Fundamentals Physics

Eleventh Edition

Halliday

Chapter 18

Temperature, Heat, and the First Law of Thermodynamics

18-1 Temperature (1 of 7)

Learning Objectives

18.01 Identify the lowest temperature as 0 on the Kelvin scale (absolute zero).

18.02 Explain the zeroth law of thermodynamics.

18.03 Explain the conditions for the triple-point temperature.

18.04 Explain the conditions for measuring a temperature with a constant-volume gas thermometer.

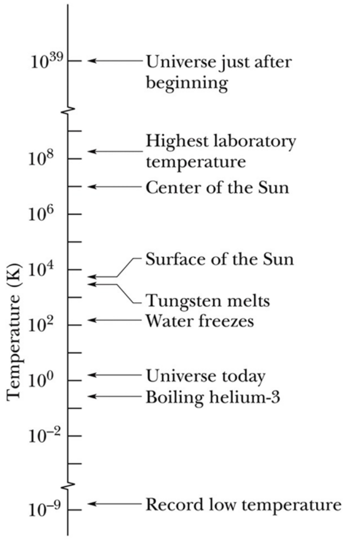
18.05 For a constant-volume gas thermometer, relate the pressure and temperature of the gas in some given state to the pressure and temperature at the triple point.

18-1 Temperature (2 of 7)

- **Thermodynamics** is the study and application of the thermal energy (often called the internal energy) of systems.
- Heat is a form of energy.
- One of the central concepts of thermodynamics is temperature.

18-1 Temperature (3 of 7)

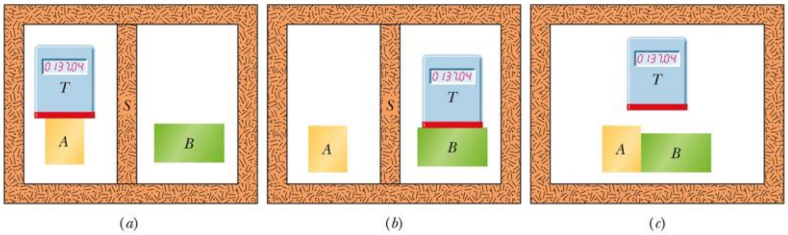
- **Temperature** is an SI base quantity related to our sense of hot and cold.
- It is measured with a thermometer, which contains a working substance with a measurable property, such as length or pressure, that changes in a regular way as the substance becomes hotter or colder.
- Physicists measure temperature on the **Kelvin scale**, which is marked in units called kelvins.



18-1 Temperature (4 of 7)

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

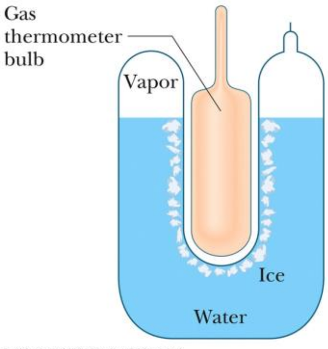


If bodies *A* and *B* are each in thermal equilibrium with a third body *T*, then *A* and *B* are in thermal equilibrium with each other.

18-1 Temperature (5 of 7)

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.



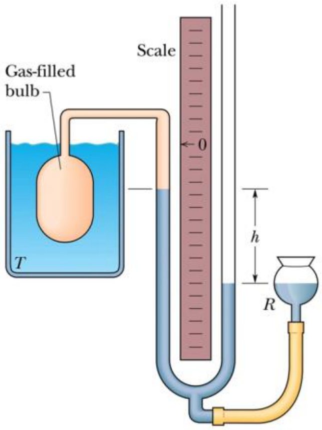
A triple-point cell

18-1 Temperature (6 of 7)

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

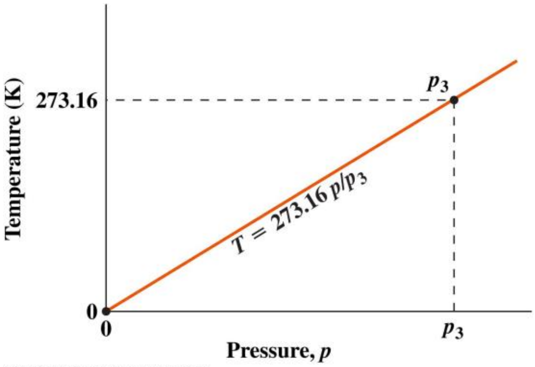
$$T = (273.16\ \text{K})\left(\lim_{\text{gas}\to 0} \frac{p}{p_3}\right).$$

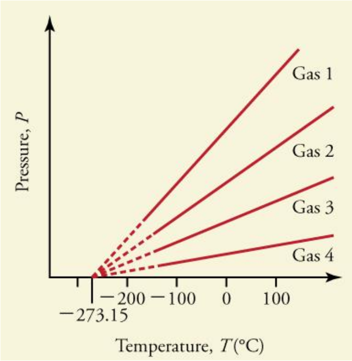


Constant-Volume Gas Thermometer

18-1 Temperature (7 of 7)

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





18-3 Thermal Expansion (1 of 12)

Learning Objectives

18.08 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.

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

18-3 Thermal Expansion (2 of 12)

18.10 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.

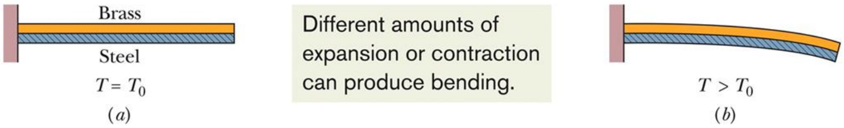
18-3 Thermal Expansion (3 of 12)

Linear Expansion

- All objects change size with changes in temperature. For a temperature change ΔT, a change ΔL in 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.

