

## What is a mathematical physicist doing out in the cold? **FREE**

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Kenneth Golden puts numbers to sea ice, melt ponds, and massive waves.

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The first time Kenneth Golden went to Antarctica, he was a college senior, majoring in math and physics. He landed the expedition through his job as a research assistant at the US Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, where he was helping to develop methods for measuring the thickness of sea ice. That was in 1980. Since then, he's been back to Antarctica a half dozen times, and to the Arctic 10 times.

Golden earned his PhD at the Courant Institute of Mathematical Sciences at New York University, and, after stints at Rutgers and Princeton Universities, he joined the faculty of the University of Utah. For a while, his research strayed from sea ice—other major focuses have been composite materials and percolation. "I didn't know it," he says, "but everything I was working on was somehow in my mind motivated by sea ice." To this day, he says, determining the thickness of sea ice is "one of the holy grails of climate science."



Ken Golden takes a sea-ice core in Antarctica during a 2012 expedition. CREDIT: David Lubbers, University of Utah.

Among other honors he has received, in 2014 Golden was inducted into the Explorers Club, putting him in the company of the likes of the earliest polar explorers, mountaineers, astronauts, Amazon.com founder Jeff Bezos, filmmaker and deep-sea explorer James Cameron, primatologist Jane Goodall, and cosmologist Neil deGrasse Tyson.

In phone calls with *Physics Today's* Toni Feder, Golden recounted where his adventures had taken him, how his passion for math led him to sea ice, and why his interest in the topic has not thawed.

**PT:** How did you start working on sea ice?

**GOLDEN:** Both of my parents were scientists—I believe there are like 15 species of nematodes named after my dad. So I was always exposed to science. I remember sitting on my front porch when I was about 10 years old. I think I had pretty much realized that math was the language of the sciences, and I decided at that point that no matter what science I went into, I was going to be a

math major.

Later, in high school in Beltsville, Maryland, I was hooked up with a glaciologist at NASA's Goddard Space Flight Center. I was using calculus and satellite imagery to figure out the height of certain icebergs. My adviser told me to go to Dartmouth, to take as much math as possible, and to go work with Steve Ackley, a sea-ice physicist at CRREL. I took his advice. It turned out to be one of the really pivotal experiences in my life. It led to so many things.

**PT:** What are some examples of what Dartmouth led to?

**GOLDEN:** I got involved in a ... mystery: measuring the thickness of sea ice. It boils down to observing the close relationship between sea-ice microstructure—namely, pure ice with brine inclusions—and so-called stealthy radar-absorbing deposits. The military coats aircraft to make them invisible to radar. It turns out that sea ice itself is radar absorbing. And because the kind of frequencies that satellites use gets sucked up by the sea ice, it's very difficult to measure sea-ice thickness.

We [at CRREL] were using ground-penetrating radar; it operates at much lower frequencies and so could get through the ice.

What we noticed was, with the antenna in one position, you get a nice big reflection from the bottom of the ice. But if you turn the antenna 90 degrees in the horizontal plane, you don't see anything. It was well known that there is a high degree of vertical anisotropy. But the horizontal anisotropy comes from the electrically conducting brine tending to line up, [because there is] a well-defined long-term current direction in those areas off the coast of Alaska. We developed a mathematical model of the statistically aligned brine microstructure and the propagation of a polarized radar wave through the sea ice that explained the observed behavior.

Later, this work I did as an undergraduate got me introduced to

George Papanicolaou [who became Golden's PhD adviser at the Courant Institute]. He was a heavy-duty math professor with a background in electrical engineering. He was just starting to work on the mathematics of composite materials. We ended up developing the underlying mathematics—namely functional analysis and complex analysis for finding bounds on the effective transport coefficients, first for two-phase composites and then for multiphase materials.

**PT:** When did you realize that the mathematics you were doing was important to understanding sea ice?

**GOLDEN:** One of the most dramatic moments in my career was during an expedition to Antarctica in 1994. It was July 24, which is Pioneer Day in Utah. There was a raging storm. The sea ice was warming and becoming more porous, and the snow was adding weight. That means the ice is being pushed down into the ocean. At that moment, I literally saw seawater percolating up and flooding the surface. Everything coalesced in my brain: This is the percolation model that I was so fascinated with. It's not just a peripheral phenomenon—it's central.

At that moment I realized that it was worth trying to figure out a theoretical understanding of the brine microstructure of sea ice, how it changes with temperature, and how [it] either [has fluid flow] or not. This epiphany about the on–off switch for fluid flow in sea ice launched me back into bringing sophisticated math and physics to the sea-ice game.

