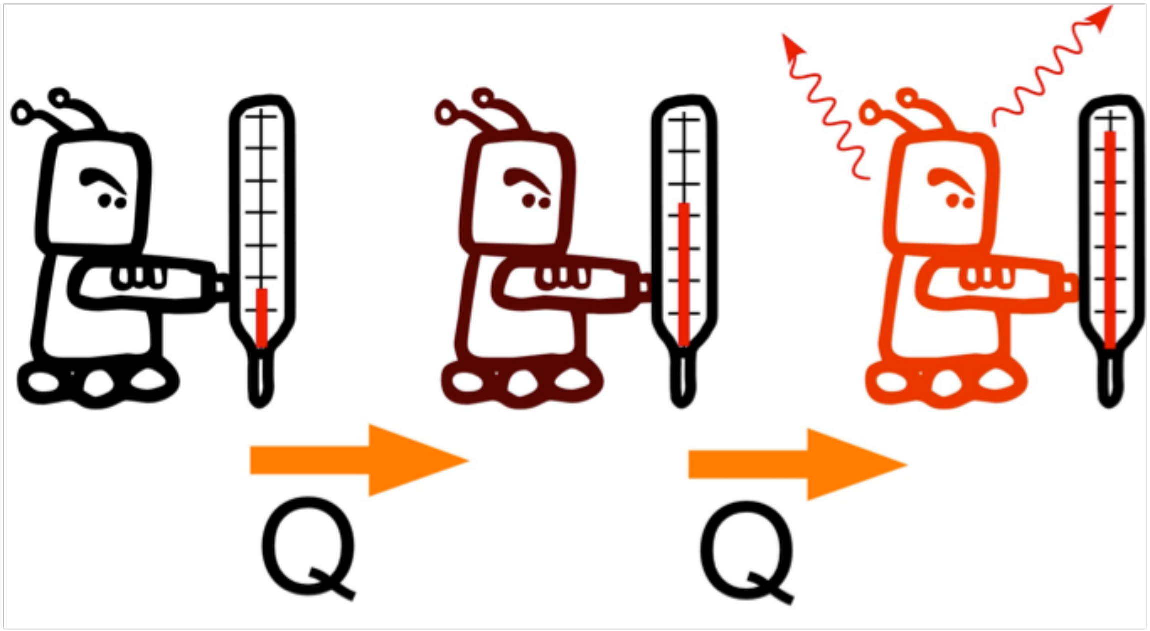


Unit 7.
Thermal Energy

Primary Authors:

Meera Chandrasekhar and Dorina Kosztin

Department of Physics and Astronomy, University of Missouri, Columbia, MO

A TIME for PHYSICS FIRST

Funded by the National Science Foundation, 2009-14

Mathematics and Science Partnership Institute Grant NSF DUE 0928924

Reading Page: Thermal Energy and Temperature

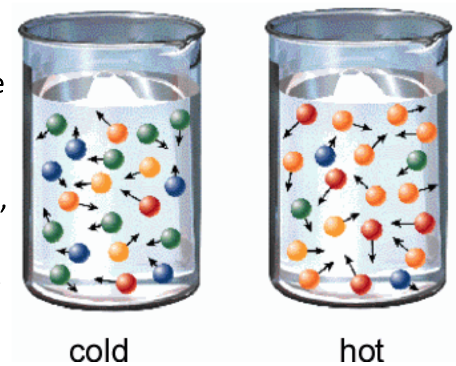
So what is the difference between thermal energy and temperature? What actually is the difference between water at 20°C and water at 50°C? How are these questions related? Can any one hypothesis answer both questions?

We are all familiar with the idea of temperature. You hear the word used nearly every day. But just what does temperature measure? For example, mass is a measure of the amount of substance in a system. Velocity is a measure of how fast a system moves. What physical property of the system does one determine by measuring its temperature?

The Particle Theory

Scientists over the years came up with many hypotheses, to explain the difference between thermal energy and temperature. One such hypothesis was suggested by Lavoisier. He suggested that thermal energy might be a substance (with mass) that he called caloric. But Lavoisier's idea was not supported by experimental observations.

Scientists now use the kinetic molecular theory, or particle theory, to explain thermal energy and temperature and the difference between, say, 20°C and 50°C. The particle theory is based on a model that suggests that all matter is made up of tiny particles too small to be seen with the naked eye. According to this model, these particles are always moving- therefore they have kinetic energy. The faster they move, the more kinetic energy they have. The sum of the kinetic energy of all particles in a system is called the thermal energy of the system.



Both hot and cold water are made up of moving particles; in hot water particles move faster and in cold water they move slower. Temperature increases as the kinetic energy increases. Temperature is a measure of the *average kinetic energy* of the system.

If we have <u>equal masses</u> of hot water and cold water, the hot water has more thermal energy than cold water or we can also say that hot water has a higher temperature than cold water. However, two cups of water at 50C, has more total thermal energy than one cup of water at 50C, even though their average kinetic energy is the same.

