Synthesizing Historical Research Leads to a Simple, Compatible, and Extensible Big History Framework and Periodization

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Abstract: Many questions remain unanswered regarding how Big History events should be organized and interpreted. For example, should Big History be divided into periods or processes, when it is clearly a complex process of simultaneous interacting processes? In such an uncertain environment, how are models constructed and evaluated? When we look at Big History, at what level of abstraction do we start?

This paper gleans important insights from a number of historical papers to develop a consistent view of Big History. It is important to consider many aspects of an evolving system. For example, how does the evolving system 1) learn from its experiences in the environment; 2) extract energy and resources to combat the trend towards chaos and higher entropy; 3) organize itself at multiple levels to meet new challenges?

Various traditional scholarly disciplines contribute to various aspects of Big History, including astronomy, geology, evolutionary biology, evolutionary anthropology, and the history of civilizations. This suggests a base framework of cosmic and terrestrial phases. The terrestrial phase saw the sequential evolution of life, humans, and civilization. Based on this framework, the various disciplines' timelines are consolidated along with their dynamic systems models. This base framework is then expanded to include more details. This simple approach meets many criteria for an effective framework: it integrates with knowledge from other disciplines; it provides a simple, understandable model; it can be extended in detail with nested transitions; and it immediately expresses the acceleration of evolving complex adaptive systems (CAS). Similarly, proposed frameworks offer slightly different perspectives.

1 Introduction

Why should the timeline of Big History be divided (instead of presenting it as one continuous narrative)? One reason is the ability to teach the subject in discrete modules. This seems to be the reason for the Thresholds approach by emphasizing some better known events and exploring their prerequisites of ingredients and conditions along with a new ability to combine them to produce a higher complexity level with new emergent properties (Christian et al., 2014; Christian, 2011; Spier, 2015).

In addition, categorizing the long list of events into groups makes it easier to understand. Research purposes can also be served by categorizing aspects of Big History. For example, categorization might be based on the important mechanisms of complex adaptive systems (CAS, e.g., information, energy flow, organization, and relationship to the environment) over the long time periods of big history (LePoire, 2023). The evolutionary process might also show punctuation leading to periods of accelerated evolution rates.

It is more fundamental, however, to explore the structure of big history for clues to some underlying patterns that will illuminate common processes. It is this last goal that distinguishes big history from a simple compilation of findings from contributory fields. By addressing these questions, we advance the discussion of big history from what happened into how and why. Big history trends have been identified using a variety of measures, including the flow rates of free energy (Chaisson, 2001), changes in the universe's predominant physical form (Loeb, 2006), and advances in adaptation through learning (Sagan, 1977).

A number of questions remain regarding how to organize and interpret Big History events. Big History, for example, is clearly a complex process of simultaneous interacting processes, so should it be divided into time periods or processes? Under such uncertainty, how are models constructed and evaluated? What is the abstraction level at which we view Big History? Do we focus on the diversity of the system, its evolution, its ecology or its pathway to emergent higher complexity? Is it also important to consider the complexity of an organism's supporting environment, its history of development, or its evolutionary potential? Is it more important to consider what actually happened on Earth, what may have happened on Earth, or what might happen on other planets?

1.1 Goals considering Uncertainty

However, these questions need to be explored when there are large uncertainties. A number of factors contribute to these uncertainties, including: 1) the unresolved questions associated with major transitions (e.g., origin of life); 2) the continuous advancement of science (with refined definitions, interpretations, and completing hypotheses); 3) the simultaneous evolution of the environment and ecosystem; 4) the dispersed findings across many disciplines; and 5) the bias of people and research tools. It would be very difficult to construct major models that connect the systems throughout the evolution of big history even if all information had been recorded at an unlimited resolution. Furthermore, evaluating a model's validity is more difficult in historical sciences, e.g., Darwin's theory of evolution, compared to experimental sciences. Often, a first step is to show it provides a consistent interpretation of events, i.e., a proof of principle, which does not necessarily exclude other interpretations. The Darwinian theory of evolution illustrates the possibilities, however, in that evidence may be evaluated at various levels of abstraction to support or refute hypotheses. Combining imperfect data sets with Bayesian analysis is one way to weigh the evidence for various hypotheses. As discussed later in this paper, this Bayesian method seems to be an important evolutionary method.

Many of these issues are still being debated in each of the limited topics of physical, biological, human and civilizational evolution (Kampourakis & McCain, 2019). Big history is even more complex than any of these separate domains because it deals with these topics at a wider range of time scales, spatial scales, and units of analysis. In this article, some issues, expectations, and boundaries will be discussed, but no answers will be found to these questions.

1.2 At what level of abstraction?

To address these questions and issues, it is important to select an appropriate level of abstraction, such that it is not too detailed nor too broad. The level of information abstraction is a major concern with information interpretation. For example, DNA contains the information for all the proteins, cellular specialization, and the organism's development. However, while all the information is present in the linear sequence of nucleic acids, the abstract information about how the information combines with the cellular "decoder" is not evident. There are various layers of abstraction such as the genetic network, the effect of epigenetics, and the specification of development processes instead of specific instructions. Similarly, the extraction of abstract information and its semantic content is not easy as exemplified in recent attempts in artificial intelligence (Vasilescu, 2022).

An engineering example might help clarify some differences in abstraction level (LePoire, 1986). Consider the development of a new remote sensing tool. The groups that were interested include scientists to understand the meaning of the measurement, analysts to apply it to obtain valuable information, and tool designers to optimize performance. These groups developed model through computer simulations, correlations with experiments, and an approximate analogy to a simpler physical system. The computer simulation was useful to designers to optimize the tool for the realistic environment but did not help analysts nor scientists because the meaning and value of the information could not be ascertained. A correlation with measurements identified structural characteristics, which was important for analysts to extract valuable information, however, the scientist was not able to identify the underlying cause of the differences. Only when scientists identified an approximate dynamic characteristic was a simple physical model successfully constructed. While this model was helpful to scientists for understanding, it was not useful to designers and analysts since it was the least numerically accurate model. This shows that although full information might be accessible through detailed modeling, it can take great effort to construct meaningful and useful models. Each model might be useful in different circumstances.

The approach taken in this paper is to 1) gather relevant previous research, 2) develop criteria for forming a periodization and framework, 3) developing a synthesized framework, 4)comparing it to other proposed frameworks, and 5) discussing specific questions and interpretations for addressing big history.

