What are definitions of life good for? Transdisciplinary and other definitions in astrobiology

Article *in* Biology & Philosophy · December 2017

DOI: 10.1007/s10539-017-9600-4

2 authors:

Tarja Knuuttila
University of Vienna

Andrea Loettgers
University of Vienna

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Tarja Knuuttila and Andrea Loettgers

Abstract

The attempt to define life has gained new momentum in the wake of novel fields such as synthetic biology, astrobiology, and artificial life. In a series of articles, Cleland, Chyba, and Machery claim that definitions of life seek to provide necessary and sufficient conditions for applying the concept of life—something that such definitions cannot, and should not do. We argue that this criticism is largely unwarranted. Cleland, Chyba, and Machery approach definitions of life as classifying devices, thereby neglecting their other epistemic roles. We identify within the discussions of the nature and origin of life three other types of definitions: theoretical, transdisciplinary, and diagnostic definitions. The primary aim of these definitions is not to distinguish life from nonlife, although they can also be used for classificatory purposes. We focus on the definitions of life within the budding field of astrobiology, paying particular attention to transdisciplinary definitions, and diagnostic definitions in the search for biosignatures from other planets.

1. Introduction

The question of the nature and origin of life has become ever more acute as biology has extended into novel, largely uncharted areas such as artificial life, synthetic biology, and astrobiology—and transformed into a highly interdisciplinary field. One strand of this invigorated discussion concerning the nature of life has concerned definitions of life. Although the attempt to define life has a long historical lineage, the present situation is marked with a breathtaking proliferation of various definitions of life (e.g., Schrödinger 1967; Sagan 1970; Kauffman 1995; Mayr 1997; Luisi 1998; Koshland 2002; Griesemer and Szathmáry 2009). As a result, it has become highly uncertain how even some tentative consensus could be reached amidst the partly different, and partly overlapping definitions.[1]

Especially philosophers have remained unimpressed by this burgeoning activity of defining life. In a series of highly influential articles, Carol Cleland and Christopher Chyba (2002, 2010) argue that defining life is "fundamentally misguided": "[…] the idea that one can answer the question 'What is life'? by defining 'life' is mistaken, resting upon confusions about the nature of definition and its capacity to answer fundamental questions about natural categories" (Cleland and Chyba 2010, 326; see also Cleland 2012). Cleland's and Chyba's claims have been supported by Edouard Machery (2012), who argues that it does not really matter whether the notion of life is considered as a folk concept or as a theoretical concept. Either way, the biologists and other theorists, whom Machery calls "life definitionists," have "wasted a lot of time, energy and money that would have been better used for other, more useful projects" (2012, 146).

[1] Bopa (2004) catalogues 40 definitions that were suggested in 2002 alone, and Trifonov (2011) lists more than 100 definitions.

Given the ongoing attempts within the life sciences and artificial life to explore and define life, these unusually harsh judgments by philosophers seem puzzling. Are scientists misguided in their attempts to define life, or are the aforementioned philosophers perhaps too strict in their interpretation and appraisal of this activity? We argue that the aforementioned philosophical critique overlooks many important aims of defining life in actual scientific practices by assuming that the definitions of life are seeking necessary and sufficient conditions of life. In so doing Cleland, Chyba, and Machery focus on the classificatory nature of definitions of life, yet this is but one of the uses they can be put to.

In a recent article, Leonardo Bich and Sara Green (Bich and Green 2017) argue against Cleland, Chyba, and Machery precisely from the perspective of scientific practice, but they, too, narrow down the focus by portraying definitions of life as operational definitions. With operational definitions they refer to "the idea that contents of a definition (e.g., the conditions of life) can be operationalised for empirical research, that is, can be built and manipulated and tested in laboratory" (3). This definition is inspired by Fleischaker (1990), for whom "[t]he force of any operational definition is its capability of exhibition in the laboratory" (Fleischaker 1990, 131). While we think that such operational definitions can be important in experimental contexts that require the combination of theoretical insights to experimental procedures, operational definitions can hardly cover the activity of defining life in all its heterogeneousness—and neither do they capture the kinds of definitions that Cleland, Chyba, and Machery are primarily addressing.

We suggest that the attempt of defining life—especially in the context of astrobiology that was the original target of Cleland and Chyba's criticisms—is better understood from three other interrelated perspectives, each of which highlights one particular type of definition of life: First, many definitions of life are *theoretical definitions* that embody and draw together theoretical ideas and experimental results by often employing some focal theoretical concept or idea. Due to the complexity of the phenomenon of life, many theoretical definitions of life seek to align theories and theoretical concepts from different disciplines. They differ from *transdisciplinary definitions*, however, in one important respect: transdisciplinary definitions are not used to argue for any particular theoretical perspective. They are transtheoretical in nature, being composed of general theoretical elements that point toward various theoretical contexts, addressed by different disciplines. In offering an encompassing and very general view into life, transdisciplinary definitions function as communicative means within highly multidisciplinary communities, such as astrobiology. Finally, and also very relevant for astrobiology, some definitions of life are geared towards what can be only indirectly observed. Such *diagnostic definitions* tend to be very sparse, and they function as diagnostic tools, or instructions for scientists on what kinds of signs of life to look for from distant planets.

In what follows, we will first discuss the philosophical criticism of defining life (Section 2). In Section 3, we examine more in detail the three different, above-mentioned categories of defining life through some characteristic examples. Transdisciplinary definitions and diagnostic definitions in search of biosignatures from distant planets are of special importance for us, since it has been suggested that definitions of life might be particularly significant in astrobiology. In the concluding section 4 we briefly discuss classifications in biology.

