Article

Transmission of information in evolution

Nicholas Hoggard [1]

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

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Abstract: The concept of cosmic evolution expands the concept of evolution from purely biological evolution to include the physical evolution of stars and planet Earth and complex prebiotic molecules, and also the cultural evolution, or technological development, of humans to the present day. The process of evolution is a process containing three essential elements: 1) variation, 2) selection, and 3) transmission to the next generation. It is an iterated process because the result of each generation is fed into the process again to give the next generation. The first living cells provided variation by mutation, and were subject to natural selection. Much later, sexual reproduction came about and the process of evolution acquired a new "layer" whereby variation was instead provided by a random combination of genes from each parent, selection was by sexual selection, and two sets of chromosomes are transmitted to the next generation. Further investigation reveals that subsequent cultural evolution, such as the use of tools and the invention of language, also conforms to the variation-selection-transmission process. Furthermore, there are indications that the transmission process follows a pattern which is commonly found in iterative processes. It changes, and incurs an increased cost, at intervals that decrease by a constant factor equal to 4.66920…, otherwise known as the Feigenbaum Constant. Such patterns of decreasing intervals normally reach an accumulation point and transition to chaotic behaviour, an event which appears to be due to occur in about two hundred years from now.

Keywords: evolution; chaos theory; cosmic evolution; complexity; period-doubling; Feigenbaum Constant δ;

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1. Chance and inevitability: Chaos theory and evolution

The dominant narrative of evolution in modern times is that it proceeds at a variable rate, largely decided by changes in the environment. This narrative has been formalized as the theory of Punctuated Equilibrium. However, research shows that rate of evolution is hardly affected by environmental changes. and then, while environment affects abundance, it has little effect on speciation or extinction [New Scientist, The chaos theory of evolution, Keith Bennett **REFERENCE**].

This opens up the possibility that evolution proceeds at a constant speed and may be predictable in certain respects.

The neo-Darwinian understanding of evolution is that it is basically a process of variation – caused by random genetic mutation – and Natural Selection. Successful variation survives and forms the basis for further variation in what is a simple iterative process.

Simple iterative processes are often studied with the help of chaos theory, but this has not been the case with evolution. However, chaos theory has been used in the study of population dynamics.

Darwin's got the idea for his theory of natural selection while reading Thomas Malthus' book on population. So there is a good precedent for applying population theory to evolutionary theory. That is what I attempt to do in this paper.

1. Aim of this paper

Here is an overview of what I try to do in this paper:

Population instabilities caused not by a temporary drop in a food supply, but a permanent drop in food supply due to faster and faster adaptation rates due to transformative events.

Food is normally in equilibrium until predator adaptation rate pulls away, causing increasing bifurcations doubling according to the number of feedback channels.

- Extend the ideas and mathematics of Population Dynamics to cosmic (physical, biological and cultural) evolution, particularly the phenomenon of population bifurcations at intervals decreasing according to the Feigenbaum Constant δ, 4.66920….
- Notice that some events in the history of evolution introduce new ways to transmit information to the next generation.
- Show how decreasing birth rate intervals in population dynamics can be translated into time intervals in evolution:
    - "Birth rate causing increased consumption"
      replaced by
    - "time (and competition?) causing increased complexity causing increased fitness causing increased consumption"
- Show a possible pattern of evolutionary events that conforms to the pattern of population bifurcations, with time intervals decreasing by the Feigenbaum Constant δ, 4.66920….
- Attempt to define common criteria for the events in order to address cherry-picking. The criterion is, "*a different way to transfer information*", where "different" is identified by increased cost of the transmission process.
- Suggest a mechanism for population bifurcations in the history of evolution.

I hope the results may be of sufficient interest to warrant further investigation.

1.2. Cosmic Evolution

1.1. Different kinds of evolution

When we think of evolution, we generally think of biological evolution. But there are other kinds of evolution, both before and after biological evolution. First there was physical evolution, which started at the moment the universe was created and which includes the evolution of stars and planets and eventually the evolution of complex molecules that were precursors of life. More recently there is cultural evolution, whereby humans progress without the need to evolve biologically [1]. The holy grail of the study of physical, biological and cultural evolution is to unite all three of them into a single theory of cosmic evolution [1].

Considering the whole history of the universe, the impression we get is that there is acceleration in evolution. For example, it took 3 billion years of single-celled life before life on Earth moved on to multicellular plants and animals, whereas much cultural evolution has happened on a timescale of a few thousand years.

1..2. Common ground

Physical, biological and cultural evolution are different, but two of them – biological and cultural evolution share at least one similarity – they both developed several means to pass on information to the next generation. The different means are shown in table mff.

Evolutionary stage	**Type of evolution**	**Means of passing on information to next generation**
Life	Biological	Passes on a copy of the genetic code (RNA or DNA).
Sexual reproduction	Biological	Passes on a random mix of the genes of both parents.
Parental teaching	Cultural	Young are taught by demonstration
Spoken language	Cultural	Teaching of and by speech
Written language	Cultural	Teaching of writing
Printing	Cultural	Information transmission via printed texts
Internet	Cultural	Instant transmission of information

Table mff. New means of passing on information

Looking at table mff it is apparent that the time interval between innovations in transmitting information to the next generation has got smaller with each event.

1.2. Population Dynamics

The study of evolution has much in common with the study of population dynamics. Populations of species in ecosystems are studied using mathematical formulae to simulate on a computer the effects of births, deaths and eating habits upon the population numbers. The population of each generation is calculated from the population of the previous generation. This calculation can be run many times to simulate many generations in order to see the long-term population trend.

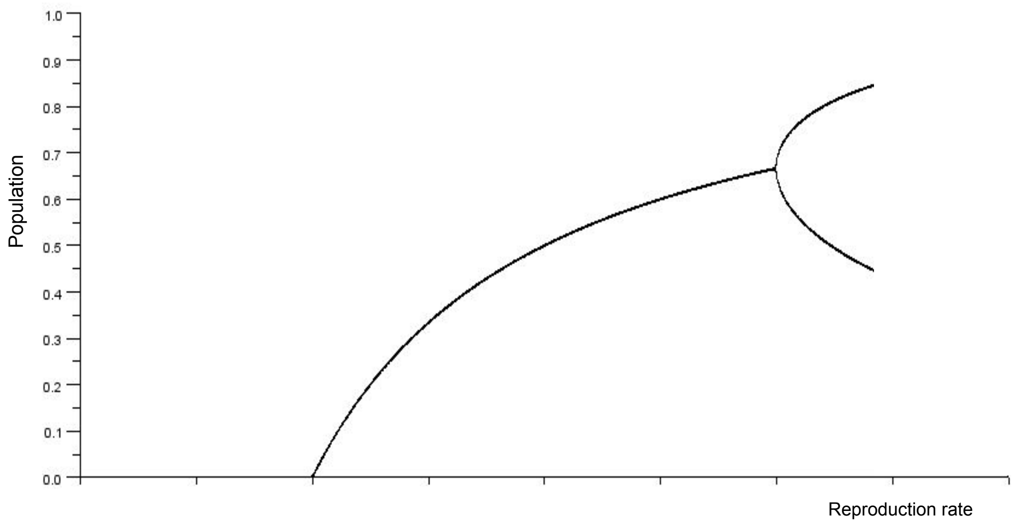

Figure 1a. The population diagram in figure 1a shows population increasing quickly at first and then more slowly as the birth rate increases. Then a bifurcation occurs, after which the population oscillates between 2 values.

