolution of computational capability, the unfolding of important steps in this field in the near future is foreseen: grid computing (2013), intelligent interface (2014), pervasive networks and virtual education (2015), optical computers (2017), biocomputing (2020), quantum computing (2022), AI (2023) and virtual reality (2027). Curiously other events for IT do not appear after 2027, but events do appear for some of the other fields considered (for example, Medicine, Energy, Transport and Space). At the end of the book, some interesting scenarios are presented: 2010 (The World Online), 2020 (High-Tech Arrives), 2030 (Crisis of Maturity), 2050 (A Global Order Emerges — Age of Consciousness). In the closure to the book, a schematic skewed S-shaped curve is shown and is said to represent the Life Cycle of Evolution, very steep at the end (between 1850 and 2050), suggesting a saturation level about 2050, a time (Age of Consciousness) for a functioning and unified world, able to integrate its efforts to manage the planet. Why the author chooses an S curve and what is being plotted are again ambiguous as in most approaches that show schematic figures.

[1] This term has been used to characterize the adopters of the new meaning of the concept of singularity, see for instance the special issue of IEEE Spectrum [31].

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The next three entries in this list are representative of a new ‘singularity school’, one that involves the new field of econophysics. Contributors to this new school combine the notion of accelerating technology change with economic models that use also the notion of accelerating growth of economic measures.

5 – Anders Johansen and Didier Sornette, 2001 [27] – These authors developed a multivariate analysis coupling the growth dynamics of population, economic output, investment in R&D and technology. Human population and its economic output have grown faster than exponential for most of known history and exhibited growth rates that are compatible with a singularity occurring at the critical time of 2052 ± 10 for both population and economic output; this is taken as signaling an abrupt transition to a new regime. The authors consider in this model that the abruptness of the transition will be smoothed by finite-size effects and friction, further suggesting that we have already entered the transition region to a new regime. They then speculate upon but do not try to answer what the nature of the new regime may be.

6 – Robin Hanson, 1994–1998 [28,29] – The emphasis of Hanson's singularity model is not on machine intelligence, AI, or intelligence explosion, but rather on ‘brain emulation’, brain copies that can be uploaded and reproduce themselves. This would be an unprecedented innovation, considered by Hanson as much more powerful than any other imagined until now by the believers in human–machine intelligence merging. The author presents logical arguments that this innovation would have an impact on the economy many times greater than the simple superhuman machine intelligence. The interesting aspect of Hanson's model is the usage of previous discontinuities like the agricultural and industrial revolutions (and other previous transitions), whose extrapolation of shortening times indicates an expected transition around 2075.

7 – Kay Hamacher, 2005 [30] – This author considers that Kurzweil's approach of accelerated change is based on a coarse-grained scale based solely in measures of computational capability, implicitly assuming that computation alone is feasible of bringing progress. Hamacher proposes a ‘microeconomic approach’ to modeling the accelerated change, considering altogether the power of ‘NBIC convergence’ (nanoscience, biotechnology, information technology and cognitive science), but did not propose a date for a singularity. Instead the paper describes a shortening of ‘time horizons’ for predicting future technological transitions that is presently approaching asymptotically some limit in the near future.

Several other authors and papers could be added to this list, but in our opinion we have in this discussion covered the great majority of significant new insights. For an interesting overview of these other contributions, as well as those from some opponents of the ‘Singularity’ idea we suggest the reader to see the IEEE Spectrum special issue [31] published in June 2008 devoted to this theme.

An important fact is that the discussion of the technological singularity is increasingly conquering space in technological-scientific discussion within the media and within the scientific community. New science fiction stories and/or science fiction speculations involving the hypothesis of superhuman intelligence surfaced in recent years; for example, the recent books from Vernor Vinge, *Rainbows End* [32] and Hugo de Garis' *The Artilect War* [33].

The Belgian physicist and AI expert Hugo de Garis, now at Xiamen University in China, believes that in the very near future human technology will be able to develop ‘Artilects’ (artificial intellects), with intellectual godlike capacities, and that humanity will split into two major ideological camps, one in favor of building artilects (the Cosmists) and those opposed (the Terrans). The ideological disagreements between these two groups on this issue will be so strong that a major ‘artilect war’, killing billions of people (a gigadeath war), will be almost inevitable before the end of the 21st century.

Table 3 abstracts the main concepts and projected dates resulting from the many different approaches to a singularity or an indicated transition published in the last few decades.

