Summary, “Evolution of Biological Complexity”
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When Charles Darwin penned *The Origin of Species* back in 1859, he noted that the succession of organisms in the geological record appears to reflect an upward movement in the “scale of nature.” This raises the question, he wrote, as to whether his theory of evolution could account for the extraordinary complexity apparent in the world. A century and a half later, this remains an open question. Recent empirical evidence from experiments using populations of self-replicating computer programs (also known as digital life) suggests that complexity does indeed evolve.

Such experiments, using an artificial life programming platform called Avida, were described by Dr. Christoph Adami, Professor of Applied Life Sciences at Keck Graduate Institute in Claremont, California, at a lecture October 20, 2005. Dr. Adami’s lecture was part of a series sponsored by the Dialogue on Science, Ethics, and Religion (DOSER), a program of the American Association for the Advancement of Science (AAAS). The experiments were conducted by Dr. Adami and colleagues at the Digital Life Laboratory at the California Institute of Technology, where he continues as a collaborator.

In the experiments, complexity is measured in terms of the adaptations of computer-generated organisms to their environment, as reflected in the number of fixed elements in their computational sequences (analogous to fixed nucleotide locations in a genome). This is, according to Dr. Adami, a very good proxy for a measure of the organism’s actual complexity.

Dr. Adami introduced his topic by describing efforts to define complexity. The ideal definition, he said, is both operational “in that it indicates unambiguously how to measure complexity” and universal, applying in all instances. Several measures of complexity have been proposed. One is *structural complexity*, measured by counting the number of different parts of an organism. Another is *hierarchical complexity*, determining where an organism fits into categories such as prokaryote, bacteria, multicellular organism, or organization of organisms. A third is *functional complexity*, measuring the number of different tasks that an organism can perform. There are specific problems with each of these methods.

A fourth option is to measure *sequence complexity*. An obvious such measure — genome length — actually fails as a proxy for complexity since some plants, fish, and amphibians have far longer genomes than the more complex mammals including humans. For that reason, the digital life experiments of Dr. Adami and colleagues rely on a different sequence complexity measure. This one is based on the idea that in evolution, as organisms obtain information about their environment, they adapt to it and become correlated to it. In practical terms, this means that a line of descent will retain in its genome certain traits that are adaptive to the environment. Those traits that are necessary for survival will become fixed in the species — that is, none in the species will be found without the trait.

This carrying forward of a trait is a form of prediction about what works in a given environment, and “prediction is a concept that can be quantified in information theory,” according to Dr. Adami. Counting the number of invariable positions within a genomic sequence turns out to be “a practical and universal measure of sequence complexity.”

This sort of sequence complexity is difficult to measure in biological experiments, because even with fast-breeding organisms such as bacteria the huge number of generations required to provide statistical information simply takes too long to reproduce. Computer-based experiments allow evolution of complexity to be tracked in a more suitable timeframe.

The physicist defended the use of artificial life for evolution experiments because evolution was formulated by Darwin as a natural algorithm, that is, as an automated sequence of events. Computer life makes use of the “exact same algorithms” as biological life but with “zeroes and ones” rather than nucleotides, he said.

Dr. Adami described the artificial life studied at Cal Tech as domesticated versions of computer viruses. These Avida organisms execute functions on a simulated computer within a real computer (so that the real research computer does not crash). The “critters,” as Dr. Adami referred to them, have a circular genome like most bacteria. Each genome processes information in a method analogous to biochemical transcription and translation.

Biological replication is fueled by energy; computational replication is fueled by CPU time, earned in the form of SIPs, or Single Instructional Programming Units. When a digital organism executes an “interesting” calculation, it is rewarded with SIPs.

In the particular experiment Dr. Adami described in his lecture, only 78 computational reactions earned CPU time, which he said was an “extraordinarily small number” compared to the possibility of biochemical reactions that provide energy. In other experiments performed by Dr. Adami and his colleagues, they have restricted the situation to even fewer calculations and demonstrated that the unfolding of evolution and complexity can occur with small numbers of reactions.