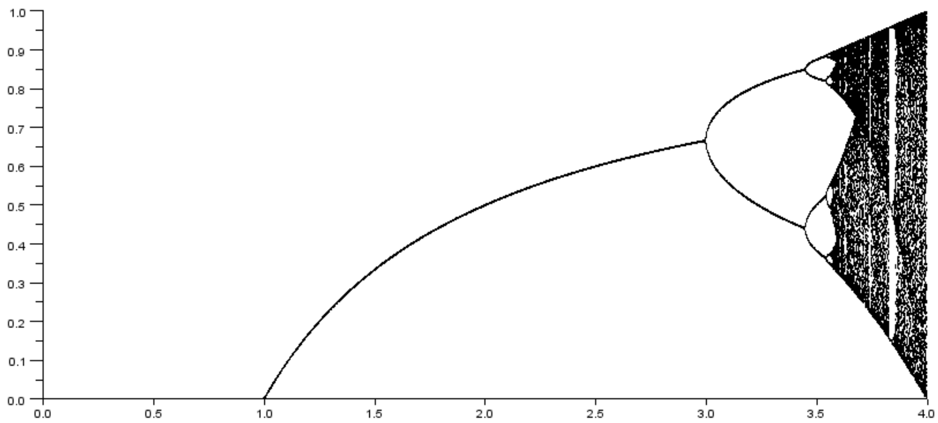

Figure 1. After the first bifurcation, further bifurcations occur. The interval between the bifurcations gets smaller and smaller by a factor which converges to 4.66920…, which is called the Feigenbaum constant δ. (The intervals decrease to zero at the so-called Accumulation Point, at birth rate of around 3.6 on the x-axis, after which the pattern becomes chaotic.)

The diagram in figure 1 shows how equilibrium population levels of a species (y-axis) can vary depending on the birth rate (x-axis) of the species. As the birth rate is increased there is an increase in population. At a certain population so much food in the environment is consumed that there is not enough food the following year. This causes the population to fall the following year. The food source then recovers, and the population also recovers. But the same over-consumption happens again and the pattern repeats. The population will eventually settle down to an equilibrium with a repetitive pattern where it alternates been a high and a low level (for example in figure 1a).

Further increases in reproduction rate cause further bifurcations and the population settles to a 4-year cycle, then 8-year, etc. At even higher reproduction rates, the population level becomes chaotic, with no fixed cycle (figure 1).

1.3. The Feigenbaum constant δ

An interesting feature of these so-called *period-doubling* bifurcations is that – no matter the exact form of the mapping – the interval between them (on the horizontal axis) always gets smaller and smaller by a factor which converges to 4.66920…, which is called the Feigenbaum constant δ. The intervals decrease to zero at the so-called Accumulation Point (at birth rate of around 3.6 in figure 1) after which the pattern becomes chaotic.

1.4. Similarities between population dynamics and evolution

There are ways in which population dynamics and evolution are similar:

- Both processes can be simulated mathematically by iteratively applying the same mapping over and over.
- They both have decreasing intervals between events:
- In population dynamics, the interval between bifurcations (measured in birth rate) decreases.
- In evolution – the interval between events (measured in time) decreases.
- Also, both may have the same pattern of feedback thresholds:
    - In population dynamics there are several thresholds of consumption of resources beyond the carrying capacity of the ecosystem due to increasing birth rates, where each threshold incurs negative feedback which affects the population level. Each threshold crossed requires twice the time to recover to the highest population level. Intervals between the thresholds diminish according to the Feigenbaum Constant

- In evolution, mentioned above, we can find at least two biological information channels and five cultural information channels (see table mff), each of which allows evolutionarily useful information to be transmitted to the next generation. Each of these channels form at different points in time when all the pieces needed for that channel fall into place. I will try to show below that the creation of these information channels follows the same pattern of thresholds and intervals diminishing according to the Feigenbaum Constant, and also cause negative feedback in the population level.

1.4. Birth rate intervals

The intervals in population diagram are not time intervals, but birth rate intervals, using the mapping:

$$x_{n+1} = a.x_n(1 - x_n)$$

where n is the generation, x_n is the population at generation n, a is the birth rate. $(1 - x_n)$ represents resources left for generation n+1. This mapping generates the bifurcations, the source of which is the lack of food resources, as mentioned previously.

1.4. Changing the parameter from birth rate to time

In trying to apply the mathematics of population dynamics to evolution, does it make sense to use time instead of birth rate? Birth rate affects population, obviously, but also affects consumption of resources.

But what if we look at what happens on an evolutionary timescale? We can expect the species to evolve towards higher complexity with time due to competition. Increased complexity would probably mean increased food consumption and increased birth rate. The causal chain "Elapsed time → Increased complexity → Increased birth rate" would mean that we could replace the birth rate on the x-axis of a population diagram with either complexity or time[1].

Population dynamics:

- Increased birth rate → increased consumption

Evolution:

- Elapsed time → increased complexity → increased fitness → increased consumption

1.4. Chance and inevitability

How does one measure complexity? There is no agreed universal measure of complexity – no less than 15 different ways to measure it are in use in different disciplines. I will assume it is a number and that it increases by the same amount with each mutation.

1.4. Evolution

For evolution, the mapping is the same as for population dynamics, but with birth rate replaced by complexity or time:

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[1] This ignores the question of linearity. But the pattern of decreasing intervals means that any smooth function will tend towards linearity as the interval gets smaller – because any smooth curve will look straighter and straighter as one looks at smaller and smaller pieces of it. So linearity can be ignored in this case.

$$x_{n+1} = c.x_n(1 - x_n)$$

where n is the generation, x_n is the population at generation n, *c* is the complexity, or time. Mathematically, this mapping should also generate population bifurcations. In population dynamics, the population bifurcations are caused by food depletion due to increased birth rate. I suggest that, on an evolutionary timescale, the increased birth rate *is caused by a step change increase in fitness of the species in question. These step changes in fitness are in turn caused by the creation of new processes at pre-determined thresholds in complexity.*

1.4. Population Bifurcation Diagram for the whole of time.

It would be very helpful to have a diagram that covers the whole of evolution, so we cannot follow just one species. We can assume that the line on the diagram always refers to species that are ancestors of modern humans. We need to choose the variables on the diagram to compensate for fact that the different species in our ancestry have had different numbers of offspring, different reproduction patterns, etc. I shall assume such changes can be made.

1.4. Calculating dates

Taking the 7 events in table mff, it happens that we know the dates of the last 3 events fairly accurately (see table 2). The Feigenbaum constant 4.66920 matches the ratio of intervals between these 3 events, within the margins of error (between 3.92 and 4.84).

New means of passing on information	Date (upper & lower limit)	Years before 2000 (upper & lower limit)	Interval since previous event (upper & lower limit)	Ratio of previous interval to this interval (upper & lower limit)
Writing	3400-2600 BCE [2]	5,400-4,600 years	*(Not applicable)*	*(Not applicable)*
Printing	1039-1048 CE [3]	961-952 years	3639 to 4448 years	*(Not applicable)*
Internet	1967 CE [4]	33 years	919 to 928 years	Between 3.92 and 4.84

Table 2. New means of passing on information

3.2. Calculation of theoretical dates

So now we have three events (Writing, Printing, Internet) with fairly accurate dates. What happens if we work backwards from them using the Feigenbaum constant to see if we can get any other dates of important evolutionary events?

