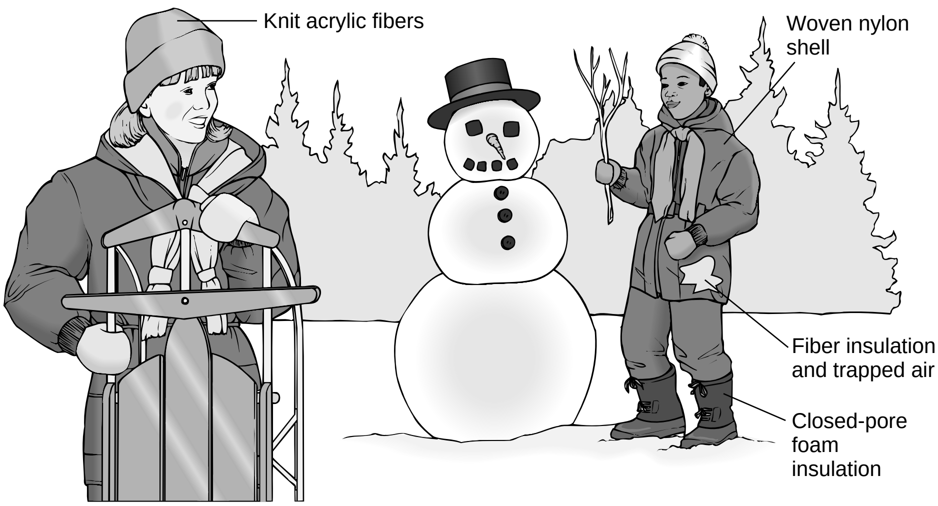

Section 6.5

Clothing and Insulation

When you sit in front of a fire on a cold winter day, your skin is warmed by heat from the hot embers. But when you walk through the snow on your way to the store, the last thing you want is heat transfer. As the hottest object around, you will become colder, not warmer. Instead, you do your best to avoid heat transfer. So you bundle up tight in your new down coat. Its thermal insulation keeps you warm in your frigid environment. In this section, we will examine thermal insulation and see how it keeps heat from moving between objects.

Questions to Think About: *When you wear a thick coat on a cold day, what provides the heat that keeps you warm? How does hair keep your head warm? Why do people sweat on hot days or during exercise? Why is good cookware often made of several different materials? Why do Thermos bottles and Space Blankets have mirrored surfaces?*

Experiments to Do: *Examine the effects of thermal insulation by touching objects with and without insulation on your hand. As you pick up a piece of hot toast with your bare hand, why does your skin feel so hot? Now try again with a towel or napkin between your skin and the toast. What has changed? Perform the same experiment with an ice cube. The towel or napkin keeps your skin comfortable when you touch either hot or cold objects. How is that possible? What happens when you use aluminum foil instead of the towel or napkin?*

You can do similar experiments with a heavy coat. The coat will obviously keep you warm in a cold environment but it will also keep you cool (at least briefly) in a very hot environment. Sit in front of a fireplace with a heavy coat on. The parts of your body that are covered by the coat will barely notice the fire's presence. In fact, you should be very careful because it's possible to scorch or even ignite your coat without feeling the heat. Firefighters use heavy fireproof coats to keep cool as they combat building fires.

The Importance of Body Temperature

Thermal insulation slows the heat transfer between objects and keeps your home warm, your refrigerator cold, and your fingers comfortable when you pick up a cup of hot coffee. One of the most important examples of thermal insulation is your clothing. The principal non-aesthetic purpose of clothing is to control the rate at which heat flows into or out of your body. Clothing helps you maintain your proper body temperature.

The goal of maintaining body temperature is unique to mammals and birds. Cold-blooded animals such as reptiles, amphibians, and fish make no attempts to control their body temperatures. Instead, they exchange heat freely with their surroundings and are generally in thermal equilibrium with their environments.

Unfortunately, the chemical processes that are responsible for life are very temperature sensitive. Many chemical reactions proceed only when thermal energy provides the necessary activation energy. As a cold-blooded animal's temperature goes down, there is less thermal energy per molecule and these chemical reactions occur more and more slowly. The animal's whole metabolism slows down and it becomes sluggish, dimwitted, and vulnerable to predators.

In contrast, warm-blooded animals have temperature regulation systems that allow them to maintain constant, optimal body temperatures. Regardless of its environment, a mammal or bird keeps the core of its body at a specific temperature so that it functions the same way in winter as in summer. The advantages of uniform temperature are enormous. On a cold day, a warm-blooded predator can easily catch and devour its slower-moving cold-blooded prey.

But there is a cost to being warm-blooded. The thermal energy associated with an animal's temperature must come from somewhere and the animal must struggle against its environment to maintain its body temperature. Without realizing it, many of our behaviors are governed by our need to maintain body temperature. Our bodies are careful about how much thermal energy they create and we work hard to control the rate at which we exchange heat with our surroundings.

