**HOW TO DO IT** 

# What Is Life? An Activity to Convey the Complexities of This Simple Question

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#### **A**BSTRACT

"What is life?" This deceptively simple question lies at the heart of biology. In this activity, students work in groups to come up with their own definition using a set of prompting cards that differs for each team. In doing so, students gain an appreciation of the complexities of addressing this question. The activity takes approximately 60–90 minutes to complete, but students often discuss its implications for weeks afterward. This activity successfully engaged freshman undergraduate students and could easily be adapted to high school and even elementary school students.

**Key Words:** Life; defining life; astrobiology; origin of life.

What is life? Life is the object of biology, yet its definition is somewhat elusive. A study of the origin of life quickly highlights the need to define what constitutes life from nonlife. At what point in evolution on the primitive Earth did a series of chemical reactions become something that we would consider "living"? In an RNA World, would

an RNA molecule be sufficient for life (Woese, 1968; Gilbert, 1986)? If Wächtershäuser's hypothesis of the origin of life is correct, would a series of organic chemical reactions near deep sea vents constitute a life form (Wächtershäuser, 1988, 1990, 2000, 2006)? Similarly, as we search for life on other worlds,

how will we know when we have found it? It is possible that extraterrestrial organisms will not have DNA, or recognizable cellular structures, or other characteristics that distinguish life on Earth. This is to be expected because all life on Earth shares a common ancestor and has inherited many of its characteristics. We should define life in the broadest terms so that when we encounter an entity on another planet or moon we will know whether to classify it as alive or non-living (McKay, 2004).

Intuitively, most people have a sense that they can recognize life, even if they cannot articulate how they make this distinction. In this regard, they are like Supreme Court Justice Potter Stewart who coined the famous phrase "I know it when I see it" (Gewirtz, 1996). Most biology textbooks list properties that characterize living organisms on Earth, which include but are not limited to the following

characteristics: metabolism, replication, evolution, responsiveness, growth, movement, and cellular structure. In the 1940s, the physicist Erwin Schrödinger identified one of the notable features of life as the tendency toward greater order, in seeming defiance of the second law of thermodynamics (Note: The laws of physics do hold in living systems, as this order comes at the cost of expended energy) (Schrödinger & Penrose, 1992). NASA uses Joyce's definition of life as "a self-sustained chemical system capable of undergoing Darwinian evolution" (Joyce, 1995). In the book *Biogenesis*, more than 48 different authorities each suggest a different definition of life (Lahav, 1999). The lack of agreement reflects the complexity of answering this seemingly, intuitively, simple question. The problem is compounded by the fact that we are attempting to define life having a sample size of one, since all life on Earth is descended from a common ancestor.

The goals of this activity are to force students to (1) articulate what differentiates living from nonliving entities, (2) test their defi-

nition against a variety of examples that may challenge their ideas, (3) identify which characteristics are necessary and sufficient to define life, (4) appreciate the complexities of establishing a definition of life, (5) evaluate their definition against the ones suggested by specialists, and (6) consider whether living and

nonliving should be considered discrete categories. This activity was carried out with freshman undergraduate students to great success (defined as student engagement, informally assessed by the level of participation in class discussions). This activity could easily be adapted for a high school or even an elementary school audience. This activity takes a minimum of 60–90 minutes to complete.

## O Methods & Materials

Prior to undertaking this activity, the instructor should prepare two series of cards. On each card labeled "A" is an image of an organism that is alive, along with its name (for an example, see Figure 1). An instructor may choose to include any organism that is considered undisputedly alive. A list of the organisms used by this author is

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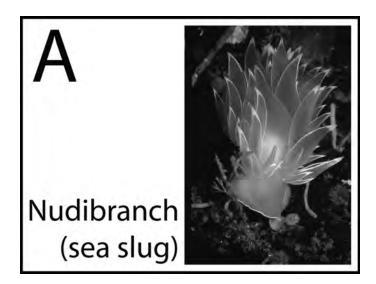


