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A rigorous periodization of ‘big’ history

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Abstract

‘Big’ history is the time between the Big Bang and contemporary technological life on Earth. The stretch of big history can be considered as a series of developments in systems that manage ever-greater levels of energy flow, or thermodynamic disequilibrium. Recent theory suggests that step-wise changes in the work accomplished by a system can be explained using steady-state non-equilibrium thermodynamics. Major transitions in big history can therefore be rigorously defined as transitions between non-equilibrium thermodynamic steady-states (or NESSTs). The time between NESSTs represents a historical period, while larger categories of time can be identified by empirically discovering breaks in the rate of change in processes underlying macrohistorical trends among qualities of NESSTs. Two levels of periodization can be identified through this procedure. First, there are two major eons: cosmological and terrestrial, which exhibit qualitatively different kinds of historical scaling laws with respect to NESST duration and the gaps between NESSTs: the first eon decelerating, the second accelerating. Accelerating rates of historical change are achieved during the Terrestrial Eon by the invention of information inheritance processes. Second, eras can also be defined within Earth history by differences in the scaling of energy flow improvement per NESST. This is because each era is based on a different kind of energy source: the material era depends on nuclear fusion, the biological era on metabolism, the cultural era on tools, and the technological era on machines. Periodizing big history allows historians to uncover the mechanisms which trigger the innovations and novel organisations that spur thermodynamic transitions, as well as the mechanisms which keep historical processes under control.

Keywords: Uniformitarian principle; Non-equilibrium steady-state thermodynamics; Scaling; Macro-history; Era; Eon

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1. Periodizing human history

A central problem in the study of human history has been the difficulty of finding a robust means of grouping events into something more than just a chronology of ‘one damn thing after another’. Scholars of human history have been unsuccessful in dividing the history of human endeavour into periods of space and time that become widely accepted among professionals; the criteria remain largely arbitrary (e.g., Hellenic Greece, the Middle Ages, the Scientific Revolution, the 1960s) [1,2].

Other types of history have been successfully periodized. For example, geologists have divided earth history into eons (e.g., the Precambrian), eras (e.g., Paleozoic), periods (e.g., Cambrian) and epochs (e.g., Pleistocene), each a subcategory of the previous, based on changes in Earth’s own composition and large-scale changes in the biota inhabiting the planet’s surface. To divide earth’s history into distinct, non-overlapping periods, geologists based their time-line on the principle of uniformitarianism, developed in the 18th century by William Whewell and James Hutton, which posits that the processes generating historical systems have operated in the same fashion and with the same intensity throughout the period considered, such that past events can be explained by phenomena and forces observable today [3]. This principle allowed geologists to infer dates for events in the distant past based on how deep in the Earth’s crust rocks associated with those events were found.

Darwin’s theory of natural selection extended the uniformitarian principle to the organisms living on the Earth’s surface by suggesting that a single process, descent with modification, could explain the origin of contemporary biological variation. Thus, using the assumption of a constant rate of mutation and selection pressure for particular kinds of genetic loci (the ‘molecular clock’ hypothesis [4]), evolutionary biologists can make inferences about the long-term evolution of species, leading to the science of phylogenetics [5]. Similarly, Edwin Hubble used a uniformitarian principle in a limited way in cosmology to infer the ages of events occurring through much of the history of the universe from the red-shift of observable stars [6].

The ‘big’ history project [7–10] seeks to extend the uniformitarian principle still further, at both ‘ends’ of the time-line: backward to the Big Bang and forward into human history, including contemporary, technologically-dominated times. It suggests that the entire history of the universe consists of a single narrative — that is, big history contends that cosmological, biological and social events can be considered within a single framework. The hope is that in this way, history can be placed within a context that might display law-like behaviour, and thus become subject to proper periodization [11]. However, the connections between events caused by very different kinds of processes seem tenuous: why should an explanation of how the French aristocracy suffered at the hands of the peasantry in the 18th century depend on the ratio of hydrogen to helium created in the first few seconds after the Big Bang?

Certainly, law-like behaviour has been found in historical processes of various kinds. For example, a consequence of the uniformitarian principle is that during a period of history, events of a given kind should have a constant probability of occurring, because the causes of that event are operating at a constant level of intensity. It might also be the case that events of a given magnitude are disproportionately less likely to occur than events of the same kind but of a smaller magnitude. For example, minor earth-tremors are rather frequent, but major earthquakes are exceedingly rare. The result is a logarithmically declining relationship in the probabilities of events of different sizes. In this way, the cumulative frequency of the severity of earthquakes [12] or the amount of rainfall [13] can be shown to exhibit a power law, or linear relationship on a logarithmic plot. Scaling laws have previously been observed in big history in terms of the cumulative proportion of significant events over time [14,15].

