

Gems

below the freezing point

A wintertime tale of surprising uses for snow and ice

Living in a warm climate, ice and snow can seem beautiful and romantic. Without a doubt, even disaster workers who deal with their devastating effects share such a viewpoint from time to time. Some scientists even regard ice as a kind of gem and it is their research, especially with regard to high-speed skating rinks, that reveal interesting insights into the relationship between man and nature.

**A brief history of snow removal
Why search for water
when you're covered
in snow?**

At the end of November, when we visited Toyama Prefecture on the Japan Sea coast in central Japan, the winds were so strong we couldn't open umbrellas without worrying about damage. According to our taxi driver, a major snowstorm was due in the nearby mountains. "When the snow starts piling up, it will seem warmer outside because the wind stops," she said. "Next year we're supposed to get a huge snowfall, the kind that comes only once every 18 years, and I'm worried."

In 1963 there was a record snowfall and Toshiichi Kobayashi, Senior Researcher at Niigata Prefecture's Nagaoka Institute of Snow and Ice Studies, still has vivid memories of working to remove snow in Nagaoka. At the time, he was a high school student and took a week off to help with disaster relief efforts. He recalled that some days they got more than three meters (10 feet) of new snow. The next major snowfall in that area came 18 years later, in 1981. Then, as a researcher at the Institute, they hardly lacked for sufficient research material, but "enough is enough," he laughed. "We still had to function if we were to study this cold white substance, but it snowed every day. Once I just looked up at the sky and threw my hands up in a helpless 'banzai' to the heavens."



This illustration was provided courtesy of Kansai Electric Power Co., Inc.



Toshiichi Kobayashi
Senior Researcher, Nagaoka Institute of Snow and Ice Studies, National Research Institute for Earth Science and Disaster Prevention Science and Technology Agency. Credited with the development of snow ditches for transporting snow to rivers. Joined the National Research Center for Disaster Prevention in 1965 as an Assistant Researcher. Born in 1946 in Nagaoka, Niigata Prefecture.

At that time, he was far too busy fighting the problematic effects of snow to consider how to put it to practical use.

About 10 minutes from the Nagaoka train station on top of a hill is the Nagaoka Institute of Snow and Ice Studies, where we spoke with Mr. Kobayashi about disaster prevention methods.

The first snow removal equipment in Japan was all imported from Switzerland, where it was originally invented. So during the huge 1963 snowfall, we only had imported machines. Unfortunately, Japan's snow is different than in other regions of the world. In Niigata Prefecture, for example, it is quite wet and this tended to clog the Swiss-made equipment, rendering it ineffective. By the late 1960's Japan had begun to develop its own snow removal equipment specifically tailored for wet snow. Thanks to domestic efforts, during the next major snowfall in Nagaoka in 1981 there were no major problems keeping the main roads clear. But that wasn't the whole story.

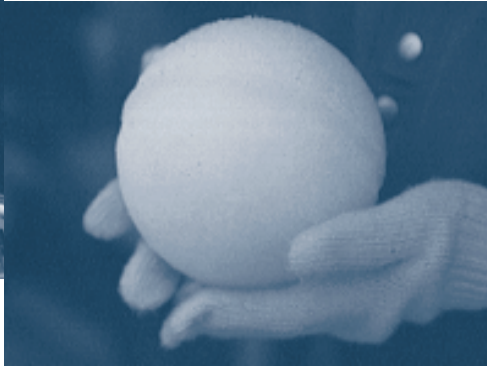
On roads too narrow for snow removal equipment, or on walkways surrounding a house, the equipment we used for clearing main roads was ineffective. It was simply too difficult to transport snow removal equipment to narrow roads and pathways. In addition, vehicles used for transporting snow removal equipment can be so large they block the main roads. Sometimes even pedestrians can't get by. In response to such problems, we invented two new methods for snow removal: the snow

A snowball-making machine. With the 2-ton compression power by a compressor, two air cylinders force two half-spheres together to form compressed balls of snow, which was placed into the hopper on top.



(In actual use, it would be connected to a transport tube)

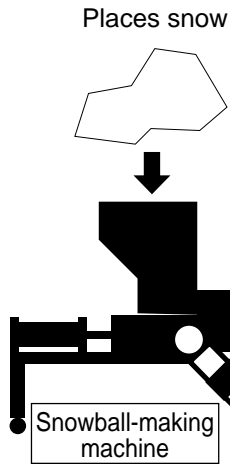
13.5 cm diameter
The surface of this ball is extremely smooth.



This transport tube is 50-60 meters long, however, successful experiments have been performed at distances of around 200 meters.



