Artificial Life VII: Looking Backward, Looking Forward (Editor's Introduction to the Special Issue)

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This issue contains highlights from the Artificial Life VII conference, held at Reed College in August 2000 [1]. A few authors who presented papers at the conference were invited to revise and expand their papers for publication in this special issue. Freed from the artificial space limits of conference proceedings, their papers provide additional details and situate their work in a broader context. One additional paper on open problems in artificial life grew out of discussion at the end of the conference. All the papers show the breadth and depth of the work presented at the conference. All address very deep questions about living systems, and most build bridges to concrete biological data and generate experimentally testable predictions.

The origin of multicellularity is one of the major transitions in the evolution of life, and differentiated multicellular life has apparently evolved independently many times. The developmental processes which create these multicellular organizations share three notable features. First, development starts with a homogeneous cell (or set of cells) that are multipotent, that is, have the ability to differentiate into many different types of specialized cells. Second, the developmental process has an intrinsic arrow of time because the differentiated cells that result are not multipotent. Third, the developmental process is stable in the face of perturbations that destroy clusters of cells. In "Complex Organization in Multicellularity as a Necessity in Evolution," Chikara Furusawa and Kunihiko Kaneko provide a minimal model of cellular dynamics that explains these universal features of multicellular differentiation. Furusawa and Kaneko numerically simulated a one-dimensional chain of cells governed by randomly generated biochemical reaction networks. They found that, while competition for resources prevents resources from flowing through chains of undifferentiated cells, cellular differentiation allows cells to share resources throughout the cellular chain. Thus, although *individual* cells taken from undifferentiated chains can grow more quickly than cells from differentiated chains, *chains* of differentiated cells can grow more quickly than chains of undifferentiated cells. These results lead to a number of experimentally testable predictions about multicellularity in biological organisms and provide a mechanism by which multicellularity inevitably arises in the evolution of cellular differentiation.

The genetic code is a nearly universal feature of life on earth, although it does have a few exceptions such as mitochondrial DNA. It is difficult to understand at first how the genetic code could evolve at all; a mutation at a given codon might be a selective advantage, of course, but any change in the code would entail wholesale changes at a vast proportion of codons. How could this but be disastrous? Hiroaki Takagi, Kunihiko Kaneko, and Tetsuya Yomo propose a solution to this problem in

"Evolution of Genetic Codes through Isologous Diversification of Cellular States." Their answer employs a solution to a second deep puzzle about life: how sympatric speciation is possible. Allopatric speciation is easier to understand, because geographically isolated subpopulations could evolve so far in different directions that they become reproductively isolated. But it is less clear how subpopulations could become reproductively isolated while they are continuously interacting. The authors' call their answer to this problem the "isologous speciation" theory. This theory says that genetically identical cells can have phenotypic differences caused by cellular interactions, and this phenotypic difference can subsequently become embedded in a genotypic differentiation.

Takagi et al. address the evolution of the genetic code by numerically simulating a dynamical system which models an intra-cellular metabolic reaction network, intercellular interactions (via chemical diffusion), and mechanisms for cell division (and death) and mutation. The system's variables are concentrations of metabolic chemicals, metabolic enzymes, chemicals for genetic information, and enzymes to translate genetic information into amino acids. The genetic code determines how genetic information is expressed phenotypically, that is, which amino acids are produced, and evolution of the genetic code takes the form of changes in the enzymes used in amino acid synthesis. Simulations of this model reveal that isologous speciation is crucial for evolution of the genetic code: Evolution creates cells with distinct genetic codes if and only if cell phenotypes can differentiate. This theory explains how the evolution of new genetic code for mitochondria could be a natural result of interactions between mitochondria and their host cells. The theory of isologous speciation has already been corroborated in *E. coli* experiments in the laboratory, and further *E. coli* experiments to test this explanation of the evolution of the genetic code are underway.

Valentino Braitenberg's charming book *Vehicles* [2] connected brain structure with observable behavior by showing how imaginary devices with simple connections among sensors and motors could generate a variety of lifelike behaviors. The work reported by Bernard D. Reger, Karen M. Fleming, Vittorio Sanguineti, Simon Alford, and Ferdinando A. Mussa-Ivaldi in their paper "Connecting Brains to Robots: An Artificial Body for Studying Computational Properties of Neural Tissues" physically instantiates Braitenberg's approach in a novel neuro-robotic system, in which a Khepera robot is connected to a lamprey brain kept alive in vitro. In this system, optical sensors on the robot transmit signals to electrodes embedded in the reticular formation of the lamprey brainstem, and additional electrodes simultaneously record neuronal activity in this brain tissue and transmit it to the Khepera's controllers. Thus, the robot is an artificial body controlled by the lamprey brain, with a continuous feedback loop connecting the living brain with its artificial body and sensors.