I tried different years within the date range 1039-1048 for the invention of the printing machine (first invented in China) and found that 1048 gives the best fit to other dates in evolution. Further dates back in time are calculated by simply multiplying every interval by the Feigenbaum constant 4.66920 as follows:

$$A_n = A_{n+1} + 4.66920 \times (A_{n+1} - A_{n+2}) \quad (2)$$

where A_n is the date of event *n*, and using following starting values:

- Date of the Internet, A_{12} = 1967 CE
- Date of the Printing Machine, A_{11} = 1048 CE

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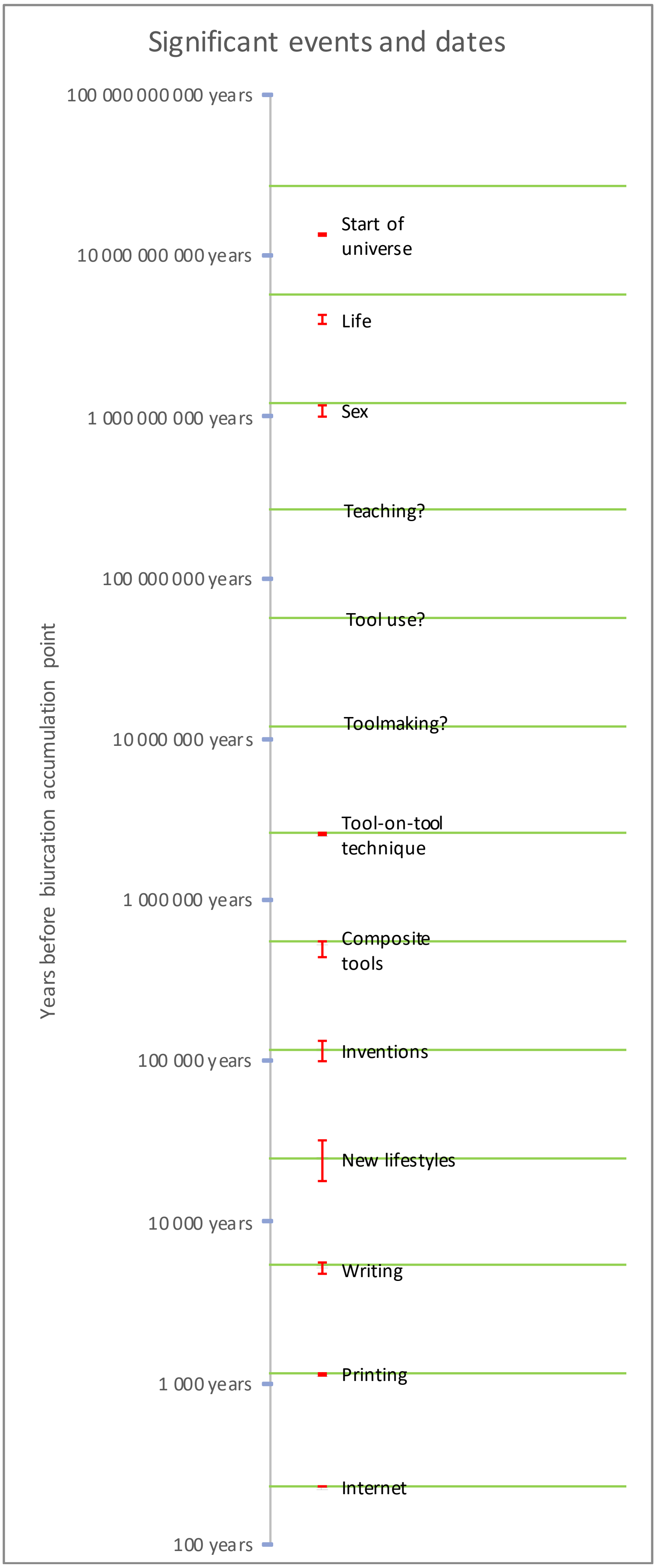
Significant events and dates
Years before biurcation accumulation point
100 000 000 000 years
10 000 000 000 years
1 000 000 000 years
100 000 000 years
10 000 000 years
1 000 000 years
100 000 years
10 000 years
1 000 years
100 years
Start of universe
Life
Sex
Teaching?
Tool use?
Toolmaking?
Tool-on-tool technique
Composite tools
Inventions
New lifestyles
Writing
Printing
Internet

Figure 1. Events in evolution shown on a logarithmic time scale (measured from the Accumulation Point, where the sequence converges around the year 2217). Green lines are the dates predicted by the Feigenbaum Constant δ (= 4.66920…). The accuracy of known dates are shown by the red error bars which show the margin of error. Dates for Teaching, Tool use, and Tool-making are not known. The other dates match the predicted dates, except for the first two dates which nevertheless indicate a growing convergence to the predicted dates, as is normal.

Innovation matching the date	Known date (years before 2000)	Known interval since previous innovation (upper & lower limit)	Theoretical interval since previous innovation	Interval error
1. Start of universe	13.820 – 13.778 by [5]	n/a	n/a	
2. Life	4.28 – 3.77 by [6]	10.05 – 9.498 by	21.13 by (=919×4.66920^{11})	110%
3. Sex & multicellularity	1.2 – 1.0 by [7] [8]	3.28 – 2.57 by	4.53 by (=919×4.66920^{10})	38%
4. Behavioural flexibility	unknown	unknown	969 my (=919×4.66920^{9})	unknown
5. Using tools	unknown	unknown	207 my (=919×4.66920^{8})	unknown
6. Making tools	unknown	unknown	44.5 my (=919×4.66920^{7})	unknown
7. Tool-made tools	2.60 – 2.55 my [9]	unknown	9.52 my (=919×4.66920^{6})	unknown
8. Composite tools	550 – 450 ty [10][11][12]	2.15 – 2.00 my	2.04 my (=919×4.66920^{5})	0%
9. New inventions	135 – 100 ty [13]	450 – 315 ty	437 ty (=919×4.66920^{4})	0%
10. New livelihoods	32 – 18 ty [14]	117 – 68 ty	93.6 ty (=919×4.66920^{3})	0%
11. Writing	5.4 – 4.6 ty (3400-2600 BCE) [2]	27.4 – 12.6 ty	20.0 ty (=919×4.66920^{2})	0%
12. Printing	961 – 952 y (1039-1048 CE) [3]	4,448 – 3.639 y	4,291 y (=919×4.66920^{1})	0%
13. Internet	33 y (1967 CE) [4]	928 – 919 y	919 y (=919×4.66920^{0})	0%
(Sum of unknowns		1.22 – 0.78 by	1.23 by	0.8%)

Key: by = billion years, my = million years, ty = thousand years, y = years

Table 1. Predicted dates and matching evolution events. The predicted dates are at intervals that decrease by the factor 4.66920, the Feigenbaum Constant δ. There are 4 unknown intervals, due to 3 events that I have assumed to be part of the series, but for which we have no dates, namely: parental teaching, tool-use, and tool-making. Note that there is a large error at the beginning (start of the universe and life), which apparently converges quickly to the theoretical value. This convergence from a different interval is normal for period-doubling bifurcations.

1.3. Events with unknown dates

I have included three events which we know definitely happened, for which we do not know the dates – 1) Behavioural flexibility & Parental teaching, 2) Tool use, and 3) Tool-making. But we know what happened around the predicted dates, so we can find circumstantial evidence to back up the events. (We know that behavioural flexibility and parental teaching came first, because tool use and tool-making rely on them, and that tool use must have come before tool-making.)

- **Behavioural Flexibility & Parental Teaching.** These two go together because when discovering new useful behaviours, they will be unlikely to have an evolutionary impact unless they are passed on to one's offspring. The date predicted for this (264 million years ago [15]) is very close to the appearance of Cynodonts (260 million years ago), which were immediate ancestors to mammals. If not Cynodonts, it may have been their ancestors, Therapsids.
- **Tool use.** The date predicted for tool use (56.6 million years ago) is soon after monkeys evolved (60 million years [16]), and we know that monkeys use tools and that now-extinct monkeys were likely the first animals to do so.

- **Tool-making.** The date predicted for tool-making (12.1 million years ago) is close to when great apes evolved (11.9 million years ago), and we know that great apes make tools. Now-extinct great apes of their immediate ancestors may have been the first animals to make tools.

1.x. Tools

The definition of a tool is an object used to extend the ability of an individual to modify features of the surrounding environment. For example, a stone can be used as a tool to break nutshells. A bird's nest is not a tool, because it is not used to perform actions on things.

To manipulate an object with a tool, the tool has to be incorporated into the tool-user's *body schema*, which is a collection of processes by which the *working surface of the tool* can be placed at the intended position and angle by moving the *held part of the tool* with (usually) the hand or fingers.

1.x. The predicted events

I have listed the predicted dates (generated backwards from the events Writing, Printing, and Internet) in table y and matched them with evolutionary events that fit the dates and also could be interpreted as representing new forms of evolution. The events are also shown on a logarithmic scale in figure x.

