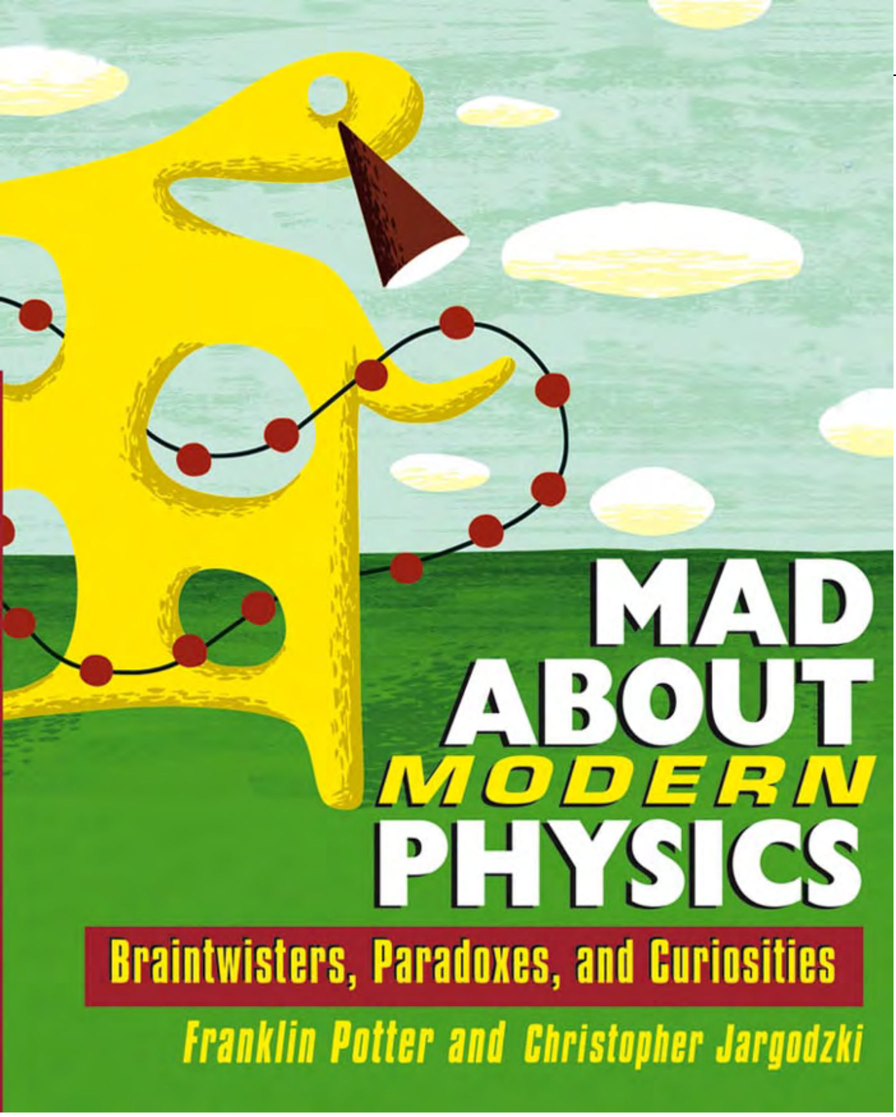

MAD ABOUT MODERN PHYSICS

Braintwisters, Paradoxes, and Curiosities

Franklin Potter and Christopher Jargodzki

Mad about
Modern Physics

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and
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John Wiley & Sons, Inc.

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To my late parents, who nourished my formative years and
have now crossed that portal to another world.

F. P.

To my late grandmother—Zofia Lesinska,
who instilled in me the idea that the visible world
owes its being to the invisible one.

C. J.

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Preface

This book of almost 250 puzzles begins where our first book, *Mad About Physics: Braintwisters, Paradoxes, and Curiosities* (2001) ended—with the physics of the late nineteenth and early twentieth centuries. The Michelson-Morley experiment of 1887, the challenges posed by atomic spectra and blackbody radiation, the unexpected discoveries of X-rays in 1895, radioactivity in 1896, and the electron in 1897 all loosened the protective belt of ad hoc hypotheses around the mechanistic physics the nineteenth century had so laboriously built. Anomalies and paradoxes abounded, ultimately necessitating a radical rethinking of the very foundations of physics and culminating in the theory of relativity and quantum mechanics. Numerous applications of these new and strange concepts followed very quickly as atomic and nuclear physics led to semiconductor devices on the small scale and nuclear energy on the large scale. Therefore we have developed a whole new set of challenges to tickle the minds of our scientifically literate readers, from science students to engineers to professionals in the sciences.

