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# Major transitions in ‘big’ history

Robert Aunger *

*DCVBU, ITD, London School of Hygiene and Tropical Medicine, Keppel St, London WC1E 7HT, United Kingdom*

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## Abstract

‘Big’ history treats events between the Big Bang and contemporary technological life on Earth as a single narrative, suggesting that cosmological, biological and social processes can be treated similarly. An obvious trend in big history is the development of increasingly complex systems. This implies that the degree to which historical systems have deviated from thermodynamic equilibrium has increased over time. Recent theory suggests that stepwise changes in the work accomplished by a system can be explained using steady-state non-equilibrium thermodynamics. This paper argues that significant macro-historical events can therefore be characterized as transitions to steady states exhibiting persistently higher levels of thermodynamic disequilibrium which result in observably novel kinds or levels of organisation. Further, non-equilibrium thermodynamics suggests that such transitions should have particular temporal structures, beginning with sustainable energy innovations which result in novelties in organisation and in control mechanisms for maintaining the new organisation against energy fluctuations. We show how events in big history which qualify as historically significant by these criteria exhibit this internal structure. Big history thus obeys law-like processes, resulting in a common pattern of major transitions between steady-state historical regimes. This common process from cosmological to contemporary times makes big history a viable and relevant field of scientific study.

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## 1. Introduction

Macro-historical projects have recently become popular again. Explaining the ‘rise of the West’ used to be the largest task historians were willing to undertake [1,2], but now the scale of historical ambition has

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* Tel.: +44 1223 881928.
*E-mail address:* robert.aunger@lshtm.ac.uk.

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become very large indeed. Some contemporary historians argue their canvas can be extended geographically to cover the world ('world history' [3,4]), others to all of human history [5,6], or even all of human prehistory [7,8]. Yet others seek to tell the story of life on earth [9,10]. The 'big' history project is perhaps the most ambitious, covering the life of the cosmos from the Big Bang to the present day in a single narrative [11–16].

What brings together events as disparate as the origin of stars, the French Revolution and the invention of windmills into a single analysis? Christian [12] argues that the grand sweep of events, linked together in a seamless explanatory framework, provides intellectual satisfaction and a richer context to human experience. However, beyond such aesthetic concerns, investigations at this scale are important because historical laws might be detected in this expanse of time: big history can serve as the foundation for 'big theory' [17].

Where exactly might such historical laws be found? Certainly, historians have long been preoccupied with identifying those events which have a special significance in determining the subsequent course of history. However, a rigorous method for selecting these events from among the myriad possibilities has been lacking. As a result, historians have been limited to the idiosyncratic identification of 'landmark' events, or to putting boundaries around temporally and spatially clustered events (the 'periodization' of history) [18,19]. These practices have fallen into disrepute in some quarters, being characterized as an attempt to break a continuously emergent process into arbitrary pieces (such as the 'Renaissance'), which then acquire an unnatural grip on the mind [20,21]. Nevertheless, the first step toward historical laws must be the discovery of a rigorous foundation for organizing historical processes into analytical units larger than individual events; otherwise one is left with chronologies that are simply 'one damn thing after another'.

At a minimum, historical narratives ascribe cause-and-effect relationships between events [20]. The dependence of effects on the prior occurrence of causes indicates that historical processes only run in one temporal direction: they are not reversible. A rigorous expectation for irreversibility can be found in thermodynamics: historical processes are irreversible because, at a macro-scale, entropy increases over time. The universe was very hot at the time of the Big Bang, but has progressively become cooler as it has grown larger, leaving less energy available to perform useful work as time passes, meaning that previous kinds or levels of order cannot be maintained.

At the same time, in the grand sweep of big history, the opposite pattern of events is obvious: a trend toward the production of increasingly complex, but localized systems. For example, organisms are more complex organisations than stars, and social systems are more complex than organisms. From a thermodynamic perspective, temporal order (i.e., history) thus requires spatial order, which implies that historical systems must be out of thermodynamic equilibrium. Any law-like description of major events in macro-history must therefore be centrally concerned with how increasing levels of thermodynamic disequilibrium can occur and be sustained. Big history can thus serve as the focus for the discovery of laws describing major transitions in the direction of historical change that account for this increase in the maximum degree of structural complexity over time, despite the imperative for thermodynamic entropy to increase.

The primary contention of this paper is that the evolution of complexity in macro-scale history can be characterized in physical terms as a sequence of transitions between non-equilibrium states of a particular kind. Despite being the result of processes ranging from star formation to the diffusion of technological inventions through societies, it will be shown that every major historical transition has a number of features in common which make it legitimate to call these transitions members of the same class. In this way, macro-history is shown to exhibit significant law-like behaviour.

## 2. Non-equilibrium steady-state thermodynamics

Physicists have long sought a way to extend their understanding of systems in equilibrium to those in disequilibrium. Currently, there is no widely-accepted quantitative description of non-linear thermodynamic transitions, especially in systems far from equilibrium [22,23]. However, a general phenomenological theory of steady-state non-equilibrium thermodynamics has recently been developed to explain transitions in the degree to which a system exhibits energetic disequilibrium [24,25]. This theory has been formulated because the simplest kind of non-equilibrium condition is a non-equilibrium steady state. This approach is phenomenological because it develops theory in terms of measurable quantities, and thus facilitates empirical testing. In particular, steady states can be characterized by values of temperature, volume, the amount of matter, and energy flux (the free energy that passes through the system within a unit time) [25]. Steady states are thus local, temporally bounded systems.

In a non-equilibrium steady-state, a constant flux of energy moves through the system. During periods of stability, historical systems engage in what can be called thermodynamic 'work cycles', or consistently repeating dynamic processes that maintain the system at a given degree of disequilibrium through the management of energy flows [26–28]. For example, a proton–proton cycle fuels fusion reactions in the cores of some stars [29], while animal metabolisms are fuelled by the Krebs cycle. Work cycles maintain a non-equilibrium steady state which shows no macroscopically observable changes, while constantly exchanging energy with the environment.

Since work cycles happen within a given organizational framework and do not significantly change the level of disequilibrium, exogenous shocks or accidental perturbations in the operation of a work cycle must arise to initiate a transition between steady-states. However, systems far from thermodynamic equilibrium can be subject to constant fluctuations in energy flow. The steady state may therefore become unstable and be replaced by another (or, perhaps, by a periodic or chaotic state). Small-scale divergences from a steady-state will often be accommodated; structural changes are caused only when some parameter exceeds a threshold value [30–32]. For this reason, a steady-state will persist for some period before a structural change at the global level becomes necessary. Because they tend to be robustly controlled, complex systems tend to evolve in step-wise fashion [33,34].

To move a system further from thermodynamic equilibrium, a perturbation must be due to an increase in energy flow through the system. This could either be the result of a random fluctuation or the input of a new source of energy. However, a random fluctuation will generally not lead to a sustained increase in energy flow. A significant transition is therefore more likely to start with a new kind or level of energy flow in a system, due to a new way of extracting energy from the system's surroundings [28,35,36].[1] This means that extracting energy will be called an 'energy novelty'.

As with a phase transition, the result of increased energy flow can be a new organisation of matter because, as energy flows through a system, physical structures can form. In effect, thermodynamic disequilibrium at point *X* induces a flow of energy toward an energy sink at point *Z*, producing a transient flow which increases disequilibrium at point *Y*. This new situation causes structure to form at point *Y*. For example, structures can be induced to form experimentally in systems far from equilibrium, such as ordered convection cells created by heating a pan of water, or oscillating ring patterns induced to form in a

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[1] Since non-equilibrium steady-states are defined along a number of dimensions, they are difficult to compare. However, arbitrary changes in the level of work performed by a given system in different disequilibrium states can be measured [37–39], an assertion that has been empirically confirmed [40,41].

chemical mixture through the Belusov–Zhabotinsky reaction. More impressively, nanotechnologists have recently been able to induce both regular and heterogeneous structures (such as electric switches) to self-assemble from various substances in a number of media by the local application of energy (e.g., creating carbon nanotubes from a graphite target by laser bombardment) [42].