2. Gathering Previous Research

Despite the fact that the term Big History was not used then, Erich Jantsch (1980) examined how energy, information, organization, environment, and evolution work in complex systems during both the physical cosmic development and also in life's evolution on planets like Earth. This evolution has been shaped by genetic life, epigenetic human evolution, and culturally based civilizations. Despite not explicitly stating it, these phases of evolution follow the traditions of astronomy, geology, biology, anthropology, and civilization history. These common disciplines are taught at all educational levels and therefor are widely understood by the public. Each of these high-level phases can be further refined by dividing them into a set of periods. These periods can be identified by examining the stages of growth, development, and evolution of these complex systems. A stage involves a complete cycle of complexity dynamics driven by their growth towards environmental capacity limits before collapsing, reorganizing, or finding new resources.

The next subsections will briefly review how others explored many of the aspects such as information, energy, organization, environment/limits, and evolutionary dynamics. Many of these aspects were identified by Jantsch, including the identification of information as the key aspect of evolution of evolution between terrestrial evolutionary phases, as was also articulated by Sagan (1977). This area of research continues to be fruitful as seen in the proposals of general evolutionary Bayesian models such as those of Friston (2010). Other aspects suggested by Jantsch were further explored, such as, the connection of energy flow and systems by Chaisson (2001); the combination principle of organization by Volk (2017), the interaction with the environment LePoire (2004) and the way evolution relates to individual development by Ekstig (1994). The investigations into the nature of the evolutionary acceleration mentioned by Jantsch was supported previously by von Neumann (Ulam, 1958), von Foerster (1960), Eigen (1971), and continued to be explored by Diakonov (1994), Modis (2002), Nazaretyan (2004), Panov (2005), and Snooks (2005).

<u>Information:</u> Sagan highlighted the importance of evolving information processing in the Dragon's of Eden book (1977). He estimated the growth of information capacity by DNA, brains, and books. Coren further advanced the role of information in evolution by demonstrating a geometric sequence of information innovations throughout evolution that is consistent with a singularity model (Solis & LePoire, 2020).

Understanding the role of information has evolved quite a bit over the years. One of the key integrating theories of evolution is Karl Friston's Free-Energy Principle (Friston, 2010; Azarian, 2022). Despite sounding like an energy perspective, it is primarily concerned with a complex adaptive system's (CAS, for example, a person) interaction with their local environments to learn, survive, and grow. Rather than acting passively, a CAS can conduct "experiments" by predicting (and sensing) environmental reactions to its actions. This drives active learning based on its internal model. When a surprise occurs, we can either alter the model to make it more compatible with reality or change the environment to make it more compatible with the model.

<u>Energy:</u> Several researchers have discussed energy extraction from the environment, storage, and use throughout evolution (Fox, 1988; Niele, 2005; Smil, 2010). However, Eric Chaisson (2001) focused on energy flow. In the course of evolution from galaxies, stars, planets, to forms of life and civilization, the energy flow density (W/kg) has increased. The system, however, had to be defined spatially and temporally in order to make these estimates. As an example, when a galaxy's black hole is active, energy flow through it can increase quite a bit. Based on these assumptions, galaxies are less complex than stars, which is contrary to a Big History textbook (Christian et al., 2014). Structure and dynamics of galaxies appear more complex with many interconnected pieces, though they are somewhat dynamically stable. There are several parts to a galaxy including the central black hole, the central bulge, arms, and a halo of dark matter.

The energy efficiency of natural and engineered systems differs as well. Computers require much more energy flow per mass and are not as complex as the human brain, which works with only 20W. Furthermore, by mitigating increasing entropy, the total energy flow (not just density) through an expanding system should increase as it evolves (LePoire, 2020).

<u>Organization:</u> Organizational change is another aspect of evolving complex adaptive systems. Many transitions occurred when previously independent entities merged, according to Volk (2017). Initially, this was due to the binding energies in the physical world. A combination of these entities (e.g., an electron and proton) would not be stable if the temperature exceeded the binding energy. In the course of expansion, the universe cooled, resulting in a sequence of merging. This occurred during the first five of the twelve steps identified by Volk, namely, fundamental quanta (e.g., quarks), nucleons, atomic nuclei, atoms,

and molecules. The four steps in biological evolution are simple (prokaryote cells), eukaryote cells, multicellular organisms, and social animal groups. Combination steps required previously independent entities to come together to achieve some environmental advantage. The most recent three steps focus on human civilization in terms of tribal groups, agro-villages, and geopolitical states. Again, the entities had to loosen their independence in order to reap the benefits of combining. Possibly this can be seen as a social cooling process, in which disagreements between groups are resolved enough to facilitate sharing common goals, such as economy of scales, a reduction of barriers, or defense.

Several ways were possible to combine the elements of the previous step to create the elements of the next step, resulting in diversity between steps. The combination of nucleons to form nuclei of elements is an example in the physical realm. It was then possible to combine the different elements to form many different molecules. These combinations undergo the evolutionary dynamics of reproduction, variation, and selection. Through this, they are able to explore new spaces in order to maintain the stability of the inherited information.

Information is clearly emphasized in this view of organization, but little is said about energy flow, environmental interactions, and challenges as the systems approach their limits. Apart from combining elements, systems can also develop complexity by growing and specializing. Animal organ evolution demonstrates this.

One information processing mechanism in social systems is the transfer of ideas between smaller systems that have reached their limits to larger systems that offer additional management for further development. One example of this can be seen in the series of leading capitalist countries, which change about once every century (LePoire, 2010). The new leading country had twice the population of the previous one at the time of the transition. Consequently, as capitalism grew, a larger population base was required to support the necessary evolving organizations.

Environment/Limits: The role of the environment is illustrated by the inverse relationship between sequential evolutionary objects and their environments (Jantsch, 1981). This relationship was extended to include modern technological civilizations (LePoire, 2004, 2020a). For example, as a result of gravitational instability, the tiny quantum fluctuations in the early universe later evolved into cosmic structures such as the cosmic web and eventually into galaxies.

Examples of this relationship continued in terrestrial evolution. These examples include single-celled organisms had to evolve aerobic respiration, as the buildup of oxygen in the planetary atmosphere was required for further evolution. A higher level of oxygen in the air allowed multicellular organisms to diffuse oxygen more easily. Also, at about 540 million years ago, the Cambrian Explosion, which occurred after about 88% of Earth's current age, brought about the dominance and diversification of multicellular organisms, which could compete in large ecosystems. Both humans and some of the tools that formed their evolving environment were similar in size during human evolution. However, as human societies grew in scope, their tools depended on technology that is more precise. For example, an environment of microchips are used to evolve a global system that exists today.

