Lecture 3
(Heat, Heat Capacity and Heat Transfer)

Physics 161-01 Spring 2012

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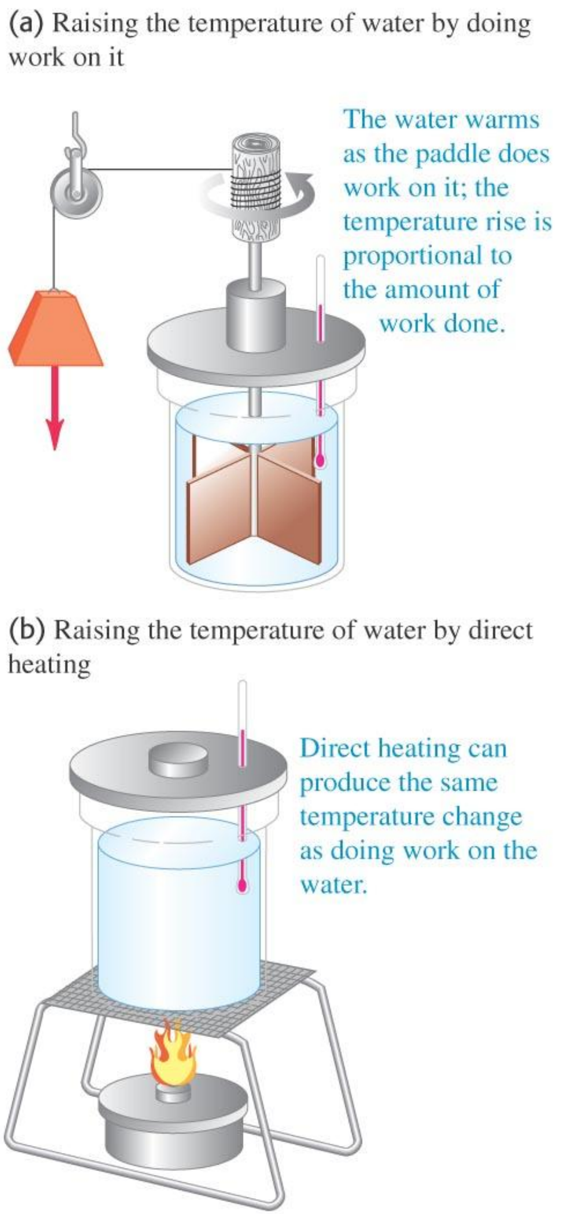
Heat as Energy

- The figure at the right illustrates that we can change the temperature of a body by doing work on it or by adding heat to it. This means that heat is a form of energy.
- The heat to cause a temperature change is $Q = mc\Delta T$, where *c* is the *specific heat* of the material, and *m* is the mass of substance involved.
- To raise 1g of water by 1K it takes 1 calorie or 4.184J of energy.



Specific Heats and Heat Capacities

Table 17.3 Approximate Specific Heats and Molar Heat Capacities (Constant Pressure)

Substance	Specific Heat, c (J/kg · K)	Molar Mass, M (kg/mol)	Molar Heat Capacity, C (J/mol · K)
Aluminum	910	0.0270	24.6
Beryllium	1970	0.00901	17.7
Copper	390	0.0635	24.8
Ethanol	2428	0.0461	111.9
Ethylene glycol	2386	0.0620	148.0
Ice (near 0°C)	2100	0.0180	37.8
Iron	470	0.0559	26.3
Lead	130	0.207	26.9
Marble ($CaCO_3$)	879	0.100	87.9
Mercury	138	0.201	27.7
Salt (NaCl)	879	0.0585	51.4
Silver	234	0.108	25.3
Water (liquid)	4190	0.0180	75.4

- Note that water has a higher specific heat than most substances.
  - This explains why most coastal locations have mild winters and summers.

Phase Changes

- The *phases* (or states) of matter are solid, liquid, and gas.
- A *phase change* is a transition from one phase to another.
- The temperature does not change during a phase change.
- The *heat of fusion*, L_f, is the heat per unit mass that is transferred in a solid-liquid phase change. The *heat of vaporization*, L_v, is the heat per unit mass transferred in a liquid-gas phase change.
- The heat transferred in a phase change is $Q = \pm mL$, where m is the mass of the substance.

