The Scientific and Philosophical Scope of Artificial Life

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ABSTRACT

The new interdisciplinary science of ALife has had a connection with the arts from its inception. This paper provides an overview of ALife, reviews its key scientific challenges and discusses its philosophical implications. It ends with a few words about the implications of ALife for the arts.

Artificial life (ALife) is a young interdisciplinary collection of research activities aimed at understanding the fundamental behavior of lifelike systems by synthesizing that behavior in artificial systems. As befits a journal for artists who use science and developing technologies, *Leonardo* regularly publishes articles discussing ALife. There is also traffic in the other direction: for example, the biennial International Conference on ALife is the primary vehicle for publishing the latest scientific developments in ALife. Nevertheless, more than 5% of the articles published in the proceedings of the most recent ALife conference [1] concerned the application of ALife to art and music [2–5]. People in both communities believe that the arts and ALife have much to offer each other. Given this mutual interest, it would useful for the two communities to come to know each other better. The resulting opportunity to counteract the hype and misleading publicity surrounding ALife would also be welcome. The truth about ALife is often more interesting and surprising than the fiction and is always more valuable.

This paper aims primarily to provide an overview of ALife, explaining its approach to science and technology, outlining its major open problems and sketching its broader philosophical implications. It ends with a few words about the implications of ALife for the arts.

An Overview of ALife

Life is an interconnected web of adaptive systems produced spontaneously by the process of evolution. Living systems exhibit impressively robust and flexible functionality at many levels of analysis. Examples range from the genomic and proteomic [6] regulatory systems that control how biological organisms develop and function to the evolving ecological networks through which members of different species interact. Human-made adaptive systems, such as the myriad communication networks that span the globe, are beginning to approach the complexity of the adaptive systems found in nature. Learning how to engineer flexible and robust adaptive complexity is one of the biggest challenges facing society in the 21st century.

Traditionally, adaptive systems of various kinds were modeled independently in different disciplines. ALife is now bringing together biologists, physicists, chemists, psychologists, economists and anthropologists with computer scientists, philosophers and artists to create a unified understanding of adaptive systems of all types. ALife studies life and lifelike processes by synthesizing them in artificial media, most often using computer technology. The goals of this activity include modeling and even creating life and lifelike systems; the goals also include developing practical applications involving new technologies that exploit intuitions and methods taken from living systems. The phrase "artificial life" was coined by Christopher Langton. He envisioned a study of life as it could be in any possible setting and organized the first conference to explicitly address this field [7]. There has since been a regular series of conferences on ALife and a number of academic journals have been launched to publish work in this new field.

ALife borrows from other, older disciplines, especially computer science, cybernetics, biology and the study of complex systems in physics. Its closest intellectual cousin is artificial intelligence (AI). There is, however, a crucial difference between the modeling strategies that AI and ALife typically employ. Most traditional AI models are top-down–specified serial systems involving a complicated, centralized controller that makes decisions based on access to all aspects of global state. The controller's decisions have the potential to affect directly any aspect of the whole system. On the other hand, many natural living systems exhibiting complex autonomous behavior are parallel, distributed networks of relatively simple low-level "agents" that simultaneously interact with each other. Each agent's decisions are based only on information about its own local situation, and its decisions directly affect only that situation. ALife's models follow nature's example. The models themselves are bottom-up–specified parallel systems of simple agents interacting locally. The local interactions are repeatedly iterated and the resulting global behavior is observed. The whole system's behavior is represented only indirectly. It arises out of the interactions of a collection of directly represented parts.

The synthetic methodology of ALife has several virtues. The discipline of expressing a theory synthetically, especially in computer code, forces precision and clarity. It also ensures that hypothesized mechanisms are feasible. Computer models also facilitate the level of abstraction required for maximally general models of phenomena. The bottom-up architecture of ALife models creates an additional virtue. Allowing micro-level entities continually to affect the context of

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their own behavior introduces a realistic complexity that is missing from analytically solvable mathematical models. Such models can reveal little about the global effects that emerge from a web of simultaneous nonlinear interactions. The obvious way to study the effects of these interactions is to build bottom-up models and then empirically investigate their emergent global behavior through computer simulations.

