How Chaos Theory Brings Order to the Evolution of Intelligence

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Abstract: This study investigates links between human evolution, information transmission processes, and Chaos Theory, revealing a mathematical pattern underlying evolutionary milestones. By examining the timing of new methods of information transmission, the research confirms a suspected correlation with the Feigenbaum constant δ, a universal factor in Chaos Theory and also found in complex systems. This pattern is prominent in cultural evolution but also extends to biological evolution, as well as to the evolution of written language, suggesting a predictable framework for understanding the progression of complexity in life. The study incorporates findings from various disciplines, including cognitive science, archaeology, and nonlinear dynamics, providing evidence that our development, while it may be random in most aspects, is deterministic in the way complexity grows steadily and evolves information transmission of increasing sophistication. This multidisciplinary approach offers new insights into the links between chaos, complexity, and information, and their role in driving the evolution of intelligent life.

Key Words: Chaos Theory, Human evolution, Feigenbaum constant δ, Information, Accelerated evolution

1. Introduction

Big History and Evolution

Big History is the discipline of studying the past all the way back to the beginning of the universe from the human point of view to understand what happened. Ideally, we would like to have a single theory of evolution that covered the whole of Big History. The methodology used in most theories is to estimate the rate of increase of one or more evolutionary factors that have existed throughout big history, such as growth in energy, complexity, information, etc. Perhaps the work that has attracted most support is Eric Chaisson's proposal common measure of complexity, Free Energy Rate Density, or FERD (Chaisson, 2003). This is useful, because there is no generally agreed definition or measure of complexity and FERD can be calculated for astronomical objects as well as for objects on Earth. FERD has been praised as a metric, but Chaisson's writings about it have been criticized (Solis, Ken, 2023).

Many theories claim that evolution is accelerating. Some of them also include the idea of a technological singularity – defined as a point in time where technology is able to evolve itself faster than humans can develop it, and that the speed of evolution becomes very fast, very quickly (Kurzweil, 2014).

Chaos theory and Evolution

This paper proposes a theory based on information and complexity examined through the lens of Chaos Theory – also known as Non-linear Dynamics. Chaos Theory has a feature called Universality whereby various processes modelled by different mathematical functions can give the same results (Feigenbaum, 1983). In Linear Dynamics it is important that the correct mathematical functions are used. Not necessarily so in Non-linear Dynamics, where iteration of functions often obscures the differences between them and it can be enough to define relationships between variables as monotonic ("always increasing", or "always decreasing") and still get the same qualitative and quantitative result.

Chaos Theory Universality is potentially interesting for taking the different kinds of evolution– from the physical evolution of stars and planets, to the biological evolution of life, and cultural and technology development – and uniting them into a single theory where each kind of evolution behaves identically.

Unfortunately, history shows that that such a theory may not be taken seriously. When Chaos Theory was discovered in the first half of the twentieth century, "what made Universality useful also made it hard for physicists to believe. Universality meant that different systems would behave identically" (Gleick, 1987).

When Gleick wrote that in 1987, one may have thought that today, 35 years later, the mathematics of Non-linear Dynamics would be as widely used as Linear Dynamics was back then. Yet it seems that today there are still aspects of Non-Linear Dynamics that are not as well-known as they could be. It is widely thought

that Chaos Theory "proves" that "sensitivity to initial conditions makes evolution completely unpredictable."

In fact, Chaos theory also proves the very opposite – that given the right conditions, both chaotic and complex systems are completely *in*sensitive to initial conditions. This misunderstanding of Chaos Theory means that the prevailing view among evolutionary biologists is to be skeptical of theories that claim that evolution can be predicted in any way.

The unpredictable rate of evolution

As well as unpredictability about how organisms will evolve, Gould and Eldredge proposed that evolution is also unpredictable in speed, with their theory of punctuated equilibria. (Eldredge & Gould, 1997; Gould, 1990). However, more recent research challenges the paradigm, with evidence that evolution may be more predictable than currently thought (Kryazhimskiy et al., 2014)

Evolution as the accumulation of information

The events on which this paper is based concern the evolution of information. Big History theories often talk about the phases of evolution – especially Physical, Biological, and Cultural. Technological Evolution, starting with the evolution of Tools, is sometimes separated from Cultural Evolution, sometimes considered a part of Cultural Evolution. Carl Sagan wrote a book showing how that information was a common thread throughout evolution (Sagan, 1977). The information in question is information about how to survive and prosper. From an information perspective it can be useful to refer to Information Technology Evolution, which begins with Written Language. This means that Information was stored in a different way for each phase of evolution. This paper uses the following classifications of information:

- **Physical evolution** saw the evolution of the universe, stars and planets, eventually resulting in cell-like molecular structures. These structures "knew" how to survive, but there was no information other than the structure itself.
- **Biological evolution** saw the first living cells that could replicate themselves, or modified versions of themselves, from coded instructions (coded, for example, in DNA). From this point the prime mechanism of evolution was no longer direct change to the cell but change to the coded instructions in the cell's DNA.
- **Cultural evolution** began when animals had sufficient awareness that they could recognize others of the same species and imitate and learn their behaviour and skills so that these useful skills can be passed on to future generations, thereby replicating the skills (Huber et al., 2009). Useful behaviour that results is stored in the phenotype (i.e. in the body – for example, in the brain) but not in the genotype (DNA). Learning led to teaching, which then co-evolved with tool development and language, all of which was a significant driver of biological evolution (Morgan et al., 2015).
- **Information Technology Evolution** began when information was stored "extrasomatically" ("outside the body") as written language.

(Note that this paper refers to evolution of Information Technology as separate phase after Cultural Evolution, and distinct from other kinds of technology such as Stone Tools, which evolved during Cultural Evolution together with communication and language.)

Also worth noting here:

- None of these phases of evolution have actually ended – all of them are still ongoing.
- Every stage has information replication, storage, and transmission, although with different formats and different information.

Looking at where humans are now, we can see that the accumulation of knowledge to survive and prosper is similar, if not identical, to the scientific search for knowledge in general as well as the knowledge to create useful things.

4.669...

Some authors have concluded that there is a characteristic rate of acceleration of evolution which can be expressed as events occurring at time intervals which become smaller. This paper also proposes an acceleration rate equal to 4.669. This number does not originate from an empirical study of history, but comes from the study of Non-linear Dynamics, also known as Chaos Theory. In particular it comes from a very common phenomenon known as a "Period-Doubling Cascade" or "Feigenbaum Cascade" (Cheung & Wong, 1987).

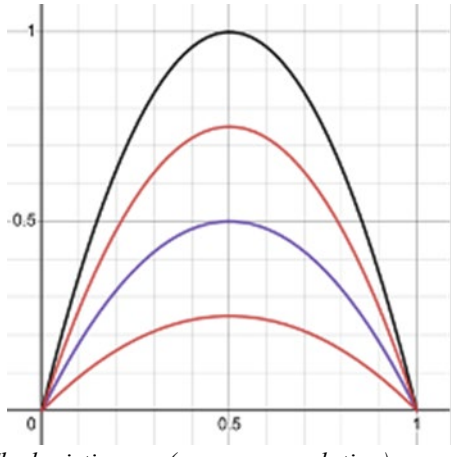

Figure 1: The logistic map (recurrence relation), $x \rightarrow r.x(1 - x/K)$, where r is population growth rate, x is population, K is carrying capacity of the ecosystem for the species. It is used to model systems with restricted resources. Shown for population growth rate, r = 1, 2, 3 and 4.

Feigenbaum Cascades are found in iterated nonlinear dynamic systems with limited resources. They are modelled using maps like the one in figure 1. (A map is a recurrence relation, which means that it is applied many times, with the output from each iteration fed back into the input.) At first the output increases as the input increases, but as the input increases to its maximum value, the output goes back down to zero and all the resources are consumed (Chen et al., 2021).

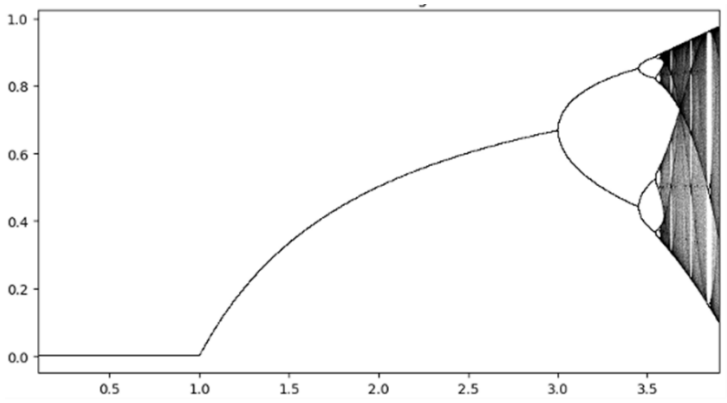

Figure 2: Feigenbaum Cascade. The simple logistic map, $x \rightarrow r.x(1 - x)$, where r is population growth rate, x is population (maximum is 1.0). When iterated, it displays chaotic behaviour, as shown. The ratio of intervals on the r axis between consecutive bifurcations converges to the Feigenbaum constant δ (4.669…). (The point where the population starts to rise above zero is called a transcritical bifurcation. The point where a line splits into two is called a flip bifurcation. Only the first three flip bifurcations can be seen on this diagram.) The bifurcations finish at the Accumulation Point (which, on this diagram, is approximately at r = 3.6) after which the chaotic region begins and cycles are non-periodic.