2. The philosophical critique of defining life

Cleland and Chyba (2002) open their influential article "Defining 'Life'" by lamenting the situation in which, despite decades of attempts and a multitude of diverse definitions, there still "remains no broadly accepted definition of 'life'" (388). According to them, the only way out of this interminable controversy concerning life's definition would be to have, instead, a general theory of the nature of living systems (389). Such a theory would be empirically testable and "delimited by nature rather than by human interests, and concerns" (390). As an illustration, Cleland and Chyba discuss how water became identified with H_2O. Such an identification was first possible with the development of the molecular theory: "[i]n the absence of a compelling molecular theory, attempts at a definition [of water] were doomed to interminable bickering over which sensible properties were essential to water's nature" (391). Yet, Cleland is careful not to identify water with H_2O since such an identity definition would entail a very limited understanding of the molecular structure of water. A more comprehensive understanding of the properties of water such as the triple point or specific heat, would require the employment of further theories within chemistry or statistical mechanics (Cleland 2012).[2]

But does the activity of defining life bear resemblance to pre-theoretic understanding of water? It does not seem to be the case. Despite the heterogeneousness of the definitions of life, they do not primarily refer to *sensible* properties of life as was the case with the pre-theoretic understanding water. The definitions of life, rather, attest to the multitude of theoretical perspectives (see below, section 3.2). But there is another sense in which the comparison between water and life is crucial. Cleland and Chyba argue that the definition of water as H_2O refers to a natural kind that provides a basis for distinguishing water from other molecules, whereas the existing definitions of life do not allow for distinguishing unambiguously between what is living and what is nonliving.

[2] Michael Weisberg points out that defining water as H_2O equates "the natural kind recognized by ordinary language user to scientific kinds" via a coordination principle that does not take into account much relevant knowledge, e.g., isotopes such as the heavy water deuterium D_2O (Weisberg 2006, 1). For a history of how water became identified as H_2O, see Chang 2014.

Cleland's "Life Without Definitions" (Cleland 2012) is an expansion and explication of the themes of Cleland and Chyba (2002, 2010). She explains that definitions "in the traditional logical sense" are definitions in terms of necessary and sufficient conditions, and assumes that this is what various definitions of life aim to accomplish. Furthermore, Cleland claims that most biologists believe that life is "most likely" a natural kind (although she does not offer any evidence for this claim) (e.g., Cleland 2012, 126, 127, footnote 7). Having thus established that definitions of life aim to capture life as a natural kind by singling out its necessary and sufficient conditions, Cleland notes the futility of this task: such definitions are not apt for capturing natural kinds. Cleland of course recognizes that not everyone, who advances a definition of life, has in mind a "traditional" philosophical notion of definition. Scientists also put forth "theoretical definitions," but, according to Cleland, such definitions nevertheless "share many of the defects of traditional definitions and few advantages of *bona fide* scientific theories" (126). In particular, "they closely resemble traditional definitions *in specifying necessary and sufficient conditions* for life based upon current scientific beliefs about life" (ibid., italics added). Thus, in Cleland's view, both "traditional definitions" and "theoretical definitions" offered by biologists are based on a wrong kind of philosophical theory of definitions that identifies them "with descriptions *qua* logical conjunctions of predicates supplying necessary and sufficient conditions for the application of the term" (131).

Theories of meaning and reference aside, Cleland's attack does not boil down to criticizing definitions of life. While she advocates formulating a theory of life instead of definitions of life, she doubts the possibility of such a theory. The reason for her skepticism is not due to the slim prospects of the highly interdisciplinary life sciences ever coming up with *the* theory of life. Rather, the problem is more fundamental in that all of these theories would currently be based on one, possibly unrepresentative, example of life: life on Earth (i.e. the so-called n = 1 problem). Because of this limitation any premature generalizations about the nature of life are more likely to cripple than enable subsequent research, according to Cleland. In arguing this way, she appears to be creating a double bind for future research: any efforts to define life are fundamentally flawed; instead, one should seek a theory of life, except that this is not a good option either, because we only have one instance of life.[3]

Interestingly, Cleland suggests alternative ways of surpassing the n = 1 problem. One strategy would be to search for anomalous systems that resemble terrestrial life, but are neither clearly living nor clearly nonliving. Another related line of research would be to find an example of life that developed independently of LUCA (Last Universal Common Ancestor) (e.g., Lazcano and Forterre 1999). Cleland and Copley (2005) have called for the search of "shadow biospheres" inhabited by microbes that make use of different biochemical and molecular processes than those hitherto known of life: "The possibility that more than one form of life arose on Earth is consistent with our current understanding of conditions on the early Earth and the biochemical and molecular possibilities for life. Arguments that microbial descendants of an alternative origin of life could not co-exist with familiar life are belied by what we know of the complexity and diversity of microbial communities" (ibid., 165). As the quote shows, Cleland and Copley do not seem to be too restricted by the n = 1 problem either, referring to biochemical and molecular possibilities of life.

Edouard Machery offers a philosophical critique of defining life along the same lines as Cleland, although he is attacking definitions of life through a more straightforward philosophical argument. His argument does not rely, like Cleland's, on claims concerning astrobiology, or biology, but can be linked to his more general agenda of concept eliminativism. Machery (2005, 2009) has suggested that the notion of concept should be

[3] Cleland seems too pessimistic since synthetic biology and artificial life study and construct forms of life that do not already exist in the natural world (see e.g. Elowitz and Lim 2010).

eliminated because it is not referring to a natural kind. Instead, the human capacity for conceptual thinking is supported by heterogeneous processes.[4] This argument from heterogeneity features prominently also in Machery's critique of defining life.

