Energy, Complexity, and Big History

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The Problem with the Concept of Complexity

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Abstract: The concept of complexity is one of the most fundamental of big history fundamentals. The concept of complexity has great potential for understanding the shared qualities of otherwise disparate systems, explaining large-scale change, and comparing different types of complex systems, including human societies. Given this potential, it seems extraordinary that the concept has not penetrated the academic zeitgeist more thoroughly. I argue that four key roadblocks are holding the concept of complexity, and by extension, big history, from broader acceptance in the academy: first, the term "complexity" in its technical usage is not intuitive to people outside the fields of big history and complexity science; second, there is a lack of consensus even among big history scholars on the definition of complexity; third, measuring large-scale change over thousands, millions, or billions of years may lead to imprecision and oversimplification; and fourth, complexity, while an objective indicator of change, is closely tied to contested, subjective, culturally-specific notions of human progress. This paper argues that the concept of complexity, despite these roadblocks, has significant utility in fields that consider large-scale change. Ultimately, this paper aims to provide more clarity and precision around the concept of complexity to strengthen one of the key foundations of big history.

1. Big History's Biggest Problem?

Big history has a problem with the concept of complexity. Working at Macquarie University, I am fortunate to be surrounded by a department of colleagues who, whether sympathetic to the aspirations of the big history project or not, are familiar with the field. This article emerged from a discussion with a colleague, an eminent historian who shall remain anonymous, about the 30-year legacy of big history within broader academia. Big history is a deeply interdisciplinary field with significant potential to impact both secondary and tertiary curricula in a period where interdisciplinary research has been promoted by universities worldwide. Nevertheless, big history has remained on the fringe of university research. My colleague argued that the core of the problem was that the concept of complexity simply "had not gained traction". Yet, complexity has emerged as a central concept in the big history story, arguably THE core concept. The reason for complexity's centrality is that most big history narratives involve telling how complexity has increased from "Big Bang to modern human society". Even when the Big Bang-to-humans narrative is not the focus, complexity provides one of the most useful tools for comparing the nature and size of complex systems that might otherwise seem to have little in common. Given the importance of the concept of complexity, any failure for it to gain wider acknowledgement and understanding will likely keep big history at the margins of academic research. This article investigates this complexity problem and aims to provide some resolutions to key issues surrounding the concept of complexity.

The concept of complexity has been well-debated among big historians and complexity scientists. The goal of this article is not to provide a single unifying definition of complexity – the Santa Fe Institute and the field of complexity science have been attempting that for decades without much success – rather I aim to clarify some of the possible meanings of the concept of complexity in big history.[1] Almost any system can experience measurable changes in complexity but not all systems are the focus of big history. Instead, big history primarily focuses on those systems which are relevant stepping stones from the Big Bang to human societies. What big history really means by complexity, then, is *useful* or *meaningful* complexity, that is increases in complexity that have meaningfully contributed to the emergence of a complex society of advanced sentient beings. While this story appears anthropocentric, there is no reason why this practical discussion of the emergence of humans cannot be applied to SETI (the Search for Extra-Terrestrial Intelligence) or to discussing potential futures for even more complex societies.[2]

So, is it a futile task then to attempt to define and develop a large-scale metric like complexity in a sufficiently precise way that meaningful conclusions can be drawn? The task is not a futile one but, given the large scale on which big history works, it is important to clarify that the level of precision which can be achieved is limited by the amount of information the authors or even a computer can gather and process. For highly complex systems like human societies, the level of precision is going to be much lower than for simple systems like molecules. For example, it is difficult to judge whether the Roman Empire was more or less complex than Ming Dynasty China or to measure small changes in complexity in a stable agrarian society over the course of a week or decade. What complexity is good for is tracking large-scale change and for comparing systems that are otherwise very different, such as a star to an ant colony, or a foraging society to an industrial one. Having a mechanism for large-scale comparison is important *because* complex systems are unpredictable; they have so many moving parts that even a small change, such as that wrought by a particularly charismatic individual or the presence of a certain type of edible plant, can disproportionately impact a society's history.[3] In practice, then, an outcome may be true or likely for complex system but so for another similar complex system; if however, a trend occurs in every or many systems of different levels of complexity, then that trend is much more likely to occur regardless of the system's complexity. Consequently, It is both reasonable and useful to track complexity on the scale of big history as it provides both a more coherent understanding of the past and a more solid foundation from which projections about future changes in complexity can be made. This is why big history's particular framing of complexity is so important. By building a framework for identifying and mapping changes in useful complexity, big historians have a unique tool for sifting through the universe and finding the systems which are most relevant to the human story. The concept of complexity provides a mechanism for binding the otherwise utterly different systems of atoms, stars, bacteria, and human societies together into a coherent narrative. Ultimately, I will argue, the concept of complexity uniquely allows big historians to not only objectively map something very close to progress but also to make normative judgements about whether complexity and progress should continue to be pursued in human societies.

Then why has such a useful tool failed to gain broad acknowledgement and understanding in the academy? I argue that big history's problem with the concept of complexity is four distinct, but interlinked problems which I outline in turn. Many of these issues are fundamental to the field and are unlikely to ever be resolved completely although there is certainly room for more clarity and precision; indeed, they should remain open questions subject to robust academic debate. Rather than seek to solve the complexity problem, I seek to provide a framework for confronting the core issues of complexity in a way that allows academic discussions within the field to move past the roadblock current definitions of complexity often create, while also allowing for communication of the concept of complexity beyond the field of big history. Ultimately, I argue that big historians need to use the concept of complexity in consistent, well-defined ways and discuss complexity with sensitivity to the potential unfamiliarity of readers outside of big history. A blessing or a curse, it may be necessary for big history authors to briefly define and justify their use of the concept of complexity in each text to ensure clarity and broader understanding.

The first of the four problems with the idea of complexity is that, in its technical usage, complexity is a term unfamiliar to many scholars in the humanities and many of the sciences. Its ordinary and natural meaning is substantially different from its technical meaning. This problem can be best confronted by both clear definitions and consistent usage of the word "complexity" within each work of big history. This should be accompanied by an assumption that the reader may not be fully aware of the important differences between common-sense uses of the term and more technical uses. Second, even within the field of big history, there is a lack of consensus about what complexity means and how it should be measured. Robust debate about the nature and features of complexity is a central part of the big history research agenda, and this debate should continue. However, most authors agree that energy flows, interconnectivity, and emergence are key aspects of "useful" increases in complexity.[4] The debate is typically about the degree to which each of these three metrics is relevant. Rather than attempting to resolve the debate, authors should acknowledge the common ground and situate their work within it. Third, the large scales of big history can lead to imprecision and oversimplification of complicated problems. This is less a problem and more a methodological question that needs to be addressed in each work of big history. It is important to acknowledge both the benefits and the limitations of the large-scale approach and to emphasise that, by taking a wide lens, the interdisciplinary view may provide further clarity into how each field of knowledge fits into the broader story of the universe. Finally, complexity is closely tied to subjective, culture-bound, and often deeply problematic notions of human progress. I argue that there are some commonalities between the many different conceptions of progress and that complexity is, or is very close to, an objective representation of these common elements. It is, therefore, important for all big historians to note that increased complexity does not necessarily lead to outcomes that will universally be regarded as positive. In the past 30 years, big history has done an excellent job of describing changing complexity but has untapped potential in normative discussions about whether complexity *should* continue to increase. I argue that a shift towards this more analytical framework allows big history to engage in deeper normative conversations with other fields.

2. The Definition Problem

The first core aspect of the complexity problem is that "complexity" is often used informally as an adjective to describe a difficult problem or situation. More precisely, the technical definition of complexity in big history and complexity science does not intuitively follow from the more vernacular usage of the word. In general parlance, complexity means "the state of being intricate or complicated".[5] There are four points of difference between the technical and vernacular definitions that are non-intuitive and therefore may create confusion. First, in technical parlance, "complex" and "complicated" are not the same thing; both complex and complicated systems have many interconnected parts, but complex systems have *emergence*.[6] Emergence occurs when a system develops a property because of its specific arrangement of parts. For example, there are multiple ways to arrange hydrogen and oxygen molecules but only in the L-shaped form of H_20 do the extraordinary bonding properties of water emerge. So, any academic definition must include the concept of emergence – although, as I argue in part 3 of this paper, emergence alone is not sufficient to define the concept of complexity.

The second point of confusion relates to the types of systems that can have complexity; a system can have complexity even if it is very simple, while a very complex system can be made up of parts that are complex systems in themselves. It does not intuitively follow that a water molecule, which is stable and comprised of a few atoms with no concept of agency, can be meaningfully compared to a human society, which is made up of conscience, complex beings each with their own agency. The former is a Complex Physical System (CPS) which derives its structure from the physical arrangement of its parts, while the latter is a Complex Adaptive System that consists of physical arrangements that can actively respond to external conditions.[7] A CPS is passive and cannot actively respond to external changes while a CAS is active and can respond – in practice living systems and non-living systems like economies which derive from human systems are CASs and all other non-living systems are CPSs.[8] Importantly a CAS must be comprised of CPSs like atoms and molecules and can be comprised of other CASs such as individual humans forming part of a human society. The unifying thread between these apparently disparate systems is that they all have complexity, albeit to different degrees.[9] Part of the value of the concept of complexity, then, is that it reveals the commonality and connections between these otherwise disparate systems in the Universe.

The third aspect of confusion is that, in CASs, parts are so intricately connected that the properties of the whole can no longer be predicted by linear equations.[10] It is reasonable for someone who has never engaged with the academic usage of complexity to ask: "why does having more moving parts make a system more unpredictable? Yes, more moving parts means inputting more initial conditions into the calculation but why is there a point where the number of initial conditions hits a critical mass whereby the calculations no longer work?" The short answer is that large numbers of initial conditions mean large numbers of possible interactions between each initial condition; two systems that are initially the same except for one small difference in a single initial condition could quickly become significantly different.[11] In this way, CASs behave like chaotic systems. For example, try to imagine the consequence of the horse – an animal key to efficient agriculture, transport, and warfare – becoming extinct in Eurasia instead of the Americas. How would human history look in the 21st century? One could make projections about faster growth in agrarian societies in the Americas, increased power of a China not harassed by horse-riding nomads from the Steppe, and significantly reduced range of movement in Eurasia limiting the exchange of goods and ideas. One could also suggest that changing the history of the horse would have had minimal impact due to other factors like geography, culture, or suitable alternatives. The most correct answer is also likely the intuitive one: that making predictions about alternate realities for modern human societies is a fraught task that requires a considerable amount of guesswork. Yet, it is possible to calculate what will happen to most chemical reactions if the initial condition of a catalyst is not present: the reaction occurs much more slowly or not at all.[12] The chemical system has a predictable outcome because it is a CPS with a limited number of initial conditions. The human system has an unpredictable outcome because it is a CAS and has many possible initial conditions. Both systems have complexity, but one is much simpler than the other and that shapes our understanding of the capabilities and limitations of each system.

So far, I have clarified the technical definition of complexity in three ways: first that any technical definition of complexity must include the concept of emergence in addition to many connected parts; second that both CPSs and CASs can have complexity; and third, that CASs are, by virtue of having many possible initial conditions, always contain some element of unpredictability which cannot be perfectly captured by quantitative modelling. I now move to the point of confusion which relates to big history's specific concept of complexity which is meaningful in the context of the "Big Bang to modern humans" story.

3. The Consensus Problem

The second aspect of the complexity problem is that there is no consensus, even within big history or complexity studies, around the definition of complexity. There are more than 40 different ways of measuring complexity, but big history has focused on four key areas: energy, interconnectivity, emergence, and information.[13] Most authors adhere closely to one of the four but I argue here that there is common ground to be found by accepting that all play a role in increasing complexity. I discuss the three first three components of complexity in turn then argue that they should be considered as inextricably linked parts of a single whole rather than being able to provide a single unifying theory on their own. I further argue that information does not need to be considered as a separate metric because, while may be an important feature of complexity, it can be effectively represented by the fundamental components of energy, interconnectivity, and emergence.

Within big history the debate about what complexity is and how to measure it is typically focused on four concepts: energy flows, interconnectivity, emergence, or information. Big history authors have typically focused on one of these four concepts as the core indicator of levels of complexity, although it is worth noting that the other three features are rarely ignored. Indeed, I argue here that any definition needs to include, at the very least, energy, interconnectivity, and emergence to effectively capture big history's concept of "useful" complexity. As stated above, information is extraneous because it can be captured by the above three elements. I argue that complexity increases when a complex system's free energy density (the amount of "useful" energy flowing through a gram of a system per second) increases, the number and diversity of interconnections rise, and new emergent properties arise. The size of the lens matters here. Shifts in these three metrics may not be visible in granular, small-scale changes in complexity but typically crystallise in large-scale leaps forward. This is why the concept of complexity is so useful in big history; when applying a lens that encompasses the history of the universe, complexity provides a way of identifying which changes matter. In other words, debate can exist as to the weight which should be given to each attribute, but the above three concepts in the concept of complexity, taken together, provide a good starting point for clarifying the concept of complexity in big history.

Interconnectivity:
Spier and Interconnected Building Blocks

Spier argues that the complexity of a system can be defined in terms of the number and diversity of its building blocks and the number and diversity of connections between those building blocks.[14] The great value of this definition is that it is probably the closest to common-sense notions of complexity. Spier proposes that complexity should be measured using four criteria: 1. The number of building blocks, 2. the number of different types of building blocks, 3. the number of interconnections between building blocks, and 4. the number of different types of interconnections between building blocks.[15] While he acknowledges that emergent properties and increased free energy density may arise as a result of the increased interconnections, Spier argues that these outcomes are correlative indicators rather than direct measures of complexity.[16]

There are two central challenges with Spier's approach. The first is acknowledged by Spier himself as being the difficulty with which the number and the diversity of building blocks in interconnections can be measured, particularly as the complexity of the system increases.[17] In a water molecule, each of Spier's criteria can be easily determined. There are three building blocks, two different types of building blocks, hydrogen, and oxygen atoms, and two interconnections, each linking a hydrogen and oxygen atom. In a more complex system like a human society, with its enormous number and diversity of building blocks and interrelationships, it is difficult to envisage how each of Spier's criteria could practically be measured. This is compounded by the unresolved question of how much weight should be given to each of Spier's four criteria. A problem may be, for example, that a system with many building blocks, like a star is less complex than a single-celled living organism, which has greatly fewer building blocks but a greater diversity of building blocks and a greater diversity of relationships within itself, and with its surroundings.

The second problem is increasing the number, diversity, and interconnectivity of building blocks alone does not always lead to increased "useful" complexity. For example, if one broke a human body down into its constituent parts, tossed them around in a giant mixer, and then attempted to reassemble that same number and variation of parts together ensuring the same number and diversity of interconnections, it is more likely than not that the reassembled set of parts would be a jumbled mess with little prospect of movement or conscious thought. In both circumstances, complexity may have increased by Spier's but only one version is useful: where those building blocks are arranged in a precise way to produce the emergent property of flight and lead to meaningfully increased complexity. The success with which the building blocks were arranged in a precise way to create greater meaningful complexity can be estimated by examining whether the arrangement has led to the production of greater free energy density and emergent features, both considered below.

Energy: Chaisson's Free Energy Rate Density (FERD)

Chaisson's Free Energy Rate Density (FERD) approach is much less intuitive but likely provides the best approximation of complexity using just a single metric. In practice, the same as power density in physics except using different units of measurement, FERD measures the amount of free energy that passes through a gram of a system each second (erg/s/g).[18] Complex systems are organised clumps of matter in an otherwise nearly empty universe. The second law of thermodynamics state that entropy will always increase. Entropy is the universe "trying" to spread all matter and energy evenly, dismantling any clumps or imperfections. The denser the clump, the more entropy will "try" to pull it apart. What this means in practice is that more complex systems tend to need to expend more energy to combat entropy as well as maintain its essential functions.[19]

If more energy becomes available, either due to increased natural supply or an evolution within the system to allow more efficient harvesting of energy, each of Spier's four features may increase.[20] Conversely, if a system is faced with a sustained decrease in energy availability, the intricacy of the system must also decrease unless the system evolves to use energy more efficiently.[21] In short, because entropy makes all forms of complexity precarious – complexity may, at best, allow a system to "evade locally and temporarily the usual entropy process." The availability of energy flows is a key factor that impacts a system's capacity to generate and sustain complexity.[22] "Energy flow regulation" – the more efficient use of existing energy flows – is also likely "a necessary part" of complexity maintenance and growth. However, figure 1 seems to indicate that systems that have made significant leaps in energy flow regulation still increase their FERD over time.[23] The great benefit of FERD is that energy can be much more easily quantified than the other metrics discussed in this part.[24] As such, FERD may provide a solution to the central challenge facing Spier's method, finding the exact ratio (if a single constant exists) by which the four features must increase for greater complexity to form.

However, measuring FERD precisely and consistently across all systems in the universe remains a challenging prospect and it is on this point that Spier is most critical of Chaisson's approach to quantitively measuring complexity.[25] The first challenge to measuring FERD relates to which part of the system the measurement should be taken from. Non-equilibrium systems, that is systems that have positive entropy, are rarely in a steady state where energy is flowing consistently and equally throughout all parts of the system. Instead, systems are in a constant state of flux, with energy flowing unevenly to different parts of the system as it is needed. This unequal spread of energy flows becomes more pronounced as the complexity of a system increases because different building blocks may require energy to perform their relevant functions only when those functions are required. For example, a cheetah's legs only require significant energy when the cheetah is moving; when the cheetah is at rest, the energy flows directed to the leg diminish. This means that a sample taken from a small part of a system may not provide an accurate indication of either FERD or complexity. The second challenge considers the point in time that the

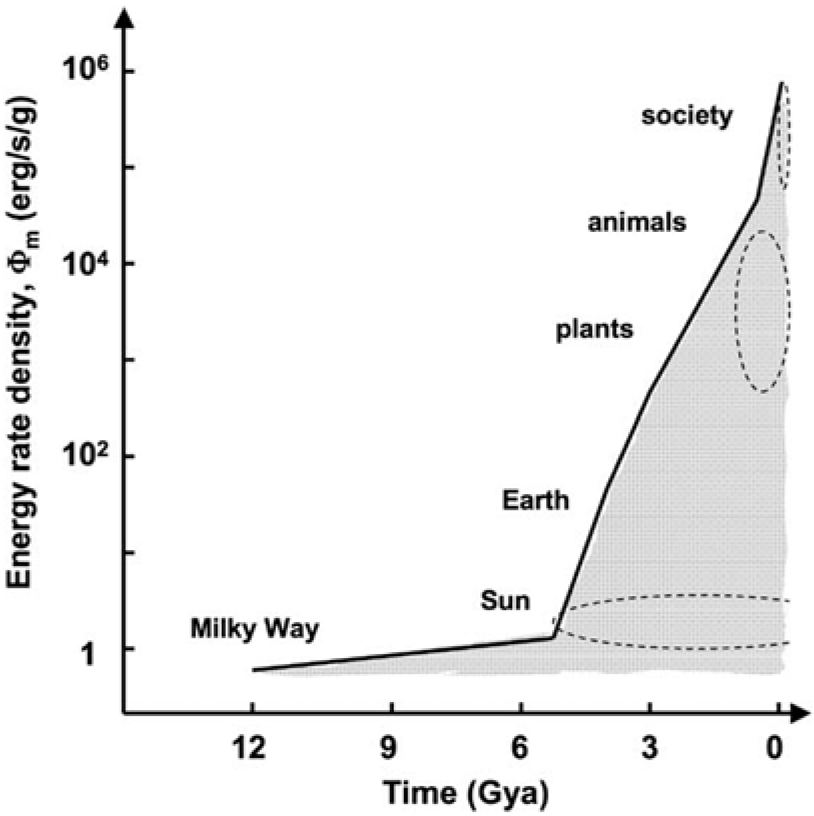

Figure 1: Chaisson's semi-logarithmic representation of FERD in select systems in big history.[26]

measurement is taken. As well as energy flows being in constant flux across different constituent parts, so too do non-equilibrium systems' energy flows trough and spike at different points in time. Periods of volatility in energy flows can be particularly violent during periods of creation or destruction of complexity. When a protostar finally gains enough mass to begin nuclear fusion and become a star, there is a massive spike in energy that blasts the protostar's gas and dust envelope away. Similarly, when a star dies through a supernova, the explosion creates a sudden spike in energy flows many orders of magnitude greater than that same star's average FERD before the supernova, yet it makes no sense to regard that spike as evidence for an increase in "useful" complexity. Even during periods of relative stability in a system's complexity, energy flows may differ if there is a need to do so. A cheetah chasing after its prey momentarily has much greater FERD than it would at rest, while a hibernating bear has a much lower FERD than when it is active. So, both the "where" and the "when" of the FERD measurement can potentially produce wildly different results.

There are multiple potential solutions to the challenges of measuring FERD. The first is to measure the system's FERD at its highest point, which should, theoretically, indicate the highest level of complexity that system achieved. This method is flawed for two reasons. First, a system's highest FERD often occurs during the power spike that arises when complexity is created or destroyed. The burst of energy that often accompanies the creation of greater complexity typically subsides quickly and the system settles at a lower, but more stable, FERD. Even more misleading would be a measurement at the moment of destruction. A supernova, an animal fighting to the death by exhaustion to protect its young, or a megalomaniac using humankind's stock of nuclear weapons to wipe out the human species would all represent the highest FERD which that star, animal, or society had ever achieved, but it would not provide a useful representation of that system's complexity. Consequently, this paper posits that FERD measurements should be taken only from stable, "controlled" uses of energy, that is from energy flows that are necessary to maintain the system's normal level of complexity.

The second method of measuring FERD is perhaps the more obvious one, and the most ideal in theory: to take an average of the energy flowing through all parts of the system over an extended period. While FERD fluctuates significantly during the creation and destruction of complexity, there is a period between the initial increase in the system's complexity and the moment when that complexity is either increased further or destroyed, where FERD remains relatively stable and energy flows are "controlled".[27] It is during this period that an average measurement for FERD should be measured. From this base measurement, it is then possible to gauge the effects of a period of increased or decreased energy flows on a system's complexity. The main practical challenge of measuring FERD based on a long-term average is the sheer amount of data required to do so with any level of accuracy, a problem that magnifies as the system becomes more intricate. It is reasonably simple to provide an accurate FERD measurement for less complex systems as both the building blocks and the interconnections between them tend to be largely uniform. For example, the FERD of stars and galaxies can be calculated by the luminosity-to-mass ratio, which indicates how much energy, in the form of light, per gram of the star is being emitted per second.[28] Similarly, the FERD of a biological system, like an animal or plant, can be measured by its metabolic rate, how quickly an organism breaks down fuel into energy that keeps the organism alive.[29] Measuring the FERD of a human society becomes much more complicated primarily because human societies tend to draw energy from an increasing diversity of sources as their complexity increases. Hunter-gatherer societies rely primarily on human food consumption to obtain the energy required to sustain their complexity, but this may be supplemented with the use of other natural energy sources like fire. Agrarian societies' FERD must not only reflect the food consumed by the human inhabitants, but also the fodder eaten by domesticated animals, and any natural energy produced by non-industrial technologies that use natural resources like water and windmills, thermal baths, kitchens, sail ships, and blacksmith's forges. Modern industrial societies have the greatest diversity of all, utilising all the energy sources of an agrarian society along with fossil fuels, nuclear, and renewable energy to create an extremely complicated network of energy usage. As a result, while it is possible to obtain data from a wide range of historical and archaeological sources to form well-informed and plausible estimates of how much energy a human society draws from each resource, it may not be possible to measure the FERD of human systems with the same precision as non-human ones.

While measuring FERD across different systems with varying levels of complexity may require diverse methodology, there remain three core principles that should be applied in each case, but particularly in systems of greater complexity, to provide optimal accuracy. First, the number of energy flow measurements should be as high as possible because, like any measurement of the interactions between matter, repeated tests tend to produce more accurate results. Second, for a general representation of a system's complexity, energy flow measurements should be taken at different points over a long period to better account for short-term spikes and troughs in energy use, although these fluctuations can be used to identify and analyse significant moments in a system's history. Third, where there are multiple different types of building blocks, energy flow measurements should be taken from as wide a variety of these building blocks as possible. So, while measuring the energy flows of a modern fighter jet in flight may produce an erroneously high representation of the FERD of a modern society, measuring many fighter jets, both in flight and at rest, along with a wide variety of other parts of that society will produce a much more accurate representation of FERD and complexity. Despite the challenges of measurement, FERD remains possibly the most effective means of quantitively measuring complexity.

Emergence

Emergence is a key part of the concept of complexity in big history because it adds further clarity to discussions around energy and interconnectivity. It is possible to have a system with the same number of interconnections and energy flows but different levels of complexity. To return to a previous example, the constituent parts of a jet plane can be connected in an infinitesimally large number of ways, but these parts must be assembled into a specific structure to generate the emergent property of being capable of flight. Each arrangement would have a similar number and diversity of interconnections and could each sustain the same amount of energy flowing through the engines. The difference between the jet plane which produces flight, and all other arrangements of the same constituent parts is not energy flows or interconnectivity, it is emergence. Emergence is a way of capturing the idea that more complex things may have novelty, and new qualities, and in this sense, tracking increasing complexity is a way of discussing the creation of the universe, and its ability to generate new types of entities. Emergence is the new features that are created because of the parts of the system being arranged in a specific way – in this case, the ability to fly in a controlled manner. It cannot be calculated by simply adding the sum of all the parts together rather, using somewhat circular logic, emergence is generated by a complex system becoming more complex. Put another way, increasing interconnections and energy density are *causes* of rising complexity while emergence is an *effect.* Emergence, then, is not a metric of increasing complexity, but rather a qualitative way of determining whether a particular event of rising complexity – the increase of energy density and interconnectivity – matters in the context of the big history story. Emergence can be used to distinguish relevant increases in complexity from amorphous explosions of energy that amount to the equivalent of evolutionary dead ends on the cosmic scale.

Emergence is an effect of rising complexity, rather than a cause, so it can only ever be used retrospectively to indicate complexity in the past. It cannot effectively be used to forecast future changes in complexity. Emergent properties cannot be predicted from the sum of parts of the system; they only exist because the system is arranged in a specific way - what Baskin (2022) terms "systemic causation".[30] To achieve this specific arrangement in highly complex systems, a significant number of exact conditions may need to be met – these exact conditions are often called "Goldilocks Conditions".[31] Until that specific arrangement has been made it is impossible to know whether emergent properties will occur and what those properties may be. Indeed, emergent properties may share some common elements but they are each unique. This is why it is crucial to include discussions of emergence when talking about rising complexity in the past: emergent properties explain the unique changes wrought by higher levels of interconnectivity and energy density at each new level of complexity. Further, while interconnections and energy density increase in line with rising complexity, emergence also occurs in clumps, appearing only when certain levels of complexity are reached. What this means in practice is that, beyond the conclusion that new emergent properties will appear with rising complexity and the right specific arrangement of constituent parts, emergence is impractical for forecasting the impacts of future rises in complexity. It also means that emergence is ineffective at tracking past changes in complexity except on a very large scale, where a new threshold, epoch, or level is crossed. It is, however, particularly useful for describing major technological transitions in human societies. At this historical moment in the transition to the Anthropocene where complexity is potentially rising faster than ever, the concept of emergence may provide much-needed clarity to the rapid changes humankind has experienced in the last 50-200 years and act as signposts for lasting changes in complexity in the present.

What about Information?

Information has been presented as a core element of complexity or even as a standalone metric of complexity. There is little doubt that information and complexity are closely connected but the exct nature of their relationship remains unclear and subject to debate. I have argued above that energy, interconnectivty, and emergence provide a quite complete estimation of a system's complexity's and I posit below that information is an unnecessary fourth component because its facets are effectively captured by the other three metrics of complexity. This is not to say that the relationship between information and complexity is unimportant but rather that one should not be considered as a metric of the other.

Information theory is a huge and complicated field on its own, but Ken Solis (2022) has noted that definitions of information get muddied by there being three different kinds: syntactic, semantic, and surprise.[32] Syntactic information is how the universe is physically arranged, semantic information is relational, arising only once it has been processed by agents, and surprise information captures unknowns that are discovered as information gathering "reduces uncertainty."[33] While more clarity is needed around information, there appear to be some similarities between syntactic information and Complex Physical Systems, between semantic information and Complex Adaptive Systems, and between surprise information and the principle of emergence. In terms of syntactic information Solis has echoed Norbert Weiner's argument that "information is fundamentally a measure of order".[34] Deacon (2011) argued that emergence and information are not only connected but part of the same process.[35] Increasing complexity generates emergent properties which generate new ways of creating, storing, and using information. Despite the diversity of emergent properties across different systems, information is often a common element. Certainly, in more complex systems, many emergent properties that are relevant to complexity involve some kind of improvement in the way information is stored and transferred. This can range from the genetic information storage in DNA in biological systems or writing and the internet in human systems. Gleick argues that "information is what the world runs on: the blood and the fuel, the vital principle" and that even a system as small as an atom contains a measurable amount of information in the form of bits.[36] So there seems to be some good basis for using information as a mechanism for measuring emergence and therefore changing complexity. Yet, there is tension here. In 2013, D W McShea argued that "information should be banned from interdisciplinary discussions of complexity in the history of the Universe" – the inclusion of information as a tool for measuring complexity is by no means agreed upon.[37]

Some of the challenges facing the use of information as a metric of complexity and emergence are the lack of definitional clarity and the lack of a consensus on how to measure it. How should uncertainty reduction be measured? Information theory scholars such as Gleick (2011), Loewenstein (1999), and Wheeler (1994) have suggested that bits, the unit of information used in computers, can be applied to other systems like atoms.[38] Recent progress in quantum computing has meant that an even smaller unit of measurement, qubits, can be used to measure information on very small scales. This method of measuring is by no means agreed upon as effective even within information theory.[39] An alternative model is information as negentropy or increased order as discussed by Solis (2022). If this model is viable then energy flows and information fit together very nicely and indeed may be measurable using the same metric. What neither the bits nor negentropy methods account for, however, is the nature of emergent properties. Instead, they record only the effect which FERD arguably does anyway; a society with new emergent properties is going to be more complex which means that FERD will increase. The importance of emergence is in describing the unquantifiable effects of increased complexity, those emergent properties that cause energy, information, and interconnectivity to leap unpredictably forward in clumps. Emergence also provides a qualitative indicator of whether a system's increase in energy density and interconnectivity is meaningful in the context of the big history story.

