A Complexity Ladder for Big History

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Abstract: Complexity is a central problem for big history because big history has made complexity a central theme, constructing a cosmological periodization based on the sequential emergence of qualitatively distinct forms of complexity. How can the big historian differentiate distinct thresholds of emergent complexity while subordinating the entire sequence of thresholds to a single metric of complexity that demonstrates the increase of complexity over multiple scales of magnitude and across qualitatively distinct forms of complexity? The cosmologists' use of a cosmic distance ladder suggests an analogous construction for complexity: a complexity ladder for big history. While no complexity ladder is formulated in this paper, the program required for a complexity ladder is sketched.

Keywords: complexity, emergence, thresholds, big history, cosmological distance ladder, scientific measurement,

The Problem of Complexity: Definition and Distinction

Complexity is a central concept of big history, which makes use of thresholds of complexity to produce a periodization that holds from the most humble detail to the largest cosmological context. Unfortunately, there is no consensus in big history on a definition of complexity, nor on a metric for the measurement of complexity. This should not surprise us. The relative recentness of big history means that we cannot expect its fundamental concepts to be adequately defined as yet. Differences among big historians keep the nascent discipline percolating with ideas; big history is nowhere near a mature formulation such as we would expect from a well-established discipline. The absence of a clear definition and metric for complexity is a deficiency, but one that need not prevent field building in big history, but it is a deficiency of which we must be mindful, and which we should want to rectify at the earliest opportunity.

Furthermore, there is an implicit tension in big history between recognizing thresholds of emergent complexity, which implies distinct kinds of emergent complexity, and the attempt (or, if the attempt hasn't been made in any serious way, then the desire) to find a common measure for emergent complexity. If distinct emergent complexity regimes represent qualitatively different kinds of being (an ontological formulation of the problem), then these qualitatively different kinds of being ought to be measured by qualitatively distinct metrics. However, were we to measure distinct forms of complexity by distinct measures of complexity, then the pretence of a periodization constructed on the basis of the increasing complexity of emergents falls apart. This, too, like the absence of a consensus definition of complexity, need not be a disaster: the claim that the universe manifests increasing complexity can be isolated from and developed independently of the claim that the history of the universe exhibits qualitatively distinct forms of complexity; both may be true, both may be false, or either may be true independently of the other.

Taking the Measure of Complexity

If the *differentia* of big history within the genus of history is periodization through thresholds of emergent complexity, then big history sets itself at odds with the entire tradition of reductivist scientific thought by seeking formulations in terms of greater comprehensivity, and placing as much weight upon the appearance of novelty as upon the persistence of consistent foundations. Ironically, however, there remains a reductivist imperative at the heart of emergentist thought by way of the very mechanism of periodization through emergent complexity: that we must unify emergent thresholds through a shared definition of complexity—whether by thermodynamic depth (Lloyd & Pagels 1988), energy flows

(Spier 2005), free energy rate density (Chaisson 2011), or some other means. Ultimately we cannot evade the scientific obligation to clarify the fundamental concepts we employ, though we can certainly delay the reckoning.

There is, however, more than one way to clarify fundamental concepts. Science offers us the opportunity, rather than attempting to *define* key theoretical terms by way of abstract concepts, of *measurement* based on empirical evidence. A metric of complexity may do as well as a definition of complexity, and in many contexts the metric is preferable, if only a sufficiently comprehensive metric can be found. This is a particular challenge for big history, as the complexities it considers range in space and time from the most minute fundamental particles to the extent of the universe itself, and from the briefest, most ephemeral processes to those that span eons and which are measured in units of Hubble time. How can these diverse phenomena be measured by a single scale?

The Cosmological Distance Ladder

There is a suggestive comparison that can be made between big history and cosmology. Astronomers today have many different methods for measuring the distance to astronomical objects. They have constructed what they call the *cosmological distance ladder* to build up a large-scale model of the universe. The astronomers are always measuring the same thing—distance—but they do so through different methods, which is analogous to the need in big history always to measure the same thing—complexity—by whatever method suggests itself, and perhaps, following the lead of cosmologists, through a variety of different methods that complement each other.