Machery claims that "life definitionists" face *a dilemma* of having "to endorse one of the two horns" of either treating life as a folk concept or a theoretical concept. If life definitionists consider the notion of life to be a folk concept, they should refrain from defining it: "[C]oncepts that are likely to be definitions are of a particular nature: Their definitions are *explicitly* known" (2012, 154). Such knowledge amounts to specifying "a set of properties that are taken to be necessary and jointly sufficient for being an instance of the concept" (151). But folk concepts cannot be given such definitions. Life as a folk concept belongs to the same class of concepts as good, justice, and knowledge, on which there are no agreed-upon definitions (153).

On the other hand, if the notion of life is considered as a theoretical concept, the life definitionists face the "embarrassment of riches." Machery points out that the question of life is studied by scientists coming from different disciplines, and addressing diverse questions. It is far from clear that the different disciplines would end up with the same definition—that was already pointed out by Sagan, who distinguished between physiological, metabolic, biochemical, genetic, and thermodynamic definitions (Sagan 1970). Such a richness of perspectives is, according to Machery, "a hard blow for the life definitionists […] for appealing to the relevant empirical sciences instead of relying on a folk concept of life was supposed to be the royal path toward *the* definition of life" (159). Although Machery does not suggest that the notion of life should be eliminated, an attempt to define it should certainly be abandoned.

[4] For a discussion of natural kinds and concept eliminativism, see Pöyhönen (2014).

In conclusion, Machery recreates the picture already painted by Cleland. According to both of them, definitions of life are misguided because of the aim to give necessary and sufficient conditions for the concept of life. This is bound to fail for philosophical and scientific reasons. As for the philosophical reasons, the notion of life cannot be given a definition because the idea of defining a concept in terms of necessary and sufficient conditions is based on an erroneous theory of how concepts such as life acquire their meaning. From the scientific perspective, this activity is not successful, since it does not lead to a univocal definition of life, either because different scientific perspectives lead to different definitions (Machery), or those definitions do not succeed in classifying concepts according to natural kinds (Cleland). The obvious question to be asked, then, is whether definitions of life really do strive to give necessary and jointly sufficient conditions for what the concept of life amounts to? Or might they, as already indicated, serve also some other purposes?

3. Definitions of life in astrobiology

The reason why Cleland, Chyba and Machery suppose that definitions of life aim to give the necessary and sufficient conditions for the concept of life is based on their assumption that these definitions are primarily classificatory devices. As such, they would need to categorize various kinds of entities as either living or nonliving. Such a classification task would include deciding whether viruses belong to either living or nonliving things as well as excluding purely physical/chemical phenomena from the extension of the definition of life, or incorporating all biological phenomena within it. The perceived importance of such a classificatory task explains why for Cleland a theory of life should capture a natural kind, and why Machery thinks that the existence of multiple, partly conflicting definitions of life should be a hard blow for life scientists. But the situation seems not to worry the scientists themselves that much. For example, in an introductory essay to the special issue of *Astrobiology* on defining life David Deamer notes: "Even the simplest micro-organisms are extra-ordinarily complex, and dictionary-style definitions do not easily encompass such diversity" (Deamer 2010, 1001). So, something else seems to be at stake.

The crucial thing to note is that there are different types and various uses of definitions of life, among which the classificatory purposes are not even the most important ones. In the literature one can distinguish, we suggest, at least three types of definitions of life that do not primarily serve classificatory purposes: theoretical definitions, transdisciplinary definitions, and diagnostic definitions.[5] In what follows, we will discuss examples of each of the three types of definitions of life by focusing on their specific characteristics. The bulk of the discussion is on the transdisciplinary and diagnostic definitions of life because they can be more readily understood in terms of necessary (and sufficient) conditions.

3.1 Theoretical definitions

Many definitions of life are presented in particular theoretical contexts and do not differ from other theoretical definitions in science. Moreover, they can take various kinds of theoretical and epistemic roles. In this section, we focus on such characterizations of life that supply a synoptic theoretical vision through employing some focal theoretical idea or concept. To exemplify how theoretical definitions focalize a particular theoretical perspective on life, we discuss two definitions of life that rely, respectively, on the seemingly opposing ideas of autonomy and cooperation as the core of biological organization.

[5] This list is not exhaustive. We do not, for example, consider "operational definitions" (Bich and Green 2017), since our primary interest is in astrobiology, where the experimental work in the laboratory is not so central as in many other biological sciences.

One important theoretical question with respect to biological organization concerns the connection between individual and collective levels. The individual level entails, among other things, a metabolic system together with genetically encoded information. This information instructs metabolic processes and is passed on to the next generation. The collective level in turn addresses selection and evolution. The definitions of life introduced by Ruiz-Mirazo, Peretó, and Moreno (2004) and Dupré and O'Malley (2009) align individual and collective levels in nearly contrasting ways with different implications as to what should count as living.

