Will we ever know how life began?

Scientists disagree on how biology got started and on whether we can ever know for sure

Sarah ScolesOctober 2026

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In a laboratory at McMaster University in Ontario, a device that seems almost alive glows purple as it churns through its work. Atop a boxy base that resembles a small kitchen island, a windowed hemispherical chamber sits. Cords and instruments poke from it like flower petals. Gas billows from its bottom. The setup's purpose is hard to fathom if you don't know what it is and even perhaps if you do. Inside that little chamber is a whole world. Its name is, appropriately, the Planet Simulator.

Maikel Rheinstädter, a professor in McMaster's physics and astronomy department, and his team can program the simulator to mimic many different environments. They can swing it through temperatures from below freezing to past boiling, change the ingredients of the tiny atmosphere, create rain and then dry it up, and shine light ranging from ultraviolet to infrared, as different stars would. In the chamber's center, a drop of water on a chip contains the chemistry of whatever earthly era or exoplanetary site the group is trying to re-create.

The scientists are watching to see what might grow in that little bit of liquid—to determine which ingredients and conditions can produce life's building blocks, get them to stick together, and maybe someday bring something to life. If it can do that, the Planet Simulator could help answer one of the biggest questions of all: How did life start on Earth?

But whether any scientists, even with whole small worlds under their command, can definitively find the answer to that question is another matter. Can we truly know the origins of our planet's life, or will we at best be able to find only plausible possibilities? This larger query remains an open question. After all, the natural experiment that first produced life is not reproducible, no matter how fancy labs become.

Some questions are human classics, asked for millennia and more. Why are we here? Are we alone? What happens when we die? Where did we come from? In some way, all those quandaries are behind the one Rheinstädter is pursuing: What is life, and how did it—we—get here in the first place?

In some traditions, the answer is spiritual. Creation stories are, after all, fundamental to most religions. There is even a kind of scientific creation story, a theory of life called spontaneous generation, most prominently proposed by Aristotle more than 2,000 years ago. Spontaneous generation is the idea that life can *poof*! arise from not-life: carcasses or trash beget maggots; scallops and clams grow in sandy spots. That thinking dominated for millennia, until Louis Pasteur sterilized some broth in 1859 and placed it in a glass container. When he cut the liquid off from outside contamination, nothing grew. But when the outside world was allowed in, the broth became quickly cloudy—teeming with microbes. Pasteur's experiment implied that being alive is hereditary—life, not *not*-life, begets life.

But if that were the case, something still had to be the first alive thing. In that earliest instance, then, the idea of spontaneous generation isn't actually so far off: at some point, the chemical and physical did have to unite in such a way that they became biological. "When you learn about biology in school, it's taught as this completely different discipline than something like chemistry or physics," says Harrison B. Smith, a complex systems and astrobiology researcher at Tokyo's Earth-Life Science Institute. "But we have to remember that biology emerged still subject to the same constraints of chemistry and physics."

Just when it emerged, and how, is tricky to pin down. Despite decades of increasingly complex research, a 2020 review noted that a then 45-year-old proclamation was still true. "It must be admitted from the beginning that we

do not know how life began," chemists Stanley Miller and Leslie Orgel wrote in their classic 1974 book *The Origins of Life on the Earth*.

Miller had conducted an experiment in the 1950s showing that if he simulated the chemical conditions of the early Earth—in a proto-version of the Planetary Simulator—and hit the chemicals with electric sparks, organic molecules started to form. "It is generally believed that a variety of processes led to the formation of simple organic compounds on the primitive earth," the quote continues. "These compounds combined together to give more and more complex structures until one was formed that could be called living." But, the authors added, "No one should be satisfied with an explanation as general as this."

And scientists aren't.

The possibly never-ending quest toward an explanation is the purview of a scientific field called Origins of Life, or OoL (a word that seems like it would be a good name for the first-ever organism). Little in this field is known for certain. There's general agreement on relatively few points and much contention and competition about others.

As far as consensus goes: Earth's oldest fossils date back to at least 3.4 billion years ago, with evidence that life may have arisen more than half a billion years before that. Scientists also generally agree that life didn't come into being in a single flash but in an extended sequence. Over time chemical reactions produced early versions of metabolism, the ability for molecules to pass down information, and the formation of compartments that would become the boundaries of cells.

The Planet Simulator at McMaster University in Ontario can mimic the radiation of different stars, as well as the surface light filtered by different planetary atmospheres, to study how life might emerge.

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That's about it, though, in terms of what's known. For the rest, scientists can't even agree on the right way to approach open questions. Some researchers take a top-down tack, looking at what modern organisms have in common, such as cell-based structure, DNA and RNA, and specific energy molecules. Those commonalities, the thinking goes, probably stem from properties fundamental to the earliest life.

