1 Introduction

The stuff of life is not stuff.

Christopher G. Langton

In this first chapter we give a brief overview of the historical origins of the relatively young field in science called Artificial Life. We also try to give the reader an idea of the controversial understandings of Natural Life and the comparatively straightforward definition of Artificial Life. In the third part of this chapter we introduce the main methodology used in Artificial Life "the synthetic approach" which can be briefly explained by the phrase "understanding by building".

1.1 Historical origins

The branch of science named "Artificial Life" (AL) came into being at a workshop in September 1987 at the Los Alamos National Laboratory (New Mexico, USA). The workshop was called the first workshop on Artificial Life and was organized by Christopher G. Langton from the Center of the Santa Fe Institute (SFI; http://www.santafe.edu/). The SFI is a private, independent organization dedicated to multidisciplinary scientific research in the natural, computational and social sciences. The driving force behind its creation in 1984 was the need to understand the complex systems that shape human life and much of our immediate world – evolution, learning processes, the immune system, and the world economy. The main objective of the SFI is to make new tools situated at the frontiers of the computational sciences and the mathematics of nonlinear dynamical systems more readily available for research in the applied physical, biological and social sciences. The purpose of this workshop was to bring together the scientists working in a new and unknown niche. Langton writes:

> *"The workshop itself grew out of my frustration with the fragmented nature of the literature on biological modeling and simulation. For years I had prowled around libraries, shifted through computer-search results, and haunted bookstores, trying to get an overview of a field, which I sensed, existed but which did not seem to have any coherence or unity. Instead, I literally kept stumbling over interesting work almost by accident, often published in obscure journals if published at all." (Langton, 1989, p. xv)*

At this workshop 160 computer scientists, biologists, physicists, anthropologists, and other "-ists" presented mathematical models for the origin of life, self-reproducing automata, computer programs using the mechanisms of Darwinian evolution, simulations of flocking birds and schooling fish, models for the growth and development of artificial plants and much more. During these five days it became apparent that all the participants with their previously isolated research efforts shared a remarkably similar set of problems and visions.

It became increasingly clear, that linear models simply could not describe many natural phenomena. In a linear model, the whole is the sum of its parts, and small changes in model parameters have little effect on the behavior of the model. However, many phenomena such as weather, growth of plants, traffic jams, flocking of birds, stock market crashes, development of multi-cellular organisms, pattern formation in nature (for example on sea shells and butterflies), evolution, intelligence, and so forth resisted any linearization; that is, no satisfying linear model was ever found.

One vision that emerged at the workshop was to look at these problems from a different angle, trying to model them as nonlinear phenomena. Nonlinear models can exhibit a number of features not present in linear ones: for example *chaos* (small changes in parameters or initial conditions can lead to qualitatively different outcomes), and the occurrence of higher level features (emergent phenomena, attractors). "Higher level" means, that these features were not explicitly modeled. However, nonlinear models have the disadvantage that they typically cannot be solved analytically, in contrast to linear models. They are investigated using computer simulations and that is the reason why nonlinear modeling is a relatively new approach. Nonlinear modeling became manageable only when fast computers were available. The fact that those nonlinear models, and in AL nonlinear models are almost always used, cannot be treated analytically has one rather surprising positive side effect: One does not have to be a mathematician to work with AL models. Langton concludes:

> *"I think that many of us went away from that tumultuous interchange of ideas with a very similar vision, strongly based on themes such as bottom-up rather than top-down modeling, local rather than global control, simple rather than complex specifications, emergent rather than pre-specified behavior, population rather than individual simulation, and so forth. Perhaps, however, the most fundamental idea to emerge at the workshop was the following: Artificial systems which exhibit lifelike behaviors are worthy of investigation on their own rights, whether or not we think that the processes that they mimic have played a role in the development or mechanics of life as we know it to be. Such systems can help us expand our understanding of life as it could be. By allowing us to view the life that has evolved here on Earth in the larger context of possible life, we may begin to derive a truly general theoretical biology capable of making universal statements about life wherever it may be found and whatever it may be made of". (Langton, 1989, p. xvi)*

1.2 Natural and artificial life

Natural life

Preliminary remark: This topic is highly controversial and there is a lot of literature on it. Thus, the discussion in this section is very limited and only intended to provide an idea of some of the issues involved. Since the topic of the class is artificial life, we should have some idea of what natural life is. We will see that there are no firm conclusions.