Existing work cycles may continue to operate after an energy novelty, but the increased flow of energy may not be handled appropriately by existing control mechanisms. If the new structure of matter is not to be reversed, it may be necessary for some novel form of control to manage the higher level of energy flow and to ensure the new structure is robust with respect to subsequent fluctuations in work cycle operation. Control occurs in dynamical systems when a mechanism manipulates the inputs to a system such that the stability of the system's output is increased [43,44]. In effect, controls constrain the flow of energy through structures. Adjustments of control typically must follow the creation of new structures, eliminating some structures and modifying others to make them appropriate within the context of the system as a whole [6,28,45–47]. The result should then be a functioning organisation. In some cases, constraints are introduced on subsequent energy flows through points where new structures have formed. The net result of these adjustments can be an increase in the power of that system, where power measures a system's ability to manage the direction and timing of energy flows, and hence to maintain its degree of organisation [28]. When this fails to happen in an appropriate way, the work cycle, and the system it supports, may not persist. Thus, not all work cycles continue to operate in the face of energy novelties, and either return to earlier, lower levels of thermodynamic disequilibrium, or cease to work altogether, and hence leave no historical record. A large proportion of innovations probably fails in this way, and therefore do not form the foundation for further advances in complexity. Work cycles that do continue to operate in the face of energy innovations will likely be based on processes that can maintain a new level of thermodynamic disequilibrium in energy flow patterns. These processes will likely have features that make them robust or flexible, such as hierarchical organisation, modularity or compartmentalization, weak interaction and redundancy — aspects of both organisation and control [48–51].

In summary, from the perspective of steady-state thermodynamics, transitions which result in significantly new levels of disequilibrium should commence with a novel source of energy being acquired, followed by a new kind or level of organisation which hierarchically encapsulates the prior level of organisation of the system, together with new forms of management for the control of structural relations within the new organisation, constituting a means for controlling energy flow through the new organisation, and thus 'steadying' the transition to the new steady-state. In this model, the first step, a novelty, invokes several consequences, suggesting that these groups of events are linked together and so should be treated as inter-independent. These related, regularly recurring events are *components* of major transitions. Such transitions can be called 'NESSTs' (non-equilibrium steady-state transitions). With new structures and control systems in place, successful steady-state transitions to higher rates of energy throughput become irreversible, giving an 'arrow of time' to the systems experiencing these transitions.

When applied to historical phenomena, the NESST-based major transition model has some additional implications. First, each phase of the adjustment process to an energy innovation is contingent: only some novelties lead to the maintenance of structure, much less new structures, and only some structures result in new control features. Hence, only a small proportion of transitions result in increased complexity, and only those with the biggest impact on organisation leave evidence of their passing in the historical record. But overall, big history exhibits a trend of advances in power, through the production of organisations capable of acquiring and managing even higher amounts of energy flow [28,35,36].

Second, once the transition processes have settled down, a new historical ‘regime’ has effectively been instituted [16,52]. A regime is the set of principles or rules which govern how a historical system operates. A period of transition, composed of the stages of novelty and adjustment in organisation and control, is thus followed by a preservation period, during which the energy flow established by the transition is maintained over time. During periods of regime preservation, energy use remains relatively stable through the repetition of work cycles. A regime tends to persist until a new transition is initiated by a new energy-extraction novelty, resulting in cycles of ‘punctuated disequilibrium’ between NESSTs and regimes (cf. [34]; see Fig. 1).

## 3. Non-equilibrium steady-state transitions in ‘big’ history

While speculative in some respects, this model of steady states punctuated by transitions to different levels of energy flow is consistent with our best current understanding of thermodynamic systems far from equilibrium [24,25]. The order of events within transitions – although logical – has not been demonstrated to characterize transitions between non-equilibrium steady-states. This pattern must be confirmed empirically.

Whether thermodynamic transitions apply to the primary dynamic of big history – the evolution of complexity – has yet to be demonstrated, even though non-equilibrium thermodynamics is the most fundamental description of such a process. However, phase transitions, which are similar to NESSTs, are ubiquitous in physical, biological and social systems [53–55]. Phase transitions occur when qualitatively different macro-scale structures arise at some threshold of gradual change in some control variable [56]. They are now considered quite general since they have been observed in the past few years in phenomena ranging from the quantum scale to the social. The many different kinds of phase transitions have also been classified into large categories which observe similar behaviour (so-called ‘universality’ classes) [53]. In thermodynamic phase transitions (such as liquid to gas), a small change in temperature suddenly results in a new kind of macro-scale organisation of matter. Phase transitions have also been demonstrated in

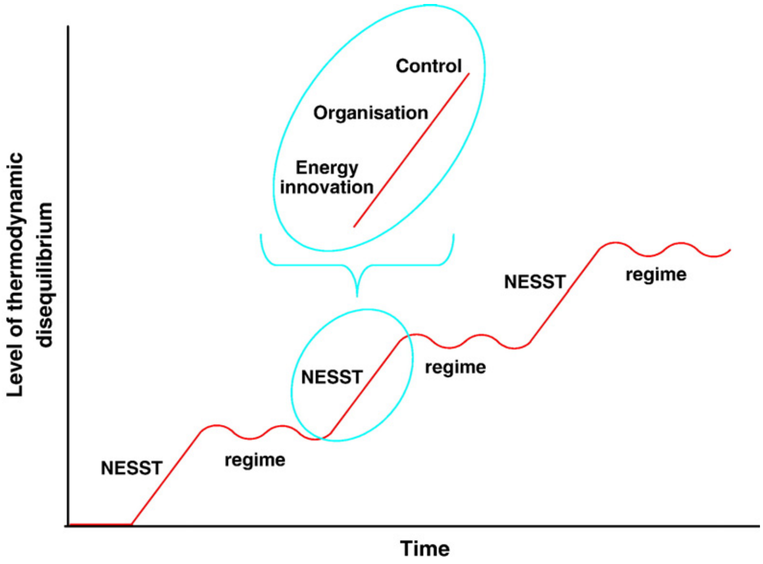

Fig. 1. A schematic view of major transitions in ‘Big’ history.

