

# Snowflake Science

*A Rich Mix of Physics,  
Mathematics, Chemistry, and Mystery*

By Kenneth Libbrecht

Growing up on a farm in North Dakota, I developed an early and intimate familiarity with snow. The cold north winds blowing down from the Canadian prairie brought us everything from quiet snow flurries to great howling blizzards. My winters were filled with snowballs, snow forts, and snowmen, with sliding, sledding, and skiing. Snow wasn't just part of the landscape where I lived; it was part of our heritage.

On snowy afternoons at school, our class sometimes trekked outdoors with magnifying glasses in hand to examine falling snowflakes. The crystals were especially well-formed on colder days, when the starlets would sparkle brightly and linger long enough for a careful inspection of their shape and symmetry. Then the activity became a frenzied treasure hunt as we vied to see who could find the largest or most spectacular specimen.

Although I've admired many a snowflake in my day, only recently have I begun to appreciate their more subtle features. In my youth, the phenomenon of snow was so familiar that I usually ignored how extraordinary it is, that nature somehow manages to craft these miniature ice masterpieces right out of thin air. Perhaps we just had too much of a good thing—it can be difficult to appreciate the inner beauty of snowflakes when the driveway is piled high with them and you have a shovel in your hand.

It was only later in life, after moving to southern California and enjoying a long hiatus from shoveling, that I began to look carefully at snowflakes. I had been examining the physics of how crystals grow and form patterns, and I suppose my heritage returned to guide my thoughts. Snowflakes are growing ice crystals, after all. Before long I was studying just how these frozen structures are created in the clouds, and even how to engineer synthetic snowflakes in my laboratory.

Investigating the physics of snowflakes is an unusual occupation, to say the least. When visitors stop by my lab,

*Kenneth Libbrecht is professor of physics and chairman of the Physics Department of the California Institute of Technology. The purpose of his research on snow crystals is to better understand pattern formation in nonlinear nonequilibrium systems. This article is excerpted with permission from The Snowflake: Winter's Secret Beauty, by Kenneth Libbrecht, 2003, Voyageur Press. Photographs © Kenneth Libbrecht.*

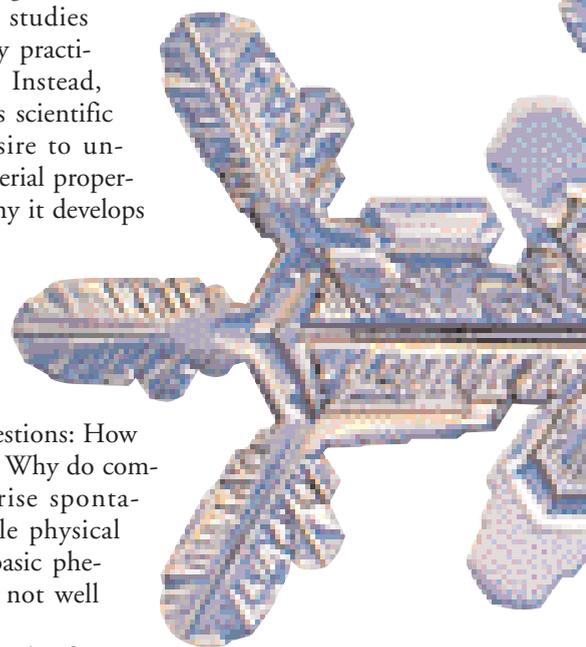
they're sometimes puzzled why anyone would spend time trying to understand snowflakes. Was I trying to work out schemes for weather modification? Could this research improve the quality of artificial snow for skiing?

No, my flaky studies are not driven by practical applications. Instead, my motivation is scientific curiosity—a desire to understand the material properties of ice and why it develops such elaborate patterns as it grows. The formation of snowflakes touches on some fundamental questions: How do crystals grow? Why do complex patterns arise spontaneously in simple physical systems? These basic phenomena are still not well understood.

Many materials form complex structures as they grow, and in the case of snowflakes, we see the results falling from the sky by the billions. I sought to understand how this works.

When most people think of snowflakes, they think of elaborate, multi-branched snow stars. These are the ever-popular icons of ski sweaters and winter-holiday decorations. Nature produces a great many variations of this type of snow crystal, each exhibiting its own style of branching and sidebranching. Some stellar crystals contain scores of sidebranches, giving them a leafy, almost fern-like appearance. Others contain fewer sidebranches, perhaps decorated with thin, patterned ice plates.