A resting person converts chemical potential energy into thermal energy at the rate of about 80 Calories-per-hour. Our bodies use that much ordered energy even when we are doing no work on the outside world. Our hearts keep pumping, we keep synthesizing useful chemicals and cells, and we keep thinking. Since the chemical energy is not doing outside work or creating much potential energy anywhere, most of it ends up as thermal energy.

80 Calories-per-hour is a measure of power, equal to about 100 W. A resting person is using about as much power as a 100 W light bulb and, as with the light bulb, most of that power ends up as thermal energy. If a person is more active, he or she will produce more thermal energy. This steady production of thermal energy is why a room filled with people can get pretty warm. 100 W may not seem like very much power, but when a hundred people are packed into a tight space, they act like a 10,000 W space heater and the whole room becomes unpleasantly hot.

If you had no way to get rid of this thermal energy of metabolism, you would become hotter and hotter. To maintain a constant temperature, you must transfer heat to your surroundings. Since heat flows naturally from a hotter object to a colder object, your body temperature must be hotter than your surroundings. This requirement is one reason why human body temperature is approximately 37 °C (98.6 °F). This temperature is higher than all but the hottest locations on earth so that heat flows naturally from your body to your surroundings.

You produce thermal energy as a byproduct of your activities and transfer this thermal energy as heat to your colder surroundings.

Since the rate at which your resting body generates thermal energy is fairly constant, the principal way in which you maintain your temperature is by controlling heat loss. You and other warm-blooded animals have developed a number of physiological and behavioral techniques for controlling heat loss. Let's examine those techniques in terms of the three mechanisms of heat transfer: conduction, convection, and radiation.

CHECK YOUR UNDERSTANDING #1: Keeping the Room Toastie Warm

A toaster oven turns electric energy into thermal energy at a rate of 500 J/s or 500 W. If the appliance's temperature remains constant, how quickly is it transferring heat to its environment?

Retaining Body Heat: Thermal Conductivity

Overall, you must lose thermal energy at the same rate as you produce it; about 100 joules each second. This modest rate is relatively easy to achieve. Except on hot days or when you are exercising hard, your body must struggle to avoid losing heat too quickly. Since all three heat-transfer mechanisms are involved in this heat loss, you must control them all in order to keep warm.

One way in which your body retains heat is by impeding conductive heat loss. Some materials are better conductors of heat than others; they have different thermal conductivities. **Thermal conductivity** measures of how rapidly heat flows through a material that is exposed to a difference in temperatures. Skin has a particularly low thermal conductivity, meaning that it conducts relatively little heat compared to materials such as glass or copper.

Because thermal conductivity is a characteristic of the material itself, not the object from which that material is made, it's defined for a small cube of material with a temperature difference of one degree across it. To determine how much heat will flow through your skin you must consider not only your skin's thermal conductivity, but also its size and shape and the temperature difference across it. The more skin surface you have and the greater the temperature difference across it, the more heat your skin will conduct. However, thickening your skin reduces the temperature difference across each cube of it and lessens the heat conduction through it.

Thus the amount of heat flowing through your skin depends on its thermal conductivity, its surface area, the temperature difference across it, and its thickness. Your body controls all of these factors in trying to minimize heat loss:

1. It uses materials with very low thermal conductivities in your skin.
2. It makes your skin as thick as possible.
3. It minimizes the surface area of your skin.
4. It minimizes the temperature difference across your skin.

Your skin and the layers immediately beneath it contain fats and other thermal insulators. Fat's thermal conductivity is about 20% that of water and only about 0.03% that of copper metal. Your body uses fat for energy storage anyway, but by locating the fat in and beneath your skin, your body improves its heat retention. Furthermore, the presence of a fatty layer beneath your skin effectively thickens your skin and reduces the temperature difference across each unit of thickness. "Thick-skinned" people retain body heat better than those who are "thin-skinned."

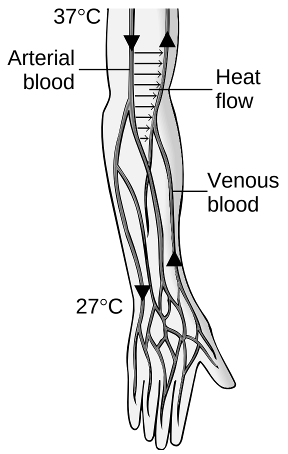

Fig. 6.5.1 - Blood flowing toward your hand through arteries exchanges heat with blood returning to your heart through veins. In this fashion, your blood is able to carry oxygen and food to your fingers without warming them all the way up to core body temperature. This adaptation reduces the rate at which you lose heat in cold weather.

Minimizing surface area means that your body is relatively compact, shaped more like a ball than a sheet of paper. Many other adaptive pressures have led to the evolution of arms, legs, and fingers that increase your total surface area. However, you have little superfluous surface through which to lose heat.

