15 Heat, Temperature, and Expansion

The little boy holding the fireworks sparkler in the Part 3 opener is Francesco Ming Giovannuzzi, the grandson of Tsing and Keith Bardin. A photo of Tsing opens Chapter 13.

Lil and I are in the second photo opener to this chapter, sampling the effects of radioactive processes in Earth's interior. Photo 3 is of Anette Zetterberg, wife of P.O. and mother of Johan, whose profile was in the previous chapter. In a visit to Gdansk, Poland, in 2004, physicist Kasia Werel showed Lil and I the birthplace of Daniel Gabriel Fahrenheit, where I snapped this photo. Photo 4 is the result of a visit to Gdansk in Poland while visiting Kasia Werel a few years ago.

The profile for this chapter is Benjamin Thompson, better known as Count Rumford—a distant relative.

Just as the chapters on Properties of Matter placed particular emphasis on water and the atmosphere, the chapters on heat do the same. Note that no attempt is made to familiarize the student with methods of temperature conversion from one scale to another. The effort saved can be better spent on physics.

The concept of heat flow between temperature differences provides some background to the concept of current flow between electric potential differences in Chapter 23. Here we introduce the concept of KE/molecule, *temperature*, which is analogous to the later concept of PE/charge, *voltage*. Both high temperatures and high voltages are ordinarily harmful only when large energies are transferred in a relatively short time (that is, when large power is transferred). The white-hot sparks of a 4th-of-July sparkler have very high temperatures, but their energies are very small. So they are quite harmless. Similarly, a balloon rubbed on your hair may have thousands of volts, but the energy stored is very small. The *ratios* energy per molecule or energy per charge may be high, but if the molecules or charges involved are small in number, the energy content is also small. Aside from the parallels between heat and electricity, the chapter serves as a prerequisite only for the three following chapters dealing with heat transfer, change of phase, and thermodynamics.

In the text, temperature is treated in terms of the kinetic energy per molecule of substances. Although strictly speaking, temperature is directly proportional to the kinetic energy per molecule only in the case of ideal gases, we take the view that temperature is related to molecular translational kinetic energy in most common substances. Rotational kinetic energy, on the other hand is only indirectly related to temperature, as illustrated in a microwave oven. In the oven the H_2O molecules are set oscillating with considerable rotational kinetic energy. But this doesn't cook the food. What does is the translational kinetic energy imparted to neighboring molecules that are bounced from the oscillating H_2Os like marbles that are set flying in all directions when they encounter the spinning blades of fans. If the neighboring atoms did not interact with the oscillating H_2O molecules, the temperature of the food would be no different before and after activation of the microwave oven. Temperature has to do with the translational kinetic energy of molecules. Degrees of freedom, rotational and vibrational states, and the complications of temperature in liquids and solids are not treated. Next course!

Care must be taken when using a microwave oven for boiling water. It can become superheated, and when disturbed, like removing the cup from the oven, it can blow up in your face. If water is heated in a microwave oven, something should be placed in the cup to diffuse energy. It is much safer to boil water in a conventional pan or teakettle.

Quantity of heat is spoken of mainly in terms of the calorie, with acknowledgement of the SI unit, the joule.

The definition of the calorie in the chapter implies that the same amount of heat will be required to change the temperature of water 1°C—whatever the temperature of the water. Although this relation holds true to a fair degree, it is not exactly correct: A calorie is precisely defined as the amount of heat required to raise a gram of water from 14° to 15°C.

The exaggeration of the volume versus temperature scale in Figure 15.21 should be pointed out, for it is easy for a student to erroneously conclude that a great change in the volume of water occurs over a relatively small temperature change. Take care our students don't interpret the volume at 0°C to be that of ice rather than ice water.

Practicing Physics Book:
- Temperature
- Thermal Expansion

Problem Solving Book:
Many problems on heat and temperature

Laboratory Manual:
- Dance of the Molecules *Observing Molecular Motion* (Demonstration)
- Bouncing off the Walls *Kinetic Theory Simulation* (Tech Lab)
- Temperature Mix *Specific Heat Capacity* (Experiment)
- Spiked Water *Specific Heat Capacity* (Experiment)

Next-Time Questions:
• Metal Ring •Sparkler Temperature • Metal Gap

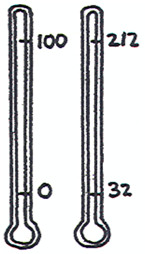
Hewitt-Drew-It! Screencasts: *•Heat and Temperature •Specific Heat •Thermal Expansion •Thermal Expansion of Water*

Check Questions are few in the following suggested lecture. By now it is hoped that this technique is a major part of your lecture method. Take pity on students who sit through lectures where the instructor poses questions that he or she immediately answers without involving the students, who are passive observers rather than participants in the learning process. Pose Check Questions before you move onto new material.