Transport tube



There are two ways to transport a snowball, pushing and pulling by the air. This system pulls the snowballs via a pipe connected to a strong suction from an electric fan.

pipe and the snow ditch.

The snow pipe works by taking water from warm underground springs and spraying it to melt the snow, while the snow ditch is simply a ditch dug next to the street. After snow has been removed from the street, it is dumped into the ditch to eventually be washed into a natural river. Both of these methods are widely used today in Niigata Prefecture and its surrounding areas. Special sensors are even used to detect snow-fall and activate the snow pipes.

Unfortunately, when it snows a lot, we use large quantities of underground water. In some areas, Muikamachi city for example, we actually lowered the water table. Some regions have restricted the use of these methods and, in general, they are on the decline. Another problem caused by all the water from underground springs and melted snow is the mess for pedestrians. Around 10 years ago in Nagaoka, "Coming of Age" day was officially put off until May. (Coming of Age day, which is the nationwide celebration set for January 15, marks the beginning of adulthood for all 20-year-olds and involves wearing expensive kimonos.) Of course, the snow ditch has its own set of problems. Even though it utilizes natural waterways, obtaining the rights for their use can be quite difficult. Finally, researchers began to look for alternate snow removal methods that did not involve water. Mr. Kobayashi looked into using air power to remove snow.

In 1985 we began studying how we might use air power to remove snow. But as wet snow tends to get stuck inside an air pipe, we had to move it through extremely fast, which required substantial air power. In 1988, we came up with the idea of forming snow into balls before using air power to move them.

**Snow: From disaster relief
to practical uses**
**The ultimate resource plan
—snowballs all over Japan**

Mr. Kobayashi took snow from a freezer and placed it into a snowball-making machine. It made a swishing sound as it compressed the snow and after about 20 seconds we had a snowball around 13.5 cm (5 1/2") in diameter, just larger than an Olympic shotput. Picking it up I was surprised to find that it was really a hard, heavy iceball. Only a giant could really use it in a snowball fight.

In spite of its size and weight, if I held it near the end of a special air pipe, it disappears into the pipe immediately, like a small animal freed from its cage. "The speed of the airflow inside this pipe is 10 meters/second (33 feet/sec.)," said Mr. Kobayashi. "For wet snow not yet formed into snowballs, it needs to be 25 meters/sec. to prevent snow from getting stuck in the pipe."

The snowballs had a travel speed of about 8 meters/sec., traversing a 50- or 60-meter-long pipe in less than 8 seconds. At the end of the pipe, they were channeled through a spiral trough into a

collection bin. When I looked inside the bin, I was surprised to see our icy shotput, miraculously unbroken!

Our calculations have shown that the suction from one machine like this can transport these snowballs for 1 kilometer (0.62 miles). Of course, we still have to overcome the technical challenge of reducing the time to actually make the snowballs. And our biggest problem is making the system cost effective.

If you only consider snow transport costs, air pipe expenses are less than half those of truck transport. But if you include the cost of making the snowballs, the air pipe method is far more expensive than using a truck. Cost reduction becomes a key issue.

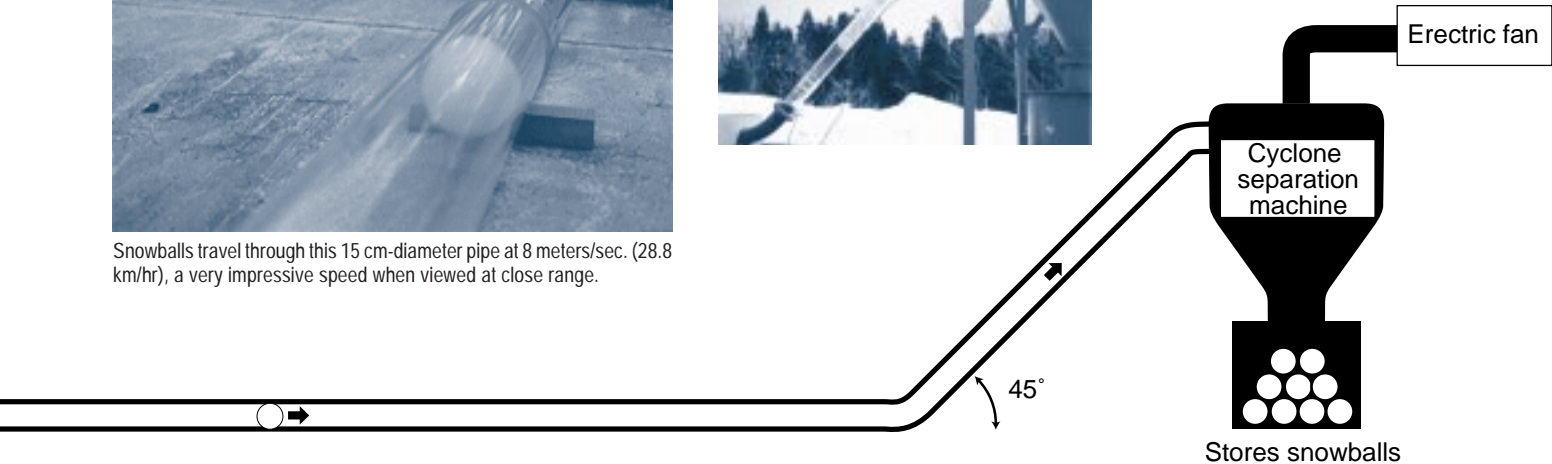
As a result, researchers began to look at these snowballs from a new perspective. If they are so expensive, why throw them away? What practical uses might justify the cost of making these snowballs? According to Mr. Kobayashi, there are several applications for snowballs already in use.

