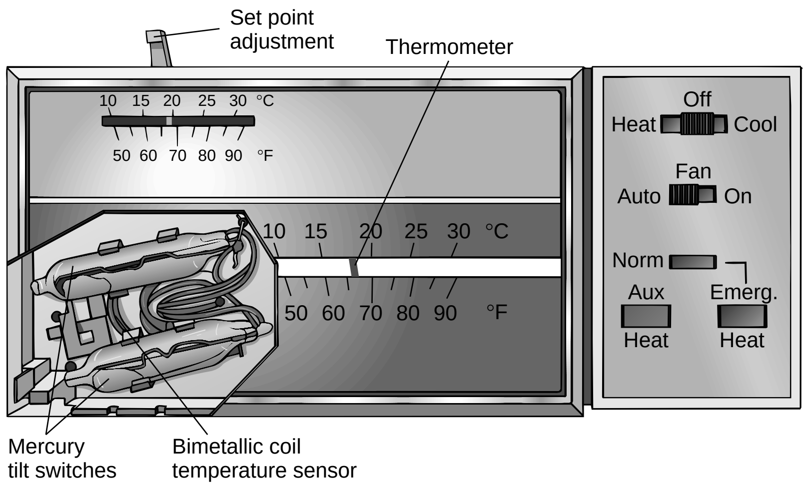

Section 6.6

Thermometers and Thermostats

Knowing temperature is important when you are going on a picnic, baking bread, or lying in bed with the flu. You use a thermometer to measure how hot it is outside, in the oven, or on your forehead. A thermometer is able to measure temperature because the characteristics of its components change with temperature. In this section, we will examine some of those changes to see how thermometers work.

There are also times when you want to control temperature. You don't just want to know how hot your house is, you want to maintain it at a certain level. In such cases, you need a thermostat, a thermometer that uses its temperature measurements to control other equipment.

Questions to Think About: *Where does the extra liquid come from when the red liquid in a glass thermometer rises with the temperature? What kind of mechanism inside a meat or candy thermometer can cause its needle to turn? On a plastic strip thermometer, the kind with the color-changing numbers printed on its surface, what happens to the numbers that are not visible? Why does it matter that the thermostat in your home is exactly level?*

Experiments to Do: *Find a thermometer and measure the temperatures of a few different objects. Watch how the thermometer changes as you move it from a hot object to a cold object. Can you see its parts moving?*

Observe the thermometer's rate of response. Does it read the temperature of a new object immediately or is there a delay? What would cause such a delay? Is the thermometer *really measuring the temperature of the object or is it measuring its own temperature? Is there a difference?*

Your home is probably full of "accidental" thermometers: windows or doors that stick in hot or cold weather, metal stripping that buckles in the heat, and floors that creak and pop at night as the temperature drops. Look around and see what you can find.

Liquid Thermometers: Thermal Expansion

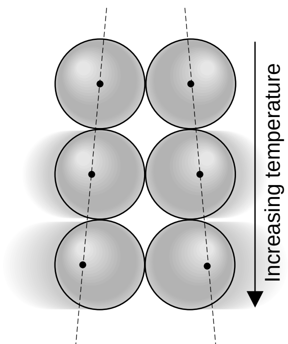

Fig. 6.6.1 - The internal kinetic energy of a solid increases with temperature, causing its atoms to bounce against one another more vigorously. As they vibrate, the atoms repel more strongly than they attract so their average separation increases slightly.