A similar relationship might also hold with respect to time itself: the probability of an event of a given magnitude can change at a constant rate with respect to time. If that rate of change is exponential, then the causes of that kind of event can be said to exhibit 'temporal scaling': the event will occur with a linear change in frequency when plotted against the logarithm of time. For example, during the Phanerozoic, the sizes of species extinction events decrease as the reciprocal of time [16]. The cause of this change is still open to question [17], but it has been argued that the pattern is due to a slow increase in average fitness among later species [16]. Models with a decreasing extinction rate due to an increasing average fitness of species mimic the paleontological record of extinctions well [18,19]. What is 'uniform' in this case is the rate of change in the operation of the process underlying the historical phenomenon in question.

This kind of temporal scaling has been previously shown in three studies for a portion of the big history spectrum: events since the origin of life [9,20,21]. However, by parameterizing this scaling slightly differently, the studies investigating this phenomenon identify different sequences of events using the same algorithm. This is because each of these studies begins with the constraint that the chosen set of events must exhibit scale invariance, and then fit points to a pre-defined line through a post-hoc selection of events. For this reason, the set of events do not seem to be members of any particular category. (For example, a list of 'canonical milestones' [21] in big history includes an asteroid collision with Earth, the first flowering plants, the first orang-utan, the Cambrian explosion, printing, the divergence of chimpanzees and humans, the differentiation of human DNA types, zero and decimals being invented, modern physics, and the transistor.)

2. Finding periods

The difficulties encountered in these studies show that a rigorous method for periodizing historical time-frames requires the use of a theoretical framework which will provide *a priori* criteria for defining periods. Since only physical principles were in operation throughout big history (biological and social rules become relevant only after certain points), this ultimate stretch of historical time must be treated as a physical system. What distinguishes historical systems from a physical point of view is the fact that they exhibit order — that is, they constitute local deviations from a perfectly entropic state [10]. Because a means of comparing all these kinds of objects in a single analysis is required, energy will be chosen here as the currency of big history.[1] This is appropriate because big history is explicitly concerned with tracing developments from the simple to complex: that is, from stars to world government — which can be considered as shifts to systems exhibiting higher levels of energetic disequilibrium [7].

A focus on energy suggests that the theory relevant for big history is thermodynamics, the study of changes in the free energy available to a system over time. Unfortunately, a quantitative treatment of the thermodynamics of a system far from equilibrium is not currently available [22,23]. However, it is possible to describe changes between non-equilibrium steady states [24,25]. This is sufficient for present

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[1] It is worth noting that the approach developed here links energy concerns to developments in information as separate aspects of a larger construct, the non-equilibrium steady-state transition, or NESST.

purposes because periodization only requires finding major cut-points in history — the transitions between different kinds of historical systems.

These transitions must begin with a fluctuation in free energy in order for a higher level of disequilibrium to be achieved. However, such fluctuations will only be recognized as important historical events if they have observable consequences. Such consequences must also persist in the historical record to provide evidence of their occurrence. Thus, big historical transitions must be manifested in novel structures. Typically, these must be maintained by new mechanisms which control the flow of energy through the new organisation. This triumvirate of energy, organisation and control constitutes the internal temporal structure of a non-equilibrium steady-state transition (or NESST) [26].

To define historical NESSTs, candidate events were selected from a variety of authoritative sources in the different disciplines relevant to big history (cosmology, biology, human pre-history and macrohistory), based on whether they represented significant energy innovations, novel organisational forms, or new means of control.[2] These events were then organised chronologically, and shown to be consistent with the structure expected of NESSTs (see Table 1) [26].

A common ‘event’ which defines major transitions in big history has thus been found: an NESST. By analogy to geology, the time between each NESST can be said to be a ‘period’. For example, events between the domestication of plants and animals and the first widespread use of machines (which were mills powered by wind and streams) can be considered the agricultural period, during which it is argued that the rate of energy flow through human groups was roughly constant. Considering NESSTs as the necessary and sufficient set of significant transition events provides a means of determining non-overlapping periods for the entire history of the universe. During a period, the same sources of energy repeatedly produce flows through essentially the same structures, making the operation of a steady state a common ‘work cycle’[27–29]. Each repetition of the cycle is not exactly the same, as there are evolutionary changes within periods and random fluctuations in the execution of each repetition of the cycle. At the same time, however, no significant change in the overall level of thermodynamic disequilibrium or organisation occurs, so a period is one in which a steady state persists, subject to normal fluctuations of energy flow.