The result is a total of 13 events where the time interval converges to the Feigenbaum Constant $\delta = 4.66920…$. The dates match remarkably well (all within the error margin of known dates), with the exception of the first two dates, which nevertheless show a convergence to the Feigenbaum constant.

1.13. Common characteristics of the events

At each event, we find the following:

- **TRANSFORMATIVE INNOVATION:** An innovation, consisting of one or more major parts, that transcends the current evolutionary process, adding a faster means of generating evolutionary solutions.
- **VARIATION:** Generation of variation in evolutionary solutions of a particular type (different type for each stage). Each new stage (for species that adopt it) provides faster rate of evolutionary variation. Each variation generated is at some point subject to selection. It can be selected (successful) or not selected (unsuccessful).
- **SELECTION:** The process of selection where solutions produced by the "VARIATION" stage are selected for continued existence, or not. There are basically three kinds of Selection: Natural Selection (of individuals), Sexual Selection (of individuals), and Conscious Selection (by animals of their own individual solutions when an animal decides to pass on information –in the form of skills or information – to their offspring.).
- **INFORMATION TRANSMISSION:** A way of passing on the successful evolutionary solutions to future generations in a suitable format to match the class of solutions being created. It is possible that true that each Transformative Innovation contains a fundamentally new kind of information, which may correspond to a new cognitive level, and that this new information may require an addition or "upgrade" in the process of Transmission for each new stage.

The characteristics of each event are shown in table v.

Stage of Evolution	Transformative Innovation	Source of variation *Each new stage becomes the main driver of evolution by providing a faster rate of useful evolutionary solutions and/or improvements*	Scope of variation	Selection	Information Transmission *to the next generation*	Comments *Each new stage:* • *Requires the previous stage* • *Does not replace, but adds to the previous stage* • *Co-evolves with previous stages*
1. Universe	The universe	Random molecular change	All possible molecular combinations	None (no life, no selection)	**None (no life, no transmission)**	
2. Self-replicating single-celled life	The self-replicating cell	Random mutation.	Single-cell physical and behaviour traits.	Natural selection	**Genetic code - passed on in cell division**	The first living cells contained many innovations.
3. Sex and Multicellularity	Sexual reproduction and complex multicellularity.	Random mixing of genes that come from parents that have already proved to have sufficient fitness to survive..	Multi-cellular - physical and behaviour traits.	Sexual selection	**2x genetic code: complete genetic code from each parent**	Two innovations here (sex enables complex multicellularity).
4. Behavioural Flexibility	Alternative behaviours in different situations, instead of a genetically programmed response.	Trial and error behaviour in different situations.	All possible behaviours.	Conscious evaluation and selection of each behaviour (instead of selection of the whole living individual)	**Parental teaching by demonstration**	.
5.	Finding ways to use found objects as tools,	Trial and error using found	All possible	(Same as above)	**Parental teaching of found tool**	Co-evolution favours genetic changes that enhance use of particular

Using found tools	thereby extending the body faster than evolving biological body extensions.	objects as tools.	uses of tools found in the environment.		**skills, including giving tool to young ("tool transfer")**	tools or tools in general, such as brain size.
6. Making tools	Techniques to replicate found tools	Trial and error manufacture of copies of found tools.	All possible hand-made tools that replicate or improve upon found tools.	(Same as above)	**Parental teaching of toolmaking skills, including tool manu-facture for teaching**	variation in the **development, production and use** of made tools?.
7. Tool-made tools	Tool-made tools, i.e. any object held as a tool in one hand while being made using a tool in the other hand, which gives complete control over the process (e.g. freehand stone knapping).	Higher precision tools possible with tool-on-tool technique.	Higher quality tools.	(Same as above)	**Parental teaching of tool-made tool skills.**	This level of tool-making may have required (and co-evolved with) a rudimentary spoken or gestural language.
8. Compo-site tools	Composite tools, i.e. tools made from separate parts fastened together	Greater possibilities to make optimal tools by using different materials.	Improve-ment on simple tools.	(Same as above)	**Parental teaching of composite tool skills.**	This level of tool-making may have required (and co-evolved with) a rudimentary spoken language.
9. New invent-tions	Made objects that have new functions (i.e. not just better versions of found objects).	Ability to imagine new kinds of tools for new kinds of uses.	Tools limited only by current techno-logy.	(Same as above)	**Parental teaching of the use of various inventions + language?**	Extending manufacturing skills beyond the traditional hunting, scavenging and gathering activities may have required some kind of primitive language to give names to new inventions.
10. Social inno-vations (and complete language?)	New forms of organisation for specific ends.	Imagining improvements and changes in livelihood. Fully developed spoken language.	Unlimited scope new for liveli-hoods.	(Same as above)	**Parental teaching of spoken language.**	Social Innovations must have been enabled by invention of communication using fully-developed spoken language.
11. Writing	The invention of Writing, which increases the	Creativity in inventing useful kinds of	All possible hand-	(Same as above)	**Parental or school teaching of**	

	mind's capacity by storing information externally on media which can be shared.	documents (contracts, accounts, laws, etc.)	written documents.		**reading and writing**	
12. Printing	The moveable type printing machine, making knowledge available to the majority, not just elites.	Knowledge and creativity.	Limited only by current knowledge.	(Same as above)	**Parental or school teaching with the aid of books**	
13. The Internet	The Internet computer network.	Creativity.	All possible online services.	(Same as above)	**Parental or school teaching with the aid of Internet**	The Internet is becoming the main repository of information, with a search facility that mimics that of the mind.
14. Subsequent events						

Table v. Layers of evolution. A change in the way information is transmitted to the next generation (column in red) seems to be the key to identifying a transformative event.

3. The stages of evolution

Here is a description of the Transformative Events that match the pattern of intervals.

- *Event number:* **1**
- *Transformative innovation:* **Beginning of the universe**
- *Form of evolutionary solutions subjected to selection:* **Atoms/molecules**
- *Information transmission to next generation:* **(Not applicable – no living organisms)**

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.

- *Event number:* **2**
- *Transformative innovation:* **Self-replication**
- *Form of evolutionary solutions subjected to selection:* **DNA-defined cellular traits**
- *Information transmission to next generation:* **DNA copying**

The earliest cells replicated 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.

- *Event number:* **3**
- *Transformative innovation:* **Sexual Reproduction and Complex (i.e. differentiated cell) multicellularity**
- *Form of evolutionary solutions subjected to selection:* **DNA-defined multicellular traits**

- *Information transmission to next generation:* **Sexual Reproduction**

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. But multicellularity is apparently not viable without sexual reproduction. The reasons are complicated and not all evolutionary biologists are in agreement, but there is evidence that they evolve 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 so that they are both in the same cell, so each cell has to evolve the same mutations on its own. Sexual reproduction combines genes from 2 parents, which is a way of collecting good mutations into a single cell. 99% of all species today reproduce sexually, so it is clearly advantageous [20].

- *Event number:* **4**
- *Transformative innovation:* **Behavioural flexibility and Parental teaching**
- *Form of evolutionary solutions subjected to selection:* **Novel behaviours**
- *Information transmission to next generation:* **Parental teaching**

Cultural evolution goes back before language and before humans. *Social learning*, whereby young animals learn from their elders seems date back to the beginning of sexual reproduction or even earlier[2]. Parental 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. For example, meerkats teach their young how eat scorpions by giving them dead or disabled scorpions [24]. The young meerkats learn by imitation or emulation, and the knowledge gets passed on, shortcutting the biological genetic route for the passing on of knowledge. So Parental Teaching would seem to count as a new way of passing on information.

