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Forecasting the growth of complexity and change

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Abstract

In the spirit of punctuated equilibrium, complexity is quantified relatively in terms of the spacing between equally important evolutionary turning points (milestones). Thirteen data sets of such milestones, obtained from a variety of scientific sources, provide data on the most important complexity jumps between the big bang and today. Forecasts for future complexity jumps are obtained via exponential and logistic fits on the data. The quality of the fits and common sense dictate that the forecast by the logistic function should be retained. This forecast stipulates that we have already reached the maximum rate of growth for complexity, and that in the future, complexity's rate of change (and the rate of change in our lives) will be declining. One corollary is that we are roughly halfway through the lifetime of the universe. Another result is that complexity's rate of growth has built up to its present high level via seven evolutionary subprocesses, themselves amenable to logistic description.

Keywords: Complexity growth; Punctuated equilibrium; Evolutionary milestones; Cosmic calendar; Change slowdown

1. Introduction

Change has always been an integral feature of life. "You cannot step twice in the same river," said Heraclitus—who has been characterized as the first Western thinker—illustrating the reality of permanent change. Heraclitus invoked an incontrovertible law of nature according to which everything is mutable, "all is flux." In the physics tradition, such laws are called universal laws, for example, the second law of thermodynamics, which stipulates that entropy always increases, and explains such things as why there can be no frictionless

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motion. In fact, there are theories that link the accumulation of complexity to the dissipation of entropy, or wasted heat.

The accelerating amount of change in technology, medicine, information exchange, and other social aspects of our life, is familiar to everyone. Progress—questionably linked to technological achievements—has been following progressively increasing growth rates. The exponential character of the growth pattern of change is not new. Whereas significant developments for mankind crowd together in recent history, they populate sparsely the immense stretches of time in the earlier world. The marvels we witnessed during the 20th century surpass what happened during the previous 1000 years, which in turn is more significant than what took place during the many thousands of years that humans lived in hunting–gathering societies. What is new is that we are now reaching a point of impasse, where change is becoming too rapid for us to follow. The amount of change we are presently confronted with is approaching the limit of the untenable. Many of us find it increasingly difficult to cope effectively with an environment that changes too rapidly.

What will happen if change continues at an accelerating rate? Is there a precise mathematical law that governs the evolution of change and complexity in the universe? And if there is one, how *universal* is it? How long has it been in effect and how far in the future can we forecast it? If this law follows a simple exponential pattern, we are heading for an imminent singularity, namely the absurd situation where change appears faster than we can become aware of it. If the law is more of a natural growth process (logistic pattern), then we cannot be very far from its inflection point, the maximum rate of change possible.

2. The task

Change is linked to complexity. Complexity increases both when the rate of change increases and when the amount of things that are changing around us increases. Our task then becomes to quantify complexity, as it evolved over time, in an objective, scientific, and therefore defensible way, and also to determine the law that best describes complexity's evolution over time, and then to forecast its future trajectory. This will throw light onto what one may reasonably expect as the future rate at which change will appear in society.

However, quantifying complexity is something easier said than done.

2.1. Complexity

We have seen much literature and extensive preoccupation of "hard" and "less hard" scientists with the subject of complexity. Yet we have neither a satisfactory definition for it, nor a practical way to measure it. The term complexity remains today vague and unscientific. In his best-selling book *Out of Control*, Kevin Kelly [1] concludes:

> How do we know one thing or process is more complex than another? Is a cucumber more complex than a Cadillac? Is a meadow more complex than a mammal brain? Is a zebra more complex than a national economy? I am aware of three or four mathematical definitions for

complexity, none of them broadly useful in answering the type of questions I just asked. We are so ignorant of complexity that we haven't yet asked the right question about what it is.

But let us look more closely at some of the things that we do know about complexity today:

- It is generally accepted that complexity increases with evolution. This becomes obvious when we compare the structure of advanced creatures (animals, humans) to primitive lifeforms (worms, bacteria).
- It is also known that evolutionary change is not gradual but proceeds by jerks. In 1972, Niles Eldredge and Stephen Jay Gould [2] introduced the term "punctuated equilibria": long periods of changelessness or *stasis*—equilibrium—interrupted by sudden and dramatic brief periods of rapid change—punctuations.

These two facts taken together imply that complexity itself must grow in a stepladder fashion, at least on a macroscopic scale.

- Another thing we know is that complexity begets complexity. A complex organism creates a niche for more complexity around it; thus, complexity is a positive feedback loop amplifying itself. In other words, complexity has the ability to "multiply" like a pair of rabbits in a meadow.
- Complexity links to connectivity. A network's complexity increases as the number of connections between its nodes increases, and this enables the network to evolve. But you can have too much of a good thing. Beyond a certain level of linking density, continued connectivity decreases the adaptability of the system as a whole. Kauffman [3] calls it "complexity catastrophe": an overly linked system is as debilitating as a mob of uncoordinated loners.

These two facts argue for a process similar to growth in competition. Complexity is endowed with a multiplication capability but its growth is capped and that necessitates some kind of a selection mechanism. Alternatively, the competitive nature of complexity's growth can be sought in its intimate relationship with evolution. One way or another, it is reasonable to expect that complexity follows logistic growth patterns as it grows.

2.2. Milestones in the history of the cosmos

The first thing that comes to mind when confronted with the image of stepwise growth for complexity over time is the major turning points in the history of evolution. Most teachers of biology, biochemistry, and geology at some time or another present to their students a list of major events in the history of life. The dates they mention invariably reflect milestones of punctuated equilibrium (or "punk eek" for short). Physicists tend to produce a different list of dates stretching over another time period with emphasis mostly on the early universe.

Such lists constitute data sets that may be plagued by numerical uncertainties and personal biases depending on the investigator's knowledge and specialty. Nevertheless, the events listed in them are "significant" because some investigator has singled them out as such among many others. Consequently, they constitute milestones that can in principle be used for the study of complexity's evolution over time. However, in practice, there are some formidable difficulties in producing a data set of turning points that cover the entire period of time (15 billion years).

I made the bold hypothesis that a law has been in effect *from the very beginning*. This was not an arbitrary decision on my part. The suggestion came when I first looked at an early compilation of milestones. In any case, I knew that confrontation with real data would be my final judge. More than once in this paper I have turned to the scientific method as defined by experimental physicists, namely: follow an observation (or hunch), make a hypothesis, and see if it can be verified by real data.

2.3. The challenges

Here are the most challenging issues concerning this paper's methodology in order of decreasing importance, and the way they were dealt with.

(1) The complexity associated with a milestone must be quantified at least in relative terms. For example, how much complexity did the Cambrian explosion bring to the system compared to the amount of complexity added to the system when humans acquired speech?

To quantify the complexity associated with an evolutionary milestone, we must look at the milestone's importance. *Importance* can be defined as equal to *the change in complexity multiplied by the time duration to the next milestone*. This definition has been derived in the classical physics tradition: you start with a magnitude (in our case *Importance*), you put an equal sign next to it, and then you proceed to list in the numerator whatever the quantity in question is proportional to, and in the denominator whatever it is inversely proportional to, keeping track of possible exponents and multiplicative constants. It is intuitively obvious that for a milestone, *Importance* is linearly proportional to the amount of complexity added by the milestone, and also linearly proportional to how long the system survives unchanged following the milestone. The greater the complexity jump at a given milestone, or the longer the ensuing stasis, the greater the milestone's importance will be (Eq. (1)):

$$\text{Importance} = \text{Complexity} \times \text{Duration}. \tag{1}$$

The complexity change associated with a certain milestone will then be inversely proportional to the time period to the next milestone. And to the extent that we are considering milestones of *comparable* importance, we have a means of quantitatively comparing the change in complexity associated with each jump.

Following each milestone, the complexity of the system increases by certain amount. At the next milestone, there is another increase in complexity. Assuming that milestones are approximately of equal importance, and according to the above definition of importance, we can conclude that the increase in complexity ΔC_i associated with milestone i of importance I is:

$$\Delta C_i = \frac{I}{\Delta T_i} \tag{2}$$

where ΔT_i is the time period between milestone i and milestone i+1.