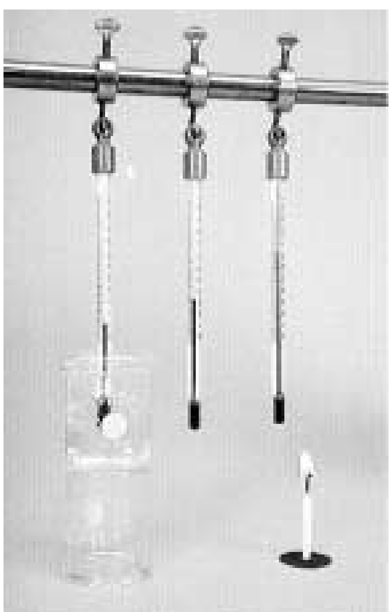

Fig. 6.6.2 - As their temperatures increase—from left to right—both the glass and the liquid in these thermometers expands. However the liquid expands more and flows up the tube inside the thermometer.

When the amount of thermal energy in an object changes, so does its temperature. But temperature isn't the only characteristic of the object that is sensitive to thermal energy. Materials change in many ways as you warm them or cool them and thermometers and thermostats are based on those changes.

One aspect of an object that changes with temperature is its volume. In most cases, the object expands uniformly as its temperature increases and contracts uniformly as its temperature decreases. Just how much an object's volume increases with temperature depends on what it's made of. There are a few special materials that contract when heated or that experience nonuniform expansions or contractions, but we won't consider those exceptional materials here.

These volume changes occur because thermal energy affects the average spacings of the object's atoms. In a solid or liquid, the atoms are touching and experience forces that push them toward their equilibrium separations. At absolute zero, the object's atoms would settle down at their equilibrium separations and form a neatly packed array that would give the object its minimal volume.

But absolute zero can't be reached because it's impossible to remove all of the thermal energy from an object. Since the object contains at least some thermal energy, its atoms vibrate back and forth about their equilibrium separations (Fig. 6.6.1). However, this vibrational motion is not symmetric. The repulsive force the atoms experience when they're too close together is stiffer than the attractive force they experience when they are too far apart. As a result, they push apart more quickly than they draw together and spend most of their time at more than their equilibrium separation. On average, their actual separation is thus more than their equilibrium separation and the object is bigger than it would be at absolute zero.

Increasing the object's temperature moves the atoms even farther apart and the object grows larger in all directions. But that is not the whole story. If it were, then a glass thermometer would simply become bigger as its temperature increased and the red or silver liquid would not move up the column. Fortunately, there is another complication. Different materials expand by different amounts as their temperatures increase. For example, the liquid inside the glass thermometer expands much more than the glass tube around it so the liquid flows up the column (Fig. 6.6.2).

The extent to which an object expands with increasing temperature is normally described by its **coefficient of volume expansion**: the fractional change in an object's volume caused by a temperature increase of 1° C. Fractional change in volume is the net change in volume divided by the total volume. Since most materials expand only a small amount when heated 1° C, coefficients of volume expansion are small, typically about 10^{-5} for metals, about 10^{-6} for special low-expansion glasses, and about 10^{-4} for liquids such as alcohol.

Now we can see how a glass thermometer works. Its hollow body contains just enough colored alcohol or mercury to completely fill the cavity in its bulb, plus a little extra (Fig. 6.6.3). The extra liquid projects part way up a fine, hollow capillary connected to the bulb. As the thermometer's temperature increases, both the liquid and the glass enclosure expand but the liquid expands more than the glass. Although the cavity in the bulb becomes slightly larger and can accommodate slightly more liquid, the liquid's expansion squeezes some of it out of the bulb and into the capillary. The column of liquid in the capillary becomes longer and you see a longer red or silver bar.

This mechanism for temperature measurement, with a liquid flowing out of a container as the temperature increases, is also found in thermostats. A typical oven thermostat uses a liquid-filled metal bulb to sense the temperature inside the oven. As the temperature increases, the liquid expands more than the metal and squeezes through a thin tube to the oven's control unit. There it pushes against a metal membrane, operating a switch that controls the flow of electricity or natural gas to the oven's burner. If the oven temperature rises above the desired value, the switch turns the burner off. The switch turns the burner back on when the oven temperature falls below the desired value. In this manner, the thermostat regulates the oven temperature.