Table 1
Candidate events in big history$^+$

| Event | Sagan | Barro with silk | Chaisson[a] | Christian[b] | Modis | Coren | Spier | Maynard Smith/Szathmary | Barbieri | Klein | Lipsey et al | Sanderson | Johnson/Earle | Freeman |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Big Bang[c] | X | X | X | X | X | X | X | | | | | | | |
| Planck era | | | X | X | | | | | | | | | | |
| Inflation | | | X | X | | | | | | | | | | |
| Gravity[c] | | | X | | | | X | | | | | | | |
| Nuclear forces[c] | | | X | X | | | X | | | | | | | |
| Electromagnetic forces[c] | | | X | X | | | X | | | | | | | |
| Hadrons | | | X | | | | | | | | | | | |
| Leptons | | | X | X | | | | | | | | | | |
| Nuclear particles | | | X | X | | | X | | | | | | | |
| Recombination | | | | X | | | | | | | | | | |
| Atoms[d] | | | X | X | | | X | | | | | | | |
| Stars[c] | | X | X | X | X | | X | | | | | | | |
| Black holes/quasars[d] | | X | X | X | | | | | | | | | | |
| Solar wind[e] | | | X | X | | | | | | | | | | |
| Galaxies[d] | X | X | X | X | | | X | | | | | | | |
| Second-generation (Population II) stars | | X | | | | | | | | | | | | |
| Population I stars | | X | | | | | | | | | | | | |
| Solar system/planets[d] | X | X | X | X | X | | | | | | | | | |
| Cratering of planets | | X | | | | | | | | | | | | |
| Formation of Earth | X | | X | X | | | | | | | | | | |
| Oldest rocks form | X | X | | | | | | | | | | | | |
| First replicators[e] | | | X | X | | | | X | X | | | | | |
| First life[d] | X | X | X | X | X | X | X | X | X | | | | | |
| Chromosomes | | | | | | | | X | | | | | | |
| RNA/DNA/protein division[e] | | | | X | | | | X | X | | | | | |
| Photosynthesis[c] | X | | X | | | | | | | | | | | |
| Eukaryotes (complex nucleus)[d] | | | X | X | | | | X | X | | | | | |
| Recombination of DNA | | | | | | | | | X | | | | | |
| Sexual reproduction[e] | X | | X | X | | | | X | | | | | | |
| Atmosphere oxygenated[c] | X | X | X | X | | | X | | | | | | | |
| Multicellular life[d] | | X | X | X | X | X | X | X | X | | | | | |
| Earliest fossils | X | X | X | | | | | | | | | | | |
| Intensive volcanism | X | | | | | | | | | | | | | |
| Worms | X | | | | | | | | | | | | | |
| Cambrian explosion (Vertebrates) | X | | | X | X | | X | | X | | | | | |
| Genetic bauplane[e] | | | | | | | | | X | | | | | |
| Trilobites | X | | | | | | | | | | | | | |
| Brains[e] | X | | X | X | | | X | | | | | | | |
| Fish | X | X | | X | | | | | | | | | | |
| Vascular plants | X | | | | | | | | | | | | | |
| Insects (Devonian) | X | | | X | | | | | | | | | | |
| Amphibians | X | | | | | | | | | | | | | |
| Reptiles | X | | | X | | | | | | | | | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dinosaurs (Permian) | X | | X | X | | | | | | | | | |
| Paleozoic | X | | X | | | | | | | | | | |
| Mammals | | | | X | X | X | | | | | | | |
| Sociality[d] | | | | X | | | | X | | | | | |
| Birds | X | | | X | | | | | | | | | |
| Cretaceous period | X | | X | X | | | | | | | | | |
| Primates | X | | X | X | X | | | | | | | | |
| Orangutan | | | | | X | | | | | | | | |
| Hominoids | X | | X | X | | | | | | X | | | |
| Proconsul | X | | | | | | | | | X | | | |
| Hominids | X | | | X | X | X | | | | X | | | |
| Stone tools[c] | X | X | | X | X | | | | | X | | | |
| Consciousness | | | X | | | | | | | | | | |
| Fire[c] | X | X | X | X | | | | | | X | | | |
| Most recent glacial period | X | | | X | | | | | | | | | |
| Settlement of Australia | X | | | | | | | | | X | | | |
| Family-level foraging[c] | | | X | X | X | | | | | X | | X | X |
| Broad-spectrum food collection[c] | | | | X | | | | | | X | | | |
| Neolithic | X | | | X | | | | | | | | X | |
| Local group/bands[d] | | | | X | | | | | | | | | X |
| Cultural learning[e] | | | X | X | | | | | | X | | | |
| Modern humans | | | | X | | X | X | | | X | | | |
| Tool kits[c] | | | X | X | | | | | X | X | | | X |
| Clan (tribe)/village[d] | | | | X | | | | | | | | | X |
| Language[e] | | | X | X | X | | | X | X | X | | | |
| Wheel | | | | | | | | | | | X | | |
| Pottery | | | | | | | | | | | X | | |
| Sedentism | | | | X | | | | | | X | | | |
| Horticulture[c] | | | | X | | | | | | | | X | |
| Corporate group/Big-man[d] | | | | X | | | | | | | | X | X |
| Neanderthal burial | | | | | | | | | X | X | | | |
| Art (cave painting)[e] | X | | X | X | X | | | | X | X | | | |
| Agriculture[c] | | X | | X | X | | | | | | X | X | |
| Domestication of animals[c] | | | | | | | | | | | X | | |
| Pastoral society | | | | X | | | | | | | | X | |
| Plow | | | | | | | | | | | X | | |
| Chiefdoms[d] | | | | X | | | | | | | | X | X |
| First cities[d] | X | | | X | | | | | | | | | |
| First dynasties (Archaic states)[d] | X | X | | X | | | | | | | | | X |
| Writing/alphabet[e] | X | | X | X | X | | | | | | X | | |
| Hammurabic legal codes, taxation[e] | X | | | X | | | | | | | | | |
| Iron metallurgy[c]/compass[e] | X | | | | | | | | | | X | | |
| Bronze metallurgy | X | | | | | | | | | | X | | |
| Kingdoms (Asokan India, Ch'in Dynasty, Athens)[d] | X | | | | | | | | | | | | |
| Christianity | X | | | | X | | | | | | | | |
| Gunpowder | | | | | X | | | | | | | | |
| Mayan and Byzantine civilizations | X | | | | | | | | | | | | |
| Pulley | | | | | | | | | | | X | | |

(continued on next page)

Table 1 (*continued*)

| Event | Sagan | Barro with silk | Chaisson [a] | Christian [b] | Modis | Coren | Spier | Maynard Smith/Szathmary | Barbieri | Klein | Lipsey et al | Sanderson | Johnson/ Earle | Freeman |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| World exploration/ migrations |  | X |  | X |  |  |  |  |  |  |  |  |  |  |
| Three-masted ship |  |  |  |  |  |  |  |  |  |  | X |  |  |  |
| Water mills [c] |  |  |  |  |  |  |  |  |  |  | X |  |  | X |
| Feudalism [d] |  |  |  | X |  |  |  |  |  |  |  | X |  |  |
| Market economy [e] |  |  |  | X | X |  |  |  |  |  |  | X | X | X |
| Rennaisance | X |  |  |  | X |  |  |  |  |  |  |  |  |  |
| Printing [e] |  |  |  |  |  | X |  |  |  |  | X |  |  |  |
| Industrial revolution (mechanization) [c] |  | X |  | X | X |  |  |  |  |  |  | X |  | X |
| Steam [d] |  |  |  | X |  |  |  |  |  |  | X |  |  | X |
| Modern science/ technology [e] | X |  | X | X | X |  |  |  |  |  |  | X |  |  |
| Democratic state |  |  |  |  | X |  |  |  |  |  |  | X |  |  |
| Factory systems [e] |  |  |  |  |  |  |  |  |  |  | X |  |  | X |
| Railways [e] |  |  |  | X |  |  |  |  |  |  | X |  |  | X |
| Electrification [c] |  |  |  |  |  |  |  |  |  |  | X |  |  | X |
| International companies [d] |  |  |  | X |  |  |  |  |  |  |  |  |  | X |
| Telegraph/ Telephone [e] |  |  |  | X |  |  |  |  |  |  |  |  |  | X |
| Motorization (internal combustion engine) [c] |  |  |  |  |  |  |  |  |  |  | X |  |  | X |
| Welfare state |  |  |  |  |  |  |  |  |  |  |  | X |  |  |
| Mass education |  |  |  |  |  |  |  |  |  |  |  | X |  |  |
| Multinational agencies [d] |  |  |  | X |  |  |  |  |  |  |  | X |  | X |
| Computing [e] |  |  |  |  |  | X |  |  |  |  |  |  |  | X |
| Nuclear energy [c] |  |  |  | X | X |  |  |  |  |  |  |  |  |  |
| Globalization [d] | X |  |  | X |  |  |  |  |  |  |  | X |  | X |
| Internet [d] |  |  |  |  | X |  |  |  |  |  |  |  |  | X |
| Electronics [e] |  |  |  | X |  |  |  |  |  |  |  |  |  |  |
| Space exploration | X |  |  | X |  |  |  |  |  |  |  |  |  |  |

See references for bibliographic details concerning the sources.

[a] This list is primarily from the website accompanying [11]: http://www.tufts.edu/as/wright_center/cosmic_evolution.

[b] Unlike the others in this Table, Christian [12] doesn't produce an explicit list, but as the most comprehensive and authoritative account of 'big history', it was necessary to include this reference. Appropriate items from the subject index were therefore used.

[c] Energy innovation.

[d] Organisational novelty.

[e] Development in control.

different kinds of networks – biological (membrane) [57], neural [58] and social [59] – where the critical variable is the degree of heterogeneity in the system (or a related variable) rather than temperature. In these non-thermodynamic phase transitions, the degree of connectivity between nodes in the network increases in continuous fashion, but a macroscopic cluster that spans a huge portion of the network arises as a threshold level of connectivity is exceeded [60].

The argument being made here is that thermodynamic transitions of a kind related to phase transitions – NESSTs – also cover systems from the cosmological to the social. Certainly, the pattern of events expected by steady-state non-equilibrium thermodynamics is consistent with the observed historical trend of sustained local disequilibria, punctuated by events which increase the degree of maximal organized complexity: the 'revolutions' of history [11,14,45,61,62]. If all major transitions in big history go through this same dynamic sequence, then NESSTs can be considered examples of a single class of events which divide historical time into periods.[2]

## 4. Materials and methods

Determining the empirical validity of the major transition perspective requires finding that the pattern of events expected of NESSTs actually occurred repeatedly from the beginning of the universe to the present day. Lists of 'significant' events in the various literatures concerned with macro-historical trends are generally variable in the types of events they include, usually due to their lack of a theoretical rationale for inclusion or exclusion. However, we are now in position to make a principled selection of events likely to have constituted significant advances in thermodynamic disequilibrium in 'big' history, and which are therefore the 'real' set of revolutions. The most authoritative sources in the relevant disciplines covering different parts of the big history spectrum (as determined by the reputation of the author, the author's academic institution and the publisher of the source), were consulted to develop a synthetic list of candidate events (see Table 1): cosmology [11,64], evolutionary biology [14,65], human prehistory [6,66], and macro-history [45,46], as well as the previous 'big' histories [12,13,15,52,67].[3] From among these candidates, only events which represent an advance in energy, organisation, control, or novel levels of hierarchical structure in an energy-based system are considered part of a NESST.