3. Finding eras

A way of defining larger-scale ‘breaks’ in big history – the equivalent to geological eras – can now be sought. Geological eras are often determined by major transitions in the earth’s biota; cosmological eras are defined by changes in phase, or the dominant structure of matter in the universe (nuclei, atoms, stars, galaxies). Physical and geological laws operate in the same way throughout some span of time, until major transitions in the context of their operation (or the objects on which they operate) define a new era of cosmological or geological history.

Since the same physical laws operate throughout the history of the universe, eras can be found empirically by examining breaks in the scaling of transitions; such breaks should represent changes in the kinds of objects on which big historical processes are operating, which can be made to change more or less rapidly. In particular, eras should be distinguishable as changes in the rate at which historical systems

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[2] What constitutes a ‘significant’ energy innovation? In effect, it must be sufficient to initiate a new, persistent, recognizably different form of organisation that survives long enough to leave evidence of its existence in the present day to qualify.

Table 1
Characteristics of non-equilibrium steady-state transitions (NESSTs)

NESST	Energy innovation	Organisation	Control	Beginning date (years before present) [a]	Duration (years)	Gap (years)	Energy flow density (ergs) [b]
Atomic	Electron capture	Atoms	Electro-magnetic forces	13.6997 BYA	1×10^{-11}	–	0.005
Stellar	Proton–proton chain reaction	First generation stars	Gravity vs gas pressure	13.5 BYA	100	199.7 M	2
Galaxy	Quasars/black holes	Galaxies	Gravity vs interstellar wind	13.0 BYA	100 M	500 M	50
Cell	Metabolism	Cell	Genetic code	3.5 BYA	500 M	9.4 B	1000
Complex cell	Mitochondria, chloroplasts, lipids	Eukaryote	Recombination/sex	2 BYA	250 M	1 B	3000
Multi-cell	Secondary aerobic reactions	Multi-cellular organism	Pattern codes; neuronal nets	700 MYA	150 M	1.1 B	10,000
Tool	(Learned) tool use and manufacture	Parental unit cluster	Tonally variant call system	25 MYA	10 M	100 M	20,000
Fire	Fire use	Band	Normative social systems (culture)	2.5 MYA	1 M	12.5 M	40,000
Multi-tool	Tool kits	Tribe	Grammatical language	500,000	200,000	1 M	60,000
Complex tool	Compound tools (e.g., bow-and-arrow)	'Big Man' society	Iconic representation (cave art)	50,000	20,000	250,000	70,000
Agriculture	Cultural symbiosis (animal domestication, plant cultivation)	Chiefdom/city–state	Symbolic representation (writing, mathematics)	10,000	5000	20,000	85,000
Machine	Watermill/windmill; 'Medieval agriculture cycle'	Autocratic (feudal) state	Measuring instruments (e.g., clock)	1000	500	3000	100,000
Steam	Steam engine	Democratic nation–state; corporation	Canal, road and rail systems	250	50	250	500,000
Electric	Electricity	International cartels; industrial research labs	Telegraph/telephone; railroad networks; bureaucracy; advertising	150	30	50	1 M
Engine	Oil/internal combustion engine	Multinational agency (e.g., UN); multinational corporation	Mass media (radio, TV); mass production; computer	90	30	30	1.6 M
Nuclear	Nuclear reactors	Global markets; World Wide Web	Digital media	40	25	20	3.2 M

[a] Present taken to be year 2000.

[b] Values for energy flow density, (from [10]) are, in sequential order, for an atom, a star (the Sun), a black hole (galaxy), average prokaryote, average eukaryote, reptile, social insect colony, hominid forager, fire-augmented human, hatchet-using human, bow-and-arrow using human, agricultural human, plow-equipped farmer, coal-based industrial age inhabitant, electric tool-augmented human, industrial system inhabitant, and contemporary American.

can achieve (and sustain) higher levels of energetic disequilibrium. This is related to the amount of energy which flows through the system per unit time. Energy flow through the structure created by an NESST will be measured as energy flow density, or the amount of free energy flowing through a gram of the relevant structure per second, in ergs. (Values for organisational systems similar to those characteristic of each NESST – such as a star, a eukaryotic cell, and fire-augmented human – have been taken from [10]; [3] see Table 1). This measure permits comparison between different kinds of physical structures by standardizing with respect to a unit of mass.

Using the criterion of energy flow profile, four different eras can be identified as breaks in the trend in energy flow density change in big history (see Fig. 1; values have been log transformed due to the range of magnitudes involved): a 'cosmological' era from the Atomic Transition through the Galaxy Transition, a 'biological' era from the Cell Transition through the Multi-Cellular Transition, a 'cultural' era from the Tool Transition through the Agriculture Transition, and a 'technological' era from the Machine Transition to the present day.[4] (The 'cultural' era is associated with a number of what are normally called 'technological' advances, such as tools, but truly human technology – of a kind which no other animal can mimic–began with machines, which justifies the distinction between animal/human culture and true technology.)