But if parental teaching is passing on information, what information is being passed on? Firstly, this is teaching of *learned* behaviour, not genetically-programmed teaching. Also, it presumably teaches behaviours which are not passed on by social learning because opportunities for observation are rare, or because learning the behaviour is difficult or dangerous. Such a case may be the meerkats' handling of scorpions. If the meerkats did not actively teach the behaviour, the behaviour may not

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[2] *Social learning* is a process whereby young animals learn from their elders. Social learning is very widespread, as most species interact with their young at the beginning of their lives [21] 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 [22]. There is even evidence of social learning in other sexually-reproducing forms of life such as plants and microbes [23]. So social learning may be an inherent feature of sexually-reproducing life, or even self-replicating cells, with juveniles learning about other members of their own species at the same time as learning about everything else in their environment. That implies that social learning evolved slowly as multicellular animals evolved that the beginning of learning may count as part of the same innovation as the first sexual reproduction or the first cells. There is no sudden evolution of social learning and insofar as social learning affects evolution, it can perhaps be considered to be "factored in", in the same way that multicellularity also seemed to appear with sexual reproduction.

get passed on. This is an evolutionary shortcut, because new useful behaviours can be passed on directly through teaching instead of through genetic code mutation, which takes a long time.

While the teacher would have taught by demonstration, the pupil would have learned from the teacher by imitation, which is considered to be a symbolic means of communication. Animals already have a talent for this, probably from having practiced social learning.

We do not know when parental teaching first appeared, but the predicted date, 264 million years ago, was about the time when Cynodonts emerged, 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 [25]. Some cynodonts were mammals, and modern mammals have been observed teaching their young [24]. Parental care is thought to date back even further to 520 million years ago [26], but that is not the same as parental teaching. That the first parental teaching could have happened 264 million years ago with the cynodonts or their immediate ancestors, the Therapsids, is not implausible.

- *Event number:* **5**
- *Transformative innovation:* **Tool use**
- *Form of evolutionary solutions subjected to selection:* **Found tools**
- *Information transmission to next generation:* **Teaching tool use**

The use of tools is undoubtedly important in evolution. A tool is, in effect, an addition to the body. It instantly extends the body without having to wait for biological evolution [27]. 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.

56.6 million years ago, the first monkeys had evolved. Monkeys use tools today [28], and it is not implausible to suggest that they were the first to use tools 56.6 million years ago.

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 [29]. 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 [30].

- *Event number:* 6
- *Transformative innovation:* **Making tools**
- *Form of evolutionary solution subjected to selection s:* **Made tools**
- *Information transmission to next generation:* **Teaching tool-making**

This is the time of the first great apes or hominids. Great apes have been observed making tools [31]. If teaching tool use is a significant new way to pass on information, then perhaps teaching tool-making is too. Teaching the making of tools is a three-part process, usually in the following sequence: 1) Demonstration of how to use the tool; 2) Repeated tool transfer until use of the tool is mastered; 3) Teaching of how to make the tool [32]. Research on this subject is not extensive and there a few detailed descriptions in the literature of teaching the making of tools. The process of teaching young chimpanzees to use and make tools takes several years.

Possible levels of language?

It is believed that language developed at some time during the period when the next 4 innovations occurred. We know that language had already developed by the time Writing was invented. But we know very little about the development of language, as no trace was left apart from the end result.

It seems unlikely that spoken language developed fully in one step, and it is often proposed that it developed in two steps: for example, a primitive language and then a more sophisticated language for the "Upper Palaeolithic Revolution" [33]. There are many different theories of language development and none have explained in any detail how language evolved. The bifurcation pattern suggests that there were four important innovations during this period. Could there have been four levels of language that evolved step-wise? Each new level of language would ideally encode a new kind of information than can be transferred to other individuals, and thus qualify as a new means of transferring information. It is possible that the earliest forms of language mainly consisted of gestures. Later forms would have been mainly spoken. There would be a progression from simple grammar, or no grammar, to the grammatical structures we have today. They may have been changes to enable discussion of imaginary scenarios, which would have been useful for problem-solving.

Brain size also co-evolved with language and tools [34]. The fact that language developed during this period suggests that language may have been required for the tool innovations to happen.

- *Event number:* **7**
- *Transformative innovation:* **Tool-on-tool technique**
- *Form of evolutionary solutions subjected to selection:* **Objects made with tools**
- *Information transmission to next generation:* **Tool-on-tool teaching (& language learning?)**

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 [35]. But the Freehand Knapping technique marks a significant advance.

A tool is an extension to 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 [27]. 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 is hit with the other to break off flakes. The movement of each hand has to be coordinated with the other hand. With the freehand technique, the tool being used and the object being made *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. The freehand technique gives greater control over the resulting flakes (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) [36]. The freehand technique required improved perceptual abilities, learning capacities and bimanual dexterity compared with the bipolar technique [37]. The improved control 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 [17]. So it may be that some form of language had evolved which enabled hominins to teach the freehand technique to others. Modern humans, with more advanced innate tool abilities, can learn the freehand knapping technique without language, but this may not have been the case for early hominins. It has been suggested that hominins at this time engaged in social foraging which demanded increased co-operation and communication, and that they may have developed gesture as a means of communication [38].

- *Event number:* **8**
- *Transformative innovation:* **Assembly techniques**
- *Form of evolutionary solutions subjected to selection:* **Composite tools**
- *Information transmission to next generation:* **Composite tool teaching (& language learning?)**

The prime candidate for this innovation is the earliest known stone-tipped spear from 550,000-450,000 years ago [10][11][12]. 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 by 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.

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 principle for making things.

Just as with the Freehand Tool Technique, it may have been that a new language innovation was required to teach the making of composite tools.

- *Event number:* **9**
- *Transformative innovation:* **Creating new objects to solve problems**
- *Form of evolutionary solutions subjected to selection:* **New inventions**
- *Information transmission to next generation:* **Teaching use of inventions (& language learning?)**

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 as though 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 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 first found and used perhaps tens of millions of years before.

New inventions are considered to be associated with the Upper Palaeolithic Revolution [39], 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 to explain to others, and may have been associated with new language abilities. A significant change in language associated with the Upper Palaeolithic Revolution has been proposed [33].

Of the earliest inventions here I use the date of the first bead necklace (135,000-100,000 years ago [13]) for this innovation, because the although the dates for the other earliest inventions - boats and clothes – fit the bifurcation pattern, evidence is circumstantial and without actual artefacts.

- *Event number:* **10**
- *Transformative innovation:* **Language and Organisational skills**
- *Form of evolutionary solutions subjected to selection:* **New livelihoods**
- *Information transmission to next generation:* **Language learning**

The Neolithic Revolution supposedly began 12,000 years ago with the domestication of sheep and various plants and led to the first agricultural civilisations. But the date predicted by the bifurcation pattern is 24,900 years ago. This agrees with the date of the first animal to be domesticated, which was the dog (32,000 - 18,000 years ago [14]). Dogs appear to have been an integral part of the Neolithic revolution [40]. It is believed that humans and dogs worked in a mutually beneficial partnership, initially in hunting [41], but later with herding. This partnership may have been important in the move away from hunting, scavenging and gathering, to organising new livelihoods leading to agriculture and civilisation.

This innovation also seems to have come from crossing a cognitive threshold that may have been associated with an advance in language. It seems to have enabled a capacity for inventing new livelihoods. Communication must have been important to make these new livelihoods work. At some point language seems have given humans to the capacity for logical reasoning and problem-solving. We know from experiments that some kinds of problems can only be solved with the aid of language [42]. 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.

- *Event number:* **11**
- *Transformative innovation:* **Writing**
- *Form of evolutionary solutions subjected to selection:* **Handwritten works**
- *Information transmission to next generation:* **Teaching of reading and writing**

We know very little about the evolution of spoken language, but we do know a lot about written language. Much information is today passed on by the written word. The first writing was called Cuneiform and it was developed as a means to record trade, debt, and tax information [43]. 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.

- *Event number:* **12**
- *Transformative innovation:* **Movable Type Printing (machine replication of writing)**
- *Form of evolutionary solutions subjected to selection:* **Printed works**
- *Information transmission to next generation:* **Replication of knowledge**

An important innovation in the transfer of information that happened after writing was invented was the invention of the printing machine. To be more precise, the invention of movable type printing in 1039-1048 CE [3]. This was perhaps the first machine for handling 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 moveable 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.