Figure 2 shows the "attractor" for a typical limited-resource map. The attractor shows the equilibrium value of x after many iterations as parameter r increases. At a certain value of r the output value x bifurcates into two values and oscillates (alternates) between the two values. Each bifurcation is usually accompanied by discontinuous changes in the process.

In a population model, the parameter r could be Population Growth Rate.

The relevance to evolution is that the Population Growth Rate could get higher as a species evolves, and there may be a link between Population Growth Rate and complexity.

Resource-Depletion Bifurcations occur in systems with limited resources, which is a substantial proportion of all systems. The bifurcations occur because a resource consumption threshold has been crossed, causing resources to be depleted to the level where starvation occurs, resulting in oscillations in the population level.

Very similar attractors can be found in, for example, 1) the pattern of drips from a dripping tap (where the parameter on the x-axis is water flow); 2) oscillations in neural networks; and 3) fluctuations of predator population in an ecosystem (where the parameter is population growth rate) (May, 1976). A remarkable feature of these bifurcations is that the ratio of distance between each resource-depletion bifurcation is always the same – namely 4.669, known as the Universal Feigenbaum constant δ. One always gets the same result from any "unimodal map" – that is, a map with a single "hump" – almost no matter what the exact function is.

The point here is that we could model say, a fish farm, using the simplest restricted-resource map – the Logistic map. Or we could study fish behaviour very closely, and make models – far more sophisticated than the Logistic Map – of how treatment with antibiotics increases the population growth rate in a fish farm. But the end result would still be a Feigenbaum Cascade with an acceleration that converges to 4.669.

Chaotic and Complex

The behaviours described here is not just applicable to simple Chaotic systems but also systems that are classed as Complex Systems, such as Life (Judd, 1990).

Teaching Methods according to Gärdenfors and Högberg

Gärdenfors and Högberg propose:

- That the most important forms of Information Transmission during Cultural Evolution – at least among human ancestors – were all forms of Intentional Teaching of offspring by parents. This was because Intentional Teaching provided the necessary fidelity for the acquired skills to be accurately passed on for an indefinite number of generations.
- That each new Teaching Method was added to the toolbox of methods and did not replace any earlier Teaching Methods, all of which remain active to this day.
- That there were six of these well-defined teaching innovation events during Cultural Evolution.

The intervals between the events in this sequence of events that appear to be close to the interval ratio 4.669. However, the question of dates is not simple.

Teaching techniques do not usually leave archaeological remains that can be dated. Gärdenfors and Högberg state that two of the teaching methods ("Demonstration" and "Communicating Concepts") enabled two important advances in toolmaking techniques ("Oldowan" and "Late Acheulean") to be taught. This implies that the teaching methods may have appeared some time before and applied to the tools later.

Relationship between teaching methods and tool innovations. I suggest an alternative scenario. It is reasonable to make the assumption that the tool innovations and the corresponding teaching method appeared simultaneously, as they are mutually dependent.

A likely scenario that one or both lay dormant until conditions reached a tipping point where they both became active – for example, when the net energy produced crosses the threshold from negative to positive). A stable equilibrium becomes unstable, which is what causes a bifurcation. It is the date of the tipping point, when the processes become active, that is the date of interest. Even if one event triggered the other (that is to say, a Teaching Method enabled a Tool Innovation, or vice versa), they can still be essentially simultaneous if one follows immediately from the other.

(Of course, seeing the tool innovation and the teaching method as two separate things is a human way of understanding them. Evolution, which produced them, does not "think" about them at all. In reality there are lots of parts and nothing works until the last piece is in place and the conditions are right.)

Assuming the Teaching Method and Innovation become active simultaneously, then if we can ascertain which teaching method belongs with which new skill, then if we know the (easy-to-find) date of the Tool Innovation, then we know the (hard-to-find) date of the Teaching Method.

Original work in this paper

Because Feigenbaum Cascades are so common, there is the possibility of finding them in Evolution, which seems to fulfil the relevant requirements of being an iterated non-linear dynamic process. The goal of this paper is to investigate whether Feigenbaum cascade has occurred during evolution resulting in its characteristic signature, the Feigenbaum constant δ, equal to 4.669201609102990671853203820466… to give the first 30 of an infinite number of decimal places, shortened, for readability, to 4.669.

The investigation begins with set of 6 methods of Intentional Teaching proposed by cognitive scientists for Information Transmission during Cultural Evolution (Gärdenfors, 2021; Gärdenfors & Högberg, 2017). These methods appear to follow a pattern similar to that of a Feigenbaum Cascade. Each new teaching method corresponds to new capabilities for the species in question. And each teaching method in Cultural Evolution transmits different information at a higher cognitive level and in a different form. Teaching methods seem to be the same across species. For example, great apes teach their young how to make tools, and so do some corvids (a group of birds including crows and birds related to crows).

Question 1. The first question asked is, does the interval between new teaching methods form a Feigenbaum Cascade? If so, the idea that evolution is completely unpredictable is disproved.

Question 2. The second question asked is, does this pattern extend into in the other phases of evolution – Physical, Biological, and Technological. If so, then we may be able to unite the different phases into one theory. In fact, we already know of two information transmission methods in Biological Evolution – cell division and sexual reproduction. So we shall be seeing whether these fit the pattern.

Information Channels. These other forms of evolution do not transmit information by teaching. The two biological methods transmit information via DNA. We can say that each new method transmits through a different Information Channel. The concept of an Information Channel works for all 4 different kinds of evolution.

Evolution Processes. Just as Information Channel is a generalization of Teaching method, we need another generalized term for Tool Innovation. I use the terms Evolution Process and Evolution Space. The Evolution Spaces are classes of phenotype traits or behaviours or extrasomatic artefacts that are adaptive (i.e. can change to give an advantage).

Just as certain tool innovations require a new teaching method, an innovation is not a new Evolution Space unless it needs a new Information Channel. Each stage of evolution has a new Evolution Process with its own Evolution Space. The new Evolution Process explores the new Evolution Space. The new Evolution Process adapts more quickly and so takes over from the previous Evolution Process and takes evolution in a new direction. Table 1 shows examples of Evolution Space / Information Channel pairs.

Are Eukaryotes an Evolution Space? Eukaryotes "invented" sexual reproduction, so are they an Evolution Space? No, because there are single-celled Eukaryotes. It is multicellularity, and the possibilities it gives, that drives evolution.

Evolution Space	Information Channel
Single-celled Organisms	Copying DNA during cell division
Complex Multicellularity	Combining DNA in sexual reproduction
Using Tools	Tool Transfer (parent gives tool to young)
Making Tools	Drawing Attention to an Object (parent signals to young to pay attention prior to a tool-making lesson)

Table 1: Examples of Evolution Space / Information Channel pairs

2. Methods

Aim of study
We suspect that intervals between dates of new Intentional Teaching Methods during Cultural Evolution to be shrinking by a constant factor equal to 4.669. So we would like to fit the curve to historical data, which should make it clear if such a pattern exists.

If the pattern is confirmed, we also want to see if we can find more events by calculating when they should happen using the Feigenbaum Constant $\delta = 4.669$.

Different kinds of dates
In this study, the events cover the whole of time up till now and can be very different in character, from single cells to human-made objects. The data is in the form of dates, with the following variations:

- Dates of Biological and Cultural Evolution, as revealed by fossils and artefacts, dated by using various techniques of different accuracies.
- Dates of more recent Cultural or Information Technology Evolution recorded in documents.
- Dates arrived at by considering many factors (e.g. Big Bang)
- The date of the Most Recent Common Ancestor may be used if a number of related species share a trait we are interested in.
-

First occurrence
In this study we are looking for the earliest confirmed date for all the events we are looking for.

Dating errors
There are different kinds of dating errors that can be made:

- A correctly identified fossil or artefact may give the wrong result from the dating technique used.
- An archaeological artefact may be identified correctly with the correct date. It may still be the wrong answer if one is looking for the earliest or the latest occurrence because there may be other artefacts that are earlier or later but have not been found.

