Chapter 18

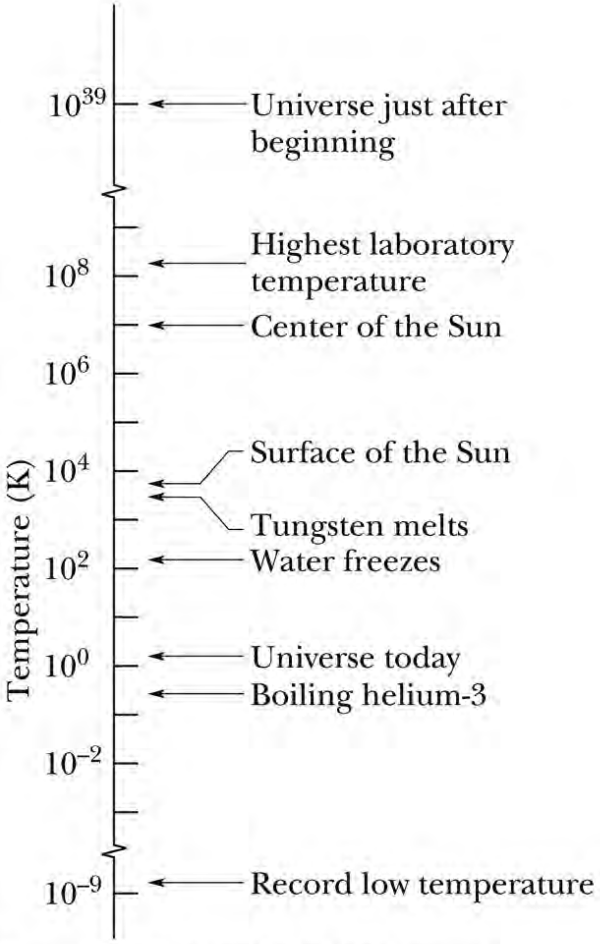
Temperature, Heat, and the First Law of Thermodynamics

18-1 Temperature

- * Identify the lowest temperature as 0 on the Kelvin scale (absolute zero).
- * Explain the zeroth law of thermodynamics.
- * Explain the conditions for the triple-point temperature.
- * Explain the conditions for measuring a temperature with a constant-volume gas thermometer.
- * For a constant-volume gas thermometer, relate the pressure and temperature of the gas in some given state to the pressure and temperature at the triple point.

18-1 Temperature

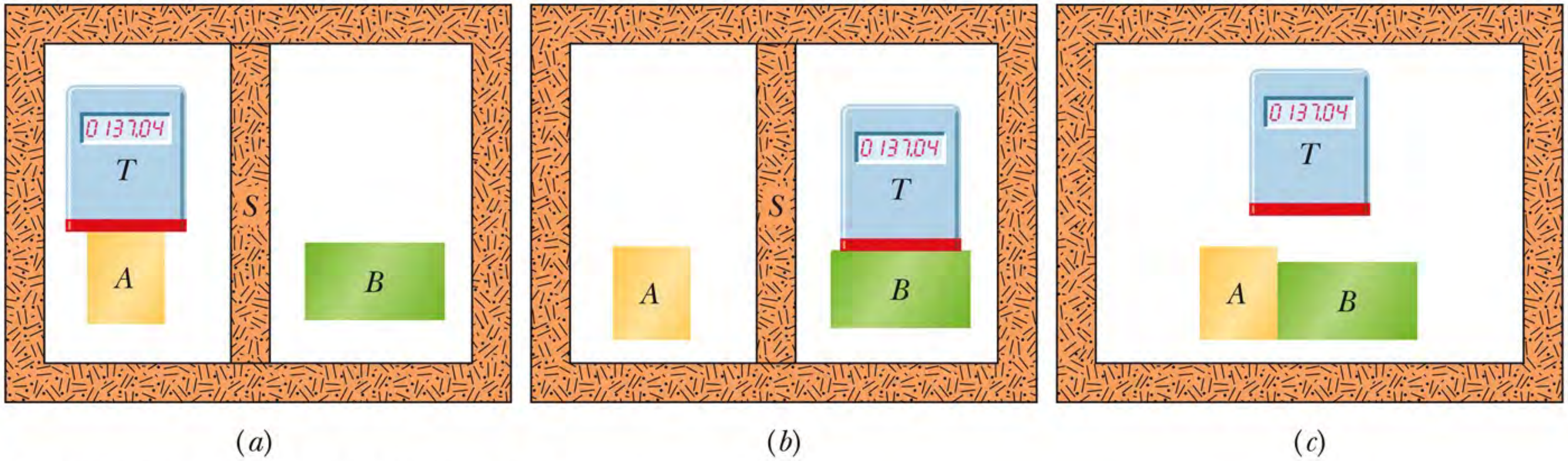
- **Thermodynamics** is the study and application of the thermal energy (often called the internal energy) of systems. One of the central concepts of thermodynamics is temperature.
- **Temperature** is an SI base quantity related to our sense of hot and cold. It is measured with a thermometer, which contains a working substance with a measurable property, such as length or pressure, that changes in a regular way as the substance becomes hotter or colder. Physicists measure temperature on the **Kelvin scale**, which is marked in units called kelvins.



18-1 Temperature

Two bodies are in thermal equilibrium if they are at the same temperature throughout and therefore no heat will flow from one body to the other.

The Zeroth Law of Thermodynamics



If bodies A and B are each in thermal equilibrium with a third body T, then A and B are in thermal equilibrium with each other.