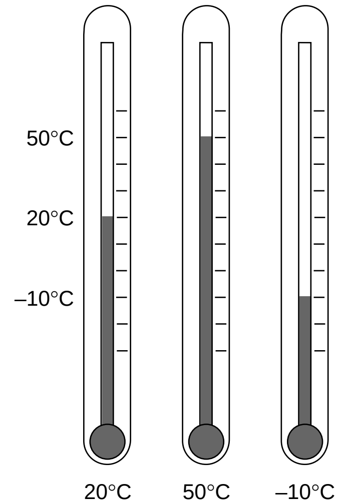

Fig. 6.6.3 - The liquid inside a glass thermometer has a larger coefficient of volume expansion than the glass. As the temperature increases, excess liquid is driven out of the cavity at the base of the thermometer and the thin column of liquid in the capillary rises. As the temperature decreases, liquid returns to the cavity and the column falls.

CHECK YOUR UNDERSTANDING #1: Overcooked
If you place a pot or saucepan on the stove and fill it to the brim with cold water, it will overflow as you heat it. Where does the extra water come from?

Metal Thermometers: Bimetallic Strips

Not all thermometers are based on expanding liquids. There are many other thermometers that use metal strips to measure temperature. However, because solids have much smaller coefficients of volume expansion than liquids, it's difficult to make sensitive metal thermometers. This distinction between liquids and solids is caused by fundamental differences in their microscopic structures. Let's take a moment to look at those structures.

The atoms and molecules of most solids are held together rigidly and form orderly structures called **crystals** (Fig. 6.6.4). Crystals are familiar to most of us as the beautiful, faceted minerals in geology exhibits and museum gift shops. The natural faceting that appears on these crystals reflects the extraordinary order present in *crystalline solids* at the atomic and molecular scale. The atoms and molecules in a crystal arrange themselves in nearly perfect **lattices**, repetitive and uniform arrangements that resemble stacks of oranges or food containers at the grocery store. *Crystalline order* is not unique to faceted minerals. Most solids, including metals, are actually *crystalline* because their particles are arranged in regular lattices.

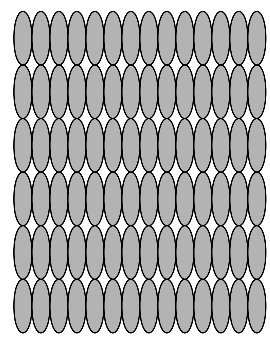

Fig. 6.6.4 - In a crystalline solid, the atoms or molecules are arranged in a highly ordered lattice.

In contrast, normal liquids are not crystalline (Fig. 6.6.5). Because the particles in a liquid don't form an orderly lattice, they have much more freedom in arranging themselves than they would have in a solid. This increased freedom is what gives liquids their large coefficients of volume expansion, as well as large specific heat capacities.

To understand how increased freedom affects specific heat capacity, we need to know what happens to a liquid when you add thermal energy to it. While some of the new thermal energy goes into making the particles vibrate harder, raising the liquid's temperature, a large fraction of it goes instead into breaking chemical bonds and separating the particles from one another. This alternative use of thermal energy increases the amount of heat you must add to the liquid to raise its temperature.

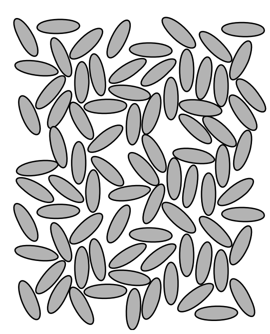

Fig. 6.6.5 - In a normal liquid, the atoms or molecules are disordered. They touch one another but don't form an ordered lattice.

In a solid, added heat goes only into making its particles vibrate harder so that its temperature increases quickly and easily. Because it takes more heat to warm 1 kg of a typical liquid by one degree than to do the same for 1 kg of a typical solid, the liquid's specific heat capacity is larger than that of the solid.

