Lecture Presentation

Chapter 12

Thermal Properties of Matter

Suggested Videos for Chapter 12

- **Prelecture Videos**
  - *The Atomic Model*
  - *Gas-Law Processes*
  - *Heat and Phase Changes*

- **Class Videos**
  - *Force and Pressure*
  - *Energy Transfer by Radiation*

- **Video Tutor Solutions**
  - *Thermal Properties of Matter*

- **Video Tutor Demos**
  - *Heating Water and Aluminum*
  - *Water Balloon Held over Candle Flame*
  - *Candle Chimneys*
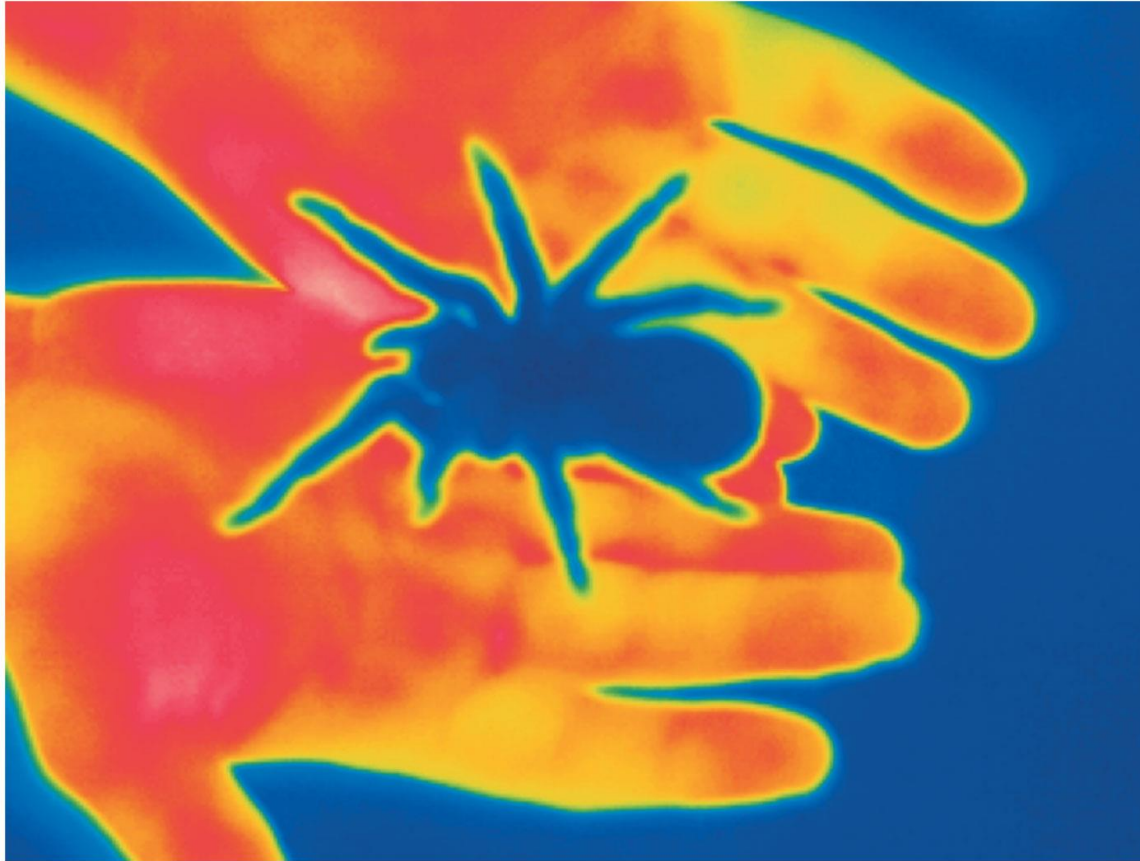
Suggested Simulations for Chapter 12

- **ActivPhysics**
  - *8.4–8.14*

- **PhETs**
  - *States of Matter*
  - *Gas Properties*
  - *Blackbody Spectrum*
  - *The Greenhouse Effect*

Chapter 12 Thermal Properties of Matter

Chapter Goal: To use the atomic model of matter to explain many properties of matter associated with heat and temperature.

