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Chaos Theory and Information Transmission in Evolution

Nicholas Hoggard [1]

[1] No affiliation; nick.hoggard+evolution@gmail.com

1. Abstract

There have been twelve occasions in the history of life on Earth when new ways of transmitting information to future generations have arisen. There are 2 biological mechanisms: Asexual Reproduction, and Sexual Reproduction. These are followed by no less than 7 cultural methods, all of them forms of intentional teaching of skills and/or language. Finally there are (so far) 3 information technology methods: Written language, Movable-type Printing, and Computers.

Remarkably, when dates are assigned to these events, they are consistent with the pattern of a period-doubling cascade described by Chaos Theory, the time between each event getting shorter by a factor which converges to 4.66920… a number known as the Universal Feigenbaum constant Delta.

Cherry-picking of data is not applicable because the 2 biological events are well known, and the 7 levels of teaching have been arrived at by studying the development of tools by early humans and without regard for dates. The information technology events reinforce the pattern.

Period-doubling cascades can be found in many phenomena in nature and apply to nonlinear iterative processes with limited resources. The period-doubling pattern in the evolution of intelligent life on Earth can be explained if the bifurcations are interpreted as population size, and if the bifurcation parameter is Darwinian fitness, and if fitness increases with complexity which in turn increases with time. Nonlinearities in these relationships do not necessarily affect the result.

Also, studies showing that rates of genetic change and speciation are largely unaffected by climate support the idea that a regular pattern is possible.

Darwinian evolution fits the definition of a nonlinear iterated process, which explains why evolution can behave as a period-doubling system, generating self-similar structures – in this case, new information channels – in a predetermined time sequence. The bifurcations (population instabilities) can be explained by each new information channel increasing the organism's speed of adaptation, which gives a fitness advantage, but also causes overconsumption of ecosystem resources, destabilizing the population level.

There have been 12 new information channels so far, but the pattern implies that more will appear, until the intervals approach zero in the relatively near future. The process governing the evolution of Life on Earth may be the same process that governed the physical evolution of the universe.

2. Introduction

2.1. Evolution may be less random than we think

Rate of change

Eldredge and Gould theorized that evolution consist of long periods of equilibrium where little changes, punctuated by sudden bursts of change, largely triggered by changes in the environment or climate[1]. However, later there is research that indicates that the rate of evolution is hardly affected by environmental changes. and that, while environment affects abundance, it has little effect on speciation or extinction[2]. The rate of change in evolution seems to be not primarily governed by adaptation to changing environment, but by internally generated genetic change such as mutation.

Direction of change

As well as punctuated equilibria, Stephen Jay Gould was also well-known for the statement that if one ran the tape of evolution again, the results would be very different, which is often quoted[3]. It builds on the perception that small initial differences in mutation inevitably become much larger differences. But a recent experiment has shown that yeast cells can evolve the same genetic changes, time after time[4]. The implication is that although mutation may be random, the direction of evolution is controlled by Natural Selection. In this scenario, initial differences in mutation become smaller differences as Natural Selection always ends up picking the same mutations in the end, even though the mutations may come in a different order.

2.2. Chaos Theory, Evolution, and Population Dynamics

Chaos Theory is frequently used in Population Dynamics to shed light on the relationship between birth rate and population. Although population dynamics and evolution theory are closely related, the application of Chaos Theory to evolution has been limited.

On the one hand we have Darwinian evolution, which is a nonlinear, iterated, dynamical system, and on the other hand we have Chaos Theory, which deals with nonlinear, iterated, dynamical systems. I hope to show that Darwinian evolution behaves as a period-doubling cascade, as described by Chaos Theory. I describe how the pattern coincides with the historical record of Information Transmission mechanisms and propose a hypothesis that explains the existence of the pattern.

2.3. Butterfly effect

Chaos Theory is perhaps most widely known for the Butterfly Effect, whereby small initial changes make it impossible to predict any outcome accurately. It is lesser known for showing that whatever the initial values, chaotic systems do produce highly predictable patterns of behavior.

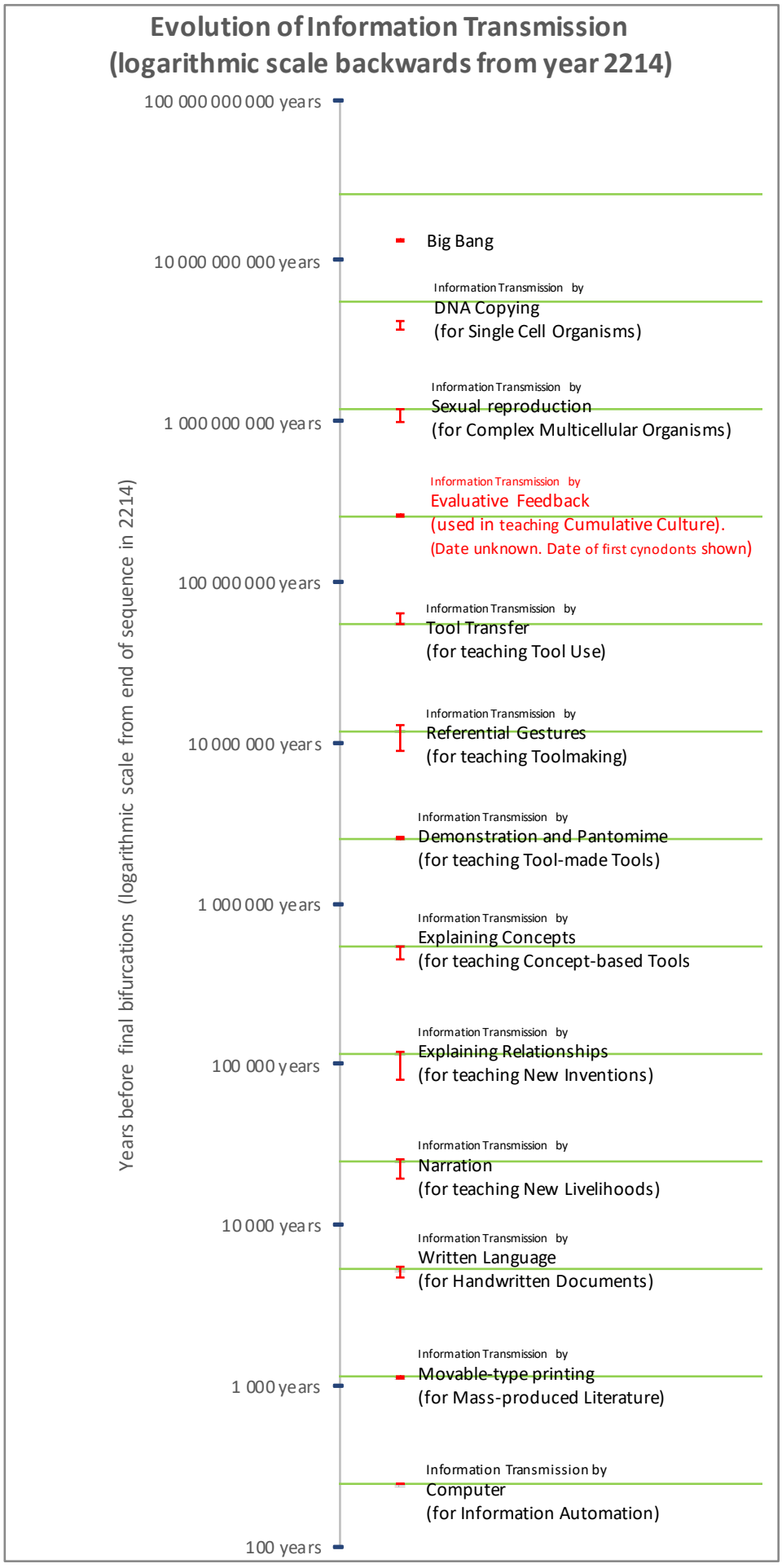
Evolution of Information Transmission
(logarithmic scale backwards from year 2214)
Years before final bifurcations (logarithmic scale from end of sequence in 2214)
100 000 000 000 years
10 000 000 000 years
1 000 000 000 years
100 000 000 years
10 000 000 years
1 000 000 years
100 000 years
10 000 years
1 000 years
100 years
Big Bang
Information Transmission by
DNA Copying
(for Single Cell Organisms)
Information Transmission by
Sexual reproduction
(for Complex Multicellular Organisms)
Information Transmission by
Evaluative Feedback
(used in teaching Cumulative Culture).
(Date unknown. Date of first cynodonts shown)
Information Transmission by
Tool Transfer
(for teaching Tool Use)
Information Transmission by
Referential Gestures
(for teaching Toolmaking)
Information Transmission by
Demonstration and Pantomime
(for teaching Tool-made Tools)
Information Transmission by
Explaining Concepts
(for teaching Concept-based Tools
Information Transmission by
Explaining Relationships
(for teaching New Inventions)
Information Transmission by
Narration
(for teaching New Livelihoods)
Information Transmission by
Written Language
(for Handwritten Documents)
Information Transmission by
Movable-type printing
(for Mass-produced Literature)
Information Transmission by
Computer
(for Information Automation)

Figure 1. The red error bars are actual dates of new Information Transmission mechanisms. It can be seen that they match the green lines, which are theoretical dates predicted by the Feigenbaum constant. Dates are measured from where the sequence converges around the year 2214. The time scale is logarithmic, so that the intervals between stages appear equidistant on the diagram even though they are actually getting smaller by a constant factor 4.66920…, known as the Feigenbaum constant. **The actual date for the first occurrence of Intentional Evaluative Feedback is not known (red text), but the predicted date suggests that Cynodonts (which later evolved into mammals) were the first animals to use Intentional Evaluative Feedback.** The first two dates do not match the dates predicted by the Feigenbaum ratio. However, in Chaos Theory it is nearly always the case that initial interval ratios do not match the Feigenbaum constant, but rapidly converge to it, which is what we see here.