Other scientists go bottom-up, mimicking in a lab what Earth's environment might have been like billions of years ago to try to produce the complex chemistry that became biology, as Miller and Rheinstädter have done. In this approach, scientists don't assume that modern life much resembles early life. Rather modern biochemistry may be largely the result of evolution.

David Catling of the University of Washington is a scientist in the latter group, having come to OoL research through his studies of planets. That started early: In an undergraduate astronomy course, Catling had to come up with a telescope project. "Other people were looking at very faint stars, which you can't even see in the viewfinder," he says. "And I thought, 'Well, I'll do Jupiter. You can't miss that.' " After measuring methane above Jupiter's clouds, he became interested in planets' atmospheres and eventually the climate of early Earth.

At first, Catling wasn't sure he had much to contribute to OoL work. "I'm not a biochemist. I'm not an organic-synthesis chemist," he says. But, he learned, chemists needed people like him to do exactly what he was interested in: to learn more about Earth's past. "What was plausible, what was not plausible," Catling says. Thirteen years ago the Simons Foundation started a big origins project, and Catling jumped onboard a few years later. The private money, he says, might have doubled the amount available for OoL studies, which are sometimes neglected because they overlap disciplines. But, as the Simons project demonstrates, attempts to understand the origins of life are necessarily interdisciplinary, drawing together the fundamental forces and rules that shape the planet and the universe and that don't, themselves, recognize academic or social boundaries.

Scientists don't differ just in *how* they study OoL. Their hypotheses about how life first animated itself are also in tension. These "how's" fall into two main camps, whose names seem designed to start a fight: "Metabolism First" and "RNA First."

In the latter, RNA was the initial important part of biology to form. RNA is single-stranded genetic material that carries information in the pattern of its four repeating chemical bases: adenine, cytosine, guanine and uracil. (DNA is made of those first three bases but replaces uracil with thymine and has two twisted-together strands instead of one.)

In scientists' vision of "RNA World," an early era in life's evolution before DNA or proteins existed, RNA stored information and catalyzed chemical reactions. RNA would have assembled into single strands that could make copies of themselves. That copying, by providing a way to reproduce and evolve, could have then kicked off the beginning of life. The more structurally complex DNA would have come later (in a process scientists don't yet understand) to play the major role in storing and passing down genetic information, and proteins would have taken over the chemical catalyzing.

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The Metabolism First idea, meanwhile, suggests the critical first development was the ability to convert basic chemicals into more complex compounds. According to this scenario, chemical reactions happened spontaneously between elements and compounds on the early Earth. Those began simply, but some happened to produce energy-storing molecules. Those molecules started more chemical reactions, which became increasingly complex as the cycle continued. Eventually the self-sustaining chemical reactions resulted in structures resembling RNA. Or at least that's the idea.

The location of either of those firsts is the source of yet another debate. Some scientists think ground zero was in Earth's surface water: a warm little pond (an idea Charles Darwin first floated) or a hot spring; others think it may have happened in a deep-sea hydrothermal vent, although this hypothesis is falling out of fashion. The heat common to all these ideas would have spurred chemical reactions along.

Another waning idea is the guess that space rocks may have seeded life on this planet. Samples of asteroids and meteorites suggest that although they have organic molecules, they don't have the kind whose structure matches what life uses here. "Clearly, there's something different that you need for the environment, for an origin of life," Catling says. "And it worked on a planetary body like Earth, but it didn't work elsewhere in the solar system."

He suspects the difference is that asteroids don't have the same environmental conditions found on Earth—or on the worlds inside the Planet Simulator. One example is wet-dry cycles: in a pond or on the simulator's chip, for instance, water may evaporate or freeze, leaving behind non-H_2O building blocks that then become more concentrated. Energy from the sun helps reactions between those blocks along, coaxing them to form polymers, or longer chains of molecules.

Hydrothermal vents as an origin site are also losing popularity at the moment for a similar reason, in Catling's view: surrounded by the entire ocean, famously large, vents could not have concentrated chemical constituents enough.

No matter where a scientist falls among the OoL options—which method, what first and where—there's still a fundamental problem: When researchers such as Rheinstädter re-create conditions from the early Earth, the ingredients readily assemble themselves into the simpler building blocks of life, among them amino acids or even cell compartments, which are made of fats called lipids. But getting those building blocks to stick together and interact in a lively way is a different story. "What's still very much a dark field is how those things become more complex," says Joana Xavier, an independent bioengineer and OoL researcher. Rheinstädter agrees. "I think what we have right now is that the building blocks—amino acids, nucleotides—they form very easily," he says. "Even if you step out in a puddle, you will find those."

Rheinstädter is using the Planet Simulator to figure out how to get those puddle parts to complexify themselves and, in particular, assemble into RNA. In that quest, he has a fairly radical idea: Maybe the chemistry soups researchers are creating are getting sufficiently complex—but scientists are missing it because they're seeking the wrong thing. "People are always looking for lab-grade RNA," he says—the kind you can order from a catalog. Perfect, in other words.