Changes in rates of energy flow between eras can be explained by the fact that each era identified coincides with a set of transitions based on an energy source of a particular kind. Cosmological transitions

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[3] [10] did not include a value for an organisational form relevant to the Electric Transition; a value for this organization was therefore interpolated from those for the transitions occurring before and after this one.

[4] A number of scholars have previously segmented big history into large-scale periods. For example, Chaisson [30] suggests big history can be divided into seven 'epochs': particle (up to atoms), galactic, stellar, planetary, chemical (early complex molecules), biological and cultural (human evolution). But these categories are not distinguished clearly by process (the galactic, stellar and planetary epochs are concerned with different organisational features of similar cosmological processes, while the chemical and biological epochs are based on the same kinds of molecular reactions). These difficulties debilitate Chaisson's scheme as the kind of eras we are looking for. Spier [8] suggests a suite of major 'regimes' in big history similar to the eras uncovered here: cosmic, planetary, organic and human (or cultural). However, Spier's categorization is based only on the admittedly vague suggestion that these constitute different kinds of historical systems. The scheme closest to the present one, because it is based on a single criterion, is that of Kurzweil [21], who identifies six eons distinguished by their kind of information processing: physics/chemistry, biology, brains, technology, machine intelligence (achieved through an integration of human brains with technological infrastructure), and the technological singularity (when patterns of matter and energy in the universe become saturated with intelligent processes; the last two are hypothetical future eras). Similar problems arise when making empirical predictions based on a priori temporal scalings of macrohistorical trends. Power laws have the property of scale invariance such that the sequence of events is a simple geometrical progression and different parts of this sequence may be obtained from each other by a scale transformation. In this way, Panov (2005) uses his scaling of events in Earth's history to retrodict the beginning of prebiotic evolution of life to 10 billion years before present, the time when second generation stars were beginning to produce the heavier elements needed for life. Similarly, some have argued that technology will continue to produce ever-faster improvements in our ability to innovate, based on a scaling law derived from 'canonical milestones' since the origin of life, and that a technological 'singularity' will soon occur in which the rate of temporal change will become infinite (analogous to the infinite rate of change in mass hypothesized to occur at the centre of a black hole) [20,21,31,32]. Here, temporal scaling has been based not on a 'scale first; find events later' procedure, which leads to ad hoc results, but rather to a theoretically derived 'identify events first; fit pattern later' approach. If events are selected a priori, based on rigorous, theoretically-founded criteria, and then plotted against time, a more reliable estimate of any scaling, as well as a replicable list of events, can be produced from a single procedure. Using events rather than scaling laws themselves to make predictions suggests that Panov's retrodiction of the extraterrestrial evolution of life is based on a uniformitarian principle being extended between eras, and thus is invalid.