18-1 Temperature

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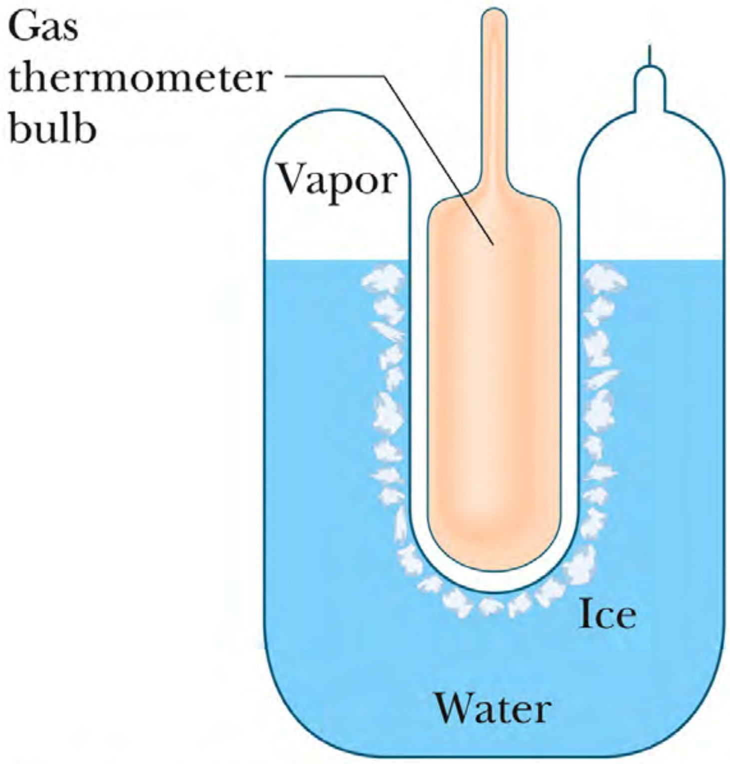
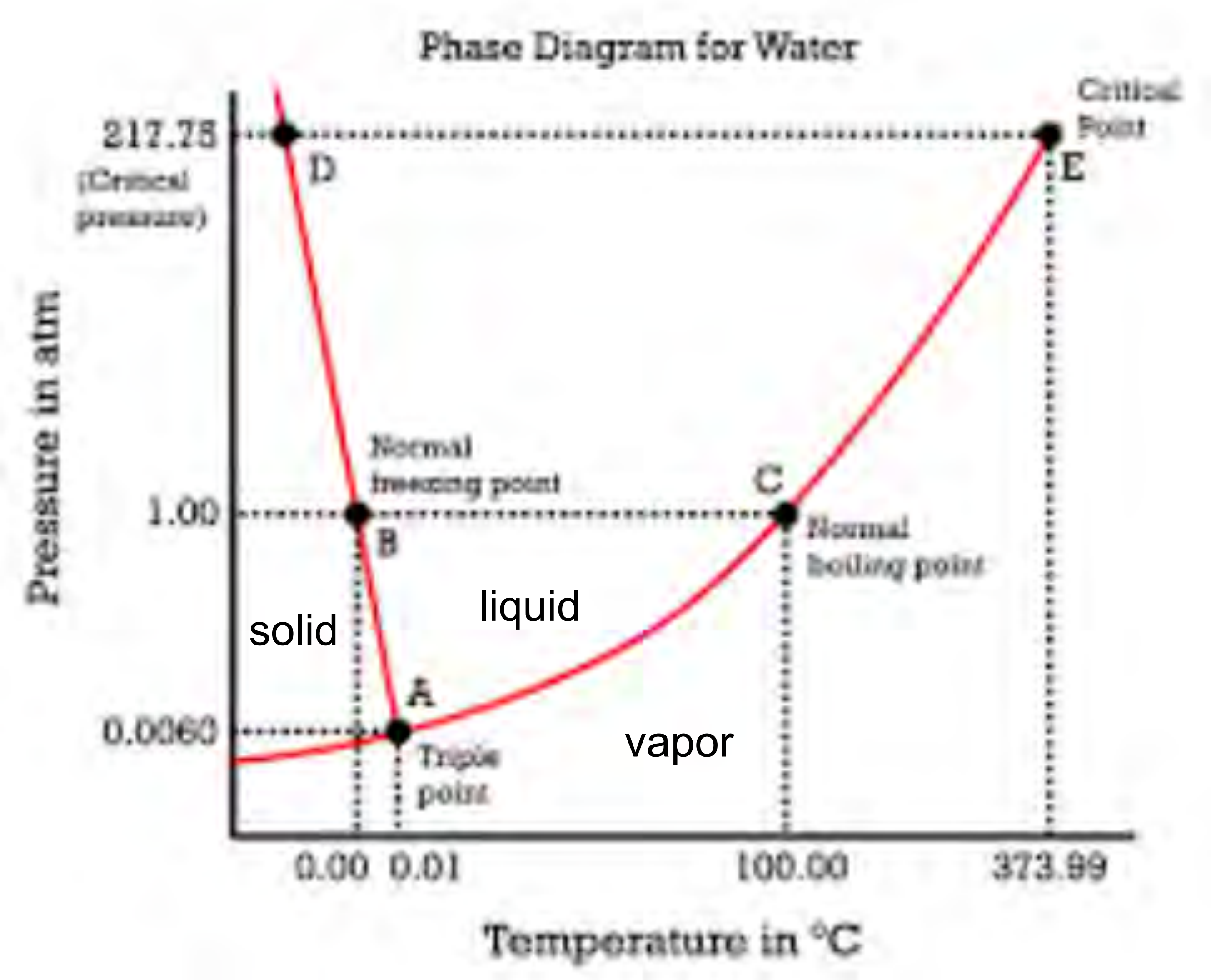
Triple Point of Water

- The Triple point of water is the point in which solid ice, liquid water, and water vapor coexist in thermal equilibrium. (This does not occur at normal atmospheric pressure.)
- By international agreement, the temperature of this mixture has been defined to be **273.16 K**. The bulb of a constant-volume gas thermometer is shown inserted into the well of the cell.



A triple-point cell


Phase Diagram for Water
217.75
(Critical pressure)
D
Critical Point
E
Normal freezing point
C
1.00
B
Normal boiling point
solid
liquid
A
0.0060
vapor
Triple point
0.00
0.01
100.00
373.99
Pressure in atm
Temperature in °C

18-2 The Celsius and Fahrenheit Scales

- Convert a temperature between any two (linear) temperature scales, including the Celsius, Fahrenheit, and Kelvin scales.

- Identify that a change of one degree is the same on the Celsius and Kelvin scales.