No.	Information Transmission	Best known date from the historical record (upper and lower limit) (Years before 2000)	Date calculated from Feigenbaum constant 4.66920…* (Years before 2000)	Deviation of known date from Feigenbaum constant**
1	No information transmission (Big Bang)	13.82 to 13.78 billion years [5]	26.6 billion years *	-52% *
2	Asexual Reproduction (used by Single-celled life)	4.28 to 3.77 billion years [6]	5.70 billion years *	-25% *
3	Sexual Reproduction (used by Complex Multicellular Organisms)	1.0 to 1.2 billion years [7] [8]	1.22 billion years	-1.6%
4	Intentional Evaluative Feedback (used in teaching Cumulative Culture)	Date unknown. Near the theoretical date, the mammal precursors known as Cynodonts (260 million years ago[9]) appeared. They were social animals living in burrows.	261 million years	Date unknown
5	Tool Transfer (used in teaching Tool Use)	65 to 55 million years ago [10][11]	56.0 million years	0%
6	Referential Gestures (used in teaching Tool-making	13 to 9 million years[12][13]	12.0 million years	0%
7	Demonstration and pantomime (used in teaching Making Tools with Tools)	2.60 to 2.55 million years [14]	2.57 million years	0%
8	Communication of Concepts (used in teaching Making Concept–Tools)	Stone spearhead 550,000 to 450,000 years [15][16][17]	550,000 years	0%
9	Explanation of relationships between concepts (used in teaching New Inventions)	Tools for making clothes 120,000 to 90,000 years[18]. Harpoon 110,000 to 80,000 years[19][20]	118,000 years	0%
10	Narration and structurally complete language (used in teaching New Livelihoods)	Domestication (of the dog) 26,000–19,700 years[21]	25,000 years	0%
11	Written Language (used for Hand-written Documents)	5,400 to 4,600 years (3400 to 2600 BCE) [22]	5,210 years	0%
12	Movable-type Printing (used for Mass-produced Literature)	961 to 952 years (1039 to 1048 CE) [23]	961 years	0%
13	Computers (used for Automating Information)	52 years (1948 CE) [24]	52 years	0%

Table I. The data used in figure 1 (Evolution of Information Transmission). * The first two events (Big Bang, and start of life) deviate from the Feigenbaum ratio, but the intervals then converge quickly to the theoretical value at the next stage. This convergence from a different interval is normal for period-doubling bifurcations.

* 0% deviation means that the date calculated from the Feigenbaum constant is within the error range of the known date.

2.4. *A pattern in evolution?*

Figure 1 shows certain events in the history of evolution. There are two things that are interesting about these events:

- The events all mark the creation of a new Information Transmission mechanism.
  Information Transmission is the passing on of information from one generation to the next, and covers, for example, the transmission of information in the form of DNA, the transfer of skills by teaching, and the invention of writing.

- The events form a regular pattern in time, known as a period-doubling cascade.
  A period-doubling cascade is a series of intervals where each interval is shorter than the previous interval by the factor 4.66920…, known as the Feigenbaum universal constant. Period-doubling cascades are found in many natural phenomena, from dripping taps[25] to the way the eye transmits images[26], that can be described as iterated nonlinear dynamic systems – *a description that matches the process of Darwinian evolution.*

What is in figure 1?

The text and the red error bars in figure 1 represent known dates when various forms of Information Transmission first evolved, with error bars showing the uncertainty in the dates.

The green lines represent theoretical dates assuming that the intervals between dates get shorter by the factor 4.66920…, the Feigenbaum constant.

The time scale in figure 1 is logarithmic, so the green lines appear to be the same distance apart, when in fact the intervals are becoming shorter. The interval between the first two green lines is about 10 billion years, and the interval between the last two green lines is 909 years.

The logarithmic timescale runs backwards from where the events are calculated to end, namely in the year 2214,. (Theoretically it is an infinite series of intervals, but because the duration shrinks to zero, they reach the end within a finite time.)

How the theoretical dates (green lines) in figure 1 were calculated

The most recent green line has been placed to coincide with the date of the First Computer. The next most recent green line has been placed within the error range for the first Movable-type Printing (invented in China between the years 1039 – 1048 CE). This is simply because they are the two dates we know with the greatest accuracy.

These two dates together from an interval. The intervals for the earlier 10 events were calculated using the ratio 4.66920… . This was repeated for each of the ten possible years when Movable-type Printing could have been invented, and the date chosen (1039 CE) was that which best matched the other 10 events. The dates are also shown in table form in table I.

What does figure 1 show?

As can be seen, the 9 most recent calculated dates all fall within the error range of the known dates. The "Cumulative Culture" event does not have a known date as yet. The earliest 3 events deviate from the Feigenbaum dates by 1.6% (Sexual Reproduction), 25% (Life on Earth) and 52% (Big Bang). These deviations are normal – all period-doubling cascades initially deviate from, and subsequently converge to, the Feigenbaum ratio.

2.5. *Is this proof of a period-doubling cascade?*

On the face of it, yes, but ideally we want some kind of cause-and-effect explanation in the form of a testable theory. I attempt to provide such an explanation in this paper.

Any research that results in greater accuracy in the dates of the 12 events may mean that the theoretical dates no longer match the data. It may be possible to tweak the theory to match the updated facts, or not.

Also, the discovery of an additional Information Transmission event in between the ones listed here, would break the pattern, unless they arise at the same time as another event. (For example Horizontal Gene Transfer, which I suggest arose at the same time as single-celled life. We may categorize phenomena as belonging to different processes to better understand them, but Nature does not necessarily "see" these processes as separate, especially if they occurred at the same time in what we call co-evolution.)

2.6. Accumulated information

So far, there have been 12 of these events in the history of evolution. So what are these events, why did they happen, and why are they happening more frequently?

Information in evolution comes in various forms, whether it be the genetic code in DNA, skills in making stone tools, knowledge published in books, or data stored in a computer. In the context of evolution, we are talking about information which is acquired in the process of evolution being passed on to the next generation. And passing on information is important because if it is not passed on, it will be lost.

2.7. The history of Information Transmission in evolution

Here is a description of all of the Information Transmission events. That is to say, events where there was an innovation in the content and format of Information Transmission between generations. They concern physical, biological, cultural, and information technology evolution.

- The universe started with the **Big Bang**, which began the physical evolution of the universe, elementary particles, stars, elements, planets, and complex molecules. There was no Information Transmission, and no information was passed on.
- **10 billion years later**, **Single-celled life** appeared on Earth. Cells pass on information when they replicate themselves by dividing into two cells. **Information transmission happens by Asexual Reproduction making a complete copy of the cell DNA** so that each cell has a copy. Cells evolve by random mutation of the genetic code.
- **2.93 billion years later** (which is roughly a third of the previous period, 10 billion years), there are still only single-celled organisms, although there are many kinds. Complex multicellular life has not evolved, because it is vulnerable to biological attack[27]. Now there comes a threshold where a more advanced Darwinian process takes advantage of what it has produced so far, namely many different kinds of cells, and **Complex Multicellular** organisms appear, which reproduce by **Sexual reproduction**. Sexual reproduction and multicellularity appear together because sexual reproduction enables multicellular organisms to protect themselves against invasive cells[8]. **Information Transmission now works by randomly combining the genome of two parents into one genome**. And evolution now happens by trying out random combinations of alleles (variants of the same gene). There is still random variation, but the only alleles used are previously successful ones, so the resulting combinations are biased towards success. Previously, with random mutation there was no guarantee the new mutation would be beneficial. However, this new Darwinian process of gene-shuffling does not replace the old Darwinian mutation process. Both processes exist side by side. Further Darwinian processes (listed below) will arise later, adding to, rather than replacing, the existing processes.

*(The next 7 Information Transmission innovations are all levels of Intentional Teaching – the last of which is **complete spoken language** – identified by Gärdenfors and Högberg[28][29]. These are described below. They are cultural evolution, but trigger biological coevolution.)*

- **960 million years later** (estimated) (which is shorter than the previous period, 2.93 billion years, by the factor 4.66920…, the Feigenbaum constant), sexual reproduction and multicellular animals have been very successful, but another Feigenbaum threshold is approaching. Life has evolved to a point where social animals exist, that are able to have primitive communication. Another threshold takes place where a new Darwinian process forms again takes advantage of what evolution has produced, namely the means to transmit information by other means than DNA. Parents are able to communicate directly with their young and teach them that their behavior is wrong by giving them **Intentional Evaluative Feedback**[29] in the form of a simple grunt or other expression of disapproval. This works because young, left to their own devices, imitate their parents. The imitating behavior seems to have arisen at the same time as the first multicellular animals. Learning may have arisen even earlier with the first living cells. However, imitation is often done incorrectly, so feedback from parents is invaluable. The parent's feedback means that learned behaviours can persist over many generations and become part of what is known as **Cumulative Cultural Evolution** or **CCE**[30]. Evolution at this stage consists of accumulating useful behaviors via teaching (i.e. feedback). Note that, although we now have cultural evolution, the other two layers of biological evolution (with the different methods of transferring information) are still active, and all three affect one other through a process of co-evolution.
- **205 million years later** (estimated) (which is shorter than the previous period, 960 million years, by the factor 4.66920…, the Feigenbaum constant), another threshold leads our ancestors to start **using tools**. Again, animals learn by imitating their parents. But there is one step they need help on. It is called **Tool Transfer**[31] and it consists simply of a parent giving a tool to a youngster when they ask for one. This gives the pupil a chance to try a tool properly selected for the task. Tool transfer can be denied if the teacher believes that the pupil is ready to find their own tools. Tool transfer fulfills the criteria for teaching because it costs the teacher in terms of the cost of the tool given away, and the pupil learns. Evolution is led by the choice and use of tools.
- **44.0 million years later** (which is shorter than the previous period, 205 million years, by the factor 4.66920…, the Feigenbaum constant), with 44 million years of improving their tool-skills, early humans were evolved enough to start **making tools**. Again, a new intentional method of transferring information arises, namely **Referential gestures to draw attention** to, for example, an object. Evolution is led by the tools that are made.
- **9.42 million years later** (which is shorter than the previous period, 44.4 million years, by the factor 4.66920…, the Feigenbaum constant), early humans used their 9 million years of experience of toolmaking to begin to **make tools with tools** by using a stone in each hand and knocking flakes off one stone with the other. This is known as freehand knapping, or Oldowan technology. Yet another form of intentional teaching is needed to teach this, and a method duly arises: **demonstration and pantomime**, which is showing how to do something, but deliberately slower. Evolution is led by the evolution of tools made with tools.
- **2.02 million years later** (which is shorter than the previous period, 9.42 million years, by the factor 4.66920…, the Feigenbaum constant)**,** skills learned from making tools with different materials led to **composite tools** made of different parts, which required **explaining concepts**, which may have needed speech. Evolution is now led by the development of these sophisticated concept-based tools.
- **432,000 years later** (which is shorter than the previous period, 2.02 million years, by the factor 4.66920…, the Feigenbaum constant)**,** experience of concept-based tools led to **new inventions**, that is to say, new tools with new functions, sprung from imagination, instead of merely improved versions of tools first found lying around 250 million years earlier. New inventions require **explanation of relationships between concepts**, certainly requiring speech. Evolution is now led by the development of new inventions.
- **92,500 years later** (which is shorter than the previous period, 432,000 years, by the factor 4.66920…, the Feigenbaum constant), living with new inventions led to organizational skills to create tool-based livelihoods, which would have required a **structurally-complete language** with

all the elements of today's languages, a language that can aid thinking and problem-solving. Evolution is led by the development of new ways to make a living, specialization, and division of labour.

(With the development of structurally-complete language, the following steps in evolution involve information technology and extrasomatic (outside the body) information storage.)