There is no generally accepted definition of life, although everyone has a concept of whether he or she would call a particular thing living or not. Stevan Harnad, a well-known psychologist and philosopher is reluctant to give an answer:

> *"What is it to be 'really alive'? I'm certainly not going to be able to answer this question here, but I can suggest one thing that's not: It's not a matter of satisfying a definition, at least not at this time, for such a definition would have to be preceded by a true theory of life, which we do not yet have." (Harnad, 1995, p. 293)*

Aristotle first made the observation that a living thing can nourish itself and almost everybody would agree that the ability to reproduce is a necessary condition for life. However, there is a problem with this last issue in that it is certainly true for species but perhaps not so true for individual organisms. Some animals are incapable of reproducing, e.g. mules, soldier ants/bees or simply infertile organisms. Does this somehow make their whole life void? Mark Bedau and Norman Packard believe that life is a property that an organism has if it is a member of a system of interacting organisms (Bedau and Packard, 1991).

In *Random House Webster's Dictionary* the following definitions for life are found. Life is

— the general condition that distinguishes organism from inorganic objects and dead organisms, being manifested by growth through metabolism, a means of reproduction, and internal regulation in response to the environment.

— the animate existence or period of animate existence of an individual.

— a corresponding state, existence, or principle of existence conceived of as belonging to the soul.

— the general or universal condition of human existence.

— any specified period of animate existence.

— the period of existence, activity, or effectiveness of something inanimate, as a machine, lease, or play.

— animation; liveliness; spirit (example: the party was full of life).

— the force that makes or keeps something alive; the vivifying or quickening principle.

For the most part of human history, the question “What is life?” was never an issue. Before the science of physics became important, everything was alive: the stars, the rivers, the mountains, the stones, etc. So the question was of no importance. Only when the deterministic mechanics of moving bodies became dominant the question was raised: If all matter follows simple physical laws, and we need no vitalistic explanation of the world's behavior, of movement in the world, then what is the difference between living and non-living things? That there is a difference is obvious, but to pin down what this difference exactly is, seems less obvious. According to Erwin Schrödinger, a famous physicist and one of the key figures in the development of quantum mechanics, it is something that cannot be explained based on the laws of physics alone. Something “extra” is required (Schrödinger, 1944). Again, what this “extra” is remains a conundrum. Still, according to Schrödinger, it can be related to the arrangements of the atoms and the interplay of these arrangements that differ in a fundamental way from those arrangements of atoms studied by physicists and chemists. Thus, it seems that Schrödinger sees the main differences in the organization of the particles rather than their intrinsic properties. This position is also endorsed by the better part of the researchers in artificial life.

Artificial Life

While natural life is very hard to precisely define, Artificial Life (AL) can be characterized in better ways. Here is the definition by Christopher Langton, the founder of the research discipline of Artificial Life:

> *"Artificial Life is the study of man-made systems that exhibit behaviors characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis of living organisms by attempting to synthesize life-like behaviors within computers and other artificial media. By extending the empirical foundation upon which biology is based beyond the carbon-chain life that has evolved on Earth, Artificial Life can contribute to theoretical biology by locating life-as-we-know-it within the larger picture of life-as-it-could-be. (Langton, 1989, p. 1)*

In other words, the goal of AL is not only to provide biological models but also to investigate general principles of life. These principles can be investigated in their own right, without necessarily having to have a direct natural equivalent. This is analogous to the field of artificial intelligence where in addition to building models of naturally intelligent systems, general principles of intelligence are explored. Figure 1 shows the three essential goals of the field of AL. In addition to studying biological issues and abstracting principles of intelligent behavior, based on these principles, practical applications are to be developed.