18-2 The Celsius and Fahrenheit Scales

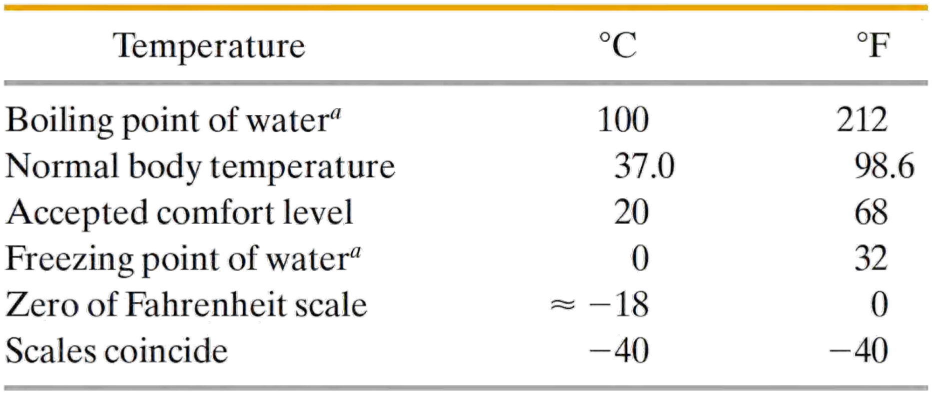
- The **Celsius temperature scale** is defined by

$$T_C = T - 273.15°,$$

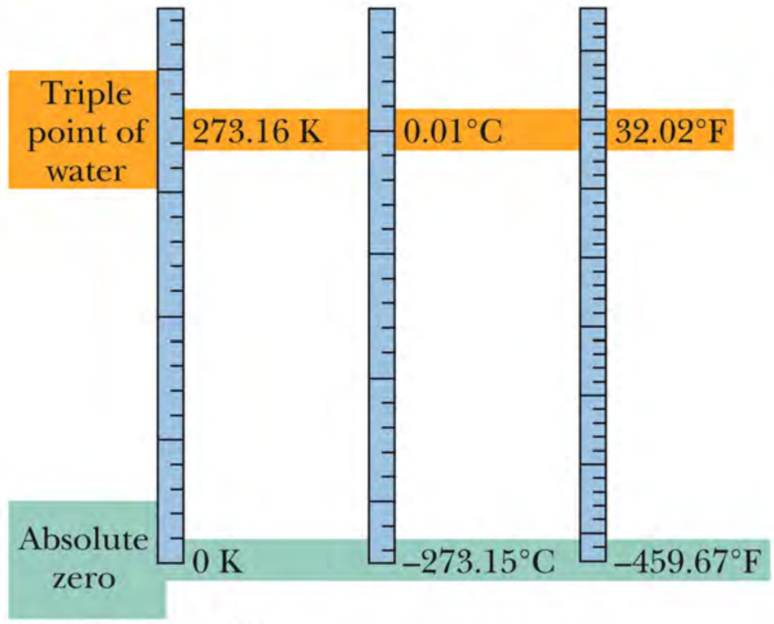
with T in kelvins.

- The **Fahrenheit temperature scale** is defined by

$$T_F = \tfrac{9}{5}T_C + 32°.$$



Temperature	°C	°F
Boiling point of water[a]	100	212
Normal body temperature	37.0	98.6
Accepted comfort level	20	68
Freezing point of water[a]	0	32
Zero of Fahrenheit scale	≈ −18	0
Scales coincide	−40	−40



The Kelvin,Celsius,and Fahrenheit temperature scales compared.

Different temperature scales:

If T and T' are two different temperature scales:

$T' = aT+b$ with $a>0$

why $a>0$?

Example: Z temperature scale

In the Z temperature scale, water boils at 65Z and freezes at -14Z. What temperature in Fahrenheit scale corresponds to temperature -98Z?

Answer: -159F

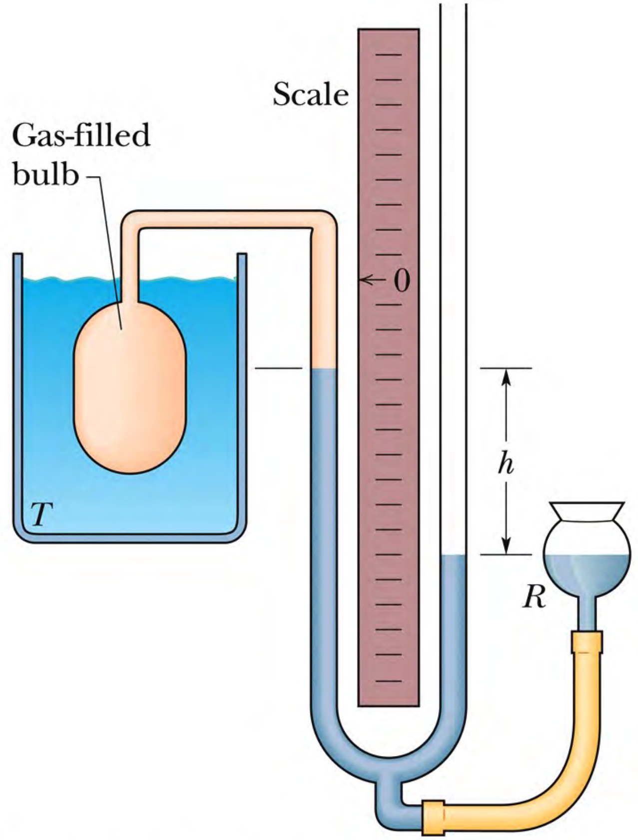
18-1 Temperature

Constant-Volume Gas Thermometer

- It consists of a gas-filled bulb connected by a tube to a mercury manometer. By raising and lowering reservoir R, the mercury level in the left arm of the U-tube can always be brought to the zero of the scale to keep the gas volume constant.

- the recipe for measuring a temperature with a gas thermometer, where *p* is the observed pressure and p_3 is the pressure at the triple point of water, is

$$T = (273.16\ \mathrm{K})\left(\lim_{\text{gas}\to 0} \frac{p}{p_3}\right).$$



Constant-Volume Gas Thermometer

18-3 Thermal Expansion

* For one-dimensional thermal expansion, apply the relationship between the temperature change ΔT, the length change ΔL, the initial length L, and the coefficient of linear expansion α.

* For two-dimensional thermal expansion, use one dimensional thermal expansion to find the change in area.