Percolation is central to the physics of sea ice, and to the biology as well. It turns out that the flow of nutrients controls the life cycle of algae, which are one of the most important components of the rich polar ecosystems. It's what everybody else lives off of.

**PT:** Your work is theoretical and computational. Why are the expeditions to the poles important for you?

**GOLDEN:** Maybe someone could have told me what happens.

But I think differently from a classically trained geologist or glaciologist, and I am going to see different things. Sea ice—and how it interacts with the ocean, the atmosphere, the waves, and so on—is a very complicated system. It's not always obvious how things are going to behave.

And then there is the wonder and the beauty of it. Hanging out with penguins and seals, seeing the massive waves and whales. It's a beautiful place to live intellectually.

**PT:** How directly is your work connected to climate science?

**GOLDEN:** Our results have been incorporated into global climate models to improve projections of how rapidly we may lose the summer Arctic sea-ice pack. And to improve projections of what the Earth's climate may do in the future.

We take information about the microstructure and we develop rigorous mathematical techniques for understanding, approximating, bounding, and studying the effective transport properties—like effective electrical conductivity, effective thermal conductivity, effective complex permittivity, the effective strength and elastic properties, and so on.

But how do you mathematically incorporate the properties? There are millions and millions of submillimeter brine inclusions. There are thousands of ice floes potentially in one grid cell [of a computational model]. How do you rigorously incorporate these very small-scale processes and structures into these very coarse-grained, large-scale models? That is the fundamental problem of composite materials, and it is one of the central issues of climate science.

I am not building those big computer models, but some of my mathematical work gets incorporated into them.

**PT:** Do you observe signs of global warming?

**GOLDEN:** Absolutely. In the Arctic, particularly, it's dramatic.

**PT:** What are you working on these days?

**GOLDEN:** Melt ponds and waves. The world's best climate models predict a general decline of summer Arctic sea ice over the 21st century. However, what's been so dramatic is that the actual rate of melting is far more rapid than expected. Then comes the question: What are we missing in the models? What is the basic physics?

The ponds are iconic features of Arctic summer sea ice. They are pools of water that form on the surface of sea ice as it's melting. The ponds are dark, whereas the sea ice is light, so it changes the albedo. Instead of solar radiation being reflected back into space, it's absorbed. It's a double whammy—the melt ponds help melt more ice.

However, the pictures of the melt ponds are fabulous. And when I look at them, I see fractals. So we started looking into that. We thought we would find some fixed fractal dimension, as with clouds, but we found a much more fascinating phenomenon, namely that the fractal dimension of the melt ponds changes as they grow and coalesce. The boundaries go from simple curves ... to wiggle and wander to such an extent that the fractal dimension approaches two.

It's like the boundaries of the ponds are trying to behave like space-filling curves. We have come up with all kinds of mathematical models that explain and predict this type of behavior, such as an Ising model originally devised to understand the Curie point in ferromagnets.

**PT:** What about waves?

**GOLDEN:** I love massive waves. One of the greatest days of my life was returning from a 2007 expedition. We were two days out from Hobart [Australia] and we awoke to hurricane-force winds.

The 300-foot-long *Aurora Australis* was getting tossed around like a matchbox.

We are trying to understand the propagation characteristics as a wave moves through not just water but through the ice pack. The waves break up the ice. That changes the way it melts, freezes, or whatever. As waves propagate through the sea ice, they break up the floes, so you are actually changing the medium. It's a highly nonlinear, very challenging problem to understand the propagation of waves and how they interact with the ice.

**PT:** Some of your work is in bioengineering. What's the connection?

**GOLDEN:** This is an example of cross pollination. I had an undergraduate working with me. She was interested in studying lungs—applying the mathematics we had developed for fluid flow through sea ice to modeling gas flow through a lung. It's a similar problem.

There is also a deep similarity between the porous microstructure of sea ice and the porous microstructure of human bone. A colleague and one of my students adapted a mathematical analysis we had done for sea ice to work with the microstructure of human bone. We developed a method of inverting bulk electromagnetic data to get information about the progression of osteoporosis without cutting someone's leg open. We have not pursued this, but we have developed the method.

Another thing I have been looking at are massive blooms of algae underneath the sea ice. The ice is thinner, there is less of it, there are more melt ponds. Is there a critical amount of light that gets through the ice pack and triggers a bloom? Are we in a new ecological regime? There are all kinds of fascinating mathematics that can help us understand what's happening.

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