Science Fact

Life, But Not Quite as We Know It?

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Right now, when we're looking for life on other planets or thinking about the origin of life on Earth, most of us fixate on microbes and, in particular, those microbes known as prokaryotes. It makes a certain amount of sense. Little more than a bit of cellular infrastructure set into cytoplasm and surrounded by a semipermeable membrane, microscopic, unicellular beings lacking internal organelles are as simple as life gets and about as prolific. These little critters are everywhere here on Earth and must surely represent the first general form life takes anywhere in the Universe.

But what if we're wrong? What if we're simply horribly biased by our own existence as walking, talking containers of autocatalytic chemical networks driven by our own selfish strands of DNA? What if we're totally overlooking the possibility that life can be something bigger and more cooperative than that? When we finally hit the cosmos, what if the first extraterrestrial life we find is actually a lagoon? Or an entire ocean? Will we be clever enough to recognize it as life? Or will we just wipe it out without realizing it?

Okay, right now, you are probably thinking what on Earth (or elsewhere) is this writer talking about? A lagoon? Or an ocean? As a living entity?

But just such a situation was almost certainly a key step in a hundreds-of-millions-of-years-long process of the origin of life here on Earth. It will very likely also turn out to be the situation for just about any planet upon which life is emerging but hasn't gotten to the point of individual organisms. So maybe we should make sure we'd be able to quickly recognize this if we stumbled across it. And maybe we should already be grappling with the question of whether this stage in the origin of life represents a precursor to life or if it qualifies as life itself.

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The people who study the origin of life on Earth have one of the coolest scientific puzzles to solve: how did rocks, with the help of water, turn themselves into the life that could evolve into the richly lush 120-terawatt biosphere that Earth sports today? You know: the biosphere that is massive, complex, diverse, and powerful enough to be burning through the same amount of energy as twenty trillion sixty-watt light bulbs (assuming that you're old enough to know what those were and can imagine them all on at the same time).

The first part of this puzzle is figuring out how to rigorously define life, because you don't get anywhere with anything until you have set some standards.

If you've ever taken a basic course in biology, you've probably already tried to define life. You've probably also discovered that, although you're enough of an expert to fairly successfully immediately recognize life when you see it, it's tricky to articulate it as a checklist of necessary features. But we can start with the most obvious, which is that living things use energy to get stuff done. Life burns fuel to locomote, twitch muscles, fire neurons, construct macromolecules, and pump ions across membranes to create electrochemical gradients, among countless other things.

But, as intro biology instructors tend to expend energy gleefully pointing out (generally with loud, growling props), chainsaws and motorcycles (not to mention locomotives) also burn energy to get stuff done, and they're not alive. Consuming energy to accomplish specific tasks is a good start, but it's not enough to define life.

Another obvious requirement for something to qualify as life is the ability to reproduce. Here is where trains, chainsaws, and motorcycles fall short, for they cannot create offspring, neither by binary fission (where one becomes two, such as via cell division) nor by sexual reproduction (although that would be interesting). Instead, these machines require teams of designers to draw up blueprints so that people and machines working in factories can churn out new individual machines. But life both contains the information needed for its own replication and carries that reproduction out, asexually in the case of those dividing cells, and sexually in the case of you combining your information with someone else's to create a baby.

But here's where things get sticky with our attempt to define life, because there is such a thing as an autocatalytic chemical set, which is, essentially, a group of interdependent chemical reactions that expends energy to run those reactions and in so doing—here's the autocatalytic bit—constructs all of the basic components needed to build new copies of its chemical infrastructure. Such a set of reactions can grow, in terms of overall mass, as more and more of the molecules it produces accumulate. As these reaction products find each other and engage in new and different chemical reactions, producing a yet wider variety of molecules, the autocatalytic chemical set can even evolve into a more complex autocatalytic chemical network, the reactions therein collectively producing each other's own substrates and increasingly more complex building blocks, all without intervention from what we would traditionally recognize as life.

Here's the difficulty: while such an autocatalytic chemical network can grow, produce its own parts piecemeal, and evolve increasing diversity and complexity within itself, what the network cannot do is reproduce itself as a whole. Thus, the network cannot give rise to further individual networks, much less populations of individual networks that could diverge into totally different species of networks via Darwinian evolution (survival of the fittest and all that). So, is an internally evolving autocatalytic chemical network the size of a lagoon or an ocean *life* or just a mindlessly endlessly sprawling set of increasingly more complicated chemical reactions?