Next, the most reliable date and place for the first occurrence of each major historical advance was determined. These were again taken from the same set of authorities as nominated potential transitions or from specialized sources such as recent academic papers. These data, together with notes concerning the functional significance of events, are recorded in Table 2.[4]

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[2] Literature on the stages of sociocultural evolution [6,35], the economics of technological change [45,46], the history of life on earth [28], and 'minor transitions' within major biological transitions [47,63], have all been characterized as a sequence of novelty → structure → control, similar to the transition model developed here.

[3] Because early cosmology is a rapidly moving field, these general overviews were supplemented with recent specialized studies on the early history of the universe, as noted in Table 2.

[4] In cases where the date of an event is not well-known, its timing was interpolated from known dates of events prior and subsequent to the focal event. For example, the dates for the first appearance of the earlier forms of social organisation are difficult to discern from prehistorical evidence, but must take the order given, because tribes are more complex than bands, and 'Big Man' societies more complex than tribes. Further, cross-category inferences can be used to isolate the timing of novelties, such as the fact that 'Big Man'-level organisation could not have been achieved without the ability to coordinate super-familial cooperation through a grammatical language system.

## 5. Example NESSTs

Table 2 shows that the hypothesized structure of events within NESSTs applies to phenomena of wildly different kinds, from the accretion of matter into planets, to the agglomeration of cells into multicellular organisms, to the unification of cities into nation-states. All historical transitions between non-equilibrium steady-states follow the same pattern: an energy innovation first, structural adjustment second, and new control mechanisms third. The fact that such causal sequences consistently recur provides significant evidence that the interpretation of macro-historical revolutions as NESSTs is appropriate.

To further justify this conclusion, this section describes how energy innovations were followed by changes in the organisational and control features of historical systems in a number of representative NESSTs spanning the full range of time and complexity of organisation (elucidating these connections for all seventeen NESSTs in big history is impossible in a single paper). These examples serve to illustrate how the causal links between these three aspects of a NESST work in widely divergent kinds of historical processes.

## 6. The electron transition

### *6.1. Energy*

300,000 years after the Big Bang, temperatures in the early universe cooled sufficiently that ionized nuclei composed of protons and neutrons could occasionally capture electrons in their electrical field as they flew past. Electrons constituted a new source of electromagnetic energy associated with the nuclei.

### *6.2. Organisation*

In some cases, the electron began to repeatedly orbit the nucleus, constituting the first organisation of matter with an internal flow of energy in a steady-state of thermodynamic disequilibrium: the atom. (Atoms are structured, whereas the constituents of atoms, such as electrons and protons, are fundamental particles.) Most atoms took the simplest possible form, hydrogen, with one proton and one electron, but other kinds of atoms also formed, such as helium, with two protons and two electrons. Although on a minute scale, these bits of matter constituted the first enduring structures maintained by a flow of energy, due to the exchange of energy between the nucleus and the electron, which moved atoms locally away from a perfectly disordered state.[5]

### *6.3. Control*

Energy flow within atoms is regulated by the repulsion between electrons as they fly about the nucleus, and by the electrostatic attraction (Coulomb force) between oppositely charged protons and electrons.

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[5] Between the Big Bang and this moment (the so-called ‘Radiation Era’), matter had no permanent existence or influence; any particle could mutate into another, or into energy. This was because nuclei were electrically charged, and hence interacted strongly with photons. Once matter became electrically neutral, it could persist. Photon/matter collisions became rare and the evolution of the universe became dominated by the behaviour of matter [11].

These two kinds of interactions – together with the possibility of excitation (the absorption or emission of photons), atomic decay (loss of nuclear particles) and ionization (loss or gain of electrons) as forms of interaction with their environment – make atoms thermodynamic systems.

## 7. The fusion transition

### 7.1. Energy

Once nearly all electrons were bound to nuclei in hydrogen and helium atoms, gravitational forces became important. Small fluctuations in the density of matter began to form. Over time, through the accretion of matter, molecules clustered into clouds. The force of gravity eventually raised the temperature and internal pressure in these clouds sufficiently high to ignite hydrogen fusion, releasing a significant flow of energy into the surrounding space.

### 7.2. Organisation

The first generation of stars is not yet observable, but are likely to have been large and short-lived, producing the heavier elements that characterize observable second-generation stars [68,69]. Based on current star formation models, it is likely that as fusion reactions continued, the first stars produced large amounts of energy, most of which was expelled into the surrounding cloud (or nebula) in the form of a 'solar wind' of particles (as well as radiation), until nearby space was largely emptied. The stellar mass may also have begun to rotate due to collisions between denser clumps of matter within the cloud, with winds and jets acting as rotation regulators. Rotation of the contracting gas can make a protostar hotter than in the absence of rotation, but also tends to counteract any contraction because of the additional kinetic (centrifugal) energy involved. If gas is also ionized, the rotation also inevitably produces a magnetic field (dynamo effect) [70–72]. The interaction of these effects gives the star a spherical or disk shape. The transition from gas cloud to star required a few million years.

### 7.3. Control

Once their shape has settled down, stars become dynamical systems in which the stability of their energy production is maintained by feedback. If a star's central temperature drops, energy generation decreases, as does the gas pressure pushing outwards. As a result, gravity pulls the star's outer layers inwards. But as the outer layers press on the core, the central temperature rises back towards its original value. The result is a delicate balance which tends to restore the star's temperature and energy production rates to steady-state equilibrium. In effect, these processes act as stellar thermostats (control systems) [73].[6]

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[6] As with the other cosmological NESSTs, this one is unusual in that some control mechanisms (in this case the fundamental force of gravity) exist prior to the transitions which they come to control. As a result, the early cosmological transitions occur very rapidly: once the energy source has been acquired, there is a response in the form of a new organisation of matter. Then the control system becomes relevant and effective, with a fundamental force operating in partnership with a force that arises as a direct result of the new organization, and which typically works in opposition to it (e.g., the expulsion of gas in jets or stellar winds caused by fusion), which make it legitimate to argue that the control system arises after the organisation itself.