18-3 Thermal Expansion (4 of 12)

Volume Expansion

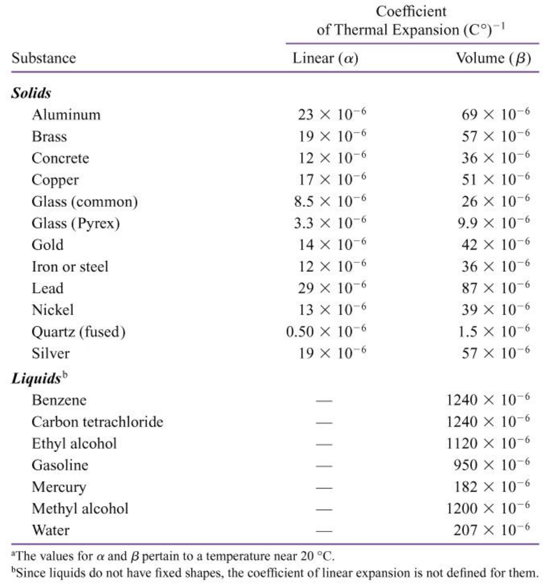
- If the temperature of a solid or liquid whose volume is V is increased by an amount ΔT, the increase in volume is found to be

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

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

$$\beta = 3\alpha.$$

18-3 Thermal Expansion (5 of 12)



Substance	Coefficient of Thermal Expansion $(C°)^{-1}$ Linear (α)	Volume (β)
Solids		
Aluminum	23×10^{-6}	69×10^{-6}
Brass	19×10^{-6}	57×10^{-6}
Concrete	12×10^{-6}	36×10^{-6}
Copper	17×10^{-6}	51×10^{-6}
Glass (common)	8.5×10^{-6}	26×10^{-6}
Glass (Pyrex)	3.3×10^{-6}	9.9×10^{-6}
Gold	14×10^{-6}	42×10^{-6}
Iron or steel	12×10^{-6}	36×10^{-6}
Lead	29×10^{-6}	87×10^{-6}
Nickel	13×10^{-6}	39×10^{-6}
Quartz (fused)	0.50×10^{-6}	1.5×10^{-6}
Silver	19×10^{-6}	57×10^{-6}
Liquids[b]		
Benzene	—	1240×10^{-6}
Carbon tetrachloride	—	1240×10^{-6}
Ethyl alcohol	—	1120×10^{-6}
Gasoline	—	950×10^{-6}
Mercury	—	182×10^{-6}
Methyl alcohol	—	1200×10^{-6}
Water	—	207×10^{-6}

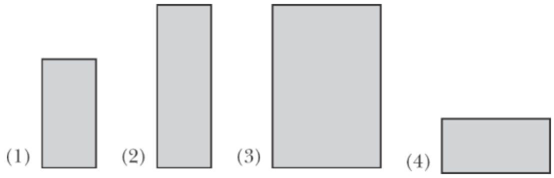
[a] The values for α and β pertain to a temperature near 20 °C.

[b] Since liquids do not have fixed shapes, the coefficient of linear expansion is not defined for them.

18-3 Thermal Expansion (6 of 12)

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.



Answer:

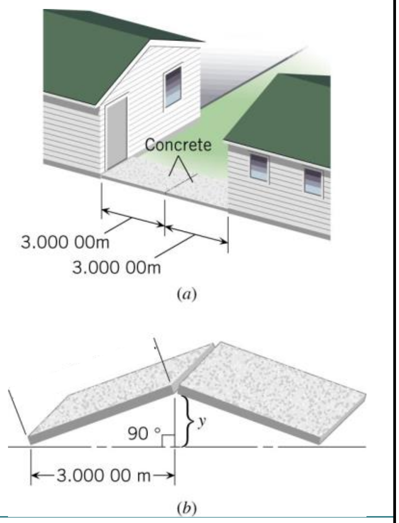
(a) −2 and 3 (same increase in height), then 1, and then 4

(b) −3, then 2, then 1 and 4 (identical increase in area)

18-3 Thermal Expansion (7 of 12)

Example The Buckling of a Sidewalk

A concrete sidewalk is constructed between two buildings on a day when the temperature is 25°C. As the temperature rises to 38°C, the slabs expand, but no space is provided for thermal expansion. Determine the distance *y* in part (b) of the drawing.

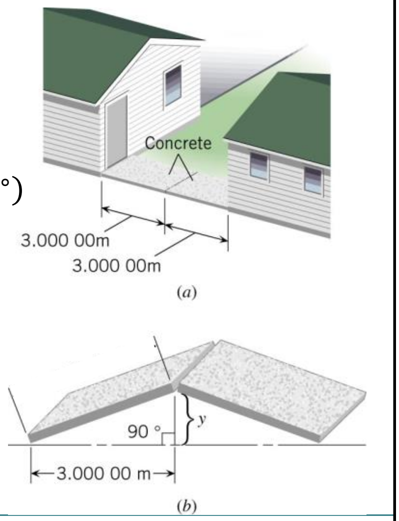


18-3 Thermal Expansion (8 of 12)

Example The Buckling of a Sidewalk

$$\begin{aligned}\Delta L &= \alpha L_o \Delta T \\ &= [12\times10^{-6}(\mathrm{C}^\circ)^{-1}](3.0\ \mathrm{m})(13\ \mathrm{C}^\circ) \\ &= 0.00047\ \mathrm{m}\end{aligned}$$

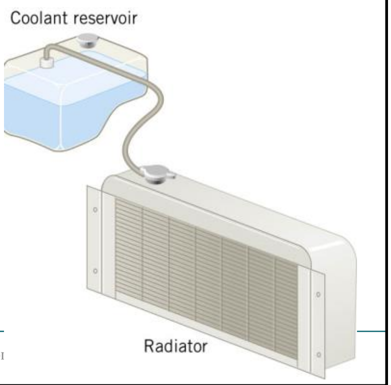
$$\begin{aligned}y &= \sqrt{(3.00047\ \mathrm{m})^2-(3.00000\ \mathrm{m})^2} \\ &= 0.053\ \mathrm{m}\end{aligned}$$



18-3 Thermal Expansion (9 of 12)

Example An Automobile Radiator

A small plastic container, called the coolant reservoir, catches the radiator fluid that overflows when an automobile engine becomes hot. The radiator is made of copper and the coolant has an expansion coefficient of $4.0 \times 10^{-4}\ (°\mathrm{C})^{-1}$. If the radiator is filled to its 15-quart capacity when the engine is cold (6°C), how much overflow will spill into the reservoir when the coolant reaches its operating temperature (92°C)?

