One Earth + One Health: An agile, evolutionary, system-of-systems, convergence paradigm for societal challenges of the Anthropocene

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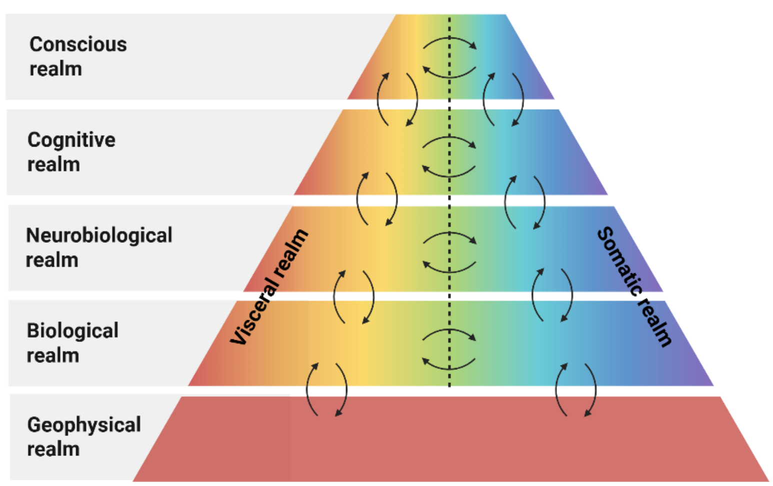


Abstract: Evolutionary mechanisms enabled humans to profoundly transform Earth systems. Because the resulting Anthropocene systems are highly interdependent and dynamically evolving, often with accelerating rates of cultural and technological evolution, the ensuing family of societal challenges must be framed and addressed in a holistic fashion. An agile, evolutionary, system-of-systems, convergence paradigm, which is based on a partially quantifiable, scientifically falsifiable, formal theoretical framework, can be used to systematically identify, decompose, characterize, and then converge, a nested, evolutionary ensemble of geophysical, biophysical, sociocultural and sociotechnical systems. The paradigm includes individual organisms (spanning plants, fungi and animals) engaging in niche construction in a global meta-ecosystem that integrates the deep evolutionary history of all Anthropocene systems. To coherently span the vast range of scales, the paradigm is divided into a somatic realm (externally oriented with respect to individual organisms) that can be applied at global, regional, urban and local scales, as well as a visceral realm (internally oriented with respect to individual organisms) that includes organs, cells, organelles, genes and proteins. The paradigm includes a causally coherent conceptual model based on a common language and reconciled ontology, with a hierarchical, extensible and scalable computational framework, an associated decision-support system and an educational pedagogy.

Keywords: modular evolution; meta-ecosystem; conceptual model; systems modeling language; hetero-functional graph theory; computational framework; decision-support system; educational pedagogy

1.0 Introduction

Humans have profoundly transformed Earth systems, creating a broad array of deeply entwined and intractable societal challenges. For example, a recent assessment of the Planetary Boundaries framework [1] revealed that Earth is now beyond six of nine planetary boundaries, concluding that anthropogenic impacts must be considered in a systemic context. In addition, a recent assessment of progress towards meeting the Sustainable Development Goals [2] found no evidence that the limited environmental improvements that have been made (in forest and water ecosystems) are linked to positive social impacts. Furthermore, addressing climate change, emerging infectious diseases, the spread of invasive species, food security and declining biodiversity will require a new era of continental-scale biology [3] with multiscale, multidisciplinary theory that extends from molecules to organisms, and from ecosystems to biomes to the biosphere.

The need to holistically address these interdependent societal challenges of the Anthropocene [4] is explicitly recognized in the re-envisioned One Health approach, which aims to sustainably balance the health of humans, animals and ecosystems [5, 6]. As shown in Figure 1, the approach intends to mobilize multiple sectors, disciplines and communities across a range of scales and organizational levels, while simultaneously addressing the need for clean water, energy and air, providing access to safe and nutritious food, and tackling climate change, disasters and sustainable development [5]. A recent assessment of the approach [7], which was published as part of The Lancet Series on One Health and Global Health Security [8], found that current frameworks do little to consider anthropogenic factors in disease, concluding that "a complex and interdependent set of challenges threaten human, animal and ecosystem health, and that we cannot afford to overlook important contextual factors, or the determinants of these shared threats."

To address these interdependent societal challenges, we need to catalyze societal transformations with strategic interventions that can be coordinated across multiple systems and scales, but a recent critical review [4] argued that this is not possible with available approaches or frameworks, in agreement with four independent assessments [1-3, 7]. The critical review outlined the evolutionary mechanisms which enabled humans to transform Earth systems, culminating in the current, globally connected, system of Anthropocene systems (noting that the Anthropocene is more than a time interval [9]). Because Anthropocene systems are highly interdependent and dynamically evolving, often with accelerating rates of cultural and technological evolution [10], the ensuing societal challenges are also highly interdependent, as is increasingly being recognized [1, 3, 7, 11-20], and need to be framed and addressed in an integrated fashion [1, 3-5, 11, 17, 18, 20-25].

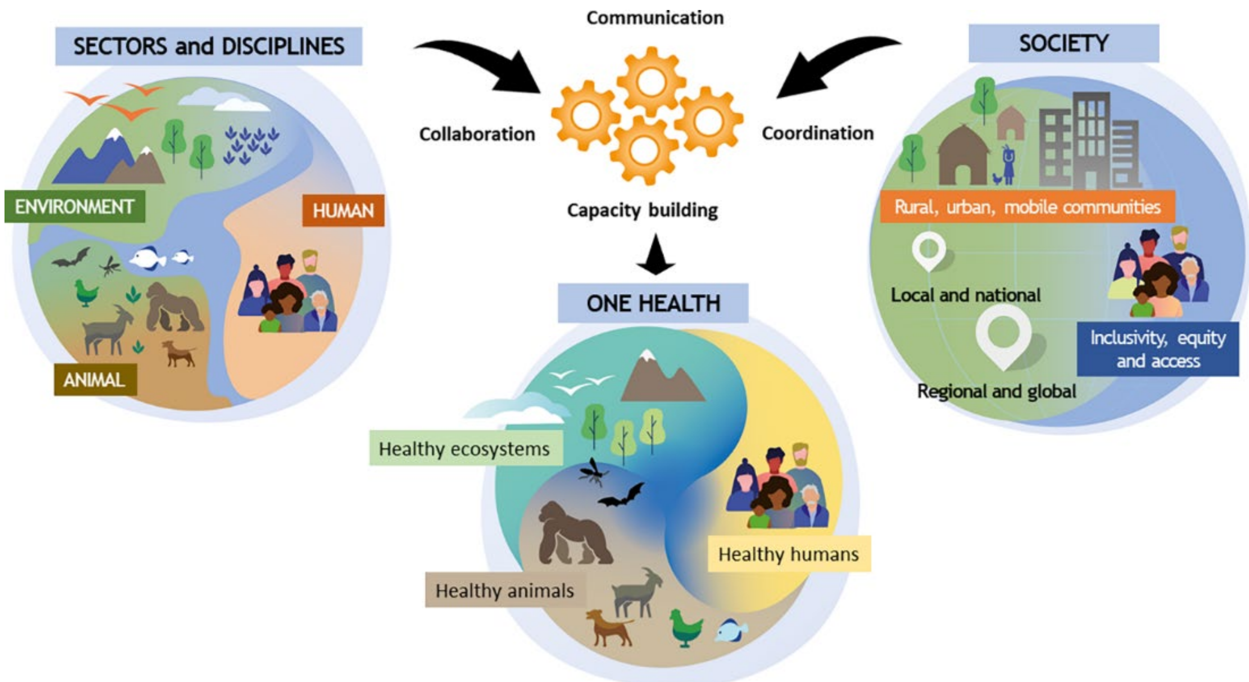


Figure 1. Conceptual representation of the One Health approach developed by the One Health High-Level Expert Panel [www.who.int/groups/one-health-high-level-expert-panel] and supported by the Quadripartite Partners (FAO, UNEP, WHO and WOAH) [8]. To sustainably balance the health of humans, animals and ecosystems the One Health approach intends to integrate multiple sectors and disciplines across local, urban, regional and global scales, simultaneously balancing the need for a healthy environment, renewable energy, and safe and nutritious food, while tackling climate change and sustainable development [5]. To successfully address these societal challenges in an integrated and holistic fashion requires extensive communication, coordination, capacity building and collaboration [8].

An evolutionary perspective can also be used to gain valuable insights into earlier societal transformations, beginning with four proposed transitions in the coevolution of early humans (see Table 4 in [4]), and continuing with agriculture, urbanization, industrialization and computerization. Understanding these earlier societal transformations, which enabled the coevolution of the Anthropocene and the emergence of the ensuing societal challenges, should prove valuable as we attempt to coordinate new systemic interventions.

In addition to these complex and almost overwhelming challenges, the partition of knowledge into many disciplines and subdisciplines is simultaneously one of the greatest scientific and societal challenges of our time [4, 26], severely impeding progress because we cannot "see the forest for the trees." The deep integration of knowledge, methods and expertise across multiple disciplines requires convergence [27, 28]. Because Anthropocene systems span a vast number of traditional disciplinary boundaries, convergence is required to address the resulting societal challenges.