Confidence levels
We are interested in the date of the earliest example of each object. Each date is really two dates representing an interval of 95% confidence. That means that there is a 95% probability that the actual date of the object is between the two dates. 95% is assumed unless explicitly stated, and all dates here are 95%. Some dates are known very accurately (small interval) and many less accurately (larger interval).

Presenting the data
The data is one-dimensional, consisting only of dates on a timeline, and the event associated with each date.

Scaling the data. The Feigenbaum Cascade is a geometric progression, which can be matched by a geometric series or a continuous exponential curve. The interval decreases geometrically in 10 steps from 13.8 billion years to a few thousand years, which is a difference of about 10 million in interval size. If we are to show the largest interval by a line that will fit on a sheet of paper, say about 20 cm, then the 6th interval will be 0.025 mm, and the following intervals will be too small to distinguish from one another.

We can solve this by using a logarithmic scale for the time axis (Lewis, 1960). This will make every interval appear the same size. This means we can see, for example, the difference between the theoretical and the actual intervals for all known events on the same diagram.

Methods Part 1: Confirming the Feigenbaum Cascade in Cultural Evolution

Least Squares Regression is a suitable method for fitting a theoretical timeline to a set of data points here. *Weighted* Least Squares Regression is better because some dates are more accurately measured, but was not possible in the time available for this study.

Methods Part 2: Extending the Feigenbaum Cascade: looking outside of Cultural Evolution

The second part concerns how the time-pattern is extrapolated forwards and backwards in time to see if the pattern indicates any more similar events before or after Cultural Evolution.

Extrapolation Method. If we have the dates of the seven Teaching Methods of Cultural Evolution and have confirmed that they are part of a Feigenbaum Cascade, we can extrapolate the sequence backwards and forwards in time to find new dates where we would expect to see more Information Channels created. The method for doing this is as follows:

1. Begin with the dates of the Cultural Teaching Methods
2. Create a best-fit timeline for the data points.
3. With the Timeline, we can extrapolate in two directions. Extend the Timeline at each end by one event, using the Feigenbaum constant $\delta = 4.669$ to scale the interval:
    - multiply the time interval by 4.669 when going back in time, and
    - divide by 4.669 when moving into the future.
4. Look at the predicted dates and see if either of them corresponds to an existing Information Channel at that date.

5. (Optional:) If a suitable event is found at the given date, but no event found to follow, try including new dates in the data set and work out a new best-fit timeline. Repeat as needed.

3. Results

Results Part 1: Confirming the Cascade. Looking for evidence of the Feigenbaum Cascade in Cultural Evolution

Ratio of which intervals?	Ratio of intervals	Error compared to 4.669
1 and 2	24.5	+412%
2 and 3	4.72	+1%
3 and 4	5.69	+22%
4 and 5	4.49	-4%

Table 2a. First attempt to find a Feigenbaum cascade with ratios near 4.669. The table shows ratios of intervals between teaching methods, using data from archaeological and palaeontological sites. The expected ratio around 4.669.) The size of the ratio between intervals 1 and 2 has a large error (412% more than 4.669), which suggests a missing event. (There are 6 dates, so 5 intervals and 4 ratios between them.) Total error is +51%.

Ratio of which intervals?	Ratio of intervals	Error compared to 4.669
1 and 2	5.85	+25%
2 and 3	3.58	-23%
3 and 4	4.72	+1%
4 and 5	5.69	+22%
5 and 6	4.49	-4%

Table 2b. Second attempt to find a Feigenbaum cascade with ratios near 4.669, after Tool Transfer has been added between the first two events. The table shows ratios of intervals between teaching methods, using data from archaeological and palaeontological sites. (7 dates, so 6 intervals and 5 ratios between intervals.) The ratios are between 3.58 and 5.85. Total error is +2%

False start. The initial attempt to match Gärdenfors and Högberg's Teaching Methods to a Feigenbaum Cascade failed because one of the intervals was too large, by a factor roughly equal to $\delta + 1$ (4.669 + 1 = 5.669). This gap indicated that there may be a Teaching Method missing from G&H's list (table 2a).

Saved by Tool Transfer. This gap in the sequence is after the first teaching technique, Parental Approval or Disapproval. This technique is applicable to both behaviour without tools and behaviour with tools. The next teaching method, Drawing Attention (to an object), is used to indicate to the student that they are about to be shown something important about the object, namely, how to make a tool. In retrospect it seems obvious that the missing behaviour should be to do with learning how to use a found tool, because Tool Use is a higher cognitive threshold than behaviours without tools, and lower than Making Tools.

However, the behaviour in question (Tool Transfer, which is when the parent gives a tool to their young) does not involve teaching in the way we think of it. But Tool Transfer nevertheless fulfills the definition of a teaching method — that the student learns, that the teacher is present, and that the process involves a cost for the teacher (in this case the time and energy to acquire the tool) (Hunt & Gray, 2007). Tool Transfer is necessary for learning Tool Use because the student needs to practice with a suitable tool before they can learn the next part of Using Tools, which is to find a suitable tool.

Tool transfer was not recognized as a Teaching Method among chimpanzees until Musgrave reported it in a paper published October 2016 (Musgrave et al., 2016). Gärdenfors and Högberg's paper was published February 2017 on researchgate.org and contains no references after 2015.

The probable reason it was not known as a teaching method among chimpanzees until 2016 is that Tool Transfer is not observed in all groups of chimpanzees, possibly because of Genetic Assimilation of Behaviour, whereby acquired behaviours can become instinctive after many generations and therefore no longer need to be taught (Tierney, 1986) (see below).

Tool Transfer is still necessary for every tool that is taught, even today. All the other methods are still in use too, although perhaps updated.

As well as fitting the cognitive gap in the series of Teaching Methods, Tool Transfer also fits the mathematical sequence using the Feigenbaum constant δ (table 2b).

Cherry-picking avoided. The problem with the missing event indicates that events have not been cherry-picked to fit the interval ratio 4.669. Indeed, the authors do not mention any mathematical rule for the events. And there is nothing in any literature about the Feigenbaum constant δ in evolution at the time their paper was published. It follows that the authors were unaware of any mathematical relationship between the dates of each event and were not cherry-picking events to match a mathematical relationship.

Genetic Assimilation of Learned Behaviour. Genetic Assimilation of learned behaviour is a process by which learned behaviour may gradually become instinctive and no longer need to be passed on by teaching because it is passed on by DNA instead. This is thought by some to happen when the behaviour is established as part of the cumulative culture. Any genetic changes that aid this behaviour may be selected. Indeed, the whole behaviour may eventually become instinctive. New Caledonian

Crows brought up in isolation from other crows make tools, but their tools are not as sophisticated as the tools of the crows that learned the behaviour from other crows (Hunt & Gray, 2007). This may be an example of genetic assimilation of behaviour. Genetic assimilation may be a reason why teaching steps might not be observed in some populations of some species.

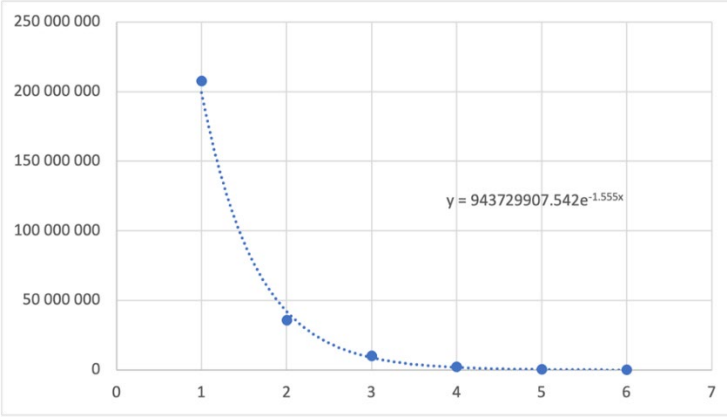

Figure 3. Event intervals and an exponential curve match to it (Microsoft Excel).

Figure 3 shows the intervals between successive events on a linear scale. Using commercial software (Microsoft Excel) an exponential curve has been fitted to the data. The formula calculated from the data by the software is

$$y = 943{,}729{,}907.542\ e^{-1.555x}$$

where x is the number of intervals. The result is averaged over all data points. If we want the average for one interval, then x = 1, and $e^{-1.555x}$ is 0.2112.

We want the reciprocal because the intervals are shrinking, not growing, which is 4.735.

This differs from the Feigenbaum Constant 4.669 by 1.4%. This is less than the combined error margins of the date measurements used, so we cannot expect a more accurate answer than this. A cascade of decreasing intervals with a ratio within 1.4% of 4.669 is very strong evidence of a Feigenbaum Cascade.