* For three-dimensional thermal expansion, apply the relationship between the temperature change ΔT, the volume change ΔV, the initial volume V, and the coefficient of volume expansion β.

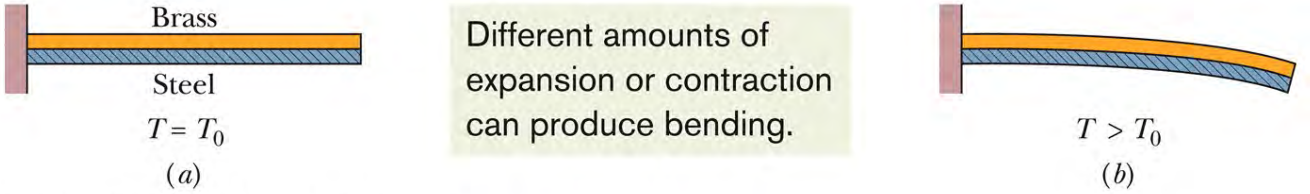
18-3 Thermal Expansion

Linear Expansion

- All objects change size with changes in temperature. For a temperature change ΔT, a change ΔL in any linear dimension L is given by

$$\Delta L = L\alpha\,\Delta T,$$

in which α is the **coefficient of linear expansion**.



Different amounts of expansion or contraction can produce bending.

The strip bends as shown at temperatures above this reference temperature. Below the reference temperature the strip bends the other way. Many thermostats operate on this principle, making and breaking an electrical contact as the temperature rises and falls.

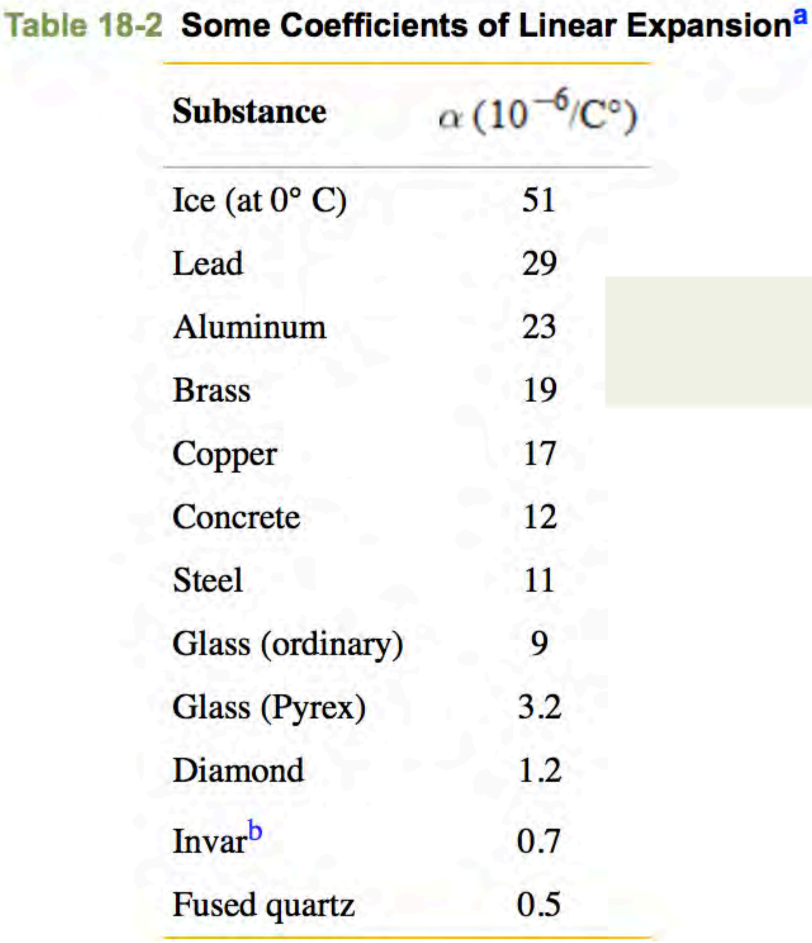


Table 18-2 Some Coefficients of Linear Expansion[a]

Substance	$\alpha\ (10^{-6}/\text{C}°)$
Ice (at 0° C)	51
Lead	29
Aluminum	23
Brass	19
Copper	17
Concrete	12
Steel	11
Glass (ordinary)	9
Glass (Pyrex)	3.2
Diamond	1.2
Invar[b]	0.7
Fused quartz	0.5

$$\Delta L = L\alpha\,\Delta T,$$

18-3 Thermal Expansion

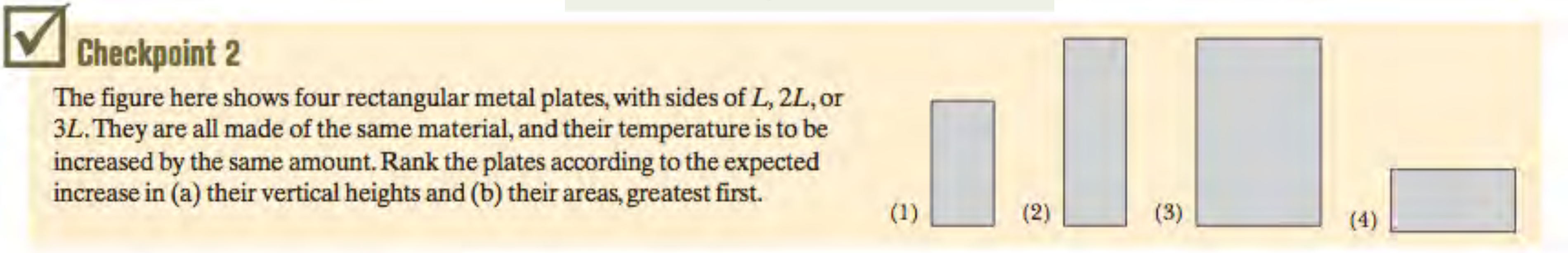
Volume Expansion

- If the temperature of a solid or liquid whose volume is *V* is increased by an amount *ΔT*, the increase in volume is found to be

$$\Delta V = V\beta\Delta T,$$

in which β is the **coefficient of volume expansion** and is related to linear expansion in this way,

$$\beta = 3\alpha.$$



☑ **Checkpoint 2**

The figure here shows four rectangular metal plates, with sides of L, $2L$, or $3L$. They are all made of the same material, and their temperature is to be increased by the same amount. Rank the plates according to the expected increase in (a) their vertical heights and (b) their areas, greatest first.