In this review, we build on the previously proposed evolutionary (evo), system-of-systems (SoS) convergence paradigm [4], which is based on a partially quantifiable, scientifically falsifiable, formal theoretical framework, and can be used to systematically identify, decompose, characterize, and then converge, a nested, evolutionary ensemble of geophysical, biophysical, sociocultural and sociotechnical systems. The previous critical review outlined the evolutionary mechanisms which enabled humans to transform Earth systems into Anthropocene systems [4], but in this new review, we broaden the scope to include the coevolution of ecosystems, animals and humans, as required for the One Health approach [5], and because an equivalent One Earth approach is needed [3, 15] with an evolutionary framework that integrates geophysical, biophysical, sociocultural and sociotechnical systems at the planetary scale [29].

As we will argue, an evolutionary perspective is essential because we need to understand the causally coherent, cross-scale, evolutionary mechanisms which enabled the family of societal challenges to emerge. A system-of-systems perspective is equally essential because we need to manage the unprecedented range of scale and complexity as effectively as possible. The extended evoSoS convergence paradigm will enable the entire family of societal challenges of the Anthropocene to be framed and addressed in an integrated fashion with causally coherent strategic interventions across multiple systems and scales. However, the development and implementation of the paradigm will require a major transformation in our approach to science and engineering with four primary elements:

1. Causally coherent, cross-scale, modular, dynamic conceptual model of a system of Anthropocene systems that is based on a common language and that reconciles disciplinary ontologies.

2. Common computational framework that builds directly on the conceptual model and is hierarchical, extensible and scalable.
3. Coherent decision-support system that is used to interact with the conceptual model and computational framework enabling effective integration of a wide range of stakeholder perspectives spanning multiple scales and organizational levels.
4. Comprehensive educational pedagogy that is used to train a new generation of Anthropocene systems integrators to develop and implement the new paradigm.

To justify the need for these four primary elements (conceptual model, computational framework, decision-support system and educational pedagogy) of the evoSoS convergence paradigm, our review takes an evolutionary perspective in Section 2, a system-of-systems perspective in Section 3, and identifies limitations of current frameworks and approaches in Section 4. In Section 5, we outline the requirements for the four primary elements, which are all crucially important to facilitate the communication, coordination, capacity building and collaboration which are essential for success [5] (see Figure 1). We conclude our review in Section 6 with a summary of research needs for the development and implementation of the paradigm. Given the vast scope, this includes the need for an agile approach [25, 30], taking place in iterations, each of which produces new insight and each of which can be refined in light of that insight, enabling a low implementation risk to the first investment and a viable roadmap towards an ambitious end goal that cannot otherwise be achieved.

2.0 An Evolutionary Perspective

Dynamic evolutionary mechanisms enabled billions of humans to profoundly transform Earth systems [31], creating a globally connected [1, 21], meta-ecosystem [32, 33], which can be represented as a system of Anthropocene systems [4].

2.1 Evolution Broadly Conceptualized

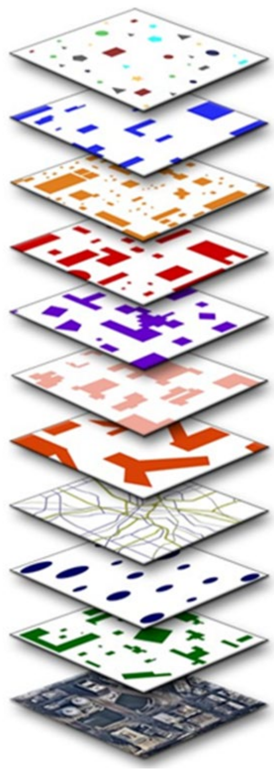
The origin story of life on Earth [34, 35] is a consequence of geological, genetic, cultural and technological evolution [4], recognizing that evolution more broadly conceptualized is not limited to biology [36] and requires only variation and selective retention [37]. The Earth can be understood as an evolving planetary system [38] with chemical elements that evolved in stars [39] enabling the evolution of minerals [40] on Earth, which in turn influence our globally connected meta-ecosystem and the coevolving ecological niche of life on Earth [41, 42]. Similarly, human organizations [43] technology [44] and knowledge [45] evolve, including our knowledge [31] of the form, function and resulting behavior of Anthropocene systems. Indeed, our understanding of evolutionary mechanisms is also evolving [42, 46-50].

Starting with this broad evolutionary perspective, a nested evolutionary ensemble of Anthropocene systems can be identified [4] as follows (see Figure 2): (1) Geophysical systems, which include, for example, geological, ocean, atmospheric, climate, and hydrological systems; (2) Biophysical systems, which integrate biological and geophysical systems and include, for example, ecological and soil systems; (3) Sociocultural systems, which are a specialized form of biophysical system that emphasizes social knowledge and culture and include, for example, cognitive, communication, education, economic, legal and governance systems; and (4) Sociotechnical systems, which are a specialized form of sociocultural system that emphasizes technical knowledge and technology and include, for example, land-use, energy, agricultural, mining, transportation, industrial and other infrastructure systems.

Although cultural and technological evolution are inextricably entwined, it is nevertheless useful to distinguish between sociocultural and sociotechnical systems because technology and socially mediated technical knowledge greatly enhance human influence and accelerate the coevolutionary mechanisms in the ensemble of Anthropocene systems. Earlier geophysical and biophysical systems were of course always connected through global climate and plate tectonics, but the more recent sociocultural and sociotechnical systems have vastly accelerated the temporal rates of interaction among the systems, and vastly increased the spatial extent of interactions across the systems, creating a much more dynamic, globally connected system of Anthropocene systems [4].

An integrated evolutionary framework will allow researchers to derive specific predictions from more general premises, an especially urgent need for behavioral science [51, 52]. For example, a more dynamic understanding of human behavior coevolving with both biophysical and sociocultural contexts [53] enables a better understanding of the dynamics of the Anthropocene.

Without a theoretical framework, results are neither expected nor unexpected based on how they fit into theory and cannot be related to research in other knowledge domains [51].



Anthropocene systems	
Sociocultural	Governance
	Legal
	Economic
	Education
	Communication
	Cognitive
Sociotechnical	Industrial
	Infrastructure
	Transportation
	Mining
	Agricultural
	Energy
	Land-use
Biophysical	Ecological
	Soil
Geophysical	Climate
	Atmospheric
	Hydrological
	Ocean
	Geological

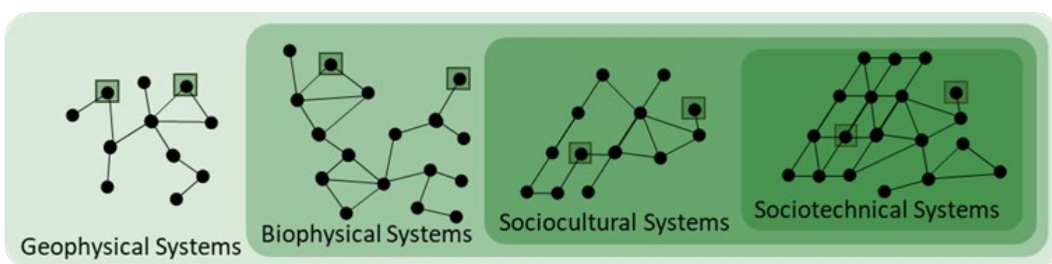


Figure 2. An initial list of 20 primary Anthropocene systems is shown on the right. The image on the left shows the "real world" on the bottom, with 10 interdependent Anthropocene systems layered above. Although the individual systems are shown separately for illustrative purposes, they are almost inextricably entwined. Each of the 10 individual systems has many elements. The elements within a system interact, creating the internal dynamics for that system. The systems interact with other systems via the elements.

Understanding coevolution more broadly, as opposed to simpler scenarios in which organisms adapt independently to a particular environment, reveals a spectrum of interactions (e.g., mutualistic, commensal, competitive and antagonistic) that provide context and nuance to ecological strategies [54]. In addition, organisms may actively modify their own and each other's ecological niche, with evolution by niche construction becoming possible when these modifications influence evolutionary selection [55]. Geophysical systems play an important role in niche construction, when organisms alter their prevailing environment, and need to be included to more completely represent the coevolutionary niche. Anthropogenic change provides a compelling example of humans both intentionally and unintentionally influencing the ecological niche [41] of life on Earth.

The evoSoS paradigm aims to coherently integrate geophysical sciences, biological sciences, health sciences, social sciences, engineering, and the humanities, providing a partially quantifiable, causally coherent, scientifically falsifiable, formal theoretical framework. Crucially, this framework can represent human behavior in sociocultural systems [51]. Unfortunately, the interdependent relationship between human behavior and context has largely been ignored [56], although progress has been made by environmental and ecological psychology [57], and more recently by historical psychology [58]. Building on these and similar initiatives [59], the evoSoS paradigm enables the integration of behavioral science – including the physical, social, and historical contexts that shape perception, deliberation and inferential reasoning – with the geophysical, biophysical, sociocultural and sociotechnical context in which the behavior occurs.