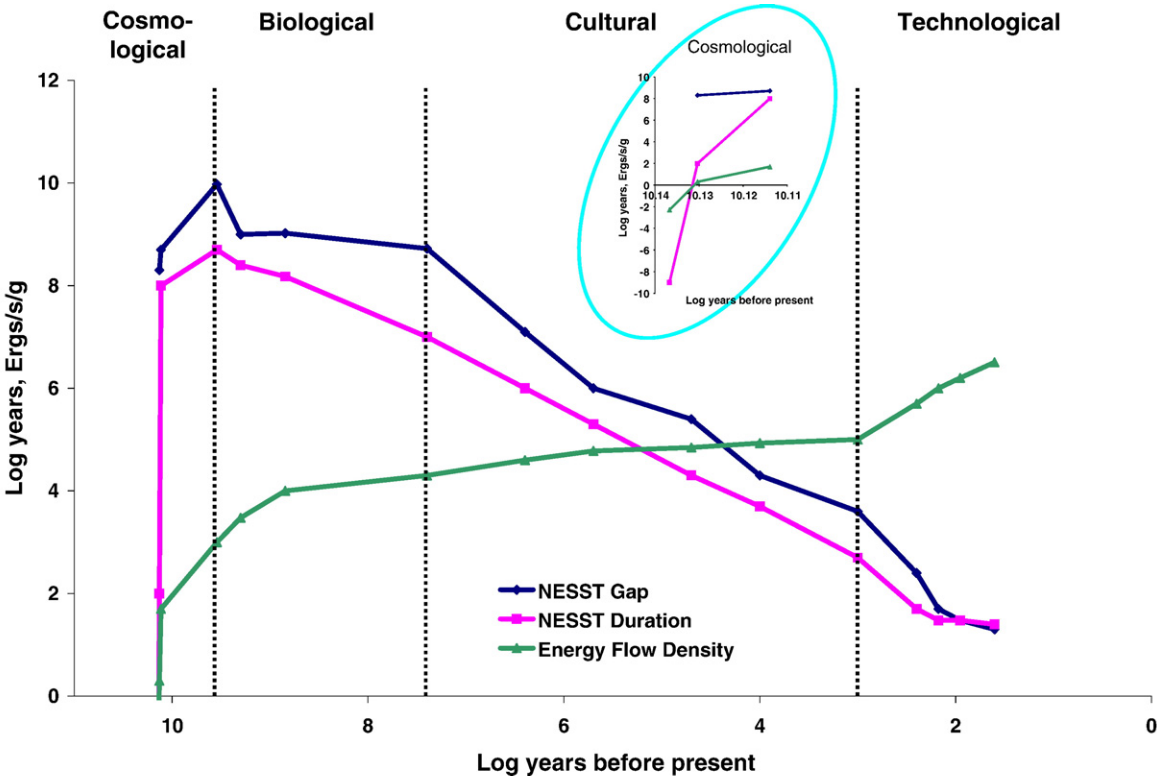

Fig. 1. Trends in transition duration, gap length and energy flow density, with eras. Energy flow density measured in ergs per second per gram [10]; NESST duration and gaps in log years. Note that the cosmological transitions are shown in a separate graphic due to the relative compression of the time scale at higher values of logged time.

involved nuclear fusion; biological transitions were based on improvements in metabolic function; cultural transitions required the invention of new kinds of tools (considering cooperation with conspecifics in the Tool transition to sociality as a kind of tool); while technological transitions commenced with the first appearance of machines (or combinations of tools exhibiting novel functionality as a unit).

4. Finding eons

Steady-state thermodynamics does not explicitly consider time, so no specific temporal patterning of NESSTs can be derived directly from theory. However, the temporal scaling previously observed in events since the origin of life [9,20,21] suggest the question of whether the entire period of big history will exhibit a similar trend. Whether all of big history is consistent with the operation of a uniformitarian principle can be investigated by looking at temporal patterns in the occurrence of qualities of NESSTs themselves.

Features of NESSTs which can be examined include the duration of the transition (‘NESST duration’, measured as the number of years between the date of the energy novelty initiating a transition and the date for the appearance of stabilized control mechanisms), and the amount of time between the end of one

Table 2
Eons, eras and periods in ‘big’ history

Eon	Era	Period
Cosmological	Material	Atomic
		Stellar
		Galaxy
Terrestrial	Biological	Cell
		Complex cell
		Multi-cell
	Cultural	Tool
		Fire
		Multi-tool
		Complex tool
		Agriculture
	Technological	Machine
		Steam
		Electric
		Engine
		Nuclear

transition and the beginning of the next (‘NESST gap’, measured as the number of years between the stabilization of control in the previous transition and the energy novelty of the transition under consideration). NESST duration measures the period of adjustment to an energy novelty, while NESST gap is the period during which the newly-instituted steady state persists. (The values for these variables in Table 1 are derived from the dates for events in [26]).

Fig. 1 shows that these characteristics of NESSTs exhibit two power law relationships: an increasing linear trend in the logarithm of time for cosmological events, and a decreasing linear trend for events occurring since the origin of life on Earth.[5] Histories occurring both in the universe at large and on one planet are thus similar in exhibiting NESSTs and scaling laws, but not in the direction of scaling.

5. Explaining the different historical periods

Fig. 1 thus indicates that big history is not the result of a single, uniform process. The cosmological transitions are independent from the others: they have a different direction and pattern of timing, in which transition durations increase, showing a decreasing momentum of change with the passage of time.[6] The origin of life thus significantly changed the tenor of history, reversing the trend in transition duration and gap-times. This difference is one of quality, not quantity, and therefore justifies the cosmological or

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[5] A number of the events cannot be securely dated [26]; however, considerable variation in the actual date of some events would not have an appreciable effect on the overall pattern of scaling, especially for events in the middle of the sequence which tend to be less certainly timed. However, because a number of the dates are uncertain, it is inappropriate to place much emphasis on the degree of fit to the log-linear trend.

[6] This trend would be even more obvious if one included the well-recognized phase transitions in the first few minutes of the universe’s history as separate transitions. However, these transitions do not qualify because no controlled, localized variation in energy flows within a material system occurred during the period prior to the independence of matter from radiation [10].

material period being considered one eon, the terrestrial periods a separate eon.[7] Further, the biological, cultural and technological cycles share a trajectory, following in line, one from another. The transitions between eras are temporally appropriate, suggesting that technological processes developed out of the cultural ones, as did cultural processes from biological ones (Table 2).

