Artificial Life: Prospects of a Synthetic Biology

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Abstract. This paper is a short critical analysis of the theoretical ambitions of Artificial Life. The discipline is described and compared with other "enlargements" of Biology. After explaining some methodological and conceptual aspects, the main issue is considered of whether this biology of the possible life may explain or reproduce, or to what extent, the biology of real life. The conclusion, even if positive with respect its potential contribution to a better knowledge of terrestrial life, reflects some degree of skepticism regarding the most ambitious artificial aims.

Keywords: Artificial Life, real/virtual, methodology, materiality, organization

1 Introduction

The purpose of this paper is to offer a short critical assessment of the theoretical aspirations of a rather recent field of study (slightly more than 20 years): Artificial Life. We may introduce the discipline in a twofold way, first by comparison with other "extensions" of Biology and then by turning to its most characteristic conceptual points. Those enlargements of biology are justified by the necessity to face the issue of the living from a point of view able to transcend as object of study the unique terrestrial case. As means to do that we already have the following approaches: exobiology, biotechnological manipulation and biochemical synthesis (*in vitro*). Their relation to biology, in particular, the last two could certainly be object of detailed consideration. As for the basic ideas of the new discipline, these revolve around the possibility of building a new form of Theoretical Biology willing to deal with life as a more general phenomenon. Once some methodological and conceptual aspects are explained, the main issue is tackled as to what extent this biology of any possible life may reflect, illuminate or reproduce the biology of the unique real life.

1.1 Realms of *enlargement* of biology

Biology is nowadays being expanded inasmuch as a way of understanding life in the Universe, at least, in three directions: besides doing it from within the very Biology, it is exploring the issue from the standpoint of Exobiology and from the point of view of Artificial Life. From within, this expansion is taking place in the research area

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regarding the origin of life with several techniques of biochemical synthesis (*in vitro*), which already enjoy a tradition of decades, and in the sphere of (new) biotechnology, more recent and experiencing a strong boost in progress. Exobiology offers a designation and a disciplinary contemporary frame to the equally traditional search for life in other "extraterrestrial" places. Artificial Life, finally, aims to explore, basically, new stuff and will center the content of this paper, therefore I will not expand on it right now.

The three expansions share a core and a key concern implying a theoretical amplification, which takes the form of a conceptual advance with respect the way to understand life at large, to define it and set its bounds beyond the most close evidence. Notwithstanding, they diverge radically regarding the way they tackle methodologically and practically their study. Whereas exobiology might be mainly characterized as an activity of search and *identification* of candidates using space probes, biochemical synthesis and the diverse biotechnologies might be understood as ways of *re- creation* of living systems departing from those already existing, and Artificial Life, either in its computational or robotic versions, seeks the *creation* of new forms of life (or new forms similar to the living). Of course, these three diverse activities (identification, re- creation, creation) interweave and, besides concurring in their theoretical challenge, may share a good deal of techniques, tools and methodological aspects.

If we focus on the practices that involve creation or re –creation, we may distinguish, first and partially following Emmeche [1], between trivial and non-trivial views of Artificial Life and classify within each of those camps diverse approximations and avenues of research. But, let's before establish the main general foundations of the field.

2 Artificial Life: the "Idea"

The definition offered in the opening article of the volume of *proceedings* of the first Conference on Artificial Life is clear and ambitiously programmatic, its is more the definition of a new field of research in the future than the description of an established scientific object:

> "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, A.L. can contribute to theoretical biology by locating *life-as-we-know-it* within the larger picture of *life-as-it-could-be*." [2, p. 1].