Human behavior [58] is shaped by billions of years of genetic evolution, millions of years of cultural evolution, and a short lifetime of accumulated knowledge and experience, offering levers for behavioral change [60]. Several major evolutionary mechanisms (e.g., kinship, reciprocity, status, leadership, signaling, punishment, norms and institutions) [37, 61-63] can be used to explain human cooperation and competition in sociocultural systems. There are other mechanism and elements of sociocultural systems that can be considered (e.g., see Table 4 and the Appendix in [4]), but as an illustrative starting point, a generic model of a sociocultural system might be represented [4] as follows. Individuals in sociocultural systems process information using their own cognitive systems, cooperate and compete with other individuals using communication systems, acquire and lose status and leadership positions, acquire and forget knowledge, norms, and institutions, and form alliances with other individuals. Similarly, groups of individuals cooperate and compete with other groups using communication systems, acquire and lose status, acquire and forget knowledge, norms and institutions, and form alliances with other groups. Governance, legal, economic and educational systems guide and constrain the coevolving dynamics. The resulting social dynamics involve individuals, groups, and groups of groups, with overlapping versions of these modular, scalable, agent-based structures (e.g., see [64]) propagating through all sociocultural systems.

An evolutionary perspective founded on an understanding of how Anthropocene systems coevolved and became increasingly interconnected, is crucially important when relating Anthropocene systems to human cognition, communication, and the resulting human behavior [58], because it was the evolution of the human brain [65, 66], combined with the evolution of culture and technology, that drove the evolution of the Anthropocene. The way we think, the way we communicate, and the way we make decisions and transform decisions into behavior, all influence, and are influenced by, the coevolving geophysical, biophysical, sociocultural and sociotechnical systems in which our lives are entwined [4].

Once it is understood that humans evolved from unicellular organisms through cooperation, co-dependence, collaboration and competition, and that this is also the case for plants, fungi and animals, the interrelatedness of all species on Earth can be embraced [49, 67], with their evolved modularity providing great potential for improving our understanding of the interconnected nature of Anthropocene systems [4]. Indeed, the coevolutionary ecological strategies already mentioned (mutualistic, commensal, competitive and antagonistic) [54] are essentially the same as the coevolutionary human strategies (cooperation, co-dependence, collaboration and competition). Furthermore, these ecological and human strategies are essentially equivalent to archetypal cellular strategies, providing persuasive evidence for the cell as the mechanistic basis for the evolution of life [42, 67, 68].

2.2 The Realms of Life on Earth

Human initiatives to address societal challenges of the Anthropocene will require coordinated strategic interventions [69] across multiple systems and scales [70], but a more holistic framing is required. The best way to understand a system of coevolved Anthropocene systems is to characterize the evolutionary mechanisms that caused their form, function and resulting behavior to evolve. Although developed while focusing on human consciousness, LeDoux's four realms of existence [71] provide a coherent evolutionary context for our approach to these challenges and can be summarized as follows. The biological realm spans all biology including plants, fungi and animals, as shown in Figure 3. The neurobiological realm is facilitated by nervous systems, which evolved in all animals, enabling control of their bodies with speed and precision that is not possible in other forms of life. Some animals with nervous systems have a cognitive realm, enabling the use of mental models to control a wide range of behaviors. Finally, the conscious realm enables inner experiences of, and thoughts about, the world. These realms [71] are hierarchical, nested and highly interdependent (see Figures 3 and 4), and can be extended to include a geophysical realm, with coevolved geophysical systems providing the foundation for the emergence and subsequent coevolution of life on Earth [4].

Building on Romer's conceptualization of the human nervous system [72], LeDoux proposed [71] that interactions of the body with the external world (also referred to as exteroception [73]) are handled by a somatic nervous system, while internal bodily functions (also referred to as interoception [73]) are serviced by a visceral nervous system. This elevates the somatic and visceral nervous systems to a primary level and makes the central and peripheral locations of their neural tissues secondary. From an evolutionary perspective, this makes more sense because the central and peripheral nervous systems were not the targets of natural selection. Instead, the targets were the modular components that performed visceral and somatic functions for the organism [71]. Indeed, the somatic and visceral realms did not start with animals, but exist in all organisms (including plants, fungi and animals), having begun with our unicellular prokaryotic ancestors, and having evolved through unicellular and multicellular eukaryotes [71], as shown in Figure 3. This means that the visceral and somatic functions of the primordial biological realm were carried forward into the current biological realm, and have also been carried forward into the current neurobiological, cognitive and conscious realms as animals evolved and diversified [71].

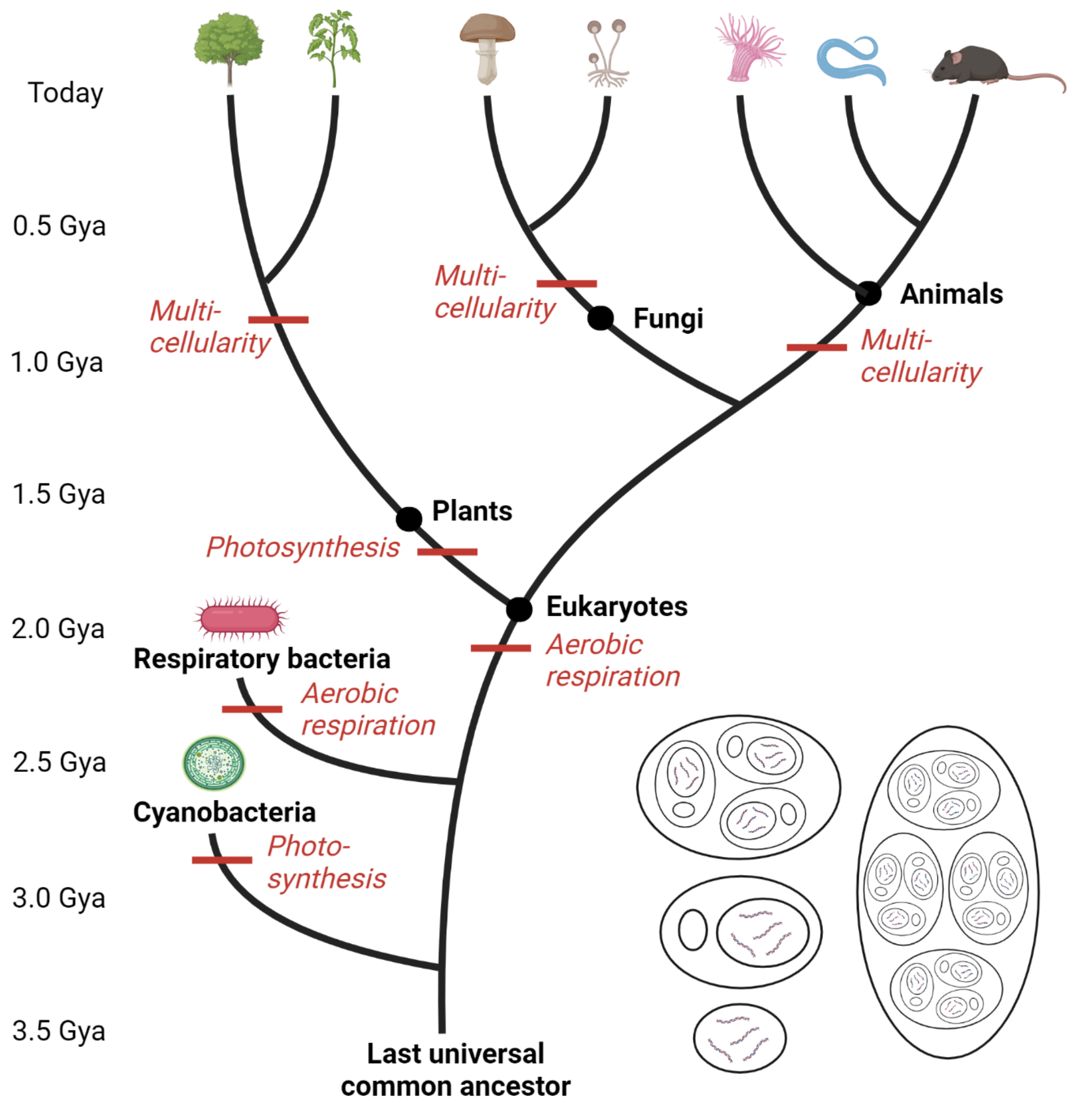


Figure 3. The evolutionary tree of life, modified from [74], with time shown in units of billions of years ago (Gya). The four images on the bottom right provide a simplified representation, modified from [71], of the modular nested evolutionary hierarchy for individual organisms with a unicellular prokaryote, a unicellular eukaryote, a simple multicellular eukaryote and a complex multicellular eukaryote.

LeDoux allocates various behavioral control processes [71] as shown in Figure 4. The neurobiological realm includes non-cognitive and non-conscious behavioral control (reflexes, instincts, Pavlovian-conditioned responses and habits). The cognitive realm includes cognitive but not conscious behavioral control (non-conscious working memory, non-conscious deliberation, non-conscious inferential reasoning, and non-conscious intuition). The conscious realm includes cognitive and conscious behavioral control (conscious working memory, conscious deliberation, and conscious inferential reasoning). Collectively, this amounts to extending the two systems associated with thinking fast and slow [75] to three systems [71]. Most importantly, however, the realms encapsulate all life on Earth, including humans. Although there remains considerable debate about current theories of consciousness [76, 77], LeDoux outlined a theory of consciousness for humans that is consistent with the proposed realms [71]. Given that the realms include all life on Earth, the potential exists to include consciousness beyond the human case [78], although the structure of the diagram may need to be revised to recognize cognition in plants and fungi [46, 79].