Figure 1. Example of a card in the "A" series (living organisms).

included below. Each card should be different, and there should be as many cards as there are students in the class. All cards labeled "B" contain an image of an object that is not alive, along with its name. The choice of objects is left to the instructor, but they should be selected such that objects share at least one of the characteristics often attributed to living organisms. For example, a crystal could be considered to have the property of replication; fire might be considered to have metabolism; a dead animal or canned meat will harbor DNA and have cellular organization. As many different cards should be created as there are students. A list of the objects used by this author is included below.

Begin the activity by asking students to contemplate why we need a definition of life. Some reasons are suggested above from the fields of astrobiology and origin of life. Students have also suggested that a clear definition of life is necessary for medical applications (deciding whether someone should be kept on life support, noting when someone is legally dead, potential applications in abortion debates), as well as in the field of artificial intelligence or synthetic biology (assessing whether a new form of life has been created). Inform students that the goal for this activity is for the class to come up with a definition of life that is broad enough to include all known life on Earth and that could be used as a guideline to determine whether an object on another planet is alive. Students are grouped into teams of three.

Each team is given a random set of three cards from the A category and a random set of three cards from the B category. Each group will therefore have a different set of six cards. The instructor may choose to explicitly mention that the A cards contain pictures of living organisms whereas the B cards contain nonliving organisms, though students will probably conclude this on their own. The students are tasked with identifying as many characteristics as possible that are shared by all of the objects on their A cards and not by those on their B cards. In other words, their task is to identify as many commonalities as possible among all living organisms, in such a way that does not characterize the objects depicted on the "nonliving" cards (it excludes them). This exercise can easily take 15 minutes.

In a whole-class discussion, ask each team to describe one characteristic of life that was identified in their discussion. The instructor

should write the team's characteristic on the board for all students to see. Each team should examine their cards to verify whether the characteristic would fit their three A cards and none of their three B cards. If the list of objects depicted on A and B cards was carefully chosen, for most of the characteristics, one team will object to the characteristic. For example, if a team lists "cellular structure" as a characteristic for all living objects, a team with the taxidermied moose head or Spam or canned tuna might object on the grounds that their nonliving object also shares that characteristic. The instructor should write on the board all of the teams' characteristics, but make an asterisk or otherwise note whenever another team raises an objection. This part of the discussion can easily take 30 minutes.

Once each team has shared all of their characteristics, the instructor should ask whether there is any one characteristic that would be necessary or sufficient to determine that something is alive. If no one characteristic is sufficient, would two suffice? If so, which two? The instructor may at this point bring up the NASA definition of life, which states that metabolism and evolution (and therefore replication) are sufficient properties. Do the students feel that these two characteristics are sufficient to determine whether something is alive? All teams should look at their cards. According to the NASA definition, would all their A objects be considered alive, and all their B objects considered not alive? Can they think of something that demonstrates both properties that is not alive? The instructor should lead students to consider how the NASA definition of life, which is quite broad, classifies a mule, which cannot have offspring and evolve. Is it alive?

The instructor can then bring up the idea that although for practical reasons we would like to have a definition of life, it may be more realistic to think of life as a continuum rather than as a discrete category of living versus nonliving. This is an ideal time to bring up the concept of a virus, and discuss where it fits within the context of life. Perhaps the distinction of the living and nonliving is a false dichotomy. It is quite possible that the chemical evolution of life on Earth was a gradual process with no clear boundary between what we might unanimously consider nonliving (geochemistry) and something we all recognize as living (biochemistry). In the author's experience, the students find this concept very thought provoking and continue to talk about this idea throughout the course. A stepwise outline of this class activity is provided below.

