

# *Gliding for Gold*

THE PHYSICS OF WINTER SPORTS

*Mark Denny*



# *Gliding for Gold*

THE PHYSICS OF WINTER SPORTS

*Mark Denny*



*The Johns Hop*

© 2011 The Johns Hopkins University Press  
All rights reserved. Published 2011  
Printed in the United States of America on acid-free paper  
9 8 7 6 5 4 3 2 1

The Johns Hopkins University Press  
2715 North Charles Street  
Baltimore, Maryland 21218-4363  
[www.press.jhu.edu](http://www.press.jhu.edu)

Library of Congress Cataloging-in-Publication Data

Denny, Mark, 1953–

Gliding for gold : the physics of winter sports / Mark Denny.  
p. cm.

Includes bibliographical references and index.

ISBN-13: 978-1-4214-0214-7 (hardcover : alk. paper)

ISBN-13: 978-1-4214-0215-4 (pbk. : alk. paper)

ISBN-10: 1-4214-0214-9 (hardcover : alk. paper)

ISBN-10: 1-4214-0215-7 (pbk. : alk. paper)

1. Force and energy. 2. Sliding friction. 3. Winter sports. I. Title.

QC73.D46 2011

530—dc22

2011000459

A catalog record for this book is available from the British Library.

*Special discounts are available for bulk purchases of this book. For more information, please contact Special Sales at 410-516-6936 or [specialsales@press.jhu.edu](mailto:specialsales@press.jhu.edu).*

The Johns Hopkins University Press uses environmentally friendly book materials, including recycled text paper that is composed of at least 30 percent post-consumer waste, whenever possible.

## **ACKNOWLEDGMENTS**

I am grateful to Amanda Bird of the U.S. Bobsled and Skeleton Federation for permission to reproduce a few of the photos from their gallery; similarly, I am happy to acknowledge the help of Terry Kolesar of U.S.A. Curling, and Katie Perhai of the U.S. Ski and Snowboard Association in providing images. For allowing me to use their photos of skaters, I thank Adnan Hussain, Caroline Paré, and Brooke Novak. At the Johns Hopkins University Press, I am grateful to editor and keen winter sportsman (in his front yard) Trevor Lipscombe, art director Martha Sewall, and copyeditor extraordinaire Carolyn Moser.

## CONTENTS

Acknowledgments      vii

The Start Lines      1

1. Solid Water—Sports and Science      4

### PART I. *Ice Sports*

2. Skating on Thin Ice      29

3. Down the Slippery Slope      55

4. Pucks and Rocks      77

### PART II. *Snow Sports*

5. Skiing—On the Slopes and on the Level      95

6. Ski Jumping and Snowboarding—  
On Snow and Air      114

The Finish Lines      141

Ponderables      145

Technical Notes      149

Bibliography      179

Index      185

## THE START LINES

Winter sports (and I mean sports played on snow or ice, not sports that happen to be played in winter, like football) are hugely popular. Ice hockey has been organized into professional leagues in many countries for decades; each team has thousands of fanatical supporters who follow every aspect of the game. Skiing is practiced as a pastime by millions; they and millions more watch professional skiers compete in high-profile events, such as the Winter Olympic Games. The 2002 Salt Lake City Games attracted 2.1 billion viewers worldwide, including 187 million in the United States. Though U.S. viewing figures were down for the 2006 Winter Olympics (to perhaps 176 million),<sup>1</sup> there is no doubt that both the familiar and the unusual sports that are contested at these games get a lot of attention.

Many of the less well-known Winter Olympic sports—for example, bobsled and related sledding events such as skeleton and luge—may pique your interest only once every four years, but anyone who watches these plucky athletes careening down an icy track at over 80 mph surely finds it exhilarating. It's more than exhilarating for the athletes, of course: "You'd be a looney if you weren't scared," Canadian luge competitor Chris Moffat said in 2006, after experiencing the fearsome Cesana track at the Turin games. "We are two inches above the ice going 130 kph in our underwear. It's not exactly the safest sport."<sup>2</sup>

1. Part of the reason for the fall in number of viewers was the inconvenient broadcast times in the United States for the live events; the 2006 Winter Olympic Games took place in Turin, Italy. Another reason might be the rise in popularity of TV reality shows, and in particular *American Idol*. Detailed analysis of viewing figures for the Salt Lake City games can be found in IOC (2002). Half the world (including 213 million Americans) watched the Vancouver 2010 games, pushing *American Idol* off the top of the ratings.

