DEFINING 'LIFE'

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(Received 2 March 2002; accepted in revised form 12 June 2002)

Abstract. There is no broadly accepted definition of 'life.' Suggested definitions face problems, often in the form of robust counter-examples. Here we use insights from philosophical investigations into language to argue that defining 'life' currently poses a dilemma analogous to that faced by those hoping to define 'water' before the existence of molecular theory. In the absence of an analogous theory of the nature of living systems, interminable controversy over the definition of life is inescapable.

Keywords: definition of life, astrobiology, Viking, Europa, natural kinds

1. Definitions of Life

The philosophical question of the definition of 'life' has increasing practical importance. As science makes progress towards understanding the origin of life on Earth, as laboratory experiments approach the synthesis of life (as measured by the criteria of some definitions), and as greater attention is focused on astrobiology and the search for life on Mars and Jupiter's moon Europa, the utility of a general definition grows. In particular, definitions of 'life' are explicit or implicit in any remote in situ search for extraterrestrial life. The design of life-detection experiments to be performed on Europa (Chyba and Phillips, 2001) or Mars (Conrad and Nealson, 2001) by spacecraft landers depends on assumptions about what life is, and what observations will count as evidence for its detection.

The *Viking* missions' searches for life on Mars in 1976 remain the only dedicated in situ searches for extraterrestrial life to date. The *Viking* biology package experiments looked for signs of microbial metabolism (Ezell and Ezell, 1984). Reviewing the results of one of the experiments in the package, the Labeled Release experiment, the head of the Viking biology team wrote in 1978 that, '. . . if information from other experiments on board the two Viking landers had not been available, this set of data would almost certainly have been interpreted as presumptive evidence of biology' (Klein, 1978).

However, such an interpretation was widely rejected for a number of reasons, including proposed chemical explanations for the observations in terms of oxidizing

Origins of Life and Evolution of the Biosphere **32:** 387–393, 2002.

compounds on the martian surface (Klein, 1979; but see also e.g. Levin and Straat, 1979; Levin and Levin, 1998; and Klein, 1999). The nonbiological interpretation of the biology package results (Klein, 1978; 1979) was strongly influenced by the failure of the *Viking* gas chromatograph mass spectrometer (GCMS) to find organic molecules to its limits of detection with sample heating up to 500 °C (Biemann *et al.*, 1977). The pyrolysis GCMS had not been intended as a 'life-detection' experiment, but became a de facto one that employed a biochemical definition (Chyba and Phillips, 2001; 2002). It now appears as though the GCMS would not have detected as many as $\sim 10^6$ bacterial cells per gram of soil (Glavin *et al.*, 2001; Bada, 2001), and that oxidation of meteoritic organics on the martian surface may have produced nonvolatile organic compounds that would not have been easily detected (Benner *et al.*, 2000). Correct or not, the interpretation of the GCMS results was psychologically powerful: no (detected) organics, no life.

Despite these practical issues, there remains no broadly accepted definition of 'life' (Chyba and McDonald, 1995). The scientific literature is filled with suggestions; three decades ago Sagan (1970) catalogued physiological, metabolic, biochemical, genetic, and thermodynamic definitions, and there have been many other attempts (see , e.g. Schrödinger, 1945; Monod, 1970; Feinberg and Shapiro, 1980; Dyson, 1985; Kamminga, 1988; Fleischaker, 1990; Joyce, 1994a;b; Shapiro and Feinberg, 1995; Rizzotti *et al.*, 1996; Koshland, 2002), all of which seem to face problems, often in the form of robust counter-examples. For example, thermodynamic and metabolic definitions have difficulty avoiding counting crystals and fire, respectively, as alive. Claiming this or that counter-example to be an 'unimportant' exception merely implicitly invokes further criteria beyond those ostensibly comprising the definition (Chyba and McDonald, 1995).