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Before you answer that question, let's consider the origin of life here on Earth. If we stick with that traditional definition of life we were groping toward earlier, life has to have a metabolism, which is the ability to collect and expend energy to run the chemical reactions that are vital to an organism's survival, growth, and reproduction. Something that is alive must also be arranged into a cohesive unit, be that the single, membrane-bound cell of an individual microbe or the multicellular symphony that is a giraffe. Life also has the ability to reproduce itself as that cohesive unit in a way that passes down to the next generation the information needed to construct and run a complete, new individual. Furthermore, this passing on of information needs to be done as absolutely perfectly as possible yet with enough error to enable evolution.

What that leaves us with, in terms of the first and simplest living cell on Earth, is a blob of protoplasm, probably no longer than one millionth of a meter in length, contained within an outer organic membrane that was semi-permeable. Anchored to this membrane would have been the cytoskeletal filaments that ran through the protoplasm, giving this first cell three-dimensional structure and organizing its contents. Although certain molecules, such as carbon dioxide (CO_2) and molecular oxygen (O_2), would have been able to diffuse through the membrane, always moving from an area of higher concentration to that of a lower one, and water could likewise cross via osmosis, everything else would have had to use channels, made of proteins, that had been set into the membrane as it was constructed. To live, this first cell would have carried out basic metabolic reactions to collect energy and then expend it constructing specific molecules. That is to say, it grew, and then, once it was big enough and filled with twice as much of the right stuff, it divided itself into two. All of these chemical reactions were mediated by proteins that had been constructed by RNA molecules whose own instructions for construction were either encoded in RNA or, perhaps at that point already, in DNA, that could be passed on from generation to generation.

In other words, the most basic possible living cell represents a dizzying amount of coordinated complexity. In other, other words, how could water and rocks doing chemistry get to this point? There's such a chasm between free-floating chemical reactions and all the stuff mentioned above bundled up into a package and working together. How did water and rocks make that jump?

This is the central, unsolved problem of the origin of life.

But the ocean, or some relatively enclosed aspect of it, hosting an internally evolving autocatalytic chemical network may very well have been what solved this problem.

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As you might expect from all that had to be developed, united, and synchronized to form the first genuine microbe, the origin of life on Earth took a while. The chemical reactions that led to the life that led to us most likely kicked off around 4.4 billion years ago, and they resulted in the first microbe by roughly 3.5 billion years ago. That's a span of nine hundred million years.

The beginning of the beginning, 4.4 billion years ago, was the Earth stopping being too hellish an inferno after its Moon-forming collision with Theia. Theia, in case you've never been introduced, was a Mars-sized planet that shared the Venus-sized proto-Earth's orbit around the Sun. Theia ran either 60° ahead of or behind the proto-Earth (at Lagrange point 4 or 5), essentially circling the proto-Earth once each full run around the Sun. Although this sounds like a Twilight Zone episode, this configuration was so stable, if the gravity of some big, wandering mass—a Jupiter not yet settled in its orbit, perhaps—hadn't tugged things out of whack, we would still be looking up at a sky today that contains Theia instead of the Moon (and just imagine if Theia had grown not just life, but *intelligent* life of its own . . .).

At any rate, things got wobbly and the two worlds collided with enough violence to fuse them together while simultaneously ejecting enough material to make the Moon. For at least the next ten million years, the surface of the Earth remained molten and the Earth's atmosphere was crushingly thick, containing as it did, not just a lot of vaporized rock, but also the entire ocean. But, by 4.4 billion years ago, things had cooled down enough after the collision for the vaporized rock to have rained out (please take a moment to imagine that) and the entire ocean as well.

In fact, judging from what few scraps of rock we have from this early moment in Earth history, by 4.4 billion years ago, the Earth had even managed to develop, not just a reasonably solid crust, but two chemically—and mineralogically-distinct types of crust (oceanic and continental) and a hydrologic cycle that had already started eroding that tiny bit of continental crust that had been thus far produced. Liquid water, continental crust, and erosion mean that by 4.4 billion years ago, conditions were cool enough and wet enough for the origin of life to have already been underway.

At the other end of the beginning, the oldest definitive evidence we have for life, in the form of convincingly biological chemical signatures recorded in ancient mineral grains, is 3.52 billion years old. Meanwhile, the oldest definitive microfossils, which happen to contain enough discernible internal cellular structure to be identifiable, not just as microbes, but as archaea and bacteria, are 3.47 billion years old. Make of that fifty-million-year gap what you will or nothing at all. Given how rare life was at the beginning, how hard it is to preserve organic microfossils, and how little geologic material we have left from all these billions of years ago, the gap in the ages may not be meaningful.

Either way, it took water and rocks doing chemistry essentially nine hundred million years to create microbial life. Now we just need to figure out *how*.

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The most likely first step in the origin of life on Earth—the invention of metabolism—probably didn't take long—more like weeks to months than nine hundred million years.