Many ALife models are designed not to represent known biological systems but to generate wholly new and extremely simple instances of lifelike phenomena. The simplest example of such a system is the famous cellular automaton called the Game of Life, devised by the mathematician John Conway in the 1960s [8]. Computer simulation is crucial for the study of complex adaptive systems. It plays the role that observation and experiment play in more conventional science. The complex self-organizing behavior of the Game of Life would never have been discovered without the simulation of thousands of generations for millions of sites [9]. The same holds for virtually all other systems studied by ALife.

Rather than merely producing computer simulations, some ALife research aims to implement systems in the real world. The products of this activity are physical devices such as robots that exhibit characteristic lifelike behavior. Some of these implementations are motivated by the desire to engineer practical devices that have some of the useful features of living systems, such as robustness, flexibility and autonomy. But some of this activity is primarily theoretical, motivated by the belief that the best way to confront the hard questions about how life occurs in the physical world is to study real physical systems. Examples range from evolvable hardware, which attempts to use biologically inspired adaptive processes to shape the configuration of micro-electronic circuitry, to biologically inspired robotics, such as using evolutionary algorithms to automate the design of robotic controllers and swarms of robots that communicate locally to achieve some collective goal.

Grand Challenges in ALife

A good way to understand a scientific community is to grasp its central aims. A second generation of scientists commencing work in ALife prompted the organizers of the last International Conference on ALife to publish a list of grand challenges [10]. Since there is still so much unknown about the emergence and evolution of living systems, the list emphasizes scientific understanding rather than applications, and the challenges take an unabashedly long-term view. They fall into three broad categories: the origin of life, life's evolutionary potential and life's connection to mind and culture.

A. How does life arise from the non-living?

1. Generate a molecular proto-organism *in vitro*.
2. Achieve the transition to life in an artificial chemistry *in silico*.
3. Determine whether fundamentally novel living organizations can arise from inanimate matter.
4. Simulate a unicellular organism over its entire life cycle.
5. Explain how rules and symbols are generated from physical dynamics in living systems.

B. What are the potentials and limits of living systems?

6. Determine what is inevitable in the open-ended evolution of life.
7. Determine minimal conditions for evolutionary transitions from specific to generic response systems.
8. Create a formal framework for synthesizing dynamical hierarchies at all scales.
9. Determine the predictability of evolutionary manipulations of organisms and ecosystems.
10. Develop a theory of information processing, information flow and information generation for evolving systems.

C. How is life related to mind, machines and culture?

11. Demonstrate the emergence of intelligence and mind in an artificial living system.
12. Evaluate the influence of machines on the next major evolutionary transition of life.
13. Provide a quantitative model of the interplay between cultural and biological evolution.
14. Establish ethical principles for ALife.

Challenges in the third category are more speculative, and some are interwoven with non-scientific issues. Some areas in which ALife plays a significant role, such as robotics and art, do not appear on the list. In part this is simply a practical expedient to shorten the list as much as possible. In the rest of this section I will briefly explain a representative selection of these challenges. More information about them all can be found in the original source.

The first challenge involves no less than the construction of a novel life-form in the laboratory from scratch. The first candidates should be the simplest possible forms of life—self-reproducing molecular structures that construct and maintain themselves in a simple environment and evolve. The environment would involve only simple forms of energy and material, and the goal would be to create an encapsulated biochemical system that can derive energy from simple chemicals or light and use information carried in primitive genes. The attempt to create a proto-organism that self-replicates and evolves using energy and nutrients from its environment illustrates ALife's concern with understanding life by synthesizing it. It also shows that ALife's interests are not just fanciful abstractions. A fundamental understanding of real life in the real world is a key part of what ALife hopes to provide.

Few questions concerning living systems are as fundamental as that of the spontaneous generation of life, and the second challenge explores this issue in artificial chemistries. Artificial chemistries are computer-based model systems composed of objects (abstractions of molecules) that are assembled by collisions among simpler objects according to predefined interaction rules. The chemistry must be constructive rather than merely descriptive, that is, with rules that determine arbitrarily complex products from arbitrarily complex collisions. Furthermore, the chemical interaction rules should be simple compared with the ultimate products that they create. This challenge reflects ALife's emphasis on understanding the amazing spontaneous emergence of structure and hierarchy that characterizes life. It also shows how ALife uses abstraction to capture the essence of such a process.