Heats of Fusion and Vaporization

Table 17.4 Heats of Fusion and Vaporization

Substance	Normal Melting Point K	Normal Melting Point °C	Heat of Fusion, L_f (J/kg)	Normal Boiling Point K	Normal Boiling Point °C	Heat of Vaporization, L_v (J/kg)
Helium	*	*	*	4.216	−268.93	20.9×10^3
Hydrogen	13.84	−259.31	58.6×10^3	20.26	−252.89	452×10^3
Nitrogen	63.18	−209.97	25.5×10^3	77.34	−195.8	201×10^3
Oxygen	54.36	−218.79	13.8×10^3	90.18	−183.0	213×10^3
Ethanol	159	−114	104.2×10^3	351	78	854×10^3
Mercury	234	−39	11.8×10^3	630	357	272×10^3
Water	273.15	0.00	334×10^3	373.15	100.00	2256×10^3
Sulfur	392	119	38.1×10^3	717.75	444.60	326×10^3
Lead	600.5	327.3	24.5×10^3	2023	1750	871×10^3
Antimony	903.65	630.50	165×10^3	1713	1440	561×10^3
Silver	1233.95	960.80	88.3×10^3	2466	2193	2336×10^3
Gold	1336.15	1063.00	64.5×10^3	2933	2660	1578×10^3
Copper	1356	1083	134×10^3	1460	1187	5069×10^3

*A pressure in excess of 25 atmospheres is required to make helium solidify. At 1 atmosphere pressure, helium remains a liquid down to absolute zero.

CPS 3-1

A pitcher contains 0.50 kg of liquid water and 0.50 kg of ice at 0°C. You let heat flow into the pitcher until there is 0.75 kg of liquid water and 0.25 kg of ice. During this process,

A. the temperature of the ice-water mixture increases slightly.

B. the temperature of the ice-water mixture decreases slightly.

C. the temperature of the ice-water mixture remains the same.

D. The answer depends on the rate at which heat flows.

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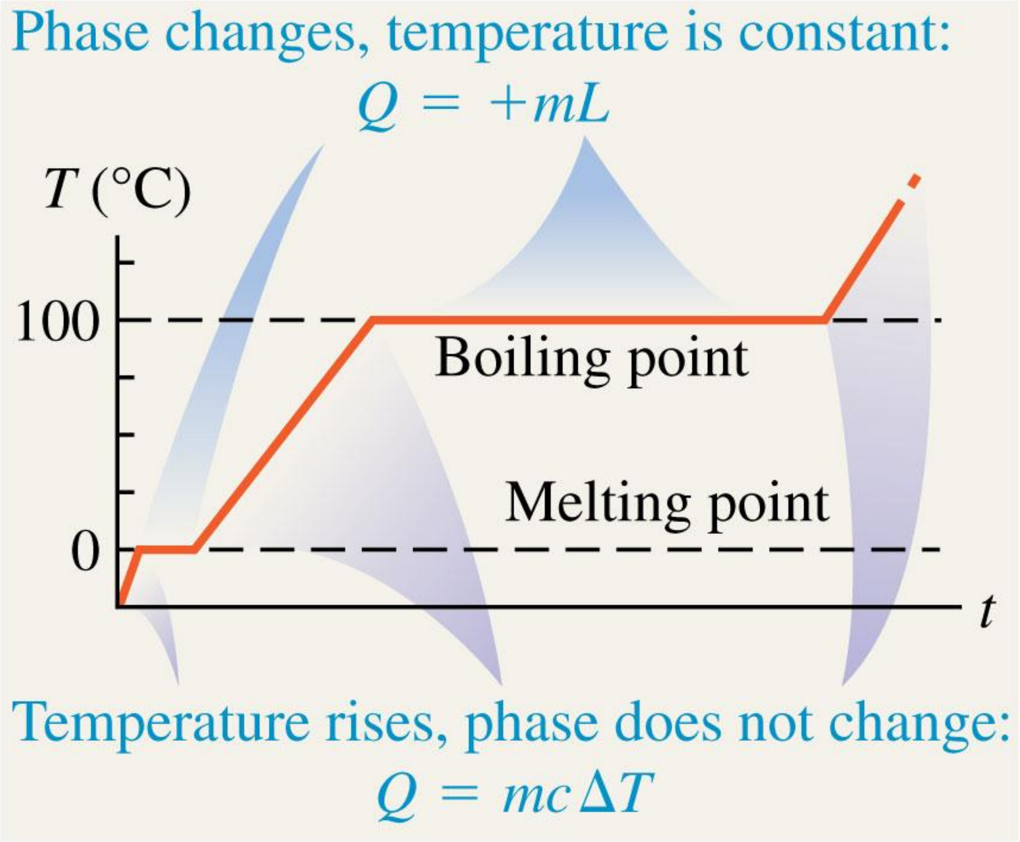
Phase Changes

