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What is life?

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"Why would NASA want to study a lake in Canada?"

Three different border guards asked me variations on that question, and while they ultimately let me pass, it was obvious they didn't understand. Why is NASA interested in a lake in Canada? And what business is it of mine?

As exotic environments go, Pavilion Lake in British Columbia is rather ordinary. Certainly it's remote – the closest major city is Vancouver, a long drive away over the mountains. The closest towns are light dustings of houses over the dry slopes, and the road winds for dozens of kilometres of empty desert country between them. The lake itself lies along a paved highway, and from the road it doesn't look different to any other modestly sized mountain lake in western North America.

But below the surface, the bottom of Pavilion Lake is dotted with something resembling coral reefs: domes and cones and weird shapes much like artichokes. These are not corals, though, which are colonies of tiny animals: they are rock formations called microbialites, made by and coated in cyanobacteria. Sometimes misleadingly referred to as 'blue-green algae', these bacteria probably even made the rocks they live on, absorbing nutrients from the water and leaving stone behind. Like plants, they live on sunlight, and they thrive in shallow waters down the steep underwater slope to the point where sunlight fades to gloom.

They are the reason for NASA's interest, and my visit. The people I've come here to see have even bigger things in mind. They want to know what the rare formations in Pavilion Lake might tell us about the origins of life on Earth, life on other worlds and, indeed, what life is, exactly.

Erwin Schrödinger was a clever guy. You may know him for the famous 'Schrödinger's cat' thought experiment, the feline in a box that is neither dead nor alive until you look inside. However, one of his most interesting works is a slim book from 1944, based on a set of lectures Schrödinger gave in Dublin. It poses a single question: What is life?

The book is significant for predicting some important properties of DNA before they were discovered. Nearly a decade before the famous double-helix structure of DNA was uncovered, Schrödinger correctly recognised the key to how organisms evolve and pass information between generations as an 'aperiodic crystal': a chain of atoms that never precisely repeats itself. Even though each link in the chain contains the same atoms (carbon, nitrogen, oxygen, hydrogen and phosphorus), their combination allows an enormous amount of information to be encoded.

Schrödinger's simile was Morse code, which reproduces an entire language with only two 'letters'. Today we know the DNA code has four letters (A, C, G and T), which by arranging and pairing can encode everything an organism needs to build proteins, run its metabolism, and live. This seems to be a significant distinction between life and non-life: the ability to pass information beyond simple reproduction.

Ordinary crystals reproduce themselves, but they only pass along the repetitious pattern of where the atoms go. They can't evolve. Or, in the words of Schrödinger, it's like the difference between "an ordinary wallpaper in which the same pattern is repeated again and again in regular periodicity and a masterpiece of embroidery, say a Raphael tapestry, which shows no dull repetition, but an elaborate, coherent, meaningful design traced by the great master."

The pontoon boat is loaded nearly to tipping point with people operating and monitoring submersible remotely operated vehicles (ROVs). These little robotic submarines are equipped with high-resolution cameras, and they're scoping out the part of the lake where human divers will go later in the week. They also carry sensors to measure water temperature, pH, GPS position, depth and current. To achieve the perfect level of buoyancy, the ROVs are rigged with a weird mix of high-tech and low-tech equipment: state-of-the-art motors, and flotation devices made of Wiffle balls and bright orange swimming pool noodles attached with plastic cable ties. One submersible is snooping around on the lake bottom, taking high-resolution images of microbialites; the other's job is to keep an eye on the first one and track general water conditions.

I'm watching all this from the NASA 'Mission Control' trailer on shore, via a video feed from the ROVs. It's an alien landscape: irregular green-grey mounds the size of tables, some in clusters, some alone, stretching farther than the camera can see into the submarine gloom. Looking at this lake bottom footage, I wonder how much this resembles early Earth. Based on fossil microbialites, ancient relatives of today's cyanobacteria were probably some of the earliest life on Earth. The oxygen in our atmosphere was probably made by cyanobacteria billions of years ago, which converted the carbon dioxide-heavy atmosphere of early Earth into today's balance of nitrogen and oxygen long before plants evolved. Modern cyanobacteria are more likely to make slimy mat-like colonies that cover the bottoms of remote lakes than the elaborate, rocky microbialites we see at Pavilion, so it's probable that was the case 3.5 billion years ago too.