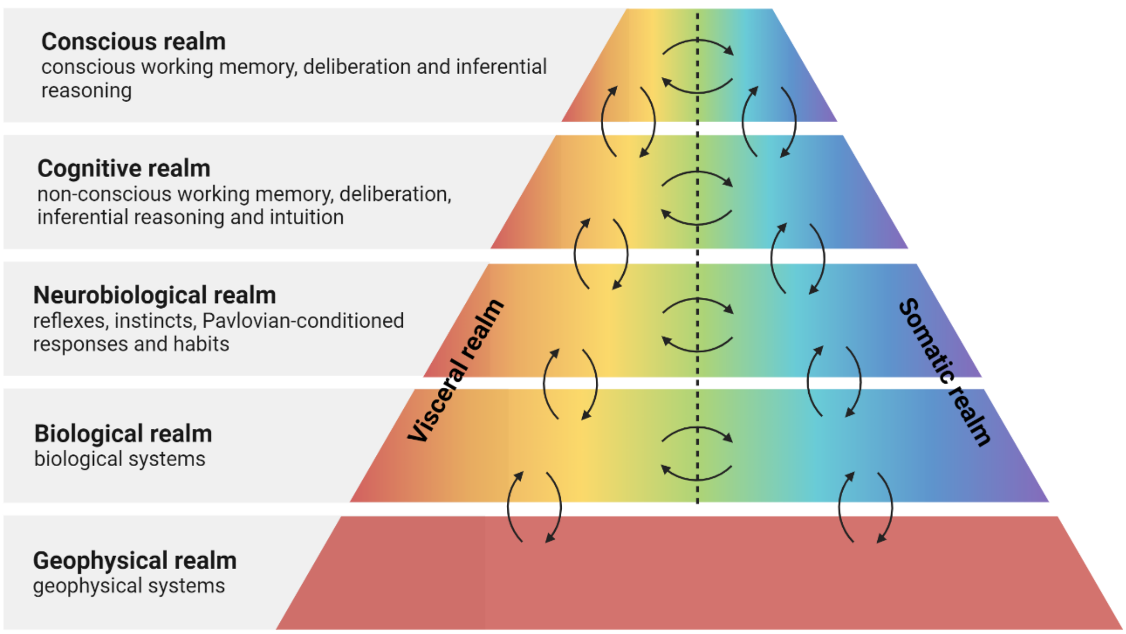


Figure 4. The realms of life on Earth, modified from [71]. The somatic realm is externally oriented with respect to individual organisms and can be applied at global, regional, urban and local scales, while the visceral realm is internally oriented with respect to individual organisms and includes (see Figure 3) organs, cells, organelles, genes and proteins for complex multicellular eukaryotes, cells, organelles, genes and proteins for simple multicellular eukaryotes, organelles, genes and proteins for unicellular eukaryotes, and genes and proteins for unicellular prokaryotes. In the case of animals, interactions between the visceral and somatic realms are orchestrated primarily by the common cognitive system.

2.3 Anthropocene Systems Are Modular and Often Hierarchical

Modularity is a focus of research across multiple disciplines including genetics, developmental biology, functional morphology, population biology and evolutionary biology [80] as well as biological, neural, social, linguistic and electronic networks [81]. Although modularity is generally recognized as a fundamental feature of all organisms, with profound consequences for evolution [80], the concept of modularity clearly depends on the context in which it is used. Our intention is to use evolved modularity to reveal the causally coherent, and often hierarchical mechanisms that gave rise to our globally connected system of Anthropocene systems.

2.3.1 Phylogenetic Refinement

Given the importance of the neurobiological, cognitive and conscious realms of life (see Figure 4), and the role these play in facilitating how humans both cause and potentially address societal challenges of the Anthropocene, an essential aspect of the evolutionary perspective is chronicling the morphological and functional modifications to the brain, and the behavioral modifications they enabled [65, 74]. Focusing for now on the evolution of the brain in the human lineage, cumulative additions to adaptive behavior included steering (or taxis navigation) in early bilaterians, reinforcing (or model-free reinforcement learning) in early vertebrates, simulating (or model-based reinforcement learning) in early mammals, mentalizing (involving the use of mental models) in early primates, and speaking (or rhythmic semantic processing) in humans [65, 74]. This theory of phylogenetic refinement [82] can be used to explain the progressive complexification of brains and the evolved adaptive behavior as the consequence of evolutionary refinement from more basic building blocks. In other words, prior innovations impose constraints on future innovations, meaning that the evolutionary design of biological systems is highly path dependent. It should be possible to gain similar insights into the form, function and resulting behavior of the coevolved ensemble of Anthropocene systems, revealing how the realms of life (see Figures 3 and 4) became increasingly complex and interconnected [4].

2.3.2 Biological and Physiological Circuits

An additional closely-related evolutionary insight helps to merge our understanding of coevolving Anthropocene systems with biological circuits in systems biology [83] and physiological circuits in systems medicine [84], integrating the deep evolutionary mechanisms that coherently connect all life on Earth [42].

The archetypal cellular capacities of cooperation, co-dependence, collaboration and competition [42, 67, 68] began in the primordial biological realm, and have been carried forward by coevolution into the current biological, neurobiological, cognitive and conscious realms [71]. Similarly, biological and physiological circuits involve networks that can be separated into modular units that perform almost independently [85]. These network motifs [85-87] are modular building blocks of the biological circuits of systems biology [83] and the physiological circuits of systems medicine [84]. Network motifs, which are also referred to as circuit motifs [84, 88, 89], are basic interaction patterns that recur much more often than in random networks. Network motifs are not randomly distributed in real networks but are combined in ways that maintain autonomy and generate emergent properties [81]. The same small set of network motifs appears to serve as the building blocks of transcription networks from bacteria to mammals, with specific network motifs also found in signal transduction networks, neural networks and other biological networks [83, 84]. Each network motif can serve as an elementary circuit with a defined function including filters, pulse generators, response accelerators and temporal pattern generators [83, 84]. Evolution appears to have converged on the same motifs, perhaps because they are the simplest and most robust circuits that perform these information processing functions [83, 84]. These modular building blocks are presumed to have evolved in response to adaptation over evolutionary timescales [90] resulting in organisms that are highly evolvable and capable of adapting quickly to new goals in coevolving ecological niches.

There are a wide range of biological systems interacting across a range of scales, which are used to process information, make decisions, and achieve specific goals of living organisms [91]. These modular and often hierarchical systems include chemical networks, neural networks, physiological circuits, individual organisms, and groups of individual organisms in communities [91]. Evolution resulted in the progressive selection of existing and novel mechanisms across goal oriented spaces, enabling adaptive migration toward specific goals in metabolic, physiological, transcriptional, morphological and behavioral space [92]. Morphological changes have complex, multi-scale feedback mechanisms that influence behavior in a way that is not directly encoded by genes [49, 92]. Because of this [93], we need to move away from considering causes acting at a single site in an organism, instigating changes in a linear pathway, to understanding the behavior of the larger interconnected system of systems. Similarly, we need to move away from studying molecular events to studying systemic patterns, which can lead to a shift from medicines that briefly control a single target to treatments that put constraints on many parts of the organism, sustained over time [93]. Despite the general awareness of redundancy and homeostatic control circuits, we need a better understanding of the corrective, self-organizing processes that reliably reach complex, systemic goals [93].

The similarity of network motifs in transcription networks (nanometer-sized molecules interacting on a time scale of hours) and neural networks (micrometer-sized cells interacting on a time scale of less than seconds) is revealing [83]. While neurons process information between sensory neurons and motor neurons, transcription networks process information between transcription factors that receive signals and genes that act on the inner or outer environment of the cell. This similarity in function suggests that evolution converged on similar network motifs in both networks to perform important information processing tasks [83]. Indeed, this evolved modularity is found at all scales of biological organization, including multi-cellular organisms, organs, unicellular organisms, cells, organelles, genes and proteins [83].

The power of this approach is revealed in Alon's Periodic Table of Diseases [84]. Using the periodic table as a metaphor, cell types can be classified by both abundance and turnover. This enables a range of diseases (degenerative, progressive fibrotic, autoimmune, toxic adenoma, immune hypersensitivity and tumor prevalence) to be classified according to organ and cell type [84]. The resulting table shows six broad patterns aligned with each of the six classes of disease. Most interesting, however, is the fact that each class of disease in the table corresponds to a specific circuit motif [84]. In addition, the patterns in the table are also relevant from the point of view of age of onset, disease prevalence, and current treatments, as well as suggesting potential future treatments [84].

2.3.3 Visceral and Somatic Realms

Evolutionary mechanisms gave rise to our system of Anthropocene systems. The resulting globally connected meta-ecosystem has causally coherent mechanisms that span a vast range of scales, starting at the global scale and essentially going "all the way down." These scales can be identified in different ways, but we need to start with global, regional, urban and local scales, as shown in Figure 1. In addition, the requirement to sustainably balance the health of humans, animals and ecosystems includes all life on Earth. As shown in Figure 3, living organisms are either unicellular prokaryotes, unicellular eukaryotes, simple multicellular eukaryotes or complex multicellular eukaryotes. The relevant scales of interest therefore extend down into these living organisms, including organs, cells, organelles, genes and proteins for complex multicellular eukaryotes, cells, organelles, genes and proteins for simple multicellular eukaryotes, organelles, genes and proteins for unicellular eukaryotes, and genes and proteins for unicellular prokaryotes. The conceptual distinctions between the science of the brain and the body are increasingly being erased, with considerable opportunity for unification into a single conceptual framework [92]. As previously emphasized, the integrated processing associated with cognition is focused both internally with the visceral realm and externally with the somatic realm (see Figure 4). This provides a useful conceptual boundary to manage the complexity associated with the vast range of scales in our system of Anthropocene systems.

