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Breaking through a biological barrier

Caltech scientists design living organisms that make chemical bonds not found in nature.

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Move over, chemists. Thanks to proteins from Icelandic bacteria, scientists at Caltech have managed to coax microbes into making silicon-carbon bonds, a feat that until now has been achieved only by humans in the lab.

The findings, published last month in the journal Science, could open the door to new avenues in organic chemistry and drug development — and could help scientists investigate essential mysteries, such as whether life could be based on silicon instead of carbon on other planets.

"My whole interest is, how do you use evolution as an innovation engine?" said senior author Frances Arnold, a chemist at Caltech. "How does evolution solve new problems that life faces? And to have a system that can create a whole new chemical bond that biology hasn't done before, to me, demonstrates the power of nature to innovate."

Life, as we know it, is carbon-based. Carbon holds four electrons in the eight vacancies in its outer "shell" — a quality that allows it to make connections with a variety of other elements. This versatility means carbon can anchor the wide range of molecules that can be found in Earth's living systems, thus serving as the backbone of organic chemistry.

Silicon has similar chemical qualities, including four electrons in its outer shell. And it's incredibly abundant, second only to oxygen in Earth's crust. But for the most part, living things haven't made a habit of taking up silicon — even though they seem to have no problems incorporating much rarer metals, such as magnesium or molybdenum, into their bodies.

"Poor silicon, abundant in the earth, but rejected by the biosphere for its wondrous evolutionary tinkering," Roald Hoffmann, a Nobel-winning theoretical chemist who was not involved in the paper, wrote in an email — though he pointed out that radiolarians (a type of protozoa), diatoms (a group of algae) and even rice "make good use of it."

This has left scientists wondering: Could life on other planets, in different environments, be potentially silicon-based, or is there some reason that nature has not yet made full use of this abundant resource?

Humans, on the other hand, have put silicon to use in solar cells and computers. And chemists have made silicon-carbon bonds (or organosilicon) in the lab because they're useful in drug development.

But Arnold and the lead author, postdoctoral researcher Jennifer Kan, wanted to know whether this apparent biological barrier could be broken.

"People are really interested in these fundamental questions: Why is life based on carbon and not silicon?" Arnold said. "It's easy to wonder; it's hard to answer, unless you've got ways to make these bonds."

The team searched around for proteins that might be able to do this — and found a likely candidate in the genetic code from *Rhodothermus marinus*, a bacterium that lives in the salt-rich hot springs of Iceland. In the bacteria, this protein probably helped move electrons around, but it also happened to act like an enzyme that made silicon-carbon bonds. (An enzyme is a kind of protein that catalyzes or facilitates chemical reactions.)

So the researchers took the genetic code for the protein (known as cytochrome c), stuck it into *Escherichia coli* bacteria and then grew the microbes on a specific cocktail of chemicals not used by nature. The ones that were best at making carbon-silicon bonds were then "bred" to improve their performance. The scientists inserted mostly random mutations into the most successful proteins' genetic code, then put it back into the bacteria and grew the next generation to see which ones performed best. Again they picked the best performers, pulled out the winning version of the gene and repeated the process.

Arnold developed this method, known as "directed evolution," in the early 1990s and it has since been used to create more environmentally friendly ways of making drugs, agricultural chemicals and fuels, among other products. This year, she became the first woman to win the Millennium Technology Prize for her groundbreaking work.

In just three rounds of mutations, the scientists had improved the bacteria's abilities roughly fortyfold, making them about 15 times more efficient than the processes used by human chemists. And unlike human chemists, they did so without harsh chemicals or rare metals whose mining is causing destruction to the planet, she said.

"There are a number of drugs on the market that use silicon; it's hard to make them and this might provide a really interesting way to make new drugs," Arnold said.

Since the study's publication, Arnold said, she has already been contacted by scientists of all stripes, interested in astrobiology, evolution and chemistry.

"Perhaps now we can start to explore what are the costs and benefits of incorporating silicon into biomolecules," she said. "What does a silicon-containing protein look like; what does it do? What does a silicon-containing lipid look like; what does it do in a cell? Maybe somebody could use these enzymes to do that."

Hoffmann called the research "beautiful work, creating new chemistry."

As for whether silicon-based life is really possible, Arnold demurred.

"That's a stretch, because 'silicon-based' implies replacing all the carbons with silicon, and I don't have any good way to do that," she said. Silicon is also less stable in water, which isn't ideal for life on Earth.

But the work may help scientists start to consider the possibilities for life on other planets, in dramatically different chemical settings from that of our home world.

"Silicon-based life on Earth doesn't make sense, but perhaps it would in some totally different environment," Arnold said.

But the scientist emphasized that her goal in this paper was just to show that a silicon-carbon bond was possible, and to offer a new tool that could help other scientists further investigate these outstanding questions.

"People think of the wildest and most wonderful things, and that's the whole joy of doing this," she said. "By making a whole new chemical bond, you open up possibilities that you never dreamed of, where others will come in and do it. So I can't predict what other people will do."

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1) What are 2 possible applications related to the discovery in the article?
2) What does carbon and silicon have in common?
3) What is the most plentiful element in the Earths' crust?
4) What 2 elements mentioned in the article are rare metals absorbed by living systems?
5) Name 2 organisms that make use of silicon.
6) According to the article give 2 examples of how humans use silicon.
7) What type of organism is *Rhodothermus marinus* and where does it live?
8) What is "directed evolution" and how was it used in the project?
9) Why would it be a challenge for a silicon based organism to live on Earth?
10) What was the date of this article?