Chapter 14: Temperature and Heat

Goals:

- To study temperature and temperature scales.
- To describe thermal expansion and its applications.
- To explore and solve problems involving heat, phase changes and calorimetry.
- To study heat transfer.
- To describe solar energy and see how technology can lead to resource conservation.

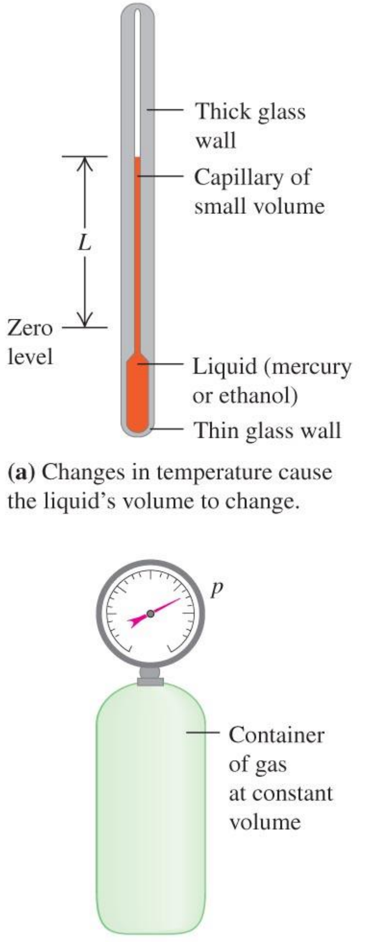
Chapter 14 Temperature and Heat

- To understand temperature and temperature scales.
- To describe thermal expansion and its applications.
- To explore and solve problems involving heat, phase changes and calorimetry.
- To understand heat transfer.

Courtesy of Wenhao Wu

14.1 Temperature and Thermal Equilibrium

- Temperature (T) is a measure of how "hot" or "cold" an object is.
- A thermometer is a calibrated device for measuring the temperature of the object.
- A thermometer is often a container filled with a substance that will expand or contract as it reaches thermal equilibrium with the object.

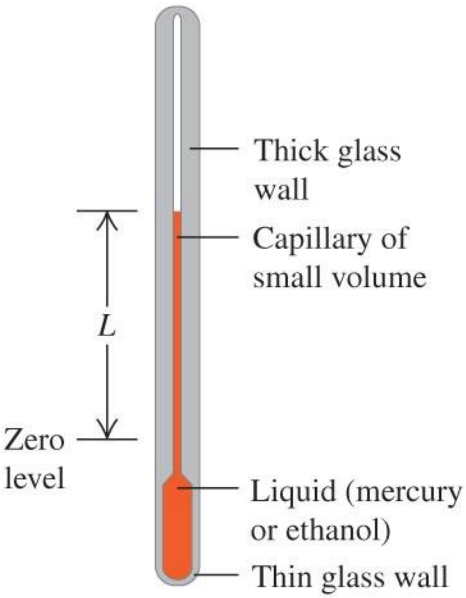


(b) Changes in temperature cause the pressure of the gas to change.

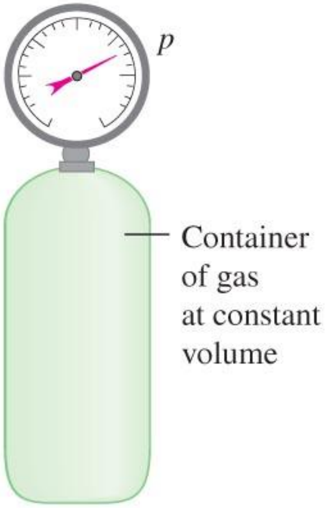
Courtesy of Wenhao Wu

Temperature – Figure 14.1

- Temperature is an attempt to measure the "hotness" or "coldness" on a scale you devise.
- A device to do this is called a thermometer and is usually calibrated by the melting and freezing points of a substance. This is most often water with corrections for atmospheric pressure well known.
- The thermometer is often a container filled with a substance that will expand or contract as heat flows in its surroundings.



(a) Changes in temperature cause the liquid's volume to change.



(b) Changes in temperature cause the pressure of the gas to change.

Q17.1

Clicker question

The illustration shows a thermometer that uses a column of liquid (usually mercury or ethanol) to measure air temperature. In thermal equilibrium, this thermometer measures the temperature of

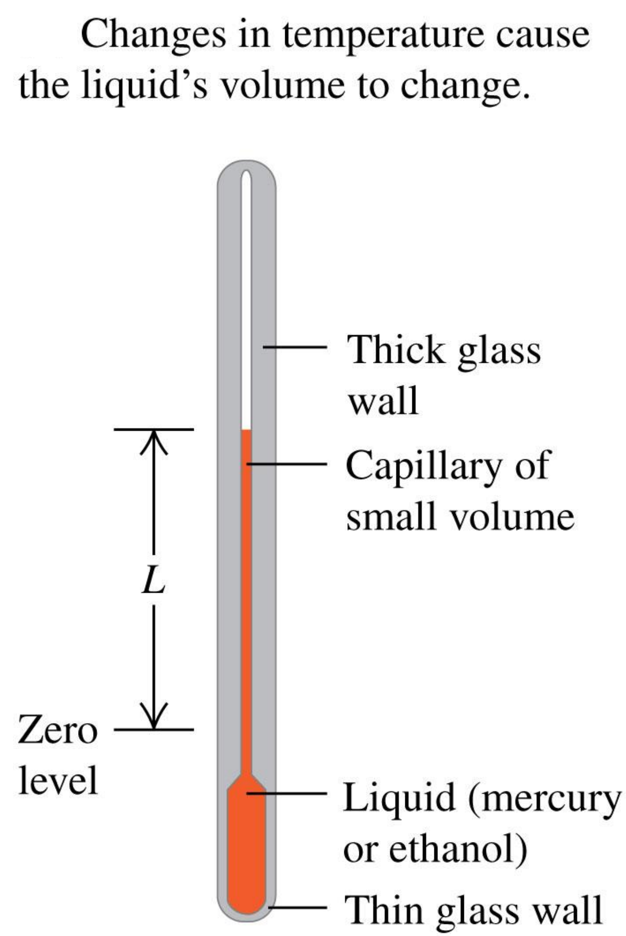
A. the column of liquid.

B. the glass that encloses the liquid.

C. the air outside the thermometer.

D. both A and B.

E. all of A, B, and C.



What is thermal equilibrium?

- If two objects are placed in contact and one is "hotter" than the other, a net amount of heat energy will flow from the hotter to the colder.
- This process cools down the hotter object and heats up the colder object.
- This process will continue until both objects reach the same temperature, in a state called thermal equilibrium.

Here are a couple simple concepts:

- Thermal conductor: a medium through which heat energy can flow.
- Thermal insulator: a medium through which heat energy can not flow.

Courtesy of Wenhao Wu

The Zeroth Law of Thermodynamics

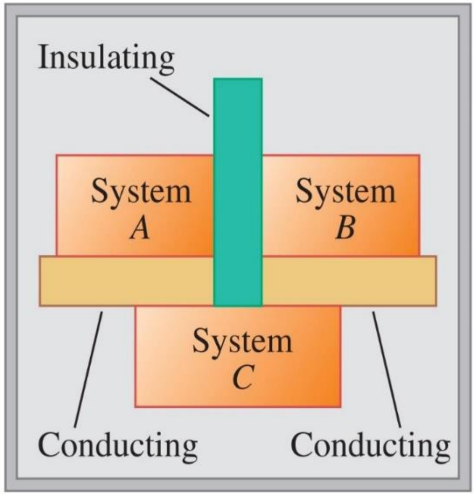
If System A is in thermal equilibrium with System C ($T_A = T_C$),

and,

if System B is in thermal equilibrium with System C ($T_B = T_C$),

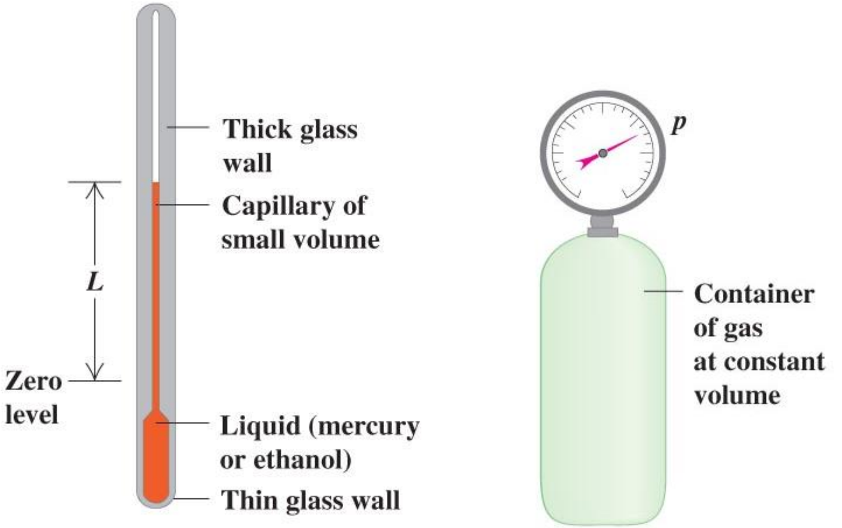
then,

System A is in thermal equilibrium with System B ($T_A = T_B$).



Courtesy of Wenhao Wu

Thermometers and thermal equilibrium



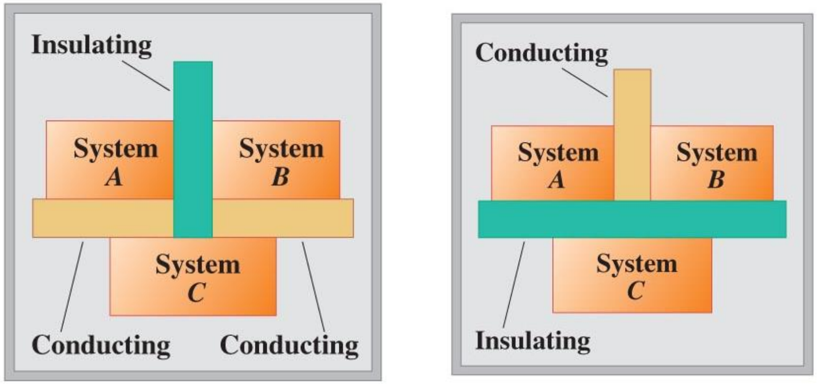
(a) Changes in temperature cause the liquid's volume to change.

(b) Changes in temperature cause the pressure of the gas to change.

Temperature and thermal equilibrium

"hot" and "cold" is quantified by thermometers.

Based on: thermal expansion (liquid or gas),change of resistance of a wire, thermoelectric effect.



(a) If systems *A* and *B* are each in thermal equilibrium with system *C* ..

(b) … then systems *A* and *B* are in thermal equilibrium with each other.

The zeroth law of thermodynamics

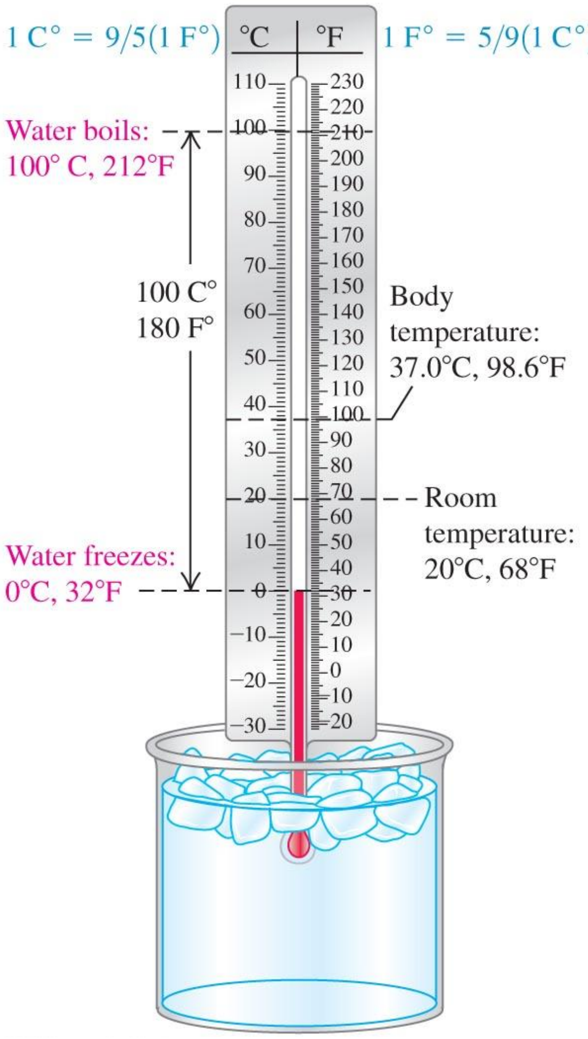
Two systems that are each in thermal equilibrium with a third system are in thermal equilibrium with each other.