The challenges begin with the classical problem of getting a cooked egg into a bottle through a narrow bottleneck and back out again and progress gradually to the famous aging-twin paradox of the theory of special relativity and eventually reach problems dealing with the large-scale universe. In between, we explore the nature of time and of space as well as how the world of films and television tends to sacrifice physics for the sake of entertainment. We also consider some of the more startling questions in relativity. For example, we ask whether a person can go on a space journey out to a star 7,000 light-years distant and return while aging only 40 years! And we certainly want to emphasize the practical applications of microphysics through an examination of some properties of exotic fluids, unusual motors running on air or on random motion, as well as thermal, electrical, and photonic properties of materials in a challenging journey into the atomic world.

Particularly important microworld challenges include: What happened to Schrödinger's cat? Can a cup of coffee be the ultimate quantum computer? Why is a Bose-Einstein condensate a new state of matter? Why is quantum mechanical coherent scattering so important in developing new detectors for neutrinos and gravitational waves? When we reach the nucleus, there are challenges about the accuracy of carbon-14 dating, the reason for neutron decay, and the amount of human radioactivity. Then our journey reverses as we reach for the stars to consider Olbers' paradox about why the night sky is dark instead of bursting with light, how gravitational lensing by galaxies works, and what the total energy in the universe might be. This book finishes with a potpourri of challenges from all categories that ranges from using bicycle tracks in the mud to determine the direction of travel, to analyzing water-spouting alligators, and ending with a space-crawling mechanical invention that seems to defy the laws of physics.

The puzzles range in difficulty from simple questions (e.g., "Will an old mechanical watch run faster or slower when taken to the mountains?") to subtle problems requiring more analysis (e.g., "Is the Bragg scattering of X-rays from an ideal crystal a coherent scattering process?") Solutions and more than 300 references are provided, and they constitute about two-thirds of the book.

As these examples demonstrate, most of the puzzles contain an element of surprise. Indeed, one finds that commonsense conjecture and proper physical reasoning often clash throughout this volume. Einstein characterized common sense as the collection of prejudices acquired by age eighteen, and we agree: at least in science, common sense is to be refined and often transcended rather than venerated. Many of the challenges were devised to undermine physical preconceptions by employing paradoxes (from the Greek *para* and *doxos,* meaning "beyond belief") to create cognitive dissonance. Far from being simply amusing, paradoxes are uniquely effective in addressing specific deficiencies in understanding. Usually the contradiction between gut instinct and physical reasoning for some people will be so painful that they will go to great lengths to escape it even if it means having to learn some physics in the process.

Philosopher Ludwig Wittgenstein considered paradoxes to be an embodiment of disquietude, and as we have learned, these disquietudes often foreshadow revolutionary developments in our thinking about the natural world. The counterintuitive upheavals resulting from relativity theory and quantum mechanics in the twentieth century only enhanced the reputation of the paradox as an agent for change in our understanding of physical reality.

Such disquietudes, rather than unexplained experimental facts, writes Gerald Holton in *Thematic Origins of Scientific Thought,* were what led Einstein to rethink the foundations of physics in his three papers of 1905. Each begins with the statement of formal asymmetries of a predominantly aesthetic nature, then proposes a general postulate, not derivable directly from experience, that removes the asymmetries. For example, in the paper on the quantum theory of light, formal asymmetry existed between the discontinuous nature of particles and the continuous functions used to describe electromagnetic radiation. As Holton notes, "The discussion of the photoelectric effect, for which this paper is mostly remembered, occurs toward the end, in a little over two pages out of the total sixteen." Consistent with this approach is Einstein's statement in *Physics and Reality* (1936), "We now realize . . . how much in error are those theorists who believe that theory comes inductively from experience," and later in *The Evolution of Physics* (1938), coauthored with the Polish physicist Leopold Infeld, "Physical concepts are free creations of the human mind, and are not, however it may seem, uniquely determined by the external world."