Evolutionary Dynamics: The great polymath John von Neumann had identified the acceleration of technological change in the 1950s (Ulam, 1958). Von Foerster (1960) identified evidence that global population was growing faster than exponentially. Kremer (1993) extended this concept into the past. In 1971, Eigen discovered that evolving systems might follow a hyperbolic trajectory. These growth patterns follow increasingly quicker exponential growth as the system adapts to its environment. A singularity trend was proposed by Modis (2002) and Panov (2005) as an explanation for cumulative learning acceleration. It is Panov's event set that comes closest to the extended Jantsch approach, due to the geometric factor of three that he discovered (independently with Snooks (2005)). Compared to the acceleration scheme with a factor of three across 19 events, Modis' list provides 28 events.

Although the difference between hyperbolic and exponential growth equations is small, it makes an enormous qualitative difference in the evolutionary process. A simple exponential growth, such as money collecting interest in a bank, will double in the same amount of time. The value of money invested with a 7% annual interest rate doubles every 10 years, for example. In the simple hyperbolic evolution model, however, progress begins very slowly. Even so, as it approaches a specific time, the singularity time, it accelerates rapidly. (For example, if a population doubles within ten years and then doubles again in half the time it took before, then the singularity time, when the population would become infinite, will only take 20 years from the beginning of the process.) Even though the trend suggests continued acceleration to ever-higher (indefinite) levels, due to finite resource limits, this growth pattern will shift to another. A delay between the growth and the impact of that growth, for example, increases the chances of the system overshooting and collapsing. There are, however, more optimistic scenarios in which growth is restrained before this condition is achieved.

A link was discovered by Ekstig (1994) between the time of an emergent feature's emergence and its expression in a developing organism. In general, the development of a characteristic follows the evolution of that characteristic. The range of characteristics includes animal tissue formation, humans' ability to walk and speak, and cultural learning levels such as reading, writing, and math. The results of this analysis later were incorporated into the identification of a super-exponential growth in complexity (Ekstig, 2012, 2015, 2017).

As discussed in Kay and Schneider (1994) and Azarian (2022), the second law of thermodynamics can be applied to the origin and evolution of life. Physical dissipative systems will self-organize when there is a gradient of entropy (e.g., temperature differences). The formation of Benard cells is a result of fluctuations around the normal conditions that lead to increased energy flows reducing this entropy gradient. In some environments, such as alkaline hydrothermal vents, this principle could even be taken further, suggesting that life originated to reduce entropy gradients (Lane, 2015).

3 Developing Criteria

There will be many ways to divide Big History into various period structures. In general, it would be nice to use what others have found in other disciplines so as to connect with their discoveries without having to reinvent some aspects of the time periods. Once the high-level stages are set based on traditional academic disciplines, further refined levels could be based on some CAS emergent properties as indicated by synchronous changes in energy flow, information/learning, organization, and interaction with the environment. Since there is so much uncertainty, it would be nice to have a simple model, perhaps based on some high-level concepts to interpret and integrate the disciplines. The model should be phenomenological such as the cumulative learning model combined with the panarchy model of system dynamics (Gunderson & Holling, 2002). This could identify some abstracted common processes that apply to all big history. Various measures can be made based on these components such as energy flow, information processing, organization, and interaction with the environment as well as dynamics that might be embedded in the development of new CAS based on the evolutionary steps. The criteria should address how the cosmic development and future might be incorporated into the terrestrial framework. The proposed frameworks should consider limitations but still provide some testable hypotheses at more refined levels to compare with other frameworks and the accumulating evidence. A proposed set of criteria is developed in Table 1 (next page).

4 Synthesizing Previous Research

This section will first introduce a summary of the synthesized framework and periodization scheme. Then this framework will be evaluated based on the criteria of the previous section. Finally, the periodization is compared to other proposed schemes.

4.1 Synthesis Summary

At this point, there have been two major phases of complexity development- the physical phase during cosmic development and the terrestrial phase encompassing the evolution of complex adaptive systems from the origin of life, the development of the biosphere, the evolution of intelligence, and the formation of civilizations. These two phases are quite different in their dynamics. The cosmic phase had a very quick succession of events immediately after the big bang, followed by slowing rates of change as the temperature cooled sue to expansion. However, the cooling led to gravitational clumping on multiple scales that returned high enough temperatures to reduce the nuclear energy potential to generate the heavier elements for formation of planets. On at least one planet, the Earth, the right conditions allowed the self-organizing effects of dissipative systems to form life. After that the complex adaptive systems

Complexity increased at an accelerating rate on earth through evolution of life, humans, and civilizations. The capacity and speed of each information mechanism has been increasing with subsequent phases, transitioning when the previous seems to reach its capacity. These new information mechanisms enabled the development of new complex structures and organization to capture more energy (e.g.,

Criteria	Description
Phenomenological Model	Is there some overall phenomenological model of why evolution to more complex systems arises but most stay simple
CAS Elements	What aspects of a complex Adaptive system does the framework address? Components, Life Cycle (development, ecosystem fit, evolution, reproduction)
List, hierarchical	What is the structure of the framework? Some examples might be lists, hierarchy (nested), major and minor events
Connection to traditional fields	Are traditional fields recognizable and used to help frame? Is there an elevator speech that someone could relate to?
Drivers	What conditions cause the new complexities?
Connection to previous BH research	Does the framework extend or address previous work by others?
Cosmic/Terrestrial split	How does the framework distinguish cosmic development versus agency in life development on Earth?
Handling on-going simpler ecosystems	Does the framework address how the rest of the system interacts with the progressively complex line?
Connections of large and small	Is there a connection between the large and small spatial scales, e.g., elements and stars?
Pattern	Is a pattern hypothesized with evidence (not proven)?
Measure	Is a measure (or combination for weight of evidence) proposed for further evidence?
Future	Does the framework extend various trends into the near (or less confidently, the far) future.
Limitations	How does the framework acknowledge and handle limitations?

Table 1. A set of proposed criteria to evaluate frameworks for periodization.

through photosynthesis). However, increased complexity requires greater energy flow to counteract the natural disordering tendencies (entropy). Balancing the increased energy flow and its wastes (e.g., heat) becomes more difficult. In return, new ways to address the wastes result from new information and organization. This continues the evolutionary process to the next growth phases. For example, multicellular organisms could develop organs that helped make the organism more energy efficient. However, a process was needed to collect and transport metabolic wastes. Eventually, this was solved with the combined respiration and circulatory systems including kidneys.