Life as we know it encodes information about hierarchically organized, spatially localized individuals in genetic structures. The third challenge involves determining whether this or any other particular form of organization is necessary for life. The question is relevant to the search for extraterrestrial life in the universe. Examples of fundamentally different organizations include those without a genetic code, without spatially localized individuals, without hierarchical organization, without a genotype-phenotype distinction or, indeed, without any symbolic representational scheme. The debate about what organizations are "fundamentally different" will clarify our understanding of the nature of life, and pursuing this challenge will expand our horizons and challenge our preconceptions about life.

The sixth challenge concerns life's contingency. ALife attempts to discern the features common to all evolutionary processes, or to broad classes of evolutionary processes. It aims to determine whether different kinds of evolutionary processes have different potentials for creativity. ALife researchers expect that many of the most fundamental features of the evolution of life on Earth will be shown to be independent of the physical media that happen to embody the process. Digital information processing in computers is very different from molecular biology, yet ALife has been building digital organisms based on genetic and cellular principles from its inception. Digital media provide considerable scope for varying the "physics" underlying the evolutionary process, so it is a straightforward matter to investigate evolutionary contingency in that context. We do not know, however, whether digital and physical systems have the same potentials for evolutionary innovation. ALife's commitment to a synthetic methodology becomes evident here. Not content with mere verbal speculation about kinds of evolutionary creativity, ALife insists on making systems that actually demonstrate those capacities.

All forms of life that we know of have a complex organization that enables them to act autonomously and in their own interests. Organisms can be transgenically manipulated to express different genes, but the evolutionary consequences and limits of such manipulations are unknown. This raises ALife's ninth challenge: determining how well we can predict the evolutionary consequences of making new forms of life. To what extent can one redesign organisms to fulfill novel functions without disrupting their viability? Is there a tradeoff between the size of modification and viability? Better understanding of the genetics of development will enable us to create novel multicellular organisms, but these organisms might not flourish or might unleash unanticipated and uncontrollable ecological consequences. Perhaps major changes to organisms can be perfected only by lengthy coevolutionary optimization. Like genetic engineering, ALife must confront questions like these because it unleashes novel autonomous beings with lives of their own. Furthermore, ALife is ideally poised to address such questions, because it can synthesize all kinds of genetic manipulation in isolated digital contexts.

Once life originated, biological evolution underwent a number of major evolutionary transitions, such as the origin of eukaryotes, the origin of multicellular life and the origin of human culture. Presumably there will be further major transitions in the future. Once culture originates, it has the capacity to evolve on its own. The past century has seen the explosion of technological culture, including the creation of computing machines and of complex distributed networks connecting them. Many believe that it is only a matter of time before ALife creates machines that are alive and intelligent, reproduce their own kind, have their own purposes, set their own goals and evolve autonomously. These machines will be part of our world, and their evolution will affect our future. Consider how machines currently influence the nature and rate of human communication and interconnection. All this suggests that machines might play an unprecedented role in the next major evolutionary transition. ALife's 12th challenge is to predict and explain this role. Machines will certainly play at least a supporting role in the next major evolutionary transition because they provide an infrastructure that influences the rate and direction of change. They might even become central players, if autonomously evolving machines proliferate. This will further expand the boundaries of what it means to be alive and display new forms of the unbounded creativity of evolution.