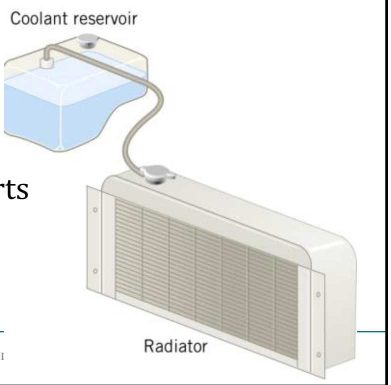


18-3 Thermal Expansion (10 of 12)

Example An Automobile Radiator

$$\Delta V_{\text{coolant}} = (4.10 \times 10^{-4} (°\mathrm{C})^{-1})(15\ \text{quarts})(86\ °\mathrm{C})$$
$$= 0.53\ \text{quarts}$$

$$\Delta V_{\text{radiator}} = (51 \times 10^{-6} (°\mathrm{C})^{-1})(15\ \text{quarts})(86\ °\mathrm{C})$$
$$= 0.066\ \text{quarts}$$



$$\Delta V_{\text{spill}} = 0.53\ \text{quarts} - 0.066\ \text{quarts}$$
$$= 0.46\ \text{quarts}$$

18-3 Thermal Expansion (11 of 12)

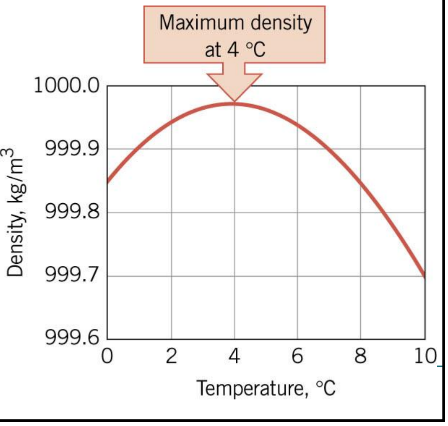
Unusual Behavior of Water

For most substances, the solid form of the *substance* is more denser than the liquid form; thus, a block of pure solid *substance* will sink in a tub of pure liquid *substance*

Not the case for water, the maximum density occurs at 4°C:

Above 4°C, expands when heated until 100°C; (its density decreases as temperature increases).

Below 4°C, expands when cooled until 0°C. Or from 0°C → 4°C, water *contracts*
4°C is the density maximum, not 0°C!

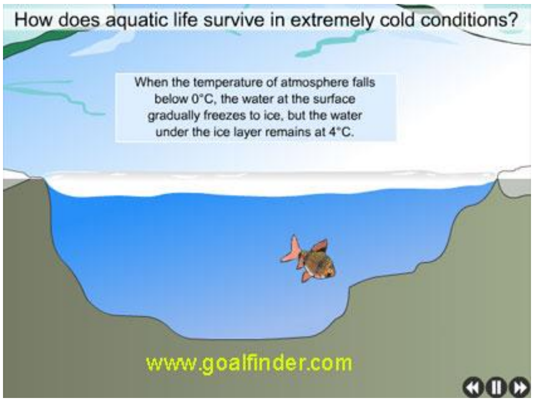


18-3 Thermal Expansion (12 of 12)

Unusual Behavior of Water

We are fortunate that water is strange

- as water (in a lake, say) cools towards 4°C, it sinks.
- below 4°C, though, it stays on top until it freezes
- so lakes freeze from the top down, not the bottom up, preventing them from becoming blocks of ice and killing all aquatic life



How does aquatic life survive in extremely cold conditions?

When the temperature of atmosphere falls below 0°C, the water at the surface gradually freezes to ice, but the water under the ice layer remains at 4°C.

18-4 Absorption of Heat (1 of 14)

Learning Objectives

18.11 Identify that thermal energy is associated with the random motions of the microscopic bodies in an object.

18.12 Identify that 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.

18.13 Convert energy units between various measurement systems.

18.14 Convert between mechanical or electrical energy and thermal energy.

18-4 Absorption of Heat (2 of 14)

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

18.16 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 (3 of 14)

18.17 Identify the three phases of matter.

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

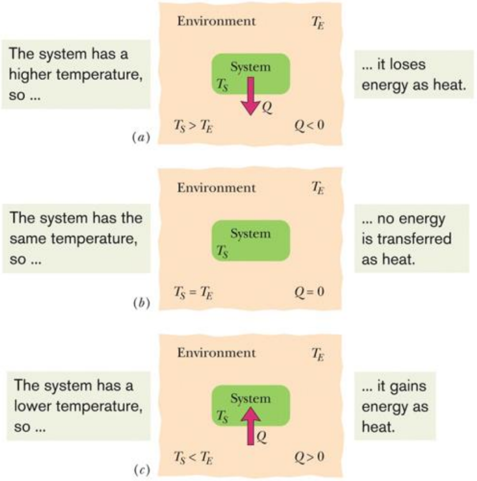
18.19 Identify that if a heat transfer *Q* takes a substance across a phase-change temperature, the transfer must be calculated in steps: (a) a temperature change to reach the phase-change temperature, (b) the phase change, and then (c) any temperature change that moves the substance away from the phase-change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

18-4 Absorption of Heat (4 of 14)

Temperature and Heat

- Heat *Q* is energy that is transferred between a system and its environment because of a temperature difference between them.
- For a given temperature, the system has a certain amount of internal energy.
- It can be measured in joules (J), calories (cal), kilocalories (Cal or kcal), or British thermal units (Btu), with

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



18-4 Absorption of Heat (5 of 14)

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.