- **19,800 years later** (which is shorter than the previous period, 92,500 years, by the factor 4.66920…, the Feigenbaum constant) the expanding amount of information being produced which was encoded in shared vocal languages, coupled with fixed brain capacity, led to a new Darwinian process involving a move to visual encoding of sounds and symbols used in speech **Written language** suitable for storing information extrasomatically on clay tablets or papyrus. The transmission of this information required the skills of reading and writing. Evolution is led by the use of **Hand-written documents** such as accounts, contracts, and laws, used in the new civilizations.
- **4,240 years later** (which is shorter than the previous period, 19,800 years, by the factor 4.66920…, the Feigenbaum constant), reading and writing were established, but copying information by hand for distribution was costly and prone to errors in the copying. **Movable-type Printing**, invented in China, enabled printed matter to be quickly composed, proof-read, corrected, and mass-produced, enabling the spread of accurate **Mass-produced literature.** Evolution is now led by the publishing of books, scientific papers, educational material, etc.
- **909 years later** (which is shorter than the previous period, 4,240 years, by the factor 4.66920…, the Feigenbaum constant), in the year 1948, handling information was a bigger part of society than ever, and the invention of **the Computer** in that year enabled the **automatic processing of information.** Evolution is now led by computerization. It is perhaps too early to see what this development will eventually lead to.
- **212 years later** (909 divided by 4.66920…) in the year 2160, a new event is due, and more events after that.
- **54 years later**, in the year 2214, the interval between events becomes less than a second, and less than a second after that, the interval between events becomes aperiodic, or chaotic, meaning that there is no longer a repeating pattern.

This is, I believe, an exhaustive list of all the innovations that have required new mechanisms for transmitting information (the kind of information that can give an evolutionary advantage). The dates for each event pair are shown in table I.

The last column in Table I shows the percentage deviation from the period-doubling cascade of each information transmission step. The deviations at the beginning (Physical evolution -49% and Life -26%) are a long way out, but after that, the dates quickly converge to the Feigenbaum ratio. Initial deviation followed by rapid convergence is normal behavior for period-doubling cascades.

2.8. Information transmisson throughout evolution

In summary, there are 12 different events of information transmission and they occur in different phases of evolution. The dates of the events are listed in table 1. We can divide evolution into 4 phases: Physical evolution of the universe (formation of stars planets, molecules, etc.), Biological evolution, Cultural evolution (which includes tool and language development)), and Information Technology evolution.

Note that, for example, Biological Evolution is still a very significant factor throughout Cultural Evolution, the 2 levels co-evolving, giving us larger brains, among other things.

2.9. Biological Information Transmission

I number these B1 – B2

B1 - Asexual Reproduction → Single-celled organisms

Information is Transmitted via DNA and cell-division.

B2 - Sexual Reproduction → Complex Multicellular organisms

Information is transmitted by mating and gene recombination. Complex multicellular organisms are more vulnerable to biological attack (illness). They invented sexual reproduction [32] to improve immunity. Also, a Gene Regulatory Network needs to be passed on to control the growth and morphology of the multicellular organism.

2.10. Information Transmission by Intentional Teaching

Of the 12 Information Transmission events in evolution, the Intentional Teaching events have more recently become known and are probably less well-known than the biological events (Asexual Reproduction and Sexual Reproduction) and the technological events (Written Language, Movable-Type Printing, Computers). It is therefore appropriate to look at Intentional Teaching events more closely.

Intentional Teaching takes up no less than 7 levels in the history of Information Transmission. The events come from list produced by Gärdenfors and Högberg (G&H)[29][28]. They have identified 6 separate levels of intentional teaching, which they believe to have evolved in sequence. All of which are still in use given the appropriate context. Together they are the steps to language and human cognition. Some of the early steps have been seen in other animals. (Note, animals have a natural ability to learn, which seems to have arisen earlier at the beginning of multicellular life, or even at the beginning of single-celled life*.) This list was compiled without any dates in mind and with no idea of matching any kind of time pattern such as a period-doubling cascade.

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* Social learning, whereby young animals learn from their elders, seems to date back to the beginning of sexual reproduction or even earlier. Social learning is very widespread, as most species interact with their young at the beginning of their lives [33] and it covers a whole spectrum of situations, including learning prior to birth. For example, the fact that new-born rats respond positively to foods that the mother ate during pregnancy is counted as social learning [34]. There is even evidence of social learning in other sexually-reproducing forms of life such as plants and microbes [35]. So social learning may be an inherent feature of life, dated to the beginning of multicellular life, or even single-celled life. Many animals seem to have an innate ability to learn skills from their parents by observation and imitation.

However, social learning does not seem to be sufficient to create a Cumulative Culture in which acquired behaviors are accurately passed on. The emergence of Intentional Teaching may be necessary to maintain the transmission fidelity needed to enable a Cumulative Culture. The question of whether cumulative culture exists

G&H suggest that "level after level has been added during the evolution of teaching. We demonstrate how different technologies depend on increasing sophistication in the levels of cognition and communication required for teaching them."

Associating teaching methods with dated events

Although Gärdenfors states that the Intentional Teaching events are all associated with tool development, he does not say with which particular development he associates every event. I explain the associations used in this paper below. I number the Intentional Teaching methods T1 to T7.

T1 - Intentional Evaluative Feedback → Cumulative Culture

Gärdenfors states that all methods of Intentional Teaching are associated with tool technology. However, the first one – Intentional Evaluative Feedback may be applied to teaching all behavior, not just tool-associated behavior. Therefore it does not need to be part of Cumulative Technological Culture, as Gärdenfors states. It can be associated with Cumulative Culture.

T2 - Tool Transfer → Tool Use

There is a form of teaching not included in Gärdenfors and Högberg's list namely "Tool Transfer", which is when a parent gives a tool to a learning youngster. Clearly associated with Tool Use, as it is observed in animals that can use but not make tools, such as some parrots [37]. Tool transfer technically counts as a form of teaching[31]. (It is not observed in all animals that use tools. It seems that some tool use is instinctive. It is not known whether there is any interaction between culturally taught tool use and instinctive tool use.)

T3 - Referential Gestures → Making Tools

Also called "drawing attention" to something. There are indications that referential gestures are connected with tool-making as both behaviours tend to be observed in the same animals, such as chimpanzees[38] and ravens[39].

T4 - Demonstration and pantomime → Making tools with tools (Oldowan technology)

Gärdenfors explicitly makes this association.

T5 - Communication of concepts → Tools based on concepts (Composite tools, Late Acheulean tools)

Gärdenfors explicitly makes the association with Late Acheulean tools. It is also appropriate for composite tools, which require the concept of "whole and parts". Both kinds of tools appeared at the same time, 500,000 years ago.

T6 - Explanation of relationships between concepts

This teaching level is appropriate for new inventions. New inventions as a phenomenon is not generally emphasized in archaeology, but all tool development so far has been improvements of the first tools used, which were originally just twigs and stones found lying around. New inventions, on the other hand, are created by the imagination. They would probably require a certain amount of explanation to be used, of "explanation of relationships between concepts." as Gärdenfors and Högberg put it. For example, teaching the manufacture and use of the harpoon requires an explanation that it is used for spearing fish and that the barbs are there so that the harpoon does not come out of the fish.

T7 - Narration (complete language)

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in animals and, if so, whether it requires teaching, is still open, and as the definition of teaching is still in flux, there is clearly more research needed[36].

This level of teaching, or of language, is appropriate for New livelihoods. This final step in intentional teaching surely must mark the completion of the development of language to essentially the same structural level that we have today. Language can now be used to transmit any information, and can also be used to reason about things, which is essential for problem-solving, which would have been necessary to successfully adopt new livelihoods. The first change in livelihood is generally agreed to be domestication of animals and plants, and the first domestication is probably the domestication of the dog[21].

2.11. New inventions: made tools with new functions

Of the above, teaching methods, I would consider all the associations to be fairly conventional except for T6 – new inventions. The examples I give are the harpoon and a tool for making clothes that does not have a name. (No physical remains of clothes have been found, but they are considered to have been invented at the same time as the clothes-making tool[18].)

The advent of what I call new inventions does not seem, in itself , to be considered an important milestone in evolution among archaeologists. My argument for the importance of new inventions is that all tools made previously, whether they be handmade tools, tool-made tools, or concept-based tools were just improvements on the stones and twigs originally found lying around and used as tools.

Although tools evolved to better perform their function, the *functions* do not seem to have evolved. Even the most exquisitely made flint spearhead is just part of a new version of a sharp stick found 55 million years earlier, and fits right into early human hunter gatherer livelihood with presumably no puzzled frowns as to how to use it. The harpoon and the tool to make clothes break this pattern. I argue that there is a fundamental difference between them and the tools made previously, because the harpoon and clothes-tool are the first made tools to have new tool functions. New inventions are new source of variation for the evolutionary process. I also speculate that new inventions over the following 100,000 years eventually enabled the next stage of evolution, the change of livelihood.

2.12. Events before and after Intentional Teaching

The 7 levels of Intentional Teaching of Skills and Language during Cultural Evolution fills a huge gap between the 2 levels of transmission of genetic information in Biological Evolution (Asexual Reproduction, Sexual Reproduction), and the 3 levels in the Evolution of Information Technology (Written language, Movable-type printing, and Computers).

2.13. Information Technology

Although language is complete, the Information Technology events are still able to improve handling of information. I number these I1 to I3

I1 – Written Language → Handwritten documents

Written language is a storage technology and a transfer technology. It is spoken language translated from sound to visual symbols. It functions as a form of memory addition to the brain's memory.

I2 - Movable-Type Printing → Mass production of books

Books, such as the bible, existed before Movable-Type Printing, but copies of the bible had to be written by hand, which made it a very expensive way to transmit information. Printing of pages with a hand-carved wooden block for each page was done, but this was also expensive. Movable type not only speeded up the composition of pages, it also made it possible to print an initial copy which could then be proof-read for mistakes, and the mistakes rapidly corrected. Movable-Type Printing enhanced science and enabled ideas to be spread.

I3 – Computers → Automated information processing

This stage of evolution is not yet halfway through, with over a hundred years left, and we cannot say with certainty what the result will be.