Not just any snow-crystal shape or pattern can be seen falling from the sky, however. Whatever their appearance, stellar snow crystals usually grow six primary branches, each supporting additional sidebranches. Sometimes



the side-branching appears to be symmetrical, but often it does not. One thing you will not find in nature is an eight-sided snow crystal. The same is true of four-, five-, and seven-sided snow crystals. The symmetry of the ice crystal does not allow such forms. Eight-sided snowflakes may be easier to cut out of paper, but real snow crystals never have eight-fold symmetry, regardless of what you see in holiday decorations. (You'll find out why shortly.) Just as the colors of the stars reveal their composition, the shapes of snow crystals tell a tale of how they were created.

## The Making of a Snowflake

Snowflakes are made of ice, yet ice alone does not a snowflake make. You could produce a million ice cubes in your freezer and not one would look even remotely like a beautiful stellar snow crystal. You cannot simply freeze water to make a snowflake; you have to freeze water in just the right way.

The mystery of snowflakes is how they are fashioned into such complex and symmetrical shapes. Snowflakes are not made by machines, nor are they alive. There is no blueprint or genetic code that guides their construction. Snowflakes are simple bits of frozen water, flecks of ice that tumble down from the clouds. So how do they develop into such intricate six-branched structures? Where is the creative genius that designs the never-ending variety of snow-crystal patterns?

Many people think snowflakes are made from frozen raindrops, but this is simply not true. Raindrops do sometimes freeze in midair as they fall, and this type of precipitation is called *sleet*. Sleet particles look like what they are—little drops of frozen water without any of the ornate patterning or symmetry seen in snowflakes.

You do not make a snowflake by freezing liquid water at all. A snowflake forms when water *vapor* in the air condenses directly into solid ice. As more vapor condenses onto a nascent snow crystal, the crystal grows and develops, and this is when its elaborate patterning emerges. To explain the mystery of snowflakes, we must look at how they grow.

In a snowflake, just an ordinary snowflake, we can find a fascinating story of the spontaneous creation of pattern and form. From nothing more than the simple act of water vapor condensing into ice, these amazing crystal structures appear—complex, symmetric, and in endlessly varying designs. Snow crystals are the product of a rich synthesis of physics, mathematics, and chemistry. They're even fun to catch on your tongue.

The scientific definition of a crystal is any material in which the atoms or molecules are lined up in a regular array. Ice is a crystal made of water molecules, and the normal form of ice is called *ice Ih*, made of sheets of water molecules arranged into “puckered” hexagons. Hexagons, of course, have a six-fold symmetry, and this symmetry ultimately carries over into snow crystals.

Besides ice, all sorts of crystals can be found in our everyday lives. Copper is crystalline, as are rubies and diamonds. Computer chips are made from silicon crystals. Most rocks are made from jumbled bits of crystalline minerals like quartz. Salt, sugar, and aluminum foil are a few crystalline materials you can pick up at your grocery store.

All crystals demonstrate an amazing organizational ability—they assemble themselves. A crystal's order and symmetry arise spontaneously, starting with a random collection of molecules. This organizational feat should not be overlooked. If you want a brick wall somewhere, it certainly does not assemble itself.

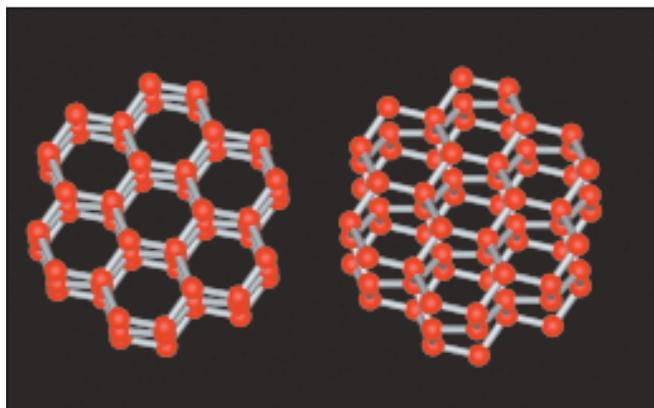
Self-assembly is how things are made in the natural world—crystals, snowflakes, plants, animals. Even you and I are made from self-assembled parts, guided by biochemical rules. Yet self-assembly is hard to fathom because it usually involves either nanoscale objects, like the molecules in a crystal, or tremendously complex objects, like living things.

