

# Evolved Open-Endedness, Not Open-Ended Evolution

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**Abstract** Open-endedness is often considered a prerequisite property of the whole evolutionary system and its dynamical behaviors. In the actual history of evolution on Earth, however, there are many examples showing that open-endedness is rather a consequence of evolution. We suggest that this view, which we call *evolved open-endedness* (EOE), be incorporated more into research on open-ended evolution. This view should allow for systematic investigation of more nuanced, more concrete research questions about open-endedness and its relationship with adaptation and sustainability.

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## Keywords

Evolved open-endedness, evolution,  
adaptation

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## I Introduction

Identifying necessary and sufficient conditions for a system to exhibit open-ended evolution (OEE) has been an important, yet difficult and elusive, challenge in artificial life research [3, 17]. There are several reasons for this difficulty. Foremost is the lack of widely accepted conceptual or formal definitions or measurements of open-endedness. For example, Taylor et al. [17] presented a useful list of the *observable behavioral hallmarks* of OEE, but open-endedness can also be discussed from other perspectives such as possibility and reachability [8]. Also, there is no widely accepted empirical test of whether a given evolutionary system (e.g., a real terrestrial ecosystem) is truly open-ended or not. Most importantly, no domain exists that displays open-endedness without any limits whatsoever. All domains and environments have lawful and logical conditions that ultimately limit how subsystems can develop within them, and it is the specific constraints defining subsystems that make them interesting and apparently open-ended. For example, the possible structures and theorems within a mathematical domain or formal symbol system are of interest and appear to be open-ended *because* they are strictly limited by the sets and axioms that define them. These issues make it a challenging task to develop theoretically rigorous definitions and investigations of OEE.

In this short article, we add to the discussion an evolutionary view of OEE itself that requires reframing some of its core research questions. In the current literature on this subject, open-endedness

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is often considered a prerequisite property of the whole evolutionary system and its dynamical behaviors. This view can naturally lead to a general but somewhat tautological statement that the open-endedness must be enabled and facilitated by the open-ended environment, that is, the sufficiently complex universe, planet, and/or laws of a real or artificial world that harbor evolution of limitless forms of organisms. Here we argue that we should consider an alternative, and possibly more constructive and productive, view of the open-endedness of evolution. Namely, instead of thinking of the open-endedness as existing conditions or properties of the evolutionary system, we consider them as the *outcome* of evolution itself. We call this view *evolved open-endedness* (EOE). In this context, the outcome can include both behavioral hallmarks and underlying mechanisms of open-endedness [17].

The fundamental requirement for biological evolution *as we know it* is self-replication in the von Neumann logical description-construction sense [18], implemented by actual physical construction guided by heritable symbolic information. A real biological example of this is the translation and folding of proteins that produce complex molecular machinery from only a small set of molecular building blocks (e.g., amino acids) [6]. What is impressive in those systems is the enormous variety and high level of complexity of constructions that evolution has synthesized from a relatively small fixed variety of simple material parts. This implies that achieving this unlimited complexity of constructions requires that the genetic description, or the representation of combinatorial composition of material parts, must be open-ended in its information capacity and controlling power. In other words, given that the material parts used for construction are strictly limited and finite, it follows that the seemingly unlimited open-endedness of their assembly into hierarchical structures depends on unlimited symbolic controlling information. This open-endedness by symbolic controlling information was not built a priori into the physical world, and therefore, we will need to take an EOE view to fully grasp the open-endedness.

## 2 Evolved Open-Endedness

When we look at the actual history of life on Earth, there is good evidence that the biological mechanisms that achieve open-endedness are a consequence of evolution. There was at least once a single cell (or some other form of first basic self-replicating unit) that had all the necessary conditions to start evolution as we know it. This cell was already bathed in a rich physical self-organizing environment on which it depended for the potential of open-ended evolution [13]. Considering the complexity of this physical self-organizing environment from which the cell arose, it would be hard to argue that this initial cell already had all the conditions and mechanisms for open-ended evolution within itself. It must have had many fewer enzymes, sensors, or motors than what typical organisms have in today's biosphere. Rather, the evolution that followed this initial cell gradually discovered and invented novel mechanisms that made evolution more open-ended. In other words, *conditions for increased open-endedness must have been gradually acquired in the course of evolution.*

This is not a new idea. The process was understood by the founders of the modern synthesis (e.g., Haldane [7]), and there are many more recent discussions related to the subject (e.g., evolution of evolvability [4, 5, 14, 19], multilevel selection [20], and major transitions [9, 16]).

Emphasis on this approach allows us to systematically explore several concrete research questions about open-endedness, including (but not limited to)

1. developing taxonomies of mechanisms and observable behaviors of open-endedness at various hierarchical levels,
2. quantitative characterization of degrees of observed open-endedness and their spatial or temporal variations (even within a single evolutionary history),
3. modeling and evaluating the potential evolutionary benefit of mechanisms of open-endedness as a form of meta-level adaptation and survival strategy, and
4. studying selection mechanisms for or against open-endedness.

