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Ray Kurzweil's book *The Singularity Is Near* dragged me back into a subject that I am familiar with. In fact, ten years ago I thought I was the first to have discovered it only to find out later that a whole cult with increasing number of followers was growing around it. I took my distance from them because at the time they sounded nonscientific. I published on my own adhering to a strictly scientific approach. But to my surprise the respected BBC television show *HORIZON* that became interested in making a program around this subject found even my publications "too speculative." In any case, for the BBC scientists the word singularity is reserved for mathematical functions and phenomena such as the big bang.

Kurzweil's book constitutes a most exhaustive compilation of "singularitarian" arguments and one of the most serious publications on the subject. And yet to me it still sounds nonscientific. Granted, the names of many renowned scientists appear prominently throughout the book, but they are generally quoted on some fundamental truth other than the direct endorsement of the so-called singularity. For

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example, Douglas Hofstadter is quoted to have mused that "it could be simply an accident of fate that our brains are too weak to understand themselves." Not exactly what Kurzweil says. Even what seems to give direct support to Kurzweil's thesis, the following quote by the celebrated information theorist John von Neumann "the ever accelerating process of technology. . .gives the appearance of approaching some essential singularity" is significantly different from saying "the singularity is near." Neumann's comment strongly hints at an illusion whereas Kurzweil's presents a far-fetched forecast as a fact.

What I want to say is that Kurzweil and the singularitarians are indulging in some sort of para-science, which differs from real science in matters of methodology and rigor. They tend to overlook rigorous scientific practices such as focusing on natural laws, giving precise definitions, verifying the data meticulously, and estimating the uncertainties. Below I list a number of scientific wrongdoings in Kurzweil's book. I try to rectify some of them in order to properly present my critique of the Singularity concept.

1. On scientific rigor

1.1. The goodness of the exponential fits

At the risk of sounding pedantic I want to point out that the correlation coefficient R^2 — which Kurzweil displays as a stamp of quality control on all his exponential fits — does not provide unequivocal evidence that a certain theoretical curve best fits a given set of data. This is demonstrated in Fig. 1 where the correlation coefficient between the data points and the gray line is maximal, i.e., $R^2 = 1.000$, but it is obvious that the line constitutes a very poor fit for the data trend.

> A much better figure of merit for the quality of fits is a simple sum of differences squared or the more sophisticated chi-square per degree of freedom.

Kurzweil's fits are no more convincing for the R^2 values he displays on them.

1.2. The reliability of the data

All the data for the graphs of Chapter One, which play a crucial role in Kurzweil's introduction of the subject, come from two articles of mine [1,2]. The data consist of fourteen sets of milestones in the

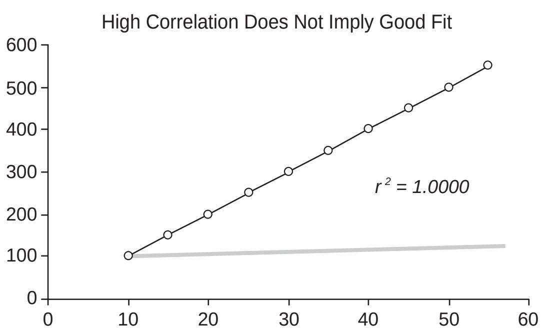

Fig. 1. For two significantly different trends (a steeply rising one and a practically horizontal one) the correlation coefficient can be 100%.

evolution of the universe, which I researched. But while I strived for the data to come from independent sources I did not succeed very well. Two sets were not independent and I made that clear in my articles. One set had been given to me without dates and I introduce them myself; the other set consisted of my own guesses. Both sets were heavily biased by the other twelve sets in my disposal. Moreover, some data were simply weak by their origin (e.g., an assignment post on the Internet by a biology professor for his class, which is no longer accessible today).

As a matter of fact only one data set (Sagan's Cosmic calendar) covers the entire range (big bang to Internet) with dates. A second complete set (by Nobel Laureate Boyer) was provided to me without dates. All the other data sets coming from various disciplines covered only restricted time windows of the overall timeframe, which results in uneven weights for the importance of the milestones as each specialist focused on his or her discipline.