Weird as they look, the microbialites might be the only remotely familiar-looking thing to a time traveller who went back to the earliest days of our planet. Because life didn't just make the air we breathe: to go anywhere, to observe anything on Earth, is to see an environment created by life. The chemistry of rocks, the oceans, the soil – everything has been shaped by life. And scientists have found organisms – mostly bacteria and archaeons, single-celled organisms that thrive in extreme environments – in every place, from rock fissures deep underground to clouds high in the atmosphere. In each environment, the organisms have adapted to their surroundings and shaped those surroundings to suit themselves in turn.

Traces of that mutual shaping are known as biosignatures, and they are one of Pavilion's major draws for Allyson Brady. A geochemist at McMaster University, Brady is looking for ways to distinguish abiotic processes – those happening without life's influence – and unambiguous biosignatures. "Once the bacteria are long dead," she says, "the rock itself might still retain the kind of chemical signature that can say 'this was created by a biological influence', as opposed to a purely abiotic chemical one. We do see that in Pavilion."

Biosignatures could be the key to telling us whether a similar stone reef we find on Mars is a fossil microbialite – a sign of ancient life that once existed – or a cruel mimic. The relative amounts of different isotopes or the presence of unusual molecules in the rock could reveal the chemical traces produced by the metabolism of microbes long gone.

Obviously, the better situation would be to see living microbes (assuming they exist), but that's trickier than science fiction makes it sound. Any sample of microorganisms collected by a rover, probe or astronaut would have to survive exposure to the equipment, and then be recognisable as living things under a microscope. That's a time-consuming process and would require some preliminary chemical hint that there's something worth looking for at the microscopic level. In the absence of Star Trek tricorders to do automatic scanning, researchers look for biosignatures in the soil on Mars, on the ice of Jupiter's satellite Europa and in the plumes of water shooting up from the ice volcanoes on Enceladus, the sixth-largest moon of Saturn.

On the banks of Pavilion, I am perpetually buzzed by iridescent blue dragonflies, while a loon paddles by. After two days of ROV-only operations, human divers are now on the scene. To accommodate them, the team is taking an extra boat out to the dive site. This time I'm out on the water with them, although my primary task is to stay out of the way. In fact, my view was better back in the trailer: I am limited to watching the scientists watch the monitors and steer the ROVs, unable to witness what the divers are actually doing.

Dragonflies, loons, divers and even unusual bacteria are recognisably alive – as a Sesame Street song says, they 'breathe and eat and grow'. But do all living things?

The hardest part of finding life elsewhere in the cosmos may be recognising it when we see it. Most life on Earth is microbial, and though we often associate bacteria with disease, most species care not for humans one way or the other. A huge number of species thrive in places that would kill us, and vice versa: deep water, acid caves, bitter cold or boiling hot. Yet there is still kinship between these organisms and us, though evolution and adaptation have separated us.

Because of that kinship, all life on Earth is built from cells; it all uses liquid water as part of its essential structure; it is all built of similar molecules containing carbon, oxygen, nitrogen and a few other common elements; and it all uses DNA and RNA to code information about itself and pass that information along to future generations. Yet we must ask: does life have to be that way? If we replayed the history of our solar system, would life use the same chemistry, make cells and shape its environment in the same way?

Life is organic, which simply means 'molecules containing carbon'. Organic molecules are pretty common in our galaxy. Astronomers have found hints of amino acids (the building blocks of proteins) in comets, and nucleobases (the genetic 'letters' of DNA and RNA) in clouds of gas between stars.

But although water may be necessary for life, it's so abundant on other worlds and in interstellar space as to be unremarkable. We've yet to find any sign of anything out there that could be construed as 'life'.