2. See Reuters (2006). A luge rider is known as a "luger" (LOO-jer).

My reaction, when I see these sleds pick up speed and swing around the bends, with the athletes more or less firmly attached, is to wonder about the physics involved. (How does the speed depend upon friction? How high up the bend does centrifugal force take them?) It's the same when I see a speed skater powering herself around a bend, leaning over at  $45^\circ$  with the fingers of one hand touching the ice, or when I see a ski jumper launch himself off a ramp. (How do skaters accelerate on such a slippery surface? How does their "stride length" vary around a curve? Why do ski jumpers always adopt a V-shape when airborne? How far can they jump?) If you have wondered about any of these questions, or many others that arise when thinking about the physics of winter sports (Why do curling rocks curl? How much do turns slow down a skier? Is the physics of snowboarding different from that of skiing? Why do most figure skaters spin counter-clockwise?) then read on.

I have analyzed the dynamics of a number of winter sports. The math is summarized in technical notes at the end of the book, for those "athletes" who are interested in the details. If you're not, but just want to understand the how and why without numbers, then stick to the main text. A lot of people are allergic to math—they would rather eat a pound of broccoli than ingest math—and yet they appreciate science and technology and want to learn about it. However, the only language that we have in common with Mother Nature is mathematics, and this can cause a problem. My job in writing this book is to act as interpreter: I have labored long and hard to translate the technical analyses (necessarily mathematical) into lucid and palatable nonmath explanations.

There are hundreds of books out there that seek to enlighten you about winter sports in general. Many of these books are intended for specialists (say, professional sportsmen or keen enthusiasts who want to refine their techniques, or who need to know about the biomechanics). Many other books are presented at a lower level that makes for easier reading but less enlightenment. Here, by way of contrast, I am aiming for a general understanding of the physical processes underlying winter sports, processes that act to influence the movement of athletes and of the equipment they use. My explanations are general but are not banal or trivial—you're getting the whole meal deal here, though packaged in a digestible format.

What kind of physics underlies winter sports? The motive power that propels an athlete toward the finish line is either muscle power or gravity (or both). Against these are the dissipative forces of sliding friction (say

between snow and ski) and aerodynamic drag. Aerodynamic lift also plays a role in some of our sports. Much of the physics that I will investigate in the pages to follow will involve the interaction of these forces. Winter sports provide a “clean” application of the dissipative forces because they are so dominant and because they act in a fairly predictable manner. Contrast this with, say, the physics of summer sports. Sailing, to take one example, involves hydrodynamic as well as aerodynamic drag, and the drag coefficients of sailing boats vary significantly during a race because the sail shape changes (because of the wind action, or the helmsman’s maneuvers). You can see that these extra complications make realistic analysis difficult. One of the appeals for a scientist to write a book explaining the physics of winter sports is the relative simplicity of the forces involved. So we anticipate pretty good predictions from our analyses. Believable predictions, in turn, tell us about the important parameters of winter sports. We will learn just how important it is to get off to a flying start in bobsled events; just how crucial aerodynamic lift, and weight, is to ski jumping success; just how sliding friction influences the skiers’ technique. In this book, using physics to analyze winter sports will tell us more about both.

Units: if you choose to follow the math, you will find that I work with the metric system in my technical notes. The main text is more variable. In most cases I will retain metric units (they’re good enough for Winter Olympics measurements, so they’re good enough for us), but many English speakers still like feet and inches, pounds and ounces, so I may from time to time slip into these awkward but venerable units.