Finally, your body tries to lessen conductive heat loss by reducing the temperature difference between your skin and the surrounding air. It does this by letting your skin temperature drop well below your core body temperature. On a cold day, your hands and feet feel cold because they are cold. The colder they get, the less heat they lose to the cold air they touch.

Allowing your hands to become cold would be simple were it not for your circulating blood. Your blood must cool down from core body temperature as it approaches your cold fingers and must warm back up to core body temperature as it approaches your heart. This change in blood temperature occurs via a mechanism called *countercurrent exchange.* As the warm blood flows through arteries toward your cold fingers, it transfers heat to the blood returning to your heart through nearby veins (Fig. 6.5.1). The blood heading toward your fingers becomes colder while the blood returning to your heart becomes warmer.

CHECK YOUR UNDERSTANDING #2: Don’t Get Burned
You have been cooking ears of corn in a pot of boiling water and it’s time to fish them out. With which are you least likely to burn your hands: copper tongs or plastic tongs? (Copper has a much higher thermal conductivity than plastic.)

Retaining Body Heat: Convection

Heat leaving your skin warms the nearby air. How quickly the air’s temperature increases depends on how much air there is and on that air’s **specific heat capacity**; that is, the amount of heat it takes to warm one kilogram of air one degree Celsius (or Kelvin). The more air you are heating and the greater its specific heat capacity, the more heat it needs to warm one degree. The colder that air was to start with, the more heat you must give it to bring it to body temperature.

Different materials have different specific heat capacities. For example, it takes about 4 times as much heat to warm a kilogram of water one degree as it does to warm a kilogram of air one degree. This difference in specific heat capacities is part of the reason why you cool off faster swimming in cold water than standing in cold air. A material’s specific heat capacity reflects the number of ways in which thermal energy can exist in that material. Since the molecules in 1 kg of water have about 4 times as many ways to hold thermal energy as the molecules in 1 kg of air, adding a certain amount of heat to each raises air’s temperature about 4 times as much as it raises the water’s temperature.

Since air is a very poor conductor of heat, your skin warms only a thin layer of it. As long as this layer of air doesn’t move, its temperature will slowly approach that of your skin and the rate of heat flow from your body will decrease. Protected by this warm air, you will feel comfortable even on a cold day.

But air is rarely still. Convection gently removes the warmed air from your skin and replaces it with cooler air. With cooler air nearby, the temperature difference across your skin remains large and heat flows more quickly out through your skin. You feel cold. A wind worsens this heat loss because it blows away any warmed air near your skin. The enhanced heat loss caused by moving air is called *wind chill*—you feel even colder on a windy day.

To combat convective heat loss and wind chill, warm-blooded animals are covered with hair or feathers. Hair is itself a poor conductor of heat but its main purpose is to block airflow. Air passing through hair experiences large drag forces that slow its motion. In the dense tangle of a sheep's wool, air is trapped and can barely move at all. Since convection requires airflow, the sheep can only lose heat via conduction through the hair and the air. Since both are terrible conductors of heat, the sheep stays warm.

We humans have relatively little hair and are thus poorly adapted to living in cold, windy climates. Our lack of natural insulation is one of the reasons we wear clothing. Like hair and feathers, our clothing traps the air and reduces convection. Finely divided strands or filaments are particularly effective at stopping the flow of air. Not surprisingly, the best insulating clothing is made of hair (natural or synthetic) and feathers (also natural or synthetic). Since motionless air has a lower thermal conductivity than the hair or feathers that trap it, the ideal coat uses only enough material to keep a thick layer of air from moving.

This discussion also applies to water and swimming. If the water around you didn't move, you would soon be nice and warm. That's why some swimmers wear wet suits. The spongy material in a wet suit keeps the layer of water near the swimmer's skin from moving. As long it remains motionless, water is a respectable thermal insulator. This is evident in Fig. 6.5.2, where heating the top of a tube of water inhibits convection.

Fig. 6.5.2 - Convection only occurs if the hotter object is below or next to the colder object so that the heated fluid is able to rise. If you heat a tube of water near its top, the hot water stays near the top and the cold water remains at the bottom. Because water itself is a poor conductor of heat, the water at the top of the tube can boil while the bottom of the tube is cool enough to hold in your hand.

CHECK YOUR UNDERSTANDING #3: When a Cold Wind is Blowing

Why does wearing a thin, nylon wind breaker make such a difference in your ability to keep warm on a cool, windy day?

Retaining Body Heat: Radiation

You also exchange heat via radiation. Your skin emits electromagnetic waves toward your surroundings and they emit electromagnetic waves toward you. The amount of heat transferred by these waves depends on the temperature of each surface and on how well they absorb and emit light. The amount of heat radiated by a surface depends roughly on the fourth power of its temperature, measured in an absolute temperature scale, so that hotter objects radiate far more heat than colder objects.