We thus have a relative measure of the complexity contributed by each milestone to the system. If milestones become progressively crowded together with time, their complexity is expected to become progressively larger (see Fig. 1).

(2) The time frame is vast and the crowding of milestones in recent times is so dense that no logistic or exponential function can be used to describe the growth process.

A logistic function does not necessarily need to be a function of time. Moreover, there are processes for which our Euclidean conception of time is not appropriate. For this analysis, a better-suited time variable is the sequential milestone number because this way we can handle the singularity as $\Delta T \rightarrow 0$. Once forecasts are obtained for complexity jumps associated with future milestones, we can use the definition of importance coupled with the equi-importance assumption to derive explicit dates for future milestones.

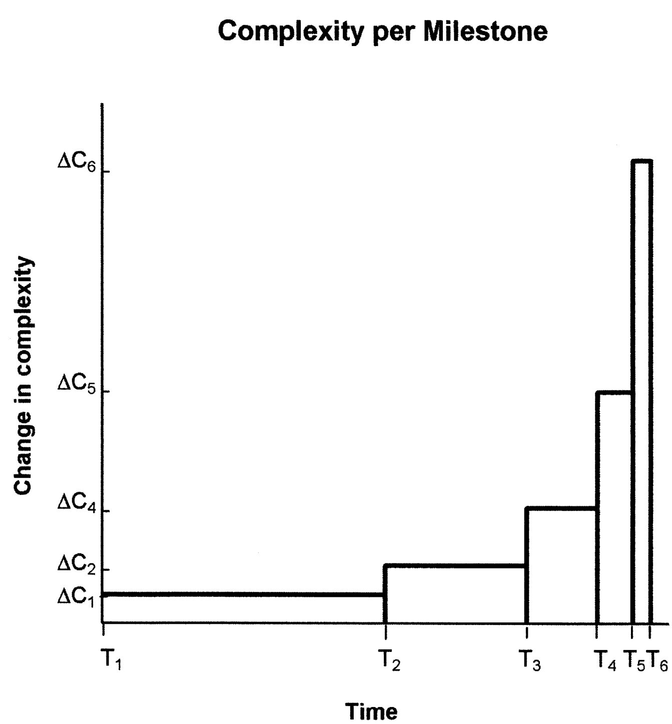

Fig. 1. To the extent that milestones of equal importance appear more frequently, their respective complexity increases. The area of each rectangle represents importance and remains constant. The scales of both axes are linear.

(3) Milestones from different evolutionary processes (cosmological, geological, biological, etc.) and by different authors (physicists, biologists, historians, etc.) need to be combined in a rigorous way. There is a need for normalization when authors furnish data sets with different numbers of milestones for the same chronological period.

The equi-importance assumption is key to dealing with both of these issues. If all milestones in a data set are equally important, then the corresponding complexity jumps—calculated as described in Challenge 1—are directly comparable no matter what evolutionary process they belong to. Similarly, if someone's data set contains more milestones than someone else's data set for the same chronological period, then the milestones in the former set must carry less importance than those in the latter. The data sets are normalized so that they give the same overall complexity contribution for the same time periods.

(4) How many turning points should an adequate data set contain? One can always argue that a large number of important events have been neglected.

If we consider only the top most important milestones, we can invoke Pareto's rule—also known as the 80/20 rule—to argue that 20% of all milestones accounts for 80% of all complexities acquired during the time period in question. Moreover, dealing with only major milestones improves the equi-importance requirement. Milestones of *large* importance are by definition milestones of *comparable* importance. Naturally, some of them will be more important than others, but the average importance will be a relatively large number, and the spread around this average a relatively small number. Therefore, on a first approximation, we can treat all milestones as being of *equal* importance.

Remark: A milestone is assigned to a point in time, i.e., a date. If more than one event is associated with the same date, the milestone's importance reflects the sum total of the importance of all such events.

3. The data

My first attempt to compile a set of milestones and determine a growth law from it turned out bittersweet. I analyzed 20 milestones compiled during a brainstorming session with colleagues. This early data set proved amenable to a description by a logistic curve, but the result was subsequently criticized on the ground that there could be bias in the choice of milestones. So I set out to find more objective data from independent and reliable sources in order to be able to defend them as unbiased.

Searching the Internet for something like "Major Events in the History of . . ." yields scores of pointers and chronologies, so-called timelines. Many of them have to do with some classroom assignment. Some of them stand out in terms of completeness and credibility. I briefly present below 6 of 13 data sets I have retained. A complete list of the data used in the analysis, including milestone descriptions and dates, can be found in Appendix A.

- *The cosmic calendar.* Carl Sagan [4] has put together a 1-year calendar matching the entire history of the Universe, and pointing out dates of major events. The set consists of

47 milestones that cover the entire time period (big bang to present) but suffer somewhat from the calendar format. Time resolution becomes insufficient for milestones that fall in the same time bucket. It happens with the calendar's monthly buckets, and again later with the buckets of seconds. In fact, it seems that during these periods of saturated time resolution, Sagan is enumerating milestones on a bucket-by-bucket basis reporting on things that happened during the time bucket, as if he is driven by the structure of the time buckets instead of the spacing of the events.

- The data sets from *Encyclopedia Britannica* and the *AMNH (American Museum of Natural History)* are free from time resolution distortions but are less exhaustive. They contain 16 and 20 milestones, respectively.
- *Major events in the history of life.* More than 1700 students, faculty, and other members of the UCLA community attended a "Major Events in the History of Life" symposium on January 11, 1991, convened by the IGPP Center for Study of Evolution and the Origin of Life at the University of California. A volume was put together making accessible the proceedings of that symposium [5].
- *Major events in the universe's history.* Two physicists published a *Scientific American* article entitled "The Structure of the Early Universe." Their data set concerns events and dates covering the prehuman evolution of the universe [6].
- Professor *Paul D. Boyer*, biochemist, Nobel Prize 1997, kindly provided me with his own set of milestones for which I assigned the dates.

The data used in the analysis incorporate milestones from 13 data sets, the last of which is the author's own. I decided to include a data set of my own for two reasons. First, I believe that having gone through all the research, I was well positioned to distill a rather complete, defensible, and scientific set of evolutionary milestones. Second, I needed data on the 20th century, neglected by the other authors. From the 12 sets considered, only Sagan's data set addresses the 20th century, and his data are plagued by the calendar format problem mentioned earlier.

From the 13 data sets, only Paul Boyer's and mine were created in direct response to the question: Which are the 25 most significant milestones in the evolution of the universe? The motivation of other authors, like Sagan and AMNH, was to put events into a time perspective. But in so doing, they answered the same question simply by selecting what to list as major events.

Because of the different number of milestones between data sets, and the fact that different sets sometimes give different dates for the same event (e.g., the time of the big bang ranges from 13 to 20 billion years ago), I decided to derive a "canonical" set of milestones and use the spread between authors to calculate errors. My assumption was that there must be some coherence among the 13 data sets, i.e., many milestone dates must be common to most sets. Combining 13 data sets into one greatly reduces the uncertainties on the results.