If evolution is about passing on information, the printing machine was the machine to do it. Before printing, books were copied by hand, which made them very expensive and mainly owned by wealthy establishments such as religious authorities.

Printing democratised knowledge, putting into the hands of many more people. Science and mathematics, which were revolutionized 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.

Event 13 – the Internet

- Event number: **13**
- *Transformative innovation:* **Internet (knowledge search and delivery)**
- *Form of evolutionary solutions subjected to selection:* **Web pages and services**
- *Information transmission to next generation:* **Search and delivery of knowledge**

If we were to look for other, more recent examples of ways of transferring information, the Internet comes to mind. The Internet is a store of information as well as a communication channel. It contains search functions that allow us to find information far more quickly than before, and also to find other people whom we might be interested in exchanging information with and instantly communicate with them in a variety of different ways.

5. General features

1.x. General features of Transformative Innovations

- Only a few species take part in the latest stage of evolution - perhaps only one species to begin with. Unrelated species can reach the same stage at a later date (e.g. tool use in crows).
- Previous stages do not disappear when the next stage starts.
- Each new stage adds to the previous stages, which remain active.
- Co-evolution: At each stage, there is likely to be co-evolution with previous (lower) stages. For example, tool development would have favoured individuals with better tool abilities, and may have favoured larger brains.

1.4. Defining Transformative Innovations by the cost of transmission to the next generation

The way to identify a Transformative Innovation seems to be whether it causes an essential change in the transmission of information to the next generation. Most events in the history of evolution don't do that.

In addition, it is not easy to define an essential change in transmission. Certainly just changing for example, the swapping of teaching how to use one tool to teaching how to use a different tool does not count. But teaching how to *make* a tool instead of just how to *use* a tool is an essential change.

One approach to this problem could be to list the costs to the parent of various information transfer activities. Table it shows the costs of transferring knowledge to the next generation.

Stage of Evolution	Costs of Information Transmission to next generation Each cost is additional to the cost of the previous stage
1. Universe	None (no life, no transmission)
2. Self-replicating life	Cost of copying genetic code for cell division.
3. Sex and Multicellularity	Cost of sex (more costly than cell division because males do not bear offspring, and mother's offspring have only half of her DNA).
4. Behavioural Flexibility	Cost of Parental teaching by demonstration
5. Using found tools	Cost of giving tool to young, known as "tool transfer". The tool itself is part of the information passed on to the next generation
6. Making tools	Cost of showing how to make a tool as well as how to use it.
7. Tool-made tools	As toolmaking, with extra cost of finding a tool to use.
8. Composite tools	Cost of teaching joining together of parts.
9. New inventions	Unknown cost (cost of teaching an incomplete spoken language?)
10. Social innovations	Cost of teaching complete language.
11. Writing	Cost of teaching reading and writing.
12. Printing	Cost of books in teaching.
13. The Internet	Cost of the Internet in teaching.
14. Subsequent events	Unknown.

Table it: Increasing costs of Information Transmission to the next generation is a possible way to identify significant changes, and thereby identify Transformative Innovations.

I have not identified an additional cost for Event 9. I suspect that an incomplete spoken language (which would involve an extra cost) was needed for this stage of development, not least because it seems unlikely that a complete language – i.e. a language with all the capabilities of any spoken language today – should appear fully-formed out of nowhere without incomplete languages to precede it. It has been proposed that language developed in two stages. I suggest that language may have developed in up to four stages, in tandem with tool use and social innovation.

The scenario I am suggesting is that one or more of the Transformative Innovations 7, 8 and 9 (tool-made tools, composite tools, new inventions, social innovation) required new levels of communication in order to pass on necessary information.

The first stage may have been a gestural language as opposed to a spoken language. I suggest that the language developments would co-evolve in lock-step with the practical innovations because the practical innovations needed the language innovations, and the language innovations needed the practical innovations in order to be used.

In this scenario, each step in language development would require some new concepts that would incur a cost in order to transmit to the next generation.

As evidence for the co-evolution of tools and language, experiments have shown that teaching modern humans the freehand flaking technique ("tool-made tools") is more effective if gestures are used during teaching, and even more effective if spoken language is used [17].

1.4. In between Transformative Innovations

In between the Transformative Innovations there are thousands of innovations that are absolutely essential to our evolution. But indispensable as they are, the hypothesis of this paper is that only a handful of then changed the way that information is passed on to the next generation. The transformative innovations are about the creation of new or enhanced channels to transmit information to the next generation, not about what innovations are transmitted on those channels.

Just to give two examples:

- **Cave paintings (44,000 years ago):** These are thought to have a religious significance and not used to teach offspring. They were nevertheless an essential innovation, not only because image-making has been and still is essential to us, but because art led to pictograms and writing.

- **The Industrial Revolution (1760 - 1820):** Despite the importance of the Industrial Revolution, it didn't originate a new way of passing on information to the next generation.

Mature stage	→	New stage
Cyclic molecular processes	→	Self-replicating Life
Complex DNA-determined single cells	→	Sex and differentiated multicellularity
Sentient multicellular animals	→	Behavioural flexibility
Established culture of trying new behaviours	→	Finding and using tools
Established tool-using skills	→	Making tools
Established tool-making skills	→	Making objects with tools
Established making- objects -with-tool skills	→	Composite tools and assembly
Established composite tool skills	→	New inventions
Established invention culture	→	New livelihoods, language
Organisational skills, labour specialisation, civilisation	→	Writing/ Handwritten works
Established importance of legal documents and ledgers	→	Printing/ Printed matter
Widespread reading and writing skills	→	Internet-connected information sources and services

Table w. The mature state of each stage serves as a basis for the next stage.

1.1. Each stage seems to build on the previous stage.

Table w shows the maturation of each stage and how it provides the biology, knowledge and skills needed for the next stage. The only part that doesn't fit this pattern is the sudden arrival of language. This could be an argument for more rudimentary language levels corresponding to the tool levels, starting with the "tool-on-tool" event.

1. Possible explanation of population bifurcations

1.5.3. Proposed reason for population bifurcation in evolution – faster predator adaptation causing shortage of prey.

In population dynamics, the population level bifurcates and oscillates between two levels because of an increase in birth rate causing overconsumption of prey. What is the corresponding mechanism for evolution where birth rate is replaced by complexity?

In general, predators are more complex creatures than their prey. But there is a "cost of complexity"[18] whereby the more complex a species is, the slower its adaptation rate. So prey should be able to adapt more quickly than their predators. In this situation, overconsumption of prey is unlikely, and under-consumption is more likely. Under-consumption of prey would give a stable population level. But if the predator were to evolve by acquiring one of the transformative innovations listed above, then the balance may well be disturbed to the advantage of the predator and result in overconsumption of prey, causing a bifurcation in the predator population level (figure gt).

In practice, such population oscillation would not be likely to have left a trace in the fossil record.