- Remember that the temperature does not change during a phase change.



Example 17.7 A temperature change with no phase change

A camper pours 0.300 kg of coffee, initially in a pot at 70.0°C, into a 0.120-kg aluminum cup initially at 20.0°C. What is the equilibrium temperature? Assume that coffee has the same specific heat as water and that no heat is exchanged with the surroundings.

SOLUTION

IDENTIFY and SET UP: The target variable is the common final temperature T of the cup and coffee. No phase changes occur, so we need only Eq. (17.13). With subscripts C for coffee, W for water, and Al for aluminum, we have $T_{0C} = 70.0°$ and $T_{0Al} = 20.0°$; Table 17.3 gives $c_W = 4190\ \text{J/kg} \cdot \text{K}$ and $c_{Al} = 910\ \text{J/kg} \cdot \text{K}$.

EXECUTE: The (negative) heat gained by the coffee is $Q_C = m_C c_W \Delta T_C$. The (positive) heat gained by the cup is $Q_{Al} = m_{Al} c_{Al} \Delta T_{Al}$. We set $Q_C + Q_{Al} = 0$ (see Problem-Solving Strategy 17.2) and substitute $\Delta T_C = T - T_{0C}$ and $\Delta T_{Al} = T - T_{0Al}$:

$$Q_C + Q_{Al} = m_C c_W \Delta T_C + m_{Al} c_{Al} \Delta T_{Al} = 0$$
$$m_C c_W (T - T_{0C}) + m_{Al} c_{Al} (T - T_{0Al}) = 0$$

Then we solve this expression for the final temperature T. A little algebra gives

$$T = \frac{m_C c_W T_{0C} + m_{Al} c_{Al} T_{0Al}}{m_C c_W + m_{Al} c_{Al}} = 66.0°\text{C}$$

EVALUATE: The final temperature is much closer to the initial temperature of the coffee than to that of the cup; water has a much higher specific heat than aluminum, and we have more than twice as much mass of water. We can also find the quantities of heat by substituting the value $T = 66.0°\text{C}$ back into the original equations. We find $Q_C = -5.0 \times 10^3\ \text{J}$ and $Q_{Al} = +5.0 \times 10^3\ \text{J}$. As expected, Q_C is negative: The coffee loses heat to the cup.

Example 17.8 Changes in both temperature and phase

A glass contains 0.25 kg of Omni-Cola (mostly water) initially at 25°C. How much ice, initially at −20°C, must you add to obtain a final temperature of 0°C with all the ice melted? Neglect the heat capacity of the glass.

SOLUTION

IDENTIFY and SET UP: The Omni-Cola and ice exchange heat. The cola undergoes a temperature change; the ice undergoes both a temperature change and a phase change from solid to liquid. We use subscripts C for cola, I for ice, and W for water. The target variable is the mass of ice, m_I. We use Eq. (17.13) to obtain an expression for the amount of heat involved in cooling the drink to $T = 0°C$ and warming the ice to $T = 0°C$, and Eq. (17.20) to obtain an expression for the heat required to melt the ice at 0°C. We have $T_{0C} = 25°C$ and $T_{0I} = -20°C$, Table 17.3 gives $c_W = 4190\ J/kg \cdot K$ and $c_I = 2100\ J/kg \cdot K$, and Table 17.4 gives $L_f = 3.34 \times 10^5\ J/kg$.