3.1. The canonical set of milestone

Fig. 2 shows a histogram of all milestone dates (a total of 302) with logarithmically increasing time buckets as we go backward in time. This choice of binning the data is not

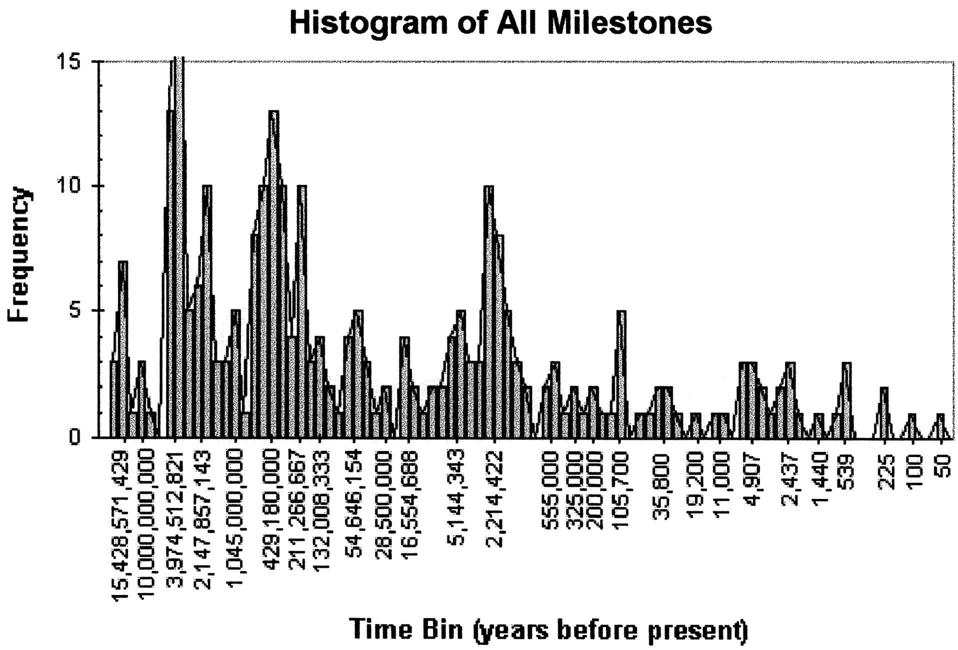

Fig. 2. A histogram of all milestones with logarithmic time buckets. The thin black line is superimposed to outline the peaks that define the dates of the "canonical" milestones. On the horizontal axis, we read the dates of these milestones.

arbitrary. It became obvious when I plotted the 302 points on a number of linear graphs with different size time buckets each. The logarithmically increasing time buckets are chosen in such a way that each bucket receives one cluster of milestones. The peak of each cluster is used to define a date for a milestone of the canonical set used as time variable in our analysis. There are 28 canonical milestones but because of complexity's definition (Eq. (2)), there are only 27 peaks in Fig. 2.

For each peak, the average complexity change is calculated, as well as an error given by the spread around the peak (1 S.D.). For peaks featuring only one entry (e.g., milestones during the last 100 years), I arbitrarily assign the average error as error. Fractional milestone numbers are assigned to all milestones according to their date.

4. The analysis

A distribution of the change of complexity per milestone for all 13 data sets is shown in Fig. 3. The different data sets have been normalized for equal cumulative complexity contributions over identical time periods. Consequently, the units of the vertical axis are arbitrary to an overall multiplicative constant. The picture comparing the normalized data for all 13 sources is rather coherent as there is good agreement between the different data sets. Furthermore, the data points generally line up on a straight line in a semilog plot, which is the

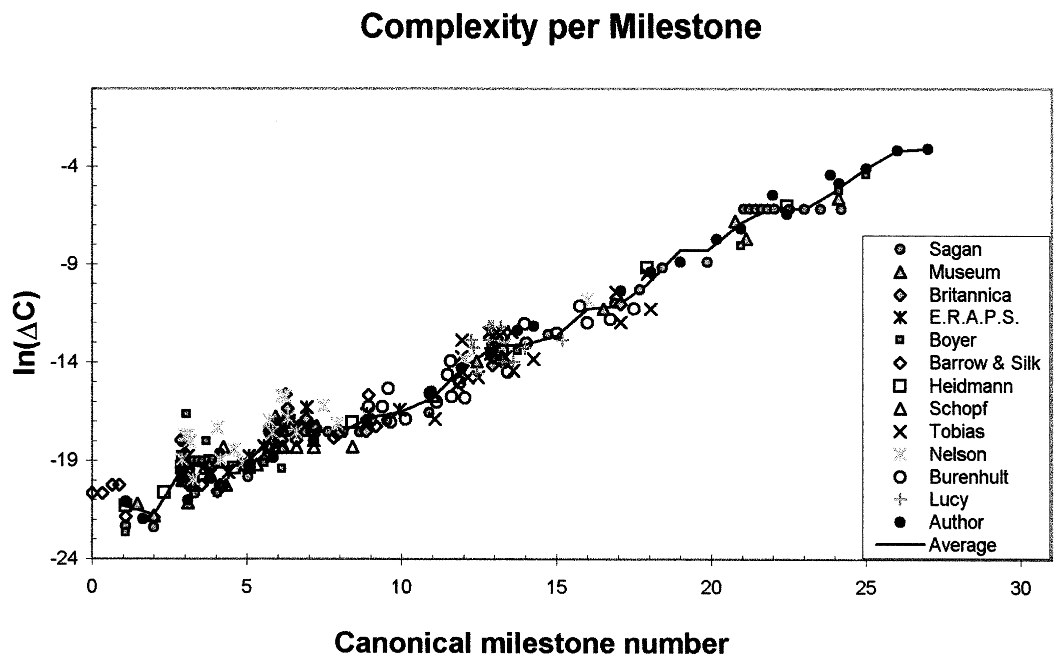

Fig. 3. Thirteen different sources of data corroborate each other. The thin black line connects the canonical milestones (see text), and also represents the average complexity change at a given milestone. The vertical axis depicts the logarithm of the change in complexity.

hallmark of exponential growth, or alternatively, the early part of logistic growth. The milestone–number axis marks the milestones of the canonical set.

We can now proceed to fit the data with an exponential and a logistic function. Given that Fig. 3 depicts complexity's *rate of growth*—i.e., complexity change per milestone—we expect the trend to follow the *first derivative* of the two functions. We therefore fit to the expressions:

$$\text{(exponential)} \qquad e^{(\alpha X+\beta)}$$

where α and β constants, and

$$\ln(\text{logistic life cycle}) \qquad \ln\frac{M\alpha}{(1+e^{-\alpha(X-X_0)})(1+e^{\alpha(X-X_0)})}$$

where M, α, and X_0 are constants and X the sequential milestone number. The logistic life cycle is the first derivative of the familiar logistic function:

$$\frac{M}{1+e^{-\alpha(X-X_0)}}.$$

Fig. 4 shows the canonical set of milestones with an exponential and a logistic fit superimposed. The logistic fit is better than the exponential one (70% confidence level compared to 30%). Table 1 shows the particular details of the fits.

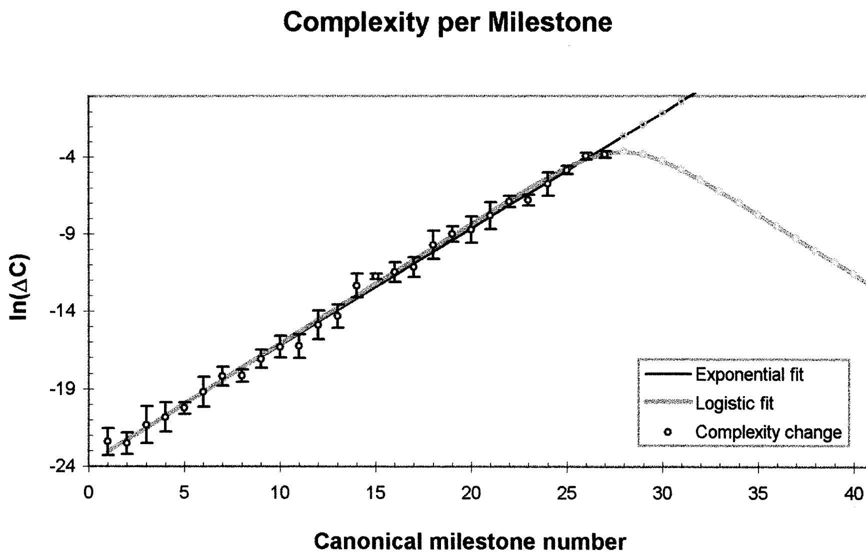

Fig. 4. Logistic and exponential fits to the data of the canonical milestone set. The vertical axis depicts the logarithm of the change in complexity. The faint circles on the forecasted trends indicate the complexity of future milestones.