Two systems are in thermal equilibrium if they have the same temperature.

14.2 Temperature Scales

Celsius and Fahrenheit Temperature Scales

- Based on the boiling and freezing points of water.
- In many other countries, the Celsius (also called Centigrade) scale is used with water freezing at 0 °C and boiling at 100 °C.
- In the United States, the Fahrenheit scale is used with water freezing at 32 °F and boiling at 212 °F.
- Conversion between them: $T_f = \frac{9}{5}T_c + 32$
- Note that the interval (degree) is smaller in the Fahrenheit scale.



Courtesy of Wenhao Wu

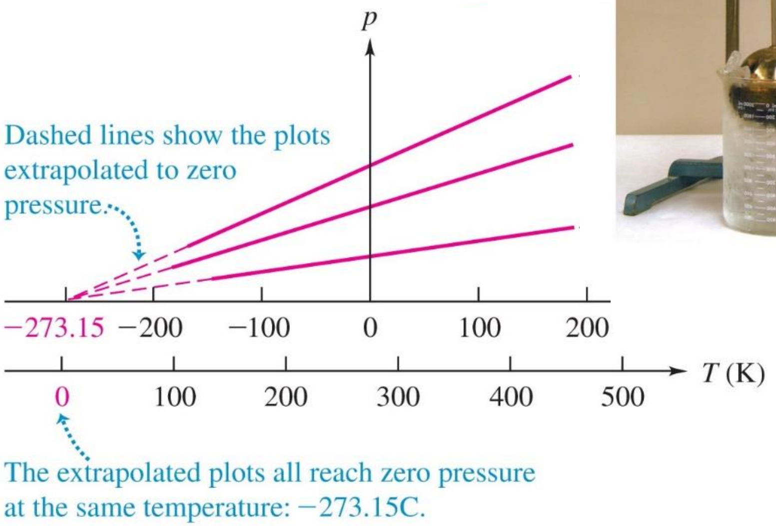
The Kelvin Scale, or, the Absolute Temperature Scales

● Some simple gases, especially helium, when placed in a constant–volume container, their pressures have a simple linear relationship with the temperature.

Conversion between Kelvin and Celsius scales:

$$T_K = T_C + 273.15$$

Water	Celsius Scale	Kelvin Scale
Freezing point K	0 °C	273.15
Boiling point K	100 °C	373.15

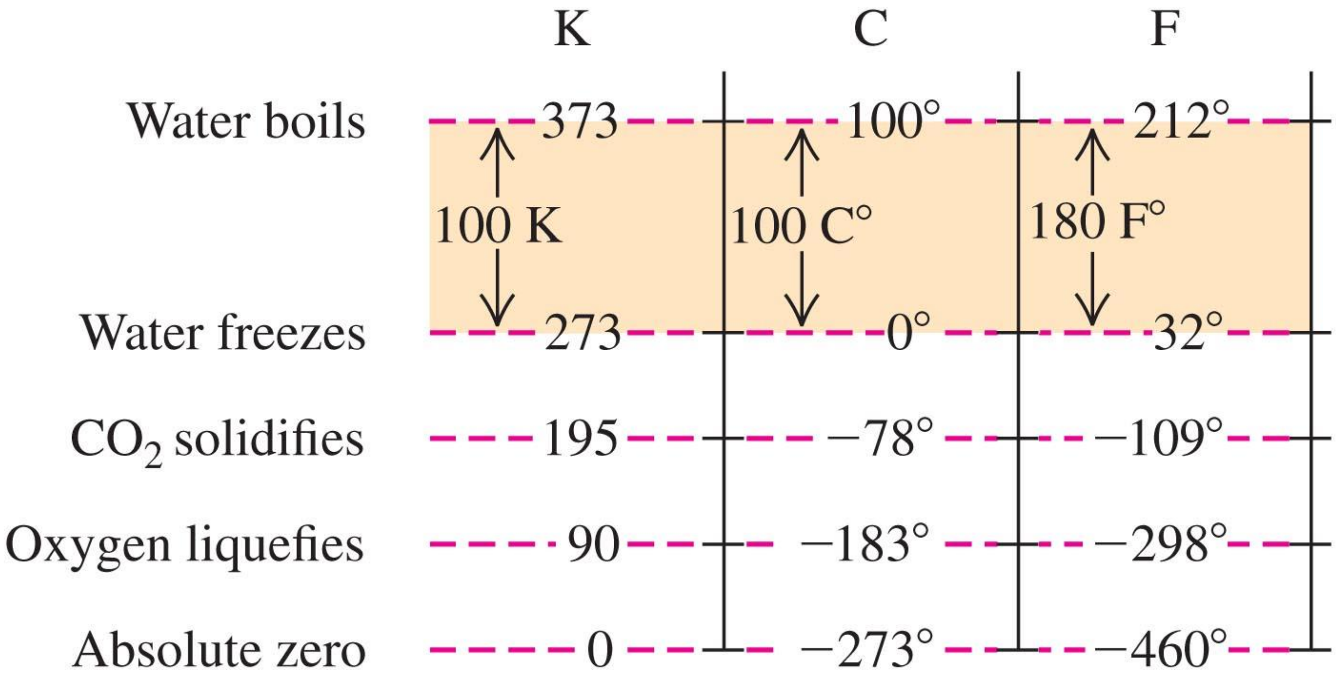


The Third Law of Thermodynamics: It is impossible by any procedure, no matter how idealized, to reduce the temperature of any system to zero temperature in a finite number of finite operations

Courtesy of Wenhao Wu

Temperature Conversions – Figure 14.5

- Be comfortable converting between the different temperature scales.



Q-RT17.1 Clicker question

Rank the following temperatures from highest to lowest.

A. 20.0°F

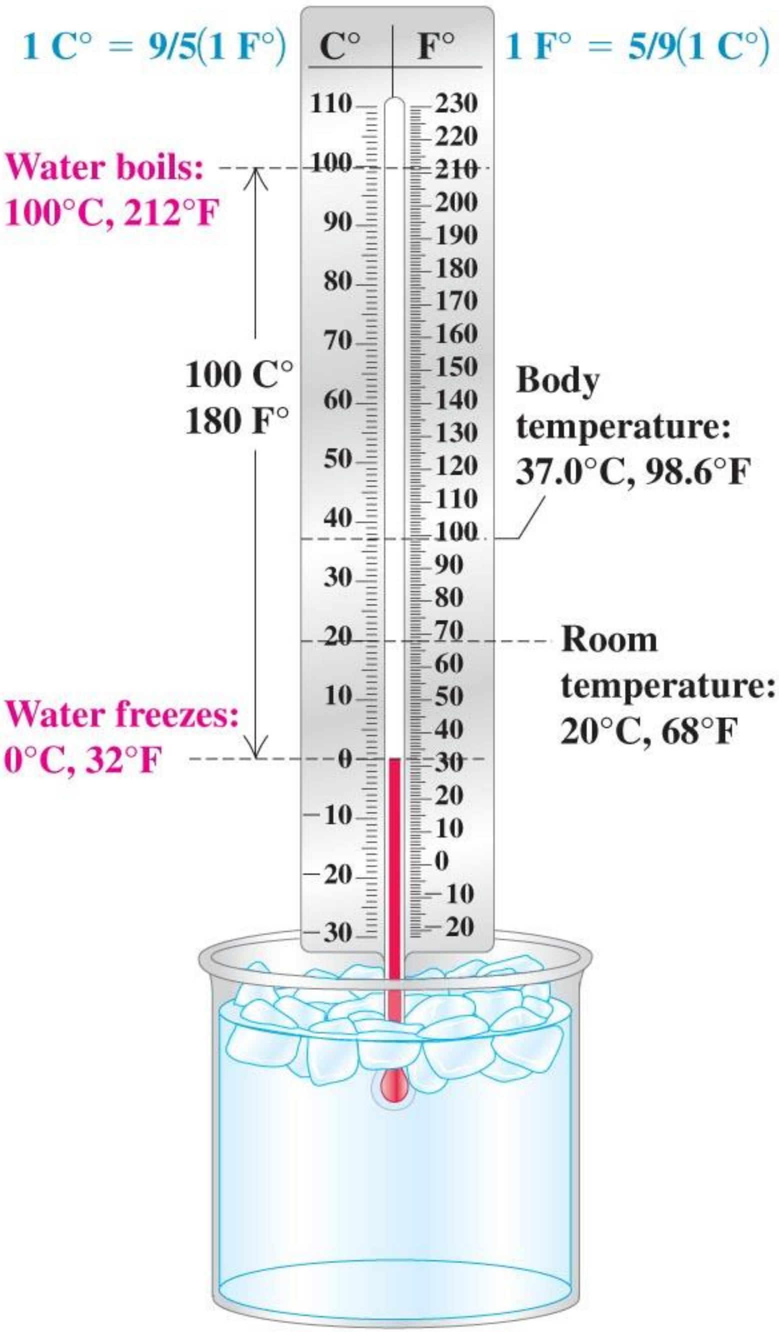
B. 20.0°C

C. 20.0 K

D. –80.0°F

E. –80.0°C

a) ABCDE b) BADEC c)EDCBA d)BADCE



Celsius temperature scale

Reference temperature 0ºC water freezes and 100ºC water boils.

Fahrenheit temperature scale

Reference temperature 32ºF water freezes and 212ºF water boils.

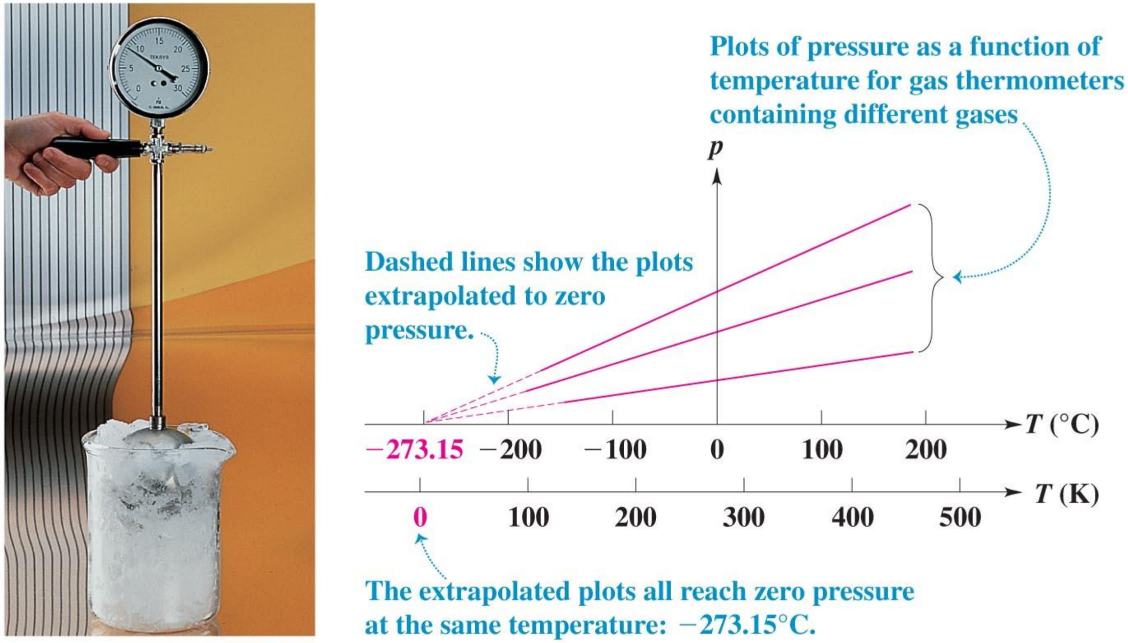
Intervals between reference temperature;