EXECUTE: From Eq. (17.13), the (negative) heat gained by the Omni-Cola is $Q_C = m_C c_W \Delta T_C$. The (positive) heat gained by the ice in warming is $Q_I = m_I c_I \Delta T_I$. The (positive) heat required to melt the ice is $Q_2 = m_I L_f$. We set $Q_C + Q_I + Q_2 = 0$, insert $\Delta T_C = T - T_{0C}$ and $\Delta T_I = T - T_{0I}$, and solve for m_I:

$$m_C c_W \Delta T_C + m_I c_I \Delta T_I + m_I L_f = 0$$

$$m_C c_W (T - T_{0C}) + m_I c_I (T - T_{0I}) + m_I L_f = 0$$

$$m_I [c_I (T - T_{0I}) + L_f] = -m_C c_W (T - T_{0C})$$

$$m_I = m_C \frac{c_W (T_{0C} - T)}{c_I (T - T_{0I}) + L_f}$$

Substituting numerical values, we find that $m_I = 0.070\ kg = 70\ g$.

EVALUATE: Three or four medium-size ice cubes would make about 70 g, which seems reasonable given the 250 g of Omni-Cola to be cooled.

Example 17.9 What's cooking?

A hot copper pot of mass 2.0 kg (including its copper lid) is at a temperature of 150°C. You pour 0.10 kg of cool water at 25°C into the pot, then quickly replace the lid so no steam can escape. Find the final temperature of the pot and its contents, and determine the phase of the water (liquid, gas, or a mixture). Assume that no heat is lost to the surroundings.

SOLUTION

IDENTIFY and SET UP: The water and the pot exchange heat. Three outcomes are possible: (1) No water boils, and the final temperature T is less than 100°C; (2) some water boils, giving a mixture of water and steam at 100°C; or (3) all the water boils, giving 0.10 kg of steam at 100°C or greater. We use Eq. (17.13) for the heat transferred in a temperature change and Eq. (17.20) for the heat transferred in a phase change.

EXECUTE: First consider case (1), which parallels Example 17.8 exactly. The equation that states that the heat flow into the water equals the heat flow out of the pot is

$$Q_W + Q_{Cu} = m_W c_W (T - T_{0W}) + m_{Cu} c_{Cu} (T - T_{0Cu}) = 0$$

Here we use subscripts W for water and Cu for copper, with $m_W = 0.10$ kg, $m_{Cu} = 2.0$ kg, $T_{0W} = 25°C$, and $T_{0Cu} = 150°C$. From Table 17.3, $c_W = 4190\ \text{J/kg} \cdot \text{K}$ and $c_{Cu} = 390\ \text{J/kg} \cdot \text{K}$. Solving for the final temperature T and substituting these values, we get

$$T = \frac{m_W c_W T_{0W} + m_{Cu} c_{Cu} T_{0Cu}}{m_W c_W + m_{Cu} c_{Cu}} = 106°\text{C}$$

But this is above the boiling point of water, which contradicts our assumption that no water boils! So at least some of the water boils.

Continued

So consider case (2), in which the final temperature is $T = 100°C$ and some unknown fraction x of the water boils, where (if this case is correct) x is greater than zero and less than or equal to 1. The (positive) amount of heat needed to vaporize this water is $x m_W L_v$. The energy-conservation condition $Q_W + Q_{Cu} = 0$ is then

$$m_W c_W (100°\text{C} - T_{0W}) + x m_W L_v + m_{Cu} c_{Cu} (100°\text{C} - T_{0Cu}) = 0$$

We solve for the target variable x:

$$x = \frac{-m_{Cu} c_{Cu} (100°\text{C} - T_{0Cu}) - m_W c_W (100°\text{C} - T_{0W})}{m_W L_v}$$

With $L_v = 2.256 \times 10^6$ J from Table 17.4, this yields $x = 0.034$. We conclude that the final temperature of the water and copper is 100°C and that $0.034(0.10\ \text{kg}) = 0.0034\ \text{kg} = 3.4\ \text{g}$ of the water is converted to steam at 100°C.