I have made an attempt to be scientifically correct. However, the reader should be aware that the chi-square estimates (and the associated confidence levels) cannot reflect all uncertainties. There are sources of error that have not been properly accounted for, for example, errors due to having widely different dates for the same event (sometimes with good reason as the exact date is still being debated), or errors due to the approximation that the milestones are equally important.

The midpoint of the logistic function is milestone no. 27.89, which corresponds to 10 years ago. In other words, complexity grew at the highest rate ever around 1990. From then onwards, complexity's rate of change began decreasing. Future milestones of comparable importance will henceforth be appearing less frequently.

But according to the exponential law, milestones punctuating complexity jumps will continue appearing closer together at the same exponential rate, and 25 years from now we should expect successive turning points of the same importance to be spaced only 5 days apart. Table 2 spells out the timing of future milestones as expected from the logistic and exponential growth laws determined by the above fits.

Table 1
Fit results

Formula fit	β	α	M	X_0	χ^2	*df*
$(\alpha X+\beta)$	−23.749	0.7554			28.3	25
$\ln\frac{M\alpha}{(1+e^{-\alpha(X-X_0)})(1+e^{\alpha(X-X_0)})}$		0.7735	0.1375	27.89	20.2	24

Table 2
Forecasts for complexity change as a function of time

Milestone number	Logistic fit		Exponential fit	
	Complexity change[a]	Years from now	Complexity change[a]	Years from now
28	0.0265	38	0.0744	13.4
29	0.0223	45	0.1584	6.3
30	0.0146	69	0.3372	3.0
31	0.0081	124	0.7178	1.4
32	0.0041	245	1.5278	0.7
33	0.0020	508	3.2518	0.3
34	0.0009	1078	6.9213	0.1
35	0.0004	2315	14.7317	0.07
36	0.0002	5000	31.3558	0.03
37	0.0001	10,800	66.7397	0.015

[a] In the same arbitrary units as Figs. 3 and 4.

The accuracy of the results, as reflected in the significant digits retained in the numbers reported, may seem overly optimistic. However, the reader should bear in mind two things. First, that the curves are extremely steep; on linear time scale, they would appear practically horizontal across billions of early universe years. Second, the significant digits in the results reflect more the *precision* of the method and less the *accuracy* of the answers because not all systematic errors have been accounted for (see earlier remark on sources of unaccounted errors).

4.1. The close-up picture

The case can be made, if less rigorously, for a finer structure in the evolution of the trajectory of complexity's change. It is has been shown that any growth processes may consist of smaller logistic subprocesses [7,8]. Looking at Fig. 3 closely, we can discern smaller S-shaped steps. Such structure indicates an alternation between periods when the milestones progressively crowd together and periods when they are roughly regularly spaced in time. This is largely due to the fact that as we move through time, we encounter a number of rather well-defined evolutionary subprocesses. The thin black line in Fig. 3 (representing the average change of complexity per milestone) suggests at least seven such subprocesses. In Fig. 5, logistic curves are adapted to these segments.

The seven logistic curves do not result from rigorous fits to the data because of too few milestones and too much jitter on the data points in each segment (otherwise said, too large errors for the fitting procedure to work). The thick gray lines are logistic functions drawn in to simply guide the eye. However, the fair agreement between thick lines and the corresponding sections of the dotted line is evidence that we are dealing with rather independent natural growth processes.

In order to better understand the seven subprocesses, Table 3 lists the relevant parameters for each process. The mathematical parameters of the logistic functions being of less interest, it is preferable to give the dates corresponding to the 10%, 50%, and 90% penetration level

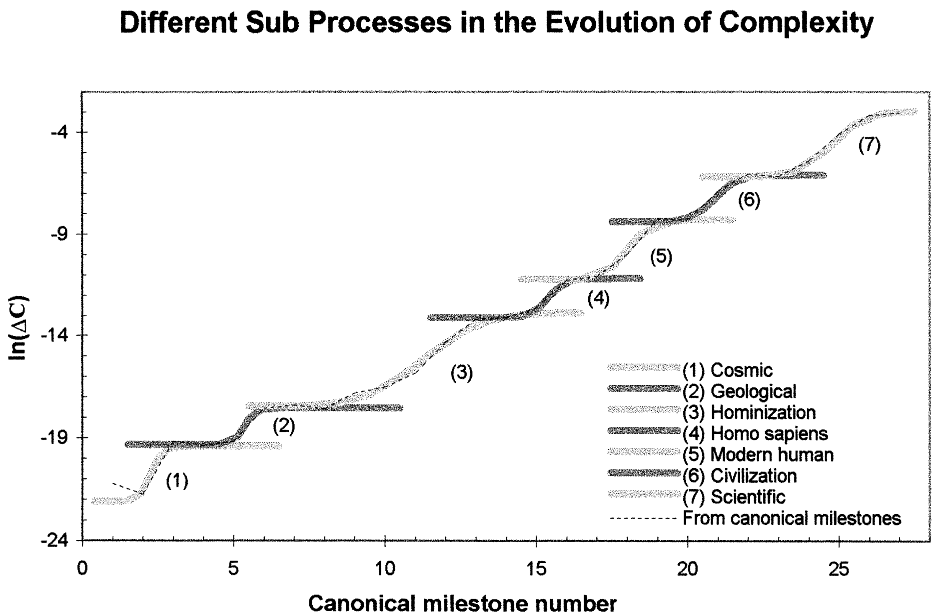

Fig. 5. Seven small logistic curves have been superimposed to point out evidence for a finer structure. The dotted line is the same as the thin black line in Fig. 3. The vertical axis depicts the logarithm of the change in complexity. The legend lists the subprocesses in chronological order.

for each process. The range 10–90% of a logistic growth process is traditionally taken as the period of main thrust toward higher growth. Above the 90% level, one can argue that a stable maximum level has been reached.

The names given to the seven phases have been inspired by what happened during each subprocess. Consequently, "Cosmic" refers to the process around the formation of our galaxy. "Geological" refers to early forms of life and is centered on the appearance of multicellular life. "Hominization" is the period between the divergence of orangutan from Hominidae and the development of speech; it is centered on the appearance of first bipedalism and stone tools. "*Homo sapiens*" is a relatively short period dominated by *Homo*

Table 3
The seven phases of complexity's growth

	10%	50%	90%
Evolutionary process	Years before present		
Cosmic	13,100,000,000	10,100,000,000	7,900,000,000
Geological	1,450,000,000	1,050,000,000	820,000,000
Hominization	19,500,000	4,020,000	625,000
Homo sapiens	434,000	308,000	239,000
Modern human	107,000	38,200	15,100
Civilization	10,700	6130	5000
Scientific	539	225	100

sapiens and the domestication of fire. "Modern human" extends between the first burial of the dead and the invention of agriculture; it is centered around the time of rock art, and includes ritual/spiritual behavior (magic shamanism). "Civilization" is a name inspired by city dwelling and religion becoming important; it is centered around the appearance of writing and the wheel. Finally, "Scientific" is the growth phase that begins with renaissance, and ends with modern physics; it is centered on the industrial revolution and the establishment of scientific method.

5. Discussion of results

This paper studies the evolution of complexity from the beginning of the universe to present day. The hypothesis, verified via a successful logistic fit on data, is that a simple diffusion law has been governing complexity's growth across diverse evolutionary processes (cosmological, geological, biological, etc.). We are obviously concerned with an anthropic universe here since we are overlooking how complexity has been evolving in other parts of the universe. Still, the author believes that such an analysis carries more weight than just the elegance and simplicity of its formulation. John Wheeler has argued that the very validity of the laws of physics depends on the existence of consciousness.[1] In a way, the human point of view is all that counts!

The work reported here links logistic growth and complexity in two different ways. One way is how complexity has been accumulating in the universe along a large logistic curve (Fig. 4). Another way is how complexity's rate of growth has been following smaller logistic curves in the close-up picture of Fig. 5. There is a fundamental difference between these two pictures. The former involves an S-shaped pattern fitted to the amount of *change accumulated*, whereas the latter involves fitting S-shaped patterns to the *rate of change*. In both cases, evidence for logistic growth argues for natural growth in competition (Darwinian in nature), but the interpretations are different.