Paradoxical as it may sound, there might be inorganic life, too: 'organic' doesn't mean 'living'. The silicon-based life that inhabits the popular sci-fi universes of Star Trek and Terry Pratchett's Discworld is the result of that kind of thinking. Silicon sits in the same column on the periodic table as carbon, so it is chemically similar. Ultimately the bonds it makes aren't quite right, so we don't see it forming the same kinds of molecules. Carbon seems uniquely able, among all the elements on the periodic table, to form structures with other atoms that are complicated enough for life.

DNA is certainly complex, which leads many researchers to wonder how it came to be in the first place. One common hypothesis is that RNA – which exists as a single chain, unlike DNA's double chain – came first, but even RNA is complex. "Maybe life didn't start with RNA, but started with something a little bit simpler," says John Chaput of Arizona State University. "Whatever that simpler material was, it helped produce RNA."

The 'D' in DNA and the 'R' in RNA represent the sugars deoxyribose and ribose, respectively. Deoxyribose and ribose are the ladder struts on which the genetic letters are rungs, but they aren't the only possible sugars for the job. Artificial genetic molecules called 'XNA' can be built from other sugars: X could be any one of a number of other possibilities.

Chaput is most interested in the sugar known as 'threose', because the resulting molecule TNA 'recognises' RNA and links up with it, just as

DNA links up with RNA. TNA is simpler than RNA and DNA, both in chemical structure and in how easy it is to make. Chaput and like-minded researchers wonder if TNA came first on early Earth: "Because TNA was simpler to synthesise, it arose early but was quickly taken over by RNA."

XNAs are only one possible alternative route for life. Carbon makes many more molecules than are used by life as we know it. Proteins don't use all the types of amino acids; DNA and RNA don't use all the nucleobase 'letters' that are chemically possible. It's possible life forms elsewhere could have the same basic organic chemistry and even have genetic codes similar to ours, but use different molecules in constructing their cells.

The weather is sunny and pleasantly warm, but Tyler Mackey and Frances Rivera-Hernandez are dressed for colder temperatures. They are in drysuits, preparing to dive into the cold waters of the lake to make sure all the equipment works before it is needed for scientific sampling later in the week.

Mackey's focus is how microbes shape and are shaped by their environments, and how those interactions might show up in the fossil record on Earth. Much of his thesis work is based on ice-capped lakes in Antarctica. Rivera-Hernandez works for the Mars Science Laboratory team, which operates the Curiosity Rover currently exploring the surface of Mars. She is interested in seeing whether lakes on Earth might share geological attributes with now-dry lakes on Mars, which in the distant past may have been ice-covered pools.

There's a lot of talk about Mars at Pavilion. The divers aren't just collecting scientific data on the microbialites: they're testing out software and protocols for doing similar things on the surface of the Red Planet. The divers are acting in the stead of astronauts walking on Mars;

the boat they dive from is their 'command centre' (like one that may someday reside on Mars' moon Phobos), and the big NASA trailer on the shore serves as 'Mission Control'.

To make the simulation even more real, the software they use to communicate builds in a five-minute delay each way between Mission Control and the boat to mimic the travel time of signals across the 55 million kilometres from Mars to Earth at their closest approach. With that delay, the divers can't get instructions directly from 'Earth', which means most actions they take must be carefully planned in advance. (By contrast, the Apollo astronauts had a less substantial communication delay of roughly one second each way.)

Future astronauts on Mars are unlikely to find anything so clearly living as the bacteria in Pavilion, but there might be the remains of dead microbialites. Palaeontologists have discovered fossils of the layered microbialites known as stromatolites in Australia, Greenland, Antarctica and beyond. Some from western Australia date back 3.5 billion years, not long after the molten Earth first solidified. If Earth-like microbes arose on Mars during a similar time period, but died out (or moved underground) when the planet dried up, there might be similar fossils.