2.14. Full list of 12 events

Here is a list of the individual events:

Physical evolution – No Information Transmission

1. Big bang (start of evolution): No information transmission

Biological evolution – Information Transmission via forms of genetic material

2. (B1) Single-celled life: *information transmitted by* Asexual reproduction
3. (B2) Complex multicellularity *information transmitted by* Sexual reproduction

Cultural evolution – Information Transmission via forms of Intentional Teaching

4. (T1) Cumulative culture: *information transmitted by* Intentional evaluative feedback
5. (T2) Tool use: *information transmitted by* Tool transfer
6. (T3) Tool-making: *information transmitted by* Drawing attention with referential gestures
7. (T4) Making tools with tools: *information transmitted by* Demonstration & pantomime
8. (T5) Concept-based tools: *information transmitted by* Communication of concepts
9. (T6) New inventions *information transmitted by* Explanation of relationships between concepts
10. (T7) New livelihoods: *information transmitted by* Narration (complete language)

Information Technology evolution - Information Transmission via forms of Information Technology

11. (I1) Hand-written documents: *information transmitted by* Written language
12. (I2) Mass-produced literature: *information transmitted by* Movable-type printing
13. (I3) Computers: *information transmitted by* Data networks

Each event in the list above consists of 2 parts:

1. An innovation of a kind that:
   a. Is a new source of variation, or in other words,
   b. is the first example of a previously absent new dimension of properties or traits.
   c. Utilizes capabilities that have evolved since the last such event
   d. Cannot be transmitted to coming generations using the current Information Transmission mechanism.
2. A new mechanism that:
   a. Is used by the each generation to actively push information to the following generation. *(This hypothesis is about actively sent knowledge. It is not about the receiving of knowledge, which can be from the previous generation, or can come from other sources, such as self- learning. This is not to say that receiving knowledge is unimportant. Without it, sending knowledge would not work.)*
   b. Can transmit information on how to replicate the above innovation to the next generation.

The new source of variation in each stage, mentioned above (1.a.), is variation in *information* – the biological information to make each new organism, and the cultural information in the form of learned skills and knowledge that are passed on by teaching each new organism.

To these may be added the extrasomatic ("outside the body") information that is stored and transferred outside the body, on paper and in computer networks. Although it may be that many more people read information than write information, writing is more work than reading, and all information is created in order to be passed on to others.

2.15. Why new methods of information transmission are needed

The list of stages below explains why the innovation at each stage requires a new method of information transmission and cannot use the previous method:

1. **Matter and energy**: There is *no information transmission.*
2. **Single-celled life:** Information is transmitted as DNA. *Information could not be transmitted before DNA came about.*
3. **Complex multicellular organism:** Made of many cells of different types, and extra information has to be sent upon reproduction such as the Genetic Regulatory Network that determines the morphological development of the species. Because multicellular organisms are very vulnerable to disease, *the genetic information has to be transmitted through sexual reproduction involving two parents, and not simple cell division.*
4. **Cumulative culture:** Young learn by imitating their parents' behavior. Skills are checked and corrected by parents using Intentional Corrective Feedback, by which incorrect information is filtered out by "disapproving grunts" to the young. *This information cannot be intentionally passed on via DNA.*
5. **Tool use:** The information passed on is the tool itself. The tool is given to the young so that they may learn with proper tools. *This tool knowledge can only be passed on by tool transfer and not by Intentional Evaluative feedback.*
6. **Toolmaking**: Research indicates that toolmaking may be associated with referential gestures. It may be that animals deliberately draw attention when they are about to make a tool. (At this stage, demonstration and pantomime are not used. The tool is made at normal speed with no slowing down or other behavior to make the allow the pupil a better chance of understanding.) *This stage cannot be taught with Tool Transfer.*
7. **Making tools with tools:** Transmission is by Demonstration and pantomime. *This cannot be taught only with referential gestures.*
8. **Concept-based tools**: Late Acheulean tools and composite tools require conceptual knowledge of the tool. This needs language or symbolic gesture. *It cannot be taught by Demonstration and Pantomime.*
9. **New inventions, or tools with new functions**: Require imagination to invent them. They require explanation of relationships between concepts. *This cannot be taught by only conveying the concept without relationships.*
10. **New livelihoods**: These require a structurally complete language to help conceive how new inventions and tasks may be pieced together into a way of living, communicate and organize others, and solve problems that may arise. *They require narration, not just relationships between concepts.*
11. **Written language:** Does things that spoken language could not do, like share definitive information, because written language is shared extrasomatic storage of information. *Written language requires people to learn to read and write, and cannot be taught orally.*
12. **Mass-produced literature**: Movable-type printing made practical the creation and mass distribution of in-depth works of science and ideas, and educational books. *To produce them by hand-copying or woodblock printing was just too expensive for there to be any demand when a book could cost as much as a house.*
13. **Computers**: *Automatic processing of information is not possible without computers.*

2.16. More about the events

Table II shows a **s**ummary of the stages, including what varies at each stage.

The 12 different kinds of information transmission are described in more detail in Appendix A.

No.	New phenomena	Means of generating variation (all of which are variations in information, skills or knowledge to be passed on in Information Transmission)	Information Transmission
1	Big Bang	Random universe	No information transmission
2	Single-celled life	DNA Mutation	Asexual reproduction
3	Multicellular Organisms	Gene shuffling	Sexual Reproduction
4	Cumulative Culture	Novel behaviour	Intentional Evaluative Feedback
5	Tool Use	New tool uses	Tool Transfer
6	Tool-making	New made tools	Referential Gestures
7	Making Tools with Tools	New tools made with tools	Demonstration and pantomime
8	Making Concept–based Tools	New concept-based tools	Communication of Concepts
9	Making New Inventions	Inventing new inventions	Explanation of relationships between concepts
10	New Livelihoods	Inventing new livelihoods	Narration, complete language
11	Hand-written Documents	Inventing new kinds of documents - accounts, contracts, laws	Written Language
12	Mass-produced Literature	Complex knowledge, theories, ideas, science, reference books, textbooks	Movable-type Printing
13	Automating Information	Instant interactive information processing	Computers

481 **Table II:** Summary of the Information Transmission stages, including what information varies at each
482 stage.

3. *The Source of the Cascade*

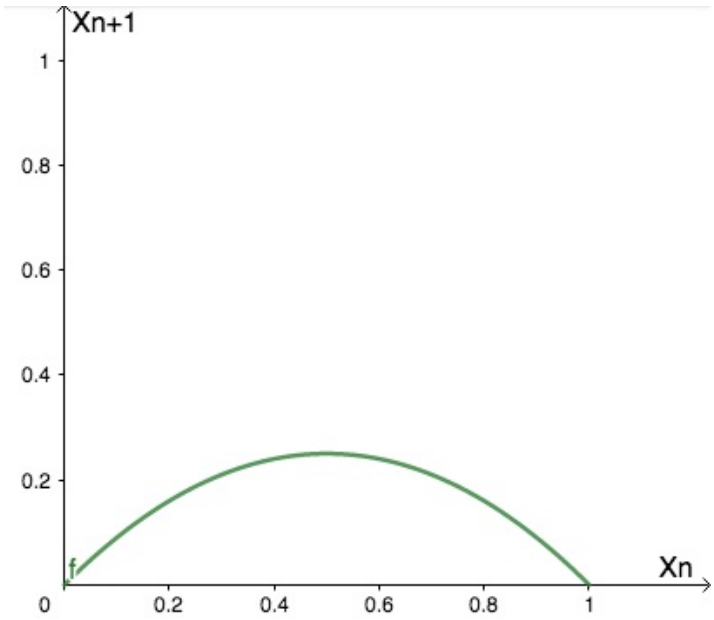

Figure 2. The logistic map $x_{n+1} = a \,.\, x_n\,(1 - x_n/K)$ for fitness a = 1.0 and carrying capacity K = 1.0. This curve, and similar ones, when multiplied by fitness (birth rate) and iterated many times, create the cascade of bifurcations.

Figure 2 shows the logistic mapping, which is a simple example of a mapping that represents how the population of a species varies from year to year. **This curve, and similar ones, when multiplied by fitness (birth rate) and iterated many times, creates the cascade of bifurcations.**

The mapping is used by finding on the x-axis a value of x that is this year's population (for example) (x_n), then reads off the population for next year (x_{n+1}) from the y-axis. The shape of the curve (a single hump) represents the fact that small populations are likely to grow, but the limits of the ecosystem mean that there a limit to population growth, and if the population gets too high, the following year's population will be smaller rather than larger.

Now, such mappings are usually used to represent a single species in the study of Population Dynamics, to see how birth rate affects population. But the concept of "fitness" is very close to birth rate, being the propensity to give birth. So if we replace birth rate with fitness, and assume fitness increases as the species evolves, we can plot the evolution of the hypothetical ancestral line stretching back from today's humans to the first life forms. (We have to adjust the numbers to deal with the transition from single-celled animals with asexual reproduction to multicellular animals with sexual reproduction.)

The mapping can be more complex mathematically, but any species living in a limited ecosystem would be likely to have a similar curve. The logistic map is too simple to model animals that take more than one breading season to reach sexual maturity. But there is a thing called Feigenbaum universality, which means that complex formulae and simple formulae give the same result, namely a *period-doubling cascade*. This universality means that we don't need the correct formula derived from reality. A simple map like the logistic map will converge to the same results,

It is difficult to measure populations of living animals, let alone long-extinct animals, but we are not interested in the population as such, we are interested in *bifurcations*, where population oscillates due to overconsumption.

Period-doubling cascades in evolution take time to develop, limited by the speed of evolution.

3.1. The logistic mapping maths

The logistic mapping is often used as the simplest possible model to demonstrate how to calculate a population p, which changes with each generation. Given the population p_n of the nth generation, the population of the next generation, p_{n+1}, is given by

$$\text{Population } p_{n+1} = a.p_n.(1 - p_n/K) \quad (1)$$

Where:

- p_n is the population of generation n
- K is the "carrying capacity", the sustainable population count of the species in the ecosystem.
- a is the Darwinian fitness, which is propensity to reproduce at a certain reproduction rate (also called birth rate). It starts at 0.0 and reaches carrying capacity at 4.0 for the logistic mapping.) This factor models how the size of the next generation, p_{n+1}, is equal to the size of the current generation, p_n, times the net birth rate, a);
- The factor $(1 - p_n/K)$ represents the limitation of resources in the ecosystem. As population p_n approaches the maximum of K, then $(1 - p_n/K)$ gets smaller, modelling how populations may grow more slowly, or even shrink, as ecosystem resources (such as food) reach their carrying capacity.

Chaotic behaviour

Applying the logistic map iteratively, and plotting population levels against reproduction rate, the logistic map gives rise to the attractor in figure 3, otherwise known as a bifurcation diagram, or a period-doubling cascade. An "attractor" is a curve where data points appear at random at first, but gradually move closer to the attractor values after a few hundred iterations. In this case, for each value of reproduction rate, a random non-zero starting value for population is chosen, and the logistic map applied a few hundred times before the population counts are plotted. This is because the data points will appear random at first, but in the long term a repeating pattern will emerge for each value of reproduction rate.