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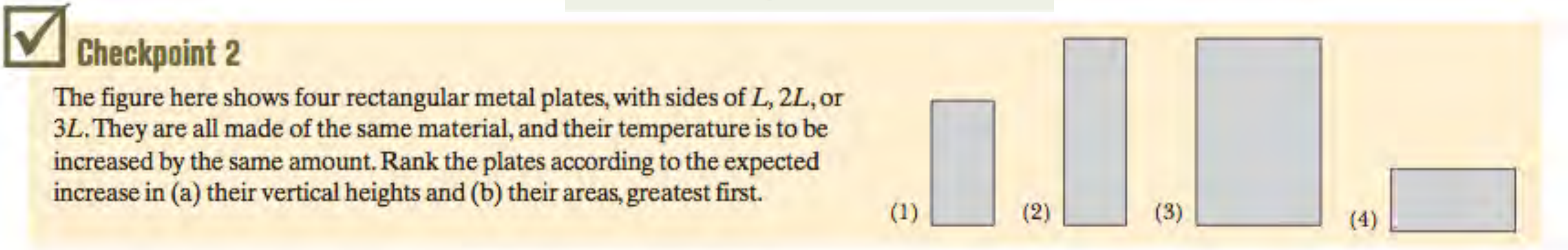

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Answer: (a) – 2 and 3 (same increase in height), then 1, and then 4
(b) – 3, then 2, then 1 and 4 (identical increase in area)

$$\Delta V = V\beta\,\Delta T,$$

$$\beta = 3\alpha.$$

why?

$$\Delta L = L\alpha\,\Delta T,$$

$V=L_1L_2L_3$

$\Delta V=L_1L_2\Delta L_3+L_1\Delta L_2L_3+\Delta L_1L_2L_3=\alpha\Delta T(L_1L_2L_3+L_1L_2L_3+L_1L_2L_3)=$

$=3\alpha\Delta TL_1L_2L_3=3\alpha\Delta TV=\beta\Delta TV$

18.6.4. A circular hole is drilled through a penny. Complete the following statement: When the penny is heated,

a) the hole decreases in diameter.

b) the metal part of the penny expands outward, but the size of the hole does not change.

c) the area of the hole increases by the same amount as a similar area of the metal does.

d) linear expansion causes the shape of the hole to become slightly oval-shaped.

e) the area of the hole increases more than a similar area of the metal does

18.6.4. A circular hole is drilled through a penny. Complete the following statement: When the penny is heated,

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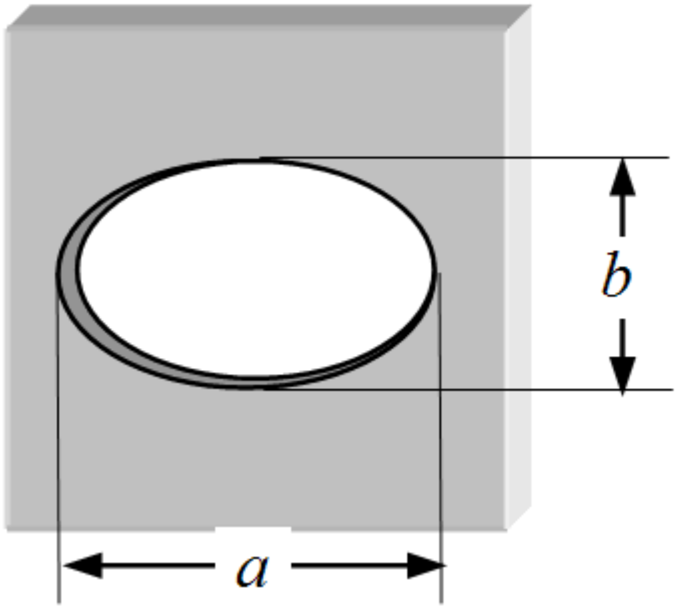
18.6.3. A square plate made of lead has an oval-shaped hole. The oval may be described by the lengths *a* and *b* as shown in the drawing. Which of the following correctly describes the plate after its temperature is increased by two hundred Celsius degrees?



a) The size of the plate will increase, but *a* and *b* will both decrease.

b) The size of the plate will remain unchanged, but *a* and *b* will both increase.

c) The size of the plate will increase, and *a* and *b* will both increase.

d) The size of the plate will remain unchanged, but *a* and *b* will both decrease.

e) The size of the plate will increase, but only *a* will increase.

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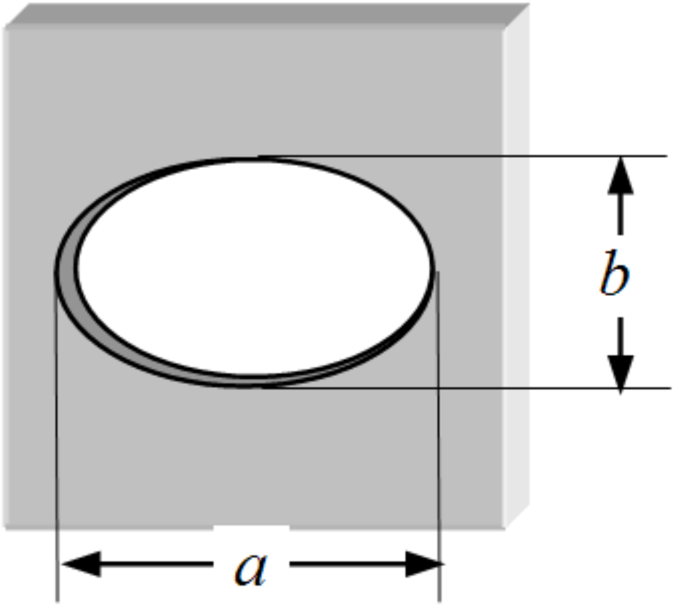