One interpretation of Big History is that three major evolutionary stages discussed before- life, humans, and civilization, formed the first half of such a transition. (The second half would be in the future.) This learning curve is a bit different as it is formed from many smaller transitions and also changes (learns) at an accelerating rate as it approaches the current time, near middle of the transition. These three major stages started at about 5 billion, 5 million, and 5 thousand years ago. (As mentioned before, while more precise times are known for the beginning of the universe at 13.8 billion years ago, and the formation of the Earth at 4.54 billion years ago, this paper works with geometric factors, so an approximation on a logarithmic scale is used.)

Each evolutionary stage developed over 6 (nested) steps with each subsequent step being about a third of the duration of the previous. These 6 steps then make the stage's geometric acceleration factor the sixth power of 3, which is about 1,000, as seen in the pattern of stages in Figure 2). Furthermore, the duration of the universe from the big bang to the present is approximately one step factor (3) larger than the history of the Earth. However, since this step is qualitatively different in that the evolution takes place through cooling and gravitational attraction rather than through evolution guided by natural selection, it is not really expected to be the same as the factor for the complex adaptive system evolution. The specifics of these stages are provided in previous papers (LePoire, 2015).

To gain a perspective on these factors, if the time values of the 3 major stages are plotted on a line (i.e., 5 billion 5 million, 5 thousand) with the line being 1 kilometer long which represents the age of Earth, then the development of humans would start at 1 meter from the end. All of written civilization history would occur in the last 1 millimeter. If the time between the Big Bang and Earth formation was added, the line would be about 3 kilometers. A human generation scale of 50 years would be 10 micrometers, less than the width of a hair.

4.2 Evaluating Criteria

Some of the criteria identified that should be constraining a periodization or framework include:

1. Consistency with previous research such as a) traditional fields, b) systems science, and c) big history
2. Structure cosmic/terrestrial split
3. Phenomenological models of complexity growth and dynamics
4. Connections between scales such as large and small big history objects
5. Handling quantitative measures, uncertainties, and limitations
6. Integrate potential future scenarios
7. Ability to identify research gaps

What follows is a self-evaluation of these criteria for an extended Jantsch framework. Clearly, there are differing opinions on the adequacy of these arguments for satisfying the criteria. These self-evaluations are provided to encourage continued discussion both on the criteria themselves and on their evaluation for specific proposed frameworks.

Consistency with previous research in traditional fields (1a). The structure of academic historical sciences might give some suggestions for the establishment of high-level periodization. Early courses covering big history topics might include the historical aspects from astronomy, biology, anthropology, and civilizations. Many of these fields are taught at the high school level. Note the beginning of each period is roughly 4.5 billion years ago for Earth formation (or 4 billion years ago for life), 4-7 million years ago for the split between the evolutionary branches that led to humans from the branch that led to chimpanzees, and 5 thousand years ago when "history" started with civilizations that had writing. That is the starting times (and also the durations) of these fields is roughly 5 billion, 5 million, and 5 thousand years ago. This is a geometric sequence that leads to a singular point in time. This means that someone with a simple familiarity of typical high school courses can immediately see the acceleration that is consistent with the more detailed global population data and the simple evolutionary model.

Consistency with previous systems science research (1b). Further lower level substeps can be identified based on complex adaptive system aspects such as emergence, energy flow, organization, environmental interactions, evolutionary dynamics, and information processing. No single measure seems to be sufficient to determine the complexity of one system relative to another. Even the definition of complexity seems to be fleeting (Holland, 2014). Both Panov and Snooks identified an accelerating factor of about 3. Panov found a value of 2.67± 0.15, a value close to e≈2.718, a factor suggested by Kaptiza (1997). This would have six substeps in each major step, since 3^6 is about 1,000 (the acceleration factor of the major steps described above). The 6-step pattern is also what was found in the development of fundamental physics. The factor of three is also the ratio of the initial growth rate to growth rate at the first bifurcation point in a complex system. An uncertainty in this factor can be made by determining the amount of change necessary to change the number of geometric periods by one. This leads to a value of 3.16± 0.22.

Consistency with previous big history research (1c). Each of these three major steps has a unique way to store and transmit information (through DNA, the human mind and language, writing and artifacts). The most debated part of this is the consideration of anthropology as a separate topic from life evolution or cultural evolution. Many researchers will talk about two mechanisms of genetic and cultural evolutionary mechanisms. Among the early pioneers that separated these into three groups were Sagan and Jantsch who focused on the changes in information processes. The human evolutionary period seems to be a mix of genetic evolution within an environment of increasing human control through the use of tools, fire, communication, and social collaboration. This phenomenon was identified by Jantsch as epigenetics. Currently the terms are co-evolution and dual inheritance (Corning).

Structure of the cosmic/terrestrial split (2). Astronomy is the only discipline that does not directly involve life. Its historical development is quite different in the unfolding of small physical structures through cooling at first. Then the universe cooled down enough for large-scale structure formation through gravitational collapse and reigniting the nuclear potential in stars. Geology (International Commission on Stratigraphy, 2022) is a field that has aspects in each one including planetary formation, the interaction with life, the changing climate, and a place for resources for growth of civilization. Books often have a somewhat equal amount of information for each of these four stages. The age of the universe to that of the Earth is about 3 (13.7 billion years / 4.54 billion years) which is consistent with the terrestrial substep acceleration factor seen above.

Phenomenological models of complexity growth and dynamics (3). The dynamics of complex systems in big history might be separated into those dynamics that apply to general evolving systems and those that apply to integrated evolution within big history. Typical patterns in general complex adaptive systems include growth until limits are reached, which triggers exploration of the environment (Waldrop, 1992; Mitchell, 2009) and the release and reuse of materials to continue another cycle of self-organized growth (Perry, 1995), e.g., the panarchy model (Gunderson & Holling, 2002). Often the evolution of such systems is based on levels of organization with modules being replaceable (Kauffman, 1995; Holland, 2014). When environmental limits are reached, there are negative marginal benefits of additional complexity (Tainter, 1996).