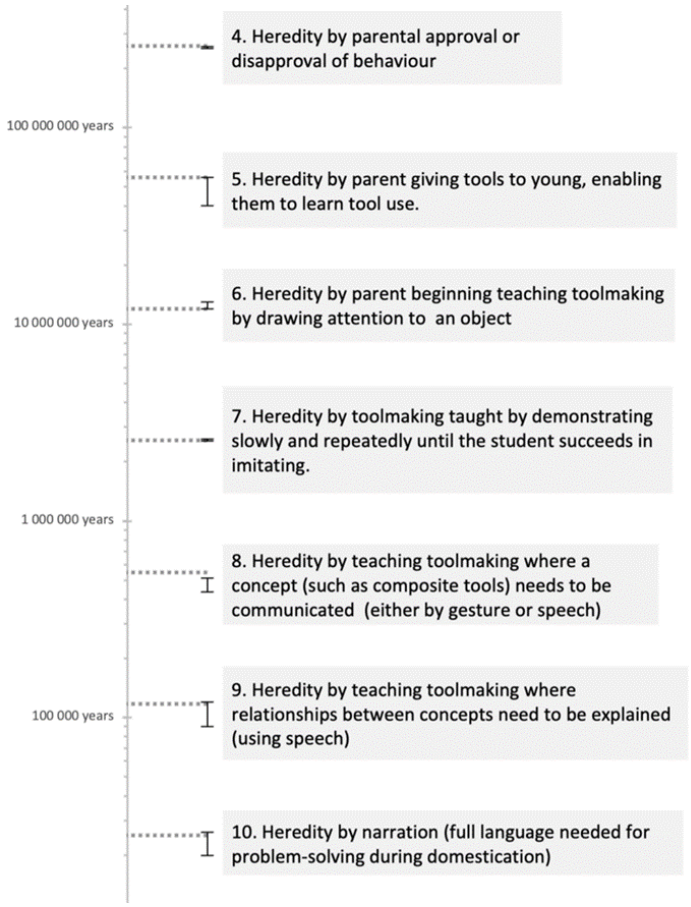

Figure 4. Timeline showing creation dates of the seven teaching methods (here called "heredity") that arose during Cultural Evolution. The error bars of each event are shown. They match the pattern of a Feigenbaum Cascade which is marked by the dotted lines. The timeline is scaled so that events appear equidistant. In linear time the interval between events decreases at each event by the factor 4.669 as predicted by Chaos Theory.

Figure 4 shows the Cultural Evolution events on a timeline. The actual date of the events are shown. The graph is scaled logarithmically as described in the methods section, so that successive intervals with the ratio 4.669 appear the same length on the graph. The dates match the pattern of a Feigenbaum Cascade (dotted lines), where successive intervals are shorter than the previous interval by the factor 4.669.

The Seven Information Channels of Cultural Evolution. The appendix shows the events of cultural evolution together. Each teaching method is an Information Channel. They are examined in

No	PREDICTED DATE years before 2000 CE	ACTUAL DATE years before 2000 CE	Actual vs predicted	INFORMATION CHANNEL	EVOLUTION SPACE
CULTURAL EVOLUTION:					
4	252 million	259 to 252 million	0%	Parental Approval and Disapproval	Sociality and Parental Care skills
5	53 million	56 to 40 million	0%	Tool transfer.	Tool Use
6	11 million	16 to12 million	-10%	Drawing attention to an object (aka Referential gestures).	Making Tools
7	2.57 million	2.60 to 2.55 million	0%	Showing by Demonstration - Performing tasks slowly and with repetition	Making Tools with Tools
8	502 thousand	550 to 450 thousand	0%	Communicating concepts.	New Concepts in Toolmaking (e.g. Composite tools)
9	106 thousand	120 to 90 thousand	0%	Explaining relationships between concepts	Tools with new functions
10	25 thousand	26 to 20 thousand	0%	Narrating (Complete language)	Domestication

Table 3. The seven Intentional Teaching Methods (Information Channels) of Cultural Evolution. Predicted dates that are within the error span of the measured dates are marked as 0% error.

No	PREDICTED DATE years before 2000 CE	ACTUAL DATE years before 2000 CE	Actual vs predicted	INFORMATION CHANNEL	EVOLUTION SPACE
PHYSICAL EVOLUTION					
1	26.8 billion	13.82 to 13.78 billion	-51%	Persistence of matter	Dissipative Systems
BIOLOGICAL EVOLUTION					
2	5.67 billion	4.28 to 3.77 billion	-25%	DNA copying during cell division	Single Cell Organisms
3	1.22 billion	1.22 to 1.17 billion	0%	Sexual Reproduction and gene recombination	Multicellularity (differentiated cells)

Table 4. Extrapolation of dates backwards from Cultural Evolution

more detail in table 3, together with descriptions of the Evolution Processes and an explanation of why the Information Channel and the Evolution Process are associated with each other. We start the numbering of the Information Channels with number 4, because we will see later that there are 3 Information Channels before Cultural Evolution.

Results Part 2a: Before Cultural Evolution.

Using the equation from the curve-fitting, and going backwards in time from the first Cultural Evolution event, gives the following results in table 4.

Date results

1. Date 1 is twice the currently accepted age of the universe.
2. Date 2, which we expected to match Single-celled Life, is off by a large margin. For it to be correct, Single-celled

Organisms would have had to evolve in space before the Earth was formed. This is not an impossible scenario, but beyond our current knowledge.

3. Date 3 is a match for Complex Multicellularity. Clearly, the date of Multicellular life is part of the same Feigenbaum Cascade as the Teaching Methods in Cultural Evolution. It has a unique Information Channel (DNA Recombination) and Evolution Process (Complex Multicellularity).

The two dates that are not close (Big Bang and Multicellular life) are not a problem for the Feigenbaum Cascade, because the first couple of numbers in a Feigenbaum Cascade often differ considerably from the ratio 4.669, depending on the non-linear map used. The important point is that the intervals converge to 4.669, and the dates above converge by event 3. Finding a non-linear map that fits the first two events in evolution is a suggestion for future research.

In summary, although the dates were not as expected, the errors can be reasonably accounted for and the data for the date nearest to the Feigenbaum Cascade in Cultural evolution strongly supports that idea that the cascade extends to the beginning of life and perhaps to the beginning of the universe.

Information Channels 1 to 3 are detailed in the appendix.

No	PREDICTED DATE years before 2000 CE	ACTUAL DATE years before 2000 CE	Actual vs pre dicted	INFORMATION CHANNEL	EVOLUTION SPACE
IT EVOLUTION					
11	4,734	4,600 to 4,500	2.9%	Teaching to Read and Write	Written Language

Table 5. Extrapolation of dates forwards from Cultural Evolution

Results Part 2b: After Cultural Evolution.

Using the equation from the curve-fitting and going forwards in time from the *last* Cultural Evolution event, gives the result in table 5.

Extrapolation into the future is difficult because of the wide confidence interval of the last event in Gärdenfors and Högberg's list, Narration/Domestication. The regression curve from Excel was used, without any calculation of errors.

The first of the dates found – Written Language – is the most reliable of the forecasts, being closest in time to previous events. Written Language is the first example of Information Technology and shows that the Feigenbaum cascade extends into the age of Information Technology Evolution.

Dates following Written Language are still under investigation.

Is this the end of evolution? Not according to the bifurcation diagram, the upper edge of which represents the maximum population, which continues to grow for a few billion years after the transition to chaotic behaviour. This is, of course, when simulating evolution with the Logistic Map. Further research may give more information about the characteristics of the actual map that fully matches evolution.

Information Channel 11 is detailed in the appendix.

Figure 5 shows the known Information Channels. Seven of them ("Parental Approval" to "Narration") are the Teaching Methods from Cognitive Science research, and the remaining ones are extrapolations of that sequence using the Feigenbaum constant δ, 4.669. It can be seen that the first two events do not match the Feigenbaum dates, but the events converge to the Feigenbaum dates by the third event "Sexual Reproduction". The initial error and rapid convergence are normal for Feigenbaum Cascades. The confidence intervals for each stage are shown. The horizontal lines represent the Feigenbaum ratio, 4.669. The scale is adjusted to a logarithmic scale (older dates are squeezed together) so that the Feigenbaum lines appear to be equidistant even though they get closer together as time passes. The results are also summarized in Table 6.

4. Discussion

Results from Part 1

We looked at the evolution of new teaching methods in Cultural Evolution. In order to date teaching methods, we made the (reasonable) assumption that new teaching methods arise simultaneously with milestones in tool technology, because they are mutually dependent. This apparently worked, because we got a positive answer to our first question, – Yes, there is a Feigenbaum Cascade in Cultural Evolution. The results clearly show the pattern of a Feigenbaum Cascade in the series of Intentional Teaching Methods during Cultural Evolution, where the difference between 4.669 and the average (mean) interval between Teaching Methods according to the fossil and archaeological record is 1.4%.