Ruiz-Mirazo, Peretó, and Moreno (2004) define life, "in a broad sense of the term" as "*a complex collective network made out of self-reproducing autonomous agents whose basic organization is instructed by material records generated through the evolutionary-historical process of that collective network*" (ibid., 339). This definition of life takes inspiration from Francisco Varela's definition of a minimal living organization in terms of autopoiesis.[6] Autopoietic systems are "networks of processes of production (synthesis and destruction) of components such that these components: (i) continuously regenerate and realize the network that produces them, and (ii) constitutes the system as a distinguishable unit in the domain in which it exists" (Varela 1979, 75). Even though they find this definition very appealing, Ruiz-Mirazo et al. criticize it for being too abstract. The definition does not specifically relate to biology, and most importantly, it does not take the evolutionary capacities of organisms into consideration.

Ruiz-Mirazo et al. (2004) expand on Varela's definition by distinguishing between the individual level comprised of the organization of an organism and the collective level of a network of interactive organisms. A further extension to Varela's definition is provided by a

[6] Tibor Gánti (2003) also developed a model of a minimal autonomous biological system, which he called chemoton.

more concrete account of metabolic systems. The self-maintaining system capable of self-producing—i.e. an autocatalytic system—lies on the individual level, whereas evolution takes place on the collective level. Ruiz-Mirazo et al. argue that, for an organism to be autocatalytic on the individual level, it needs to be enclosed by a semi-permeable active boundary through which energy can enter the system and become converted into ATP.[7] The endeavor is interdisciplinary: Ruiz-Mirazo et al. explicitly refer to theoretical insights from, for example, non-equilibrium thermodynamics, as well as to a body of experimental results within biochemistry and molecular biology.

What happens if one applies the definition of life advocated by Ruiz-Mirazo et al. to borderline cases such as viruses? According to their definition viruses would not count as living, because they are not forming autonomous, metabolic wholes as required by the view of metabolic systems as autocatalytic systems. The requirement of metabolic wholeness need not be, however, an inevitable part of a definition of life as shown by John Dupré's and Maureen O'Malley's collaborative understanding of life. They view life "[…] as a continuum of variably structured collaborative systems" (1). From the collaborative perspective, viruses would count as living even though they do not possess a metabolic system by themselves, but instead make use of the metabolic systems of their hosts. Viruses and hosts engage in collaborative relationships: "[…] matter is living when lineages are involved—directly or indirectly in metabolic processes" (Dupré and O'Malley 2009, 1).

The conceptual change from competitive to collaborative relationships between biological systems opens up an interesting new perspective on our perception of life. Cooperation between organisms may be much more common than has been earlier granted (Roughgarden 2009). Peter Godfrey-Smith (2016) has argued that there are no autonomous organisms as such in nature. All organisms, from microbes to multicellular organisms engage with their

[7] Adenosine Triphosphate (ATP) is the molecular unit of intracellular energy transfer.

organismal and other environments. For Dupré and O'Malley, metabolic networks are not autonomous but shared systems instead. This means that selection does not work on a network consisting of individual autonomous systems, but on a network of collaborating individuals. Their notion of collaboration comprises cooperation as well as competition—competition and cooperation are "points on a continuum of collaboration" (1).

In conclusion, Ruiz-Mirazo et al. (2004) and Dupré and O'Malley (2009) present apparently contrasting perspectives on the nature of life based on their respective notions of autonomy and collaboration. Accordingly, the boundaries between living and nonliving are also drawn differently. As we have seen, for instance, viruses count as living according to Dupré and O'Malley, but do not count as such according to Ruiz-Mirazo et al. However, in the discussions on the nature and origin of life, life is usually considered as being both a historically and synchronically transitional phenomenon (e.g., Lange 1996, Tsokolov 2009). Borderline cases do not, therefore, necessarily imply that the two approaches could not be, at least partly, complementary—and this is underlined by the fact that both the autonomy-based and collaborative notions of life have difficulties in explaining some important, although different, biological phenomena. The use of conflicting models is commonplace in scientific practice and there is no reason to expect that the use of theoretical definitions would differ in this respect. Be that as it may, the way the definitions of Ruiz-Mirazo et al. and Dupré and O'Malley are built around some central general concepts shows that their primary goal is not to identify a set of properties that would conclusively settle whether a certain thing should be considered as either living or nonliving.

3.2. Transdisciplinary definitions

Instead of being built around a focal concept encapsulating a particular theoretical perspective, many definitions of life appear as collections of properties. These definitions are the main targets by Cleland, Chyba, and Machery, as they combine several general properties into the form of one statement, or present them as a list of properties. According to the "traditional" descriptivist view, "sense determines reference," and so meaning has been identified with necessary and sufficient conditions determining the referent of a term or a proper name. Applied to defining life, this means that the conjunction of necessary and sufficient conditions given by a list of properties could tell whether a particular entity falls under the extension of "life." Cleland, Chyba, and Machery have provided a convincing case that definitions of life cannot accomplish what classical definitions are supposed to do—but the question we wish to raise is whether most definitions of life are even aiming at anything like this.[8] Namely, the properties that many definitions of life ascribe to life are of a very general and theoretical nature, with heterogeneous disciplinary origins. The seven pillar definition of life introduced by Daniel Koshland (2002), and the so-called NASA definition of life exemplify such heterogeneous transdisciplinarity.

