Over time, calcite has evolved into many forms that can be seen (from left) in caves, fossilized microbial mounds called stromatolites, and the shells of phytoplankton.

COMPLEXITY THEORY

Life evolves. How about everything else?

Support grows for "natural law" that applies evolution to mineralogy, chemistry, and fusion

By **Paul Voosen**

For Robert Hazen, a mineralogist at the Carnegie Institution for Science, Charles Darwin didn't think big enough. Look out the window, he says. "You see the flowers. You see the trees. You see all the buildings, all the things we've constructed, the language we've constructed." What can explain why over time, everything on Earth—not just living things—seems to get ever more rich and complex?

Last year, in a paper published in the *Proceedings of the National Academy of Sciences*, a team led by Hazen and Michael Wong, an astrobiologist at Carnegie, proposed an answer. They say there is a missing "natural law" akin to evolution that boosts the complexity not just of life, but of systems in mineralogy, chemistry, and the inner workings of stars. Last week, Wong and Hazen welcomed a diverse group of nearly 100 scientists, from microbiology to neuroscience, for a workshop on how complexity emerges and evolves. It was also a referendum on their audacious proposal, which, Wong said in a talk, is "an explanatory framework for the evolution of physical systems writ large, including, but not limited to, biology."

Put simply, the paper describes how systems made up of diverse interacting components, when put in environments that allow some configurations to persist better than others, will inexorably drive toward states of "increasing functional information." That is, as time goes on, a system will grow more diverse and complex, enriched in the functions needed for survival, through a kind of natural selection. Biological evolution, with DNA mutations creating the configurations that persist through reproduction and natural selection, would then be only one subset of this broader law.

It's an appealing idea, says Loren Williams, a biochemist at the Georgia Institute of Technology who studies the origin of life and attended the workshop. "To me it seems very clear that there is evolution outside of biology." Take the polypeptide backbone, the chain of molecules that forms the spine of all amino acids, he says. "[Biological] evolution doesn't touch that, right? It's the same in everything alive. It always has been. But it's a product of evolution, I'm convinced." It's just that the evolution happened before life began, he says. And so when Hazen and his co-authors proposed their overarching theory, he says, "that just resonated with me."

The idea has its roots in the nearly 2 decades Hazen has spent documenting the evolution of minerals—the crystalline building blocks of rocks. Over Earth's history, they evolved from just a few dozen at its start to thousands today. Earth's earliest forms of calcite, for example, developed through the watery alteration of meteorites; microbes then began to build other calcite structures 2.5 billion years ago, and snails and clams created new combinations beginning only 100 million years ago.

When Hazen first floated the idea in 2008, colleagues were skeptical, he says. "It was like a just-so story." But since then, research has tied thousands of minerals to dates when they first appear in the geological record, confirming that they form a tree that has branched over time, like phylogenetic trees in biology. Researchers are now starting to pinpoint where and when certain precious or critical minerals appeared, and in which rocks—a fact that has not gone unnoticed by the mining industry, Hazen says. "There's the old expression, gold is where you find it," he says. "Well, now we say gold is where our machine learning algorithms predict it will be."

Minerals are also the most well-developed case study for Hazen and Wong's new law. In a paper published in July in *PNAS Nexus*, they walk through multiple stages of mineral evolution, calculating the number of possible distinct mineral configurations and showing that, over time, the number of these minerals that persisted has relentlessly increased—a growth in their total functional information.

Some scientists accept Hazen and Wong's idea but are not sure it necessarily rises to being a new law of nature. "I wouldn't

PHOTOS: (LEFT TO RIGHT) JEAN E. ROCHE/NPL/MINDEN; JOHN CANCALOSI/NPL/MINDEN; ALEX HYDE/NPL/MINDEN

call it a new law of physics, just to not piss off the physicists," says Johannes Jäger, an independent systems biologist affiliated with the University of Vienna. Others say it doesn't easily generate hypotheses to test. "We can't really use it yet," says Elisa Biondi, an astrobiologist at the Foundation for Applied Molecular Evolution, who stresses she likes the idea. "Not for the generality they are trying to cover."

Nevertheless, Hazen and Wong seem to be gaining acolytes in other fields. "When I first saw the paper, I could not sleep for two nights," says Frédéric Thomas, an evolutionary biologist at the University of Montpellier who studies tumor growth. Unlike the cells that make them up and the animals they kill, tumors themselves do not follow traditional Darwinian evolution: A tumor does not seek to reproduce or typically compete with other tumors in an organ. "But we know certain tumors evolve and get more complex and sophisticated," Thomas says. In a study published in September in *Evolution, Medicine, & Public Health*, Thomas and colleagues borrow from Hazen and Wong in their description of tumor evolution.