Table 2
First known instances of non-equilibrium steady-state transitions

| Transition | Aspect | Novelty | Function | Date[a] | Place |
|---|---|---|---|---|---|
| Electron (atomic) transition | Energy | Electron capture by nuclei[b] | Neutralize atomic charge, separate matter and energy | 13.7 billion | ‘Our’ universe |
| | Organisation | Atoms (hydrogen, helium) | Electrically neutral and hence complex, stable matter | 13.7 billion | ‘Our’ universe |
| | Control | Electro-magnetic forces | Nucleus/electron structural mediation | 13.7 billion | ‘Our’ universe |
| Fusion (stellar) transition | Energy | Proton–Proton reaction[c] | Ignition of proto-stars into stars | 13.5 billion | ‘Our’ universe |
| | Organisation | First generation stars[d] | First large-scale regulated structures | 13.5 billion | ‘Our’ universe |
| | Control | Gravity vs gas pressure | Debris removal and star shaping | 13.5 billion | ‘Our’ universe |
| Quasar (galaxy) transition | Energy | Quasars/black holes[e] | High-intensity electromagnetic radiation | 13 billion | ‘Our’ universe |
| | Organisation | Galaxies[f] | Super-scale, hierarchical structures (star clusters)[g] | 12 billion (?) | ‘Our’ universe |
| | Control | Gravity vs interstellar wind (produced by quasar) | Force operational over long distances, galaxy shaping | 13 billion | ‘Our’ universe |
| Metabolic (cell) transition | Energy | ‘Metabolism’ (e.g., photo-synthesis)[h] | A chemical reaction transition that produces energy in a form harnessed by other processes | 3.75 billion | Planet Earth; deep sea vents? |
| | Organisation | Cell | Protected micro-environment | 3.6 billion | Ocean? |
| | Control | Genetic code (e.g., RNA, DNA) | Self-catalyzing, durable inter-generational information storage system | 3.25 billion (?) | Ocean? |
| Organelle (complex cell) transition | Energy | Mitochondria (animals), chloroplasts (plants), lipids [133] | Use of free oxygen and photons as energy-rich source of ‘food’ | 2 billion (?) | Ocean? |
| | Organisation | Eukaryote | Nested protective envelopes (cell nucleus) | 1.75 billion[i] | Ocean? |
| | Control | Splicing codes (e.g. transfer RNA); genetic recombination [sex] | Intracellular communication; division of labour and controlled trait recombination | 1.75 billion (?) | Ocean? |
| Secondary aerobic reactions (multicell) transition | Energy | Complex aerobic reaction cycles | (Collection of) cells with improved long-term energy throughput and management | 700 million (?) | Ocean? |
| | Organisation | Multicellular organism; sexual reproduction | Greater variety of genotypes and phenotypes, including specialist tissues and organs | 650 million | Ocean? |
| | Control | Pattern codes [65]; neuronal networks (brains) | Chemical messengers and regulatory signals for determining body plans; intra-generational memory system (learning) | 550 million | Ocean? |
| Tool (multi-organism) transition | Energy | Cooperative foraging;[j] (learned) tool use and manufacture | Extraction of inaccessible foods | 25 million[k] | Land |
| | Organisation | Parental unit cluster (‘family’) | Loosely-linked group sharing kinship | 20 million (?) | Land |
| | Control | Call system [e.g., birdsong][l] | Coordination of groups through conventional signaling system | 15 million (?) | Land |
| Fire (band) transition | Energy | Fire use [early *Homo*] | Increased diet breadth and efficiency of consumption (cooked tubers) | 2.5 million | Africa |
| | Organisation | Band | Egalitarian collection of intermarrying parental clusters | 2 million (?) | Africa |
| | Control | Cultural traditions/norms | Use of arbitrary signs, symbols or behaviours to identify group membership | 1.5 million (?) | Africa |
| Multi-tool (tribal) transition | Energy | Tool kits (wooden spears etc.) [*Homo heidelbergensis*] | Increased diet breadth (new prey species) | 500,000 | Africa |
| | Organisation | Tribe[m] | Large-scale affiliation, sharing common ancestry and culture with neither formalized nor permanent leadership | 400,000 (?) | Africa |
| | Control | Grammatical language;[n] abstractly decorated tools | Sophisticated inter-personal information transmission system; aesthetics | 300,000 (?) | Africa |

| | | | | | |
|---|---|---|---|---|---|
| Compound tool (cultural) transition | Energy | Horticulture; compound tools (e.g., bow-and-arrow), tools for making tools (e.g., burins) [*Homo sapiens*] | Increased diet breadth (prey killed at distance); reduced variance in dietary intake | 50,000 | Africa |
| | Organisation | 'Big Man' society | Large-scale group with political leadership role based on personal ability (first division of labour) | 40,000 (?) | Africa, Europe |
| | Control | Iconic representation (cave art); common mythology (e.g., Venus figurines) | Simple extrasomatic (environmental) memory system | 30,000 | Africa, Europe |
| Agricultural (chiefdom) transition | Energy | Cultural symbiosis (animal domestication/plant cultivation); metallurgy; irrigation | Increased regularity of dietary intake (domesticated species); stronger tools; increased ecological capacity | 10,000 | Middle East, Central America, Asia |
| | Organisation | Chiefdom/city-state | Institutionalized leadership with power to collect, store, and distribute surplus resources | 7,500 | Middle East, Central America, Asia |
| | Control | Symbolic representation (cuneiform writing, alphabet); legal system; mathematics; money | Sophisticated extra-somatic memory; regulation of social relations on principles other than kinship; system for managing technical information; coordination of market exchange | 5,000 | Middle East, Central America, Asia |
| Machine (second agricultural) transition | Energy | Watermill/windmill; medieval "agriculture transition" | Muscles largely replaced as energy source; higher productivity levels | 1,000 | Europe/China |
| | Organisation | Autocratic (feudal) state | Centrally directed super-institution | 800 | Europe/China |
| | Control | "Measuring instruments" (mechanical clock, astrolabe); printing press; science [o] | "Active" information processing by artifacts; widespread dissemination of information; organized knowledge acquisition | 500 | Europe/China |
| Steam (industrial) transition | Energy | Steam | More efficient, portable power source | 250 | Europe, USA |
| | Organisation | Democratic nation state, corporation | Increased institutional stability (through legitimation), financial risk reduction (limited liability) | 250 | Europe, USA |
| | Control | Canal, road and rail systems | Greatly reduced transport costs | 200 | Europe, USA |
| Electricity (cartel) transition | Energy | Electricity | Systematic urban infrastructure for power generation and distribution | 150 | Europe, USA |
| | Organisation | International cartels; 'Taylorist' shop floors; industrial research laboratories | Collaborative international production; scientific management of production | 150 | Europe, USA |
| | Control | Telegraph/telephone; bureaucracy; advertising | Information transmission at a distance; rapid circulation of people; continuity management within state; mass manipulation of consumer motivation | 120 | Europe, USA |
| Engine (multinational) transition | Energy | Oil/internal combustion engine | Efficient, portable power | 90 | USA, Europe |
| | Organisation | Multinational agency (e.g., UN); multinational corporation (e.g., Standard Oil, Microsoft) | Supra-national government; international capitalism | 70 | USA, Europe |
| | Control | Mass media (radio, TV); mass production; computer | Fast, broad-scale information dissemination; standardized production; universal computation | 60 | USA, Europe |
| Nuclear (globalization) transition | Energy | Nuclear reactors [p] | Controlled atomic fission | 40 | USA, Europe |
| | Organisation | Global markets; World Wide Web | Significant international capital flows and investment; globalized social and economic network | 30 | USA, Europe |
| | Control | Digital media | Unified representation system for multimodal data | 15 | USA, Europe |

Notes to Table 2:

[a] Dates in years before present; present taken to be year 2000. Uncertain dates include '(?)'.

[b] The Big Bang is dated to 13.7 billion years ago by the Wilkinson Microwave Anisotropy Probe (WMAP) (http://map.gsfc.nasa.gov/m_mm.html). While the Big Bang was obviously the event which represents the source of all energy later used by history, it does not explain complexity *within* the universe. The first complex particles (in the form of simple atoms) begin to appear in the 'recombination' period approximately 300,000 years after the Big Bang, when the 'Age of Matter' began. Prior to this, a number of phase transitions occurred, including separation of the fundamental forces. These early transitions were due strictly to universe expansion and hence reduced temperatures; they thus don't exhibit the features of a NESST.

[c] [29]. Later stars were able to burn at a higher rate than the proton-proton reactions of first generation stars allowed; they used a carbon nitrogen oxygen cycle, thanks to the availability of higher density fuels (so-called 'metals'). This CNO cycle can be considered a variant of the principle of nuclear fusion which defines the Stellar NESST. This later generation of stars ('Population II' stars), due their higher metallicity, were also sometimes circled by dense material, which in some cases congealed into planets, a variant of the fog of dust which surrounded early stars.

[d] It is still debated whether independent stars were the first macroscale objects to form in the universe, or whether black holes and galaxies of stars coevolved from large agglomerations of cold matter. However, recent simulations and Wilkinson Microwave Anisotropy Probe data suggest that massive first generation (non-metallic) stars arose around 200 million years after the Big Bang [68,69]. In this scenario, black holes were only created later, through major accretions of matter (e.g., the merging of multiple stars or the collision of galaxies), just as atoms were created by the capture of electrons by nuclear particles, and molecules by the aggregation of atoms. The presence of black holes resulted in a burst of star formation, and major inflows of gas to the black hole, powering the formation of a quasar, which then releases energy and gas that quenches star formation and further black hole growth [124]. Quasars are a phase in the early life of supermassive black holes during which they emit intense x-rays and a powerful wind of interstellar gas. The number and size of stars in a galaxy and the size of black holes at their centres are thus co-regulated by the competing forces of this wind and gravity (just as stars are controlled by similar competing forces); only this kind of interaction between a supermassive black hole, quasar and their surroundings can give galaxies a particular shape, and thus make them a new level of organisation, as required by a NESST. (Note that I restrict the notion of galaxy to structured clusters of stars and dust regulated by supermassive black holes and quasars, and thus exclude the amorphous clouds, knots and filaments of gas often called galaxies which did not constitute energy flow systems.) Further, there are significant indications of the early build-up of heavy elements in the universe: the oldest Population II star currently observed is about 12.8 billion years old at redshift 6.3, while the oldest known planet is 12.7 billion years old [125]. The precedence of stars before galaxies is also the only ordering consistent with the principle of hierarchical structure formation which seems to be characteristic of a cold dark matter universe such as ours. Thus, while it is possible that supermassive black holes formed within 800 million years of the Big Bang from a monolithic collapse without help from stars, simulations of this early history, the WMAP data, the known presence of second generation stars and planets with metallicity soon after this, and the principle of hierarchical structure formation all suggest that there was a first generation of stars which produced the heavier elements on which second generation stars and quasars fed.