SUGGESTED LECTURE PRESENTATION

Begin by asking what the difference is between a hot cup of coffee and a cold cup of coffee. Think small for the answer: The molecules in the hot cup of coffee are moving faster—they are more energetic. Heat and temperature involves kinetic energies of the molecules in substances. Heat and temperature are different: To begin with, **heat** is energy that is measured in joules, or calories. **Temperature** is measured in degrees. More on this soon.

Temperature Calibration: Describe how the increased jostling of molecules in a substance result in expansion and show how this property underlies the common thermometer. Draw a sketch of an uncalibrated thermometer on the board, with its mercury vessel at the bottom, and describe how the energy of jostling molecules is transferred from the outer environment to the mercury within. If placed in boiling water, energy of the jostling water molecules would transfer to the mercury, which would expand and squeeze its way up the tube. State that one could make a scratch on the glass at this level and label it 100. And then describe how, if placed in a container of ice water, the molecules of mercury would give energy to the cold water and slow down, contract, and fall to a lower level in the tube.



One could again make a scratch and call this point zero. Then, if 100 equally-spaced scratches are made between the two reference points, one would have a centigrade thermometer.

In a vein of humor draw a second uncalibrated thermometer on the board and repeat your discussion (in abbreviated fashion) of placing it in boiling water. State that the upper level needn't be called 100, that any number would do so long as all thermometers were calibrated the same. Ask the class for any random number. Someone will say 212. Casually acknowledge the 212 response and write that on your diagram. Repeat the bit about placing the instrument in ice water and state that the position on the scale needn't be called zero, that any number would do. Ask for a random number. You'll have several students volunteer 32, which you graciously accept. The class should be in a good mood at this point, and you briefly discuss the two scales and lead into the idea of absolute zero and the Kelvin scale. (For humor, named after "Lord Scale"?)

> CHECK QUESTION: Which has the largest degrees, a Celsius thermometer or a Fahrenheit thermometer? [Celsius.]
>
> CHECK QUESTION: True or false: Cold is the absence of fast-moving molecules. [False; cold refers to very slow-moving molecules, not their absence. If you have no molecules at all, the concept of temperature is inapplicable.]

Absolute Zero: The treatment of the Kelvin scale is very brief in this chapter, and it is not really treated until Chapter 18. So you can gloss over it and explain that it is "nature's scale" beginning at the coldest possible value for its zero point. In case your treatment of heat is brief and you will not be including the Thermodynamics Chapter 18, you may want to develop the idea of absolute zero here, in which case you should consider the following lecture skit (which is repeated in the suggested lecture of Chapter 18).

Begin by supposing you order at your friendly restaurant a piece of hot apple pie. The waitress brings you cold pie, straight from the fridge and at 0°C. You tell her you'd like hotter pie, in fact, twice as hot. Question: What will be the temperature of the pie? Encourage neighbor discussion. Many will say zero degrees. Then ask what the new temperature would be if the pie were initially 10°C, and acknowledge that the answer is *not* 20°C! Now you're ready for the "Celsius, the Village Tailor" story.

> Celsius, the Village Tailor: To answer the pie temperature questions and develop the idea of absolute zero, hold a measuring stick against the wall of the lecture room (so that the bottom of the vertically-oriented stick is about 1 meter above the floor) and state that you are Celsius, the village tailor, and that you measure the heights of your customers against the stick, which is firmly fastened to the wall. You state that the stick need not extend all the way to the floor, nor to the ceiling, for your shortest and tallest customers fall within the extremities of the stick. Mention that all tailors using the same method could communicate meaningfully with each other about the relative heights of their customers providing the measuring sticks in each shop were fastened the same distance above the "absolute zero" of height. It just so happens that the distance to the floor, the "absolute zero," is 273 notches—the same size notches on the stick itself. Then one day, a very short woman enters your shop and stands against the wall, the top of her head coinciding with the zero mark on the measuring stick. As you take her zero reading, she comments that she has a brother who is twice her height. Ask the class for the height of her brother. Then ask for the temperature of the twice-as-hot apple pie. (There is a difficulty with the pie example, for twice the energy involves a phase change—the subject of Chapter 17. So the pie will not *really* be 273°C. Strictly speaking, your example should use helium gas or a metal that doesn't change phase in the temperature range in question. But the pie is more interesting!)