5. Revisiting the technological singularity

Until recently, discussion of a possible technological singularity has mostly been restricted to the realm of futures studies. However, this issue is apparently being noticed in other areas including the thinking of decision makers due to its evident importance to development and economic planning. Evidence for its spread is the numerous institutions and web pages devoted to singularity studies including: “The Singularity Institute for Artificial Intelligence” [34], “The Acceleration Watch” [35], and “The Singularity University” [36]. The latter was founded jointly by Peter Diamandis and Ray Kurzweil in November 2008 with the support of a dozen private donors and corporations (among them Google, ePlanet Ventures, Autodesk, Nokia) and is based at the NASA Ames Campus in Silicon Valley.

Undoubtedly “The Singularity University” is a positive output of this recent interest in the idea of a Singularity. It has now the support of a broad range of leaders of academia, business and government, and we hope that it can indeed reach its goal of stimulating groundbreaking, disruptive thinking and solutions aimed at solving some of the planet's most pressing challenges.

The review in the preceding sections demonstrates two key findings:

1. A wide variety of approaches lead to the concept of a major human transition — probably in or before the middle of the current century;
2. None of the approaches – despite their variety – fully escapes the weaknesses of subjectivity concerning events to consider and therefore none of the approaches can be considered well-grounded empirically.

In the remainder of this section, these two points, timing and empirical grounding, will be discussed briefly relative to Vinge's and Kurzweil's work.

In his famous 1993 talk [13] Vinge made the bold statement that “*within* ***thirty years****, we will have the technological means to create superhuman intelligence. Shortly after the human era will be ended*” (bold of our own). We recognize that for an exponential

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Table 3
Projecting the future.

Author (Ref.)(date)	Main concepts	Defining label	Approach	Limit date
Coren [5] (1998)	Information transfer as a measure for evolutionary change. Shortening time spans between critical transitions	Critical transitions	Empirical extrapolation of events	2140
Modis [7] (2002)	Complexity growth as a measure for complexity change. Maximum for complexity growth already attained.	Milestones/complexity jumps	Empirical logistic fit of events	Max. rate of complexity growth in 1990
Hawkins [1] (1983)	Five dramatic mind steps toward shaping the human mind	Mindsteps	Qualitative extrapolation of events, with mathematical projection of geometric series	2053
Marchetti [9]	Slight acceleration in the characteristic time of inventions and innovations bursts	K-waves succession	Empirical logistic fit of inventions/innovations	None, but pointing to some limit in three centuries
Peeters [12] (1979)	Speeding up of progress measured by the time elapsed between discovery and general adoption	Diminishing resistance to progress	Semi-empirical extrapolation of events	2000
Vinge [13] (1993)	Superhuman intelligence through artificial intelligence and intelligence amplification	Technological singularity	Qualitative extrapolation	Before 2030
Moravec [16] (1988)	Superhumanly intelligent robots	Post biological human race	Empirical extrapolation of computer capacity	2030–2040
Kurzweil [17–19] (1990–2005)	Superhuman intelligence. Merging of technology and human intelligence. Universe saturation with intelligent processes and knowledge	Technologically induced transformation of humanity	Empirical extrapolation of computer capacity	2045
Nottale et al. [21] (2000)	Fractal tree of the time sequences of major evolutionary leaps. Acceleration of the succession of crisis/non-crisis	Fractal Evolution	Empirical extrapolation of events	2080
Heylighen [23,24] (2004–2005)	Metasystem transition with the emergence of a global super-organism	Global brain	Qualitative extrapolation	None, but agrees with a transition before 2040
Schimidhuber [25] (2006)	Exponential speed-up of time intervals between most notable events in 40,000 years of human history	Omega point	Semi-empirical extrapolation of events	2040
Halal [26] (2008)	Technological forecasting survey for 61 leading technologies embracing 9 technological fields	Global consciousness	Qualitative extrapolation using S-curve	Global consciousness to be attained around 2050
Johansen-Sornette [27] (2001)	Multivariate analysis coupling the growth dynamics of population and economic output	Growth dynamics	Empirical extrapolation of economic and other measures	2052 ± 10
Hanson [28,29] (1994–1998)	Brain emulation as the most powerful innovation in an economic sense	Brain emulation	Qualitative extrapolation	Transition around 2075
Hamacher [30] (2005)	Microeconomic modeling of accelerated change considering the "NBIC convergence"	Microeconomics of NBIR	Mathematical model	None, but with asymptotically approaching limit for time-horizons. Transition within this century
De Garis [33] (2005)	Development of artificial intellects that will lead humanity to a final confront between two major ideological camps	Artilect war	Qualitative speculation	Giga-death war before the end of this century

