NATIONAL CENTER FOR CASE STUDY TEACHING IN SCIENCE

What Is the Meaning of Life? In Search of an Answer

by

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> *What is the characteristic feature of life? When is a piece of matter said to be alive? When it goes on "doing something," exchanging material with its environment, and so forth, and that for a much longer period than we would expect in inanimate piece of matter to "keep going" under similar circumstances.* — *Erwin Schrödinger*

> *A living organism ... feeds upon negative entropy. Thus the device by which an organism maintains itself at a fairly high level of orderliness (= fairly low level of entropy) really consists in continually sucking orderliness from its environment.* — *Erwin Schrödinger*

> *I'd look for an entropy reduction, since this must be a general characteristic of life.* — *James Lovelock*

> *[T]he general battle for existence of living organisms is not one for the basic substances—these substances are abundant in the air, in water and on the ground—also not for energy that every body contains abundantly, though unfortunately in a non-available form, but for entropy which becomes available by the transition of energy from the hot sun to the cold earth.* — *Ludwig Boltzmann*

Part I – What Is the Meaning of Life?

John: Hey Dave, Mary, did you hear that story on the news about a big breakthrough in the search for life in the universe? They said they've found Earth-like planets in the habitable zones of their parent stars.

Dave: Yeah, I did, and it sounds like it's an important step forward. But when you're searching for extraterrestrial life, you have to remember that we don't yet have a definition of "life" that everyone agrees on. So it's unclear what it is that we're looking for.

John: Why do we need a definition? Isn't it just obvious that some physical systems are living when compared to their non-living backgrounds?

Dave: Well, no, not really. And without a definition, how do you know exactly what you're looking for? Isn't there a risk that you'd fail to recognize it even if you stumbled upon it? Or maybe just the opposite; maybe you'd think that some non-living system was actually living. No, what you really want is a definition of life that includes everything that we all agree is clearly alive, and at the same time excludes everything that we're confident isn't. But actually it's even more complicated than that, because a good definition should at least cover life forms that we haven't yet discovered here on Earth; and maybe even extraterrestrial life forms, which could be very different from life as we know it. The definition will need to separate clearly what is essential for life anywhere in the universe from what is an incidental result of the history of life on Earth.

John: What do you mean by an incidental result of the history of life on Earth?

Credit: Cosmic Buddha meditating on the Flower of Life, © Nikki Zalewski | Dreamstime, ID 103431000.

Mary: Let me try to explain. Imagine a city in which all taxicabs are painted yellow. The city doesn't allow for a taxicab to be of any different color. It's a particular shade of yellow. And the city also mandates that only taxicabs are allowed to be painted yellow; no other car can be yellow. So someone who lives in this city could define a taxicab as a yellow car. And this definition would work fine for this city. But there are two problems with it. The first problem is that it really misses the essence of "taxiness." The second problem is that the definition could be confusing if you visited another city in which taxicabs were a different color, say black.

John: I still think that we could get a good definition by looking at obvious cases of living and non-living systems.

Dave: Well, go ahead, give it a shot. How would you define it then?

John: Let's see, for starters, I'd say that life is the quality that separates a vital and functional being from a dead body.

Mary: That definition is similar to what you could find in a dictionary. But from a scientific point of view, it's not very useful. It explains the word "life" as it is commonly used, but it's too vague to be helpful. It refers to a quality that separates life from non-life, but it doesn't say anything about what that quality is.

Dave: I agree with Mary. Along the same lines, you could say that life is the period between birth and death. But as Mary just pointed out, while useful for some purposes, for our purposes it's not very helpful. I could perhaps go a little beyond that, and say that something's alive if it can be born and can die. I think this is no longer a definition similar to what can be found in dictionaries, and I like that it captures the fact that anything alive must eventually die. But it's still too vague to help us identify a living system, especially if it's unlike anything we've seen before, which extraterrestrial life might be.

John: I'm thinking about the properties that all living systems have in common. All life forms grow, metabolize, and reproduce. They also respond to stimuli and are ordered and organized, and manage to keep themselves in a relatively stable or steady condition. So I'd define a living system as something that does all those things.