Heat: Distinguish between *heat* and *temperature*. Heat has to do with energy flow while temperature is a ratio of energy per molecules. They are very different. A Fourth-of-July-type sparkler emits sparks with temperature about 2000°C, but the heat one receives when one of these sparks lands on one's face is very small. High temperature means a high ratio of heat per molecule (as cited by the boy with the fireworks sparkler in the Part 3 opening photo). The *ratio* and the *amount* of heat energy transferred are different things. Relatively few molecules comprise the tiny bit of white-hot matter that makes up the sparks of the sparkler. (Later you'll involve a similar argument when you discuss the small energy associated with the high voltage of a charge Van de Graaff generator or party balloon rubbed on your hair.)

> CHECK QUESTION: How are the sparks from a sparkler that strike your skin akin to tiny droplets of boiling water striking your skin? [Both have high temperatures, but safe levels of internal energy to transfer to your skin.]

Distinguish between *heat* and *internal energy*. (Internal energy is treated in more detail in Chapter 18.) Internal energy is loosely referred to as heat energy, although by definition, heat is the energy that flows from one place to another by virtue of a temperature difference. Heat is energy in transit.

Quantity of Heat: Define the calorie, and distinguish it from the Calorie, the concern of people who watch their diet.

Specific Heat Capacity: Lead into a distinction between the difference between calories and degrees, and the concept of specific heat capacity by asking your class to consider the difference in touching an empty iron frying pan that has been placed on a hot stove for one minute (ouch!) and touching water in a frying pan in the oven for the same time. With the water, you could place your hand in it safely even if it were on the stove for several minutes. Ask which has the higher temperature, the empty pan or the one filled with water. Clearly, it is the empty pan. Ask which absorbed the greater amount of energy. The answer is the water-filled pan because it was on the stove for a longer time. The water has absorbed more energy for a smaller rise in temperature! Physics types have a name for this idea—specific heat *capacity*, or for short, *specific heat*. Cite the different specific heat capacities of cooked foods, of a hot TV dinner and the aluminum foil that can be removed with bare hands while the food is still too hot to touch.

Water's High Specific Heat: Cite examples of water's high specific heat—old fashioned hot water bottles on cold winter nights, cooling systems in cars, and the climate in places where there is much water. With the aid of a large world map, globe, or chalkboard sketch, show the sameness of latitudes for England and the Hudson Bay, and the French and Italian Rivieras with Canada. State how the fact that water requires so long a time to heat and cool, enables the Gulf Stream to hold heat energy long enough to reach the North Atlantic. There it cools off. In accord with the conservation of energy, when the water cools something else warms. What is that something? The air. The cooling water warms the air, and the winds blow westerly at that latitude. So warmed air moves over the continent of Europe. If this weren't the case, Europe would have the same climate as regions of northern Canada. A similar situation occurs in the United States. The Atlantic Ocean off the coast of the eastern states is considerably warmer than the Pacific Ocean off the coast of Washington, Oregon, and California, yet in winter months the east coast is considerably colder. This has to do with the high specific heat of water and the westerly winds. Air that is warmed by cooling water on the west coast moves landward and gives mild winters to Washington, Oregon, and California. But on the east coast, this warmed air moves seaward, leaving the east coast frigid in winter months. In summer months, when the air is warmer than the water, the air cools and the water warms. So summer months on the west coast states are relatively cool, while the east coast is relatively hot. The high specific heat of water serves to moderate climates. The climates on islands, for example, are fairly free of temperature variations. San Francisco, a peninsula that is close to being an island, has the most stable climate of any city in continental America.

4°C Water: To lead into the idea of water's low density at 4°C you can ask if anyone in class happens to know what the temperature at the bottom of Lake Michigan was on a particular date, for example, New Year's eve in 1905. Then for the bottom of Lake Tahoe in California for any other date. And for another, until many are responding "4°C."

> CHECK QUESTION: Ask the same for the bottom of a rain puddle outside the building and be prepared for some to say 4°C.