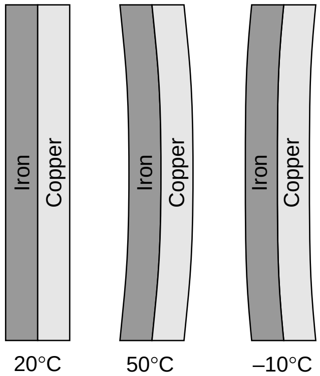

Fig. 6.6.6 - A copper and an iron strip are bonded together to form a bimetallic strip. Since copper has a larger coefficient of volume expansion than iron, the strip curls in response to changes in temperature. The strip's shape is an accurate indication of its temperature.

Fig. 6.6.7 - This refrigerator thermometer uses a coiled bimetallic strip to measure temperature. The coil unwinds as it cools.

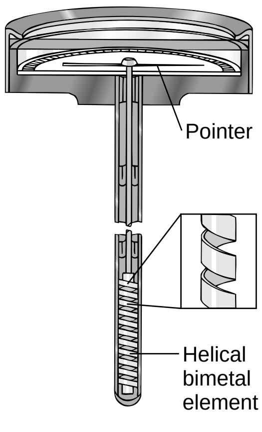

Fig. 6.6.8 - A kitchen thermometer is based on a bimetallic strip that has been wound into a helix. As the temperature changes, the helical element coils or uncoils and turns the pointer.

There are two important consequences to the breaking of bonds in a liquid when you heat it. First, the liquid's viscosity decreases and it flows more easily. That's why pancake syrup is easier to pour if you heat it first. Second, the liquid's volume increases because the liquid's particles become even more loosely packed and take up additional space. This volume increase is larger than in a solid, where the particles remain in their lattice during heating, so the liquid expands more than the solid. Thus liquids generally have larger coefficients of volume expansion than solids.

Despite their small coefficients of volume expansion, metals are often used in thermometers. The most common type of metal thermometer is based on a *bimetallic strip*. In this design, narrow sheets of two different metals (often copper and iron) are permanently bonded together to make a thin metal sandwich (Fig. 6.6.6). Since these two metals have different coefficients of volume expansion, the bimetallic strip deforms as its temperature changes. Copper has the larger coefficient of volume expansion, so the strip's copper layer expands more when the strip is heated and shrinks more when the strip is cooled.

As the two layers of the bimetallic strip expand or shrink, the strip curls to one side or the other. There is only one temperature at which the strip is straight (Fig. 6.6.6). Above that temperature, the strip curls so that the longer copper layer is outside the iron and below that temperature, the strip curls so that the shorter copper layer is inside the iron. Since the strip's shape depends on its current temperature, it makes a fine thermometer.

Most dial thermometers, including meat and candy thermometers, are based on bimetallic strips. To increase the sensitivities of these thermometers, their bimetallic strips are wound into small coils (Fig. 6.6.7) or spirals (Fig. 6.6.8) that curl or uncurl with temperature. One end of the bimetallic coil is fixed to the thermometer's frame while the other end is attached to the pointer. As the thermometer's temperature changes, the curling bimetallic coil moves the pointer to indicate the current temperature.

Bimetallic coils are used in many home-heating thermostats. Switches attached to the bimetallic coil in such a thermostat control the furnace. When the temperature becomes too high, the coil and switch turn the furnace off. When the temperature becomes too low, the coil and switch turn the furnace back on.

The furnace switch is usually a glass tube that is partially filled with liquid mercury metal (Fig. 6.6.9). This tube is attached to the movable end of the bimetallic coil, the end that normally turns the pointer of a dial thermometer. As the coil winds or unwinds, it tips the mercury from one end of the glass tube to the other. Two electric contacts are embedded in the wall of the tube. When the mercury is at one side of the tube, it connects these two contacts so that electricity can flow from one to the other. When the mercury tips to the other side of the tube, the contacts are not connected and no electricity flows. This mercury tilt switch allows the shape of the bimetallic coil to control the furnace.