After an introductory chapter dealing with the slippery science of snow and ice, we delve into the science of snow sports and then ice sports. A hefty slice of this book follows in the wake of this delving—a metaphorical track left in the snow, if you like—and includes a section called Ponderables and the technical notes. Ponderables is a series of questions “for the interested reader” that arise from material covered in the main text. For some of these questions I provide hints to guide you toward the answer. The technical notes contain all the math analysis, gathered together so as to avoid breaking up the flow of the main text. The extensive bibliography includes primary and secondary sources, plus a number of Web references, including YouTube videos that demonstrate aspects of winter sports far better than can any written explanation.



# **1 SOLID WATER— SPORTS AND SCIENCE**

Welcome to the warm-up. In the next chapter you will be metaphorically hurled headfirst into the cold water of winter sports physics. By way of preparation, so that you may brace yourself, this chapter permits you to first dip a toe. Stated more mundanely (but also less alarmingly—I wouldn't want you to think that reading this book is going to be like taking a cold bath), I will spend a chapter describing these winter sports. More: you will need to know something about the ice and snow surfaces they are played on, and be brought up to speed about the frictional forces that act upon athletes and their equipment. So, first an overview of winter sports (those which are included in the Winter Olympic Games), second a description of the interesting and unusual physical properties of ice and snow, and third an introduction to the physics of sliding friction and of aerodynamic drag.

## **LET THE GAMES BEGIN**

The Winter Olympic Games are a modern invention that began in Chamonix, France, in 1924. The last such games were held in Vancouver, Canada, in 2010, and the next will be in Sochi, Russia, in 2014. As we will see, not all of the sports began in Chamonix. Some—particularly the women's events—are much more recent. Here is the list of Winter Olympic sports that are played on ice:

- bobsled
- luge
- skeleton
- figure skating (including ice dancing)
- long-track speed skating

- short-track speed skating
- ice hockey
- curling

And on the fluffier form of solid water, these sports are played:

- alpine skiing
- snowboarding
- cross-country skiing
- ski jumping
- biathlon
- nordic combined

The 2010 Games were divided into 86 events (up from the original number of 16). Over half of them come from four sports: speed skating, cross-country skiing, alpine skiing, and biathlon.

Given that you are reading this book, it seems likely that you are familiar with one or two of these sports—perhaps you *sweep*, or *poptart*, or *hotdog*, or *axel*. Even so, the majority of winter sports may still be something of a mystery to you, and so, to clarify fuzzy notions, I will here provide a brief description of each.

*Bobsled.* Two-man, four-man, or two-woman bobsleds hurtle down artificial tracks that are typically 1,250 meters long (with about 15 bends). Bobsleds are steered. Competitors begin from a standing start and push their sled as much as 50 meters (hereafter abbreviated “m”) before boarding. This sport has been part of the Winter Olympics since its inception and has been dominated by American, German, and Swiss athletes.

*Luge.* One or two men (or one woman) jump onto a sled feet first, on their backs, and steer down the bobsled track. As with bobsled and skeleton, multiple runs are timed to decide the winner. Germans and Italians have been particularly successful at luge events, which have been part of the Winter Olympics since 1964.

*Skeleton.* One athlete dives onto a small sled, which uses the same track as for bobsled events. The skeleton competitor lies prone, facing forward, and steers by body movement only. Skeleton sledding has been an Olympic event (for both men and women) only since 2002 and has been dominated by U.S. athletes.

*Figure skating.* Single skaters and pairs (including “mixed doubles” for

ice dancing events) perform maneuvers—jumps, rotations, lifts, and combinations—of varying difficulty over a set time and are awarded points for their performance of each maneuver. An Olympic sport since 1924, figure skating has been dominated by Soviet and Russian skaters.

*Long-track speed skating.* Long-track skating competitions are timed events over set distances, around an oval track. Usually competitors start in pairs (at opposite ends of the oval, for team pursuit events). Distances vary from 500 to 10,000 m, although there is also a 40-kilometer (km) marathon (with a mass start). Very popular with the Dutch, speed skating has been an Olympic event for men since 1924; women's events did not appear until 1960.