EVALUATE: Had x turned out to be greater than 1, case (3) would have held; all the water would have vaporized, and the final temperature would have been greater than 100°C. Can you show that this would have been the case if we had originally poured less than 15 g of 25°C water into the pot?

Heat Flow Processes

- Heat can move from one object to another in one of three main processes:
  - Conduction
  - Convection
  - Radiation

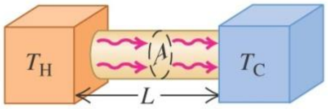
Conduction

- *Conduction* occurs between bodies in contact.
- The figure at right illustrates steady-state heat flow.
- The *heat current* is:

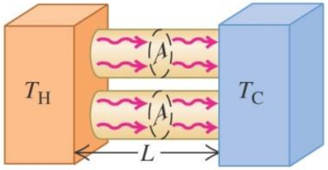
$$H = dQ/dt = kA(T_H - T_C)/L.$$

- Table 17.5 lists some thermal conductivities, k.

(a) Heat current H



(b) Doubling the cross-sectional area of the conductor doubles the heat current (H is proportional to A).



(c) Doubling the length of the conductor halves the heat current (H is inversely proportional to L).

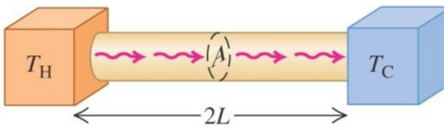


Table 17.5 Thermal Conductivities

Substance	k (W/m·K)
Metals	
Aluminum	205.0
Brass	109.0
Copper	385.0
Lead	34.7
Mercury	8.3
Silver	406.0
Steel	50.2
Solids (representative values)	
Brick, insulating	0.15
Brick, red	0.6
Concret	0.8
Cork	0.04
Felt	0.04
Fiberglass	0.04
Glass	0.8
Ice	1.6
Rock wool	0.04
Styrofoam	0.01
Wood	0.12–0.04
Gases	
Air	0.024
Argon	0.016
Helium	0.14
Hydrogen	0.14
Oxygen	0.023

CPS 3-2

A chair has a wooden seat but metal legs. The chair legs feel colder to the touch than does the seat. Why is this?

A. The metal is at a lower temperature than the wood.

B. The metal has a higher specific heat than the wood.

C. The metal has a lower specific heat than the wood.

D. The metal has a higher thermal conductivity than the wood.

E. The metal has a lower thermal conductivity than the wood.

CPS 3-2

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B. The metal has a higher specific heat than the wood.

C. The metal has a lower specific heat than the wood.

D. The metal has a higher thermal conductivity than the wood.

E. The metal has a lower thermal conductivity than the wood.

Conduction

Example 17.11 Conduction into a picnic cooler

A Styrofoam cooler (Fig. 17.24a) has total wall area (including the lid) of 0.80 m^2 and wall thickness 2.0 cm. It is filled with ice, water, and cans of Omni-Cola, all at 0°C. What is the rate of heat flow into the cooler if the temperature of the outside wall is 30°C? How much ice melts in 3 hours?

SOLUTION

IDENTIFY and SET UP: The target variables are the heat current H and the mass m of ice melted. We use Eq. (17.21) to determine H and Eq. (17.20) to determine m.

EXECUTE: We assume that the total heat flow is the same as it would be through a flat Styrofoam slab of area 0.80 m^2 and thickness 2.0 cm = 0.020 m (Fig. 17.24b). We find k from Table 17.5. From Eq. (17.21),

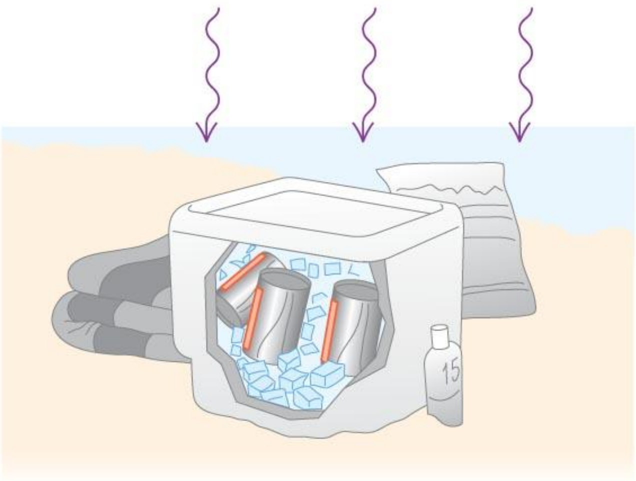
$$H = kA\frac{T_H - T_C}{L} = (0.027\ \mathrm{W/m\cdot K})(0.80\ \mathrm{m}^2)\frac{30°\mathrm{C} - 0°\mathrm{C}}{0.020\ \mathrm{m}}$$
$$= 32.4\ \mathrm{W} = 32.4\ \mathrm{J/s}$$