Culture is one of the products of human existence, and culture itself evolves. ALife's 13th challenge is to understand the connection between biological and cultural evolution. Examples of cultural evolution include the development of economic markets, the changes in technological infrastructure (see the previous challenge) and growth and revolution in scientific opinion. Some treatments of cultural evolution (e.g. sociobiology and evolutionary psychology) consider how cultural traits evolve owing to their impact on biological fitness. But one can also consider how cultural traits evolve in their own right, as Richard Dawkins did when he coined the word "meme" [11]. This sort of "pure" cultural evolution is driven by mechanisms similar to those behind biological evolution, but there are important differences. In each case traits exhibit variation, heritability and differential fitness; but cultural traits are transmitted not genetically but psychologically, and their fitness depends not on biological survival and reproduction but on retention in and proliferation across minds. One question concerns the similarities and differences in the behavior of biological and cultural evolution. Do both exhibit the same kind of creative explosions, and for similar reasons? Another question concerns how they are interconnected. Confronting these questions invites us to reconceptualize life, culture and technology. ALife gives us an increasingly constructive role in our future. Even if we do not try to shape our future to fit our current preconceptions of what is possible, ALife can help us to understand and appreciate the open-ended creative process in which we are all embedded.

Philosophical Implications of ALife

ALife is not just a scientific and engineering enterprise. It offers a new perspective on the essential nature of many fundamental aspects of reality, such as life, adaptation and creation. Thus it has rich implications for a number of broad philosophical issues. In fact, philosophy and ALife are natural intellectual partners for a variety of reasons. Both seek to understand phenomena at a level of generality that is sufficiently deep to ignore contingencies and reveal essential natures. In addition, by creating wholly new kinds of lifelike phenomena, ALife continually forces us to re-examine what it is to be alive, intelligent, creative, etc. Furthermore, ALife's computational methodology is a direct and natural extension of philosophy's traditional methodology of the a priori thought experiment. In the attempt to capture the simple essence of vital processes, ALife models abstract away as many details of living systems as possible. These models are thought experiments that are explored with the help of a computer. Like the traditional armchair thought experiments, ALife simulations attempt to answer "What if X?" questions, but the premises they pose are complicated enough that their implications can be explored only by computer simulation; armchair analysis is simply inconclusive. Synthesizing thought experiments on a computer brings a new kind of clarity and constructive evidence to philosophy. In this section I illustrate ALife's broad implications for several philosophical topics: emergence, evolution, life and mind.

Emergence

One of life's amazing features is that the whole is more than the sum of its parts. This is called emergence. In general, emergent phenomena share two broad hallmarks: They both depend on and are autonomous from underlying phenomena. Although apparent emergent phenomena are all around us, these two hallmarks of emergence seem inconsistent or philosophically illegitimate. How can something be autonomous from underlying phenomena if it depends upon them? This is the traditional philosophical problem of emergence. A solution to this problem would both negate the appearance of illegitimate metaphysics and show how emergence plays a constructive role in scientific explanations of phenomena involving life and mind.

The aggregate global behavior of the complex systems studied in ALife offers a new way to view emergence. According to this view, a system's macro-level state is considered emergent if it can be derived from the system's boundary conditions and its micro-level dynamical processes but only through the process of iterating and aggregating all its micro-level effects [12]. This new view explains the two hallmarks of emergence. Macro-level phenomena clearly depend upon micro-level phenomena; consider how a bottom-up ALife model works. At the same time, macro-level phenomena are autonomous, because the micro-level interactions in such bottom-up models produce such complex macro-level effects that the only way to recognize or predict them is by observing macro-level behavior. This form of emergence is common in complex systems found in nature, and ALife's models exhibit it as well. This conception attributes the unpredictability and inexplicability of emergent phenomena to the complex consequences of myriad non-linear, context-dependent, local micro-level interactions. In this view, emergent phenomena can have causal powers, but only by aggregating micro-level causal powers. There is nothing inconsistent or metaphysically illegitimate about the idea of underlying processes constituting and generating phenomena by iteration and aggregation. Furthermore, this form of emergence is prominent in scientific accounts of the exact natural phenomena, such as life and mind, that apparently involve emergence.

Thus ALife will play an active role in future philosophical debates about emergence and related notions such as explanation, reduction, complexity and hierarchy. Living systems are one of the primary sources of emergent phenomena, and ALife's bottom-up models generate impressive macro-level phenomena wholly out of micro-level interactions. ALife expands our sense of what is possible and provides a constructive way to explore it.