To assemble ice crystals, water molecules form chemical bonds between themselves, and these bonds make the molecules line up and stick together. The bonds have certain preferred orientations, and this dictates how the water molecules stack up. Thermal agitation (the constant motion of atoms and molecules that becomes faster as the temperature rises) jostles them into position, and soon you're left with an ordered arrangement of water molecules—an ice crystal.

## Snow Crystal Symmetry

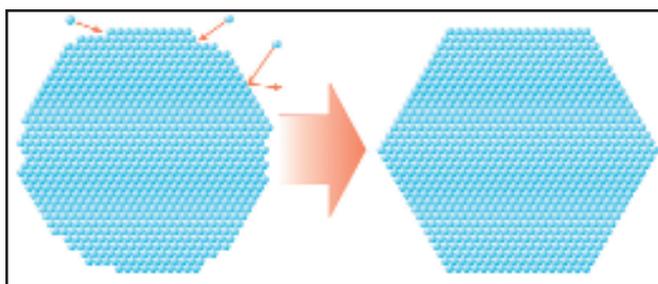
Snow crystals, like all naturally faceted crystals, always show characteristic symmetry in the angles between the facets. This symmetry comes from the chemical forces that determine the angles of the molecular bonds inside the crystals. The natural facets we see in crystals, however, including snowflakes, are far larger than the molecules inside the crystal. So the question arises: How can molecular forces, operating only at the nanoscale, determine the shapes of large crystals? How does one end of a crystal facet manage to grow the same as the other end? Does one end know what the other end is doing?

The molecules on opposite corners of a growing faceted crystal do not communicate with one another to determine the crystal shape. Nor do they have to. The reason facets form is simply because some surfaces acquire material and advance more slowly than others. As a crystal grows, the slow-moving facet surfaces eventually define its shape.



### HEXAGONAL STRUCTURE

*These two different views show the crystal structure of the normal form of ice, known as ice Ih. The red balls represent oxygen atoms in the H<sub>2</sub>O molecules; each gray bar is a hydrogen atom. The hexagonal lattice structure of the ice crystal is what ultimately gives snow crystals their six-fold symmetry.*

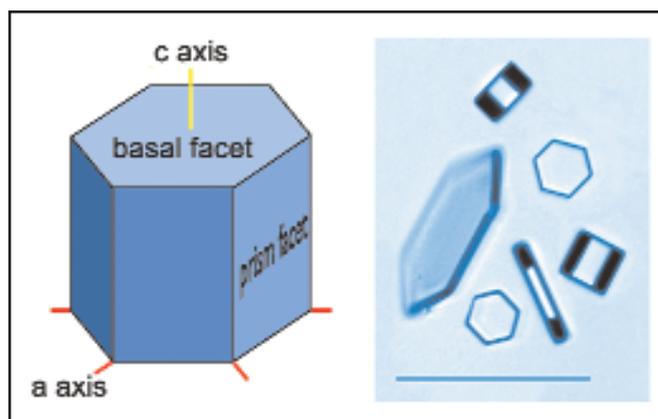


#### WHERE DO FACETS COME FROM?

*Facets form as molecules are added to a crystal. If we start with a small, round crystal, molecules quickly attach themselves to the molecular steps on the surface, because that's where they will be most tightly bound. The smooth, flat, facet surfaces only accumulate molecules slowly, because molecules don't stick so readily there. After the fast-growing regions fill in, all that remains are the slow-growing facet surfaces, which then define the shape of the crystal.*

How fast a given surface collects material and advances depends on the molecular structure of the crystal. If you could cut a crystal at a random angle and look at the individual molecules on the cut surface, you would find lots of dangling chemical bonds. Those surface molecules miss their former neighbors and are anxious to find new ones. Therefore, molecules that hit the surface are rapidly incorporated into it. Put another way, a randomly cut crystal surface is rough on the molecular scale, and rough surfaces accrue material quickly.

If you carefully cut your crystal along a facet plane, however, the surface would be relatively smooth on the molecular scale. The crystal structure is such that the facet surfaces have fewer dangling chemical bonds. In a sense, the molecules are arranged in straight rows, and if you cut along a row, the cut will be cleaner. With fewer dangling bonds, free molecules are incorporated into the crystal at a slower pace.