In part, this is because metabolism only has two parts, anabolism (a set of reactions that use energy to build up organic molecules) and catabolism (a set of reactions that release energy by breaking down organic molecules). But it is also because, under certain environmental conditions, it's hard to avoid inventing the most basic reactions of metabolism as we know it, starting with reactions that create organic molecules like acetate (H_3CCOO^-) and methane (CH_4) out of CO_2 and H_2. These certain environmental conditions can be found along the periphery of mid-ocean ridges, those long, skinny mountain chains, such as the East Pacific Rise, the Mid-Atlantic Ridge, and the Central Indian Ridge, that run along the bottom of the ocean.

Mid-ocean ridges exist over magma that is welling up from deep within the Earth's mantle. As magma is incredibly hot, seawater sinking down through cracks and fissures in the seafloor on these ridges heats up as it nears the magma chamber beneath the seafloor, eventually becoming hot enough to react with the silicate rock it is passing through. This weathering, as it is known, chemically alters both the rock and the seawater. This changes the solute content of the seawater enough for us to start calling it a hydrothermal fluid. When this hydrothermal fluid finally gets hot enough to become buoyant, it begins to rise, and it escapes back out to the ocean. This escape happens most dramatically at the famous black smoker vents that belch plumes, thick with metal sulfides, of 450ºC (840ºF) liquid near the axis of a mid-ocean ridge.

But these are not the vents we're interested in.

Far more interesting are the less showy, warm alkaline springs located on the sides of mid-ocean ridges. These springs gently seep out hydrothermal fluids that, at 100°C (212°F), are not too hot for life and its associated molecules, at least not in the deep sea where the pressure prevents this water from boiling. Yet the hydrothermal fluids that come out of these warm, alkaline springs are hot enough to have reacted with the silicate minerals of the oceanic crust in what are known as serpentinization reactions. It is these serpentinization reactions that almost certainly kicked off the chemistry that led to life on Earth.

During serpentinization, the heated seawater reacts with a silicate mineral known as peridotite, and the subsequent chain of reactions that occurs produces the minerals serpentine and magnetite as well as giving off H_2. As we know from the outflows from the Lost City warm springs (found on the Atlantis Massif, at the periphery of the Mid-Atlantic Ridge), the H_2 produced by serpentinization quickly reacts with CO_2 dissolved in seawater to produce formate ($HCOO^-$) and methane (CH_4), making them very possibly the first two organic molecules ever synthesized on Earth. That they're so easily created in these hydrothermal systems is exciting because life is both made of organic compounds and requires them to operate and, for the most part, organic compounds are not easy to make. For the longest time, in fact, chemists thought that only that master chemist known as life, with its arsenal of tools like ATP, NADPH, ion pumps, enzymes, and catalysts, honed through billions of years of evolution, could manage it.

The key, in this case, isn't the biology but the catalysts. Deep-sea hydrothermal mounds, being big deposits of metallic minerals that precipitated from hydrothermal fluids as they cooled, abound with minerals that possess catalytic powers. For instance, the nickel-iron mineral awaruite (of chemical formula Ni_3Fe) briefly binds bicarbonate ions (a form of dissolved CO_2) and hydrogen in the water flowing past it, enabling these molecules to react together to form the aforementioned formate. Metallic minerals in these hydrothermal systems also catalyze the addition of hydrogen to existing molecules to create other organic molecules such as acetate and methane. The exciting thing about that is that the most ancestral microbes on Earth are the acetogens (which make their living making acetate) and the methanogens (which make their living making methane), suggesting the origin of their metabolisms in the abiotic chemical reactions of alkaline warm springs.

Another fun fact: when living creatures synthesize formate, they also use a nickel-iron catalyst. If the first step toward life on Earth was serpentinization reactions in deep sea warm springs, this is also no coincidence.

But we're not yet finished with inventing metabolism. We need to go a few more metallic mineral catalyzed reactions down the line from methane, formate, acetate, and H_2 before, voila, out pops the organic molecule famously known to biology as coenzyme A (CoA for short). It's not an enormous molecule, just of overall chemical formula $C_{21}H_{36}N_7O_{16}P_3S$, where those letters refer to atoms of carbon, hydrogen, oxygen, phosphorus, and sulfur—the basic constituents of the organic matter that makes up all Earthly living things. Once we have coenzyme A in this system, its reaction with CO_2 and hydrogen to produce the even more biologically famous acetyl-CoA, which is just coenzyme A with an acetyl group (CH_3CO) joined to it at one end, is energetically inevitable.