Using another analogy from biochemistry, Dr. Adami noted that an enzyme is needed to cause a reaction between two chemicals to make a third one that is energy-rich. Likewise in the digital experiments, random numbers are placed in the environment that the digital organisms can use to compute. The organisms earn SIPs if they find these numbers and execute appropriate sequences with them.

Unlike computer viruses, the digital organisms in the experiments are subject to mutation. "We made sure if there was a copy command, that we had an error probability," Dr. Adami explained. Mutations over generations create the variation that provides a framework in which natural selection can operate.

"On Earth it would be great if we could replay the tape of evolution," Dr. Adami noted. That is not possible, but it is possible in the digital world to rerun experiments and collect statistical information about various evolutionary paths. The experiments show that species tend to move toward greater complexity though there may be temporary drops. These aberrations occur when populations of very fast replicators grow, Dr. Adami explained. A population emerges that is almost identical in every position. Subsequently, over generations, new mutations randomize those points in the genome that do not represent information (that do not reflect adaptations to the environment) and so complexity as measured by fixed points in the genome goes down.

Another phenomenon that causes complexity to decrease is when sudden shifts in the environment cause information held about the old environment to no longer be useful for survival. Complexity crashes then occur, followed by increases in complexity as populations readapt. Complexity, in other words, is "a trend that can be reversed in short time-scales."

Dr. Adami asserted that these experiments empirically refute the foundation of a hypothesis called intelligent design, which posits that certain traits of organisms are so sophisticated that they could not have emerged through incremental evolutionary processes. According to this idea, such traits are "irreducibly complex" and must have been created in whole through the intervention of an intelligent designer. The vertebrate eye and the blood clotting system are frequently cited by intelligent design advocates as examples of irreducibly complex systems. Intelligent design is a challenge to macroevolution, the idea that novel genes can emerge in populations. (Intelligent design does not conflict with microevolution, in which genes present in a species change in their frequency within a population.)

Dr. Adami and his colleagues wrote up a study that covered 50 digital populations, each subject to the same mutation rate. "The evolutionary origin of complex features," authored by Richard Lenski, Charles Ofria, Robert T. Pennock, and Dr. Adami, was published in *Nature* on May 8, 2003. "It created quite a stir," Dr. Adami said in understatement.

In the study, digital organisms were rewarded when they were able to complete a full task that consisted of a score or more computational steps; the task was to compare pairs of binary numbers and determine if each pair of digits is the same. Rewards of SIPS were received only upon completion of the full task. The likelihood that such a random sequence would occur is 10^{-27}. Through a series of incremental mutations, organisms were able to evolve a computational sequence to complete the task — but not always the most efficient sequence. “There are many alternative sequences — that is one of the main points that this experiment teaches you,” said Dr. Adami.

Since in the digital world every organism has only one “parent,” the researchers could trace back through a single line of descent and count the number of mutations it took to arrive at the computation sequence or “gene” for the task. In the experiments, digital organisms were able to develop the complex trait after anywhere from 50 to 721 mutations. Once the complex trait was evolved, the researchers were able to make it fail by knocking out certain point mutations. This was evidence that the evolved traits were “irreducibly complex,” yet their observed incremental evolution refutes a central tenet of the intelligent design argument.

To reach the complex sequence, some lines of digital organisms acquired mutations that were deleterious in terms of replication rate but which, after a few generations, led to further mutations that provided a major boost in replication rate. In one example detailed by Dr. Adami, a mutation reduced fitness by a factor of three, but eight “updates” later another mutation allowed fitness to triple. “Severely compromised organisms can actually exist,” he emphasized, adding that the importance here is that some beneficial mutations build upon prior mutations that, when viewed from hindsight, appear to have been harmful.

“These deleterious mutations on the line of descent can change the genetic background, and we found this to be quite important element of evolving complex genes. A mutation that is deleterious to a predecessor can be in fact beneficial to a successor.”

Dr. Adami concluded, “Darwinian evolution very successfully accounts for the evolution of complex features. Here we have a complex experiment that can actually show that, step by step.”

As a counterpoint to Dr. Adami’s presentation, Jim Miller presented some “meta-suggestions” about how evolutionary theory can be aligned with conceptions of God. He suggested a view that presents God as coaxing but not coercing or predetermining the future.