- The high pressure in a car tire is due to the countless collisions between the air molecules inside and the tire's walls.

- You'll learn how gas properties are related to the microscopic motion of the gas molecules.

Chapter 12 Preview
Looking Ahead: Heat and Temperature

- Adding ice cools your drink as heat is transferred from the warm drink to the cold ice; even more heat is used to melt the ice.
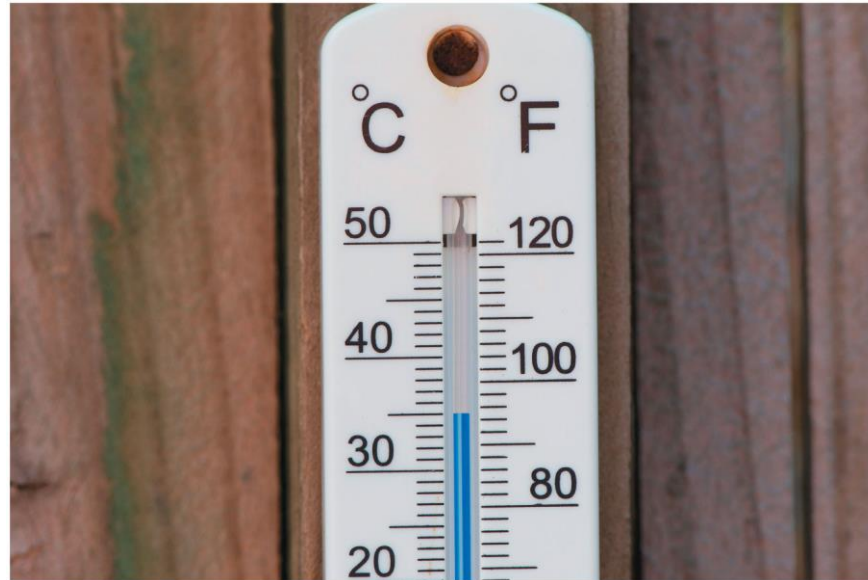

- You'll learn how to compute the temperature changes that occur when heat is transferred or a **phase change** such as melting occurs.

Chapter 12 Preview
Looking Ahead: Thermal Expansion

- Materials expand when heated. The liquid in this thermometer expands, rising up the glass tube, as the temperature is increased.

- You'll learn how the length of a solid object, or the volume of a liquid, changes with temperature.

Chapter 12 Preview
Looking Ahead

The Ideal Gas

The high pressure in a car tire is due to the countless collisions between the air molecules inside and the tire's walls.

You'll learn how gas properties are related to the microscopic motion of the gas molecules.
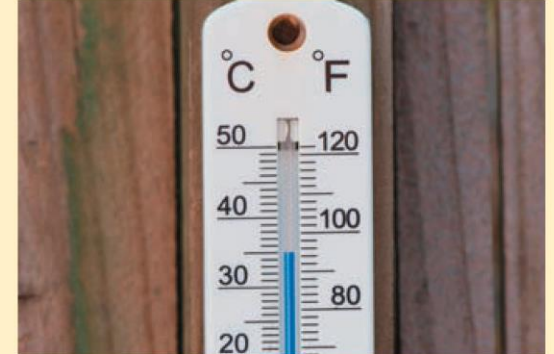
Heat and Temperature

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Thermal Expansion

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You'll learn how the length of a solid object, or the volume of a liquid, changes with temperature.

Text: p. 356

Chapter 12 Preview
Looking Back: Heat

- In Section 11.4 you learned about heat and the first law of thermodynamics. In this chapter we will explore some of the consequences of transferring heat to or from a system, and doing work on the system.

- You learned that a system's energy can be changed by doing work on it *or* by transferring heat to it.

Chapter 12 Preview
Stop to Think

A blender does 5000 J of work on the food in its bowl. During the time the blender runs, 2000 J of heat transferred from the warm food to the cooler environment. What is the change in the thermal energy of the food?