When two objects with different temperatures (or thermal energies) are placed in contact with each other, energy is transferred from the higher temperature object to the lower temperature object. *The transfer of energy due to a difference in temperature between the two objects is called heating*. The amount of energy transferred is called heat.

Now we can see the difference between temperature and heating:
temperature is a physical quantity that measures the degree of thermal energy, and heating is an energy transfer process.

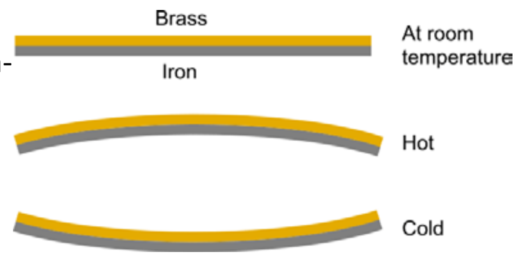
Thermometers and Temperature Scales

But how does one measure the temperature of a system? This is what a thermometer does. A thermometer can be any small macroscopic system that undergoes a measurable change as it heats up when placed in contact with a warmer object.

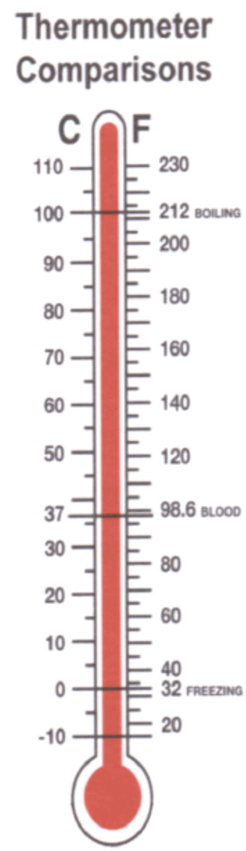
In a common glass-tube thermometer, for example, a small volume of mercury or alcohol expands or contracts when placed in contact with a "hot" or "cold" object. The object's temperature is determined by the length of the column of liquid.

Other thermometers include:

- Bimetallic strips (two strips of different metals sandwiched together) that curl and uncurl as the temperature changes. These are used in thermostats, such as the one in your house.
- Thermocouples generate a small voltage depending on the temperature. Thermocouples are widely used for sensing temperatures in inhospitable environments, such as in your car's engine.



A thermometer needs a temperature scale to be a useful measuring device. In 1742, the Swedish astronomer Anders Celsius sealed mercury into a small capillary tube and observed how it moved up and down the tube as the temperature changed. He selected two temperatures that anyone could reproduce, the freezing and boiling points of pure water, and labeled them 0 and 100. He then marked off the glass tube into one hundred equal intervals between these two reference points. By doing so, he invented the temperature scale that we today call the Celsius scale. The units of the Celsius temperature scale are "degrees Celsius," which we abbreviate °C. Note that the degree symbol is part of the unit, not part of the number. (Note: Because of the 100 equal intervals, the Celsius scale is also called the centigrade scale.)



The Fahrenheit scale, still widely used in the United States, is related to the Celsius scale by

$$T_F = \frac{9}{5}T_C + 32° \quad \text{or} \quad T_C = \frac{5}{9}\left(T_F - 32°\right)$$

In this scale, the freezing point of water is at 32 °F and the boiling point of water is at 212 °F. You might want to research the history of why Fahrenheit used these numbers.

Scientists use the Kelvin temperature scale, where the scale begins at absolute zero: $T_K = T_C + 273.15$

Definitions:

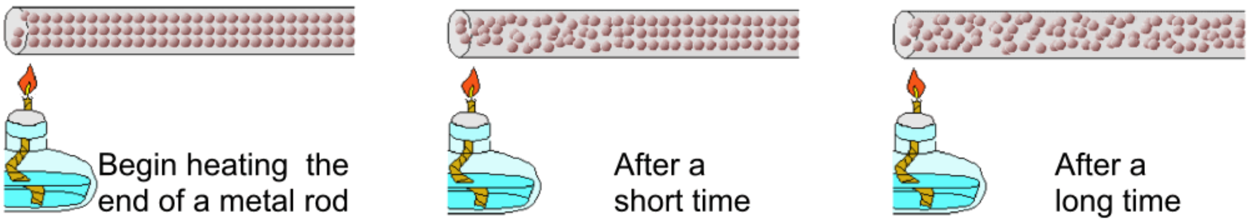
Thermal energy = energy of a system at a particular temperature

Heat energy is denoted by Q, measured in units of joules [J].

Temperature is denoted by T, measured in units of ˚C, ˚F or K.

Reading Page: Conduction

Heating (transfer of energy) can take place through three methods: *conduction, convection* and *radiation*. *<u>Conduction</u>* is the process where energy is transferred through *<u>direct contact</u>* with an object. Energy is transferred from the hot side of the object to the cold side through the vibrations of the atoms (see the figures below). Metals conduct energy well, while insulators do not. It is more correct to say that metals transfer energy quickly, while insulators are extremely slow. The key, then, is to figure out how <u>fast</u> energy is transferred. (We will get to the other two methods in a bit).

