The Bare Necessities

Several times thus far we have encountered qualities that appear essential to life on Earth. In this lecture we will address them together. We will argue that life needs certain critical chemical building blocks, a source of energy, a liquid environment (although I consider this less fundamental) and reasonable stability. There is also the question about what is necessary to *sustain* life that has already emerged, versus originating life.

Chemical building blocks

Hydrogen, carbon, nitrogen, and oxygen make up 96% of the mass of living organisms on Earth. It is not hard to see why these make good candidates. Their advantages are:

- They have high abundances in the universe. Hydrogen is the most common element around, and although helium is nonreactive the next most abundant elements are oxygen and carbon, and nitrogen is sixth (trailing neon, which is another noble gas and thus nonreactive). Therefore, given at least a couple of generations of stars that have given up their lives to distribute elements heavier than helium, these atoms will be widespread.
- They form strong chemical bonds. This allows the resulting molecules to exist in a wide variety of environments.
- Their chemistry can be complex, especially that of carbon. An apparent key here is that the strength of the bonds carbon makes with other elements is similar to the strength of the bonds it makes with itself. This is not true of, e.g., silicon or any other element to that extent. In addition, carbon has four free bonds, so large numbers of combinations are possible. Nitrogen has three and oxygen two. Carbon, though, can form long chains with itself with single or double bonds, leading to remarkably flexible chemistry.

Other atoms also play essential roles in life on Earth. For example, phosphorus (a critical component of cell membranes) and sulfur are found in every organism we know. Iron is essential in the transport of oxygen in blood, and additional atoms perform a variety of functions. However, I think it is fair to say that we do not know for sure whether these are truly critical for life anywhere, or whether the molecules they form are simply more efficient at some tasks than corresponding ones formed of just hydrogen, carbon, nitrogen, and oxygen.

When considering substitutes for our four critical atoms, we are naturally drawn to atoms with equivalent numbers of atomic bonds. This would suggest silicon for carbon, phosphorus for nitrogen, and sulfur for oxygen. All these do appear in life on Earth, but as primary atoms they have significant problems. First, these are all heavier than the elements for which they might substitute, meaning that their abundances in the universe are much lower. As a result, in any stellar system that has a decent amount of the heavier elements, it is a guarantee that it has much more than that in carbon, nitrogen, and oxygen.

To be open-minded, though, we should note that silicon, for example, is hugely overrepresented in terrestrial planets because it can form grains at the relatively high temperatures that define the zone of formation of terrestrials. Nonetheless, with all the sand exposed on the surface of the Earth we have no organisms whose biology is based mainly on silicon. This may well be because silicon does not bond nearly as strongly with itself as it does with other elements such as oxygen. Therefore, long chains of silicon are harder to produce than long chains of carbon. It also means that although large rocks can in principle be extremely complicated — with defects, inclusions, and so on — this does not easily transfer into information and reproduction because (unlike with carbon molecules) it is difficult to unzip silicon molecules, duplicate them, and rezip them. My personal opinion is that this likely disqualifies silicon from being a serious carbon substitute, even though it does play a role in, e.g., plant life.

Energy sources

The origin and evolution of life obviously requires energy sources. At first glance it seems obvious that life requires sunlight in one form or another. By this I mean that although, e.g., humans could live their entire lives with zero sunlight (you could spend a miserable but viable existence locked in a room if someone fed you and gave you vitamin D supplements), what we eat relies on plants which photosynthesize. It is therefore tempting to argue for the necessity of *sufficient* light, leading us to rule out life on planets that are too far away from their host stars because the $1/r^2$ dimming with distance r reduces the available energy from light.

However, our survey of extremophiles suggests caution with such conclusions. Recall that “endoliths”, which by definition live in rocks, pores between mineral grains, and the like, may well comprise the majority of the biomass on Earth. Since many of them exist deep in rock where no light can reach, they don’t use the Sun’s light directly. They use traces of iron, potassium, and sulfur for food.

We do note, though, that endoliths aren’t exactly the model of complex organisms that might evolve intelligence. They tend to be single-celled, and they reproduce very slowly indeed given the limited nutrients available. Estimates for some endoliths are that they engage in cell division only about once per century! Apparently at least this light-free environment is a dead end for little green men.

Exploring further we remember that deep-sea hydrothermal vents such as “black smokers" have around them pretty complicated ecosystems that include large tubular creatures and not just microbes. We don't know much about the evolution of these systems, and it is possible that life originally evolved to take advantage of the Sun and then opportunistically occupied niches such as those near the vents (although the most recent research has it the other way around; live might have emerged near vents first, then spread out). However, we must allow that life might be able to not just originate, but diversify significantly, even without significant light.

A light-poor environment could obviously exist for a planet sufficiently far from its star, but that's not the only way. Consider a planet that is massive enough that it holds onto a thick atmosphere that prevents the star's light from reaching directly to the ground. Yes, some light will eventually filter down after being absorbed and re-emitted, but it will tend to be lower-energy light (infrared rather than visible). Also, depending on how reflective the cloud cover is, the light received directly from the star could be so minimal that it effectively doesn't add to the energy budget. What then?