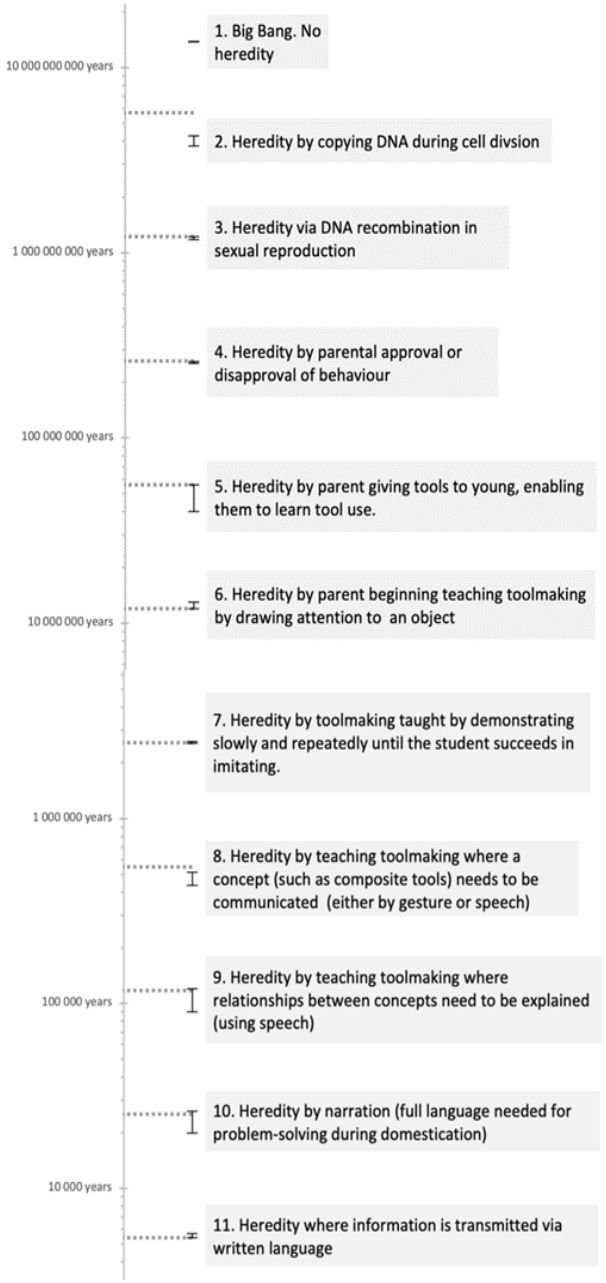

Figure 5. Timeline showing creation dates of the first eleven Information Channels (here called "heredity") that arose during Physical, Biological, Cultural and Information Technology Evolution. The error bars of each event are shown. They match the pattern of a Feigenbaum Cascade which is marked by the dotted lines, except events 1 and 2. The timeline is scaled so that events appear equidistant. In linear time the interval between events decreases at each event by the factor 4.669 as predicted by Chaos Theory.

Results from Part 2

We also generalized teaching methods to Information Channels and related innovations to Evolution Processes in order to find similar events in Physical, Biological and Information Technology Evolution.

This also apparently worked because we got the answer to the second question– Yes, this cascade extends into Physical, Biological and Information Technology Evolution.

Non-random Evolution

We can also state that evolution is not completely random, at least when it comes to the rate of decreasing intervals in Information Transmission.

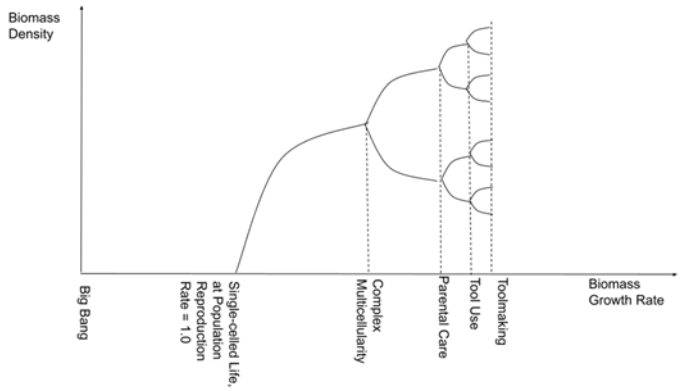

Figure 6. The first six stages of evolution of humans

The bifurcation diagram for Evolution

Figure 6 shows the beginning of a bifurcation diagram for the evolution of humans. Bifurcation diagrams are often used to show how population of a species varies as population growth rate (or birth rate) changes. Normally one would draw a diagram for a single species, with the horizontal axis being birth rate and the vertical axis is population. For a given birth rate the map is iterated until the population settles down to an equilibrium value. It is the equilibrium value for each birth rate that is shown on the diagram. With no essential change in meaning of the axes, a bifurcation diagram can be used to represent evolution:

1. The diagram usually represents one species, but we shall be looking at a diagram for all human ancestors back as far as the beginning of prebiotic evolution.
2. The vertical axis is normally population, but as species change during evolution and individuals change in size – especially in the transition from unicellular to multicellular organisms – it is more useful to measure the biomass density (biomass per unit area).
3. The horizontal axis commonly shows birth rate for a population. In an evolutionary context, the equivalent

measure is Population Growth Rate, which is a measure of Darwinian fitness. Again, to allow for size of individuals we shall use Biomass Growth Rate. But we shall make 2 assumptions –

- The biomass growth rate increases with complexity
- Complexity increases with time.

No	PREDICTED DATE years before 2000 CE	ACTUAL DATE years before 2000 CE	Actual vs pre- dicted	INFORMATION CHANNEL	EVOLUTION SPACE
			PHYSICAL EVOLUTION		
1	26.8 billion	13.82 to 13.78 billion	-51%	Persistence of matter	Dissipative Systems
			BIOLOGICAL EVOLUTION		
2	5.67 billion	4.28 to 3.77 billion	-25%	DNA copying during cell division	Single Cell Organisms
3	1.22 billion	1.22 to 1.17 billion	0%	Sexual Reproduction and gene recombination	Multicellularity (differentiated cells)
			CULTURAL EVOLUTION:		
4	252 million	259 to 252 million	0%	Parental Approval and Disapproval	Sociality and Parental Care skills
5	53 million	56 to 40 million	0%	Tool transfer.	Tool Use
6	11 million	16 to12 million	-10%	Drawing attention to an object (aka Referential gestures).	Making Tools
7	2.57 million	2.60 to 2.55 million	0%	Showing by Demonstration - Performing tasks slowly and with repetition	Making Tools with Tools
8	502 thousand	550 to 450 thousand	0%	Communicating concepts.	New Concepts in Toolmaking (e.g. Composite tools)
9	106 thousand	120 to 90 thousand	0%	Explaining relationships between concepts	Tools with new functions
10	25 thousand	26 to 20 thousand	0%	Narrating (Complete language)	Domestication
			IT EVOLUTION		
11	4,734	4,600 to 4,500	2.9%	Teaching to Read and Write	Written Language

Table 6. Actual and predicted dates for all stages of evolution

The diagram starts with the Big Bang at the origin. Physical and pre-biotic evolution take place, the Earth is formed, and at some moment in time on Earth, the population of the first living cells begins to rise above zero at the first complexity threshold, when complexity is high enough for proto-cells to become sustainable living cells, in other words, when their Growth Rate is greater than 1.0.

In Population Dynamics, bifurcations are caused by overconsumption due to delayed negative feedback increasing above a threshold, which can be caused by various reasons, such as the weather. Overconsumption causes disturbs population, causing it to oscillate. The oscillation appears as a bifurcation in the diagram. The population oscillates or alternates between two values instead of settling on one value. It is a cycle of feast and famine, of starvation and population recovery.

Step Change in Adaptation Speed

I propose that overconsumption and population oscillation is also happening in evolution, but that the cause is step changes in adaptation speed at each bifurcation (for example, at multicellularity, Parental Care, Tool Use, etc). This agrees with what is seen in bifurcation diagrams – at a bifurcation, the population starts increasing at a sudden higher rate, which can be explained by a sudden increase in adaptability causing a greater increase in population. Increase in population requires more food, but because food is limited, there will a shortage of food the next year because the food source it is not able to replenish itself in time. This is delayed negative feedback, causing starvation.

Paradoxically, the oscillations punish the increased adaptability. But this does not necessarily matter because there may be other advantages that do not show up in a bifurcation diagram, such as the ability to adapt to other habitats. It is important to note that any such oscillations would not affect the complexity, and the complexity would not oscillate. The causation would be in one direction.