Koshland's seven pillar definition of life presents a list covering the "essential principles—thermodynamic and kinetic—by which a living system operates" (2002, 2215). The seven pillars are named Program, Improvisation, Compartmentalization, Energy, Regeneration, Adaptability and Seclusion, and are abbreviated as PICERAS. The first pillar *Program* describes the organization of an organism (i.e., its entities and interactions between them) that is encoded in the DNA. The second pillar *Improvisation* stands for the ability of organisms to adapt to changes in the environment via mutation and selection. The third pillar

[8] Other philosophical explanations for what definitions as collections of properties are attempting to do are provided by the cluster theory that has its origins in Wittgenstein's (1953) discussion on "games," and homeostatic property cluster theory of natural kinds (Boyd 1991). Neither of them supposes that property-clusters would give necessary and sufficient conditions in the classical sense. Cleland (2012) argues that the cluster theory "rejects a definitional understanding of natural kinds" (135), and that Boyd is "using the term 'definition' in a nonstandard way" (136). In other words, Cleland's criticism concerns definitions making use of necessary and sufficient conditions. She regards these kinds of definitions as "standard."

Compartmentalization refers to the organization of organisms into compartments, or modules, with different chemical processes and functions. The fourth pillar *Energy* is a key ingredient for a self-maintaining organism. Organisms are thermodynamically open systems, which means that they are non-equilibrium systems. Such systems are able to develop dissipative structures and self-organize by being connected to the environment, which provides energy in order to keep the system within a non-equilibrium state (Prigogine 1961). The fifth pillar *Regeneration* describes the ability of organisms to reproduce elements that need to be replaced from time to time such as kidney proteins and brain synapses. The sixth pillar *Adaptation* entails the processes by which organisms react to changes in the environment. The last pillar *Seclusion* means that metabolic reactions do not interfere with each other. This is ensured by enzymatic specificity.

It is difficult to see how the seven pillars could furnish necessary and jointly sufficient conditions for distinguishing some entity as living or nonliving. First, the different pillars are meant to capture general *principles* by which a living system operates. In order to think of them as properties that would help to identify some particular entity as living, the pillars would need to be much more specific. Such specification would require a lot of theoretical and empirical articulation, and even in this case it would still be difficult, if not impossible to say what, for example, Improvisation would amount to, concretely, at the level of entities we might encounter. Some other pillars, like Energy, in turn, point to a huge array of diverse theoretical perspectives across different disciplines (see below). Second, the pillars are interconnected in a myriad of ways. Because of the aforementioned characteristics it is difficult to think of the seven pillars in terms of separable properties, or simpler, or better-defined concepts, the conjunction of which would succeed in fixing the extension of the concept of life.

The second example, the so-called NASA definition of life, provides another example of such general, transdisciplinary definitions. The NASA definition of life has the following form: "Life is a self-sustaining chemical system capable of Darwinian evolution." (Joyce, 1994).[9] Different from Koshland's list definition of life, the NASA definition covers some general properties of life into one statement. The NASA definition is a clever arrangement of two parts, whose overt simplicity masks a lot of theoretical considerations. The first part, the property of being self-sustained[10] is not exclusive to biological systems but can also be found in crystals and other physical phenomena, so another part is needed. Enter the Darwinian evolution: Only biological systems allow for natural selection as a key mechanism of evolution. According to Steven A. Benner, Darwinian evolution is "the only way matter can become organized to give the properties that we value in living systems" (2010, 1022). The formation of dissipative structures on the basis of non-equilibrium thermodynamics observed in physical and chemical systems is not enough for biological systems to emerge. Life is different because of Darwinian evolution acting on self-sustaining chemical systems (see also Sagan 1970). According to this reading, Darwinian evolution provides a bridge between physics, chemistry, and biology. It allows complex systems to persist in a changing environment via the molecular genetic information passed on by Darwinian evolution (Mullen 2013).

Although it might look as if the NASA definition offered two necessary and jointly sufficient conditions of life, the definition is once again too general, and theoretically ambiguous in character. Benner prefers to talk about "definition-theories," rejecting explicitly the idea that definitions of life would provide any necessary and sufficient conditions for it.

[9] The NASA definition was developed in a panel organized by NASA in 1992.
[10] In this definition, the notion of self-sustaining, instead of self-maintaining, is used.

He explains: "What do we generally do when reality is too complex to meet our constructive needs: we ignore it and continue with a simpler, if arguably false view" (2010).

Not all scientists have been as enthusiastic as Benner about the NASA definition, and one reason is due to its ambiguity. While biologists have a good understanding of Darwinian evolution, the same does not apply to the notion of self-sustaining. The NASA definition does not explain how exactly should it be understood, and whether or not self-sustaining and Darwinian evolution are overlapping notions (Tsokolov 2009). However, this kind of conceptual ambiguity also applies to many other definitions of life and their component notions, e.g. energy, organization, order, autonomy, and complexity. Depending on the theoretical background they will have different meanings. And this is true of many scientific concepts even in more restricted senses and bounded contexts. Putnam's discussion of kinetic energy furnishes a good example (Putnam 1962). Depending on the theoretical framework—classical mechanics or relativity theory—the concept of kinetic energy is defined by the equation $E_{kin/class} = \frac{1}{2}mv^2$ or $E_{kin/rela} = \left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right)$. In both of these cases, kinetic energy will still generally be understood as energy due to motion, but the various roles the notion of kinetic energy plays in different theories and laws enriches its semantic content. And the polysemousness becomes much more radical when the scope is widened to cover the meanings of the term "energy" in a multidisciplinary setting. Energy is a central concept not only in physics but also in chemistry and biology, and their subfields. "Energy" and the other very general notions used to define life in the seven pillar and the NASA definitions suggest that their main intended task is not classificatory.

