Reexamining “Free Energy Rate Density” as a Complexity Metric

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Abstract: *Cosmic Evolution*, by Eric J. Chaisson is arguably one of the original “core” texts of big history. Despite being published over 20 years ago, it is still relevant for its explanation of the cosmological and thermodynamic underpinnings of the evolution of complex systems over the span of time. It was also a pioneering work because it proposed that we can quantify the degree of complexity of systems by determining the quantity of the “free energy rate density” or FERD (abbreviated as “Ω_m” in *Cosmic Evolution*) that flows through a system. Although Chaisson advises that his correlations of FERD to complexity degree is subject to various limitations and generalizations, careful analysis of the arguments and examples used to support FERD indicates that it is even less likely to be as reliable and quantifiable than he purports for at least the following reasons:

1. The author offers a relatively short list of criteria for a system to qualify being “complex” that in turn results in the inclusion of systems that are not classified as complex by usual criteria.
2. Free energy rate density is not compared against other complexity metrics and subsequently seems to serve as its own “gold standard.” The lack of comparisons results in a tautological argument and sometimes questionable conclusions.
3. The argument for FERD sometimes deviates from the hypothesis that FERD is a good way to measure the degree of a s*ystem’s* complexity to a claim that it also measures complex *functions* and *structures* as well.
4. The FERD that he reports are often actually for the total energy flow through a system. Hence, a much more efficient complexity might only *appear* to be less complex.
5. Complex systems have many variables that can confound attempts to make reliable and precise generalizations, including good metrics for their degree.

Cosmic Evolution still deserves to be essential reading for big historians. Its explanation of relevant cosmologic and thermodynamic physics that are essential to the evolution of complexities help us to have a more profound understanding of the physical processes that have made the ontology of complexity and its advancement possible over the course of time. *Cosmic Evolution* has also greatly influenced the idea that increasing complexity is perhaps *the* overarching theme of big history. Unfortunately, as with every other proposed complexity metric, however, FERD appears to have significant limitations that *might* only be addressed with more complete, “unabridged” analyses.

Thermodynamics and Cosmology of Historical Complexity

Published in 2001, *Cosmic Evolution* (CE) is arguably one of the “founding” texts of big history and even predates the first publication of other seminal books like David Christian’s *Maps of Time – An Introduction to Big History* (2004), Cynthia Stokes Brown’s *Big History: From the Big Bang to the Present* (2007), and Fred Spier’s *Big History and the Future of Humanity* (2010). Written by Harvard astrophysicist, Eric J. Chaisson, CE’s impact was such that “the increasing complexity of systems,” is still arguably the most cited overarching theme that binds the events of big history together. Chaisson’s explanation of how cosmology and the laws of thermodynamics made everything from stars and galaxies to birds and human society possible, perhaps even probable, makes CE almost mandatory reading for any big historian. Although some of the details have changed since its publication due to scientific progress, e.g., the Big Bang is now more precisely believed to have occurred 13.8 billion years ago, the main points undoubtedly remain valid. The non-mathematician might be daunted by the number of equations that are sprinkled through much of the book, but Chaisson’s explanations should make the science qualitatively understandable by most with a basic science background. In particular, his determinations of the “free energy flow rate densities” (FERD*) of various systems from stars to bacteria to human society are unique, fascinating, and even counterintuitive at times. For example, Chaisson calculates that the FERD that flows through a gram of an active star is much less than that of a gram of human brain!

*Free energy flow rate density (FERD) is the amount of “effective” energy that flows through a given amount of mass in a given amount of time. Note that Chaisson abbreviates free energy rate density as “Ω_m” in *Cosmic Evolution.*

A Proposed New Metric for Complexity

Chaisson's observation that the complexity of systems has progressed over time is widely acknowledged by others in big history as well as in other fields (Christian 2004, Fewster 2016, Spier 2010, Morowitz H 2004, Kurzweil R 2005). While this observation is hardly disputed, demonstrating it on a deeper or even quantitative level rather than "well-considered estimates" or rules of thumb is more challenging. For example, can we determine if a dog or a house cat is more complex? Is a metropolis more, or less complex than a coral reef? How do we know that complexity has truly almost inexorably increased over the span of time – at least on Earth? Are we still "progressing" towards greater social, technological, and even biological complexity, or is complexity progression slowing down or even being reversed due to environmental degradation or other factors?