As another sore point, the term "quantum *mechanics*" is really a misnomer: quantum systems cannot be regarded as made up of separate building blocks. In the helium atom, for instance, we do not have electron A and electron B but simply a two-electron pattern in which all separate identity is lost. This indivisible unity of the quantum world is paralleled by another kind of unity—between subject and object. Is light a wave or a particle? The answer seems to depend on the experimental setup. In the double-slit experiment, the observations of light yield characteristics of the box and its slits as much as of light itself. Is reality then observer-dependent? And would this justify Einstein's insistence on the power of pure thought in the construction of physical reality? Modern physics seems particularly adept at generating such disquietudes. If that's the case, then perhaps the word *Mad* in the title of our book should not be construed as a mere metaphor!

Acknowledgments

We all "stand on the shoulders of giants" as we develop our minds to become individuals living today on our planet Earth. And we owe so much to so many people that we cannot acknowledge all of them.

Franklin Potter would like to express appreciation to his wife, Patricia, and their two sons, David and Steven, for their love and inspiration through many wonderful years of family adventures. He also treasures the numerous inspiring physics discussions over the decades with many friends and colleagues: Howard G. Preston, Gregory Endo, Fletcher Goldin, David M. Scott, John Priest, Lowell Wood, Julius S. Miller, George E. Miller, Leigh H. Palmer, Charles W. Peck, Myron Bander, Joseph Weber, Richard Feynman, Willard Libby, Edward Teller, and Kamal Das Gupta.

Christopher Jargodzki would like to express appreciation to Myron Bander of the University of California at Irvine; Stephen Reucroft of Northeastern University in Boston; and James H. Taylor of Central Missouri State University in Warrensburg. His interactions with close to twenty thousand students (and counting!) in his classes at UC Irvine, Northeastern University, and CMSU have been, over the years, never-ending sources of stimulation, as well as occasional exasperation. In fact, the present volume got its start in 1975 when one of us (C. J.), still a graduate student at UC Irvine, put together a proposal for a book of paradoxes in modern physics, partly to allay his own exasperation with the koanlike conundrums that abound in modern physics. Alas, the project had to wait several decades for the author to mature and join forces with Franklin Potter in our joint inquiry into the nature of physical reality. The authors hope that physical reality is duly impressed with their efforts.

Both authors sincerely thank Kate C. Bradford, senior editor at John Wiley & Sons, Inc., who continues to support our paradoxical adventures into the world of physics.

To the Reader

These puzzles are meant to be fun. How many puzzles you solve is not as important as how many you enjoy thinking about. Some of them are even challenging to research physicists, and some were generated by research articles that have appeared only recently in physics journals, so these topics may not have been part of physics just 10 years ago! It would be a rare reader who could provide detailed solutions to all the puzzles. Indeed, sometimes you may need to think a bit to even understand the answer. If we included all the steps, this book would double its present size. We offer no apologies, but we do try to provide all the key steps to make each answer complete on its own. If you find the puzzles perplexing and intriguing, we have succeeded in our mission.

Mad about Modern Physics can be read with profit by anyone who has had some exposure to a year of introductory physics and is eager to learn more about its applications and its more recent discoveries. Most puzzles are nonmathematical in character and require only a qualitative application of fundamental physics principles. Many physics concepts are defined directly or indirectly in the questions or in the answers, so they can be found with the aid of the index. However, even someone who knows the subject will quickly realize that the application of physics to the real world can be quite challenging, and in this sense this is not an elementary book.

More than three hundred follow-up references provide further resources for interested readers. These references—to journal research papers, books, and magazine articles—are included with only some of the puzzles, typically those that are either controversial or that involve relatively new concepts. There was no space to include a more complete list of references. Consequently we had to make choices, and we apologize to the authors whose work may have been left out or inadvertently overlooked.

Any errors are solely those of the authors, and we would appreciate your communications via e-mail to Franklin Potter (see www.sciencegems.com) with regard to the puzzles and their answers.