(Note: the sequence of the entries in this table is the same as in the text and is not based on its relevance or any other criterion).

process the reality of a prediction is not noticed until very few years before "it" happens. However, the fact that 17 years have already passed certainly leaves room to seriously doubt the prediction. Indeed, in a more recent article [37] published in the already mentioned special issue of Spectrum IEEE [31] Vinge replies to some critics published in the same issue saying that what he really has said is that he would be surprised if the singularity had not happened before 2030. He uses in this piece the language of "ifs" and states his beliefs in a more careful fashion.

Using a not very convincing set of arguments in order to show 'signs of the singularity', as for instance that the Moore's law is still at work and that the world is today far more strongly interconnected, he insists that we are not far away from a future world that passes beyond human ken, becoming intrinsically unintelligible to the likes of us, a "*world seriously strange from the point of view of unenhanced humans*". But the most important aspect in Vinge's new piece is that he now discusses the possibility of a '*soft takeoff*' (or smooth transition in other words) that "*might be as gentle as changes that humanity has encountered in the past*", considering that there have been in human history a number of technological changes (fire, language, reading, mathematics, agriculture, Industrial Revolution), to which we could reasonably apply the term singularity. That is a crucial point that we intend to utilize in this article and that we will develop in the following two sections. Our final point in this section is that Vinge (implicitly) and Kurzweil [explicitly but he also includes progress in some other enabling technologies like genetics-nanotech-robotics (GNR)] base much of their quantitative

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thinking on trends in computational competence. A threshold greater than a single human's computational capability or perhaps the sum of human computational capability is considered the marker for disruption of human society as we know it. Neither considers in any depth the human, social or institutional aspects of the transition despite much prior work pointing to the necessity to do so (for an example, see Ref. [38]). Neither gives any justification of why the disruption predicted might be linked to the thresholds they utilize. In the following section, we consider two events that might be considered as singularities or at least as clear change quite disruptive to human living. We examine how the social transitions relate to the quantitative aspects of technological change in an attempt to clarify if future "singularities" can be forecast from related technical metrics.

6. Investigating technological singularities with some examples

In this paper, we essentially accept the possibility and even probability of an upcoming transition, for this kind of singularity or transition (considering the 'new' meaning of the word) occurring a number of times before. The questions that remain open are how abrupt or soft will be the next transition, and at what level of technical progress will it happen. We will see that these questions are not simply answered by extrapolation through considering briefly some other technology-based advances in human progress.

We will focus in this section on two instances in the human record in which a large scale societal transition was realized: the birth of globalization in the 15th–16th centuries and the evolution of time measurement over the past centuries. Both cases involve a singularity-like transition to a new order and/or a new 'Weltanschaung' with significant impact on the world system construction. We choose these two cases to demonstrate conceptually how two kinds of metrics for technological progress can illuminate transitions of importance. These two kinds of metrics have been utilized by "singularitarians" (and "anti-singularitarians") but typically without enough differentiation so it is important to consider both to minimize possible uncertainties in our findings. The globalization case involves a *metric* that reflects the spreading or *diffusion* of a related set of developing technologies and such metrics have clear limits and have been fairly generally shown to follow a logistic curve [39]. Time measurement directly involves the technological capability involved with the accuracy of clocks and thus is a *technological capability metric*. Technological capability metrics generally follow exponential or hyper-exponential curves [40,41] and can even potentially contain their own singularity.

6.1. The onset of globalization

At the dawn of the 15th century the Portuguese paved the way to a very important transition in the formation of the modern world system by establishing the basis of the first global network together with instruments of global reach and initiated the debut in the rush toward a globalized world, and hence the onset of globalization [42,43]. The Portuguese saga in the Atlantic and Indian oceans, and what has been called the Age of Discoveries, was an endeavor not only strongly based on empiricism but also was marked by the introduction of several very important technological and scientific innovations as demonstrated by Devezas and Modelski [42].