[e] Black holes release bursts of energy ('outflows' of superheated gas) but also serve as gravity sinks, due to their great mass, which causes nearby stars to cluster around them (and even for galaxies to cluster around supermassive black holes, or quasars) [126]. The formation of the first galaxy is therefore assumed to have occurred roughly simultaneously with the appearance of the first quasars at roughly 13 billion years ago [127].

[f] Dating a galaxy is somewhat arbitrary since they continue to evolve over a considerable period of time due to their immense scale, but the quasar period in a galaxy's lifespan is approximately 100 million years (see previous footnote).

[g] Clusters and superclusters of galaxies have been shown to characterize the large-scale structure of the universe. However, these structures are generated by the same processes as galaxies themselves — that is, the aggregation of star systems by gravitational forces, combated by the explosive force of dying stars and quasars, based on the statistical density fluctuations generated by the Big Bang [128].

[h] Two major alternatives dominate the literature attempting to explain the origin of life: the 'replicator first' and 'metabolism first' options [129]. The NESST perspective suggests that a primitive metabolic reaction chain preceded the evolution of a reliable information inheritance mechanism for controlling incipient organisms [130–132]. In particular, it implies that genes arose after cell membranes, contrary to the replicator first tradition. However, it is possible that the origin of primitive replicators predates that of cells in the history of life; in this case, the replicators would have lived independently before being incorporated into cells, where they took on the role of controlling metabolic and other cellular functions, thus conforming to the expectation that the control function follows organisation.

[i] Genetic evidence suggests a date of almost 2 billion years ago [134]; fossil evidence 1.2 billion years ago [135].

[j] Social insects obviously predate the development of social interdependence in mammals and birds, but are not in the phylogenetic line of later developments, and so are treated as a special case of genetically-determined 'eusociality' which did not further develop.

[k] The recent discovery of tool-*making* in both birds and primates [136,137] means that hominids were not the first to engage in this kind of activity phylogenetically; thus the date has been pushed back to the divergence of the avian and mammalian lineages.

[l] Signaling systems are not mentioned by any of the sources of significant historical events, but is an obvious requirement for social coordination.

[m] Based on current archaeological remains, tribes arose around 13,000 years ago in the Fertile Crescent [5]. This dating implies that primate-style bands persisted in all human societies until quite recently. However, it is likely that there were several steps in social complexity between bands and state systems [138]. Table 2 therefore pushes back the date for the first tribes, and adds an intermediate stage of social organization prior to states. It is posited that individuals with unusual symbolic, social or entrepreneurial skills gained authority over one or more tribes, becoming the first political leaders, or 'Big Men' [6]. The kinds of evidence used to identify complex social organization in the past (such as prestige goods and public architecture) did not characterize these intermediate social forms, which therefore remain invisible to the archaeological record.

[n] The origin of language is notoriously speculative, even if restricted, as here, to its most sophisticated form, grammatical language. Use of grammar depends essentially on complex cognitive capacities such as mental recursion and embedded mental representation, as well as sophisticated motor control over speech, talents that many feel are specific to the hominid line [139]. The ability to make complex tools suggests the existence of problem-solving and task planning abilities related to grammar use [140]. Grammar also must have occurred in conjunction with complex social organization. All of this evidence suggests a date around 300,000 years ago.

[o] The development of science was not a monolithic, unidirectional process. Pinpointing the beginning of science is therefore arguably nonsensical. Considering science as an institution makes the problem a bit easier, although it is still reasonable to say that the process of developing the institution was a gradual one, rather than a 'revolution', as normally thought [21]. Nevertheless, an emphasis on experimentation and gentlemanly societies pursuing this activity points to an origin during the Renaissance in Europe, particularly around 1500 [61,141].

[p] While nuclear power generation has arguably not had a significant impact on world power production because of social and political reluctance to risk the environmental dangers nuclear power plants are perceived to involve, the availability of this invention, most importantly in its form as a bomb, has nevertheless powerfully shaped the course of world history. In particular, the Cold War led the opposing super-powers to form strong international defensive collaborations such as NATO, but also facilitated by cross-national economic institutions such as the World Trade Organization and International Monetary Fund, accompanied by reduced barriers to free trade within alliances. Meanwhile, the American defense agency DARPA, constructed the first network of linked computers, ARPANET, in the late 1960s to provide redundant communications in the event of nuclear attack [142].

## 8. The secondary aerobic reaction transition

### 8.1. Energy

Life is dependent on non-equilibrium cycles of electron transfers between only a few molecules: hydrogen, carbon, nitrogen, oxygen and sulphur [74]. Oxidation of the Earth's atmosphere around 2.2 billion years ago made the use of oxygen as an energy source possible. A variety of unicellular organisms then solved the fundamental problems of energy fixation, metabolism and biosynthesis using oxygen; they could manage chemical reactions that maximized the expenditure of free energy [75]. This was the transition to life. Subsequent organisms incorporated the ability to produce these metabolic pathways in their genomes. However, at some point, an organism developed the ability to squeeze additional energy from the Earth's atmosphere compared to its fellows. By evolving the ability to synthesize new enzymes, it created more complex metabolic pathways, giving it an evolutionary advantage of increased energetic throughput. This initiated the second biological transition.

### 8.2. Organisation

Whether the ability to make use of free oxygen in the atmosphere in this way was a consequence or cause of multicellularity remains to be determined [76], but when multicellular animals appeared around 650 million years ago, they likely had the ability to perform additional kinds of oxidation reactions [76].[7] So in this case, the order of precedence between a new level of organization and energy innovation is not yet clear. But there are theoretical reasons to expect that competition among unicellular organisms for the ability to metabolize oxygen could have led to the evolution of multicellularity. In one model, implemented via computer simulation, undifferentiated clusters of interacting cells (i.e., primitive multicellular organisms) evolve due to their ability to share the use of external energy sources, and to exclude non-cooperative cells from that use [77]. Similarly, a game-theoretic model suggests that selection via density-dependent competitive interactions can explain the transition to multicellularity as a function of the energy throughput an organism can sustain, based only on the assumption that organisms are mobile (i.e., energy-expending) self-replicators [78]. Empirically, it is also the case that for each of the multiple origins of multicellularity in the Earth's history, the multicellular forms of life exhibit advantages in energy throughput compared to their unicellular ancestors [79].

### 8.3. Control

With massive redundancy in functionality, cells could afford to differentiate. Cellular diversification increases the stability of the overall system to perturbations in the degree of variation in chemical concentrations between cells due to intercellular interactions, or the loss of some cells in a network [80]. To assist in this control over intercellular interactions, a kind of cell arose which specialized in information transmission, the neuron. These neurons coordinated behavioural responses of the body as a whole to environmental stimuli. Neurons themselves then organised into an interconnected network, first spread through the body to monitor conditions throughout, but then also forming a mass at the

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[7] This is the only NESST for which there was not an obvious energy innovation mentioned in the relevant literature. This is probably because secondary aerobic reactions have only recently been related to the transition to multicellularity.

front of the body to enable quick reactions to the stimuli coming into the body as it moved forward—a brain [81,82].

## 9. The fire transition

### 9.1. Energy

Early humans would first have made use of fires ignited by natural causes such as lightening, seen the advantages of it's use — such as the provision of light, heat, and the control of germs in cooked animals [46]. At some point, they would have invented a means of managing (carrying and rekindling), and then actively producing, new fires (through friction). These distinctions in fire use are very hard to document in the archaeological record. Direct evidence for the first controlled use of fire comes about 1.6 million years ago [83]. However, various forms of indirect evidence suggest that *Homo erectus* used fire from the time the species first shows up in the archaeological record—that is, 2 million years ago [84]. For example, *H. erectus* was already living in cold climates in northeast Asia 1.4 million years ago [85], suggesting the need to survive cold temperatures during long-distance migrations.