Mary: I think that life is more a process than a system. But isn't this definition too broad? It allows for many things that we would normally not consider as living to fall under the definition. For example, fire or crystals can grow, but they aren't living. Fire, again, or cars metabolize in some sense of the word. I mean, fire doesn't just spend energy, but uses it in order to grow and reproduce. Fire also uses the same chemical process that we use when we metabolize. Fire takes organic molecules and uses oxygen to convert them into carbon dioxide, water, and excess energy. In a living organism we call this process cellular respiration, and the organic molecule which is used is glucose. Fire burns anything organic though, not just glucose.

Dave: A mule is living but it can't reproduce. A computer virus can reproduce but it isn't alive. A cyclone has order, but it's not living.

Mary: And a thermostat responds to stimuli. A ball at the bottom of a bowl remains in a stable homeostasis, if I may use the word in this context, but it isn't living.

John: Fair enough, you can think of a counterexample to anything in the definition I proposed. So perhaps it isn't good enough. What other definitions can you propose?

Mary: NASA has a working definition, the Joyce definition. As a biology major I got to work on a summer research program for undergrads at NASA. It was a project on astrobiology, the science of life in the universe. NASA defines life as a "self-sustained chemical system capable of undergoing Darwinian evolution." I think that's a pretty good working definition.

Dave: Well, let's examine what's assumed with this working definition. For starters, it assumes life is chemical; but that would exclude possible life forms that might be, say, electronic. What if you had robots that could build factories that make other robots? Perhaps you could also include some software that allows for some advantage for better performing variations, and some mechanism that would introduce random "mutations" of code, thereby allowing for Darwinian evolution. Why would we exclude those?

Mary: I'll have to think about that. Go on.

Dave: Another difficulty with the NASA working definition is that it says that life is a system capable of undergoing Darwinian evolution. But Darwinian evolution isn't a property of an organism, it's a property of the lineage, of the population, of the species, etc. The NASA working definition confuses a living entity with a life form. The living entity is chemically self-sustained, whereas it's the life form that undergoes Darwinian evolution. To make it more clear why we shouldn't confuse the two, let me ask you this: is a rabbit alive?

John: Of course!

Dave: But an individual male or female rabbit doesn't reproduce by itself. Therefore, they are incapable of undergoing Darwinian evolution. So according to NASA's working definition, a single rabbit is not alive. Another example is humans. Humans who are too young or too old are unable to reproduce. But both babies and very old people are still alive. A living entity results from Darwinian evolution, but as an individual, it only has the potential to engage in further Darwinian evolution. Moreover, from a practical point of view, it's difficult to verify Darwinian evolution on the time scale of a space mission or of a typical duration of a research project.

John: Yeah, and something else occurs to me that's problematic with this NASA definition; it's stipulative. In other words, it decides to use the word "life" in a certain way. It assigns a meaning to the word; it determines that what is described is called life, and what is not described is called non-life. And this determination can be arbitrary.

Dave: Exactly! A definition of that kind can only be useful or not useful, or be clear or unclear, but it can't be true or false.

Mary: You mentioned electronic-based life. What if somewhere in this universe there are fast electronic-based interactions that occur naturally and that could be lifelike? While I'm thinking if we must exclude those, I'd like to suggest that we want to look for life that is similar to the life we know on Earth. This is a big universe, and maybe someday we could find exotic life forms that are nothing like life as we know it, but I don't think these should be our first things to look for.

Dave: I think that scientists appreciate more and more that life doesn't have to be limited to organic matter. Life doesn't have to depend on water and carbon. There's an extremely speculative but thought-provoking book I read called *Life Beyond Earth* by Feinberg and Shapiro; it considers the possibilities of exotic extraterrestrial life. The authors make the case for exotic life forms that are based on plasmas, electromagnetic field energy, magnetic domains in neutron stars, life based on silicon, or a variety of other bizarre systems.

John: Okay, but what about the other elements of the NASA definition?

Dave: Another element in NASA's working definition is that life grows and sustains itself by gathering energy and materials from its surrounding, which is the essence of metabolism. This is implied by the "self-sustained" part of the NASA definition.

Mary: I don't think there should be much debate over this element. There must be an energy source, and any life must interact with its environment. Here the definition is broad enough because it doesn't specify what kind of energy source or what kinds of materials.

John: We can even classify all life according to its source of energy, whether it's chemical or light energy, and according to its source of material, whether it's from other living organisms or directly from the non-living environment.

Dave: The last element of the NASA working definition is that living entities must display variation. Natural selection of the more fit individuals will inevitably lead to evolution and the emergence of more complex entities.