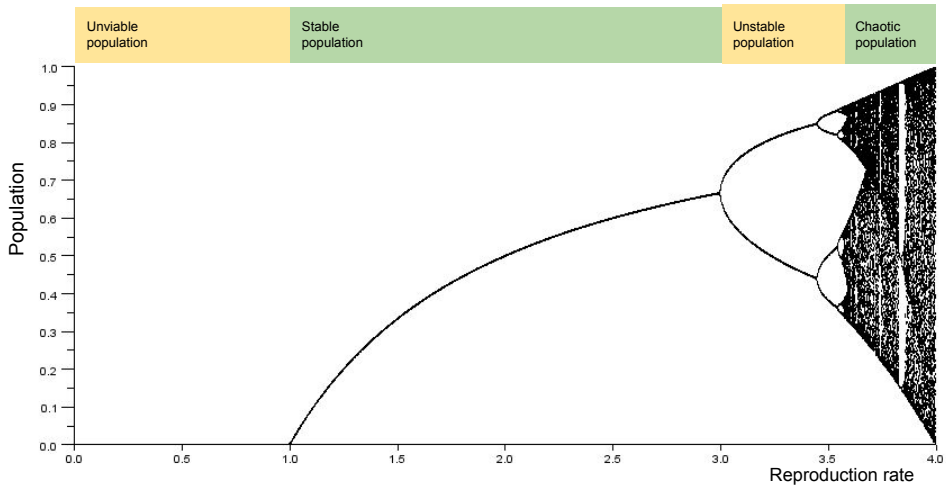

Figure 3. Regions of the period-doubling bifurcation diagram. Characteristic of period-doubling bifurcation diagrams is that intervals between successive bifurcations (seen here in regions "stable populations" and "unstable populations") always get smaller by a ratio that converges to 4.66920…, a number known as the Feigenbaum constant.

Regions of the period-doubling bifurcation diagram

A period-doubling bifurcation diagram can be described as having the following regions:

- "Unviable population", where the reproduction rate is less than one. For the first self-replicating cells to be viable, they need to exceed a reproduction rate of 1.0.
- "Stable population" where the population settles down to a stable value. The higher the reproduction rate is, the higher the population level. But higher reproduction rates give rise to lower populations than might be expected, as the carrying capacity comes closer and resources become harder to find.
- "Unstable population" or "period-doubling cascade". As the reproduction rate rises, the population level bifurcates into 2 values and the population alternates between them. (If the system being studied is the reproduction of a species, and the breeding season is once pear, the population level would typically alternate every breeding season, being at the high value every other year, and at the low level every year in between.) At even higher reproduction rate, each bifurcation bifurcates again, giving 4 values, repeating every 4 iterations (typically every 4 years).. The number of levels before repeating is always a power of 2, for example 1 level, 2 levels, 4 levels, 8 levels, 16 levels, and so on. This is called a period-doubling cascade.
- "Non-repeating (chaotic) population". At a certain point, the period theoretically tends to infinity and population levels numbers becomes non-repeating, also called chaotic.

3.2. Comparison of two period-doubling systems, a dripping tap and evolution

It is useful to compare two period-doubling systems – a simple dripping tap and the evolution of the universe – to see how they can be so different and yet both follow the same pattern (or, in the language of Chaos Theory, share the same attractor).

System 1: Dripping tap

572 The system ”a tap with a flow of water” produces drips, and it does so with a drip pattern that
573 grows more complex as the flow is increased and thresholds are crossed.
574 • At very low flow rates, the water evaporates before the drips can form.
575 • The first threshold produces a steady flow of drips with a constant time interval. A steady
576 “drip…drip…drip”.
577 • At the second threshold, increasing the flow causes a drip to take some water from the next drip.
578 This imbalance feeds back into subsequent cycles, causing the time interval between drips to
579 alternate between two values (a bifurcation) in the pattern “drip-drip…drip-drip…drip-drip”.
580 • A new such feedback loop appears at each subsequent threshold, and the drip time-interval
581 periodicity doubles each time from 2 to 4, to 8, and so on. The second bifurcation, period-4, would
582 be something like “drip-drip—drip-drip… drip-drip—drip-drip… drip-drip—drip-drip”.
583

System 2: Evolution

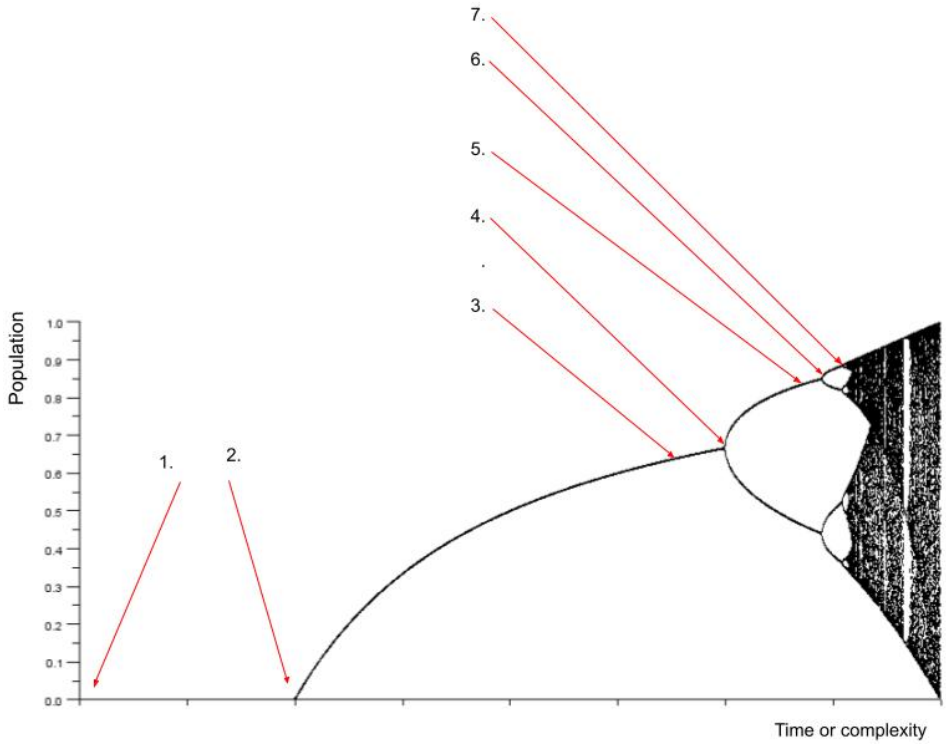

Figure 4. Evolutionary events matched to a period-doubling bifurcation diagram (not to scale)

"The universe with its random flows of matter and energy" is a system that creates life as complexity increases.

Let us assume that the reproduction rate of life starts at zero at the Big Bang, and increases through evolution. The first part, physical evolution, occurs throughout the universe, and partly on Earth. During this stage, the reproduction rate is less than 1.0, which means that life has not yet evolved. It is not known how long life has existed in the universe. The first life on Earth started about 10 billion years after the Big Bang. In figure 4, I map the stages of evolution onto the period-doubling bifurcation diagram. The x-axis, reproduction rate, can be replaced by time, if one assumes that reproduction rate increases with complexity, and that complexity increases with time. (The question of linearity in the relationships between reproduction rate, complexity and time is taken care of by the nature of the period-doubling cascade itself, that is, the intervals which shorten by the factor 4.66920…. Looking at figure 4, only 5 or so intervals are visible. The remaining 7 intervals are so small as to be invisible. Looking at a relatively smooth nonlinear function, the shorter the interval, the more linear the function is over that interval, as the function is effectively "stretched". That is why the ratio in a period-doubling cascade converges rapidly and accurately to the expected ratio.)

- Point 1: The diagram starts at time zero, with the Big Bang.
- Point 2: Single celled life with mutation begins. Populations rise rapidly on the virgin Earth.
- Point 3: Population rise is slower as competition for resources increases.
- Point 4: First period-doubling bifurcation, and the first threshold of the logistic map (and similar one-humped maps) where complex multicellularity becomes viable. The increased information transmission (via sexual reproduction) to the next generation increases adaptation rate, which increases fitness and thus population, which results in the upper curve. This increased population occurs at a cost of overconsumption of (slower-adapting, asexually-reproducing) food sources by the species in question, and the following year there is a reduced population due to lack of food caused by the previous year's overconsumption. This reduced population is

shown by the lower curve of the bifurcation. The population recovers the year after, and there is a so-called period-2 instability of population count, as the population alternates between overconsumption and recovery. The *average* population count increases at the same rate as before the bifurcation.

- Point 5: The *average* population rise (counting all branches of the bifurcation, in this case two branches) continues to slow down. (This could be due to diminishing returns as evolutionary improvements give fewer returns as the ecosystem matures.)
- Point 6: Second period-doubling threshold of the logistic map, and the next innovation in evolution (Cumulative culture) requiring new information transmission (Intentional evaluative feedback). Increased information causes increased adaptation rate again, and deeper (period-4) instability as not only next year's food supply, but the year after's food supply is also eaten into.
- Point 7: Remaining bifurcations rapidly become too small to see in the diagram.

Issues

There are many obvious issues with the above. First, it is not a diagram for a single species, but for all the ancestors of homo sapiens, although in the later stages, it is a single species, homo sapiens, differing only in the level of information technology. The organism changes from single cell to multicellular at one point, which may affect how population is to be counted. Reproduction rate must take into account all the relevant factors such as birth rate, mortality, longevity, population age profiles ("survivorship curves"), breeding seasons, carrying capacity, biomass, invasion of new territories, and any other factors that ensure that there are no discontinuities in measurements as organisms evolve. It is no easy matter to find all the relevant data in the literature and produce such a diagram, and some of the data does not exist because the events left no lasting trace. We saw earlier that the intervals following the first two events (Big Bang, and Life) do not match the Feigenbaum ratio as extrapolated from the later events. The match of these two event dates to the logistic map is even lower. It would be useful to find a mapping that matches the first two event dates and which can be derived from theory, but it is probably not a trivial task. The standard logistic mapping used above does not attempt to match the dates of the Big Bang or Life, but matches subsequent events.

Similarities

There are clear similarities between the dripping tap and evolution:

- In each system (dripping tap, or universe), at every threshold (water flow threshold, or complexity threshold) there is overconsumption of resources (water, or food) affecting periodicity of periodic values (time interval, or population) in the form of period-doubling bifurcations.[†]
- The tap is a system that produces water drips. As the flow rate of the water increases, the drips exhibit a period-doubling cascade of bifurcations, each of which marks the crossing of a threshold.
- The universe is a system that creates life. As complexity increases with time, the universe exhibits a period-doubling cascade of population bifurcations, each of which marks the crossing of a threshold, and each of which I suggest is caused by a sudden increase in adaptation rate, giving

[†] It is easy to get confused here between:

- **Period**, here meaning how many periods before a pattern repeats, for example *period-2* or *period-8*.
- **Interval**, here meaning difference between two values, such as the interval in water flow rate (for example, the interval between x m^3/sec and y m^3/sec, is $(y - x)$ m^3/sec), or the interval in *complexity* (I do not specify units for complexity, as there are many different definitions of complexity, and, as long as complexity increases with time, nonlinearity is not an issue, for reasons already mentioned).
- **Time interval**, such as 2 seconds.

a competitive advantage that leads to persistent overconsumption and subsequent food shortages, resulting in population alternating between two different values.