Then ask why 4°C was the right answer for the deep lakes but the wrong answer for a puddle. Then go into the explanation as given in the book—how the microscopic slush forms as the freezing temperature is approached, yielding a net expansion below 4°C. (I haven't done this, but I have thought of showing a

Galileo-type thermometer in class—a small flask with a narrow glass tube filled with colored water, so changes in temperature would be clearly evident by different levels of water in the narrow tube. Then surround the flask with perhaps dry ice to rapidly chill the water. The water level drops as the temperature of the water decreases, but its rate slows as it nears 4°C, and then the direction reverses as cooling continues. This expansion of the water is due to the formation of "microscopic slush." The level of water observed, as a function of time, yields the graphs of Figures 15.20 and 5.21.)

Ice Formation on Lakes: Discuss the formation of ice, and why it forms at the surface and why it floats. And why deep bodies of water don't freeze over in winter because all the water in the lake has to be cooled to 4°C before colder water will remain at the surface to be cooled to the freezing temperature, 0°C. State that before one can cool a teaspoonful of water to 3°C, let alone 0°C, all the water beneath must be cooled to 4°C and that winters are neither cold or long enough for this to happen in the United States.

> CHECK QUESTION: Will a chunk of lead float on melted lead as ice floats on water? [No, solid lead is more dense than liquid lead. Water is almost unique in that it is less dense in the solid phase.]

Expansion: (Note the order differs from the text—in lecture I stay with the topic of water.) State that steel lengths expand about 1 part 100,000 for each 1°C increase in temperature. Show a steel rod and ask if anybody would be afraid to stand with their stomach between the end of the rigidly held steel rod and a wall while the temperature of the rod is increased a few degrees. This is a safe activity, for the slight expansion of the rod would hardly be noticeable. Now ask for volunteers for a steel rod several kilometers in length. This is much different, for although the rate of change in length is the same, the total change in length could impale you! Then discuss the expansion joints of large structures (Figures 15.12 and 15.13).

The photo in Figure 15.14 is intriguing. Much has been learned about laying railroad tracks, so this photo goes back many years ago.

> DEMONSTRATION: Place the middle of a bimetallic strip in a flame to show the unequal expansions of different metals, and the subsequent bending.

> CHECK QUESTION: When a metal ball is heated in a Bunsen flame, which undergoes a change: Volume, mass, or density? [Only volume and density change. Mass remains the same.]

Point out that different substances expand or contract (length, area, and volume) at their own characteristic rates (coefficients of expansion). Cite examples such as the need for the same expansion rate in teeth and teeth fillings; iron reinforcing rods and concrete; and the metal wires that are encased in glass light bulbs and the glass itself. Provision must be made when materials with different expansion rates interact; like the piston rings when aluminum pistons are enclosed in steel cylinders in a car, and the rockers on bridges (Figure 15.12), and the overflow pipe for gasoline in a steel tank.

A common consequence of expansion with increased temperature occurs with power lines. They expand and sag on hot days and when they carry large currents. Power lines short out when they sag against trees (or when overgrowth of trees touch the lines).

> CHECK QUESTION: How would a thermometer differ if glass expanded with increasing temperature more than mercury? [Answer: The scale would be upside down because the reservoir would enlarge (like the enlarged hole in the heated metal ring), and mercury in the column would rise with increasing temperature.]

> CHECK QUESTION: Why is it advisable to not completely fill the gas tank of a car that may sit in sunlight on a hot day after being filled? [As the fuel warms it expands, likely overflowing and causing a hazard.]

> NEXT-TIME QUESTION: Ask your students to place an ice cube in a glass of ice water at home, and compare the water level at the side of the glass before and after the ice melts. Ask them to

account for the volume of ice that extends above the water line after it melts. [The answer to the original question is, of course, that the level remains unchanged. This can be explained from the principles learned in Chapter 13. The floating ice cube displaces its own weight of water, so if the ice cube weighs say a newton, then when placed in the glass, one newton of water is displaced and the water level rises. If it is first melted and then poured in the glass, again the water line would be higher, but by one newton, the same amount.] More interesting is to account for the volume of floating ice that extends above the water line (Think and Discuss 105). The ice expanded upon freezing because of the hexagonal open structures of the crystals. Ask the class if they have any idea of how much volume all those billions and billions of open spaces constitute. [Their combined volume is essentially that of the part of ice extending above the water line! When the ice melts, the part above the water line fills in the open structures within the ice upon collapse.] Discuss this idea in terms of icebergs, and whether or not the coastline would change if all the *floating* icebergs in the world melted. [The oceans would rise a bit, but only because icebergs are composed of fresh water. (They form above sea level and break off and then fall into sea.) The slight rise is more easily understood by exaggerating the circumstance—think of ice cubes floating in mercury. When they melt, the depth of fluid (water on mercury) is higher than before.]