Of what use, then, could such general definitions of life as the seven pillar and the NASA definitions be? We call them transdisciplinary definitions in order to highlight their role in bridging different theoretical and disciplinary perspectives through the use of general concepts inhabiting various fields of study. The concepts used by transdisciplinary definitions are typically transtheoretical in that they abide in the intersection of different theories and disciplines.

The notion of a transtheoretical term was introduced by Shapere (1969). Putnam (1973) endorsed the notion instead of his earlier "cluster-laws,"—which he discussed with regard to kinetic energy—and took transtheoretical terms to be "terms that have the same reference in different theories" (197). Shapere used "electron" as an example of a transtheoretical term. At different times, in different theoretical and experimental settings, scientists such as J.J. Thomson and Richard Feynman used the term "electron," yet ascribing different properties to it. Shapere's understanding of transtheoretical terms is wider than that of Putnam's: "Electrons can thus be understood as 'transtheoretical', something about which we can have competing theories, without assuming that there is either a common meaning or *a common reference of the term 'electron'*. (1982, 22, emphasis added)[11]

Depending on the perspective, the properties ascribed to entities, and even the entities themselves, falling under a transtheoretical term can change; a characteristic feature of transtheoretical terms is their interpretative openness. Yet, the ambiguity of many general concepts featuring in transdisciplinary definitions do not just render such definitions as defective classificatory tools, they also have their productive side. Because of their interpretative flexibility, transdisciplinary definitions function as valuable heuristic tools. For example, to take up the notion of self-sustaining once more; self-sustaining processes may include metabolic processes, self-replication, reproduction, mutability, and heritability. Depending on their interests, scientists can include different kinds of entities and processes in

[11] For a detailed account of the development of the various theoretical representations of electrons, see the book *Representing Electrons* (Arabatzis 2006).

the range of these concepts, and hence transdisciplinary definitions are capable of drawing together various lines of research.

In highly interdisciplinary research fields like astrobiology, the communicative function of transdisciplinary definitions is equally as important as the heuristic one. Although scientists with different disciplinary backgrounds most probably have different understandings on what processes should be subsumed under, for example, the notion of self-sustaining, such notions and the definitions including them nevertheless offer some common ground. Transdisciplinary definitions and their parts provide scientists valuable tools that are plastic enough to coordinate and articulate different perspectives, functioning much like *boundary objects* between scientists coming from different fields (Star and Griesemer 1989).

To conclude, even though the seven pillar and NASA definitions do not provide in their generality and interpretative openness theoretically and conceptually unambiguous definitions of life, they nevertheless function as valuable heuristic and communicative tools for the exploration of different aspects of life. But as this short discussion has shown, the theoretical insights, empirical background knowledge, and other epistemic benefits that transdisciplinary definitions have up their sleeves are not easily readable from these definitions alone. As a result, their further articulation involves a lot of theoretical and experimental work.

3.3 Diagnostic definitions: Detecting biosignature gases

Several scientists have suggested that while biologists usually do not need a definition of life to do fruitful research, the situation is different when it comes to astrobiology (e.g., Luisi 1998; Chodasewicz 2014). The scenarios they have in mind are comet material returned to Earth by the Stardust Mission 2007, or Viking missions to Mars 1975–1976, during which robotic experiments on Martian soil were performed. The results of these missions and experiments raise the question of what should be identified as life, and how to deal with the n = 1 problem. The paradox of the situation is that, for a sufficiently general definition of life, we need an example of life, which is of a different origin than life on Earth. Yet in order to identify such a life as life, a definition of life already has to be in place. While this question may seem pressing with regard possible life on some planets in our own solar system, the research on life at exoplanets in other solar systems cannot deal with life directly, but only through biosignatures. Given this situation, does exoplanet research make use of definitions of life?

A common strategy in the exoplanet research makes use of minimal definitions of life relying, for instance, on an assumption that all living entities possess a metabolic system. As we have seen, this particular property of life can be part and parcel of more encompassing transdisciplinary definitions, like the NASA definition. We call such definitions diagnostic, because they are closely tied to what could possibly be detected and measured and, as such, geared towards "signs of life"[12] instead of life itself. Some particular signs, or biosignatures, can enable scientists in making the diagnosis that there might be life on a certain exoplanet. Analogies to metabolic processes known from Earth provide the basis for these diagnostic definitions, yet astrobiologists also make use of other kinds of knowledge from physics, chemistry, and biochemistry. Sara Seager, a well-known astrobiologist, argues: "All life on Earth makes gas products, and *basic chemistry suggests the same will be true of any other possible biochemistry*" (Seager and Bains, 2015, 6, emphasis added).

In making use of diagnostic definitions, scientists attempt to causally link the measured molecules in the atmosphere of planets in our solar system, as well as in exoplanets, to some

[12] Lange (1996) distinguishes between the concept of life and "signs of life" that are "neither individually necessary nor jointly sufficient for living" (231). According to Lange certain things display a given "sign of life" because they are alive, while nonliving things may display them for other reasons.

metabolic processes of possible extraterrestrial life. The measurements depend critically on the distance between the planet and the measuring device. Our knowledge and empirical data about atmospheric and environmental conditions on planets in our solar system is much richer than on exoplanets, which are located outside of our solar system. In the case of exoplanets[13] the exploration of hypothetical scenarios plays a much greater role. Such scenarios are based on a combination of known or expected properties of exoplanets, data gained from observations on planets in our own solar system and theoretical frameworks based on a multitude of scientific disciplines such as physics, chemistry, and biochemistry. In the next section this multifaceted research practice will be discussed in more detail.

