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 in the research of 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.

Introduction

Identifying necessary and sufficient conditions for a system to exhibit open-ended evolution (OEE) has been an important yet difficult, elusive challenge in Artificial Life research (Bedau et al., 2000; Taylor et al., 2016). There are several reasons for this difficulty. Foremost is the lack of widely accepted conceptual or formal definitions or measurements of "open-endedness." Also, there is no empirical test of whether a given evolutionary system (e.g., real terrestrial ecosystem) is truly open-ended or not. While theoretically challenging, these issues may be addressed in the coming years in a pragmatic manner toward a consensus among researchers, as more concrete, operationalized artificial evolutionary models are developed and critically evaluated.

Meanwhile, in this short paper, we add to the discussion an evolutionary view of OEE itself which requires reframing some of its core research questions.

In the current literature on this subject, open-endedness is often considered a prerequisite property of the whole evolutionary system and its dynamical behaviors. This view can naturally lead to a general statement that the open-endedness must be enabled and facilitated by the sufficiently complex Universe, planet, environment, and/or laws of a real or artificial world that harbor evolution of limitless forms of organisms. We believe this statement is definitely true, as illustrated by numerous theoretical and real-world examples such as von Neumann's universal constructor that heavily relies on its logical description-construction rules (von Neumann & Burks, 1966) and on the molecular protein folding whose construction process is largely guided by complex, rich physical and chemical laws (Gething & Sambrook, 1992). However, this view is somewhat cyclical in claiming that open-ended evolution depends on an open-ended environment. Also, it does not provide much insight into more nuanced questions such as why some evolutionary lineages showed great open-endedness while others did not, even if they both evolved in the same physical environment on Earth.

Here we argue that we should consider an alternative, and possibly more constructive and productive, view of the open-endedness of evolution. That is, 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).

Evolved Open-Endedness

There is good evidence that open-endedness is a consequence of evolution when we look at the actual history of life on Earth. 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 (Rocha, 1998). 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 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 (1932), and there are many more recent discussions related to the subject, e.g., evolution of evolvability (Rössler, 1979; Conrad & Rizki, 1980; Conrad, 1990; Wagner & Altenberg, 1996), multilevel selection (Wilson, 1997), and major transitions (Maynard-Smith & Szathmáry, 1997; Szathmáry, 2015).

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 various hierarchical levels of open-endedness

2. quantitative characterization of degrees of open-endedness and their spatial or temporal variations (even within a single evolutionary history)
3. modeling and evaluating the potential evolutionary benefit of open-endedness as a form of meta-level adaptation and survival strategy
4. studying selection mechanisms for or against open-endedness

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

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), 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 (Pattee, 1995; Pattee, 2001).

The second example is the formation of higher levels of organizations, or hierarchies (Pattee, 1973; Sayama 2018). 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, society). 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.

The third example is the acquisition of new sensory modalities and information processing abilities that suddenly opens up entirely novel possibilities that organisms could explore and exploit. For example, the invention of chemical gradient sensing in microbes made them develop complex sensorimotor coupling (action plans), and also some internal "representation" of the environment (primitive form of cognition). More evolutionarily recent examples include the evolution of optical eyes that completely changed the possibility space of cognitions and strategies for animals (which is linked to the Cambrian explosion), and the evolution of complex nervous systems that allowed more complex internal representation of the environment in both space and time, eventually leading to intelligence and consciousness.

These three examples mentioned above are very different from each other in nature. 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.

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

Discussions

An important yet tricky problem is how open-endedness is related to sustainability/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 (Conrad, 1990). As an extreme example, a solid rock, whose "evolution" is definitely not open-ended but its internal rigid structure is well "adapted" to endure various external physical stresses, could survive an orders-of-magnitude longer time period, and therefore it could be more sustainable, than more dynamic biological systems. In contrast, almost all (>99.9%) biological species that had appeared in the history of life have been 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 evolution 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 thermo-dynamical death. If one zooms into 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 get 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 re-iterate, our objective in this short paper was to emphasize the value of considering the open-endedness as the outcome of evolution. What we call "open-endedness" is not a set of predictable pre-conditions, but 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 reconceptualization 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 evolution was still 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 in research on open-endedness.

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