These questions have both theoretical depth and practical value, but it would be rather difficult to address them if open-endedness were considered as preexisting conditions or properties of an entire evolutionary system.

### 3 Examples

We point out that there are already several known evolved mechanisms that significantly facilitated the open-endedness in the evolution of life.

The most salient example is the evolution of symbolic languages at two very different scales: the genetic language to describe DNA sequences (and proteins) using nucleotides (and amino acids) [1, 2], and the symbolic language spoken by humans to express and communicate complex ideas. These languages are, to the best of our knowledge, the only languages that possess such great, apparently open-ended descriptive power. But these languages must have evolved from much simpler, less open-ended languages. The evolution of such biosemiotic mechanisms must have played an essential role in enabling the open-endedness that followed [11, 12].

The second example is the formation of higher levels of organizations, or hierarchies [10, 15]. This includes evolution of enzyme systems (i.e., cooperation of multiple molecules), symbiosis of eukaryotes and mitochondria, evolution of multicellularity, and formation of cooperative groups (e.g., colonies, societies). In each of these examples, formation of a higher-level organizational entity requires additional mechanisms that were not present when evolution was going on at a lower level. But once the relevant level goes up, the number of possibilities and functionalities expands combinatorically, making the evolution more open-ended than before. In this sense, open-endedness requires much more than adaptability in a changing physical environment. The origin of what we perceive as true novelties involves a fortuitous coordination or actual incorporation of genetic materials from more than one organism or species (eukaryotes, multicellularity, sex, mutualism, commensalism, parasitism, eusociality, etc.). These combinations of genomes occur in a diverse biological environment of many organisms and species. Such major transitions are as unpredictable as evolution itself.<sup>1</sup>

The third example is the acquisition of new sensory modalities and information-processing abilities, which suddenly opens up entirely novel possibilities that organisms can explore and exploit. For example, the invention of complex chemical sensing (e.g., olfactory sensing that detects specific molecules coming from other individuals) made organisms develop sophisticated sensorimotor coupling (behavioral strategies, action plans), and also some internal *representation* of the environment (primitive form of cognition). More evolutionarily recent examples include the evolution of optical eyes, which completely changed the possibility space of cognitions and strategies for animals, a development that is linked to the Cambrian explosion. These evolutionary breakthroughs in perception and cognition of external environment facilitated the evolution of complex central nervous systems, such as brains, that allowed more complex internal representation of the environment in both space and time, eventually leading to intelligence and consciousness. The acquisition of the brain itself may also be considered as the fourth example of EOE, since it represents the acquisition of universal computational power.

These examples mentioned above are very different in nature from each other. They were not straightforward adaptive traits in a traditional sense, because each of them would involve substantial investment of costs. What are common among them are that

1. they were definitely acquired through evolution,
2. their appearance made a disruptive change in the landscape of the game of evolution, and
3. each of them significantly expanded what would be possible for organisms to accomplish.

<sup>1</sup> However, even this ability to coordinate or combine different genomes to create novelty does not automatically guarantee open-endedness. For example, although lichens have adapted to the most extreme habitats and exhibit enormous variety, there has been no evidence of continuous, open-ended novelty production in their evolution for over 400 million years.

These evolutionary events could be understood simply as a trajectory in an a priori rich and complex OEE, or they could be understood as EOE's that keep modifying what is possible in evolution itself.

#### 4 Discussion

An important yet tricky problem is how open-endedness is related to sustainability and survival. One might think that these two would certainly be positively linked, but this issue is not as simple as it may sound. The problem is similar to the relation of adaptedness and adaptability, which are seldom compatible [5]. As an extreme example, a solid rock, whose "evolution" is definitely not open-ended but whose internal rigid structure is well "adapted" to endure various external physical stresses, could survive an orders-of-magnitude longer time period, and therefore could be more sustainable, than more dynamic biological systems. In contrast, almost all (>99.9%) biological species that have appeared in the history of life are already extinct, which means that those species were not sustainable (which, by definition, makes their fates not open-ended either). Meanwhile, it would be difficult to argue that the currently existing species survived because they are more open-ended than others. Their survival is more likely due to the luck of having the right kind of variation at the right time, which does not imply that there is some specific property of open-endedness in those surviving species, at least from a conventional adaptation viewpoint.

The points discussed above suggest that the behavior of an evolutionary system may or may not *appear* open-ended, depending on the temporal or spatial scope an observer uses. At an extreme, the entire universe may ultimately be considered not open-ended if it eventually converges to its thermodynamical death. If one zooms to a planetary spatiotemporal scale, evolution of living things on a planet may appear to be more open-ended. And within a single evolutionary history, any lineage starting from any individual is almost certainly not open-ended, because the lineage will almost certainly become extinct eventually. But within a much shorter time window, some lineages may produce more variations and thus look more open-ended than others. Mapping all of these onto conventional concepts of evolutionary adaptations would be quite misleading and inappropriate. A novel way of re-conceptualization would be needed.