The great variety of metrics that have been proposed by various authorities – over 40 and counting (Lloyd) – generally agree with central importance of syntactical information, with some also giving recognition to a system's formative/evolutionary informational depth, "hierarchy of organization," and other aspects as well (Mitchell 2009). However, even though Chaisson acknowledges that one determinate of complexity degree is, "the information needed to describe a system's structure and function" (measured in bits) he and others conclude that measuring the informational content of even a "simple" complex system would be a daunting if not impossible task (Chaisson 2001, Schumacher 2015, Mitchell M 2009). Therefore, Chaisson proposes that we measure a complexity's FERD which he chooses to express by the units of "ergs sec^{-1} gm^{-1}." At face value, it makes sense that greater complexities will tend to have a greater amount of energy flowing through it on a per mass basis. Greater complexities tend to have more "layers" of constituents (e.g., atoms, then amino acids, then proteins, then cells, then tissues . . .) that must remain within a certain range of specific relationships (or order) for the system to persist, and they also tend to have more ongoing functions – all of which requires *free* energy to sustain and maintain. The "free" descriptor preceding "energy" is also important because it is the portion of energy that is used for the "work" of sustaining structural integrity and ongoing processes, as opposed to energy that is inevitably wasted as heat and other byproducts. As a well-known foundational fact in physics and elaborated upon in CE, the laws of thermodynamics state that there will *always* be some wasted energy when any process occurs. Hence, the total energy flow density will always be greater than the free energy flow density.

Despite the seemingly intuitive relationship between free energy and degree of complexity, it is curious that the Santa Fe Institute (SFI), a multidisciplinary academic center dedicated to the study of complexity since 1983, does not acknowledge this metric. Indeed, Seth Lloyd, a physicist at SFI who has collected and listed over 40 complexity metrics, thanked me for bringing it to his attention in an email exchange (Lloyd S, personal communication, October 2022). Of course, the apparent absence of a particular metric being noted by him or even SFI does not invalidate or diminish its potential validity and utility. Chaisson might simply have discovered a unique metric that has been missed by many others within the complexity science community even over 20 years later. Nevertheless, its absence despite physicists being present at SFI since its founding, gives one pause.

Regardless, any proposed metric should have several characteristics to be pragmatic. At the very least, it should be reliable across different kinds and levels of complexity and with good agreement of how the relevant factor(s) are defined and determined. It should also have a precision that exceeds approximations made by gross assessments such as levels of organization or perhaps the time of origination in big history. There might be little utility for a metric that has less precision if these bars are not met. Prior attempts by various authorities in complexity science demonstrate these are difficult criteria to meet (Mitchell 2009). Chaisson, however, argues that he has found such a metric in the "free energy rate density" (FERD) of complex systems. (For brevity's sake, I will simplify FERD from ergs sec^{-1} gm^{-1}" to simply "units.")

At first glance, it appears that he might be on to something. After all, energy and the relevant physics of thermodynamics are well understood which contrasts with the problems that plague information-based metrics. Energy flows have also been determined for many systems by various authorities in various fields. A graph early in CE's discussion of FERD also shows an increase of several different complex systems correlating with an increase FERD (p140). Unfortunately, however, several later important examples of FERD correlations to complexity as reported in CE fail to support its reliability. The author admits that there are incongruities in the correlations but states that we should not be overly concerned with what he believes are distracting outliers (p184), and that CE is an abridged attempt to show general correlations of FERD to degree of complexity (p143-4). The disjuncture of a number of correlations is nevertheless severe enough that it has to make one wonder if FERD's utility, never mind its reliability, is at risk of being undermined. Furthermore, on closer analysis errors in logic, form of argument, and even an admission that the actual FERD is not being used, undermine this metric further.

Definitions of "Complexity" versus its Characterization

Before formulating a metric, we must first define *what* we are trying to measure. Chaisson's definition of "complexity" in the prologue is arguably information-centric: "Complexity" is *a state of intricacy, complication, variety, or involvement, as in the interconnected parts of a structure – a quality of having many interacting, different components* (p13). Chaisson also adds that he will identify complexity operationally as, "a measure of the information needed to describe a system's structure and function, or as a measure of the rate of energy flowing through a system of given mass."