Mary: Actually, I disagree with the complexity part, Dave. Evolution is random, it has no direction. If less complexity provides better adaptation to some changing environmental conditions, evolution might go in the direction of less complexity. How do you measure complexity of an organism, anyway? The amoeboid *Polychaos dubium* has a genome that includes 670 billion base pairs, whereas the *Homo sapiens* genome includes "only" 3.2 billion base pairs. Is this amoeboid 200 times more complex than humans? Another example: rice has 37,000 genes, and humans "only" 25,000 genes. Is rice more complex than humans?

John: According to this last element of the working definition, a mule is not living, because it cannot reproduce and therefore is incapable of undergoing Darwinian evolution. But this only exemplifies my problem with this working definition. If we were to go to some other planet and find a mule there, should we still say we haven't found extraterrestrial life?

Mary: You will never find a mule on another planet, unless you brought it there yourself, or if someone else did.

Dave: But we know about many unrelated species that adapted to similar environmental conditions in similar ways, and these species did so completely independently of each other. Examples could be the streamlined bodies of sharks and dolphins, say, or the wing structure of pterodactyls, bats, and birds. It's called convergent evolution.

Mary: Okay, so let me qualify by saying not an *exact* mule; that is, not an organism identical to mules in every and all respects. Organisms are the result of very many random adaptations in response to historic environmental and accidental conditions. The chances that those would repeat themselves exactly are so small, that even if they are not exactly zero, they can be considered to be zero for all practical purposes. Aliens are not likely to have the general appearance and body plans of humans either, despite what Hollywood may think, even if you make them slender with big heads. Moreover, if you find a true mule, there must also be horses and donkeys there. So a mule would have to be brought there from Earth, because the chances that horses and donkeys identical to those on Earth would evolve on another planet independently are practically zero. But I reckon there are some gaps in this definition. This is why it's a working definition. Could we perhaps find a better one?

John: Being a chemistry student, I think I'd like to propose an approach that goes around the definition of life itself, and instead defines the chemical elements that life needs. All life forms that we know are based on six and only six elements: hydrogen, oxygen (or their compound form, water), carbon, nitrogen, sulfur, and phosphorous. Perhaps we could find a definition that ties these six elements with energy in a way that would define life.

Mary: But this direction again defines life only as we know it. It too would miss on all the hypothetical possibilities that Feinberg and Shapiro list in *Life Beyond Earth*. Moreover, some years ago there was a suggestion that arsenic could perhaps replace phosphorous.

Dave: That particular proposal turned out to be incorrect, but I think its greater contribution was to make us aware that such exotic cases could in principle exist. I think that if we want to keep all options open, we shouldn't restrict ourselves only to life as we know it, and perhaps should look for a definition based on what life does, rather than what life is made of. As a physics student, I'd like to try to emphasize that living organisms are physical systems. Any life must satisfy the laws of physics, and the laws of physics are the same throughout the universe. The laws of biology are not; not necessarily anyway. Some alien life forms could possibly use something different than DNA for transferring genetic information, and possibly use molecules different than ATP for storing energy, or use arsenic instead of phosphorous, as Mary said. A good definition of life should therefore depend on physical principles, not on biological ones.

Mary: That's very typical of a physicist, Dave, but let's examine this approach. What physical principles do you think a definition of life should include?

Questions

1. What is a working definition? Why does NASA have a working definition for life?

2. Some define life based on properties of life as we know it. The list of properties typically includes: organization, metabolism, homeostasis, growth, reproduction, response, and evolution.
    a. What are each of these properties?

    b. Find counterexamples for each of these properties (other than those discussed in the text).

3. There is ongoing debate whether viruses should be considered living or not. What are the arguments for and against classifying viruses as living organisms? Suppose you analyze data from a spacecraft visiting one of the moons in the solar system, and you identify a virus there. Would you argue you have found extraterrestrial life? Why, or why not?

4. What is a habitable zone, and why is the finding of Earth-like planets in a habitable zone important for the search for life in the universe?

5. Give examples for what the text calls "exotic" life.

6. In addition to the Joyce working definition of life, NASA also uses the Coleman definition, which states that "life is a self-organized system capable of processing energy sources to its advantage." What are the main differences between the two?

7. Mary asks, "What physical principles do you think a definition of life should include?" Before reading Part II, which principles would you suggest, and why?