Developing causally coherent models with well-established mechanisms is the most reliable way [94-96] to improve our understanding of meta-ecosystems that span multiple scales. The models should also be hierarchically coherent, but this is facilitated in many cases by the evolved nature of Anthropocene systems (e.g., see [97, 98] and Figure 3).

The examples of primary Anthropocene systems we have chosen to identify (summarized in Figure 2) will need to be extended and refined as the evoSoS paradigm is developed, but they can in principle be applied across local, urban, regional and global scales, with individual organisms forming communities and meta-ecosystems. This range of scales is likely the limit for an externally oriented conceptual model and associated computational framework (see Section 3). However, the causally coherent cross-scale mechanisms can be extended down into individual organisms by connecting with evolutionary systems biology and systems medicine, which are already embracing cross-scale systems-oriented frameworks [83, 84, 92, 99-101]. In this way, an internally oriented conceptual model and associated computational framework could be created, building on current knowledge in evolutionary systems biology, network biology, biomedical engineering and systems medicine. Interactions between the internally oriented (visceral) and externally oriented (somatic) realms would be orchestrated primarily through the common cognitive system (see Figure 4). As will be emphasized in Section 3, effective communication between the two realms may only be possible if a common language and reconciled ontology is used for both.

3.0 A System-of-Systems Perspective

We are using an evolutionary perspective to outline a causally coherent, modular, dynamic conceptual model of a globally connected meta-ecosystem. Integrating the evolutionary perspective with a system-of-systems perspective means that we can take advantage of decades of fundamental advances in systems engineering, which has traditionally focused on sociotechnical systems, including human systems integration [102], to help address societal challenges of the Anthropocene [25]. In particular, model-based systems engineering (MBSE) [103, 104], the systems modeling language (SysML) [105] and hetero-functional graph theory (HFGT) [106, 107] collectively provide a potentially powerful methodology to address these complex challenges. As suggested in Figure 5, the unprecedented scale and complexity of a system of Anthropocene systems is only tractable in the computing domain. MBSE has evolved as a generic approach to realize a wide range of modeling systems [103], and is designed to handle systems of substantial scale and complexity. In the following sections, we briefly review conceptual models, modeling languages and ontologies from a systems engineering perspective.

3.1 Conceptual Model, Modeling Language and Ontology

Briefly, a conceptual model [108, 109] of an Anthropocene system of interest (with examples in Figure 2) has a purpose, a boundary, and system elements that interact with one another across well-defined interfaces, creating system form and function. The boundary defines the scope of the system and can be either physical or conceptual. The system and the elements have well-defined attributes, requirements and constraints. The attributes include functions, which together with the system form create the behavior of the system. Stakeholders have an interest in the system but are outside the boundary of the system of interest. There may be other enabling systems, which also lie outside the boundary of the system of interest, that interact with the system of interest through well-defined interfaces at the system boundary. Systems that are hierarchical are also possible where system elements can be aggregated (zooming out) or disaggregated (zooming in). Finally, a system of systems can be created where the system elements of the system of interest are themselves systems.

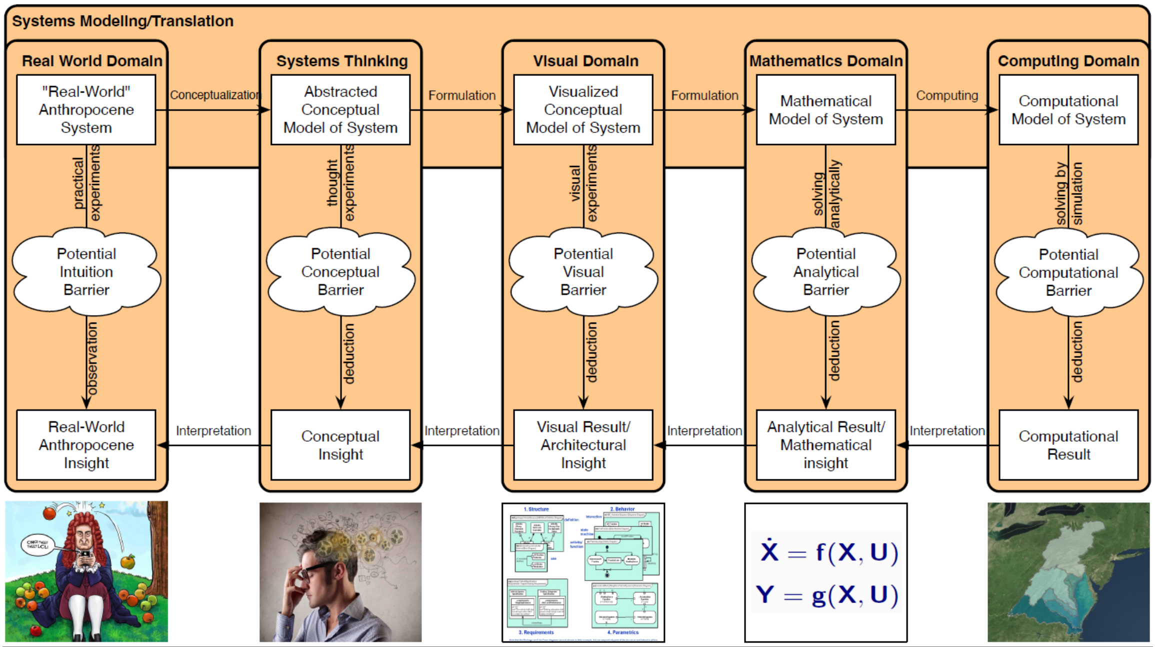


Figure 5. Developing models of Anthropocene systems involves the creation and use of scientific knowledge and the subsequent translation of this knowledge among the real world, systems thinking, visual, mathematical and computing domains. Systems thinking is the primary means of managing cognitive complexity using individual thought experiments but is subjective and often constrained by disciplinary knowledge. The visual domain is where we begin to converge our individual systems thinking conceptualizations into a shared visual representation that reconciles our individual mental models. Mathematics is the premier domain for analysis and logic and Anthropocene challenges have scale and heterogeneity that is only tractable in the computing domain.

The need for a system-of-systems perspective arises because of problems with complexity (e.g., when complexity is not identified and therefore cannot be managed or controlled), communication (e.g., when communication fails or is ambiguous) and understanding (e.g., when different points of view are not taken into account, and incorrect assumptions are made), with the three problems collectively compounding one another [103]. When developing a model of an Anthropocene system, one of the main approaches to improve communication (which occurs among the people, organizations and stakeholders who develop and use a model, as well as between and within systems and system components) is to use a common language [103]. In fact, MBSE uses a combined spoken and visual common language (the systems modeling language, or SysML) as well as multiple domain- or discipline-specific languages, all of which must be systematically managed to ensure effective communication. SysML can be thought of as a dialect of the unified modeling language [103] which was created to manage communication in complex software systems. As emphasized in Figure 5, the semantic and graphical nature of SysML are both essential when attempting to simultaneously improve communication and reconcile the vast array of domain- or discipline-specific ontologies in a system of Anthropocene systems.

From a system engineering perspective, an ontology can be thought of as a formal, explicit specification of a shared domain conceptualization [110] describing the relationship between reality (the knowledge domain), the understanding of reality (the domain conceptualization), and the description of reality (using a language). Ontologies can make the form and function of systems and their elements explicit, and can help stakeholders better understand the complexities inherent in large scale systems [110]. A conceptual model [109] of a system of systems needs a well-defined foundational, universal, general, necessary and sufficient ontology that renders concepts and terms precise and unambiguous [110]. Ontologies avoid ambiguity and provide an accepted and consistent vocabulary, facilitating semantic interoperability between humans as well as between humans and computers [110].

Now consider the convergence challenge associated with a system of multiple Anthropocene systems [106], each with its own domain conceptualization and associated language and ontology. First, humans are typically trained in a single domain conceptualization, rather than multiple domain conceptualizations. Indeed, it is doubtful that a single human (let alone many) has sufficient knowledge of multiple domains. In the absence of such an individual, a group of individuals – each with their own individual domain conceptualizations – must collaborate and reach agreement on the integration of multiple domain conceptualizations. They immediately find that each domain conceptualization comes with its associated language, and a language of languages emerges. Because each of these languages was developed independently to address the needs of its associated domain, the language of languages is highly divergent and a common, convergent understanding between languages is very difficult to achieve. To overcome this impasse, it is possible that the language of languages develops a translation capability between each of the languages for each domain. While this strategy is relatively straightforward for only two languages with a single translator, it does not scale when there are N domains that require N(N-1) translators between N languages (e.g., 90 translators are needed for 10 systems). The only alternative is to invest in the development of a language of languages that reconciles the individual languages into a single common language. HFGT adopts the latter approach where a single common language (SysML) serves as a language of languages. The development of a single common language for a system of systems requires instantiated, reference and meta-architectures.

