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Explaining Ice: The Answers Are Slippery

By KENNETH CHANG

Here is one question that probably won't cross the minds of Sasha Cohen, Irina Slutskaya and the other Olympic women figure skaters today, even if they fall: Why is ice slippery?

But maybe it should. After all, ice is a solid, and trying to glide on thin metal blades across the surfaces of most solids — concrete, wood, glass, to name a few — results in ear-piercing sounds and ungraceful stumbles. Though the question may seem to be a simple one, physicists are still searching for a simple answer.

The explanation once commonly dispensed in textbooks turns out to be wrong. And slipperiness is just one of the unanswered puzzles about ice. Besides the everyday ice that you slip on, there are about a dozen other forms, some of which experts suspect exist in the hot interior of Earth or on the surface of Pluto. Scientists expect to discover still more variations in the coming years.

Ice, said Robert M. Rosenberg, an emeritus professor of chemistry at Lawrence University in Appleton, Wis., and a visiting scholar at Northwestern University, "is a very mysterious solid."

Dr. Rosenberg wrote an article looking at the slipperiness of ice in the December issue of Physics Today, because he kept coming across the wrong explanation for it, one that dates back more than a century.

This explanation takes advantage of an unusual property of water: the solid form, ice, is less dense than the liquid form. That is why ice floats on water, while a cube of frozen alcohol — which has a freezing temperature of minus 173 degrees Fahrenheit — would plummet to the bottom of a glass of liquid alcohol. The lower density of ice also means that the melting temperature of ice can be lowered below the usual 32 degrees by squeezing on it.

According to the frequently cited — if incorrect — explanation of why ice is slippery under an ice skate, the pressure exerted along the blade lowers the melting temperature of the top layer of ice, the ice melts and the blade glides on a thin layer of water that refreezes to ice as soon as the blade passes.

"People will still say that when you ask them," Dr. Rosenberg said. "Textbooks are full of it."

But the explanation fails, he said, because the pressure-melting effect is small. A 150-pound person standing on ice wearing a pair of ice skates exerts a pressure of only 50 pounds per square inch on the ice. (A typical blade edge, which is not razor sharp, is about one-eighth of an inch wide and about 12 inches long, yielding a surface area of 1.5 square inches each or 3 square inches for two blades.) That amount of pressure lowers the melting temperature only a small amount, from 32 degrees to 31.97 degrees. Yet ice skaters can easily slip and fall at temperatures much colder.

The pressure-melting explanation also fails to explain why someone wearing flat-bottom shoes, with a much greater surface area that exerts even less pressure on the ice, can also slip on ice.

Two alternative explanations have arisen to take the pressure argument's place. One, now more widely accepted, invokes friction: the rubbing of a skate blade or a shoe bottom over ice, according to this view, heats the ice and melts it, creating a slippery layer.

The other, which emerged a decade ago, rests on the idea that perhaps the surface of ice is simply slippery. This argument holds that water molecules at the ice surface vibrate more, because there are no molecules above them to help hold them in place, and they thus remain an unfrozen liquid even at temperatures far below freezing.

Scientists continue to debate whether friction or the liquid layer plays the more important role. Dr. Rosenberg, asked his opinion, chose a indecisive answer: "I say there are two major reasons."

The notion that ice has an intrinsic liquid layer is not a new concept. It was first proposed by the physicist Michael Faraday in 1850 after a simple experiment: he pressed two cubes of ice against each other, and they fused together. Faraday argued that the liquid layers froze solid when they were no longer at the surface. Because the layer is so thin, however, it was hard for scientists to see.

In 1996, Gabor A. Somorjai, a scientist at Lawrence Berkeley Laboratory, bombarded the surface of ice with electrons and watched how they bounced off, producing a pattern that looked at least partially liquid at temperatures down to minus 235 degrees. A couple of years later, a team of German scientists bounced helium atoms off ice and found results that corroborated the Lawrence Berkeley findings.

"The water layer is absolutely intrinsic to ice," Dr. Somorjai said.

The findings, he said, fit with a simple observation that suggests friction cannot be the one and only explanation of slipperiness. When a person stands on ice, he added, no heat is generated through friction, and yet "ice is still slippery."

But a colleague of Dr. Somorjai's at Lawrence Berkeley, Miquel Salmeron, while he does not dispute Dr. Somorjai's experiment, does dispute the importance of the intrinsic liquid layer to slipperiness.