The movement of Earth around the Sun means that our observational position in the universe changes by two astronomical units when Earth passes through opposing points in its orbit around the sun. Our movement should make stars closer to us appear to move in relation to more distant stars, which apparent movement is called parallax. Astronomers realized this opportunity early in the scientific revolution, but it took time to produce instruments of sufficient precision even to be able to measure the parallax for relatively nearby stars in comparison to more distant stars. Eventually, however, it became possible to measure parallax, and this gave us our distances to the nearest stars.[1]

Harlow Shapley had been a pioneer of the use of Cepheid variables to map the structure of the Milky Way, first finding Cepheid variables close enough to obtain a distance by parallax, and then extending the first rungs of the cosmological distance ladder by finding Cepheid variables throughout the Milky Way. Shapley especially focused on finding Cepheid variables in the globular clusters that surround the Milky Way, and in so mapping the globular clusters found that they roughly defined a sphere, within which we were offset from the center. Shapley correctly made the intuitive leap that we are not at the center of the Milky Way, as roughly defined by the globular clusters surrounding it, but we are, rather, located some distance out from the center: another Copernican demotion from centrality.

Later, using the 100 inch Hooker telescope at the Mt. Wilson Observatory—again, a new scientific instrument incorporating more advanced technology—Edwin Hubble was able to resolve Cepheid variable stars in a nebula known as N.G.C. 6822 (Hubble 1925), as well as in the nebulae M31 (Hubble 1929) and M33 (Hubble 1926), that is to say, in the Andromeda and Triangulum galaxies. By applying Henrietta Swan Leavitt's period-luminosity relationship for Cepheid variables, Hubble estimated the distance to the nebula N.G.C. 6822 at about 700,000 light years, which implies that it is a system of stars entirely distinct from the Milky Way, because this distance is more than double the largest estimate for the size of the Milky Way, which was Shapley's figure of 300,000 light years across. Heber Curtis had estimated the diameter of the Milky Way to be an order of magnitude smaller, about 30,000 light years across.[2] By either measure, 700,000 light

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[1] This story repeats itself throughout the history of modern science: the idea of a possible measurement that might be taken prompts the construction of increasingly precise scientific instruments intended to measure the postulated quantity. Attempts to measure gravity waves began with resonant mass antennas, cryogenic bar antennas, and spherical cryogenic antennas, but it was not until the laser interferometer LIGO was built that gravitational waves were first detected.

[2] Harlow Shapley and Heber Curtis were the participants in the Shapely-Curtis Debate of 26 April 1920, which took on these

years put N.G.C. 6822 well outside the Milky Way.[3]

These initial rungs on the cosmological distance ladder—stellar parallax and Cepheid variable stars—where joined soon after by the use of red shifts (Zwicky 1929) and, some time later, by Type Ia supernovae standard candles (Branch 1992), which pushed the cosmological distance ladder to the farthest reaches of the universe. As astrophysics and cosmology has flourished, a multiplicity of methods of determining astronomical distances have been added to the familiar rungs of the cosmological distance ladder, including, *inter alia*, planetary-nebula luminosity functions (PNLF) (Ciardullo 1993), Main sequence fitting, also known as cluster fitting (Turner 1994), surface-brightness fluctuations (SBF) (Blakeslee 1999), fundamental-plane relationships for elliptical galaxies (D_n - sigma) (Mobasher 1999), baryon acoustic oscillations (BAO) (Seo 2007), the eclipsing-binary method (Clausen 2004), H I-line-width relations (Tamburro 2009), globular-cluster luminosity functions (GCLF) (Rejkuba 2012), and now the possibility of a "standard shriek" of gravitational waves.

The cosmological distance ladder evolves through improvements and refinements to existing scientific instruments (for example, stellar parallax measurements have been greatly extended by the precision of the Hubble Space Telescope's Wide Field Camera 3), and to existing scientific techniques, as well as through the introduction of novel scientific technologies and techniques of measurement. The methods change, and how the distance is expressed—in light years, parsecs, galaxy diameters, etc.—changes, but throughout all it is distance that is measured, with an eye toward accurately reconstructing the shape and extent of the universe from our peculiar vantage point on Earth.

A Cosmological Complexity ladder

As astronomers seek always to measure distance but by different methods, might big historians seek to measure complexity, but by different methods, which ultimately can be expressed through the formulation of an emergent complexity ladder of overlapping techniques for measuring complexity across multiple scales of increasing complexity? This can be done if the complexity measured by a given metric extends beyond a single qualitative form of complexity, allowing the metric in question to overlap with the metrics of distinct forms of complexity. Given that later forms of complexity supervene upon early forms of complexity, and that the latter must continue to exist in order for the former to appear, and to be the basis for further metrics, the conditions for a cosmological complexity ladder appear to be met, although the devil will remain in the details.