3.2 System Architecture

System architecture generally consists of three parts: the real world or structural architecture (i.e., form), the functional architecture (i.e., function), and the mapping of function onto form in a system concept or allocated architecture. The structural architecture is a description of the decomposed elements of the system without any specification of the performance characteristics of the system resources that comprise each element. The functional architecture is a description of the system processes in a solution-neutral way, structured in serial, or parallel, and potentially in hierarchical arrangements. The system concept, which is a mapping of the functional architecture onto the structural architecture, completes the system architecture.

An instantiated systems architecture is a case-specific architecture, which represents a real-world scenario. At this level, the structural architecture consists of a set of instantiated system resources, and the functional architecture consists of a set of instantiated system processes. The mapping in the system concept defines which resources perform what processes.

The reference architecture generalizes instantiated system architectures. Instead of using individual instances as elements of the structural and functional architecture, the reference architecture is expressed in terms of domain-specific classes of these instances. In this way, the reference architecture captures the essence of existing instantiated architectures. It also provides a vision of future needs that can provide guidance for developing new instantiated system architectures. Such a reference architecture facilitates a shared understanding across multiple disciplines or organizations about the current architecture and its future evolution. A reference architecture is based on concepts proven in practice. Most often, preceding architectures are mined for these proven concepts. The reference architecture, therefore, generalizes instantiated system architectures to define an architecture that is generally applicable in a discipline or knowledge domain. However, the reference architecture does not generalize beyond the domain conceptualization.

The meta-architecture further generalizes reference architectures. Instead of domain specific elements, it is expressed in terms of domain-neutral classes. A reference architecture is composed of "primitive elements" that generalize the domain-specific functional and structural elements into their domain-neutral equivalents. While no single engineering system meta-architecture has been developed for all purposes, several modeling methodologies have been developed that span several discipline-specific domains. In the design of dynamic systems, bond graphs [111] and linear graphs [112] use generalized capacitors, resistors, inductors, gyrators and transformers as primitive elements. In system dynamics, stocks and flows are often used as primitives [113], while in graph theory [114, 115] nodes and edges are used as primitive elements. Each of these domains has their respective sets of applications. However, their sufficiency must ultimately be tested by an ontological analysis of soundness, completeness, lucidity, and laconicity (for more detail, see [106]). Hetero-functional graph theory utilizes its own meta-architecture that has been shown to generalize linear graphs, bond graphs, system dynamics, and formal graph theory [107, 116, 117]. Given the importance of ontological clarity, HFGT has taken special care in the translation of this meta-architecture from its description in the systems modeling language (SysML) [105] to its mathematical and computational representations, as shown in Figure 5.

3.3 Hetero-Functional Graph Theory

HFGT [106, 107] is a fusion of network science (including formal graph theory and multi-layer networks) and MBSE. Graph theory focuses primarily on an abstract model of a system's form, neglecting an explicit description of a system's function. For example, in a formal graph with nodes and edges, nodes typically represent locations while edges represent connections between nodes. The nodes and edges in a formal graph are described by nouns. Because many complex systems include multiple elements with several layers of connectivity, formal graphs are frequently scaled-up to create multi-layer networks (e.g., [118]). In either case, operands are transported along the edges between the nodes. In real-world Anthropocene systems, however, operands are subject to both transport and transformation processes as they move between nodes. HFGT overcomes the limitations of formal graphs and multi-layer networks (for example, it has been shown that HFGT overcomes eight previously identified modeling constraints in multi-layer networks [106, 119]), enabling the inclusion of nouns and verb phrases that are needed to describe system form and function.

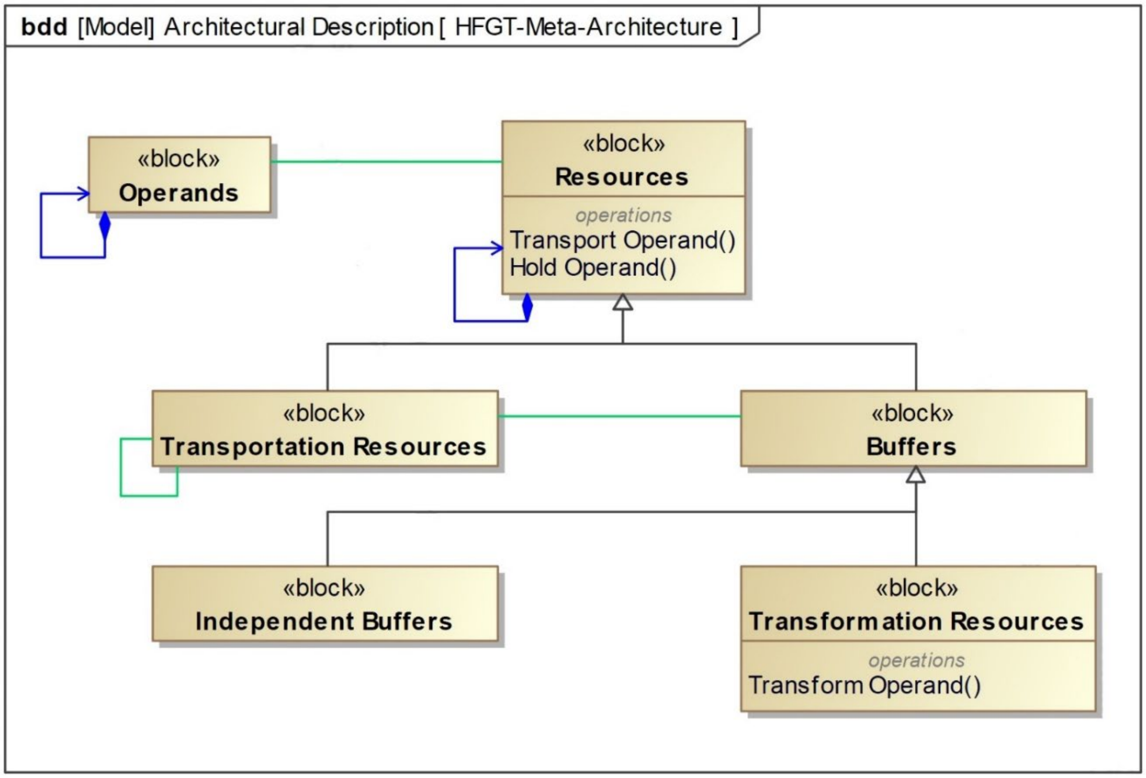


Figure 6. The hetero-functional graph theory (HFGT) meta-architecture [106] drawn using the systems modeling language (SysML). The HFGT meta-architecture consists of three types of resources (transportation resources, independent buffers and transformation resources) that are capable of two types of processes (transport operand, which implicitly includes hold operand, and transform operand). The operands can include matter, energy, information (money can be represented separately), and living organisms (individuals of any scale and complexity). The abstract nature of the meta-architecture is highly extensible meaning that new operands, new resources and new processes can be added as required. In addition, HFGT is highly scalable meaning that elements of the reference architecture can be instantiated as many times as needed. Once the form and function of a specific element is defined in the reference architecture, multiple versions (e.g., thousands or millions) of the same elements can be easily included at different locations in the spatially resolved instantiated architecture.

Figure 6 represents the meta-architecture for HFGT expressed in SysML. A reference architecture describes all the potential system capabilities, while an instantiated version of this reference architecture includes multiple operands, capabilities, buffers, system resources and system processes. As shown in Figure 6, HFGT makes the connection to the common language explicit through a set of system resources as subjects, a set of system processes as predicates, and a set of operands as their constituent objects. In this way, system processes can be allocated to system resources to create subject + verb + object sentences called system capabilities. As a result, SysML and HFGT together create a common language and computational framework, providing the means to produce an ontologically coherent computational model that is hierarchical, extensible and scalable.

HFGT can be used to conduct analyses of system form as well as simulations of system behavior [106, 119-126]. HFGT has already demonstrated its relevance to convergent Anthropocene systems with results in electric power, water distribution, natural gas, oil, coal, hydrogen, transportation, manufacturing and healthcare systems [106, 121-126]. Perhaps more importantly, it has been used for combinations of these systems such as the American Multi-Modal Energy System [127], which is a system of systems comprised of four separate but interdependent infrastructure enterprises: the electric grid, the natural gas enterprise, the oil enterprise, and the coal enterprise. HFGT can model an arbitrary number of systems of arbitrary size and topology connected to each other in an arbitrary manner [106]. To an engineer or natural scientist, HFGs can reconstitute the conservation laws of matter and energy for systems with explicitly heterogeneous resource-subjects, process-verbs and operands. To social scientists, the semantic roots of HFGs provide a straightforward means of traversing the often-formidable gap between qualitative knowledge and quantitative models. Finally, to applied mathematicians, HFGT builds upon extensive foundations in graph theory, tensor analysis and network optimization. In essence, HFGT begins with a generic meta-architecture (Figure 6) that is independent of any system and then uses this to create a computational model of a specific system which is hierarchical, extensible and scalable.

To summarize, SysML can be used to create an ontologically coherent conceptual model using a common spoken and visual language. HFGT builds directly on the conceptual model, providing the means to produce an ontologically coherent computational model. Within the conceptual model and associated computational framework, the operands that are subject to transport and transformation processes can include matter, energy, information and individual organisms. As a result, we can in principle develop models of an ensemble of geophysical, biophysical, sociocultural and sociotechnical systems that include niche construction in meta-ecosystems.