But that kind of RNA wouldn't have done well on the four-billion-year-old Earth. It's too fragile. "If you take it out of the fridge, it degrades immediately," Rheinstädter says. Maybe, he continues, that means the RNA in RNA World wouldn't have been the same as the RNA in *our* world. He came to this idea somewhat by accident, while

poking around the Planet Simulator. When the simulator was set to mimic the ancient Earth, Rheinstädter and his team found that molecules *do* link up to form RNA strands of about 100 bases long. "However, they're not perfect," he says. "They have structural defects." But what they lack in prettiness they make up for in strength. "You cannot destroy them," Rheinstädter says.

He started to wonder: "What if nature didn't start off perfect?" What if, instead, it started out with a precursor version of genetic material? The RNA of today may have come later, with evolution. "Maybe it's just silly to expect that from the beginning," he says. Perhaps the mixed-up version of RNA that spews from the Planet Simulator was the kind that first bubbled up from some terrestrial pond. After all, what—besides a creation story—starts out with a fully formed version of life?

Other scientists, Rheinstädter posits, may have actually been creating this flawed RNA all along in similar experiments, unaware—because they weren't looking for it. Now the team is working on whether imperfect RNA can actually do what perfect RNA does: catalyze and transmit information.

Catling, meanwhile, is pursuing a shakeup idea of his own involving the "where" debate. He's been looking recently at what scientists call the "phosphate problem," first identified in the 1950s. The issue: Phosphate is key to many things life does and needs—the compound is part of the genome, the cell compartment and metabolism, for instance. "Yet in the environment, if you go to a river or the ocean, the level of dissolved phosphate is really tiny," Catling says.

If there's not much in the water, it's hard to understand how proto-life could have gathered enough. But when Catling was working on the Simons project, he and colleagues found a kind of water body with plenty of phosphate: soda lakes, which are a bit like big ponds someone dissolved a lot of baking soda into. These water bodies with an abundance of carbonate and extremely high alkalinity are found around the world; the best-known examples are in Africa and North America. The calcium in them binds with carbonate (the baking soda bit), allowing natural phosphates to accumulate instead of sticking to calcium as they would in less carbonate-rich water.

The most phosphate-rich lake in the world is Last Chance Lake in Canada. In summertime, it—and most soda lakes—evaporates, leaving a crusty white landscape; as the seasons progress, they get wet and become like lakes again. The wet-dry cycle concentrates the existing phosphate. It could, Catling thinks, be precisely the type of place where chemistry and physics became biology. Maybe it would more appropriately be called First Chance Lake.

Of course, neither Rheinstädter nor Catling knows if their ideas represent the true "first" or "where." And scientists disagree about whether we will ever know for sure. Even if researchers can reproduce the conditions of early Earth and coax life from it, that success would represent just one way the story might have gone. Knowing for sure that it is *the way* it happened is a different story. The tape can never be rewound.

Plenty of OoL scientists, though, think that doubt is naive. After all, if cellular biology flows from physics and chemistry through a set of logical laws and processes, maybe there is only one path between the three. "A diamond forms in a very specific set of conditions. It's only in that set of conditions," Xavier says. "And the diamond is rare because those conditions happen only on those rare occasions. I think the formation of cells is exactly the same type of question."

Catling, though, disagrees. "I think it would be a plausible answer rather than definitive." He does, though, think that looking beyond Earth could yield more certainty, in that it could help scientists understand whether the origin of cellular life is actually deterministic—that is, whether, given certain conditions, it always emerges in a certain way. If, for instance, we see it on other planets with similar environmental histories and if it has the same biochemical makeup, then researchers could infer that there's a set process by which life like ours arises.

Still, those are huge ifs: *If* there's life out there, *if* we know how and where to look for it, and *if* we find it. That's a lot of physical and philosophical difficulty to bring together. But it's also not impossible. "It's always dangerous in the history of science to say that we will never know something, because later on, people have found it," says David Dunér, a historian and philosopher of science at Lund University in Sweden.

Before the field of OoL can get close to that point, though, it needs a cultural change. At the moment, it's a fairly

contentious discipline, with researchers personally invested in their versions of how and what first and where. This competition is amplified by how little direct evidence is available, Xavier contended in a *Nature* comment. To help researchers collaborate and focus on the big picture, she co-founded the Origin of Life Early-career Network, bringing together younger scientists. But schisms and heel digging are probably inevitable in such uncertain fields, Catling says.

Maybe more evidence for the origin of life will come from a soda lake, or a planet simulator, or an actual planet far, far away. But at least some scientists are okay with the uncertainty about uncertainty. “I sometimes think about how lucky I am, in some ways, to exist in this moment of time when this still is an unanswered question, and how exciting it is to think about all the possibilities out there,” Smith says. “I think that it will be answered, but I think it will be some time because a lot of the right questions aren’t even articulated.”

Join the discussion: What is your favorite origin of life theory?

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Discussions

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