Fire also helps to soften vegetable matter. Roots in particular – no doubt a staple food at this time – are more nutritious when cooked and easier to process for eating. Cooked foods can thus account for the rounder, smaller teeth observed in *H. erectus*, since the new diet required less chewing and gnawing, as well as the reduction in the gut and size of the rib-cage that occurred at this time. The energy requirements of the bigger brains boasted by hominids could also be supported by this enriched diet [86]. Fire use meant that greater amounts of energy flowed through the environment surrounding human groups than was possible before.

### 9.2. Organisation

In the absence of direct archaeological evidence, the social organization of early human groups is best investigated by comparing it to that of humans' closest living relative, the common chimpanzee. Chimps live in large communities of perhaps several hundred individuals (i.e., bands); however, they tend to interact in fluid ('fission–fusion') subgroups or parties of around ten individuals when foraging or sleeping. There is a linear dominance hierarchy among males; females emigrate to other groups at adolescence, and have their own dominance relationships in these new groups. Males cooperate to defend a territory, maintain their social status, guard their females, hunt prey species, and to attack other groups of chimps [87]. The most likely social organization of the common ancestor of chimpanzees and the Homo lineage was therefore a collection of intermarrying parental clusters.

Like chimpanzees, groups of early human hunters could also have used fire to drive large animals into traps or tight places where multiple people could perform a coordinated attack on them. Fire may have also been important in hardening wooden tools like spears used against large prey as well. Up to ten percent of early hominid fossils exhibit evidence of having died from predation [88], so another important advantage of fire is its ability to ward off predators. Certainly, *H. erectus* exhibits decreased sexual dimorphism, which is probably due to pair bonding. For a number of reasons, then, significant advantages might also have accrued to early hominids living in social bands. In particular, knowledge of fire-making might have been better secured against accidental loss of experts in larger social groups.

### 9.3. Control

The evidence that other apes have cultural traditions [89] suggests that these hominids must have had some form of culture by this time. These traditions would have been disseminated through the group via some form of signaling process, and led to the establishment of group-specific behaviours. Vocal signaling would also help coordinate group-level activities like group hunts, or to warn other bands of territorial encroachment. Fire thus necessitated aggregation into larger social groups, which maintained their efficient operation through new communication strategies that regulated interactions among group members.

## 10. The machine transition

### 10.1. Energy

Water-mills were invented by the Hellenic Greeks in the first century B.C., but not widely used because of the ready availability of the surplus labour in the classical world. By the 10th century AD, however, human muscles were in short supply; it became advantageous for the metabolic function of society to be off-loaded onto artifacts [90]. Thus machines came to generate energy flows, allowing social systems to achieve higher levels of throughput than when they depended strictly on muscle-power. Medieval Europe was thus driven by water-and wind-power. Although used at first strictly for milling grain, water power gradually spread to other industries, such as beer-making, tanning leather, sawing logs, and making paper. Watermills powered the cutting of wood into lumber, the grinding of grains into flour, and the forging of iron.

### 10.2. Organisation

Mills represented large capital investments: they were expensive to build and often required dams to create a sufficient head of water. As a result, techniques for pooling capital had to be introduced, and conflicts could arise over the use of water on heavily exploited rivers, leading to the need for property rights to be adjusted to control the use of this new technology [91]. In this way, mills created the need for new community structures.

Simultaneous developments also required peasants to pool their resources. In particular, the introduction of the heavy plough, a three-field system that allowed the cultivation of a greater variety of crops than the earlier two-field system, and enjoyment of a warm climate throughout this period helped agrarian productivity, but also led to changes in social organisation. Use of the new plow required a team of eight oxen rather than the two that could pull earlier scratch ploughs. Also, the difficulty of turning this heavy implement required fields to be laid out in long strips, and so necessitated new allocations of land. The system that emerged from the invention of the heavy plough, the three-field system and efficient horse harnesses could not have evolved incrementally out of the earlier Roman system of latifundia; rather, it required a major structural reorganization from a system of large farms manned by slaves to one based on peasants working their own land, largely for their own benefit [46]. In particular, it created the need for joint decisions on local agricultural matters, which gave a new kind of purpose to the village [90].

### 10.3. Control

Economic surpluses were thus sufficiently great to allow trade specialization, including an incipient leisure class, some of whom dabbled in amateur scientific experimentation [21]. The result was a period of innovation during the 14th and 15th centuries of instruments like the astrolabe (which found its way into Europe from Islamic Spain in the 15th century) that had parts whose changing relationships could process information acquired from the environment, as well as spectacles, and the compass and clock, which aided navigation [92]. Then in the mid-15th century, another instrument, Gutenberg's movable type printing press, together with paper production by paper mills, made it possible for large groups to share particular forms of knowledge, such as Biblical scripture.[8] This shared, proscriptive enculturation was a powerful means of social control in the hands of the Church, but also an instrument of propagandizing by the State, to gain support for policy measures [94,95]. The spread of literacy beyond the power elites, however, also had unintended consequences: an educated peasantry and rise of a bourgeois class, with new interpretations of scripture, broke the hegemony of the Church and landed gentry, and thus helped create the national state supported by a broad mercantile base [95–97]. Scientific communities were also created through this new means of rapidly sharing of knowledge. The first universities were established in Europe during this time as well (beginning in 1080). The printing press thus served not only as the control mechanism for the Medieval period, but also sowed the seeds for the next NESST.

The production of complex devices such as mills, astrolabes, clocks and printing presses required highly specialized knowledge to build and maintain in working order. It was also difficult to use them without considerable training. Thus the first rudiments of scientific understanding occurred at this time; the invention of methods of invention, sustained through professional organizations devoted to training and supporting the specialists who built, maintained and taught the use of the tools of their trade. However, it would not be until the next NESST that science became institutionalized, or incorporated into the very fabric of social organization, with a further division of labour until professional scientists, or people who gained their livelihoods by knowledge discovery (not just "gentlemen" amateurs), came into existence.

## 11. The electricity transition

### 11.1. Energy

Electricity was investigated by laboratory scientists such as Volta and Faraday in the early 19th century. The first non-scientific use was the electric battery, invented by Volta in 1800, and used to power a revolution in communications, the telegraph. Volta's battery was the first easy way to produce electricity in quantities. Faraday learned how to generate electrical currents from rotating magnets, and produced the first dynamo, which was used for power generation by the 1860s. Edison's electric light brought the use of electricity into the household.

Electricity rapidly took over from other energy sources, becoming universal in US factories within 40 years, and in households within 60; it came to power transportation, industry, city street-lights, and spawned the development of new kinds of consumer durables, including washing machines, dish washers, vacuum cleaners, irons, refrigerators, deep freezers, and electric stoves [45]. By adding these new kinds of machines, together with the resulting infrastructural networks, energy flows through human societies became higher than before thanks to the widespread use of electricity.

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[8] Movable type was invented several centuries earlier in China, but due to the large number characters in the Chinese language, and lack of a press machine, it did not have the same effect on Chinese society until use of the printing press spread to China. In fact, a similar story for this NESST could be told of China through this same period, although subsequent developments in Europe and China then diverge [93].

### *11.2. Organisation*

Taking full advantage of electricity required the restructuring of factory layouts. First, electric motors merely replaced steam or water power without redesign. Later, separate motors were attached to each machine on the shop floor, requiring the factory to be redesigned to arrange the machines according to the flow of production, such as Henry Ford's automated assembly line [45,98].

Using alternating current, power could be transmitted over long distances, which meant producers could consolidate electricity generation in large dynamo-driven stations to take advantages of economies of scale. Electricity generation became a natural monopoly [46]. Economies of scale caused the provision of these services to cross national lines. Since they required integrated management, this led to the development of companies which operated through alliances in multiple countries—especially in Europe, where there was a common cultural heritage and long-term relationships [45,99]. These were the first market-oriented firms of large scale – General Electric being a prime example – mostly in the industry of infrastructure control. These companies were vertically integrated, bringing the supply of intermediate components within their own structure to achieve higher throughput and greater control over prices [45].

Because so many technical artifacts require a power source, the introduction of a new one, such as electrical power generation and transmission, caused a cascade of technical innovations which taken together contribute to the changes associated with an industrial revolution. This makes electricity what economists call a 'general purpose' technology with implications for the entire economic system [46,100,101] Electricity was among the first technological systems [102] which increasingly structured the industrialized world. Edison and his associates built a system around the provision of electricity including utilities, manufacturers and investment banks. Transportation, communication, and energy systems superimposed grids and networks on the landscape which shaped where people lived, worked and played. Layering diagrams of these systems on a map of a heavily industrialized region would reveal a web of long-lived lines of force shaping social life.