#### HEXAGONAL PRISMS

*The most basic snow-crystal shape is the hexagonal prism, left, which includes two basal facets and six prism facets. The small, laboratory-grown snow crystals, right, are all shaped like hexagonal prisms. Depending on which facets grow faster, a hexagonal prism can become a thin plate or long column. The crystals shown are tiny, smaller than the width of a human hair.*

WINTER 2004/05

If you start out with a small lump of a growing crystalline material, the molecular rough spots on the surface will incorporate new molecules quickly, so these surfaces will advance outward quickly. Meanwhile, the adjacent smooth surfaces will not advance so rapidly, and these slowly moving surfaces will broaden to form facets. Before long, only the slow-moving faceted surfaces are left, defining the shape of the growing crystal. The molecular forces act locally and on a small scale, but long-range order and structure result. This is how the geometry of a molecule governs the geometry of a large crystal.

The symmetry you see in a snowflake descends directly from the most fundamental mathematical symmetries of nature. The snowflake's hexagonal patterning derives from the structure of the ice-crystal lattice. The lattice structure in turn derives from the geometry of water molecules and how they connect. This is determined by the quantum mechanics of how atoms interact to form chemical bonds. The chain of reasoning quickly brings us to the most elementary laws of physics.

#### Symmetry and Complexity

The real puzzle of snowflakes is not their symmetry alone. The real puzzle is their combination of symmetry and complexity—the fact that snow crystals grow into such complex shapes that are *also* symmetrical. Just look at an elaborate snow star and it begs the questions: How do the six arms each develop the same ornate shape? How do the branches coordinate the intricacies of their growth?

The key to unlocking this mystery was the observation that snow-crystal growth is exceedingly sensitive to temperature and humidity.

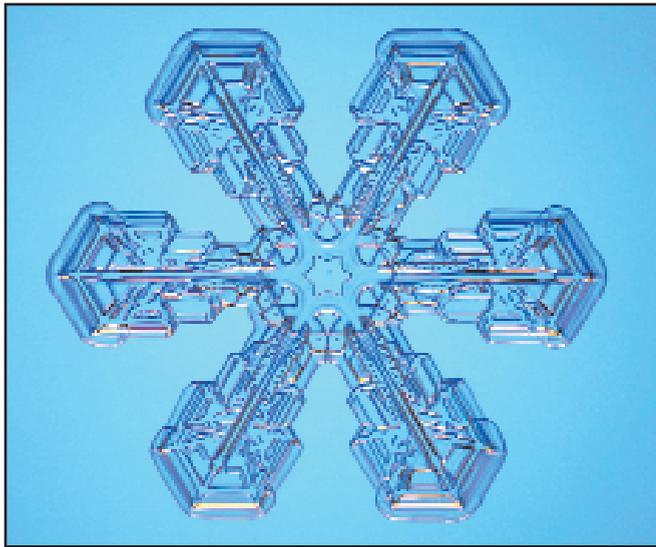
Consider the life story of an individual snowflake—a large symmetrical snow star that you might catch on your



#### ASYMMETRICAL SNOWFLAKES

*Most snow crystals are not beautifully symmetric, but are more irregular in shape. Some, like this one, are downright odd.*

AMERICAN FEDERATION OF TEACHERS 



### COMPLEX SYMMETRY

*Many snow crystals show remarkably complex symmetry, which comes from nothing but the simple interactions among water molecules. This sliver of ice contains a great many small markings—and most are faithfully reproduced on each of the six arms. In addition to its six-fold symmetry, each arm of the crystal is also symmetric about its central axis.*

mitten during a quiet snowfall. In the beginning, your crystal was born as a tiny nucleus of ice, and by its good fortune, this nascent snowflake quickly grew into a well-formed single crystal of ice, a minute hexagonal prism.

While in its youth, fortune again smiled by placing the crystal in a region of the cloud where the humidity was just right and the temperature was a perfect  $-15^{\circ}\text{C}$  ( $5^{\circ}\text{F}$ ). There, the tiny crystal grew into a thin, flat hexagonal plate. In this early phase in its growth, the crystal shape was being determined mainly by faceting.

As it reached snow crystal adolescence, the crystal blew suddenly into a region of the cloud with high humidity. The increased water supply made the crystal grow faster, which in turn caused the corners of the plate to sprout small arms. Because the humidity increased suddenly, each of the six corners sprouted an arm at the same time. The arms sprouted independently of one another, yet their growth was coordinated because of the motion of the crystal through the cloud.