1 The Heat Is On

SCIENCE IN THE HOME CONTRIBUTES IMMENSELY to our everyday repertoire of activities, although most of us are unaware of exactly how science does so. Physics, in particular, is all around us and plays a crucial role in determining what we can and cannot do. One enjoyable activity for many people is cooking, which is an application of physics and chemistry to satisfy our gastronomical tastes. Or are physics and chemistry just other modes of cooking? We'll let you decide. Most of the challenges in this chapter involve physics from a high-school-level course. But be careful. Quick responses may be correct occasionally, but you should not rely on your intuition very much, for Nature, particularly in the kitchen, is nonintuitive for the most part. Anyone who has tried to make a soufflé can attest to how limited a recipe can be!

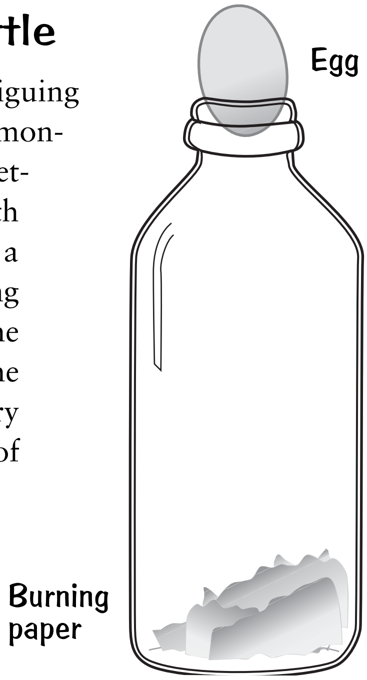
We can detect five basic tastes—four are very familiar: sweet, sour, bitter, and salty. The fifth, while familiar in East Asia, is less well known in Western cuisine—it is called *Umami* and is the taste of monosodium glutamate, MSG. MSG is used widely in Eastern cooking and that is probably why it is recognized as a separate taste sensation more readily by those familiar with that cuisine. However, many common western foods contain large amounts of MSG, notably tomatoes and parmesan cheese.

—Peter Barham, *The Science of Cooking*

I was raised in Alabama and Florida a Southern Baptist, a lad given simple answers to profound questions. At the same time I came to love science, which seeks profound answers to simple questions.

—Edward O. Wilson

1. Egg into a Bottle



Perhaps the most intriguing physics-in-the-kitchen demonstration for all ages is getting a hard-boiled egg with the shell removed into a bottle that has an opening diameter smaller than the minimum diameter of the egg. One solution is to very carefully drop some bits of burning paper into the upright bottle and then place the egg at the opening. Soon, if the sequence is done with the correct timing, the egg will have the urge to go inside. What is the correct timing, and why does the egg have this urge?

2. Egg out of a Bottle

Perhaps the most *challenging* physics-in-the-kitchen demonstration for all ages is getting a hard-boiled egg with the shell removed out of a bottle that has an opening diameter smaller than the minimum diameter of the egg. Of course, one could cut up the egg with a knife inserted into the bottle and then pour out the pieces. However, we want the egg out whole and undamaged.

Long ago, physics professor Julius Sumner Miller, (who was Professor Wonderful on the early *Mickey Mouse Club* shows) was on the *Tonight Show* with host Johnny Carson and showed first how to get the egg into the bottle and then, taking no more than three seconds, had the same egg back in his hand. What is the procedure? (Hint: the same physics principles that put the egg into the bottle can get the egg out.)

3. Sugar

Add two cups of sugar to one cup of water in a saucepan and stir while heating slightly. All the sugar will dissolve. About how much total sugar will dissolve in one cup of water? What is the physics?

4. Kneading Bread

Bread made with yeast is usually kneaded—that is, drawn out and pressed together to create a distribution of the ingredients. Then the bread dough is set aside to "rise." Why is some bread then kneaded a second time and sometimes even a third time before baking?

5. Measuring Out Butter

Suppose you have a solid chunk of butter and a measuring cup in the kitchen. You desire to accurately measure one-half cup of butter chunks without melting them. What is a quick, easy way to do so? Often one encounters the statement in cookbooks that Archimedes' principle is being used. What is this principle, and why is the statement erroneous?

6. Milk and Cream

You are given two identical bottles, one with milk and the other with cream, both filled to the top. Quick now, which is heavier? And is light cream lighter than heavy cream?