In the first quarter of the 15th century, initiatives were set in motion by Prince Henry initiating a dialog with experts, scholars, and scientists from other parts of the world, and in this way creating for the first time a kind of think tank (some call it the School of Sagres, although its real physical existence is in dispute). This was soon followed in the early 1480s by the initiative of King John II who convened a scientific commission to seek improved methods for measuring the '*altura*' (the height above the horizon of the sun or a star) that resulted in a written text called the '*Regimento do Astrolábioi e do Quadrante*' and led to expeditions in the Atlantic Ocean and down the African coast, with the sole intention of elaborating precise tables to convert the *altura* to latitude, as well as to ascertain the exact latitudes of important coastal features. During this time the Portuguese evolved quickly their (and the world's) sailing-ship capability, introducing the lateen-rigged caravel (1420s), the Nau (great ship, 1490s) and the galleon (1510s), as well as (the most important and decisive step) very robust decks to carry a collection of deck-mounted heavy cast bronze cannons. Accompanying all these innovations were the accelerated developments in cartography and the usage of navigation instruments (quadrant, astrolabe, etc…), to which Portuguese (and foreign experts attracted to Portugal) artisans and craftsman contributed significantly.

The innovations just described enabled the Portuguese within a time span of less than a century to master an immense ocean surface in the Atlantic and Indian oceans. This was supported by a network of coastal bases and patrol fleets that constituted by itself a very important geopolitical innovation: that of an ocean wide maritime Empire, instead of the millennia-old concept of continental empire. Importantly, such ocean-wide dominance was the unplanned result (as is usual in technological advancement) of another innovation introduced by the Portuguese – this time in operation procedures – necessary for the successful working of the caravel in its southwesterly enterprise along the Atlantic coast of Africa.

The major problem that Portuguese sailors faced after turning past Cape Bojador, the classic point of no return, was how to come back to Lisbon or Algarve, sailing against the winds and the strong Canaries current, or in other words, how to return home using the same route along the coastal line. At some unrecorded point, Portuguese sailors developed a technical navigation 'trick' that consisted in putting to good use the adverse Atlantic winds and currents by beating out their caravels to seaward, away from the Moroccan coast, heading first northwesterly and then taking a more northerly course until the westerlies and North Atlantic drift were encountered, making it possible to head east in the direction of the Portuguese coast. As the route along the Atlantic African coast went further south, the circle (the 'volta' in Portuguese) necessary to come back to Lisbon or Algarve increased in size. In some history books this 'volta' is sometimes referred as the 'volta da Mina' or 'volta da Guine', but the last seems to have been developed later as a route sailing round the Cape Verde Islands. Undoubtedly it was this navigation trick that allowed the Portuguese to be the first navigators to master most of the Atlantic Ocean, first southwards and then also northwards. As a consequence it was possible for a Portuguese ship to touch the

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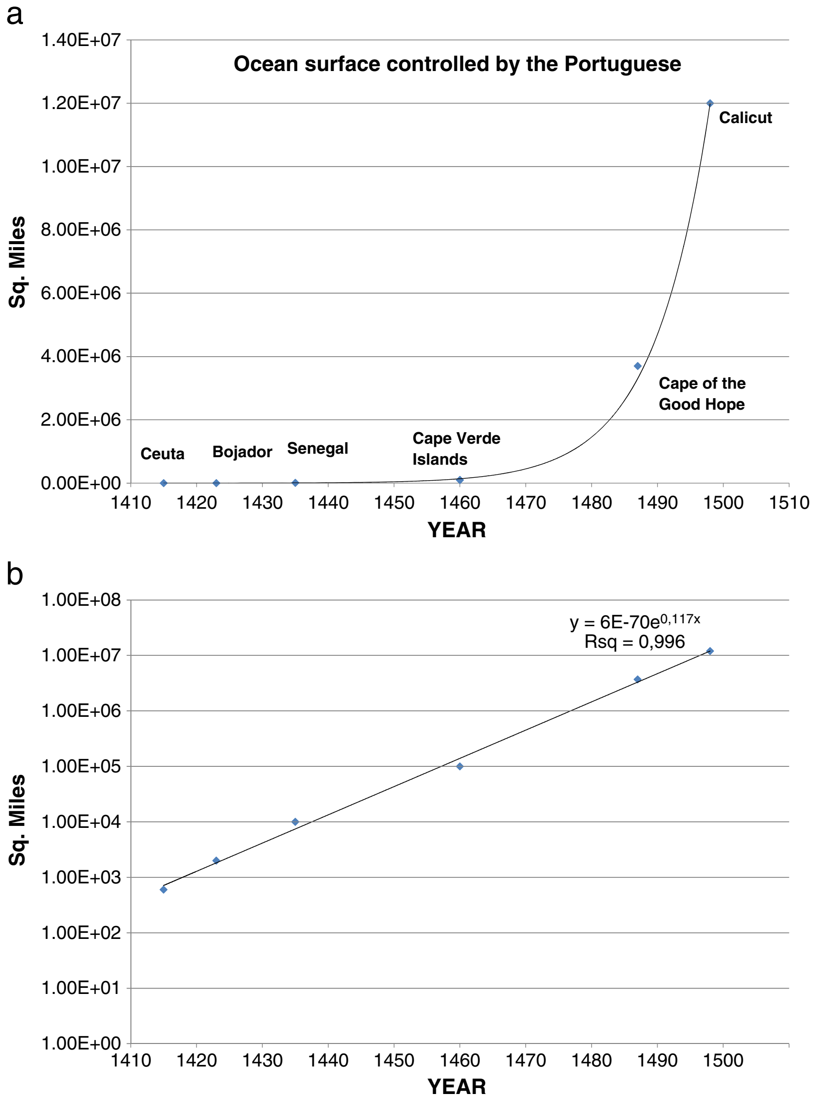