Any hard-core scientist would try to double-check the quality of the data that support his or her central thesis and/or estimate the uncertainties involved. Kurzweil does neither. Instead he augments the number of data sets by one adding the set from my second publication — which is the average of 13 of the previous data sets — and thus boasts evidence from 15 *independent* sources!

1.3. Adherence to natural laws

Kurzweil is possessed by the exponential function. He criticizes people who make forecasts by simply extrapolating straight lines on linear trends. But he does the very same thing on logarithmic paper.

Naiveté is not associated with the graph paper being linear or logarithmic. Kurzweil's wrongdoing is relying on mathematical functions rather than on natural laws. The exponential function represents only part of a natural law. Nothing in nature follows a pure exponential. All natural growth follows the logistic function, which indeed can be approximated by an exponential in its early stages. Explosions may seem exponential but even they, at a closer look, display well-defined phases of beginning, maturity, and end, the integral of which yields a logistic. Explosions can be described from beginning to end far more accurately by a logistic — albeit a sharply rising one — than by a pure exponential.

As for his double exponential, it corresponds to reality even less than a simple exponential. Kurzweil observes double exponentials only when he divides by the price, for example "calculations per second per $1000." He obtains a double exponential because he is dividing two logistics. One is the increase in processor performance (page 64) and the other is the decrease in processor cost (page 62). However, mathematically the ratio of two logistics is not necessarily a double exponential. It can easily yield a pattern growing less aggressively than a simple exponential depending on the parameters of the two logistics.

Why then Kurzweil feels confident that the double exponential will continue for a long time to come? It is an assumption as naïve as that of extrapolating a straight line. A pattern can be used to make forecasts only as long as it represents a natural law that guarantees invariability. The law here is logistic growth and the ratio should be taken only after the two logistics have been estimated.

Another manifestation of sloppiness is Kurzweil's discussion of the "knee" of an exponential curve, the stage at which an exponential begins to become explosive, see Pages 9 in the book.

It is impossible to define such a knee in a rigorous way because of the subjective aspect of the word "explosive." Fig. 2 displays four sections of the *same* exponential function. On graph (a) at the top the knee could well be at time = 70 but as we look closer it progressively moves down to time = 7 in graph (d) at the bottom. It is still the same exponential function with the vertical scale expanded.

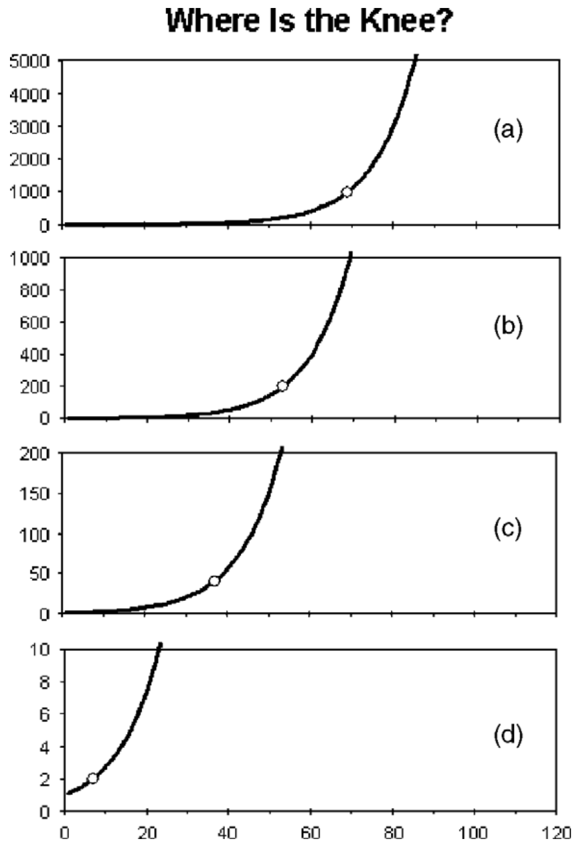

Fig. 2. The same exponential is displayed with different vertical scales. Kurzweil's knee can be positioned anywhere depending on the perception of the observer at the time.