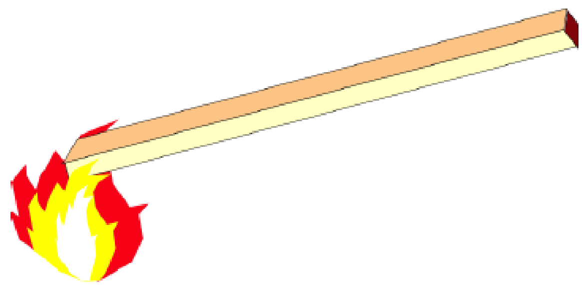


From: http://www.kangwon.ac.kr/~sericc/sci_lab/physics/conduction/conduction.html
Also visit http://www.spaceflight.esa.int/impress/text/education/Heat Transfer/Conduction 01.html for animations

The energy transfer rate H, is the energy transferred per second, given by the heat Q (in Joules), divided by the time taken Δt (in sec):

$$H = \frac{Q}{\Delta t}$$

$$\text{Units}: [H] = \frac{\text{Joules}}{\text{sec}}$$



Here's what decides the energy transfer rate:

- The energy transfer rate depends on <u>how long</u> the object is (length L): if the rod is long, it takes a long time to reach the other end (H is small); if it is short, thermal energy is transferred fast (H is large).

  H is inversely proportional to L: $H \propto \frac{1}{L}$

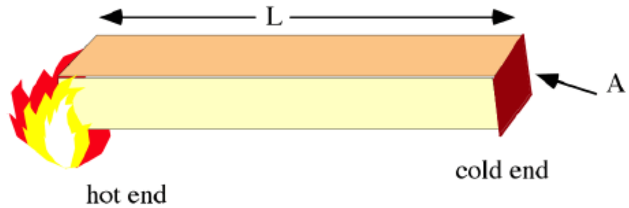
- The energy transfer rate depends on the <u>cross sectional area A</u>: if the rod is fat, energy reaches the other end quickly; if it is skinny, heat is transferred slowly.
  H is proportional to A: $H \propto A$

- The energy transfer rate depends on the <u>temperature difference</u> between the hot and the cold end, $\Delta T = T_{hot} - T_{cold}$. if the temperature difference is large, the cold end will warm up faster, which means that the energy transfer rate is large
  H is proportional to ΔT: $H \propto \Delta T = T_{hot} - T_{cold}$

- Finally, the energy transfer rate depends on the <u>material used</u>: a good conductor will transfer heat fast, while a poor conductor (insulator) will transfer heat slowly. This characteristic is described by a property called the *thermal conductivity of the material,*
  H is proportional to the thermal conductivity, k: $H \propto k$

Putting all these variables together, the energy transfer rate can be summarized by the equation:

$$H = kA\left[\frac{T_{hot} - T_{cold}}{L}\right]$$



The units for the energy transfer rate H is Joules/sec (or Watts).

The unit for k is $\frac{\text{Joules}}{(\text{sec}).(\text{meter})(°\text{C})}$

where A is in square meters, L is in meters, and the temperatures T_{hot} and T_{cold} are in ˚C.

Example 1:

A copper rod is 10 cm long. Its hot end is at 80°C and the cold end is at 30°C. A second copper rod of the same dimensions has its hot end at 80°C but its cold end at 5°C. Would there be any difference in how fast energy travels down the two rods?

Answer: Yes, there would. Although both rods are identical in size, and have their hot ends at the same temperature, their cold ends are at different temperatures. Remember,

The heat transfer rate *H is proportional to* ΔT: $H \propto \Delta T = T_{hot} - T_{cold}$

The temperature difference $\Delta T = T_{hot} - T_{cold}$ for the first rod is (80-20)= 60°C.

For the second rod, $\Delta T = T_{hot} - T_{cold}$ is (80-5) = 75°C

The rate of energy transfer depends on the temperature difference between the two ends, so the energy transfer rate is higher (that is, thermal energy transfer occurs faster) for the second rod than for the first.

Example 2:

A bent copper rod is 10 cm long. Its ends are placed in two cups. The hot cup is at 80°C and the cold cup is at 30°C. A second copper rod with half the radius (one quarter the cross sectional area) is placed with its ends in the same cups. Would there be any difference in how fast energy travels down the two rods?

Answer: Yes, there would. Although both rods have their ends in the same pair of hot and cold cups, the second rod has a quarter of the cross sectional area, so thermal energy travels down it slower than through the fatter rod. Remember,

The heat transfer rate *H is proportional to* A: $H \propto A$

The rate of thermal energy transfer (in J/sec) is 4 times slower for the second (skinnier) rod.

Example 3.