Fig. 1. a-Spike-like growth of the ocean surface accessed/controlled by the Portuguese in the 15th century. b-Straight line fit (semi-log plot) of the ocean surface accessed/controlled by the Portuguese in the 15th century.

coast of Brazil and then heading eastwards to the tip of South Africa and reach the shores of India. That happened in 1500, only 65 years after crossing the point of no return (Bojador).

Considering the evolution in water surface harnessed by the Portuguese in this short time span we can construct a graph that shows the spike-like growth of this measure, pointing to a water surface area bigger than the sum of all oceans on Earth well before 1520, as shown in Fig. 1a and b. The straight line fit in Fig. 1b is a superb fit. We can imagine the hypothetical scene of a mathematician of King Manuel I court's showing to his king such a graphical representation and forecasting his possession of most planetary waters in the next two decades.

Such possession did not happen (but was not very far from it when the Portuguese reached Japan in the 1540s) for various reasons. Nonetheless, world commerce and geopolitics dramatically changed in the early part of the sixteenth century and even the basic human conception of the Earth's geography changed drastically. This is the essence of the critical transition of naval globalization but how does it relate to the innovations and to the metrics in Fig. 1? We note that most of the important innovations were well before the hyper-exponential in Fig. 1 took off so predicting accelerated metric advance from innovation data is questionable. Similarly, it is difficult to see how mathematical extrapolation of Fig. 1 helps in pinpointing dates for societal change. More significantly, the societal changes and human re-conceptualization that trailed the innovations were not continued most strongly in Portugal but elsewhere in Europe. Thus, even if we consider the technical advances made by the Portuguese in this period in some sense inevitable, the nature of the societal changes (maritime empires, the rise of Europe relative to Asia, discovery of new Continents by Europeans, etc.) was clearly not inevitable.

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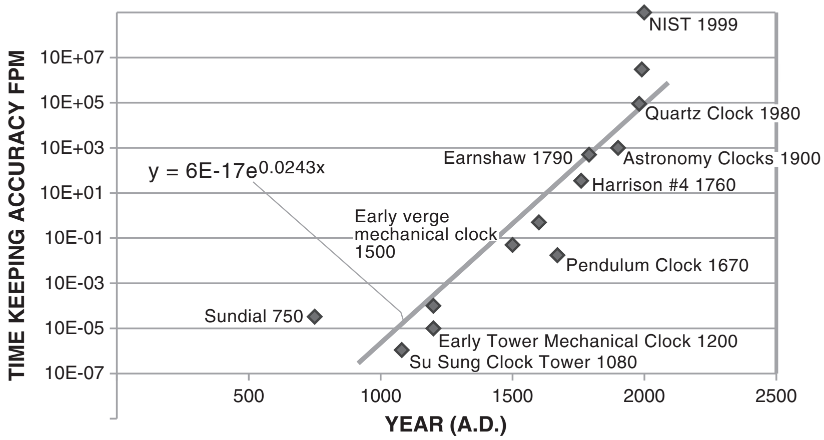

Fig. 2. Technical progress from years 800 to 2000 for the function of time keeping expressed as exponential of 1/drift (accuracy) divided by volume, to adjust for clock size. These results and figure are adapted from reference (43) where the unlabeled points are named.