Now, finally, we're in bona fide metabolism territory. Coenzyme A is not merely good at picking up an acetyl group to become acetyl-CoA, it's also good at passing the acetyl group on to another molecule in either a reaction that releases energy (catabolism!) or helps build up a different organic molecule (anabolism!). Also, the reason that CoA and acetyl-CoA are so famous to biology is that every organism on Earth relies on them for some of their core metabolic reactions. Turning CoA into acteyl-CoA using metallic metal catalysts and CO_2 is also how those two most ancestral types of earthly microbes, the acetogens and the methanogens, convert inorganic carbon into organic molecules to use in constructing all the other organic molecules that they need. And the acetogens and the methanogens almost certainly got this habit from the Last Universal Common Ancestor (LUCA) of all life on Earth that more directly gave rise to them.

To sum up: warmly weather silicate rock at the bottom of the ocean, and you'll easily and abiotically end up with an abundance of CoA and acetyl-CoA, the ultimate basis for the metabolism of every creature of Earth that has ever lived.

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Now for the hard part: coming up with an inheritable mechanism for both managing the work of and faithfully reproducing a cell and getting it together with the metabolic reactions and a semipermeable membrane to form the world's first life form. That's the part of the origin of life that seems impossible. It's the chasm that's been hard to see how rocks and water doing chemistry could have jumped.

But here is where some sort of enclosed body of water (or, more likely, a string of them down through nearly one billion years) that hosted an ever increasingly complex autocatalytic chemical network rides to the rescue.

Serpentinization reactions in alkaline warm springs started the chemical network off by creating the first organic compounds and inventing the basic reactions of metabolism. The products of these reactions, especially the anabolic ones, reacted together to form a diversity of increasingly larger organic compounds that reacted with all the other ones until all sorts of useful anabolic and catabolic reactions were going on, back and forth, over and over, churning out the energy and end products to drive additional reactions.

Eventually, the network developed reactions that made nucleobases—like guanine and cytosine—those molecules that, strung together, would come to serve as DNA and RNA's code for the construction of proteins. Creating the first nucleobases probably wasn't difficult; with chemical formulas such as $C_5H_5N_5O$, nucleobases are not large molecules. They're smaller, even, than coenzyme A, which was so easy to make, it was already kicking around. Then, once enough nucleobases had accumulated in the waters of this ocean or lagoon, some joined up with a type of sugar and some phosphate groups to form the world's first molecules of RNA.

After that, the autocatalytic chemical network would have started creating all sorts of different strands of RNA, which, also being autocatalytic, started to gather peptides out of the water to form proteins. These proteins then started triggering all sorts of other reactions, including making membranes, which, inevitably started enclosing bits of seawater and the machinery that was carrying out metabolic reactions. This created protocells.

Eventually, some protocells started picking up strands of RNA from the environment, enabling the protocells to start producing their own proteins. Most of these proteins would have been useless to the protocell, but some of these proteins could have done something useful, like facilitate the metabolic reactions. But, lacking the ability to reproduce, these protocells lived, made molecules, and died after some sort of lifetime of trading molecules with all the other protocells living within that great communal soup of the autocatalytic chemical network.

Then one day, the enormous autocatalytic chemical network got so complex, the whole ocean, lagoon, or alkaline warm spring that contained it was running all the reactions (and then some!) that life would need to bring together and synchronize in order to coalesce into a single, reproducible, entity enclosed within a semi-permeable membrane.

But the day everything changed was the day truly all the RNA needed to produce the proteins that could take charge of constructing and running an entire living cell managed to find itself together in one single cell, along with everything it needed to get the cell's internal components made and the cell's metabolic reactions humming along. At some point, all that RNA made copies of itself and triggered the protocol for cell division and . . . it worked! And the world now had two individual *living cells* and would shortly have four, then eight, and so on. Mistakes in copying the genetic material would be made, most of them fatal, but some of them useful, and evolution was now on its merry way toward creating all the creatures, great and small, as they say, who have thus far trod the boards of Earth's biosphere.

When you consider that all of this had all of those nine hundred million years to happen, the jump no longer feels like a jump but billions to trillions of tiny steps. Within such a span of time and within the confines of an evolving autocatalytic chemical network, the "jump" no longer sounds absurd. Rather, all those years of an autocatalytic chemical network begins to seem like a reasonable way for life to have gotten from just a couple of metabolic reactions happening in a hydrothermal system to the world's first genuine living cell.

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The lesson here for us as searchers for life on other planets is that, given how long this environmental autocatalytic chemical network phase appears to have taken during the process of the origin of life, it may very well be the phase that we stumble on out there on our explorations. Then we will have some decisions to make. Assuming that we will have recognized the existence of the autocatalytic chemical network in the first place, do we land on the planet hosting it and contaminate the environment with the microbes we've brought with us from Earth? Or do we leave the planet in peace to someday finally form the first microbe of its own and start that long, slow, grand dance that is the evolution of wondrous biosphere?

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