As always, heat flows from the hotter object to the colder object. However, while conduction and convection transfer heat in proportion to the temperature difference between objects, radiation transfers heat in proportion to the difference between the *fourth powers* of their temperatures. That is why radiative heat transfer to or from your skin is most noticeable when you are exposed to an unusually hot or cold object.

The sun warms your skin quickly because it radiates more heat at you than the rest of your surroundings combined. Measured on an absolute temperature scale, the sun's surface temperature (6000 K) is about 20 times that of your skin (310 K). Though it's very distant and appears small to your eye, the sun radiates about 20^4 or 160,000 times as much heat toward you as you radiate toward it.

In contrast, the dark night sky cools you quickly because of its extremely low temperature. The mostly empty space beyond the earth's atmosphere is only a few degrees above absolute zero. When you stand in an open field at night, you radiate about a hundred watts of thermal power toward space but it radiates very little back toward you. Since you lose heat quickly, you feel cold. You can improve your situation by standing under a leafy tree. Even in cold weather, the tree is much hotter than space and emits far more thermal radiation. While the tree can't replace a crackling campfire, it will still help to keep you warm.

You might wonder why the air overhead doesn't radiate heat toward you to compensate for the heat you radiate toward the sky. The answer is that air is reasonably transparent to infrared light, absorbing and emitting relatively little of it. Only water vapor, carbon dioxide, and a few other gases in air interact with infrared light. Thus most of this exchange of energy by radiation is between you and empty space.

Not all surfaces absorb and emit thermal radiation well. A mirrored surface reflects thermal radiation while a white surface scatters it in all directions. Because they don't interact strongly with thermal radiation, they act as thermal insulators.

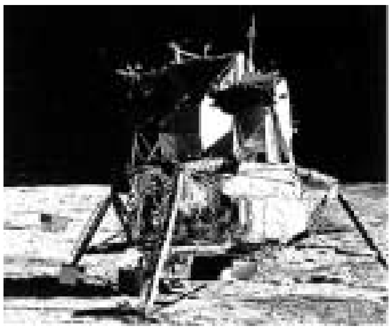

Fig. 6.5.3 - This Lunar Lander is wrapped in reflective foil to reduce its emissivity. As a result, it emits and absorbs relatively little thermal radiation.

A material's ability to absorb and emit thermal radiation is called its **emissivity**. A perfectly black object has an emissivity of 1, meaning that it absorbs all thermal radiation that hits it and emits thermal radiation of its own as efficiently as possible. A highly reflecting or purely white object will have an emissivity close to 0, meaning that it reflects or scatters almost all the thermal radiation that hits it and doesn't emit very much thermal radiation of its own (Fig. 6.5.3). Because most thermal radiation is infrared light, which we can't see, it's not always easy to guess an object's emissivity by looking at it. An object that is white or shiny to visible light may be nearly black to infrared light.

Because a larger surface has more opportunity to emit thermal radiation than a smaller surface, the heat an object radiates is also proportional to its surface area. We can combine that observation with our previous ones to obtain a single relationship between an object's temperature, emissivity, and surface area and the power it emits through thermal radiation. This relationship can be written as a word equation:

$$\text{radiated power} = \text{emissivity} \cdot \text{Stefan} - \text{Boltzmann constant} \cdot \text{temperature}^4 \cdot \text{surface area}, \tag{6.5.1}$$

in symbols:

$$P = e \cdot \sigma \cdot T^4 \cdot A,$$

and in everyday language:

You don't have to expose much warm skin to radiate away lots of heat. You do better to expose only the cool, light-colored surfaces of your clothes.

This relationship is called the **Stefan–Boltzmann law** and the **Stefan–Boltzmann constant** that appears in it has a measured value of $5.67 \cdot 10^{-8}\ \mathrm{J/(s \cdot m^2 \cdot K^4)}$. Remember that the temperature must be measured in Kelvin.

These issues of radiative heat transfer explain why we wear certain colors and why we are careful about exposing ourselves to the sun. On hot, sunny days, it makes sense to wear light colors and sit in the shade. Both actions reduce the amount of heat transferred to you by the sun. Light colored clothes have low emissivities, at least for visible light, so they don't absorb much sunlight. Sitting in the shade prevents the sun from exchanging heat with you directly.

Less obvious is the fact that white or reflective clothing also keeps you warmer in cold surroundings when there is no sun. Such clothing usually has a low emissivity in the infrared so that it doesn't radiate your body heat efficiently. Since you retain heat better in white or reflective clothing, you feel warmer. Highly reflective plastic blankets, found in emergency rescue kits, help to keep you warm in very cold surroundings by reducing the amount of heat you lose as thermal radiation.

CHECK YOUR UNDERSTANDING #4: Foil Wrapping

Wrapping a hot dish of food in shiny aluminum foil seems to keep it warm longer than wrapping it in clear plastic wrap. Aluminum is a good conductor of heat, so why does it impede the flow of heat so well?