2. The Darwinian Definition

One working definition of 'life' that has become increasingly accepted within the origins-of-life community is the 'chemical Darwinian' definition. A careful formulation (Joyce, 1994a;b) is: 'Life is a self-sustained chemical system capable of undergoing Darwinian evolution.' Darwinian definitions have become quite influential, shaping not only our ideas of what life *is*, but also of what we recognize as its origin. By the Darwinian definition, the origin of life is the same as the origin of (Darwinian) evolution.

But there are problems with Darwinian definitions of 'life'. It is conceivable (though not currently favored among theories of the origin of life on Earth) that early cellular life on Earth or some other world passed through a period of reproduction without replication, during which Darwinian evolution was not yet established (Dyson, 1985). In this hypothesis, protein-based creatures capable of metabolism predated the development of nucleic acid-based exact replication. Conceptually, one can at least imagine a mechanism of biological evolution that is non-Darwinian; if such organisms were to be discovered, we would be unlikely to declare them not to be alive *by definition*. A hint of the possibilities that we may encounter is that a world of naked RNA molecular life would conflate phenotype with genotype, thereby permitting limited Lamarckian as well as Darwinian evolution.

Another concern with the Darwinian definition is that living sterile organisms such as mules cannot reproduce, so they are not 'capable of Darwinian evolution'. Trying to defuse this dilemma by dividing our subject into two categories, 'life' and 'living entities', needs to be explained as more than an ad hoc effort to protect a particular definition.

There is also a practical drawback to Darwinian definitions: In an in situ search for life on other planets, how long would we wait for a system to demonstrate that it is 'capable' of Darwinian evolution, and under what conditions (Fleischaker, 1990)? This objection alone is not decisive, however, as an operational objection is not an objection in principle, and future work might point to ways to operationalize the definition.

Here we show that insights gained from philosophical investigations into language and logic strongly suggest that the seemingly interminable nature of the controversy over life's definition is inescapable as long as we lack a general theory of the nature of living systems and their emergence from the physical world. Whether such a theory will in fact prove possible is a hypothesis to be investigated.

3. The Nature of Definition

Definitions specify meanings of terms. An 'ideal' definition (in the logician's sense) specifies necessary and sufficient conditions for the application of the term being defined (see, e.g., Audi, 1995). The classic example is the definition of 'bachelor' as 'unmarried human male.'

This definition is a matter of linguistic convention, and is inescapably vague. Is a two-year-old boy a 'bachelor'? Probably not; probably what we really mean by 'bachelor' is an unmarried adult human male. But this clarification also suffers from vagueness; how old does one have to be to be considered an adult? It is characteristic of most definitions that they have vague boundaries. The notable exception is stipulative definitions (Audi, 1995) that explicitly supply technical meanings for terms independently of ordinary linguistic usage. For example, in Euclidean geometry, 'triangle' may be defined as a plane figure enclosed by three straight lines (Heath, 1908). It is irrelevant to this stipulative definition that the physical objects designated as 'triangles' in everyday discourse never have perfectly straight sides.

Definitions specify meanings of terms by dissecting concepts that we already possess. This works fairly well for terms such as 'bachelor' or 'fortnight' or 'chair', which designate categories whose existence depends solely upon human interests and concerns. But it does not work for terms such as 'water', which designate *natural* categories that are delimited by nature rather than by human interests and concerns. Consider the definition of the word 'water'. One could try to define 'water' by reference to its sensible properties, such as being wet, odorless, tasteless, and thirst quenching. (This is analogous to some suggested definitions of 'life', e.g. Koshland, 2002.) This 'definition' of water is not a simple matter of linguistic convention, as was the case for the definition of 'bachelor.' Nevertheless, reference to a list of sensible properties could still allow substances that superficially resemble water to be incorrectly classified as water. This is one reason why 'defining' a thing by specifying a conjunction of its properties is problematic (see e.g. Schwartz, 1977 for a review). This problem is exacerbated by the fact that different observers are likely to include different properties in their own 'definitions' of the term.