*Short-track speed skating.* Short-track skating events are races (final position is all that matters) each with a mass start of four to six skaters, on a short oval track of circumference 110 m (365 ft). Distances raced are 500–1,500 m (always counterclockwise around the track), plus relay events of 5,000 m (men) and 3,000 m (women). This event was first part of the Olympics in 1992.

*Ice hockey.* The men's game dates back to Chamonix, but women (and professional National Hockey League players) had to wait until 1998 before they could compete at the Olympics. The rules of Olympic hockey are a little different from those of the NHL, but it's basically the same game. Canada and Russia dominate.

*Curling.* A strange and venerable sport, curling requires two teams, each of four players, to take turns sliding heavy granite rocks into a bull's-eye target. Closest to the center wins the “end.” Ten such ends decide the game. Curling has been an occasional Olympic sport since the Winter Games started but has been a fixture only since 1998. Canada, Great Britain (in practice, Scotland), or Sweden usually win these events.

*Alpine skiing.* Alpine skiing is the downhill variety of skiing (with fixed heel bindings, in contrast to the hinged bindings of nordic skiing). It is another timed event, with medals awarded for the fastest times over one or two runs down a set course. *Mogul* events take place over bumpy terrain; *freestyle* involves getting airborne. Part of the Olympics since 1936, alpine events have been dominated by Austria, France, Italy, Switzerland, and the United States.

*Snowboarding.* Skiing with a single wide ski was introduced to the 1998 Winter Olympics in Nagano, Japan. *Halfpipe* events take place on a track shaped like half a cylinder, with steep sides. *Slalom* events, as in skiing,

involve maneuvering around poles or through gates. Americans and Swiss have been particularly successful at Olympic snowboarding.

*Cross-country skiing.* Long-distance endurance competitions across relatively level ground, this nordic style of skiing has been an Olympic sport since 1924 for men (1952 for women). The medal tables usually feature Finns, Norwegians, Russians, and Swedes.

*Ski jumping.* The lunatic fringe competes in Olympic Games by launching themselves off of a slope and remaining airborne for over 100 m. Points are awarded for style as well as distance. Only male lunatics are allowed at the Winter Olympics (where they have been competing since its inception). Austrians, Finns, and Norwegians dominate.

*Biathlon.* A combination of cross-country skiing and rifle shooting (.22 cal), biathlon has been an Olympic event since the Squaw Valley, California, games of 1960. Germany, Norway, and Russia usually hit the target.

*Nordic combined.* A combo of cross-country and ski jumping, Nordic combined has been a men's event since 1924, dominated by Norwegians.

## THE SCIENCE OF SOLID WATER

It may be a tautology to say that water dominates the Earth's oceans, but it is a less well-known fact that it also dominates the land, in solid form: 23% of the surface of our planet is covered in snow. Snow is water that freezes into crystals from a gaseous state in the atmosphere; ice is water that freezes from the liquid phase. Both forms of solid water are unusual and complex materials; their slipperiness is rare among solids and is not yet fully understood by scientists. Snow is a myriad of delicate ice crystal structures, and so snow is more complex even than ice: to the intricacies of ice crystal structure must be added the manner in which individual crystals combine. A sensible way for me to proceed, therefore, is to begin with a discussion of monolithic ice and then move on to its fluffier form.

"Whoa," you say. "I bought a book about winter sports—you don't need to tell me about ice and snow. I've been there; I know an ice cube when I've drunk one, and snow is snow. Get on with the sports and leave out the physics lecture—I know enough already about ice and snow." Ha! Read on.

## Ice

There are many different ways in which liquid water molecules can arrange themselves to form a solid crystalline structure when circumstances dictate. These circumstances—which determine the *phase transition* from liquid to solid—depend mostly upon temperature and pressure, but other environmental factors (such as humidity, or the presence of dust or other contaminants) can influence the freezing process. Figure 1.1 shows the *phase diagram* for water, over the range of temperatures and pressures that are commonly found in nature. Phase transitions occur when a line is crossed. Thus, liquid water evaporates into steam, which condenses back to the liquid phase; water freezes to become ice, which melts back into water; ice sublimates to steam, which can turn into ice by deposition. The *triple point* of figure 1.1 is the combination of temperature and pressure at which water can exist in all three phases at once: solid, liquid, and gas. Water is the only common substance with a triple point that occurs at everyday temperatures and pressures.

