Orig Life Evol Biosph (2010) 40:137–143
DOI 10.1007/s11084-010-9192-3

Is it Useful to Have a Clear-cut Definition of Life? On the Use of Fuzzy Logic in Prebiotic Chemistry

Gilles Bruylants · Kristin Bartik · Jacques Reisse

Received: 22 December 2008 / Accepted: 12 May 2009 /
Published online: 5 March 2010

Abstract Many scientists, including one of the authors of the present paper, have devoted time to try to find a definition for life (Bersini and Reisse 2007). It is clear that a consensus will never be reached but, more importantly, it seems that the issue itself could be without major interest. It is indeed impossible to define a "natural" frontier between non-living and living systems and therefore also impossible to define dichotomic criteria which could be used in order to classify systems in one of these two classes (living or non-living). Fuzzy logic provides a natural way to deal with problems where class membership lacks sharply defined criteria. It also offers the possibility to avoid losing time with unnecessary controversies such as deciding whether a virus is, or is not, a living system.

Keywords Darwin · Fuzzy logic · Lamarck · Origin of life · Species

Introduction

At first glance the question raised in the title of this paper could seem surprising. Indeed, it is generally considered that, in order to undertake good scientific research, objects and concepts should be well defined. Many people, including scientists, believe that it would, for example, not be possible to be a good physicist without being in possession of a precise definition of some basic concepts. This is in fact not true. Physics Nobel laureate Richard Feynman clearly pointed out that: "*It is important to realize that in physics today, we have no knowledge of what energy is*" (Feynman et al. 1963, p4–2). He also pointed out, regarding the lack of a definition for "time": "*Maybe it is just as well if we face the fact that time is one of the things we probably cannot define (in the dictionary sense) and just say that it is what we already know it to be: it is how long we wait*" (Feynman et al. 1963, p5–1).

As soon as we are convinced that, even in physics, precise definitions of concepts are not always required, we should be able to accept that it is also possible to be a good

G. Bruylants · K. Bartik · J. Reisse (✉)
Ingénierie Moléculaire et Biomoléculaire, Université Libre de Bruxelles, Belgium, 50 av. F.D. Roosevelt, 1050 Brussels, Belgium
e-mail: jreisse@ulb.ac.be

biologist without a rigorous definition of a living system. In fact, in the majority of general treaties devoted to biology or biochemistry, the words “life” and “living” are never defined. It is probable that biologists in front of the definition of these words face the same quandary as Augustine, in front of the definition of time, as stated in his Confessions (book 11): “*What then is time? If no one asks me, I know. If I wish to explain it to one that asked, I know not*”. Biologists know what a living system is and they do not need to define it. When a definition is requested, they frequently limit themselves to a list of properties shared by many, if not all, living systems. Implicitly, biologists like physicists agree with the statement of the well known Dutch physicist Hendrik A. Kramers who said: “*In the world of human thought generally, and in physical science in particular, the most important and most fruitful concepts are those to which it is impossible to attach a well-defined meaning*” (Dresden 1987, p539).

In this context, it is interesting to try and elucidate why certain scientists wish to be in possession of a clear-cut definition for the terms “life” and “living” (Bersini and Reisse 2007). These scientists are generally not biologists but in essence members of one of three communities: scientists searching for the presence of extraterrestrial living systems, scientists involved in research related to artificial life, including the building of “*in silico* living systems”, and scientists interested by the origin of life on Earth. Before focusing on why scientists interested in the origin of life on Earth wish to have a definition for “life”, and also why this quest is essentially without hope, we will briefly state the reasons why the members of the two other communities are searching for a definition.

The discovery of living systems on an extraterrestrial body, inside or outside our Solar system, would be a major event. It is clear that in order to search for traces of extraterrestrial living systems it is essential to know how to classify them as such. Generally, scientists involved in this type of research focus their interest on the search of probable molecular components of living systems or metabolic products of these. The search for the presence of liquid water on Mars and the search for oxygen and ozone in the atmosphere of extra-solar planets, illustrate this type of approach.

The development of sophisticated computer programs and micro-machines has lead to the design of virtual objects and robots, which exhibit certain behavioral characteristics similar to those observed in living systems. The specialists working in these fields need a definition of living systems which is as broad as possible in order to be able to qualify their objects as living. They do not consider that the presence of components such as water and organic molecules is a significant criterion. They insist on properties and functions of their systems, which, for them, are similar to those of living systems.

Is it Necessary, or Even Possible, to Find a Definition of Life Acceptable for Scientists Interested in its Origin?

