Orig Life Evol Biosph (2010) 40:131–136
DOI 10.1007/s11084-010-9191-4

Defining Life: Connecting Robotics and Chemistry

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Received: 13 January 2009 / Accepted: 15 May 2009 /
Published online: 5 March 2010

Abstract Life is commonly referred as open systems driven by organic chemistry capable to self reproduce and to evolve. The notion of life has also been extended to non chemical systems such as robots. The key characteristics of living systems, i.e. autonomy, self-replication, self-reproduction, self-organization, self-aggregation, autocatalysis, as defined in chemistry and in robotics, are compared in a dialogue between a chemist and a robotitian.

Keywords Aggregation · Autocatalysis · Autonomy · Chemical evolution · Robotics · Self-organization · Self-replication

Introduction

Defining life is a difficult task and the intriguing and eternal question "What is life?" has not yet received a commonly accepted answer, even for what could be defined as minimal life, the simplest possible form of life (Luisi 1998). On the occasion of a Workshop on Life, held in Modena in 2003, each member of the International Society for the Study of the Origins of Life was asked to give a definition of life. The 78 different answers occupy 40 pages in the proceedings of the workshop (Palyi et al. 2002). In this query, the connection with chemical systems was implicit, although the concept of life is also used in robotic sciences. This paper aims to compare the two approaches in a dialogue between a chemist (A.B.) and a robotitian (M.T.).

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Defining Life

A.B. Perhaps the most general working definition is that adopted in October 1992 by the NASA Exobiology Program: "Life is a self-sustained chemical system capable of undergoing Darwinian evolution". Implicit in this definition is the fact that the system uses external matter and energy provided by the environment. In other words, primitive life can be defined, *a minima*, as an open chemical system capable of self-reproduction, i.e. making more of itself by itself, and also capable of evolving. The concept of evolution implies that the chemical system normally transfers its information fairly faithfully but makes a few random errors. These may potentially lead to a higher complexity/efficiency and possibly to a better adaptation to changes under the existing environmental constraints.

M.T. Robots are physicochemical machines which have to preserve the integrity of their structure while being faced with infinite variable constraints within an environment which can degrade them. The mandatory characteristic of robots is autonomy. To fulfill the requirement of autonomy, these physicochemical machines must be able to categorize in a coherent way the infinite variety of shapes of objects which are perceived by their sensors. It is not necessary for an autonomous robot to be able to reproduce itself, self-reproduction being only a secondary property. Evolutionary robotics, based on self-reproducing mechanisms, appears therefore to be a restricted branch of robotics. It is suggested that the mandatory notion of autonomy could help to create "chemical" life in a test tube.

Self-Replication Versus Self-Reproduction

A.B. The concept of self-replication is borrowed from the molecular biology of DNA, that is transferring the sequence information to a daughter chain *via* template polymerization. The daughter chain is not a true image of the mother chain but rather a "negative" so that a second step is required to obtain a true copy of the original. Primordial living systems were perhaps able to produce true copies in one step. One can therefore imagine autocatalytic growth of specific sequences on mineral surfaces followed by chain cleavages generating new chain primers. So far, no such sequence information amplification *via* chain elongation has been obtained in the laboratory.

M.T. From the point of view of evolutionary robotics, the self-replication of a DNA strand can be seen as the self-reproduction of a list of characters or a 'robotic genome' pertaining to a mother robot, which would transmit fortuitously-acquired functional features to a daughter robot. This mother genome is decoded by a specific computing module or controller to monitor functions, such as "forward", "backward", etc. The self-reproduction of the characters of a robotic genome can be spontaneous, like footprints in clay.

However, the functions attached to these genomic characters cannot be transmitted spontaneously to the daughter robot without the help of a technician. This is because the relative positions of the various characters of the genome known by the mother controller are strictly indistinguishable by the daughter controller. This factor of "indiscernibility" between the localization of the characters is due to the fact that the mother and daughter robotic genomes do not occupy the same position in space, thus requiring a new additional descriptor of the genome (Watanabe 1985). Self-reproduction of the robotic genome, in terms of function, is thus impossible. Therefore, evolutionary robotics is not a pertinent mechanism for the creation of autonomous robots.

The impossibility of transferring functions can perhaps be connected to the difficulty in obtaining self-replicating RNAs in a test tube.