5.1. Seeing complexity as a competitive growth process

Observation of logistic growth enables one to argue for the existence of Darwinian competition. Such competition implies that:

- Some "species" are capable of growing via multiplication.
- Members of the "species" compete for a limited resource.
- There is natural selection.

In the logistic function of Fig. 4, the "species" is the system's complexity and its members are the complexity chunks carried by the milestones. The limited resource is the system's

[1] John Wheeler is professor at Princeton University and presently director of the Center for Theoretical Physics at the University of Texas, Austin.

cumulated final complexity. It is limited because too much complexity may hurt survival as per Kauffman's argument for complexity catastrophe mentioned earlier.

In the logistic functions of Fig. 5, the ''species'' is the speed with which each evolutionary subprocess proceeds, and its members are the jumps in speed during the rapid growth phase (when turning points appear progressively more frequently). The limited resource is maximum speed, characteristic of the evolutionary subprocess in question (e.g., geological evolution reached higher levels of complexity per milestone than cosmic evolution).

There is selection everywhere. Changes, be it in complexity, or in the rate of growth of complexity, are like mutants; only the best-fit ones survive. Potential changes lurk around like potential accidents, waiting for the opportunity to become realized. If a change represents too large or too small a step for the moment in history of the evolutionary process it belongs to, it will not survive (i.e., it will not become realized). At the same time, if the system's cumulated complexity approaches saturation—some billion years from now—changes, and the evolutionary subprocess they belong to, will have to be confined to miniscule sizes. Big mutations at that point in time will simply have no chance of being realized.

5.2. The ultimate S-curve

The large-scale logistic description of Fig. 4 indicates that the evolution of complexity in the universe has been following a logistic growth pattern from the very beginning, i.e., from the big bang. This is remarkable considering the vastness of the time scale, and also the fact that complexity resulted from very different evolutionary processes, for example, planetary, biological, social, and technological. The fitted logistic curve has its inflection point—the time of the highest rate of change—around 1990. Considering the symmetry of the logistic growth pattern, we can thus conclude that the end of the universe is roughly another 15 billion years away. Such a conclusion is not really at odds with the latest scientific thinking that places the end of the solar system some 5 billion years from now.

The ultimate S-curve of Fig. 4 is not a function of time but of milestone number. The S-shaped pattern would be rather distorted if we plotted complexity as a function of time (very flat for billions of years and very steep at present). But the forecasts of complexity per future milestone can be translated to complexity per future date according to Eq. (2). We therefore see from Table 2 that the next three milestones are due 38, 45, and 69 years from now. To give some perspectives, we can look at the last three milestones:

- 5 years ago: Internet/human genome sequenced;
- 50 years ago: DNA/transistor/nuclear energy;
- 100 years ago: modern physics (radio, electricity, etc.)/automobile/airplane.

In other words, dates for world-shaking milestone like the above three should be expected around 2038, and then again around 2083 and 2152.

5.3. Independent corroboration

During this paper's reviewing process, one of the reviewers brought to my attention that Richard Coren [9] has done a similar analysis on a set of 13 events he described as "critical transitions in evolution on Earth" in his book *The Evolutionary Trajectory*. Coren looked at evolution in terms of information transfer, much like what Smith and Szathmary [10] did with their small set of six transitions. I could not resist trying my approach on Coren's data set.

The logistic fit turned out excellent with a midpoint around 1860 AD. I consider this to be in exceptionally good agreement with my result (1990 AD) given that Coren's sampling is much coarser; his data set has less than half the data points I have in my canonical set. Data sets with few points, when individually analyzed, generally gave much poorer agreement. Moreover, in view of the earlier discussion on unaccounted systematic errors, such agreement must be considered as fortuitous. Nevertheless, it brings certain corroboration.

For the sake of completeness, Coren's data set, my logistic fit to it, and the corresponding graph are given in Appendix B.

5.4. Other insights

According to the classification of Table 3, events like the Cambrian explosion are not the singular turning points purported to be. Once the Geological subprocess was completed, important events continued to take place for a long stretch of time (almost 800 million years) at a maximum but rather *constant* rate. Cambrian explosion was one such event; others were:

- Appearance of invertebrates
- Plants colonized land
- Appearance of amphibians
- Appearance of insects
- Appearance of reptiles
- Mass extinction (trilobites)
- Appearance of dinosaurs and mammals
- Birds evolved from reptiles
- Appearance of flowering plants
- Asteroid collision and the ensuing mass extinction (including dinosaurs).

All these events took place between the end of Geological (around 800 million years ago) and the beginning of Hominization growth phases (around 20 million years ago), and are roughly of comparable time spacing (hence, complexity) and importance.

Special significance has been attributed to the Cambrian explosion—and other events like the invention of agriculture, the discovery of DNA and nuclear energy, and Internet and the sequencing of the human genome—and yet they do not constitute turning points between distinct evolutionary growth processes but rather occupy the stretches of time characterized by uniform change between the end of one subprocess and the beginning of the next one. Contrary to what one may have expected, complexity increased at a rather *constant* rate—

albeit large—during the 20th century. The major thrust forward of the scientific evolutionary process took place earlier, around the discovery of the steam engine.

A better identification for the seven evolutionary subprocesses is provided by events that occupy the time period when the rate of growth of complexity underwent a sharp increase. These are events around the 50% points of Table 3 such as:

- Star formation (Cosmic)
- The appearance of multicellular life (Geological)
- First bipedalism and stone tools (Hominization)
- The domestication of fire (*Homo sapiens*)
- Rock art (Modern human)
- The appearance of writing and the discovery of the wheel (Civilization)
- The discovery of the steam engine (Scientific).

Another interesting observation in the close-up picture of Fig. 5 is the miniscule rate of growth of complexity before significant lifeforms appeared (i.e., before hominization). This fact concords with the well-accepted notion that there was no complex matter in the universe before life. According to astrochemists, we cannot find complex molecules in the universe outside of life.

6. Sitting on top of the world

Summarizing the conclusions, we can say that the universe's complexity has been growing along a large-scale logistic pattern that has just reached its midpoint. In fact, the rate of complexity's growth has just reached its maximum, after having gone through seven steps, each of which can itself be interpreted as a natural growth subprocess. As the rate of change begins declining, the next subprocess is expected to be a downward step following an upside–down S-curve.

But the analysis of complexity's evolution also gave an exponential pattern—if with lower confidence level—as a possibility for the appearance of future milestones. For skeptics of logistics, those who advocate that complexity can continue growing exponentially, Table 2 tells us that the next milestone should be in 13.4 years, the following one in 6.3 years, the one after that in 3 years, and then again in 1.4 years, and so on. But the pattern becomes so steep that all future milestones are expected to appear in less than 26 years from now.[2] In other words, people who will still be alive in 2026—i.e., the generation of people born in the mid-1940s or later—will have witnessed before they die all the change that can ever take place!

Therefore, in addition to the goodness-of-fit argument, there is a common sense argument that favors the logistic law alternative. But the logistic life cycle also peaks during the lifetime

[2] The pattern of a decaying exponential is asymptotic, i.e., it needs infinite time to reach zero, but its definite integral between x and ∞ is finite.

of people born in the mid-1940s. In particular, it spells out that we are presently traversing the only time in the history of the universe in which 80 calendar years can witness change in complexity coming from as many as three evolutionary milestones. We happen to be positioned at the world's prime!

Coincidentally, the mid-1940s is the time of the baby boom that creates a bulge on the population distribution. As if by some divine artifact, a larger-than-usual sample of individuals was meant to experience this exceptionally turbulent moment in the evolution of the cosmos.

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Appendix A

This appendix contains the raw data used in the paper. The first 12 data sets, provided by independent sources, influence to some extent the 13th data set compiled by the author. Milestones denote dates; consequently, events occurring at the same time are represented by a single milestone.