Distinguish between the melting of floating icebergs and the melting of ice on land—the floating icebergs contribute nil to a rising ocean level upon melting, where the melting ice on land can appreciably raise ocean levels.

Take note that ocean levels also rise due to thermal expansion. If you had a water-filled test tube that was 2 miles high (an average depth in most oceans), even a slight increase in temperature would raise the level of water appreciably. Fortunately, temperature changes occur near the surface, not all the way down. So changes in sea level are smaller due to thermal expansion. (Too often we attribute rising oceans only to ice-cap melting.)

Tidbits on frozen food: Experts say not to refreeze food that has been thawed. If the food spends too much time above refrigeration temperature (40°F) it may be unsafe to eat due to bacteria growth. So you'd be refreezing unsafe food. If the food still contains ice crystals and is as cold as if it were refrigerated, it may be refrozen safely. Ice cream and frozen yogurt are exceptions and should be discarded. For food such as bread that never needs freezing in the first place, refreezing is safe even if fully thawed.

NEXT-TIME QUESTION: Think and Solve 41, the ring around Earth.

Answers and Solutions for Chapter 15

Reading Check Questions

1. Water freezes at 0°C and 32°F, and boils at 100°C and 212°F.
2. Freezing water is 273K and boiling water is 373K.
3. Translational kinetic energy is the energy of to-and-fro molecular motion.
4. Temperature is a measure of the *average* translational KE per molecule.
5. The necessary condition is thermal equilibrium, for only then will the thermometer and thing being measured have the same temperature.
6. They are two terms for the same thing. Physicists prefer the term *internal* energy.
7. Energy transfers from warmer objects to cooler objects.
8. Hot objects contain internal energy, not heat.
9. Heat is internal energy that flows from hot to cold locations. They are not two terms for the same thing.
10. The direction of internal energy flow is from objects at higher temperatures to objects at lower temperatures.
11. Food is burned and the energy release measured.
12. One Calorie is 1000 calories.
13. One calorie is equivalent to 4.19 joules.
14. The energy needed is 4.19 J.
15. Silver heats more quickly and therefore has a lower specific heat capacity.
16. A substance that heats quickly has a low specific heat capacity.
17. A substance that cools quickly has a low specific heat capacity.
18. Water has an appreciably higher specific heat capacity than other common materials.
19. Internal energy is carried in the Gulf Stream from tropical waters to the North Atlantic where it warms the otherwise cold climate.
20. The air above the cooling water warms.
21. Water has a moderating effect, slow to warm and slow to cool.
22. Molecules move faster with increasing temperature and take more space.
23. The strip bends due to its two metals with different rates of thermal expansion.
24. Liquids generally expand more for equal increases in temperature.
25. Ice-cold water contracts with increasing temperature, until it reaches 4°C.
26. Ice is less dense than water due to its ice crystals that have open structures.
27. Microscopic slush makes water less dense.
28. As temperature increases, microscopic slush melts.
29. The smallest volume of water (and the densest) occurs when water is at 4°C.
30. Only when water below is more dense than water above, can water remain at the surface to freeze.

Think and Do

31. If you use a 0.6-gram peanut, your value should be about 1400 calories, assuming all the heat energy transfers to the water.

32. Tell your grandparents that heat is energy in transit, not energy inside something, which you refer as internal energy.

Plug and Chug

33. $Q = cm\Delta T$ = (1 cal/g·°C)(300 g)(30°C - 22°C) = 3000 cal.
34. $Q = cm\Delta T$ = (4,190 J/kg·°C)(0.30 kg)(30°C - 22°C) = 12,570 J.
35. 3000 cal (4.19 J/1 cal) = 12570 J

Think and Solve

36. (a) The amount of heat absorbed by the water is
    $Q = cm\Delta T$ = (1.0 cal/g·°C)(50.0 g)(50°C – 22°C) = 1400 cal. At 40% efficiency only 0.4 the energy from the peanut raises the water temperature, so the calorie content of the peanut is 1400 cal/0.4 = 3500 cal.
    (b) The food value of a peanut is 3500 cal/0.6 g = 5.8 kilocalories/gram = 5.8 Cal/g.

37. Each kg requires 1 kcal for each degree change, so 50 kg needs 50 kcal for each degree change. Twenty degrees means twenty times 50 kcal, which is 1000 kcal.