Organization and Self-Organization

A.B. Amphiphilic molecules, with a hydrophobic hydrocarbon tail and a hydrophilic polar head, self associate spontaneously in water to form vesicles or micelles. Harold Morowitz (Morowitz 1992) postulated that vesicles were the first step toward the origin of life. Examples of autocatalytic micelle growth have been published by the group of Luisi (Bachmann et al. 1992). The formation of vesicles is a passive response to environmental conditions. They do not really store hereditary information and cannot therefore evolve by natural selection. However, Szostak (Hanczyc et al. 2007) found that clay particles, such as montmorillonite, can help the vesicles to assemble and, in the process, to bring bound RNA into the interior of the vesicles, thus providing information to the vesicular system. Computer modeling by Doron Lancet (Shenhav et al. 2005) may also help to support this vesicular life. Even more ambitious, the "minimal cell project" aims to synthesize a cell model that has the minimal number of components in order to be defined as living. Liposomes are used as shell membranes and attempts are made to introduce a minimal genome (Luisi 2007; Solé et al. 2007).

M.T. A robot is autonomous if it is able to face alone the various deleterious and useful constraints of its environment. The concept of autonomy implies being able to distinguish between order and organization. Order results from stereotyped attractive physicochemical processes, i.e. spontaneous interactions possibly accelerated by catalysts, induced by physical laws, like the association of sodium with chlorine in sodium chloride. These spontaneous reactions are inescapable events due to the combinational properties of matter. Organization results from opportunistic physicochemical processes, which have the basic property of being able to categorize the infinite variety of object shapes perceived by a system and for which the system has no particular physicochemical affinity.

In the view of the above distinction, vesicles made of amphiphilic molecules (Désaubry et al. 2003) are by no means self-organized structures; they are only ordered structures considering the physicochemical affinities between their elements. Thus, these vesicles alone cannot be considered as approaching living species. Similarly, dissipative structures far from thermal equilibrium (Prigogine 1969) are only ordered and are not self-organized structures capable of generating life, as generally asserted. The same holds for the cyclic networks of Stuart Kaufman (Kaufman 1993), which only lead to more or less complex ordered objects. All these prebiotic candidates do not have any of the opportunist functions characterizing life. The interactions shaping their organization relate only to elements sharing more or less pre-established affinities.

Aggregation and Selective Aggregation

A.B. Strictly homochiral polypeptides, with alternating charged hydrophilic and hydrophobic residues, are soluble in water. At neutral pH, the charged side-chains are ionized and the charge repulsion impedes the formation of ordered conformations. Addition of salt produces a screening of the charges and allows the polypeptide to adopt a β-sheet structure (Brack and Orgel 1975). The polypeptide chains aggregate into asymmetrical bilayers with a hydrophobic interior and a hydrophilic exterior because of hydrophobic side-chain clustering.

Aggregation of alternating sequences to form β-sheets is possible only with homochiral (all-L or all-D) polypeptides. When increasing amounts of L-residues are introduced into a racemic alternating polypeptide, the proportion of β-sheets increases and there is a good relationship between the percentage of the β-form and the amount of L-residues in the polymer. The molecules can be described as a mixture of β-sheets and disordered segments. Those segments containing six or more homochiral residues aggregate, thus forming stable nuclei of optically pure β-sheets surrounded by heterochiral unordered segments. In these polypeptides containing both L-and D-residues, only those segments containing six or more homochiral residues aggregate to form stable optically pure β-sheet islands surrounded by heterochiral unordered segments (Spach and Brack 1979).

M.T. Aggregation of polypeptide chains leads to an ordered object. Owing to their nature, these ordered structures have stereotyped properties that are antithetic to the nature of life, which implies opportunist actions. These attractive interactions between identical molecules result from their reciprocal recognition that differs radically from the recognition process of a robot, which recognizes objects for which it has no particular physicochemical affinity.

To undertake relevant actions to ensure the durability of its structure, the robot must therefore make the distinction between the various objects perceived by its sensors. However, according to the 'indiscernibility principle' of the formal theory of 'Pattern recognition' (Watanabe 1985), it is actually possible to prove that « for any physical system—whatever its complexity—two unspecified objects having no specific physicochemical affinities with the system are basically strictly indistinguishable one from the other ».

It appears therefore logically impossible to build an autonomous robot by implementing only mechanisms that involve necessary physico-chemical attractive interactions between elements, like those generating the vesicles.