- In the tap, the first bifurcation threshold is where a drip begins to affect the next drip, causing period-2 fluctuations. Then a pair of drips affects the next pair, causing period-4 fluctuations, and so on.
- In evolution, the first bifurcation threshold is where sexual reproduction arose, resulting in faster adaptation rate, which is where a generation of animals begins to take food needed for the next generation, causing period-2 fluctuations whereby the population alternates between two values, repeating the same value every other breeding season. (This assumes offspring reach maturity before the next breeding season. The reality may be more complicated and require further investigation, but is unlikely to challenge the robustness of the cascade pattern.) Then a generation takes food needed for the next 2 generations, causing a period-4 fluctuation before it can recover and repeat, and so on.
- Table VIII shows how the water tap and evolution both fit into the framework of a period-doubling cascade.

The water tap *is a nonlinear, dynamic period-doubling system that produces* **turbulence**.	**Evolution** *is a nonlinear, dynamic period-doubling system that produces* **Darwinian processes**.
As the bifurcation parameter – **flow rate** – *increases,*	*As the bifurcation parameter* – **fitness (which depends on complexity, which depends on elapsed time)** – *increases,*
new **forms of turbulence** *are produced at decreasing intervals,*	*new* **sources of variation and new mechanisms for Information Transmission** *are produced at decreasing intervals,*
causing bifurcations, so that the **drip interval** *cycles through twice as many values, which takes twice as many periods or* **drips**.	*causing bifurcations, so that the* **population level** *cycles though twice as many values, which takes twice as many periods or* **reproduction cycles**.

Table VIII: Similarities and differences between two examples of the creation of bifurcations in period-doubling systems: a water tap and evolution

3.3. *Future events*

Event	Year of event	Interval until next event
13 (The computer)	1948	212 years
14	2160	41.7 years
15	2202	8.93 years
16	2211	1.91 years
17	2213	150 days
18	2214	32 days
19	2214	6.9 days
…	…	…
Aperiodic stage	2214 onwards	No more intervals

Table VI. Predicted future events, with intervals and dates. The intervals are easily calculated by dividing the previous interval by the Feigenbaum Constant 4.66920… . The cascade of bifurcations come to an end in the year 2214, and the population level is chaotic (aperiodic) from 2214 onwards. The years stated may vary by a year or two in practice.

Table VI shows how the cascade might continue into the future if it continues the same pattern. In just a handful more events, the interval till the next event shortens to a few days, much less than it takes a human to grow to adulthood. This scenario may be possible if, for example, the events become pure software events, evolving on their own. In any case the bifurcations cease in 2214 and the population level becomes aperiodic. Theoretically at least, there are an infinite number of bifurcations before the aperiodic phase starts, but the interval shrinks to zero and the resulting time is finite (in the same way as the length of a plank of wood is the sum of the infinite series "half the plank + half of what's left + half of what's left + etc.).

I don't know what will happen in 2214 or whether the cascade will end with a bang or a whimper.

3.4. *Effect of fossil fuels?*

For most of the history of most life on Earth, evolution has been powered by the sun only. It is not inconceivable that evolution of humans has accelerated due to the consumption of energy from fossil fuels, which became significant in the 20th century, and that this may cause the transition from the bifurcation stage to the aperiodic stage to come sooner than 2214.

4. *Summary of hypothesis*

4.1. *Cascades*

The period-doubling cascade appears when modeling "iterated nonlinear systems with limited resources and delayed feedback", using the logistic mapping or a similar mapping. The mapping converts the value of a parameter to another value of the same parameter. For example, calculating next year's blackbird population from this year's blackbird population. The logistic mapping is a simple quadratic "hump", starting at 0 and ending at 0 with a maximum in between. The upward slope of the hump represents small populations that have abundant food to expand. The downward slope represents large populations that have unsustainably expanded beyond available food sources and who are doomed to a smaller population the following year.

In mathematical language, the mapping is a "stretch and fold" operation. The mapping that results from running the "stretching and folding" logistic mapping millions of times depends on how high the "hump" is stretched, which in population dynamics is stretched by the birth rate. I suggest depends on "fitness". The higher the fitness, the higher the initial hump.

Assuming fitness to start at zero and increase with evolution, the mapping "bifurcates" at higher fitness values, meaning the initially steady population alternates between 2 values. What happens here is that the delayed feedback is not fast enough regulate the population at a steady level. Instead,

consumption of resources overshoots and there is a resource shortage in the next iteration, which causes the population level to dip. The population becomes periodic with a period of 2. That is to say a high population followed by a low population, repeating every 2 years.

If the "amplification", or fitness, is turned up further, the period becomes 4, then 8, then 16, etc, doubling every time. That is why these systems are called period-doubling systems.

A Feigenbaum bifurcation cascade occurs for any mapping similar to the logistic mapping. It may be that millions of iterations filter out the differences between the mappings, resulting in the universal pattern following the Universal Feigenbaum constant, 4.66920… .

4.2. Evolution in a nutshell

The universe has (or is) an evolution process (which is an "iterated nonlinear system with limited resources and delayed feedback") with increasing "amplification" being increasing reproduction rate (caused by increased complexity, in turn increasing with time. (This means that the period-doubling cascade in evolution plays out in the time dimension, which is not usually the case with period-doubling cascades)). This has produced self-replicating cells, an essential part of which is the transmission of information to new cells. (This information is in the form of DNA.) Having created life that self-replicates and passes on information, it is perfectly reasonable that evolution should produce new ways to transmit information, all conforming to the generalized definition of a Darwinian process, and to do so at decreasing intervals.

Each bifurcation in evolution corresponds to the creation of a new dimension of possibilities that were previously impossible or very hard to realize (such as Multicellularity, or Tool Use that cannot be transmitted to coming generations using existing mechanisms, but require a new mechanism to transmit the information about variation in the new dimensions to coming generations.

Each additional information channel causes a sudden step-change increase in the adaptation rate of the organism.

Tight pattern

Evolution follows the pattern of Period-doubling Cascades remarkably accurately. This suggests that if evolution were to be re-run, it would follow the same pattern so again, because evolution does not seem to be spending a lot of time looking for directions to evolve in. It seems as if the path is already staked out.

Same stages?

If the pattern is the same when evolution is re-run, it is tempting to imagine that the stages would also be the same. The inevitability of these stages seems to be backed up by what we know about tool use and tool-making in Corvids. A deeper analysis of the events may reveal that the stages are always the same, or that the stages might not be that same under changed conditions, or on another planet.

Also, we have only been considering the "apex" species. An ecosystem demands many plants and animals to fill different niches, and this would not be possible if every species (including bacteria and plants) is obliged to evolve into intelligent animals.

Entropy production

What is powering evolution to follow the Period-doubling Cascade accurately to within 1%? There is a principle often cited in theories of evolution called the Maximum Entropy Production Principle, which obliges evolving structures to become as complex as possible for the given physical parameters, so that their rate of entropy production is as high as possible[40][41]. Applying this principle to period-doubling evolution, it is possible that evolution is obliged to evolve processes of maximum possible complexity.

It seems reasonable that the most complex structures are also the most intelligent structures, and that there is also a correlation with cognitive level.

The maximum complexity supported at any given moment probably depends on (is limited by) two factors:

- The rate of energy, free energy, or negentropy input into ecosystems from, in our case, the sun.
- The amount of time elapsed since evolution started, since evolution takes a long time to evolve the complexity required.

Advantage

Each step provides an advantage over the previous stage, possibly because it increases the rate of adaptation. which may well be unassailable from organisms from the previous bifurcation. It may be possible, and perhaps even trivial, to calculate numerically the advantage at every stage. The cascade suggests each stage has similar mathematical characteristics, and that they may be similar on a deeper structural level.

So everything is predetermined?

Not everything is predetermined, just some things. Things like the levels of evolution and the earliest date they can occur are likely to be predetermined, as the pattern is so regular. Although they may not necessarily come to fruition if, for example, humans manage to make themselves extinct in the near future. Flora and fauna are different all over the planet, so humans perhaps did not need to evolve exactly as they have. If the hypothesis presented in this paper is partly or wholly correct, there is no reason to conclude that our lives would be to any reasonable extent more predetermined than otherwise.

5. Discussion

The presence of a period-doubling cascade that controls evolution is a new and probably contentious idea. There are many aspects that are counter to current evolutionary theory and it is worthwhile to explicitly answer questions that are bound to arise.

5.1. Aren't adaptation and evolution two different things?

A simple answer is that they are both change, but on different timescales. The hypothesis presented here may change our perception as we see that there have been 12 stages of evolution and that the timescale of each is shorter than the previous.

5.2. Cherry-picking?

The main basis of the information transfer events proposed in this paper is the sequence of innovations in intentional teaching as specified by Gärdenfors and Högberg. There can be no question of cherry-picking of these events to match a time pattern, because time is not a factor in their list, only the sequence in which the different forms of intentional teaching arise.

5.3. Tool Transfer – a legitimate addition?

Tool transfer is a much-studied behavior in, for example, chimpanzees. Tool transfers meet functional criteria for teaching: they occur in a learner's presence, are costly to the teacher, and improve the learner's performance[31]. Tools are objects used to manipulate something indirectly with the tool rather than directly with the hand (or beak, etc.). The tool effectively becomes an extension to the body and requires changes to the animal's Body Schema[42] which is used by the mind to control the body. When a parent gives a tool to a youngster, it is almost like giving the pupil an extension to their body. It is important for the pupil to gain experience with a tool suitable for the job before finding tools for itself. Although it is usually the pupil that initiates tool transfer, it is the teacher's decision whether to grant it or whether they judge that the pupil is capable of finding a tool itself, and therefore is intentional on the part of the teacher.

Also, Gärdenfors and Högberg's list does not appear to have a form of intentional teaching specifically for Tool Use, although it has forms for other specific levels of tool development like tool-making.

Gifting a tool may not generally be thought of as intentional teaching, but the same may be said of the first two levels in Gärdenfors and Högberg's list, Intentional Evaluative Feedback ("a grunt"), and Drawing Attention ("pointing at something"). Tool Transfer fits in between these two behaviours.

(Tool Transfer is not always used, but this may be because the behaviour has become innate through genetic assimilation[43].)

5.4. Isn't the rate of evolution very variable?

This is answered in the introduction.

5.5. Isn't it true that if one ran the tape of evolution again, the results would be very different?

This is answered in the introduction.