This definition is reached, in certain sense, through the organization of a scientific gathering that sets the starting point of the new discipline. As Langton tells in the preface to the aforesaid volume, the first "Workshop" on Artificial Life took place in September 1987 at the Los Alamos National Laboratory (LANL). It was sponsored by the Center for Nonlinear Studies, the Santa Fe institute and Apple Computer Inc. It was attended by 160 computer scientists, biologists, physicists, anthropologists and other various kinds of researchers sharing "a common interest in the simulation and synthesis of living systems" [3, p. xv]. At the conference a great variety of models of living systems were presented. Langton, the main organizer and who may rightly be consider the *father* of this undertaking tell that the very workshop is the result of his "frustration with the fragmented nature of the literature on biological modeling and simulation". He felt that field existed but could not find any coherent vision but just dispersed and unknown proposals. Therefore the main object of the workshop was to put all that together in as a general and open way as possible.

In any case, his judgment is that, by the end, it grew an "emerging consensus among the participants of the "essence" of Artificial Life", which, quite significantly, is rather methodological since revolve around themes such as [3, p. xvi]:

* *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, etc.

From all that Langton concludes that the main idea that emerged from 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 placed 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 Herat 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." [3, p. xvi]

Summing up, he ends up his preface asserting the distilled essence of AL in these terms:

> "Artificial Life involves the *realization* of lifelike behaviors on the part of man-made systems consisting of *populations* of semi-autonomous entities whose *local interactions* with one another are governed by a set of *simple rules*. Such systems contain *no* rules for the behavior of the population at the global level, and the often complex, high-level dynamics and structures observed are *emergent* properties, which develop over time from out of all the local interactions among low-level primitives by a process highly reminiscent of *embryological development*, in which *local hierarchies* of higher order structures develop and *compete* with one another for support among the low-level entities. These emergent structures play a vital role in organizing the behavior of the lowest-level entities by establishing the context within which those entities invoke their local rules and, as a consequence, these structures may *evolve* in time." [3, p. xxii]

Therefore, we may conclude that Artificial Life aims at a Biology of *life-as-it-could-be* from a formalist starting point with a clear methodological characterization when determining its distinctive traits as a discipline.

As Bonabeau & Theraulaz [4] have quite rightly argued (despite I have criticized another claim of that paper as their depiction of AL as fully reductionist field [5]), AL as a scientific discipline is best characterized methodologically and not as much regarding its object of study, which the authors assume it shares with Biology.

3 History and Delimitation of the Area of Research

We may distinguish between a history which we may call "internal" and a wider and more inclusive one, which would be the "external" within which the former is framed.

3.1 "Internal" history

To this respect we should mention some milestones that mark the birth and consolidation of Artificial Life as a field of research: the conferences that, quickly, with annual combined periodicity will indicate its development.

First, the *International Conference on the Simulation and Synthesis of Living Systems* (*Artificial Life*) that gives continuity to the inaugural Workshop in 1987 and that, since its second edition in 1990, is held biannually having reached in 2008 its eleventh one. It is known by its short name of *Artificial Life* plus the number of the corresponding edition, and their results are published simultaneously with the conferences by MIT Press, with the exception of the first three whose Proceedings were published by Addison-Wesley after the conferences were held (*vid.* Appendix).

Then, the *European Conference on Artificial Life* (*ECAL*) that already in 1991 held its foundational meeting in Paris and continues to do so, also biannually in alternation with the former one and reached its 9th edition in Lisbon in 2007. Its name is reduced to ECAL plus the last two digits of the corresponding years and their proceedings are published by Springer, with the exception of the first one's that were published by MIT Press and the second one that did not produced a book by a publishing house.

There are also other related but more specific academic events that draw as well the attention of the researchers on Artificial Life as, to mention one of the most representative, the *International Conference on Simulation Adaptive Behavior* (*SAB*) that is held biannually since 1990 and publishes its proceedings with MIT Press.