6.2. Accuracy of time measurement

In the previous case, we could further imagine the mathematician in King Manuel's court projecting Fig. 1 for 200 or more years and the extent of the ocean controlled by the Portuguese would have been far greater than the size of the earth. This is of course nonsense but the point is important because many adopters (and opponents) of the 'Singularity' idea do not differentiate between capability and usage (or diffusion) and sometimes seem to assume that *both* (*or neither*) can go on exponentially or hyper-exponentially forever. In the case considered here, we explore how a hyper-exponential increase in capability without apparent limit impacts societal change. Capability changes – unlike usage or diffusion – often show no limit and are hyper-exponential and many speculations about singularities revolve around such metrics [Moore's Law is an example but there are many more—see Koh and Magee [40,41].

Fig. 2 plots a significant capability metric relative to time-keeping over approximately the last 1000 years [44]. The metric assesses time keeping accuracy (1/inaccuracy) divided by the volume occupied by the timepiece in question. It is important to divide by volume because the accuracy of clocks can almost always be improved by simply making them bigger but this is often not of practical use. Indeed, getting accurate clocks that were small enough for all of us to carry on our person was one key to societal change. Overall, these kinds of tradeoff metrics are always more meaningful [40] than simple metrics such as accuracy.

In the case of Fig. 2, we first note the tremendous change in the metric (more than 14 orders of magnitude over the thousand year period). We also see that the progress is generally exponential with clear evidence in the last century of accelerating improvement in capability — thus we have a hyper exponential with indications for a singularity occurring now (or very soon). However, let us examine the impact of time keeping accuracy on societal change.

The enormous social and human changes brought about by improved time-keeping happened in the 17th, 18th (navigation), 19th and early 20th centuries as explained in Landes' classic book *Revolution in Time* [45]. This was when clocks first became accurate enough to establish work times, and even eventually to allow individuals to carry small watches with minute hand accuracy. This allowed all of us to first move from sun-time and its inherent inaccuracy eventually to where some people schedule their time down to minutes and many of us are basically on at least an hourly schedule. Of course, for some this "going on the clock" that was enabled by the tremendous inventions that underlie Fig. 2 was not entirely positive (as is often the case with technically enabled social change). For the purposes of this paper, it is important to explore questions associated with the singularity.

The first of these questions is — what are the impacts of the more recent hyperbolic changes – see Fig. 2 for the past 40 years – in time-keeping technological capability? The recent radical change in the metric has minimal societal impact because the capability (quartz oscillators and beyond) allows much smaller timekeeping devices but the size of the display dial as dictated by human vision soon reached a minimum below which increased capability of time-keeping was moot. Moreover, the more recent immense increase in accuracy of atomic clocks is of a magnitude far beyond what anyone needs, except for a few research astronomers. In fact, many of us now carry a hand-held device that can allow us to wirelessly access the most accurate clocks in the world so carrying an accurate time-piece has been superseded by totally different and new technology on its own journey through exponential increases in capability.

The second singularity related question is — what was the nature of the transitions as clock accuracy improved? There were profound changes in how people worked and lived as detailed by Landes. These large changes were absorbed over time apparently without major disruption; for example, no mention is made of "clock riots" even though there was resistance and adaptation was needed. In given communities, the large changes apparently happened within less than a generation.

This case demonstrates two important points for our overall discussion of singularities in this paper. First, rapid and accelerating technical change can result in profound societal change but it is not at all necessary or expected that these societal changes will occur at the time of most rapid improvement in capability. Indeed, no extrapolation of the metric is sufficient for prediction of the major societal change. This is partly because capability beyond what most humans can utilize does not easily result in social change. The second point is that large societal change occurring even in a regime of very rapid technological change can occur fairly smoothly as the adaptive capability of humans is immense.

Thus, it appears that people living through a 'Singularity' do not necessarily experience it as profound and rapid change. It is logical that subjective time speeds up until the rate of progress is merely fast for the inhabitants of the social realm experiencing the change, not as superfast as an observer on the outside and particularly from another time might perceive it. The evidence from these two cases suggests that singularities are not apparent to those who live through them.