From a materialistic point of view, a living system is a highly complex form of matter, a supra-molecular assembly exchanging matter and energy with its surroundings. Scientists interested in the elucidation of the steps leading to the origin of life, focus their search on the transition between a molecular assembly which is not yet living and a molecular assembly which can be described as living (Luisi et al. 1996; Luisi 2006). It consequently seems fully justified to try to define the frontier between a non-living and a living system. A difficulty however automatically arises, difficulty which presents many similarities with those encountered by Darwin and Lamarck in their attempts to find a definition for a biological species. These two illustrious scientists modified profoundly our way of thinking about the living world and about the place occupied by *Homo sapiens* in this world. Both naturalists were interested in classification. Classification requires clear-cut criteria with which one can decide if a particular object is a member of category A or of category B. Faced with the task of finding criteria which could enable the classification of animals into species, Darwin and Lamarck both came to the conclusion that these criteria always result from some arbitrary agreement, that they are never offered by nature itself. In his book *Philosophie zoologique* first published in 1809 Lamarck wrote: *« But these classifications from which many have been so well imagined by the naturalists and the divisions and sub-divisions they introduce, are artificial means. Nothing like that, I insist, can be found in nature...*"(Lamarck [1809] 1994, p79). Darwin wrote in his book *The origin of species by means of natural selection* first published in 1859: ≪*I look at the term species, as one arbitrarily given for the sake of convenience to a set of individuals closely resembling each other, and that it does not essentially differ from the term variety, which is given to less distinct and more fluctuating forms*≫ (Darwin [1859] 1978, p108). He also wrote: "*Certainly no clear line of demarcation has as yet been drawn between species and sub-species—that is, the forms which in the opinion of some naturalists come very near to, but do not quite arrive at the rank of species; or again, between sub-species and well-marked varieties, or between lesser varieties and individual differences. These differences blend into each other in an insensible series; and a series impressed the mind with the idea of an actual passage"* (Darwin [1859] 1978, p107).

Lamarck and Darwin both came to these conclusions not only through their careful observation of the living world, but also because they were convinced that species change with time (by variation inside a population and natural selection for Darwin) and that new species arise necessarily from previous ones. For an evolutionist, the separation between species cannot be absolute and time independent. If a species A evolves from a species B, at some stage some individuals must have been partially A but also, partially, B. As pointed out by Darwin: "*No one definition* [of species] *has yet satisfied all naturalists; yet every naturalist knows vaguely what he means when he speaks of a species*" (Darwin [1859] 1978, p101).

On the basis of these remarks, it seems necessary to ask another question: is it possible to draw a clear-cut frontier between a non-living state of matter and a living system? Our answer is without hesitation no. The transition from non-living to living, at the so-called origin of life, must have evolved through systems which were "not yet living" but already "not fully non-living". This means, and this is the main point that we wish to make, that Aristotelian logic should not be used by people interested in the origin of life.

Aristotelian logic is based on three axioms considered as self-evident:

– the law of contradiction which states that "x" cannot be both "A" and "non-A";
– the law of identity which states that "x" will always be "x";
– the law of excluded middle which states that "x" must be "A" or "non-A".

These three axioms are not compatible with an evolutionary description of the living world and they are also in contradiction with an evolutionary description of the transition from non-living to living. Between the prebiotic world and the biotic world, a "partially prebiotic/partially biotic" world must necessarily have existed. As soon as Aristotelian logic cannot be applied to differentiate non-living from living, any definition of life, or any definition of a living system must necessarily result from an agreement. Consequently, it is highly improbable that a consensus will ever be reached and as a result the concept "living" will remain ill-defined and thus, according to Kramer, an important and fruitful concept (Dresden 1987, p539).

On the Use of Fuzzy Logic in Prebiotic Chemistry

It is possible to deal with ill-defined concepts by using a non-Aristotelian logic called fuzzy, or multi-valued, logic. An excellent introduction to fuzzy logic is given in a chapter of Rouvray's book (Rouvray 1997) devoted to the treatment of uncertainty in the physical sciences. A few very illustrative quotations related to the concept of vagueness in science are given in this chapter. One is from Bertrand Russel who in 1923 said: "*apart from representation...there can be no such things as vagueness or precision; things are what they are and there is an end of it*" (Russel 1923). Another is from Williamson who said: "*vagueness is indeed one manifestation of the fact that our classification are not fixed by natural boundaries*" (Williamson 1989).