Two serving spoons are placed in a hot bowl of soup. Both are made of the same material, and their handles have the same thickness, but are different lengths. Spoon A has 10 cm of its length sticking out of the pot, while spoon B has 20 cm sticking out. Would there be any difference in how fast thermal energy travels up the two rods?

Answer: Yes, there would. Since spoon A is half as short as spoon B, thermal travels up it faster than through the longer rod. Remember,

The heat transfer rate *H is inversely proportional to L:* $H \propto \frac{1}{L}$

The rate of heat transfer (in J/sec) is 2 times faster for the first (shorter) rod.

Thermal conductors and Insulators:

Just as some materials are good conductors of electricity (usually called conductors) and others are poor conductors of electricity (called insulators), materials can also be classified as thermal conductors and thermal insulators. In fact, it turns out that many materials that are conductors of electricity are also thermal conductors.

The thermal conductivity of a material determines whether it is a thermal conductor or insulator. The larger the thermal conductivity k, the better the conductor. The table below lists values of K in units of J/sec.m.˚C for several materials.

Thermal Conductors		Thermal Insulators	
Material	**k in J/s.m.˚C)**	**Material**	**k in J/s.m.˚C**
Stainless Steel	17	Air	0.024
Iron	80	Styrofoam	0.033
Brass	120	Fiberglass	0.045
Gold	315	Snow	0.05
Copper	385	Wood	0.04-0.17
Silver	410	Glass	1.0
Diamond (natural)	2200	Concrete	1.0

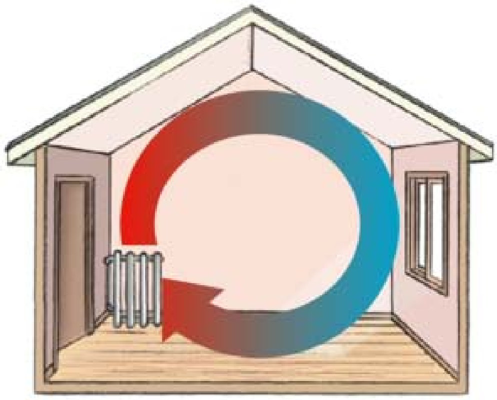
Example 4.

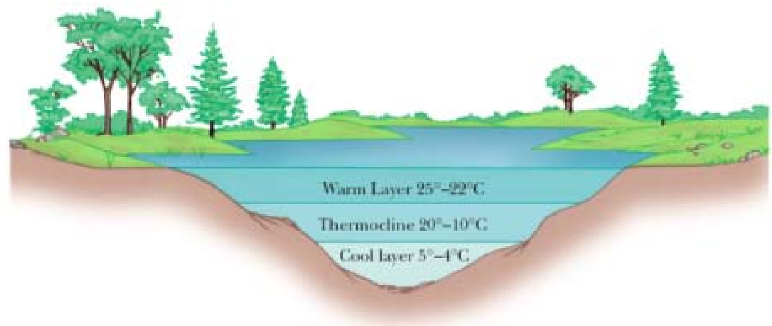
Two teaspoons are placed in a hot cup of chocolate. One spoon is made of silver, the other of stainless steel. Which spoon's handle gets hot quicker?

Answer: Silver conducts heat up the handle faster than the stainless steel, so the silver gets hot faster. Remember,

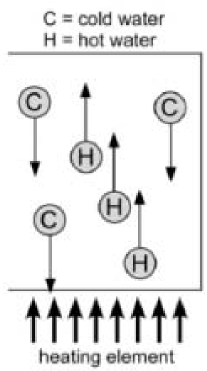
The heat transfer rate *H is proportional to the thermal conductivity, k:* $H \propto k$

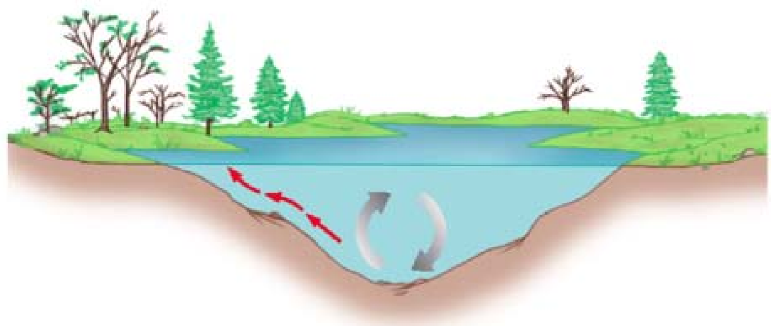
Reading Page: Convection





(a) Summer layering of water





(b) Fall and spring upwelling

Convection is the flow of energy through a movement of matter from a hot region (at high temperature) to a cool region (at low temperature), as opposed to the microscopic transfer of energy between atoms as in conduction. Suppose we consider heating a local region of air. As this air heats, the molecules spread out, causing this region to become less dense than the surrounding, unheated air. Being less dense, the hot air will then rise. When it rises, it cools of and falls down again. This movement of hot air into a cooler region is called heating by *convection*.