Cause of Step Change in Adaptation Speed

What causes the step change in adaptation rate and why does it behave as a Feigenbaum Cascade? Feigenbaum Cascades are an indicator of limited resources, which express themselves (in life, at least) as patterns of starvation and population recovery. What is the limited resource in evolution? Food is a limited resource, but not a diminishing one on an evolutionary timescale. Any shortage is essentially temporary.

Another possibility is the amount of free energy from the sun. But this is only limited by our ability to use it, and there is far more than we can use for a long time.

Cost of Complexity

A more likely possibility is complexity. There is something called the Cost of Complexity which says that as the complexity of an organism increases, it gives diminishing returns because beneficial changes become less and less likely (Allen Orr, 2000). This means diminishing returns on an evolutionary timescale. Looking at the Bifurcation Diagram for Evolution, this explains the reason why all curves at every bifurcation start out steep and become less steep as time moves on and complexity increases.

New evolution processes at complexity thresholds

This would also explain the opportunity for new Evolution Processes. Due to the cost of complexity, an Evolution Process inevitably exhausts the possibilities for adaptation that exist in its Evolution Space, and slows down, giving a chance for another Evolution Process to take over. Because although complexity has caused the slowdown, complexity is increasing elsewhere, creating a new evolution process ready to take over at the next threshold when its contribution to population growth exceeds 1.0 (echoing the first appearance of life, and perhaps the Big Bang was a similar threshold). A new Evolution Process takes hold of evolution at a bifurcation and takes it in a completely new direction which is outside the box of the previous Evolution Process, and explores a different Evolution Space, where things are simple again and innovations come thick and fast.

Complex and Simple at the same time – Encapsulation of Complexity

Things that are complex in one Evolution Space can be simple in other Evolution Space. For example, single cells are complex inside, but for the Evolution Process that drives multicellularity, all of that complexity is hidden inside the cell. Multicellular complexity is about how cells work together, in which the function provided by cells is important, but not how that function is achieved. In a sense, the cells provide various services to the body, and the body does not have to know about the inner workings, just how to control them by sending signals. The knowledge in the cells is encapsulated.

This is probably true of the relationship between every level. For example, the evolution of Tool Use involves changes to adjust the body schema (a hypothetical map of the body) to make Tool Use easier. Higher levels of evolution can make use of the body schema without having to know details of its implementation.

Levels of Information

Each stage of evolution has a new Evolution Process, new Evolution Space, and a new Information Channel. The new

Information Channel stores a new kind of data compared with the previous stage. Just as each new stage uses the products of the previous stage as if they were service-providing opaque boxes with hidden complexity, so the information for each stage is also limited to a single level, so that every level has its own unique level of information, and which may be stored in a completely different way on, or in, entirely different media.

Levels of Cognition may match Information Levels

It would make sense if the subjective interpretation of information, and the ability to understand it, are divided into the very same levels. G&H associate each Teaching Method (i.e. Information Channels 4 to 10) with a new cognitive level, requiring an increasing level of mind reading, cognition and communication. This raises the question of whether the other stages can be considered to have increasing level of these attributes, or whether equivalent attributes can be defined. Single cells are considered to have cognition (Shapiro, 2021). And Written Language is considered to have impacted human cognition (Pegado, 2022). This supports the idea that the stages of evolution are also stages of cognition.

The old Evolution Processes continue

When an Evolution Process hands on the baton of evolution to another Evolution Process, it does not stop operating. It continues in co-evolution with the new Evolution Process. The new Evolution Process determines the direction of evolution, and the old Evolution Processes continue to generate variation, albeit at a slower rate than the current Evolution Process, and variations that help the current Evolution Process will tend to be selected. For example, biological changes in early humans to improve communication by speech. The very same changes would not have given any advantage before speech began to be used and would not have been selected.

Period-doubling absence

Period-doubling population bifurcations have not been found in real ecosystems. They are considered sensitive to external perturbations (in the forms of noise or immigration) (Rohani & Miramontes, 1996). This need not be a concern. The cause of bifurcations is increased complexity, which may create adaptations anyway, no matter what. In any case, it seems that if period-doubling is too sensitive to exist in real ecosystems, it is often replaced by quasiperiodic bifurcations instead and they can also follow the Feigenbaum constant 4.669 (Van Veen, 2005).

Recursion

Each new Evolution Process uses some capabilities that are the products of the previous Evolution Process. In this sense, evolution is recursive. A product of evolution becomes part of the process of making more products of evolution.

Linearity

It is in the nature of the bifurcation diagram that the exact relationship between variables such as time, complexity, population/biomass density growth rate, etc., do not have to be linear – it is enough that they are monotonic (roughly, that they increase together). The decreasing intervals have the effect of sampling a shorter and shorter part of any curve, so that they become more and more linear.

The stages shown in the diagram are stages 1 to 5 in evolution. There are an infinite number of bifurcations in theory (in reality there will be a minimum size limit below which there will no more bifurcations) which finish at the Accumulation Point. After that, the biomass density is non-periodic (that is, non-repeating, or in other words, with an infinite period).

More on Bifurcations

It may seem strange to equate the evolution of intelligent life with a dripping tap. It can be done because Chaos Theory takes control of certain kinds of process and imposes a Feigenbaum Cascade onto the process. This a consequence of applying *iterations* to the process.

At every bifurcation, the process that has been taken over repeats the thing it started with, but with increasing complexity.

For example:

- In a dripping water tap, every bifurcation changes the pattern of water drops.
- Treating a fish farm population with antibiotics can cause bifurcations that change the number of fish that die of starvation.
- In evolution, each bifurcation marks the creation of a new Evolution Process and a new Information Channel. The first single-celled life created an Evolution Process and an Information Channel, and every subsequent bifurcation does the same.

Within a particular process, each bifurcation will be of the same type, but also different in some respects to the previous bifurcation. This applies whether the Bifurcation Parameter is time, amount of antibiotics, or water flow rate.

Self-replication involves all the stages of evolution in the same sequence

Self-replication of an organism goes through all of the stages that arose during evolution. Single-celled organisms simply divide into two independent daughter cells, copying the DNA in the process.

Complex multicellular organisms have another Information Channel in Sexual Reproduction, where DNA

from two parents is combined. Once the DNA has been combined in a single cell, the Information Channel for single-celled organisms takes over. Using the Information Channel for single celled organisms, the single cell divides into two daughter cells, copying the DNA for several kinds of cell, plus instructions for development from single cell to mature organism. But as cell division continues, the cells stay together and differentiate, as the cells begin to follow new instructions on how to grow from one cell to maturity.

Replication of organisms at higher states of evolution involves not just biological replication, but also teaching (or "transmission of cultural information through the Information Channels that evolved during Cultural Evolution"). Replication of an organism is only complete when transmission on all Information Channels is complete (aka "upbringing").

Bifurcations of permanent advantage

I have claimed that mismatch in adaptation rate causes a permanent alternating population bifurcation among the species involved. This is partly corroborated by Adams & Matsuda who find that differential Evolution Process rates cause permanent population oscillations, even when different parameters would result in a steady state (Abrams,Peter & Matsuda,Hiroyuki, 1997). That these are period-doubling bifurcations is not confirmed.

Simple life is also needed

Humans need the ecosystems of the Earth. We do not photosynthesize and are not primary producers. It follows that not all forms of life on Earth can evolve in the same direction as humans, or to high complexity in any direction. Single-celled organisms are still well-represented in the total biomass of the Earth. This does not mean they have a different Feigenbaum Constant. Their evolution has stopped perhaps because they have no need to evolve, just a need to adapt to change. Or perhaps there is no route for them out of the ecological niche they find themselves in.

The route to intelligence may be the same for all

Some animals have been evolving in the same direction as humans have done, and the stages towards intelligence seem to be universal, at least on Earth. The Great Apes and some Corvids (New Caledonian crows, ravens) have climbed the same event ladder, past Tool Use, and have reached the stage of Toolmaking.

Does this hypothesis mean that evolution is predictable?

This paper is about the increase in complexity with time and how thresholds of complexity predicted by the Feigenbaum Constant 4.669 give rise to new Information Channels and Evolution Processes, and an increase in adaptation rate. It does not predict what animals may evolve, only the capabilities of the most advanced species. Only the complexity of life follows a regular predictable pattern. All other aspects of evolution may still be completely random.

Heredity vs Communication

During Cultural Evolution, information begins to be transmitted horizontally – that is, within the same generation – and not just strictly from parent to offspring.

How did this pattern not show signs of shocks by meteorites, epidemics, climate change, etc?