CHECK YOUR FIGURES #1: The Cold of Deep Space

Suppose that an accident in the depths of space leaves you exposed to an environment near absolute zero. Since your surroundings radiate almost no heat toward you, you are losing heat fast. If your surface area is 2 m^2, your skin temperature is 310° K, and your emissivity is 0.5, how much power will you radiate?

Keeping Cool When It's Hot Outside

Slowing heat loss isn't always a good idea. If you retain heat too well, you will overheat. When exercising or on a very hot day, it may be necessary to encourage heat transfer to your surroundings by enhancing conduction, convection, or radiation.

You can increase conductive heat loss by moving into cold air or, even better, cold water. With a larger temperature difference across your skin, the rate of heat conduction through it will increase. You can increase convective heat loss by actively circulating the air or water with a fan or pump. The more cold air or water that directly touches your skin, the more heat you will lose. You can increase radiative heat loss by wearing black clothing while staying out of the sun. Actually, controlling radiative heat transfer is tricky, because even indirect sunlight can transfer heat to you. You may do better to avoid radiative heat transfer altogether by wearing white.

But what happens when you are put in an environment that is hotter than body temperature? If you are the coldest object around, you are going to get hotter and hotter. For a minute or two, insulating clothing can slow the rate at which your temperature rises so that you can pull a casserole from a hot oven or rescue a person from a fire. But even when you are perfectly insulated from your surroundings, your metabolism will cause your body temperature to rise. What does your body do to keep from overheating?

It sweats. By covering your skin with water, your body uses a new trick to eliminate heat. For water to evaporate, changing from a liquid to a gas, it needs energy. The molecules in liquid water are held together by chemical bonds that must be broken during evaporation. The energy that breaks these bonds is drawn from your body as heat. The faster the water evaporates, the more heat must flow out of your skin. Animals with hair can't sweat directly because there is little air circulation near their skin. Instead, these animals pant. Evaporation from their mouths and lungs draws heat from their bodies.

CHECK YOUR UNDERSTANDING #5: The Wind in Your Face

When you're traveling in a car on a warm day, opening the car windows cools you off. Explain.

Insulating Houses

The same techniques that keep people and animals warm are used to control heat flow in houses and household objects. However, because houses and their contents don't move much, they can make use of insulating methods that are heavy, bulky, rigid, or fragile. Let's take a look at some of the insulating schemes in the world around you.

The goal of housing insulation is to render a house's internal temperature effectively independent of the outside temperature. When it's cold outside, you want as little heat as possible to flow out of your warm house. When it's hot outside, you want as little heat as possible to flow into your cool house. So you or the builder fill its walls with insulating materials.

While there are many solid materials that are poor conductors of heat, including glass, plastic, hair, sand, and clay, the best insulator used in normal construction is air. Most modern buildings use air insulation. Unfortunately, air tends to undergo convection so it can't be used by itself. To prevent convection, air is trapped in porous or fibrous materials such as glass wool, saw dust, plastic foam, or narrow channels.

Glass wool or fiberglass is made by spinning glass into very long, thin fibers that are then matted together like cotton candy. Solid glass is already a poor conductor of heat but reducing it to fibers makes it even more insulating. The path that heat must take as it's conducted through the tangled fibers is very long and circuitous and very little heat gets through. Most of the volume in glass wool is taken up by trapped air. The glass fibers keep the air from undergoing convection so the air must carry heat by conduction.

Overall, glass wool and the air trapped in it are very good insulators. They also have the advantage of being nonflammable. In addition to its use in buildings, glass wool serves as insulation in ovens, hot water heaters, and many other machines that require nonflammable insulation. Most modern houses have about 10 cm to 20 cm of glass wool insulation built into their outside walls, along with a vapor barrier to keep the wind from blowing air directly through the insulation. (For a discussion of older insulating techniques, see Fig. 6.5.4.)

Fig. 6.5.4 - While stone is not a good conductor of heat, it's not nearly as good an insulator as air trapped in a fibrous mat. Medieval stone castles were notoriously cold in winter because heat flowed too easily out of them through their stone walls. The tapestry on the wall of this French Chateau slows the flow of heat to the outside air and helps to keep the room warm.

Because hot air rises and cold air sinks, the temperature difference between the hot air just below the ceiling and cold air just above the roof can become quite large. The ceiling/roof is thus a very important site of unwanted heat transfer and requires heavy insulation. Glass wool inserted between the ceiling and the roof of a new house may be more than 30 cm thick.

Fig. 6.5.5 - The best thermal insulators currently under study are tenuous materials called aerogels. These porous glassy structures are almost entirely air and resemble frozen smoke. There's hope that aerogels and other high performance insulators will dramatically improve the energy efficiencies of refrigerators and other machines.

While glass wool is a very good insulator, other materials are used in certain situations. Urethane and polystyrene foam sheets are both waterproof and better insulators than glass wool. Unfortunately, they are also flammable and relatively difficult to work with. Nonetheless, they are used in construction and are particularly well suited for refrigerators and coffee cups, where rigidity and flammability are not problems. (For an even better insulator, see Fig. 6.5.5.)