When you set the temperature of the thermostat, you are actually changing the orientation of the bimetallic coil. This coil is attached to the temperature control knob so that turning that knob tilts both the coil and the mercury switch. When you turn up the temperature, you are tilting the coil so that it won't operate the mercury switch until the room becomes hotter. When you turn down the temperature, you are tilting the coil the other way so that it operates the switch at a relatively low temperature. Once the room reaches the desired temperature, the thermostat turns the furnace on and off as needed to maintain a nearly constant temperature.

Bimetallic strip thermostats are also used in clothes irons, toasters, and portable space heaters, where they directly control the flow of electricity through heating elements. As its temperature drops, the bimetallic strip in one of these simple thermostats bends until it touches a second piece of metal. Once contact is made, electricity flows from the strip to its contact and then through the heating element. That way, whenever the thermostat becomes too cold, it turns on the heating element. (For an interesting application of bimetallic strips, see ❐ at the top of the following page.)

Direct contact thermostats aren't as sensitive, precise, or durable as those that use mercury tilt switches, but they operate well in any orientation. Tilt switch thermostats are sensitive to orientation because they use gravity to move the mercury around. To keep them operating at the right temperatures, tilt switch thermostats must be permanently mounted so that they always remain level.

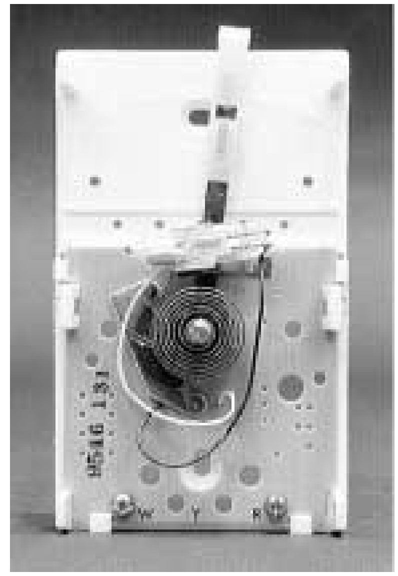

Fig. 6.6.9 - The coiled bimetallic strip in this home thermostat controls the orientation of a mercury tilt switch. As the ball of liquid mercury tips from one end of the glass switch to the other, it turns the furnace on or off.

CHECK YOUR UNDERSTANDING #2: Not So Flat Bottomed Pots
The bottoms of some stainless steel pots are copper coated so that they distribute heat more evenly to the food inside. When these pots are heated, they bow outward slightly and will rock when placed on a flat surface. What causes this bowing?

Plastic Strip Thermometers: Liquid Crystals

The plastic strip thermometer is a relatively recent development. This thermometer is a thin flexible strip that displays the current temperature as a brightly colored number. The strip has a whole range of temperatures printed on it, but only one number is easily visible at any given temperature. As the temperature changes, that number vanishes into the background and another number becomes visible. A plastic strip thermometer is particularly useful for measuring the temperature of a surface, such as the glass wall of a tropical fish aquarium or a child's fevered brow.

The strip is not really a solid piece of plastic. It's a multi-layer sandwich containing a remarkable material phase called a liquid crystal. A liquid crystal has properties intermediate between a solid and a liquid. Behind each number on the strip is its own drop of liquid crystal that reflects colored light only at the temperature associated with that number.

To understand liquid crystals, we must return again to the microscopic structures of solids and liquids. Crystalline solids are highly ordered materials. The spacings between particles in a crystal are so regular that, once you know exactly where a few of the particles are located, you also know exactly where millions of other nearby particles are located. This regularity is called **positional order**. This positional order is visible in Fig. 6.6.4. The particles in a crystal are also highly oriented, so that if you know the orientations of a few particles, you also know exactly how millions of other nearby particles are oriented. This second regularity is called **orientational order**. In contrast, normal liquids don't have positional or orientational order (see Fig. 6.6.5). Knowing the positions and orientations of a few particles in a liquid tells you little about the positions and orientations of nearby particles.