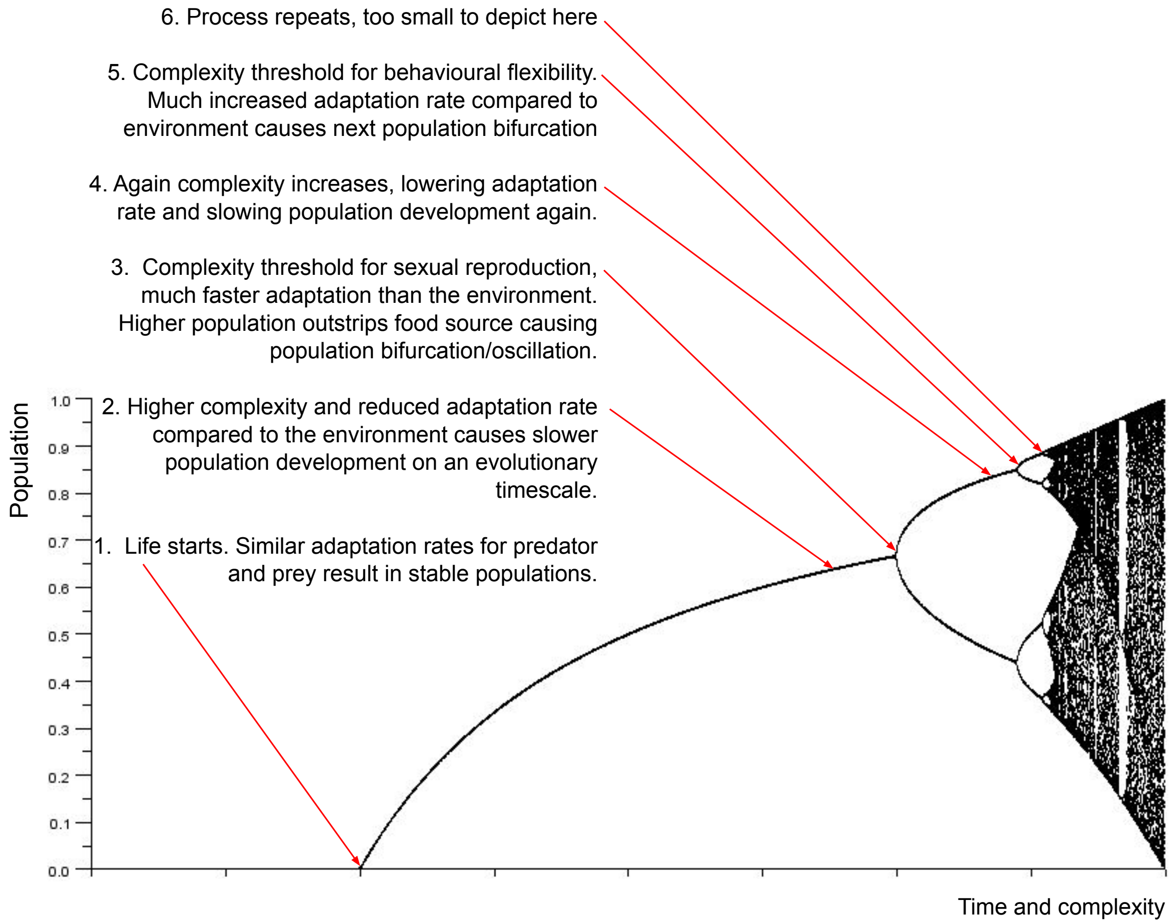

Figure gt. Suggested mechanism for population bifurcations in evolution. The "cost of complexity" reduces the adaptation rate of the most complex species. When a transformative event occurs, the adaptation rate increases, causing overconsumption and a population bifurcation.

1.4.1 Self-similarity

The hypothesis of new levels of the TRANSFORMATIVE INNOVATION-VARIATION-SELECTION-TRANSMISSION evolution process is reminiscent of the self-similarity of fractal structures. For example, the Mandelbrot Set (figure ms) is a fractal figure generated by iteration of a mapping which is not significantly different from that of the population bifurcation diagram, but is "shown from above" in the complex number plane. Figure ms shows the relationship between the Feigenbaum Tree and the Mandelbrot Set. The Mandelbrot Set shows self-similarity in the form of small copies of the Mandelbrot set within the Mandelbrot Set pattern (figure mms). There are an infinite number of mini-Mandelbrot Sets in the Mandelbrot Set, and each one is different in size and slightly different in form. This is analogous to an infinite number of evolutionary stages, all containing the pattern TRANSFORMATIVE INNOVATION-VARIATION-SELECTION-TRANSMISSION, but all different in size and detail. The smaller the mini-Mandelbrot, the more iterations are required for it to appear.

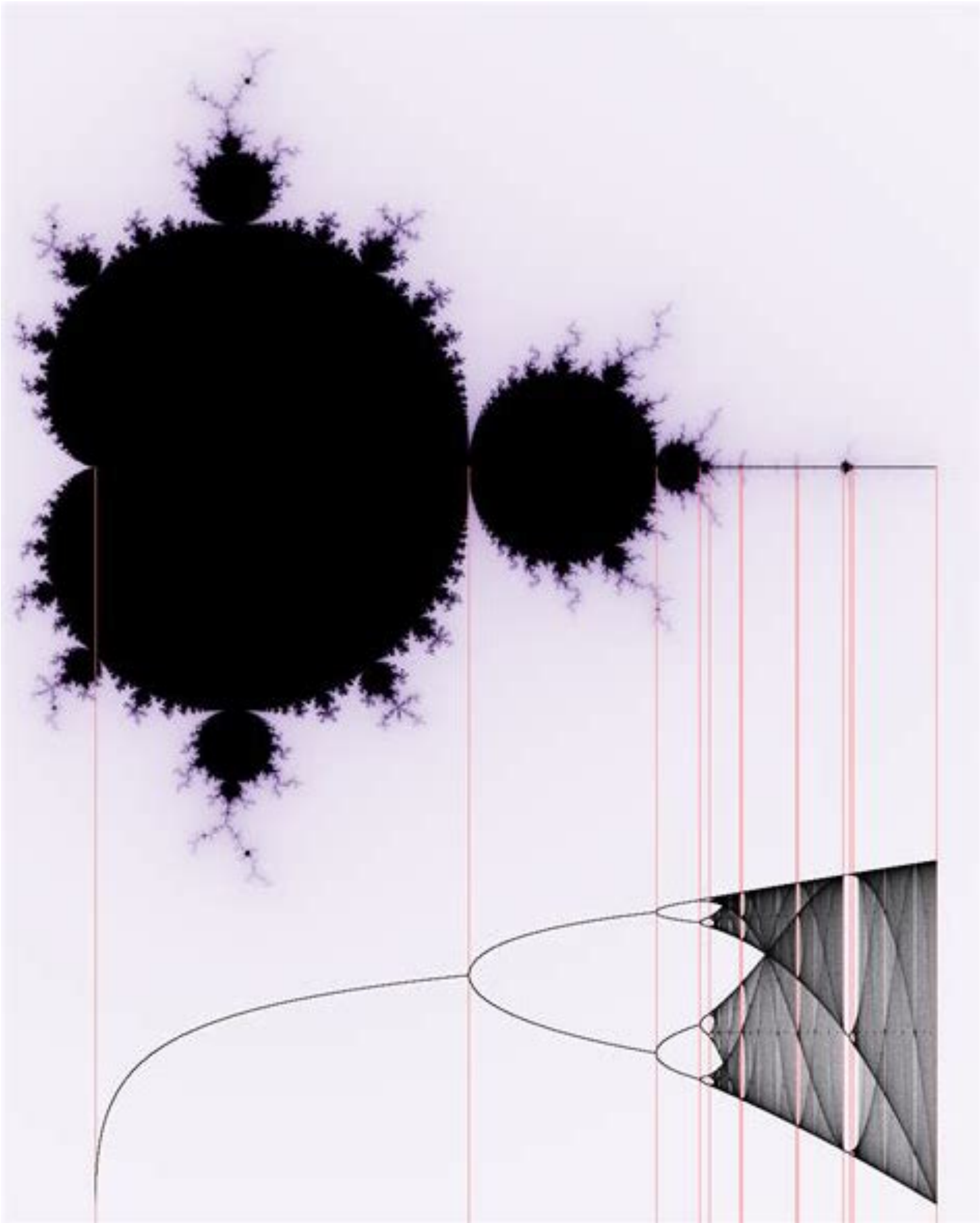

Figure ms. The Mandelbrot set, which is a bifurcation diagram shown from "above" in the complex number plane.