A.1. The data set of Carl Sagan [4] as outlined in his Cosmic Calendar. The precise year numbers have been assigned by the author

	Milestone	Years ago
(1)	Big bang	1.5E+10
(2)	Origin of Milky Way Galaxy	1.0E+10
(3)	Origin of the solar system	4.6E+09
(4)	Formation of the Earth	4.4E+09
(5)	Origin of life on Earth	4.0E+09
(6)	Formation of the oldest rocks known on Earth	3.7E+09
(7)	Date of oldest fossils (bacteria and blue green algae)	3.4E+09
(8)	Invention of sex (by microorganisms)	2.5E+09
(9)	Oldest fossil photosynthetic plants	2.0E+09
(10)	Eukaryotes (first cells with nuclei) flourish	1.9E+09
(11)	Significant oxygen atmosphere begins to develop on Earth	1.2E+09
(12)	Extensive volcanism and channel formation on Mars	1.0E+09
(13)	First worms	6.2E+08
(14)	Precambrian ends; Paleozoic Era and Cambrian Period begin; invertebrates flourish	5.7E+08

(15)	First oceanic plankton; trilobites flourish	5.3E+08
(16)	Ordovician Period; first fish, first vertebrates	4.9E+08
(17)	Silurian Period; first vascular plants; plants begin colonization of land	4.5E+08
(18)	Devonian Period begins; first insects; animals begin colonization of land	4.1E+08
(19)	First amphibians; first winged insects	3.7E+08
(20)	Carboniferous Period; first trees; first reptiles	3.3E+08
(21)	Permian Period begins; first dinosaurs	2.9E+08
(22)	Paleozoic Era ends; Mesozoic Era begins	2.5E+08
(23)	Triassic period; first mammals	2.1E+08
(24)	Jurassic Period; first birds	1.6E+08
(25)	Cretaceous Period; first flowers; dinosaurs become extinct	1.2E+08
(26)	Mesozoic Era ends; Cenozoic Era Tertiary Period begins; first cetaceans; first primates	8.2E+07
(27)	First evolution of frontal lobes in the brain of primates; first hominids; giant mammals flourish	4.1E+07
(28)	Origin of *Proconsul* and *Ramapithecus*, probable ancestors of apes and men	1.8E+07
(29)	First humans	2.6E+06
(30)	Widespread use of stone tools	1.7E+06
(31)	Domestication of fire by Peking man	4.1E+05
(32)	Beginning of most recent glacial period	1.2E+05
(33)	Seafarers settle Australia	5.8E+04
(34)	Extensive cave painting in Europe	2.9E+04
(35)	Invention of agriculture	1.9E+04
(36)	Neolithic civilization; first cities	1.2E+04
(37)	First dynasties in Summer, Ebla, and Egypt; development of astronomy	4800
(38)	Invention of the alphabet; Akkadian Empire	4300
(39)	Hammurabic legal codes in Babylon; Middle Kingdom in Egypt	3800
(40)	Bronze metallurgy; Mycenaean culture; Trojan War; Olmec culture; invention of the compass	3400
(41)	Iron metallurgy; first Assyrian Empire; Kingdom of Israel; founding of Carthage by Phoenicia	2900
(42)	Asokan India; Ch'in Dynasty China; Periclean Athens; birth of Buddha	2400
(43)	Euclidian geometry; Archimedean physics; Ptolemaic astronomy; Roman Empire; Christ	1900
(44)	Zero and decimals invented in Indian arithmetic; Rome falls; Moslem conquests	1400
(45)	Mayan civilization; Sung Dynasty China; Byzantine empire; Mongol invasion; crusades	1000

(46)	Renaissance in Europe; voyages of discovery from Europe and from Ming Dynasty China; emergence of the experimental method in science	500
(47)	Widespread development of science and technology; emergence of global culture; acquisition of the means of self-destruction of the human species; first steps in space craft planetary exploration and the search of extraterrestrial intelligence	0

A.2. The data set found in the AMNH [11]. The precise date numbers have been provided by the author

	Milestone	Years ago
(1)	Big bang	1.3E+10
(2)	Milky Way forms	1.0E+10
(3)	Sun and planets form	4.5E+09
(4)	Oldest known life (single cell)	3.8E+09
(5)	First multicellular organisms	1.0E+09
(6)	Cambrian explosion (burst of new lifeforms)	5.5E+08
(7)	Emergence of first vertebrates	4.8E+08
(8)	Early land plants	4.4E+08
(9)	Variety of insects begin to flourish	3.9E+08
(10)	First dinosaurs appear	2.3E+08
(11)	First mammalian ancestors appear	1.9E+08
(12)	First known birds	1.4E+08
(13)	Dinosaurs wiped out by asteroid or comet	6.5E+07
(14)	Apes appear	1.6E+07
(15)	First human ancestors to walk upright	3.9E+06
(16)	*H. erectus* appears	1.8E+06
(17)	Anatomically modern humans appear	1.5E+04
(18)	Invention of writing	6300
(19)	Pyramids built in Egypt	4600
(20)	Voyage of Christopher Columbus	508

A.3. The data set ''important events in the history of life'' as found in the Encyclopedia Britannica?

	Milestone	Years ago
(1)	Oldest prokaryotic fossils	3.5E+09
(2)	Oxygen begins to accumulate in atmosphere	2.5E+09
(3)	Oldest eukaryotic fossils	2.1E+09
(4)	Simple multicellular organisms evolve	7.0E+08
(5)	Plants colonize land	4.2E+08
(6)	Amphibians appear	3.7E+08

(7) First insects	3.6E+08
(8) Reptiles appear	3.4E+08
(9) Mass extinction	2.8E+08
(10) First dinosaurs and mammals	2.3E+08
(11) Birds evolve from reptiles	2.0E+08
(12) First flowering plants	1.4E+08
(13) Mass extinction	6.6E+07
(14) Ice age	2.4E+06
(15) Advent of modern humans	1.0E+05
(16) Present	0

A.4. A ''timeline for the evolution of life on earth'' as given in the web site of the Educational Resources in Astronomy and Planetary Science (ERAPS), University of Arizona

Milestone	Years ago
(1) No life; shallow seas	4.0E+09
(2) Origin of simple cells	3.8E+09
(3) Origin of cyanobacteria	3.5E+09
(4) Oxygen accumulates in atmosphere	2.5E+09
(5) Protists and green algae	1.7E+09
(6) Simple multicellular life (sponges, seaweeds)	1.0E+09
(7) More invertebrates (flatworms, jellyfish)	7.0E+08
(8) Early animals with hard parts in oceans	5.2E+08
(9) Planets invade land	4.1E+08
(10) Vertebrates invade land	3.5E+08
(11) Coal-forming forests, amphibians, big insects	3.0E+08
(12) Mass extinction (trilobites)	2.3E+08
(13) Pangaea, first mammals, first reptiles	2.0E+08
(14) Mass extinction (including dinosaurs)	6.5E+07
(15) Small mammals, humanoids	3.0E+07
(16) Early humans	2.0E+06
(17) Us	0

A.5. The milestones below have been kindly provided by Paul D. Boyer, biochemist, Nobel Prize 1997 [12]. The precise dates have been assigned by the author. The last two milestones have been ignored as futuristic

Milestone	Years ago
(1) Big bang	1.5E+10
(2) Solar system forms	4.8E+09
(3) Earth forms	4.6E+09
(4) Nitrogen atmosphere (for winds) is present or acquired	4.0E+09