Why is it that tea made with microwave-heated water doesn't taste as good as tea made with teakettle water? The main reason is that microwaves heat only the outer inch or so of the water all around the cup, because that's as far as they can penetrate. The water in the middle of the cup gets hot more slowly, through contact with the outer portions. When the outer portions of the water have reached boiling temperature and start to bubble, you can be tricked into thinking that all the water in the cup is that hot. But the average temperature may be much lower, and your tea will be shortchanged of good flavor.

—ROBERT L. WOLKE, *WHAT EINSTEIN TOLD HIS COOK: KITCHEN SCIENCE EXPLAINED*

If there were one drop
of water less in the
universe,
the whole world would
thirst.

—UGO BETTI,
ITALIAN PLAYWRIGHT

CALORIC REQUIREMENT BASED ON BODY WEIGHT

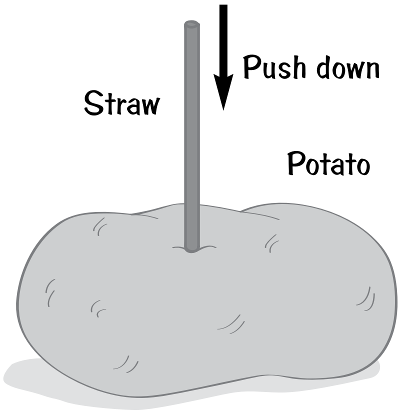
The basal calorie requirement of the average adult is ten times the ideal weight in pounds (e.g., 1,270 for 127 lbs.), plus 30 percent for light activity (i.e., 1,650 kcal), 50 percent for moderate activity (1,905 kcal), and 100 percent for heavy activity (2,540 kcal). Expressed slightly differently, the basal energy requirement is about 1 kilocalorie per hour for every kilogram (2.2 lbs.) of ideal body weight. Of course, any estimate of calorie requirements based on such formulas is just that—an *estimate*. Individual requirements vary widely with age, health, body size, and environmental temperature.

When men reach their sixties and retire, they go to pieces. Women go right on cooking.

—GAIL SHEEHY, AMERICAN JOURNALIST

7. Straw and Potato

A paper or plastic drinking straw can be pushed through an uncooked potato. Explain the physics. If you plan to try this demonstration, be sure that you take appropriate safety precautions—keep your hands and body out of harm's way.



8. Blueberry Muffins

Marion loves to bake warm, fresh blueberry muffins, with the blueberries almost uniformly distributed throughout the muffin. She knows that if one simply prepares the batter and mixes in the blueberries, they may be uniformly distributed before entering the oven, but upon baking they will gravitate to lodge in the lower part of the muffin. How does she prevent this natural downward drift?

9. Can of Soup

Some people buy canned soup and store the cans in the cupboard. Some people even turn these soup cans upside down for storage. If we open a can of soup that was stored in the upright position by removing the top, quite often all the concentrated ingredients are on the bottom and must be scooped out with a spoon. Even then, not all the concentrate is removed. Suppose, instead, we turn the same can upside down and open the bottom. Upon turning the can over, the soup simply rushes out into the pot. Why so?

10. Salt and Sugar

Salts have been used for thousands of years to preserve meats, and sugar has been used to preserve fruits and berries. How do they work?

11. Defrosting Tray

In catalogs and cookware stores one can buy a "miracle" defrosting tray advertised as made of an "advanced, space-age super-conductive alloy" that "takes heat right out of the air." How does this defrosting tray work?

12. Ice Cream Delight

Most of us have made ice cream or seen ice cream being made. Milk, eggs, sugar, and flavorings are slowly chilled. Terri likes to make ice cream in a simpler and more efficient way. Practicing proper safety precautions, she pours liquid nitrogen directly into the ingredients in a metal bowl. About equal volumes of liquid nitrogen and the mixture are used for ice cream or sorbet, and she stirs while adding the coolant until the ice cream is nicely stiff. Why does this method produce absolutely marvelous ice cream, and what is the physics here?

13. Cooking a Roast

For many types of meat—beef, pork, lamb, etc.—one can buy a roast from the butcher with or without the bone inside. Suppose we have two beef roasts of the same

The boiling temperature of water decreases about 1.9°F for every 1,000 feet above sea level. So in Denver, the mile-high city, water will boil at 202°F—that is, at 94.4°C. Temperatures above 165°F are generally thought to be high enough to kill most germs, so there is no danger on this account until you get to about 25,000 feet.