To reiterate, our objective in this short article was to emphasize the value of considering open-endedness, in both its mechanisms and its observed behaviors, as the outcome of evolution. What we call "open-endedness" is not based on a set of predictable preconditions, but on the gradually collected products of evolution over a long period of time. As we stated, the present genetic and human languages must have evolved from much simpler self-replicating or reproducible symbol systems by gradually discovering more and more strategies that may have allowed them to escape the most probable fate of extinction. However, the adaptive benefit of such open-endedness is far from trivial. There probably needs to be a major re-conceptualization of evolution, in order to properly describe and analyze the evolution of open-endedness. What is clear, however, is that there were times when those mechanisms did not exist, yet back then the evolution was already ongoing that eventually discovered the present open-ended expressive power. We think the clear historical evidence of how open-endedness has evolved over time should be incorporated more into research on open-endedness. This may not only advance our understanding of evolution, but also inspire new ways of creating open-ended artificial evolutionary systems.

#### References

1. Barricelli, N. A. (1977). On the origin and evolution of the genetic code. I. Wobbling and its potential significance. *Journal of Theoretical Biology*, 67(1), 85–109.
2. Barricelli, N. A. (1979). On the origin and evolution of the genetic code. II. Origin of the genetic code as a primordial collector language. The pairing-release hypothesis. *BioSystems*, 11(1), 19–28.
3. Bedau, M. A., McCaskill, J. S., Packard, N. H., Rasmussen, S., Adami, C., Green, D. G., Ikegami, T., Kaneko, K., & Ray, T. S. (2000). Open problems in artificial life. *Artificial Life*, 6(4), 363–376.

4. Conrad, M., & Rizki, M. (1980). Computational illustration of the bootstrap effect. *Biosystems*, 13(1–2), 57–64.
5. Conrad, M. (1990). The geometry of evolution. *BioSystems*, 24(1), 61–81.
6. Gething, M. J., & Sambrook, J. (1992). Protein folding in the cell. *Nature*, 355(6355), 33.
7. Haldane, J. B. S. (1932). *The causes of evolution*. London, New York: Longmans, Green. Reprinted (1990), Princeton: Princeton University Press.
8. Kauffman, S., Logan, R. K., Este, R., Goebel, R., Hobill, D., & Shmulevich, I. (2008). Propagating organization: An enquiry. *Biology & Philosophy*, 23(1), 27–45.
9. Maynard-Smith, J., & Szathmáry, E. (1997). *The major transitions in evolution*. Oxford: Oxford University Press.
10. Pattee, H. H. (1973). *Hierarchy theory: The challenge of complex systems*. New York: George Braziller.
11. Pattee, H. H. (1995). Artificial life needs a real epistemology. In F. Moran, A. Moreno, J. J. Merelo, & P. Chacon (Eds.), *Advances in artificial life: Third European Conference on Artificial Life, Granada, Spain, June 4–6, 1995, proceedings* (pp. 21–38). Berlin: Springer.
12. Pattee, H. H. (2001). The physics of symbols: Bridging the epistemic cut. *Biosystems*, 60(1–3), 5–21.
13. Rocha, L. M. (1998). Selected self-organization and the semiotics of evolutionary systems. In S. Salthe, G. Van de Vijver, & M. Delpo (Eds.), *Evolutionary systems: Biological and epistemological perspectives on selection and self-organization* (pp. 341–358). Dordrecht: Kluwer Academic Publishers.
14. Rössler, O. E. (1979). Recursive evolution. *BioSystems*, 11(2–3), 193–199.
15. Sayama, H. (2019). Cardinality leap for open-ended evolution: Theoretical consideration and demonstration by “hash chemistry.” *Artificial Life*, in press. Available at <https://arxiv.org/abs/1806.06628> (accessed December 2018).
16. Szathmáry, E. (2015). Toward major evolutionary transitions theory 2.0. *Proceedings of the National Academy of Sciences of the U.S.A.*, 112(33), 10104–10111.
17. Taylor, T., Bedau, M., Channon, A., Ackley, D., Banzhaf, W., Beslon, G., Dolson, E., Froese, T., Hickinbotham, S., Ikegami, T., McMullin, B., Packard, N., Rasmussen, S., Virgo, N., Agmon, E., Clark, E., McGregor, S., Ofria, C., Ropella, G., Spector, L., Stanley, K. O., Stanton, A., Timperley, C., Vostinar, A., & Wisner, M. (2016). Open-ended evolution: Perspectives from the OEE workshop in York. *Artificial Life*, 22(3), 408–423.
18. von Neumann, J., & Burks, A. W. (1996). *Theory of self-reproducing automata*. Champaign: University of Illinois Press.
19. Wagner, G. P., & Altenberg, L. (1996). Perspective: Complex adaptations and the evolution of evolvability. *Evolution*, 50(3), 967–976.
20. Wilson, D. S. (1997). Altruism and organism: Disentangling the themes of multilevel selection theory. *The American Naturalist*, 150(S1), S122–S134.