The simplest procedure for reckoning a quantitative determination of complexity is by counting,[4] so let us begin a simple cosmological complexity ladder by counting the kinds of things there are at each threshold of emergent complexity. This procedure is not without ambiguity, as there are sometimes multiple taxonomies at any given level of complexity; carving nature at the joints, as contemporary metaphysics would put it, can be done in more than one way. However, in the context of a cosmological complexity ladder, this ambiguity works in our favor: each taxonomy may extend above or below its given level of complexity in a distinctive way, which creates an overlap among metrics that allows for the possibility of a complexity ladder.

It has been speculated that, in the immediate aftermath of the big bang, the fundamental forces of nature were unified in a single force. If we begin by counting fundamental forces, we begin with a single force (taking this physics speculation at face value, and subject to change without notice), and complexification begins when the single fundamental force

questions of cosmology a few years before Hubble settled them by observation. (cf. Trimble 1995)

[3] Contemporary estimates for the distance to N.G.C. 6822 put it about 1.6 million light years away, or more than twice the distance estimated by Hubble. Proportional initial values were obtained for M31 and M33, with similar revisions made later with improved technologies and techniques. Current estimates place the diameter of the Milky Way at about 150,000 to 200,000 light years in diameter.

[4] This was recognized in the nineteenth century by Lord Kelvin: "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever the matter may be." (Kelvin 1883)

divides into the four fundamental forces between 10^{-50} and 10^{-10} seconds following the big bang. The particle zoo of the standard model begins to take shape as matter precipitates out of energy as the universe expands and cools. At present, there are 150 known particles in the particle zoo; once matter appears, we can begin to count these particles as they appear as a measure of the complexity of the early universe. As fundamental particles are assembled into matter, we can begin counting elements, beginning with hydrogen and helium. As stellar nucleosynthesis, and then supernovae[5], synthesize more complex forms of matter, we begin to fill out the periodic table of elements. The elements can also be expressed in terms of the fundamental particles that constitute them, so the quantification of fundamental particles and chemical elements can be reduced to their constituent parts, and this means that these measures overlap and can serve as a transitional stage in the complexity ladder.

At the same time as more complex forms of matter are appearing in the universe, more complex planets and planetary systems are forming.[6] Thus the growth in the complexity of matter overlaps with the growth in complexity of planets and planetary systems. We can count the growth of the complexity of planets[7] in terms of the number of mineral species present in the universe. The more complex planets become—the more forces at work on a given planet—the more mineral species form. Earth, as the most complex planet we know, has by far and away a greater number of mineral species than other astronomical bodies in the solar system. There are, for example, many mineral species that incorporate biological processes in their formation, and which are therefore mineral species that can only exist where biological processes supervene upon geological processes, so that the quantification of mineral species overlaps with quantifications of biological complexity. Greater mineralogical complexity supervenes on greater biological complexity, so that as the biosphere becomes more complex, the geosphere also becomes more complex; moreover, these measures of complexity systematically overlap.

There are other possibilities for counting the complexity at the level of planets and planetary systems that represent an ellipsis in our knowledge. We have no metric for assessing the complexity of planets or of planetary systems directly, without relying upon the proxy of mineral species, but it is conceivable that such a metric could be formulated, giving us another overlapping complexity count to span between anterior and subsequent forms of complexity. For example, the complexity of a planet might be quantified by the number of differentiated concentric layers of its internal structure, or by the number of geological, geomorphological, and geochemical processes that shape its crust. A planet might also be accounted more or less complex depending upon its particular situation within its planetary system: its number of moons, number of other planets, the degree of exchange of matter with other planets, the enrichment of its surface

[5] More exotic events such as neutron star mergers are thought to produce heavier *r*-process elements not produced in stellar nucleosynthesis or by supernovae (Freiburghaus et al. 1999). That chemical elements are produced by distinctive cosmological processes suggests another overlapping complexity metric, which is the number of kinds of astronomical objects and processes there are. The universe cannot be populated with black holes until black holes form, and black holes cannot form until a stellar remnant that exceeds the Tolman–Oppenheimer–Volkoff limit forms, and such a stellar remnant cannot form until a star of sufficient mass completes its lifetime on the main sequence.

[6] We have little or no understanding at present of the planets that formed in the protoplanetary discs of population III stars of the early universe, but with the paucity of chemical elements available (i.e., low metallicity of the protoplanetary disk) we can infer the likelihood of the earliest planets being gas giants primarily composed of hydrogen and helium. Chemically these planets would have been relatively geophysically simple in comparison to the planets of population I or II stars, but they may have incorporated exotic states of matter such as metallic hydrogen, so it may be worth considering a quantification of the possible states of matter as another overlapping metric of complexity.