Random external mass-extinction events, such as the extinction of dinosaurs by meteorite, is an oft-quoted reason for unpredictability. However, Natural Selection is constantly removing species, usually those species that are at the bottom of the scale of adaptability, allowing the more adaptable species at the top of the scale to live on. Whether circumstances and conditions remove 1% or 99% of species, the most adaptable and most evolved species are more likely to survive.

The theory presented is largely about organisms that are the most advanced and most adaptable, those at the cutting edge of evolutionary complexity and have advanced furthest along the proposed stages.

Also, the theory is about stages of evolution, not population levels, so evidence of low population level does count as disruption unless it led to delays.

There is every reason to believe that it is possible for even the most resilient species to be disrupted, there was no obvious evidence to that effect.

Evidence for a Fiegenbaum Cascade.

- Cherry-picking has been ruled out.
- Evolution is an iterative, nonlinear, dynamic process.
- The dates match a Feigenbaum Cascade
    - Decreasing interval between events.
    - Interval ratio converges rapidly to 4.669.
    - Bifurcations signify a physical change that is similar but different to the previous one.
- All selected events are of the same type:
    - Information is new
    - Information is of one level of evolution.
    - Format of information may be new
    - Means of transmitting information may be new
    - Means of storing information may be new
- Evolution stages can be explained by Chaos-Theory Universality (different processes, same qualitative and quantitative result).
- The bifurcation tree (Feigenbaum Cascade) can be explained as follows:
    - horizontal axis matches

        - biomass density (population) growth rate,
        - which increases monotonically with complexity,
        - which in turn increases monotonically with time
    - vertical axis matches Biomass density (biomass per unit area) (population)
- There are diminishing resources over the course of evolution, causing the population instabilities. (The diminishing resource is possibly "beneficial changes", due to increasing complexity)
- There is evidence that the Feigenbaum Cascade is also found in complex systems (Judd, 1990).

Summary of argument.

- As evidence that the cherry-picking of events to match dates has not occurred, the original series of teaching events is based on a paper on cognitive archaeology research which does not mention dates or Feigenbaum cascades.
- As further evidence that the events where not cherry-picked, the original series did not conform to the Feigenbaum cascade because one of the events (Tool Transfer) was missing. The series, once corrected for reasons of cognitive archaeology, also now fulfilled the chaos theory conditions for a Feigenbaum cascade.
- Extrapolation, using the equation of the regression curve of the series, finds:
    - 2 events at the beginning of evolution that show expected rapid convergence to the cascade interval ratio. (Physically, the difference for the first two events may be due to the fact that the first event and possibly the second event, did not occur on Earth because they occurred before the Earth was formed.)
    - The date of Written Language very close to the cascade interval ratio.
- All of the known events are of the same kind and represent distinct stages of type and format of information during evolution.

Limitations of the study

- Lack of specification of Evolution Process in G&H's paper.
- Lack of associations between Teaching Methods and Evolution Process in G&H's paper.
- The following assumptions have been made:
    - That new Evolution Process and Information Channels become active at the same time
    - That sex and multicellularity are mutually dependent
    - That the worked stones found at Lomekwi 3 are not tools, but were used as a mineral diet supplement as modern capuchin monkeys do.
    - That Full Modern Language and domestication are mutually dependent.
- The theory rests rather heavily on Gärdenfors and Högberg's articles.
- The processing of numerical results could be improved.

Conclusions

Information and Evolution

This study began as an investigation into whether it was significant that the sequence of new information transmission (inheritance) processes (which during Cultural Evolution took the form of new methods of Intentional Teaching, proposed by Gärdenfors and Högberg) seemed to follow the same pattern found in many chaotic processes.

The result is a hypothesis that proposes that the entire history of evolution is a Feigenbaum Cascade of new Information Transmission processes (Information Channels), each of which was needed for passing on innovations in the way organisms adapt and evolve.

Evolution has followed a mathematical series, which suggests that the milestones of evolution – such as tool-use or language – are generated by the evolution of life, not by external events. It follows that evolution is a result of the increasing complexity of life. As each stage slows, it supports, and is revitalized by, newer stages. These new stages are the result of new Evolution Processes at complexity thresholds. These Evolution Processes produce innovations that lie within the Evolution Space of the Evolution process. Successful innovations are passed on by new transmission methods (Information Channels).

Knowledge is Power

The hypothesis follows Carl Sagan's insight that information unites the different phases of evolution. It supports the idea that the evolution of life, once started, is compelled to evolve intelligent life. Cells began by exploring which random sequence of instructions in DNA survive best. Each subsequent stage of evolution accumulates more information for the same reason.

It should not be surprising that information is at the heart of evolution. From the beginning of life, the amount of resources – such as energy and food – that could be captured and consumed by a cell depended on the information in the DNA. Information becomes active when it is converted into physical complexity and into behaviour. And the importance of replication and transmission of information to the next

generation is underlined by the fact that it is a distinct set of processes within the replication of the species.

Universality

While not being a proof, the universality found in Chaos Theory explains how it is possible that each stage of evolution can fit into a Feigenbaum Cascade, despite the fact that the evolution process changes at every stage. The first two dates have the biggest deviation from the logistic map, but we don't know whether the logistic map is the best model for Physical evolution and single-cell evolution. Neither do we know how much of the first two stages took place on Earth, which may have different rate of evolution. However, the remaining stages (Stage 3 onwards) fit the Fiegenbaum Cascade reasonably well.

Significance.

If the hypothesis is proved correct, it could potentially have a wide impact because it covers a wide span of subjects from physics to behaviour. It is likely to also influence the debate about humankind and our place within the universe. And it offers a simple yet rigorous theoretical framework for understanding Big History.

Directions for further research

- Find more events that may have occurred since the invention of Written Language.
- Develop a reliable and clear definition of important events that fits only the events within the cascade and excludes all other events.
- Find quantitative predictions or metrics that can be verified. For example, the speed of the Evolution Processes, or the effect on speciation at each level.
- Create a theory from first principles that explains the entire evolution sequence in detail.
- Find a non-linear map that fits the Big Bang and Single-celled Organisms.

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Appendix

Information Channel 1

Information Channel: Limited Heredity
Evolution Process: Dissipative Systems

Description: The Big Bang is thought to be the beginning of the universe and is used here as a reference point. There is no life, self-replication, heredity, or modification. But there is Physical Evolution which will eventually produce these things(Lazcano, 2018).

Why did they appear together? Dissipative Systems, far-from-equilibrium systems that create order at the cost of increasing entropy, are considered to be a possible route to the evolution of Life. Dissipative Systems have a form of heredity that is limited, and not sufficient for life.

Earliest known date? 13.82 to 13.77 billion years before 2000 CE (Planck Collaboration et al., 2020) (-50% compared to predicted interval)

Information Channel 2

Information Channel: DNA copying
Evolution Process: Single-celled life

Description: Information Channel: DNA copying during cell division (Lemmens & Lindqvist, 2019). Evolution Process: Single-celled life (Brunet & King, 2020).

(Variation: Mutation(Griffiths,Anthony, 2023).)

Why did they appear together? They both appeared at the same time in the first living cells.

Earliest known date? 4.28 to 3.77 billion years before 2000 CE (Dodd et al., 2017) (-25% compared to predicted interval).

Information Channel 3

Information Channel: Sexual Reproduction
Evolution Process: Multicellularity

Description: Heredity: Sexual Reproduction (Butterfield, 2000). Evolution Process: Multicellularity (Butterfield, 2000).

(Variation: Recombination of gene alleles (Britannica editors, 2023).)

Why did they appear together? It is suggested that Sexual Reproduction arose first and solved the problems that made Complex Multicellularity unviable, and that Multicellularity began immediately afterwards (Butterfield, 2000).

Earliest known date? 1.22 to 1.17 billion years before 2000 CE (Butterfield, 2000).

Information Channel 4

Information Channel: Parental Approval
Evolution Process: Parental Care

Description: Parental approval or disapproval is when a parent signals to their offspring that their behaviour is correct or incorrect. Intentional teaching can be a simple "grunt of disapproval". It improves the fidelity of their learning so that it is sufficient to be passed on indefinitely (Gärdenfors & Högberg, 2017). Teaching requires learning of course. The theory of Social Learning in humans concerns how humans learn from each other. Social Learning is thought to occur by observation and imitation. Imitation requires the evolution of vision. Parental Care is adaptive as it can increase offspring fitness.

Why did they appear together? Parental Care is needed for teaching by Parental Approval/Disapproval. The earliest teaching among animals is not known, but from an energetic point of view it is reasonable to assume that would have arisen at the same time as parental care, because looking after offspring must in the long term take more energy than teaching them to look after themselves (Gärdenfors & Högberg, 2017).