$$\frac{100\ (celsius)}{180\ (fahrenheit)} = \frac{5}{9} \approx \frac{1}{2}$$

Convert Celsius to Fahrenheit;

$$T_F = \frac{9}{5}T_C + 32°\ (obtain\ Fahrenheit)$$

$$T_C = \frac{5}{9}T_F - 32°\ (obtain\ Celsius)$$



(a) A constant-volume gas thermometer

(b) Graphs of pressure versus temperature at constant volume for three gases

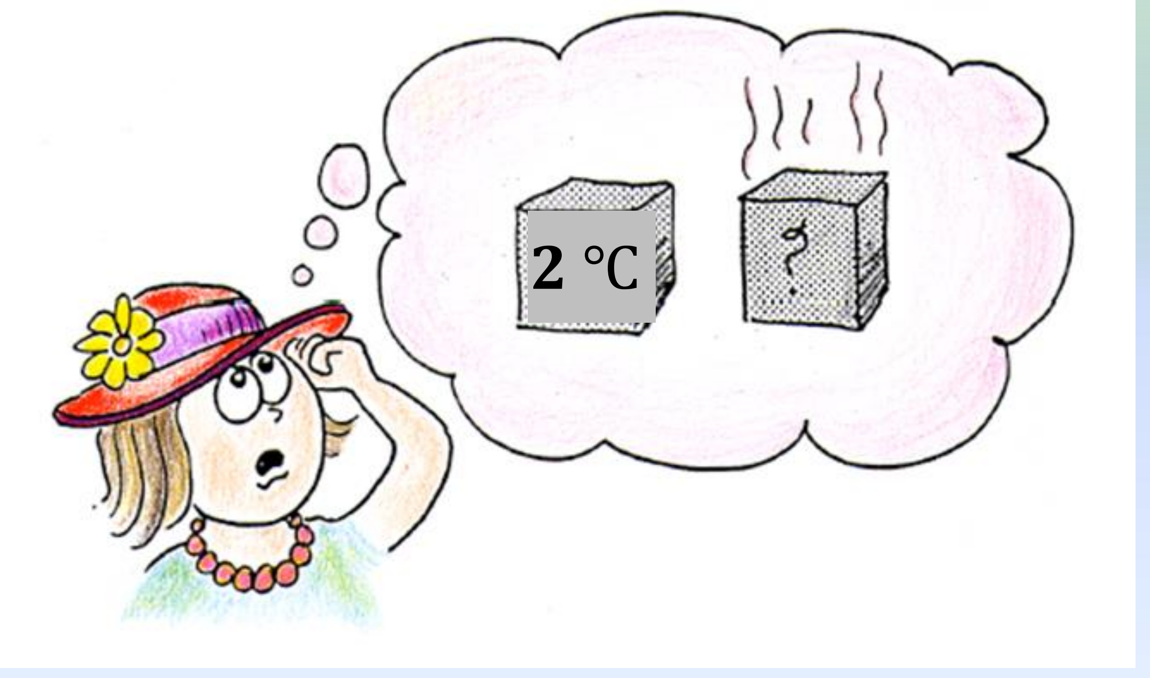
The Kelvin scale (scientific)

$$T_K = T_C + 273.15°$$

	K	C	F
Water boils	373	100°	212°
	100 K	100 C°	180 F°
Water freezes	273	0°	32°
CO_2 solidifies	195	−78°	−109°
Oxygen liquifies	90	−183°	−298°
Absolute zero	0	−273°	−460°

Clicker - Questions

A piece of iron has a temperature of 2^{o}C. A second identical piece of iron is twice as hot. What is the temperature of the second piece of iron?a



a) 4^{o}C b) 277^{o}C c) 8^{o}C d) 275 K

Answer: 277°C

Its temperature will be 277°C, and most certainly not 4°C! At twice the internal energy, the iron will have twice the absolute temperature. Its initial absolute temperature is 273 K + 2 K = 275 K. Twice this is 550 K. Expressed in Celsius, 550 K − 273 K = 277°C.

14.3 Thermal Expansion

Linear Expansion

Under a moderate change in temperature:

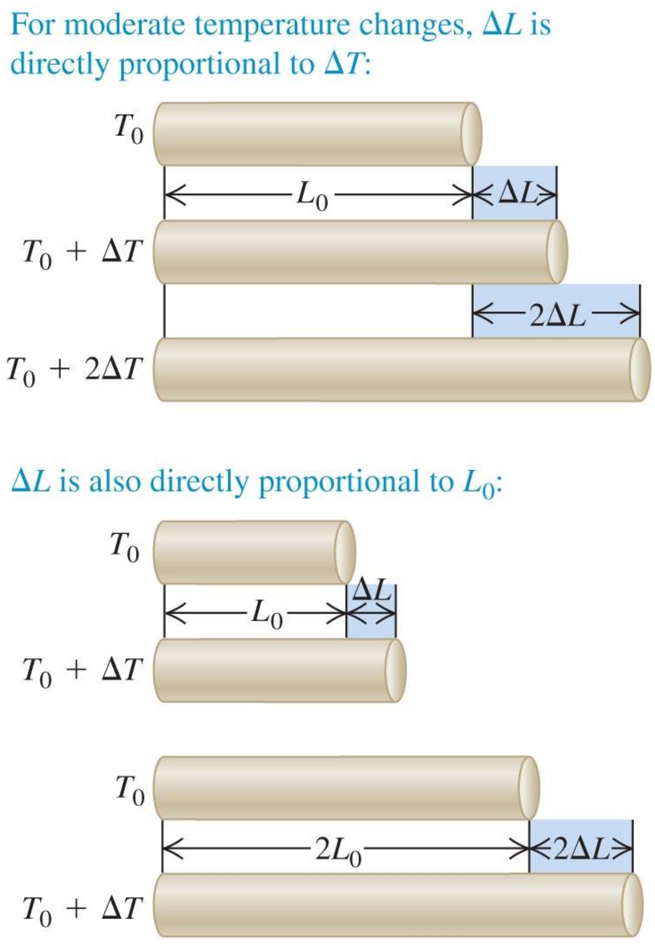
- Length change is proportional to the original length.
- Length change is proportional to temperature change.

$$\Delta L = \alpha L_0 \Delta T$$

$$L = L_0 + \Delta L = L_0(1 + \alpha \Delta T)$$

Note:

- $\Delta T = T - T_0$ is the change in temperature.
- L_0 is the initial length at the initial temperature T_0.
- The coefficient of linear expansion α is material dependent (see Table 14.1), in units of K^{-1} or $(°C)^{-1}$.
- ΔL can be positive (expansion) or negative (contraction).



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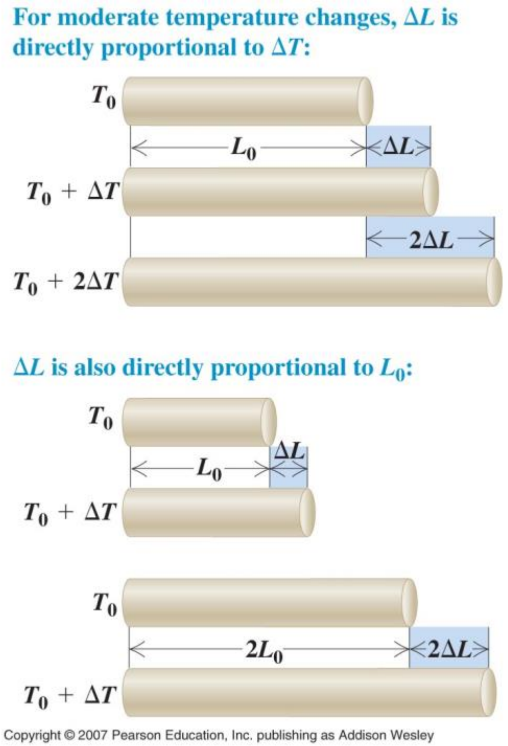
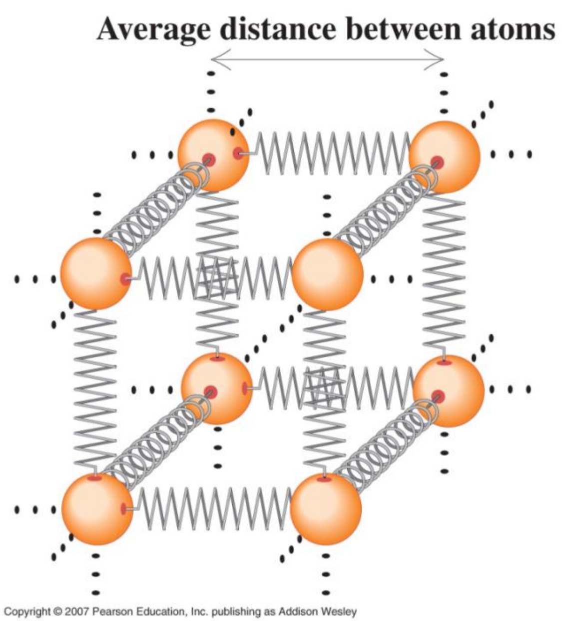




Thermal Expansion

$$\Delta \underbrace{L}_{length} = \alpha L_o \Delta \underbrace{T}_{temperature}$$

Here; α is coefficient of linear expansion [K^{-1} or C^{-1}] (Fractional change in length during one degree temperature change)

$$L = L_o + \Delta L = L_o(1 + \alpha\Delta T)$$

Total length expansion of two connected rods of different materials

$$\Delta L_1 + \Delta L_2 = \alpha_a L_{o1} \Delta \underbrace{T} + \alpha_b L_{o2} \Delta \underbrace{T}$$

TABLE 14.2 Coefficients of volume expansion

Material	β (K^{-1})
Solids	
Quartz (fused)	0.12×10^{-5}
Invar	0.27×10^{-5}
Glass	$1.2–2.7 \times 10^{-5}$
Steel	3.6×10^{-5}
Copper	5.1×10^{-5}
Brass	6.0×10^{-5}
Aluminum	7.2×10^{-5}
Liquids	
Mercury	18×10^{-5}
Glycerin	49×10^{-5}
Ethanol	75×10^{-5}
Carbon disulfide	115×10^{-5}

TABLE 14.1 Coefficients of linear expansion for selected materials

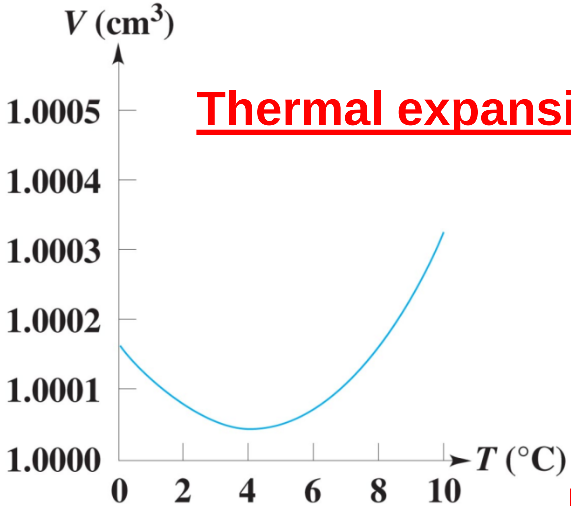
Material	α (K^{-1} or $C°^{-1}$)
Quartz (fused)	0.04×10^{-5}
Invar (nickel–iron alloy)	0.09×10^{-5}
Glass	$0.4–0.9 \times 10^{-5}$
Steel	1.2×10^{-5}
Copper	1.7×10^{-5}
Brass	2.0×10^{-5}
Aluminum	2.4×10^{-5}

Volume Expansion

$$\Delta V = \beta V_o \Delta T$$
$$V = V_o(1 + \underbrace{\beta}_{} \Delta T)$$

Coeffficient of volume expansion (K^{-1} *or* C^{-1})

