for the next decade, until the Intelligent Design discussion began and the American science-religion quarrel gained new life.

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—M.R.

Artificial Life programs and evolution

Evolution is the defining property and creative process of life, on earth and wherever it may occur. The cheetah running down its prey, the hummingbird pollinating a flower, and the drama of the human mind are all products of evolution. Life has completely reshaped the surface of our planet and is beginning to probe the rest of our solar system. Since Darwin and Wallace unraveled the mystery of evolution, many scientists have studied its details. A relatively new approach to the study of evolution is to create new instances of evolution, an approach that has been called Artificial Life.

While millions of living species currently exist on earth, it is believed that they all trace back to a common ancestor, billions of years ago; thus there is only a single tree of life on earth. From this perspective, our entire science of biology and our experience with evolution is based on a sample size of one. A truly comparative biology and a truly broad perspective on evolution would require knowledge of other instances of life and its generative process, evolution. It is believed that life exists on many planets throughout the universe but, unfortunately, they are out of our reach.

In its essence, the process of evolution involves self-replicating entities with genetic variation and differential survival, which leads to changes in the characteristics of the population of entities over the course of generations. Life on earth is the product of evolution inhabiting the medium of carbon chemistry; however, the process of evolution can operate in other media as well.

There has been some speculation among physicists that the universe itself may be the product of evolution. Some have suggested that black holes give birth to new universes, and that the fundamental constants of physics may vary among universes. Universes that produce more black holes have a higher Darwinian fitness, leading to the evolution of the fundamental constants of physics, which govern the characteristics of universes.

Speculation aside, we have discovered that evolution can inhabit the medium of digital computation. If we accept that evolution is the defining property and creative process of life, then instances of digital evolution may also be considered instances of life, albeit dramatically alien life. If we had the opportunity to observe life on other planets, it likely would be carbon-based life and thus would have that much in common with life on earth. Artificial life in the digital medium shares only the evolutionary process itself in common with life on earth, and so is more alien than life on other planets.

The digital computational medium is not a physical/chemical medium; it is a logical/informational medium. Thus these new instances of evolution are not subject to the same physical laws as organic evolution (e.g., the laws of thermodynamics), and therefore they exist in what amounts to another universe, governed by the "physical laws" of the logic of the computer. They never "see" the actual material from which the computer is constructed; they see only the logic and rules of the CPU and the operating system. These rules are the only "natural laws" that govern their behavior. Thus they live in a radically alien universe. Inoculating evolution into the digital medium gives us a broader perspective on what evolution is and what it does.

One of the most successful approaches for creating digital evolution is to write self-replicating computer programs, which have been called "digital organisms" or simply "creatures," and run them on a computer with a Darwinian operating system. A Darwinian operating system manages a population of replicating digital organisms in such a way that when new creatures are born, older ones die to free space in the memory inhabited by the programs. The Darwinian operating system also introduces mutation by flipping bits (between zero and one) in the code of the creatures. The random mutations cause genetic variation in the population, with the result that some individuals are able to reproduce better than others, which leads to a natural process of Darwinian evolution in an artificial digital medium.

Although this produces a dramatically alien instance of evolution, it is found to have some striking parallels to organic evolution on earth. Perhaps the most significant finding is that the digital organisms evolve adaptations to the presence of other digital organisms in their environment. A digital ecology emerges, which becomes the main driving force of evolution.

A computer can be seeded with a single self-replicating digital organism, which will quickly reproduce and fill the memory of the computer with a population of creatures. The creatures are then a very prominent feature of the environment and become an important source of selective forces. Parasites are one of the first things that typically evolve, and they set off an ecological-evolutionary dynamic that leads to an ongoing series of evolutionary innovations.

Whatever kind of creature is most common becomes a target for exploitation by other creatures. Or if parasites become common, they drive other creatures to evolve defenses. A typical scenario would begin with the evolution of parasites, followed by the evolution of immunity by their hosts. This cycle can repeat several times but may progress to the evolution of "hyper-parasites" that actually attack parasites, stealing their energy.

Sometimes, when one kind of creature completely dominates the memory, such that all the creatures are closely related, they will evolve a kind of sociality in which individual creatures living in isolation are not able to reproduce, but creatures living in groups are able to reproduce. The creatures in this kind of digital world are typically asexual in the sense that they do not mate to produce young but reproduce individually, copying only their own genetic material into their offspring. However, it was discovered that evolution continued even when mutations were turned off. This was because the creatures had invented a kind of primitive sexuality in which offspring were produced containing mixtures of genetic material from more than one parent. It involves a kind of sex with the dead, in which offspring include the genetic material from their parent, mixed with some genes from creatures that have died.

