Exploring the Concept of Open-Ended Evolution

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Extended Abstract

The term *open-ended evolution* ("OEE") is used by the ALife community to refer to the kind of long-term evolutionary dynamics observed in the biosphere. It is generally taken to refer to evolutionary systems which display a continual production of adaptively significant innovations. Furthermore, some authors use the term to imply a sustained increase in complexity and/or diversity of some components of the evolving system; a system capable of open-ended evolution could spontaneously generate rich ecosystems of complex organisms.

For ALife practitioners who seek to build virtual worlds capable of OEE, there is a need for a *particular type of understanding* of the issues involved; in addition to the *analytic* understanding of evolutionary dynamics provided by theoretical biologists, there is also the need for a *synthetic* understanding of how to design systems that can produce these dynamics. In the following paragraphs, an attempt is made to unpack the concept of OEE into a number of separate (but related) issues, with particular focus on issues which apply to the synthesis of OEE systems.

Basic requirements

A number of common themes are apparent in previous work on OEE. At a very general level, three basic requirements can be identified for an evolutionary system if it is to exhibit the continual appearance of new adaptive forms:

1. **A practically unlimited space of potential phenotypes.** Clearly, if a system is to be capable of the continual production of new organisms without practical limit, there should be an unlimited space of potential organisms that could be represented in the medium. It is usually assumed that this requires a mechanism with the potential for transmitting an unlimited amount of genetic information from one generation to the next; that is, unlimited heredity replicators. However, Waddington (1969) and others emphasize the two-way interaction between genetic information and the environment in determining the adult form of an organism. In this case, where the same genotype can produce different phenotypes in different environments, unlimited heredity may not be strictly necessary if there exists an unlimited variety of potential environments.

2. **Mutational pathways of practically unlimited length between potential phenotypes.** It is insufficient to require just an unlimited space of potential phenotypes; these potential forms must be reachable by the evolutionary process. OEE requires that pathways of practically unlimited length exist in this possibility space from the original ancestral organisms to an wide variety of possible future organisms. The shape of the adaptive landscape will depend upon the nature of the information transmitted from parent to offspring, on the properties of the evolutionary operators (e.g. mutation and recombination), on the way in which an adult organism is generated from this information, and on the properties of the environment. These factors will interact in complex ways to determine the properties of the adaptive landscape with respect to features such as neutrality and portals to new adaptive landscapes (Schuster, 2011; Crutchfield, 2003).[1]

3. **Changing adaptive landscapes to drive continual evolution.** The first two requirements endow a system with the *potential* for OEE. If that potential is to be realized, without external assistance, the system must generate an intrinsic *drive* for continual adaptive evolution. This requires that the adaptive landscape experienced by organisms is changing rather than static, at least over evolutionary time scales. A changing adaptive landscape can come about intrinsically if the fitness of an organism depends on its local environment rather than on the organism in isolation. This can be introduced into a virtual world through the property of *connectedness*, described below.

[1]von Neumann (1966) proposed an architecture that theoretically allows mutational pathways of unlimited length, although this kind of architecture would appear to be unnecessary in digital worlds lacking complex environmental dynamics, such as *Tierra* (Ray, 1991), where replication by self-inspection seems to be sufficient.

Connectedness

The fitness of an organism will depend on its local environment if there is a *connectedness* between organism and environment. Such connectedness can come about if organisms engage in the consumption, transformation and excretion of nutrients and energy, creating a food web which connects a whole ecosystem of organisms. Connectedness can also come about by physical aspects of the environment, such as the transmission of forces, the transmission of signals, or modification of physical aspects of an ecosystem. The effect of connectedness, however it is achieved, is that changes in the behavior of one organism in the system, or the introduction of a new type of organism, or removal of an existing type, will have significant consequences for other organisms in the system. Connectedness therefore means that organisms in an ecosystem live in a delicate balance, and evolutionary change in one species will change the adaptive landscape of other species in the ecosystem.

In order to achieve connectedness through the emergence of food webs, the elementary material resources in the system must be conserved. If it is possible to create new resources "out of thin air" (as in *Tierra* when a program writes a new copy of itself in memory), then there is no need for resources to be recycled, and hence no need for food webs; such systems will therefore lack this type of connectedness.

Particular kinds of connectedness can also promote the evolution of diversity and complexity in the system. For example, a predator-prey relationship can lead to an evolutionary increase in complexity of the species involved (Van Valen, 1973). It has also been argued that connectedness through physical ecosystem engineering can result in a net increase in species diversity over long time scales (Jones et al., 1997).

Final comments

In the ways described above, the various forms of connectedness between individuals in an evolving system can lead to changing adaptive landscapes, which drive continual evolution. However, when designing a system that might be capable of OEE, there are additional important considerations to take into account. These are hinted at by the requirements listed above, and include:

1. **A complex physical environment.** OEE can be promoted by providing an environmental medium that can support rich, complex features and processes. This can help OEE in a number of ways, many of which have been discussed above (e.g. by supporting connectedness through food webs, and by providing mechanisms for communication via environment-mediated signals). The richer the range of phenomena available in the environment, the richer the potential for organisms to evolve ways of capturing and manipulating these phenomena for their own purposes. Not only does complexity in the physical environment expand the range of possible organism behaviors, but it also means that the full specification of complex behaviors can be distributed between the organism's genetic information, and the physics of the environment (thereby reducing the required information capacity of the genome).

2. **Embeddedness of organisms in the environment.** If some parts of the organism are reproduced automatically according to a specific mechanism (i.e. not embedded in the medium of the environment), there must be a predefined procedure to decide *when and how* such a mechanism operates. Such parts will therefore not be subject to variation and evolution, or, at best, only subject to evolve in certain predefined ways. In order to avoid any hard-wired restrictions on evolvability, the organisms must therefore be *fully embedded* in the shared medium of the world. Only then will all aspects of the organism, including its very organization, mode of reproduction, etc., be evolvable. Depending on the design goals of the system, one might choose to forgo total evolvability in the interests of more easily achieving particular outcomes.

Lack of space prevents further elaboration of these issues here; a detailed examination is presented in (Taylor, 2013). The present discussion has at least highlighted that the design of virtual worlds with a capacity for OEE requires much more than the consideration of information processing capacities, including careful consideration of the nature of the relationship between organisms, and of the relationship between an organism and its physical environment.

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