Part II – In Search of an Answer

John: I'd like to propose that energy is important for life. We can think of a living organism as a machine that uses energy. Perhaps this use of energy from the environment to sustain the system can play a role in a definition based on physical principles?

Mary: That reminds me of the philosophy course I took last semester to for my Gen Ed requirement. Your question follows Descartes, who tried to base the definition of life on mechanisms, as opposed to Aristotle, who emphasized life as animation, or the state of being alive.

Dave: Well, the net energy flow of any living organism—that is, the energy coming in minus the energy going out—has to be zero. More accurately, its average over time must be zero. If it weren't—say if the energy input were greater than the output—the organism would quickly warm up and eventually cook itself to death. The use of energy in itself cannot be the center of a definition. Also, it would bring us back to the question of metabolism that we discussed earlier.

John: What other physical principle or principles can you propose then?

Dave: Well, it's often said that the most important law of physics is the second law of thermodynamics, which states that in any isolated system the entropy always increases, or at the least never decreases.

Mary: But thermodynamics is formulated as the passage from one equilibrium state to another equilibrium state. I don't think that this formulation is appropriate for living organisms, because living organisms are never in thermodynamic equilibrium.

Dave: I agree with you, Mary. But there's also another way to formulate thermodynamics. I mean, approach thermodynamics through cyclic processes. As a fair approximation, an organism cycles its state from one day to another. We wake up in the morning quite similar to our state when we woke up the day before, or to our state when we wake up the day after. There are of course small changes that accumulate over time, but overall, we live on a one-day cycle.

John: Isn't that why you said earlier that it's the average over time of our energy balance that's zero? That is, the average over a daily cycle? After all, right after we have a meal we have a net intake of energy; but right after we finish a jog in the park we have a net outflow of energy.

Dave: Yes. We have a one-day cycle during which we return to approximately the same state. But during the same time the entropy of the environment increases. For example, we use the energy in the food, we warm up, and release heat into the environment. The entropy of the environment doesn't go back to its previous value. Schrödinger said that life feeds on negative entropy.

Mary: So, you're proposing to define life with the concept of entropy. This means that we're also talking about the concepts of orderliness and organization. These concepts are closely related, and again it reminds me of my philosophy class in which we also learned about the German philosopher Kant. You see, Aristotle emphasized animation, Descartes emphasized mechanisms, but Kant emphasized organization. What it sounds to me like you're now suggesting is that the essential thing that separates life from non-life is the preservation or gradual increase of internal order. I think that could be very insightful.

John: Wait a minute, I want to go back to what Dave just said: "life feeds on negative entropy." What does that even mean? When I eat steak, I think I fare much better than if I were to eat negative entropy. I bet the steak is tastier too. Is negative entropy what Schrödinger fed his cat?

Dave: But John, when you're eating steak, you actually *are* feeding on negative entropy. You are keeping your own entropy low, and you must have the energy source and atoms in the steak to keep your entropy low, but then you raise the entropy of the rest of the universe by even more, so that the total entropy of the universe increases. Keeping your own entropy low instead of its natural tendency to increase, while raising the entropy of the environment is a flow of positive entropy from you to the environment. But this is the same as the flow of negative entropy from the environment to you. That's why Schrödinger said that life feeds on negative entropy.

John: But didn't you say before that entropy always increases? How can life be consistent with thermodynamics if entropy is to remain low?

Dave: You just "proved" that refrigerators can't exist, or that a leaf can't grow.

John: I proved what? Of course refrigerators exist!

Dave: Right. And therefore, you were mistaken about life and entropy. The second law only talks about isolated systems. But life is necessarily an open system.

John: Why does life have to be an open system?

Dave: Life has to be an open system, because it needs energy and materials from the outside, and it also should remove waste products to the environment. A refrigerator can keep its temperature cooler than that of the kitchen because there's a constant supply of energy from the outside through the power cord. The entropy of the outside constantly increases while the inside temperature remains lower than that of the environment.

John: I see. A working refrigerator must be an open system to allow for the flow of energy from the outside.

Dave: It's interesting, John, that you mentioned before Schrödinger's cat. Perhaps one of the difficulties with the borderline cases, the cases that are in the twilight of life, is that we tend to think in terms of binary, or true-or-false logic, that something can be either living or non-living, but can't be both at the same time.

John: How can something be both dead and alive?