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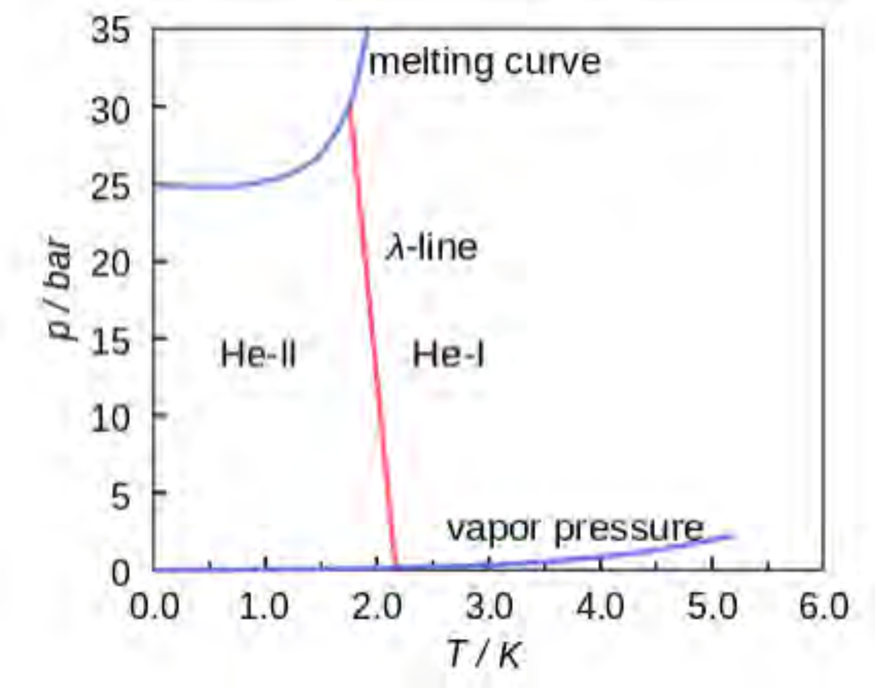
e) The size of the plate will increase, but only *a* will increase.

$$\Delta V = V\beta\Delta T,$$

Can β be negative?

1) Water between 4°C and 0°C expands when cooled

2) Helium below 2.17K expands when cooled

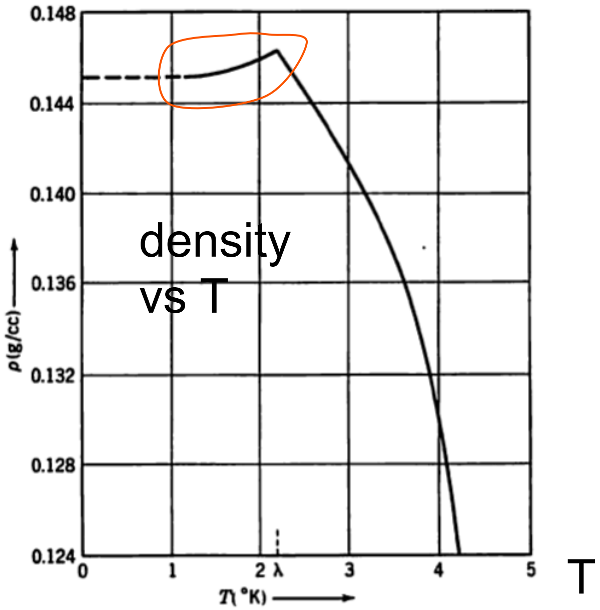


Lambda transition in superfluid ^{4}He:

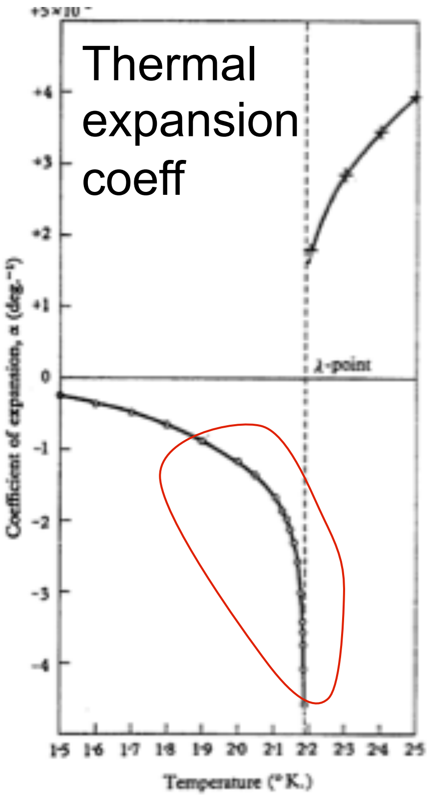
System expands below T_λ

(density decreases)

(Onnes 1911)

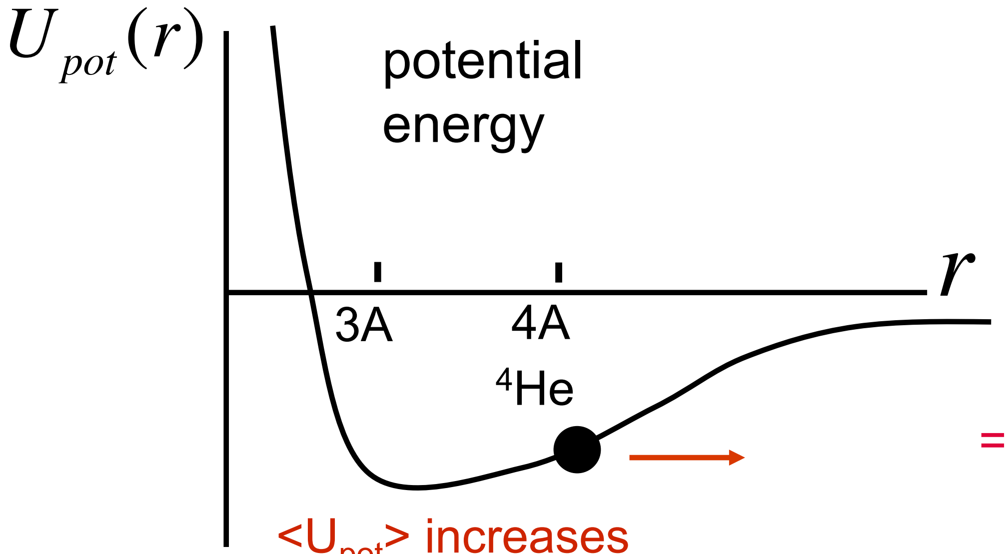


density vs T



Thermal expansion coeff

Atkins+ Edwards (1955)



potential energy

<U_{pot}> increases when system expands

Energy = potential energy (U_{pot}) + kinetic energy

==> kinetic energy decreases in the transition to the superfluid state

18-4 Absorption of Heat

* *thermal energy* is associated with the random motions of the microscopic bodies in an object.