As Chaisson and others point out, a universally accepted succinct definition of "complexity" *has* eluded the scientific community (Johnson 2007, Page 2009, Mitchell 2009) and CE's definitions are as reasonable as many that have been proposed. The difficulty in defining complexity is not unique because other terms like "life," and "culture" are often better defined by their key characteristics rather than one salient feature (Oxford Dictionary 2023). A review of several texts and lectures that list key characteristics of complexity typically include at least most of the non-exhaustive list given below (Mitchell 2009; Ladyman J et al 2012, Johnson 2007; Waldrop 1992; Gribbin 2004; Page 2009). Although CE does not include all of these characteristics in its definition, most of the qualities are noted, sometimes with caveats, somewhere in different parts of the text. To wit, a complex system has:

1. *Multiple interactive components* (a.k.a., "agents") as noted as well in CE's definition. Many sources also note that there is no centralized control for these interactions (Johnson 2007, Mitchell 2009).
2. *Dynamism,* or the system consistently varies over time. Although this quality is only implicit in CE's definition, it is arguably CE central thesis, as it notes that complexities are systems that are in disequilibrium and require energy flows to be sustained.
3. Structure and processes that are *neither too ordered nor too disordered*. The balance between not being too ordered, like a crystal, nor too disordered, like a room of air molecules, is in reference to structure. CE also wants to include having the right degree of energy flow (p 144): too low of an energy flow and the system is stultified, too high and its structure is ruined as might occur in a supernova explosion.
4. Behaviors or qualities that would not be predicted from those of its more fundamental components, which is often referred to as "emergence." This characteristic is noted towards the end of CE (p215) and in the glossary. Admittedly "emergence," which is the most interesting feature of complexity, is also a loaded term with a variety of interpretations and associated subtleties regarding its ontology and how it is best understood (Bedau & Humphreys 2008).
5. The ability to *self-organize and self-regulate* its structure and processes. CE wants to exclude these properties because complexities are not truly independent, but rely on its surroundings for its energy, materials, and the right conditions (p61, 122).
6. *Non-linear system outcomes* which makes its future behavior and sometimes its structure hard to predict, i.e., for any given input, the resulting output is statistical, not deterministic. This characteristic is briefly noted in CE as well (p13).
7. The *ability to adapt*, which is often a requisite criterium or authors will divide complex systems into "non-adaptive" complex systems (e.g., stars, hurricanes), and "adaptive" complex systems (e.g., living organisms, the internet). Chaisson is well aware of this distinction as well and a more strict definition of "adaptation" is included in CE's glossary. Because CE examines systems that preceded life on Earth, a more liberal interpretation of adaptation is justifiably used.

Because CE mentions the great majority of proposed complexity's characteristics in the text, if not in its definition, it might at first seem that the author would be quite selective for deciding which systems would be included in its analyses. However, the author admits in the beginning (p13) and towards the end (p215) that he was consciously liberal with the term "complexity." That decision is understandable and even necessary given the task at hand, but it comes at a price.

Sensitivity versus Specificity

Although not necessarily obvious to those outside of the healthcare profession, medical research, with which I am familiar, has much to offer in the study of complex systems. Afterall, over a million medical studies are published in thousands of journals each year (Landhuis E 2016, Dai N et al 2014) to try to better understand the many maladies that can affect the complex human body and its psychology. Most studies rely on statistical concepts and methods because too many variables affect outcomes to allow for deterministic analyses. Relevant to the discussion of what systems qualify as being complex is the concept of "sensitivity versus specificity."

In the best of worlds, a medical researcher would like definitions, treatments, outcomes, etc., to be both sensitive *and* specific. For example, pregnancy tests are one of only a few tests that are both highly sensitive (almost always positive after a person is pregnant a few days), and specific (unlikely to give a positive result if a person is *not* pregnant). Contrarily, medicine has not been able to find a test for most cancers that is so sensitive and specific that doctors can offer it to the general public without potentially causing more harms than benefits, e.g., causing undue anxiety, or subjecting many people to the expense and potential injury of invasive procedures.

If complexity is determined based on its inclusion of two or three characteristics rather than five to seven, that determination will be quite "sensitive" but at the expense of being less "specific" (Parikh R 2008, Monaghan TF 2021). In other words, the pared down qualifications of CE's criteria set means that it will likely qualify all or nearly all systems that are complex, but at the expense of also including systems that are *not* considered complex by most metrics and authorities. For the purposes of this paper, I will suggest that a reasonable standard for a system to qualify as being complex would be when a majority of authorities in complexity science agree that a system meets at least five of the seven criteria listed above. The converse is also true. If we are very specific about what to include as a complexity, e.g., require seven or even more characteristics, then it will be at the expense of being less sensitive, or missing some systems that most would consider to be a valid complexity.

More formally, sensitivity in this case would be the number of those complexities included in CE for analysis divided by the number of CE's included systems that are a complexity as determined by some gold standard, or at least by most authorities in this field (Monaghan 2021). A liberal definition of complexity as offered in CE would likely result in a ratio of "1," or expressed in another manner, a 100% sensitivity rate. Some of the systems considered to be complex in CE (and with which most authorities would likely concur) are *non-adaptive* complex systems that include stars, galaxies, the Earth's "climasphere" (atmosphere and upper ocean layer as defined in CE), and gas giant planets. *Adaptive* complexities that CE includes are any listed life forms, nervous systems, ecosystems, and societies. There are no generally agreed upon complex systems mistakenly listed by the author as *not* being complex, which results in CE's definition for "complexity" having 100% sensitivity as I predicted.