4.0 Limitations of Related Frameworks and Approaches

Substantial progress is being made in modeling coupled systems in several closely related, interdisciplinary fields of research. There are of course many cases where integrated or coupled models provide the best approach for the intended purpose, but if the goal is to address the interdependent societal challenges in Figure 1, then these interdisciplinary fields exhibit three primary limitations: (1) they are not based on the evolutionary mechanisms which gave rise to the Anthropocene and the ensuing societal challenges; (2) they include elements of social systems, but the elements are not based on a causally-coherent theoretical framework of evolved behavior; and (3) they do not start with a framing that is holistic enough for addressing many interconnected societal challenges with multiple systems that are highly interdependent and dynamically evolving. Because of these limitations, it is not possible to make coordinated interventions across multiple systems and scales.

These closely-related interdisciplinary fields that involve model coupling include Earth system science [31], integrated assessment and modeling [128], social-ecological systems research [129], socio-hydrology [130], land systems science [131], socio-environmental systems (SES) modeling [132], multi-sector dynamics [133], disaster resilience [134] and the global polycrisis [17, 18]. Participatory processes that support social learning and decision making [132] are often included in the development of such coupled models. In addition, several major challenges associated with developing integrated SES models have been identified [132] including: bridging ontologies across disciplines, multi-dimensional uncertainty assessment and management, scales and scaling issues, combining qualitative and quantitative methods and data, furthering the adoption and impacts of SES modeling on policy, capturing structural changes, representing human dimensions in SES, and leveraging new data types and sources. It is fundamental that the evoSoS convergence paradigm capitalizes on these valuable initiatives, making sure to provide an approach that is appropriately holistic in representing systems of Anthropocene systems.

Societal challenges of the Anthropocene are usually addressed as if they are disconnected [4, 24, 25] in what may be characterized as "bottom-up, incremental" research [4]. As a result, many closely related research initiatives (perhaps tens of thousands) are currently in progress worldwide. Many new frameworks and approaches for the various societal challenges are being produced, most involving many of the same systems (e.g., watershed, climate, land-use, energy, transportation, communication, economic, and most other sociocultural systems are common across all challenges), and most will require extensive interventions within many of the same systems. The initiatives all have their own preferred languages and ontologies, with a rapidly increasing number of initiatives including elements of social systems.

Now imagine a city [135] within a surrounding region that has multiple interdependent societal challenges and multiple systems that are nested, highly interdependent, and dynamically evolving, with accelerating rates of cultural and technological evolution. If different groups are addressing different societal challenges in the same urban area using different frameworks and ontologies, we have to ask ourselves: Will the coevolution of the Anthropocene systems of interest be represented in a causally coherent fashion? How will the many different ontologies be reconciled? In particular, how will the many different approaches to human behavior (e.g., see [136]) be converged, and do they have a scientifically falsifiable theoretical basis? How will the complexity and uncertainty be systematically managed and who will coordinate and integrate the required interventions? So far, we are only imagining one city in one region, but there are thousands of urban areas (perhaps 10,000 cities worldwide, with about 40 megacities where the population is greater than 10 million) where similar questions apply. Again, we have to ask ourselves: How will these globally distributed initiatives be coordinated? How will newly-acquired knowledge be shared, and can this new knowledge be rapidly included in the many frameworks that are being developed?

While the interdisciplinary fields of research mentioned previously (i.e., [17, 18, 31, 128-134]) should all be recognized and applauded for the valuable progress they have made while attempting to address problems involving coupled systems, they do not start with a framing that is holistic enough for addressing several interconnected societal challenges with causally-coherent strategic interventions across multiple systems and scales.

5.0 An Evolutionary, System-of-Systems, Convergence Paradigm

The evoSoS convergence paradigm requires that evolutionary scientists, behavioral scientists, natural scientists, health scientists, systems scientists and engineers systematically identify, decompose, characterize, and then converge the nested, evolutionary ensemble of geophysical, biophysical, sociocultural and sociotechnical systems. Here we briefly describe the four primary elements (conceptual model, computational framework, decision-support system and educational pedagogy) which are required to holistically address societal challenges of the Anthropocene.

5.1 Evolutionary SoS Conceptual Model

We have outlined a conceptual model of a system of Anthropocene systems with individual organisms engaging in niche construction in a globally connected meta-ecosystem. Living organisms that can be represented in the conceptual model include unicellular prokaryotes, unicellular eukaryotes, simple multicellular eukaryotes and complex multicellular eukaryotes, essentially spanning all life on Earth including plants, fungi and animals (Figure 3). The conceptual model is based on the geophysical, biological, neurobiological, cognitive and conscious realms of life, integrating the deep evolutionary mechanisms of all Anthropocene systems. The causally coherent, cross-scale mechanisms of the conceptual model can be applied at global, regional, urban and local scales in the somatic realm, but can also be extended down into individual organisms in the visceral realm (Figure 4). Although SysML, which was designed for sociotechnical systems, including human systems integration [102], is proposed as the common visual and spoken language for the conceptual model, it may need to be retooled for some Anthropocene systems [25]. For example, integrating SysML with existing standards such as SBML (the systems biology markup language) [137] may be of value.

5.2 Evolutionary SoS Computational Framework

The evoSoS computational framework must be designed to coherently converge the nested evolutionary ensemble of geophysical, biophysical, sociocultural and sociotechnical systems in a multi-scale modelling architecture that explicitly represents the different levels of abstraction underlying the form and function of the system of Anthropocene systems. The architecture must enable the development and use of a causally coherent ontology, coherent conceptual models, and interoperable computational tools, and must enable application to address specific societal challenges based on the location and scales of interest.

MBSE [25], SysML [105] and HFGT [106] provide a potentially powerful way to address these issues. As shown in Figure 5, the methodology first translates real-world Anthropocene systems into SysML to integrate and reconcile ontologies [105] and then uses HFGT [106, 107] to algorithmically traverse the gap from the graphical SysML model to the associated mathematical model, and ultimately to the computational model. An important advantage of the common language and ontology is that it enhances clarity and understanding, thereby reducing complexity.

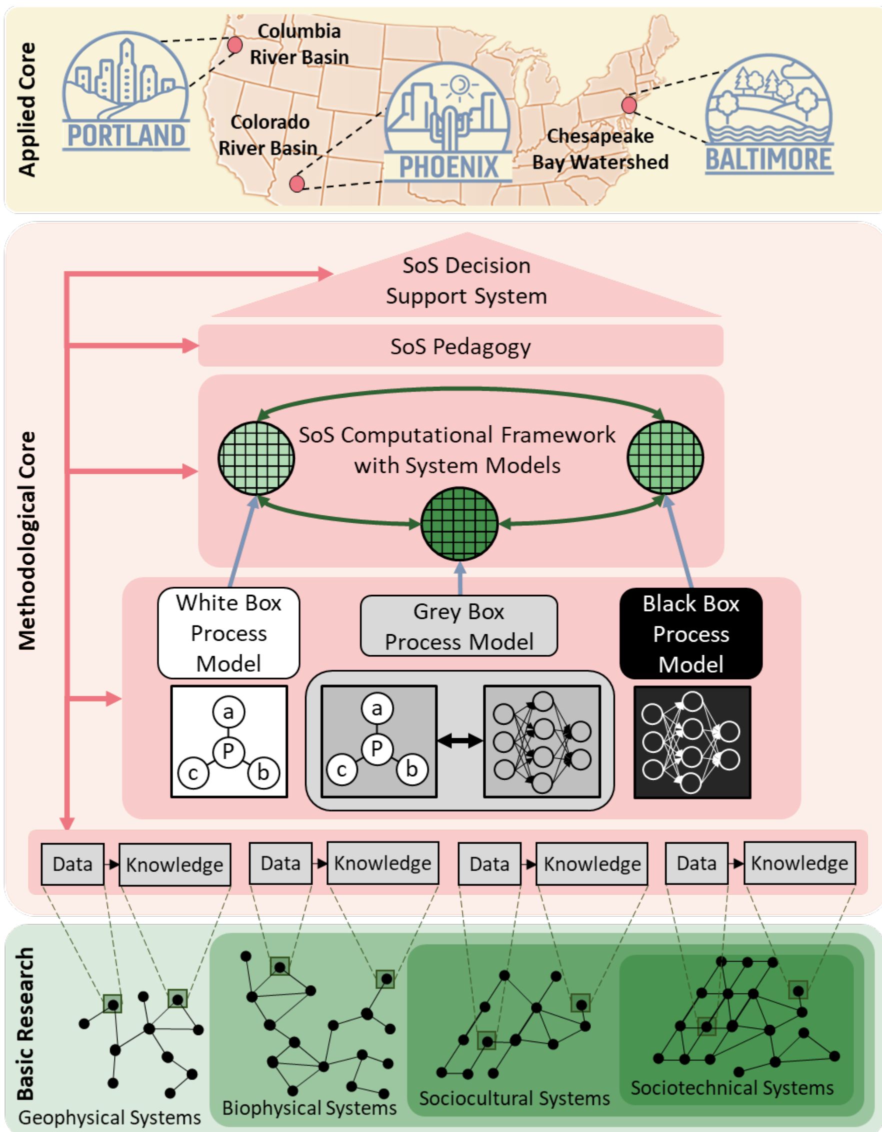


Figure 7. Simplified schematic representation of an evolutionary, system-of-systems, convergence paradigm for framing and addressing the many societal challenges of the Anthropocene. The ontologically coherent, hierarchical, extensible and scalable computational framework can include mechanistic "white box" models, theory-guided, machine-learning "grey box" models, and machine-learning "black box" models, and can be used to coordinate strategic interventions across multiple systems and scales.