The crystal subsequently blew to and fro in the cloud while it grew, following the will of the wind. As it traveled, the crystal was exposed to different conditions. Since a snow crystal's growth depends strongly on its local environment, each change of the wind caused a change in the way the crystal grew. Again, each change was felt by all six arms at the same time, so the arms grew synchronously while the crystal danced through the clouds.

As the crystal grew larger and ever more ornate, it eventually became so heavy that it floated gently downward, out of the clouds, to land on your mitten. The exact shape of each of the six arms reflects the history of the crystal's growth. The arms are nearly identical because they share the same history.

The precise morphology of each falling crystal is determined by its random and erratic motions through the atmosphere. A complex path yields a complex snowflake. And since no two crystals follow exactly the same path to the ground, no two crystals will be identical in appearance.

So where is the creative genius capable of designing snow crystals in an endless variety of beautiful patterns? It lives in the ever-changing wind.

**F**aceting explains how the structure of the ice lattice is imparted onto a snow crystal's growth and form, so faceting explains a snow crystal's six-fold symmetry. But if the slow-growing facets were the whole story, then all snowflakes would look like simple hexagonal prisms. We need something more to explain why snow crystals fall to earth in such complex, lacy structures. There are endless variations of snow-crystal shapes, but each and every one is produced by the same simple process—water vapor condensing into ice. How does the simple act of freezing produce such elaborate structures?

Growth is the key ingredient for the generation of snow-crystal patterns. Left in isolation for a long time, an ice crystal will eventually turn into a plain hexagonal prism. Ornate patterns appear only when a snow crystal is out of equilibrium, while it is growing.

A snow crystal grows by grabbing water molecules out of the air and incorporating them into itself. Water vapor molecules are assimilated into the existing ice lattice, which then increases in size. As long as the humidity is sufficiently high, the crystal will grow; there will be a flow of water from air to ice.

As a crystal grows, however, it consumes the excess water vapor around it, depleting the nearby air and reducing its humidity. To keep growing, water molecules from farther



### HOLLOW COLUMNS

*Columnar snow crystals may be less beautiful than their stellar cousins but are more common. This form can be found in abundance during warmer snowfalls. Many columns, like this one, include two conical-shaped hollow regions inside the crystal.*

away must diffuse through the air into the depleted region near the crystal. This process takes time, so diffusion impedes the crystal's growth. Under such circumstances we say the growth is *diffusion limited*. The crystal development is governed by how quickly molecules can make their way to the crystal. Diffusion-limited growth often leads to branching.

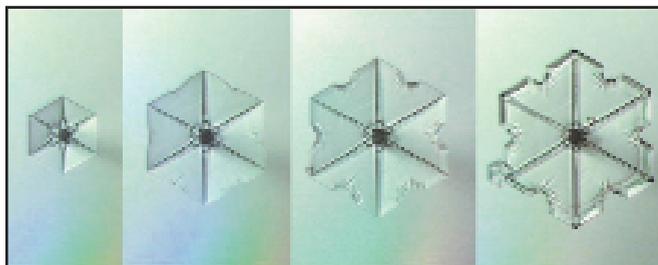
Consider a simple hexagonal plate crystal as it floats through a cloud. Because the hexagon's six points stick out a tiny bit, water molecules are a bit more likely to diffuse to the points than to anywhere else on the crystal. The points then tend to grow a bit faster, and before long they stick out farther than they did before. Thus the points grow faster still. The growth becomes an unstable cycle: The points stick out a bit, they grow faster, they stick out more, they grow faster still.

This kind of positive feedback produces what is called a *branching instability*—even the tiniest protruding points will grow faster than their surroundings and thus protrude even more. Small corners grow into branches; random bumps on the branches grow into sidebranches. Complexity is born.

Instabilities like this are the heart of pattern formation, and nature is one unstable system heaped on top of another. The sun heats the air near the ground and the warm air rises—a convective instability that drives the wind, clouds, and all of our weather. The resulting wind blows on the surface of the ocean, making the ocean surface unstable, and waves are generated. The waves travel across the ocean, and when they run into a shallow beach, the waves become unstable and break. Instabilities are responsible for many of the patterns you see in nature, including snowflakes.

If you look at enough snowflakes, you can see that their growth is governed by a delicate balance between faceting and branching. In most cases, neither faceting nor branching is completely dominant. It's the combination of both that gives a snow crystal its character. In a large stellar crystal, for example, the slow-growing basal facets give the crystal its overall flatness. The branching instability produces the crystal's complex fern-like structure, but the 60-degree angles between the branches are set by faceting. Both faceting and branching play important roles in these crystals.