There is no way to single out a particular region on an exponential curve because the pattern has no intricate structure. It is basically a one-parameter mathematical function that varies continually and identically from $-\infty$ to $+\infty$. It always grows at the same percentage rate. In contrast, the S-curve has a ceiling and a center point, which can be used as reference points.

Kurzweil's knee depends on the judgment of the observer, namely that the curve attained a *relatively* high value. The knee can be defined as a threshold, an absolute level characterized as *high* by the majority of observers. This is clearly a source of bias.

2. Where are we on the curve?

Toward the end of his book Kurzweil addresses the question of logistic growth. In fact he admits that there are always limits and that even his exponential growth curves will eventually turn into S-curves, but this will happen very long time from now. So he stops there, closes the S-curve topic, and goes back to his discussion of the exponentials.

It seems to me that the obvious question for any scientifically inclined mind would be "if we know there is an S-curve, can we defined more rigorously our position on the curve given that S-curves have reference points." In other words, instead of saying that we are at a point "very high" with respect to where we have been, but "very low" with respect to where we are going — exponential knee — we can now estimate how far is the ceiling of the corresponding logistic?

One way to do this (besides fitting the data to a logistic) would be to establish a relationship between the level of the exponential knee and the level of the logistic ceiling from well-documented and universally accepted cases. For example, how long did it take to populate the earth from the time a population explosion was first noticed?

Three such cases are presented below.

2.1. World population

World population has grown significantly during the 20th century during which it traced an archetypical logistic growth pattern, see Fig. 3. Its evolution during the early decades depicts an exponential pattern, which later becomes an S-curve as expected. The deviation from the exponential begins in the 1970s.

The crucial question is where is Kurzweil's knee. We can translate the question as "when did the population explosion begin?" I believe it was right after WWII around 1950 when world population reached 2.5 billion, as indicated by the big circle on Fig. 3.

The data are of good quality and come from a reliable source [3]. The logistic fit is excellent, as can be appreciated by simple inspection. The final ceiling is forecasted at 9 billion and this number is generally accepted by most experts including Kurzweil.

It then becomes evident that the exponential knee occurred when world population reached 28% of its final ceiling.

However, by some historians the population explosion began in the West, around the middle of the 17th century. The number of people in the world had grown from about 150 million at the time of Christ to somewhere around 700 million in the middle of the 17th century. But then the rate of growth increased dramatically to reach 1.2 billion by 1850.

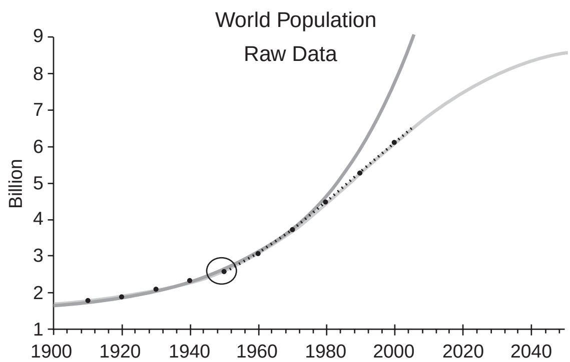

Fig. 3. An exponential (dark gray line) and a logistic (light gray line) fit on world-population data. The graph focuses on the 20th century during which we have accurate and detailed data (yearly numbers from 1950 onward). The logistic fit is exemplary. The circle indicates what in my opinion could be taken as the exponential curve's knee.

In this case the exponential knee would have occurred when world population reached 8% of its final ceiling.

2.2. Oil production

A completely different growth process, oil production in the US, can also help us establish a relationship between the knee threshold and the ceiling. Oil began being produced commercially in 1859, but production picked up significantly only in the early twentieth century. Cumulative oil production in the US turned out to be a smooth process that followed the logistic growth pattern extremely closely. The logistic fit is excellent, see Fig. 4.

The knee as shown represents 10% of the ceiling.