Mary: Viruses can't reproduce when they are outside the host cell, when they are in the virion phase. I think it's reasonable to say that they are not alive as virions. But they can reproduce in their reproductive phase, when inside the host cell. So in this sense viruses are both dead and alive, depending on whether they are outside or inside the cell.

John: But they are still not non-living and living at the same time!

Mary: Think about entering a house through the door. When you are just passing through the door, can't you say that you are both inside and outside the house? It's a transitional step between the outside state and the inside state. Perhaps we could think of viruses, when transitioning from the virion phase to the reproductive phase as transitioning from a non-living phase to a living phase.

Dave: This is an example to logic that is not made of just true or false statements, it's not binary logic like the classical Aristotelian logic, it's non-binary logic. But there's another type of non-binary logic, and that is to accept that life and non-life are two extremes of a spectrum, and that there could be intermediate states in between. That kind of thinking is called fuzzy logic. It's a similar view to the particle-wave dualism in quantum physics. Particles and waves are two extreme models that we construct, but electrons, say, behave sometimes like one and sometimes like the other, and therefore have characteristics of both. The electron has a property called the de Broglie wavelength that depends on the mass of the electron and on its speed. If the de Broglie wavelength is very short, the electron behaves more like a classical particle. It would be a classical particle when this wavelength is exactly zero. And the longer the de Broglie wavelength, the more wavelike is the behavior of the electron. So perhaps the borderline cases are difficult because our definition for life is binary, but if we allow for non-classical logic, either being both living and non-living or the other possibility of fuzzy logic, the borderline cases could be better understood.

John: But then, if we expand the definition of life to include those borderline cases, we wouldn't need to abandon our binary logic.

Dave: That's exactly what some people have tried to do. For example, to include viruses in the definition of life. There are a number of arguments why viruses should be considered living. One of them, for example, is that viruses can get sick when attacked by another virus, which hijacks the replication mechanism of the infected virus for their own replication.

Mary: Another argument is that sometimes we confuse the virion with the virus when it's inside the host cell, and use the same word, "virus," for both. The infected host cell transforms into a virion factory, that is, into a virus. This virus is alive because it metabolizes and reproduces by producing virions. The virion then is not a virus any more than a sperm cell is a human being. When the genome of the virus is the only one that is expressed inside a bacterial cell, I think we can argue that the infected cell is no more a bacterium, but a virus with a cellular appearance.

John: Okay, let's go back to our discussion of the thermodynamic direction for the definition of life. Let's assume that a definition of life should include an open thermodynamic system and should include the idea of maintaining low entropy. I will not disagree that the flow of negative entropy from the environment is necessary for life, but it still can't be considered a sign of life.

Dave: I'm not so sure about that, John. Let's focus on what life does rather than on what life is. That may be an easier approach to see why negative entropy can be thought of as a sign of life, and under what circumstances. Think of an ice cube. If you put it in a glass of warm water, what will happen?

John: Well, the ice cube would melt, and we would end up with a glass of lukewarm water.

Dave: Yes, and this is Clausius's version of the second law: objects in thermal contact evolve toward a common temperature, what physicists call thermal equilibrium. Heat always flows from the warmer object to the cooler one until their temperatures equalize, but not the other way around. This conclusion is true also for objects made of different substances: say if we put a "plastic ice cube" in the water, they will still get to the same common temperature. Non-living physical systems tend to wind down and come to rest.

John: Why do they have to come to rest?

Dave: They do because if their temperature is the same as that of the environment, there can't be any flow of energy in. It's called a heat death.

John: But the temperature doesn't have to be high!

Dave: Right. But it's called a heat death not because the temperature is necessarily high, but because there cannot be heat flow when the temperatures are equal, and therefore no heat engines can work, no thermodynamic processes can occur. By the way, heat does not mean temperature. Heat is the physics term for the exchange of energy between a system and the environment.

Mary: I agree. But what about living systems?

Dave: What happens if you put a goldfish in the water?

Mary: The fish will just swim there, at least for a while, assuming the water temperature is not too high or too low.

Dave: Yes, the goldfish will not just equilibrate with the water like the ice cube does, at least not within a few minutes like the ice cube, or even hours. It will stay alive, doing something, swimming, exchanging material and heat with its environment.

Mary: If you also add food into the glass, the goldfish will keep going for even much longer.