While the ecological coevolutionary dynamic described above is the main driving force for evolution, there is also perpetual selection for efficiency. One form of efficiency involves reducing the amount of time it takes to produce an offspring. This is usually accomplished by reducing the size of the genome that describes the organism, thereby reducing the time that it takes to make a copy. However, some optimizations have been achieved through the evolution of more complex computer code.

The evolution of more complex code is a tantalizing example of the holy grail of Artificial Life. Evolution transformed simple molecules into the complex and beautiful life forms that we find on earth today. It is the ability to generate complexity that is the source of evolution's power. It remains an unrealized goal of Artificial Life to produce an artificial system that exhibits open-ended evolution, leading to ever more complex artificial life forms, such as occurred on earth.

Life appeared on earth roughly 3.5 billion years ago, but remained in the form of single-celled organisms until about 600 million years ago. At that point in time, life made an abrupt transformation from simple microscopic, single-celled forms lacking nervous systems to large and complex multicelled forms with complex anatomies, physiologies, ecologies, and nervous systems capable of coordinating sophisticated behavior. This transformation occurred so abruptly that evolutionary biologists refer to it as the "Cambrian explosion of diversity."

Some have put forth a vision of a digital nature, a kind of biodiversity reserve for digital organisms, perhaps distributed across the Internet. People could contribute some of their memory and CPU cycles to the digital nature preserve, and digital organisms could live in the space, migrating from computer to computer, feeding on unused memory and CPU cycles. The idea is that if a large and complex region of cyberspace could be set aside for digital nature, then a digital Cambrian explosion of diversity and complexity might occur there.

Humans have been managing the evolution of other species for tens of thousands of years through the domestication of plants and animals. It forms the basis of the agriculture that underpins our civilizations. We manage evolution through breeding, the application of artificial selection to captive populations.

Similar approaches have been developed for working with evolution in the digital domain. It forms the basis of the fields of genetic algorithms and genetic programming. However, because digital evolution has not yet passed through its version of the Cambrian explosion, there exists the possibility to use a radically different approach to "managing" digital evolution. We need not limit ourselves to using evolution to produce superior versions of existing software applications. Rather, we should allow evolution to find the new applications for us. To see this process more clearly, consider how we manage applications through organic evolution.

Some of the applications provided by organic evolution are rice, corn, wheat, carrots, beef cattle, dairy cattle, pigs, chickens, dogs, cats, guppies, cotton, mahogany, tobacco, mink, sheep, silk moths, yeast, and penicillin mold. If we had never encountered any one of these organisms, we would never have thought of them either. We have made them into applications because we recognized the potential in some organism that was spontaneously generated within an ecosystem of organisms evolving freely by natural selection.

Many different kinds of things occur within evolution. Breeding relates to evolution within the species, producing new and different, possibly "better," forms of existing species. However, evolution is also capable of generating species. Even more significantly, evolution is capable of causing an explosive increase in the complexity of replicators, through many orders of magnitude of complexity. The Cambrian explosion may have generated a complexity increase of eight orders of magnitude in a span of 40 million years. Harnessing these enormously more creative properties of evolution requires a completely different approach.

We know how to apply artificial selection to convert poor-quality wild corn into high-yield corn. However, we do not know how to breed algae into corn. There are two bases to this inability: (1) if all we know is algae, we could not envision corn; and (2) even if we know all about corn, we do not know how to guide the evolution of algae along the route to corn. Our experience with managing evolution consists of guiding evolution of species through variations on existing themes. It does not consist of managing the generation of the themes themselves.

An alternative is to let natural selection do most of the work of directing evolution and producing complex software. This software will be "wild," living free in the digital biodiversity reserve. In order to reap the rewards and create useful applications, we will need to domesticate some of the wild digital organisms, much as our ancestors began domesticating the ancestors of dogs and corn thousands of years ago.

This vision of digital nature is currently unattainable, and may always remain so. Still, many researchers in the field of Artificial Life are still working toward an open-ended evolution in the digital medium.

Although the vast increases in complexity envisioned for digital nature are out of reach, more modest increases in complexity have been achieved. One approach has been to feed numbers to digital organisms and reward them for performing computations on them; greater rewards are given for more complex computations. This approach has led to the evolution of quite complex algorithms and has been used as a demonstration of the ability of evolution to produce what appear to be "irreducibly" complex structures.

Studying organic evolution can be frustrating because it is a process that occurs over vast scales of time and space. Artificial Life is an exciting approach to the study of evolution because it provides an opportunity to observe the process of evolution in action, generating novelty, ecologies, and modest complexity. Also, it broadens our perspective on life and evolution by allowing us to know the evolutionary process in a nonorganic medium.

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Ayala's career has coincided with and, to a large extent, has led the rise and expansion of molecular evolution and the philosophy of biology. Indeed, he has been a leader in both fields for many years. After his early investigations of