#### Additional Exercises

Three ideas are suggested as follow-up assignments to this activity. In the first, done in class, students compare their own definition with those proposed by experts. The instructor provides a card containing a different definition of life to each team (for sample definitions, see Table 1). Each team evaluates whether the expert's definition would properly assign the objects on their A and B cards to living and non-living categories. Students also compare their assigned definition with the class definition of life. Each team presents its conclusions to the whole class for further discussion.

In the second activity, students research one of the following controversial discoveries: nanobacteria (Young & Martel, 2009), the "fossilized Martian bacteria" observed on the meteorite ALH84001 (McKay et al., 1996), or Craig Venter's 2010 announcement of the first creation of "synthetic life" (Gibson et al., 2010). Students review the claims made by the researchers who announced the discovery. Do

Table 1. Definitions of life.

Author	Definition of Life
Bedau & Packard (1991)	We propose to [] view life from a more global, statistical perspective. No single molecule of gas has a macroscopic property like temperature; temperature is meaningful only for a large population of molecules. Similarly, no single organism exhibits indefinitely ongoing life []. From a global perspective, only the complex web of interacting organisms – the entire biosphere – remains "alive" in the long run, through the continual cycle of birth and death of individual organisms. [] An organism is alive only if it is a member of an actively evolving biosphere.
Harold (2001)	Life is first and foremost a microbial phenomenon. [] Living things display complex organization [] they carry out metabolism (energy generation in particular) reproduce their own kinds, and have functional parts adapted to their environment. [] Life is a quality or attribute of entities that meet the criteria. They come in a vast range of shapes and sizes, from Escherichia coli to the blue whale, but the minimal units that meet all the criteria are microbial cells, both prokaryotic and eukaryotic.
Joyce (1995)	Life is a self-sustained chemical system capable of undergoing Darwinian evolution.  [Definition adopted by NASA]
Kauffman	Life is an expected collectively self-organized property of catalytic polymers.
Korzeniewski (2001)	Life [] is defined as a network of inferior negative feedbacks (regulatory mechanisms [in the service of sustaining the identity of the individual – any deviation from some parameter sets in motion a series of steps to get back to the default value, like a thermostat]) subordinated to (being at service of) a superior positive feedback (potential of expansion [i.e. replication]).
Koshland (2002)	There are seven pillars of life: a Program (an organized plan), Improvisation (a way to change the program), Compartmentalization (a means of separating self from the outside world), Energy (to fuel chemical reactions), Regeneration (to repair and replace itself), Adaptability (to respond to the environment), and Seclusion (to insulate chemical reactions from one another).
Langton	Life is a property of form, not matter, a result of the organization of matter rather than something that inheres in the matter itself. Neither nucleotides nor amino acids nor any other carbon-chain molecule is alive – yet put them together in the right way, and the dynamic behaviour that emerges out of their interactions is what we call life. It is effects, not things, upon which life is based – life is a kind of behavior, not a kind of stuff – and as such it is constituted of simpler behaviors, not simpler stuff.
Margulis & Sagan (2000)	Living organisms are autopoietic systems. [In other words, they make more of themselves]
McKay (1991)	Life is a material system that undergoes reproduction, mutation, and natural selection.
Morales (1998)	Living things are systems that tend to respond to changes in their environment, and inside themselves, in such a way as to promote their own continuation.
Nealson	Life can be recognized by what it does: living organisms create hallmark molecules and create chemical disequilibrium.
Pace (2001)	Life is a self-replicating, evolving system based on organic chemistry.
Schrödinger (1992)	Living matter is that which avoids the decay into equilibrium. The second law of thermodynamics says that entropy (disorder) always increases. Living things are highly ordered and seem to go against the second law of thermodynamics; however, they can only do this at the cost of increasing the entropy in the environment around them.
Trifonov (2011)	Life is self-reproduction with variations.  [Trifanov identified the commonalities in 150 definitions of life to get to this idea]

Notes: This table contains some of the proposed definitions of life. There are many more, and instructors should consult Lahav (1999), McKay (2004), or Hazen (2006) for additional ideas. The definitions can be broadly grouped into those that favor a focus on reproduction/evolution, metabolism, thermodynamics, the biosphere (ecosystems), complexity, or "other." The definition supplied for Ken Nealson was obtained from "Classification of Living Things" (University of California, San Diego, 2002), Kauffman's definition was cited in Lahav (1999), and the one for Chris Langton came from Adami (1997).

the organisms fit a definition of life? How so? Students write a twopage paper wherein they espouse a clear definition of life and where they summarize the evidence that the finding is alive or not alive.