A Unified Approach

Energy, interconnectivity, and emergence considered together rather than in isolation present the most workable picture of complexity. Any measure of complexity cannot be wholly quantitative because knowing the initial conditions of very complex systems in their totality is impossible. Qualitative indicators, particularly that of emergence, provide clarity where the quantitative indicators fail, such as where there are large explosions of energy flows. There is enough common ground between the three main metrics of complexity in big history for them to be considered together; Indeed, it may be a more difficult task – and an unhelpful one for the field – to disentangle them from each other.

4. The Scale Problem

The third aspect of the complexity problem is the imprecision created by a large-scale approach. A favourite metaphor of David Christian's is that "from the top of a mountain, you can see the forest rather than just the trees". A former colleague of mine who worked on much smaller scales pointed out that a whole army could be dead in that forest, and you would not know from the top of the mountain. This summarises a common critique of big history and its discussions of large-scale changes in complexity: the bird's eye view approach is too imprecise and leads to problematic oversimplifications. So, is big history too big? No, but it is important to acknowledge the limitations of the approach. Big history is not, should not, and cannot be a universal descriptor of everything that ever happened and will happen – and no other subfield of history is or should be held to such a standard. It can provide large-scale insights and identify trends that smaller-scale approaches cannot; from inside the forest, one cannot see the whole forest. To gain the deepest understanding of the forest, the universe, or human history, one must look at it on a large scale and a small scale. Of course, a large-scale approach will miss details, just as a very small-scale study of a single person's life, or a certain type of frog, an interaction between two specific molecules will miss the implications of each of those stories for the larger whole. The interdisciplinary nature of big history is meant to be collaborative and to draw on a range of sources from other fields. It is not, and I think this should be emphasised in every work of big history, meant to replace those individual fields.

big historians are often interpreters that can facilitate a conversation between many diverse fields. It is, however, important to emphasise that big history research is not simply an act of making these connections but also providing valuable and unique insights based on them. The future is difficult to forecast and, as the discussion about emergence above demonstrates, every new level of complexity leads to new and unique emergent properties. There is, then, a risk that the Anthropocene is so unprecedented that the lessons of the past can no longer be applied. There is a real risk, for example, that the lessons drawn from the rise and fall of a certain society, say the Roman Empire, cannot be applied to modern techno-industrial societies – they are just too different in size, technology, culture, and organisation. This risk is reduced in the large-scale comparison of the rise and fall of different agrarian societies because the diversity of structures means that the results are more likely to apply when circumstances are different. However, a study of agrarian societies is most likely to produce results applicable only to agrarian societies. What big history does is consider the common trends between all human societies, regardless of their structure, and even all complex systems. If many highly diverse systems produce similar results, then it is much more likely that those results will be applicable across all complex systems, including future human societies (Fig 2). Put another way, the study of each complex system can be treated like a laboratory experiment. If each experiment produces the same results despite having widely different variables, it is much more likely that the results will be the same *regardless* of the variables.

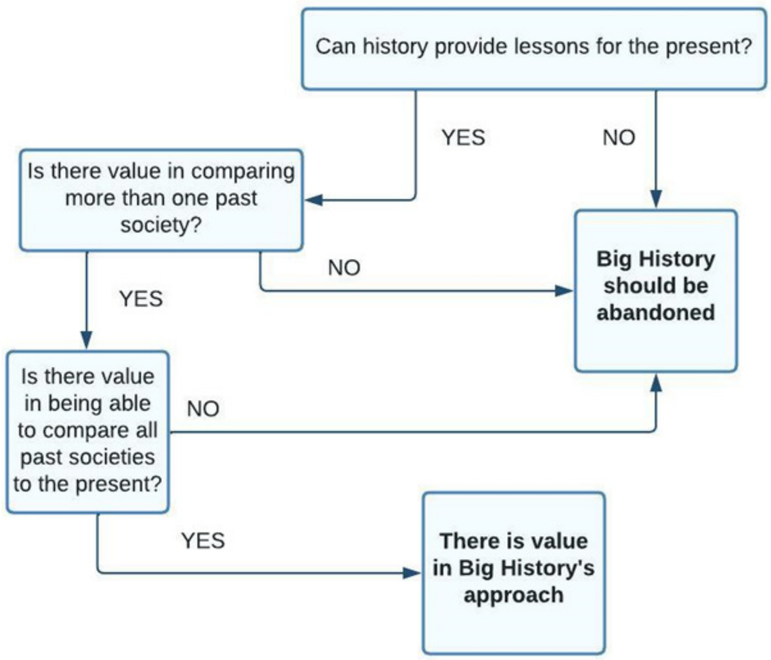

Figure 2:
The Value of Large-Scale Comparative Approaches.

5. The Progress Problem

The final aspect of the complexity problem relates to using complexity to make normative judgements, rather than just as a descriptor, to answer the question of whether increasing complexity aligns with the betterment of human societies. big historians are no strangers to discussing normative questions about the present and future of humankind and beyond. In the past five years, big historians have used complexity theory to foray into discussions about ethics,[40] SETI,[41] the singularity,[42] and the Anthropocene.[43] It is, in practice, very difficult to disentangle describing increasing complexity from value judgements, express or implied, about whether rising or higher complexity is a positive outcome for a system. It is a dangerous assumption indeed to say that because increasing complexity led to our present human society, increased complexity should be pursued in the future. I argue here that complexity is, or is very close to, an objective measure of 21st-century conceptions of human progress. Acknowledging this close relationship and engaging with it has two potential benefits for big history. First, it directly confronts the potential critique of big history from humanities scholars that the field uncritically advocates for human progress. Second, it creates a foundation from which big history can have a meaningful and nuanced conversation about whether complexity should be maintained and pursued. This question is very relevant to recent discussions by Graebar and Wengrow about whether a better future may not be a simpler future,[44] and it is in answering this question that some of big history's biggest untapped potential lies.

Enlightenment Notions of Progress

Progress, particularly when used in the context of the 'betterment' of society, is a slippery, subjective, and highly contested term. Progress has problematic roots, being used to justify imperialism, colonialism, and racial discrimination throughout the 18th, 19th, and 20th centuries. By the 19th century, the ideas of Hobbes and Rousseau had both been co-opted into justifying the necessity of human progress. Hobbesians believed that life in a "state of nature" – life without the structures of the nation-state, life in a society of low complexity – was "nasty, brutish, and short";[45] people could not be trusted to act selflessly, so needed the state, needed complex structures, to regulate their behaviour. Rousseau's view on the state of nature is of humans as idyllic, gentle dreamers but he nevertheless argues that "civilisation" becomes necessary for confronting economic hardship.[46] The Hobbesian and Rousseauian views about the state of nature, apparently diametrically opposed, have formed the basis of narratives of progress for the past 200 years, although Graeber and Wengrow (2021) have recently argued against this dichotomy, suggesting that it only applies if one assumes that increasing complexity is inevitable.[47]

The real problem with the use of the word "progress" is that ideas of betterment became linked with the concept of 'civilisation' and social Darwinism in European colonialism. These ideas were then employed used as a justification for colonial oppression by white 'civilised' Europeans against a non-white 'savage' or 'barbarian' other. [48] In the West, the racial dimension persisted at least until the Post-War period, where the aftershock of the Second World War, decolonisation, and civil rights movements forced a rethinking of the relationship between social Darwinism and progress. The result was the more amorphous, flexible modern notion of progress as a desirable societal improvement.

It is important then, for big history to be sensitive to how enlightenment conceptions of progress were used to justify colonialism, racial policy, and other atrocities. Claims, or even implications, that being more complex is better has dangerous connotations. Is the more complex society of 21st-Century USA superior to the less complex, pre-colonial indigenous societies? When the question is posed so directly, few authors would answer yes, but the danger is the implication of "more complexity = better" creeping into discussions about increased complexity.

The "Modern" Notion of Progress

So how can big history engage in discussions of progress and complexity in a sensitive and productive way? A good place to start is by considering modern conceptions of "progress". The nebulous, elastic nature of the word progress makes it easily manipulated to serve the user's ends. For this reason, it remains a favourite of politicians the world over. Democracy or dictatorship, monarchy or theocracy, leaders can and do employ 'progress' to imply they are improving the lives of their citizens and thus court public opinion. One does not have to dig deeper to find mentions of progress by politicians on all sides of the political spectrum. A brief survey of political speeches by different politicians across the world since the 1950s finds progress employed by leaders across the political spectrum – from Stalin to Obama, Mugabe to Nehru.[49] Despite all employing the word 'progress,' each leader has a different outcome in mind when using it, typically coloured by national interest and ideology. For example, where Stalin employs it to mean the continued spread of communism, Barack Obama uses it to mean continued economic growth and democratisation under Western liberal capitalism. With such diverse, often directly conflicting conceptions of what progress might look like, is it possible to draw out any commonalities beyond a vague, subjective sense of 'moving forward towards something better'?

While individual interpretations of progress are varied, these are not so varied to render the term 'progress' meaningless. Coccia and Belitto (2018) argue that the concept of progress in the 21st century has five central driving forces: scientific advancement, technological advancement, energy control, economic growth, and democratisation.[50] While the authors do not claim to be providing a comprehensive list of possible features – this would be impossible given that progress means something different to each individual – they do claim their list encompasses the main driving forces behind modern progress.[51] That democratisation is tied to progress is their most controversial claim, which the authors acknowledge: "In principle, with due caution, it can be said that the economically healthier societies, with higher innovative outputs, are also the most democratic."[52] While generally the case, the economic giant that is modern China would suggest that Western democracy is not the only way to achieve the socio-economic dimensions of progress. Indeed, it is important to be open to the possibility that new or different forms of social organisation may be necessary for managing challenges facing human society in the future.[53]

The other four elements are less controversial – there are, few political leaders that would argue that 'progress' means less scientific knowledge, less technology, less economic growth, and reduced energy use (although there are plenty that would argue for less democracy). Excepting democratisation, the other four driving forces link closely to complexity. They form part of an interlinked process of cause and effect: scientific and technological advancement stemming from emergence creates improvements in energy harvesting, efficiency, and storage, generating greater energy flows and economic growth which in turn creates more opportunities for more emergent scientific and technological advancement. When stable energy flows increase in human societies, a greater number and diversity of economic, social, and political interconnections form to manage them. In short, a call for 'progress' typically implies a package of improvements to economic, social, cultural, and political life. Depending on the context of the speaker, the contents of that package may vary significantly. Nevertheless, an increase in complexity, through increased energy flows as economic growth, greater interconnections as socio-economic and political structures, and emergence as scientific and technological innovation, almost always forms a key part of that package. As such, while progress and complexity are different concepts, the two cannot be easily disentangled because a call for progress almost always involves a call for increased complexity.

Human Development as a Pathway to Normative Discussions of Complexity

I have presented above a way to connect big history discussions of complexity to modern conceptions of progress in a way that avoids the value-laden judgements about whether increasing complexity and progress is a good outcome. Yet, earlier in this paper, I argued that big history can, and indeed should, use its findings about the impacts of increasing complexity to make normative "should" arguments. To do this, a framework for positive progress is needed. As I have discussed already, the idea of progress is highly subjective but there is a framework that has, at least in principle, agreement from nearly all nations in the world: human development. The term development emerged in the 1970s first from scholars in the Global South critiquing the use of economic growth in the form of GDP as the primary measure of human progress. Development economists Mahbub ul Haq, Üner Kirdar, and Amartya Sen argued that economic growth alone failed to adequately capture whether the lives of people were improving and proposed the more wholistic approach of human development.[54] As of 2015 193 UN member states are signatories to the Sustainable Development Goals (SDGs) making them the closest global human society has come to a consensus on the shape of positive human progress.[55] Human development has three core metrics as set out in the Human Development Index (HDI): longevity, education, and control over resources to achieve a basic standard of living.[56] The methodology for measuring these metrics has between refined over the past 30 years but the principle behind them remains the same: it is difficult to argue against the idea that living longer, having better access to education, and having more resources are measures of betterment.

While the metrics of the HDI are not directly in line with the complexity metrics discussed in this paper, there is some basis to suggest that increased complexity may lead to greater development. There is, at the very least, a close correlation between the control of resources and per capita energy density. Resources are either energy – in the form of food or electricity – or things that require energy to produce. Greater interconnectivity results in more elaborate systems including education systems and, because emergence very often relates to innovations in information storage and transfer, increased complexity results in higher levels of education. Finally, increased complexity leads to greater resource availability, access to services, and technological innovation, all of which contribute to increased life expectancy. In short, while development and complexity are not interchangeable concepts, increased complexity seems likely to lead to increased development.

Development may be the closest global human society has come to a consensus on the meaning of positive progress. If this is the case, then any normative discussions which stem from the concept of complexity should be done with reference to human development. Making clear connections between complexity and human development allows big history to provide practical advice and solutions around increasing development. Discussion of complexity and its impacts, which are less value-laden than progress and development, can then be used to engage in normative discussions about whether progress, complexity, and development should be pursued.

6. The Way Forward

Considering how the concept of complexity in big history fits into the broader academic discussion of complexity provides both useful clarity for the field and an opportunity to consider how big history can gain deeper academic traction going forward. I have presented four potential roadblocks which I have suggested have been preventing the concept of complexity from gaining traction and I have provided four potential paths around the roadblocks. First, it is important for works of big history to clearly articulate how they are using complexity. Not only does the big history definition differ from the intuitive concept of complexity but it is also much narrower than that of complexity science. While it acknowledges that there are many forms of complexity, big history focuses primarily on those forms which are relevant to the "Big Bang to modern society" story. I have referred to this narrower conception of complexity as "useful" or "meaningful" complexity. Second, much time and effort has been devoted to defining complexity clearly within the field of big history. The debate around precise metrics of complexity will (and should) continue, but it is important to acknowledge some common ground. Discussions of complexity in big history almost always include three features: energy density, interconnectivity, and emergence. I have argued here that these three features must be considered together, and given similar, if not equal, weight in determining a system's level of complexity. Third, I have provided a brief defence of the utility and relevance of the large-scale approach in the modern academy. In particular, I have argued that complexity is an effective tool for making comparisons of vastly different systems in order to provide relevant conclusions for present and future human societies (themselves vastly different from anything that has come before). Finally, I have argued that complexity has very close correlations to subjective notions of progress and development, and that this close correlation should be used by big historians to provide useful and unique insights into normative discussions about whether complexity, progress, and development should be pursued.

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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 <u>total</u> 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 (CH4). 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 (~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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What can we learn from a master plot of energy rate *versus* mass for a very wide variety of (complex) systems?

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Abstract: Mass and energy rate (ER) data have been collected for a wide variety of (complex) systems from the biological, cultural, and cosmological realms. They range from the cytochrome oxidase protein (10^{-22} kg and $6x10^{-19}$ W) to the observable universe ($1.5x10^{53}$ kg and 10^{48} W) and, thus, span 75 mass and 66 ER orders of magnitude. Many of these systems are relevant for the big history (BH) narrative, *i.e.*, the development of complexity over "big time" from the Big Bang up to the human society on Earth of today. The purpose of this paper is not *per se* to describe their history though, but to explore a master plot of ER *vs*. mass. Notably, the development of systems over big time has followed a rather tortuous path criss-crossing over this ER *vs.* mass master plot. The true mass of the system as a whole is used (for example trees including the non-living wood, living organisms including their intrinsic water, and social systems including the built constructs), because these inactive parts are essential for the performance of the system and facilitate its ER. A double logarithmic master plot of all ER *vs.* mass data shows clusters of data points. To some extent, this provides quantitative support for the distinction between the (sub-)realms, which is based on a qualitative description of their material structure and energy processing. In the master plot, small systems with low mass and ER converge into larger systems with larger mass and ER, which is typically accompanied by a decrease of the energy rate density (ERD = ER/mass). Correlation of ER with mass for various groups of systems demonstrates both sub- and supra-linear scaling with the power law β constant varying between 0.5 and 4.0, showing that the mechanisms of self-organisation are quite different for the corresponding system groups. The combination of convergence and scaling with β always larger than zero explains why the ER & mass data points fall in a diagonal band with a width of 17 orders of magnitude.

ER and mass have changed over wide ranges during the evolution of groups of systems, suggesting that evolution can be viewed as a process of systems exploring a larger ER *vs.* mass area until they run into ER and/or mass limitations. Indeed, there is a diagonal ER *vs.* mass limit for stable systems in all realms, corresponding to an ERD value of around 10^5 W/kg. Systems with ER & mass combinations above this limit, such as bombs, super-novae and cosmological transients, are unstable and "explosive". This raises the interesting question of whether such an ERD maximum puts a limit on the development of complexity over big time. It seems that the low, right side of the master plot is empty. However, it is argued here that it is full of systems with low ER, such as dormant, living organisms, technological systems with their power adjusted or even switched off, as well as cooling, cosmological objects. Such systems are typically considered of less interest in a BH context, but they are viewed here as simple, complex systems which are out of equilibrium with matter, energy and information stored in their structure. While ERD appears to increase with the 'advancement' of systems over big time [5,51,52], there are quite some confounding factors regarding the efficacy of ERD as a metric for complexity in BH. For example, ERD decreases during the lifetime of a human and the human society (the mass of human-made constructs has grown faster than the global energy consumption), as well as during the evolution of living organisms and stars, whereas complexity is considered to increase. High ERD values of system parts may be illustrative for the complexity of the larger system, but are not representative for ERD of the system itself. Machines with an increased efficiency of energy conversion have a lower ERD, but could be considered more complex. The smallest and largest ERD values observed for the various realms appear to correlate with activity level and reciprocally with size, which do not *per se* reflect complexity. It is hoped that the raw data collected and the major trends observed in this paper will offer new insights into various aspects of the evolution of the universe over big time, and serve as an important resource for other related studies.

1. Introduction

Our world is full of systems with sizes varying over a very wide range [1,2] from the tiniest quarks (theoretically considered as point-like entities with zero size; experimentally smaller than 10^{-19} m [3]) to the immense and still expanding, observable universe (today 8.8x10^{26} m in diameter [4]). Our human eyes can visualise proximate systems of intermediate sizes, including living organisms, such as plants, animals, and other humans, as well as human-made constructs, such as tools, machines, buildings, and infrastructure. Advanced instruments enable us to observe and study much smaller, as well as much larger systems in and outside the visible light regime. Scattering and collision experiments, as well as spectroscopy and spectrometry allow the study of very small physical systems, such as fundamental particles, nuclei, atoms, and molecules. Magnifying microscopes provide detailed pictures of very small biological objects, such as microbes and cells of living organisms. Powerful telescopes, operating in a range of spectral frequencies, provide images of very large but distant, cosmological objects, such as (exo-)planets, stars, black holes, galaxies, and the cosmic web. In addition, our human mind allows us to discern more abstract systems, such as families, cities, nations, stock markets, the economy, and the world wide web. All the mentioned systems are characterised by:

i) their composition, internal structure, and boundary with their surroundings, as well as
ii) their processes for the transfer (internally and with the external environment), conversion, as well as storage of matter, energy, and information for their origination, growth, maintenance, and decay.

The complexity of these systems is characterised by the intricacy of their structure and processes, as well as the emergence of new functions and performance on the system level, which are not shown by their constituting parts. Complexity is judged here not as a black *vs.* white distinction, but rather on a gradual scale from very simple to very complex. The various systems from the physical, biological, cultural, and cosmological realms, mentioned above, not only show a strong variation in their size, but also in their complexity. At the low end of the complexity scale come systems which consist of just structured matter in equilibrium; at the high end come systems with self-organisation, self-control, and adaptability*1. In a more strict thermodynamic sense, complex systems are open, out-of-equilibrium systems with some sort of self-organisation. Energy and matter are flowing in, as well as thermal energy (heat) and waste are flowing out to maintain energy and matter gradients, respectively. The energy inflow from the environment into open, complex systems facilitates the local increase of entropy, while at same time a larger amount of entropy is released to the environment and, thus, global entropy increases [5]. Additional characteristics of such complex systems are a certain stability of its material structure and a certain steady state of its energy and matter flows. Emphasis of this paper will be on such active and stable systems. Admittedly, dead and inactive systems without energy flow, stability and steady state, as well as unstable, "explosive" systems will be addressed too. It is felt that this will make the discussion not just broader, but also more interesting.

The purpose of this paper is to compare a wide variety of systems from the biological, cultural, and cosmological realms in terms of:

i) their mass (in kg) as a measure of the size of the system*2, and
ii) their energy rate (ER*3 in W = J/s; equivalent to power) as a measure for the effort of the system to maintain its complexity [5,6].

The use of mass and ER data allows a quantitative comparison and discussion of the qualitative aspects of systems (structure, processes, and complexity). Quantitative data on mass and ER have been collected for a vast collection of systems with varying complexity from the biological, cultural, and cosmological realms, as will be explained in more detail in the next section on data collection. Many of these systems of varying mass and ER are relevant for the development of complexity over "big" time from the Big Bang up to the human society on Earth of today, *i.e.,* in cosmological evolution [5] and big history (BH) [7-9], although the purpose of this paper is not *per se* to describe their history. Systems from the physical realm that make up matter, such as fundamental particles (including quarks and electrons), nucleons (protons and neutrons), nuclei, atoms, ions, molecules, salts, and metals are characterised by a certain energy density (in J/kg), but not by an energy flow (ER = 0 W). Consequently, these particles as such are excluded from this inventory, which limits the lower mass of the systems investigated to around 3x10^{-9} m. Systems powered by the conversion of such particles *via* nuclear and (bio)chemical reactions, for example in stars and plants,

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*1. Note that "complexity" is here defined in a broader fashion than typically done in complexity science; this does not have any consequences for the storyline and the discussions below.

*2. The terms "small" and "large", as used in this text, refer strictly speaking to size, whereas quantitative data are presented for mass, *i.e.,* "small" and "large" are used as synonyms for "light" and "heavy", respectively.

*3. A list of abbreviations is added at the end of the paper.

respectively, which are accompanied by energy flows, are included though. Physical phenomena at the border of our current, scientific understanding, such as anti-matter, as well as the elusive dark matter and dark energy, are outside the scope of this overview. The same applies for abstract systems without mass (and ER), such as consciousness and the economy. The collected mass & ER datapoints have been plotted in a so-called master plot of ER *vs.* mass with "master" referring to the very wide variety of systems. Such a master plot not only allows a straightforward presentation of the strongly varying ER *vs.* mass data of all the systems from the various realms, but also a direct comparison and an in-depth discussion of the similarities of and differences between the systems.

Plots of ER *vs.* mass are quite common in many disciplines, as indicated by the following non-comprehensive overview. In biology, plots of metabolic rate (MR) and total energy expenditure (TEE) *vs.* mass of living organisms are used for allometric scaling for groups of biological species [10-13]. Such plots are also used in the studies on the evolution of hominins [14-16] and, in an even broader context, the evolution of living organisms [17-20]. MR *vs.* mass plots are applied in scaling studies of social systems, as in insect colonies [21,22] and human cities [23]. In health sciences, average dietary (read: energy) requirements are correlated with mass as a function of sex, age, and physical activity level [24]. In cycling and tracks, plots of power *vs.* mass of sporters are used to compare their performance. Such plots enable a distinction between short-distance sprinting with emphasis on the power to accelerate *vs.* long-distance endurance and climbing with emphasis on the power-to-mass ratio [25,26]. In technology, power *vs.* mass data are used to compare the performance of machines and devices that generate, store, and convert energy, such as cars, trucks, motorcycles, boats, airplanes, pumps, batteries, and fuel cells [27-36]. In cosmology, plots of luminosity (absolute measure of radiation energy) *vs.* mass of main-sequence (MS) stars are used to illustrate their well-defined luminosity/mass correlations [37-39]. Similar luminosity *vs.* mass plots are used to illustrate the development of stars over their lifetimes [40,41]. The latter plots are complementary to the well-known Hertzsprung-Russell (HR) diagram, more typically used to visualise the development of stars with the logarithm of stellar luminosity plotted *vs.* the negative logarithm of surface temperature with the mass of stars as running parameter [37,42]. Luminosity/mass planes are also used to position matter-accreting objects, such as black holes, quasars, and blazars, relatively to their Eddington limits (explained in section 7.2) [43-48], as well as the cooling of exoplanets [49,50]. The data of all these studies from different disciplines and many more have been collected, and form the basis for the ER *vs.* mass master plot presented in this paper.

Correlations between ER and mass are connected to the concept of energy rate density (ERD), as introduced by Chaisson as a practical metric for the complexity of systems in BH [5,51,52]. Note that ERD values as provided by Chaisson are expressed in erg/s/g, which corresponds to 10^{-4} W/kg. ERD of a system corresponds to the amount of free energy flowing thermodynamically through that system to maintain its complexity, normalised to its mass. It is calculated as the ratio of ER and mass of the system (in W/kg). Parameters identical to ERD, such as mass-specific MR and power, power density, power-to-weight and -tonnage ratio, as well as luminosity-to-mass ratio, are used in many other disciplines [53]. The elegance of the ERD metric is that it captures the complexity of a system in a single parameter that can be easily calculated and, thus, allows the quantitative comparison of the complexity of a very wide range of systems. In a BH context, Chaisson has shown that ERD increases over "big time" from the Big Bang up to the human society on Earth of today and it does so at an accelerating rate. This corresponds fully to the intuitive notion that complexity has increased in an exponential fashion over big time [7-9], but now quantifies this complexity increase. Aunger has applied Chaisson's ERD data over big time to establish a more rigorous periodisation of BH [54]. ERD has also been used as a metric for the complexity of systems in other contexts, such as for binary star systems in accretion [55] and central processing units (CPUs) [56]. ERD as a single and practical parameter for describing the development of something so complicated as complexity over big time does have its issues though [9]. For example, ERD is typically applied for mature systems in steady states, but not during their growth and decay [57]. It does not apply to simple physical systems, such as stable molecules or parked cars, without energy flow (ER = 0). In addition, the definition of some systems and, thus, the quantification of their corresponding mass is not trivial (Earth: just mass of climasphere ? human society: just mass of humans ? mass of economy ?). Some of these issues will be addressed in this study. A drawback of ERD, being a single parameter, is that the original ER and mass details of the systems are lost. A master plot of ER *vs.* mass presents the full variation and, thus, enables the observation of:

- the convergence of smaller systems into larger systems,
- the scaling of ER with mass for groups of systems, and
- the observation of an ERD threshold separating stable from "explosive" systems over all realms.

The data presented by Chaisson [5,52] have provided a good starting point for the current overview. Many more data for a wider variety of systems have been collected here, which allows a comparison and discussion from other angles than just big time. Connections between the ER *vs.*

mass master plot, as presented in this paper, and ERD will be made where appropriate in the discussions below, especially in section 8.

This paper does not simply supply a large and, by itself, interesting collection of mass and ER data, varying over a huge range, as well as the corresponding master plot. The data and plot will be discussed with emphasis on the material structure, as well as the processing (transfer, conversion, and storage) of matter and energy in an effort to enhance the understanding of systems in the world around us. ER *vs.* mass data of (groups of) systems will be discussed from various viewpoints in the sections below, typically following the sequence from systems with lower mass and ER to those with larger mass and ER. First, in a zoomed-out fashion, it will be shown that the data belonging to the biological, cultural, and cosmological realms form ER *vs*. mass clusters (section 3). The ER *vs.* mass data for all systems appear to fall in a diagonal band of the master plot, which is mainly the result of convergence (section 4). Inspecting the data in the master plot in detail is rather difficult, because of the very large number of mass and ER data, varying over very wide mass and ER ranges. Therefore, separate, zoomed-in versions of the ER *vs.* mass master plot will be presented for the three realms. This allows more in-depth discussions, for example on the differences in scaling of ER as a function of mass for groups of systems (section 5). The development of ER *vs.* mass over the lifetime of a single system, as well as over the evolution of a group of systems also follows different trends for the various realms (section 6). Next, minimum and maximum ER values will be discussed for each of the three realms (section 7). It will be argued that some systems with ER = 0 have energy stored in their structure and, thus, could still be considered as simple, complex systems. An ERD maximum appears to limit the diagonal ER *vs.* mass data in the master plot, which separates stable systems from non-stable ("explosive") systems. This paper ends with some consequences of the preceding discussions with respect to ERD (section 8).

2. Data collection*[4]

A database has been set up in excel format with mass and ER data, as well as the corresponding ERD values for all sorts of systems, collected from original sources and studies. Because of the wide variety and diversity of the systems, this database is being updated almost on a daily basis with new data for relevant systems, which in a way is an open-ended exercise. A cleaned up and consolidated version of the "living" database is provided in the supplementary material (SM). The mass and ER data in the original sources are expressed in a variety of units, including pound, solar mass, horsepower, calory, erg, solar luminosity, year, day, and hour. These have all been converted to the corresponding International System of Units of kg, J, and s with W = J/s. Since the values of the collected mass and ER data cover a huge range, the scientific notation with 10 as basis will be applied (for example 1,000,000 = 10^6 and 0.000001 = 10^{-6}) for convenience sake, except for values between 0.001 and 1000. It has been tried to collect data representing all types of systems without making an effort to be comprehensive. Note that the spread of the data over the various (sub-)realms is partly determined by the availability and accessibility of quantitative data. For living organisms, machines, and stars, large numbers of mass and ER data are available, whereas for other systems, such as cell organelles, cities, and planetary systems, just a few data have been found (so far). The ERD data collected by Chaisson for systems following the BH narrative [5,52] have served as a useful checklist for the inventory of this paper (SM VI). Admittedly, Chaisson has sometimes followed a course-grained approach and, because of the focus on ERD, not all corresponding mass and ER date are given. Preferably, data have been collected from original studies. Note that ER is defined as the amount of free energy flowing thermodynamically through a system. Typically, either the amount of useful energy flowing in or out is known:

- ER_{in}: for example, food and molecular oxygen (O_2) consumption by a living, aerobic organism, fuel consumption of vehicles, total energy consumption by a city and society, as well as gravitational energy of an accreting system;
- ER_{out}: for example, amount of carbohydrates produced by photosynthesising plants, power of athletes, machines and energy-generating devices, as well as luminosity of stars.