As with so much about life in the universe, we can't give a definite answer. We are therefore reduced to speculation, which is fun! My guess is that a planet two or three times Earth's mass at a couple of times Earth's orbital radius might have a reasonable balance of energy: little from its star, but enough leftover heat from formation that it can make up the difference. If the internal heat is too great, of course, we end up with molten lava everywhere that is hot enough to wipe out any biological molecules.

The next option, then, is that the internal heat is *not* left over from the heat of formation. Instead, it could be a situation similar to that of some of Jupiter's moons. Via gravitational interactions between Jupiter and the large moons Io, Europa, and Ganymede, those three moons are squeezed and kneaded enough to produce active volcanoes and lava on Io, a liquid water ocean covered by thick ice on Europa, and (almost certainly) a liquid water ocean under thicker ice at Ganymede. If this tidal squeezing is enough to produce vents at the water-crust interface, might there be complex life at the bottom of those oceans? If so, my guess is that unlike on Earth the life will be confined to near those vents or at least near the bottom of the ocean, because otherwise the energy sources are minimal. It is likely to be a long time before we can find out, because the ice layer on even Europa is believe to be several miles thick and thus drilling will be challenging.

Finally, let's really stretch our minds regarding energy sources. The very first planets discovered outside of the Solar System were not around a regular star. Instead, they were found around a pulsar, which is a remnant of a supernova that packs about one and a half solar masses into a region the size of a city. Their ultra-regular rotation makes them extraordinarily good clocks, meaning that the gravitational pull of even a planet can be detected by the Doppler shift: when the pulsar moves towards us the pulse rate we get is increased, and when it moves away the pulse rate is decreased. Three planets were discovered in this way around the romantically named PSR 1257+12 starting in 1992. The two outer ones are both about three times the mass of the Earth. One is about a third of an astronomical unit (AU) from the pulsar (remember, an AU is the average distance between the Earth and Sun), and the other is about half an AU away.

Tiny though the pulsar is, its spin and magnetic field mean that it puts out about five times as much energy per time as our Sun does. However, instead of coming out as light, most of the energy emerges in the form of protons moving at nearly the speed of light. The planets therefore have plenty of energy; in fact, at that distance there would be too much to allow water to exist as a liquid. But what if we imagined planets farther away? If they were a bit more than 2 AU from the pulsar, they'd get the same illumination that we do. The particles are so energetic they would wipe out any molecule that absorbed them, but could it be that a thick enough atmosphere or strong enough planetary magnetic field could deflect the particles enough to allow the energy to filter down in a more usable form? Could such a situation even evolve into intelligent life? I don't know...

As a final comment on this section, I should mention that some analyses of the conditions for life suggest that it is more specifically conditions of *disequilibrium* that matter. That is, you need variation in temperature, or chemical concentrations, or something to tap into the available energy. If, for example, you are in a homogeneous medium of constant temperature and you don't have more light from one direction to the next, and you are at equilibrium with your environment, you're sunk. This is similar to our previous argument that the universe had to form structure for life to be possible.

Liquids, water in particular

We have emphasized that in environments at too high a temperature complex molecules can't exist. But is it necessary that there be substantial liquids around? For example, Jupiter's atmosphere is gaseous but it contains methane, ammonia, and a number of other promising molecules. Could a gas do just as well as a liquid? Or how about a solid, which would open up the prospect of much colder planets?

Molecular reactions obviously require that the molecules get near each other. Solids are not a good candidate because the atoms are very restricted in their motion. Gases could work in principle but their typically low density and the fast relative motion of the molecules in them make it a bit questionable whether the frequency and complexity of molecular interactions would be enough for life. Still, we can think about the atmospheres of the gas giants (Jupiter, Saturn, Uranus, Neptune) and realize that the density of the gas becomes higher at deeper levels. Perhaps somewhere there molecular interactions are facilitated. Indeed, for a dense enough gas the distinction between gas and liquid is rather blurred.

In my opinion, then, solids are out as the main medium for life but liquids and sufficiently dense gases have to be considered. On Earth it is liquid water that performs several vital roles. It allows transport of molecules and movement of molecules within cells, and mediates or enables most biochemical reactions. In fact, water is special in a number of ways such as:

- Water is the "universal solvent" meaning that it can dissolve more substances than any other liquid. Fundamentally, water has this property because although it is not electrically charged, there is a slight positive charge towards the two hydrogen atoms and a slight negative charge towards the oxygen atom. This makes it a "polar" molecule because it is an electrical dipole. Another polar molecule immersed in water orients itself so that it has attraction with the water, and this molecule is thus dissolved. Water also has a neutral pH, allowing it to dissolve both acids and bases. However, water does not break down nonpolar molecules such as oils, which is a good thing because those are the basis of a lot of important biology! Water's good solvation characteristics allow it to play many important roles, e.g., the transport of toxins out of our body; if they didn't dissolve in water they would accumulate in our body. This is why you can consume gigantic amounts of some water-soluble things (e.g., vitamin C) without serious problems. In contrast, vitamin A is water-insoluble but fat soluble, so if you overconsume it you store it in your body and suffer the effects.
- Water has a high specific heat capacity, meaning that you need to put a lot of energy into it to raise the temperature. This is why coastal areas often have more moderate temperatures than ones far from large bodies of water; compare the climates of Seattle, Washington and Fargo, North Dakota, both of which are at about 47 degrees north latitude. This acts as a moderating influence on temperature throughout the year.
- Frozen water is less dense than liquid water. This is a very rare property for a substance. Whether this is critical to life we don't know, but it does mean that liquid water can remain in a lake even if the surface is frozen.