In older houses that were not insulated properly during construction, insulation can be blown into the walls or ceilings through holes drilled in the surfaces. As always, these insulators are porous or fibrous materials so that the main insulator is trapped air. Urea-formaldehyde foams are convenient for filling walls and ceilings because they can be pumped into cavities before they harden. However, concerns that they release toxic chemicals have reduced their appeal. Vermiculite and fireproofed cellulose chips are among the most common loose fill insulations.

CHECK YOUR UNDERSTANDING #6: Is More Always Better?
Glass wool insulation is easily compressed so that you can put two or three layers into the space that one layer will normally fill. To improve a building's insulation, why not pack as much glass wool insulation into the walls as possible?

Other Types of Insulation

While most household insulation revolves around air trapped in pores or around fibers, there are a few special circumstances in which finely divided materials just will not do. Windows have a special requirement that they must be transparent. They can't be filled with foam or fiberglass and solid glass is just not a good enough insulator.

The most common way to insulate windows is to use several panes of glass separated by narrow gaps of air or another gas. The air gaps prevent the easy conduction of heat from one side of the window to the other. While convection does occur in the air between the panes, their nearness creates tall, thin convection cells that are relatively ineffective at carrying heat from one side of the window to the other.

However, even a multiple-pane window transfers much more heat than a properly insulated wall. Glass conducts heat reasonably well and doesn't block radiative heat transfer completely. Shades and curtains not only block the view, they also reduce heat transfer through the window. Some energy efficient houses have special quilted shades that dramatically reduce this heat transfer.

A more sophisticated way to lower radiative heat transfer through a window is to use low-emissivity glass. This glass has a special coating to reduce the amount of infrared radiation it absorbs and emits. In effect, the glass acts like a mirror for infrared light. Coating the inner surfaces of a multipane window improves the window's insulating ability significantly because the panes exchange relatively little thermal radiation.

Food storage also depends on thermal insulations such as plastic foam and fiber mats. But if you try to keep food hot or cold for a very long time, you will find that even a fairly thick blanket of foam or fiber insulation will not be a sufficient barrier against heat transport. You do better with a glass or metal Thermos bottle, which makes use of a completely different technique of insulation: a vacuum.

A Thermos bottle is a consumer version of a Dewar flask, named after Sir James Dewar who invented it in the late 1800's. Instead of using air as insulation and inserting a tenuous material to prevent convection, a Thermos surrounds the food with a region that contains nothing at all, not even air (Fig. 6.5.6). In order to withstand atmospheric pressure, the Thermos has two strong walls. One wall surrounds the food and the other surrounds the first wall at a small distance. Since there is nothing between the two walls, there is no conduction and no convection. The two walls have mirror finishes so that they reflect thermal radiation and have very low emissivities. This mirroring dramatically reduces the radiative heat exchange between the walls. Since the only way heat can flow to or from the

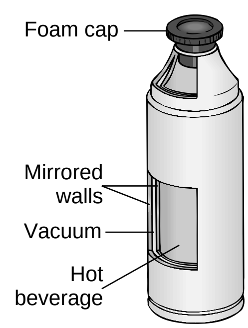

Fig. 6.5.6 - A Dewar flask or Thermos bottle uses a vacuum to insulate its inner volume. The vacuum can't conduct heat or undergo convection and mirrored walls reduce the role of radiative heat transport as well. The only significant heat transfer occurs through the narrow mouth of the vessel.

food is through its narrow mouth, a properly made Thermos bottle can keep food hot or cold for a remarkably long time.

Cookware itself presents an interesting challenge to manufacturers. An ideal pot should cook food evenly by conducting heat from the burner outside to the food inside. Its surfaces should be non-toxic, non-stick, chemically inert, and resistant to discoloration and abrasion. And its handles should stay cool.

Naturally, one material can't meet all these requirements. At their core, pots are usually made of a good conductor of heat, such as aluminum or copper. Pure stainless steel is a relatively poor conductor of heat and is not suitable for pots without help from aluminum or copper. To render them non-toxic, non-stick, inert, and resistant to discoloration and abrasion, pots are often coated with stainless steel, anodized aluminum, or a non-stick plastic such as Teflon or Silverstone. Their handles are typically made out of a heat resistant thermal insulator such as a durable plastic.

CHECK YOUR UNDERSTANDING #7: Keeping a Satellite Cool
How does a satellite in earth orbit eliminate the waste heat produced by its electronic components?

Bringing Fresh Air into a House

While it might seem ideal to block all movement of air into or out of a house, so as to prevent all heat transfer, a truly sealed house isn't very pleasant or healthy. Every smell will linger for weeks because it can't get out of the house. Older houses are drafty enough that the air inside is exchanged with outside air many times a day. But modern, energy efficient houses are nearly sealed and exchange air with the outside only a few times a day.