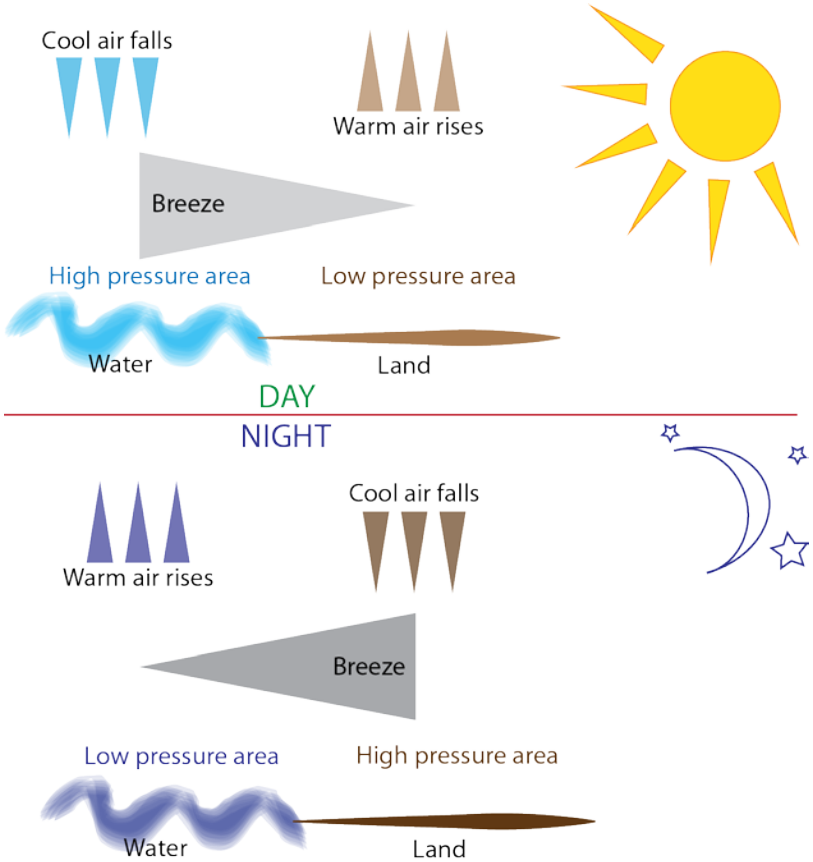
Heating a pot of water on a stove is a good example of heating by convection. When the stove is turned on, energy is first transferred by conduction from the heater, through the bottom of the pot, to the water. However, eventually the water starts bubbling - these bubbles are actually local regions of hot water rising to the surface, transferring energy from the hot water at the bottom to the cooler water at the top by convection. At the same time, the cooler, more dense water at the top will sink to the bottom, where it is subsequently heated. These convection currents are illustrated in the figure at right.

Convection is used in modern baking ovens. In a conventional oven, a thin layer of stable air surrounds and insulates the food, which slows the cooking process. Also, the hot air generated by the heating element in the oven rises to the top of the oven, making it hard to evenly cook more than one rack of food. In a convection oven a small fan is used to blow air around the inside of the oven. By moving air over and around the food, convection ovens lower the amount of time it takes for it to cook.

Wind chill is another example of convection: on a cold, blustery day the fast-moving air steals heat away from our bodies, lowering body temperatures and causing us to feel colder than we would in calmer conditions.

Convection and Weather

An important example of convection currents is the creation of breezes over land masses next to large bodies of water. It takes more energy to warm up water than it takes to warm up land. During the day, when the sun provides energy at the same rate to the land and the nearby sea, the water heats up less than the land, and the air above the water will be cooler than that over the land. This creates a low-pressure area over the land, relative to the high-pressure area over the water, and therefore breezes blow from the water to the land. On the other hand, during the night water cools off more slowly than the land, and the air above the water is slightly warmer than over the land. This creates a low-pressure area over the water relative to the high-pressure area over the land, and breezes will now blow from the land to the water. These are illustrated in the following figure.