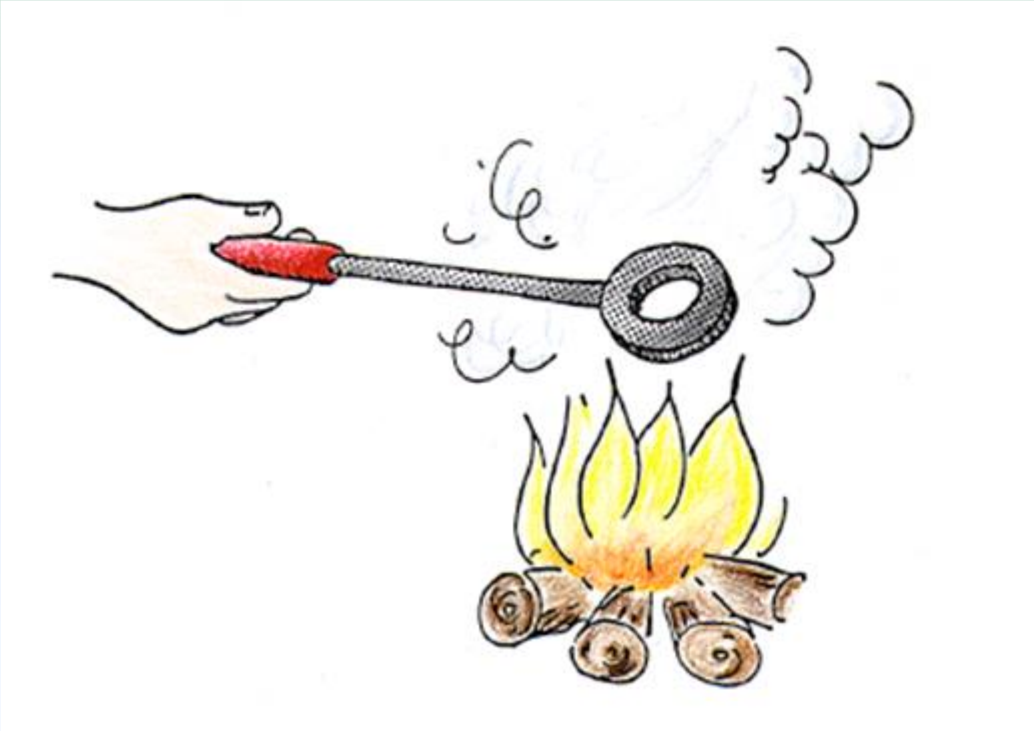
Thermal expansion of water

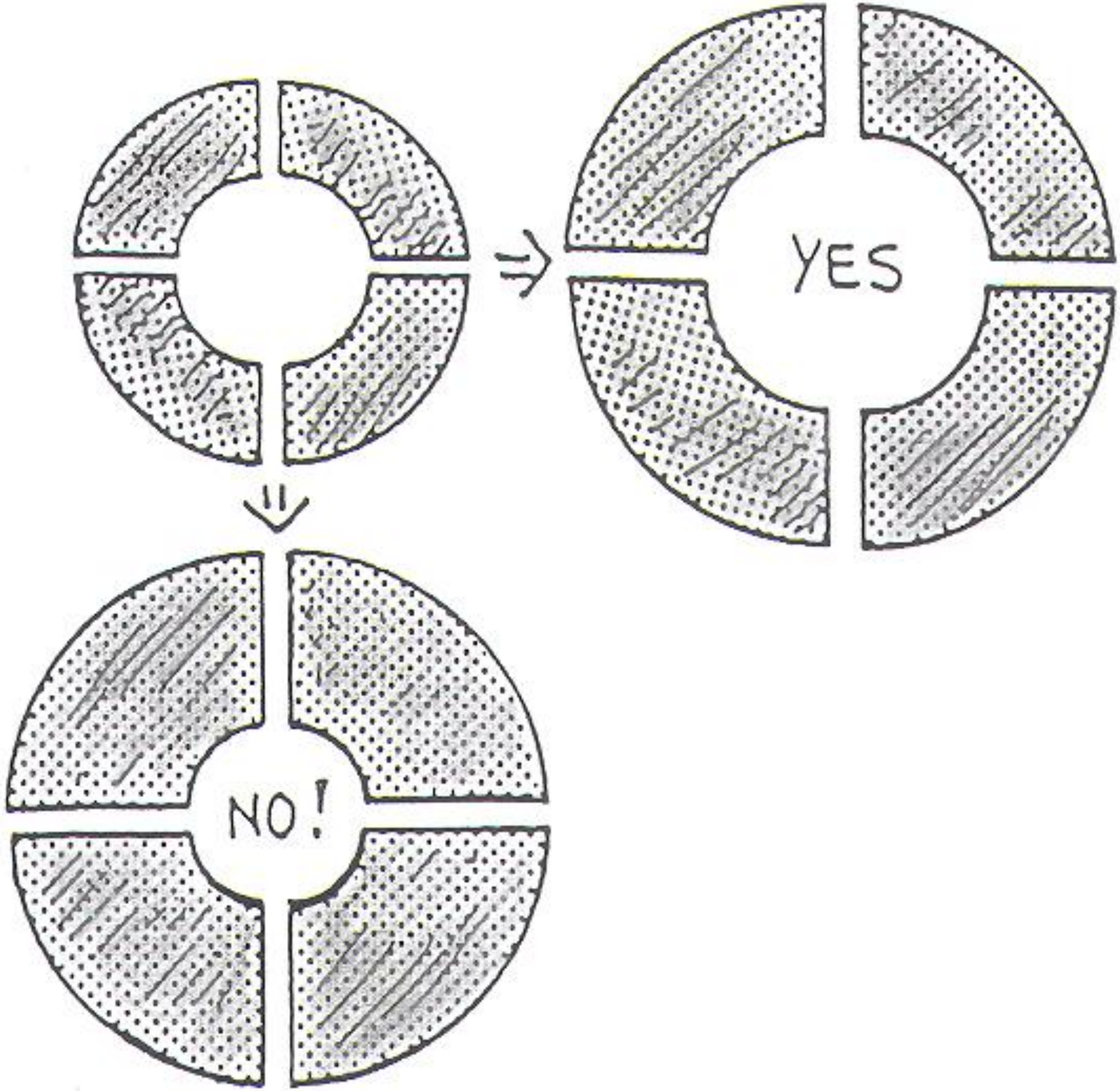


Note: water is densest at 4°C

Clicker - Questions

When the temperature of a metal ring increases, does the hole become a)larger b)smaller c) remain the same size?



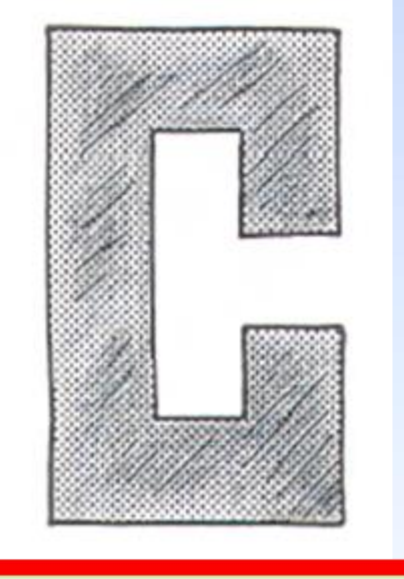

YES
NO!

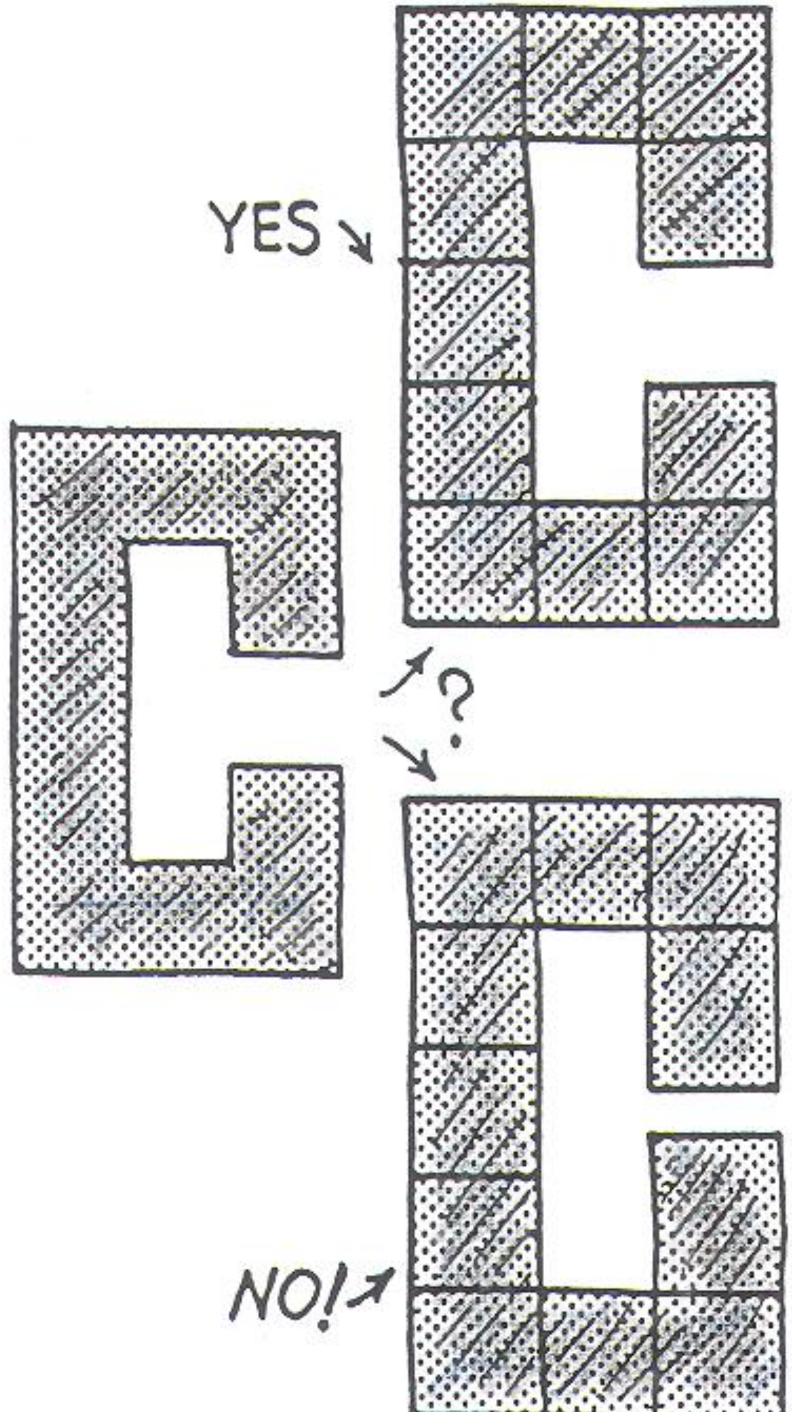
Clicker - Questions

When the temperature of the piece of metal is increased and the metal expands.

Will the gap between the ends become

a)narrower, b)wider, c) remain unchanged?




YES
?
NO!

14.3 Thermal Expansion

Linear Expansion

Under a moderate change in temperature:

- Length change is proportional to the original length.
- Length change is proportional to temperature change.

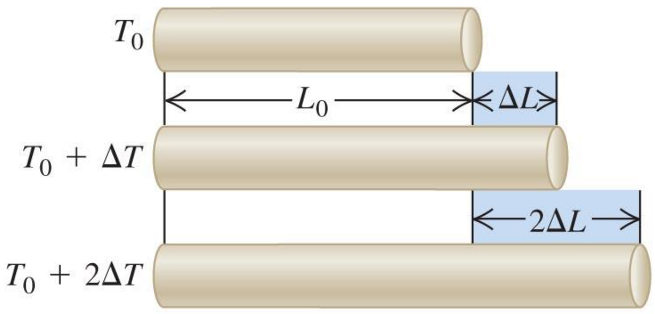
$$\Delta L = \alpha L_0 \Delta T$$

$$L = L_0 + \Delta L = L_0(1 + \alpha \Delta T)$$

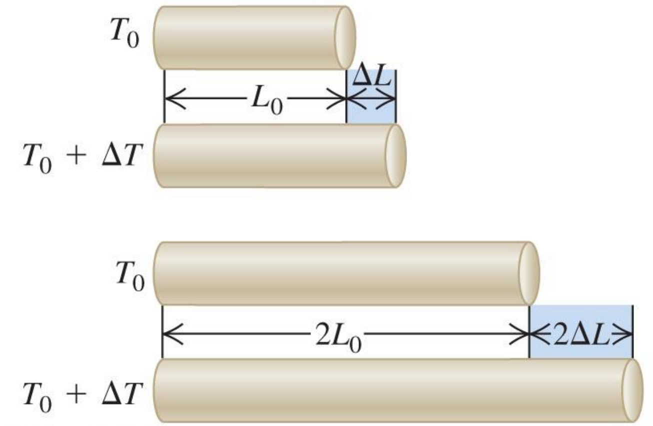
Note:

- $\Delta T = T - T_0$ is the change in temperature.
- L_0 is the initial length at the initial temperature T_0.
- The coefficient of linear expansion α is material dependent (see Table 14.1), in units of K^{-1} or $(°C)^{-1}$.
- ΔL can be positive (expansion) or negative (contraction).