3.3.1 Searching for life on exoplanets

The difference between the attempts to detect life on planets in our solar system and planets outside of our solar system manifests itself in the distance between us and those exoplanets. The nearest exoplanets are about 15 pc (1 par second = 31 trillion kilometers) away from Earth. Analogies to conditions and life on Earth cannot be drawn on the basis of direct measurements like in the case of detecting methane in the atmosphere of Mars. The research of exoplanets focuses on the exploration of *possible* conditions on these planets that becomes the basis on which reasoning about the potential existence of life is based. Firstly, in considering the habitability of exoplanets, the large diversity of exoplanets in terms of their masses, sizes and orbits, should be taken into consideration. Moreover, planet specific conditions such as clement temperatures, water, a rocky surface and the existence of an atmosphere are crucial (Seager 2013). Astrophysics provides the necessary methods and tools

[13] Exoplanets are planets located outside of our solar system orbiting stars other than our Sun. The first exoplanet was detected 1992 (Wolszczan and Frail 1992). By September 6, 2017, already 3,513 confirmed exoplanets in 2,618 solar systems have been found. https://exoplanets.nasa.gov

for the calculation of these properties, which in turn provides some important clues on conditions on exoplanets. For example, the distance of an exoplanet to its star allows for an estimation of the temperature that is critical when it comes to the question of whether water could possibly exist on the exoplanet. Computer simulations are used to study other possible existing and past conditions for life on exoplanets. In those computer simulations, by making use of theoretical elements from climate physics, astrophysics, biochemistry, geochemistry, and molecular biology, scientists address different aspects of the environment forming conditions for life, such as the interior composition of the planet, its surface and atmosphere and the processes taking place in them. The simulations are distributed among different research groups, each specializing on different methods, tools, and phenomena. For example, modeling possible atmospheres of an exoplanet means modeling complex dynamical processes such as convections and turbulences. Such phenomena are well known and have been studied extensively in the context of fluid dynamics. This coincidence on the phenomenological level allows astrophysicist to make use of concepts, methods and techniques from the research of fluids (Heng 2017).

Computer simulations give some insight on what kind of biosignatures to expect under given conditions. Biosignatures of molecules such as methane or oxygen could be identified by what is called the transit method. It makes use of the fact that when an exoplanet transits the star it is orbiting, it blocks some of the light from the star. This is shown by a dip in the light curve of the star. This method only became available with space observatories like Kepler 2009. Once a new exoplanet has been found, astrophysicists want to know if the exoplanet possesses an atmosphere. In case such an atmosphere exists, the light from the star will pass through the atmosphere generating absorption lines in the spectra of the exoplanet. In principle, it is possible to infer from these absorption bands the presence of biosignature gases. But in order to draw any further conclusions from the spectra, more detailed knowledge about the composition of the exoplanet's atmosphere is needed. This knowledge is indispensable for an interpretation of the measured spectra because the absorption bands will not exclusively result from biosignature gases but also from gases from, for example, the early formation of atmospheres such as outgassing or the gravitational capture surrounding protoplanetary nebula (Seager 2014). Astrophysicist Seager is very clear about this point: "However, we must be able to characterize exoplanet atmospheres to make any progress." (Seager and Bains 2015, 2).

In the research on biosignatures, the conditions in the exoplanetary atmosphere are considered more important than the measurements of actual absorption lines of biosignature gases. Here the computer simulations play an important role, as we have seen. But these computer simulations do not stand alone. They are related to measurements on atmospheres of exoplanets such as Hot Jupiters, which are close enough so that measurements via spectroscopes are possible (Charbonneau et al. 2002). In the exploration of *atmospheric conditions* astrobiologists and astrophysicists compare, for example, the measured spectra to simulated cloud-free spectra in order to see if clouds could have an effect on the absorption of the light coming from the star. These measurements are difficult, time intensive, and expensive, and the signals are very faint. Some progress will most likely be made by the space telescopes, such as the James Webb Space Telescope, which is expected to be launched in 2018.

As our discussion of detecting possible life in exoplanets shows, diagnostic definitions of life form but a part of an interrelated fabric making use of sophisticated detection technologies and simulations, empirical data from the research of metabolic processes on Earth, and theoretical knowledge on general physical, chemical, geological and biochemical processes. All of these theoretical, hypothetical and empirical elements, provide some further guidance in the quest for signs of and atmospheric conditions for life. Two questions concerning diagnostic definitions qua definitions remain to be answered. First, do diagnostic definitions qualify as actual definitions? The answer depends, of course, on what counts, philosophically and scientifically, as a definition—a question to which we cannot give an answer within the confines of this paper. Nevertheless, the property of all living things having a metabolism, a property on which the search for biosignatures depends on, is part of most (if not all) definitions of life. So, second, do such diagnostic definitions make use of at least *one* necessary condition of life, lending some support to Cleland, Chyba, and Machery's claims concerning the aims of defining life—and also to Cleland's criticism concerning the Earth-centrism of the definitions and theories of life. We will briefly discuss these questions in the next, concluding section.

