Answer to Essential Question 13.5: A whole range of masses of ice can produce a mixture with a final temperature of 0°C. The mixture could be all liquid, as in Exploration 13.5, but by increasing the mass of the ice we could have some ice left, all the ice left, some liquid solidifying, or even all the liquid solidifying. We get such a range because the final temperature is 0°C, the temperature of the phase change. This issue is explored further in end-of-chapter exercise 45.

13-6 Energy-Transfer Mechanisms

Let's investigate in more detail the mechanisms by which energy is transferred when there is a temperature difference. In Exploration 13.5, we did not concern ourselves with exactly how energy is transferred from the burner through the pot to the water. That process is known as thermal conduction. Two other important energy-transfer processes are convection and radiation. Let's first discuss those two processes qualitatively, and then discuss conduction in more detail.

Convection

Energy transfer in fluids generally takes place via convection, in which flowing fluid carries energy from one place to another. Convection currents are produced by temperature differences. Hotter (less dense) parts of the fluid rise, while cooler (more dense) areas sink. Birds and gliders make use of upward convection currents to rise, and we also rely on convection to remove ground-level pollution. Forced convection, where the fluid is forced to flow, is often used for heating (e.g., forced-air furnaces) or cooling (e.g., fans, automobile cooling systems).

Thermal Radiation

Thermal radiation involves energy transferred via electromagnetic waves. Often this is infrared radiation (which we can detect with the backs of our hands), but it can also be visible light or radiation of higher energy.

All objects continually absorb energy and radiate it away again. When everything is at the same temperature, the amount of energy received is equal to the amount given off and no changes in temperature occur. If an object emits more than it absorbs, though, it tends to cool down unless some other process replenishes its energy. For an object with a temperature *T* (in Kelvin) and a surface area *A*, the net rate of radiated energy P_{net} depends strongly on temperature:

$$P_{net} = P_{radiated} - P_{absorbed} = A\varepsilon\sigma\left(T^4 - T_{env}^4\right),$$ (Equation 13.12: **Net radiated power**)

where T_{env} is the temperature of the surrounding environment; *A* is the object's surface area; the Stefan-Boltzmann constant has a value $\sigma = 5.67\times10^{-8}\ \mathrm{W/m^2}$; and ε is the emissivity, which depends on the object. If an object readily absorbs or emits radiation, its emissivity is close to 1 (if it is exactly 1 the object is a **perfect blackbody**); if an object is highly reflective and does not absorb (or emit) radiation readily, its emissivity is close to 0. The best absorbers are also the best emitters. Black objects heat up faster than shiny ones, but they cool down faster too.

Thermal Conduction

Thermal conduction involves energy being transferred from a hot region to a cooler region through a material, without a net flow of the material. At the hotter end, the atoms, molecules, and electrons vibrate with more energy than they do at the cooler end. The energy flows through the material, passed along by these vibrations. One thing the rate at which energy is conducted through a uniform slab of material depends on is the temperature difference between the two faces of the slab. The rate of energy transfer is directly proportional to the temperature difference. Let's examine other contributing factors.

EXPLORATION 13.6 – The house beside the ice factory

You're planning to build a house, so you buy a small plot of land that is right next to a factory that makes ice. To get maximum use out of your land, one wall of your house will be built against the wall of the ice factory, where the ice is stored at –20°C. This might help keep your house cool in the summer, but you're more worried about staying warm in the winter.

Step 1 - ***You plan to build a rectangular house. To minimize the rate at which energy is transferred from inside your house, at +20°C, to the ice factory in the winter, should you place a large-area wall or a small-area wall of your house against the wall of the ice factory? Why?*** Imagine drawing a grid of equal-area squares on the wall. The more squares you have (that is, the larger the area of the wall), the more heat is transferred. To minimize your heat transfer, you need to minimize the wall area, because the rate of heat transfer is proportional to the area, A.

Step 2 – ***You put a layer of insulating material in the walls of your house. To be most effective, should the material be thin or thick?*** The thicker the insulation, the lower the rate of heat transfer. The rate of heat transfer is inversely proportional to L, the thickness of the insulation.

Step 3 – ***While shopping at Insulation World you notice that they have slabs of copper on sale for 10% less than the slabs of Styrofoam insulation you intended to buy. Check the thermal conductivity of these materials in Table 13.5 below. Should you save 10% and buy the copper?*** Absolutely not! The larger the thermal conductivity, the more effectively the material transfers heat. This is why copper is used in the base of pots and pans, efficiently transferring heat through the pot to the food. In insulating your house, however, you want to minimize the rate of heat transfer, so choose the material with the lowest thermal conductivity you can find.

Key idea: The rate at which heat is transferred (i.e., the power, P) through a slab of area A, thermal conductivity k, and thickness L is $P = \frac{k\,A}{L}(T_H - T_L)$. (Equation 13.13)

T_H is the temperature at the higher-temperature face of the slab, while T_L is the temperature at the lower-temperature face. **Related End-of-Chapter Exercises: 61, 62.**

R-values of insulation

Insulating materials are rated in terms of their resistance to conduction, or their R-value, also known as their thermal resistance. The larger the R-value, the better the insulating properties. R-values also make some calculations easier, because the total R-value of two materials placed back to back is the sum of their individual R-values. The R-value for a layer of material is found by dividing the material's thickness, L, by its thermal conductivity, k:

$$R = \frac{L}{k}.$$ (Eq. 13.14: **R-values for insulation)**

Material	**Thermal Conductivity, k [W/(m K)]**
Air	0.0262
Aluminum	237
Brass	120
Copper	401
Diamond	895-2300
Ice	2.2
Glass	1.35
Styrofoam	0.033

Table 13.5: Thermal conductivities for various materials. These values are valid at 25°C, except for the value for ice which applies to ice at 0°C.

Essential Question 13.6: In the United States, R-values for insulation are specified in units of °F h ft^2 / BTU. BTU stands for British Thermal Unit, where 1 BTU = 1055 J. You have some insulation rated at R-15, so its R-value is 15 °F h ft^2 / BTU. What is this in units of K m^2 / W?