Statistical *specificity* in this case would be more formally described as the number of systems that are labeled correctly by Chaisson's definition as *not* being complex divided by the number of systems listed that are not considered complex by a gold standard or majority of authorities (Monaghan 2021). In the case of CE, I would argue that the specificity would be ~1/5 or 20% for the reasons noted below.

For the determination of specificity above, the numerator included "human activities" for which Chaisson provides FERD for sewing, bicycling, and a few other activities. Although he provides their estimated FERD's he correctly notes that they are *not* complex systems, but "functions." The denominator includes human activities as well as the following four systems that he states or infers are complex systems, but which do not clearly meet the standard proposed above: hydrothermal vents, automobiles, aircraft, and computer chips. Hydrothermal vent ecological communities *would be* complexities like any other ecosystem. However, it is questionable whether a hydrothermal vent itself meets sufficient criteria to qualify as a complex system. If we argue that the water, hydrogen sulfide, minerals and other molecules that emanate from a vent have the degree of intricate interactions needed to meet his definition for a complexity, then an active volcano, geyser, and other dynamic geologic features would seem to qualify as well. If one argues that the inherent complexity of hydrothermal vents made it possible for life *emerge* and persist, then the same argument should hold for a clay surface or a "warm pond" which are other contenders for being the terrestrial nursery of the first life forms. It is additionally debatable whether these geologic features are self-regulating, exhibit emergent properties, non-linear behavior, and exist in the optimum zone between order and disorder required for complexities.

Systems that CE discusses as being complexities, but more definitely fail to qualify as complexities, include automobiles, aircraft, and computer chips. These artifacts *do* consist of many interacting parts but fail to meet every other criterium. Most importantly, they are not dynamic systems with a continual flow of energy to sustain their structures and functions – one of the major theses forwarded in CE about the nature of complexities. These "systems" also have a very high degree of *set* order, do not self-organize, do not have unexpected emergent behavior, and do not exhibit unpredictable non-linear behavior - thankfully! If machines exhibited true emergence and unpredictable behavior, engineers would be surprised that a jet they designed actually flew, and pilots would not be sure that the jet would respond predictably to the controls.

(Note: CE also gives the "energy of combustion" for coal, dried grass (hay), softwood, and hardwood, which he believes are indicative of their complexity in *structure* rather than as a system. However, because he was not citing their FERD, they were excluded from the calculation for specificity.)

A Tautological Argument for FERD

Another type of error that can occur with the proposal for a new metric is to fail to compare its accuracy to other established metrics, and especially a gold standard if one exists. Failing to do so can lead to a circular or tautological argument in support of the new metric. For example, the researcher might claim that a newly proposed metric (a.k.a., diagnostic test) detected every heart attack because it was *determined to have occurred solely based on the new test's results*. At the very least, the researcher should compare the new test to results from established standards like ECG's and relevant blood tests. Eventually, the new test might well prove to be a new "gold standard," or have some other important characteristics like being less expensive or providing quicker results. Until that time, however, the test's predictive value remains an unproven hypothesis.

Admittedly, complexity is not like a heart attack where there are widely accepted and reasonably accurate metrics for determining if it is present or not. Instead, complexity is more like the autoimmune disease "systemic lupus erythematosus" (SLE). SLE can have many different manifestations and there is no single blood test or exam finding to make the diagnosis. Instead, the patient must have a combination of physical signs, symptoms, and positive blood tests for a physician to make the diagnosis (Aringer M & Petri M 2020). Analogous to medicine's situation with SLE, it is desirable that we have a reliable and accurate metric for determining the degree of a complexity, never mind its mere presence. Unfortunately, such a metric has not been universally recognized so we must judge a newly proposed one against several other proposed metrics and agreed upon criteria.