Leaving aside those highlights, it is also indicative of the internal history of Artificial Life, the relatively early advent of specialized academic journals that issues the relevant work in the field. To this respect, we should mention the journal *Artificial Life* that, published by MIT Press, was started in 1994 under the editorial direction of Chris Langton (whom was substituted a few years later by its current editor Mark Bedau). This journal was preceded by other closely related but more specific ones, among which we may mention *Adaptive Behavior*, started in 1992, or *Evolutionary Computation*, started in 1993, both likewise published by MIT Press. At the other side of he spectrum, as an example of related but more general journals, we may mention *Complexity* that was started in 1996, published by Wiley, and that gives a voice to most of the new approaches arising, in the same way as the very Artificial Life, from the Santa Fe Institute in New Mexico around the clearly interdisciplinary issues of complex systems allegedly common to very diverse clusters of phenomena from physics to economics, through biology or linguistics.

We might also pay attention to the books that dealt from the very beginning with the subject (be it as critical essays, informative popular science monographs or, lately, textbooks). Curiously, two of the first monographs are a book in Danish by Claus Emmeche [1] and another one in Spanish by Julio Fernández and Alvaro Moreno [6], both offering and in depth review of the discipline and an assessment of its potentials and difficulties. Other books in those initial years are, for instance, [7] as popular science introduction of the field to the general public, [8] as an early anthology of philosophical contributions and [9] which put together the review articles published in the opening three issues of the journal he edited. This list may be appended with those books that attempt to introduce, in general, the new scope of research labeled as *sciences of complexity* and that cannot but devote a good amount of their content to the description of what amounts to Artificial Life; among them we may select the first ones, [10] and [11] as an indication of a extensive subsequent production.

A final significant element in this history (which might also be reconstructed as the history, within the parameters of the sociology of science, of the progressive strengthening and institutionalization of a scientific discipline) is the founding in May 2001 of the *International Society of Artificial Life* (ISAL), the scientific society that gathers the researchers of the field and adopts *Artificial Life* as its official journal and the *International Conference* as its official meeting.

3.2 "External" history

The account of the previous point is, to say it so, the "official history" of Artificial Life as such, with this label. That is why I say is the "internal" one. However, how not, there is an "external" history with a lot of years behind and that may carried back until ages quite remote and that, it must be said, Langton acknowledges and relates with detail in his introductory article [2]. This is not a completely trivial account since, despite the fact that basically the achievements evoked are more odd toys than useful machines, they do reflect with remarkable accuracy the degree of progress in the techniques of each epoch and, above all, the conceptual sediment on which they are built. A good indication and measure of this progress is given by the early history of clocks. Of course there are more sophisticated "machines" than clocks, even anteceding them, but clocks possess a very peculiar feature: they are machines that claim to be, in certain sense, autonomous inasmuch as they generate their own behavior. Later on, clocks with figures connect with another tradition, that of automata, dating also far back but reaching its glorious moment with the mechanical automata of the 18th century.

This history changes radically in the 20th century with the conception of the algorithm as the formal equivalent of the machine. Here really begins *another* history. In this sense, let's leave established, in order no one to get deceived or think that anyone is pretending to reinvent the wheel, that Artificial Life is indebted to a whole path beginning with the work on logic and formalization by Kleene, Gödel, Church, Turing, Post, etc., continued by the efforts of von Neumann and his theory of automata or Wiener and cybernetics, passing by the clear antecedents of the connectionist approach as McCulloch and Pitts or Rosenblatt, up to, even, the very official way to Artificial Intelligence.

This brief allusion to a recent history that cannot be pursued here, is aimed just to put the new discipline straight, to specify the frame within which Artificial Life is placed. Nor its guiding idea –simulate life– neither properly its tools are entirely new. What is indeed new to certain extent is the way to blend them and the dimension it is conferred: to transcend real life and point towards the abstracted form of the phenomenon of life as a means to synthesize it[1].

4 Versions of Artificial Life

Once explained the foundational parameters of the discipline, we may proceed to explore the diverse options open to it in the task of widening biology, departing from the modalities of creation or re- creation mentioned in the Introduction

4.1 Trivial versions of Artificial Life

4.1.1 Models of living systems (conceptual, mathematical, physical or computational). When it comes to consider these models, the relevant issues to face are, in any case, those having to do with the reliability and efficacy of the representation and with the difference between the model and the real object. That is, those general epistemological questions regarding the nature and quality of models and the global and specific assumptions along which they are built [i.e., 12, 13, 14].