What alternatives exist to water, in terms of being a good liquid medium? Commonly suggested possibilities include methane, ethane, and ammonia. One potential drawback to these three is that they are only liquid at very cold temperatures. At standard pressures, water is liquid between 0°C and 100°C. Ammonia is liquid from −78°C to −33°C, methane from −182°C to −164°C, and ethane from −183°C to −89°C. Methane is liquid in such a small temperature range than we'd have to be pretty lucky to find it in the liquid form. For the others, though, what is the problem with low temperatures? At first blush it might seem that this simply opens up a wider range where life could exist.

The answer that is usually given is that chemical reactions go more slowly at cold temperatures. For example, consider a piece of paper in your hand. Stare at it. Has it burst into flame yet? Now try putting that piece of paper in an oven; not one at flame temperature, but instead at somewhere in the 400s of Farenheit (sources are mixed about the autoignition temperature). The paper will spontaneously burst into flame because the reactions are fast enough to release energy that heats the paper further, speeding the reactions. The same thing works in reverse: reactions are slow at low temperatures. Therefore, goes the argument, if the temperature is low enough that ammonia or ethane are liquid, it would simply take too long to develop any interesting biochemistry.

Maybe so, but from my perspective this argument isn't complete. After all, vast numbers of reactions occur in our bodies all the time where the temperature "needed" for the reaction is far in excess of our body temperature. The reason they happen is the intermediate action of enzymes (usually proteins, sometimes ribosomes). Enzymes act as catalysts; although not modified themselves, they lower the amount of energy that needs to be put into a system to start the reaction. Could it not be that in colder environments enzymes could play similar and more extreme roles? I think this is open to question, and if so then water is not the only possibility.

Stability and our solar system

A little variation is not a bad thing for life, especially if it occurs over long time scales. Given time, life can adjust and fill the new ecological niches that emerge, and this can even stimulate evolution. However, drastic short-term changes cannot be accommodated so easily, especially by complex creatures. This has led to suggestions that Earth's rotation and orbit are particularly special and necessary for the origin and evolution of life.

For example, Earth's stable and relatively small 23.5° tilt relative to its orbit means that we have mild seasons. In contrast, Uranus (tilted at 97°) would have very extreme seasons except that its large cloud layer redistributes heat effectively. If we were like Mars and had a changing tilt with time, then over millions of years life would have to adjust. This is long enough that I don't think it would be a disqualifier.

The orbit is potentially another story. Earth's orbit, like the orbit of the other major planets, is close to circular. Now, any stellar planetary system has to satisfy the conditions for stability: if planetary orbits cross in a way that can lead to close encounters, the mutual gravity of the planets will lead to ejections eventually. For those of you who wonder: it is true that Pluto's orbit crosses Neptune's, but Pluto is protected from ejection because its orbit takes 3/2 times the time of Neptune's, so the crossing of orbits occurs only when the two are far from each other.

Suppose that we have a system in which the planetary orbits are stable but the orbits are much more eccentric than ours. This is in fact the case in many extrasolar planetary systems. On a particular such planet, the high eccentricity means that the planet is much closer to the star in one part of the year than another; for this planet the seasons really would be caused by changing distance rather than the angle at which rays hit the planet's surface (which is by far more important on Earth). If we imagine a closest distance that is a quarter of the farthest distance, any inhabitants would receive sixteen times more radiation close than far. This would easily span the range between freezing and boiling, and might prevent life from originating or complex life from persisting.

Another aspect of stability involves the host star. Our Sun puts out a nicely consistent illumination over short times. In contrast, lower-mass stars have significant flares. Therefore, life around such a star would have to be able to deal with large fluctuations in the radiation it received. Since complicated organisms are less able to deal with such changes, it might hurt the chances for evolution of intelligent life.

Finally, I should note that some people seem to have a strong desire to show that life on Earth couldn't have arisen naturally, and one of their approaches is to assert that Earth is so specially and improbably placed that it can't have been an accident. Some such arguments are really ridiculous. One of my favorites is the jaw-droppingly absurd argument that Earth's rotation rate had to be just as it is. Why? Because it allows us a perfect eight hours per day to work, eight hours per day to rest, and eight hours per day to sleep. On Jupiter it would be just over three hours each, and hence not productive. Er... might it be that this is how life evolved here? It's a bit like being astonished at the amazing coincidence that when we stand, our legs are each just exactly long enough to reach the ground!