### *11.3. Control*

The size of these companies and infrastructural systems necessitated new kinds of internal control: professional management staff, accountants, and shop-floor foremen. To ensure their operations were standardized between regional and international offices, rapid communication became an important component of organizational control, facilitated by the telephone and telegraph networks which stretched across the industrialized world [45]. Face-to-face meetings between company elites from different offices were made possible by train and highway networks linking far-flung cities. To ensure demand, control over consumption of the products made by large companies was ensured by the development of marketing campaigns beginning in the late 19th century [103].

## 12. Discussion

It should be clear from these example descriptions of NESSTs that organisational and informational changes are necessary consequences of an historically successful major energy advance. Historical NESSTs are also cumulative: preceding modes of organisation tend not to disappear, but to coexist with the newer, more complex forms. Thus, the overall diversity of organisational forms tends to increase with time.

Table 2 shows that the events identified as belonging to a NESST can be sensibly linked together by place and time, but the causal connection between the energy innovation, organisational consequences, and control system of a given NESST may not always be intuitively clear. As has become evident through this investigation, some NESSTs (especially later ones, when historical systems become complex) involve multiple kinds of control or organisational systems; what joins these advances together is that they can all be causally linked to the initial energy innovation which defines that NESST.

The examples of NESSTs presented above suggest that we can rigorously define the three components of a NESST. First, an energy innovation is a physical change which results in an increase in the energy flow through a structure. This new flow of energy is associated with the production of new physical structures which require organisation, or a change in the way interactions within the system of structures take place. In some cases, this change in the local concentration of physical structure is stabilized by control mechanisms. The control mechanisms themselves are also physical structures which regulate energy flows such that fluctuations in that flow do not result in loss of organisation. At a very gross level, one can say that innovations, organisation and control represent the energetic, material and informational aspects of historical advances, respectively.

It is traditional to explain events occurring in different periods of time in terms intrinsic to different sciences. Hence, changes in biological regimes are typically explained in evolutionary terms, and dynamics in recently-arising regimes in socio-economic, political or cultural terms. This would seem to suggest that no single paradigm is appropriate for the explanation of all of history. However, I would suggest that this ignores an important division of labour within the discipline of history. In particular, NESSTs – and the regimes they produce – exhibit the fundamental characteristics of non-equilibrium thermodynamic systems: the transitions occur as the result of a significant, exogenous fluctuation in energy (i.e., a randomly produced energy innovation whose timing and nature remained unexplained by ‘big’ history), and the regimes arising from these innovations exhibit higher rates of energy flow and increased temporal and spatial limitations, as one would expect of systems exhibiting increasing degrees of thermodynamic disequilibrium. I therefore suggest that ‘big’ history, as restricted to the explanation of major transitions, is properly seen as thermodynamic in nature. On the other hand, what might be called ‘little’ history, whose task it is to explain events *within* regimes, can appropriately make use of the explanatory principles of various sciences, as these are the most parsimonious kinds of explanation available for regimes characterized by systems of varying complexity. Thus, it is not necessary to describe the everyday operation of cultural or technological systems in thermodynamic terms, as such events contribute to micro-scale patterns (i.e., ‘little’ history), while the events constituting transitions between energy-based regimes contribute to the macro-scale patterning of ‘big’ history, which is properly explained in thermodynamic terms.

Other characteristics of NESSTs testify to their thermodynamic nature. In particular, all NESSTs are ‘local’ in the sense of being restricted to parts of the universe where physical structures form. Thus, an atom is a very small-scale structure surrounded by empty space, while contemporary ‘global’ society is a very complex structure on the surface of our planet supported by simpler geological structures. At the same time, however, the space within which a NESST is likely to occur has become progressively smaller over time: at first, atoms could appear anywhere in the universe with some probability, while much later, technological innovations arise only in particular regions of the Earth (so far as we know). This is because NESST transitions were relatively ‘easy’ at first: the transition to atoms took place many many times (the number of atoms in the observable universe has been estimated on the order of $10^{80}$), because few prerequisites are required for that transition to occur. On the other hand, the probability of any biological or cultural transition occurring anywhere except on the surface of a certain class of planets is rather small. In particular, the transition to a nuclear society has occurred only once, due to its dependence on every previous transition having already happened in the same physical space. Events in some locales have thus become increasingly sequence dependent with time.

## 13. Conclusion

History has traditionally been seen as a discipline allied to the humanities, with little evidence of the empirical regularities that would qualify as laws equivalent to those seen in the sciences. Nevertheless, a number of law-like patterns have been shown in historical events, such as the 'rise and fall of civilizations' [104–106], or the existence of historical 'waves'—either roughly timed [101,107–110] or exactly [45,111–116]. Those who define recurrent periods of specific length do not identify particular events by their characteristics but rather iterate an algorithm to identify set periods of history from some arbitrary starting point (e.g., the origin of life [115], or the beginning of the 'world system' in the Middle Ages [117]). Those who see only roughly timed patterns do the opposite: they pick events by particular characteristics (e.g., a major upturn or downturn in economic productivity).

The present paper follows a third approach, by beginning with a theoretical foundation for finding patterning in history: non-equilibrium steady-state thermodynamics [24,25]. This theory suggests that significant historical transitions should be treated as examples of transitions between non-equilibrium steady-states, or NESSTs. Expectations derived from this theory concern the temporal order of events within NESSTs: an energy innovation first, followed by a new kind or level of organisation, then the emergence of novel mechanisms of control. This foundation provides specific criteria for determining what events qualify as historically significant: they must constitute increasing deviations from energetic equilibrium which result in observable organisational novelties. The selection of significant events can thus be conducted reliably and with validity, rather than arbitrarily and idiosyncratically.

Here, non-equilibrium steady-state thermodynamics has been used to define strict criteria for selecting 'important' events in history. It was then demonstrated that these events can be grouped into repeating sequences of causally related events — the NESSTs expected by non-equilibrium steady-state thermodynamics occurred historically (with the minor caveats that the pre-existence of control mechanisms which come to be used on new organisations during cosmological transitions, and the absence of one energy innovation in the literature).

The recurrence of NESSTs and their attendant regimes provides a plausible account of major transitions in big history using a common thermodynamic model of structural transformations.[9] This major transition model has been shown to be a viable description of significant structural change in any historical system, from atoms to technological systems (social groups embedded in infrastructures powered by machines). The fact that a tractable model can describe the thermodynamics of a large class of non-equilibrium steady states shows that these states are not generated arbitrarily by past events but are subject to a strict thermodynamic process [25]. Demonstrating the existence of NESSTs represents a

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[9] The NESST model can be seen as a generalization of the 'major transitions in evolution' framework [14], which also seeks to explain the origins of complexity. It has been recognized that the events in the list of major evolutionary transitions are of different kinds [118,119], but they have not previously been placed within a larger context which demonstrates their interrelationships. Here, major evolutionary transitions play different roles within a NESST (e.g., replication and sexual reproduction are control features, while eukaryote and multicellular organisms are organisational).

boon to historical science because it provides a common framework, strongly founded in physical theory, which can be used to explain macro-historical trends since the origin of the universe. Big history thus becomes a viable and important perspective because it has a proper subject matter: the recurrence of NESSTs. Events at the beginning of the universe are relevant to the understanding of contemporary events because similar causal structures have been responsible for major revolutions throughout *all* history. The cosmological, biological, social and technological sciences can be mutually illuminating through examination of the shared transition process. The major transition approach itself links macro-history based on stages of energy use [11,120] to that based on developments in information storage mechanisms [121–123] in a common framework. Describing in proper historical detail the causal linkages within NESSTs, and discovering whether the periods between NESSTs can be usefully described as the operation of work cycles within historical regimes, remain projects for future big historians. Only through such empirical work can the utility of the major transition approach to big history be shown to have real value.

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**Robert Aunger** has a Master's degree in Urban Planning and a PhD in biological anthropology from UCLA. He was a post-doctoral fellow at the University of Chicago in culture and mental health and at King's College Cambridge in evolutionary psychology. He is currently Senior Lecturer in Evolutionary Public Health at the London School of Hygiene and Tropical Medicine.