One way we utilize snow is with refrigeration. For example, snow is used to help cool a huge rice storage plant in Numatamachi city, Hokkaido (Japan's northernmost main island). There's a refrigeration plant in Niigata Prefecture that uses snow as well. Some people say it is superior to a conventional refrigerator because of the higher humidity, which makes vegetables taste sweeter. In neighboring Yamagata Prefecture at the Agricultural Research Laboratory in Funagatamachi city they even have an

This system is capable of about 2.5 meters in elevation gain, even at a 45 degree slope. Snowballs are deposited in the bin after being separated from the air stream by a cyclone separation machine.



Snowballs travel through this 15 cm-diameter pipe at 8 meters/sec. (28.8 km/hr), a very impressive speed when viewed at close range.



air conditioning system employing air that has been forced through snow. Not only does this provide cooling, it has the additional benefit that snow acts as a natural filter, and purifies the air.

Mr. Kobayashi hopes to send snowballs everywhere cooling is needed, and his plans don't end there. He has also conceived of a grand scheme to send snowballs from Japan's snow-heavy prefectures on the Sea of Japan to the Pacific Coast side, where large cities often run short of water during the winter.

This is only in the dream stage, and very far from being practical yet. There are many problems to solve, such as: Do we have a constant and reliable supply of snow? Do we have enough power to transport snowballs over the high mountains separating the coasts? Is this cost effective? I don't think this is too radical to pursue. In fact, I think of snow as an important natural resource. Success on such a project would be the pinnacle of my entire career.



On the wall of Mr. Kobayashi's laboratory is a picture of an icicle shoot sprouting up from the ground, like a young bamboo plant.

It was big news when professor Tsushima of Toyama University planted this icicle in a skating rink. I was one of his students at the time, and distinctly remember the way he stayed up all night in freezing weather to study how a single ice crystal grew. I have tremendous respect for him and consider him to be a person of rare dedication.

Icicle shoots research and applications Single ice crystals growing in tunnels

In 1980, just one year before the huge snowstorm of 1981, Katsutoshi Tsushima joined the faculty of Toyama University. A longtime colleague of Mr. Tsushima, he said, "I've known Mr. Kobayashi over 20 years, starting from when we worked together at Hokkaido University's Institute of Low Temperature Science. He then told us the story of an unexpected discovery.

A tremendous avalanche had occurred in Kurobe Valley (known for its hydroelectric plants) near Nagano Prefecture, and it had washed away an entire 80-person company housing complex. It was during one of my many trips to study the effects of this avalanche that I came across the icicle shoot.

At that time, he had no idea how important his discovery was to become. He said it was inside one of the maintenance tunnels near the dam where he first discovered icicle shoots.

There were so many of them, we had to kick them out of the way in order to walk through the tunnel. And though they were beautiful, they were so numerous they didn't seem worthy of taking home to study. It was two more winters before their importance was recognized. Without any serious intentions in mind, Mr. Tsushima simply began analyzing these strange icicle shoots out of curiosity.

I realized that the first 10 cm (4") of the shoot had a multiple crystalline structure. But, to my surprise, above that point it was a huge single crystal extending for 30 or 40 cm (12" to 16").

Though it has a similar shape, what most people call icicles are wholly comprised of a multicrystalline structure. They are made up of many layers, each new one created by cold air, which freezes water that drips down from above. Essentially, the center of a common icicle is formed long before its outermost layers.