The big break in big history is the advent of biological processes, from which all later history (on Earth) follows. What distinguishes biological from physical processes? Many argue it is the mechanism identified by Darwin: natural selection, which can produce adaptations. The complexity achieved by biological systems is much greater than that of physical systems because thermodynamic order becomes functional organisation — purposive designs that represent adaptations to specific environments. As a result, hierarchical organisation can arise, such as societies composed of organisms, which in turn are composed of cells [33]. A related argument is that control distinguishes biology from physics. Control is defined as purposive or intended movement toward a pre-defined goal, which requires cybernetic feedback and the communication of information. By contrast, physical systems only have order, or statistical regularities of structure (e.g., crystalline shape) [34].

However, cosmological processes produced galaxies composed of star systems, which are not simply statistically non-random systems, but hierarchically organised physical structures. Purely physical systems can also regulate themselves through the use of a mechanism of discrepancy measurement and dampening (e.g., James Watt's steam engine governor). Even if one defines control more narrowly as a teleonomic function dependent on the operation of a programme based on coded information that guides a process toward a given end, modern artefacts such as computers satisfy this condition. Even 'simple' cosmological systems exhibit control features, such as solar wind and gravitational torques, which resemble – albeit in primitive form – the teleonomic adaptations of the biological world.

What truly distinguishes biological processes is the fact that life forms not only engage in work cycles but reproduce themselves as well [28]. Only biological processes engage in the *replication* of structure. Replication can be compared to normal thermodynamic processes in purely physico-chemical terms [35]. Consider two catalytic reactions involving two reactants and a single product. If the product is different from any of the other constituents, then 6×10^{23} reactions are required to produce a mole of the product. On the other hand, if the product is the catalyst itself, then only 79 reactions are required — the autocatalytic (or replicative) reaction is 20 orders of magnitude faster [36]. In a physical system, any movement toward or away from equilibrium is governed by both thermodynamic factors such as the availability of reactants and energy, and kinetic factors associated with the speed of reaction. However, replication should dominate any other consideration in determining the course of events in an area in which replicative chemistry is at work. Such areas will be, in effect, biological zones whose history is determined by evolutionary processes rather than physical constraints [35].

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[7] The length of the gap between the last cosmological transition and the first terrestrial one is also the largest by an order of magnitude (nearly 10 billion years). This is probably because of our ignorance of history on other planets. Earth is the offspring of a third-generation star born relatively recently (only 4.5 billion years ago). The temporal trend in novelties suggests that the *first* origin of life may have occurred earlier, on another planet. Since life began on Earth almost as soon as conditions permitted (only a few million years after meteoric bombardment of the planet's surface abated), and planets are quite commonly found circling stars, it appears likely that Earth is not the proper place to identify with the first instance of the transition to life. Generally speaking, however, the gaps between NESSTs tend to deviate to a greater degree from trend than NESST duration. This is probably because there is greater stochasticity in the development of energy novelties (as might be expected of a 'creative' process) than the consequences of this creativity, which follow naturally from the new energy flow: it appears to be harder to locate a new energy solution than to deal with it effectively once it has been found.

Thus, both thermodynamic and biological processes are subject to selection, but are distinguished by the kind of selection mechanism in operation. Physical processes experience *thermodynamic* selection, which maximizes thermodynamic stability, associated with a state of entropy. Thermodynamic selection may produce significant localized complexity, but it will take significant time, because equilibration processes tend to reduce any order back into disorder. By contrast, biological processes are exposed to *kinetic* selection [37]. Transformations from one replication system to another will be biased towards systems that exhibit increased kinetic stability (a kinetically stable replicator being defined as one that can maintain a significant equilibrium population of members under existing environmental conditions). Because complex replicators are kinetically more stable than simple ones, kinetic selection exhibits a concerted and cumulative tendency away from equilibrium [37].[8]

In physical systems, control is achieved through constraining structures; in biology, through information channels, or replicated structures. This represents a more powerful means of controlling energy flows because information transmission through the replication of structure allows the accumulated 'wisdom' of previous generations to be inherited by successive generations, as a form of inborn control over the implementation of functionality, through the advent of developmental programmes. Controlled development also allows the structures that control work cycles to emerge gradually and iteratively in variable forms sensitive to environmental conditions during the period of development. This process is quite different from the rapid production of regularized structural forms seen in physical systems.

Since Watson and Crick, it has also been clear that the replication of genetic structure (such as an amino acid sequence) results in the transmission of information to 'daughter' replicators (i.e., next-generation DNA). Autocatalysis thus introduces information inheritance, and thereby the possibility of both evolution and development. Because replication links generations in a descent relationship, information has been passed down continuously from the origin of life to the present day, which probably explains why the trends in big history have been consistent since the advent of life-forms. Iterative development also produces an increased variety of forms on which kinetic selection can act, increasing the rate of change in biological cycles.