    A. +2000 J

    B. +3000 J

    C. +7000 J

    D. −2000 J

    E. −3000 J

Reading Question 12.1

An atom's atomic mass number is the number of its

    A. Protons.

    B. Electrons.

    C. Neutrons.

    D. Protons + neutrons.

Reading Question 12.1

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Reading Question 12.2

A sample of nitrogen gas is inside a sealed container. The container is slowly compressed, while the temperature is kept constant. This is a _____ process.

    A. Constant-volume

    B. Isobaric

    C. Isothermal

    D. Adiabatic

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Reading Question 12.3

A sample of nitrogen gas is in a sealed container with a constant volume. Heat is added to the gas. The pressure

    A. Increases.

    B. Stays the same.

    C. Decreases.

    D. Can't be determined with the information given.

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✔ A. Increases.

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Reading Question 12.4

When steam condenses into water,

A. Heat is given off by the water.

B. Heat is absorbed by the water.

C. No heat is given off or absorbed.

Reading Question 12.4

When steam condenses into water,

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Reading Question 12.5

The defining equation for calorimetry is

    A. $\Delta Q_1 = \Delta Q_2 = 0$

    B. $Q_1 + Q_2 = 0$

    C. $\Delta T_1 + \Delta T_2 = 0$

    D. $Q = ML$

Reading Question 12.5

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✔ B. $Q_1 + Q_2 = 0$

C. $\Delta T_1 + \Delta T_2 = 0$

D. $Q = ML$

Reading Question 12.6

Which type of heat transfer can happen through empty space?

   A. Conduction

   B. Evaporation

   C. Convection

   D. Radiation

Reading Question 12.6
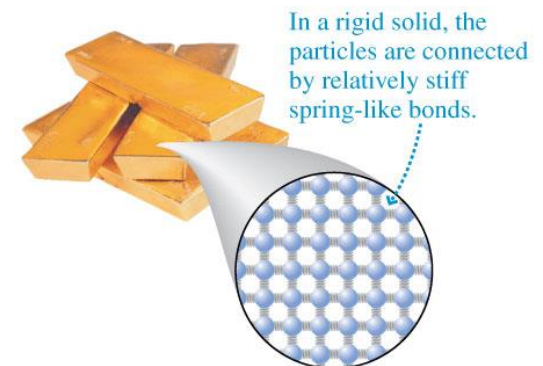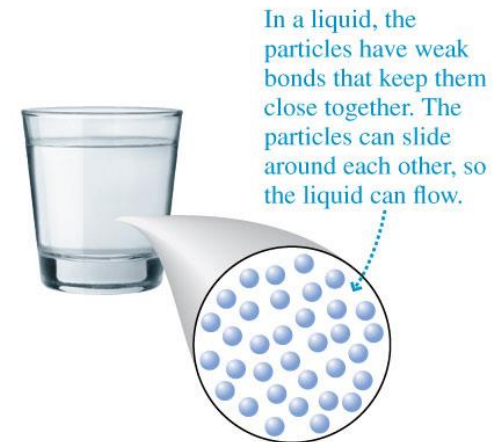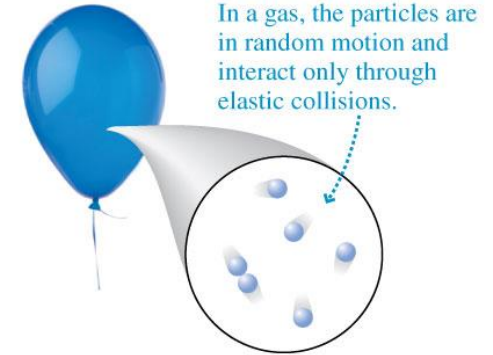
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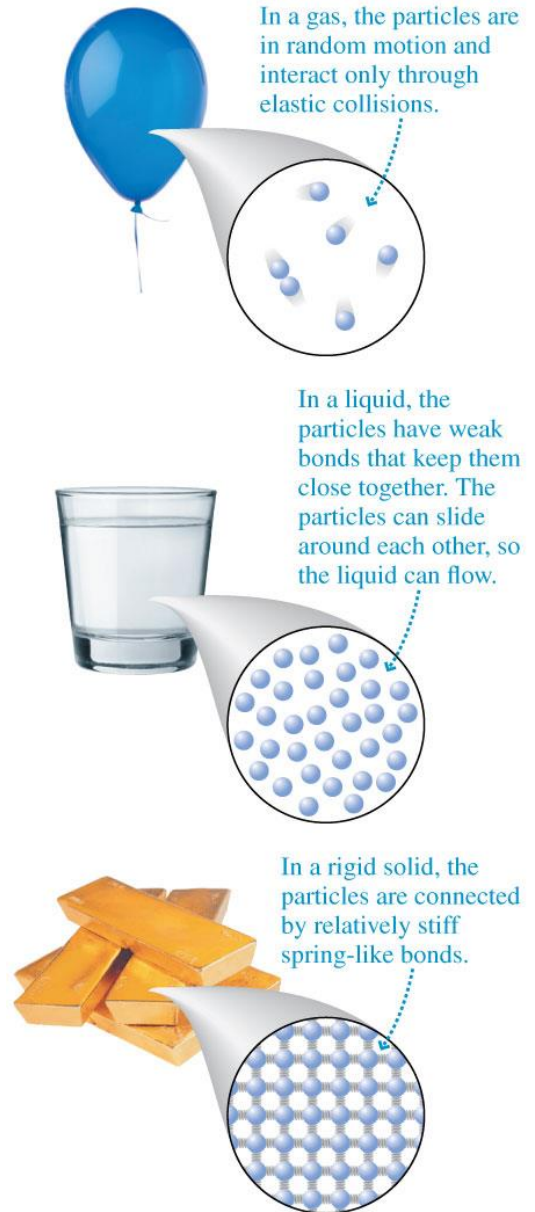✔   D. Radiation