[7] "Planets" is here used loosely to mean any astronomical body in orbit in a planetary system. Given an adequate taxonomy of the kinds of planetary bodies—dust, asteroids, comets, dwarf planets, planets, etc.—we could also count these varieties of matter that clump into masses orbiting stars. The complexity of a planetary system, however, is intrinsically reducible to a star and its accompanying mass, though if a taxonomy of planetary systems were formulated and the possible permutations extrapolated, we could count the number of taxa exemplified in actual planetary systems as an overall metric of the complexity of the universe at a given stage of its development.

through asteroid and cometary impacts, etc.

There are a number of quantitative measures of life that could be employed. In the earliest history of life, when the biosphere was dominated by horizontal gene transfer and species were not as clearly defined as would be the case later, it would not be clear how to individuate organisms and thus to count them, but it would be possible to count the base pairs in DNA. Another metric could be based on the quantitative measure of biomass, and various divisions that can be made within the biomass of the early biosphere, e.g., marine and terrestrial biomass, autotroph and heterotroph biomass, etc. (Crockford 2023). Once distinct species emerge we can count species, but we can also count other clades. It is commonplace to express the loss of biodiversity from mass extinction events not only in terms of species loss, but also in terms of loss of genera, families, and so on up the Linnaean taxonomic hierarchy (cf., e.g., Elewa 2008).[8] In adaptive radiation, not only species, but also genera, families, and so on can expand in number. Note that we could continue to quantify the complexity of life in terms of the complexity of the underlying chemistry, or even the complexity of fundamental particles constituting living matter, which would be cumbersome, but, insofar as it is still possible, it demonstrates the possibility of overlapping complexity metrics from which a complexity metric can be constructed.

The appearance of central nervous systems, consciousness[9], and intelligence represent further stages in the complexification of biological organisms, each of which comes with its own quantification. The number of neurons in the average brain (or central nervous system) of a representative of a given species is a metric that will overlap for all animals with brains. Encephalization is another familiar metric (Jerison 1977). Behavioral complexity can be counted by the number of social institutions of these animals, and the behavioral complexity of other species overlaps with the behavioral complexity of human beings, who in turn introduce new metrics such as IQ.[10] In the case of human complexity, social institutions eventually include agriculture of increasing levels of sophistication, and eventually cities, and the metrics for social institutions will overlap with metrics for cities (e.g., number of cities in a given civilization, or the average or peak population of cities).

The future holds out the prospect of further novel metrics of complexity that will supervene upon, and therefore overlap with, existing complexity metrics, allowing us to extend the cosmological complexity ladder. A species that has transcended its homeworld can be measured by the number of off-world habitats it builds, or the number of *kinds* of off-world habitats it constructs, and, if that civilization eventually builds cities beyond its planet of origin, the continued count of cities will overlap with this newest metric of off-world habitats. A technologically sophisticated species that transcends its legacy biology could be measured by the number of technological modes of overcoming biology that it employs, or by extending existing metrics, or by both, which again would provide us with overlapping metrics and a more robust complexity ladder. For example, cognitive enhancement could be measured by IQ testing, while biological enhancement could be measured in terms of longevity or endurance, *inter alia*.

Just as in the cosmological distance ladder, no one method for the measurement of distance will work across all scales of measurement—Cepheid variables do not function as standard candles at the distances that Type 1a supernovae

[8] Darwin already foreshadowed this metric for the biosphere in his *The Voyage of the Beagle* (written before he had formulated the idea of natural selection); he describes the novel ecosystems he explored not only in terms of the distinctive species, but also noting the genera and families present or absent.

[9] There are tantalizing possibilities for the quantitative measurement of consciousness. Analogous to intelligence testing, as mentioned below in note 10, consciousness studies of animals and human beings have not been formulated in a common framework, which limits their utility. As distinct from consciousness and intelligence, encephalization *has* been formulated as a common framework across species, and as such we have seen it employed extensively in the study of early hominids prior to anthropogenesis, wherever we happen to locate this juncture.

[10] Intelligence testing could itself be made a more comprehensive metric by developing methods that extend the human measurement of intelligence to other species. There is already considerable research into measuring animal intelligence, but animal and human intelligence measures have not been, for the most part, formulated in a common framework.

serve as standard candles—just so, no one complexity metric will be translatable to every level of complexity, but all the metrics taken together will overlap sufficiently to bind the whole structure of complexity together. Moreover, familiar scales of measurement themselves can be extended beyond their customary scope of application in order to ensure that there is a robust overlap of distinct metrics incorporated into the complexity ladder. The totality of assembled complexity metrics will interact to the ultimate benefit of the complexity scale; the less well-defined metrics can be given greater clarity and precision by the metrics with which they overlap, just as carbon 14 dates have been calibrated by the precision of dendrochronological sequences, which, to the extent of their extrapolation, provide a year-by-year record of the past—a much finer granularity than carbon 14, or any of the other techniques such as the principle of faunal succession, employed before high technology methods such as radiometric dating.