5.6. Dinosaurs and meteorites

It is often said that the extinction of the dinosaurs by the impact of large meteor allowed mammals to flourish, otherwise we might not have evolved further. This is again based on the belief that evolution was very much subject to chance happenings.

5.7. Isn't the relationship between time, complexity and fitness nonlinear?

The most important characteristic of the period-doubling cascade is that it is *universal*. So if the bifurcation variable is non-linear with respect to time, the resulting cascade will still converge to the Feigenbaum constant. This is because the intervals are getting smaller. As the bifurcation parameter interval gets smaller, the more linear the relationship between time and the bifurcation parameter (complexity or fitness) becomes. This is true of any smooth nonlinear relationship when intervals get smaller.

5.8. Isn't the rate of evolution dependent on population?

Maybe, but the reason given in the previous paragraph applies here also.

5.9. The theory is incomplete, lacking an explanation

I have an explanation for the creation of information thresholds at regular intervals, but not a full explanation that predicts the nature of each new information transmission. The different kinds of information are shown in table II. The information transmitted is also the new source of variation for that stage of evolution.

5.10. Information and variation

The variation needed in evolution occurs in the information transmitted to the next generation. At the first stage, the variation is random mutations in a 1-dimensional sequence of DNA codes. According to Fisher's Geometric Model the resulting cell phenotype is represented as a point in a high-dimensional data space, where the dimensions of that space correspond to the traits of the organism. A 1-dimensional DNA genotype becomes a multidimensional organism.

At each stage the new variation of information at each stage can be thought of as variation in one dimension or a low number of dimensions. The low-dimensional information variation often causes co-evolution, resulting in changes in several dimensions or traits in Fisher's Geometric Model of the organism.

5.11. What about Social Learning?

It seems that the period-doubling cascade is only related to information that is pushed from one generation to the next, whether it be DNA or tool skills. Even if skills are learned by young animals imitating parents or others, only those skills that meet with the approval of parents seem to become part of Cumulative Culture. Gärdenfors and Högberg also emphasize that their results only concern intentional teaching.

In the case of Intentional Evaluative feedback, most of the actual information is probably transferred by Social Learning. However, the final decision about whether the information is to be used or not is taken by the parent, by Intentional Evaluative Feedback. In the following Intentional Teaching methods – Tool Transfer, Referential Gestures, Demonstration and Pantomime, Communication of Concepts, Explanation of Relationships Between Concepts, and Narration – the proportion of the information pushed as compared with information pulled, increases.

Learning

Today we can make artificial neural networks that learn, and we know that these networks are extremely simple. They would probably have been an early function of the nervous system, given their simplicity and usefulness. As multicellular organisms evolved senses such as vision, hearing, etc, these senses would be integrated into the learning function. All this would evolve genetically, and learning would be an instinctive behaviour where information is gathered by the individual alone.

Imitation

Imitation of parents is also useful, and would also evolve genetically as instinctive behaviour, the individual gathering information itself.

Learning is not part of the cascade

Learning is necessary for teaching, but learning does seem to be part of the cascade pattern in itself. Learning and imitation evolved together with multicellularity in a long process. The innovation of Intentional Teaching, where parents intentionally take control of what learned behaviour their offspring should keep or discard, marks a step change in Information Transmission. In this case the extra information consists of approval or disapproval of each learned behaviour.

5.12. Single cosmic evolution process

The fact that all the stages of transmission of information to the next generation conform to a single period-doubling cascade implies that there is a single process, or at least a similar set of processes, that has produced the whole of the evolution of the universe and life within it from the Big Bang, to life on Earth, to the computer, and whatever awaits us in the future. The process expresses itself as different forms of Darwinian evolution.

If the processes at each stage are identical on different planets, it does not necessarily mean that the results would be identical. In any case, the conditions are different on different planets.

5.13. Arguments for using Chaos Theory to explain evolution

Here is a list of reasons why evolution is a match with Chaos Theory:

- Chaos Theory is used in the study of population dynamics, a subject close to evolution studies. After all, Darwin's theory of natural selection was a result of Darwin reading Malthus' treaty on population. The period-doubling cascade is based on mappings (for example the logistic mapping) that model populations in a real-world situation of limited resources.
- Chaos Theory is a theory of iterated, nonlinear processes. Evolution is an iterated, nonlinear process.
- It is generally thought that events such as the first living cells are such rare and improbable events that it is impossible to predict when they occur. It is also argued that evolution will produce

different results if it is re-run. For example, kangaroos have only evolved in Australia, and nowhere else on Earth. But perhaps it is the case that the amount of increase in complexity that comes about over evolutionary timescales is predictable[2]. In other words it may be that the speed and level of evolution is predictable even if the exact manifestation is unpredictable.

- Evolution seems to show a series of similar events, "self-replicating Darwinian processes with variation and selection, requiring a new Information Transmission process", that has a pattern similar to a period-doubling cascade of events.
- The historical record matches a period-doubling cascade very well, although it depends on educated guesswork for periods where fossil or archaeological evidence is lacking.
- It is a feasible scenario. Given that 10 billion years of physical evolution can result in a Darwinian process (descent with modification and selection) in the form of the first single-celled life on Earth, it is not unrealistic that further Darwinian processes should emerge at intervals, or that these Darwinian processes should be different in order to take advantage of the products of evolution thus far.

In their influential paper on Punctuated Equilibria, Eldredge and Gould considered it important to argue for the position that there is no observation without theory, and that palaeontologists should reinterpret apparent facts in the light of new ideas before making judgement. One cannot but agree.

6. Summary

In this article, I have:

- Taken Gärdenfors and Högberg's 6 levels of intentional teaching and added "Tool Transfer", (used by, for example, chimpanzees) which fulfils the definition of teaching.
- In order to estimate dates, I paired each level of teaching with a newly evolved innovation that needed it.
- Extended Gärdenfors and Högberg's list to cover biological information transfer (Big bang (as a reference point), Single-celled Life/Asexual Reproduction, and Multicellularity/Sexual Reproduction) and information technology (Writing, Movable Type printing, and Computers).
- Shown that the known dates of information transfer innovations in evolution accurately converge to a period-doubling cascade (within 1%). Of the 13 dates, 3 are unknown, but if one only takes the known dates after that (from tool-made tools to the computer), one still has 7 consecutive events which conform to a period-doubling cascade within 1%.
- I have assumed that reproduction rate increases with complexity, which increases with time, and that these are stable relationships, giving very similar results for reproduction rate every time evolution is "run" (noting that species are "free" to evolve more slowly than this, but not faster).
- I do not provide any way to predict the next events given a list of preceding events.

The study of Population Dynamics provides the model, using reproduction rate as the bifurcation parameter. In the world of farming, reproduction rates can be artificially increased. The same model can be used for evolution if reproduction rate is assumed to increase with complexity and complexity is assumed to increase with time.

A concise description

Evolution is a period-doubling complexification process, the reflexive nature of which, in common with all period-doubling systems, gives rise to self-similar structures at thresholds with decreasing intervals. In evolution these take the form of new channels to transmit information to future generations at increasing cognitive levels, each channel causing a stepwise increase in adaptation speed and in unsustainability, resulting in population instability in the form of a bifurcation of population levels.

Conclusions

If the evolution of life is indeed a period-doubling cascade as described, then the following conclusions may be drawn:

- Evolution happens in stages
- Each stage adds a new Information Transmission level which transfers new information to future generations.
- A new level does not replace the previous level, it adds to it. All levels down to the lowest are still active.
- Each new level uses capabilities that have evolved during the previous level.
- Additionally, these information transmission events are each part of a generalized Darwinian process, each of which has a different search space, source of variation, selection, and cognitive level.
- The time interval between each stage is shorter by the factor 4.66920…, the Feigenbaum constant Delta, thereby forming a period-doubling cascade in the time dimension.
- The steps so far are 1) Big bang, 2) Life, 3) Multicellularity, 4) Cumulative culture, 5) Using tools, 6) Making tools, 7) Making tools with tools, 8) Concept-based tools, 9) New inventions, 10) New livelihoods, 11) Writing, 12) Printing, 13) Computer.
- There is progression, in the sense of the number of the level or stage that each organism has reached.
- There is progression in cognitive level at each stage[44].
- Evolution appears to be predictable in time, at least for the most advanced species at the "forefront" of evolution.
- From our observations of chimpanzees, New Caledonian crows, and other animals, the stages seem to be the same for all organisms.
- There will be more events, culminating in the chaotic zone around the year 2214.

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8. *Appendix A – The stages in more detail*

The 13 stages of evolution are described in more detail here.

Stage 1. Physical evolution

Starting from a state of low complexity, the state of the universe increased in complexity through various processes until organic molecules developed and, after about 10 billion years, self-replicating life.

Stage 2 . Single-celled life + Asexual Reproduction

Cells replicate themselves by growing and dividing into two cells. Each cell has copies of the genetic code which contains all the information the cell needs to grow and replicate itself. DNA mutations are also copied.

Stage 3. Sexual Reproduction and Multicellularity + Gene shuffling and fertilization

Multicellularity with differentiated cells (e.g. muscle cells, brain cells, etc) – known as *complex multicellularity* – is probably necessary for intelligent life to evolve. Plants and animals are multicellular. However, multicellularity is apparently not viable without sexual reproduction. Not all evolutionary biologists are in agreement about this, but there is evidence that sex and multicellularity evolved at the same time in red algae found in 1.2 billion year old rocks [8]. If this is the case, then sexual reproduction and complex multicellularity could be seen as different aspects of the same innovation.

Sexual reproduction also seems to evolve faster than simple self-replication (which is basically cloning). With self-replication, useful mutations occur, but often in different cells. There is no mechanism for the mutations to move into the same cell, so each cell has to evolve the same mutations on its own. Sexual reproduction combines genes from 2 parents, which enables good mutations to be collected into a single organism.

In addition, the genes used in sexual reproduction are all genes that come from fit individual organisms, increasing the chances of fit offspring.

99% of all species today reproduce sexually, so it is clearly advantageous [45].

Stage 4. Cumulative Culture + Intentional Evaluative Feedback

Cumulative culture can be due to learning or teaching. It seems that social learning has been around at earlier stages and that the innovation in this stage is Intentional Teaching.

Social learning, whereby young animals learn from their elders seems date back to the beginning of sexual reproduction or even earlier. Social learning is very widespread, as most species interact with their young at the beginning of their lives [33] and it covers a whole spectrum of situations, including learning prior to birth. For example, the fact that new-born rats respond positively to foods that the mother ate during pregnancy is counted as social learning [34]. There is even evidence of social learning in other sexually-reproducing forms of life such as plants and microbes [35]. So social learning may be an inherent feature of life.

Teaching, on the other hand, is a deliberate act which is more in keeping with the theme of deliberately pushing knowledge to the next generation (c.f. passing on DNA during self-replication, and shuffling genes for the benefit of offspring during sexual reproduction). Teaching is any deliberate behaviour or change in behaviour in order to pass on information, such as performing a task more slowly in order to demonstrate it to another of the species.