4.1.2 Living organisms artificially modified. The triviality of these cases demands two specific qualifications and a general one. The latter, though evident, must be stated in the sense that we do not intend, on no account, to describe as trivial in absolute terms the outcomes of the diverse areas of biotechnology that could be contained in this section. The first specific qualification, hence, attempts to determine the relative sense of this depiction: they are trivial in what respects the questions and problems posed by Artificial Life as a discipline strictly understood. The second qualification, notwithstanding, is more a warning (or caveat) in the sense that, maybe, this very consideration of triviality, nowadays justifiable, may change due both to the development of biotechnology or, especially, to the evolution of AL as a discipline in a direction that might entail an expansion of its postulates regarding materiality.

4.2 Non-trivial versions of Artificial Life

4.2.1 Artificial Life as computational life (virtual systems). We have to include here those computational systems with emergent *lifelike* phenomena at a degree of complexity that for the observer come close to that of natural organisms. They are virtual systems (computer programs) that because they implement or instantiate a certain property unequivocally associated with life (reproduction, selection, evolution, …), would be considered by some instances of life in the computer and not only

[1] We also leave aside here the literary and artistic expression or even the mythological or religious one of this dream (or nightmare), so characteristically human, of creating life (from the Golem to Frankestein), though, as it might be guessed, it has been present both in the preliminary evocations of the founders and in many subsequent assessments as well.

computational simulations of attributes of natural life. This gives place, in unavoidable parallelism to the divisions within Artificial Intelligence, to what has been called the strong version of Artificial Life [15, 16].

There are works at many levels, from minimal *digital organisms* as the RNA-like sequences of Tierra, Tom Ray's simulation, to all kinds of populations of virtual organisms, isolated or within rich environments as computational ecosystems. We may even consider chemical levels as the algorithmic chemistry of Fontana.

4.2.2 Artificial Life as *animats* (and robots). Facing up many reactions that question the relevance of Artificial Life inasmuch as it remains confined within the computer, it has come out with strength and it is experiencing a big development what might be considered a new generation of robotics or, perhaps, with greater precision, a new and specific way to confront robotics that is the explicit outcome of the influence of Artificial Life and meets its assumptions, methodologies and goals.

a) Weak Artificial Life robotics:

Although they are not as representative of the efforts in Artificial Life, we may also include here the robots built with technical (and leisure) purposes and that seem to act lifelike. The more interesting ones among those that are made from within an Artificial Life spirit are, of course, those intending to explore and resolve, even in an apparently conventional way, tasks and capacities that have traditionally resisted (at their most obstinate) their artificial reproduction (or that have been left aside due to a combination of high difficulty and scarce immediate technical revenue). An example is locomotion with limbs; let it be precision (equilibrium in an upright posture), rapidity (run) or ability to overcome obstacles (climb stairs). In this sense, there are impressive (literally) some prototypes that have been built in the last decade and which we have been able to watch even at mass media. Nevertheless, these accomplishments and projects, extraordinary as they are from a technological point of view and as challenge, are in general wholly dependent on a generous interpretation by the observer trapped inside the mechanical simulation of capacities that look inextricably linked to life, as movement, but that lack the minimum degree of autonomy (beyond the assigned quota of energy) characterizing properly that movement when indicative of life.

b) "Evolutionary robotics" (autonomous):

