# Habitability is a binary property

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# Habitability is a binary property

Researchers are debating whether habitability is a binary concept or not. We propose that the habitability of environments is a continuum defined by a series of binary questions.

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The term habitability pervades the astronomical and astrobiological literature[1], so its meaning is important. A point of debate is whether the claim that an environment is habitable is an assessment that lies across a continuum or whether it is a binary (yes or no) decision[2–6].

A non-binary view has been unequivocally stated in *An Astrobiology Strategy for the Search for Life in the Universe* by the US National Academies of Sciences, Engineering and Medicine[7]. It proposes that: “Due to the complexity of interactions between physical, chemical, and biological parameters and processes, habitability is not a binary property but is best thought of as a continuum of degrees of habitability.” It concludes that: “The definition of habitability is an environment’s ability, or inability, to support life, which can be misinterpreted as a simple yes/no proposition.”

In contrast, here we propose that habitability is a binary concept at a fundamental level. Consider an environment with respect to one microorganism. The environment either can support the metabolic activity of that organism at some minimum level of maintenance or it cannot. This is a thermodynamic threshold set by the available free energy in the environment and the energy required to repair and maintain a cell[8] (assuming that all other nutritional requirements for that organism are met). An environment, for that specific organism and at a specific time, cannot be ‘partially habitable’ as it either meets this threshold or it does not. Furthermore, for a population of organisms to be maintained, they must be able to reproduce, placing an additional thermodynamic threshold on the environment.

If we wanted to assess the habitability of a particular environment, we could consider a large range of organisms and go through each of them asking whether that environment is habitable for each of them, yes or no. In this way, we would build up a series of binary answers. These binary answers are not independent. For example, in syntrophy, one microorganism’s waste is another one’s food. Ecosystem interactions mean that the habitability of an environment to a given organism will depend on the other organisms present, including competitors and predators. Nevertheless, for a given organism within that system, the habitability of the environment is a binary question.

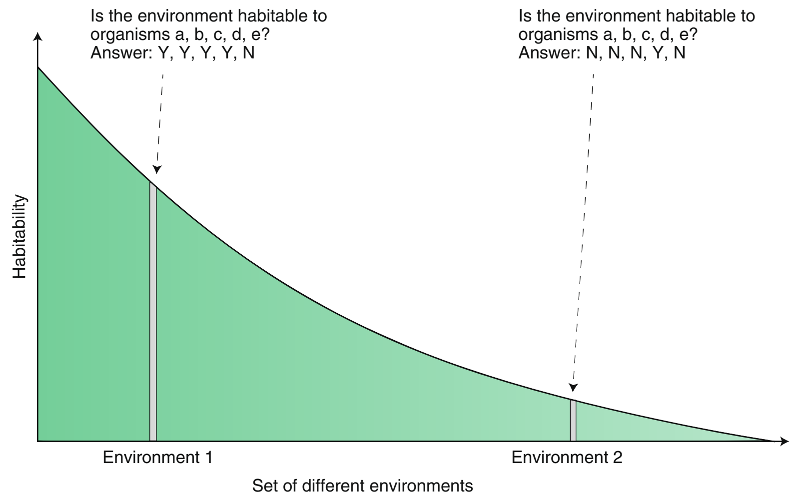


**Fig. 1 | Habitability continuum derived from a series of binary states.** The habitability of an environment can be assessed as a continuum, but each point on that continuum represents the integration of a series of binary questions about whether the environment will support a given set of organisms. In this example, where different environments are examined, environment 1 can be described as ‘more habitable’ than environment 2 because it can support a greater diversity of life. Environments can be ordered on a scale from more to less habitable, where the *y* axis corresponds to the number of species (species richness).

By integrating all of these answers, we derive a continuum (Fig. 1). ‘More habitable’ environments are those where the question “is this environment habitable to a given organism?” returns a greater number of yes answers than ‘less habitable’ environments. We can therefore define environments, even planets, as being ‘more’ or ‘less’ habitable across a continuum derived from binary states.

In theory, to complete this assessment comprehensively, we would have to consider all known organisms. Our capacity to assess habitability will always be stymied by the known existence of organisms for which there is no, or limited, physiological data, our lack of knowledge about how terrestrial organisms would respond to exotic alien environments, and the question of whether there are entirely alien biochemistries that might alter the currently known requirements for habitability. Thus, the assessment of habitability is circumscribed by the state of biological knowledge and it is always open to improvement.