The coupled neuro-robotic system created by Mussa-Ivaldi and his collaborators can illuminate the connection between neurobiology and adaptive behavior only if its behavior is stable and repeatable in baseline conditions, so demonstrating this stability is an important first achievement of their paper. Their second achievement is showing that the system produced systematically different behaviors (positive and negative phototaxis) under different conditions. Their results also suggest that the robot's behavior can reflect and discriminate between short- and long-term adaptive changes in synaptic activity. Since the Khepera's behavior physically displays how the lamprey's neuronal tissue adapts to various modifications and treatments, the neuro-robotic system provides a new tool for illuminating the neurobiological and computational activity underlying adaptive behavior in living systems.

One measure of the success of a scientific enterprise is its usefulness for solving practical problems. In "Exploring the Relationship between Neutral and Selective Mutations in Cancer" Carlo Maley and Stephanie Forrest apply artificial life methods to the

problem of understanding why normal cells evolve into cancerous cells. This work departs from artificial life's typical perspective on evolutionary models in two ways. First, instead of considering the evolution of a population of organisms, Maley and Forrest study the evolution of a population of cells inside a single organism over the course of its lifetime. Second, instead of focusing on how to make the evolutionary process as creative and powerful as possible, they focus on learning how to thwart the course of evolution so that the threat of cancer will be minimized. Even though the evolutionary model studied by Maley and Forrest has a number of simplifications and some parameter values are chosen somewhat arbitrarily from an range of realistic values, their work on the evolution of cancer leads to testable predictions and suggestions for new approaches to cancer treatment.

John von Neumann's work on self-replicating automata is now universally hailed as a foundational result in artificial life, but it is controversial exactly where the substance of this work lies. Barry McMullin's paper "John von Neumann and the Evolutionary Growth of Complexity" provides a new perspective on this issue. McMullin argues that, contrary to what most people believe, von Neumann's result concerns not self-replication per se but how, in a general and open-ended way, machines can construct other machines more complex than themselves. Self-replicating machines in and of themselves do not solve the problem of the evolutionary *growth* of complexity, for a self-reproducing entity produces something with the same complexity as itself. But McMullin argues that von Neumann's real concern was the evolutionary growth of complexity and that his famous construction of a self-replicating automaton in fact is the first and arguably the simplest solution to this problem. McMullin ends his paper by listing five key open questions that the effort to understand the evolutionary growth of complexity now must confront.

The theme of the Artificial Life VII conference was "Looking backward, looking forward." Coinciding with the birth of a new millennium, the conference was an opportunity to take stock of the field's main achievements and central open questions and thereby help shape artificial life's research agenda. Toward this end, the conference concluded with a round table on artificial life's most important open problems—what could be called "grand challenges" in artificial life. The round table presentations and subsequent open discussion have now been digested and restructured in the paper "Open Problems in Artificial Life," with which this volume closes. The paper describes fourteen problems falling under three broad questions: How does life arise from the nonliving? What are the potentials and limits of living systems? How is life related to mind, machines, and culture?

Publishing these grand challenges can positively influence artificial life's future in many ways. The most obvious is that, like Hilbert's problems in mathematics a century ago, these problems can guide future research in productive directions. A related benefit will come if the present list catalyzes the creation of new and better lists of central open problems. Distilling a list of grand challenges also counteracts the centrifugal force tending to pull apart interdisciplinary research activities. It is challenging to keep abreast of relevant work spread across different fields and to follow methodologies arising out of different disciplines. Consciously and collectively looking to the future promotes cross-disciplinary communication and renews and redefines artificial life's interdisciplinary center of gravity. Finally, publishing the grand challenges encourages us to assess our scientific progress over time. At future conferences, we can look back to this list and measure achievements on these fundamental problems. We can also gauge the thematic development of the field by seeing how problems are added or dropped from the list. It is fitting that this issue, highlighting a conference on "Looking backward, looking forward," should end with this snapshot of the central problems in artificial life's future.

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References

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