That deficiency is precisely what those involved in evolutionary robotics or, directly, autonomous robotics aim to face. Now, certainly, we are dealing with artifacts with a "life of their own", in colloquial terms, that go beyond the arduous implementation of wheel-less motion. Even more, generally, in what respects technological complexity and spectacular nature of the emulated behaviors, we find ourselves quite far from what the techniques of the previous point achieve: very small devices, without any superficial resemblance to humans or other animals, incorporating wheels (or caterpillar) and resorting to the most simple and compact designs in order to yield as less difficulties as possible to the designer. However, unlike the preceding robots, these gadgets have no pre-specified program for their behavior, do not rely on an unconditional energy source and do not have predetermined tasks or objectives. These devices, in order to endure, have first to secure themselves the exploitation of matter and energy resources from those available in their environment. Besides, they have to be able to move through an space within which they locate themselves overcoming obstacles, following unsettled paths and finding their way around in order to find (again and again) those supplies. Even, in some cases, researchers are developing small systems that seem to exhibit certain rudimentary capacity to reconstruct and/or reproduce themselves with the help of components previously scattered in the surroundings. Certainly, for now, the environments we cite are relatively controlled (laboratory settings) and the energy sources are suppliers of electricity or luminosity located in the room, the same way as components are provided. Nevertheless, some prototypes obeying to those principles of Artificial Life, along with others from other fields, have been fabricated for the exploration of unknown (Moon, Mars, …) or unpredictable (fire, explosion, war situation, …) environments and are beginning to be used experimentally

4.3 Chemical Artificial Life (*in vitro*)

To finish, although commonly Artificial Life is associated (to certain extent rightly) to computational or mechanical systems, we should also take into account the attempts to create biochemical material systems with *lifelike* features. These are *in vitro* models of pre-biotic processes, primitive metabolic systems, proto-membrane formation patterns, hyper cycles, replicating micelles, etc. While in the initial years of the discipline these approaches were not frequent at all, eventually they have become more common and abundant, and nowadays they enjoy their own place within what is considered Artificial Life, as for specialized conferences and journals. In any case, the goal would be to turn *in vitro* experiments into life *ex novo*, beyond using them as an experimental methodology to investigate life currently in existence.

5 Challenges and Problems

5.1 Problems of Integration

Obviously, this multiplicity of approaches and the disparity of their ambitions (and promises) provoke already a first and serious problem for the integration of all those individual avenues of research within a coherent frame of research. All these lines of investigation put forward fascinating and deep methodological issues. Questions we may gather around the issue of the interpretation of those works. A whole range of questions regarding in what sense we may talk of life, in what sense does form abstraction take in the entire dimension of living phenomena, which are the virtues and limitations of the approach, etc.

5.2 Nature of results

Particularly, in order to clarify a quite general methodological issue which has to do with the ontological one of the dichotomy between real and virtual, we may point to the issue regarding the status or nature of the works and results offered. We may classify them, following Fernández & Moreno [6, pp. 30-31] who elaborate some ideas of Pattee [17], into models, simulations and realizations, in the following sense:

Model: a conceptual structure that, keeping some kind of relation with a material system, does not explicitly include any structural or temporal development of the represented system.

Simulation: is characterized by the idea of formal duplication (of the functioning) of a certain object system, together with the fact that this process is realized in a formal universe, regardless of the real space and time where the laws of physics act. Besides, the simulation makes explicit a temporal development (as a function of computation steps) of the emulated system. The digital computer is the paradigmatic expression of any simulation process. This is achieved through a process of detailed enough discretization to reproduce, at the desired level of accuracy in each case, the dynamical-continuous processes of the object system.

Realization: a physical duplication of the defining elements of the object system, i.e., of its distinctive organization and structure. By physical reproduction it is meant a three-dimensional construction whose operations or functioning are developed in real time and, therefore, in the physical universe, what entails that the behavior of the system does not only obey the laws of physics but it derived from them once the appropriate boundary conditions are set.

Though, obviously, a scientific discipline might aspire to give answers at all three levels, the difficulty ensue when the allegations of having accomplished the goal, artificial life, are made in any of them simultaneously and unconditionally for any particular proposal. I will mention now briefly a few more philosophical or conceptual issues, which I have discussed elsewhere, that would take us too far if considered here but that may help to indicate the broad reach of the theses defended by Artificial Life.