There are two specific ways it is possible to misunderstand habitability as being non-binary. First, if some of the required physical and chemical conditions for life are met, for example, a carbon source and liquid water, this may suggest that an environment is partially habitable. However, if only some of the requirements for an organism to be sustained are met, the environment will be uninhabitable to it. Second, consider that any organism has a probability of successfully being supported by any given environment. A probabilistic distribution could be viewed as a continuum of habitability. However, that probability distribution either exists for the environment in question, allowing for the possibility of an organism being sustained, or it does not. The fundamental habitability of the environment remains a binary property.

The binary view also applies to environments as they change over time[9,10]. These changes could be local, such as a change in the activity of a fumarole, or at the planetary scale, such as alterations in plate tectonics. Environments can change on timescales of seconds, as fluid flow through a rock fracture changes, for example, or over millions of years, caused by long-term climatic cycles, for example. As these changes occur, the type and number of organisms for which the question "is this environment habitable?" returns a yes will change. Thus, temporal changes in the habitability of environments can also be represented as a continuum. For a single environment, the *x* axis in Fig. 1 can be replaced by a time axis.

As environments change over time, they may become uninhabitable to a particular organism, or perhaps uninhabitable to all life. A completely uninhabitable environment is merely one that returns the answer no to all binary questions of whether it is habitable to any known organism. Uninhabitable states are not necessarily permanent. For example, organisms could remain viable but inactive (for example, sporulating microorganisms) and could start reproducing again if environmental conditions become more clement. This transition can be understood in binary terms.

These assessments are regularly carried out by ecologists. They do not usually speak about habitability, but rather they assess biomass or different metrics of diversity. On Earth, environments are colonized by many organisms[11], although a single-organism ecosystem has been reported[12]. Ecologists count the number of organisms present in a given set of samples, for example by DNA sequencing, to determine the species richness of that environment. This ecological analysis is essentially a direct integration of the yes answers to the binary question of whether the environment is habitable to a particular set of organisms.

The binary view similarly underpins how astronomers and planetary scientists assess the habitability of exoplanets and Solar System bodies. When these scientists describe a planetary body as being potentially habitable they are saying, in shorthand, "we have assessed that this planetary body, in at least one of its environments, across some defined time period, would return a yes to the binary question of whether it is habitable for one or more organisms".

In the case of exoplanets, knowledge about surface conditions is usually limited and thus an assessment of habitability is made for the whole planet. The assessment is usually predicated on the detection of some, but not all, of the basic requirements for life, most often water. Hence, the 'habitable zone' is the volume around a star where surface liquid water can be stable on a planet. This definition is misleading, since more than liquid water is required to sustain life[13]. Thus, although the habitable zone is fundamentally a binary concept in that it addresses whether liquid water can be stable or not, our lack of knowledge about the other requirements for life means we cannot usually make a complete binary assessment of habitability. Nevertheless, the habitable zone is a useful first-order way to identify potential planetary bodies for which further investigation is warranted.

Thus, the astronomical concept of habitability is congruent with the ecological one. Both ecologists and astronomers are attempting to carrying out an integration of a binary question, but are using different approaches. In the case of Earth-based ecologists, direct access to, and sampling of, the environment of interest is usually possible. In the case of astronomers and planetary scientists, the biological potential of an environment must be assessed remotely using telescopic methods of observation or additionally robotic analysis in the case of Solar System bodies.

Once we find an environment that can support organisms, we can ask a wide range of non-binary questions. For example, we can investigate the quantity of sustainable biomass. Ecologists determine the stability of ecosystems and whether there are keystone species that control interactions between organisms, among other things. These questions fall into the purview of population or community ecology[14]. As studying environments that host life includes quantifying these ecological characteristics, then the topic of planetary habitability in its broadest scope can include these non-binary assessments.

In conclusion, we believe that habitability is binary at a fundamental level. Once an environment has been established as supporting life, a series of non-binary questions can be asked about that life. Understanding the binary and non-binary aspects of habitability is likely to help advance clarity in the use of this term. ❐

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