Earliest known date? There are two possible fossil candidates:

- One candidate is fossils of a group of Cynodonts (precursors to mammals) of adult and juvenile age, known to live underground in burrows, and therefore probably social by necessity and have the opportunity for Parental Care, 259.1 to 251.9 million years before 2000 CE (Damiani et al., 2003).
- There is another candidate, although only one adult and one juvenile reptile together, under a tree. It is a less clear case that the Cynodonts. The reptiles may not have been related, and could simply have been sheltering from a storm under the same tree. This fossil is dated 309 to 306 million years before 2000 CE (Maddin et al., 2019).

Given the relative uncertainty of the reptile case and the more relatively clear reptile Cynodonts, it seems admissible to exercise some discretion and choose the event that best suits the theory.

Cynodonts, 259.1 to 251.9 million years before 2000 CE, or
Reptiles, 309 to 306 million years before 2000 CE

The result is that the Cynodont case fits the Feigenbaum Cascade much better than the reptile case.

Information Channel 5

Information Channel: Tool Transfer
Evolution Process: Using Tools

Description: Use of tools refers to Found Tools, objects found and used as tools. But a tool is not just an object that is found or made by an animal. A tool is an extension to the body that is used to manipulate the environment, although there are alternative definitions (Cabrera-Álvarez & Clayton, 2020). Many animals are thought to have a Body Schema which tracks the body and limbs in 3D space. Tool-users are thought to have a flexible Body Schema that can incorporate tools and, for example, track the working tip of the tool in three-dimensional space. Using tools is a Evolution Process without DNA changes. Tools can be added and discarded at will and in real time. Tools do not work with the Parental Approval Information Channel, because offspring need to be given an appropriate tool for the task being taught. The giving of the tool is called Tool Transfer. Only after mastering the tool can the student find their own tools.

Why did they appear together? Tool Transfer is the most basic of the tool actions and naturally belongs with the first use of tools (Musgrave et al., 2016)

Earliest known date? The use, as tools, of rocks and twigs found lying on the ground, has left no trace in the archaeological record. We don't know the exact date of first tool use, but we can narrow down the range by estimating both the earliest and latest likely dates of the first tool use. The earliest date of first tool use is most likely when the first primates appeared 56 million years before 2000 CE, because many, though not all, primates use tools today and it is likely that they were the first tool users (Steiper & Seiffert, 2012). Because they live in trees, their front legs and feet have evolved into arms and hands with opposable thumbs for grasping branches and holding onto fruit while they eat.

We don't know if the earliest primates used tools. Not all primates today use tools. But if we assume that all the descendants of first tool-using primate also use tools, then that primate is likely to be the Most Recent Common Ancestor of all the primates that use tools today. These include tool-using new world capuchins (Judd, 1990) and old world tool-using primates (humans, gorillas, chimpanzees, orangutans, and macaques). The Most Recent Common Ancestor of these was around 40 million years before 2000 CE, which we can use as the last likely date of first tool use.

Likely least recent date of first tool use = 56 million years before 2000 CE.

Likely most recent date of first tool use = 40 million years before 2000 CE.

*Most Recent Common Ancestor (or Last Common Ancestor) method. If two species share a rare trait and share ancestors, then there is a high likelihood that both inherited the trait from their Most Recent Common Ancestor (Haslam, 2014). The date of the Most Recent Common Ancestor gives the most recent date by which the trait had appeared. (Not to be confused with LUCA, the Last Universal Common Ancestor of all life on Earth).

Information Channel 6

Information Channel: Drawing Attention, aka Referential Gestures
Evolution Process: Making tools

Description: Young are naturally curious when they see their parents using tools to get food, and naturally try to join in. Seeing the parent making a tool does not elicit the same interest. The parent must draw their attention, indicating that they should watch how to make a tool (Locke et al., 2011). The Evolution Process is the making of, and improvement of, tools.

Why did they appear together? Both are concerned with the simplest means of making tools. Teaching how to make tools belongs naturally with Making Tools (Gärdenfors & Högberg, 2017).

Earliest known date? 16-12 million years before 2000 CE. Last Common Ancestor of toolmakers orangutans (Laumer et al., 2018) and humans (Locke et al., 2011).

Information Channel 7

Information Channel: Demonstration
Evolution Process: Making Tools with Tools

Description: Hands can strip leaves from a twig, but they cannot make a sharp stone knife. Another tool is needed that is harder than the tool that is being made. Also, a tool is made at the same time as a tool used These tools need to be taught by demonstration. In other words, the teacher slows down and repeats actions, for example (Gärdenfors & Högberg, 2017).

Why did they appear together? Teaching how to use a tool to make a tool using Oldowan stone technology requires careful instruction (Gärdenfors & Högberg, 2017).

Earliest known date? 2.60 to 2.55 million years before 2000 CE.

Notes. A site in Africa known as Lomekwi 3 apparently has tools with conchoidal flakes that are as old as 3 million years (Harmand et al., 2015). If true, that will be a problem for this paper. But this interpretation of the findings at the site has been questioned. Capuchin monkeys in Brazil have been filmed producing conchoidal flakes accidentally while breaking rocks to obtain quartz to supplement their diet(Proffitt et al., 2016). “The accumulation and the stones, if discovered in a three-million-year-old context in Africa, might be taken as evidence of an early stone tool culture.” Also, the Lomekwi 3 “tools” are not considered to require the same level of cognition as the Oldowan tools (Gärdenfors & Högberg, 2017).

Information Channel 8

Information Channel: Communication of Concepts
Evolution Process: Tools with Concepts

Description: The use of tools that have a concept that needs explaining may give a competitive advantage (Gärdenfors & Högberg, 2017). Having tools made up of different materials is also a concept, and timewise, the first composite tools (wood spears with a stone head) also appeared at this time (Wilkins et al., 2012).

Why did they appear together? According to G&H, late Acheulean tools incorporated concepts that needed communication, either by gesture or by speech. One concept that originates from this event is Composite tools. The oldest composite tool artefact is a spearhead from South Africa. When dated with optically stimulated luminescence (OSL), a sample taken from sediments in direct association with the lithic artifact gives an age estimate of 511 to 417 thousand years, and an Equus capensis tooth recovered adjacent to the OSL sample gives a U-series/ESR age of 582 to 435 thousand years before 2000 CE, which is similar to and overlaps the other date (Wilkins et al., 2012). Assuming there is no reason to think that one method is more accurate than the other in this case, the simplest way to combine these is to simply take the interval of the overlap. This gives an interval of 513 to 435 thousand years before 2000 CE.

Earliest known date? Composite tool, 513,000 to 435,000 years before 2000 CE (Wilkins et al., 2012).

Information Channel 9

Information Channel: Explaining Relationships between
Evolution Process: Tools with new functions

Description: Information Channels 6, 7, and 8 improved on the original Found Tools, but this event saw the beginning of "Complex Culture and Cognition" and tools that had new functions (Hallett et al., 2021). The first definite example was a tool for making clothes, although no clothes survive from this time. The harpoon – a spear with barbs for catching fish – appeared thereafter, followed by more and more inventions. This stage may have required speech to explain the usage of the tools (Gärdenfors & Högberg, 2017).

Why did they appear together? New inventions required more explanation than improvements on existing tools (Gärdenfors & Högberg, 2017).

Earliest known date? Tools for making clothes. 120,000 to 90,000 years before 2000 CE (Hallett et al., 2021)

Information Channel 10

Information Channel: Narration (Complete Language)
Evolution Process: Domestication (New Livelihoods)

Description: The creation of new livelihoods is the new Evolution Process , beginning with the domestication of animals and plants. And the first of these was the domestication of the dog (Perri et al., 2021). Narration is the last stage of language development in Gärdenfors' hypothesis (Gärdenfors & Högberg, 2017).

Why did they appear together? The challenges of a change of lifestyle from the instinctive hunter-gatherer lifestyle require a complete language to enable logical thought in order to solve problems (Gärdenfors & Högberg, 2017).

Earliest known date? Domestication (of the dog) 25,950 to 19,650 years before 2000 CE (Perri et al., 2021).

Information Channel 11

Information Channel: Teaching Reading and Writing
Evolution Process: Written Language

Description: Heredity: transmission of information is by visual symbols. Information is stored "extrasomatically" (outside the body) on clay tablets or paper, which means the human memory capacity no longer restricts the amount of knowledge that can be accumulated.
The first Written Language developed out of Cuneiform, which had been used for bookkeeping for hundreds of years before it expanded to become a "true" Writing System, i.e. a system that can express everything that a spoken language can. Many texts have been found, but writing was not "coherent" until 4600 to 4500 years before 2000 CE.

Why did they appear together? They are both aspects of the same innovation.

Earliest known date? 4600 to 4500 years before 2000 CE (Cooper, 1999)