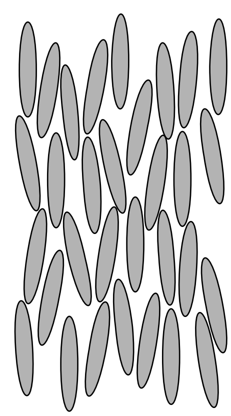

Fig. 6.6.10 - In a liquid crystal, the rod-like or disk-like molecules don't have positional order but they do have orientational order. Here all the rod-like molecules point in more or less the same direction, a behavior characteristic of a nematic liquid crystal.

Liquid crystals lie in between solids and liquids. Like normal liquids, liquid crystals have little positional order. Knowing where some of the particles in the liquid crystal are won't help you locate other nearby particles. But liquid crystals do have substantial orientational order. Liquid crystals are composed of rod-like or disk-like molecules that align themselves with one another, even though their positions are free to change (Fig. 6.6.10). These molecules move about like those in a normal liquid but they remain highly oriented, like those in a crystalline solid. Hence the name "liquid crystal."

Liquid crystals are actually quite common in biological systems. For example, cell membranes in animals are liquid crystals. Among the most familiar liquid crystals are the pearly, iridescent liquid hand soaps and shampoos. Their striking optical properties come about because of their remarkable orientational order. Liquid crystals interact strangely with light, a feature that makes them useful in electronic watch displays and computer screens. It's just such a strange interaction between a liquid crystal and light that makes a plastic film thermometer work.

❐ Light blinkers used in automobiles and holiday lights contain a bimetallic strip thermostat. Electricity flowing through the blinker heats its filament. When the temperature of the filament becomes high enough, the thermostat stops the current flow and turns off the filament. When it cools down, the thermostat again permits electricity to flow and the filament heats up. This process repeats over and over and causes any lights attached to the blinker to wink on and off endlessly.

The liquid crystal used in a thermometer is not quite as simple as that depicted in Fig. 6.6.10. That figure shows a *nematic liquid crystal*, which has molecules that can be located anywhere, but that all point in roughly the same direction throughout the material. The liquid crystal used in a thermometer is a *chiral nematic liquid crystal*, which has a natural twist to it so that the preferred molecular orientation spirals around like a corkscrew as you look across the liquid in one particular direction (Fig. 6.6.11). A chiral nematic liquid crystal still has only orientation order, but that orientational order is a complicated spiral one.

The spiral orientation of its molecules gives the chiral nematic liquid crystal a twisting, wave-like appearance. It even has "crests," where the molecules all tend to point up and down, rather than to the side. The spacing between adjacent crests is called the *pitch*, the same word used to describe the distance between adjacent threads on a screw. The pitch of a chiral nematic liquid crystal is responsible for its remarkable optical properties.

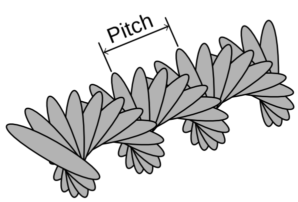

Fig. 6.6.11 - The molecules in a chiral nematic liquid crystal have an orientation that rotates in a smooth spiral along one direction through the liquid. The spacing between adjacent regions of upward pointing molecules is called the pitch.

This pitch may be only a few tens of nanometers or many microns, depending on the liquid crystal's chemical composition and *on its temperature*. Increasing the temperature shortens the pitch. This dependence of pitch on temperature is what makes liquid crystal thermometers possible. In a particular chiral nematic liquid crystal, there may be a narrow range of temperatures over which the pitch of the spiral is equal to the wavelengths of visible light in that liquid. When the liquid crystal's temperature is in this range, it suddenly begins to reflect colored light!