2.3. Moore's Law

The celebrated Moore's Law is a growth process that has been evolving along an exponential growth pattern for four decades. The number of transistors in Intel microprocessors has doubled every two years since the early 1970s. But it is now unanimously expected that the growth pattern will eventually turn into an S-curve and reach a ceiling. On page 63 of his book Kurzweil claims that Moore's Law is one of the many technological exponential trends whose knee we are approaching. But he also agrees that Moore's law will reach the end of its S-curve before 2020.

Moore himself says that "sometime in the next several years we get to some finite limits, but not before we get through five generations." According to one study, the physical limitations could be reached by 2017.

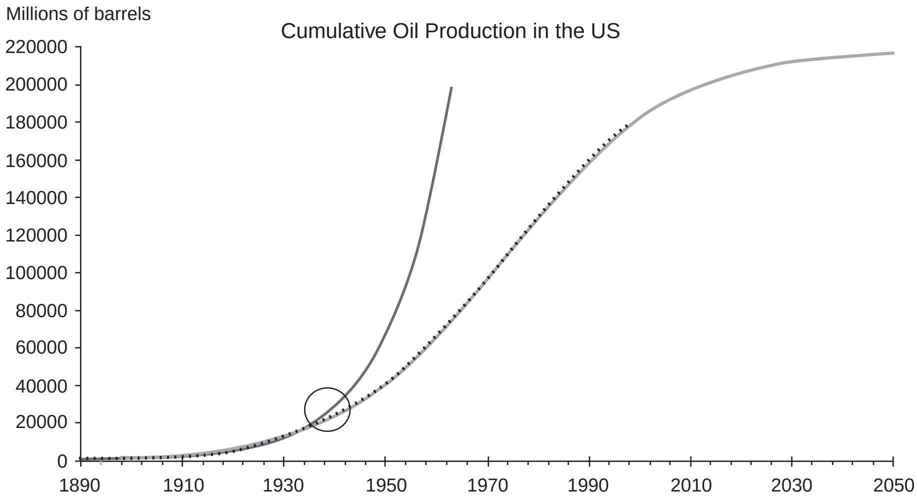

Fig. 4. Yearly data points (small dots) are fitted with exponential (dark gray line) and logistic (light gray line) functions. The data and the logistic fit are taken from my book *Predictions — 10 Years Later* [4]. The circle indicates a reasonable position for Kurzweil's knee.

Given that we are dealing with an S-curve, the slowing down in speed improvement must be gradual so that five generations may bring an overall increase with respect to today's numbers by a factor smaller than $2^5 = 32$. But even if the factor is around 30, the position of the exponential knee translates to around 3% of the S-curve's ceiling.

Based on the above three examples we can say that the knee of the exponential curve tends to occur at a threshold situated between 3% and 28% of the ceiling of the corresponding S-curve. This translates to a factor smaller than 30 between the level of the knee and the final ceiling. This factor is less than two orders of magnitude and has been estimated rather generously.

Let us then apply this knowledge to Kurzweil's exponentials.

3. On the singularity

Armed with the knowledge that all exponentials will eventually turn into logistics and that the exponential knee generally occurs at the level of a few percent of the ceiling let us confront some of Kurzweil's predictions.

3.1. Supercomputer power

From the graph on page 71 of Kurzweil's book and assuming that the exponential trend will continue until 2045 (which I personally doubt) we find that computer power will reach 6×10^{23} Flops (floating-point operations per second) at "singularity time." But from 2045 onward and until computer power reaches a final ceiling, there must be further growth of less than two orders of magnitude. This translates to an *ultimate* computer power of less than 10^{25} Flops, which is in flagrant contradiction with Kurzweil's forecast of 10^{50} and beyond!

3.2. The time to the next evolutionary milestone

In my article "Forecasting the Growth of Complexity and Change" I related complexity to the inverse of the time intervals between evolutionary milestones. Kurzweil points out that this is not always true because while the time to the next milestone has been steadily decreasing complexity did not always increase. There have been occasional decreases in complexity between milestones, e.g., the mass extinctions.

I agree that immediately after a mass extinction the world's complexity may seem reduced, but it is also true that the fundamental change produced by a mass extinction gives rise to all kinds of new mutations and species. By the next evolutionary milestone the complexity of the world is higher than it was before the catastrophic event.