18-4 Absorption of Heat (6 of 14)

Checkpoint 3

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

Answer:

Material *A* has the greater specific heat

18-4 Absorption of Heat (7 of 14)

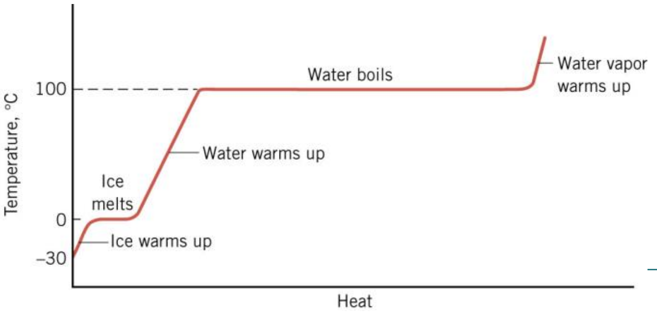
- When quantities are expressed in moles, specific heats must also involve moles (rather than a mass unit); they are then called **molar specific heats**. Table shows the values for some elemental solids (each consisting of a single element) at room temperature.

Substance	Specific Heat $\frac{cal}{g \cdot K}$	Specific Heat $\frac{J}{kg \cdot K}$	Molar Specific Heat $\frac{J}{mol \cdot K}$
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	

18-4 Absorption of Heat (8 of 14)

Absorption of Heat by Solids and Liquids

- Sometimes, when you add or remove heat, the temperature does not change at all
- This occurs when the substance is undergoing a "phase transition"
  - example: ice melting into water, water freezing into ice, water vaporizing into steam, etc.



18-4 Absorption of Heat (9 of 14)

- 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

$$Q = Lm.$$

Some Heats of Transformation

	Melting		Boiling	
Substance	Melting Point (K)	Heat of Fusion L_F (kJ/kg)	Boiling Point (K)	Heat of Vaporization L_V (kJ/kg)
Hydrogen	14.0	58.0	20.3	455
Oxygen	54.8	13.9	90.2	213
Mercury	234	11.4	630	296
Water	273	333	373	2256
Lead	601	23.2	2017	858
Silver	1235	105	2323	2336
Copper	1356	207	2868	4730

18-4 Absorption of Heat (10 of 14)

Example A Hot Jogger

In a half-hour, a 65-kg jogger can generate 8.0x10^{5}J of heat. This heat is removed from the body by a variety of means, including the body's own temperature-regulating mechanisms. If the heat were not removed, how much would the body temperature increase? Assume that the specific heat of a human body is 3500 J/(kg °C).

$$Q = mc\Delta T$$

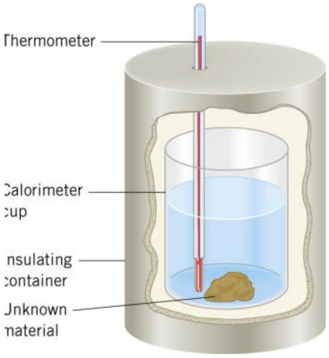
$$\Delta T = \frac{Q}{mc} = \frac{8.0 \times 10^5 \mathrm{J}}{(65\ \mathrm{kg})[3500\ \mathrm{J}/(\mathrm{kg} \cdot \mathrm{C}°)]} = 3.5\ °\mathrm{C}$$

18-4 Absorption of Heat (11 of 14)

Example Measuring the Specific Heat Capacity

The calorimeter is made of 0.15 kg of aluminum and contains 0.20 kg of water. Initially, the water and cup have the same temperature of 18.0°C. A 0.040 kg mass of unknown material is heated to a temperature of 97.0°C and then added to the water.

After thermal equilibrium is reached, the temperature of the water, the cup, and the material is 22.0°C. Ignoring the small Amount of heat gained by the thermometer, find the specific heat capacity of the unknown material.



18-4 Absorption of Heat (12 of 14)

Example Measuring the Specific Heat Capacity

$$(mc\Delta T)_{\text{Al}} + (mc\Delta T)_{\text{water}} = (mc\Delta T)_{\text{unknown}}$$

$$\Downarrow$$

$$c_{\text{unknown}} = \frac{(mc\Delta T)_{\text{Al}} + (mc\Delta T)_{\text{water}}}{(m\Delta T)_{\text{unknown}}}$$

$$= \frac{[9.00 \times 10^2\ \text{J}/(\text{kg}\cdot{}^\circ\text{C})](0.15\ \text{kg})(4.0\ {}^\circ\text{C})}{(0.040\ \text{kg})(75.0\ {}^\circ\text{C})} + \frac{[4186\ \text{J}/(\text{kg}\cdot{}^\circ\text{C})](0.20\ \text{kg})(4.0\ {}^\circ\text{C})}{(0.040\ \text{kg})(75.0\ {}^\circ\text{C})}$$

$$= 1300\ \text{J}/(\text{kg}\cdot{}^\circ\text{C})$$

18-4 Absorption of Heat (13 of 14)

Example Copper bowl and water

A 150 g copper bowl contains 220 g of water, both at 20.0˚C. A very hot 300 g copper cylinder is dropped into the water, causing the water to boil, with 5.00 g being converted to steam. The final temperature of the system is 100˚C. (a) How much heat was transferred to the water? (b) How much to the bowl? (c) What was the original temperature of the cylinder?