Note that data on carbon dioxide (CO_2) flow rates either correspond to the uptake of building blocks for carbohydrate production in photosynthesising plants [58] or to the exhalation of reaction products of the oxidation of organic matter with O_2 [59]. Thus, these represent ER_{out} or ER_{in}, respectively. According to the first law of thermodynamics, energy is conserved during the transfer and conversion of energy [60]. However, ER_{out} is typically smaller than ER_{in}, because part of the useful, free energy flowing in the system is not fully converted to useful energy and work by the system. Part of ER_{in} is dissipated as non-useful, non-directional energy, such as heat, light, and sound. In other words, the energy efficiency defined as 100 * ER_{out} / ER_{in} (in %) is typically (much) smaller than 100%. This agrees

*4. Readers, who want to keep track of the main story line, could skip section 2 and continue reading with section 3.

with the second law of thermodynamics that in a closed system entropy increases when energy is converted [60]. Thus, the amount of heat generated provides, in principle, a lower and crude estimate of ER_{in}. Note that heat is sometimes useful energy, such as for homeostasis of living organisms, cooking of food, heating of a house, and gas expansion in engines. Similarly, stellar light, radiating in all directions is viewed as non-useful energy, though with the exception of the $5x10^{-8}$ % of Solar light that is reaching the Earth. There it heats the Earth surface, drives air and water flow, as well as is partly captured by photosynthesising organisms. Since the conversion efficiency of nuclear to radiant energy in stars is close to 100 %, stellar luminosity as non-useful ER_{out} is more or less identical to stellar nuclear energy as ER_{in}. This explains why stellar luminosity, representing heat radiation ER_{out}, is used as a measure for energy production ER_{in} from nuclear fusion. Another example of an efficiency close to 100 % is the conversion of electricity to heat in electric boilers, heaters, and irons. Such high energy conversion efficiencies close to 100 % are exceptions though, as illustrated by the (very) low energy efficiencies of:

- internal combustion engines: 30 to 40 % of chemical energy of fuel is converted to mechanical energy;
- food metabolism in human beings: ~25 % of chemical energy in food is converted to mechanical energy;
- silicon photovoltaic cells in solar panels: increased over last 40 years from 15 to 25% for conversion of infalling Solar radiation energy to electric energy;
- burning of wood in a stove: ~10 % of chemical energy of wood is converted to useful heat for cooking;
- photosynthesis in green plants: ~1 % of absorbed Solar radiant energy is converted to chemical energy stored in carbohydrates;
- incandescent lamps: ~1 % of electrical energy is converted to light.

Note that energy is often converted in a cascade, such as nuclear fusion in Sun → radiation from Solar surface → carbohydrates in plants → underground, fossilised coal → heat of combustion in engine → locomotion of machines. This results in a continuous loss of useful energy down the cascade. For the purpose of this study, either ER_{in} or ER_{out} data should preferably be used and compared, but in literature and databases just ER_{in} or ER_{out} data are typically available. It is beyond the scope of this study to align all the ER data from so many disciplines to the same definition. Therefore, ER_{in} and ER_{out} data are used as they have been found in the original sources, which does unfortunately result in an "apples-and-pears" comparison. Fortunately, the energy efficiency of systems belonging to a particular group is usually quite similar and, thus, ER data may be compared. With energy efficiencies typically ranging between 1 and 100 %, the effect of differences in efficiencies in the master plot with double logarithmic axes (see below) are considerable (up to two orders of magnitude). However, differences between systems belonging to various groups and (sub-)realms are even larger and, again, comparisons are feasible.

Some notes on mass and ER data for living organisms are in place. In biological studies often the dry mass or the nitrogen content of archaea, bacteria, and plants is used, because these reflect the energetically active parts of such organisms [18,61]. Sometimes, the mass of trees is corrected for the presence of wood, since the latter is viewed as just a structural feature and not contributing to the tree metabolism [18]. For animals corrections for the presence of water and skeleton are typically not applied, although for humans sometimes fat-free body mass is used [14]. Anyway, such corrected masses do not represent the true systems, because without water, wood and fat such systems would simply not live. An effort has been made to use mass data that have been corrected back to the wet masses of the actual living organisms. Such corrections can be quite large, since the water content for bacteria and plants is typically 70 % and for gelatinous organisms even up to 95 % [18]. Endogenous and basal MR (EMR and BMR, respectively) are typically used in biological allometry studies, because they allow a sound scaling of ER of living organisms with their mass, resulting in optimum fits of the experimental data. EMR and BMR of micro-organisms and animals reflect ER in the absence of growth, food digestion and physical activities, as well as adjusted to a reference temperature (for example [10,11,17,18]). For plants and trees BMR corresponds to the respiratory rate, typically measured *via* CO_2 production, in darkness in absence of photosynthesis. The additional energy expenditure of living organisms as a result of growth, food digestion, physical activities and photosynthesis may vary quite a bit and, thus, results in more scatter when scaled with mass. Although the E/BMR data do not reflect the true, metabolic performance of living organisms in "real life", they have still been included. When available TEE, daily energy expenditure and field MR data, *i.e.,* average ER values for a full daily cycle, have been included (for example [12,14]), which may be up to 30 times larger than B/EMR (for more details see section 7.2). For extinct dinosaurs (for example [62]) and hominin species during human evolution (for example [63]), reconstructed mass and ER data, obtained from theoretical models, have been collected.

In the technological sub-realm, the mass data for vehicles, motorcycles, ships and airplanes are often curb and dry weights, *i.e.,* without driver, captain, pilot, passengers, fuel, load and cargo. These have not been adjusted, although especially fuel, as well as a driver, captain, or pilot are essential for their functioning. ER of these vehicles, as well as for other machines and electrical equipment are typically maximum and peak powers. Note that such values are (much) larger than the typical ER values in regular use. For example, the maximum power of a 2012 compact car with a performance engine is 1.5×10^5 W [64], while the typical, useful energy output is calculated as 1.8×10^4 W [65], which is eight times smaller. Sometimes the mass of a device has been estimated to enable the calculation of ER from ERD. For explosives and bombs the explosion time has been estimated to calculate ER(D) from energy (density). In the social sub-realm, ER of the system is typically discussed in terms of the number of individuals or their corresponding mass. An interesting comment has been made by Makarieva *cs.* that nests and buildings should not be included when assessing MR of birds and humans, respectively [66]. In this study the opposite approach is followed, *i.e.,* emphasis is on the system as it is in operation and, thus, ER is correlated with the mass of the whole system. Consequently, mass data of social systems have been adjusted by including the mass of the constructs build and used by the systems as a whole. Note that such a choice on the precise definition of the system is are not about being correct or incorrect, but is dependent on the purpose of the study. For example, in metabolic studies on bee colonies typically just the mass of the bees is given [21]. These have been adjusted to include also the mass of the beehive and the honey produced [67], which are both essential parts of the living bee colony. Similarly, ER data for human social systems are often normalised to the population expressed in *per capita* units, *i.e.,* ERD* in W/*capita* [68-70]. Chaisson and also Barton have converted such *per capita* ERD* data to W/kg by normalising to the total mass of the human population, using an average mass of 60 kg [5,71]. However, ER of the human society is the resultant of the energy flows through all the equipment, machinery, and industrial plants. It is facilitated by all the infrastructure and architecture that have been developed, constructed and used by humans. Therefore, the complete human energy-converting system and its full mass should be considered. Isalgue *et al.* have done an elegant study on the scaling of ER of cities with their true mass, by estimating the mass of cities from corresponding data on city area and an average mass *per* area [23]. For the human society as a whole, energy consumption data [72] have been combined with the total mass of human-made mass in use from 1900 until 2018, as recently quantified by Elhacham *et al.* [73]. The mass of a human, averaged over age, sex, site and time, is assumed to be 50 kg [74].

Mass and ER data in the cosmological realm are typically given in solar mass (1 Mo = 1.99×10^{30} kg) and solar luminosity (1 Lo = 3.83×10^{26} W), which have been converted to kg and W, respectively. Dark matter is excluded in the mass of galaxies and the universe. Unfortunately, for matter-accreting objects, such as white dwarfs and neutron stars in binary systems, only the mass of the larger accreting object is known, but not that of the smaller donor companion [55]. Thus, the mass listed for these systems is on the low side. The same holds for larger, matter-accreting objects, such as (super-massive) black holes, but for these the error due to the missing mass that is accreted from the environment is probably negligible. Absolute magnitude (M) data have been converted to luminosity (L) *via*:

$$L = 3.01 \times 10^{28} * 10^{(-0.4\,M)}$$

ER predictions for matter-accreting objects [for example [55]), stars over their lifetimes (for example [75]) and cooling, cosmological objects (for example [76]) are based on theoretical models in the original studies. The net heat radiation (= ER) of brown dwarfs, some (exo-)planets, moons, asteroids, meteoroids, and interstellar dust has been calculated using the Stephan-Boltzmann law for black-body radiation for spheres:

$$ER = 4\,\pi\,\sigma\,R^2\,(T^4 - T_c^{\,4})$$

with σ is 5.67×10^{-8} $Wm^{-2}K^{-4}$, R is radius (in m), and T and T_c are (surface) temperature of object and colder surrounding (in K), respectively [186]. In case of a surrounding with a much lower temperature, the $T_c^{\,4}$ term may be neglected. Sometimes assumptions have been made regarding the mass and/or luminosity of more exotic, cosmological objects (for example neutron stars and white dwarfs in binaries, magnetars, SN, hyper-novae, fast blue optical transients, and gamma-ray bursts), as indicated in SM III.

The SM provides the full mass and ER dataset as presented in the plots and discussed below, including comments (for example on the use of non-standard units in the original studies, ER being ER_{in} or ER_{out}, calculations necessary to achieve the required ER data) and the references to the original sources. Sometimes mass and ER data have been estimated (SM: under-lined) or obtained *via* preliminary calculations (SM: in italic; especially for “explosive” systems). For some groups of systems, ER data have been calculated for the lower and upper mass systems, using fitted ER *vs.* mass equations from the original studies These calculated values have been used instead of the tens to hundreds of individual data for practical reasons of data collection, to limit the size of the dataset, and to reduce the number of points in the master plot.

3. Distinction of (sub-)realms in master plot

3.1. General

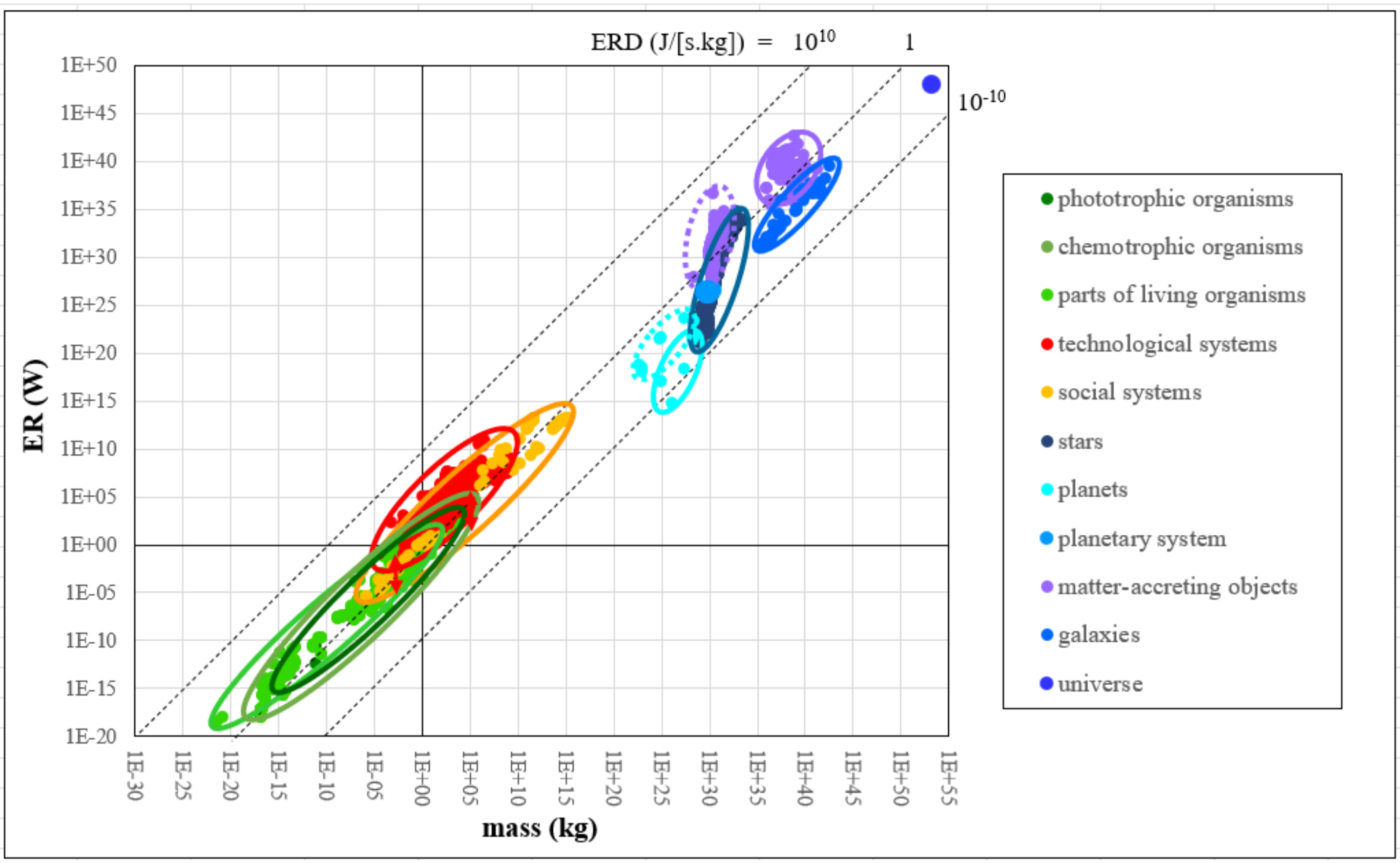
A first inspection of the consolidated dataset in the SM with around 3200 rows shows that the mass and ER data span a range from:

- $3x10^{-22}$ kg and $6x10^{-19}$ W for cytochrome oxidase, *i.e.,* the large transmembrane protein serving as the last enzyme in the respiratory electron transport chain in archaea, bacteria, and the mitochondria of eukaryotes [10], up to
- $1.5x10^{53}$ kg and 10^{48} W for the universe (only ordinary matter and stellar luminosity, respectively), which is the largest system that we can observe [77].

The data are distributed over the three realms as follows: 25 % biological, 40 % cultural, and 35 % cosmological. The use of fitted ER *vs.* mass scaling correlations for many groups of living organisms instead of the use of the original data for the individual organisms has strongly reduced the number of data for the biological realm. The distribution is not representative for the actual abundance of systems, but tells more about the practical availability of the ER and mass data (cf. comment on red and brown dwarfs in section 3.4) and the personal interest, but it is still well balanced.

When the ER data are plotted against the corresponding mass data on linear scales, the data points of all systems disappear in the origin of the plot and only one point, *i.e.,* that for the universe, is visible in the top right corner (Figure i in SM). To have an effective presentation of all ER *vs.* mass data in one plot and, thus, enable a meaningful comparison and discussion, both ER and mass data have been plotted on logarithmic scales with 10 as basis (Figure 1). All data points are now visible in one plot with the ER data covering a range of 66 orders of magnitude and the mass data 75 orders of magnitude. Additional advantages of such a double logarithmic plot are that the issues of data choices, mentioned in section 2, and possible errors in the data have only minor effects on the observations and trends. A disadvantage of a double-logarithmic plot is that small but significant differences in ER and mass data between systems, as well as true scatter in the data are suppressed and become invisible. Another disadvantage is that the logarithm

Figure 1: Double logarithmic plot of ER *vs.* mass for a wide variety of stable systems from the biological, cultural, and cosmological realms (green, red and blue data points, respectively). Diagonal, dotted lines of constant ERD of 10^{10}, 10^{0} (= 1) and 10^{-10} W/kg are guides to the eyes.



of zero is undefined and, thus, systems with ER = 0 cannot be presented in the plot (see section 6). As a consequence, the origin of the linear plot, characterised by both ER and mass values of zero, is lost in the double logarithmic plot. The origin of the latter plot corresponds to a system with ER and mass of 10^0 = 1 W and 1 kg, respectively.

The full plot of ER *vs.* mass with all the individual data points is enormously crowded and, thus, hard to read, while the overlap between the data points prevents a sensible discussion. Therefore, the data points in Figure 1 have been clustered for the biological (green ovals at lower, left side), cultural (red ovals in center), and cosmological sub-realms (blue ovals at upper, right side*5). The distinction between these three realms is not just following what is commonly used in BH [78], but emerges to some extent from the distribution of the data in the master plot itself. It seems that the different (sub-)realms can be distinguished not only in a qualitative way by considering their different material structure and energy processing, but also quantitatively by their ER *vs.* mass ranges and, thus, their positions in the master plot. Note that the various sub-realms correspond to groups of systems with the same type of material structures and energy processes, which distinguishes them from other groups. In the next sections descriptions of these (sub-) realms will be given with emphasis on the material structure and energy processing of the corresponding systems. Also some details on mass limitations, resulting in minimum and maximum masses for a particular sub-realm, will be mentioned. Three zoomed-in versions of the master plot for the biological, cultural, and cosmological realms will be presented in section 5, enabling more in-depth discussions. Table 1 provides an overview of the systems with the smallest and largest mass and ER values for each sub-realm. Note that often the system with the smallest mass also has the smallest ER and that with the largest mass has the largest ER, but this is not always the case.

3.2 Biological realm

The biological realm is situated on the lower, left side of the master plot with relatively low mass and ER values, ranging from:

- 3.3×10^{-22} kg and 5.8×10^{-19} W for cytochrome oxidase protein [10] to
- 2.5×10^5 kg and 1.1×10^4 W, as reconstructed for Triassic ichthyosaurs, a group of extinct super-predators [95], or
- alternatively, 1.2×10^5 kg and 4.4×10^4 W for the blue whale, the largest animal living today [96].

Note that even larger mass and ER values are listed for grass fields as well as plantations of pine and mahogany trees (SM Ia), but those values do not reflect individual systems, but groups of systems. Three biological sub-realms are distinguished, viz:

i) phototrophic organisms, powered by photosynthesis (Figure 1: dark-green points; SM Ia);
ii) chemotrophic organisms, feeding on other organisms (green points; SM Ib);
iii) smaller parts of living organisms of the other two sub-realms (light-green points; SM Ic).

Social colonies of living organisms are discussed in the cultural sub-realm (section 3.3).

Living, cellular organisms on Earth grow and are maintained by, amongst others, biochemical reactions with adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide (phosphate) as the intermediate energy carriers, proteins as the biochemical catalysts, as well as (deoxy) ribonucleic acid polymers ([D]NA) for storing information [97,98]. Biochemical energy is required to perform not only all the biological functions, such as maintenance, repair, response to stimuli, growth, and reproduction, but also for mechanical movement. The structure of living organisms consists of organic chemicals and polymers, such as carbohydrates, proteins, and fats based on carbon (C), hydrogen (H), oxygen (O), and nitrogen (N), often combined with calcium-based minerals (shells, bones). Liquid water (H_2O) is a major component of living organisms, acting as transport and reaction medium. Two sub-realms of living organisms with different energy processes are distinguished. First, phototrophic organisms (cyanobacteria, green algae, plants, and trees; Figure 1: dark-green oval) derive their chemical energy from radiant energy (Sun light) *via* photosynthesis, converting CO_2 and H_2O to carbohydrates and O_2. Secondly, chemotrophic organisms (many archaea and bacteria as well as fungi and animals; green oval) typically derive their chemical energy from O_2 used as oxidant [99], though sometimes from nitrite, nitrate and sulphate, for the oxidation of reducing chemicals. The latter can either be inorganic (iron[II], H_2, sulphide, sulphur, ammonia, and nitrite), as well as organic of character (carbohydrates, proteins, and fats produced by the phototrophic organisms). Note that the C-based building blocks of living organisms are derived from simple chemicals, typically CO_2, for autotrophs, but from organic chemicals, such as carbohydrates and proteins, for heterotrophs. Chemoheterotrophic organisms use organic matter both as energy source and raw material for their structure. Note that the "food pyramid" combines both energy and C processing in one scheme with:

- cyanobacteria, algae, plants, and trees as primary pro-

*5. These colour codes will be used consistently throughout this paper.

Table 1: Mass and ER data of systems with smallest and largest mass and energy rate from all (sub-)realms in dataset[#].

realm	sub-realm	smallest system	mass (kg)	ER (W)	ref.	largest system	mass (kg)	ER (W)	ref.
biological	phototrophic organisms	*Gloeobacter violaceus* and *Coccochloris peniocystis* cyanobacteria	$7x10^{-16}$; 10^{-15}	$2.0x10^{-14}$; $8.5x10^{-15}$	17	large tree in darkness (no photosynthesis)	5200; 4700	200; 450	79, 112
	chemotrophic organisms	*Francisella tularensis* bacterium	10^{-17}	$9.9x10^{-18}$	17	Triassic ichthyosaur; blue whale *	$2.5x10^{5}$; $1.2x10^{5}$	$1.1x10^{4}$; $4.4x10^{4}$	95; 96
	parts of living organisms	cytochrome oxidase protein	$3.3x10^{-22}$	$5.8x10^{-19}$	10	human skeletal muscle; *Meleagris gallopavo* bird muscle during take-off flight	27; 0.72	14; 7800	80; 17
cultural	technological systems	integrated circuit of Intel 4004	$2x10^{-5}$	0.12	81	Eemshaven power plant; Saturn V space rocket	10^{9} $; $2.8x10^{6}$ @	$1.6x10^{9}$; $1.2x10^{11}$	82; 83&84
	social systems	beehive with 2000 bees	1.7 ##	0.93	21&67,SM IIb	human society in 2019	$1.1x10^{15}$ **	$1.9x10^{13}$	72&73
cosmological	stars	SIMP 0136+0933 and J1237+6526 ultra-cool, brown dwarfs	$4.4x10^{28}$; $7.8x10^{28}$	$9.0x10^{21}$; $1.7x10^{21}$	85	Westerhout 49-2 ultra-massive star; Godzilla variable star $$	$5.0x10^{32}$; $$	$1.7x10^{33}$; $7x10^{34}$	86;87
	planets	Earth and Uranus	$6.0x10^{24}$; $8.7x10^{25}$	$1.3x10^{17}$; $7.1x10^{14}$	88; 110	HR 8799 b&c and 2M1207 b exoplanets	$1.9x10^{28}$; $1.5x10^{28}$	$7.6x10^{21}$; $1.2x10^{22}$	89
	matter accreting objects	VW Vul and V1454 Cyg white dwarf binaries in accretion	$7.0x10^{29}$; $1.5x10^{30}$	$4.0x10^{30}$; $1.1x10^{27}$	55	PKS 1502+106 blazar; PKS 0558 -504 active galactic nucleus	$8.7x10^{39}$; $6.0x10^{38}$	$2.0x10^{39}$; $5.6x10^{42}$	90; 91
	planetary system	@@				Solar system	$2.0x10^{30}$	$3.8x10^{26}$	92
	galaxies	dw 1312-4218, dwarf galaxy	$3.0x10^{35}$ ###	$3.1x10^{31}$	93	giant elliptical galaxy	$3.0x10^{42}$ ###	$3.8x10^{39}$	94
	universe	@@				observable universe	$1.5x10^{53}$ ***	10^{48} ***	77

As present in dataset, *i.e.,* not *per se* system with smallest or largest mass or ER of all existing systems; * extinct and living today, respectively; $ rounded off mass of concrete, piles, cable, and steel; @ fully fuelled at lift off; ## mass of just bees without beehive: 0.23 kg; ** including human-made mass in use; mass of just humans without human-made mass: $3.5x10^{11}$ kg; $$ Godzilla is most luminous star ever observed; mass is not known; @@ only one example listed; ### only ordinary matter (dark matter excluded); *** only total stellar mass and luminosity (dark matter/energy, SN, gamma-ray bursts and black holes excluded).

ducers at the bottom level,
- herbivores and carnivores as consumers at subsequent higher levels, as well as
- fungi and bacteria as detritivores, recycling dead organic matter from all levels back to the environment again.

A further sub-distinction of living organisms is made between the three domains of cellular life, *i.e.,* the archaea, bacteria, and eukaryotes with differences in cellular structure, genetic code and chemical structures of cellular organelles. The former two domains consist of unicellular organisms only, whereas the latter consist of both uni- and multicellular organisms, including fungi, plants, and animals. From an energy perspective, warm- and cold-blooded animals (endo- *vs.* ectotherms) are distinguished. Note that for the latter, heat is not considered as lost, free energy, but as useful energy for optimum performance and survival. Finally, the third biological sub-realm consists of smaller parts of living organisms, such as molecular complexes, organelles, cells, and (parts of) organs (light-green oval).

Living organism have lower and upper mass limitations, which delimitate the borders of the ER & mass ovals of the phototrophic and chemotrophic sub-realms in the horizontal direction of the master plot. The smallest unicellular organisms and single cells of multicellular organisms have a lower mass limit of around 10^{-18} kg. This probably corresponds to the minimum cell size, which still contains all the necessary biochemical systems resulting from biological evolution and still allow the DNA in the nucleus to fit in [100]. The maximum cell size is 10^{-7} kg, because the cell's surface area becomes limiting for mass transfer and the diffusion distances become too long [19]. The minimum mass of mammals is determined by restrictions in laminar flow through the terminal capillaries of their branched, vascular transport networks, which thus corresponds to ER limitations [10]. Shrews have a mass of 2.5×10^{-3} kg just above the predicted, lower mass limit of around 10^{-3} kg. On the other extreme, elephants as the largest animals living on the land have a mass of 4000 kg, because of limitations of mass (corresponds to volume and scales with dimension to power three) *vs.* bone strength (corresponds to cross-section and scales with dimension to power two) [101]. The fictional Godzilla would simply collapse under its own weight. It has been calculated that extinct dinosaurs had even larger masses up to 2.5×10^{5} kg for the Triassic ichthyosaurs [95], which is probably explained by their ectothermal metabolism and unique bone structure with air sacs. Blue whales with a mass of 1.2×10^{5} kg are the largest, living marine animals, which is close to the theoretical mass limit of 10^{5} kg resulting from quadratic scaling of ER *vs.* mass [102]. The reconstructed weight of the extinct *Perucetus colossus* whale is 1.8×10^{5} kg is above the theoretical maximum though [187]. Energy constraints also predict a maximum mass of 17 kg for birds to maintain flight [32]. Indeed, larger males of the kori bustard, the largest flying bird today, weigh 16 to 19 kg with exceptional birds reported to weigh 20 kg [188]. Ostriches, emus and extinct dodos have masses above this limit, but these birds cannot truly fly. Extinct pterosaurs were flying mesotherms and weighted up to 250 kg [189].

3.3. Cultural realm

The cultural realm is situated in the center of the master plot in between the biological, and cosmological realms with intermediate mass and ER values (Table 1), ranging from:
- 2×10^{-5} kg and 0.12 W for the integrated circuit (IC) of the Intel 4004 CPU [81] to
- 1.1×10^{18} kg and 1.9×10^{13} W for the industrialised society of today [72].

Two cultural sub-realms are distinguished, viz.:

i) human-made technological systems, used for all sorts of energy conversions (Figure 1: red points; SM IIa) and

ii social systems, combining living organisms from the biological realm and for human social systems also with technological systems (orange points; SM IIb).

First, technological systems have driven the human revolution and are essential today for converting free energy to useful work. Many of the technological systems have mechanical energy as output, as in steam locomotives, motorcycles and cars on land, boats and ships in water, airplanes and rockets in air, as well as pumps and compressors for transporting fluids and gasses. Chemical energy from fossil fuels is converted to thermal energy as useful energy intermediate, which is converted to mechanical energy in the combustion engines of the vehicles mentioned above. Alternatively, thermal energy is first converted to electric energy in generators and power plants. Electric energy is also generated from nuclear energy in radio-active compounds, kinetic energy as in the case of hydro (dams and water mills) and wind energy (windmills), as well as Solar radiant energy (solar panels). Electric energy is a very versatile energy type, easy to transport, as well as can be stored in batteries and fuel cells. It is easily converted to mechanical energy in the same vehicles mentioned above, as well as in many smaller household appliances and electric tools. Electric energy is also used for heating (room heater, bread toaster, electric oven), and lighting (incandescent and light-emitting diode [LED] lamps), as well as powering today's communication (telephones), computation (computers), and information technologies (radio, television, and again computers). Simple tools, such as a knife, hammer, and hand saw, are excluded here, because these by themselves have ER = 0 and require human, physical activities for their operation. All these technological systems have a designed, material structure, composed of (many) parts providing specific functions to the system. Materials used in technological systems typically comprise metals, mainly iron and aluminium for structural parts as well as copper for electrical wiring, often combined with plastics and glass. The lower mass of technological systems is limited by their production technologies. It has decreased over time as a result of downsizing, as is illustrated by the size of today's smallest IC being determined by the wavelength of the laser used (micro-chips with 3 nm nodes using 13.5 nm extreme ultra-violet laser [103]). There are even smaller technological systems, viz. molecular nano-machines with molar mass as low as 450 atomic units (au) corresponding to 7.5×10^{-25} kg. This mass is 450 times smaller than that of the natural cytochrome oxidase protein (2×10^{5} au ~ 3.3×10^{-22} kg) and may be close to an absolute, lower limit of energy processing systems (a certain number of atoms will be needed to generate a system with the emergent property to process energy). These are synthesised bottom-up from small chemical building blocks [104], but unfortunately ER data are not available. The maximum mass of many machines (ship, airplane, rocket, crane *etc.*) is typically limited by:

- size *vs.* strength maxima, as detailed by Bejan's constructal law, *i.e.*, the design of systems and their development over lifetime and evolution is result of the optimisation of physical forces and energy flow [105], and
- size *vs.* cost effectivity.

In principle, there seems to be no maximum limit for the size of factories and production plants built on the surface of our planet.

Secondly, social systems correspond to collectives of living organisms from the biological realm. Insect colonies are typically characterised by enhanced energy efficiency, as a result of collaboration between and specialisation of the individuals, as well as a hierarchical organisation of the colony as a whole. Insect colonies are often characterised by constructs build to live in, such as hills for ants, hives for bees, and mounds for termites. These constructs do have a certain mass, but do not consume energy. Our human society has evolved further and consists of not only human individuals, as well as buildings and constructions, but also exploits domesticated plants and animals for chemical energy in food. In addition, pack animals are exploited for generating mechanical energy for ploughing, transporting, and milling. From an energy perspective, our human society combines these living organisms, which process biochemical energy, with technological systems from the technological sub-realm, which process predominantly chemical energy from fossil fuels. Characteristic institutes and functions of today's human society, such as households, cities, nations, education, communication, leisure, industry, trade, administration *etc.* all continuously require energy (see above). In addition to the materials used for the construction of technological systems, human society is characterised by its buildings and constructions, which mainly consist of stone, concrete, bitumen, but also steel, plastic, wood, and glass. They are typically characterised by large mass, but low or no ER. The lower mass limit of social systems is determined by the number of individuals of the smallest social system, which still shows some sort of economy of scale. The upper limit is probably determined by the availability of resources, *i.e.,* raw materials and energy, as for example explored for the human society in the "Limits to Growth" study (1972), as commissioned by the Club of Rome, and its more recent updates including "People and Planet" (2023).