Presently, surface water on Mars seems to be ephemeral and very salty, but that wasn't always the case. "If there ever was abundant water [on Mars] – which there is plenty of surface evidence for – it probably would have been frozen over," says Rivera-Hernandez. That makes cold-water lakes on Earth particularly interesting for someone with an eye on Martian life. Pavilion freezes every winter, and it might even have been covered with a year-round cap of ice during the last Ice Age. Some microbialite structures seem to be old enough to have survived that freezing-over.

In the 71 years since Schrödinger's book, scientists have come a long way toward understanding how life works, but there is still no clear definition of what life is. Evolution is part of it, as is the related concept of passing genetic information from one generation to the next. Metabolism is part of it, altering the chemical balance of its environment in a way that wouldn't happen otherwise. But while some things are definitely non-living and others decidedly alive, there's a shadowy region in between.

That's the realm of the viruses and the rogue proteins called prions – infamous for causing bovine spongiform encephalopathy ('mad cow disease'). Viruses have DNA or RNA but must invade cells to reproduce. Prions are notable because they can transmit information and reproduce without DNA by hijacking other proteins, most damagingly inside brain tissue. Viruses and prions are often harmful, but some types of yeast benefit from prions, and mammals use virus DNA to keep mothers from rejecting fetuses in the womb. Neither are alive in a strict sense – they don't grow or multiply without joining themselves to an organism – yet they can mutate and evolve under the pressure of natural selection.

"Clearly [a virus] has the capability of following Darwinian evolutionary principles, but not without a host cell," says David Lynn of Emory University. To him, life and non-life lie on a continuum: "There is some transition where we might be able to distinguish something that is evolvable on a chemical level and something that is evolvable at a biological level." In other words, there's a blurry division between something that requires an external catalyst – a host cell, brain tissue – to evolve, and something that can evolve and reproduce on its own. At some point, lifeless chemical processes slipped across that division and became recognisably alive.

Lynn thinks a lot about the biochemical information carried in complex molecules, and how to understand evolution in that context. He and his collaborators are investigating whether proteins (which, in a chemical sense, are relatively long chains of organic molecules used in building cells) could store and pass along the same information that the genetic molecules do, without the need for DNA or RNA. But both DNA and proteins are complicated, so the question is whether something else came first in the history of life on Earth that set the stage for both of those complex chemicals.

The small Canadian lake of Pavilion is one place we can learn how to ask such questions. The various researchers at Pavilion, the biochemists working with XNA and the astrobiologists pondering life on other worlds – all of them are trying to understand life's adaptations using the chemistries and materials in each place.

Bacteria like the ones living in Pavilion Lake today rarely build microbialite structures; although Pavilion is slightly more alkaline than other nearby lakes and has a higher mineral content, there's no obvious reason for the structures' existence. "What's enabling these microbialites to exist in this lake? What is it that's potentially so special about this lake?" asks Darlene Lim, the principal researcher at Pavilion. "That's a pretty complicated thing to solve, and it needs a lot of different angles of perspective on it."

All life on Earth is related, with a common ancestor deep in the geologic past. But perhaps life as we know it once coexisted with other biochemistries. If that's true, over time our distant ancestors were more successful than organisms based on alternative molecular structures, using and shaping the environment until the other forms of life became extinct. That thought is sobering: the death not of a species, but of an entire avenue that might have grown to dominate the planet if history had taken another path.

These might-have-beens and never-weres aren't merely the province of speculation. With Mars, with Europa, with thousands of catalogued exoplanets, the range of chemical possibilities could be huge. We cannot afford to assume all life would follow the same path it did on Earth, biologically or chemically.

'What is life?' is not a single question and doesn't have a single answer. Perhaps it doesn't need one. Wise souls such as Charles Darwin skipped over such philosophical shenanigans.

A tall chimney of rock stands on the mountainside overlooking Pavilion Lake. The Ts'kw'aylaxw First Nation people, whose land includes this whole area, speak of a great dragon living there, watching over the children of the lake. The cyanobacteria are in some sense the offspring of life from the youth of the world. But they are also modern, as all life is: adapted to its environment by the forces of evolution. And although it's a vague definition, that's what life is: the shaper, the shaped, the ever-evolving.

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