(a) The heat transferred to the water of mass m_w and steam of mass m_s is:

$$\begin{aligned} Q_w &= c_w m_w \Delta T + L_V m_s \\ &= \left(1\frac{cal}{g℃}\right)(220g)(100℃ - 20.0℃) \\ &\quad +(539\ cal/g)(5.00\ g) = \ 20.3\ kcal \end{aligned}$$

18-4 Absorption of Heat (14 of 14)

Example Copper bowl and water

(b) The heat transferred to the bowl is:

$$\begin{aligned} Q_b \ &= \ c_b m_b \Delta T \\ &= \left(0.0923\frac{cal}{g℃}\right)(150g)(100℃ - 20.0℃) \\ &= \ 1.11\ kcal \end{aligned}$$

(c) Let it be T_i, then

$$-Q_w \ - \ Q_b \ = \ c_c m_c (T_f - Ti)$$

$$T_i = \frac{Q_w + Q_b}{c_c m_c} + T_f = 873°\mathrm{C}$$

18-5 The First Law of Thermodynamics
(1 of 8)

Learning Objectives

18.20 If an enclosed gas expands or contracts, calculate the work *W* done by the gas by integrating the gas pressure with respect to the volume of the enclosure.

18.21 Identify the algebraic sign of work *W* associated with expansion and contraction of a gas.

18.22 Given a *p*-*V* graph of pressure versus volume for a process, identify the starting point (the initial state) and the final point (the final state) and calculate the work by using graphical integration.

18.23 On a *p*-*V* graph of pressure versus volume for a gas, identify the algebraic sign of the work associated with a right-going process and a left-going process.

18-5 The First Law of Thermodynamics
(2 of 8)

18.24 Apply the first law of thermodynamics to relate the change in the internal energy ΔE_{int} of a gas, the energy *Q* transferred as heat to or from the gas, and the work *W* done on or by the gas.

18.25 Identify the algebraic sign of a heat transfer *Q* that is associated with a transfer to a gas and a transfer from the gas.

18.26 Identify that the internal energy ΔE_{int} of a gas tends to increase if the heat transfer is to the gas, and it tends to decrease if the gas does work on its environment.

18-5 The First Law of Thermodynamics

(3 of 8)

18.27 Identify that in an adiabatic process with a gas, there is no heat transfer Q with the environment.

18.28 Identify that in a constant-volume process with a gas, there is no work W done by the gas.

18.29 Identify that in a cyclical process with a gas, there is no net change in the internal energy ΔE_{int}.

18.30 Identify that in a free expansion with a gas, the heat transfer Q, work done W, and change in internal energy ΔE_{int} are each zero.

18-5 The First Law of Thermodynamics

(4 of 8)

Heat and Work

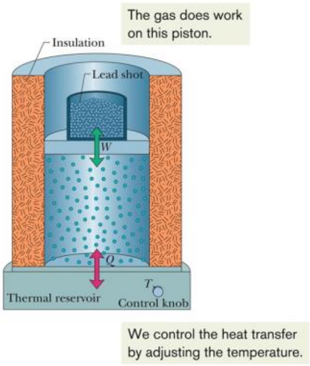
A gas may exchange energy with its surroundings through work. The amount of work W done by a gas

$$dW = F \cdot ds = pA \cdot ds = pdV$$

as it expands or contracts from an initial volume V_i to a final volume V_f is given by

$$W = \int dW = \int_{v_i}^{v_f} pdV\,.$$

The integration is necessary because the pressure p may vary during the volume change.



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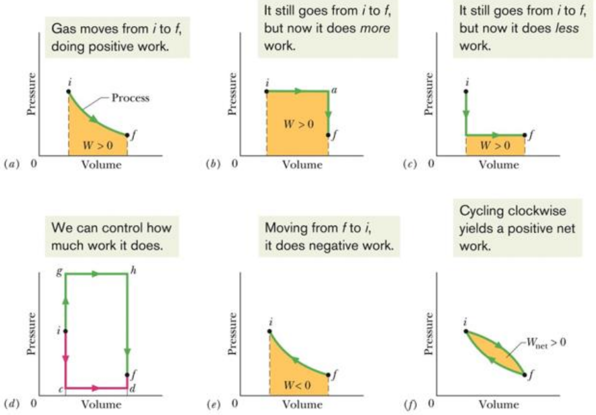
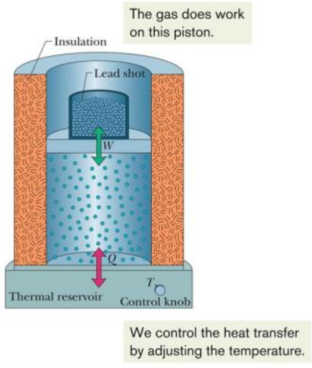
A gas confined to a cylinder with a movable piston.

18-5 The First Law of Thermodynamics

(5 of 8)

Heat and Work





A gas confined to a cylinder with a movable piston.

18-5 The First Law of Thermodynamics

(6 of 8)

The First Law of Thermodynamics

The principle of conservation of energy for a thermodynamic process is expressed in the first law of thermodynamics, which may assume either of the forms:

$$\Delta E_{\text{int}} = E_{\text{int},\,f} - E_{\text{int},\,i} = Q - W \quad \text{(first law).}$$

Or, if the thermodynamic system undergoes only a differential change, we can write the first law as:

$$dE_{\text{int}} = dQ - dW \quad \text{(first law).}$$

The internal energy E_{int} of a system tends to increase if energy is added as heat Q and tends to decrease if energy is lost as work W done by the system.