In contrast, icicle shoots are formed by drips of water that fall every 20-30 seconds onto a shoot growing up from the ground. Each drop slightly melts the surface of the icicle shoot, and refreezes as if it had been a single body of liquid. As we can see, single-crystal icicle shoots can actually be formed quite easily.

In fact, the technique of remelting existing ice each time new water is added is employed at most skating rinks. Icicle shoots only differ in terms of water temperature, amount and the frequency with which it is added.

What other characteristics are shared by icicle shoots and skating rinks? When Mr. Tsushima presented his findings on single-crystal icicle shoots at a conference in 1983, he had no practical applications in mind. But this would change dramatically in 1997, just one year before the Nagano Olympic Games. It was then that he analyzed some ice samples from a new skating rink called the M-Wave.



Icicle shoot factory at Kurobe Valley's Akazawa horizontal tunnel. This 190-meter-long room is used to grow some 4,800 icicle shoots. IV control systems regulate the rate at which water drops fall, and shoots are monitored around the clock. They grow approximately 1.5 cm per day. (Photo provided courtesy of Kansai Electric Power Co., Inc.)

In icicle shoot discovered in a tunnel in Kurobe Valley. (Photo provided courtesy of Kansai Electric Power Co., Inc.)



Vertical cross-section of an ice sample from the M-Wave rink. On the right, icicle shoots have been inserted to take advantage of their slicker end-face surface. On the left is a conventional rink. The rink employing icicle shoots has about 20% less friction.

An area where icicle shoots have been implanted. Note that the individual shoots are no longer visible.
— The ice in this area was produced using conventional methods.



Horizontal cross-section of an icicle shoot that is 10 cm (4") in diameter.

If you examine a vertical cross-section of a tubular ice sample from the rink, you'll find many long, cylindrical crystals about 5 mm in diameter running from bottom to top. This is what prompted me to try and apply some of my findings on icicle shoots. I then learned that not only did the rink designer have a special technique for growing these cylindrical ice crystals, the ice was frequently repaired by shaving the surface and adding hot water. At that point, I began to believe it was possible to produce an entire rink of ice crystals by starting with many single-crystal icicle shoots.

Imagine, a skating rink comprised of single-crystal icicles! But let's not jump to conclusions. In contrast to the thin cylindrical ice crystals produced by the rink designer, icicle shoots are 10-15 cm in diameter. And while using larger icicle shoots would reduce the number of gaps between crystals, it wouldn't necessarily mean a faster skating rink.

Since we added hot water on many occasions and refroze it each time, the water molecules became connected to one another over a very large area. Because of this phenomenon, there was no significant difference between using

large- or small-diameter icicle crystals. In fact, if large crystals are poorly oriented, the rink can end up being slower than if you had just used small crystals. Aha, the orientation of the icicle crystals is the secret of high-speed skating rinks!

Two conflicting theories of friction Another kind of competition on skating rinks

Ice crystals are comprised of six-sided crystal slabs stacked on top of each other, in layers. The top end of this crystal cylinder is very slippery compared to the sides, which can have twice as much the friction (see Figure 1). So by positioning slippery faces side by side over a large area, you create a skating rink with extremely low friction. For the M-wave rink, the ice crystals already grow from bottom to top ensuring a slippery face is always on top, so everything is fine, right?

Wrong. The problem is that ice crystal growth is not uniform, which means the top faces are not necessarily parallel to one another. One of our greatest challenges was to control the orientation of

the crystal surfaces, and it was for this reason that we tried using icicle shoots (see Figure 2).

Skate friction over the side faces of ice crystals varies depending on direction of travel.

If your skate runs parallel to joints between ice crystal slabs, the friction is much less than running perpendicular to them.

These findings have significant implications that go far beyond skating rinks. But to appreciate this, we need to look at the theory behind the phenomenon of friction. Any material, even if it appears perfectly smooth, has a rough surface at the molecular level. And when one material rubs against another, the pressure where the high points make contact can be high enough to deform them like starch syrup. The deformed surfaces then stick to one another, as if they had been soldered together. The force required to break them apart again is what we call friction. At least, this is the adhesion theory, that is, the basic theory of friction.

Compared to the friction between most materials, skis on snow only have about 1/10th as much, and skates on ice have about only about 1/100th. As a result,

skiing and skating cannot be well understood using this theory of friction. In 1939, an English scientist named Dr. Bowden developed a fusion-friction theory for ice and snow. He postulated that a warm “fever” at the point of contact would generate a small amount of water that acts as a lubricant to reduce friction. Over the years, many new types of friction phenomena have been reported, but there is still no theory considered more useful than the theory by Dr. Bowden.