The potential error of using FERD as its own gold standard as a complexity metric is demonstrated by several questionable examples of its predictive value for degree of complexity as offered in CE. For example, according to Chaisson, galaxies have a lower FERD (0.5 units) than our Sun (2 units) which he selects as being representative of stars and their attendant complexity. Furthermore, he states that galaxies' low FERD is expected because they are "among the least complex physical systems" (pp 136-7). However, stars like our Sun are important *components or sub-systems* of galaxies along with nebulas, planets, comets, black holes, and dark matter to name a few. Complex systems are also typically conceived as being more complex than the "prior order" components of which they are comprised if only because you add their complexities to that of the additional interactions and phenomena that results from the entirety of the greater system. For example, if one were to determine the complexity of a tree or horse, we would include the complexity of its tissues or organs before considering the added complexity that results from their interactions to comprise the entire organism. Similarly, even though the brain consists of neurons, as well as glial cells, blood vessels, and many other cell types, you would typically consider the neurons to be less complex than the entire brain, even if neurons have a higher FERD than the greater entirety. We can still "save" FERD as being correlated to the progression in complexity of stars to galaxies by noting that 75-80% of stars in the galaxy are red dwarves and that *they* are representative of "typical" stars rather than yellow stars like our sun. Red dwarves have a FERD of 0.1 units as reported in CE (p157), which is substantially less than yellow stars like our sun which compose only 7-8% of the galaxy's stars (Hubblesite/NASA 2020, Gregersen E 2017).

The citing of our Sun's FERD rather than the more common red dwarfs' FERD could just be a judgment that warrants challenging rather than a true sign of a tautology. However, other examples of FERD serving as its own gold standard occur in the text as well. Perhaps the most striking one is the claim that the higher FERD of the Pentium II computer chip reflects its higher complexity compared to the human brain: *"The (computer) chips FERD values exceed those of human brains because computers number-crunch a lot faster than do our neurological systems. That doesn't make today's microelectronic machines more sentient than humans, but it does make them more complex . . ."* (p202). As noted above, most complexity authorities would not even include computer chips as being complexities because they do not meet criteria number 3,5,6, and 7 listed above, and arguably number 4 (emergence) as well.

Asserting that computer chips are more complex than human brains, widely considered to be the most complex (sub)system of which we are aware, is unusual to say the least (Ackerman 1992, Page SE 2009, Zuckerman C 2009)! Even Chaisson proclaims earlier in the text that the adult human brain is "the most exquisite clump of matter in the known universe" (p138) – a seeming contradiction. Nevertheless, claiming that computer chips are more complex than brains based on their ability solely to do syntactical computations faster than human brains ignores the brain's multitude of other emergent abilities such as self-awareness, creativity, emotions, reflection on the past, unconsciously sustaining bodily functions, and intentionality to name a few. For raw structural-interactive complexity, the brain also has about 86-100 billion neurons (Herculano-Houzel 2012) with a common estimate of about 100 trillion synaptic connections (Zimmer 2011). The synapses are in turn modulated by a great variety of neurochemicals, hormones, and other factors. The brain undoubtedly uses far less FERD (1.5×10^5 units) than computer chips (10^{11} units for 1999's Pentium II chip), especially if we just consider the extra FERD actually used for doing cognitive tasks. The majority of the energy used by the brain is for maintaining its structures, sustaining electrical gradients, and its many noncognitive functions (Engl E 2015). The added energy needed for computations is difficult to determine but is negligible to perhaps about 5% of its energy budget (Jabr F 2012, Heid M 2018). This estimation even further emphasizes the brain's low use of FERD for computations or other cognitive tasks is highly efficient. Unlike a computer chip, however, it cannot be turned "off" without causing the death of the greater corporeal system.

Free Energy versus Total Energy Rate Density

As noted above, brains are undoubtedly magnitudes more efficient than our best computer chips – even those developed over 20 years since CE's publication. Consistent with this assertion, Chaisson admits that the energy rate density type that he cites for different systems throughout the book is actually the *total* energy rate density rather than the *free* energy rate density (p143). The total energy used is due to both the amount of free energy used *and* the amount of energy that is wasted as heat or other byproducts. Using total ERD rather than actual FERD means that a difference in a system's efficiency can be easily overlooked and give a false impression of lesser complexity. Therefore, it would have been desirable to use a separate notation if someone is providing the total energy rate density, e.g., Ω_T or ERD. He acknowledges several times through CE that it would take a more thorough analysis to determine the latter quantity and that his calculations and attendant arguments are meant to provide "estimates to display general trends" (p144).

Unfortunately, this admission alone means that the "FERD" reported in CE might not have any greater resolution and accuracy for determining a systems degree of complexity than the utilization of other proposed metrics like other estimations of informational content, hierarchical level, and perhaps even just "well-considered estimations" - especially for systems that have a high degree of complexity. Measuring a complex system's true FERD, might be extraordinarily difficult for many systems. For example, what is the FERD for a large city, i.e., how much of the energy is used by these systems for maintaining its structures, transporting people and material goods, and so forth, versus wasted energy? Should we include the mass or at least the manufacture of buildings, sidewalks, and roads in calculations for ERD? Chaisson indicates that he does not (p254). Also, what and where are the boundaries of some complex system, which we need to calculate mass, like a coral reef system where many animals and phytoplankton move freely in and out of the reefs proper. Where do economies, besides the global one, end? Of course, the same concerns would apply to other proposed metrics as well.