Section 12.1 The Atomic Model of Matter

The Atomic Model of Matter

- We use the atomic models to illustrate the three **phases** of matter: solid, liquid, and gas.

In a gas, the particles are in random motion and interact only through elastic collisions.

In a liquid, the particles have weak bonds that keep them close together. The particles can slide around each other, so the liquid can flow.

In a rigid solid, the particles are connected by relatively stiff spring-like bonds.

The Atomic Model of Matter

- A **gas** is a system in which each particle moves freely though space until, on occasion, it collides with another particle or the wall.

- In a **liquid**, weak bonds permit motion while keeping the particles close together.

- A rigid **solid** has a definite shape and can be compressed only slightly.

In a gas, the particles are in random motion and interact only through elastic collisions.

In a liquid, the particles have weak bonds that keep them close together. The particles can slide around each other, so the liquid can flow.

In a rigid solid, the particles are connected by relatively stiff spring-like bonds.

Atomic Mass and Atomic Mass Number

- The **atomic mass number** *A* is the *sum* of the number of protons and the number of neutrons in an atom.

$$A = \text{number of protons} + \text{number of neutrons}$$

- The **atomic mass** scale is established by defining the mass of ^{21}C to be exactly 12 u.

- u is the symbol for the *atomic mass unit*:

$$1\ u = 1.66 \times 10^{-27}\ kg$$

- Molecular mass is the sum of the atomic masses of the atoms that form the molecule.

Atomic Mass and Atomic Mass Number

TABLE 12.1 Some atomic mass numbers

Element	Symbol	A
Hydrogen	^1H	1
Helium	^4He	4
Carbon	^{12}C	12
Nitrogen	^{14}N	14
Oxygen	^{16}O	16
Neon	^{20}Ne	20
Aluminum	^{27}Al	27
Argon	^{40}Ar	40
Lead	^{207}Pb	207

QuickCheck 12.1

What is the mass, in u, of a molecule of carbon dioxide, CO_2?