On the average we get about 9 (food) calories (kcal) of energy from each gram of fat and 4 calories from each gram of protein or carbohydrate. To lose a pound (454 g) of fat, we have to cut the food intake by 3,500 calories. The discrepancy in numbers is due to the fact that body fat is only about 85 percent actual fat, the rest coming from connective tissue, blood vessels, and other things.

weight of 4.4 pounds (2 kg) and cook them in identical ovens at the same temperature. One roast has the bone in and the other does not. Which roast cooks faster? Why?

14. Cooking Chinese Style

Estimates of Chinese meals include more than 3,000 varieties, possibly more meal types than the total number of meals by all other cultures combined. Many of the Chinese dishes use meats cut into small cubes or other small volumes. Certainly, these small volumes are much easier to eat with chopsticks. Are there any significant scientific reasons for cutting up the meats into small volumes?

15. Baked Beans

If you buy dry beans in bulk, they must be soaked in water overnight in a covered container before they are ready to be baked. To bake them without soaking would require an enormous amount of cooking time. An alternative preparation is to "parboil" them in a cooking pot—that is, simmer them. Simmer means "to be on the verge of boiling."

How does one know that the beans have simmered enough? The test involves good physics. Take up a few beans in a spoon and, after making sure that no liquid is in the spoon, blow a stream of air gently with pursed lips against the beans. If the bean skin cracks, the beans are ready for baking. Why must the lips be pursed, and why do the bean skins then crack open?

16. Ice Water

Normally, to cool a pitcher of water quickly, one adds ice. The ice floats at the top. Suppose one could add the same amount of ice so it could be held in the water at

Light bounces off mirrors; microwaves bounce off metal. If what you put in the microwave oven reflects too many microwaves back instead of absorbing them, the magnetron tube that generates the microwaves can be damaged. There must always be something in the oven to absorb microwaves. That's why you should never run it empty.

Metals in microwave ovens can behave unpredictably. Microwaves set up electrical currents in metals, and if the metal object is too thin it may not be able to support the current and will turn red hot and melt. And if it has sharp points, it may even act like a lightning rod and concentrate so much microwave energy at the points that it will send off lightning-like sparks.

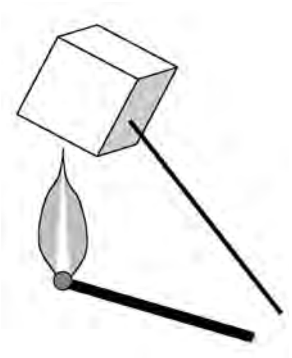
—Robert L. Wolke, *What Einstein Told His Cook: Kitchen Science Explained* the bottom of the pitcher. Which technique would lead to faster cooling of the water?

17. Peeling Vegetables

A friend of ours peels ripe tomatoes by impaling the tomato on a fork, then holding it over a gas flame and rotating gently. If you try this procedure, use appropriate safety procedures to protect your eyes and body.

Peeling fresh beets is also a messy chore. Their colored liquid stains everything, including your fingers. Another friend of ours peels fresh beets by first boiling them, then immediately holding them under cold water with a fork. What is the physics in both of these methods used for preparing vegetables for peeling?

18. Igniting a Sugar Cube



Sugar burns in air. But igniting a sugar cube is much more difficult than expected. Put a sugar cube on the end of a toothpick and bring a lighted match flame under a remote corner. The sugar melts instead of burning, and the brown, gooey stuff is caramel.

However, we wish to burn the sugar, not melt it! We want to see it on fire with a flame of its own. Why is this process so difficult to achieve? How can we succeed in lighting the sugar cube with the burning match?

19. Water Boiling

An open pot of water is boiling on the kitchen stove. Sprinkle some room-temperature table salt (which

A standard 12-ounce aluminum can, whose wall surfaces are thinner than two pages from this book (about 0.00762 cm), withstands more than 90 pounds of pressure per square inch—three times the pressure in an automobile tire.