"Complex" Structure and Function – Deviating from the Original Hypothesis

One way to conceive of complex systems is that they are entities with a dynamic interplay between *structure* and *function(s)*. For reasons that are not clear, Chaisson separates them to determine if FERD is predictive of their respective degree of complexity – with "complexity" here being used even more liberally or even idiosyncratically. For example, he seems to equate complex *structure* with "degree of order." As noted earlier in *Cosmic Evolution* by Chaisson as well as others, however, complex systems exist somewhere between the high degree of order of something like a crystal and the high degree of disorder of something like a supernova (p144). Too much in either direction and the structure becomes stultified if too ordered, and then too chaotic in a randomized sense if too disordered. Unfortunately, it is not clear where those thresholds might be crossed, and other typical characteristics of complexity are not invoked in the discussion. Nevertheless, the author gives us two sets of examples that he believes demonstrate that a higher FERD is due to a higher degree of structural order which he claims in turn reflects greater structural complexity: 1. In ascending order, dried hay, softwood, hardwood, and coal (p185); and 2. A living "average" plant, cornfield, and sugarcane field.

Unfortunately, we must take Chaisson's word that the ordering and, hence, the complexity of the first set of examples increase from grass (usually consists of dried grasses or alfalfa) through to coal, which he determines indirectly by reporting the energy released from the combustion of their equivalent masses. It is not clear if that increase in ordering is on a macroscopic, cellular, or molecular level or some combination. Softwoods, which are lumber derived from conifers, have less cell specialization and microscopic complexity than hardwoods which are derived from deciduous trees (Stagno V et al 2022). Therefore, on a cellular level, hardwoods are arguably more complex than softwood. Coal has the highest FERD in this set of examples, but differs substantially from simply dried plants, because it is ancient plant material of some kind that has been fossilized and compressed by geologic forces. Hence, the equivalent of an "apple" (coal) has been placed amongst the "oranges" (hay and wood) for comparison. Also, as a clear counterexample, natural gas, which he notes is also a fossil fuel (p185) derived from ancient plants is not included in the analysis. Notably, its energy content on combustion is about twice that of anthracite coal (World Nuclear Association 2022) even though its structure is extremely disordered as it is with any gas. The molecular structure of methane, its main component, is also quite simple (CH_4). Hence, in this case, there is a clear disconnect between FERD and degree of order. In short, the examples are incoherent for making associations from structural order to degree of complexity, and then to FERD, or even total ERD.

The second set of examples is puzzling as well. At least in this case, the "average" plant, cornfields, and sugarcane fields are all composed primarily of living plants, but again CE seems to focus on an alleged association between FERD, and degree of order of structure as a proxy for the complexity of their structure. Fields of corn and sugarcane are more ordered from a *macroscopic* aerial view perspective compared to the environs of the "average plant" that would typically live in the context of an ecosystem like a savanna, forest, grassland, etc. In other words, although agricultural fields have more order from a gross perspective, at every other level corn and sugar cane fields are demonstrably *much* less ordered than all but the most degraded or sparse ecosystem. Perplexingly, Chaisson also notes the deep ordering of natural ecosystems (p194-5.) The gross ordering of fields also occurs at the expense of an ability to self-organize, be resilient, and other hallmarks of advanced complexity. It is worth noting as well that corn and sugarcane are both "warm season" grasses that use C4 photosynthesis, whereas trees, cool season grasses and most plants in general use C3 photosynthesis (Garrett 2022, Ubeda 2018). In the right environmental circumstances, plants with C4 photosynthesis can be 50% more energy productive than plants that use the C3 type (Benton 2023, Ubeda 2018, Osborn C & Sack L 2012). Therefore, warm-season grasses, some of which are used to make hay, produce more energy than trees. This could contrast with the energy released in the combustion of hay, depending on the type of grass used for the calculation, i.e., "hay" which can be composed of either cool-season or warm-season grasses, as well as alfalfa (a legume) is not a specific enough term for the argument at hand.