(5) Abundant water is present or acquired	3.9E+09
(6) Organic precursors for lifeforms accumulate in special environment	3.9E+09
(7) Primitive living organisms arise or (less likely) come from space	3.9E+09
(8) Land temperature stabilizes so that most of the water is liquid	3.5E+09
(9) Some lifeforms get energy from oxidation–reduction reactions	3.2E+09
(10) Organisms evolve to gain many present biochemical characteristics	3.0E+09
(11) Photosynthetic capacity is acquired, and oxygen evolution begins	2.7E+09
(12) Land surfaces form and plate tetonics established	2.6E+09
(13) Evolution produces organisms that can use oxygen to make ATP	2.4E+09
(14) Abundant microorganisms colonize the entire Earth	2.1E+09
(15) Multicellular organisms arise with increased capacity for structural differentiation	7.0E+08
(16) Primitive plant forms begin to evolve stems, roots, and leaves	4.0E+08
(17) First humans	2.6E+06
(18) Widespread use of stone tools	1.7E+06
(19) Acquisition of spoken language	1.0E+06
(20) Acquisition of written language	5000
(21) They learn that knowledge comes from observation and experiment (scientific method)	500
(22) Ability to control nature gives rise to a human population explosion	200
(23) The above abilities give rise to a remarkable understanding of nature	100
(24) Human activities devastate species and the environment	–
(25) Humans disappear; geological forces and evolution continue	–

A.6. The data set below represents ''major events in the universe history'' as published in Scientific American by John D. Barrow and Joseph Silk [13]

Milestone	Years ago
(1) Big bang	2.00E+10
(2) Galaxies begin to form	1.85E+10
(3) Galaxies begin to cluster	1.70E+10
(4) Our protogalaxy collapses; first stars form	1.60E+10
(5) Quasars are born; population II stars form	1.50E+10
(6) Population I stars form	1.00E+10
(7) Our parent interstellar cloud forms	4.80E+09
(8) Collapse of protosolar nebula	4.70E+09
(9) Planets form; rock solidifies	4.60E+09
(10) Intense cratering of planets	4.30E+09
(11) Oldest terrestrial rocks form	3.90E+09
(12) Microscopic lifeforms	3.00E+09
(13) Oxygen-rich atmosphere develops	2.00E+09
(14) Macroscopic lifeforms	1.00E+09
(15) Earliest fossil record	6.00E+08

(16) First fishes	4.50E+08
(17) Early land plants	4.00E+08
(18) Ferns, conifers	3.00E+08
(19) First mammals	2.00E+08
(20) First birds	1.50E+08
(21) First primates	6.00E+07
(22) Mammals increase	5.00E+07
(23) *H. sapiens*	1.00E+05

A.7. The milestones below appear in the book of Jean Heidmann [14], Cosmic Odyssey

Milestone	Years ago
(1) Big bang, etc.	1.5E+10
(2) Age of most distant galaxies	8.0E+09
(3) Formation of the Sun and the Earth	4.5E+09
(4) First bacteria	3.5E+09
(5) First eukaryotic organisms	1.5E+09
(6) Explosion of life in the Cambria era	5.0E+08
(7) The dawn of *Australopithecus*	3.5E+06
(8) *H. habilis* uses tools	2.5E+06
(9) *H. erectus* masters the use of fire	1.0E+06
(10) Invention of writing	4.0E+04
(11) Eratosthenes measures the size of the Earth	2000
(12) Copernicus, Galileo	400

A.8. The data set below is taken from a table ''illustrating the temporal distribution of major events in the history of life.'' The table is found in a volume that makes accessible the proceedings of the 1991 Symposium ''Major Events in the History of Life'' convened by the IGPP Center for the Study of Evolution and the Origin of Life at the University of California, Los Angeles [5]

Milestone	Years ago
(1) Formation of the Earth	4.6E+09
(2) Origin of life on Earth	4.0E+09
(3) Formation of the oldest rocks known on Earth	3.8E+09
(4) Date of oldest fossils and stromatolites	3.5E+09
(5) Abundant cyanobacteria and stromatolites	2.8E+09
(6) Abundant iron formations	2.5E+09
(7) Latest detrital uraninite/pyrite	2.1E+09
(8) Atmospheric oxygen	1.9E+09
(9) Nucleated cells (phytoplankton)	1.8E+09
(10) Complex (sexual) phytoplankton	1.1E+09

(11) Seaweeds and protozoans	8.5E+08
(12) Animals without backbones	6.0E+08
(13) Fish	5.0E+08
(14) Land plants and animals	4.0E+08
(15) Coal swamps	3.0E+08
(16) Dinosaurs and birds	2.0E+08
(17) Flowering plants	1.0E+08
(18) Humans	2.0E+06

A.9. The data set below is compiled from tables in ''Major Events in the History of Mankind'' by Phillip V. Tobias [15], Director, Palaeo-anthropology Research Unit, Department of Anatomy and Human Biology, University of the Witwatersrand, Johannesburg, South Africa

Milestone	Years ago
(1) Divergence of orangutan lineage from Hominoidea	1.6E+07
(2) Divergence of gorilla from other African hominoids	7.5E+06
(3) Uplift, cooling, and aridification of Africa	6.0E+06
(4) Chimpanzee−hominid divergence, inferred appearance of Hominidae	5.7E+06
(5) "Messinian crisis", the drying up of the Mediterranean/spread of African savannah/etc.	5.5E+06
(6) Earliest known fossils identifiable as probable hominid	4.8E+06
(7) Earliest fossil evidence of hominid bipedalism	3.8E+06
(8) Hominid fossils known	2.8E+06
(9) Differentiation of postulated "derived *Aust. africanus*"	2.7E+06
(10) One or more splittings of hominid lineage; earliest known *Australopithecus boisei* fossils; earliest known stone cultural remains	2.6E+06
(11) Acquisition of spoken language (as here inferred); many changes in mammalian fauna of Africa (baboons, elephants, pigs, bovids, hippopotami, sabertoothed cats, rodents)	2.3E+06
(12) Earliest known *H. habilis* fossils	2.1E+06
(13) Earliest modern human brain form; earliest signs of marked brain enlargement in hominids	2.0E+06
(14) Movement of hominids from Africa to Asia and Europe	1.8E+06
(15) Emergence of *H. erectus*	1.7E+06
(16) Acquisition of fire by *H. erectus*	1.3E+06
(17) Extinction of robust and hyperrobust australopithecines	1.2E+06
(18) Emergence of *H. sapiens*	5.0E+05
(19) Earliest known "anatomically modern *H. sapiens*"	1.1E+05
(20) Earliest burial of the dead	1.0E+05
(21) Emergence of "modern human culture"	4.0E+04
(22) Earliest rock art; earliest protowriting	3.5E+04
(23) Earliest writing	5000

A.10. The milestones below represent a ''timeline for major events in the history of life on earth'' as given by David R. Nelson, Department of Biochemistry at the University of Memphis, Tennessee [16]

	Milestone	Years ago
(1)	Planet earth forms	4.5E+09
(2)	Planet surface cools and bombardment from space slows, so life has the possibility of the existing planet; oldest Earth rocks dated by radioactivity	4.0E+09
(3)	Evidence for life seen in Greenland rocks enriched in C12 isotope; prokaryotes diverge from archaea; chlorophyll and photosynthesis evolve in the bacterial lineage	3.9E+09
(4)	First banded iron formation seen; implies oxygen made by photosynthesis	3.7E+09
(5)	First stromatolites seen	3.5E+09
(6)	First tentative evidence of a eukaryotic microfossil	2.1E+09
(7)	Oxygen begins to rise in the atmosphere after oxygen sinks saturated	2.0E+09
(8)	Oxygen level in the atmosphere reaches present-day level and stabilizes; more convincing evidence of eukaryotic microfossils; chloroplasts and mitochondria present	1.5E+09
(9)	Major eukaryotic phyla diverge; plants branched before animals/fungi	1.2E+09
(10)	Invertebrates and vertebrates diverge; Hox gene cluster exists	6.0E+08
(11)	Cambrian explosion of fossil record	5.3E+08
(12)	Fish and other vertebrates diverge; plants and fungi invade the land	4.0E+08
(13)	Vertebrates move onto land	3.8E+08
(14)	Gymnosperms (naked seed plants) diverge from angiosperms (flowering plants)	3.6E+08
(15)	Birds and other vertebrates diverge	3.0E+08
(16)	Monocots diverge from dicots	1.8E+08
(17)	Oldest angiosperm fossil	1.4E+08
(18)	Last common ancestor of all polymorphism sequences	6.0E+07
(19)	Chimpanzees and humans diverge	5.0E+06
(20)	*H. sapiens*	1.7E+06
(21)	Last common ancestor of all human mitochondrial DNA types	2.0E+05
(22)	Modern humans	5.9E+04