In any case, whether one talks about complexity increase or its inverse, i.e., the decreasing time interval between evolutionary milestones, one deals with a growth process that seems exponential (as a function of milestone number) from the very beginning, i.e., the big bang. But like all natural-growth processes it will certainly turn into an S-curve sometime in the future.

And here again we are facing the same question. Will the process continue along its exponential path sufficiently long to "explode" (tantamount to a singularity) or will it turn into an S-curve sooner rather than later? In my articles I argued in favor of the latter and not only because the quality of the S-curve fit was a little better than the exponential one (there are too many uncertainties involved to take these fits seriously).

But let us approach the same question via Kurzweil's knee. He says that we happen to be around the knee of the exponential curve at present. The ceiling then of the corresponding S-curve should be less than two orders of magnitude higher (or two orders of magnitude lower if we are dealing with an upside-down S-curve—time to next event is getting smaller).

This places the midpoint of the S-curve at the 4th future milestone (canonical number #32). Future milestones will keep appearing at shorter and shorter time intervals but not indefinitely. The 1st future milestone should be in 13.4 years from Internet's time (taken as 1995). By the 4th future milestone (25 years from Internet's time) there will be a new milestone every half a year. But from then onward the frequency of milestone appearance will begin to slowdown. My logistic fit had positioned the midpoint of the S-curve at canonical milestone #27 implying an immediate beginning of the slowdown, and the 1st future milestone in 38 years from 1995. The two estimates are in good agreement considering the crudeness of the methods. But they are both in violent disagreement with a singularity condition such as Kurzweil describes.

3.3. Acceleration in general

Kurzweil positions the singularity in the year 2045. This is strongly dependent on the evolution of the performance of computational power, see earlier discussion. But independently of the earlier discussion, and if we make it to year 2045 at all, given that this date corresponds to the ultimate "knee" of the overall runaway exponential trend, one should expect a further increase in acceleration of no more than an additional factor of less than 100.

This factor of 100 is the upper limit of what should be expected for all trends that display an exponential "knee."

4. In summary

- All exponential curves that represent a real growth process constitute part of some logistic curve.
- The "knee" of an exponential curve defined as "the stage at which the pattern begins to appear explosive" represents a threshold of the order of at least few percent of the corresponding S-curve ceiling. Consequently, between the level of the exponential knee and the level of the ceiling of the S-curve there is a factor of less than 100.
- Evolutionary milestones, as we perceive them today, will at some point begin to appear less and less frequently. This point in time is most likely between now and year 2045.
- Despite an impressive amount of technological progress still remaining to be achieved, there is no convincing argument that a singularity of the Kurzweil type will ever take place.

5. My comments

Scientific sloppiness is a contradiction in terms. Kurzweil and the singularitarians are more believers than they are scientists. Kurzweil recounts how he agreed with a Nobel Laureate during a meeting, but I suspect that there is no Nobel Laureate who would agree with Kurzweil's thesis. The #1 endorsement on the back cover of his book comes from Bill Gates whose scientific credentials stop at college dropout in junior year.

One Nobel Laureate, Paul D. Boyer — whose data Kurzweil uses when he makes his central point — has anticipated two future milestones very different from Kurzweil's. Boyer's 1st future milestone is "Human activities devastate species and the environment," and the 2nd is "Humans disappear; geological forces and evolution continue." I estimated above that the next milestone should be between 13.4 and 38 years from 1995. I suspect that there are many hard-core scientists who would agree with Boyer's first milestone and my time estimates.

One could argue that Boyer is acting himself as a believer rather than a scientist in this case, and could be right. But Boyer does not go on to write a 650-page book on the subject. Maybe because it simply wouldn't sell!

I must admit that I did not read Kurzweil's book to the end. Around page 150 I got fed up and stopped. There is a large collection of facts and references in this book and from this point of view the book merits a place in one's library. But as science fiction goes, even realistic one like Kurzweil's, I prefer more literary prose with plot, romance, and less of this science.

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