But how to explain the increasingly rapid achievement of complexity with each successive era? I argue the answer is the *number* of replication mechanisms – or, equivalently, the number of information inheritance systems – operating in each era. Cultural evolution began once organisms could transmit information to subsequent generations through social learning, as well as through the replication of genetic information [38,39]. Artefacts were not particularly adept at storing information when they were restricted to simple tools, during the cultural era. But once they became complex, information could be stored in the relative position of their parts, and manipulated by changing these relationships (for example, in astrolabes or abacuses). Symbolic information could also be stored in artefacts, once writing had been invented, which occurred shortly before machines were available. Artefacts have recently been developed which can even exchange information among themselves, in the form of computer networks, creating the possibility of an entirely artefact-based information inheritance system [39]. By contrast, it seems that physical processes reached a dead end: without a mechanism for passing on developments from one organisation to another (information inheritance), the physical era accumulated certain advances in

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[8] One need only compare the simple replicators produced by artificial selection to the complex products of billions of years of natural selection to establish this correlation: in vitro replicators such as oligonucleotides are fragile while those produced by nature (such as bacteria) are robust to environmental perturbations.

structure, such as hierarchically structured galaxies, but then its creative impetus diminished. Without a mechanism of information inheritance, physical systems cannot evolve.

Thus, history began without a mechanism of information inheritance in the physical era. With genes, the biological era introduced the first information inheritance system; the cultural era added culture, and had two mechanisms; while the technological era had three mechanisms, adding artefact-based inheritance to those already present. The constant increase in control mechanisms with each era meant that more complex organisations could be sustained, and new novelties managed increasingly rapidly, accounting for the increasing pace of history during the last four billion years on Planet Earth.

6. The necessity of invention

It is also the case that the various eras were instigated by novelties of increasing complexity: physical era cycles depended on the power of nuclear fusion in stars, the biological era on organic metabolisms, the cultural era on tool use, and the technological era on machines. Novelties of each of these later types depended on the prior invention of the earlier types. This suggests that each era had to satisfy certain preconditions before it could begin. Even the physical era, if it was to result in increasingly complex structures of matter, had to be restricted to 'our' universe, which exhibits precisely the set of physical conditions necessary for matter to persist and aggregate into large, stable configurations. These features – such as the amount of matter, the number of spatial dimensions, the ratio of electrical to gravitational force, the ratio of actual to critical density, the ratio of gravity to antigravity – are finely tuned within the small band of values that make our universe 'anthropic', or capable of supporting (complex) life [40]. Only given these special conditions can thermodynamic selection for maximum entropy still lead to localized complexity.

The biological era depended on the origin of life. Life is a process seen in certain self-sustaining systems that can avoid entropy or decay [41]. As Darwin pointed out, the distinguishing features of the life process are survival and reproduction. Astrobiology suggests that life is based on matter, and is likely to be associated with planets (one of the last products of the physical era) [42]. The example of life on Earth suggests that the right ingredients in the right proportions, once placed in the right conditions, reorganise themselves and as a consequence initiate the Darwinian process. After a period of bombardment by asteroids, Planet Earth acquired the necessary stability for material structures to evolve on its surface. Life began very shortly after these conditions were fulfilled, about 3.8 billion years ago [43,44].

Did culture begin as soon as it was possible? Cultural traditions evolve in organisms faced with environments that vary uncertainly on intermediate time scales (a few to a few hundred generations), because innate mechanisms are an efficient source of adaptive behaviour when environments change over thousands of generations, while individual trial-and-error learning is the best strategy when the environment is so unstable that both social and innate influences are unreliable [38]. The learning of socially-transmitted information requires individuals to possess information-processing devices with memory capabilities — a brain. Cumulative cultural evolution, however, requires the generation and maintenance of new traditions in a population. This in turn requires individuals to have brains capable of efficiently learning new traits from the observation of others' behaviour [45]. Multiple cultural traditions have been documented in great apes and odontocetes (toothed whales); these are also the only two lineages of animals with truly large brains (relative to their body size) [46]. What the two lineages do not share is similarly complex ecologies: the oceanic habitat of the cetaceans is much more stable than the terrestrial environment of apes. What led to convergent cognitive evolution between these lineages is the complexity of their social lives [46]. This comparison thus suggests that large brains only become necessary when social, rather than ecological, niches become complex, because the intelligence needed to track the relationships among specific individuals in one's group increases exponentially with group size [47]. Sufficiently large social groups to produce cultural evolution were created and supported by cooperative foraging by the end of the biological era.