5.3 Synthetic methodology

I have insisted on the methodological depiction of the field, but I find it is not easy at all to determine, beyond the purely technological or engineering sphere, which are the attributes of a synthetic (not analytical) methodology able to contribute not only to the (re-)creation but also to the scientific *explanation* of the phenomenon of life, for instance at the axis reduction/emergence [*vid.* 5].

5.4 Materiality

A key aspect of the proposals of Artificial life, at least in its strong version, is that the goal is to reproduce artificially the *form* of life and not its specific *matter*, accepting therefore that this set of formal properties may be instantiated, at least in principle, in any material medium or even in a non-material computational universe. Whereas it is definitely interesting to make the effort to abstract, as far as possible, those traits of life we might consider universal and, therefore, transcending any particular earthly expression based on carbon with features we might reasonably considered contingent;

it is not sufficiently established that we may disregard the material constraints without loosing essential aspects of life [*vid*. 17, 18, 19].

5.5 Definition of life

We find ourselves also in a serious problem regarding the identification of the object of study since there is no univocal and agreed upon definition of life. We do indeed have several lists of characteristics that partially overlap but do not manage to be free of counterexamples [see, for instance, 20, 21]. We also have some recent and very interesting proposals as well as emphatic denial of their importance. In any case, this is a challenge shared with biology and that, we could say, would constitute the core of any effort to build a Theoretical Biology up to the demands of, for instance, Waddington's attempt [22]. Unluckily, the situation in Artificial Life is more delicate since it does not even count on the intuitive familiarity provided by a long enough history of biological sciences and their naturalist predecessors [*vid.* 23].

6 Conclusion

After this summary evaluation of the field we may attempt to judge the question of to what extent may this biology of the possible life (life-as-it-could-be) reflect, illuminate or reproduce the biology of real life (life-as-it-is).

A first and early appraisal, appended to the book of proceedings of the second conference, offered an optimistic forecast, though quite wise in the temporal estimate, according to which:

> "(w)ithin fifty to a hundred years, a new class of organisms is likely to emerge. These organisms will be artificial in the sense that they will originally be designed by humans. However, they will reproduce, and will evolve into something other than their initial form; they will be "alive" under any reasonable definition of the word." [21, p. 815][2].

The judgment exposed by the organizers of the tenth edition of the conference, 20 years after the inception, is slightly more moderate focusing on the scientific contribution that the new discipline has implied, particularly in the methodological realm (advance in the understanding of the relation between information/distributed dynamics, network studies, systemic features, etc.):

> "In the two decades since its inception, this methodology and its powerful set of tools have successfully leaked into other domains, including biology. (…) While the methods and tools of artificial life have been adopted in more traditional domains, artificial life remains an independent and well-grounded research endeavour." [24, p. xi].

[2] The authors ponder also about the responsibility that such a perspective demands and conclude: "With the advent of artificial life, *we may be the first species to create its own successors*. What will these successors be like? If we fail in our task as creators, they may indeed be cold and malevolent. However, if we succeed, they may be glorious, enlightened creatures that far surpass us in their intelligence and wisdom." [21, p. 836]

We might highlight that, in this case, the justification focuses not as much on the final goal ("a new class of organisms") as on the methods and tools that the discipline has been able to develop and even export, though they insist that these appropriation by other disciplines has not diminished the independence or grounding of Artificial Life as a sound discipline.

There have, of course, been criticisms of all kinds and many of them have come precisely from biology, that mistrusts an explicitly non-natural approach (for instance Maynard Smith, branded it as "poetic science"), and also from philosophical perspectives questioning its c independence as field of study or its capacity to deliver new knowledge as, for instance, Godfrey-Smith has recently done in a text book of philosophy of science:

> "All of this was impressive work, and it pointed the way forward to a consolidation of what these imaginative individuals had done. But the consolidation never happened. (…). The field never made a transition into anything resembling normal science. And it has now ground to a halt." (25, p. 85)

In my case the assessment of the field of Artificial Life is more positive with respect to its potential contribution to a better understanding of terrestrial life, even though tinged with certain skepticism regarding its more ambitious artificial (virtual, digital) aspirations of creating *life*. This skepticism is precisely grounded in the importance of those aspects of (terrestrial) life that more unlikely are able to be conveyed, in a non-trivial way, to a virtual (an even artificial in general) realm; in particular those aspects relative to the three following attributes of life: materiality (chemistry, dynamics, matter dependence, etc.), organization (complexity, levels, immanent functionality, etc.), and historicity (particularities at the origin of life, evolution, etc.). But this is already a much wider discussion.