The third suggestion is a reflective assignment that consists of asking students to first research the literature for other ideas on what

constitutes "life." Suggested texts include Erwin Schrödinger's published lectures, *What is Life?* (Schrödinger & Penrose, 1992); Robert Hazen's summary article on this topic (Hazen, 2006); the introductory chapters of the book *Astrobiology* by Plaxco & Gross (2006); and the book *Biogenesis* (Lahav, 1999). Students may also wish to

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explore the contributions of astrobiologists, origin of life researchers, philosophers, lawyers, and artificial- or synthetic-life experts. The assignment is to write a one-page synopsis that summarizes their thoughts on the definition of life, inspired by the variety of different perspectives explored through this activity.

### List of Organisms Used in Card Series A

The following organisms are considered undisputedly living by most biologists. In addition to their name, the description of some organisms also contains a brief comment, to draw the students' attention to a particular feature of the organism.

- Polar bear
- *Tyrannosaurus rex* (the animal, not the fossil!)
- Homo sapiens
- · Cancer cell
- Nudibranch (sea slug)
- Lichen
- Seaweed
- · Palm tree
- Seedless orange tree
- E. coli
- Diatom
- · Genetically modified corn plant growing in a field
- · Syphilis bacteria
- Giardia
- Red blood cell (these cells have no DNA and cannot replicate)
- Mule (infertile offspring of a male donkey and female horse)
- Worker bees (sterile caste)
- Yeast
- Bed bugs
- · Human sperm cell
- Infertile human couple
- Human with suicidal thoughts
- Frozen frog (in "hibernation" all processes halted)
- *Mycoplasma genitalium* (must live inside a human cell; otherwise it dies)
- Chlamydia bacteria (can replicate and survive only inside a mammalian cell)

## List of Organisms Used in Card Series B

The following organisms are considered nonliving by most biologists. These objects were selected because they share at least one of the characteristics typically used to describe living organisms in biology textbooks.

- Atomic bomb
- Soap bubbles
- · Taxidermied moose head
- · Frost on a window
- Lava
- Star

- Car
- Fire
- Compass
- Smart phone
- Crystals
- · Dead tree
- Cloud
- Lake
- · Petrified wood
- Snowflake
- Salt
- · Canned tuna
- Spam
- Computer virus
- · All-Bran cereal
- Tornado
- Hurricane
- Lightning
- Clay
- Prion protein (proteins that can trigger other proteins to fold improperly like themselves)

## Outline of the "What Is Life?" Classroom Activity

- Step 1: Instructor preparation. Print the A and B cards.
- Step 2: Whole-class discussion. Why do we need a definition of life?
- Step 3: Form teams of 3 students.
- *Step 4:* Small-team work. Each team picks 3 A cards and 3 B cards and identifies characteristics present in all A cards but not in B cards.
- Step 5: Whole-class discussion. Each team contributes one characteristic of life. Instructor writes characteristic on board. Other teams comment on whether the characteristic would fit with their card set.
- *Step 6*: Whole-class discussion. Which characteristics are necessary and/or sufficient for life?
- *Step 7*: Whole-class discussion. Compare class definition of life with NASA definition (metabolism and evolution).
- Step 8: Whole-class discussion. Are life and nonlife a continuum rather than discrete categories? (e.g., Is a virus alive?)
- *Step 9*: Optional. Select one of the additional activities, in-class or out-of-class.

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