3.4. Cosmological realm

The cosmological realm is situated in the upper, right corner of the master plot with very large mass and ER values (Table 1), ranging from:

- 6×10^{27} kg and 1.3×10^{17} W for our Earth [88] and
- 10^{53} kg and 10^{48} W for the Universe as a whole [77].

Six cosmological sub-realms are distinguished (Table 1):

i) stars fuelled by nuclear fusion (Figure 1: steel-blue points; SM IIIa);
ii) spherical planets with flow patterns and in orbits around stars (light-blue points; SM IIIb);
iii) planetary systems (large blue point; SM IIId);
iv) matter-accreting objects, including stellar remnants in binaries and (super-massive) black holes (purple points; SM IIIc);
v) galaxies (blue points; SM IIIe);
vi) the observable universe itself (large, dark blue point; SM IIIf).

The structures, dynamics and energy processing mechanisms of the systems from the first three cosmological sub-realms are well-understood, whereas those from the last three sub-realms these are currently less understood [106,107].

The first sub-realm consists of stars, which are self-radiating, cosmological objects which are powered by nuclear fusion. The structural matter of active stars, *i.e.,* mainly hydrogen (H), some helium (He), and even less of the heavier elements ("metals"), is also the star's source of nuclear energy. Stars have such a high mass that gravitational collapse has resulted in core temperatures above 10^{7} K, resulting in its turn in ignition of nuclear fusion. Nuclear energy is converted to thermal energy, which in its turn is converted to radiant energy at the star's surface. In red, orange, and yellow dwarf stars in the MS with masses larger than $1.6x10^{29}$, H is fused to He. The outward thermal pressure balances the inward gravitational force, resulting in stable stars in hydrostatic equilibrium (balance between self-gravity and rigid body forces). Brown dwarfs with lower masses between $2.5x10^{28}$ to $1.6x10^{29}$ kg are considered failed stars with temperatures reaching up to 10^6 K. They still ignite nuclear fusion albeit not of H to He but of deuterium and sometimes lithium to He, *i.e.,* just a different type of nuclear fuel. Objects with a mass below $2.4x10^{28}$ kg will not reach sufficiently high temperatures and, thus, nuclear fusion will not be ignited. These objects will not become stars, but planets (see below). In (sub-, bright, super-, and hyper-)giant stars in the giant branches outside the MS, He is fused to heavier nuclei (C, N and O), and, sometimes, these are fused further to even heavier metals, such as neon, magnesium and silicon up to iron. Depending on the starting mass and life time, stars may consist of different shells, either convective or radiative as well as varying in elemental enrichment. There is no accepted mass limit for stars, but the largest star ever observed, viz. Westerhout 49-2E, has a mass of $5.0x10^{32}$ kg. It is hypothesised that many of the first generation stars were super-massive stars with masses up to10^{34} kg [108]. Eventually when the nuclear fuel is consumed, nuclear fusion in all these stars will terminate and the stars themselves will convert to stellar remnants, such as:

- compact objects including white dwarfs (1.0 to $2.8x10^{30}$ kg; composed of partially crystallised C and O), neutron stars (2.8 to $6x10^{30}$ kg; all protons and electrons converted to degenerate neutrons), and black holes ($>6x10^{30}$ kg), as well as
- hypothetical blue and black dwarfs.

Compact, stellar remnants in isolation are just fading away, whereas in proximity of other objects they may form matter-accreting objects (see below). Note that red and brown dwarfs with relatively low ER & mass combinations are hard to observe, but probably make up 90 % of all the stars.

The second cosmological sub-realm consists of planets, which are defined as objects without nuclear fusion, in orbits around a star (note that so-called rogue planets, not gravitationally bound to a star and wandering in interstellar space, may outnumber planets in stellar orbits), as well as with sufficient mass to assume hydrostatic equilibrium, have a (nearly) round shape, and having cleared the neighbourhood around their orbit [109]. Gravitational forces are governing both the orbits and shapes of planets. The light-blue oval represents planets today, whereas the dotted, light-blue oval represents much hotter planets in their formative stage. The lower mass of planets ($\sim 6x10^{23}$ kg) is determined by the occurrence of hydrostatic equilibrium, while the upper mass limit (around 13 times mass of Jupiter $\sim 2.4x10^{28}$ kg) is determined by the absence of any nuclear fusion. Gas giants, like Jupiter and Saturn, are most distant from their central stars. They are thought to consist of an outer layer of compressed H_2 surrounding a layer of liquid, metallic H_2, with probably a molten rocky core inside. Ice giants, such as Uranus and Neptune, are primarily composed of low-boiling-point materials such as water, methane, and ammonia, with thick atmospheres of H_2 and He. Rocky planets, such as Mercury, Venus, Earth, and Mars, are most proximate to their central stars. These are composed primarily of silicate rocks and metals, organised in various liquid and solid layers. In astronomy, planets are typically considered as inactive objects, because they lack nuclear fusion in contrast to stars. However, most planets are characterised by:

- a stable, elliptical orbit around their central star and rotation around their polar axis, resulting from balanced kinetic and gravitational energies;
- convection flow patterns in their atmospheres, oceans and/or molten interiors, driven by temperature gradients, resulting from the cooling of the hot proto-planets, radio-active decay and infalling stellar radiation;
- recognisable climate zones and seasons, day & night cycles and weather patterns as well as stable magnetic fields.

Such planets are here viewed as active systems and included as a second, cosmological sub-realm. Our Earth is an illustrative example with an elliptical orbit around the Sun of 365 days of 24 hr, while the Moon orbits around the Earth in ~30 days. Hadley, Ferell, and polar circulation cells as well as jet streams and trade winds (both driven by the Coriolis force) in the Earth atmosphere govern the global climate zones, the local weather and the water cycle. The thermohaline circulation determines the gulfstreams in the oceans. Magma convection cells govern the plate tectonics (these not only determine the Earth surface topology, but also the subduction and recycling of minerals, water and C), the spinning of the inner, metallic core and the convection currents in the outer, metallic core, thus generating the Earth magnetic field. The Earth surface provides the geosphere, *i.e.,* the lithosphere, cryosphere, hydrosphere, and atmosphere, for living organisms and cultural systems from the previous two sections.

Planetary systems, consisting of planets (with moons and rings), orbiting around a central star in a plane, plus asteroids and comets, are hold together by gravitational forces and comprise the third sub-realm. ER and mass data are listed for just one planetary system, viz. our Solar system. As explained in section 4, ER and mass of the Solar system and, probably, of all other planetary systems are governed by the ER and mass of our Sun and their central stars, respectively. Thus, the corresponding data points overlap and cannot be distinguished in the master plot (Figure 1: large blue dot for Solar system overlapping with point for the Sun in the middle of oval of star points).

Compact objects, powered by the accretion of matter, comprise the fourth sub-realm. These consist of:

- stellar core remnants in binary systems, such as white dwarfs (1.0 to 2.8x10^{30} kg [Chandrasekhar limit]), neutron stars including pulsars and magnetars (2.8 to 6x10^{30} kg), accreting matter from a companion star, and
- (super-massive) black holes (mass above 6x10^{30} kg to as high as 10^{40} kg), accreting all matter from their galactic surroundings, including gas and dust as well as stars.

Two purple ER & mass ovals represent these two types of matter-accreting objects in Figure 1 (dotted for stellar remnants). White dwarfs and neutron stars have very small diameters (~10^7 and 2x10^4 m, respectively) and, thus, are extremely dense objects (~10^9 and 5x10^{17} kg/m^3, respectively). (Super-massive) black holes have such extreme densities that their centers are considered as singularities, where the laws of physics break down. No light nor matter can escape beyond their event horizons. They are characterised by their mass, electric charge and spin rate. Super-massive black holes (SMBH: mass above 2x10^{36} kg), including active, galactic nuclei, quasars and blazars, consist of a disc of accreted matter with strong magnetic fields shaping two perpendicular plasma jets, and probably emit Hawking's radiation. They are typically found in the center of galaxies. For all these systems, gravitational energy from the attraction of matter by the very dense object is converted *via* kinetic energy of the collapsing matter colliding into each other, and, subsequently, heat to radiant energy.

The fifth cosmological sub-realm consists of galaxies, such as our Milky Way, Andromeda and Whirlpool. These are large, gravitationally bound systems composed of stars (single, binary or multiple stellar systems), stellar remnants, and other objects from planetary systems, as well as interstellar gas and dust, typically rotating around a SMBH in their centers. Galaxies are elliptical, lenticular, (barred) spiral or irregular shaped. Two groups of galaxies are distinguished depending on their colour as an indicator for star formation, viz. blue star-forming (mainly spiral) and red, quiescent (mainly elliptical) galaxies. Hot gas is expelled by galaxies *via* strong stellar winds, SN explosions and SMBH jets. It may be transported back to the galaxy upon sufficient cooling and subsequent density increase in the circum- and intergalactic media, facilitating renewed star formation [195]. SMBHs and galaxies co-evolve [196]. The SMBH attracts and accretes matter from its host galaxy, but also ejects energy into it. It seems to affect the distribution of chemicals in the galaxy and star formation in the galactic center [197]. Galaxies can be viewed as the stellar "nurseries" and metal-generating "machines" in the universe with stars converting H and He to heavier elements in a continuous cycle of stellar birth and death. The ER & mass oval of galaxies is positioned at the upper, right of that of stars and to the lower, right to that of matter-accreting objects, as a result of convergence. Galaxy (super-) clusters have not been included as separate sub-realms, because of the lack of available ER data.

The observable universe is the sixth and final, cosmological sub-realm and comprises all the cosmological objects visible from Earth and, thus, combines all galaxies and the intergalactic medium. Its "foamy", large-scale structure consists of "empty" bubbles surrounded by filaments of galaxies and dark matter connected by nodes of galaxy clusters, *i.e.*, the cosmic web. The universe is not gravitationally bound and expanding at an accelerating rate, due to the action of dark energy. The ER & mass point of the universe is more or less an extrapolation of the elongated galaxy ER & mass oval, when dark matter and energy are excluded.

In summary, the huge amount of mass and ER data collected for the very large number of systems span enormous mass and ER ranges over 67 and 75 orders of magnitude, respectively, necessitating a double-logarithmic plot for a sensible presentation of the data in the master plot. The data points of the biological, cultural and cosmological realms cluster for the various sub-realms. This shows that these sub-realms are not only distinguished qualitatively by their material structures and energy processes, but to some extent also quantitatively by their ER *vs.* mass data. Note that for stars and matter-accreting objects, matter not only provides the structure to the systems, but also the energy powering the system (nuclear and gravitational energy, respectively). In contrast, the matter of the structures of living, technological and social systems is separated from the fuel used as energy source.

4. Systems parallel to the ER *vs.* mass diagonal

In a first approximation, the ER *vs.* mass data points of all systems seem to follow the y = x diagonal from the lower, left corner to the upper, right corner of the master plot in Figure 1. Indeed, prokaryotes (unicellular archaea and bacteria) and unicellular eukaryotes with very small masses have very small ER, while cosmological systems with very large masses have very large ER. Often the system with the smallest mass in a particular sub-realm also has the smallest ER and, *vice versa*, that with the largest mass has the largest ER (Table 1). However, in the cultural realm machines like space rockets and jet aircrafts, engines, and generators, as well as ICs and CPUs have relatively large

ER for their mass. In contrast, human social systems, such as cities and the human society as a whole, have relatively low ER for their mass. This demonstrates that there are other factors than just mass that determine ER. As a matter of fact, the data points in Figure 1 do not fall on the y = x diagonal line, but in a broad, diagonal band with a vertical and horizontal width of approximately 17 ER and mass orders of magnitude, respectively. Similarly, the ovals that represent the clusters of datapoints, belonging to systems of the same sub-realm, are oriented with their longitudinal axis more or less in parallel to the y = x diagonal. Such a positioning of (groups of) data in one diagonal band may be somewhat surprising on first sight, since the systems in the various (sub-)realms are characterised by very different material structures and energy processes. However, the observed diagonal positioning is simply the result of:

1) the convergence of small sub-systems (parts) with low mass and ER into larger systems with higher mass and ER, which in their turn converge into even larger super-systems with even higher mass and ER *etc.* and
2) the scaling of ER with mass for groups of systems (see below and section 5).

Convergence is the result of complex systems being thermodynamically defined as open systems, requiring the inflow of matter and energy, as well as the outflow of waste and heat through its boundaries from and to its environment, respectively. The latter can then be viewed as the larger system. Admittedly, no complex system can exist fully independent of its environment and, thus, a system always converges into a larger system. Such a sequence of converging systems corresponds to a nested hierarchy of complex systems with the next-level system often showing new, emergent functions and performance. The small systems converging into a larger system may be similar and dissimilar, as illustrated by the following examples (the systems in *italic* are not listed in SM nor shown in the master plot; the starting systems are simple, physical systems with ER = 0):

- biological realm: *C, H, N, O atoms* → cytochrome oxidase protein + *other biomolecules* → respiratory complex; + *other associates* → mitochondrion; + *other organelles* → neuron; + *other cells* → cerebellar cortex; + other brain regions → brain; + other organs + tissues + *bones* + *fluids* + gut bacteria → human body;
- technological sub-realm: *metals, polymers, and glass* → engine + pumps + battery + lamps + radio + *chassis* + *body panels* + *tubes* + *many other parts* → automobile, truck, and bus;
- social sub-realm:
  - bees + beehive → bee colony;
  - human individuals + machines + *buildings and constructions* → city; + other cities + *farms with* cattle and crops + power *and chemical plants* + *roads* + *railways* + *other human-made constructs* → today's, global human society;
- cosmological realm: *H/He plasma* → Sun; + planets + moons + asteroids → Solar system; + *other planetary systems* + stellar remnants + SMBH + *interstellar medium* → Milky Way; + other galaxies + *intergalactic medium* → universe.

The larger, next-level system does not only have a larger mass, but also requires a larger ER to maintain its larger structure and complexity, which consequently shows up as a shift to the right and up more or less parallel to the y = x diagonal in the ER *vs.* mass master plot. When the sub-systems hardly interact and collaborate, the mass and ER values can simply be added up, yielding the mass and ER of the larger system. When the sub-systems do interact and collaborate, the mass of the larger system is still the sum of the masses of the sub-systems. However, ER is not simply the sum anymore but will typically scale according to some power law with mass (see section 5). Both mass and ER values of the next-level system may be dominated by one very large sub-system. For example, the mass and ER of the Solar system is dominated by the Sun with negligible contributions of the numerous but much smaller planets, moons, and asteroids. Thus, the ER & mass point of the Solar system coincides essentially with that of the Sun. Alternatively, the mass and ER values of the next-level system may be dominated by a large number of smaller sub-systems with hardly any contribution of the largest sub-system. For example, the mass and ER of a galaxy is dominated by the huge number of dwarf stars, which have relatively low mass and low luminosity. The very massive and luminous, SMBH at the galaxy center has a negligible contribution. Thus, the ER & mass points of galaxies are positioned to the right of the datapoints of SMBHs and more or less in a diagonal extrapolation of the ER & mass datapoints of stars. A next-level system may also contain inactive sub-systems with a certain mass but with ER = 0 in addition to active sub-systems. Such a system will have a total mass derived from both the inactive and active sub-systems, but an ER derived from the active sub-systems only. For example, the mass of an automobile is the sum of many parts (chassis, panels, wheels, engine *etc.*), but its ER is just determined by the engine and its fuel consumption. Therefore, the ER & mass point of a car is simply to the right of that of the engine. Similarly, the mass of our world system today is dominated by buildings and constructions that do not have any ER, whereas its ER is the sum of the contributions of fuel for machines, industrial plants *etc.* and food. As a result, the ER & mass point of our human society is positioned far to the right of the ER &

mass datapoints for technological systems and the human body. The combined result of all these different types of convergences is that the ER & mass points are not perfectly aligned parallel to the y = x diagonal line, but fall in a diagonal band with a certain width.

Note that as a result of convergence of sub-systems into larger systems, the distinction between the various biological, cultural, and cosmological (sub-)realms becomes somewhat fuzzy. Living organisms with social behaviour, such as ants, bees, and humans, form colonies and, thus, are considered to be part of the cultural realm. Our human society comprises not only human individuals, but also includes other living organisms. Plants and trees, cattle and fish, but also bacteria and fungi are exploited for food (production), construction materials, mechanical power, pets, medicines, and other purposes. In addition, all the machineries from the technological sub-realm are included. All these biological and cultural systems are present on the surface of the Earth with the Sun as main energy source. Therefore, these are part of the Solar system, and subsequently of the Milky Way with the universe as the terminal system of convergence through all realms.

The correlation of ER with mass parallel to the y= x diagonal as a result of convergence and scaling in a way explains why Chaisson has proposed to normalise ER to mass, yielding ERD (= ER/mass) as a suitable metric for complexity [5]. By definition the diagonals in the ER *vs.* mass master plot correspond to iso-lines of constant ERD, similar to diagonals of constant density in a plot of mass *vs.* volume. In Figure 1 such diagonals for constant ERD of 10^{10}, 10^{0} (= 1) and 10^{-10} W/kg have been drawn to guide the eyes. The distance between the two ERD diagonals encompassing all datapoints from all systems in Figure 1 corresponds to the range of ERD values of these systems, which spans 17 orders of magnitude from 8.2×10^{-12} W/kg for Uranus [110] to 6.1×10^{5} W/kg for the IC of the modern Intel Core i7 CPU [81]. Note that ERD of a larger system is not obtained by summing all ERD's of the individual sub-systems, but by ratioing the total ER and total mass of all sub-systems, but is a weighted average.

In summary, the ER & mass data points follow a broad diagonal band in the master plot. This is the combined result of convergence of small systems with low ER and mass values to larger systems with higher ER and mass values as well as of scaling of ER with mass for groups of systems (next section). The width of this band corresponds to ERD values varying over 17 orders of magnitude.

5. Scaling

5.1. General

When zooming in on the ER *vs.* mass master plots for the various realms, correlations between the logarithmic ER and mass data are observed for quite some groups of systems. Typically, such scaling is captured *via* so-called power laws [101]:

$$ER = \alpha \text{ mass } \beta.$$

with β is the power law constant (dimensionless) and α is the proportionality constant, which in a way reflects the intrinsic energy requirement of a group of systems. With kg and W as units for mass and ER, respectively, α is the group's ER at 1 kg mass (in J/[s.kg$^{\beta}$]). Note that a power law assumes that there is no energy flow (ER = 0) at mass = 0, *i.e.,* the correlation of ER *vs.* mass always goes through the origin of the linear ER *vs.* mass plot. In a double logarithmic plot as in Figure 1, the power law becomes:

$$\log ER = \log \alpha + \beta \log \text{mass}.$$

A system composed of sub-systems without any interaction and collaboration is characterised by simple additivity of the individual mass and ER contributions of the sub-systems. This results in linear scaling (β = 1), which in a linear plot shows up as a linear correlation with the slope α corresponding to a constant ERD. In a double logarithmic plot, linear scaling shows up as a linear correlation parallel to the y = x diagonal with an intercept of log α. In contrast, a group of systems composed of interacting parts shows non-linear scaling ($\beta \neq 1$). Sub-linear scaling with $\beta < 1$ results typically from collaboration, economy of scale, and increased efficiency for the larger system as a whole. It is indicative for self-organising behaviour[6], following a single, underlying mechanism [101]. The opposite, super-linear scaling with $\beta > 1$ results from diminishing returns, decreased efficiency and bureaucracy. Accordingly, in a linear plot sub- and super-linear scaling show up as concave or convex curves of ER as a function of mass, respectively. In a double logarithmic plot, ER shows a linear correlation with a slope less or more steep, respectively, than the y = x diagonal. Note that in the case of sub- and super-linear scaling for a group of systems, ERD of the individual systems is not the same, but varies with mass. Also note that super-linear scaling should not be confused with exponential behaviour, as in:

$$ER = a\, e^{b.\text{mass}}$$

with e is Euler's number (2.72).

A non-comprehensive overview of scaling results of ER *vs.* mass for groups of systems in the various realms is presented in Table 2, with a particularly large number of examples from the biological realm. For the scaling of ER

6 Note that the term "self-organising" is somewhat misleading, as the organisation of sub-systems in a larger system does not happen spontaneously, but requires matter, energy and information inflow [5,6].

Table 2: Overview of power law constants β and proportionality constants α for scaling of ER *vs.* mass for groups of systems from various (sub-)realms. Logarithms of ER and mass data from original studies have been refitted with a linear regression model.

realm	sub-realm	group of systems	power law constant β (-)	proportionality constant (W/kg$^{\beta}$)	reference
biological	phototrophic	cyanobacteria #	1.12	123	18
		eukaryotic micro-algae #	0.99	6.6	
		vascular plants: tree saplings #	1.02	14	
		vascular plants: seedlings #	1.06	2.1	
		above-ground plants and trees #	0.84	0.14	79
		whole plants and trees #	0.86	0.13	
	chemotrophic	flat worms (single species)	0.74	0.024	111
		prokaryotes*: active	1.93	3.4×10^{15}	19
		protists$: active	1.02	22	
		metazoans##: active	0.80	0.31	
		ectotherms	0.84	0.33	62
		mesotherms	0.76	1.7	
		endotherms	0.75	3.4	
		dinosaurs	0.82	0.58	
		polar mammals	0.70	4.6	112
		desert mammals	0.76	3.3	
		insects	0.81	0.6	
		ants	0.56 to 0.83	0.014 to 0.47	22
		bees in rest	0.60	0.097	113
		bees in flight	1.08	72	
		flightless birds	0.81	3.3	112
		birds and bats in rest	1.13	48	114
		birds and bats in flight	0.78	52	
cultural	technological	(turbo-) propellor airplanes	1.13	69	32
		jet transport planes	0.98	1200	
		ornithopters	0.92	66	
		model airplanes	1.53	250	
		internal combustion engine vehicles	0.97	60	115
		hybrid vehicles	1.02	25	
		full electric vehicles	0.87	33	
		container ships	0.88	5.4	116
		tanker ships	0.50	1800	117
	social	colonies of various ant species	0.60 to 0.79	0.23 to 11.2	22
		bee colonies	0.70	2.6	21,SM

		bee colonies with beehive and honey	0.64	0.6	21,67,SM
		city with population	1.11	5.4	23,SM
		city with population as well as buildings and constructions	0.86	0.57	
cosmological	MS stars	mass < $8.6x10^{29}$ kg	2.3	$1.8x10^{-44}$	118
		$8.6x10^{29}$ kg < mass < $4.0x10^{30}$ kg	4.0	$4.8x10^{-96}$	
		$4.0x10^{30}$ kg < mass < $1.1x10^{32}$ kg	3.5	$5.9x10^{-80}$	
		$1.1x10^{32}$ kg < mass	1.0	1.21	
	galaxies	dwarf galaxies	0.97 and 1.08	$1.2x10^{-3}$ and $1.3x10^{-7}$	93,119
all data**			0.92	37	

in darkness, *i.e.,* respiration, but not photosynthesis; * comprising archaea and bacteria; $ corresponding roughly to unicellular eukaryotes; ## small, multicellular, aquatic animals; ** excluding data for "dead", "explosive" and "unrealistic" systems.

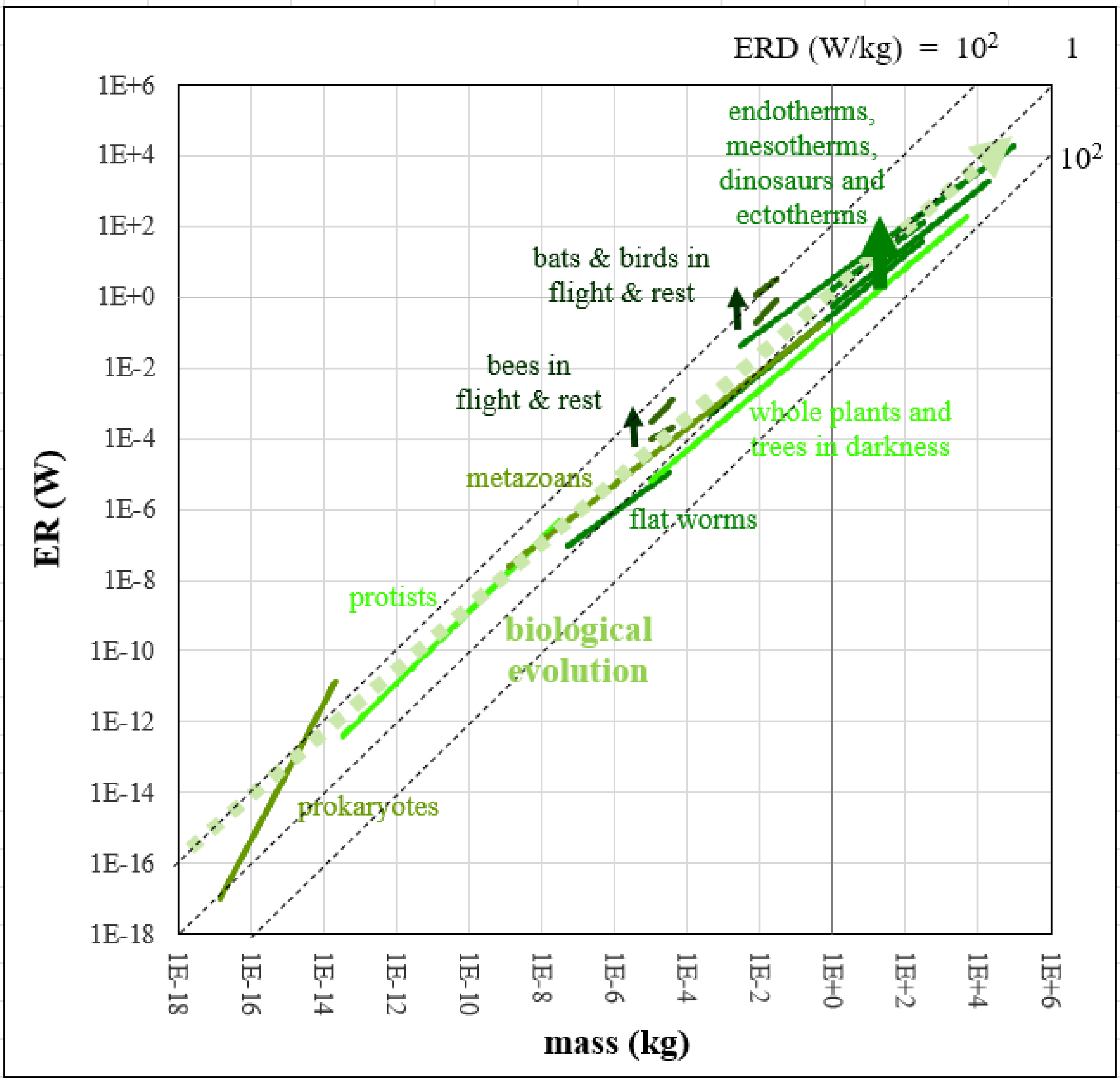
vs. mass data with a power law, the logarithms of the ER and mass data have been fitted *via* linear regression, yielding the power law constant β and the proportionality constant α. Because of this re-fitting of the data plus the use of W and kg as units, the β and α constants listed here may deviate from those reported in the original studies. Note that the power law fits suggests good scaling, but in reality there may be quite some scatter of the ER data around the scaling correlation, sometimes as large as one order of magnitude. Emphasis in the discussion will be on a comparison of the power law constants β. A comparison of the proportionality constants α only makes sense when system groups have the same β. For selected examples, the actual scaling correlations are shown in zoomed-in versions of the ER *vs.* mass master plot (Figures 2 to 4). Note that scaling is only appropriate for a group of systems which are qualitatively similar, *i.e.,* with comparable material structures and energy processes, and in comparable stages of their lifetimes and evolutions. Data for (groups of) systems over their lifetimes and evolutions should not be used for scaling purposes. The systems in such groups are not only different in a quantitative fashion in terms of ER and mass, but also in a qualitative fashion, because of growth, development, and evolution, resulting in a change of α and/or β over their lifetime and evolution. Changes in mass and ER over the lifetimes and evolution of (groups of) systems will be discussed in section 6.

5.2. Biological realm

In the biological realm allometric studies typically relate to the scaling of BMR and EMR with mass. Optimum scaling fits are achieved by excluding fluctuations as result of food digestion and physical activities. Kleiber was the first to observe that MR of a wide variety of mammals, ranging from a small mouse to a big elephant, scales with mass with a power law constant β of 3/4 [120]. Accordingly, the BMR *vs.* mass correlation has a less steep slope, compared to the y = x diagonal and larger mammals need proportionally less energy than smaller species. Kleiber's law was the first and is probably the most well-known of a series of so-called quarter laws in biological scaling [101]. Numerous follow-up studies, covering more or less all biological taxa (unicellular organisms, plants, trees, reptiles, amphibians, fish, mammals, insects, and birds), as well as using more sophisticated, statistical fitting approaches, have shown that β often deviates from 0.75 and actually varies between 0.6 and 1.9 (Table 2). For prokaryotes β is as high as 1.9, while for phototrophic organisms and unicellular eukaryotes β is more close to 1.0 [19]. For multicellular eukaryotes, metabolic scaling is somewhat more complicated. For animals there is a transition between limiting effects upon increasing size [112]. For plants and trees there is a change in structure from only metabolic active parts to more structural parts upon increasing size. These phenomena result in allometric scaling models with two β power law constants, viz. β_1 is 2/3 (animals) or 0.75 (plants) and β_2 is 1.0 (both) [79]. This explains partly the variation of β values for plants and animals in Table 2, which have been fitted with a single power law. The decrease of β from prokaryotes (unicellular organisms with ATP production throughout their cells) *via* unicellular eukaryotes (ATP production in mitochondria) to larger, multicellular eukaryotes (specialised cells for metabolism and energy/matter transport *via* vascular system) is explained by the changes in limiting factors in their metabolism*, i.e.,* energy processing (Figure 2: subtle change of slopes) [19]. A sound assessment of scaling is only possible when the mass of the systems varies over a sufficiently large range. Flat worms under starvation or fed on calf liver paste vary in their mass over three orders of magnitude ($5x10^{-8}$ to $3x10^{-5}$ kg), as a result of reversible (de)growth [111]. BMR scales with mass within this single species with β = 0.74 (Figure 2), following Kleiber's law.