One way to deliberately exchange air but not heat with the outside is to use countercurrent exchange. Special ventilators are available in which entering and leaving air pass near one another on opposite sides of thin metal ducts. In such a ventilator, air entering a house is allowed to exchange heat with air leaving the house. By the time it reaches the inside, the entering air is almost at room temperature. In principle, very little heat should be exchanged with the outside by a countercurrent exchange ventilator. Unfortunately, this concept is hard to implement effectively and operating these ventilators often requires more energy than they save.

CHECK YOUR UNDERSTANDING #8: Good Things Take Time
For countercurrent exchange to work well, the air flowing in or out of the house must move slowly. Why?

Sound Insulation

Heat isn't the only thing that we try to keep from moving around. We often try to keep sounds and vibrations from moving from one room to another or from entering our homes in the first place. To reduce the movement of sound, we make use of acoustic insulation. To understand how acoustic insulation works, we need to have some idea of what sound it.

Sound is a mechanical disturbance that travels through a gas, liquid, or solid. As sound passes through a material, each particle in the material oscillates back and forth repetitively. Nearby atoms and molecules move in unison, creating regions of high and low density in the material. Although the atoms and molecules themselves don't move very far, the regions of altered density travel through the medium at the speed of sound. These compressed and rarefied regions contain energy and this energy also travels through the medium. We'll look further at mechanical waves and the energy that they carry in Chapter 7.

The most important measure of how sound travels in a material is its speed. The speed of sound is determined by how dense the material is and by how much it resists compression. The less dense a material is, the faster it can respond to pushes or pulls and the faster sound will travel through it. The more a material resists compression, the harder each region can push on its neighbors and the faster sound travels through it. While air has a low density, it's easily compressed and sound travels through it relatively slowly. The long delay between a lightening flash and the sound of thunder reflects the slow pace at which sound travels through air.

Because they are so resistant to compression, liquids and solids have very high speeds of sound. The speed of sound in a typical solid is about 25,000 km / h (about 5 miles-per-second). In general, the speed of sound is the fastest speed that any kind of mechanical signal can travel in the medium: vibrations, pressure changes, and even explosions. When dynamite is detonated, the explosion moves through the dynamite at its speed of sound.

So how do you stop sound from traveling through a material? You put several different materials in the path of the sound and make sure that the speeds of sound are different for the different materials. For example, a good way to stop sound from traveling from one room to the next is to insert several separate sheets of metal between the rooms. The sound will then have to travel through air, through metal, through air, ..., through air to get to the other room. Sound travels relatively slowly through air but relatively quickly through metal. Each time the sound must change its speed, a good fraction of it is reflected. By the time it gets to the second room, most of the sound will have been lost.

Why should changing the speed of sound lead to reflections? The answer is complicated and beyond the scope of this book. But the phenomenon is common throughout the physical world. Whenever a wave-like disturbance changes speed, part of it is reflected. For example, when light waves are made to travel through a material such as glass, they travel with a speed that is somewhat less than their speed in air or empty space. As a result, when light passes from air into glass or from glass into air, some of it is reflected.

Similar reflective effects occur when you use the wrong type of cable to connect your television to an antenna or to a cable network. Electric signals travel as electromagnetic waves in the cable and are affected by a characteristic of the cable known as its **impedance**. Impedance is related to the speed at which the waves move through the cable and is an important characteristic of that cable. Each time the signal traveling along a cable encounters a change in impedance, part of it is reflected. If the cable's impedance changes frequently along its length, the signal that arrives at your television will be contaminated by multiple reflections. These reflections reduce the quality of your reception.

The technical term for the abrupt change in impedance that occurs when two cables are improperly connected to one another is an **impedance mismatch**. An impedance mismatch in a cable creates a reflection. While the concepts of impedance and impedance mismatch were developed to describing the propagation of electric signals through cables, they are also appropriate to describing the movement of other waves through different media. An abrupt change in light's speed as it goes from air to glass is actually an impedance mismatch, as is a change in sound's speed as it goes from air to metal. In each case, part of the wave reflects.

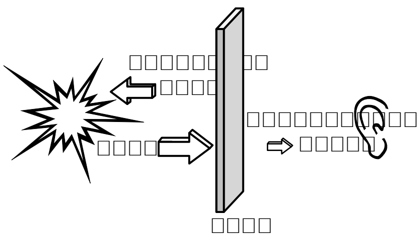

Fig. 6.5.7 - A dense wall provides a substantial amount of acoustic insulation because much of the sound on one side is reflected as it tries to enter the wall. Sound traveling in the wall is again mostly reflected as it tries to enter the air in the other room.

The reflections that occur at impedance mismatches are an important fact of life for electric, acoustic, and optical engineers. The coatings put on camera lenses try to reduce reflections by reducing the impedance mismatches. Wiring in radios, televisions, and computers is optimized to avoid impedance mismatches. And the very best way to stop sound from propagating from one region to another is to create terrible impedance mismatches in between.