18-5 The First Law of Thermodynamics

(7 of 8)

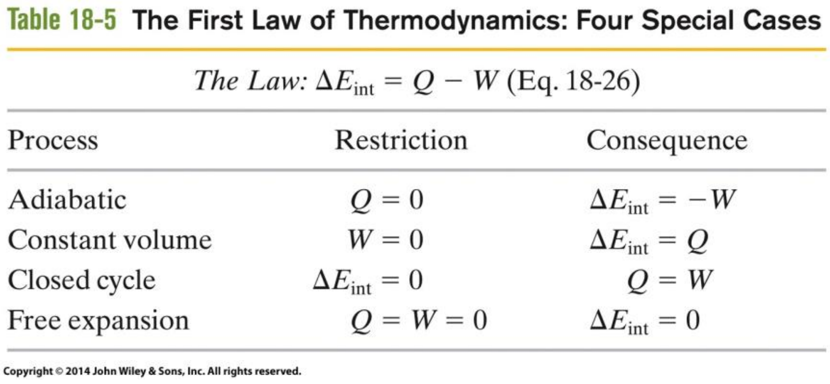


Table 18-5 **The First Law of Thermodynamics: Four Special Cases**

The Law: $\Delta E_{\text{int}} = Q - W$ (Eq. 18-26)

Process	Restriction	Consequence
Adiabatic	$Q = 0$	$\Delta E_{\text{int}} = -W$
Constant volume	$W = 0$	$\Delta E_{\text{int}} = Q$
Closed cycle	$\Delta E_{\text{int}} = 0$	$Q = W$
Free expansion	$Q = W = 0$	$\Delta E_{\text{int}} = 0$

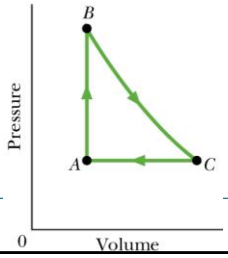
18-5 The First Law of Thermodynamics

(8 of 8)

Example A Cycle

Gas within a chamber passes through the cycle shown in figure. Determine the net heat added to the system during process *CA* if the heat Q_{AB} added during process *AB* is 20.0 J, no heat is transferred during process *BC*, and the net work done during the cycle is 15.0 J.

Since the process is a complete cycle (beginning and ending in the same thermodynamic state), $\Delta E_{\text{int}} = 0$ and Q = W,



$$Q_{AB} + QBC + QCA = W$$

$$Q_{CA} = W - QAB - QBC$$

$$= 15.0\,J - 20.0\,J - 0 = -5.0\,J$$

$5.0\,J$ of energy leaves the gas in the form of heat.

18-6 Heat Transfer Mechanisms (1 of 14)

Learning Objectives

18.31 For thermal conduction through a layer, apply the relationship between the energy-transfer rate P_{cond} and the layer's area A, thermal conductivity k, thickness L, and temperature difference ΔT (between its two sides).

18.32 For a composite slab (two or more layers) that has reached the steady state in which temperatures are no longer changing, identify that (by the conservation of energy) the rates of thermal conduction P_{cond} through the layers must be equal.

18-6 Heat Transfer Mechanisms (2 of 14)

18.33 For thermal conduction through a layer, apply the relationship between thermal resistance R, thickness L, and thermal conductivity k.

18.34 Identify that thermal energy can be transferred by convection, in which a warmer fluid (gas or liquid) tends to rise in a cooler fluid.

18.35 In the emission of thermal radiation by an object, apply the relationship between the energy-transfer rate P_{rad} and the object's surface area A, emissivity ε, and surface temperature T (in kelvins).

18-6 Heat Transfer Mechanisms (3 of 14)

18.36 In the absorption of thermal radiation by an object, apply the relationship between the energy-transfer rate P_{abs} and the object's surface area A and emissivity ε, and the environmental temperature T (in kelvins).

18.37 Calculate the net energy transfer rate P_{net} of an object emitting radiation to its environment and absorbing radiation from that environment.

18-6 Heat Transfer Mechanisms (4 of 14)

Thermal Conduction

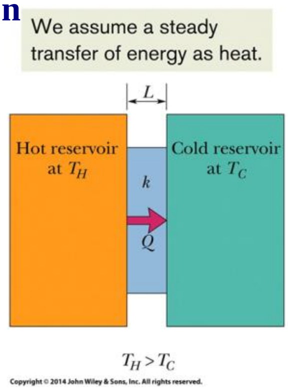
The rate P_{cond} at which energy is conducted through a slab for which one face is maintained at the higher temperature T_H and the other face is maintained at the lower temperature T_C is

$$P_{\text{cond}} = \frac{Q}{t} = kA\frac{T_H - T_C}{L},$$

Here each face of the slab has area A, the length of the slab (the distance between the faces) is L, and k is the thermal conductivity of the material.

18-6 Heat Transfer Mechanisms (5 of 14)

Thermal Conduction



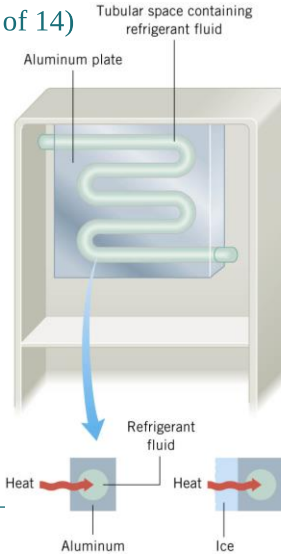
Energy is transferred as heat from a reservoir at temperature T_H to a cooler reservoir at temperature T_C through a conducting slab of thickness L and thermal conductivity k.