For example, if at 28 °C the pitch of a particular liquid crystal is equal to the wavelength of blue light, then that liquid will appear brilliantly blue when illuminated by white light because it will reflect blue light back toward your eyes. If at 26 °C, the pitch is longer and is equal to the wavelength of red light, then the liquid will appear red. If at 24 °C, the pitch is longer than the wavelength of any visible light, then the liquid will reflect only infrared light and will appear transparent. This phenomenon is called **selective reflection** and is caused by *constructive interference*, a wave behavior that we will examine in Chapter 12. (This effect also appears in nature—see ❐.)

A plastic strip thermometer contains a series of different chiral nematic liquid crystals that are viewed through clear number-shaped openings in the otherwise opaque strip. Behind each temperature number is a liquid crystal that reflects visible light only at the temperature represented by that number. Because the liquid crystals have black plastic behind them, they appear black unless they are selectively reflecting light. For any given temperature, only one patch of liquid crystal is selectively reflecting light and it illuminates the number corresponding to the strip's temperature.

❐ Some insects obtain their striking colorations from chiral nematic liquid crystals. These liquid crystals contain oriented molecules that selectively reflect light of certain colors. In insects, these liquid crystal secretions harden to form solids that retain both the special spiral molecular order and the unusual optical effects.

CHECK YOUR UNDERSTANDING #3: Hot Spots

An engineer can measure the temperature distribution of a flat surface by laying a thin liquid crystal sheet on it. Different temperatures appear as different colors in the light reflected by that sheet. Explain.

Electronic Thermometers

With the advent of modern consumer electronics, digital electronic thermometers have become important and desirable. We no longer want to read a dial or the height of a column of liquid—we want a digital display. Presenting the temperature as a number is something a computer can do easily. However, the computer needs a sensor that measures the temperature in electronic form in order to display it.

The most common electronic temperature sensors are thermocouples and thermistors. These two devices operate on different principles but both are based on electronic properties that change with temperature.

Thermocouples are based on the **Seebeck effect**. We noted in Section 6.1 that the principal carriers of heat through a metal are the mobile conduction electrons. The conduction electrons at the hot end of a metal rod have extra kinetic energy and are faster-moving than those at the cold end. On average, conduction electrons tend to carry heat from the rod's hot end toward its cold end. The added vigor with which conduction electrons leave the hot end of the rod for the cold end also creates a small imbalance of electric charge. The cold end of the rod ends up with a few too many conduction electrons that are now missing from the hot end. This redistribution of electric charge is the Seebeck effect.

While charge imbalances due to the Seebeck effect are extremely small, they can be measured by delicate electronic equipment. However, it's tricky to measure a charge imbalance between a hot metal and a cold metal. It's much easier to make such a measurement between two metals that are at the same temperature. For this reason, a *thermocouple* is constructed by joining two wires made of different metals together at one point. When the junction between the wires is heated, each wire experiences the Seebeck effect but the amount of charge imbalance that occurs in each depends on the type of metal. Because electrons can flow freely across the heated junction, the two different charge imbalances that appear in the metal wires create an overall charge imbalance between the two cold ends of the wires. For example, a standard thermocouple is made by joining a platinum wire with a platinum-rhodium alloy wire. When the junction between the wires is heated, electrons flow away from it through both wires, but more electrons flow out the platinum wire than out the platinum-rhodium alloy wire. As a result, there are more electrons on the room temperature end of the platinum wire than on the room temperature end of the platinum-rhodium wire. Measuring this imbalance in electric charge is relatively easy.

Thermocouples appear frequently in temperature control units for furnaces and manufacturing equipment. They can measure very high temperatures with ease, even in a blast furnace. Thermocouples can also measure very low temperatures because the Seebeck effect works in reverse if you make the junction colder than the free ends of the wires. Just which two metals are used in a thermocouple depends on the desired temperature range and on the chemical environment that these metals must endure. Platinum and Platinum-Rhodium are wonderfully inert metals so that they tolerate almost any environment up to 1769 °C, the temperature at which platinum melts. Unfortunately, both metals are extremely expensive. Less costly thermocouple metals include iron, copper, and a variety of copper, nickel, chromium, and aluminum alloys.