Evolution

The evolution of life has shown a remarkable growth in complexity. Simple prokaryotic one-celled life led to more complex eukaryotic single-celled life, which then led to multicellular life, then to large-bodied vertebrate creatures with sophisticated sensory processing capacities and ultimately to highly intelligent creatures that use language and develop sophisticated technology. This illustration of evolution's creative potential leads to a deep question about that potential: Does evolution have an inherent tendency to create greater and greater adaptive complexity, or is the complexity of life just a contingent and incidental byproduct of evolution?

Stephen Jay Gould [13] devised a clever way to address this issue: the thought experiment of replaying the tape of life. Imagine that the process of evolution were recorded on a tape. Gould's thought experiment entails rewinding the evolutionary process backward in time, erasing the tape, and then playing it forward again, but allowing events to be shaped by wholly different contingencies. The outcome of the thought experiment is not clear. Gould himself suggests that "any replay of the tape would lead evolution down a pathway radically different from the road actually taken" [14]. He concludes that the contingency of evolution destroys any possibility of a necessary growth in adaptive complexity. Daniel Dennett [15] draws exactly the opposite conclusion. He argues that complex features such as sophisticated sensory processing provide such a distinct adaptive advantage that natural selection would almost inevitably discover it in one form or another. Dennett concludes that replaying life's tape will almost inevitably produce highly intelligent creatures that use language and develop sophisticated technology.

ALife can make a number of contributions to this debate. Experience in ALife has shown time and again that armchair expectations about the outcome of thought experiments such as replaying life's tape are highly fallible. The only sure way to know what to expect is to create the relevant system and observe the results of repeated simulation. In fact, ALife is exactly where the activity of creating and studying such systems occurs. However, we cannot yet conduct the experiment of replaying life's tape, because no one has yet been able to create a system that exhibits continual open-ended evolution. Achieving this goal is a key outstanding problem in ALife, related to its sixth grand challenge. All conjectures about evolution's inherent creativity will remain unsettled until we actually study what happens when the tape of life is replayed.

Life

Philosophers from Aristotle to Kant have addressed the nature of life, but philosophers today ignore the issue, perhaps because it seems too scientific. At the same time, most biologists also ignore the issue, perhaps because it seems too philosophical. The advent of ALife has revitalized the question. This is partly because one can simulate or synthesize living systems only if one has some idea what life is. ALife's self-conscious aim to discern the essence of life encourages liberal experimentation with novel life-like organizations and processes. Thus, ALife fosters a broad perspective on life. In the final analysis, the question of the nature of life will be settled by whatever perspective provides the best explanation of the rich range of natural phenomena that living systems exhibit. Better understanding of how to explain these phenomena will also help resolve a cluster of puzzles about life, such as whether life admits of degrees, how the notion of life applies at different levels in the biological hierarchy and the relationship between the material embodiment of life and the dynamical processes in which those materials participate.

ALife highlights the question of whether artificial constructions, especially purely digital systems existing in computers, could ever literally be alive. This question will be easier to answer once there is agreement about the nature of life; but that agreement should not be expected until we have experienced a much broader range of possibilities. So the debate continues as to whether real—but artificial—life is possible. Some critics complain that it is a simple category mistake to confuse a computer simulation of life with a real instance of it [16]. A flight simulation for an airplane, no matter how detailed and realistic, does not really fly. A simulation of a hurricane does not create real rain driven by real gale-force winds. Similarly, a computer simulation of a living system produces merely a symbolic representation of the living system. The intrinsic ontological status of this symbolic representation is nothing more than certain electronic states inside the computer (e.g. patterns of high and low voltages). This constellation of electronic states is no more alive than is a series of English sentences describing an organism. It seems alive only when it is given an appropriate interpretation. But this charge of category mistake can be blunted. ALife systems are not typically simulations or models of any familiar living system but new digital worlds. Conway's Game of Life, for example, is not a simulation or model of any real biochemical system but a digital universe that exhibits spontaneous macroscopic self-organization. Thus, when the Game of Life is actually running on a computer, the world contains a new physical instance of self-organization. Processes such as self-organization and evolution are realizable in multiple forms and can be embodied in a wide variety of media, including the physical media of suitably programmed computers. So, to the extent that the essential properties of living systems involve processes such as self-organization and evolution, suitably programmed computers will actually be novel realizations of life.