By formula: $Q = cm\Delta T$ = (1 cal/g·°C)(50,000 g)(20°C) = 1000 kcal. We can convert this to joules knowing that 4.19 J = 1 cal. In joules this quantity of heat is 4190 kJ (about 4200 kJ).

38. Raising the temperature of 10 kg of steel by one degree takes 10kg(450 J/kg ·°C) = 4500 J. Raising it through 100 degrees takes 100 times as much, or 450,000 J.
By formula, $Q = cm\Delta T$ = (450 J/kg ·°C)(10 kg)(100°C) = 450,000 J.
Heating 10 kg of water through the same temperature difference takes 1,000,000 calories, which is [1,000,000 cal(4.18 J/cal)] = 41,800,000 J, nearly ten times that for the piece of steel—another reminder that water has a large specific heat capacity.

39. If a 1-m long bar expands 0.6 cm when heated, a bar of the same material that is 100 times as long will expand 100 times as much, 0.6 cm for each meter, or 60 cm. (The heated bar will be 100.6 m long.)

40. By equation: $\Delta L = L\alpha\Delta T$ = (1300 m)(11 x 10^{-6}/°C)(20°C) = 0.29 m, nearly 0.3 m.

41. If a snugly fitting steel pipe that girdled the world were heated by 1 C°, it would stand about 70 m off the ground! The most straight-forward way to see this is to consider the radius of the 40,000 long kilometer pipe, which is the radius of Earth, 6370 kilometers. Steel will expand 11 parts in a million for each C° increase in temperature; the radius as well as the circumference will expand by this fraction. So 11 millionths of 6370 km = 70 m. Is this not astounding?

Think and Rank

42. Ans: B, A, C. (1 cal = 4.18 J; so 1 J = 0.23 cal. So 1 J > 1 cal. 1 Calorie = 1,000 cal = 4180 J. So 1 Cal > 1 cal > 1 J.)

43. C, A, B.

44. B, A, C. The wire to mostly sag is the wire that elongates more for equal changes in temperature.

45. C, A, B.

Think and Explain

46. Inanimate things such as chairs and tables have the same temperature as the surrounding air. People and other mammals, however, generate their own heat and have body temperatures that are normally higher than air temperature.

47. Since Celsius degrees are larger than Fahrenheit degrees, an increase of 1 C° is larger. It’s 9/5 as large.

48. No, they have the same average speed, but not the same instantaneous speed. At any moment molecules with the same average speed can have enormously different instantaneous speeds.

49. Gas molecules move haphazardly and move at random speeds. They continually run into one another, sometimes giving kinetic energy to neighbors and sometimes receiving kinetic energy. In this continual interaction, it would be statistically impossible for any large number of molecules to have the same speed. Temperature has to do with average speeds.

50. You cannot establish by your own touch to determine whether or not you are running a fever because there would be no temperature difference between your hand and forehead. If your forehead is a couple of degrees higher in temperature than normal, your hand is also a couple of degrees higher.

51. A molecule in a gram of steam has considerably more kinetic energy, as evidenced by its higher temperature.

52. The hot coffee has a higher temperature, but not a greater internal energy. Although the iceberg has less internal energy per mass, its enormously greater mass gives it a greater total energy than that in the small cup of coffee. (For a smaller volume of ice, the fewer number of more energetic molecules in the hot cup of coffee may constitute a greater total amount of internal energy—but not compared to an iceberg.)

53. Mercury must expand more than glass. If the expansion rates were the same there would be no different readings for different temperature. All temperatures would have the same reading.

54. Calorie is largest, which is 1000 calories.

55. The average speed of molecules in both containers is the same. There is greater internal energy in the full glass (twice the matter at the same temperature). More heat will be required to increase the temperature of the full glass by 1°C, twice as much, in fact.

56. Gaseous pressure changes with changes in temperature.

57. Increasing temperature means increasing KE which means increasing momentum of molecules, which means greater impact and greater pressure against the walls of the container. Simply put, as the temperature of a confined gas is increased, the molecules move faster and exert a greater pressure as they rebound from the walls of the container.

58. Different substances have different thermal properties due to differences in the way energy is stored internally in the substances. When the same amount of heat produces different changes in temperatures in two substances of the same mass, we say they have different specific heat capacities. Each substance has its own characteristic specific heat capacity. Temperature measures the average translational kinetic energy of random motion, but not other kinds of energy.