From an energy processing perspective, a comparison of animals with various levels of temperature regulation are of interest. For ectotherms (cold-blooded organisms), mesotherms (organisms with body temperature control in between those of cold- and warm-blooded organisms) and endotherms (warm-blooded organisms) β is rather similar (around 0.75). More interestingly, α increases from ectotherms *via* mesotherms to endotherms, showing that enhanced temperature regulation requires faster metabolism (thick, upward arrow in Figure 2). The mass and ER data of extinct dinosaurs (1 to 10^4 kg and 0.6 to 2000 W, respectively) have been reconstructed. The scaling results in Figure 2 show that dinosaurs fall in between mesotherms and ectotherms. Similarly, mammals living in polar regions have higher BMR than those in deserts [79]. Scaling also applies for animals with higher activity levels such as for flying birds, bats, and bees, resulting in an upward shift of

Figure 2: Scaling and evolution of ER *vs.* mass for selected groups of living organisms in the biological realm. Diagonal, dotted lines of constant ERD of 100, 1, and 0.01 W/kg are guides to the eyes. The green, solid lines correspond to ER *vs.* mass scaling. The green, upward arrows indicate increased ER for a given mass, resulting from increased activity levels. The thick, light-green, dotted arrow represents the combined increase of ER and mass of living organisms during biological evolution.



the scaling correlations observed for these species in rest with a factor three to six [113,114] (thin, upward arrows). Although, the empirical systematics of metabolic scaling for living organisms is known for almost a century, their origins are still under debate [13]. Most probably they result from a combination of isometric, geometric, and allometric mechanisms, such as heat generation in the body *vs.* heat loss at the surface, flow restrictions of energy resources in fractal-like transport networks, and proportionality to actively metabolic parts, respectively [13,79].

5.3. Cultural realm

Scaling in the technological sub-realm is often applied for engineering and design purposes. For example, ER of (turbo-)propeller airplanes scales with a power law constant $\beta = 1.13$ [32] (Figure 3). This is in good agreement with the theoretical prediction from Bejan's constructal law [105] of $\beta = 7/6 = 1.17$, which is based on a combination of geometrical similarity (length and area characteristics scale with mass to power 1/3 and 2/3, respectively) and aerodynamic similarity (speed scales with mass to power 1/6). For jet transport planes, ornithopters, *i.e.,* aircrafts that fly by flapping their wings, and model airplanes, different values for β (between 0.9 and 1.5) are obtained (Table 2). This shows that these types of airplanes have different scaling behaviour than the propellor planes, because of the differences in their flight principle and energy efficiency [32]. Depending on the airplane type and its corresponding β value, airplanes with larger mass have proportionally larger (propeller planes and ornithopters: $\beta > 1$) or smaller energy requirements (jet transports and model airplanes: $\beta < 1$) than those with smaller mass. Today, the automotive industry is at the forefront of the energy transition with hybrid vehicles (HV) and full-electric vehicles (FEV) replacing conventional vehicles with internal combustion engines (ICEV). ER of these vehicles scales with mass over a 800 to 2700 kg range though with quite some scatter with β varying between 0.87 and 1.02 [115]. For a given mass of 2000 kg, calculated ER decreases from ICEV: 8.7×10^4 W *via* HV: 5.9×10^4 W to FEV: 2.5×10^4 W, which reflects an interesting reduction in energy consumption. Note that for many groups of machines scaling is not possible, since the ER *vs.* mass data are highly scattered instead of falling on a single correlation. The point is that machines are typically designed in a conscious process, where mass and ER are chosen and optimised more or less freely in a way that matches best with the primary application requirements. For example, for cars spanning a mass range of 800 to 6000 kg:

- a passenger car should provide sufficient space for a few passengers and some luggage, at low fuel consumption, while also satisfying high safety standards at a reasonable price;
- a limousine should provide much more space and luxury to its passengers;
- a racing car should be as fast as possible for a given minimum mass;
- a drag car should have maximum thrust for extremely fast acceleration over short times.

For machines and devices that span a mass range of 2×10^{-5} to 6×10^6 kg (Table 1), the differences in design requirements are even larger, because their primary functions are completely different. For example, computer chips should be as "fast" but also as small as possible, household appliances should combine effective functionality with maximum comfort and good-looking design, while a space rocket should have maximum thrust. These different application requirements translate not only into a wide variation of mass and ER values, but also into a decoupling of ER and mass values, and, thus, scaling is absent.

In the social sub-realm, scaling of ER *vs.* mass has been demonstrated for social colonies of insects, such as ants and bees [21,22,121]. Typically, sub-linear scaling is observed for the individual ants with β between 0.56 to 0.83, as well as for the ant and bee colonies with β between 0.60 and 0.79 (Table 2). These β ranges scatter around Kleiber's $\beta = 0.75$, suggesting that ER of both individual insects and colonies are determined by similar, evolutionary optimisation, just like for other animals. The values of the proportionality constant α for the ant colonies lie above those for the individual ants, showing that the ant colonies collect more energy resources. Note that in the original studies ER is related to the mass of all insects, but the mass of the ant hills and beehives, respectively, is not included. However, these constructs are critical for the performance and survival of the corresponding colonies. Therefore, as explained in section 2, ER *vs.* mass data for bees [22] have been extended with the mass of the corresponding beehive and the honey produced [67,SM Ib]. The power law correlation shifts to the right (orange arrow in Figure 3), as is expected when the mass increases for a given ER. This is accompanied by a decrease of α (Table 2). β decreases from 0.70 to 0.64 (correlation in Figure 3 tilts slightly clockwise), indicating an improved metabolic efficiency of bee colonies living in beehives. For modern cities it has been shown that usable, electrical energy scales with city population with $\beta = 1.07$ (Germany) and electric energy delivery to households with $\beta = 1.00$ (Germany) and 1.05 (China) [70,122]. However, city mass data are not available in the corresponding studies and, thus, scaling of ER *vs.* true city mass is not possible. Fortunately, Isalgue *et al.* have collected ER data for cities, including consumption of fossil fuels and electricity, as well as have calculated the corresponding city mass [23]. As for the bee colonies, the

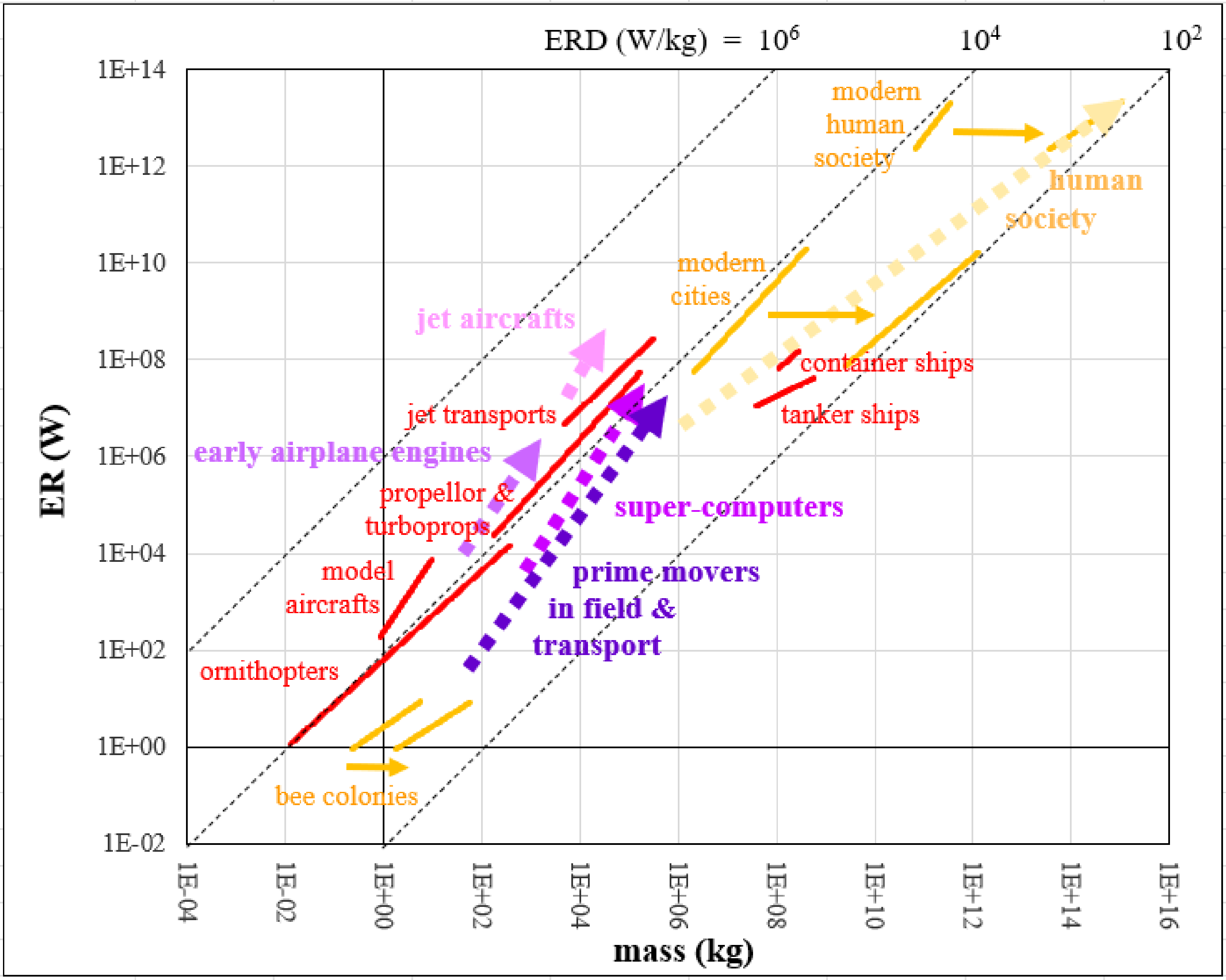


Figure 3: Scaling and evolution of ER *vs.* mass for selected groups of technological and social systems in the cultural realm. Diagonal, dotted lines of constant ERD of 10^6, 10^4, and 10^2 W/kg are guides to the eyes. The red and orange, solid lines correspond to ER *vs.* mass scaling. The rightward, orange arrows indicate the change in correlations for social systems, when mass of constructs is included. The thick, dotted arrows represent the combined increase of ER and mass of machines during technological innovation for early airplane engines (1919 to 1945), super-computers (last 70 years), prime movers (1700 until today), and post-WOII jet aircrafts, as well as human society from 1.000.000 BC until today.

power law correlation shifts to the right (orange arrow) and is tilted clockwise, when the mass of the city population is adjusted to include human-made mass. The accompanying decrease of α is quite similar to that for the bee colonies (cf. Table 2). β decreases from 1.11 to 0.86, therefore including the human-made city mass results in a change from super- to sub-linear scaling. The larger β value for human cities, compared to that for bee colonies, is probably the result of the human focus on growth during its cultural (r)evolution (see section 6.2). This has resulted in increased energy requirements over time which overshadow the increased energy efficiency (witnessed by $\beta < 1$). The energy consumption of the human society as a whole has grown faster over time than the human population itself.

In terms of scaling, one may even conclude that the ER of human society scales super-linearly *vs.* human mass with β of 1.32. This is much larger than for insect colonies, which suggests that the human society is an exception in this respect. However, this super-linear correlation does not represent simple scaling of ER with mass, but the evolution of human society over time, *i.e.,* technological innovation, in parallel to growth. In addition, when ER is scaled *vs.* human-made mass, which has grown even faster than human ER, the apparent β becomes 0.67. The evolution of human society will be further discussed in section 6.3.

5.4 Cosmological realm

In the cosmological realm, the scaling of the luminosity of MS stars (not for red giants and white dwarfs) with their mass is well-known with an average power law constant of 3.5 over the mass range of 4×10^{30} to 1.1×10^{32} kg [118]. In principle, this empirical scaling rule for MS stars is fully rationalised and determined by stellar physics. More stellar mass results in more adiabatic compression and the subsequent higher temperature results in an enhanced nuclear fusion rate and, thus, larger luminosity [37,107]. When zooming in on data for MS stars, four different scaling regimes can be distinguished. For stellar masses:

- up to 8.6×10^{29} kg: β = 2.3;
- between 8.6×10^{29} and 4×10^{30} kg: β = 4.0;
- between 4×10^{30} and 1.1×10^{32} kg: β = 3.5;
- above 1.1×10^{32} kg: β = 1.0 (corresponding to the Eddington limit: cf. section 7.2).

In the mid mass range, β is the largest and, thus, ER follows the steepest dependency *vs.* mass, resulting in a $\int$ -shaped correlation of ER *vs.* mass over the whole mass range (Figure 4) [118]. Scaling can also be applied for dwarf galaxies [93,119], yielding β of 1.0. Apparently, the underlying self-organisation mechanism of dwarf galaxies (β = 1; probably simple convergence of stars with gravitational binding force not affecting luminosity) differs from that of its composing stars (β ~ 3.5: accelerated nuclear fusion).

In summary, scaling of ER *vs.* mass data is observed for many groups of systems in all three realms. In the biological realm scaling depends on the taxon. For prokaryotes super-linear scaling (β ~1.8), for phototrophic organisms and unicellular eukaryotes linear scaling (β ~1.0), and for animals sub-linear scaling (β ~0.8) is observed. In the technological sub-realm scaling varies around unity (β ~ 0.9 to 1.5), whereas in the social sub-realm it is sub-linear (β ~ 0.6 to 0.9). In the cosmological realm, scaling for MS stars is super-linear (β = 1 to 4; on average ~3.5), whereas for dwarf galaxies it is linear (β ~ 1). Adjusting the mass of social systems to include constructs results in a decreased proportionality constant α, while β tilts slightly clockwise. The large variety of β values ranging from 0.5 to 4.0 shows that the self-organising mechanisms of the corresponding groups of systems are quite different, which is not surprising considering the large differences in their material structures and energy processing mechanisms. Although β varies for the different sub-realms, β has always a positive value (> 0) and, thus, ER always increases with mass, *i.e.,* larger systems need larger energy flows. This is the second reason in addition to convergence, explaining why ER *vs.* mass data of the systems from the three realms are all positioned in a band parallel to the y = x diagonal of the master plot (section 4). Variations in β and α explain partly why the ER *vs.* mass data points do not lie on one single diagonal line, but fall in a diagonal band. The scaling results show that for one particular group of systems, ER always increases with mass. Figure 1 shows that ER may be constant or even decrease with increasing mass, when moving from one sub-realm to another sub-realm in both cases resulting in a decreasing ERD. Finally, scaling of the ER *vs.* mass data of all systems in the dataset (excluding those for "dead" and "explosive" systems) results in an excellent fit (Figure ii in SM; R^2 = 0.98) with β = 0.92. This is close to unity and again confirms the alignment of the data more or less parallel to the y = x diagonal. However, this finding should not be over-interpreted, because it is the combined result of convergence of smaller into larger systems and scaling of very different groups of systems.

6. Lifetime and evolution

6.1. General

In the previous section, the scaling of ER as a function of mass has been discussed for similar systems at comparable stages of their development. Most systems in the biological, cultural, and cosmological realms change over time:

- either as a single system over its lifetime from its origination ("birth") *via* maturity to its end ("death") or
- as a group of similar systems with shared characteristics, changing over successive generations during its evolution.

The changes of a system (group) during its lifetime or evolution are both qualitative in terms of material structure, energy processes and, thus, complexity, as well as quantitative, as illustrated by the changes in mass and ER values. Complex systems require matter and energy for their origination, growth, and development, as well as to maintain their complexity over their lifetime. During the evolution of a group of complex systems, these matter and energy requirements typically change to a much larger extent than during the lifetime of one particular system. The changes of mass and ER over lifetime and evolution (Figures 2 to 4) will be discussed here for some (groups of) systems representative for each energy realm. The tracks of ER *vs.* mass

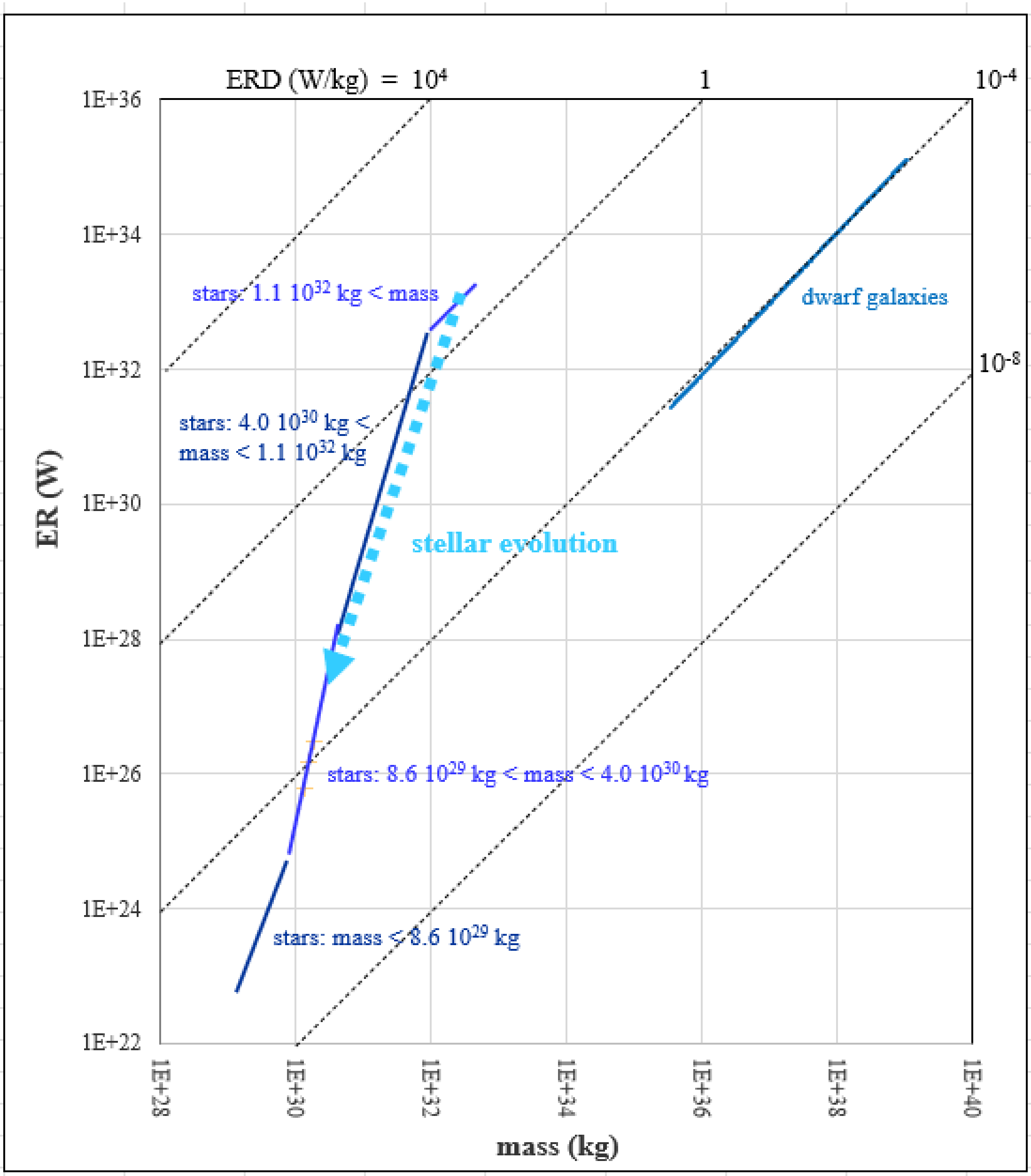
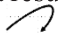


Figure 4: Scaling and evolution of ER *vs.* mass for stars and dwarf galaxies in the cosmological realm. Diagonal, dotted lines of constant ERD of 10^4, 1, 10^{-4}, and 10^{-8} W/kg are guides to the eyes. The blue, solid lines correspond to ER *vs.* mass scaling. The thick, blue, dotted arrow represents the combined decrease of ER and mass during stellar evolution.

over the lifetimes of these systems cover only relatively small ranges and are hardly visible, even in the zoomed-in, double-logarithmic master plots in Figures 2 to 4. Thus, they are just discussed in the text below, but not represented in the figures. In a dedicated paper the changes of ER(D) and mass over the lifetimes of a low-mass star like our Sun, a human, and the Roman empire will be discussed in much more detail [57].

6.2 Biological realm

Both mass and TEE of a human strongly vary during his lifetime. First, the mass and TEE (average data for males) increase strongly from a baby at birth (3.3 kg; ~10 W) *via* a child at 7 yr (26 kg; 83 W) to an early adult at 20 yr (74 kg; 162 W) [123]. The human body is then full-grown with its physical, reproductive, and possibly intellectual capabilities at a peak. Next, both mass and TEE level off with age up to 60 yr with mass increasing to 88 kg and TEE decreasing somewhat to 155 W. These changes reflect a slow decrease of the physical, reproductive, and intellectual capabilities of a human, though typically accompanied by an increase of emotional and social capabilities. Finally, both mass and TEE decrease substantially during senescence, eventually reaching 63 kg and 88 W, respectively, at

94 yr, witnessing a faster physical and intellectual decline. The ER and mass data of an average female follow similar profiles. As a result of these changes over a human lifetime, ER shows a  shaped correlation with mass. Note that next to these gradual changes in mass and ER over the lifetime, there are strong, daily fluctuations in ER_{in} as a result of food uptake (three daily meals and some snacks result in ER_{in} peaks), as well as ER_{out} as a result of the daily activity cycle (active, relaxing, and sleeping). Still, a human body in homeostasis, with temperature, heart rate, blood pressure, and other factors varying within certain ranges, is considered a stable system in balance.

The evolution of life on Earth can be characterised by several main trends from ER and mass perspectives. First, the evolution from asexual to sexual reproduction and from unicellular to multicellular organisms has resulted in a dramatic increase of the mass of living organisms [124] and a corresponding increase of ER. Indeed, the diversity of life is largely a matter of size, spanning more than 20 orders of magnitude [190]. These changes have been accompanied by a differentiation and specialisation of cells, resulting in more complex tissues, organs, and functional systems with relatively large ER for a given mass [125]. Organs and tissues differ both in mass and resting MR, as illustrated by average values for a human [80]:

- skeletal muscles: 27 kg and 14 W;
- skin: 5.0 kg and 1.5 W;
- heart: 3.0 kg and 9.7 W;
- liver: 1.4 kg and 17 W;
- brain: 1.3 kg and 15 W;
- kidneys: 0.3 kg and 7.0 W.

For animals, the evolution of ectotherms *via* mesotherms to endotherms has resulted in an increased ER for a given mass to maintain body temperature [62] (thick, upward arrow in Figure 2). Finally, the evolution of animals living in different environments with increased gravitational forces, viz. first in water, next on land, and finally in air, has also resulted in increased energy requirements for locomotion [105]. Note that all these evolutionary changes have occurred, while the same basic, organic material structure and biochemical processes were exploited. The overall, combined result of these evolutionary changes has been an increase of ER and mass over 11 and 12 orders of magnitude, respectively. Correspondingly, ERD has slightly decreased during biological evolution, as witnessed by the slope of the light-green, dotted arrow with a slope of ~0.9 in the double-logarithmic ER *vs.* mass plot in Figure 2. Note that this slope exceeds Kleiber's power law constant of 0.75, but is smaller than unity. Apparently, the ERD decrease resulting from sub-linear scaling of ER with increasing mass has been slightly larger than the increase in ERD, resulting from increased complexity. Note that this arrow corresponds to the overall evolutionary trend, while in parallel, new organisms with mass and ER combinations within the existing range have evolved. The evolution of hominins has roughly followed a similar trend of increasing mass and TEE, as shown by average data for male adults [126,127]:

- *Australopitecus afarensis* (3 to 4 Myr ago: 45 kg and 69 W) and *Australopitecus africanus* (2 to 3 Myr ago: 41 kg and 65 W) →
- *Homo erectus* (0.5 to 1.6 Myr ago: 63 kg and 110 W) and early hominin (0.2 to 0.5 Myr ago: 57 kg and 115 W) →
- Neanderthals (0.5 to 0.04 Myr ago: 75 to 80 kg and 162 to 228 W) and the somewhat smaller, anatomically modern humans, living as hunter-gatherers (0.3 Myr ago: 66 to 70 kg and 152 to 214 W); ranges are given for the latter two hominin species, showing the dependence on climate zone.

Note that the increases of the hominin body mass and ER have been accompanied by disproportionately larger growth of both mass and ER of the hominin brain [128]. Also note that mass and ER (food consumption only) of *Homo sapiens* did somewhat decrease in the early stages of the agricultural revolution. It may even have been close to subsistence, because of decreased food quality, spread of diseases and crop failures [7,9,129]. They have increased substantially again over the last centuries for modern humans living in developed countries (average male today: 81 kg and 148 W [130]). Obviously, the biological mass and ER of humans has been surpassed by the non-biological mass and ER (2700 W *per capita*) in our modern society (see section 6.3).

6.3. Cultural realm

The changes of mass and ER over the lifetime of systems in the technological sub-realm are somewhat special in the sense that these systems can be switched on and off (see also section 7.1) and that ER can often be adjusted to a desired value on a sliding scale. Both are rather unique features. Despite these large variations of ER, technological systems in operation are considered stable systems. As a result of dimensional changes and wear during use, the energy efficiency of technological systems typically decreases over its lifetime, resulting in a decrease of maximum ER_{out} and/or an increase of ER_{in}. The mass of technological systems hardly changes over their lifetime, except for the minor mass loss as a result of wear, as well as the mass increase due the uptake of fuel, passengers, and cargo as in vehicles. ER *vs.* mass over the lifetime of a technological system would be represented in the master plot by data points moving up and down (varying ER) along a vertical line (constant mass). The evolution of machines (innovation) has dramatically accelerated during the Industrial

Revolution in both quantitative and qualitative aspects. On the one hand, larger and more powerful machines with higher mass and ER, respectively, have been developed. On the other hand, the design, principle of operation, and the energy efficiency of machines have further evolved. The increase of the maximum power (= ER) during the innovation of prime movers over time is an illustrative example, as shown by Smil [68]:

- field work: Chinese peasant hoeing cabbage field (50 W) → Italian peasant harrowing with old, weak ox (200 W) → English farmer ploughing with two small horses (1000 W) → North Dakota farmer ploughing with six powerful horses (4000 W) → Californian farmer using 32 horses to pull combine (2.2×10^4 W) → French farmer harvesting with small tractor (5.0×10^4 W) → Manitoba farmer ploughing with large diesel tractor (3.0×10^5 W);
- land transportation: two oxen pulling cart (700 W) → four horses pulling coach (2500 W) → English steam locomotive (2×10^5 W) → fastest American steam locomotive (10^6 W) → powerful German diesel locomotive (2×10^6 W) → French TGV train by Alstom (9.6×10^6 W) → N700 series high-velocity Shinkansen train (1.7×10^7 W).

For both types of prime movers, ER has increased with time from 1700 until today over four orders of magnitude. The mass of both types of prime movers has also increased, viz. over three orders of magnitude, but not as strictly as ER. For example, the mass of prime movers actually decreased by a factor ten, when machines pulled by large horse teams were replaced by small tractors and steam-powered machines. As a result, ER does increase together with mass during the evolution of prime movers (dark-purple, dotted arrow in Figure 3), though with quite some scatter. Koh and Magee have shown that the evolution of early airplane engines from 1919 to 1945 corresponds to a nearly continuous increase of both ER and mass over two and one orders of magnitude, respectively [106] (light-purple, dotted arrow). This evolution towards more powerful and corresponding heavier engines facilitated the development of larger and more load-carrying airplanes. However, the evolutions of the passenger car and its engine from 1896 to 1994 show different trends. The engine ER increased over more than two orders of magnitude, whereas the mass of both engine and car was more or less constant after a small, initial increase before 1920 [131] (SM IIa). This evolution reflects more powerful car engines for cars carrying a similar number of passengers, but at higher speeds. The innovation of jet aircrafts shows a substantial increase of ER by a factor ten, while the mass shows a modest increase by a factor four [52] (pink, dotted arrow). The development of both ER and mass during the evolution of super-computers from the Z3 in 1943 to the HPE Cray Frontier in 2022 are also somewhat erratic [132]. The overall increase of both ER and mass over four and two orders of magnitude, respectively, (purple, dotted arrow) has been interrupted by the down-sizing from radio-tubes *via* transistors to chips. Interestingly, ER has grown faster than mass for all these technological innovations, resulting in slopes somewhat larger than unity. As in the biological realm, the general evolutionary trend in the technological sub-realm has been towards new machines with larger mass and ER combinations. In parallel, new tools and machines with mass and ER combinations within the existing range have been developed with a more recent trend towards miniaturisation with smaller mass and ER (see section 7.2).