The description of nature is, in certain cases, unavoidably vague and, as scientists, we must accept that frequently Aristotelian logic cannot be applied and must be replaced by fuzzy logic. It is widely recognized that Zadeh was the first to introduce the concept of the fuzzy set which is at the basis of fuzzy logic (Zadeh 1965). He defines a fuzzy set as "*a class of objects with a continuum of grades of membership*". According to Zadeh, the concept of fuzzy set could provide "*a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership*". It is clear that biological species are fuzzy sets and, for reasons previously discussed, prebiotic systems and living systems are also examples of fuzzy sets. Fuzzy logic allows partial set membership rather than crisp set membership or non-membership. If an object is without doubt in class "A", its membership will be 1; if it is without doubt in the class "non-A", its membership will be 0 in class "A"; it can however also be characterized by a different membership value, which means that it is partially member of class "A" but also partially member of class "non-A".

Even if fuzzy logic can help us deal with vague issues, and even if vagueness or imprecision can be useful in science, an excess of imprecision is not acceptable. A limit must necessarily be fixed in order to define the 0 and 1 values for membership to the class "living system". We could decide that a membership of 1 is restricted to systems classified today as Bacteria, Archaea or Eukarya. This decision could be accepted by any scientist, and also non-scientist, interested in the origin of life on Earth and furthermore does not require a definition of life. On the basis of this, a cat, a sequoia or a bacteria would be characterized by a membership of 1 in the class "living system". A virus would however be characterized by a membership lower than 1 in this class. However, in order to determine its membership value an agreement must first be found for a membership scale. This is a very important aspect of fuzzy sets: the degree of membership will vary with the choice of classification criteria. This is however not a major drawback as what is important is to be able to apply a logic which is not constrained by the law of excluded middle. In science, we must reject the use of concepts or methods that generate false problems! Deciding whether or not a virus is a living system, is an example of a false problem which originates from the vain attempt to try to define, in a very precise way, what "living system" means. Of course, a virus does not posses all the attributes of a unicellular organism but it has some of these attributes and, as we will see later, on the basis of our definition of the zero value of the membership scale, a virus is indeed characterized by a non-zero membership in the class "living system".

Scientists interested in prebiotic chemistry will most probably accept that a hypothetical vesicle which can be prepared under physico-chemical conditions compatible with what is known about Earth's primitive hydrosphere, can be considered as a partially living system, as it corresponds to a plausible step towards a first unicellular organism. As in the case of a virus, the degree of membership of this vesicle to the class "living system" will depend on chosen criteria. This degree of membership will generally be considered to be high by those working on artificial membranes while those interested, for example, in the origin of prebiotic polynucleotides will most probably challenge this stance. For them, important criteria are information and catalysis and a hypothetical RNA-type polymer, able to catalyze its own synthesis (autocatalysis) and other reactions, would most certainly be considered an important step towards a first unicellular organism. An ensemble of such molecules confined in a small volume, would undoubtedly be considered by them as a partially living system with an associated membership higher than 0. The confinement of these RNA-type polymers inside the vesicle previously described would probably have an even higher membership value (be considered as "more alive") than the two sub-systems taken separately. This membership would however remain lower than 1, because, as previously mentioned, we suggest that the 1 value only be given to Bacteria, Archaea and Eukarya.

Regarding the zero on the living system membership scale, and coming back to the vesicles and the RNA-type polymers, it is possible to find what is common to these systems, and also to every living system on Earth today. These two "partially living" systems (i) are composed of organic molecules and liquid water; (ii) are ensembles of interacting or reacting molecules and (iii) have properties which are different from those of the isolated components. It is precisely because the two systems have these three characteristics that we have considered that their membership in the class "living system" is higher than 0. On the basis of these three simple criteria considered together we can now decide if a system has a non-zero membership to the class "living systems" and we therefore have a definition for the 0 of the membership scale.

The criteria presented above to define the zero of the membership scale are of course just a suggestion and others might wish to recommend other criteria, but the concept of collective properties of supramolecular ensembles of organic molecules immersed in liquid water has many advantages. Indeed, with these criteria, pure liquid water, ensembles of amino acids, nucleic bases, polypeptides, polynucleotides, ribose, polysaccharides or their water solutions have a membership of 0. On the contrary, a water solution of RNA molecules, which act as templates for their own reproduction, in a reactor containing nucleotides and enzymes would be considered as partially living with, consequently, a membership in the class "living system" higher than 0. A system composed of peptide nucleic acid (PNA) polymers interacting with single stranded DNA in liquid water leading to double helical molecules would also be described as partially living, even if PNA is not a component of the living world today. The membership of this system would be non-zero because the duplex resulting from the molecular recognition of DNA by PNA has properties which are different from those of the isolated polymers dissolved in water. This means that even in an extraterrestrial environment with liquid water and organic molecules, the criteria could be used to qualify the non-zero membership of hypothetical organic supramolecular systems, even if the polymers used as information support or as catalysts were not DNA, RNA or polypeptides. For extraterrestrial systems new criteria would necessarily be required to define the 1 value of a membership scale, and these criteria will probably differ from the ones used to describe the transition from "non living" to "living" on Earth. We prefer not to consider here exotic forms of life, with silicon in place of carbon or liquid methane in place of water (Schulze-Makuch and Irwin 2006), because for reasons discussed elsewhere (Bruylants et al. 2009), such a scenario is, from our point of view, not at all realistic.

