

Exploring universal principles and emergent properties of biological complexity across levels of life

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Executive Summary

The combination of simple units forming more complex ones is a general pattern observed across all life. Yet, this concept of biological assembly has proven challenging to test empirically and comparatively across levels of biological organization. We argue that developing a unifying model of biological assembly that spans all levels of biological organization requires developing a shared framework with universal currencies that can be quantified in different types of systems. We propose using functional specialization as one way to build an underlying framework that can be tested using the currencies of energy and information. Measuring the relationships between these currencies and metrics of biological complexity at different levels may help allow researchers to identify the emergence of new biological phenomenon across life. We are poised for new breakthroughs on this classic problem because of new computational tools in the realm of information science and the ability to better characterize function across different levels of biological organization. These ideas will not only bring together scientists from different disciplines--including those outside of biology--but also link those that typically are siloed by different federal funding agencies (e.g. NASA and NIH) that are also currently interested in these ideas. Ultimately, gaining a better understanding of the shared patterns and processes underlying functional specialization influences biological assembly could impact the development of biomaterials by predicting assembly constraints of the systems, eliminate barriers to generating synthetic biology, and be of interest to diverse fields of study ranging from robotics to epidemiology to information theory.

Problem and Importance

Across all levels of biological organization, simple units often combine to create more complex ones: atoms combine to form molecules, cells aggregate to form tissues, individuals group to form societies, species assemble to form communities. This general pattern of biological

assembly is often referred to as an increase in biological complexity across increasing levels of life, an idea framed in an evolutionary sense by the formation of a cooperative group followed by a transition to a new level of organization (Maynard Smith and Szathmary 1995). Yet, this and other frameworks of biological assembly have served more as heuristic tools and have proven challenging to test empirically across levels of biological organization. Indeed, testing the idea that basic rules underlie biological assembly remains a fundamental but unsolved problem.

Although there are obvious connections between levels of biological organization in the ways that biologists think about this idea, exemplified by common key words like “function and structure”, “interaction/signaling”, and “robustness/resilience”, testing any unifying model of biological assembly requires “currencies” that are comparable across levels. Two such *universal currencies* that have received attention previously but remain only loosely linked through different levels of biological organization are *energy* and *information*. It is likely that there are other universal currencies that we are not yet able to measure or have not yet considered, but we focus on these two currencies here.

Our Proposal

We propose to develop a unifying model of biological assembly that spans all levels of biological organization and builds from the idea that an increase in biological complexity is associated with changes in a universal principle (e.g. from physics) or force (e.g. natural selection) that can be quantified and compared across levels by using universal currencies like information or energy. One example of how we might approach addressing these forces at higher levels may be thinking about functional specialization, a topic we outline below.

Predictions from any unifying model must be testable at any level of biological organization. In an effort to identify the general principles (e.g. attraction vs. repulsion) and forces (e.g. cooperation vs. conflict) that underlie the assembly of biological systems across different levels, this model must examine the relationships among the properties of simple units and the properties of the more complex units that they form. Such a model will help determine if there are common principles that describe these relationships across different biological levels of organization.

Current approaches to understanding the driving forces (e.g. natural selection) that shape biology are often examined through a field specific lens that prohibits understanding across biological levels. Some processes are easily explained in constrained specific systems, but are difficult to evaluate in a broader biological context. We believe that only by generating a unifying model can we facilitate the comparison of biological assembly across levels.

One Potential Framework of Biological Assembly: Functional Specialization

Complexity means different things at different levels of biological organization and in different fields of biology. Often biological complexity is defined by *structure* or *function* within the level

described. At a conceptual level, the transition from simple to more complex structures may be accompanied by a transition from functional generalization (i.e., one unit performs multiple functions) to functional specialization (i.e., one unit performs one or few functions), while maintaining or increasing the function of the complex structure. Importantly, a functional increase of the entire structure relative to each individual unit could be considered as a type of emergent property.

Specific examples of functional specialization leading to emergent properties and the transition to another level of biological organization are seen across life. Cells in the bodies of multicellular organisms become increasingly specialized for different functions compared to unicellular organisms, particularly for higher order taxonomic groups. Similarly, insect societies are characterized by a general loss of individuality where organisms must perform multiple behaviors (reproduction, foraging, defense) and a gain of specialized roles shared by members of the collective (i.e., castes: reproductives, foragers, soldiers, etc.). Perhaps, then, an increase in complexity at all levels of biological organization is associated with an increase in functional specialization.

If relationships between complexity and specialization can be compared, it may result in the discovery critical points representing emergent phenomenon or new functions (**Figure 1**). When a function is generated that does not have an analogy at lower levels, we often invoke the idea of *emergence*. These steps may have special significance or indicate that the models we are using are insufficient, but it seems clear that emergent behaviors may need to be treated as a special case.