Once we had an understanding of the molecular nature of matter, however, we could identify water in such a way that all ambiguity disappears: water *is* H_2O. This identification holds regardless of whether the water is in any of its familiar solid, liquid, or vapor phases, and it will hold equally well for water in less familiar high-pressure solid phases. Historically, it was the development of molecular theory that made an unambiguous understanding of 'water' possible. The identification started out as a testable empirical conjecture (situated within a new theoretical framework for chemistry) about the nature of water. It ended up *taking on the character* of a stipulative definition, which is the source of its striking precision. Of course, since all physical theories are subject to empirical test, the status of the statement 'water is H_2O' differs from the stipulative definition of 'triangle', which is independent of empirical observation.

Nevertheless, reference to H_20 does not capture the everyday *meaning* of the term 'water.' The claim that 'water is H_2O' cannot be viewed as defining the familiar English word 'water' since the stuff ordinarily called 'water' in day-to-day language varies widely in chemical and physical composition; it is not just H_2O. What the molecular account of water as H_20 achieves is a broad, theoretically grounded, scientific understanding of the behavior of what we ordinarily call 'water' under a wide range of chemical and physical circumstances. It allows us to explain why and how, for example, stream 'water' differs from ocean 'water'. The claim that water is H_20 therefore may be viewed as introducing ('stipulating') a new meaning for the old, familiar term 'water' within the context of an empirically testable scientific theory. But it is more accurate to view it as encapsulating a scientific discovery about the nature of water, rather than as representing a linguistic decision to assign a different meaning to an old term in our language.

4. Natural Kinds

Water is an example of what philosophers call 'natural kinds' (Putnam, 1973; 1975; Schwartz, 1977). Natural kinds differ from non-natural kinds in that nature, rather than human convention, determines their membership. Terms (e.g., 'bachelor') designating non-natural kinds can be defined in terms of the properties that we use to recognize them because they do not have an inherent nature independent of those properties. Natural kinds are different, however. Something can fully satisfy the properties that are typically used to recognize a natural kind and yet still fail to qualify as a thing of that kind. As an example, consider the seventeenth century debate over whether bats are birds. In the absence of an adequate theoretical understanding of mammalian and avian physiology, bats seemed more similar to birds than to rodents (Locke, 1689). Similarly, jadeite and nephrite were once both included under the common term 'jade' but it is now clear from chemical analysis and microscopic examination that they are different (Bauer, 1968; Putnam, 1975).

Before the invention of molecular theory, people may (or may not) have believed that 'water' could be precisely defined, but the best they could do in 'defining' it would be to discuss its sensible properties. In the absence of a compelling molecular theory, attempts at definition were doomed to interminable bickering over which of its sensible properties were essential to water's nature. We suggest that current attempts to define 'life' face exactly the same quandary. It is possible that in the future we will elaborate a theory of biology that allows us to attain a deep understanding of the nature of life and formulate a precise theoretical identity for life comparable to the statement 'water is H_20.' In the absence of that theory, however, we are in a position analogous to that faced by someone hoping to understand water before the advent of molecular theory by 'defining' it in terms of the observable features used to recognize it. (See Lange (1996) for further discussion of the relation between the concept of life and the features that we use to recognize it.)

Prior to the elaboration of such a theory, it is not possible to be certain that it will, in fact, ever be formulated – or that it is even possible. Perhaps life is not a natural kind. If it is not, how we define it will forever remain a matter of no more than linguistic choice. But if life is a natural kind, we need a theoretical framework for biology that will support a deeper understanding of life than can be provided by the features that we currently use to recognize it on Earth. There is a scientific program, based on laboratory investigations (for example, investigations into the RNA world) and the empirical search for examples of extraterrestrial life, that are important steps towards formulating such a theory. Indeed, it is hard to imagine what could better help us to understand the nature of life than the synthesis of candidate living systems in the laboratory or the discovery of independent extraterrestrial biologies.

Acknowledgments

This work was supported in part by a NASA grant to the University of Colorado's Astrobiology Center, the NASA exobiology program, and a Presidential Early Career Award for Scientists and Engineers.

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