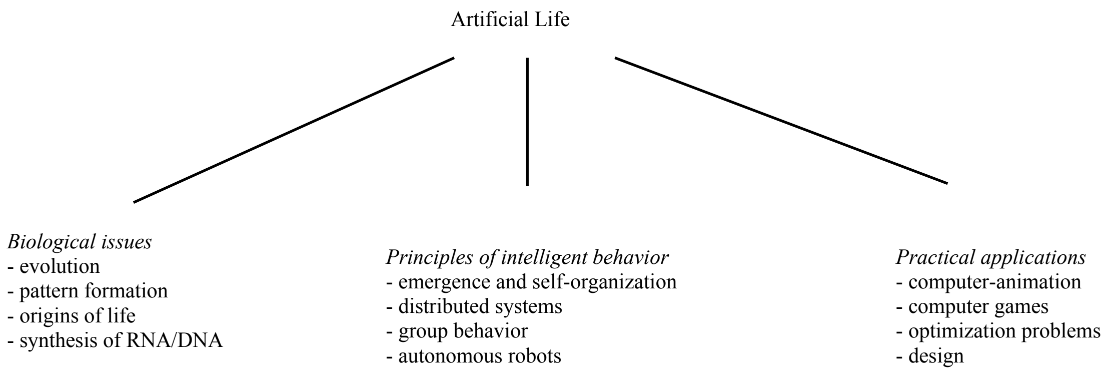

Figure 1: *The goals of Artificial Life.*

1.3 Methodological issues and basic definitions

The Synthetic Approach

The field of AL is by definition synthetic. It works on the basis of "understanding by building": In order to understand a phenomenon, say the food distribution in an ant society, we build aspects of the ant society's behavior. Typically, computer simulations are employed, but sometimes researchers use robots.

Biology is the scientific study of life based on carbon-chain chemistry. AL tries to transcend this limitation to Earth bound life based on the assumption, that life is a property of the *organization* of matter, rather than a property of the matter itself. Furthermore, biology traditionally starts at the top, for example at the organism level, seeking explanations in terms of lower level entities in an analytic way, whereas AL starts at the bottom, for example at the molecular level, working its way up the hierarchy by synthesizing complex systems from many simple interacting entities. Biology works in an analytic way: Scientists are aiming to understand living beings by teasing them apart, looking for constituents, the constituents of the constituents, and so on down to cells, molecules, atoms, and elementary particles. Only recently scientists started to put these parts together again, to look how simple components can be combined to build larger systems.

Imagine, for example, that we wanted to build a model an ant colony. We would start specifying simple behavioral repertoires for the ants, and then, typically in a computer simulation, put many of these simple ants or "vants" (virtual ants) in a simulated environment. Then the vants would behave according to their (simple) rules and according to their environment. If we captured the essential spirit of ant behavior in the rules for our vants, the vants in the simulation in the simulated ant colony should behave as real ants in a real ant colony.

The analytic approach to science has been extremely successful in many disciplines like physics or chemistry. Most scientists believe that the universe is governed by laws of nature that apply for stars and galaxies as well as for elementary particles and atoms and living organisms. The question is whether — once we know the fundamental laws — we can explain everything in these terms: Can everything, including biological systems, be reduced to these principles? There is general agreement that this is not the case and that additional — organizational — principles are required (see also Schrödinger's comments above). The synthetic methodology is particularly suited to investigate such principles.

Levels of Organization

Life, as we know it on Earth, is organized into at least four levels of structure: the *molecular* level, the *cellular* level, the *organism* level, and the *population-ecosystem* level. Of course, and fortunately, AL studies do not have to start at the lowest level. At each level behavior of the entities and their interaction can be specified and the behavior of interest then is allowed to emerge.

AL researchers have developed a variety of models at each of these levels of organization, from the molecular to the population level, sometimes even covering two or three levels in a single model. The interesting point is that at each level, entirely new properties appear. Also, at each stage new laws, concepts and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology and biology is not applied chemistry (Anderson, cited in Waldrop, 1992).

Time perspectives on explanation

Explanations of behavior can be given at different temporal perspectives, (1) short-term, (2) ontogenetic and learning, and (3) phylogenetic. The short-term perspective explains why a particular behavior is displayed by an agent based on its current internal and sensory-motor state (in this context the term agent, which can be understood as human, animal or artificial creature, means robot). It is concerned with the immediate cause of behavior. The second perspective, ontogenetic and learning, not only resorts to current internal state, but to some events in the more distant past in order to explain current behavior. The third, the phylogenetic one, asks how particular behaviors evolved during the history of the species. Often, an additional, non-temporal, perspective is added. One can ask what a particular behavior is for, i.e. how it contributes to the agent's overall fitness. These perspectives are closely related to what is called "the four whys" in biology (Huxley, 1942; Tinbergen, 1963). For a full explanation of a particular behavior all of these levels have to be considered.

The Frame-of-Reference Problem

Whenever we want to explain behavior we have to be aware of the frame-of-reference problem (Clancey, 1991). The frame-of-reference problem conceptualizes the relationship between designer, observer, agent to be modeled (or artifact to be built) and environment. There are three distinct issues (Pfeifer and Scheier, 1999), perspective, behavior vs. mechanism, and complexity.