Reference: http://theory.uwinnipeg.ca/mod_tech/node76.html

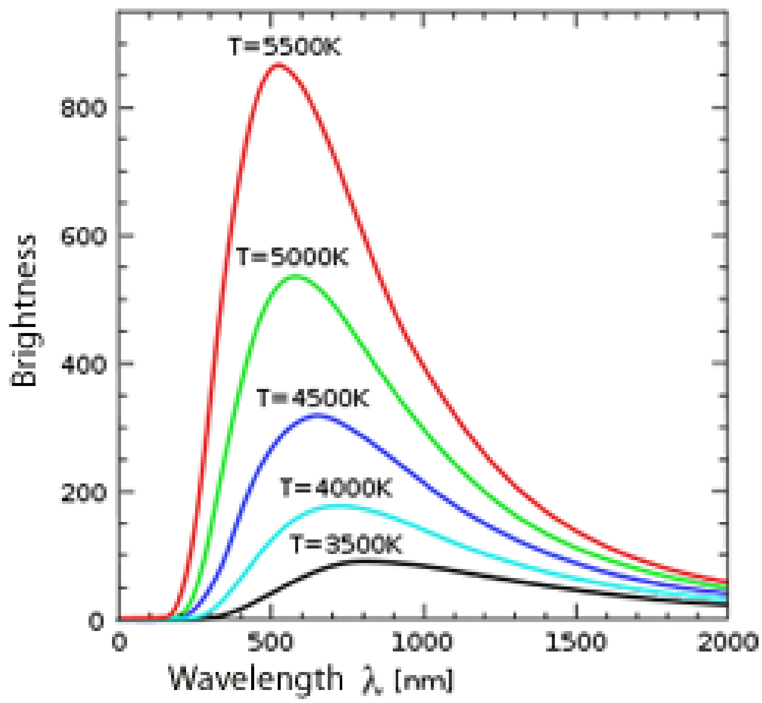
Reading Page: Radiation

Light from the sun passes through space, and then through the Earth's atmosphere. It brings energy from the sun to warm the Earth's surface. This energy does not pass through the atmosphere by conduction, since air is a poor conductor. Nor does it pass through by convection, since convection begins only after the Earth is warmed. We also know that neither convection nor conduction is possible in the empty space between the sun and our atmosphere because there is no matter. The sun's energy must be transmitted some other way -- and that method is called radiation. *Radiation is a heating mechanism that takes place through electromagnetic waves.*

The sun produces energy through a nuclear reaction where hydrogen atoms are converted into helium. This reaction takes place inside of the sun. The surface of the sun is cooler than the inside, but is still at a temperature of about 5500˚C. The energy from the surface leaves the sun through electromagnetic waves. These waves have a range of wavelengths, with most of the energy being in the ultraviolet, visible light and infrared wavelengths.

The "color" of radiation

What decides the mix of wavelengths? It turns out that the intensity (brightness) of the radiation, and the range of wavelengths depends on the temperature of the object. Moreover, it is not only the hot sun that emits electromagnetic waves (also called electromagnetic radiation, or just radiation, for short). All objects emit electromagnetic radiation, because they are hot to one degree or another. As the object gets hotter, it emits more (or is brighter). The wavelength at the peak of the emission shifts more and more toward shorter wavelengths. The spectral curve (brightness vs. wavelength) for objects at several temperatures is shown in the figure. Notice that we don't say what the object is made of, all that is defined is the object's temperature. That's because it does not matter what the object is made of, only its temperature defines the emission curve.



http://en.wikipedia.org/wiki/Wien%27s_displacement_law

A perfect radiating body emits energy in all possible wavelengths, but the wave energies are not emitted equally in all wavelengths; a spectrum will show a distinct maximum in energy at a particular wavelength depending upon the temperature of the radiating body. As the temperature increases, the maximum radiation occurs at shorter and shorter wavelengths. The hotter the radiating body, the shorter the wavelength of maximum radiation. For example, a very hot metal rod will emit visible radiation and produce a white glow. On cooling, it will emit more of its energy in longer wavelengths and will glow a reddish color. Eventually no light will be given off, but if you place your hand near the rod, the infrared radiation will be detectable as heat.

It turns out that there is a simple law that defines the relationship between the peak wavelength of emission and the temperature of the object. This law is called Wien's Law, which states that , λT = constant, where λ is the wavelength at the peak of the curve in nm, and T is the temperature in K and the constant is = 3 x10^6 nm K

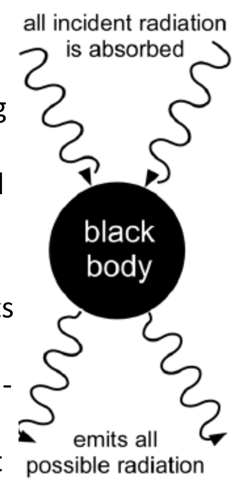
Examples of emission from hot objects

The Sun has a surface temperature, or more correctly, an effective temperature, of 5778 K. This temperature corresponds to a peak emission at a wavelength of 500 nm or 5000 Å. This wavelength is (not by accident) nearly in the middle of the most sensitive part of the range of vision of most land animals (including humans). Even nocturnal and twilight-hunting animals must sense light from the waning day and from the moon, which is reflected sunlight with this same wavelength distribution. Also, the average wavelength of starlight is in this region, since the sun is in the middle of a common temperature range of stars.

Light from incandescent bulbs and fires glow at somewhat lower temperatures, resulting in yellow light. Something that is "red hot" has even lower temperatures. A wood fire at 1500 K puts out peak radiation at 2000 nm = 20,000 Å.

Mammals and the living human body also emit radiation. Mammals at roughly 300 K (27 C) emit peak radiation at 10 μm, in the far infrared. This is therefore the range of infrared wavelengths that pit viper snakes and infrared cameras sense.