In 2002, Dr. Salmeron and colleagues performed an experiment. They dragged the tip of an atomic force microscope, resembling a tiny phonograph needle, across the surface of ice.

"We found the friction of ice to be very high," Dr. Salmeron said. That is, ice is not really that slippery, after all.

Dr. Salmeron said that this finding indicates that while the top layer of ice may be liquid, it is too thin to contribute much to slipperiness except near the melting temperature. In his view, friction is the primary reason ice is slippery. (The microscope tip was so small that its friction melted only a tiny bit of water, which immediately refroze and therefore did not provide the usual lubrication, he said.)

Dr. Salmeron concedes, however, that he cannot definitively prove that his view is the correct one.

"It's amazing," he said. "We're in 2006, and we're still talking about this thing."

Ice formed by water behaves even more strangely at lower temperatures and higher pressures.

Water — H_2O — seems to be a simple molecule: two hydrogen atoms connected to a central oxygen atom in a V-shape. In everyday ice, which scientists call Ice Ih, the water molecules line up in a hexagonal pattern; this is why snowflakes all have six-sided patterns. (The "h" stands for hexagonal. A variation called Ice Ic, found in ice crystals floating high up in the atmosphere, forms cubic crystals.)

The crystal structure of the ice is fairly loose — the reason that Ice Ih is less dense than liquid water — and the bonds that the hydrogen atoms form between water molecules, called hydrogen bonds, are weaker than most atomic bonds.

At higher pressures, the usual hexagonal structure breaks down, and the bonds rearrange themselves in more compact, denser crystal structures, neatly labeled with Roman numerals: Ice II, Ice III, Ice IV and so on. Scientists have also discovered several forms of ice in which the water molecules are arranged randomly, as in glass.

At a pressure of about 30,000 pounds per square inch, Ice Ih turns into a different type of crystalline ice, Ice II. Ice II does not occur naturally on Earth. Even at the bottom of the thickest portions of the Antarctic ice cap, the weight of three miles of ice pushes down at only one-quarter of the pressure necessary to make Ice II. But planetary scientists expect that Ice II, and possibly some other variations, like Ice VI, exist inside icier bodies in the outer solar system, like the Jupiter moons Ganymede and Callisto.

With pressure high enough, the temperature need not even be cold for ice to form. Several Februaries ago, Alexandra Navrotsky, a professor of chemistry, materials science and geology at the University of California, Davis, was visiting Northwestern. She was sitting in office of Craig R. Bina, a geophysicist, and looking out over frozen Lake Michigan. "Ice might have been on our minds," she recalled.

The scientists started considering what happens to tectonic plates after they are pushed back down into Earth's interior. At about 100 miles down, the temperature of these descending plates is 300 to 400 degrees — well above the boiling point of water at the surface — but cool compared with that of surrounding rocks. The pressure of 700,000 pounds per square inch at this depth, Dr. Bina and Dr. Navrotsky calculated, could be great enough to transform any water that was there into a solid phase known as Ice VII.

No one knows whether ice can be found inside Earth, because no one has yet figured out a way to look 100 miles underground. Just as salt melts ice at the surface, other molecules mixing with the water could impede the freezing that Dr. Bina and Dr. Navrotsky have predicted.

Ice also changes form with dropping temperatures. In hexagonal ice, the usual form, the oxygen atoms are fixed in position, but the hydrogen bonds between water molecules are continually breaking and reattaching, tens of thousands of times a second.

At temperatures cold enough — below minus 330 degrees — the hydrogen bonds freeze as well, and normal ice starts changing into Ice XI.

William B. McKinnon, a professor of earth and planetary sciences at Washington University in St. Louis, said that astronomers were probably already looking at Ice XI on the surface of Pluto and on the moons of Neptune and Uranus. But instruments currently are not sensitive enough to distinguish the slight differences among the ices.

The most recently discovered form of ice, Ice XII, was found just a decade ago, although hints of it had been seen years earlier. John L. Finney of University College London, one of the discoverers of Ice XII, said that trying to understand all the different forms of ice was important for an understanding of how the water molecule works, and that was important in understanding how water interacts with all the biological molecules in living organisms.

"It gives you a very stringent test for our understanding of the water molecule itself," he said.

And could there be an Ice XIII?

"Yes," Dr. Finney said. "Call me in a month."

But scientists have given no word on whether any of these other types of ice are slippery enough to land a triple axel.