For moderate temperature changes, ΔL is directly proportional to ΔT:



ΔL is also directly proportional to L_0:



Courtesy of Wenhao Wu

Volume Expansion

Under a moderate change in temperature:

- Volume change is proportional to the original volume.
- Volume change is proportional to temperature change.

$$\Delta V = \beta V_0 \Delta T$$

$$V = V_0 + \Delta V = V_0(1 + \beta \Delta T)$$

Note:

- $\Delta T = T - T_0$ is the change in temperature.
- V_0 is the initial volume at the initial temperature T_0.
- The coefficient of volume expansion β is material dependent (see Table 14.2), in units of K^{-1} or $(°C)^{-1}$.
- ΔV can be positive (expansion) or negative (contraction).

Courtesy of Wenhao Wu

Volume expansion

$$\Delta V = \beta V_o \Delta T$$
$$V = V_o(1 + \beta \Delta T)$$

β = coefficient of volume expansion = [K^{-1}]

Note: β is much larger for liquids than for solids.

TABLE 14.2 Coefficients of volume expansion

Material	β (K^{-1})
Solids	
Quartz (fused)	0.12×10^{-5}
Invar	0.27×10^{-5}
Glass	$1.2 - 2.7 \times 10^{-5}$
Steel	3.6×10^{-5}
Copper	5.1×10^{-5}
Brass	6.0×10^{-5}
Aluminum	7.2×10^{-5}
Liquids	
Mercury	18×10^{-5}
Glycerin	49×10^{-5}
Ethanol	75×10^{-5}
Carbon disulfide	115×10^{-5}

Example 14.4: Expansion of mercury

A glass disk filled with a volume of 200 cm^3 is filled to the brim with mercury at 20°C. When the temperature is raised to 100°C, does the mercury overflow? The volume of expansion coefficient are;

$$glass = 18x10^{-5}\ K^{-1}$$
$$mercury = 1.2x10^{-5}\ K^{-1}$$

$$\Delta V(flask) = \beta_{glass} V_o \Delta T = (1.2x10^{-5}\ K^{-1})(200\ cm^3)(100°C - 20°\ C) = 0.19 cm^3$$
$$\Delta V(mercury) = \beta_{Hg} V_o \Delta T = (18x10^{-5}\ K^{-1})(200\ cm^3)(100°C - 20°\ C) = 2.9\ cm^3$$

$$\Delta V_{mercury} - \Delta V_{glass} = (2.9 - 0.19)\ cm^3 = 2.7\ cm^3 \text{ (overflow)}$$

Q17.4

Clicker question

When the temperature of a certain solid, rectangular object increases by ΔT, the length of one side of the object increases by $0.010\% = 1.0 \times 10^{-4}$ of the original length. The increase in *volume* of the object due to this temperature increase is

A. $0.010\% = 1.0 \times 10^{-4}$ of the original volume.

B. $(0.010)^3\% = 0.0000010\% = 1.0 \times 10^{-8}$ of the original volume.

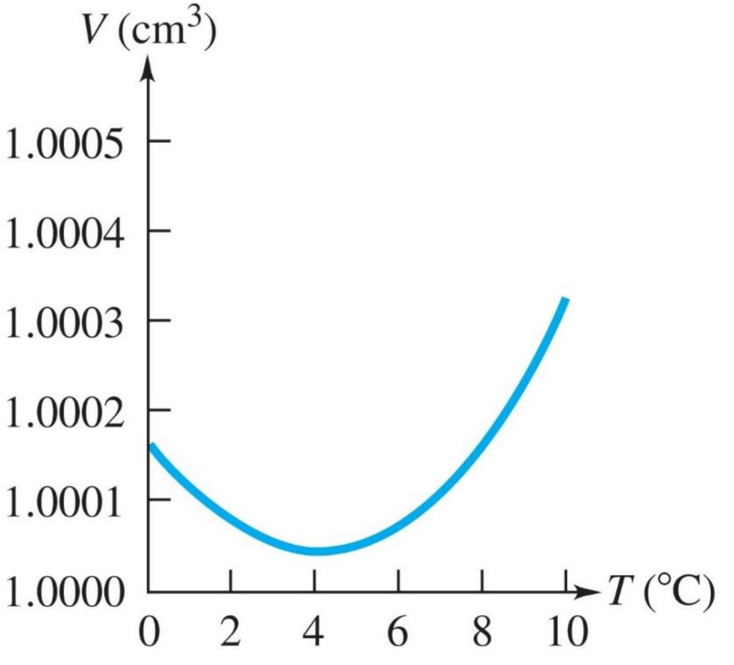
C. $(1.0 \times 10^{-4})^3 = 0.00000000010\% = 1.0 \times 10^{-12}$ of the original volume.

D. $0.030\% = 3.0 \times 10^{-4}$ of the original volume.

E. Not enough information is given to decide.

(The Anomalous) Expansion of Water

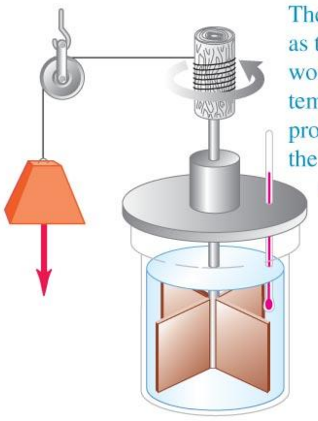
Water has the smallest volume (largest density) near 4 °C.



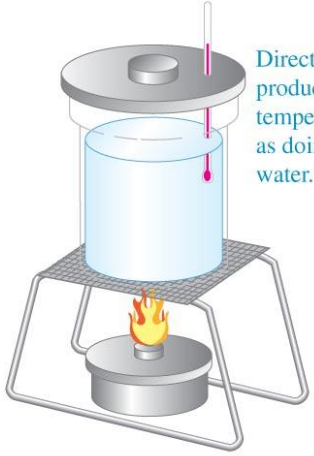
14.4 Heat Energy

The Mechanical Equivalent of Heat

- Done by James Joule in the 1800s.
- Potential energy stored in a raised mass was used to pull a cord wound on a rod mounted to a paddle in a water bath.
- The measured temperature change of the water proved the equivalence of mechanical energy and heat.
- The unit for potential energy, kinetic energy, and heat is the Joule in honor of his work.



(a) Raising the temperature of water by doing work on it



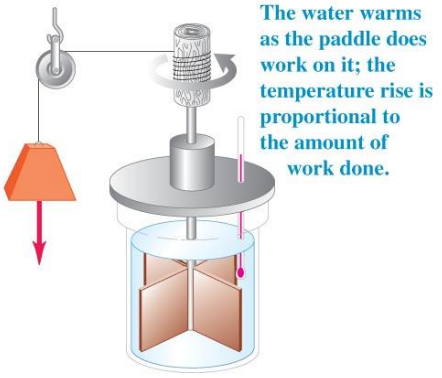
(b) Raising the temperature of water by direct heating

Some Simple Numbers:

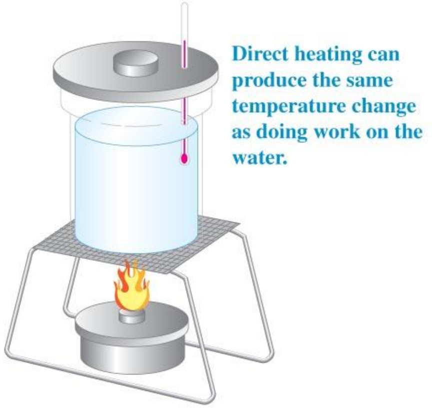
- On food labels, 1 calorie is 1 kilocalorie (kcal) in SI units.
- 1 cal is 4.184 J.
- The Big Mac contains about 3.5 million joules.
- The heat energy released by a 1000-W cooktop in 1000 s is 1 million joules.

Courtesy of Wenhao Wu

Quantity of Heat



(a) Raising the temperature of water by doing work on it



(b) Raising the temperature of water by direct heating

Heat flow = energy in transit

1 cal = 4.186 J
1 kcal = 1000 cal = 4186 J
1 Btu = 778 ft.lb = 252 cal = 1055 J

TABLE 14.3 Mean specific heat capacities (constant pressure, temperature range 0°C to 100°C)

	Specific heat capacity (c)	
Material	**J/(kg·K)**	**cal/(g·K)**
Solids		
Lead	0.13×10^3	0.031
Mercury	0.14×10^3	0.033
Silver	0.23×10^3	0.056
Copper	0.39×10^3	0.093
Iron	0.47×10^3	0.112
Marble ($CaCO_3$)	0.88×10^3	0.21
Salt	0.88×10^3	0.21
Aluminum	0.91×10^3	0.217
Beryllium	1.97×10^3	0.471
Ice (−25°C to 0°C)	2.01×10^3	0.48
Liquids		
Ethylene glycol	2.39×10^3	0.57
Ethanol	2.43×10^3	0.58
Water	4.19×10^3	1.00

Definition of Calorie

1 cal is equal to the amount of heat required to raise the temperature of 1g of water from 14.5°C to 15.5°C

$$Q = m \underbrace{c}_{} \Delta T$$

$$specific\ heat\ capacity\ [\frac{J}{kg.K}]$$

Note: 1K = 1°C

- The food calorie is properly noted as a kilocalorie in SI units.
- A calorie is 4.184J.
- So, the Big Mac you're about to eat will cost your diet about two and a half million joules.

Foods > Fast Foods > Burger Sandwiches > Hamburgers

Calories in Big Mac

Without Cheese

Tags: mcdonalds, fast food

Wondering how many calories are in Big Mac?
Free calorie and nutrition data information from Calorie Count.

576 food calories = $576 * 10^3 cal$

Convert to joules

$$576 * 10^3 cal\left(\frac{4.186 J}{1 cal}\right) = 2.4 * 10^6 J$$

Search our food database

1 x sandwich(215.0 g)

Add to Log
Add to Meal
Add to Recipe
Favorite

Nutrition Grade	Calories
C-	576

About nutr. grade   Report bad grade

Nutrition Facts

Serving Size 1 sandwich (215.0 g)

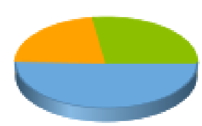
Amount Per Serving	
Calories 576	Calories from Fat 292
	% Daily Value*
Total Fat 32.5g	**50%**
Saturated Fat 12.0g	**60%**
Polyunsaturated Fat 2.8g	
Monounsaturated Fat 14.1g	
Cholesterol 103mg	**34%**
Sodium 742mg	**31%**
Total Carbohydrates 38.7g	**13%**
Protein 31.8g	
Vitamin A 1% •	Vitamin C 2%
Calcium 9% •	Iron 31%

* Based on a 2000 calorie diet

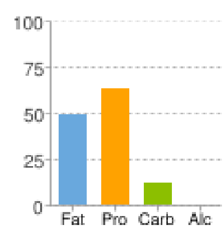
See more extended nutritional details

Nutritional Analysis

Breakdown



Daily Values



Related Foods & Categories

Specific Heat

How much heat energy Q is needed to change the temperature of a substance of mass m by an amount ΔT?

$$Q = mc\Delta T$$

Note:

(a) The heat energy is proportional to m and ΔT.

(b) The proportionality constant c is called the specific heat, which is a material-dependent quantity (see Table 14.3).

(c) The specific heat has the units of J/(kg•K).

(d) Q is positive if it is transferred into the system, and, negative otherwise.