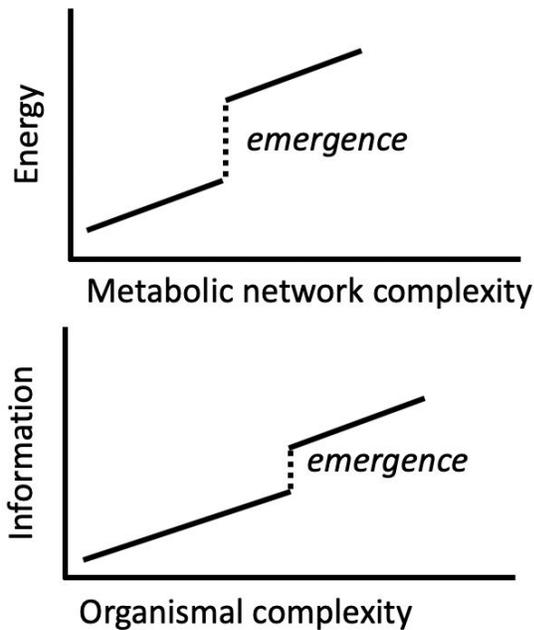


Figure 1. Linking biological complexity and universal currencies to explain the emergence of new functions and transitions in levels of biological organization. The emergence of new functions may be compared across levels of biological organization by examining the relationships among measures of biological complexity and universal currencies, which may or may not be linear, as shown here. It is likely that there are places where these relationships fail, and these disconnects can help us understand the emergence of new biological phenomenon across levels of biological organization. For example, exploring the relationship between metabolic network complexity and energy production may help explain the formation of mitochondria (top panel). Similarly, exploring the relationship between organismal complexity and information transfer might explain the advance from single cellularity to multicellularity or the transition from individuality to complex animal societies.

Linking Our Framework of Biological Assembly to Universal Currencies

The transition towards functional specialization of more complex units often occurs with the transition to new energy sources (e.g. the co-option of mitochondria in cells) or the optimal gathering and use of energy (e.g. task specialization in eusocial insect societies). Similarly, information gathered from both the environment (both extrinsic and intrinsic to the organism) and from other entities is critical to biological assembly at all levels of biological organization. For example, as pH changes molecular reactivity changes (e.g. polymerization), allowing for molecules to come together. Similarly, climatic factors promote group-living in numerous vertebrate species, and the ability to distinguish kin from non-kin drives basic social interactions and forms the bedrock of societal formation in animal.

Barriers and Challenges

Although it appears that different levels of biological organization exhibit analogous patterns of biological assembly that are likely to be governed by both similar forces of natural selection and physics (e.g. information transfer and energy optimization), it is possible that these levels are not directly comparable (much like the breakdown of Newtonian physics at the quantum mechanical scale). However, by studying biological systems with the views outlined in this paper, it may be possible to determine if and when comparisons fail, but this will only be possible if progress is made to better define energetic states and optimization, information transfer, and complexity within well studied biological systems and then defining and discovering emergence within these systems.

Likewise, it may be possible that all of biology is constrained by the underlying physical forces an evolutionary processes that are already well defined for other fields. Through developing this model within biology and harnessing new technologies, the relationship between already well defined organizing principles and biological systems may begin to reveal themselves.

How Does This Reintegrate Biology?

There already exists a strong body of literature on biological complexity (Oltvai and Barabási, 2002), emergence (Morowitz, 2002), information (Hazen et al 2007), evolution (Gould 1994; Maynard Smith and Szathmáry 1995), and energy in biological systems. There is also some prior work that discusses scaling within these broader topics. Yet, one of the challenges of this work is to generate a unifying model that can assess systems that are astoundingly complex, by choosing metrics that are meaningful and quantifiable for comparison across levels . It is entirely possible that we do not yet have the technology to gather meaningful data, but without experts within each field to identify and develop these technologies/methodologies this task becomes impossible. Therefore, we hope to highlight the importance of understanding an contextualizing these ideas within each field to allow for the integration of these concepts between levels.

Ours is a problem that inevitably forces scientists to think across levels of biological organization. This a challenging endeavour for any question. Doing so effectively and in a way that generates empirical data that is comparable across levels requires bringing together not just scientists with different traditional forms of biological expertise, but perhaps most importantly, systems biologists, physicists, chemists, and scientists from other non-traditionally biological disciplines.

Scientific Impact and Opportunity

Determining how simple units combine to form more complex ones is a fundamental problem that spans all levels of biological organization from molecules to ecosystems. Although the problem is by no means new, we are poised for new breakthroughs on this classic question because of new computational tools in the realm of information science and the ability to better characterize function across different levels of biological organization. The ideas presented here around biological assembly are also of great interest to federal agencies beyond NSF. For example, NASA is funding research on the origins of multicellularity and NIH is funding research on emergence and transmission of disease in complex groups. We envision this problem as a way to not only bring together scientists from different disciplines (including those outside of biology), but also those that typically are siloed by different federal funding agencies.

Societal Impact

Gaining a better understanding of functional specialization would impact both the development of biomaterials by predicting assembly constraint of the systems. More ambitiously, understanding the connections between these levels would eliminate barriers to generating synthetic biology, including of human organs. Finally, understanding the tradeoffs in individual versus group specialization might impact everything from robotics to epidemiology to information theory.

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