Although we need a causally coherent, cross-scale, meta-ecosystem model, it would be impossible to develop a single monolithic computational framework that applies over all spatial and temporal scales. However, given that we primarily need to make interventions or policy decisions at local, urban, regional or global scales, we believe that it would be possible to develop a coherently structured system of models that interact and inform one another across scales. A hierarchical structure with different levels of abstraction is therefore required [22], as shown schematically in Figure 7.

Developing causally coherent models with well-established mechanisms is the most reliable way of improving the transferability of cross-scale ecological models [94-96]. The models should also be hierarchically coherent, but this is facilitated in some cases by the evolved nature of Anthropocene systems (e.g., see Figure 3). In addition, HFGT is helpful as it can be used to coherently span spatial and temporal scales. Models that are based on mass and energy balances (which is often the case for geophysical systems, and the technical subsystems of sociotechnical systems) are well-suited for spanning spatial scales with HFGT.

5.3 Evolutionary SoS Decision-Support System

Developers of decision-support systems face stakeholder-oriented, model-oriented and system-oriented issues, with a recent review [138] providing recommendations on how to build them. Approaches include stakeholder engagement and participatory modeling, constructing future scenarios while balancing synergies and trade-offs across multiple systems, and supporting decision-making under uncertainty [132, 139, 140]. An evoSoS decision-support system must provide salient insights about interventions and scenarios in a manner that aligns with stakeholder affect and cognition [141]. The computational results must be visualized to support graphical storytelling so that real-world insights are gained easily, and decisions are made effectively.

Recent work on strategic environmental crisis management offers guidelines for the design of decision-support systems capable of integrating knowledge on issues of high complexity and uncertainty. The challenge is to address long-term path dependencies while navigating urgent anthropogenic crises [141] and decision-support systems should provide a platform for egalitarian deliberations among experts and policymakers. The agenda for the deliberations should be structured around alternative futures that provoke the imagination and facilitate critical questioning of cognitive biases. Tools to enhance imagination and questioning include audio-visual dashboards that take the decision-makers to an imagined future, illustrate the implications of the decisions considered [142], and facilitate analysis of how strategic interventions can fail under plausible disruption scenarios.

Societal challenges involving Anthropocene systems are characterized by deep uncertainty, with many approaches to decision-making that enable quantitative analyses and support deliberation among multiple parties [143]. These methods can be used to generally identify robust or low regret management strategies that perform well across a wide range of uncertain conditions. While decision-making under deep uncertainty holds paramount significance in the management of human-natural systems [139], the reality of Anthropocene systems, characterized by substantial interdependencies and dynamic evolution, underscores the profound challenges we face in our endeavors to navigate this uncertainty effectively.

From a holistic perspective, the goal should be to optimally manage both complexity and uncertainty. For example, coarse scale models inherently average fine scale complexity [22] and may have reduced uncertainty. It may also be that some systems (e.g., geophysical and sociotechnical systems) have rates of change that are slow, where the models are more predictable and more amenable to uncertainty analysis. Overall, the best approach will likely involve a coherently structured system of models that interact across scales.

5.4 Evolutionary SoS Educational Pedagogy

Given the vast scope of the family of societal challenges, we need an evoSoS pedagogy to train a new generation [22] of Anthropocene System Integrators (including students, academics, practitioners and stakeholders) to conceptualize Anthropocene challenges holistically, think coherently in terms of common ontological constructs, develop conceptual models and simulate the associated computational models, facilitate decision-support conversations filled with coherent, data-driven, real-world insights, and use these insights to once again conceptualize societal challenges. We envision at least seven components to the evoSoS pedagogy: (1)

introduction to convergent Anthropocene systems including an overview of our "origin story" which reveals the nested evolutionary ensemble of geophysical, biophysical, sociocultural and sociotechnical systems [4]; (2) clear understanding of the causally coherent, cross-scale, conceptual model of a system of Anthropocene systems; (3) convergent Anthropocene-systems thinking as a translation from real-world systems to SysML; (4) HFGT as a translation from SysML to mathematical and computational models; (5) data analytics, visualization and machine learning; (6) stakeholder-based decision-support systems; and (7) principles of convergence [28], team science [144] and good modeling practice [145].

Facilitating the seamless integration of knowledge across multiple Anthropocene systems encompassing spatial, temporal and organizational scales [23], while simultaneously transforming disparate forms of knowledge into the evoSoS framework, necessitates that scientists and engineers across multiple disciplines collectively surmount numerous cognitive hurdles. Participants need to be aware of and question their assumptions and biases, understand how knowledge is produced in their respective disciplines, become aware of the limitations and strengths of individual disciplines, and overcome semantic, ontological, cultural and organizational barriers [28]. Good modeling practice that spans multiple disciplines is clearly vital for success [145]. For example, potential issues, traps and pitfalls in the process of decision-making on scale have recently been identified [146] with proposed guidelines in four categories: identifying suitable scales, identifying appropriate dimensions for scale-matching, validating scale decisions, and communicating scale decisions.

6.0 Summary and Research Needs

Humans have been addressing societal challenges since our species evolved roughly 200,000 years ago. An important difference now is that we are using scientific research to help us address societal challenges that are far more complex than previously attempted or currently recognized. While this is an exciting opportunity for research, the fragmented nature of the prevailing academic and scientific culture [15] is arguably the biggest barrier that prevents us from using our rapidly accumulating collective knowledge more effectively.

Holistically addressing societal challenges of the Anthropocene requires communication, coordination, capacity building and collaboration [5]. However, these crucial requirements will be essentially impossible to achieve without a common language and reconciled ontology, a common conceptual model, and a common computational framework. The proposed evoSoS convergence paradigm attempts to address these requirements. Although we again acknowledge the daunting and ambitious nature of the paradigm [4], effectively addressing the family of societal challenges can only begin with a broad overview of the entire knowledge domain including all Anthropocene systems.

The evoSoS convergence paradigm intends to address the entire range of societal challenges in an integrated and unified fashion, requiring coordinated interventions across multiple systems and scales. However, as we change scale from global to regional to urban to local, it should be clear that potential interventions are scale dependent, with different intervention opportunities and societal transformation pathways becoming accessible as we zoom in or out. We therefore need a causally coherent meta-ecosystem model that applies over the range of scales of interest. The model should also be hierarchically coherent, which is inherently facilitated by the evolved form and function of many Anthropocene systems. Unfortunately, we are not aware of any conceptual models where coevolved systems are identified and decomposed from the larger system of Anthropocene systems and then coherently characterized in a way that will enable their convergence, clarifying the primary cross-scale causal connections among the various systems.

A major coordinated initiative is needed to develop cross-scale models of sociocultural systems, and their causally coherent connections with other Anthropocene systems. While all causal influences are clearly not equally important, human behavior influences, and is influenced by, the globally connected system of Anthropocene systems. An outline of a more generic model of a sociocultural system is given in Section 2.1, with social dynamics that involve individuals, groups, and groups of groups, providing a way to scale these interacting systems coherently. Indeed, there is growing recognition that a complex systems approach is needed to represent the multiscale, multidimensional, dynamic and interacting nature of sociocultural systems (e.g., see [147, 148]). To be successful, however, we must overcome the fragmented nature of research on human behavior (e.g., see [136]) enabling a more coherent integration of sociocultural systems and their causally coherent connections with other Anthropocene systems (e.g., Figure 2). Furthermore, the need to sustainably balance the health of humans, animals and ecosystems means that we must overcome the fragmented nature of research on human, animal and ecosystem behavior enabling a more coherent integration across the realms of life (e.g., Figure 4).

The required communication, coordination, capacity building and collaboration will be facilitated by the conceptual model, which is modular and causally coherent, as well as the computational framework, which is hierarchical, extensible and scalable. However, we need new research programs that facilitate this much broader research agenda. For example, national and global funding agencies could solicit research on best approaches to identify, decompose, characterize and then converge the system of Anthropocene systems. This could enable the emergence of a global community of practice (e.g., [149]) to develop community models (e.g., [149] and [150, 151]) for specific Anthropocene systems that can be integrated in a wide range of geophysical, biophysical, sociocultural and sociotechnical contexts. SysML can be used to create reference architectures for Anthropocene systems that are shared on open-science platforms (e.g., the Open Modeling Foundation [152, 153]), and ultimately linked to a cloud-based computational environment (e.g., the HFGT Toolbox [120]). Effective capacity building will also require an agile approach [25, 154], meaning that development and implementation of the evoSoS paradigm should take place in carefully planned iterations. We too often invest in incremental approaches because they offer short term insight, without asking whether they lead to analytical dead ends.

The 50-year old saying [48] that "nothing in biology makes sense except in the light of evolution" has recently been extended to both cultural evolution [155] and cognition-based evolution [49, 50, 77]. Indeed, it appears that nothing in the Anthropocene makes sense except in the light of geological, genetic, cultural and technological evolution. The evoSoS convergence paradigm will require a major transformation in our national and global approach to science and engineering, establishing a new generation of Anthropocene systems integrators, and enabling the creation of a meta-discipline that spans all the disciplines associated with the family of societal challenges of the Anthropocene.

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Data Statement

There are no new data sets associated with this manuscript.

Declaration of Interests

The authors declare no competing interests.

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