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References

1. Emmeche, C.: Det Levende Spil. Munksgaard, Copenhagen (1991) [English version: The Garden in the Machine. Princeton Univ. Press, Princeton, transl. S. Sampson (1994)]
2. Langton, C.G.: Artificial Life. In: Langton, C.G (ed.) Artificial Life, pp. 1-47 (1989)
3. Langton, C.G.: Preface. In: Langton, C.G (ed.) Artificial Life, Addison-Wesley, Reading pp. xv-xxvi (1989)
4. Bonabeau, E., Theraulaz, T.: Why do we need Artificial Life? Art. Life 1, 303-325 (1994)
5. Umerez, J.: Is there any Reason to be More Reductionist in AL than in Biology? Theoria et Historia Scientiarum (Forthcoming)

6. Fernández, J., Moreno, A.: Vida Artificial. Eudema, Madrid (1992) [French version: La vie artificielle. Ed. du Seuil, Paris, transl. M. de Fabrique Saint-Tours & P. Rey (1997)]
7. Levy, S.: Artificial Life. Pantheon, NewYork (1992)
8. Boden, M. (ed.): The Philosophy of Artificial Life. Oxford University Press, Oxford (1996)
9. Langton, C.G. (ed.): Artificial Life. An overview. MIT Pr., Cambridge MA (1995)
10. Lewin, R.: Complexity: Life at the Edge of Chaos. Macmillan, New York (1992)
11. Waldrop, M.M.: Complexity: The Emerging Science at the Edge of Order and Chaos. Simon & Schuster, New York (1992)
12. Hesse, M.: Models and Analogies in Science. Univ. Notre Dame Pr., Notre Dame (1966)
13. Suppe, F. (ed.): The Structure of Scientific Theories. Univ. Illinois Pr., Chicago (1977)
14. Giere, R.: Explaining Science: A Cognitive Approach. Univ. Chicago Pr., Chicago (1988)
15. Sober, E.: Learning from Functionalism-Prospects for Strong Artificial Life. In: Langton, C.G. et al (eds.) Artificial Life II, pp. 749-765 (1992)
16. Keeley, B.C.: Against the Global Replacement: On the Application of the Philosophy of Artificial Intelligence to Artificial Life. In: Langton, C.G. (ed.) Artificial Life III, Addison-Wesley, Reading pp. 569-587 (1994)
17. Pattee, H.H.: Simulations, Realizations, and Theories of Life. In: Langton, C.G (ed.) Artificial Life, pp. 63-78 (1989)
18. Moreno, A. Etxeberria, A., Umerez, J.: Universality Without Matter? In: Brooks, R., Maes, P. (eds.) Artificial Life IV, MIT Pr., Cambridge MA, pp. 406-410 (1994)
19. Umerez, J.: The Evolution of the Symbolic Domain in Living Systems and Artificial Life. In: van der Vijver, G., Salthe, S., Delpos, M. (eds.) Evolutionary Systems. Biological and Epistemological Perspectives on Selection and Self-Organization, Kluwer, Dordrecht pp. 377-396 (1998)
20. Mayr, E.: The Growth of Biological Thought. Harvard Univ. Pr., Cambridge MA (1982)
21. Farmer, J.D., Belin, A. d'A.: Artificial Life: The Coming Evolution. In: Langton, C.G. Taylor, C., Farmer, J.D., Rasmussen, S. (eds.) Artificial Life II, Addison-Wesley, Reading pp. 815-840 (1992)
22. Waddington, C.H.: Towards a Theoretical Biology (4 vols.). Edinburgh Univ. Pr. and Aldine, Edinburgh and Chicago (1968-1972)
23. Umerez, J.: Semantic Closure: A Guiding Notion to Ground Artificial Life. In: Morán, F., Moreno, A., Merelo, JJ., Chacón, P. (eds.) Advances in Artificial Life, Springer, Berlin, pp. 77-94 (1995)
24. Rocha, L.M., Yaeger, L.S., Bedau, M.A., Floreano, D., Goldstone, R.L., Vespignani, A. (eds.): Artificial Life X. MIT Pr., Cambridge MA (2006)
25. Godfrey-Smith, P.: Theory and Reality. Univ. Chicago Pr., Chicago (2003)