Dave: Yes. What life does is stave off the natural tendency toward equilibrium with the surroundings. At first glance, the usual properties of life—complexity, organization, metabolism, information processing, reproducing, responding to stimuli, ageing—are nowhere to be found in this definition. But if we start thinking about why organisms are able to keep doing something long after non-living things would wind down, why the goldfish is still swimming long after the ice cube would have melted, we are immediately drawn to the complexity of the organism and its capacity for processing information. The outward sign of life is the ability of an organism to keep going for a long time.

Mary: In what sense are the usual properties of life a consequence of Schrödinger's definition? Say, metabolism. It's a biochemical process. Can you explain how metabolism can be explained using Schrödinger's language?

Dave: Yes! Schrödinger himself said that the essential thing in metabolism is that the organism succeeds in freeing itself of all the entropy it must produce to stay alive. You see, to stay alive, an organism must eat, drink, and breathe. Each of these actions increases the organism's entropy. So how does its entropy remain low? By bringing in negative entropy from the environment. The environment's entropy is increasing, but the organism's entropy remains low.

John: But both living and non-living open systems can maintain their low entropy, at the expense of the increase of the entropy of the environment. If that's so, what is the essential difference between living and non-living open systems?

Dave: Life is a process driving the universe more efficiently toward disorder than non-living processes. Life degrades order and spends energy faster that non-biological processes, and therefore is a more efficient second law machine.

John: But it must be more complex than just that. After all, the second law only tells us that entropy of an isolated system never decreases. It doesn't say how fast entropy increases. Living entities change with the passage of time, they are not just a snapshot of a physical state.

Dave: Right, a better definition of life will have to include also what Mary said, that if we feed the goldfish it will "keep going" for much longer. From a physics point of view, food is simply a supply of free energy, which a living organism can use to power its metabolism.

John: Free energy? Try telling that to customer service of the electric power company when complaining about your bill.

Dave: Free energy doesn't mean you can get it for nothing. It's free in the sense that it's available to be used for some purpose. Gibbs realized that he could use the concept of entropy to cleanly divide the total amount of energy into the useful part, which he called "free," and the useless part: total energy = free energy + useless (high-entropy) energy. When a physical process creates entropy with a fixed total amount of energy, it uses up free energy; once all the free energy is gone, we've reached equilibrium.

Mary: How is this related with Schrödinger's definition of life?

Dave: Life strives to maintain order in the face of the demands of the second law, and it does so in a specific way: by degrading free energy in the outside world in the cause of keeping itself far from thermal equilibrium. At some basic level, the purpose of life boils down to survival: the organism wants to preserve the smooth operation of its own complex structure. Free energy and information are the keys to making it happen.

Mary: When a plant photosynthesizes it decreases the free energy of the environment to increase the orderliness in the plant. And while doing so it stores the free energy in it in the form of the glucose that it produces, which the plant can use at a later time.

Dave: Although sometimes the storage of free energy does happen, that's not the crucial element in the process. The crucial part is the inflow of one kind of energy, the useable energy that's called free energy, and the outflow of low-grade, un-useable energy that's high on entropy.

Mary: But aren't there difficulties with this definition? In addition to ridding itself of the high internal entropy an organism creates to stay alive by feeding on negative entropy, it can also rid itself of the high internal entropy by radiating heat. Isn't that right?

Dave: Can you give me an example of an organism that does that?

Mary: I have to confess that I can't think of one at the moment, but it should be possible in principle.

Dave: That's an interesting idea, a life form that keeps its entropy low by radiating heat. Using Gell-Mann's paraphrase of the Totalitarian Principle, if it is not forbidden it is compulsory. So somewhere in the universe there must be some life form that instead of feeding on negative entropy stays alive by radiating heat. I'll have to think about that one.

Mary: Here's another difficulty. Consider, say, a crystal. When crystals grow, they too take free energy from the environment and create order. They take disordered atoms, and put them in a very highly ordered lattice. According to your definition, Dave, crystals should be considered living.