The total heat flow is $Q = Ht$, with $t = 3\ \mathrm{h} = 10{,}800\ \mathrm{s}$. From Table 17.4, the heat of fusion of ice is $L_f = 3.34 \times 10^5$ J/kg, so from Eq. (17.20) the mass of ice that melts is

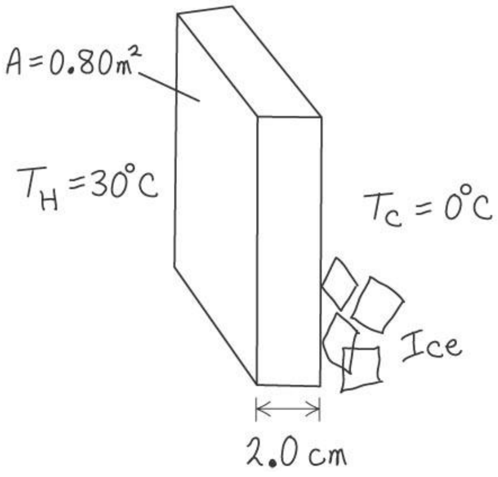
$$m = \frac{Q}{L_f} = \frac{(32.4\ \mathrm{J/s})(10{,}800\ \mathrm{s})}{3.34 \times 10^5\ \mathrm{J/kg}} = 1.0\ \mathrm{kg}$$

EVALUATE: The low heat current is a result of the low thermal conductivity of Styrofoam.

(a) A cooler at the beach



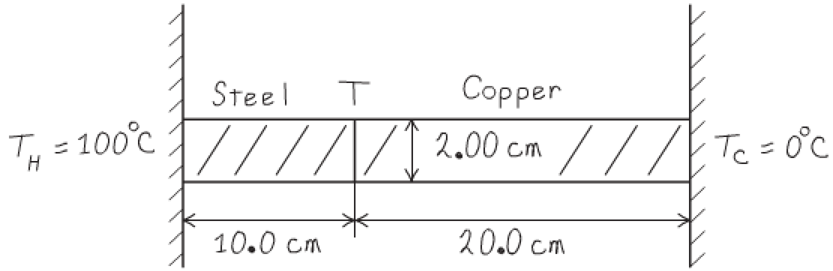
(b) Our sketch for this problem



Conduction

Example 17.12 Conduction through two bars I

A steel bar 10.0 cm long is welded end to end to a copper bar 20.0 cm long. Each bar has a square cross section, 2.00 cm on a side. The free end of the steel bar is kept at 100°C by placing it in contact with steam, and the free end of the copper bar is kept at 0°C by placing it in contact with ice. Both bars are perfectly insulated on their sides. Find the steady-state temperature at the junction of the two bars and the total rate of heat flow through the bars.



SOLUTION

IDENTIFY and SET UP: Figure 17.25 shows the situation. The heat currents in these end-to-end bars must be the same (see Problem-Solving Strategy 17.3). We are given "hot" and "cold" temperatures $T_H = 100°C$ and $T_C = 0°C$. With subscripts S for steel and Cu for copper, we write Eq. (17.21) separately for the heat currents H_S and H_{Cu} and set the resulting expressions equal to each other.