As mentioned before, John von Neumann, expressed in the 1950's that the rate of technology change was faster than exponential and it seemed to be on a path to a singular time in the future where it would be infinite if no limitations were encountered (Ulam, 1958). This singularity theme in global population growth was identified by von Foerster (1960), who predicted the singularity time would occur in 2026, if the trend continued. Again, this assumed no limitations being encountered, which he knew was not true. In fact, this singularity global population trend started showing deviations in the mid 1970's as the growth rate slowed. A singularity trend is not as usual in natural sciences as exponential or logistic growth. However, the fact that simple evolution models of improvement over time, naturally lead to a singularity trend, was found by Nobel Prize winner Manfred Eigen in the mid 1970's. This combination of simple model and its measured reality in the evolution of humans with technology make this an empirically tested phenomenological model. A general model of global growth were developed (Korotayev et al., 2006). The straightforward idea is that the growth constant of an exponential trend changes with time and is based on the accumulated knowledge up to that time, i.e., $dy/dt = k(y)\ y = c\ y\ y = c\ y^2$. This is a formulation of the cumulative (or collective) learning happening throughout the evolutionary history on Earth. This sequence will come to a specific time where this hyperbolic growth pattern is not defined.

Connections between scales such as large and small big history objects (4). Some of the major patterns discovered when analyzing the relationship of large and small units in big history include the Evolution-Development relationship of Ekstig (1994), the relationship between evolving units and its environment by Jantsch (1980), the connection of a few physical parameters to the sizes of big history objects from the atom to the universe (Carr & Rees, 1979; Press & Lightman, 1983).

Handling quantitative measures, uncertainties, and limitations (5). As mentioned before there were many approaches from the various aspects of complex adaptive systems such as energy, information, organization, environment, and dynamics. Jantsch (1980) and Aunger (2007) treated them at the same time. Aunger's non-equilibrium steady-state transitions (NESST) approach satisfies this condition of looking at a consistent combination of the various CAS aspects. The framework is extensible through adding nested levels, as evidence justifies. The framework is also flexible because it defines large phases, which have durations (not just event times). The phases can be defined by the beginning and end of transitions (as it is here) or by shifting perspective to the midpoint of the transitions (similar to the TOK/Combogenesis model of Henriques & Volk). The framework phases differ from the traditional periodization of geology and history, but this is expected for such a simple model with highly uncertain data. This allows for further discussion to refine or explain these differences.

Integrate potential future scenarios (6). The framework might also contain trends to extrapolate into potential future scenarios. Some complex systems demonstrate complexity reversal after reaching some environmental limits

(Stone, 1993). Panov (2020) considers the implications of a singularity growth trend for the development of life in the galaxy. LePoire (2019) considers various patterns that might continue after the trend to a singularity breaks down. The idea of a long-term modified logistic pattern, e.g., a cone is explored. Some have speculated that life is not just a fluke in the universe but rather an important determinant in organizing energy and information to form greater complex organization (Azarian, 2022).

Ability to identify research gaps (7) The framework is consistent with a high-level view of big history's integrated evolution, however, there are many remaining issues. Having a framework can help identify these. For example, in the discussion section of this paper some events that seem to be different are explored. These include how the cosmic phase fits in, why life seemed to originate so fast on Earth, and why human evolution was a combination of genetic and cultural influences. As pointed out in another paper in this issue (Solis & LePoire, 2023) there is much work to be done in grounding the event phases in more quantitative evidence such as overall energy flow and emergent properties.

4.3 Comparison to other frameworks

Some comparisons might lead to insights for periodization (Solis & LePoire 2023). Previous comparisons of different event lists have been analyzed by Aunger (2007) and Vidal (2014). The structure of the time periods can also be compared with the traditional time scales of geologic and historical periods. Selected geologic, human prehistory, and history periods seem to reasonably match with the extended Jantsch framework, which incorporate cumulative learning acceleration periods towards a singularity. The geologic periods (from various levels) covers Earth's history up to the split of the branches that led to humans and chimpanzees. The human prehistory timeline covers from that point forward to the formation of historical civilizations. The historical timeline covers the remaining time. This correspondence of traditional discipline timeline periods and the extended Jantsch framework is shown in Table 2.

To go from the Big Bang to a timescale of a human life (50 years) there are 17 steps expected ($\log_3$ (Age of Universe/Human lifetime)). Modis and Panov proposed sets of events, which led to an interpretation of the cumulative learning acceleration (i.e., a singularity trend). Panov's is the closest to the extended Jantsch approach since he worked with a geometric factor of 3 which he discovered (independently along with Snooks). There are only two of additional events from Panov (during the control of fire by humans, and the division of the ancient/classical civilization period). Modis' list contains 28 events, which is 9 more than the acceleration scheme with a factor of 3. Note that the periods in Table 2 are labeled by the processes that occurred in that period and not just by the specific events at the beginning of the period.

This periodization is also consistent with the Thresholds, Tree of Knowledge/ Combogenesis, and Grinin models (Figure 1). The threshold approach has more detail in the cosmic phase and one additional threshold for the modern era and a mini-threshold brink at the formation of civilizations. Otherwise, the thresholds of life, hominids, and agriculture is consistently aligned with the extended Jantsch model. This points to the need to further develop a separate perspective (in the extended Jantsch framework) during the cosmic phase where the rate of events slowed down over time due to cooling of the universe.

The combined Tree of Knowledge and Combogenesis frameworks of Henriques (2019) and Volk (2017) (respectively) demonstrates their focus on the periods of most rapid change, e.g., at the inflection point of transitions. This includes the Big Bang, the origin of life on Earth, the development of animal brains, the development of human culture, and the development of enlightened and scientific understanding. This notes that during the cosmic phase the rapid changes occurred during the beginning and end, i.e., the big bang, followed by a long duration of structural and chemical change with the development of galaxies and stars, then leading to the relatively quick formation of planets from later generation stellar formation and the surprisingly quick development of life on one of those planets (Earth).