* heat *Q* is the amount of transferred energy (either to or from an object's thermal energy) due to a temperature difference between the object and its environment.

* Convert energy units between various measurement systems.

* Convert between mechanical or electrical energy and thermal energy.

* For a temperature change ΔT of a substance, relate the change to the heat transfer Q and the substance's heat capacity *C*.

* For a temperature change ΔT of a substance, relate the change to the heat transfer Q and the substance's specific heat *c* and mass *m*.

18-4 Absorption of Heat

* Identify the three phases of matter.

* For a phase change of a substance, relate the heat transfer *Q*, the heat of transformation *L*, and the amount of mass *m* transformed.

* Identify that if a heat transfer *Q* takes a substance across a phase-change temperature, the transfer must be calculated in steps: (a) a temperature change to reach the phase-change temperature, (b) the phase change, and then (c) any temperature change that moves the substance away from the phase-change temperature.

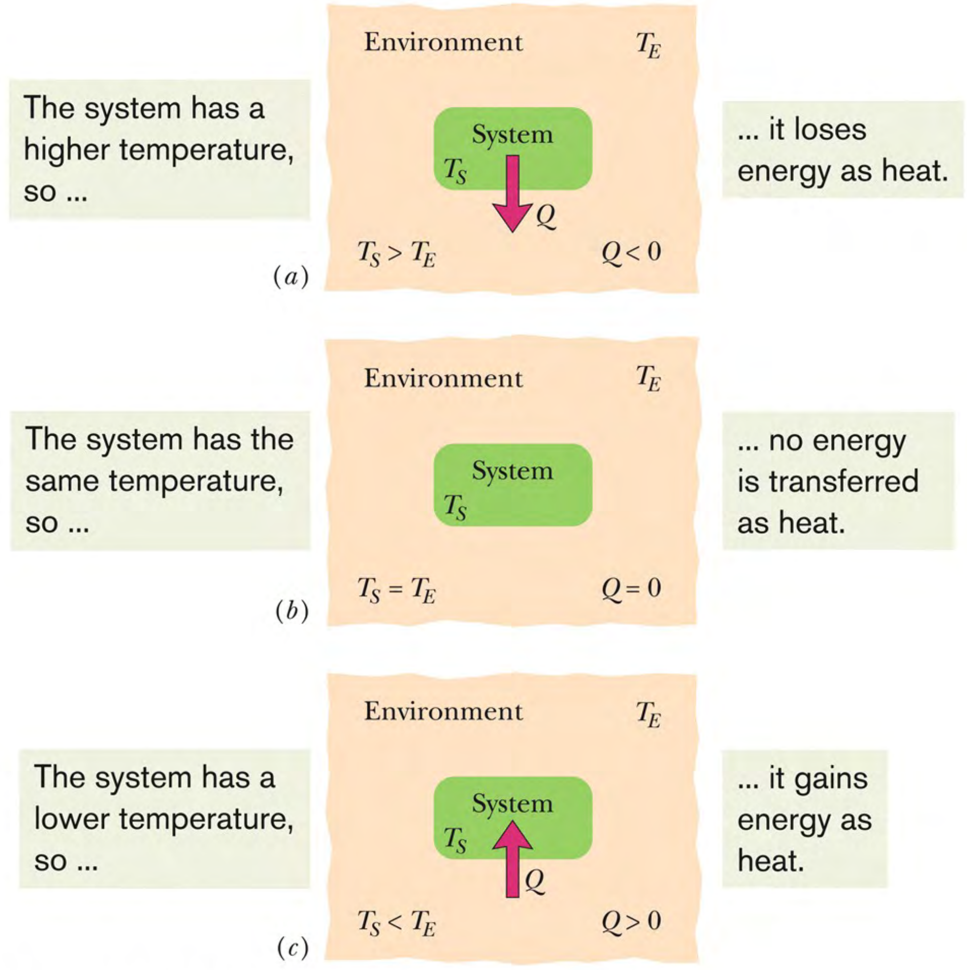
18-4 Absorption of Heat

Temperature and Heat

- Heat Q is energy that is transferred between a system and its environment because of a temperature difference between them.

- It can be measured in joules (J), calories (cal), kilocalories (Cal or kcal), or British thermal units (Btu).**We won't use BTU**

$$1 \text{ cal} = 3.968 \times 10^{-3} \text{ Btu} = 4.1868 \text{ J.}$$


The system has a higher temperature, so ...

... it loses energy as heat.

The system has the same temperature, so ...

... no energy is transferred as heat.

The system has a lower temperature, so ...

... it gains energy as heat.

Absorption of Heat by Solids and Liquids

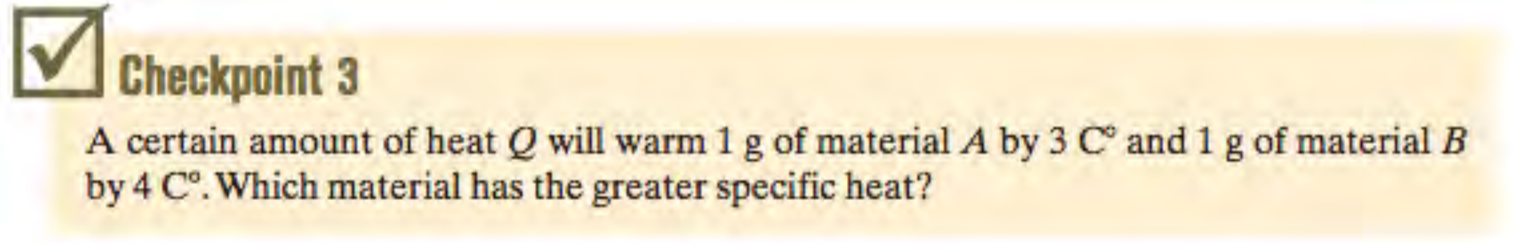
- The **heat capacity** *C* of an object is the proportionality constant between the heat *Q* that the object absorbs or loses and the resulting temperature change *ΔT* of the object; that is,

$$Q = C\,\Delta T = C(T_f - T_i),$$

in which T_i and T_f are the initial and final temperatures of the object. If the object has mass m, then,

$$Q = cm\,\Delta T = cm(T_f - T_i).$$

where *c* is the **specific heat** of the material making up the object.