On the other hand, Mr. Tsushima has been working for years at applying theories to snow and ice that are based on the earlier adhesion theory. Until recently, he did not have the confidence to oppose Dr. Bowden’s theory and chose to say that both theories of friction were valid.

But today I’ve changed. By the time I retire, nine years from now, I want to prove that my theories are right and that Dr. Bowden’s is wrong. The results of my research on icicle shoots can only be explained by adhesion theory. For example, friction varies depending on the orientation and the face of a crystal. If we apply the friction-fusion theory, the amount of water acting as a lubricant would have to be different for each face. My research indicates, however, that slippery high-speed ice faces have more water, and less friction. This contradicts Dr. Bowden’s theory, which says lower friction comes from increased water that is the result of a warmer “fever.” Yet a smoother face would have less “fever” because it’s so smooth. So where does all of the extra water come from? In practice, you can have an extremely slippery surface without a lot of water on it. Why? One possibility is that ice crystals are extremely weak in the horizontal direction, and the stacks of crystal slabs separate from one another and slip, which would reduce the friction.

Mr. Tsushima came across another interesting discovery by examining the track of the knife-edge of a skate he found on the corner of the rink where he had been working with skaters to give the technical instruction.

Looking closely at where the blade had cut the ice, I found a small mountain on either side of the groove. If I apply the friction-fusion theory, the water generated should have spread immediately

and made the mountains very shallow. But, in fact, they were very sharp and steep, the result of the ice material being pushed past its tensile strength limit. And it is yet another example which supports my adhesion theory. I am currently considering how to utilize this phenomenon on next-generation skating rinks. For example, though a rink is flat, these tiny mountains might help improve cornering much like a banked track at a bicycle velodrome. If this is true, we should then utilize the sides, not the top, of ice crystals in cornering areas as they are not as slippery. We could even optimize the banking effect by adjusting their orientation (see figure 3).

Using everything we have learned about ice to make the best possible straight-aways and cornering sections, we could look for new records to be set as rinks bring out more of a skater’s ability. If this, in fact, happens, friction experts all around the world will probably wish they had devoted more time to the study of ice crystals.

I’m always telling my students we are surrounded by a treasure chest of precious gems, full of unknown possibilities. The way I see true research is simple taking a new jewel out of the treasure chest. And since we each have a unique perspective on the world, there

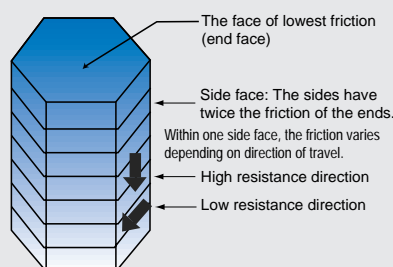


Katsutoshi Tsushima
Professor at Toyama University, Department of Earth Sciences, Geosphere Physics Department, since 1980. Joined Hokkaido University’s Low Temperature Laboratory in 1969. Born in 1943.

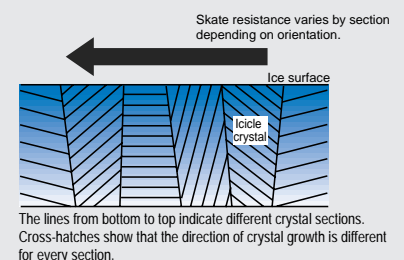
are many gems to be found. That’s also why I tell students it’s important to live your unique, individual life, different from the lives of others.

Like a glittering crystal, the icicle shoot skating rink is quietly waiting for the day when new records will replace old ones, and old theories are replaced by new ones.

■ **Figure 1 Ice crystal structure and friction coefficient**

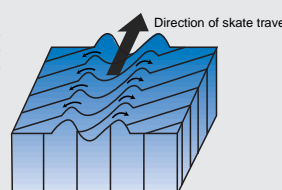


■ **Figure 2 Vertical cross-section of a conventional skating rink (conceptual diagram)**

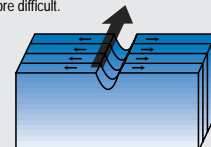


■ **Figure 3 The amount of banking effect at the corners of a skating rink varies with crystal orientation (conceptual diagram)**

Because these small mountains are formed so readily, it is easier for skaters to overcome the outward centrifugal force during cornering.



Mountains are not formed as easily due to increased ice movement at the molecular level, which makes cornering more difficult.



Nagano’s M-wave ice rink utilizes icicle shoots and was completed in October 1997. The first international competition at the rink was the World Cup, held in December the same year. The rink is considered one of the fastest in the world.