59. The substance with the smaller specific heat capacity, iron, undergoes the greater change in temperature.

60. In the same environment, the slowly cooling object has the greater specific heat capacity.

61. Less specific heat means shorter time for temperature change, and a shorter hot bath.

62. Water in the melon has more “thermal inertia”—a higher specific heat than sandwich ingredients. Be glad water has a high specific heat capacity the next time you’re enjoying cool watermelon on a hot day!

63. Alcohol, for less specific heat means less thermal inertia and a greater change in temperature.

64. Both the pan and water undergo the same temperature change. But water, with its greater specific heat capacity, absorbs more heat.

65. The brick will cool off too fast and you’ll be cold in the middle of the night. Bring a jug of hot water with its higher specific heat to bed and you’ll make it through the night.

66. The climate of Bermuda, like that of all islands, is moderated by the high specific heat of water. What moderates the climates are the large amounts of energy given off and absorbed by water for small changes in temperature. When the air is cooler than the water, the water warms the air; when the air is warmer than the water, the water cools the air. (Warmth due to the Gulf Stream helps as well.)

67. The climate of Iceland, like that of Bermuda in the previous exercise, is moderated by the surrounding water. (Warmth due to the Gulf Stream helps as well.)

68. In winter months when the water is warmer than the air, the air is warmed by the water to produce a seacoast climate warmer than inland. In summer months when the air is warmer than the water, the air is cooled by the water to produce a seacoast climate cooler than inland. This is why seacoast communities and especially islands do not experience the high and low temperature extremes that characterize inland locations.

69. As the ocean off the coast of San Francisco cools in the winter, the heat it loses (transfers) warms the atmosphere it comes in contact with. This warmed air blows over the California coastline to produce a relatively warm climate. If the winds were easterly instead of westerly, the climate of San Francisco would be chilled by winter winds from dry and cold Nevada. The climate would be reversed also in Washington, D.C. because air warmed by the cooling of the Atlantic Ocean would blow over Washington, D.C. and produce a warmer climate in winter there.

70. Sand has a low specific heat capacity, as evidenced by its relatively large temperature changes for small changes in internal energy. A substance with a high specific heat capacity, on the other hand, must absorb or give off large amounts of internal energy for comparable temperature changes.

71. Water between 0°C and 4°C is an exception.

72. No, the different expansions are what bends the strip or coil. Without the different expansions a bimetallic strip would not bend when heated.

73. When the rivets cool they contract. This tightens the plates being attached.

74. When doused, the outer part of the boulders cooled while the insides were still hot. This caused a difference in contraction, which fractured the boulders.

75. The tires heat up, which heats the air within. The molecules in the heated air move faster, which increases air pressure in the tires. (See question 57.)

76. Temperature differences cause differences in expansion and contraction, which produce sounds as structures expand or contract.

77. Cool the inner glass and heat the outer glass. If it's done the other way around, the glasses will stick even tighter (if not break).

78. Higher expansion rate would mean greater difference in shape with different temperature, a liability for a telescope mirror.

79. If they expanded differently, as for different materials, the key and lock wouldn't match.

80. A chimney undergoes more changes in temperature than any other part of the building, and therefore more changes in expansion and contraction. Such changes should be the same for all parts of the building that bear the building's weight. Otherwise, sags and worse occur.

81. The photo was likely taken on a warm day. If it were taken on a cold day there would be more space between the segments.

82. Gas is sold by volume. The gas meter that tallies your gas bill operates by measuring the number of volume units (such as cubic feet) that pass through it. Warm gas is expanded gas and occupies more space, and if it passes through your meter, it will be registered as more gas than if it were cooled and more compact. The gas company gains if gas is warm when it goes through your meter because the same amount of warmer gas has a greater volume.

83. Overflow is the result of liquid gasoline expanding more than the solid tank.

84. When a mercury thermometer is warmed, the outside glass is heated before heat gets to the mercury inside. So the glass is the first to expand, momentarily opening (like the heated ring in the third chapter-opener photo) which allows the mercury to drop from the glass tube into the slightly enlarged reservoir. When the mercury warms to the same temperature of the glass, it is then forced up the glass tube because of its greater expansion rate.

85. The U shape takes up the slack of expansion or contraction, without changing the positions of the end points.

86. Thin glass is used because of the sudden temperature changes. If the glass were thicker, unequal expansions and contractions would break the glass with sudden temperature changes.

87. In the construction of a light bulb, it is important that the metal leads and the glass have the same rate of heat expansion. If the metal leads expand more than glass, the glass may crack. If the metal expands less than glass upon being heated, air will leak in through the resulting gaps.