7. Conclusions and implications

In this section, we integrate the previous sections and address two particular points further. First, we will return to the conceptual framework about what is meant in general by the term singularity as applied to technologically-induced major societal transformation. In this context, we will discuss our findings from study of past singularities. Secondly, we will discuss possible upcoming transitions ("singularities") while speculating about the relationship of ever increasing computational capability to such transitions.

Because of the friction and size effects discussed by Johansen and Sornette [27], it seems doubtful that a mathematically rigorous singularity can occur for the case of technological change. Thus the generalization of the singularity concept to technologically driven broad-scope societal change suggested by recent writing on future events is quite logical. In fact, we used this framework to examine two previous singularities. In declaring any past event a singularity, we begin to move into the same subjectivity as others who discuss this topic but we feel at this point that such subjectivity is still necessary to proceed. We can only hope that more objective means for determining social rates of change and transitions of sufficient magnitude to qualify as singularities will be developed in the future. By identifying previous technological singularities, it becomes possible to use historical analysis to at least tentatively begin to be objective about the characteristics of disruptive transitions in society that are driven by technological progress. It appears to us that the transitions discussed by Hawkins as mind-steps as well as the Industrial Revolution are outstanding candidates to include on a consensus list of singularities and thus they might be subjected to an analysis similar to that we covered in Section 5.

The two cases we examined in Section 5 involve metrics that come from two very different classes of the measures used to quantitatively assess technological change. The basic curves that are associated with diffusion (logistic) and technological capability (usually hyper exponential) are quite different. Our major conclusions from these cases are treated as working hypotheses for the remainder of this discussion partly because they are at least robust to which kind of metric is under consideration. The three major findings are:

- People undergoing profound societal change do not sense a singularity.
- The societal impacts depend in complicated ways on human needs, institutional variables and other more uncertain factors and thus are particularly hard to project.
- The societal impact is apparently not determined by the rate of progress on either type of metric or by projections to mathematical points with either kind of metric.

They are only working hypotheses because a more objective way of assessing societal impact is still in the future for future studies. With this development and study of many more cases, one could begin to be assured that we really have a stable basis for analysis of future singularities. Nonetheless, we proceed to speculatively discuss such future events utilizing the findings from our two cases.

As noted previously in this paper, many of the writers forecasting profound societal change in this century point to the ever-rising computation capability as the (or a) major driver. Computation capability is generally important but perhaps the sharp focus on this area has arisen because of the great awareness of rapid progress in this area as heralded by Moore's Law. The fact that such exponential progress is quite general in technological capability progress (at various rates of change but some are at an even greater rate than for the number of chips on a die for IC) raises the question whether this particular technological capability is in fact the critical driver of everything else. If we consider such potentially important technologies as augmented reality, realistic artificial travel and others, computation capability is clearly one enabler but one can reasonably doubt whether it is sufficient by itself to fully achieve these technologies at a level sufficient to drive profound societal change. For a computation capability driven singularity (and for any other) we need to at least consider three questions:

1. What human benefits come from the increases in capability and/or diffusion?
2. What is the timing of the societal transition and what is the basis of the prediction?
3. How quickly is the transition going to occur? Is it likely to be so quick that our finding from our cases (people in singularities do not recognize them) is overthrown?

In regard to question 1, it seems possible that the major benefits of increasing computation capability to individual humans may have already been realized. However, even if this is true (and it is not proven at all), increased computation might enable analysis to support design of very different devices that do have significant human benefit. On the other hand, the leading application of the highest computational capability today seems to be in video games and while this may lead in directions of higher societal impact, such speculation is also not proven at all. It is evident to us that the tremendous increase in another functional area (information storage as measured by information stored per unit volume or per dollar — see Ref. [40]) has gone past obvious utility to many of us. More storage on thumb drives (and many other portable devices) seems unnecessary for most users, cheaper thumb drives are going to be limited by logistic costs not memory cost and smaller thumb drives may well be of low value because they may be even easier to lose.

In regard to question 2, the projections of dates for the societal transition made by prior writers are often set at the date when extrapolated artificial computational capability is greater than single or groups of estimated human computational capability. This has

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the merit of being a fundamentally objective criterion; however, the correspondence between computational capability and the human brain is less than complete. For example, recent research on group intelligence [46] shows no correlation with individual maximum or average intelligence in the group but instead is strongly determined by social intelligence and group processes such as fairness in allocating time for speaking within the group.[2] Emotion, lifetime experience, adaptive capability, knowledge embodiment and other non-computational capabilities play strong roles in human learning, decision-making and creativity. Therefore, the calculated threshold – to us – appears far from convincing as a marker for extremely profound societal change. Indeed, there is not a guarantee that Artificial Intelligence (AI) will ever fully match human brainpower and thus computers may still be in a human assistance role long into the future independent of computational capability.