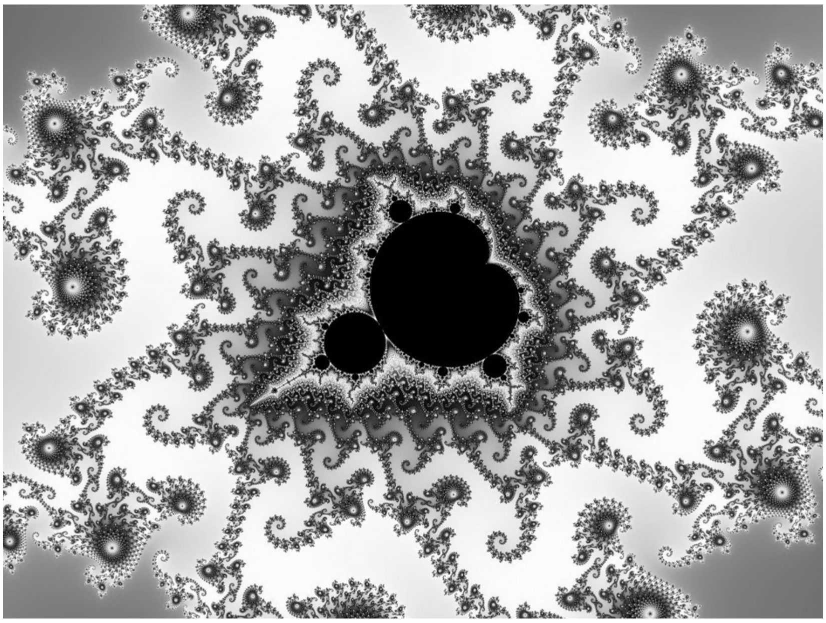

Figure mms. A mini-Mandelbrot set – of which there are an infinite number, in various sizes – is part of the detail of the Mandelbrot set. It is an example of self-similarity which is often found in iterated systems. It is analogous to transformative innovations providing alternative evolutionary processes.

8.2. Evolutionary steps seem to be getting smaller, complexity-wise

The intervals get shorter and there seems to be less evolution (i.e. less increase in complexity) involved at each stage. For example, consider from a subjective point of view the amount of evolution between "Multicellularity" and "Behavioural flexibility" (where life evolved from single cells to animals with legs, eyes, and brains), and compare it with the amount of evolution between "Using tools" and "Making tools". Intuitively it seems clear that less evolution is happening at each step.

Event number	Year of Event	Interval until Next Event
13 (The Internet)	1967	197 years
14	2164	42.2 years
15	2206	9.03 years
16	2215	1.93 years
17	2217	0.41 years
18	2217	32 days
19	2217	6.9 days
20	2217	1.47 days
21	2217	7.56 hours
22	2217	1.61 hours
23	2217	20.8 mins
24	2217	4.45 mins
25	2217	57.2 secs
26	2217	12.2 secs
27	2217	2.62 secs
28	2217	0.56 secs
(Infinite number of events here)		(Intervals approach 0)
∞	2217	Accumulation Point
(Post-bifurcation stage)	2217 onwards	Chaotic zone

Table 3. Predicted future events, with intervals and dates. The intervals are easy calculated by dividing the previous interval by the Feigenbaum Constant 4.66920. The years stated may not be exact - they are based on the date of the invention of the computer network (Internet).

1.11. Future events

Evolution is still going on, and the bifurcation pattern predicts further dates for the future, shown in table 3. I do not know what these events might be, but they should continue the pattern of transformative innovations. It seems unlikely that there will really be an infinite number of infinitely short events, because there ought to be a physical limit on how small and quick events can be. It may be that the events become less important as they become smaller and shorter.

9. Conclusion – symbolic information transmission across generations

The way information is passed on from one generation to the next is the key to this paper. That and the idea that it must happen symbolically, which emphasizes the importance of spoken language and writing (as opposed to analogue forms of communication such as paintings or television) and links them to the symbolic codes (or perhaps more accurately, *discrete* codes) of DNA, and also to parental teaching through demonstration – which is essentially a symbolic process whereby, for example, hand movements by the teacher trigger in the pupil so-called mirror neurons which control the same movement in the pupil's hand [19].

It is changes in the information transmission process that indicate a new mode of evolution in a pattern apparently governed by chaos theory. It seems that each change is accompanied by a transmission cost which is essentially higher at each new evolution mode – if one factors out the complexity of the particular thing being transmitted – because the transmission process has an extra stage.

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Appendix A – Other possible events

There are other innovations which are not included in the bifurcation-predicted pattern, and this exclusion must of course be justified. A number of possible innovations are discussed below.

B.1. Other information innovations.

Table p shows a list of other communication innovations for comparison.

Information Transfer Innovations	Date
Various forms of animal communication:	
- Hormone communication	Unknown
- Auditory communication	Unknown
- Visual communication	Unknown
- Olfactory communication	Unknown
- Electrical communication	Unknown
- Touch communication	Unknown
- Seismic communication	Unknown
- Thermal communication	Unknown
Predicted date of parental teaching	264 million years ago
Cave paintings	44,000 years ago
Music/Singing	Unknown
Courier/postal service	Unknown
Drawings, Pictures	Pre-date writing
Visual signalling at a distance (Nuragic towers)	1800 BCE
Smoke signals	800 BCE
Printed Newspapers	1609 CE
Semaphore Telegraph	1792 CE
Photography	1822 CE
Cinema	1830 CE
Fax	1843 CE
Telephone	1876 CE
Sound recording	1877 CE
Radio transmission	1888 CE
Telex	1926 CE
TV transmission	1926 CE
Teletext	Early 1970s CE
Internet email	1971 CE
World Wide Web	1989 CE
Smartphone	1995 CE

Table p. Alternative means of communication.

B.2. Other information innovations using discrete coding rather than continuous analqgue signals..

The transformative events all involve discrete code systems, as opposed to what we might call analogue systems. If we restrict ourselves to discrete code systems, we get the list in table q.

Discrete Information Transfer Innovations	Date
Various forms of animal communication	>300 M years
Visual signalling at a distance (Nuragic towers)	1800 BCE
Smoke signals	800 BCE
Semaphore Telegraph	1792 CE
Telex	1926 CE
Teletext	Early 1970s CE
Internet email	1971 CE
World Wide Web	1989 CE
Smartphone	1995 CE

Table q. Alternative means of communication using discrete coding.

Animal communication – such as alarm calls – was, as far as we know, not used in or for parental teaching.

The different forms of signalling at a distance (Nuragic towers, smoke signals, telegraph, telex, teletext) are not suitable for passing on more than small amounts of information.

The other inventions in the table (Internet email, World Wide Web, smartphone) are really subordinate to the data network Internet (1967 CE) which predated them.

Stage of Evolution	How is it driving evolution? Add these to appendix?
3. Sex and Multi-cellularity	Sex and multicellularity. Sex is invented, in which two members of the same species combine their genetic codes. Whereas mutations often result in new genes that do not work, causing the death of the organism, sex only uses genes that have already worked, albeit in new combinations. Some advantages of sex are: • Only using previously successful genes means the offspring is more likely to be viable. • Sex also provides a way for advantageous genes to come together in a single organism. • The genomes of both parents are randomly shuffled for each offspring. The random shuffling, plus the reliance on tested genes mean that the generation of viable yet unique variations of a species is faster than ever. And multicellularity allows complex forms such as plants and animals to evolve, which was not possible before.
11. Writing	Hand-written Documents

	The written word is not just communication, it is a shared memory and reference. A hand-written 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, 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 innovation in human society, taking over the role as the main driver of evolution of intelligent life on Earth. Various kinds of hand-written documents quickly became established, such as contracts, accounts, and descriptions of laws. Such documents enabled 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.
12. Printing	Printed works Before the movable type printing machine, books were hand-copied and could cost as much as a house. Knowledge was expensive. There was a need for inexpensive replication of knowledge. The printing machine provided that. Until recently, most of our knowledge was in the form of printed matter. The most established knowledge is in the school and university textbooks. Less established knowledge is in other books and journals.
	Variation driving evolution?
14. Subsequent Innovations	

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