Technological cycles were particularly adept at producing novelties associated with significant increases in energy flow density. This is because social group were no longer restricted to using the bodies of its members to 'fuel' social functions [48]. Machines provided a source of energy independent of organic metabolisms. The technological era thus begins in earnest with the first machines. Making a machine requires a mechanism for maintaining control over the progress of iterated behaviours leading toward a distant goal. A large brain can perform this function, and both lineages of contemporary animals which exhibit culture, the apes and odontocetes, have them. However, artefact production also requires fine control over physical movement to put a machine's parts together [49]. Odontocetes lack the physical ability to manage multiple objects simultaneously, and so have not developed technology. Hominids have hands with opposable thumbs, which aid the precise manipulation of even small objects. Inventing new machines also requires an ability to generate alternative forms of a device, and to test and compare the resulting structures for performance [50,51]. A reliable procedure for generating and testing alternatives, science, was one of the last products of the cultural era, in *Homo sapiens* [52]. Given the need to have invented a range of tools to put together into machines, the need for an institutionalized means of producing complex novelties, and the rate of information inheritance provided by the cultural era, the invention of machine-based technology began as soon as it was feasible (Fig. 1). It therefore appears that each era began as soon as its preconditions were fulfilled, given the speed of advance at that time. The law of big history, at least since the beginning of the biological era, is the necessity of invention.

7. Conclusion

At the scale of big history, temporal and substantive patterns have been shown to emerge which are not evident over smaller ranges of time. These patterns enable us to periodize history. Specific criteria have been used here for making three hierarchical levels of periods: the applicability of a uniformitarian principle for defining eons, changes in the rate of the fundamental process of big history (achievement of a new level of complexity) to define eras, and the occurrence of a particular class of transitional event to define periods. Further, these criteria have been used empirically to determine the actual points at which each level of division should be made. Causes for the divisibility of big history into these hierarchical levels of periodization have also been provided: eons differ by the existence of an information inheritance process, and eras by different kinds of energy sources producing NESSTs. This categorization provides an opportunity for historians to examine in greater detail the commonality of historical processes within each period and to look for the causes which triggered the transitions to new kinds of processes at different levels of thermodynamic disequilibrium in each case.

Interesting patterns appear over the course of macrohistory which are not evident at smaller scales. For example, a clear pattern is that the spatial magnitude of the systems achieved by subsequent transitions increases, perhaps because more complex organisations tend to be larger than simpler ones or because, given a certain kind of organisation, higher levels of energy flow require physically larger systems to control that flow. This is particularly suggested by the fact that system size increases only within eras, which are supported by different kinds of energy innovations. Thus, developments during cosmological history exhibit the bottom-up aggregation of hierarchical structure, progressing from atoms through stars and galaxies. Similarly, in biological transitions, we move from cells to organisms to social groups; in cultural transitions, populations become ever larger, from small groups to many millions of people; and in the technological transitions, we reach nearly global scale.

Further, there is no temporal overlap between eras in terms of the appearance of the first areas to undergo a given transition. As far as we know, no cosmological transition has first occurred anywhere since very early in the history of the universe (i.e., new cosmological macro-structures are not still being created), and the first biological transition occurred long after the end of the cosmological transitions. Thus, the scale of the systems which can be said to have undergone NESSTs get progressively smaller as time goes on, being restricted first to one planet, then to particular regions of the Earth. Transitions to systems able to sustain higher degrees of thermodynamic disequilibrium are thus increasingly rare and increasingly dependent on a prior history of having attained some baseline degree of disequilibrium; they are also increasingly short-lived. All of these characteristics are expected of systems characterised by thermodynamic disequilibrium. It thus seems that periodizing big history can provide additional insights into the nature of the processes at work at the macro scale.

The temporal pattern exhibited by NESSTs also provides the basis for prediction. The dates of events which have not yet occurred can be inferred from the trends exhibited in Table 1 and Fig. 1. First, extrapolating the technological era trend suggests the next NESST should begin around 2010 and last for 20 to 25 years. Second, some have argued that technology will continue to produce ever-faster improvements in our ability to innovate, based on technological scaling laws (e.g., Moore's Law), and that a technological 'singularity' will soon occur in which the rate of temporal change will become infinite (analogous to the infinite rate of change in mass hypothesized to occur at the centre of a black hole) [20,31,32]. However, using events rather than scaling laws themselves to predict the future suggests that the rates at which major technological changes arrive and are processed seem to have plateaued about a hundred years ago, when transition lengths stabilized (Fig. 1). The ability of historical systems to *manage* change thus appears to have reached a limit, perhaps because a fundamental constraint in transition length has become effective. Implementation of technological change is a social process; it is difficult to imagine that the rate of change in social life – the way people deal with one another and their built environments – could become infinite. The realization of a temporal, rather than spatial, singularity therefore appears implausible. This result will no doubt come as a relief to some futurists, but as a disappointment to others.

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