Our human society, as the example of the social sub-realm, has known a series of energy revolutions over its lifetime, such as the use of fire, the domestication of animals, the implementation of agriculture, the use of water- and wind energies, the Industrial Revolution driven by the use of fossil fuels, the electrification of industry and society, the use of nuclear energy and today the change to the use of sustainable energy resources (especially solar and wind energies). The development of the human society is strongly interconnected with technological innovation as described above [68,69]. Note that many of the primary energy sources of the human society in the past and today (food, wood, peat, coal, oil, and natural gas) act as reducing agents, releasing the chemical energy stored in O_2 as oxidant [99]. Also note that these primary energy sources plus water, wind, and solar energies are all derived from Solar radiant energy (tidal energy and energy from radioactive decay are some exceptions). The total human energy consumption (= ER) has grown exponentially over its lifetime, as a result of both an increased world population and an increased ER *per capita*. The global human ER in 1,000,000 and 10,000 BCE are estimated at 2×10^6 and 5×10^8 W, respectively [133]. The agricultural revolution resulted in an accelerated growth not only of the global population, but also of ER *per capita*, yielding an estimated global ER of 1.4×10^{11} W at the start of the common era [133]. Since the Industrial Revolution, global power consumption has grown even stronger from 6.5×10^{11} W in 1800 *via* 1.4×10^{12} W in 1900, 3.2×10^{12} W in 1950 and 1.3×10^{13} W in 2000 to a gigantic 1.8×10^{13} W today [72]. The growth of the global ER on a *per capita* basis has levelled off over the last decades as a result of energy saving measures, which is fortunate considering the depletion of fossil fuels and global warming. Human-made mass is defined as the accumulated mass embedded in inanimate, solid objects made by humans, excluding waste and unused, excavated mass (mine waste *etc*.), *i.e*., the total mass of concrete, aggregate, bricks, asphalt, metals, plastics *etc.* used in buildings and constructions. It has grown exponentially from $3.6x10^{13}$ kg in 1900 *via* $8.2x10^{13}$ kg in 1950 and $5.7x10^{14}$ kg in 2000 to $1.1x10^{15}$ kg today (no data before 1900) [73]. Note that the raw data, mentioned above for the human energy consumption and human-made mass from the original sources, have been corrected in SM IIb for the chemical energy in food consumed by humans and the mass of humans themselves, respectively. These corrections are rather small though, compared to total human ER and human-made mass, and have decreased over time (1900: 10 and 0.19 % → 2019: 4 and 0.03 %, respectively). Plotting the changes of global ER and mass of just humans with time from 1900 onwards results in an increase of ER correlated with an increase of mass, but with the former growing faster (more steeply than y = x diagonal). Plotting ER *vs*. human-made mass instead results in a shift of the correlation to the right (orange arrow) and a clockwise tilting (similar as observed for bee colonies and cities; cf. section 5.3). Despite large fluctuations in ER over its lifetime (resulting from daily, seasonal, and conjunctural cycles), as well as temporary hick ups (related to natural disasters, pandemics, and wars), human society is considered a stable system.

6.4 Cosmological realm

The luminosity (= ER) of a star is fully determined by its surface temperature and radius, according to the Stephan-Boltzmann law (section 2). It shows major fluctuations when it develops through its lifetime (in cosmology termed "evolution") as will be illustrated for our Sun, which is a star with a starting mass of $1.99x10^{30}$ kg and consisting mainly of H and He (low metallicity) [75,134,135]. As a result of gravitational attraction, an initial molecular cloud of gas and dust contracts and, subsequently, collapses to a protostar. At the same time the internal pressure and temperature increase dramatically with as net result a luminosity strongly decreasing to 10^{28} W. Once the stellar core temperature surpasses 10^7 K, nuclear fusion of H to He is ignited, resulting in hydrostatic equilibrium. The low-mass star has become a stable, yellow dwarf in its MS with a luminosity that increases somewhat from $2.7x10^{26}$ W *via* $3.8x10^{26}$ W after 4.6 Gyr (our Sun today) to finally $8.5x10^{26}$ W after 11 Gyr. Then H in the core of the star becomes depleted and the star changes into an expanding red giant, accompanied by a strong luminosity increase. After a series of dramatic He shell flashes with the luminosity strongly fluctuating between $5x10^{28}$ and $2x10^{30}$ W, the low-mass star turns into a strongly expanding planetary nebula and loses about half of its original mass. The stellar residue becomes a white dwarf with a luminosity of $5x10^{29}$ W at 12.5 Gyr. The white dwarf does not show nuclear fusion anymore but is simply cooling, resulting in a strong luminosity reduction over time until it becomes a cold, black dwarf. In a double-logarithmic plot the ER *vs.* mass profile of a low-mass star, like our Sun, shows a strongly fluctuating ER with a mass which is hardly changing [57]. The luminosity of a low-mass star slowly increases with a factor three during its 11 Gyr MS. In addition, there are smaller fluctuations, as evidenced by temperature differences on the Solar surface, the 11 yr Solar spot cycle, as well as Solar flares and coronal mass ejections. Still, MS stars including our Sun are in hydrostatic equilibrium and considered as stable systems.

The lifetime of a galaxy (again in cosmology, typically termed evolution) will be described qualitatively [136]. Spiral galaxies are formed bottom up from smaller matter clumps. They have a black hole in their centers and are star forming. Spiral galaxies grow by colliding and merging with other galaxies, eventually resulting in an elliptical galaxy with a SMBH in its center and with both larger mass and ER. In parallel, the most massive stars in a galaxy die quickly and the overall metallicity increases. Less and less gas remains to be concentrated from the environment and initiate new star formation. As a result, blue, star-forming galaxies change into red, quiescent galaxies. Star formation in galaxies has peaked at around 3 Gyr after the Big Bang. ER of an older galaxy will eventually decrease at more or less constant mass. In summary, ER *vs.* mass follows a > shaped profile during galaxy lifetime. On very short time scales, ER of a galaxy shows huge fluctuations, resulting from SN explosions, tidal disruption events (TDE) and gamma-ray bursts (GRB). The universe as a whole has probably the most exotic history of all systems discussed in this paper with dramatic steps occurring in the first seconds, minutes and years after the Big Bang, such as inflation, bifurcation of the fundamental forces, formation of the fundamental particles, as well as "freezing out" of nucleons, nuclei and atoms, to name a few. Expansion of the universe has resulted in a larger radius, a lower energy-matter density, as well as a lower temperature, which corresponds to a continuous decrease of ER.

True evolution of stars is best described following the evolution of stellar populations, which proceeds while the galaxy of which stars are part develops simultaneously, as described above. Three stellar populations are distinguished, each characterised by a huge variety of stars with different masses, compositions, luminosities, and lifetimes [37,107,136]. Population III stars are the first and oldest stars. These stars were formed from the primordial gas, which consisted mainly of H and He with only traces of metals (Z/H $\sim 10^{-10}$) and originated from nuclear fusion when the primordial universe had sufficiently cooled (100 Myr after Big Bang). Nuclear H fusion in these stars resulted in higher levels of He and traces of metals. Population III stars were most probably of very high mass (1.2

to $6x10^{32}$ kg; may be $2x10^{32}$ to 10^{33} kg [40] or even 10^{34} kg [108]), because higher temperatures are required to ignite H fusion at low metallicity. This resulted in very fast, nuclear fusion reactions, accompanied by very large luminosities, and, consequently, in very short lifetimes (<5 Myr). As a result, population III stars are hypothetical, since they do not exist anymore today (age of universe is 13.8 Gyr) and have not (yet) been observed. Population II stars have on average lower mass (typically $4x10^{31}$ to $2.6x10^{32}$ kg). They are formed from gas and dust of primordial origin, but also as distributed by stellar winds, planetary nebulae and SN explosions of population III stars. Thus, population II stars are characterised by a higher metallicity (Z/H ~ 10^{-3} to 10^{-1}), which further increases upon nuclear fusion of H and He. They have relatively long lifetimes (1 to 10 Gyr) and are the oldest stars that have been observed today. In our Milky Way they are mainly located in the spiral bulge, the galactic halo, and globular clusters. Finally, population I stars are the youngest generation of stars, which are formed from a mixture of gas and dust originating from the primordial universe, as well as dispersed by population III and II stars. Population I stars, including our Sun, have the highest metallicities (Z/H ~ 10^{-1} to $10^{+0.5}$), the lowest masses, the lowest temperatures, the smallest luminosities and, thus, the longest lifetimes. Numerically, they are dominated by small, red dwarfs and, possibly, even smaller brown dwarfs. Population I stars are mainly located in the spiral arms of the galactic disc and most likely orbited by planets. Overall, the evolution of stars from population III *via* population II to population I stars corresponds to a decrease of mass and a corresponding decrease of luminosity, following the ∫ track from the scaling of stellar ER with mass (section 5.4). In addition, the increase of the stellar metallicity results in an increased opaqueness and, thus, in a decreased surface temperature and luminosity for a given stellar mass. Consequently, the ∫ track shifts to lower luminosity values, thereby reinforcing the overall trend of luminosity decreasing during stellar evolution (blue dotted arrow in Figure 4).

In summary, both qualitative (structure, processes, and complexity) and quantitative aspects (mass and ER) of (groups of) systems change during their lifetimes and evolutions in all three realms with the details varying with the particular system (group). Mass and ER of "mature" systems, such as humans between 20 and 65 year, as well as stars in their MS, show only relatively small variations during their lifetimes, and these are stable systems indeed. For technological systems ER can be varied reversibly from 0 to maximum power at constant mass. In contrast, ER and mass change over wide ranges during the evolution of groups of systems either towards much larger ER and mass (living organisms, machines, and human society), or to smaller ER and mass (stars). In a way, evolution can be viewed as the process of systems trying to explore a larger ER *vs.* mass area until they run into ER and/or mass limitations, which is the topic of the next section. Note that in all three realms the general evolutionary direction does not exclude the evolution of new types of systems with mass and ER combinations within the existing range.

7. Minimum and maximum values of ER

ER and mass are often correlated, as was shown in the discussions on convergence and scaling as well as on lifetimes and evolutions of (groups of) systems in the previous sections. Focus will be here on systems in the various (sub-)realms with minimum and maximum ER values in relation to their mass (Figure 5), which partly corresponds to a discussion on minimum and maximum ERD (= ER/mass ratio).

7.1. Minimum ER values

In the biological realm, low ER values are found for living organisms in the absence of any (physical) activities. Plants and trees in darkness, *i.e.,* in the absence of photosynthesis, are characterised by low ER values. For micro-organisms and animals, a relatively low ER (= BMR) is measured, when in rest, quite some time after food digestion, and at ambient temperature. Animals that are sleeping have a relatively low MR value, which is not zero though but close to BMR, since even while sleeping energy is required for homeostasis and repair. The same goes for animals that have a "pause and play control", resulting in the freezing of all movement, stopping or reducing of breathing, and slowing down of heart rate [191]. Animals during daily torpor, *i.e.,* a state of decreased activity and temperature lasting less than 24 hr to conserve energy, have MR values that have decreased by a factor of 2 to 30 relative to their BMR [137]. Animals during seasonal hibernation (a state of minimal activity, slow breathing and heart-rate, and low body-temperature in order to survive longer periods of reduced food availability), have a size-independent specific MR of ~0.2 W/kg [17,137,138]. This corresponds to a decrease by a factor 6 to 100 compared to BMR of the non-hibernating species and is comparable to the specific BMR of the largest animal (blue whale: 0.18 W/kg). Many deep-water microbes have MR reduced by a factor two to five, due to high-pressure effects [139]. Living organisms in the absence of O_2 (anoxia) have a specific MR of around 0.07 W/kg, corresponding to a MR decrease with a factor of 20 to 300 [17]. Micro-organisms in extremely cold conditions, as in arctic bore cores, have a very low MR, which is a factor thousand smaller than BMR and just sufficient to

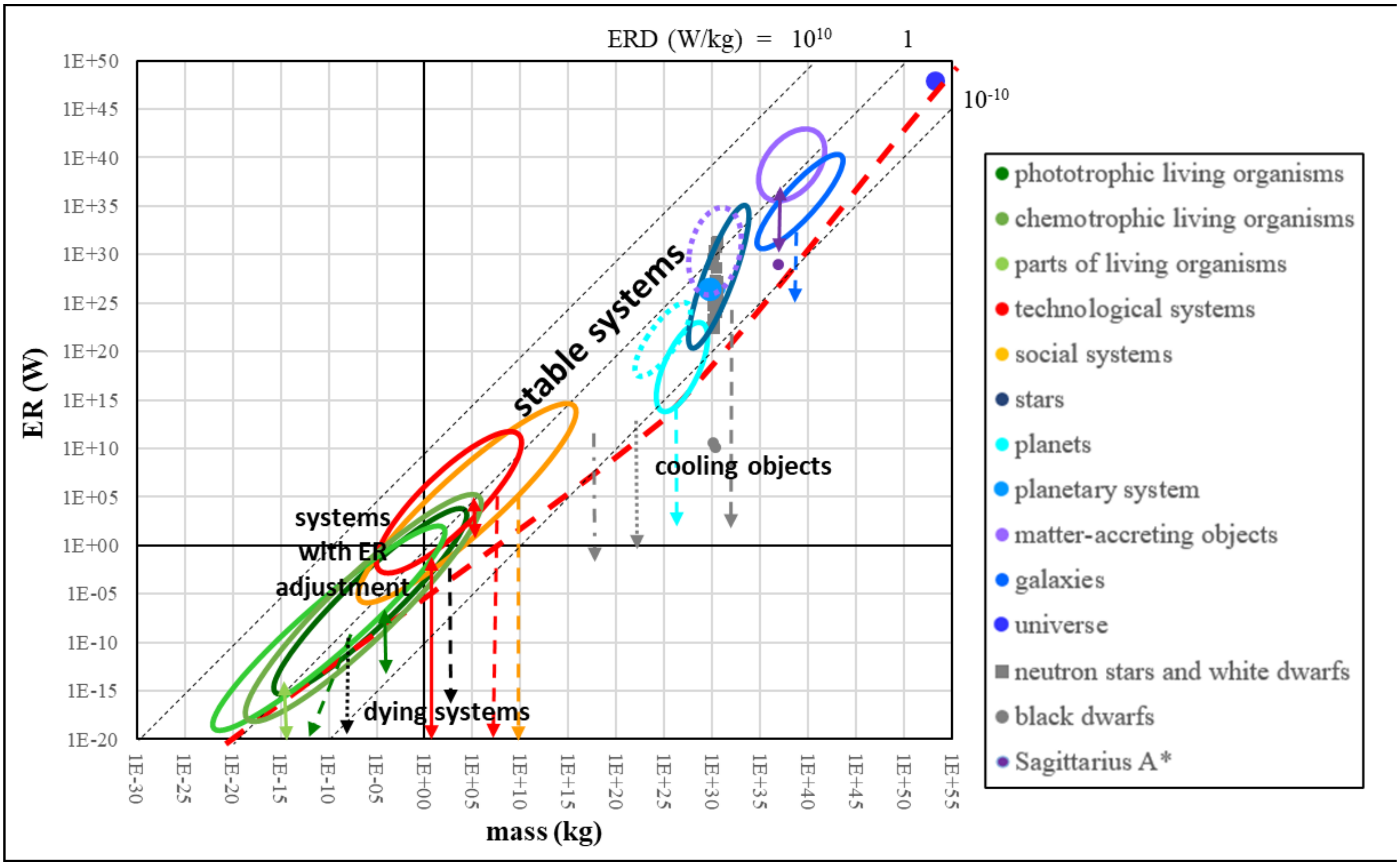


Figure 5: Double logarithmic plot of ER *vs.* mass for a wide variety of stable systems from the biological, cultural and cosmological realms (green, red and blue ovals, respectively; cf. Figure 1), extended with systems with low and no activity. Diagonal, dotted lines of constant ERD of 10^{10}, 1, and 10^{-10} W/kg are guides to the eyes. The red, dashed curve indicates a "soft" lower limit of ER *vs.* mass. Coloured, vertical arrows indicate possible variations of ER below this lower limit for systems in the various realms (solid, double-pointed arrows: reversible ER variation; dashed and dotted arrows: continuously decreasing ER; for further explanations, see text). "Dead" systems with ER = 0 are at the bottom of the plot, but cannot be positioned in a logarithmic fashion.

repair random cellular damage [140]. Predictions using sophisticated models have shown that microbes (both chemotrophic archaea and bacteria), living in quaternary-age marine sediments (spongy, dense mud and detritus, accumulated at bottom of oceans and extending for kilometers beneath ocean floor) have MR around one million times smaller than cells in surface habitats. They are living very slowly and barely divide [192]. ER *per* cell ranges from a 10^{-21} (minimum power level for cell to remain viable to 10^{-17} W [193]. All these variations of ER for living organisms over six orders of magnitude below BMR are represented by the green, vertical, double-pointed arrow in Figure 5. Spores do not have any detectable metabolism (ER < 10^{-5} BMR), do not show any signs of life [141,142] and, thus, are considered cryptobiotic. They can lie dormant for extended periods up to centuries even under extreme conditions, but can be "revived" again under suitable conditions to become fully vegetative, bacterial cells (Figure 5: light-green arrow). Viruses cannot generate or store energy in the form of ATP themselves, but derive their basic building blocks, energy, and all other metabolic functions from their host cells [143]. Therefore, viruses are considered to be organisms at the edge of life or simply replicators. Only when a living organism dies, ER truly and typically very quickly drops to zero. Upon death, the mass of an organism is also affected and decreases *via* decay by decomposers and digestion by consumers at different levels in the food pyramid. The combined decrease of both ER and mass to zero for dead organisms is shown by the dashed, green arrow, pointing left, downwards in Figure 5. As mentioned earlier, the logarithm of zero is ill-defined and, thus, this light-green arrow is just indicative.

As already mentioned in section 6.3, technological systems can typically be switched on and off (ER = 0) and their power can often be adjusted to a desired level on a sliding scale. Reducing the speed of a vehicle, dimming a lamp and lowering room heating are typical examples. Note that a idling car still consumes ~20% of its maximum power, while the alarm installation of a parked car still consumes 0.5 W. Typically, the lowest, practical ER of a machine is ~1% of its maximum power, *i.e.,* two orders of magnitude, as indicated by the short, red, double-pointed arrow in Figure 5. The long, red, double-pointed arrow represents the switching on and off machines. These are rather unique features of machines, since biological and cosmological systems are either in operation with some fluctuations in ER around a steady state or they are dead and inactive. Only machines that are discarded or broken down, such as a worn-out car with a broken engine and a lamp with its filament burned through, are "dead" (Figure 5: red, dashed arrow). From a thermodynamic point of view, systems with ER = 0 are inactive, explaining why Chaisson has excluded systems with ER(D) = 0 from his overviews [5]. He did not consider such systems to be true systems, because there is no energy flow that maintains an energy gradient and complexity. It seems somewhat odd though to define, for example, a running car and a burning lamp as complex systems (with their complexities actually changing when their speed and light intensity, respectively, varies), while excluding the same car when temporarily parked and the same lamp when not burning. Instead of introducing another term, like "complicated system", here a preference is for a less stringent definition of complex systems following a gradual complexity scale. At the bottom of this scale come systems with zero ER(D), but through which energy has flowed in the past or can flow in the future. It is argued that such systems are also out of equilibrium and matter, energy, and information has been stored in their structures with the potential to still be used in the future.

In the social sub-realm, ER and to a lesser extent mass of social systems are continuously fluctuating over their lifetimes. History is full of examples of dramatic ER decreases to zero. For example cities have been destroyed by enemy armies or earthquakes, as well as states and civilisations have declined due to enemy invasions or climate changes (orange arrow). Still, some people do survive these disasters and continue to live in the same area. Thus, ER will not fully dwindle to zero and often new cities and nations emerge over time in the same location. There is no guarantee though that such a rebound will always occur, so there is no reason why today's human society might not fully succumb to a nuclear winter or excessive global warming.

In the cosmological realm, matter is often powering the system (gravitational and nuclear energies in stars and matter-accreting objects, respectively.) and, thus, ER relates in a very direct fashion to mass. Therefore, the discussion on minimum and maximum ER will be partly a discussion on minimum and maximum ERD (= ER/mass ratio). The lowest ER values of stars are found for those with the lowest mass. Red dwarfs have ER values between 10^{23} and $3x10^{25}$ W with masses of 10^{29} to 10^{30} kg, corresponding to ERD of $7x10^{-7}$ to $2x10^{-5}$ W/kg. Brown dwarfs have even lower ER of $2x10^{21}$ to $8x10^{23}$ W with masses of $2x10^{28}$ to $1.8x10^{29}$ kg, corresponding to ERD of $2x10^{-8}$ to $3x10^{-5}$ W/kg. Ultra-cool, brown dwarfs have ER values of $2x10^{21}$ to 10^{24} W with masses of $4x10^{28}$ to $1.8x10^{29}$ kg, corresponding to ERD of $2x10^{-8}$ to $5x10^{-6}$ W/kg. Stellar remnants, such as white dwarfs, neutron stars, and black holes are the relicts of explosions of stars at the end of their lifetimes. They do not show nuclear fusion anymore and, in isolation, do not accrete matter and, thus, are considered as inactive systems. These stellar remnants with a very high, initial, surface temperature will cool over time, as result of the conversion of thermal energy to heat radiation at their surface. Note that such radiative cooling is simply the result of the very large temperature difference between these inactive cosmological objects and the cold, interplanetary and interstellar space. In other words, "dead" cosmological objects do not "die" immediately, in the way living organisms do, but they fade away. For example, the luminosity of a neutron star of $4.0x10^{30}$ kg decreases from $1.6x10^{27}$ W at 200 yr after its formation in a convex fashion over time *via* $1.4x10^{26}$ W after 10^4 yr to $4.5x10^{24}$ W after $3x10^5$ yr [144]. This corresponds to an ERD decrease from $4x10^{-4}$ *via* $4x10^{-5}$ to 10^{-6} W/kg. Isolated, white dwarfs and neutron stars with mass between 10^{30} and $8x10^{30}$ kg (Figure 5: grey squares) show a decreasing ER, as indicated by the dashed, grey arrow. Stellar remnants accreting matter from a companion star belong to the matter-accretion sub-realm. Black dwarfs are hypothetical, inactive stars that have cooled to ~5 K, corresponding to an estimated ER of 10^{10} W for a mass of 10^{30} to $2x10^{30}$ kg (grey circles). Similarly, star formation in elliptical galaxies is eventually quenched, resulting in decreasing ER (blue arrow).

Sagittarius A*, the SMBH ($8x10^{36}$ kg) in the center of our Milky Way galaxy, has an interesting characteristic, which resembles machines with adjustable power. It has a very low luminosity of just 10^{29} W (purple point in Figure 5), which is very small for a SMBH of its mass and the result of a very small matter accretion rate. Indeed, Sagittarius A* would not be visible, if it were not so proximate to Earth. Sagittarius A* is not an active, galactic center as most other SMBHs, which have much larger matter accretion rates and correspondingly larger ER (10^{36} to $6x10^{42}$ W; SM IIc; purple oval). Sagittarius A* has a continuous radio and infra-red flux, but with strong fluctuations and X-ray flares sometimes brightening up to 400 times its normal luminosity. 200 yr ago it was at least 1 million times more brighter than today [198]. These ER fluctuations are indicated by the purple, double-pointed arrow.

Planets take a somewhat intermediate position in this context. They are here considered as active systems in a separate, cosmological sub-realm, because they have a stable orbit and convective flow patterns. However, over the long run planets are also cooling just like stellar remnants, resulting in a decreasing ER from hot planets in their formative stage (dotted, light-blue oval) *via* planets today (light-blue oval) to ageing planets (dotted, light-blue arrow). In the Solar system, Uranus ($8.7x10^{25}$ kg) is the second furthest planet away from the Sun. Consequently, it has a very low temperature of just 60 K, a small ER of just $7x10^{14}$ W and a correspondingly small ERD of $8x10^{-12}$ W/kg. Our Earth ($6.0x10^{24}$ kg) is more proximate to the Sun with a higher average temperature of 287 K (14 °C), a larger ER of $1.3x10^{17}$ W, and a larger ERD of $2.1x10^{-8}$ W/kg. The Earth has cooled over its lifetime. A hot planet was formed 4.5 Gyr ago *via* matter accretion in the protoplanetary disc around the young Sun. The Theia impact some 20 to 100 Myr later not only resulted in the creation of the Moon, but also in a dramatic increase of the Earth's temperature to as high as 2300 K. Since then, the Earth has been cooling again and will cool even further, when our Sun will become a white dwarf in 8 Gyr (unless the Earth in the meantime has been swallowed by the Sun when the latter is in its red giant phase). For smaller, inactive, cosmological objects (moons, asteroids, meteoroids, and interstellar dust), the surrounding temperature (T_c) is not precisely known. Therefore, ER has been estimated using the Stephan-Boltzmann law, neglecting the T_c^4 term, resulting in maximum ER values (cf. SM IIIg). Because of the uncertainty in these ER values, these data are not shown in Figure 5. The grey and black, downward arrows in Figure 5 do reflect the decreasing ER as a result of cooling of these smaller, inactive objects:

- larger moons in the Solar system (10^{21} to 10^{23} kg) with estimated ER values below 10^{13} to 10^{16} W (dotted, grey arrow);
- larger asteroids in the Solar system (10^{16} to 10^{21} kg) with estimated ER values below 10^{11} to 10^{14} W (dotted & dashed, grey arrow);
- meteoroids (200 to 500 kg) with estimated ER values below 10 to 10^4 W (dashed, black arrow);
- interstellar dust (50 to 500 μm; 10^{-10} to 10^{-7} kg) with estimated ER values below 10^{-11} to 10^{-8} W (dotted, black arrow).

A consequence of many of the cosmological objects cooling and fading away is that most of them are invisible for human observation. As mentioned before, red and brown dwarfs are probably the most abundant stars, but typically cannot be observed because of their low luminosity. Exoplanets are probably present around most stars. The combination of a relatively small luminosity and a huge distance from Earth results in a very low magnitude, which prevents direct observation. Most exoplanets have been detected *via* small decreases of their stars' luminosity, when they pass in front of their stars, and the wobbling of their stars' orbit, due to gravitational interactions [145]. Note that only a few rogue planets, *i.e.,* planets that have been kicked out of their stellar orbits, are wondering through interstellar space, and may outnumber planets which are orbiting stars with a factor 20, have been observed so far [146]. Even ER of the universe will decrease, as it further expands and cools. The ultimate fate of the universe may be heat death (Big Chill), viz. a state of zero thermodynamic free energy as well as unable to sustain processes that increase local entropy and, thus, maintain complexity [147].

In summary, the area on the lower and right side of the ER *vs.* mass master plot in Figure 1 looks empty. However, it is actually filled with a huge number (probably even more abundant as active systems) of dormant, living organisms, machines operating below their maximum power or temporarily switched off, as well as inactive, cosmological objects fading away (indicated by the various coloured arrows, pointing downward in Figure 5). These could be viewed as simple, complex systems, which are out of equilibrium and with matter, energy, and information stored in their structure. There is no clear boundary between active and inactive systems in the ER *vs.* mass master plot. In BH studies such simple systems are typically ignored, perhaps because they are less interesting than the active systems in the diagonal band and are lost out of sight when the focus is on increased complexity over big time. Note that many "dead" systems are used as energy source and converted back to raw materials for "living" systems in all realms. Well-known examples are the decomposition of dead organisms to small organic molecules by bacteria and fungi in the biological realm, the recycling of scrap metal, glass and plastics from worn cars and other machines in the cultural realm, as well as H, He and metals being distributed in space by stellar winds, planetary nebulae, and SN in the cosmological realm ("we are all made of star dust").

7.2. Maximum ER values

For the biological realm, mass and ER data have been collected for a variety of living organisms with very high activity levels (cf. SM). Because ER correlates with mass, focus will be on systems with the largest ERD (= ER/mass). For example, the average daily BMR of a male human at 20 yr (76 kg) in rest is 87 W, corresponding to ERD of 1.2 W/kg [123]. As a result of physical activities, average daily TEE is almost two times larger, viz. 160 W, corresponding to an ERD of 2.2 W/kg. The track sprinter Usain Bolt (86 kg) has reached maximum power (= ER) levels of 2800 W over the less than 10 s sprint over 100 m, corresponding to ERD of 33 W/kg [148]. Similarly, cyclist Mathieu van der Poel (76 kg) reached maximum ER values of 960 W, when climbing on very steep mountain tracks, and 1540 W in the final meters before the finish, corresponding to ERD of 13 and 21 W/kg, respectively [149]. Top athletes can only achieve such very high ERD values for very short times, because of limitations in conversion and transport rates of biochemical energy in the human body. The peak ERD values of these two athletes are 6 to 15 times larger than the average daily ERD, which may not seem that impressive. However, here ER_{out} for sport performance is compared with ER_{in} from food and, thus, the energy efficiency of respiration also needs to be considered. When exposed in an environment of 50 °C and 50 % relative humidity, BMR of humans increases with a factor 1.6, which is accompanied by an 1 °C increase of core temperature and increased heart rate [150]. A variety of flying animals, such as birds and bats (0.008 to 0.03 kg) have a MR in flight which is three to six times larger than MR in rest with ERD reaching maximum values of 160 W/kg [114]. *Megachile rotundata* bees (10^{-5} to $4x10^{-5}$ kg) have a MR in flight which is three to six times larger than MR in rest, reaching maximum ERD values of 32 W/kg [113]. Similarly, a variety of (non-)passeriformes birds (0.0055 to 3.9 kg) have a MR in flight, which is two to five times larger than MR in rest, reaching maximum ERD values of 120 W/kg [32]. Also similarly, perch-hunting insectivorous *Rhinolophus* bats (0.011 to 0.013 kg) achieve even higher ERD values of 160 to 200 W/kg, which is related to the high energy costs of manoeuvring in flight [151]. Apparently, all these animals at maximum activity outperform human, top athletes in terms of ERD. *Escherichia coli* (*E. coli*) bacteria during growth reach ERD values of 5800 W/kg. Plants and trees have 5 to 30 times higher MR in light than in darkness [152], yielding maximum ERD values of approx. 600 W/kg. Note that these MR values of plants and trees are measured *via* CO_2 production and correspond to the respiratory processes in which carbohydrates are converted to CO_2. Therefore, these are not representative for and probably substantially smaller than ER of plants and trees during photosynthesis in which CO_2 and H_2O are converted to carbohydrates plus O_2. For some reason, ER data for photo-synthesising plants are hard to find. Based on $^{14}CO_2$ incorporation, sugarcane varieties have ERD_{out} values of 1.5 to 4 W/kg [58]. Chaisson has calculated ERD_{out} values of 0.05 to 1.0 W/kg for grass, pine tree, mahogany tree, corn, and sugar cane by converting biomass build up to ER using the corresponding heats of combustion [5]. These values seem all rather small. Note that ERD_{in} for photosynthesising plants is much larger, considering the low energy efficiency of just a few percent [153]. The largest ERD values in the database are for the muscles of animals at take-off for flight or jump with 8900 W/kg as the maximum for the muscles of the *Galago senegalensisa* primate [17]. In summary, (parts of) living organisms at highest activity levels have ER values up to 30 times larger than BMR, but their ERD never exceeds 10^4 W/kg.