Perspective issue

We have to distinguish between the perspective of an observer looking at an agent and the perspective of the agent itself. In particular, descriptions of behavior from an observer's perspective must not be taken as the internal mechanisms underlying the described behavior of the agent.

Behavior-versus-mechanism issue

The observed behavior of an agent is always the result of a system-environment interaction. It cannot be explained on the basis of internal mechanisms only. Doing so would constitute a category error.

Complexity issue

Seemingly complex behavior does not necessarily require complex internal mechanisms. Seemingly simple behavior is not necessarily the results of simple internal mechanisms.

Synthetic tools

The tools of the synthetic methodology are computer simulations and robots. The field of behavior-based artificial intelligence or embodied cognitive science uses robots as modeling tools. However, in the field of artificial life, simulation is the tool of choice. Thus, for the present class we investigate mostly computer simulation. It is an open debate on where the description of behavior ends and where the description of the mechanism begins. Using an analytic approach we always end up with a description. If we employ the synthetic approach we not only have a description but a mechanism that actually underlies the observed behavior.

Self-Organization

In AL the process of self-organization means the spontaneous formation of complex patterns or complex behavior emerging from the interaction of simple lower-level elements/organisms. It is an important concept and needs to be observed closely. The process of self-organization can either lead to the formation of reversible patterns (self-organization without structural changes) or to structural and therefore irreversible changes in the self-organizing system.

Emergence

The term emergence as used in AL means a property of a system as a whole not contained in any of its parts, i.e. the whole of a system being greater than the sum of its parts. Such emergent behavior results from the interaction of the elements of such system, which act following local, low-level rules. The emergent behavior of the system is often unexpected (but not inexplicable!) and cannot be deduced directly from the behavior of the lower-level elements.

Artificial Life and Artificial Intelligence

AL is concerned with the generation of *life-like* behavior. The related field of Artificial Intelligence (AI) is concerned with generating *intelligent* behavior. In fact, AL and AI, at least new approaches in Artificial Intelligence have many topics in common. Mainly because AL and the new approaches in AI both work bottom-up, combining many simple elements into more complicated ones, looking for emergence and principles of self-organization, using the synthetic methodology.

> In summary: AL is based on the ideas of emergence and self-organization in distributed systems with many elements that interact with each other by means of local rules.

1.4 Bibliography

Adami, C. (1998). *Artificial Life: An Introduction*. Springer-Verlag: New York, Berlin, Heidelberg.

Ball, P. (2004). *Critical mass*. Random House Group Limited: London, Sydney.

Bedau, M. A. and Packard, N. H. (1991). Measurement of evolutionary activity, teleology and life. In C. G. Langton, C. Taylor, J. D. (eds.) *Proc. of Artificial Life II*, Addison-Wesley.

Brooks, R.A. (2002). The relationship between matter and life. *Nature*, 409, 409-411.

Clancey, W. J. (1991). The frame of reference problem in the design of intelligent machines. In K. van Lehn (ed.). *Architectures for Intelligence*. Hillsdale, N.J.: Erlbaum.

Harnad, S. (1995). Levels of Functional Equivalence in Reverse Bioengineering. In C.G. Langton (ed.): *Artificial Life, An Overview*, 293-301. MIT Press: Cambridge, MA.

Huxley, J. S. (1942). *Evolution the modern synthesis*. Allen and Unwin: London.

Kaneko, K. (2006). *Life: An Introduction to Complex Systems Biology*. Springer-Verlag: Berlin, Heidelberg.

Kaufmann, S. (1993). *The Origins of Order*. Oxford University Press: New York, Oxford.

Langton, C. G. (1989). Artificial Life. *Proc.of 1st Int. Workshop on the Synthesis and Simulation of Living Systems*. Addison-Wesley.

Levy, S. (1993). *Artificial Life*. Vintage: Reprint edition.

Margulis, L. and Sagan, D. (1995). *What is Life?* University of California Press: Berkeley, CA.

Pfeifer, R. and Scheier, C. (1999) *Understanding Intelligence*. MIT Press: Cambridge, MA.

Pfeifer, R. and Bongard, J.C. (2007). *How the Body Shapes the Way we Think*. MIT Press: Cambridge, MA.

Schrödinger, E. (1944). *What is Life?* Cambridge University Press.

Tinbergen, N. (1963). On aims and methods of ethology. *Z. Tierpsychologie*, 20, 410-433.

Waldrop, M. M. (1992). *Complexity: The Emerging Science at the Edge of Order and Chaos*. Simon & Schuster.