The case of artificial "living systems" presents similarities with the issues just discussed for extraterrestrial life. A robot, despite its performances and the similarities of these performances with those of an organism, is not a living system in the biological sense.

Specialists of artificial life are certainly interested in defining, for their own work, a membership scale. They would be obliged to define what is, for them, an artificial living system which has a membership of 1 in the class “living systems”. For a biologist, the cell is the archetype of a living system while for people working in robotics, dogs and men seems to be their archetypes. This clearly highlights that the membership scales must necessarily be different for the scientist interested in the origin of life, on the one hand, and for the engineer developing robots, on the other. This however does not mean that these scientists and engineers have nothing to learn from each other: it means that attempts to compare, on the same scale, the membership of a vesicle and the membership of a robot in the class “living systems” has no heuristic value.

Conclusions

Cats and dogs are different species and today nobody would challenge this conclusion. However mammals living on Earth in the past must have been the ancestors of both cats and dogs. Therefore for the evolutionist, the division of cats and dogs into different species is without any particular interest; what is important for the evolutionist is to be able to explain the divergence of an initial population into two separate populations. In the past, some mammals were necessarily “not yet fully cats” or “not yet fully dogs”.

Scientists working on the origin of life are evolutionists interested in steps of evolution which preceded the first population of prokaryotes and they are exactly in the same position as biologists. They are interested in the sub-systems, of various levels of complexity, which were the components of the systems which were, for the first time, able to reproduce themselves, to compete, to evolve and to become the first population of cells from which all forms of life originated on the surface of the Earth. These sub-systems were not yet living but they were already partially living.

It seems clear that it will never be possible to obtain a clear-cut definition for the concepts “life” and “living” which can satisfy all scientists. Life, and especially the progressive transition from non-living to living matter, is a concept to which traditional Aristotelian logic cannot be applied. Fuzzy logic provides a natural way of dealing with these types of problems in which class membership lacks sharply defined criteria.

Acknowledgements G.B. thanks the Belgian Fonds de la Recherche Scientifique—FNRS for a post-doctoral fellowship.

References

Bersini H, Reisse J (2007) Comment définir la vie? Vuibert, Paris

Bruylants G, Locci E, Reisse J, Bartik K (2009) Liquid water: a necessary condition for all forms of life? In: Gargaud M, Lopez-Garcia P, Martin H, Montmerle Th (eds) Origin of life: an astrobiology perspective. Cambridge University Press, in press

Darwin C ([1859] 1978) The origin of species. Gramercy Books, New York

Dresden M (1987) H.A. Kramers: between tradition and revolution. Springer-Verlag, New-York

Feynman R, Leighton R, Sands M (1963) The Feynman lectures on physics. Addison-Wesley, Reading (Massachusetts), Palo Alto, London

Lamarck JB ([1809] 1994) *Philosophie zoologique*. GF-Flammarion, Paris, What Lamarck wrote was in French: «*Mais ces classifications, dont plusieurs ont été si heureusement imaginées par les naturalistes,*

ainsi que les divisions et sous divisions qu'elles présentent, sont des moyens tout à fait artificiels. Rien de tout cela, je le répète ne se trouve dans la nature ... »
Luisi PL (2006) The emergence of life. Cambridge University Press, New York
Luisi PL, Lazcano A, Varela F (1996) What is Life? defining life and the transition to life. In: Rizzotti M (ed) Defining life: the central problem in theoretical biology? Padova University Press, Padova, pp 149–165
Rouvray DH (1997) The treatment of uncertainty in the physical sciences. In: Rouvray DH (ed) Fuzzy logic in chemistry. Academic, San Diego, pp 1–26
Russel B (1923) Vagueness. Australas J Philos 1:84–92
Schulze-Makuch D, Irwin LN (2006) The prospect of alien life in exotic forms on other worlds. Naturwissenschaften 93:155–172
Williamson T (1989) Being and being so. Acta Analytica 4:93–114
Zadeh LA (1965) Fuzzy sets. Information and control 8:338–353