For the technological sub-realm, ERD data have been collected for the most powerful machines (cf. SM IIa). For example, early cars (mass up to 500 kg) typically had ERD values up to 10 W/kg [27]. Today's passenger cars (up to 2500 kg) have ERD up to 250 W/kg [154], and racing cars (up to 1000 kg) up to 2000 W/kg [27]. However, the largest ERD values of cars are found for the world-record, land-speed cars (up to 10^4 kg) with ERD up to $2.5x10^4$ W/kg [27]. Transport airplanes (up to $3.5x10^5$ kg) have ERD values up to 250 W/kg, with just the engines (up to $2x10^4$ kg) reaching values of 3000 W/kg [27,155,156]. Military fighter planes (up to $2.5x10^4$ kg) reach 500 W/kg [27,157]. Space rockets ($3x10^6$ kg mass at lift off when fully loaded with propellant) with ERD up to $6x10^4$ W/kg (cf. SM IIa) have the largest ERD value for all vehicles listed. The main engine fuel turbopump of the space shuttle has an ERD as high as $1.5x10^5$ (W.kg) [158]. Actually, the propulsion of space rockets can be viewed as "controlled explosions" (see section 7.3). Interestingly, very large ERD values have also been collected for very small, technological devices. This shows that maximum energy performance in the technological sub-realm is not only achieved *via* up-scaling, but also *via* down-scaling (miniaturisation). Recent innovation in rechargeable batteries has resulted in supercapacitors and aluminium electrolytic capacitors with ERD values as high as 10^4 and $1.5x10^5$ W/kg, respectively [159]. The development of CPUs has reached a temporary record ERD of $2.6x10^4$ W/kg for the Intel Core i7 (estimated mass of 0.01 kg and ER of 260 W) [56,81], which is the most modern processor for a gaming computer produced with 14 nm lithography. The corresponding IC ($4.3x10^{-4}$ kg and the same 260 W) has an extremely high ERD of $6.1x10^5$ W/kg. It will be interesting to see where Moore's law will lead us in the future in this *ER vs.* mass perspective. In summary, maximum ERD of machines is not exceeding 10^6 W/kg with smaller parts reaching the highest ERD values (cf. section 8.4). Systems in the social sub-realm have very large ER (SM IIb: New York: $1.6x10^{10}$ W; world in 2019: $1.9x10^{13}$ W). However, because of their very large mass ($1.6x10^{10}$ and $1.1x10^{18}$ kg, respectively), the corresponding ERD values (0.012 and $1.7x10^{-5}$ W/kg, respectively) are relatively low and much smaller compared to those for systems in the technological sub-realm. Interestingly, the largest ERD for the social sub-realm is found for a rather small beehive with 2000 bees (0.54 W/kg).

ER of stars scales super-linearly with mass (see section 5.4) and, thus, the largest ER is found for the largest stars. However, when stellar ER exceeds the Eddington luminosity limit:

L_{Edd} = 6.3 * stellar mass (in W)

the hydrostatic equilibrium between the outward radiation and the inward gravitational forces is disrupted [37,160,161]. Very intense, stellar winds develop, that will blow away the outer stellar layers. ER of MS stars increases with mass, according to the super-linear scaling discussed in section 5, up to a mass of around $1.1x10^{32}$ kg, which corresponds to an ER of $7x10^{32}$ W. At stellar mass above $1.1x10^{32}$ kg, ER as a function of mass follows the Eddington limit (Figure 4), which corresponds to a maximum stellar ERD of 6 W/kg. Outside the MS, red, yellow, and blue hyper-giants have masses ranging from 10^{31} to $2x10^{32}$ kg, and ER from $3x10^{30}$ to $7x10^{32}$ W, corresponding to ERD ranging from 0.2 to 10 W/kg [162]. Luminous blue variables are very rare, unstable hyper-giants at the top of the HR diagram with masses from $2x10^{31}$ to $2x10^{32}$ kg, ER from 10^{32} to $4x10^{33}$ (exceeding their Eddington limits for brief times) and corresponding ERD from 1 to 60 W/kg [163]. The most luminous star, dubbed Godzilla, has an average ER of $7x10^{34}$ W [87], yielding an ERD of 150 W/kg for an estimated mass of $5x10^{32}$ kg. The first stars in the universe, *i.e.,* population III stars, with masses up to $2x10^{33}$ will have had very large luminosities up to 10^{34} W [164] with a maximum ERD up to 5 W/kg. The very first, but hypothetical, super-massive stars may have had ER of $6x10^{34}$ W, which with an estimated mass of 10^{33} kg yields ERD of 60 W/kg.

Many matter-accreting objects have larger ERDs than (giant) stars, because of their very energy-efficient, matter-accretion mechanism combined with their relatively small mass (mass is in ERD denominator). Transient black holes with masses ranging from $5x10^{30}$ to $3x10^{31}$ kg have ER from 10^{31} to 10^{35} W and corresponding ERD from 1 to 2000 W/kg [55]. SMBHs, including active galactic nuclei, quasars, and blazars, are the most luminous, stable cosmological objects with extremely high ER (10^{36} to $5x10^{42}$ W). They also have extremely large mass (10^{36} to 10^{41} kg), resulting in "moderate" ERD of 10^{-3} to 10^{4} W/kg. Accreting neutron stars in binary systems have estimated masses of $2.8x10^{30}$ kg, ER ranging from $2x10^{31}$ to 10^{34}, and corresponding ERD from 8 to 3000 W/kg [55]. The matter-accretion rate of these objects and, thus, their luminosity is theoretically limited by the Eddington limit, but ultra-luminous X-ray sources exceed this limit. For example, M82 X-2 probably consists of a neutron star of $2.8x10^{30}$ kg with a donor star of at least 10^{33} kg. It has an ER of around 10^{33} W, yielding an ERD of 78 W/kg (see SM). The young stellar object V866 Sco with a mass of $2.7x10^{30}$ kg and an ER of $2.9x10^{34}$ has the largest ERD of $1.1x10^{4}$ W/kg [91] of the matter-accretion objects listed. Dark stars and quasi-stars are hypothetical objects. They are not true stars, because they are not powered by nuclear fusion, but by matter accretion. They have quite exotic structures, but have moderate ERD values (0.2 and 7 W/kg, respectively). Planets, planetary systems, galaxies, and the universe as a whole have much smaller ERD than stars and matter-accreting objects. In summary, the largest ERD of cosmological objects is around 10^{4} W/kg.

In conclusion, upper ERD limits are observed in all three realms. There seem to be no stable systems in the biological and cosmological realms with ERD exceeding 10^{4} W/kg nor in the cultural realm exceeding 10^{6} W/kg. Indeed, a plot of ERD *vs.* mass for all systems (SM – Figure iii) shows a maximum ERD of around 10^{5} W/kg. This maximum ERD value corresponds with the observation of an upper limit of ER *vs.* mass, running diagonally from the lower, left corner to the upper right corner of the master plot (red line in Figure 6). Given the very different principles of material structures and energy processing of the systems in the various realms, such a shared upper limit for ER *vs.* mass is far from obvious. Kempes *et al.* observed that ERD goes through a maximum and does not exceed 10^{4} W/kg during the evolution of systems over big time [20], but did not consider this as a threshold.

7.3. "Explosive" regime

There seem to be no stable systems above the diagonal in the ER *vs.* mass master plot, corresponding to ERD ~10^{5} W/kg (Figure 1). Still, data have been found for systems with even higher ER & mass combinations, which are positioned above this apparent ERD limit (Figure 6). However, these systems, which include explosions, implosions, and collisions, are unstable. Thus, they should not be considered true systems. First, two hypothetical examples with extremely high ERD values will be discussed (SM V - downscaling). Today, our Sun ($2.0x10^{30}$ kg) has an ER of $3.8x10^{26}$ W. The corresponding ERD of $1.9x10^{-4}$ W/kg lies far below the upper ERD limit of 10^{5} W/kg and, indeed, the Sun is considered a stable system. Now assume a hypothetical, downscaled system with just four H nuclei fusing to one He nucleus at the same rate as in the Sun. Then $4.1x10^{-12}$ W energy would be released for a system with a mass of just $6.7x10^{-27}$ kg, corresponding to an ERD of $6.2x10^{14}$ W/kg. This yields an ER & mass data point (light-purple) in the left, lower corner of Figure 6 far above the diagonal, upper ERD limit. However, nuclear fusion will not occur in such an isolated system, because its temperature will not reach 10^7 K required for ignition of H nuclear fusion. Thus, this extreme ER & mass data point represents an unrealistic system. Similarly, in a modern, electrical power plant coal is combusted in the presence of O_2, yielding mainly CO_2 as product. Secondly, the new coal-fired Eemshaven power plant in the Netherlands (NL) has an estimated mass of 10^9 kg and a scheduled ER of 1.6×10^9 W [82]. The corresponding ERD value of 1.6 W/kg lies well below the upper ERD limit. Now assume a downscaled system of just one C atom reacting with one molecule O_2 at the same rate as coal in the power plant. Then 7.1×10^{-19} W would be released by a system with a mass of just 7.3×10^{-26} kg, corresponding to an ERD of 9.7×10^6 W/kg. This yields another light-purple datapoint in the left, lower corner of the master plot above the diagonal ERD limit. However, this C combustion system is neither realistic nor useful, since the equipment to drive and control the combustion, as well as for converting the released thermal energy to electricity is missing. Note that in the real systems a large amount of matter is needed to provide the conditions and structure for stable systems with a steady ER.

There are real systems that have ER *vs.* mass combinations (far) above the diagonal ERD limit. In the technological sub-realm, humans have developed all sorts of powerful explosives and bombs. These are based on the conversion of chemical and nuclear energy, respectively, to kinetic energy (useful blast and heat, but also flash and sound). ER *vs.* mass data have been calculated for chemical explosives, such as gun powder, trinitroglycerin, and dynamite (SM IIc). The corresponding ER & mass data points lie well above the diagonal threshold (Figure 6: pink diamonds) and the estimated ERD values, ranging from 10^6 to 10^{13} W/kg, are indeed far above the upper ERD limit. Such systems are literally used as explosives and should not be considered as stable systems. The ER & mass data points

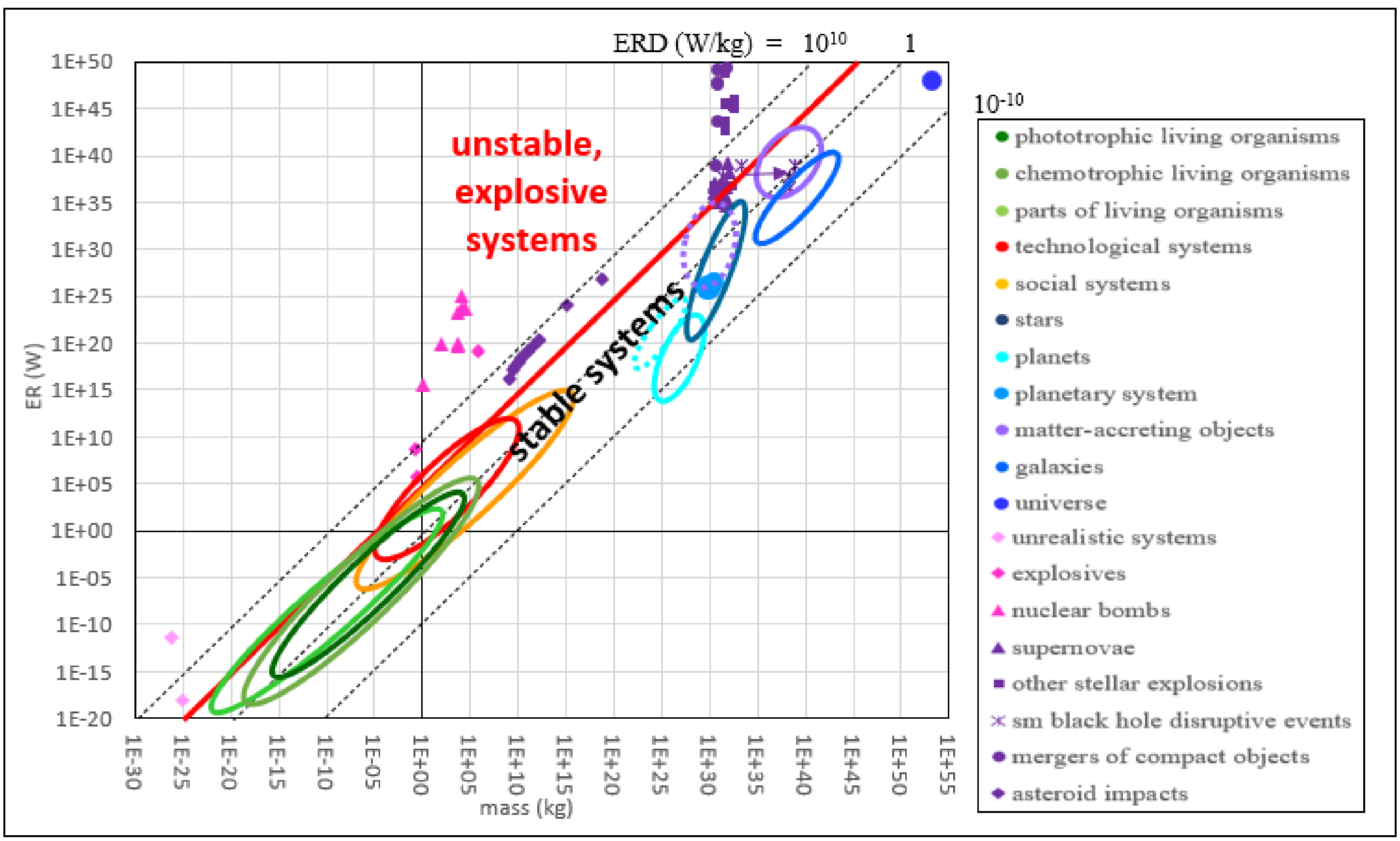


Figure 6: Double logarithmic plot of ER *vs.* mass for a wide variety of stable systems from the biological, cultural, and cosmological realms (green, red and blue ovals, respectively; cf. Figure 1), extended with unstable, "explosive" systems. Diagonal, dotted lines of constant ERD of 10^{10}, 1, and 10^{-10} W/kg are guides to the eyes. The red, diagonal line represents a "hard" upper ER *vs.* mass limit of $\sim 10^5$ W/kg. The purple data points above this upper limit represent unstable systems, both, unrealistic and "explosive" systems.

for nuclear bombs, such as the Little Boy atomic bomb and the Tsar Bomba hydrogen bomb (pink triangles) with ERD values of 10^{18} and 10^{21} W/kg [66], respectively, lie even further above the upper limit. This shows that nuclear bombs should also be considered as unstable systems and confirms that they are more powerful and destructive, compared to conventional explosives. Note that in the technological sub-realm "controlled explosions" find widespread applications. In some devices chemical energy is converted to kinetic energy in a controlled fashion without damaging the device. Typical examples are the use of high-energy density fuel in space rockets, the fuelling of internal combustion engines in vehicles, and the firing of guns.

In the cosmological realm, similar unstable, "explosive" systems are known. Four types of these so-called cosmological transients (SM IIIh) are distinguished here:

i) super-nova (SN) explosions (Figure 6: purple triangles);
ii) other stellar explosions that may be related to SN (purple squares);
iii) disruptive events resulting from matter-accretion by SMBHs (purple ж symbols);
iv) collisions and mergers of compact objects (purple points).

SN Ib, Ic, and II are the blasts of giant stars at the end of their lifetime, when the star is not able anymore to produce sufficient energy from nuclear fusion to counteract its own gravity [165]. So much heat is generated during the subsequent contraction, which cannot be contained within the stellar structure anymore, that the star collapses and implodes. SN Ia explosions are the result of the re-ignition of white dwarfs in binary systems. The star's temperature is raised so much that runaway, nuclear fusion is triggered, completely disrupting the star. The mass of the precursors of the SN types I and II ranges from $2x10^{30}$ to 10^{32} kg, while the SN themselves have ER values ranging from $6x10^{34}$ to $2x10^{39}$ W. This yields ERD values between 10^{3} and $3x10^{7}$ W/kg. The corresponding ER & mass datapoints partly overlap and partly lie above the upper ERD limit. So-called failed SNs are astronomical events in which stars suddenly brighten, as a result of core collapse as in the early SN stage, but then do not continue as SN explosions [166]. These failed SN combine mass ($2x10^{31}$ to 10^{32} kg) with ER values ($3.5x10^{31}$ to 10^{33} W) that yield ERD values of 2 to 11 W/kg. These ERD values are below the ERD threshold, corroborating that these systems are indeed not "explosive". Other cosmological explosions that are less well understood, but may be related to SN, comprise the second group of cosmological explosions. Fast blue optical transients are very high-energy phenomena thought to be some type of SN with ERD between 10^{4} and 10^{6} W/kg [165]. Hyper-novae are believed to be very energetic SN, resulting from extreme core-collapse scenarios [165] with ERD between 10^{11} and 10^{14} W/kg. Pair-instability SNs are hypothetical SNs of massive population III stars [165] with ERD of 10^{12} to 10^{14} W/kg. The estimated ERD values of the latter three types of cosmological transients are (far) above the 10^{5} W/kg limit. These are surpassed though by long GRBs, which are exceptionally bright phenomena, supposed to be the immediate after-glow following on the collapse of a massive star (>$5x10^{31}$ kg) to a black hole [165]. The recently observed long GRB 221009A is the "brightest of all time" (BOAT; ER around $4x10^{48}$ W and ERD around 10^{17} W/kg) [167], outshining for a short time all stars in the universe. Note that He shell flashes in the later stages of stellar lifetimes do result in very strong ER fluctuations with high ER peaks (for example: Sun today: $1.9x10^{-4}$ W/kg *vs.* He shell flashes: 1 to 2 W/kg [75]), but not to the extent that the corresponding ERD values cross the diagonal threshold. These are typically viewed as preludes to stellar "death".

Matter accretion by SMBHs causes the disruption of interstellar gas clouds and stars, comprising the third group of ultra-luminous transients. The very recently observed AT2021lwx, also called Scary Baby, is an explosive event lasting for three years now and probably caused by the accretion of a gas cloud by a SMBH [168]. TDEs are similar, but more short-lived explosive events, resulting from matter-accretion by SMBHs from stars [169]. When just the mass of the disrupted cloud and stars is considered, ERD values of $2x10^{5}$ to $3x10^{6}$ W/kg are estimated, which fall above the explosive ERD limit. When using the mass of the full system, including the SMBH, ERD values between 0.01 and 0.7 W/kg are estimated. These systems then behave like "regular" matter-accreting objects and, indeed, the ER & mass points shift to the corresponding oval (Figure 6: rightward, purple arrow). Mergers of compact objects, such as neutron stars and black holes, comprise the fourth and last group of cosmological transients. Short GRBs are brief, brilliant flares of gamma radiation releasing as much energy as our Sun will produce in 10^{10} yr, but compressed into bursts of less than 2 s [165]. Short GRBs probably result from the collision of two massive stellar remnants (neutron stars and black holes) and are characterised by huge ERD values between 10^{13} and 10^{17} W/kg. Compact binary mergers resulting from collapsing binaries of neutron stars and black holes, as recently detected *via* their gravitational waves [170], have extreme ERD values estimated around 10^{18} W/kg. These represent the largest ERD values of all systems listed and, indeed, these systems are positioned farther above the diagonal ERD limit than any of the other unstable, explosive systems discussed.

Interestingly, the biological realm lacks this type of unstable, "explosive" systems, positioned above the upper ERD limit. Maybe, living organisms are *per* definition stable, have intrinsic routines to prevent too high ER values, and/or simply die with subsequently ER falling to zero, before they could reach or surpass an ERD value of 10^5 W/kg. Makarieva *et al.* have suggested that biological evolution has resulted in optimised ERD values of 1 to 10 W/kg [17], which is far below the threshold. The mantis shrimp is a marine crustacean of approximately 10 g that can take "punches" with its claw, reaching speeds of 23 m/s and creating 1500 newtons of force per punch [194]. This corresponds to an ERD of 7×10^5 W/kg, which is above the ERD limit though just for a fraction of a second. Note that the shrimp itself and its claw are not disrupted, but its preys are. "Exploding" beetles and termites, releasing noxious gases for their defenses [171], may be viewed as "controlled explosions" with local rupture of tissue, and do not relate to particularly high ERD levels of the insects as a whole. Epidemics and pandemics of diseases, as well as plagues of mice, rats, and locusts may grow exponentially over time under favourable conditions and could be considered as biological "explosions". However from an energy processing perspective, the increasing ER will typically scale sub-linearly with the increasing number of organisms and, thus, with the increasing total mass (cf. section 5.2). For such "exploding" biological systems ERD will actually decrease with size and remain far below the ERD limit. For social systems "explosions", as in revolutions and wars, relate to the disruption of their abstract, non-materialistic structures and boundaries, but not to excessive ERD values. ER of the human society has increased exponentially with time, which may result in energy depletion issues. Interestingly, human society ER scales supra-linear with human population, but ERD has decreased over time because of even faster increasing human-made mass, thus remaining far below the ERD threshold outside the explosive regime.

It appears that the border line of ER *vs.* mass, running diagonally through the master plot and corresponding to a maximum ERD of around 10^5 W/kg, separates stable systems below the limit (section 7.2) from unstable, "explosive" systems above the limit. Chaisson has also noted that complex systems require sustained order with an "optimised" energy flow and that too large ER results in damage, breakdown, and catastrophic destruction of systems [5]. Indeed, for a system with a particular material structure and, thus, mass, ER cannot be increased infinitely. Heat is always generated during energy conversions, because the efficiency of energy conversion is always (far) below 100 %. With increasing ER, it will become increasingly difficult to remove this heat fast enough from the system. As a result, the temperature of the system will increase to the point that the system's structure may start to soften and melt, as well as thermally degrade and oxidise in the presence of air, thereby weakening the system's structure and boundaries. Increased temperature may also result in an increase of the internal pressure up to the point that the boundaries of the system will rupture. With increasing heat, the mechanical stresses between parts of the system's internal structure and in the system's boundaries will increase, which may eventually lead to failure. Similarly, a large energy flow may result in a high speed of a system, which in turn may lead to enhanced friction and, thus, in heating and wear. Eventually, the combined effects of a too high temperature and pressure as well as too much wear will lead to disintegration of the system, resulting in an upper ER value for a given mass. When ER is far above this limit, the rate of disintegration will be so fast, that the system will explode. These considerations may partly explain the difference in maximum ERD values of 10^4 W/kg observed for stable biological and cosmological systems *vs.* 10^6 W/kg for technological systems. Similarly, they may explain the difference in minimum ERD values of 10^6 W/kg observed for technological explosions *vs.* 10^3 W/kg for cosmological explosions. Notably, the heat and oxidation resistance as well as the physical strength of biological structures (made from organic molecules and polymers with covalent bonds as well as interacting *via* dipolar interactions and H-bonding) are lower than those of machines (made out of metals, such as steel and aluminium, thermoset resins, as well as composites). In contrast, cosmological systems are typically held together by gravitational forces, which are viewed as the weakest of the fundamental forces. In addition, true material boundaries, which can degrade or rupture at elevated ER, are absent. Note that the instability and disintegration of a system above the ERD limit is a consequence of a disbalance of forces and energies, similar to the mechanical restrictions in the maximum size of systems [101,105] (section 2).

The ERD threshold at around 10^5 W/kg separates the stable systems with smaller ERD from the unstable systems with larger ERD. The latter are viewed as explosive and self-destructive. Note that not only explosive systems, but also stable systems may be destructive for other systems in their neighbourhood. Energy may be transferred from a first system to a second, proximate system, resulting in an ERD increase of the second system depending on the amount of energy transferred and the mass of the second system. When the increased ERD of the second system exceeds the ERD threshold, it will become unstable, damaged and even destructed. For the explosives and nuclear bombs in the technological sub-realm, this energy transfer is the purpose of their applications. All the vehicles from the technological sub-realm, ranging from cars, ships to airplanes, are by themselves stable systems with ERD up to 10^4 W/kg, *i.e.,* below the ERD threshold. They may become highly damaging though, when they impact another object, depending on the mass of this object. Similarly, in the biological realm excessive energy transfer as in a predator jumping on, flying into or setting their teeth or claws into a prey, a snake constricting its prey, as well as a buffalo stampede over-running other animals, are harmful and often lethal. Principally, all living organisms in the higher levels of the food pyramid should be viewed as destructive. Although being stable systems themselves, they obtain their energy and raw materials from feeding on organisms from the lower levels.

Cosmological explosions are self-destructive, but may also be destructive for other cosmological objects, such as planets, stars, and even galaxies, when these are in proximity and sufficient energy is transferred. Matter-accreting systems are considered here as a class of stable, cosmological systems with ERD between 10^{-3} and 10^{4} W/kg. However, calculating ERD for just the matter in accretion yields ERD values far above 10^{5} W/kg and, thus, is destructive from that perspective (cf. various ERD data for OJ 287 blazar in SM IIIc). Similarly, TDEs are positioned as stable matter-accreting systems, when they are considered as SMBHs being fuelled with accreting matter. On the other hand, they are positioned as explosions, when the disruption of the donor stars with low mass is emphasised (Figure 6: compare purple ж symbols in matter-accreting realm and explosive regime, respectively). The ERD threshold around 10^{5} W/kg may help to have a better perspective of certain cosmological events, which are characterised by the release of huge amounts of energy. For example, an impressive amount of $2x10^{38}$ W of energy was released during the CIZA J1358.9-4750 merger of two galaxy clusters [172]. Considering the combined mass of two galaxy clusters (estimated at 10^{45} kg), the corresponding ERD of $2x10^{-7}$ W/kg is small and shows that the merger is not in the explosive regime. It will not be self-destructive for the two merging clusters themselves, but the resulting shockwave will be highly destructive for cosmological objects in proximity.

Amongst the Earth systems, asteroids are stable systems when in flight in space, but they may incidentally impact Earth. Asteroids with diameters of 100 to 1000 m have an estimated impact ER of 10^{16} to 10^{20} W [173]. When only the mass of the asteroids themselves ($1.4x10^{9}$ to $1.4x10^{12}$ kg) is considered, ERD values ranging from 10^{7} to 10^{8} W/kg (SM IV) are estimated, which are above the 10^{5} W/kg limit (Figure 6: purple diamonds). Indeed, asteroids are fully destroyed themselves upon impact and, thus, are explosive, self-destructive systems. However, because of the transfer of kinetic energy from the asteroid to the Earth surface, the latter is also affected by the impact, resulting in crater formation and other damage. The kinetic energy of impacting asteroids, which is determined by its mass and velocity, govern the damage on the Earth surface. The Chicxulub impactor may have had a mass of 10^{14} to $5x10^{18}$ kg and an impact ER of 10^{24} to $6x10^{26}$ W [174], yielding an estimated ERD ranging between 10^{8} to 10^{9} W/kg. This explains its huge impact on Earth, probably triggering the Cretaceous mass extinction and wiping out of the dinosaurs $6.6x10^{7}$ yr ago. From an ERD perspective, impacting asteroids are in a way the opposites of machines. As discussed above, machines are systems with ERD > 0 when in operation. They can be switched off to ERD = 0 though and then could be considered as simple, complex systems. In contrast, asteroids are moving at very high, but more or less constant speed and, thus, have ERD = 0 from a mechanical energy perspective (no acceleration/deceleration). However, upon impact a huge amount of kinetic energy is transferred within a very short time, resulting in an extremely large ERD. Thus, asteroids in flight could be considered as simple, complex systems, that are switched on upon impact. Hurricanes are stormy weather systems with high-speed winds rotating around a low-pressure “eye,” occurring in tropical and mid-latitude regions and comprising another Earth system. Hurricanes are energised by the condensation of water vapour, which has previously evaporated at warm sea water surfaces. The mass and ER values of a large hurricane are impressive ($2.4x10^{11}$ kg and $6.0x10^{14}$ W, respectively) [175, SM IV]. However, the corresponding ERD of 2500 W/kg is well below the ERD threshold, confirming that hurricanes by themselves are stable systems. When hurricanes contact buildings and constructions with relatively low mass on the Earth surface, energy transfer may again result in very substantial damage including loss of human lives. Other natural phenomena on Earth, such as earthquakes, volcano eruptions and lightnings release enormous amounts of energy in relatively short times (SM IV: estimates between 10^{9} and 10^{14} W). Unfortunately, it is hard to define the corresponding mass of these natural phenomena. As a result, ERD cannot be calculated and these phenomena cannot be positioned in the ER *vs.* mass master plot. Because of their highly destructive nature, they probably are explosive systems with ERD values above the diagonal ERD limit.

In summary, a diagonal, upper limit of ER *vs.* mass is observed for stable systems in the master plot, corresponding to a maximum ERD of around 10^{5} W/kg. Systems below this limit are stable. Unstable and “explosive” systems from the technological and cosmological realms are characterised by ERD values above this threshold. The material structure of such systems with a given mass is not able to withstand the strong forces corresponding to their relatively large ER. For the biological realm such “explosive” systems do not seem to exist. Both explosive and stable systems with large ERD values may be destructive to other systems in neighbourhood, if sufficient energy is transferred and/or the latter have sufficiently low mass. Controlled explosions are known for the technological and biological sub-realms. It is finally noted that systems may be damaged and destructed for other reasons than excessive energy transfer, such as poisoning and neural diseases in living organisms, as well as electrical short circuit and computer failure for technological systems.

8. Connections with ERD

In this final section, further connections between the ER *vs.* mass master plot and ERD will be discussed. The master plot shows the full details of ER *vs.* mass for a wide variety of systems from all energy realms with diagonals corresponding to lines of constant ERD. Chaisson has introduced ERD as a single and practical metric for complexity in BH [5,51,52]. He has shown that ERD of systems representative for the BH narrative increases at an increasing rate, confirming in a quantitative way the intuitive notion that complexity has increased over big time. Table 3 provides an overview of systems with minimum and maximum ERD values (for details see SM) for the various sub-realms, which can be viewed as an extension of Table 1 with minimum and maximum mass and ER values and is helpful in the discussion below.

8.1. ERD threshold and complexity

First, the observation of an ERD threshold, as shown and discussed in sections 6 and 7, will be further elaborated upon. It seems that the evolution of systems has resulted in a very wide coverage of the ER *vs.* mass area in all energy realms, until systems ran into principal ER and mass limitations. Only by considering the full collection of ER & mass data of "all" systems from all realms as shown in the master plot, the ERD threshold at 10^5 W/kg becomes apparent. Systems with ERD values above the ERD limit are not stable and typically "explosive". This raises the interesting question, whether such an ERD maximum corresponds to a maximum complexity that systems can achieve, not only in the past and today but also in the future.