A.11. The milestones below have been compiled from information in The First Humans: Human Origins and History to 10,000 BC, edited by Goran Burenhult [17]

	Milestone	Years ago
(1)	*Purgatorius*	6.0E+07
(2)	Petrolemuridae	5.5E+07
(3)	Adapiformes, omomylformes	4.5E+07
(4)	*Aegyptopithecus*, *Propliapithecus*, *Oligopithecus*, *Catopithecus*	4.0E+07
(5)	*Afrotarsius*	3.8E+07

(6) Omomylformes, Branisella	2.7E+07
(7) Prohylobates, *Micropithecus*, *Afropithecus Proconsul*	1.8E+07
(8) *Kenyopithecus*, *Dryopithecus*	1.5E+07
(9) *Krishnapithecus*	1.1E+07
(10) *Sivapithecus*	1.0E+07
(11) *Ouranopithecus*	9.5E+06
(12) Samburu maxilla	6.5E+06
(13) *Gigantopithecus*	5.0E+06
(14) Orangutans, emergence of stone tools	1.8E+06
(15) Appearance of the erectines	1.5E+06
(16) Acheulian technology	6.3E+05
(17) *H. erectus*	5.5E+05
(18) *H. heidelbergensis*	3.5E+05
(19) Control of fire	2.3E+05
(20) *H. sapiens*, modern humans	2.0E+05
(21) Neanderthalis	1.3E+05
(22) Mousterian technology	7.0E+04
(23) Art	3.5E+04

A.12. The data set below is adapted from a chart on Human Evolution based on the book From Lucy to Language [18]

Milestone	Years ago
(1) *Ardipithecus ramidus*	4.4E+06
(2) *Aust. anamensis*	4.2E+06
(3) *Aust. afarensis*	3.9E+06
(4) *Aust. africanus*	2.8E+06
(5) *Aust. aethiopicus*	2.7E+06
(6) *Homo* sp.?	2.5E+06
(7) *H. rudolfensis*	2.4E+06
(8) *Aust. boisei*	2.3E+06
(9) *H. habilis/Aust. habilis*	1.9E+06
(10) *H. ergaster*	1.8E+06
(11) *H. erectus*	1.2E+06
(12) *H. heldelbergensis*	6.0E+05
(13) *H. neanderthalensis*	3.0E+05
(14) *H. sapiens*	1.0E+05

A.13. The milestones below have been compiled by the author and are influenced to some extent by the preceding 12 sets. In bold I highlight the main feature of each milestone

Milestone	Years ago
(1) **Big bang**/quarks/protons and neutrons/atoms of elements	1.5E+10

(2) **First stars**	1.2E+10
(3) **First planets**/rock solidification/solar system	4.6E+09
(4) **First life**/cooling of Earth/formation of first rocks/water forms	3.8E+09
(5) **First multicelluar life** (sponges, seaweeds)	1.0E+09
(6) **Cambrian explosion**/invertebrates/vertebrates	5.3E+08
(7) **First mammals**	2.0E+08
(8) **First primates**/asteroid collision	6.5E+07
(9) **First orangutan**	1.7E+07
(10) **First hominids**	6.0E+06
(11) **First stone tools**	2.6E+06
(12) **Development of speech**/*H. sapiens*	1.0E+06
(13) **Discovery of fire**/hunting–gathering society	5.0E+05
(14) Emergence of "**modern humans"**/earliest burial of the dead/agrarian pastoral/sociocultural systems	1.0E+05
(15) **Rock art**/ptotowriting	3.5E+04
(16) **Agriculture**/prehistoric nomadic bands/techniques for starting fire	1.0E+04
(17) **Discovery of the wheel/writing**/archaic empires/large civilizations/ Egypt/Mesopotamia	5000
(18) **Democracy**/city states/Greeks/Buddha	2500
(19) **Christianity**	2000
(20) **Gunpowder**	675
(21) **Renaissance** (printing press)/discovery of new world/the scientific method	500
(22) **Industrial revolution** (**steam engine**)/political revolutions (French, USA)	225
(23) **Modern physics**/radio/electricity/automobile/airplane/capitalism and colonialism	100
(24) **DNA/transistor/nuclear energy**/WWII/cold war/Sputnik	50
(25) **Internet/human genome sequenced**	5

Appendix B

The milestones below appear in the book of Richard L. Coren [9], *The Evolutionary Trajectory.*

He refers to them as "critical transitions in evolution on Earth."

Milestone	Years ago (centered)
(1) Big bang	1.5E+10
(2) Solidification of Earth prokaryotic life	3.5E+09
(3) Eukaryotic radiation	7.5E+08
(4) Appearance of class Mammalia	01.75E+08

(5) Appearance of superfamily Hominoidea	3.25E+07
(6) Appearance of family Hominidae	7.0E+06
(7) Appearance of genus *Homo*	1.75E+06
(8) Appearance of archaic *H. sapiens*	2.5E+05
(9) Appearance of *H. sapiens sapiens*	7.0E+04
(10) Development of communal villages	1.5E+04
(11) Development of writing	4000
(12) Development of printing	695*
(13) Development of digital electronics and computing	195*

*These dates are taken with respect to calendar year 2140.
See Table 4 and Fig. 6.

Table 4
Fit results

Formula fit	α	M	X_0	R	Average percent deviation
$ln\frac{M\alpha}{(1+e^{-\alpha(X-X_0)})(1+e^{\alpha(X-X_0)})}$	1.567	0.0092	12.83	.99956	1.33

The correlation coefficient R and the average percent deviation are given as measures of the fit goodness (no estimates for χ^2 possible)

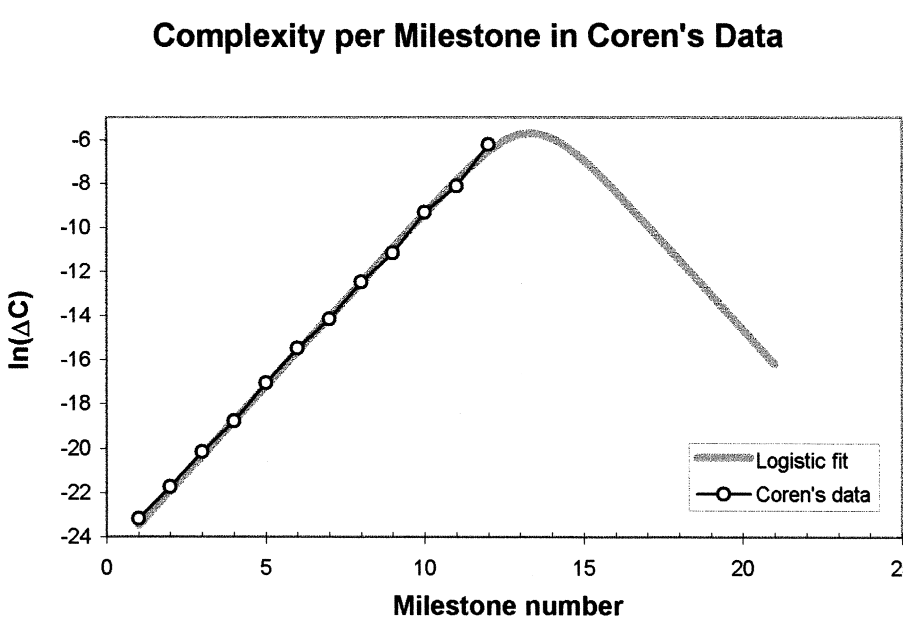

Fig. 6. Logistic fit to the data of Coren. The vertical axis depicts the logarithm of the change in complexity. The units of complexity are arbitrary and different from those in Figs. 3–5.

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