In your home, the walls act as impedance mismatches. To move from one room to another, the sound has to go from the air in the first room, through all the surfaces inside the wall, and then into the air of the second room (Fig. 6.5.7). Because a typical wall has a hard surface on each side of a hollow space, sound passing through that wall must make at least four transitions between air and solid. Since the sound has a difficult time passing through each transition, only a small fraction of the sound passes through the wall. However, even a small hole in the wall spoils the insulating effect. To improve the insulation and make nearly sound-proof rooms, people use double sheet walls—placing two separate solid surfaces on each side of the wall, spaced by small air gaps, so that the sound has to go back and forth from air to solid a total of 8 times on its way through the wall. Very little sound gets through.

Of course, reflected sound can be a problem, too. If all that our walls did was reflect sound, every room in a house would sound like a tile bathroom or a Gothic cathedral—we would hear long echoes all the time. Fortunately, walls also absorb sound. Vibrations never last for ever because sound energy is turned into thermal energy sooner or later. In some materials, such as quartz or aluminum, sound energy stays nicely ordered for a long time. In other materials, such as cloth, foam rubber, or glass wool, sound energy is quickly turned into thermal energy. As sound causes the molecules in these latter materials to vibrate back and forth, they experience internal sliding frictional forces. This friction turns the ordered sound energy into disordered thermal energy. The walls of our homes usually have materials inside them to absorb sound energy and turn it into thermal energy. Together with the impedance mismatch effects, walls can be very good at acoustic insulation.

In situations where no actual acoustic insulation is possible or even desirable, such as a concert hall, sound absorbing materials are still important. A room that has only rigid walls will have terrible echo problems. After all, the sound will not enter the walls because of the impedance mismatch. Instead, it will reflect and bounce around the room for a long time. Designers of concert halls work hard to control reflection and absorption so as to obtain just the right mixtures of sounds (see ❐). No reflections make the hall sound dead, as though the music were being performed outside in a field. Too many reflections blur the sound until it becomes featureless. Though based on the science of reflection and absorption, the design of great concert halls still requires a great deal of artistry and skill.

❐ The design of a concert hall requires a careful balance between reflectivity and absorption. Because skin and clothing are fairly good at absorbing sound, a designer must consider the presence and location of the audience when planning the hall. The hall will actually sound different when there is a large audience present than it will when it's empty.

CHECK YOUR UNDERSTANDING #9:
How do earplugs and ear protectors reduce the volume of sound in your ears?

Electric Insulation

The last form of insulation that appears frequently in homes is electric insulation. To understand what electric insulation is, we must first have some idea of what electricity is—the movement of electrically charged particles. In house wiring, these charged particles are electrons. In materials such as metals, some of the electrons are free to roam around and move from one atom to the next. These mobile electrons are the conduction electrons and materials that have them are called **electric conductors**. The more conduction electrons a material has and the easier it is for them to move, the better the conductor. Many metals are excellent electric conductors. In addition to carrying electricity, conduction electrons carry most of the heat that travels through metals.

There are also many materials that have no free electrons—all of their electrons are localized near particular atoms or molecules and can't move around over long distances. Materials that don't have any conduction electrons and that are entirely incapable of moving electric charges from one region to another are called **electric insulators**. Most electric insulators are also poor conductors of heat. Without any conduction electrons to help speed the transfer, heat must be passed from atom to atom across the material.

Electric currents are discussed in much more detail in Chapters 8 and 9. For now, we'll simply note that the free movement of conduction electrons permits a material to transport energy. The electrons can have significant kinetic energies and they are very strongly attracted to particles of the opposite electric charge—remember the old adage that "opposites attract." If extra electrons are pumped into a piece of wire, they will try to find some way to leave. If you touch the wire, some of them will enter you. If you provide a path for them to leave you, you will find that you have electrons flowing through your body and if a lot of electrons flow through your body, you are in trouble.

Fortunately, your skin is an electric insulator. When you touch the terminals of a household battery (1.5 volt or 9 volt), so little electricity flows through your skin that you aren't likely to feel anything special. But if you touch the two terminals of a 9 volt battery with your tongue, you will feel a very strong, unpleasant sensation. Your saliva, like most of the fluids inside your body, is a moderately good conductor of electricity. Even water, a relatively poor conductor of electricity, is less insulating than your skin. It's only your skin itself that protects you against shocks from batteries.

But even your insulating skin isn't adequate protection against household electric power. To keep electrons from flowing out of the wires and all through your home and your body, the wires are always coated with electrically insulating materials. Electric insulation keeps the electric power where it belongs. The electrons are forced to travel only through the wires and through devices that expect electric currents.

CHECK YOUR UNDERSTANDING #10:
Why is it dangerous to use a hair dryer while soaking in the bathtub?