In another deviation from the original hypothesis that FERD is a proxy for the degree of a *system's* complexity, Chaisson looks briefly (and he admits superficially), at the energy demands of four human activities or functions: fishing leisurely, cutting trees, sewing by hand, and bicycling. Even for a brief, superficial analysis, however, there is not enough information provided in CE to make a meaningful argument for a relationship between FERD and the "complexity" of a function like a human activity. First, we have no definition or criteria for determining what is meant by "complex function because we cannot necessarily extrapolate from his definition of a "*complex system."* Is it the number of muscle fibers or muscle groups used? Is it the degree of coordination needed to complete the activity? Is it the amount of mental concentration or practice required, or some other factor(s)? Second, we would need more information about the exemplified activities themselves. For example, is a 70 kg person who is cutting trees for an hour, using an axe slowly (280 calories), using an axe quickly (1121 calories), using a chainsaw (245 calories per hour) (Fitday website) or using some other method? Of course, CE consistently uses ergs sec^{-1} gm^{-1} rather than calories per 70kg person per hour, but regardless of units, the proportionality remains the same.

Also, at face value it is dubious that bicycling (at what speed?) is the most complex activity of the four that are compared in CE simply based on its higher FERD ($\sim 10^5$ units) – which would be a tautological argument again. The overwhelming determinant of its energy demands is undoubtedly the requisite use of the large leg muscle groups that are required to move our mass over distance and against gravity. Chaisson seems to infer that it is the added complexity of balancing a moving bicycle that adds to the complexity of this activity and, hence, its FERD (p191). However, the additional energy needed for balance would be quite small in comparison to the use of large muscles (Jabr F 2012). Activities like sewing by hand according to the resources I could locate, requires between 65 and 125 calories per hour (Fitday website) of energy, while for some reason, the citation used by CE (Smil V 1999) claims an energy expenditure of over 7 METS (~515 calories per hour), which is extraordinary and equivalent to cutting trees with an axe or riding a bicycle at moderate intensity. Because sewing mainly requires the muscles to keep upright while sitting and, more importantly, the intricately coordinated use of relatively small muscles of the forearms, wrists, and fingers, it is hard to imagine that this activity equals the energy needed by the many large muscle groups used to forcefully swing an approximately 1 kg axe while standing. Regardless of all these concerns, activities like sewing, handwriting a book, or playing a musical instrument that require the fine, complicated, and practiced control of small muscles seem like better candidates for "complexity" in function despite their lower energy requirements. In brief, while there are too many unaddressed factors to help us decide if FERD is a good metric for "complexity" of function, the few examples of human activities offered make it seem doubtful.

The Complexity of Complexity

Admirably but somewhat perplexingly, CE notes a number of other instances where FERD does not correlate well with their apparent degree of complexity. As perhaps the most remarkable set of examples, CE notes that *Azobacter*, a common genus of soil bacteria, can exhibit a FERD of 10^7 units (p188). Another bacterium, E. coli, has a FERD of 10^6 units, and paramecia, single cell eukaryotes, have a FERD of 10^4 units (p174). In an apparent continued marked disconnect between FERD and degree of complexity, Chaisson states that the average plant has an even lesser FERD of 900 units. Amazingly, even a human riding a bicycle has a FERD of "only" about 10^5 units as noted earlier - still less than "lowly" *Azobacter* and E. coli. CE does note that many bacteria that live in environments with little resources can have a very low FERD of perhaps only 1 unit (less than the Sun). Chaisson also explains that the amazingly high FERD of *Azobacter* is likely because it will convert to the very low energy using state of being a "spore" when resources are scarce. However, E. coli and paramecia do not form spores, and plants can be dormant for long periods as spores or seeds as well. Hence, periods of inactivity do not fully explain the poor correlations between FERD and complexity. Chaisson does add that smaller organisms have a large surface to volume ratio and that a single cell must perform the entirety of life's functions, amongst other possible factors that might explain their enormous potential FERD values. Still at the worst the examples noted above invalidate FERD as a reliable metric for the degree of complexity, at least for living organisms. At best, it means that much more data needs to be collected to determine if there is a correlation between FERD and degree of complexity *on average.*

Perhaps the most fundamental reason why complexity is difficult to define, almost as hard to characterize, and in search of a reliable and precise metric is because of the very thing that makes them complex – their many variables. In many and perhaps most situations, the numerous variables will "confound" any attempt at simplified solutions for a metric or attempts to make other broad rules and generalizations. In addition, if we place a complex system like a living organism in a complex ecosystem that is in turn situated in the complex biosphere, the variables literally multiply. In contrast, a metric like FERD will likely have a greater chance of accuracy and reliability for simpler physical systems in simpler surroundings as in the case of stars located in nearly empty space. To illustrate the diversity of potential "environments" even better, consider parasitic organisms which may make up 40% or more of the multicellular species on Earth (De Baets K & Warren Huntley K 2021, Dobson et al 2008, Yong E 2016). Parasites each find that an essential part of their lifecycle depends on drawing energy and material resources in or on other species that range from other parasites themselves to plants to whales. Every host species is a unique environment with their own set of chemical compositions, body temperature, immune systems that attempt to thwart them, etc. Furthermore, for many parasites, part of their lifecycle additionally depends on surviving in the external world that is proximate to their host or even yet another secondary host. For example, malaria depends on both mosquitos and vertebrates like humans, which are quite different "environments" to complete their life cycle. Hence, living organisms need survival strategies that cope with environments that drastically vary from the north pole to south pole, from mountain tops to deep in the Earth's crust and ocean layers, and often times in another organism. These confounding variables will likely affect and perhaps overwhelm correlations between an organism's FERD and their degree of complexity – or any other simple metric.