Note that the ice of figure 1.1 is labeled *Ih*. We currently know of 15 forms of ice (numbered *I* to *XV*); more will be discovered, no doubt, before this book goes to press. The *h* in *Ih* stands for “hexagonal,” which describes the organization of water molecules within the ice crystal. Almost all the ice that is found naturally on earth is of this form. High up in the atmosphere, where the temperatures and pressures are different from the ranges shown in figure 1.1, a cubic structure, *Ic*, is found.<sup>1</sup> At higher temperatures and pressures—different locations in the real estate of the phase diagram—other crystalline structures appear. These 15 (and counting) forms of ice have different physical properties. This multiplicity of structures is extreme: no other substance has so many known solid forms.

The lattice structure of *Ih* ice is known completely and is illustrated in figure 1.2. A single molecule of water,  $\text{H}_2\text{O}$ , consists of one oxygen atom and two hydrogen atoms, at an angle of  $104.45^\circ$  (fig. 1.2a). This angle is close to the angles that are found in two-dimensional hexagons (fig. 1.2b) and three-dimensional tetrahedra, so it is not surprising that ice in the form *Ih* can be viewed as sheets of water molecules arranged as hexagons, or as a repeated tetrahedral structure (fig. 1.2c).

1. *Ic* ice forms in the upper atmosphere by vapor deposition at temperatures below  $-130^\circ\text{C}$ .

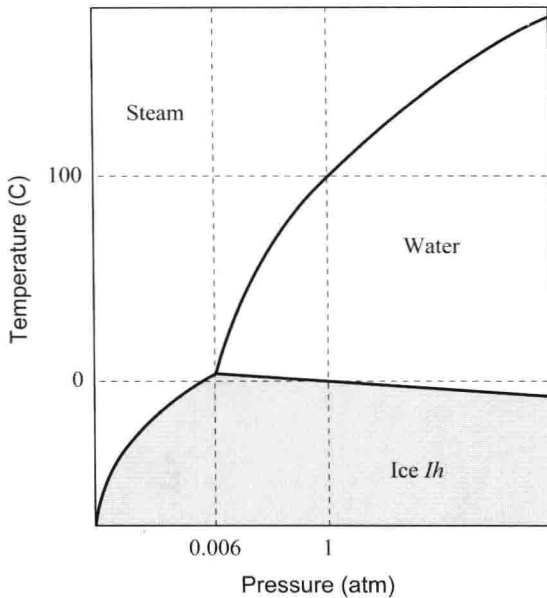


Figure 1.1. Phase diagram for water at familiar temperatures and pressures. Ice, the solid phase of water, can take at least 15 structural forms. By far the most common form in nature is *Ih* ice.

*Ih* ice has a density of 917 kilograms per cubic meter ( $\text{kg}/\text{m}^3$ ) near  $0^\circ\text{C}$ , whereas the density of water is  $1,000 \text{ kg}/\text{m}^3$ . It is unusual for a chemical compound to have a solid form that is less dense than its liquid form. In the case of water this phenomenon arises because of the crystalline structure—there is a lot of space between molecules arranged in a hexagon. Ice density varies with temperature, as do other physical properties of this solid (indeed, of most solids). In figure 1.3 you can see how the density, thermal conductivity, and specific heat of *Ih* ice change as ice temperature changes. (We will not need to know this level of detail about the properties of ice in the chapters to follow; I include it here merely to demonstrate the complexity of materials science and to show that crystalline structure influences the physical properties of a material. Different forms of ice have different densities, for example.)