A **thermistor** is quite different from a thermocouple. It indicates its temperature by changing its electric resistance. Thermistors are made out of **semiconductors**, materials that are neither good electric conductors like metals nor good electric insulators like glasses or plastics. A true semiconductor has no conduction electrons at all at very low temperature, so that it behaves like an insulator. Without any mobile conduction electrons, a semiconductor can't carry an electric current from one side to the other.

But a semiconductor stops being a good insulator as it warms up. Thermal energy causes some electrons to break away from atoms and move free throughout the material. The semiconductor begins to conduct current. At low temperatures, semiconductors are still very poor conductors of electricity but at high temperatures, semiconductors conduct electricity pretty well. With proper electronics to measure electric resistance, a piece of semiconductor does an excellent job of measuring temperature. Commercial thermistors, such as those found in electronic fever thermometers and other household electronic thermometers, are built out of specialized semiconductors. These semiconductors are designed so that their resistances change dramatically over the ranges of temperatures they are supposed to measure. Properly made thermistors can be very accurate over a considerable range of temperatures. Some thermistors can even measure temperatures close to absolute zero. However, thermistors can't be used to measure very high temperatures without suffering permanent damage because semiconductor crystals are just not as robust as the metals used in thermocouples.

CHECK YOUR UNDERSTANDING #4: This Poker is Hot, Electrically

If you use an iron poker to stir the coals in a fireplace, the coal end of the poker becomes much hotter than the handle end. Which end of the poker develops a small excess of electrons?

Thermal Expansion

Thermal expansion in liquids rarely causes trouble because liquids don't break. The same can't be said for solids. Thermal expansion in solids often creates problems. Differences in coefficients of thermal expansion or in the rates at which different parts of the same object are heated or cooled can cause damage when temperatures change. Concrete pavement, bridges, and railroad tracks all expand differently than the ground on which they rest. Without careful design, concrete pavement will crack or buckle, a bridge will tear itself away from the roads at either end, and railroad tracks will bend into so much steel spaghetti. To remedy these potential disasters, special joints are introduced in each case. Concrete pavement is poured as individual slabs that are joined by a soft material so that the slabs can expand or contract without buckling or breaking. A bridge is separated from the roadways at either end by special expansion joints so that thermal changes in the bridge's length don't cause damage to its surface. Train rails are interrupted periodically by expansion joints, which permit the rails to expand or contract safely.

Even objects that are made of a single material may be damaged by non-uniform temperatures. A metal pan may bend and contort when you put it in the oven because non-uniform heating causes different parts of the pan to expand by different amounts. Only metal's flexibility keeps it from breaking. Glass isn't so flexible and is particularly susceptible to thermal damage. Normal window glass has a large coefficient of thermal expansion and will shatter if you heat it non-uniformly—the rigid, brittle glass literally tears itself apart. One of the most important developments in glass fabrication has been the formulation of heat-resistant glasses—glasses that expand very little when heated. As is discussed in Chapter 16, Pyrex and Kimax glasses have relatively small coefficients of thermal expansion and can tolerate fairly non-uniform temperatures without shattering. Most glassware used in cooking is made from these glasses. However, even Pyrex or Kimax cookware will crumble if you move it straight from the oven to cold water or put it directly on the red-hot burner of an electric stove. These special conditions create such extremely non-uniform temperatures that only a glass with a remarkably low coefficient of thermal expansion can survive. Special quartz glasses meet this requirement and are used in stovetop glass cookware.

CHECK YOUR UNDERSTANDING #5: More Work for the Contractor?
Why are concrete sidewalks divided into small rectangles?