A way to increase complexity beyond this apparent ERD limit may be *via* completely different principles for material structures and energy processes. In the biological and cosmological realms this seems quite unlikely since the structures and processes are given. For the technological sub-realm this may be a different matter, since understanding of the ERD limitations may allow scientists and engineers to develop new systems based on different design principles with larger ERD values. A high concentration of energy is possible by itself, as illustrated by the very large ER values of unstable, "explosive" systems. It is the stability of the system's structure and its boundaries that is limiting and, thus, should be addressed. Maybe larger ERD values can be obtained by going to smaller systems with smaller masses. The heat generation in a system scales with its dimension to the power three, whereas heat transfer scales with dimension to the power two. Therefore, smaller systems with more efficient cooling and less heat build-up will allow performance at higher ERD values, as witnessed by the trend towards downsizing, *i.e.,* miniaturisation [176] as shown for CPU's and chemical micro-reactors. Smaller systems may be built up *via* chemical synthesis, as has been shown for nano-machines [104]. Alternatively, new materials with higher melting temperature, heat resistance and (specific) strength, such as super-metal-alloys, super-thermosets or super-composites, may enable larger ERD values. The development of new technologies for compartmentalisation of systems may also overcome today's stability limitations. For example, efforts to use nuclear fusion for power generation are limited by the fact that there are no materials able to withstand the extremely high temperature (> 10^8 K) of the nuclear plasma. Exploiting strong magnetic fields to shape and control the plasma in so-called tokamak reactors may be a way out. Yet another possible way for by-passing the ERD limit is by exploring new energy realms, which differ from the realms discussed here and may have different material structure demands.

It also seems possible to increase the complexity of systems, but remain below the ERD threshold by simultaneous growth of ER and mass. This is to some extent how biological, technical and social evolution seem to have operated until today. New, more complex systems have evolved over time which are larger in size and have a larger mass and, thus, require larger ER. However, as long as ER does not grow (much) faster than mass, the system will not run into ERD limitations (cf. dotted arrows in Figures 2 and 3). For example for animals, sub-linear scaling (section 5) has resulted in larger size but smaller ERD. For technological systems, increasing energy efficiency allows larger mass at smaller ERD (cf. section 8.3). For social systems ER grows slower than mass indeed(sections 5.3 and 6.3), resulting in smaller ERD. Convergence of smaller systems may result in the creation of a larger system, which typically results in a smaller ERD (cf. section 8.4) but with emerging performance and, thus, higher complexity.

Kardashev has proposed a logarithmic scale for the development of a civilisation over time with energy consumption as a complexity metric [177]. A civilisation may develop from type 1 (able to access and harness all energy available on its planet) *via* type 2 (able to directly consume all energy of its star) to type 3 (able to capture all energy emitted by its galaxy). As a result, the corresponding ER

Table 3: Systems with smallest and largest ERD for all (sub-)realms in dataset#.

realm	sub-realm	smallest ERD system	ERD (W/kg)	largest ERD system	ERD (W/kg)
biological	phototrophic organisms	large tree in darkness	0.038	*Gloeobacter violaceus* cyano-bacterium	28
	chemotrophic organisms	Chrysemys picta tortoise in anoxic hibernation	$6.3x10^{-4}$	*E. coli* fastest growth	5800
	parts of living organisms	human adipose tissue	0.22	*Galago senegalensis* primate muscle during jumping take-off	8900
cultural	technological systems	first steam water pump by Savery	0.02	Intel Core i7 processor	$6.1x10^{5}$
	social systems	New York	0.012*	beehive with 2000 bees	0.54
cosmological	stars	J1237+6526 ultra-cool, brown dwarf	$2.2x10^{-8}$	Godzilla variable star	150
	planets	Uranus	$8.2x10^{-12}$	Jupiter in formative stage	0.003
	matter accreting objects	V1454 Cyg white dwarf binary	$7.6x10^{-4}$	V866 Cco young stellar object	$1.1x10^{4}$
	planetary system	Solar system $	$1.9x10^{-4}$		
	galaxies	dwarf elliptical galaxy	$1.3x10^{-5}$	JADES-GS-z13-0	0.035
	universe	observable universe $	$6.7x10^{-6}$ @		

As present in dataset in SM, *i.e.,* not *per se* system with smallest or largest ERD of all existing systems; * including human-made mass in use; $ only one example listed; @ only ordinary matter and stellar luminosity (dark matter/energy, SN, gamma-ray bursts and black holes excluded).

will dramatically increase from $1.3x10^{17}$ W (Solar luminosity at Earth) *via* $3.8x10^{26}$ W (Solar luminosity) to $6.3x10^{36}$ W (luminosity of Milky Way). Global ER of our human society today corresponds to a score of 0.73. One may wonder whether a civilisation with a much higher score will run into ERD limitations ? However, applying different principles for material structures and energy processes or increasing the civilisation-build mass simultaneously with ER may be ways out to prevent such issues.

A third way of increasing complexity without running into an ERD limit may be by applying the current principles of material structure and energy processing and, thus, stay within the ERD = 10^{5} W/kg limit, but advancing in information processing. Processing (transfer, storage, and conversion) of matter, energy, and information is viewed here as the key characteristic of active, complex systems. In a way, the ER *vs.* mass master plot only describes complexity in the 2D surface, set up by the first two characteristic. This leaves room for increasing complexity in the third dimension of the 3D complexity space, *i.e., via* evolution and innovation of information processing within the ERD limit. The average human brain [80] has roughly the same ERD of 0.012 W/kg as the IBM AN/FSQ-7 computer from 1958 [178], but probably a better information processing performance, showing that complexity is not just determined by energy flow. Further development of the worldwide web and artificial intelligence will correspond to a further increase of complexity *via* the information dimension without requiring an ERD increase.

8.2. Change of ERD over big time and evolution

A second observation is that the development of complexity over big time from the Big Bang to our human society, as presented in BH narratives [7-9], did not proceed *via* cosmological systems with the highest ERD values. Our Sun has a relatively low ERD value ($1.9x10^{-4}$ W/kg), compared to other cosmological objects (SM III), such as:

- MS stars with higher masses, for example, $1.2x10^{32}$ kg MS star of spectral type O: 2.5 W/kg;
- giant stars beyond MS, like Godzilla: 58 W/kg [87];
- neutron stars in binaries: 10 to 500 W/kg [55];
- black holes: 10 to 1000 W/kg [55,91];
- SMBHs: 300 to 8500 W/kg [91].

Our Earth also has an ERD value ($2.1x10^{-8}$ W/kg) which is relatively low compared to other (exo)planets ($2x10^{-7}$ to $8x10^{-7}$ W/kg [89]) and planets in formative stage [5] that are larger and/or hotter, because they:

- are either younger and, thus, had less time to cool,
- are more proximate to their stars and, thus, receive more heat, or
- still have more internal radio-activity and, thus generate more heat.

Apparently, the evolution towards living and cultural systems with increasing ERD, as we know them on Earth today, did not occur on nor in the neighbourhood of such cosmological objects with very high ERD. Amongst others, the development of living and cultural systems is prevented by the high temperatures and high levels of radiation (in the neighbourhood) of these cosmological objects and required environments with more suitable conditions (habitable zone, Goldilocks conditions). In this respect, it may not be coincidental that life on Earth originated:

- in a galaxy with a SMBH with low activity at its center,
- in a planetary system with in its center a star with relatively low mass and luminosity (considering the full mass and luminosity ranges of stars), as well as
- on a planet with a medium temperature.

Homo sapiens is often viewed as the hallmark of biological evolution, but humans have a modest ERD value (20 year old male: BMR- and TEE-based 1.2 and 2.2 W/kg, respectively) compared to other living organisms (SM I):

- cyanobacteria: up to 28 W/kg [18];
- chemotrophic archaea and bacteria: up to 500 W/kg [19];
- plant and tree seedlings: up to 14 W/kg [18];
- aquatic invertebrates: up to 12 W/kg [18];
- insects: up to 14 W/kg [112];
- small endotherms, mammals, and primates, such as shrew, deer mouse, and Microcebus: up to 40 W/kg [SM Ib];
- birds (in flight): up to 40 (100) W/kg [SM Ib].

In terms of an ERD *vs.* time plot, ERD does progress to higher values over big time, as shown by Chaisson [5,51,52], but not necessarily from the highest peak to the highest peak. Actually, the development of complexity over big time has followed a rather tortuous path through the ER *vs.* mass master plot over big time, viz. from the cosmological realm on the right side *via* the biological realm on left side to the cultural realm in the middle. Finally, the ERD ranges as set up by the minimum and maximum ERD values in the cosmological, biological and cultural realms (Table 3) are very broad, resulting in substantial overlap between these three realms. Given these wide ranges, it is remarkable that systems in all three realms have evolved in parallel to a maximum ERD value of approximately 10^5 W/kg.

8.3. Change of ERD during lifetime and evolution

A third observation is that ERD does not always increase monotonously, but often decreases over the lifetimes and during the evolutions of some (groups of) systems in the biological, cultural, and cosmological realms. This raises some questions on the efficacy of ERD as a metric for complexity in big time. Starting in the biological realm, both mass and ER increase strongly when a human grows over its lifetime from a baby to a young adult, but mass grows more strongly than ER (section 6.2: 22 *vs.* 16x). As a result, ERD decreases from 3.1 W/kg at birth to 2.2 W/kg at 20 years, whereas one would state that complexity in terms of social, emotional, and, intellectual performance of the young human has increased [57]. Because ER is more or less constant, but mass somewhat increases further up to 65 yr, ERD decreases somewhat more to 1.7 W/kg for an elderly. This does not correspond with the generally viewed opinion of more life experience, stability, and wisdom, which suggest increased complexity. ER scales sub-linearly with mass with a power law constant β of around 0.75 for animals (Table 2). *i.e.,* larger animals need proportionally less energy than smaller animals. The consequence is that ERD, defined as the ratio of ER and mass, scales reciprocally with mass to the power -0.25 (= 0.75 - 1). For example, for endotherms ERD decreases from 14 to 0.2 W/kg with increasing size, for mesotherms from 2.0 to 0.4 W/kg, and for ectotherms from 1.2 to 0.2 W/kg [62]. Thus and as already noted by Makarieva *et al*. [17,18], ERD has actually decreased when living organisms evolved within the same taxon from smaller to larger species during biological evolution. These authors have also concluded that specific MR (= ERD) has reached a constant value of around 1 to 10 W/kg for all biological taxa during biological evolution. This was explained to be the result of biologically evolutionary optimisation in the context of thermodynamic and physical constraints [18]. DeLong *et al.* have shown that ERD increases with mass for prokaryotes (archaea and bacteria), next levels off for unicellular eukaryotes with higher mass, and then decreases for small, multicellular, aquatic animals with the highest mass. The power constant β for ER *vs.* mass scaling (Table 2) changes from ~1.8 *via* 1.0 to 0.75 and, thus, the power law constant for ERD *vs.* mass scaling changes from +0.8 *via* 0.0 to -0.25 [19]. First of all, this shows that the metabolic mechanisms and limitations are different for various biological taxa. In addition, it also shows that ERD went through a maximum of around 50 W/kg for unicellular eukaryotes during biological evolution from prokaryotes *via* unicellular eukaryotes to multicellular eukaryotes. In summary, these variations in ERD and especially the absence of a continuous ERD increase are not aligned with an increase of complexity during biological evolution. Interestingly, the changes of TEE (just biological food requirements and excluding energy for technological uses) and mass during the evolution of hominins from the early, rather small hominin species *via* the larger Neanderthals to today's, somewhat smaller *Homo sapiens* (section 6.2), correspond to a continuous increase of ERD (1.5 to 2.2 → 2.2 to 2.9 → 2.5 to 3.1 W/kg). Again, this does align with the apparent, increased complexity.

For small tools, big machines, as well as huge power and chemical plants in the technological sub-realm, there has been a continuous drive towards increased energy efficiency, often because of economic reasons. Typical examples of the last decades are the improved fuel efficiency of car engines (with a factor larger than two over the last fifty years [179]) and the increased efficiency of thermal power plants (from 32 to 36 % from 1990 to 2015 [180]), both motivated by increased energy prices. A higher energy efficiency may allow a better performance in terms of increased energy output for a given energy input, but also a decreased energy input for a given performance output, *i.e.,* energy savings. In the first case, ERD typically increases (larger ER for same mass, for example increased efficiency of solar panels). However, in the second case ERD decreases (smaller ER for same mass; for example replacement of incandescent by LED lamps), whereas more refined and optimised technology to save energy, resulting from innovation, could be considered as increased complexity. Indeed, Kempes considers a large ERD as an indication of energy inefficiency [20]. Similarly, there is a drive to maximise the carrying load of machines used for the transport of goods, such as trucks, cargo planes, as well as container and tanker ships. The combined result of maximising load mass and minimising energy consumption is again a decreased ERD, while the complexity of the transport machines has increased. Innovation may also result in the simplification of the design of products, for example by reducing the size of over-designed components or leaving out redundant parts. Interestingly, the product complexity is then reduced, while ERD may increase because of mass reduction.

In the cultural sub-realm, ER of bee colonies and human cities scale sub-linearly with colony and city mass with β = 0.64 and 0.86, respectively (section 5.3). As a result, ERD scales inversely with mass with a power law constant of 0.36 and -0.14, respectively. Indeed, ERD decreases with city size from 0.025 W/kg for Vic (France) to 0.012 W/kg for New York (USA) [23]. This is rather counter-intuitive in view of increased social complexity, but makes sense when one realises that larger cities have economy of scale and improved energy efficiency. Early *Homo sapiens* had an ERD of 2 to 3 W/kg, based on just chemical energy from food and mass of the human body. Making a jump to our modern, industrialised society, both mass and ER have dramatically increased over the last 120 years (Figure 3). Because human-made mass has grown faster than ER, ERD has decreased from 0.043 W/kg in 1900 to 0.017 W/kg today. In contrast, the general opinion is that complexity has increased strongly, when the human society developed from:

- the first humans, living rather isolated and from what nature had to offer, *via*
- the steam-powered society in 1900, still somewhat focussed on regional affairs with the telephone as most efficient communication technology, to
- the electricity-powered society of today, characterised by its global economy and internet communication.

Note that this conclusion is in strong contrast to those of Chaisson (increased ERD over human [r]evolution from hunter gatherer to human in industrialised world) [51, 52] and Barton (strong increase of ERD of human society since 1900, but levelling off since 1980) [71]. Both Chaisson and Barton have normalised the increasing, global energy consumption to the mass of the human population only. However, humans do not eat coal, do not drink oil, and do not inhale natural gas, while high-voltage electricity is harmful to them. The only energy that flows through human bodies is chemical energy from food and oxygen, corresponding to the average, daily 2500 kcal dietary energy requirement per person, which has hardly changed over time. It is here argued that the mass of the whole human system should be considered for the calculation of ERD, just as ER is considered for the whole system. Without the human-made mass in buildings and constructions, human society would not be able to achieve such a high ER. This then results in the question whether ER itself and not ERD is a better measure for social complexity ?

Finally and as explained in section 5.4, ER of MS stars scales super-linearly with mass with an average β of 3.5. As a result, ERD scales with mass with an average power law exponent of 2.5 and, thus, a larger-mass star will have a larger ERD. This is in agreement with a higher complexity, as witnessed by the production of higher-mass elements *via* nuclear fusion and the presence of more, element-enriched layers. Since the average mass of stars formed during the evolution of stars from population III *via* population II to population I has decreased, ERD of stars also has decreased. This is another example showing that evolution, in this case stellar evolution, has resulted in smaller ERD.

Inspection of the smallest and largest ERD values for systems in the various sub-realms in Table 3 shows two general trends:

- a very small system often has a very large ERD (cyano- and *E. coli* bacteria, the Intel Core i7 micro-processor, and a beehive with a small number of bees), where-

as a very large system often has a very small ERD (a large tree, the first steam water pump, and New York city); this is probably due to sub-linear scaling of ER *vs.* mass ($\beta < 1$) in the corresponding sub-realms;
- a system with very low activity often has a very small ERD (a tree in darkness, a tortoise in hibernation, adipose tissue, and an ultra-cool dwarf star), whereas a system with very high activity often has a very large ERD (fast growing *E. coli*, primate muscles during jumping, and Jupiter in formative stage); this is simply because higher activity levels require more energy.

For both ERD trends it is questionable whether the complexity of the systems varies accordingly. The calculation of ERD of a system by normalising ER by mass makes sense in a first approach, but inexplicitly assumes $\beta = 1$ for all groups of systems, which is not correct (section 5). Actually, $\beta = 1$ applies to systems with linear scaling with the system as a whole being simply the sum of its parts, whereas the key feature of complexity is that a complex system as a whole is not just the sum of its parts. Possibly, ERD values of systems in normal operation should be compared, similar to the use of BMR in biological scaling studies. Six out of eleven maximum ERD values in Table 3 are (much) larger than those of a young-adult male (food energy only: 1.2 W/kg) and our society (0.017 W/kg). However, it is questionable whether the complexity of the six corresponding systems is larger than those of a human and the human society.

8.4. Use of ERD of parts to represent complexity of systems

A fourth observation connecting ERD with the ER *vs.* mass master plot relates to a warning for using sub-systems (parts) with high ERD values as indicative for the complexity of the larger system. Such *pars pro toto* reasoning often gives a wrong impression. First some examples for the biological realm will be presented. It may be obvious that the cytochrome oxidase protein and the respiratory complex with very large ERD values (1700 and 1200 W/kg [10], respectively) are not representative for living, aerobic organisms. But in the same way, high-energy-demanding organs of the human body (heart, kidneys, liver, and brain) with large resting ERD values (32, 23, 12, and 11 W/kg, respectively [80]; similar data in [181]) are not representative for the human body as a whole. The skeleton muscles in rest have a low ERD of 0.5 W/kg, while the abundant but inactive adipose tissue acting as energy reservoir has an even lower ERD of just 0.2 W/kg. The ERD data of all these organs and tissues converge to a basal ERD of the human body as a whole of just ~2 W/kg. It is interesting to note that the human organ with the highest ERD is not the brain, *i.e.,* the center of the nervous system considered to be the most complex organ responsible for cognition, intellect, and emotions, but the heart which is "just" the pump continuously conveying blood through our body! In his respect it is also interesting to note that ER during playing chess is hardly different from BMR [182], whereas ER during physical activities (physical labour, sports) is much larger (cf. section 7.2).

In the technological sub-realm there is often just one part of a technological system that is processing energy and, thus, governing ER, but its relatively large ERD is not representative for the system as a whole. The main engine fuel turbopump of the space shuttle has an ERD of $1.5x10^5$ (W.kg) [158], while the space shuttle itself has an ERD of "just" $1.4x10^4$ W/kg. Similarly, the engines of other vehicles have ERD values which are four to twenty times larger than those of the machines themselves (SM IIa). ERD values of ICs for the old Intel 4004 and modern Intel Core i7 CPUs of $6x10^3$ and $6x10^5$ W/kg, respectively, are much larger than those of the corresponding CPUs themselves, viz. 12 and $2.6x10^4$ W/kg, respectively [81]. When converging from the technological sub-realm into the social sub-realm, the very large ERD values for electrical household appliances (0.3 to 4000 W/kg), cars (70 to 250 W/kg) and super-computers (3 to 250 W/kg) are indeed illustrative for the high complexity of our modern society [5]. However, the high ERD values of such devices are not representative for ERD of the human social systems as a whole. The admittedly high ERD values of the machines mentioned are averaged out, when considering the huge amount of inactive, human-made mass of buildings and constructions. This results in modest ERD values of 0.012 to 0.031 W/kg for cities and $1.7x10^{-5}$ W/kg for the human society of today. For the same reason in the cosmological realm ERD of (super-massive) black holes (1 to 9000 W/kg) do not represent ERD of a galaxy ($2x10^{-5}$ to $4x10^{-2}$ W/kg) nor that of the universe as a whole (10^{-5} W/kg). This brings us to another question: how to compare systems from different realms ? Which parts and which whole systems may be compared ? This question will be addressed in another study by making a rigorous distinction between sub-realms and examining ERD over their corresponding complexity hierarchy [183].

8.5. ERD in converging systems

A related and final observation is that the subsequent convergence of smaller sub-systems to larger systems and these in their turn to even larger super-systems *etc.* corresponds to a natural system hierarchy. Intuitively, this should also correspond to an increase of complexity, because the super-systems consist of a number of smaller systems, which in their turn consist of a number of even smaller sub-systems. In addition, the transition from such smaller to larger systems is often accompanied by the emergence of additional properties and functions, which are not present at the previous level, *i.e.,* "the sum is often greater than the parts". Also, for this reason it can be stated that complexity increases when following the natural hierarchy. Bonner has elaborated exactly on this point for biological and social systems [125]. Reeves has done the same for systems, ranging from quarks to organisms, in his pyramid of increasing complexity [184]. However, the ER *vs.* mass data for small systems merging into larger systems (section 4), show that ERD does not simply increase, but in a way is averaged out. Note that in contrast to mass and ER, ERD of a larger system is not the sum of the ERDs of its parts, but the weighted average. The larger systems typically consist of various smaller systems representing a whole range of ER's and masses, including inactive systems with ER = 0 but a certain mass. As a result, ERD decreases when going up in the complexity pyramid. In this respect, ERD of the universe of $7x10^{-6}$ W/kg is the ultimate average, which is very low ERD value for an active system indeed. *Vice versa* this also means that ERD increases when going down in the complexity pyramid, which may partly explain why parts of a system span a wider range of ERDs than the ERD value of the system itself. This is illustrated by the examples of convergence as presented in section 4, but now with ERD data in W/kg between brackets.

- biological realm: cytochrome oxidase protein (1730) → respiratory complex (1170) → mitochondrion (310) → neuron (27) → cerebellar cortex (15) → brain (11) → human body (2.0);
- technological sub-realm: car engine (800) → car (130) (1990 data);
- social sub-realm:
- bees (41) → bee colony in beehive (0.54);
- humans (2.0) + machines (~250) → cities (~0.02) → today's, global human society (0.017);
- cosmological realm: Sun ($1.9x10^{-4}$) → Solar system ($1.9x10^{-4}$) → Milky Way ($2.1x10^{-5}$) → universe ($7x 10^{-6}$).

In summary, ERD is admittedly a very elegant metric for the development of complexity over big time. However, there seem to be some issues related to decreasing ERD over the lifetime of a human and the human society, as well as during the evolution of larger, living organisms and stars. In addition, increased energy efficiency of machines results in decreased ERD, but innovation is viewed as increasing complexity. Care should be taken to include the correct mass of the full system through which energy flows including the mass of inactive parts, which for social systems results in significantly lower ERD values. High ERD values of parts of systems are not representative for the system as a whole. The anthropocentric view on BH developing *via* Sun, Earth and human does not reflect the path of highest ERD values of stars, planets and living organisms, respectively. In general, focussing on ERD as a single parameter for systems which are only relevant to BH [5], does not allow the full interpretation of ER *vs.* mass details for "all" systems in the universe.

9. Conclusions

Convergence and scaling: As a start and in response to the question in the title: much can be learned from a master plot of ER *vs.* mass for a wide variety of (complex) systems from the biological, cultural, and cosmological realms ! Especially when plotted in a double-logarithmic fashion the full details of the ER and mass data (spanning 67 and 75 orders of magnitude, respectively) become visible and allow a discussion that is not possible when just considering ERD (= ER/mass ratio) data. The ER & mass datapoints of systems belonging to the various (sub-)realms form clusters, which provide a quantitative distinction of the sub-realms and is aligned with their qualitative distinction in BH with respect to material structure and energy processing. Small sub-systems with low mass and ER converge into larger systems with larger mass and ER, which in their turn converge into super-systems with even larger mass and ER. In addition, ER scales with mass for various groups of systems in sub- and super-linear fashions. The value of the power law constant is dependent on the particular group of systems (β varies between 0.5 and 4.0), showing that the self-organising mechanisms of these groups of systems are quite different. The combination of convergence and scaling with β always larger than zero explains why the ER & mass data fall in a broad, diagonal band from the lower left to the upper right side of the master plot with an ERD width of 17 orders of magnitude.

Lifetime and evolution: Typically, both ER and mass vary during the lifetimes of systems, but with a steady state in their mature stage with minor fluctuations around stable ER and mass levels. The human society is an exception though, because, so far, its ER has increased, but its mass even more so. Note that in contrast to Chaisson [5,51], the mass of a social system is defined here as the sum of the mass of the living organisms plus that of the built constructs, which are essential to achieve its particular ER value. ER and mass vary over the lifetime of systems, but even more during the evolution of groups of systems, either to larger ER and mass (living organisms, machines) or to smaller ER and mass (stars). Notably, the development of complexity over big time has followed a rather tortuous path criss-crossing over the ER *vs.* mass master plot.

Minimum and maximum ER: The area on the lower and right side of the master plot seems empty. However, it is filled with a huge number of dormant, living organisms, machines with the unique features that their power can be switched on & off and adjusted to a desired level, as well as cooling, cosmological objects (stellar remnants, planets, asteroids *etc*.) that are fading away. In a BH context, such systems are typically considered less interesting compared to active systems. It is argued here that these are all simple, complex systems, which are out of equilibrium and with matter, energy and information stored in their structure. Evolution can be viewed as the process of systems trying to explore a larger ER *vs.* mass area until they run into ER and/or mass limitations. There seems to be an upper ER *vs.* mass limit for stable systems running diagonally through the master plot, corresponding to a maximum ERD of around 10^5 W/kg. In the technological and cosmological realms, systems with ER *vs.* mass values above this limit do exist, but these are "explosive" and are considered as unstable. Such "explosive" systems in terms of energy transfer do not exist for the biological and social realms. The observation of an ERD limit for all systems over the whole master plot, raises the interesting question of whether such a threshold puts a limit on the development of complexity over big time.

Consequences for ERD as complexity metric: While ERD appears to increase with the 'advancement' of systems over big time [5,51,52], there are quite a number confounding factors regarding the efficacy of ERD as a metric for complexity in BH. The tracks of ER *vs.* mass of some (groups of) systems over their lifetimes (human body, human society) and evolutions (living organisms, stars) show that ERD decreases, whereas their complexity is believed to increase. The convergence of parts to a larger system often comprises the inclusion of inactive parts with a certain mass but with ER = 0. As a result, ERD decreases from parts to systems with the observable universe as the ultimate convergence having a very low ERD. Note that high ERD values of system parts may be illustrative for the complexity of the larger system, but are not representative for ERD of the system itself (*e.g.* heart > body, engine > machine, SMBH > galaxy, *etc.*). Also machines with an increased efficiency of energy utilisation can be more complex, but have a smaller ERD. Finally, the smallest and largest ERD values for the various realms appear to correlate with activity level and reciprocally with size, which do not *per se* reflect complexity. The anthropocentric view on BH developing *via* Sun, Earth and human does not reflect the path of the highest ERD values of stars, planets and living organisms, respectively.

It is hoped that the raw data collected and the major trends observed in this paper will offer new insights into various aspects of the evolution of the universe over big time, and serve as an important resource for other related studies.

10. Follow up

The current dataset of mass and ER values of systems is very large, but not complete and can still be further expanded by including data for important groups of systems that are missing For example, enzymes, cell organelles, photosynthesizing plants, tumors, virus-infected cells, eco-systems, molecular nano-machines, chemical plants, countries, and galaxy clusters are but a few other systems that warrant inclusion. In addition, the comparison and interpretation of the data along the various angles can be done more in-depth than sketched in the various sections of this paper. In a way, this paper should be considered as an invitation to readers to:

i) identify missing (groups of) systems and providing additional ER *vs.* mass data to update the master plot;
ii) provide more in-depth analyses of the data;
iii) suggest other viewpoints for discussing and interpretating the data.

Mass and ER are just two dimensions of the 3D complexity space. It would be interesting to explore the full 3D space by including information flow and using a corresponding, suitable metric. Admittedly, the author of this type of broad studies cannot be an expert in all the underlying disciplines nor can (s)he have read all relevant papers. Therefore, comments on factual descriptions and argumentation are also welcome. In a subsequent study the development of ER(D) and mass of a low-mass star like our Sun, a human, and the Roman empire will be explored over their lifetimes in more detail, showing some more limitations of ERD as a metric for complexity [57]. In another study, a rigorous distinction of systems in different sub-realms will be made and the change of ERD over their corresponding complexity hierarchy will be examined [183]. In yet another study, the collected ER and mass data will be correlated with additional data on lifetime of systems, resulting in a mass-invariant, total energy density for different groups of systems [185].

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Supplementary material

The supplementary material provides all mass and ER data as well as the corresponding ERD values of the systems ,as presented in the master plot and discussed in this study. Also calculations, sources, and other comments are included. Data have been categorised as follows:

- I: living organisms: Ia: phototrophic; Ib: chemotrophic; Ic: parts of living organisms;
- II: cultural systems: IIa: technological systems; IIb: social systems; IIc: human-made explosives;
- III: cosmological objects: IIIa: stars; IIIb: planets; IIIc: matter-accreting objects; IIId: planetary systems; IIIe: galaxies; IIIf: universe; IIIg: dead cosmological objects; III: cosmological explosions;
- IV: Earth systems;
- V: simple systems;
- VI: Chaisson's dataset.

Also figures referred to with roman numbers, but not shown in the main text are included:

- Figure i: linear plot of ER *vs.* mass, showing just one datapoint *e.g.* for universe, while datapoints of all other systems disappear in origin;
- Figure ii: ER *vs.* mass scaling of all data in double-logarithmic master plot except for dead, explosive and downscaled systems, yielding an overall power law constant β of 0.92; and
- Figure iii: plot of ERD *vs.* mass, showing ERD limit of 10^5 W/kg, separating stable from unstable systems.

Abbreviations

au	atomic unit
ATP	adenosine triphosphate
BH	big history
BMR	basal metabolic rate
C	carbon
CPU	central processing unit
(D)NA	(deoxy)ribonucleic acid
E. coli	*Escherichia coli*
EMR	endogenous metabolic rate
ER	energy rate
ERD	energy rate density
EV	full-electric vehicle
GRB	gamma-ray burst
H	hydrogen
He	helium
HR	Hertzsprung-Russell
HV	hybrid vehicle
IC	integrated circuit
ICEV	internal-combustion engine vehicles
L	luminosity
LED	light-emitting diode
M	absolute magnitude
MR	metabolic rate
MS	main sequence
N	nitrogen
NL	Netherlands
O	oxygen
SM	supplementary material
SMBH	super-massive black hole
SN	super-nova
TDE	tidal disruption event
TEE	total energy expenditure
T_c	temperature of colder surrounding

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