The duo's proposal has also been adopted in microbial ecology. In a preprint posted earlier this year on EcoEvoRxiv, two fungal ecologists, Nancy Johnson at Northern Arizona University and César Marín at the University of Santo Tomas, adapt the idea to propose "functional team selection" as a way to explain how native plants and their roots select different combinations of soil microbes and fungi, year to year, to increase their resilience to disturbance. "This law is really necessary," Johnson says. "In my world, in microbial ecology, it is so helpful."

There are even echoes of it in computer science research into artificial life, says Blaise Agüera y Arcas, chief technology officer of technology & society at Google. "I'm totally down with it," he says. "What persists, exists."

During the workshop, Agüera y Arcas presented work his team has done using minimalist programming languages to create random sequences of computer instructions in a virtual soup, released as a preprint on arXiv in August. In each round, two sequences of code are put together, executed, and broken apart. No mutations are added and the environment has no fitness pressures. At first, the result was nothing, just errors when the combined codes were run. But over millions of rounds, complex code emerged—as if a natural evolutionary law were at work.

It was tricky to figure out what these complex looping code snippets were doing, he said. "But of course, what they were doing was reproducing." ■

PHOTO: PBH IMAGES/ALAMY

SCIENTIFIC COMMUNITY

NIH dental institute director on leave for nearly 7 months

Rena D'Souza, who faces allegations of workplace misconduct, is suing the agency for discrimination

By **Meredith Wadman**

Rena D'Souza, director of the U.S. National Institute of Dental and Craniofacial Research (NIDCR), has been on paid administrative leave since April during a probe into allegations about her behavior. It is the third action the National Institutes of Health has taken against D'Souza, who was born in India and is the first woman of color to direct an NIH institute. Last year, after two previous suspensions—for 2 days in December 2022 and 2 weeks in late July and early August 2023—D'Souza sued the Department of Health and Human Services (HHS), NIH's parent agency, alleging discrimination on the basis of sex, race, national origin, and skin color.

D'Souza, 69, a dental surgeon with a Ph.D. in pathology and expertise in craniofacial development and genetics, has directed the $520 million NIDCR since 2020. On 15 April, NIH Principal Deputy Director Lawrence Tabak "placed [me] on a paid administrative leave … at short notice and with no details provided other than the broad allegations of retaliation and misconduct," she told *Science* in a written statement.

The next day, Tabak emailed all employees at the dental institute informing them, without mentioning D'Souza, that her deputy, Jennifer Webster-Cyriaque, would serve as NIDCR's acting director "for the immediate future." Since then, D'Souza's leave has been extended monthly, most recently through November.

D'Souza's statement said she is not "aware of the motives underlying this disproportionate and cruel treatment" and that her "efforts to bring clarity and resolution to this matter in a fair and mediated process have been ignored." The statement says she learned NIH's probe was completed in early August. She then requested it be sent to HHS's National Labor and Employee Relations Office for higher level review but has heard no updates since. At the same time, she asked to be returned to her position, she says, but that request was denied.

The statement adds that D'Souza has been prohibited from communicating with all but a handful of NIH employees, and has not been allowed to perform any official duties or mentor her laboratory personnel.

She declined to elaborate further about the complaints against her or other topics.

NIH would not comment, saying in a statement the agency "does not discuss personnel matters." An HHS spokesperson also said the department "does not comment on pending litigation or personnel matters."

D'Souza came to NIH after a long academic career in dental research. She was previously a professor at Baylor College of Dentistry, part of Texas A&M University.

Rena D'Souza, director of the National Institutes of Health's National Institute of Dental and Craniofacial Research, has been on involuntary leave since April.

In 2013, she was recruited as inaugural dean of the dental school at the University of Utah. One year later, she was removed from that job, although she remained there as a tenured professor until she moved to NIDCR.

At NIH, D'Souza's unpaid 2022 and 2023 suspensions triggered her lawsuit, filed in September 2023 in U.S. District Court for the Southern District of Maryland. In it she accuses Tabak, then acting NIH director, and Tara Schwetz, then the agency's acting principal deputy director, of taking "severe disciplinary actions" with the goal