You can get a feeling for how the balancing act between



#### THE BIRTH OF BRANCHES

*This series of photographs shows the growth of a simple plate-like snow crystal, demonstrating the transition from faceting to branching. Faceting dominates when the plate is small, yielding a hexagonal plate. When it grows larger, the corners of the hexagon stick out so far that branches form.*



#### COMPLEX PATTERNS

*Snow crystals form complex structures through a combination of faceting and branching. Faceting produces thin plates and flat edges while branching promotes the growth of more elaborate patterns.*

branching and faceting works by again considering the growth of a simple hexagonal prism crystal. When the crystal is small, diffusion is not an important factor. Water molecules readily diffuse the short distance from one end of a tiny crystal to the other, so the supply of water is essentially the same over the entire surface. In this case, the growth is not diffusion-limited at all, so faceting determines the crystal shape. Extremely small crystals often look like simple hexagonal prisms for this reason.

As the prism becomes larger, diffusion starts to limit the growth, so the corners start to grow a bit faster than the centers of the crystal faces. But as soon as that happens, the facets will no longer remain exactly flat. When the face centers start to lag behind, their surfaces become lightly curved, exposing some extra molecular bonds. Since surfaces with exposed bonds accrue material more quickly than flat faceted surfaces, the faces are able to keep up with the corners, even though their water supply is lower.

For a while, the forces of branching and faceting are held in balance, and the ice surface maintains just the right curvature. If it gets a bit too flat, then branching begins to kick in, causing the corners to grow faster, increasing the curvature. If the curvature is too great, the faces grow faster and catch up. A dynamic equilibrium is maintained automatically, and for a while, the crystal keeps its simple faceted appearance. The facets are not precisely flat on the molecular scale, but they look flat because the curvature is so slight.

As the crystal grows still larger, however, the branching instability becomes an even greater force. The faces become even more curved and thus rougher on the molecular scale.

*(Continued on page I-viii)*

## Snowflakes

*(Continued from page I-vii)*

Eventually, the face centers become completely rough, and their growth is then limited only by diffusion. Soon after all this happens, the faces will no longer be able to keep up the pace and the hexagonal prism will sprout arms. Branching has won; instability kicks in.

The bottom line is that both faceting and branching are simultaneously important for determining snow-crystal structure. Furthermore, the interplay between these two growth mechanisms is complicated. It depends on temperature, humidity, and even the size and shape of the growing crystal. The delicate balance between these two forces gives snow crystals their tremendous diversity.

### Thinking about Snowflakes

As a child watching the falling snow in North Dakota, I never imagined I would someday be thinking about the science of snowflakes. Now, having worked on the subject for many years, I still find it extremely rich and endlessly fascinating.

The physics governing snowflake growth touches on many topics, from the structure of crystals and their surfaces to the mathematical subtleties of self-assembly. A careful examination of the inner workings of a snowflake reveals much more than just a sliver of ice. The symmetric patterns demonstrate the spontaneous generation of complex structures in the physical world.

I whiled away the cold winters of my youth throwing snowballs and building frozen fortresses out of packed snow. Now I construct designer snow crystals in my laboratory, trying to gain insights into the molecular dynamics of crystal growth. There are many mysteries left. We currently don't understand the surface structure of ice in detail, or how it affects crystal growth.

So here we sit at the beginning of the 21st century and we cannot yet explain exactly why snowflakes are what they are. Snowflakes are full of surprises, and there are still some fundamental aspects of snowflakes we do not understand. A bit of mystery remains in these delicate ice structures.

One thing I've learned from my research is that snowflakes are fascinating little structures that are full of surprises. It is my desire that this article inspires you to look at snowflakes differently, to see them with new eyes. Perhaps the next time you find yourself surrounded by a gentle snowfall, you'll pick up a magnifying glass and discover firsthand the intriguing beauty of snowflakes. And should you find yourself examining one of these diminutive ice sculptures, I hope you pause to think about what snowflakes really are, where they come from, and how they are created.

There is a great beauty in a large, symmetrical stellar snow crystal. The beauty is enhanced by the magnifying lens that brings out the fine structures in the ice. The beauty is enhanced still further by an understanding of the process that created it. □