—William Hosford and John Duncan, "The Aluminum Beverage Can," *Scientific American*, September 1994

Decaffeinated coffee still contains caffeine! A regular cup of coffee has 80 to 135 milligrams of caffeine. For a coffee to be considered decaffeinated, at least 97 percent of the coffee's caffeine must be removed. Testing shows that decafs typically have 2 to 6 milligrams of caffeine per cup.

contains mostly NaCl and some KCl) into the clear boiling water, and the boiling ceases. Isn't it amazing how the water ceases its boiling as the salt warms up! Can you explain the physics? What is the surprise here?

An object at room temperature (20°C) emits radiation with a peak at the wavelength 9.89 micrometers, roughly .01 mm, in the infrared region of the electromagnetic spectrum.

20. Put the Kettle On

Bring water to a boil in a teakettle with a spout. Let it cook! Now watch the mouth of the spout carefully. What do you see? Can you see the water vapor come out?

21. The Watched Pot

You have probably heard the expression "A watched pot never boils." Is this statement correct physics? That is, when would this statement be good physics? (Hint: One should interpret the phrase "never boils" here to mean that the cooking takes a longer time.)

For an isolated water molecule the H-O-H angle is 104.5°. In ice each water molecule forms hydrogen bonds to four nearest neighbors in a tetrahedral arrangement. The tetrahedral bond geometry explains the openness and relatively low density of ice (i.e., why water expands upon freezing). In ice the H-O-H angles are nearly the same as the perfect tetrahedral angle of 109.5°.

22. Ice in a Microwave

The microwave oven emits microwaves that are absorbed by water molecules in food. Microwaves make the polar water molecules rotate or oscillate, and their "friction" within the material converts some of this kinetic energy into thermal energy to raise the temperature of the food.

Suppose you made an ice block that had liquid water trapped in a large cavity inside and then you placed the block into a microwave oven. Could the trapped water be brought to a boil while the ice remained ice?

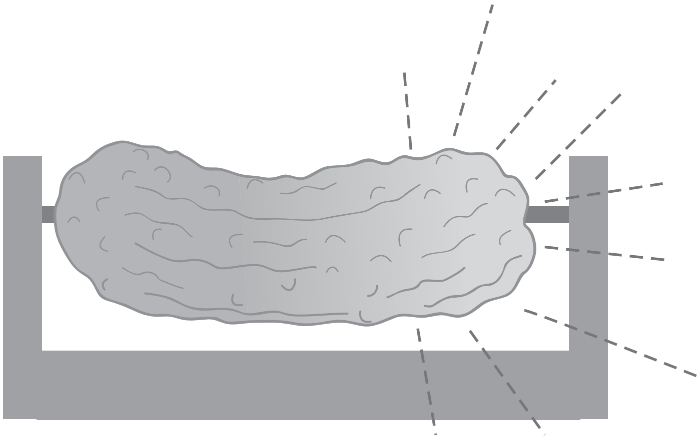
23. The Glycemic Index

The glycemic index is an important number for anyone concerned with the conversion of food to blood sugar (sucrose), for the gylcemic index gives the measured rate of this conversion process. The higher the glycemic index value, the faster the conversion rate to sucrose. There are types of sugar molecules other than sucrose. Glucose, for example, is normally the standard reference for the conversion rate to sucrose, with a value of 100.

Some sample values of the glycemic index for foods are: brown rice, 59; white rice, 88; table sugar, 65; grapefruit, 25; spaghetti, 25 to 45; potato, boiled, 55; potato, baked, 85; and dates, 103. Brown rice has more outer layer intact than white rice, so its lower value is evident. But why would a baked potato have a much higher glycemic index than a boiled potato? And how could the value for dates, or any food, be higher than 100?

24. Electric Pickle

Some specialty and novelty stores sell an electrical "appliance" that cooks hot dogs between two metal electrodes. A protective cover with a safety interlock



Night cooling by evaporation of water and heat radiation had been perfected by the peoples of Egypt and India, and several ancient cultures had partially investigated the ability of salts to lower the freezing temperature of water. Both the ancient Greeks and Romans had figured out that previously boiled water will cool more rapidly than unboiled water, but they did not know why; boiling rids the water of carbon dioxide and other gases that otherwise retard the lowering of water temperature.

—Tom Shachtman, *Absolute Zero and the Conquest of Cold*

Interestingly, microwave ovens are not very good at melting ice. The water molecules in ice are bound pretty tightly together into a crystal lattice, so they can't flip back and forth under the influence of microwaves' oscillation.