Some of the mechanical properties of ice (for example, Young's modulus—a measure of elasticity and, in particular, of shear stress) vary with direction—again, a consequence of the crystalline structure. There exist planes of weakness within the ice, so that it shears more easily in one plane

than in another plane. For us, the most important property of ice happens at the surface: it is slippery. Slipperiness is unusual in solid materials, and the slipperiness of ice particularly so—indeed, it is not yet fully understood. I will get to grips, so to speak, with this subject in the next section. Material scientists think that part of the slipperiness is, like shear stress, due to the crystalline structure of *Ih* ice. At surfaces the crystal structure

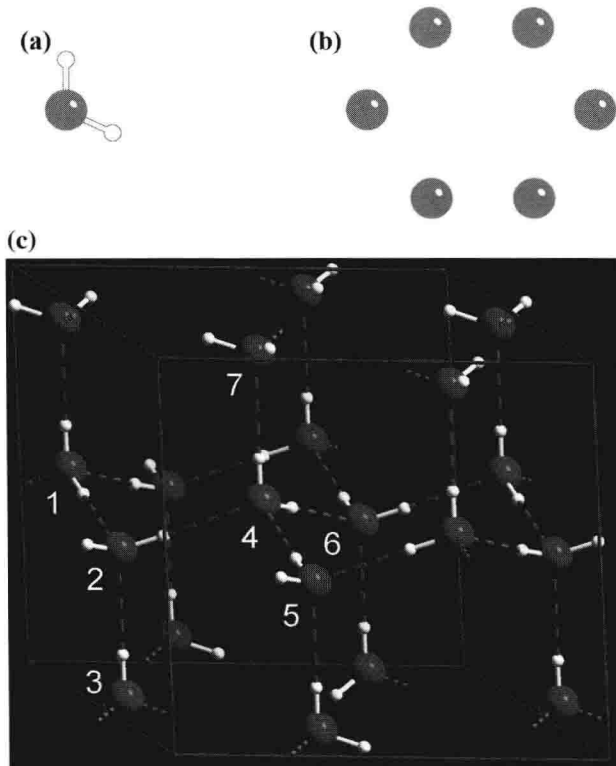


Figure 1.2. Hexagonal structure of ice. (a) A single water molecule consisting of one oxygen atom (large sphere) and two hydrogen atoms (small loops). (b) In *Ih* ice the oxygen atoms of six water molecules arrange themselves in a hexagon. The hydrogen atoms (not shown) are arranged differently in different forms of ice. (c) The 3-D structure of *Ih* ice. We can see the hexagonal component (or half of one) in molecules 1, 2, and 3, for example. Molecules 2, 5, 6, and 7 form a tetrahedron, with molecule 4 at its center. There are lots of gaps in this structure, which means that ice has a lower density than liquid water. The solid white lines and dashed gray lines show different types of chemical bond. Adapted from a Wikipedia figure.