Emission and Absorption



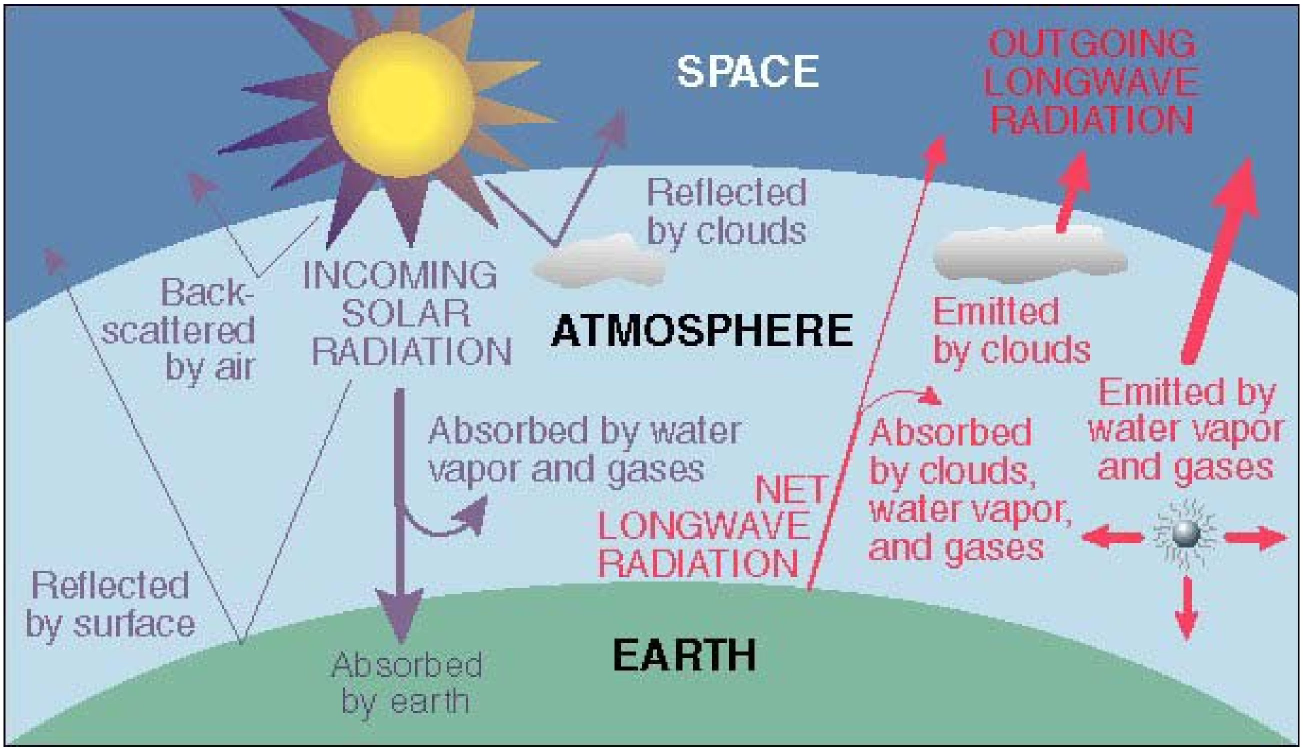
When radiant energy encounters an object, it is partly reflected and partly absorbed. The part that is absorbed increases the thermal energy of the object. If this object happens to be your skin, you feel the radiation as warmth. If everything is emitting energy, why doesn't everything finally run out of it? The answer is, everything is also absorbing energy. Good emitters of radiant energy are also good absorbers; poor emitters are poor absorbers.

Every surface, hot or cold, both absorbs and emits radiant energy. If the surface absorbs more than it emits, it is a net absorber and its temperature rises. If it emits more than it absorbs, it is a net emitter and its temperature drops. Whether a surface plays the role of net emitter or net absorber depends on whether its temperature is above or below that of its surroundings. If it's hotter than its surroundings the surface will be a net emitter and will cool. If it's colder than its surroundings, it will be a net absorber and will become warmer.

Absorption and reflection are opposite processes. A good absorber of radiant energy reflects very little radiant energy, including visible light. Hence, a surface that reflects very little or no radiant energy looks dark. So a good absorber appears dark and a perfect absorber reflects no radiant energy and appears completely black. The pupil of the eye, for example, allows light to enter with no reflection, which is why it appears black. (An exception occurs in flash photography when pupils appear pink, which occurs when very bright light is reflected off the eye's inner pink surface and back through the pupil.)

Good reflectors, on the other hand, are poor absorbers. Clean snow is a good reflector and therefore does not melt rapidly in sunlight. If the snow is dirty, it absorbs radiant energy from the sun and melts faster. Dropping black soot from an aircraft onto snow-covered mountains is a technique sometimes used in flood control. Melting can be controlled and made to occur at convenient times rather than have a sudden runoff of melting snow if spring temperatures warm up quicker than expected.