Mind

Life-forms are sensitive to the environment in various ways, and this environmental sensitivity affects their behavior in various ways. Forms of life thus come to have broadly mental capacities. Furthermore, the sophistication of these mental capacities seems to correspond to the complexity of those forms of life. So it is natural to ask whether life and mind have some deep connection. Since all forms of life must cope in one way or another with a complex, dynamic and unpredictable world, perhaps this adaptive flexibility inseparably connects life and mind.

It is well known in the philosophy of mind and artificial intelligence that the emergent dynamic patterns among human mental states are especially difficult to describe and explain. Descriptions of these patterns must be qualified by *ceteris paribus* clauses, as the following example illustrates: If someone wants a goal and believes that performing a certain action is a means to that goal, then *ceteris paribus* he or she will perform that action. For example, if John wants a beer and believes that there is one in the kitchen, then he will go get one—unless, as the *ceteris paribus* clause entails, he does not want to miss any of the conversation, or he does not want to offend his guest by leaving in mid-sentence, or he does not want to drink beer in front of his mother-in-law, or he thinks he had better flee the house because it is on fire, etc. This pattern exhibits a special property that I will call "suppleness." Suppleness involves a distinctive kind of exception to the patterns in our mental lives—specifically, those exceptions that reflect our *ability to act appropriately* in the face of an open-ended range of contextual contingencies. These exceptions to the norm occur when we make *appropriate* adjustment to contingencies. The ability to adjust our behavior appropriately in context is a central component of the capacity for intelligent behavior.

A promising strategy for explaining mental suppleness is to follow the lead of ALife [17], for there is a similar suppleness in vital processes such as metabolism, adaptation and even flocking. For example, a flock does not always maintain its cohesion but only does so for the most part—only *ceteris paribus*—for the cohesion can be broken when the flock flies into an obstacle (such as a tree). In such a context, the best way to "preserve" the flock might be for the flock to divide into subflocks. ALife models of flocking exhibit just this sort of supple flocking behavior. Or consider another example, concerning the process of adaptation itself. Successful adaptation depends on the ability to explore an appropriate number of viable evolutionary alternatives; too many or too few can make adaptation difficult or even impossible. In other words, success requires striking a balance between the competing demands for "creativity" (trying new alternatives) and "memory" (retaining what has proved successful). Furthermore, as the context for evolution changes, the appropriate balance between creativity and memory can shift in a way that resists precise and exceptionless formulation. Nevertheless, ALife models can show a supple flexibility in how they balance creativity and novelty.

Implications for the Arts

ALife's central aim is to develop a coherent theory of life in all its manifestations. It embraces the possibility of discovering life in unfamiliar settings and creating unfamiliar forms of life. In the long run, ALife will contribute to the development of practical adaptive systems in many fields, such as software development and management, design and manufacture of robots including distributed swarms of autonomous agents, automated trading in financial markets, pharmaceutical design, ecological sustainability and extraterrestrial exploration. The economic potential of harnessing natural adaptive systems can be compared with that of cracking the genetic code. Natural adaptive systems vastly exceed the complexity of anything humans have yet created. Understanding and harnessing life's adaptive creativity will spawn a wealth of new technologies and entrepreneurial opportunities.

ALife also has aesthetic applications. There are at least three ways in which artists might find ALife useful. First, ALife technology can be used for a variety of aesthetic purposes. They range from commercial applications in computer animations of life-forms to new kinds of active art, evolving art and interactive art [18,19]. Second, ALife is radically changing human culture and technology, and art often responds to and comments on such changes [20,21]. Third, art has a long tradition of representing and responding to our understanding of nature; therefore, insights about life revealed by ALife can spark the creation of new aesthetic objects [22–24].

Just as ALife can be beneficial for artists, artists can provide complementary benefits to ALife. For one thing, artists using ALife techniques and insights can be counted among the consumers of the product that ALife produces, and one spur to producing better products is consumer demand. Scientists can also gain a broader perspective on their own scientific activity when artists explore the implications of that science and subject it to commentary and social criticism. Finally, human aesthetic activity is itself one distinctive manifestation of the creative potential contained within life. It would behoove those who want to understand nature's creative potential to keep an eye on the latest aesthetic developments.

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