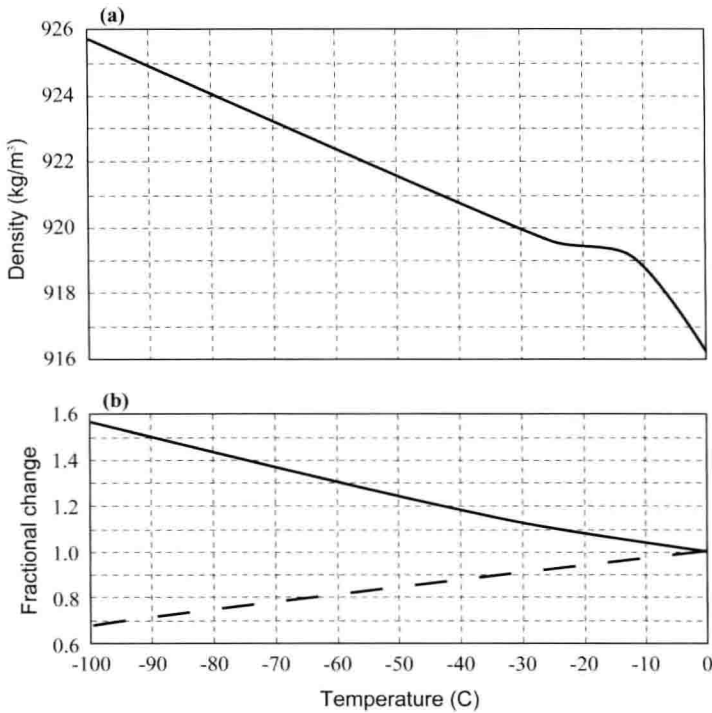


Figure 1.3. Three physical properties of *Ih* ice: (a) the density of *Ih* ice as a function of temperature; (b) fractional change in *Ih* ice thermal conductivity (solid line) and specific heat (dashed line) vs. temperature.

leaves many dangling, broken chemical bonds that give rise to a liquid-like behavior which accounts for certain familiar yet unique properties, including sintering and regelation as well as slipperiness. *Sintering* is the welding together of ice crystals without melting, as when loose snow combines to form a snowball. *Regelation* is the property of melting under pressure and freezing when the pressure is released. This property is often demonstrated to physics and engineering students as shown in figure 1.4.<sup>2</sup>

## Snow

Water vapor crystallizes around dust particles in the atmosphere when the temperature is low enough and the humidity high enough. These crystals

2. For a readable, popular account of the structure and properties of *Ih* ice see Chang (2006). For technical details, see Schulson (1999).



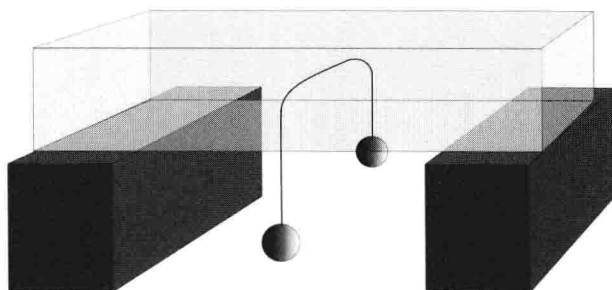


Figure 1.4. This classroom demonstration shows a strange property of ice—regelation—in action. Two weights are suspended from a thin wire that has been draped over a block of ice. Pressure melts the ice immediately beneath the wire, so that it cuts through the block. But once the pressure is released, the ice refreezes, so the block remains intact. Thus, the wire passes right through the block of ice without breaking it.

grow in a myriad of hexagonal patterns, forming snowflakes (fig. 1.5); the snowflakes quickly become too large to float around in the air and so they fall to the ground. There are no fewer than 10 forms of frozen precipitation, of which 7 are snow.<sup>3</sup> The shape of snowflakes is very sensitive to the meteorological conditions in the atmosphere where they form. Hexagonal ice crystals can aggregate into stars and plates, or into needles and columns. Stars and plates predominate when the air temperature is  $-2^{\circ}\text{C}$ ; columns and needles are produced more often when the temperature falls to  $-5^{\circ}\text{C}$ ; stars and plates again dominate at  $-15^{\circ}\text{C}$ ; at  $-30^{\circ}\text{C}$  all types are common. More complex shapes result if humidity is very high.<sup>4</sup>

Whatever shape the snowflakes choose for themselves, when they hit the ground they add to the *snowpack*. Snow on the ground is often layered; each day the top level melts and then freezes at night, producing a crust of ice, which is then covered by another layer of snow during the next snowfall. Snowpack layers may consist of different types of snow with different

3. The other three types of frozen precipitation are *hail*, *sleet*, and *graupel*. Hail is frozen raindrops; sleet consists of smaller particles that are part frozen and part liquid. Graupel is snow that has accumulated a lot of *rime*. Rime is the white ice that forms when water droplets freeze to an object. If the object happens to be a snowflake, the rime growth results in graupel.

4. See Kenneth Libbrecht's Web site, [www.snowcrystals.com](http://www.snowcrystals.com), or the Microsoft *Encarta* article on snow (Microsoft 2005), for popular accounts of snow formation. For a detailed technical account see Libbrecht (2005).