The Grinin and Grinin (2021) production principle timeline identifies 4 stages of production principle of hunter-gatherers, craft-agrarian, trade-industrial, and scientific-cybernetic. Each stage has 6 life cycle phases as it matures and is eventually replaced. Of these four, the craft-agrarian is most misaligned with the extended Jantsch framework. The craft-agrarian stage covers the period from about 10,000 years ago to 600 years ago, whereas the extended Jantsch framework has about 3 stages during this period- the pre-civilization agricultural, ancient/classical

Extended Jantsch Framework	Geologic and Historical Named Periods
Simple cellular (prokaryotic life)	Hadean and Archean Eras
Complex cellular (eukaryotic life)	Proterozoic Era
Multicellular organisms	Paleozoic Era
Land/reptiles	Mesozoic Era
Mammals	Cenozoic Era / Paleogene Period
Early hominoid evolution	Cenozoic Era/ Neogene Period
Bipedal	Lower Paleolithic
Tools	
Fire / Modern Humans	Middle Paleolithic
Modern Humans	
Migrations	Upper Paleolithic
Agriculture	Mesolithic, Neolithic, Copper Age
Ancient & Classical Civilization	Also Bronze and Iron Age
Trade	Middle Ages
Commercial	Early Modern
Industrial	Late Modern
Information	Contemporary

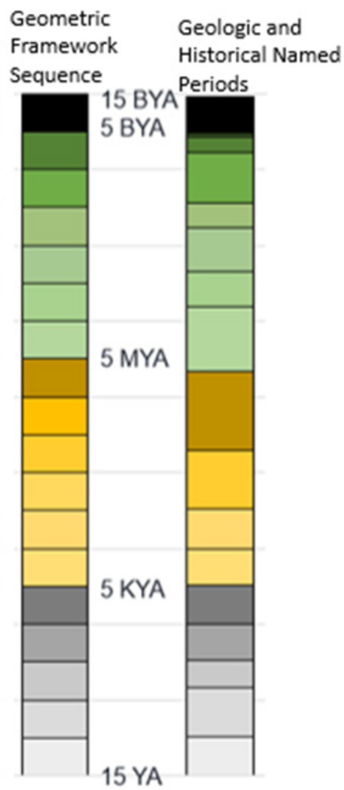

Table 2: Comparison of an Extended Jantsch Framework (with stages for every reduction in time by a factor of three) to the combination of geologic and historical named periods. Left: Corresponding transitions and named periods. Right: Comparison of geometric framework sequence with times of named geologic periods on a log scale from the present.

civilization, and middle ages mercantilism. While pairs of the phases of this craft-agrarian stage might be identified with the three detailed stages. This breakup of this agrarian stage makes sense when considering the social technologies involved from simple agricultural communities, to civilization with urban specialization and a high dependence on forced labor, to the emergence of trade based on freer labor supply supplemented by new energy sources such as wind and water. This breakdown of that period is supported by technological and economic changes (Mokyr, 1990; Gimpel, 1976).

Niele's (2005) energy framework identifies seven historical sequential sources of energy- physical in the cosmic phase; then a quick series of transitions in early life from thermal, anaerobic solar, and aerobic solar; and then a series of human led energy transitions from the use of fire, the development of agriculture, to the use of fossil fuels. For the human history era, this framework mixes both the extended Jantsch and the TOK/Combogenesis frameworks in identifying key energy source changes at the beginning and inflection points of major transitions. One possible explanation for the difference might be the important of energy use transitions (e.g., animals moving to land, mammals developing ways to regulate internal temperatures (warm-blooded) as compared with the just the energy source transitions of Niele.

5 Discussion

The transitions from different levels of big history are examined as to how they fit within this framework. This includes the transition from the cooling cosmic phase to the accelerating CAS on Earth with the origin of life. At the next nested level of the three terrestrial levels, the emergence of humans is discussed. Then at the lowest nested level, of the six steps in human evolution, the emergence of agricultural society is discussed.

The reasons for selecting these four differ. The cosmic phase is quite different in that the rate of events slowed as the universe cooled through expansion. Yet there are large structures to be formed to set the stage for advances of life. The origin of life is quite surprising since it did not take relatively long but it marked the transition between the cosmic and terrestrial phases. However, it is the least documented since early life left little record in fossils or in genetic material. The development of humans is one of the three major terrestrial phases, so intermediate steps can be

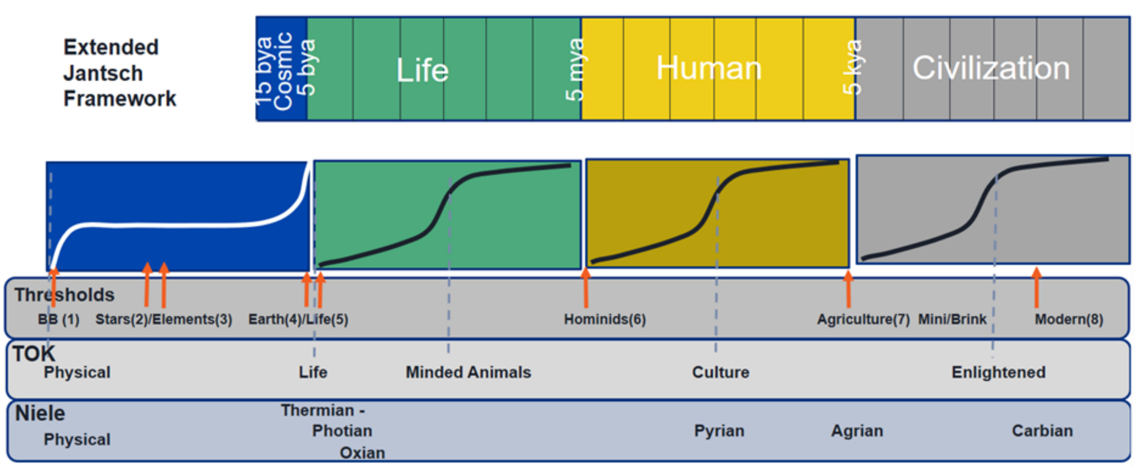

Figure 1: *The Extended Jantsch Framework (top; with stages for every reduction in time by a factor of 3), the same framework showing an expanded cosmic phase and the transitions of the three major terrestrial phases (bottom figure), and the corresponding relationship to events and phases in the standard big history threshold approach, the Tree of Knowledge/ Combogenesis approach, Niele's energy approach, and that of Grinin & Grinin.*

identified. Remember that the time for humans to develop to civilization from the branching from the chimpanzee line was 1,000 times longer than the history of civilization. Since the major biological change was in the size and structure of the brain, mostly external evidence of tool use helps in delineating these developments. While the brain size can be measured from fossil skulls, the new abilities enabled by the brain size are difficult to interpret since we have such little understanding of animal and human brains. The development of agriculture is labeled as a step (secondary) transition between the human evolution and history of civilization phases. There is sufficient archeological evidence to construct a timeline of emergent behaviors to attempt to analyze the transition pattern.