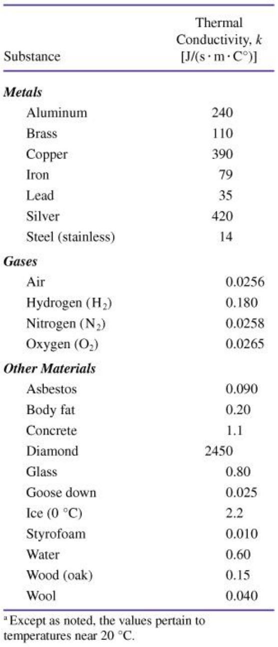
18-6 Heat Transfer Mechanisms (6 of 14)

Thermal Conduction

Checkpoint
An Iced-Up Refrigerator

In a refrigerator, heat is removed by a cold refrigerant fluid that circulates within a tubular space embedded within a metal plate. Decide whether the plate should be made from aluminum or stainless steel and whether the arrangement works better or worse when it becomes coated with a layer of ice.





Substance	Thermal Conductivity, k [J/(s · m · C°)]
Metals	
Aluminum	240
Brass	110
Copper	390
Iron	79
Lead	35
Silver	420
Steel (stainless)	14
Gases	
Air	0.0256
Hydrogen (H_2)	0.180
Nitrogen (N_2)	0.0258
Oxygen (O_2)	0.0265
Other Materials	
Asbestos	0.090
Body fat	0.20
Concrete	1.1
Diamond	2450
Glass	0.80
Goose down	0.025
Ice (0 °C)	2.2
Styrofoam	0.010
Water	0.60
Wood (oak)	0.15
Wool	0.040

[a] Except as noted, the values pertain to temperatures near 20 °C.

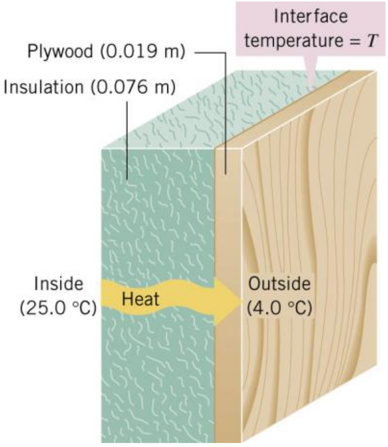
18-6 Heat Transfer Mechanisms (7 of 14)

Thermal Conduction

Example Layered insulation

One wall of a house consists of plywood backed by insulation. The thermal conductivities of the insulation and plywood are, respectively, 0.030 and 0.080 J/(s·m·°C), and the area of the wall is 35m^2.

Find the amount of heat conducted through the wall in one hour.



18-6 Heat Transfer Mechanisms (8 of 14)

Thermal Conduction

Example Layered insulation

$$Q = Q_{\text{insulation}} = Q_{\text{plywood}}$$

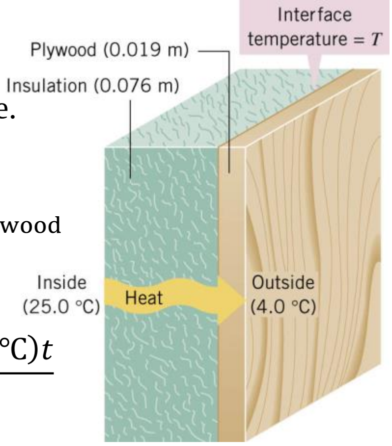
First, solve for the interface temperature.

$$\left[\frac{(kA\Delta T)t}{L}\right]_{\text{insulation}} = \left[\frac{(kA\Delta T)t}{L}\right]_{\text{plywood}}$$

$$\frac{[0.030\ \text{J}/(\text{s}\cdot\text{m}\cdot{}^\circ\text{C})]A(25.0^\circ\text{C} - T)t}{0.076\ \text{m}}$$

$$= \frac{[0.080\ \text{J}/(\text{s}\cdot\text{m}\cdot{}^\circ\text{C})]A(T - 4.0^\circ\text{C})t}{0.019\ \text{m}}$$

$$T = 5.8^\circ\text{C}$$

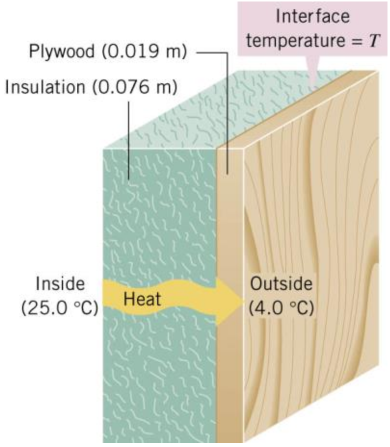


18-6 Heat Transfer Mechanisms (9 of 14)

Thermal Conduction

Example Layered insulation

$$Q_{insulation} = \frac{[0.030\,\mathrm{J/(s \cdot m \cdot C^\circ)}](35\,\mathrm{m}^2)}{0.076\,\mathrm{m}}(25.0^\circ\mathrm{C} - 5.8^\circ\mathrm{C})(3600\,\mathrm{s}) = 9.5 \times 10^5\,\mathrm{J}$$



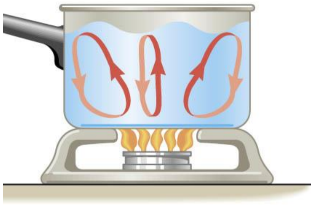
18-6 Heat Transfer Mechanisms (10 of 14)

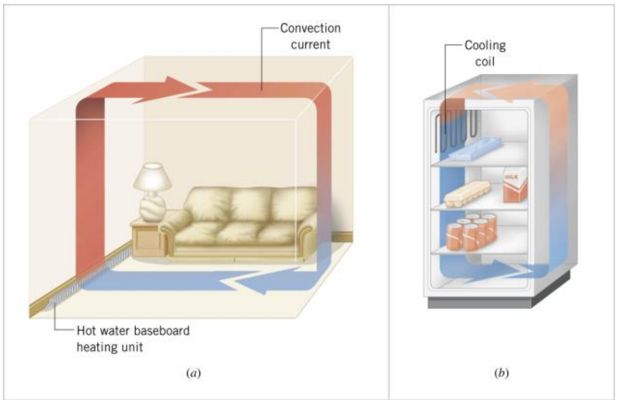
Convection

- Convection occurs when temperature differences cause an energy transfer by motion within a fluid.
- When you look at the flame of a candle or a match, you are watching thermal energy being transported upward by convection.
- Convection is part of many natural processes. Atmospheric convection plays a fundamental role in determining global climate patterns and daily weather variations. Glider pilots and birds alike seek rising thermals (convection currents of warm air) that keep them aloft. Huge energy transfers take place within the oceans by the same process.