Light-colored buildings stay cooler in summer because they reflect much of the incoming radiant energy. Light-colored buildings are also poor emitters, and so they retain more of their internal energy than darker buildings and stay warmer in winter. Paint your house a light color if you live in a place with hot summers and cold winters!



Source: USGS http://geochange.er.usgs.gov/pub/carbon/fs97137/

Reading Page: Specific Heat and Thermal Expansion

Specific Heat:

You might have noticed that some foods remain hotter much longer than others do. If you take a piece of toast from a toaster and pour hot soup into a bowl at the same time, a few minutes later the soup is still pleasantly warm while the toast has cooled off. Similarly, if you wait a short while before eating a slice of pizza, the sauce, the cheese and the bread crust are not at the same temperature, though they were when they came out of the oven.

Different substances have different capacities for storing thermal energy. If we warm a pot of water on a stove, we might find that it requires 15 minutes to raise its temperature from room temperature to its boiling temperature (100 C). But if we put an equal mass of iron on the same flame, we will find that it rises to 100 C in only about 2 minutes. For silver, the time would be less than a minute. Different materials require different quantities of energy to raise the temperature of a given mass of the material by a specified number of degrees.

A property of the material called the specific heat determines how much energy must be added to raise the temperature of 1 kg of the substance by 1˚C. This property is called specific heat. Copper requires 385 J, silver 233 J, iron 450 J and water needs a whole lot more: 4180 J. This explains why it takes so much more energy to warm water to 100˚C in comparison to iron.

The specific heat of a few common substances:	
Material	**Specific heat (**J/kg˚C)
Copper	385
Silver	233
Iron	450
Water	4180
Aluminum	910
Brass	377
Zinc	390
Lead	130

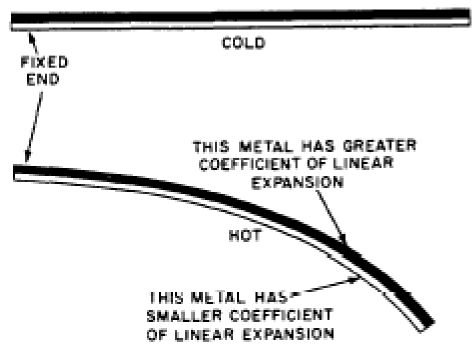
Thermal Expansion:

When the temperature of a substance is increased, its molecules or atoms jiggle faster and move farther apart, on the average. The result is an expansion of the substance. With few exceptions, all forms of matter—solids, liquids, gases, and plasmas—generally expand when they are heated and contract when they are cooled.

In most cases involving solids, these changes in volume are not very noticeable, but careful observation usually detects them. Telephone wires become longer and sag more on a hot summer day than they do on a cold winter day. Metal lids on glass jars can often be loosened by heating them under hot water. If one part of a piece of glass is heated or cooled more rapidly than adjacent parts, the resulting expansion or contraction may break the glass, especially if the glass is thick.

The expansion of substances must be allowed for in structures and devices of all kinds. A dentist uses filling material that has the same rate of expansion as teeth. A civil engineer uses reinforcing steel of the same expansion rate as concrete. Long steel bridges commonly have one end fixed while the other rests on rockers. The Golden Gate Bridge in San Francisco contracts more than a meter in cold weather. The roadway itself is segmented with tongue-and-groove type gaps called expansion joints. Similarly, concrete roadways and sidewalks are intersected by gaps, sometimes filled with tar, so that the concrete can expand freely in summer and contract in winter.

Different substances expand at different rates. When two strips of different metals, say one of brass and the other of iron, are welded or riveted together, the greater expansion of one metal results in the bending shown. Such a compound thin bar is called a bimetallic strip. When the strip is heated, one side of the double strip becomes longer than the other, causing the strip to bend into a curve. On the other hand, when the strip is cooled, it tends to bend in the opposite direction, because the metal that expands more also shrinks more. The movement of the strip may be used to turn a pointer, regulate a valve, or close a switch.



(Figure from http://www.tpub.com/fluid/ch2t.htm)

Liquids expand appreciably with increases in temperature. In most cases the expansion of liquids is greater than the expansion of solids. The gasoline overflowing a car's tank on a hot day is evidence for this. If the tank and contents expanded at the same rate, they would expand together and no overflow would occur. Similarly, if the expansion of the glass of a thermometer were as great as the expansion of the mercury, the mercury would not rise with increasing temperature. The reason the mercury in a thermometer rises with increasing temperature is that the expansion of liquid mercury is greater than the expansion of glass.

One of the anomalies is the expansion of water. If one cools water down from 100^{o}C, it contracts until it reaches a temperature of 4^{o}C. Between 4^{o}C and 0^{o}C, it actually *expands*. When it becomes ice at 0^{o}C it expands some more, by about 8%. This is why we leave a little "head room" for expansion if we want to freeze a bottle of water. If we don't allow space for expansion, the forces are so large that the bottle might break when it freezes.