5.1 The Cosmic Phase

In the simple extended Jantsch framework, the cosmic phase is just the first phase followed about two-thirds of the age of the universe later by the formation of the Earth (i.e., a factor of 3 acceleration, similar to the later acceleration in the terrestrial stages). Of course much happened during this time covering the Big Bang, the development of structures such as the cosmic web, galaxies, stars, and planets. The big bang phase saw the cooling of the hot mix of particles as it expanded. For each quadrupling of the age of the universe (during the first few minutes) the temperature dropped by a factor of 2. The various binding energies in the sequence of protons, nuclei, atoms, molecules, and solids is lower by about three orders of magnitude (from 1,000 MeV for protons to thermal energies of 25 meV).

Active debates surround the events and interpretation of the big bang. Peter Atkins (2018) claimed that this unfolding of events of forces and particles during the big bang was quite uneventful as physics laws were followed. Gleiser (2010) takes a different perspective in highlighting all the symmetries that had to be broken to produce an interesting universe. For example, the asymmetry of matter and anti-matter was required so that at least some matter remained (1 part in a billion) after temperatures dropped below the formation of pair production. Hawking (Hertog, 2023) and Davies (2006) consider the possibility that there might have been some self-consistent participatory universe during this phase to explain some of the coincidences that led to a universe, which can harbor life.

The formation of structure in the universe started with the gravitational forces acting on the small density variations of dark matter to help form the cosmic web. Dark matter was able to react before normal ionized matter. Large flows reduced the gravitational potential energy in forming this structure which facilitated the movement of matter to nodes where galaxies developed (Hogan, 2001). This flow of matter continues through galaxies (Walter, 2020) although star formation in galaxies seems to have peaked about 10 billion years ago (Sobral, 2013), which is long before our solar system formed (about 5 billion years ago). The large energy flows resulting from the reduction of the gravitational and nuclear potential (which had led to the dissipative structures of the cosmic web, galaxies, and stars) began to calm down. After a few generations of stars to build up the necessary heavier elements, planets formed, and life formed on at least one. Then true complex adaptive systems (life) could form with the resulting increase in energy flow (Chaisson, 2001).

5.2 Beginning of Terrestrial Life

This event is special since it marks the transition from a physical dissipative system evolution of the cosmos to one based on complex adaptive agents based on information. In the framework, however, it just marks the early phase of life on earth. An ongoing mystery is how life evolved so quickly after the earth cooled enough for the chemical reactions to take place. The first evidence for life has been found anywhere from 3.5 to 4.0 billion years ago, i.e., when the Earth was about half a billion to 1 billion years old. While this is fossil evidence, there must have been many steps taken toward life before some evidence survived.

As an example of one the steps from which life emerged, Manfred Eigen (1977) identified a problem with the DNA genetic processes in that the error rate in constructing a useful length of protein would be too large unless there were a sophisticated process to perform error corrections. While modern and even early cells have these error correcting mechanisms, these processes require the complicated proteins. So just a system of DNA could not evolve to generate complex proteins of useful length because the error rate would be too large in the beginning of the evolution. This is called Eigen's paradox.

However, there are ways self-reproducing molecular cycles might breach this limit without DNA. For example, a system of catalysts which catalyzed each other (but not themselves). A system with more than two catalysts in a cycle, where at least one extracts energy from the outside, is stable and can form self-organizing systems, such as the BZ diffusion reaction. The system can evolve by finding improved catalytic substitutes for each component in the cycle. Catalysts that try to commandeer the system are not successful at parasitism, so the system can evolve further.

Eigen (1977) also found that these evolving systems not only tend to grow and compete for resources of energy and materials, but these evolving systems also improve through this substitution. Improvement (or evolution) and growth tend to speed the process by which the system fits into the environment, causing the learning to accelerate and, as he found, tend to point where the learning becomes very quick in this process of positive feedback. He recognized that this might be a reason that CAS evolution did not take very long (relative to the age of the Earth) for life to originate. Once it started, however, the ability to extract resources from the environment and thrive was sufficient until some challenge directly impacted its environment. One case was the oxygen that the new life produced, which was a poison to early life. One reason it took life so long to evolve from the simple cellular form to one that could utilize the oxygen was that the oxygen level in the oceans around the world had to increase in concentration after being naturally removed by forming rust after oxidizing the iron in the ocean water. A more detailed version of both the processes leading to origin of life and the difficulties progressing to eukaryotic cells process has been explored within the environment of alkaline hydrothermal vents (Lane 2015).

However, the question of how life began has not been resolved. Other hypothesis, such as the origin life off of Earth is being debated (Markov et al., 2018; Sharov, 2018; Davies, 1999).

5.3 Appearance of "humans"

Humans did not one day just appear. Many hominoid species evolved over 4-8 million years, after splitting with the branch that led to chimpanzees, the closest great ape to humans. It should be noted that human history (i.e. writing) in civilizations did not start until 99.9% of this time had elapsed (i.e., 5,000 years ago). This is the same fraction that human evolution is compared to the evolution of life on Earth. This then is a major evolutionary phase. Many steps took place during that time as bipedalism, tool use, controlled fire, language, and agriculture developed over this time before civilization started.

The branch in the primate evolutionary tree leading to humans split from the other apes about 5 million years ago. Weather conditions in Africa's Great Rift Valley led to the expansion of grasslands into the previously forested areas. Hominids adapted to this situation by developing a more general way of living including a more varied diet (e.g., scavenging) and the ability to walk on two legs (about 1.6 million years ago with Homo erectus) which helped in seeing further, carrying food, and running.

The lack of any well-honed predator characteristic (such as claws or sharp teeth) or defensive strategy (such as speed or protection) led groups to form with rudimentary communication to coordinate food gathering and defense. About 0.5 million years ago, the control of fire helped in the digestion process by cooking foods so that energy could be allocated from digestion to increasing brain size. The generalization of humans' capability to adapt to environments enabled great migrations across much of the Eurasian continent.

A positive feedback then continued among larger brain size, social organization, and better control of the environment (through technology). The human brain size mostly increased after about 160 thousand years ago when modern humans, Homo sapiens, first developed with an expanding toolkit of abstract language, which led to refined tools about 50,000 years ago. Pressures on resources in certain locations led to a more intensive use of the land started about 15,000 years ago and later led to the agricultural revolution. These sedentary cultures led to villages that needed to store and protect the agricultural harvests, which prepared the environmental conditions for the development of larger communities in civilization (starting about 5,000 years ago).