    A. 12
    B. 24
    C. 32
    D. 36
    E. 44

QuickCheck 12.1

What is the mass, in u, of a molecule of carbon dioxide, CO_2?

    A. 12
    B. 24
    C. 32
    D. 36
✔ E. 44

The Definition of the Mole

- One way to specify the amount of substance in a system is to give its mass. Another way is to measure the amount of substance in *moles*.

- **1 mole of a substance, abbreviated 1 mol, is 6.02×10^{23} basic particles.**

- The basic particle depends on the substance.

- **Monatomic gas** means that the basic particles are atoms, such as helium.

- **Diatomic gas** means the basic particle is a two-atom diatomic molecule, like O_2.

QuickCheck 12.2

Which contains more molecules, a mole of hydrogen gas (H_2) or a mole of oxygen gas (O_2)?

    A. The hydrogen

    B. The oxygen

    C. They each contain the same number of molecules.

    D. Can't tell without knowing their temperatures.

QuickCheck 12.2

Which contains more molecules, a mole of hydrogen gas (H_2) or a mole of oxygen gas (O_2)?

   A. The hydrogen
   B. The oxygen
✔ C. They each contain the same number of molecules.
   D. Can't tell without knowing their temperatures.

The Definition of the Mole

TABLE 12.2 Monatomic and diatomic gases

Monatomic	Diatomic
Helium (He)	Hydrogen (H_2)
Neon (Ne)	Nitrogen (N_2)
Argon (Ar)	Oxygen (O_2)

The Definition of the Mole

- The number of basic particles per mole of a substance is called **Avogadro's number** N_A:

$$N_A = 6.02 \times 10^{23} \text{ mol}^{-1}$$

- The number n of moles in a substance containing N basic particles is

$$n = \frac{N}{N_A}$$

Moles of a substance in terms of the number of basic particles

The Definition of the Mole

- The **molar mass** of a substance, M_{mol}, is the mass *in grams* of 1 mol of substance:

$$n = \frac{M \text{ (in grams)}}{M_{mol}}$$

Moles of a substance in terms of its mass

QuickCheck 12.3

Rank the following in terms of the number of moles, from greatest number of moles to least:

a. 20 g of He

b. 60 g of Ne

c. 128 g of O_2

d. 160 g of Ar

e. 200 g of Pb

A. e > d > c > b > a

B. a > b > c > d > e

C. a > c = d > b > e

D. d > e > b = c > a

E. c > a > b > e > d

QuickCheck 12.3

Rank the following in terms of the number of moles, from greatest number of moles to least:

 a. 20 g of He   b. 60 g of Ne

 c. 128 g of O_2 d. 160 g of Ar

 e. 200 g of Pb

A. $e > d > c > b > a$

B. $a > b > c > d > e$

✔ C. $a > c = d > b > e$

D. $d > e > b = c > a$

E. $c > a > b > e > d$

Example 12.1 Determining quantities of oxygen

A system contains 100 g of oxygen. How many moles does it contain? How many molecules?

SOLVE The diatomic oxygen molecule O_2 has molar mass $M_{mol} = 32$ g/mol. From Equation 12.2,

$$n = \frac{100 \text{ g}}{32 \text{ g/mol}} = 3.1 \text{ mol}$$

Each mole contains N_A molecules, so the total number is $N = nN_A = 1.9 \times 10^{24}$ molecules.

Volume

- Volume V is an important property that describes the amount of space the system occupies.

- The SI unit of volume is m^3.

- It is important to note that although 1 m = 100 cm, it is *not* true that $1\ m^3 = 100\ cm^3$.

Subdivide the 1 m × 1 m × 1 m cube into little cubes 1 cm on a side. You will get 100 subdivisions along each edge.