Appendix

A) *International Conference on the Simulation and Synthesis of Living Systems* (*Artificial Life*)

Artificial Life I, Los Alamos, NM, Septiembre, 1987. Ed. Langton 1989, Addison-Wesley.
Artificial Life II, Santa Fe, NM, Febrero, 1990. Eds. Langton, Taylor, Farmer & Rasmussen 1992, Addison-Wesley.
Artificial Life III, Santa Fe, NM, Junio, 1992. Ed. Langton 1994, Addison-Wesley.
Artificial Life IV, Cambridge, MA, Julio, 1994. Eds. Brooks & P Maes 1994, MIT Press.
Artificial Life V, Nara, Japón, Mayo, 1996. Eds. Langton & Shimohara 1997, MIT Press.
Artificial Life VI, Los Angeles, CA, marzo 1998. Eds. Adami, Belew, Kitano & Taylor 1998, MIT Press.
Artificial Life VII, Portland, OR, abril 2000. Eds. Bedau, McCaskill, Packard & Rasmussen 2000, MIT Press.
Artificial Life VIII, Sidney, Australia 2002. Eds. Standish, Bedau, & Abbass 2002, MIT Press.
Artificial Life IX, Boston, MA, septiembre 2004. Eds. Pollack, Bedau, Husbands, Ikegami & Watson 2004, MIT Press.
Artificial Life X, Bloomington, IN, Junio 2006. Eds. Rocha, Yaeger, Bedau, Floreano, Goldstone & Vespignani 2006, MIT Press.
Artificial Life XI, Winchester, UK, August 2008. Eds. Bullock, S., J. Noble, R. Watson, and M. A. Bedau, MIT Press.

B) *European Conference on Artificial Life* (*ECAL*)

1st European Conference on Artificial Life (ECAL´91), Paris, December 1991. Eds. Varela & Bourgine 1992, MIT Press.
2nd European Conference on Artificial Life (ECAL'93), Bruselas, May 1993 (no Proceedings editados en forma de libro).
3rd European Conference on Artificial Life (ECAL'95), Granada, June 1995. Eds. Morán, Moreno, Merelo & Chacón 1995, Springer.
4th European Conference on Artificial Life (ECAL'97), Brighton, UK, July 1997. Eds. Husbands & Harvey 1997, MIT.
5th European Conference on Artificial Life (ECAL´99), Lausanne, September 1999. Eds. Floreano, Nicoud & Mondada 1999, Springer.
6th European Conference on Artificial Life (ECAL'01), Praga, September 2001. Eds. Kelemen & Sosík 1999, Springer.
7th European Conference on Artificial Life (ECAL'03), Dortmund, September 2003. Eds. Banzhaf, Christaller, Dittrich, Kim & Ziegler 1995, Springer.
8th European Conference on Artificial Life (ECAL'05), Canterbury, September 2005. Eds. Capcarrere, Freitas, Bentley, Johnson & Timmis 2005, Springer.
9th European Conference on Artificial Life (ECAL'07), Lisbon, September 2005. Eds. Almeida e Costa, Rocha, Costa, Harvey & Coutinho 2007, Springer.