Medical research faces that same conundrum of trying to determine outcomes that can be affected by multiple confounding variables. To combat the vagaries that occur when studying complex (and long-lived) humans in complex contexts, studies typically involve many hundreds to many thousands of subjects, and in different countries if possible. As but one of countless examples, researchers at Harvard combined the data from two large, long-term studies to determine which diets are best for promoting human longevity. The studies included over 119,000 men and women over a study period of about 35 years to eventually identify 4 general diets that decreased the risk of dying during the study time period by 20 percent (Shan Z et al 2023). The large number of subjects was necessary to try to minimize the chance that confounding variables like smoking, genetics, local pollutants, random chance, etc., could have affected the outcomes rather than a particular diet. Experience in medical research has repeatedly demonstrated that without scientific rigor, large numbers of subjects, and time duration that we can be misled with "the best healthcare-related theories being killed by an ugly empirical fact." Similarly, before we can determine if FERD or any other metric is accurate or even helpful, we would need to apply it to many different samples at the various levels of complexity. If any metric fails to be better than well-considered estimations, or rough rules of thumb, then it will likely have little utility – at least by itself.

Finally, but not comprehensively, complexity itself is highly varied and multidimensional even if we restrict our analyses to living organisms and exclude others like societies and economies. While humans are unarguably the most complex organism in part because of our ability to detect (with technology), process, and manipulate information, there are many other dimensions to complexity that will likely make any metric of complexity context sensitive. If we consider complexity as an abstraction, it is not a point-like entity sitting on an x-axis of complexity degree where it can only move forward, backward (e.g., cave dwelling animals that lose their pigment and vison) or remain in place. Instead, it is like a spherical blob sending out searching tendrils of possibilities along multiple axes of complexity while probing for ways that might enhance its likelihood of survival and reproduction. Some of those tendrils might eventually find flight, others echolocation, sharper or more durable teeth, or perhaps lower demands for FERD.

In short, complex systems like living organisms are beyond complicated. They are complexity within other layers of complexities.

Conclusion

Admittedly, the foregoing critique of *Cosmic Evolution's* proposal for a complexity metric did not review the many instances where FERD values concur with other complexity metrics, criteria, and general estimations The apparent consistent accuracy of FERD as a metric for complexity in *Cosmic* Evolution, however, is illusory because of several analytic missteps: 1. A definition of "complexity" that is nonspecific, 2. The lack of comparison to other metrics that leads to a tautology, 3. Making unexplained deviations from the original hypothesis, 4. The analyses actually providing *total* rather than *free* energy rate densities, and 5. Complexities, especially at the level of living organisms, have many confounding variables that will make it challenging to identify *any* universally accurate metric. The rationale for discussing CE's arguable missteps in some of its analyses is to make the case that FERD has not yet been shown to be the sine qua non for determining a system's degree of complexity. Instead, if it is employed as a metric, it should be done with caution and by considering other metrics and criteria, including well-considered estimates.

Despite these limitations, I suspect that FERD will generally be in alignment with most of the major complexity progressions that big historians typically cite as benchmarks for major transitions in the history of the universe. At the very least, however, we would need to first look at many examples of instances at different "levels" of hierarchy to see if there is a general correlation between FERD and degree of complexity. It might very well be that *on average* FERD increases from stars to prokaryotes to eukaryotes to multicellular life and beyond.

Importantly, it is worth repeating that *Cosmic Evolution* does provide big historians with many valuable insights into the cosmological and thermodynamic conditions and laws that must be considered when trying to understand complex systems' genesis, progression, structure, functions, and interactions over the course of time. The many valuable insights and facts upon which CE elaborates, more than compensates for the limitations of FERD appears to have, at least when applied to living organisms. In fact, in my estimation, *Cosmic Evolution* remains at the forefront for explaining not just *what* happened in big history, but *why it was possible.*

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