18-6 Heat Transfer Mechanisms (11 of 14)

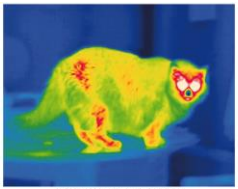
Convection





18-6 Heat Transfer Mechanisms (12 of 14)

Thermal Radiation



Edward Kinsman/Photo Researchers, Inc.

Radiation is an energy transfer via the emission of electromagnetic energy. The rate P_{rad} at which an object emits energy via thermal radiation is

$$P_{\text{rad}} = \sigma \varepsilon A T^4.$$

Here $\sigma (= 5.6704 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4)$ is the Stefan– Boltzmann constant, ε is the emissivity of the object's surface, A is its surface area, and T is its surface temperature (in kelvins). The rate P_{abs} at which an object absorbs energy via thermal radiation from its environment, which is at the uniform temperature T_{env} (in kelvins), is

$$P_{\text{abs}} = \sigma \varepsilon A T_{\text{env}}^4.$$

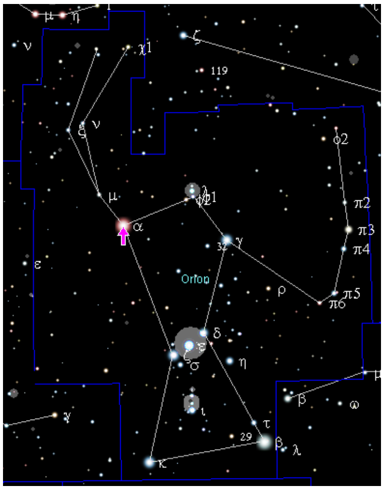
18-6 Heat Transfer Mechanisms (13 of 14)

Thermal Radiation

Example A Supergiant Star

The supergiant star Betelgeuse has a surface temperature of about 2900 K and emits a power of approximately $4 \times 10^{30}\ W$.

Assuming that Betelgeuse is a perfect emitter and spherical, find its radius.



Betelgeuse is a star located approximately 640 light-years from the Earth. It is also known as Alpha Orionis (α Orionis / α Ori), and it is the second brightest star in the constellation Orion and the ninth brightest star in the night sky.

18-6 Heat Transfer Mechanisms (14 of 14)

Thermal Radiation

$4\pi r^2$

$$Q = e\sigma T^4 A t$$

$$Q = e\sigma T^4 4\pi r^2 t$$

$$r = \sqrt{\frac{Q/t}{4\pi e\sigma T^4}}$$

$$= \sqrt{\frac{4 \times 10^{30}\,\mathrm{W}}{4\pi(1)[5.67 \times 10^{-8}\,\mathrm{J/(s \cdot m^2 \cdot K^4)}](2900\ \mathrm{K})^4}}$$

$$= 3 \times 10^{11}\,\mathrm{m}$$

Summary (1 of 5)

Temperature and Thermometer

- SI base quantity related to our sense of hot and cold.
- It is measured using thermometer

Zeroth Law of Thermodynamics

- If bodies *A* and *B* are each in thermal equilibrium with a third body *C* (the thermometer), then *A* and *B* are in thermal equilibrium with each other.

The Kelvin Temperature Scale

- We define the temperature *T* as measured with a gas thermometer to be

$$T = (273.16\ \mathrm{K})\left(\lim_{\text{gas}\to 0} \frac{p}{p_3}\right).$$ **Equation 18-6**

Summary (2 of 5)

Celsius and Fahrenheit Scale

- The Celsius temperature scale is defined by

$$T_C = T - 273.15^\circ$$ **Equation 18-7**

- The Fahrenheit temperature scale is defined by

$$T_F = \tfrac{9}{5} T_C + 32^\circ.$$ **Equation 18-8**

Thermal Expansion

- Linear Expansion

$$\Delta L = L\alpha\ \Delta T,$$ **Equation 18-9**

Summary (3 of 5)

- Volume Expansion

$$\Delta V = V\beta\,\Delta T.$$ **Equation 18-10**

Heat Capacity and Specific Heat

- Heat Capacity:

$$Q = C\left(T_f - T_i\right)$$ **Equation 18-13**

- Specific Heat

$$Q = cm\left(T_f - T_i\right),$$ **Equation 18-14**

Summary (4 of 5)

First Law of Thermodynamics

- The principle of conservation of energy for a thermodynamic process is expressed in:

$$\Delta E_{\text{int}} = E_{\text{int},\,f} - E_{\text{int},\,i} = Q - W$$ **Equation 18-26**

$$dE_{\text{int}} = dQ - dW$$ **Equation 18-27**

Summary (5 of 5)

Application of First Law

adiabatic processes: $Q = 0, \Delta E_{\text{int}} = -W$

constant-volume processes: $W = 0, \Delta E_{\text{int}} = Q$

cyclical processes: $\Delta E_{\text{int}} = 0, Q = W$

free expansions: $Q = W = \Delta E_{\text{int}} = 0$

Conduction, Convection, Radiation

- Conduction

$$P_{\text{cond}} = \frac{Q}{t} = kA\frac{T_H - T_C}{L}$$ **Equation 18-32**

- Radiation:

$$P_{\text{rad}} = \sigma\varepsilon AT^4.$$ **Equation 18-39**

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