Influencing our conception of God and nature are ideas about how the world exists, Dr. Miller said. An older philosophical tradition of “essentialism” holds that “a thing becomes what it is… particular manifestations of things are simply less than perfect expressions of the ideal form." This notion is basically deterministic, in that what things are is determined from the outset. By contrast, the notion of "existentialism" is that "a thing is what it becomes… there is no essence that pre-exists, and there is no necessary end-point, since becoming itself doesn't necessarily stop." Indeterminacy and contingency are features of an existential system.

Evolutionary theory, noted Dr. Miller, is "a much more existential way of understanding the nature of things." The question, then, is where divine action takes place in the evolutionary process.

Theologians have offered a variety of responses to this question. One response is to say that evolution cannot explain everything and that God enacts design and makes complex structures appear. This is the position taken by advocates of intelligent design. Another response is to say that God acts in the domain of uncertainty: "God determines the indeterminance." Yet another is to propose that God introduces information into the system. Dr. Miller commented that these explanations are problematic because further advances in science may ultimately explain naturalistically the activity ascribed to God.

By way of introducing an alternative response, Dr. Miller noted that the view of God as being able to see into the future as well as the present and past implies a fundamentally deterministic system. Another possibility, then, is that the past is fixed but the future is not knowable even by God: the future is a "domain of potentiality." The present is where what is potential becomes actual and fixed.

In such a view, the past is moments of history, and the present is where events are actualized relating the fixed past with the potentialities of the future, "following an initial aim." Dr. Miller said this can be theistically interpreted by seeing the future as a "*graded* potentiality which allows for judgments of better or worse, more or less" and the "initial aim" as the "call of God" toward the actualization of a particular qualitative potential. So, some new events are more responsive to the call of God than others, he suggested.

"In terms of the presence of God in this process, the moment forms itself. It does so in relationship to a past it is already given, in relationship to a domain of potentiality from which it can draw. The call of God doesn't determine it, but gives it an initial direction." Dr. Miller reiterated that while the "graded potentiality" of possible events establishes comparative values, the event forms itself. "So its freedom is not diminished and its potential for novelty is not diminished. The opportunity for the emergence of novel or complex structures is not lost."

In the question and answer session, Dr. Adami defended the idea that his computer model relates to biological life. "Darwinian theory is a proposition of an algorithm that acts on hereditary material; Darwin himself did not know what the hereditary material was. Such an algorithm creates a novelty by adaptation and natural selection and so on. Our system is implementing precisely the elements of the algorithm that he had proposed. As a consequence, from a logical point of view, there is no difference between the form of life that we have created within the computer as far as the evolution is concerned." The physicist conceded that there are "huge differences" between artificial and natural life in terms of sensation. "I would never try to convince you that the stuff that lives inside the computer is bacterial or wet or squishy or any of these things."

A questioner wondered whether deleterious mutations always precede greater jumps in complexity. Dr. Adami said, no, although such instances were highlighted in the lecture because they are such a spectacular phenomenon. Statistically, however, they are rare.

Another questioner wanted to know whether the computer experiments demonstrate the effects of anything equivalent to the recombination that occurs in sexual reproduction. Dr. Adami said that demonstrating that process is possible, "though in the type of experiments that I have shown you tonight we have explicitly turned it off" so as to study one element of evolution at a time. By doing so, they have been able to show that it is sufficient with single substitutions, insertions, and deletions for complex systems to evolve.

In other experiments, they have been able to model recombination and multi-niche environments. Eventually, they hope to test other phenomena such as co-evolution, gene regulation, and the Baldwin effect (in which an acquired characteristic significantly affects the further evolution of the species with respect to that characteristic).

A question directed at Dr. Miller was whether a God who cannot foresee or control the future is a more threatening concept to Christian theology than a God who determines everything. Dr. Miller said that one could think of God as knowing "what can be known: the traditional categories of omniscience and so forth would still apply, but there are certain things God can't know as actual, only as potential." Dr. Miller also suggested that his model asks for a rethinking of the concept of a powerful God. "We have tended to think about power, particularly in the West, using largely monarchial images — to think of power as coercion." In the image he is suggesting, God operates "by means of persuasion rather than coercion. And frankly I don't find that odd within the context of Christian theology."