Catalysis, Autocatalysis and Competition

A.B. "All replicating systems are, by definition, autocatalytic and all autocatalytic systems result, in some sense, in replication" (Orgel 1992). Autocatalysis is observed when the coupling of two reactants A-o and •-B is catalyzed by product A-B of the reaction. Different templates have been tested (Terfort and von Kiedrowski 1992; Wintner et al. 1994; Burmeister 1998). In most cases, the rate of the autocatalytic growth did not vary in a linear sense. The initial rate of autocatalytic synthesis was found to be proportional to the square root of the template concentration, i.e. the reaction order in these autocatalytic self-replicating systems was found to be 1/2 rather than 1, a finding in contrast to most autocatalytic reactions known so far. The reaction is slowed down by the fact that the A-B/A-B duplex produced is more stable than the starting A-B/A, B triplex. Two preformed fragments of a peptide have been demonstrated to be autocatalytically ligated by the whole peptide acting as a template (Lee et al. 1996; Severin et al. 1997). Moreover, the replicated molecules contain only two "letters" and therefore a very low level of information. As for the writing, the use of bifunctional letters allows the information to be infinitely enriched:

$$\bullet\!-\!A - o + \bullet\!-\!B - o \rightarrow \bullet\!-\!A - B - o$$

Now it becomes possible to enrich the information by simple lengthening of the chain. On the other hand, the coupling reaction must be highly selective since bifunctional molecules can also lead to the unwanted combinations •-A-A-o, •-B-B-o and •-B-A-o. Self-replication must therefore combine autocatalysis and information transfer. Autocatalytic reactions are particularly attractive since they might amplify small enantiomeric excesses, of extraterrestrial origin, for example, to homochirality (Shibata et al. 1998). Some investigations are also focusing on autocatalytic systems adsorbed on mineral surfaces (Orgel 1998; Luther et al. 1998).

So far, the replication of a complete peptide sequence fed with a mixture of amino acids has not been yet achieved. Orgel (Orgel 2000) examined the plausibility of theories that postulate the development of complex chemical organization without requiring the replication of genetic polymers such as RNA. He emphasized the implausibility of the suggestion that relatively pure, complex organic molecules might be made available in large amounts *via* complicated, self-organizing, autocatalytic cycles.

M.T. A catalyst (or enzyme) is a substance which increases the rate of an already existing physicochemical reaction. The problem to be solved is not the replication of the object RNA, whether or not accelerated by a catalyst, but rather the replication of all of its functional information.

In the field of evolutionary robotics, the functional self-reproduction of the robotic genome is logically impossible to achieve. *Mutatis mutandis*, that would imply that the functional self-reproduction of RNA, whether or not accelerated by an enzyme, is a mechanism that cannot develop spontaneously. For a daughter reading the instructions (bases) of the duplicated object RNA in order to build new proteins, these instructions are logically indistinguishable one from another, whereas those of the RNA source were perfectly decipherable by the mother.

Conclusion

M.T. Autonomy is the basic feature for robotic life rather than functional self-reproduction which is logically impossible to achieve. The empirical way to build an autonomous robot requires the help of a human operator: a car becomes autonomous when a driver takes over the controls. To solve the problem of autonomy, one could imagine equipping the robot with a sensitive controller having 'reactive features' corresponding to particular feelings experienced by human beings, such as pain, pleasure, etc. An elementary robot equipped with a controller device possessing a 'reactive feature' to temperature, would be able to systematically move away from any hot object which threatens its integrity. A specific sensitivity to temperature would make it indifferent to the non-deleterious hot objects encountered, thus bypassing the 'indiscernibility principle', which prevents such a coherent operation.

If we apply these theoretical and experimental results derived from the analysis of robotized systems to chemical living structures, current research dedicated to the origin and evolution of life, which consists of building increasingly complex ordered systems presenting chemical dynamisms characteristic of life, would thus be doomed to failure.

Based on the assumption that in order to be autonomous any physicochemical system must have reactive features, it would be necessary to search for specific structures in living organisms whose architecture or structure, would allow the emergence of such reactive features. From the knowledge of the geometry and the nature of living structures which have the property to be 'sensitive', one could then try to create artificial sensitive structures in the laboratory that would generate a machine made up of sensors and actuators leading to autonomy and ultimately to life.

A.B. Obviously, some words have not the same meaning or importance in chemistry and in robotics. For example, the word autonomy implies the capability of making more of itself by itself as well as the capacity to escape deleterious factors in the surroundings. In fact, making more is also a way of ensuring the survival of a chemical species. Evolution is a key factor in the chemical approach, whereas it is secondary for robotics. However, the two approaches have in common the search for "reactive features". The short homochiral sheet-forming peptides represent a preliminary result in this direction. When diluted by non-sheet forming sequences, they form small reactive islands resisting deleterious environmental conditions. More productive sensitive features are still to be discovered to come closer to self-replicating chemical systems.

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