Courtesy of Wenhao Wu

Specific heat

The specific heat capacity of water is approximately;

$$C_{water} = 4190[\frac{J}{kg.K}] \approx 1[\frac{cal}{g.K}] \approx 1[\frac{Btu}{lb.F^\circ}]$$

Note: specific heat capacity is the amount of heat needed per unit mass and per unit temperature change.

$$Q = \underbrace{m}_{\substack{unit\\mass}} \; c \; \underbrace{\Delta t}_{\substack{unit\\temperature\\change}} \rightarrow Q = 1 * c * 1$$

TABLE 14.3 Mean specific heat capacities (constant pressure, temperature range 0°C to 100°C)

	Specific heat capacity (c)	
Material	**J/(kg·K)**	**cal/(g·K)**
Solids		
Lead	0.13×10^3	0.031
Mercury	0.14×10^3	0.033
Silver	0.23×10^3	0.056
Copper	0.39×10^3	0.093
Iron	0.47×10^3	0.112
Marble ($CaCO_3$)	0.88×10^3	0.21
Salt	0.88×10^3	0.21
Aluminum	0.91×10^3	0.217
Beryllium	1.97×10^3	0.471
Ice (−25°C to 0°C)	2.01×10^3	0.48
Liquids		
Ethylene glycol	2.39×10^3	0.57
Ethanol	2.43×10^3	0.58
Water	4.19×10^3	1.00

Q17.5 **Clicker question**

You wish to increase the temperature of a 1.00-kg block of a certain solid substance from 20°C to 25°C. (The block remains solid as its temperature increases.) To calculate the amount of heat required to do this, you need to know

A. the specific heat capacity of the substance.

B. the molar heat capacity of the substance.

C. the heat of fusion of the substance.

D. the thermal conductivity of the substance.

E. more than one of the above.

Heat Capacity

- Substances have an ability to "hold heat" that goes to the atomic level.
- One of the best reasons to spray water on a fire is that it suffocates combustion. Another reason is that water has a huge heat capacity. Stated differently, it has immense thermal inertia. In plain terms, it's good at cooling things off because it's good at holding heat.
- Taking a copper frying pan off the stove with your bare hands is an awful idea because metals have almost no heat capacity. In plain terms, metals give heat away as fast as they can.

Clicker - Questions

You can reach with your bare hand inside a 300°C pizza oven briefly without harm. But you cannot reach into a pot of boiling water at 100°C without being burned. The explanation has to do with differences in;

A. Conductivities
B. Specific heat capacities.
C. Both of these.
D. Neither of these.

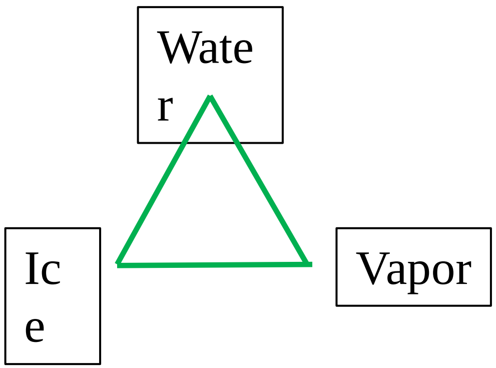
Clicker - Questions

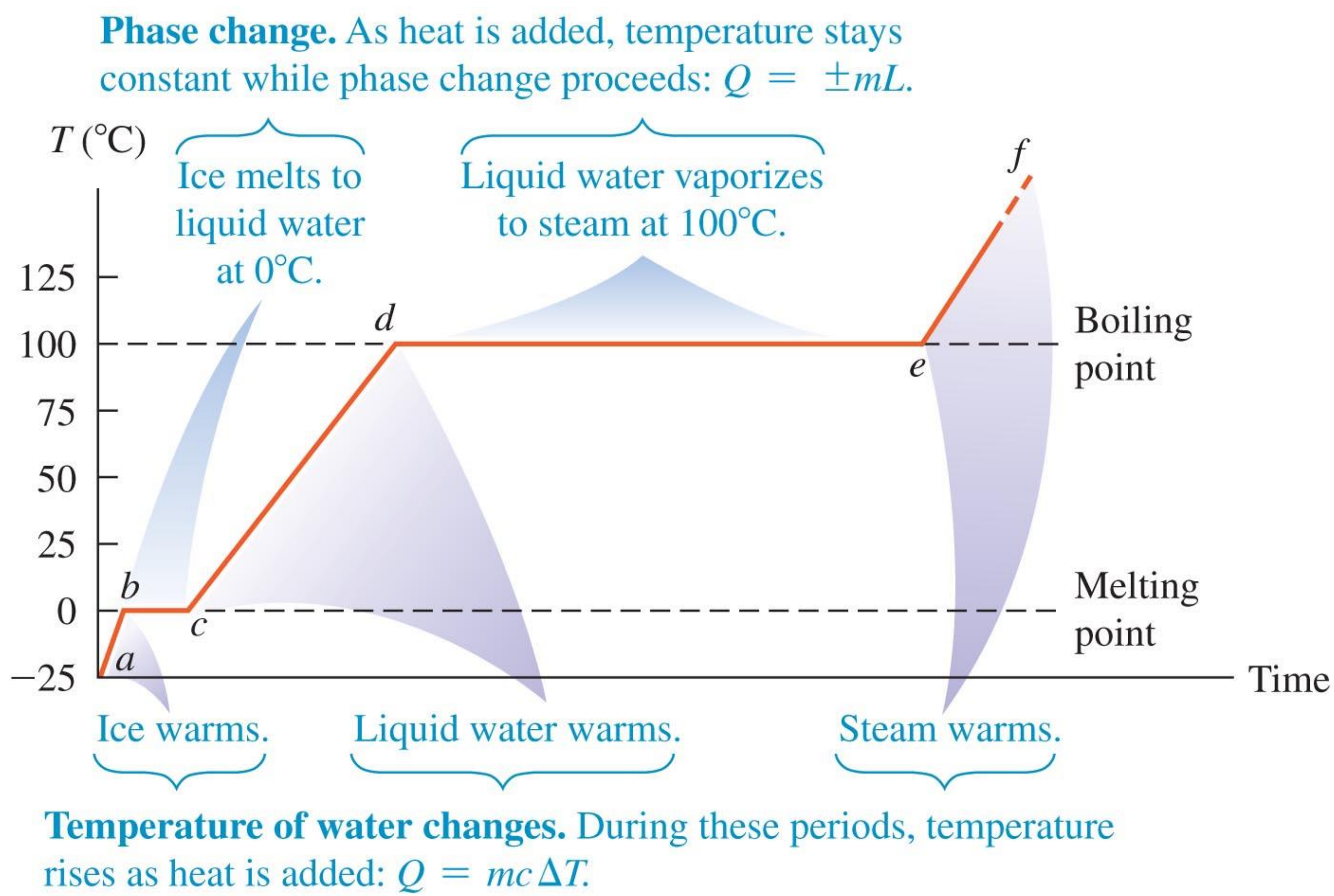
You immerse a 1-kg block of iron in 1-kg of water in an insulated chamber, add 100J of heat, and allow the iron and water to equilibrate to the same temperature. Which has absorbed more heat, the iron or the water?

A. They absorb the same amount of heat.
B. The iron absorbs more heat.
C. The water absorbs more heat.

Water has 10 times the specific heat of iron Q= mc\delta T

14.5 Phase Changes



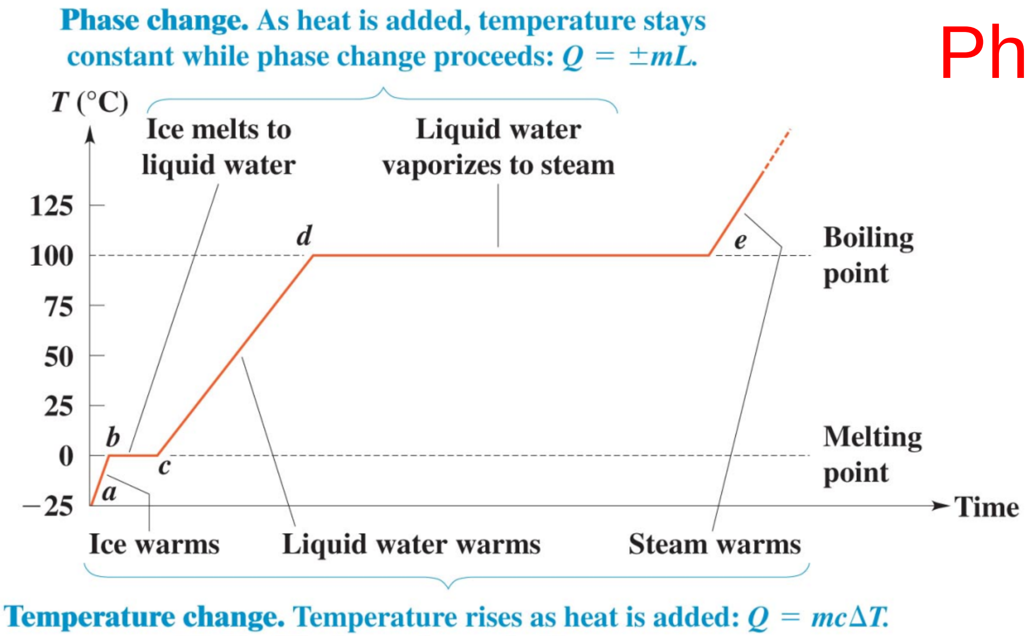


Courtesy of Wenhao Wu

Phase Changes and the Snowflake

- Which is worse to touch for a burn: 100ºC water or 100ºC steam? The steam, because it also contains the energy that it took to become a gas. In the case of water, this is 2.3 MILLION joules per kg of water.
- The snowflake on the left needs to absorb the latent heat of fusion to become a liquid. The metal in the person's hand to the right just did that from the person's body temperature.
- Put ice in water. You have a refreshing drink but also solid water and liquid water in equilibrium.

Phase changes



Example of H_2O

Solid phase = ice
Liquid phase = water
Gaseous phase = steam

Phase changes take place at a definite temperature and are accompanied by absorption or emission of heat.

1kg of ice at 0ºC becomes 1kg of water at 0ºC with supplying the heat of fusion.

Heat of fusion $L_f = 3.34x10^5 \frac{j}{kg}$

$$\underbrace{Q}_{heat} = \pm \underbrace{m}_{mass} L_f$$

This process is reversible

Heat of evaporation $L_v = 2.26x10^6 \frac{j}{kg}$

TABLE 14.4 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	−195.81	201×10^3
Oxygen	54.36	−218.79	13.8×10^3	90.18	−182.97	213×10^3
Ethyl alcohol	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

Note: Boiling and condensation depend on the atmospheric pressure. Water boils in Denver at 95ºC and at 100ºC in Aggieland.

Q17.6

Clicker question

A pitcher contains 0.50 kg of liquid water at 0°C 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, the temperature of the ice-water mixture

A. increases slightly.

B. decreases slightly.

C. first increases slightly, then decreases slightly.

D. remains the same.

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

Example: An ice water mixture comes to equilibrium

$$\Delta Q(water) = mc\Delta T = T_f - T_i$$

$$\Delta Q(\text{ice}) = mc\Delta T + mL_F + mc\Delta T$$

equilibrium : $\Delta Q(water) + \Delta Q(\text{ice}) = 0$

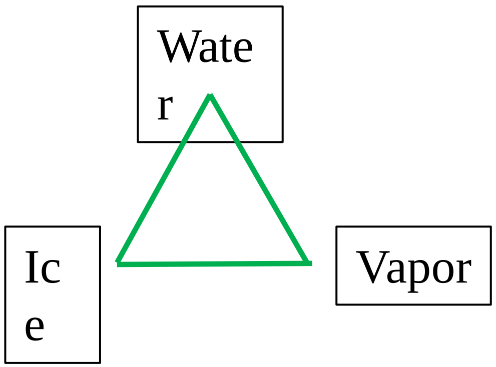
Clicker - Questions

Which requires more heat: Bringing a pan of liquid water from room temperature (20^oC) to the boiling point at 100^oC or converting all of the liquid water to steam at a constant 100^oC?

A. Heating the liquid water.
B. Converting the liquid water to steam.
C. They require the same amount of heat.

B

Phase Changes



Heat Transfer
in Phase Change

$$Q = \pm mL$$

Latent heat of infusion ice:

● The heat energy needs to be absorbed in order to change 1 kg of ice at 0 ºC and normal pressure to 1 kg of water at 0 ºC and normal pressure.

$$L_f = 3.34\times10^5 \text{ J/kg}$$

● The same amount of heat energy is released in a reverse process.