Checkpoint 3

A certain amount of heat Q will warm 1 g of material A by 3 C° and 1 g of material B by 4 C°. Which material has the greater specific heat?

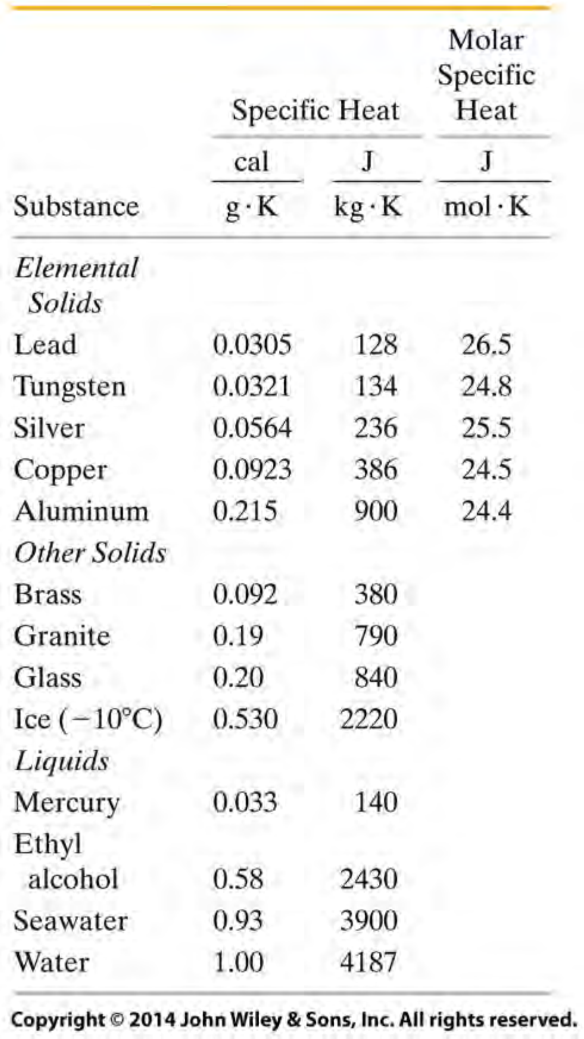
Answer: Material A has the greater specific heat

18-4 Absorption of Heat

- When quantities are expressed in moles, specific heats must also involve moles (rather than a mass unit); they are then called **molar specific heats**. Table shows the values for some elemental solids (each consisting of a single element) at room temperature.

- The amount of energy per unit mass that must be transferred as heat when a sample completely undergoes a phase change is called the **heat of transformation** *L*. Thus, when a sample of mass *m* completely undergoes a phase change, the total energy transferred is

$$Q = Lm.$$



	Specific Heat		Molar Specific Heat
Substance	$\frac{\text{cal}}{\text{g}\cdot\text{K}}$	$\frac{\text{J}}{\text{kg}\cdot\text{K}}$	$\frac{\text{J}}{\text{mol}\cdot\text{K}}$
Elemental Solids			
Lead	0.0305	128	26.5
Tungsten	0.0321	134	24.8
Silver	0.0564	236	25.5
Copper	0.0923	386	24.5
Aluminum	0.215	900	24.4
Other Solids			
Brass	0.092	380	
Granite	0.19	790	
Glass	0.20	840	
Ice (−10°C)	0.530	2220	
Liquids			
Mercury	0.033	140	
Ethyl alcohol	0.58	2430	
Seawater	0.93	3900	
Water	1.00	4187	

Heat of transformation=latent heat

vaporization -- condensation

melting/fusion -- freezing

Water:

L_V=heat of vaporization=539cal/g=2256kJ/kg=40.7kJ/mol

L_F=heat of fusion=79.5cal/g=333kJ/kg=6.01kJ/mol

Example: 3 bodies put in thermal contact

body i has mass m_i, is at temperature T_i. i = 1, 2, 3

What is the final temperature? T_f

$Q_1=c_1m_1(T_f-T_1)$

$Q_2=c_2m_2(T_f-T_2)$

$Q_3=c_3m_3(T_f-T_3)$

$Q_1+Q_2+Q_3=?$

$$\boxed{T_f = \frac{c_1m_1T_1 + c_2m_2T_2 + c_3m_3T_3}{c_1m_1 + c_2m_2 + c_3m_3}}$$

Example: how much heat must be absorbed by 720g of ice at -10°C to convert to water at 15°C?

$Q_1=c_{ice}m(T_f-T_1)$

$Q_2=L_Fm$ L_F: latent heat of fusion

$Q_3=c_{water}m(T_2-T_f)$

$Q=Q_1+Q_2+Q_3=300\text{kJ}$

(b) If we supply only 201kJ, what is the final state and temperature?

580g water and 140g ice at 0°C

18.7.2. Heat is expressed in the same units as which one of the following quantities?

a) temperature

b) power

c) force/time

d) specific heat capacity

e) work

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c) force/time

d) specific heat capacity

[✓ e) work]

18.8.1. Two balls, one made of copper and one made of gold, have the same mass and temperature. The same amount of heat is added to each sphere, but the final temperature of the two spheres is different. Which one of the following statements best explains the reason for these temperature differences?

a) The specific heat capacity of the two spheres is different.

b) The density of the two spheres is different.

c) The volumes of the two spheres are different.

d) The coefficient of volume expansion of the two spheres is different.

e) The latent heat of vaporization of the two spheres is different.

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a) the amount of energy required to change the temperature of an object

b) the total amount of energy an object can store

c) the thermal potential energy of the object

d) the amount of work done by the object

e) the amount of energy required to melt a solid object

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