The reason that human evolution is treated as a phase, i.e., a top-level evolutionary step, is its unique mode of evolutionary process. While the genetic changes were important to cause differences, humans also gained more control of their evolving environment through the use of tools (sticks, stones, and bones), fire for cooking, security, heat, light, land preparation, and social cooperation. Genetic changes were important in brain growth, hip structure for bipedal walking, gut size, support of larynx for speech, and hairlessness for cooling down- especially since a large brain which took about 20% of the energy resources for a 2% fraction of the body's mass. However, these genetic changes helped the human ancestors survive in an environment over which they increasingly had control. This has also been referred to as dual inheritance or epigenetic processes by Jantsch. In one sense, it was an early form of self-domestication which was later applied to changing the genetics of plants and animals for agricultural lifestyle.

It seems as if the brain growth facilitated grater social cooperation as it was identified by Robin Dunbar that there is a correlation between primate neocortex brain size and the number of relationships an individual could maintain. This number is often quote as being around 150 people which is often the size of groups in schools (e.g. dormitories) and businesses (divisions). The social relationships required the large brain size because of the development of the theory of mind in humans. That is an individual could empathetically view the world from someone else's character and experiences. This included knowing their skills and the other person's relationship with themselves and others in the group.

To summarize, in this stage the branch of primates leading to humans expanded the ability to adapt in various environments with bipedalism, basic communication, control of fire, and an adaptable mind. This led to a positive feedback cycle focusing on refined levels of symbolic language, tools (from stone, bone, and antler), social organization, and the step towards better control of the environment through agriculture. These events followed the time sequence with an acceleration factor of 3 at roughly 5 million, 1.5 million, 500 thousand, 150 thousand, 50 thousand, 15 thousand, and 5 thousand years ago.

The importance of this phase can also be seen in Ekstig evolutionary-development relationship since the important events in development that relate to being human and social take about 1/3 of the time scale. These events include walking, tools use, speech, and socialization.

5.4 Appearance of agriculture

The development of agriculture went through many steps starting with sedentary hunters about 15,000 years ago. This was followed by development of tools to harvest wild grains, formation of villages around natural abundant grain resources, plant domestication through selective reproduction of beneficial plant characteristics, animal domestication, the development of storage systems with pottery, and the political establishment of chiefdoms, and the eventual replacement of more primitive tools with metal tools. These events form a logistic transition with a midpoint of about 9,000 years ago over a duration of about 10,000 years.

The appearance of agriculture is a step in the human evolution phase because the genetic-cultural process continued with the way the domesticated plants and animals evolved through the artificial selection by humans. During this step, many substeps were required as outline by Jared Diamond in Guns, Germs, and Steel. If each of these substeps are of equal importance then the growth can be plotted to show a logistic pattern in which the process started off slowly, sped up when some fundamental techniques were shared, and then slowed as the process hit some limit.

Domestication of other species by humans started long before the agricultural transition. The domestication of wolves into dogs was started about 30,000 years ago by hunter-gatherers. The process was co-evolutionary in which dogs and humans both gained benefits of the increased relationship. The resulting history of civilization shows a continual expansion of cooperation of humans to accomplish more complex tasks while being motivated to create competitive military technology (Nazaretyan, 2020; Turchin, 2016).

5.5 Further work

One factor that might be best for quantitative measurement is the energy flow during the various levels and steps. While Chaisson argues for the energy flow per unit mass (FERD), a complex system that grows through combinations usually has an overall increase in total energy flow, as has been discussed elsewhere. One problem with this later approach is that on the cosmic scale the tendency was for systems to separate into small units instead of combining, e.g., galaxies, stars, and planets. Besides the energy flows identified by Chaisson of mostly stellar nuclear fusion, there have been other energy flows due to the decrease in gravitational potential as matter clouds "collapsed" when cool enough. This started with the cosmic web and continued with galaxies and stars. It is now known that galaxies maintain a matter flow, siphoning off matter through the cosmic web and expelling it when the massive central black hole is active.

Another area of research is to understand the nature of the transitions to better estimate the probability of a successful transition. For historical periods, this might be done with semi-independent civilizations. For life, it might concern the extinction of species and the convergent evolution of emergent phenomena such as eyes and flight. Simple models have been constructed at the phenomenological level and some of the various hypothesis of historical transitions are being tested with correlations of archeological data, such as the Seshat Project (Turchin, 2019).

Finally, there are the questions about the geometric acceleration factors involved of 1,000 and 3. Where do these come from? Would they be different under other circumstances? What happens when a level or step is unsuccessful? (LePoire, 2020)

6 Conclusion

The case has been made for a need to develop a periodization framework for Big History based on previous research and insights, despite the limitations of uncertainty, definitions, and changing understanding. A set of criteria has also been developed which include the alignment with existing fields within Big History such as those in geology and biology, anthropology, and human history. These three major fields have periods of coverage that are close to a geometric sequence with the duration of each phase about 1,000 times less than the previous. Therefore this division is not just a linear list of terrestrial periods but instead motivated by the traditional disciplines it forms a hierarchy of three main phases of life, human, and civilization evolution (forming half of a full logistic curve), which is then recursively each divided into 6 subphases. The beginning and ending times indicate only an approximation, while the events unfold during the period as the complexity increases with emergence of new behaviors.

Various aspects of complexity might be used to characterize these events or transitions. The aspects of complex adaptive systems include in which way the evolutionary information is inherited, the source and amount of energy flow, the levels of organizations, and the interaction with the environment. Patterns from previous research were identified in each of these including the transition of the information mechanism from genetic in a natural environment, genetic in a gradually self-defined environment to cultural evolution. The energy flow density has been estimated to increase over the course of both cosmic and terrestrial evolution of the most complex systems. Organization includes the ability of systems to combine or to grow and then specialize. Environmental relationships tend to show an increasing size of the evolving system while the environment's scope decreases. The sizes of complex systems in Big History seems to be related to a few simple physical constants.

Three specific "events" were chosen to demonstrate the difficulty in resolving the understanding and timing, and framework placement when applied to big history. The origin of life is clearly a major event in this sequence but while it is not fully understood, a large mystery is why it was relatively rapid, especially compared to the much longer phase of single celled life on Earth. The evolution of the human species is quite distinct from the evolution of life up to that point. It is unclear why consciousness evolved or that such a general characteristic could eventually survive in an ecosystem that was highly tuned. The human evolution is one of the three major evolutionary phases on Earth with the evolutionary mechanism being facilitate by the increasing control over the environment with the use of tools, fire, and collaboration especially coordinated through language. The development of agriculture took place over a long duration of about 10,000 years due to the development of beneficial domesticated plants and animals, and the motivation towards the lifestyle based on the growing population density and environmental stresses.

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