Latent heat of vaporization of water:

● The heat energy needs to be absorbed in order to vaporize 1 kg of water at 100 ºC and normal pressure to 1 kg of vapor at 100 ºC and normal pressure.

$$L_v = 2.26\times10^6 \text{ J/kg}$$

● The same amount of heat energy is released in a reverse process.

Courtesy of Wenhao Wu

14.6 Calorimetry----"Measuring Heat"

Rule: For a "closed" system, the total heat energy is conserved, or $\sum Q = 0$.

Example 14.9 on page 442---Chilling your soda

Given: $m_{\text{lemonade}} = 0.25$ kg, initially at $T_{\text{lemonade, i}} = 20$ ºC, and, ice initially at $T_{\text{ice, i}} = -20$ ºC.

Find: How much ice is to be mixed with the lemonade so that the combined mix has a $T = 0$ ºC with all the ice melted?

Solution: Assume that the ice needed is m_{ice}. This mixing can be separated into a few steps.

(a) The heat that ice absorbs as it warms up from − 20 ºC to 0 ºC:

$$Q_1 = m_{\text{ice}}c_{\text{ice}}[0 - (-20\ ^\circ\text{C})] = m_{\text{ice}}c_{\text{ice}}(20\ ^\circ\text{C}) \qquad \text{(positive)}$$

(a) The heat that ice absorbs as it melts at 0 ºC :

$$Q_2 = m_{\text{ice}}L_{\text{f}} \qquad \text{(positive)}$$

(b) The heat that lemonade releases as it cools from 20 ºC to 0 ºC :

$$Q_3 = m_{\text{lemonade}}c_{\text{water}}[0 - (20)] = -m_{\text{lemonade}}c_{\text{water}}(20\ ^\circ\text{C}) \qquad \text{(negative)}$$

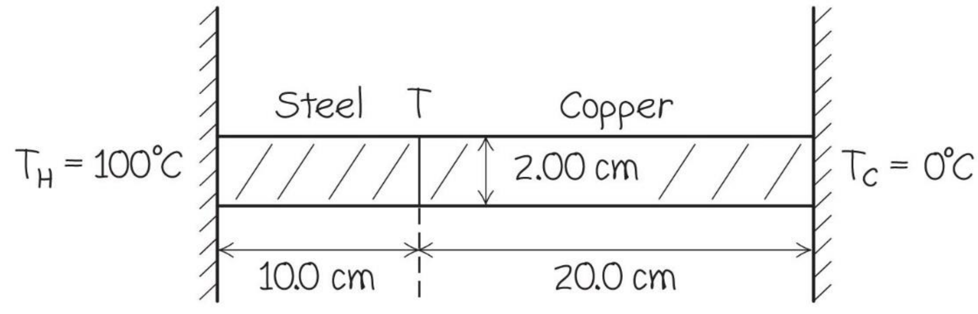
Therefore, $Q_1 + Q_2 + Q_3 = m_{\text{ice}}c_{\text{ice}}(20\ ^\circ\text{C}) + m_{\text{ice}}L_{\text{f}} + [-m_{\text{lemonade}}c_{\text{water}}(20\ ^\circ\text{C})] = 0$,

or, $m_{\text{ice}} = 0.056$ kg

Courtesy of Wenhao Wu

Example 14.11 on page 446
Conduction in two bars in series

Given: As shown in the sketch.
Find: (a) T at the joint
(b) Rate of heat flow.



Solution:
Assume that the joint has temperature T.

Heat flow in the steel bar: $H_s = k_s A \frac{T_H - T}{L_s}$.

Heat flow in the copper bar: $H_c = k_c A \frac{T - T_C}{L_c}$.

Therefore, $k_s A \frac{T_H - T}{L_s} = k_c A \frac{T - T_C}{L_c}$,

or, $(50.2\ \text{W/m•K}) \frac{100\ ^{\circ}\text{C} - T}{0.100\ m} = (385\ \text{W/m•K}) \frac{T - 0\ ^{\circ}\text{C}}{0.200\ m}$.

Joint temperature T = 20.7 ºC.

Heat flow $H_s = k_s A \frac{T_H - T}{L_s} = (50.2\ \text{W/m•K})(0.0200\ m)^2 \frac{100\ ^{\circ}\text{C} - 20.7\ ^{\circ}\text{C}}{0.100\ m} = 15.9\ \text{W}$

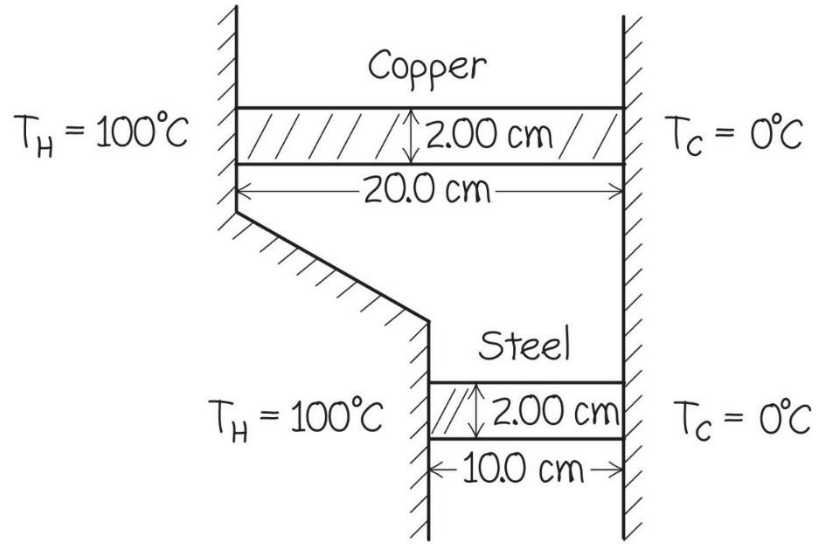
Courtesy of Wenhao Wu

Example 14.12 on page 446

Conduction in two bars in parallel

Given: As shown in the sketch.

Find: Rate of total heat flow in the two bars.



Solution:

Heat flow in the steel bar: $H_s = k_s A \frac{T_H - T}{L_s}$.

Heat flow in the copper bar: $H_c = k_c A \frac{T - T_C}{L_c}$.

Therefore, total heat flow

$$H = k_s A_s \frac{T_H - T}{L_s} + k_c A_c \frac{T - T_C}{L_c},$$

$$= (50.2 \text{ W/m•K})(0.0200\ m)^2 \frac{100\ ^{\circ}\text{C} - 0\ ^{\circ}\text{C}}{0.100\ m} + (385 \text{ W/m•K})(0.0200\ m)^2 \frac{100\ ^{\circ}\text{C} - 0\ ^{\circ}\text{C}}{0.200\ m}.$$

$$= 77.0 \text{ W} + 20.1 \text{ W}$$

$$= 97.1 \text{ W}$$

Courtesy of Wenhao Wu

Heat of combustion

Gasoline $L_c = 46{,}000 \frac{J}{g} = 46x10^6 \frac{J}{kg}$

Energy value of food is measured in kilo-calories (Calories with capital C)

$$1\ kcal = 1000\ cal = 4186\ J$$

Example: 1g of peanut butter “contains 6K calorie”. If completely burned by exercising; it would release;

$$6\ K * 4186 \frac{J}{K} = 25{,}000\ J$$

Note: Efficiency of energy conservation later, body is not totally efficient in “burning” food

The quantity of heat required depends on the material.

Water used about 4 times more than aluminum.

$$\Delta Q = m \underbrace{c}_{specific\,heat\,capacity} \Delta T$$

$$C_{water} = 4190\,J\,kg^{-1}\,(C°)^{-1} = 4.19\,J\,g^{-1}\,(C°)^{-1} = 1\,cal\,g^{-1}\,(C°)^{-1}$$

14.6 Example person with fever

80kg person ran fever at 39^{o}C instead of normal 37^{o}C. Assume human body is mostly water, how much more heat is required?

$$\Delta Q = mc\Delta T = 80 * 4190 * 2 = 6.7x10^{5}J\,\frac{1cal}{4.19J}$$
$$= 1.6x10^{5}\ cal = 160\ kcal = 160\ food\ value\ calories$$

14.7 Heat transfer

Conduction

Heat energy is transferred from one place to another via the interactions between the electrons and lattices.

Convection

Heat energy is transferred from one place to another via the flow of mass.

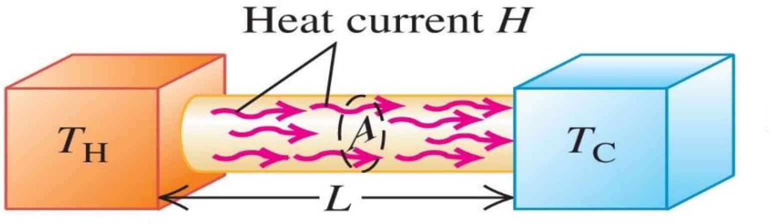
Radiation

Heat energy is transferred from one place to another via electromagnetic radiation.

Courtesy of Wenhao Wu

Heat Conduction

$$H = \frac{\Delta Q}{\Delta t} = kA\frac{T_H - T_C}{L}.$$



Notes:

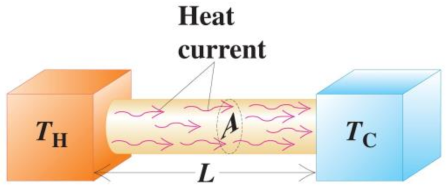
(a) The temperature T can be given in either Kelvin or Celsius.

(b) $H = \Delta Q/\Delta t$ is the rate of heat transfer.

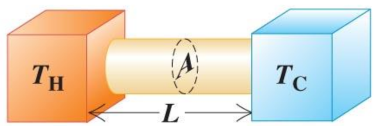
(c) The thermal conductivity k is material-dependent (see Table 14.5).

(d) A is the cross-section area of the object and L is the length.

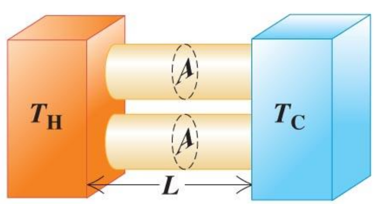
Courtesy of Wenhao Wu



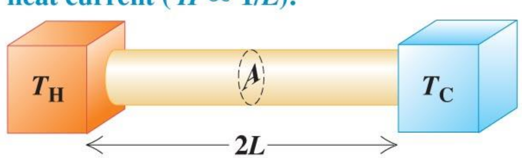
Heat current $H = kA\frac{T_H - T_C}{L}$



Doubling the cross-sectional area of the conductor doubles the heat current ($H \propto A$ **):**



Doubling the length of the conductor halves the heat current ($H \propto 1/L$ **):**



Heat Transfer

a) Conduction
b) Convection
c) Radiation

1. Conduction:

Objects are in contact and heat is transferred from the hotter to the colder object.

$$\underbrace{H}_{\substack{heat\\current}} = \frac{\Delta Q}{\Delta t}$$

Experimentally, it is proportional to contact area and ΔT , and inversely to length "L".

$$H = \frac{\Delta Q}{\Delta t} = \underbrace{k}_{\substack{thermal\\conductivity}} \; \underbrace{A}_{area} \; \underbrace{\left(\frac{T_H - T_C}{L}\right)}_{\substack{\frac{temperature\ difference}{unit\ length}\\=temperature\ gradient}}$$

$$\rightarrow \text{Watt} = \frac{\text{J}}{\text{s}} = \frac{W.m^2.K}{m.K.m} \qquad \text{unit of k} = \left[\frac{W}{m.K}\right]$$

Note: Be consistent in units.

Standard units are W, m, K, kg etc.