So Teaching would seem to count as a new way of passing on information.

However, if teaching is passing on information, what information is being passed on? Firstly, this is teaching of *learned* behaviour, not genetically programmed teaching. At this stage, offspring are copying their parent's behaviour, but not copying it reliably. According to Gärdenfors, the parent intervenes when the youngster does something wrong (Teaching Level i)[29].

This is an evolutionary shortcut, because new useful behaviours can be passed on directly through teaching instead of through genetic code mutation.

We do not know when teaching first appeared, but the predicted date, 264 million years ago, was about the time when Cynodonts emerged, 260 million years ago[9], which were descendants of pelycosaurs ("mammal-like reptiles"), had mammal-like skulls and were ancestors of modern mammals. Some cynodonts are thought to have engaged in parental care [46]. Some cynodonts were mammals, and modern mammals have been observed teaching their young [47]. Parental care is thought to date back even further to 520 million years ago [48], but that is not the same as teaching. That the first teaching could have happened 264 million years ago with the cynodonts or their immediate ancestors, the Therapsids, is not implausible.

Stage 5. Using tools + Tool Transfer

The use of tools is undoubtedly important in evolution. In effect, a tool is an addition to the body. It instantly extends the body without waiting for biological evolution [42]. The tools in question would basically be sticks and stones that happen to be lying around on the ground and used without modification for a useful purpose.

Chimpanzees have been observed teaching their offspring how to place nuts on a so-called anvil stone and crack them open using a stone of suitable size and weight [25]. While they are learning, young chimpanzees are allowed to use their mother's tools. This is called "tool transfer" and even without additional teaching, it fulfils all the criteria to qualify as teaching on its own because 1) it has a "cost" (giving up the tool to the pupil), and 2) the pupil learns from practicing with the tool [26]. Being different from teaching by demonstration, it would seem to be a new way of transferring information. Clearly, teaching the hands-on feel and use of a tool can really only be done by giving the tool to the pupil. If the tool is seen as an extension of the body, then Tool Transfer is equivalent to handing a body extension directly to a pupil. This can be compared with biological information transmission, where DNA hands over instructions for growing body parts.

Many primates use tools and most have opposable thumbs, which makes tool use easier. They may have been the first to use tools and arose between 65 and 55 million years ago[11][10].

Stage 6. Making tools + Drawing attention with referential gestures

Tools are made by humans, great apes and birds of the corvid family. Humans, great apes, and ravens (members of the corvid family) are the only animals confirmed to use referential gestures [39] [38]. It is not unlikely that there is a connection between these two facts, namely that referential gestures are needed to teach tool-making. The earliest tool manufacture is likely to be by the last common ancestor of tool-making great apes (humans, orangutans[12]) 13,000,000-9,000,000 years ago[13].

Stage 7. Making tools with tools (Oldowan technology) + Demonstration and Pantomime

2.6 million years ago was not the first time that stone tools were made. Stone tools made with the "bipolar" technique using with an anvil stone have been dated to 700,000 years earlier [50]. However, the freehand knapping technique (also known as Oldowan technology) marks a significant advancement.

A tool is an extension of the body. When a tool is held in the hand, it has to be incorporated into mind's "body schema" so that the working tip of the tool can be moved as if it were a part of the body [42]. Modern humans can do this easily, but our ancestors may not have been as proficient.

With the freehand knapping technique, a stone is held in each hand, without the support of an anvil stone. One stone was hit with the other to break off flakes. The movement of each hand has to be coordinated with the other hand. The method provides complete manual control over the tool being used and the object being made, and they both become extensions of the body.

Although it required greater dexterity, early humans clearly found that this technique gave better results, because they used it from then onwards (although the bipolar anvil technique continued to be used for certain types of stone and smaller stones that were difficult to work with the freehand technique) [51]. The freehand technique required improved perceptual abilities, learning capacities and bimanual dexterity compared with the bipolar technique [52]. The complete control involved eventually led to very finely made stone tools, such as spear heads.

Experiments have shown that teaching modern humans the freehand flaking technique is more effective if gestures are used during teaching, and even more effective if spoken language is used [53]. Thus it appears that a new form of teaching enabled hominins to teach the freehand technique to others. According to Gärdenfors, this would have been done by demonstration and pantomime (Teaching Level iv)[29].

Stage 8. Making concept-based tools + Communication of concepts

One of the prime candidates for this innovation is the earliest known stone-tipped spear from 550,000-450,000 years ago [15][16][17]. The significance of this spear is that it is the first known example of a composite tool. It had a wooden shaft and a sharpened stone tip attached to the shaft using a method known as hafting. From this point onwards, early humans had the ability to conceive of a human-made object made of more than one component and were able to construct one. This is a significant skill as most things made by humans today are composite objects. Composite tools require the concepts of "whole" and "part" are understood. This would have required Gärdenfors' Teaching Level v, Communication of Concepts[29], as do Late Acheulean tools which date from the same time.

Note that this is not a new tool, because spears had already been in use for a very long time, but making a tool by making separate parts and joining them together is a new and important concept for making things.

Stage 9. New inventions + Explanation of relationships between concepts

Boats, clothes, beads, harpoons, sewing needles, mortars and pestles, cloth, flutes, rope, pottery. These are just some of the new things that humans started to make, beginning around 119,000 years ago. It seems that humans suddenly gained the ability to invent new things. It is significant that everything that humans had made until this point were copies of the first tools used, which were originally stones, twigs and sharp sticks that were found lying around. The previous pinnacle of human technology - the stone-tipped wooden spear - was a just superior version of a sharp stick that was first found and used perhaps tens of millions of years before.

New inventions are considered to be associated with the Upper Palaeolithic Revolution [54], but the first inventions came earlier and the archaeological record agrees with the bifurcation-predicted date of 119,000 years ago.

This new ability for invention did not seem to require much advance in manual techniques so much as a new creativity or problem-solving ability. These new inventions would also possibly require new cognitive abilities to use and a new form of teaching to pass on usage to others. Gärdenfors' teaching level vi, Explaining Relationships between Concepts, would have been appropriate[29]. A significant change in language associated with the Upper Palaeolithic Revolution has been proposed [55].

Of the earliest inventions here the date of the first tools for making clothes (120,000 to 90,000 years ago[18]), and the harpoon (110,000 to 80,000 years ago[19] [20]) seem most relevant, as there is concrete evidence for them and they are true tools.

Stage 10. New livelihoods + Narration and structurally complete language

The Neolithic Revolution supposedly began 12,000 years ago with the domestication of sheep and various plants and led to the first agricultural civilization. However, the date predicted by the bifurcation pattern was 24,900 years ago. This agrees with the date of the first animal to be domesticated, which was the dog (26,000–19,700 years ago[21]). Dogs appear to have been an integral part of the Neolithic revolution [56]. It is believed that humans and dogs worked in a mutually beneficial partnership, initially in hunting [57], but later with herding. This partnership may have been important in the move away from hunting, scavenging, and gathering, to organize new livelihoods leading to agriculture and civilization.

This innovation also seems to have come from crossing a cognitive threshold that may have been associated with an advance in language. This seems to have enabled the capacity to invent new livelihoods. Communication must have been important to make these new livelihoods work. At some point language seems to have given humans to the capacity for logical reasoning and problem-solving. From experiments we know that some kinds of problems can only be solved with the aid of language [58]. Certainly, some kind of logical reasoning and problem-solving ability must have been necessary for humans to abandon scavenging, hunting and gathering (which for tens of millions of years was the only thing they knew how to do) and invent new ways of living, ending up with civilisation and the specialisation of labour.

Stage 11: Hand-written documents + Written language

We know very little about the evolution of spoken language, but we do know a lot about written language. Much information is now being passed on by written words. The first writing was called Cuneiform and it was developed as a means to record trade, debt, and tax information [59]. It also enabled the recording of religious knowledge, literature, and medical texts. Without the aid of writing, humans would have had to evolve much increased memory abilities which, even if possible, would take a long time to evolve.

The written word is not just communication: it is a shared memory and reference. A handwritten document is a persisting object that can record things that two or more people have agreed upon. Such a document enables agreements to be made, accounts to be opened, and laws to be reliably documented. It became an essential part of society.

The invention and use of new kinds of documents became the main source of variation and entirely new source of human society, taking over the role of the main driver of evolution of intelligent life on Earth. Various types of handwritten documents quickly became established, such as contracts, accounts, and descriptions of laws. Such documents enabled the organisation of groups of people on a larger scale and led to what we know of as cities and civilisation and an even greater degree of labour specialisation.

Writing is a form of information technology. The gestural and vocal parts of spoken language are translated into visual symbols on clay tablets or paper-like sheets of papyrus. Where spoken language is ephemeral, written language is persistent. Information in written form does not have to

be remembered in detail. It can be referred to when necessary. It effectively forms a storage medium that extends the storage capacity of the mind.

Writing consists of a common, mutually understood core, but often extended with specialist languages for such things as mathematics, as well as with other media, such as pictures. But writing is essential, unlike pictures. Pictures without writing have ambiguous meaning.

Stage 12: Mass-produced literature + Movable-type printing

An important entirely new source of the transfer of information that happened after the invention of written language, was the invention of a machine to replicate information. To be more precise, the invention of movable type printing in 1039-1048 CE . This was perhaps the first machine to handle symbols. Movable-type printing had small printing blocks for each character which could be assembled together in a frame and used to print text onto paper. The movable type made the process of composing a page of text very quick compared with the previous technique of carving wood blocks for printing. Movable type printing was invented in China and later spread to Europe. The 400-year delay before it spread to Europe could be thought to have slowed European development. When movable type printing arrived in Europe, it was an instant success and may have made up for lost time by incorporating new technological developments that had taken place in the meantime.

Before printing, books were copied by hand, which made them very expensive and mainly owned by wealthy establishments such as religious authorities.

Movable-type printing had the effect of democratising knowledge, putting into the hands of many more people. Science and mathematics, which were revolutionised by the invention of writing, were again boosted by the ability of printing to spread accurately replicated knowledge, without the errors often caused by hand-copying.

Stage 13. The computer + Software

Information technology began with the creation of the first working computer. There are many candidates for this, but the Manchester Baby, 1948[60], was the first stored-program computer, programmed with software rather than by plugging wires into sockets.

Like spoken language, writing, and printing, the computer was an invention based on symbols. Indeed, writing and printing can both be seen as early forms of information technology.

Computers can handle information automatically. Computers can also be used to extend the human mind by running simulations of scientific models of various phenomena. Such computer simulations are recognized as a new way to run scientific experiments. Networks of computers, such as the Internet, allow information to be exchanged virtually instantly between any locations. All knowledge is currently being transferred from books to the Internet.