Rationalizing the Complexity Ladder

Does the complexity ladder need the complexity equivalent of a calendar epoch, i.e., a point of origin, which would make the complexity ladder a ratio scale? At present, the recognized thresholds of emergent complexity constitute an ordinal scale, in which the order of thresholds is definitive, but the interval between the thresholds is not. There seems to be no reason to believe that there is an orderly and uniform interval between thresholds of complexity, so that it may not be possible to transform the ordinal scale of complexity into an interval scale of complexity. Wherever in the world we observe diverging forms of complexity, as soon as the lineages are distinct, their destinies differ, with some evolving rapidly, some slowly, and some becoming virtually unchanged living fossils. However, it may be possible to define a purely conventional interval that can be placed over the surprising leaps of complexity with which the world presents us. An interval scale based on convention, and not upon those natural divisions that suggest themselves to us as thresholds, would not give us the satisfaction of "carving nature at the joints," but it would allow us to further rationalize the complexity ladder. And we may find, when immersing ourselves in the details of overlapping scales of complexity measures, that a conventional scale would provide a framework that none of the individual complexity measures provides.

Beyond the possibility of an interval scale for complexity lies the possibility of ratio scale, which would require an interval scale as well as establishing a zero point for the scale. To institute a zero point for the complexity ladder would embroil us in further difficulties. Zero complexity is pure nothingness, which is a philosophical rather than a scientific concept, so we will leave this aside for the moment. However, Willem De Sitter (De Sitter 1932) demonstrated that an empty universe (in which density is zero) is a better approximation to known cosmology than a static universe (in which density is stable and there is no expansion), and we could count an empty universe, even if it is only empty in a formal mathematical sense, as a zero point for cosmology, though De Sitter's empty universe is in no sense bereft of complexity. We can see that, while there are problems in fully rationalizing the complexity ladder, there are also opportunities, and more opportunities may suggest themselves in working through the details of a complexity ladder.

Permutations of Counting Complexity

This quantitative account of a complexity ladder makes it possible for us to overleap the qualitative gaps that emergent complexity thresholds present to us, and thus to assimilate all these various forms of complexity to a single, overall scale that is assembled from the many overlapping quantitative scales of measuring the complexity of matter, planetary systems, geology, life, social organization, intelligence, and so on. With such a quantitative scale we can remain agnostic on the qualitative nature of complexity, i.e., we can continue to study complexity without attempting to make any definitive claim about the nature of complexity, which we measure by quantifiable observations that serve as proxies for qualitative complexity. Indeed, the act of distancing ourselves from any claim regarding the ontology of complexity, and seeking to measure it only quantitatively, frees us both to extrapolate a complexity ladder even while continuing to explore the nature of complexity itself.

There is both a reductive and an emergentist interpretation of the numerical complexity ladder described herein. Reductively, each later form of emergent complexity counted can be reduced to the previous form (or to several previous forms) of emergent complexity counted. Such a reduction is a blunt instrument—information is lost in the reduction—but science flourishes to the extent that it can converge upon robust abstractions that allow for the explanation of many phenomena by one or a few mechanisms. In regard to emergentism, each new convention adopted for counting beyond a new threshold of emergent complexity represents a qualitatively distinct metric, which therefore qualitatively expands the complexity ladder itself. This process is indefinitely iterable, so that there is no intrinsic limitation on the extrapolation of the complexity ladder. This, in turn, means that an extended complexity ladder will always place previous conceptions of complexity in a new light, by placing them in a larger (and systematic) context, which will mean newly emergent forms of understanding the universe so measured.

The potential iteration of the cosmological complexity ladder makes it pre-adapted to the unsuspected forms of complexity we may yet discover in the exploration of the universe. If alternative emergent complexities are to be found on other worlds,[11] the inherit flexibility of counting complexity (due to its ontological agnosticism) will not only allow this method to be employed in contexts of alternative emergent complexity, but it will also allow for the comparison of peer complexities, inconceivable to us at present, but perhaps only waiting to be found and described by future generations.

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[11] The possibility of alternative forms of emergent complexity is discussed in my paper “Peer Complexity during the Stelliferous Era.”

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