4. Some notes on classification

We have argued that the recent wholesale attack of philosophers of science on definitions of life is at least partially unfounded (e.g., Cleland and Chyba 2002, 2010; Cleland 2012; Machery 2012). What is at stake here is whether or not the enterprise of defining life is by and large a futile endeavor as Cleland, Chyba, and Machery claim. Their criticism of defining life is based on two interrelated assumptions. First, the basic function of definitions of life is classificatory, aiming to distinguish between living and nonliving entities. Second, in order to assist life scientists in such a classificatory task, definitions of life attempt to spell out the necessary and sufficient conditions for unambiguously applying the notion of life. In response to these claims, we studied several different definitions of life in order to show, on the one hand, that they have many other uses than classificatory ones. On the other hand, the closer look at these definitions revealed features (e.g., generality, ambiguousness, and minimality), which do not easily comply with the goal of presenting sufficient and necessary conditions for entities falling under the notion of life.

Obviously, many definitions of life can also be used for classificatory purposes—we consider definitions of life as multifunctional tools at best, although different kinds of definitions have different enablings. How should one, then, proceed in such classificatory tasks? Cleland and Chyba suggested looking for a natural kind in an analogy to the case of water. However, there are important differences between chemistry and physics, on the one hand, and biology, on the other. Natural kinds in chemistry, such as chemical elements, and in physics, such as elementary particles, allow for a unitary classification because their "essences" can be identified. Gold provides a classic example. It has the atomic number 79 that allows for the classification of chemical elements with that number as gold. The atomic number provides the "essence" for deciding whether an element is gold or not. The word "essence" seems legitimate in the case of atomic numbers, because they are spatio-temporally unrestricted, unchanging, and intrinsic.

Organisms are different, as shown by the example of species. They have supplied a paradigmatic example of natural kinds in biology. Yet a biological species is subject to evolution and natural selection, and changes over time. Consequently, "if members of biological taxa vary over time, and across populations, it is not at all obvious that there is a single set of essential properties that are necessary and sufficient to be that kind of thing" (Richards 2016, 43).[14] In the same vein, Philip Kitcher (1992) has observed that there are many complicated and interesting relations between organisms that could be used to define a species. Hence, "there is no unique relation, which is privileged in that the species taxa it generates will answer to the needs of all biologists and will be applicable to all groups of

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[14] Kelly Smith (2016) also argues that definitions based on necessary and sufficient conditions form a logical ideal that misrepresents biology reality.

organisms" (317, see also Khalidi 2013). It is indeed striking how the concept of species has been variously understood and employed in biological research. Like the notion of life, it defies any unique general definition. And the phenomenon of life, even more than that of speciation, bears a high degree of structural, as well as dynamical complexity. It thus seems that any attempt to define a set of properties that would unilaterally decide whether an entity is living or nonliving is not likely to succeed. But could the situation be different with respect to a more modest aim, that of providing necessary condition(s) of life?

One might want to argue that instead of providing necessary and sufficient conditions, definitions of life only attempt to spell out some general characteristics of life in the form of necessary conditions of life. In fact, there have been attempts to find out whether the various definitions of life would converge (Trifonov 2011). There is some initial plausibility to the idea that definitions of life could provide necessary conditions of life, once it is recognized that there are some fairly constant characteristics across contemporary definitions of life. Metabolic processes—independent of their specific form—as well as the fact that organisms take part in evolution, are pivotal parts of many, if not most, current definitions of life. Moreover, many definitions seek to link conceptually or theoretically these two processes, one of which grants the self-maintenance and self-repair of an organism, and the other one its evolution over time.

We saw how one crucial difference between the theoretical definitions of Ruiz-Mirazo et al. (2004) and Dupré and O'Malley (2009) concerned precisely how the boundaries of the metabolic processes of living things are drawn. NASA's working definition of life, in turn, makes self-sustaining—which can be understood in terms of metabolic processes—and Darwinian evolution, the two tiers of life. Koshland's seven pillars definition contains more components, but of these pillars *Energy, Regeneration, and Adaptation* are linked to the metabolic system of an organism. *Improvisation*, in turn, takes place on the level of evolution. That living things possess a metabolism and undergo evolution comprise central parts of all definitions discussed above except for the diagnostic definition for biosignature gases, which only concentrates on the requirement of metabolism. Thus, one could claim that anything that qualifies as living should satisfy at least these two conditions, but that does not yet provide sufficient conditions.

Of all the definitions we discussed, only the diagnostic one relying on gas products of metabolic processes is actually used in detecting non-terrestrial life. The status of such a definition in the search for biosignature gases should thus be revealing as to how central defining life is for finding life. The possible life on exoplanets is only accessible through indirect measurement of biomarkers linked to possible metabolic products such as oxygen and methane in the atmospheres of exoplanets. But as important as the signs of life are, the study of non-signs of life are equally as crucial in astrobiology. There are usually a number of different biochemical as well as geochemical processes that those biomarkers could result from. Thus, in focusing, more broadly, on the habitability of the exoplanet, astrobiologists aim to narrow down the various possibilities. The study of non-signs of life has important implications for the significance and usability of definitions of life in astrobiology. To avoid false positives, one also needs to understand the inorganic chemistry of the environment. Cleland (2012) discusses the unsuccessful *Viking* experiments on Mars. In her view, the problems were due to misguided definitions of life. This may partly be the case, but the moral of the story does not lie only in too Earth-centered definitions or theories of life. Rather, instead of attempting to look for life directly, relying on this or that theory or definition of life, one might do better in relying on a broader theoretical approach (see Catling 2013, 97). It is precisely this broader interdisciplinary and transtheoretical framework for the study of life that many definitions of life aim to offer.

Acknowledgments

We are grateful to the two anonymous reviewers of this journal for valuable and constructive comments on the previous version of this paper. This research was supported by the Academy of Finland, grant no. 290079 and the Center for Space and Habitability (CSH) at the University of Bern.

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