TABLE 14.5 Thermal conductivities

Material	k (W/(m·K))
Metals	
Lead	34.7
Steel	50.2
Brass	109
Aluminum	205
Copper	385
Silver	406
Other solids (representative values)	
Styrofoam™	0.01
Fiberglass	0.04
Wood	0.12–0.04
Insulating brick	0.15
Red brick	0.6
Concrete	0.8
Glass	0.8
Ice	1.6
Gases	
Air	0.024
Helium	0.14

A house has a layer of wood 3cm thick on the outside and a layer of Styrofoam insulation 2.2 cm thick on the inside wall surface. The wood has a thermal conductivity of k= 0.08 W/m K and Styrofoam has k=0.01W/m K. The interior surface is is at 19 $°C$ and the exterior surface is at -10 $°C$

a) what is the temperature where wood and Styrofoam meet?

b) What is the rate of heat flow per square meter through that wall?

14.54. Set Up: The heat current Q/t is the same through the wood as through the Styrofoam™.

Solve: (a) $\frac{Q}{t} = \frac{kA(T_H - T_C)}{L}$ and $\left(\frac{Q}{t}\right)_w = \left(\frac{Q}{t}\right)_s$ gives $\frac{k_w A(T - [-10.0°C])}{L_w} = \frac{k_s A(19.0°C - T)}{L_s}$.

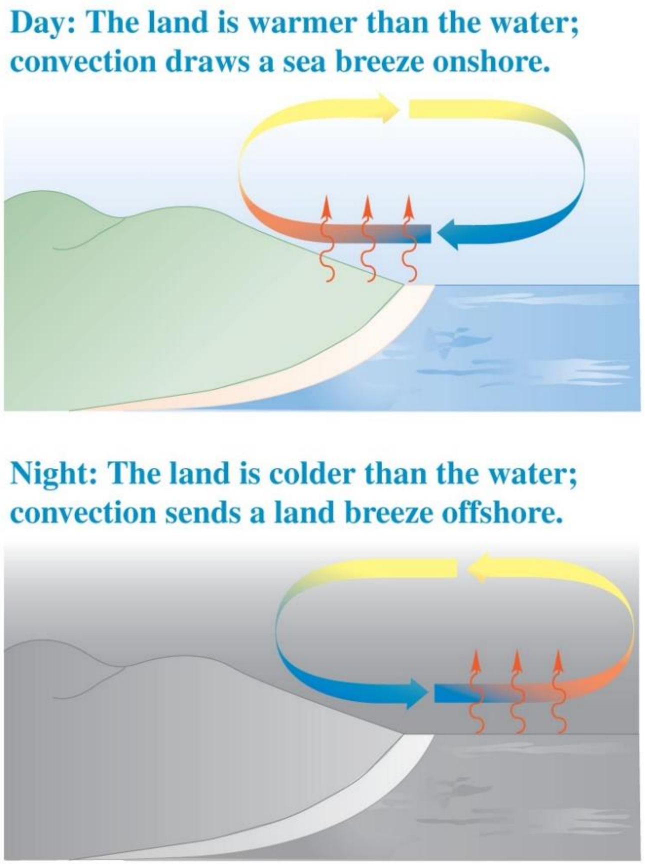
$$\frac{[0.080\ W/(m\cdot K)](T + 10.0°C)}{0.030\ m} = \frac{[0.010\ W/(m\cdot K)](19.0°C - T)}{0.022\ m}$$

$2.67(T + 10.0°C) = 0.455(19.0°C - T)$ and $T = \frac{26.7°C - 8.65°C}{2\ 3.125} = -5.8°C$

(b) $\left(\frac{Q}{tA}\right)_w = \frac{k(T_H - T_C)}{L} = \frac{[0.080\ W/(m\cdot K)](-5.8°C + 10.0°C)}{0.030\ m} = 11\ W/m^2$

Or, $\left(\frac{Q}{tA}\right)_s = \frac{[0.010\ W/(m\cdot K)](19.0°C - [-5.8°C])}{0.022\ m} = 11\ W/m^2$, which checks.

Reflect: k is much smaller for the Styrofoam™ so the temperature gradient across it is much larger than across the wood.



2. Convection

Transfer of heat by the motion of a mass of fluid from one region of space to another.

Examples:
(a) Hot air and hot water home heating systems.
(b) Cooling by radiator of a car
(c) Heating of our body by blood flow
(d) Convection in the atmosphere, glider pilots use thermal updrafts

Heat Q is proportional to surface area and proportional to $\frac{5}{4}\Delta T$, complicated "wind-chill factors"

3. Radiation

Heat transfer by light in particular infra-red light

$$H = Ae\sigma T^4$$ Stefan-Boltzmann

$$\sigma = 5.6705x10^{-8}\frac{W}{m^2K^4}$$

e = emissivity (dimensionless)
e = 1 blackbody

Emissivity varies zero to one
Emissivity of the earths atmosphere varies with cloud cover (on a clear sky e =1)

Clicker - Questions

Doctor john can quickly walk barefoot across red hot coals of wood without harm because of ?

A. Mind of matter.
B. Reasons that are outside mainstream physics.
C. Basic physics concepts.

Clicker - Questions

Why is it significantly colder on a winter night under a clear sky than a cloudy sky?

Radiation

Stefan-Boltzmann law of heat radiation: $H = \frac{\Delta Q}{\Delta t} = Ae\sigma T^4$.

Notes: (a) The temperature T must be in the Kelvin scale.

(b) $\sigma = 5.6705 \times 10^{-8}$ W/(m^2•K^4) is the Stefan-Boltzmann constant.

(c) A is the surface area of the object.

(d) e is the emissivity of the object, and is less than 1.

Example 14.14 on page 449---radiation from human body

Given: A, e, body temperature T_b = 30 ºC, surrounding temperature T_s = 20 ºC.

Find: Net rate of heat loss.

Solution:

(a) Heat loss to surrounding: $H = Ae\sigma T_b^4$ with T_b = (273 + 30) K = 303 K

(b) Heat received from the surrounding:

$H = Ae\sigma T_s^4$ with T_b = (273 + 20) K = 293 K

(c) Net heat loss = $H = Ae\sigma T_b^4 - Ae\sigma T_s^4 = Ae\sigma\left(T_b^4 - T_s^4\right) = 72$ W

Courtesy of Wenhao Wu

3. Radiation

Radiation from the human body; T=30^{o}C=30+273=303K and surrounding T=20^{o}C=20+273=293K. (Assume emissivity ≈1) Also the body area is $1.2\ m^2$ 1.2

Loss

$$H = Ae\sigma T^4 = (1.2\ m^2)1\left(5.67x10^{-8}\frac{W}{m^2K^4}\right)(303)^4 = 574\ W$$

Gain

$$H = Ae\sigma(T^4 - T_s{}^4) = 1.2(5.67x10^{-8})(303^4 - 293^4) = 72W$$

Clicker - Questions

Suppose in a restaurant your coffee is served about 5 or 10 minutes before you are ready for it. In order that it be as hot as possible when you drink it, should you pour in the room-temperature cream

a)right away b) when you are ready to drink the coffee c) It does not matter?

Example 14.9 Chilling your soda

A physics student wants to cool 0.25 kg of Diet Omni-Cola (mostly water) initially at 20°C by adding ice initially at -20°C. How much ice should she add so that the final temperature will be 0°C with all the ice melted? Assumer that the heat capacity of the paper container may be neglected.

$$\boldsymbol{Q_{OCola}} = m_{OCola}C_{OCola}\Delta T_{OCola} = (0.25\text{ kg})\left(4190\,\frac{\text{J}}{\text{kg}\cdot K}\right)(0°\text{C} - 20°\text{C}) = \mathbf{-21{,}000\ J}$$

$$\boldsymbol{Q_{ice}} = m_{ice}C_{ice}\Delta T_{ice} = (m_{ice})\left(2.0\times10^{3}\,\frac{J}{kg\cdot K}\right)(0°C - (-20°\text{C})) = \boldsymbol{m_{ice}}\left(\mathbf{4.0\times10^{4}\,\frac{J}{kg}}\right)$$

$$\boldsymbol{Q_{melt}} = m_{ice}L_f = \boldsymbol{m_{ice}}\left(\mathbf{3.34\times10^{5}}\,\boldsymbol{\frac{J}{kg}}\right)$$

$$Q_{OCola} + Q_{ice} + Q_{melt} = 0$$

$$-21{,}000\,J + m_{ice}\left(4.0\times10^{4}\,\frac{J}{kg}\right) + m_{ice}\left(3.34\times10^{5}\,\frac{J}{kg}\right) = 0$$

$$m_{ice} = 0.056\,kg = 56\text{ g}$$

Clicker - Questions

You are a consultant for a cookware manufacturer who wishes to make a pan that will have two features:

1. Absorb thermal energy from a flame as quickly as possible.
2. Have a cooking surface that stays as hot as possible when heated

You should recommend a pan with the

A. Outer and cooking surface black.
B. Outer and cooking surface shiny.
C. Outer surface shiny and cooking surface black.
D. Outer surface black and cooking surface shiny.

C

Problem 14.74: Hot air in a physics lecture

(a) Student listening has a heat output of 100W. How much heat goes into the lecture hall from 90 students over a 50 min lecture?
(b) Assume that all that heat goes to the 3200 m^3 of air in the room and no air escapes. How much will the temperature raise during the 50 min lecture? ($c_{air} = 1020 \frac{J}{kg.K}$ and $\rho_{air} = 1.2 \frac{kg}{m^3}$)
(c) If a class takes an exam, the heat output per student is 280W. What is the room temperature after the 50 min exam?

Mass of air = $m = \rho.V = 1.2 \frac{kg}{m^3} * 3200 m^3 = 3840 kg$ and $1W = 1\frac{J}{s}$

$(a)\, Q = mc\Delta T \;\rightarrow\; \Delta T = \frac{Q}{mc}$ and $Q = 50 * 60 s * 90 students * 100 \frac{J}{s} = 2.7x10^7\, J$

(b)) $\Delta T = 2.7x10^7 \frac{J}{3840 kg\; 1020 \frac{J}{kg.K}} = 6.89°C$

(c) $\Delta T = 6.89°C \frac{280W}{100W} = 19.3°C$

BIO **Jogging in the heat of the day.** You have probably seen people jogging in extremely hot weather and wondered "Why?" As we shall see, there are good reasons not to do this! When jogging strenuously, an average runner of mass 68 kg and surface area 1.85 m^2 produces energy at a rate of up to 1300 W, 80% of which is converted to heat. The jogger radiates heat, but actually absorbs more from the hot air than he radiates away. At such high levels of activity, the skin's temperature can be elevated to around 33°C instead of the usual 30°C. (We shall neglect conduction, which would bring even more heat into his body.) The only way for the body to get rid of this extra heat is by evaporating water (sweating). (a) How much heat per second is produced just by the act of jogging? (b) How much *net* heat per second does the runner gain just from radiation if the air temperature is 40.0°C (104°F)? (Remember that he radiates out, but the environment radiates back in.) (c) What is the *total* amount of excess heat this runner's body must get rid of per second? (d) How much water must the jogger's body evaporate every minute due to his activity? The heat of vaporization of water at body temperature is 2.42×10^6 J/kg. (e) How many 750 mL bottles of water must he drink after (or preferably before!) jogging for a half hour? Recall that a liter of water has a mass of 1.0 kg.

Jogging in the heat of the day

Assume a runner produces a rate of energy of 1.3 kW wit 80% into heat

(a) How much heat is generated by jogging? (use 80% of power is converted by jogging)

$$P_{jog} = 0.8 * 1300 = 1.04x10^3 \frac{J}{s}$$

(b) How much heat does the runner gain from 40ºC air of the environment?

$$H_{net} = Ae\sigma(T^4 - T_s^4) = 1.85 * 1 * (5.67x10^{-8})[306^4 - 313^4] = -87.1 \text{ W}$$

The person gains 87.1 J/s by radiation.

(c) The total excess heat (1040+87) J/s=1130 J/s

(d) In 1min=60s the runner must dispose 60s*1130J/s=6.78x10^{4}J. This heat goes into sweating = evaporation of water;

Mass of water $m = \frac{Q}{L_v} = \frac{6.78x10^4}{2.42x10^5} = 28g$

(e) In a half hours or 30 minutes the runner looses 30minX0.028kg/min=0.84kg. The runner must drink 0.84kg(1L/1kg)=0.84L of water

Clicker - Questions

If you wish to save fuel and you are going to leave your cool house for a half day or so on a very hot day. Should you turn your air conditioning thermostat?

A. Up a bit
B. Off altogether.
C. Let it remain at the cool room temperature you desire.