In regard to question 3, we have just argued about the ambiguous foundation for the timing of the hypothesized transition (singularity). Ignoring this and assuming a strong transition is yet to come, there are reasons to question whether increasing computation capability will lead to a particularly sharp or quick societal transition. One such reason is that computation (and other information technology) is already delivering significant benefits from AI in lots of computer programs and machine applications. Moreover, Google and others are pushing to deliver much more AI impact in the near term which means that any impact of AI is sure to spread over a fairly long time frame. A second reason for a probably long transition due to computation (and IT generally) is that when human brainpower is closer to being "matched", it seems highly unlikely that the research to achieve the deep understanding needed to support "matching humans"[3] will all come to a conclusion in a short period of time. Some of the problems with "matching" (AI containing emotional input, group and social effects, the diversity of knowledge and experience in human groups) are different enough to make it unreasonable to assume simultaneous solutions in a short period of time. Solutions to any of these before others are solved will lead to earlier as well as delayed applications thus spreading further the transition time. Overall, it appears to us that computation capability and even more broadly, information technology, are already having a profound impact on how humans live and there is more to come with no doubt. However, it seems just as likely that the major effects are just now occurring as it is that they will occur in 30 years or so (we remind the reader that those living through singularities do not sense them). The possibility of a major singularity due to computational capability in 30 years certainly cannot be dismissed but it – in our opinion – appears improbable. But does this mean we are predicting a technologically calm 21st century with no major societal change? Our answer is certainly *no*.

Singularities (defined as technologically-driven major societal changes) are almost surely coming in the present century but these may not rely on computational capability. An important example is life extension. Significant changes in life expectancy have already occurred and are just beginning to receive attention — much more attention is needed as the societal impacts are huge. As the rate of life expectancy increase accelerates – as it may well – even larger effects will occur but the main effect could easily occur well before humans begin to live to shocking levels such as reaching 1000 years and more lifespan. Indeed it is possible that the approximate doubling of lifespan over the past 150 years — or in much less time for later longevity achieving countries such as some in Asia [47] has been the opening of this important transition. We again note that those living through singularities do not perceive them and if we are within a "double singularity", we may not be able to objectively perceive that either.

A second example of a non-computation driven singularity that may be in the present century is the rapid evolution away from the fossil fuels that have driven much economic growth since the Industrial Revolution. It is possible that we are also living through the beginnings of this transition as already pointed out by the study of Devezas et al. [48], whose extrapolations of the actual trends in the exploration of primary energy sources, considering "efficiency" as the most significant technological factor in the modern energy usage, point to a share for alternative energy sources (carbon free) of about 75% in 2075. An even faster transition is possible with recent accelerations in applications of solar PVs. Such a transition would have enormous implications to global income distribution and to many other aspects of human life but the timing for the major societal changes is not clear even if we are confident about prediction of the timing of the technological parameters. For example, if we are confident about when energy from solar PVs becomes less costly than energy from fossil fuels, this time does not determine the transition of high speed transport to renewable energy. Moreover, the full societal transition – even with perfect knowledge of the driving technical change – is not yet predictable as far as our review of the cases from the past has shown.

Acknowledgments

The authors wish to thank the members and leadership of MIT's Engineering Systems Division (ESD) for support during the research. Professor Magee is grateful for the support of the International Design Center of SUTD/MIT. Professor Devezas additionally thanks Professor Magee for the kind invitation and opportunity to stay with the ESD staff during his sabbatical license from the University of Beira Interior. Tessaleno Devezas is also indebted to the Fundação de Ciência e Tecnologia (Portugal) for funding his sabbatical during this period.

[2] Group processes are generally recognized as fundamental to human creativity.

[3] We have placed "matching" in quotes because – as noted in addressing question 2 – considering all aspects of human wisdom (social, emotional, knowledge diversity, etc.) as somehow reducible to any particular combination of technical metrics is not logical.

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Please cite this article as: C.L. Magee, T.C. Devezas, How many singularities are near and how will they disrupt human history?, Technol. Forecast. Soc. Change (2011), doi:10.1016/j.techfore.2011.07.013