Dave: We indeed need to have a way to tell apart life from non-life processes that also increase order by ingesting free energy. I'd like to make two points to respond to your example of crystal growth. First, there is a big difference between a crystal, even in a growth phase, and living organisms. The parts of the crystal that already formed do not need any more energy or any additional atoms for maintenance. The boundary of the crystal, where growth happens, may be misleading. The bulk of the crystal is clearly inanimate. My second point is that Schrödinger argued that a living organism could stay out of thermodynamic equilibrium for much longer than we would expect a non-living object under similar conditions. A characteristic feature of life is that it is able to exist for a long time in an improbable state. We could explain crystal growth based just on the laws of physics and chemistry. We don't need to invoke life to explain crystals. When the crystal is not in a growth phase we can explain its orderly structure again by simple physical properties. It remains ordered exactly as we would expect it to. A key element of Schrödinger's definition that is missing in the example of crystals is that, like the goldfish we talked about earlier, a living system stays un-thermalized for much longer than a non-living system would. To distinguish life from other, non-life processes that increase order by ingesting free energy, we need to extend the definition to include this element.

Mary: I'm still unconvinced. How is a crystal then different from a coral reef? The coral too is alive only on the surface, and the deeper layers are dead.

Dave: It's only alive in a figurative sense. The coral reef itself is a non-living calcium carbonate structure. The living parts are large numbers of tiny animals, which build the coral reef. It's a colony, really. The living organism is not the coral reef, but the tiny animals that build it.

John: How is this definition consistent with the other properties of a living system, say, with reproduction?

Dave: A living system increases the number of "islands" where the increase in entropy is delayed. Eventually, any living system would lose its battle against the second law. That's what we usually call death. But it can, before it dies, create other systems that can continue this battle. That is what we would call "reproduction."

John: So we can be satisfied with Schrödinger's definition then.

Mary: Not quite. I think that basing the definition of life on Schrödinger's approach is prone to false positives. For example, take the Labeled Release experiment of the Viking mission. I think it reproduces an improbable event, and also satisfies Schrödinger's criterion of negative entropy. But it is widely considered to be a false positive.

Dave: I disagree. Schrödinger's definition does not say that any system that maintains its low entropy while increasing the environment's entropy is necessarily living. Schrödinger's definition includes a comparison of the candidate system to similar non-living systems. We can determine that the system under investigation is a living system only after we have examined it in detail.

Mary: We are defining life based on a set of exactly one example. Maybe for now, while searching for the first example of extraterrestrial life, it's best to go with the Potter Stewart approach: we will know it when we see it. Maybe we don't have to have a precise definition for now.

Dave: The "we will know it when we see it" approach could be good, except that it limits what we are searching for. The experiments and tests we will design, like the ones on the Viking, will only look for life as we know it. On the other hand, it does not restrict SETI. Perhaps all we can presently say is that life is what the scientific establishment, probably after some healthy disagreement, will accept as life.

Mary: Well then, perhaps we don't know enough about life to define it.

Questions

8. Dave says that "[t]he most important law of physics is arguably the second law of thermodynamics, which states that in any isolated system entropy always increases." Why is this specific law arguably the most important law of physics?

9. How does Schrödinger's approach include reproduction and Darwinian evolution?

10. In what sense is life a "Maxwell's Demon?"

11. Explain the refrigerator and leaf analogy.

12. What disadvantages in Schrödinger's approach can you identify?

13. Give examples of Clausius's version of the second law of thermodynamics.

14. In the reading Dave says, "Life is a process driving the universe more efficiently toward disorder than non-living processes," but then he says that life "staves off" the second law.
    a. Why is there apparent conflict between the two statements?

    b. Reconcile the two statements.

    c. Taking the first viewpoint in this question, why do you think life is successful despite the second law?

15. Gell-Mann's paraphrase of the Totalitarian Principle, "if it is not forbidden it is compulsory," is used by Mary to argue that some exotic life forms must exist in the universe. Explain her reasoning.

16. Dave says, "A characteristic feature of life is that it is able to exist for a long time in an improbable state." Explain.

17. The Viking missions included experiments for searching for extant life on Mars.
    a. What were the experiments done for the Viking missions?

    b. What were their results?

    c. What conclusions could be drawn from these results?

    d. What perspective on the Viking experiments can we gain from later experiments done on Mars by the Phoenix lander in 2008?

18. Dave says that searching for life as we know it limits laboratory and exploratory searches, but does not limit SETI. What is SETI, and why isn't SETI restricted by that approach?

19. Mary suggests that "[m]aybe for now, while searching for the first example of extraterrestrial life, it's best to go with the Potter Stewart approach, we will know it when we see it." What is the Potter Stewart approach? Why does Mary propose it?

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