EXECUTE: Setting $H_S = H_{Cu}$, we have from Eq. (17.21)

$$H_S = k_S A \frac{T_H - T}{L_S} = H_{Cu} = k_{Cu} A \frac{T - T_C}{L_{Cu}}$$

We divide out the equal cross-sectional areas A and solve for T:

$$T = \frac{\dfrac{k_S}{L_S} T_H + \dfrac{k_{Cu}}{L_{Cu}} T_C}{\left(\dfrac{k_S}{L_S} + \dfrac{k_{Cu}}{L_{Cu}}\right)}$$

Substituting $L_S = 10.0$ cm and $L_{Cu} = 20.0$ cm, the given values of T_H and T_C, and the values of k_S and k_{Cu} from Table 17.5, we find $T = 20.7°C$.

We can find the total heat current by substituting this value of T into either the expression for H_S or the one for H_{Cu}:

$$H_S = (50.2 \text{ W/m}\cdot\text{K})(0.0200 \text{ m})^2 \frac{100°C - 20.7°C}{0.100 \text{ m}} = 15.9 \text{ W}$$

$$H_{Cu} = (385 \text{ W/m}\cdot\text{K})(0.0200 \text{ m})^2 \frac{20.7°C}{0.200 \text{ m}} = 15.9 \text{ W}$$

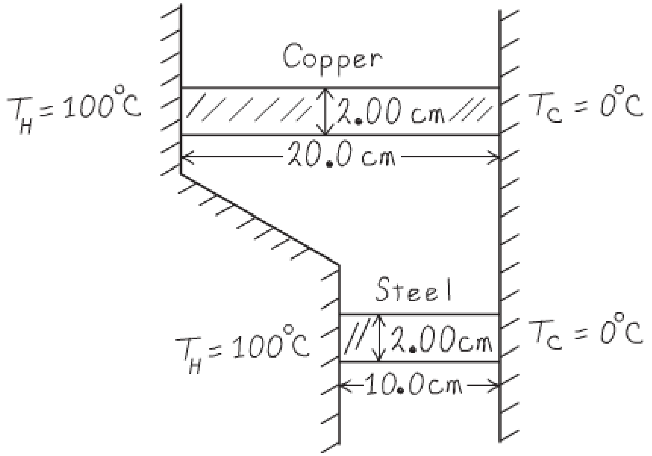
EVALUATE: Even though the steel bar is shorter, the temperature drop across it is much greater (from 100°C to 20.7°C) than across the copper bar (from 20.7°C to 0°C). That's because steel is a much poorer conductor than copper.

Conduction

Example 17.13 Conduction through two bars II

Suppose the two bars of Example 17.12 are separated. One end of each bar is kept at 100°C and the other end of each bar is kept at 0°C. What is the *total* heat current in the two bars?

17.26 Our sketch for this problem.



SOLUTION

IDENTIFY and SET UP: Figure 17.26 shows the situation. For each bar, $T_H - T_C = 100°C - 0°C = 100\text{ K}$. The total heat current is the sum of the currents in the two bars, $H_S + H_{Cu}$.

EXECUTE: We write the heat currents for the two rods individually, and then add them to get the total heat current:

$$\begin{aligned}H &= H_S + H_{Cu} = k_S A \frac{T_H - T_C}{L_S} + k_{Cu} A \frac{T_H - T_C}{L_{Cu}} \\ &= (50.2\text{ W/m}\cdot\text{K})(0.0200\text{ m})^2 \frac{100\text{ K}}{0.100\text{ m}} \\ &\quad + (385\text{ W/m}\cdot\text{K})(0.0200\text{ m})^2 \frac{100\text{ K}}{0.200\text{ m}} \\ &= 20.1\text{ W} + 77.0\text{ W} = 97.1\text{ W}\end{aligned}$$

EVALUATE: The heat flow in the copper bar is much greater than that in the steel bar, even though it is longer, because the thermal conductivity of copper is much larger. The total heat flow is greater than in Example 17.12 because the total cross section for heat flow is greater and because the full 100-K temperature difference appears across each bar.

Convection

- *Convection* is the transfer of heat by the mass motion of fluid.
- The figure at right illustrates the convection due to a heating element submerged in water.

Radiation

- *Radiation* is the transfer of heat by electromagnetic waves, such as visible light or infrared.
- The figure at right is a false-color infrared photo in which red is the strongest emission.
- *Stefan-Boltzmann law*: The *heat current* in radiation is $H = Ae\sigma T^4$.