88. 4°C.

89. Water has the greatest density at 4°C; therefore, either cooling or heating at this temperature will result in an expansion of the water. A small rise in water level would be ambiguous and make a water thermometer impractical in this temperature region.

90. The atoms and molecules of most substances are more closely packed in solids than in liquids. So most substances are denser in the solid phase than in the liquid phase. Such is the case for iron and aluminum and most all other metals. But water is different. In the solid phase the structure is open-spaced and ice is less dense than water. Hence ice floats in water.

91. Volume increases.

92. At 0°C it will contract when warmed a little; at 4°C it will expand, and at 6°C it will expand.

93. It is important to keep water in pipes from freezing because when the temperature drops below freezing, the water expands as it freezes and the pipes (if metal) will fracture if water in them freezes.

94. Ponds would be more likely to freeze if water had a lower specific heat capacity. This is because the temperature would decrease more when water releases energy; water would more readily be cooled to the freezing point.

95. If cooling occurred at the bottom of a pond instead of at the surface, ice would still form at the surface, but it would take much longer for ponds to freeze. This is because all the water in the pond would have to be reduced to a temperature of 0°C rather than 4°C before the first ice would form. Ice that forms at the bottom where the cooling process is occurring would be less dense and would float to the surface (except for ice that may form on materials anchored to the bottom of the pond).

Think and Discuss

96. The hot rock will cool and the cool water will warm, regardless of the relative amounts of each. The amount of temperature change, however, does depend in great part on the relative masses of the materials. For a hot rock dropped into the Atlantic Ocean, the change in the ocean's temperature would be too small to measure. Keep increasing the mass of the rock or keep decreasing the mass of the ocean and the change will be evident.

97. Other effects aside, the temperature should be slightly higher, because the PE of the water above has been transformed to KE below, which in turn is transformed to heat and internal energy when the falling water is stopped. (On his honeymoon, James Prescott Joule could not be long diverted from his preoccupation with heat, and he attempted to measure the temperature of the water above and below a waterfall in Chamonix. The temperature increase he expected, however, was offset by cooling due to evaporation as the water fell.)

98. A high specific heat capacity. The more ways a molecule can move internally, the more energy it can absorb to excite these internal motions, which don't raise the temperature of the substance. This greater capacity for absorbing energy makes a higher specific heat capacity.

99. Every part of a metal ring expands when it is heated—not only the thickness, but the outer and inner circumference as well. Hence the ball that normally passes through the hole when the temperatures are equal will more easily pass through the expanded hole when the ring is heated. (Interestingly enough, the hole will expand as much as a disk of the same metal undergoing the same increase in temperature. Blacksmiths mounted metal rims in wooden wagon wheels by first heating the rims. Upon cooling, the contraction resulted in a snug fit.)

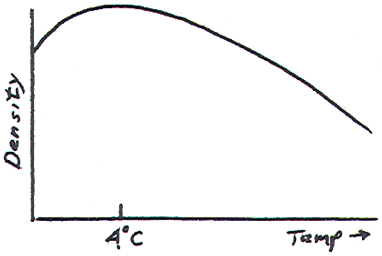
100. The heated balls would have the same diameter.

101. Brass expands and contracts more than iron for the same changes in temperature. Once the iron has cooled and has its "iron grip" on the brass, the two materials, being good conductors and being in contact with each other, are heated or cooled together. If the temperature is increased, the iron expands—but the brass expands even more. Even cooling them won't produce separation.

102. The gap in the ring will become wider when the ring is heated. Try this: Draw a couple of lines on a ring where you pretend a gap to be. When you heat the ring, the lines will be farther apart—the same amount as if a real gap were there. Every part of the ring expands proportionally when heated uniformly—thickness, length, gap and all.

103. On a hot day a steel tape expands more than the ground. You will be measuring land with a "stretched" tape. So your measurements of a plot of land will be smaller than measurements taken on a cold day. Measurements taken on a cold day will show the ground to be larger. (If, on the other hand, you're staking off land not already plotted, then on a hot day you'll get more land.)

104. The curve for density versus temperature is:



105. The combined volume of all the billions of "open rooms" in the hexagonal ice crystals of a piece of ice is equal to the volume of the part of the ice that extends above water when ice floats. When the ice melts, the open spaces are filled in by the amount of ice that extends above the water level. This is why the water level doesn't rise when ice in a glass of ice water melts—the melting ice "caves in" and nicely fills the open spaces.