$1\ cm^3$

100 cm deep

100 cm across

$1\ m^3$

1 m

100 cm down

1 m

1 m
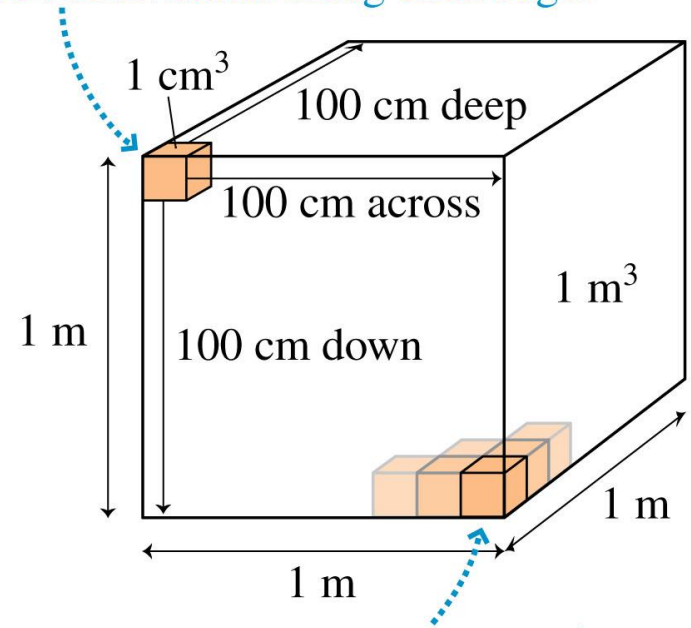
There are $100 \times 100 \times 100 = 10^6$ little $1\ cm^3$ cubes in the big $1\ m^3$ cube.

QuickCheck 12.4

The volume of this cube is
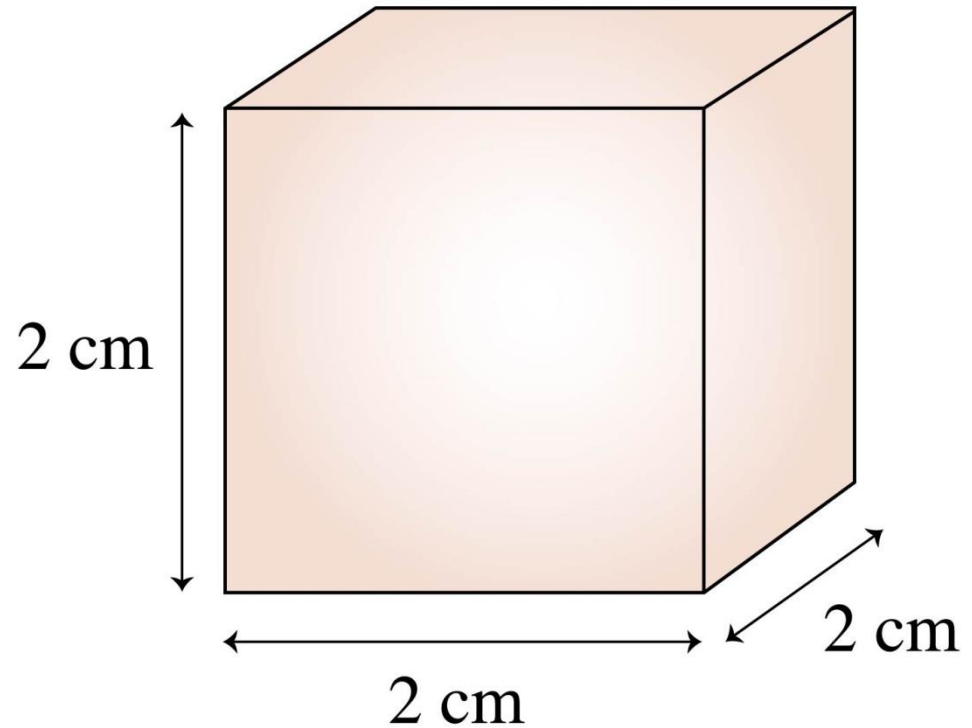
A. 8×10^2 m³

B. 8 m³

C. 8×10^{-2} m³

D. 8×10^{-4} m³

E. 8×10^{-6} m³

2 cm

2 cm

2 cm

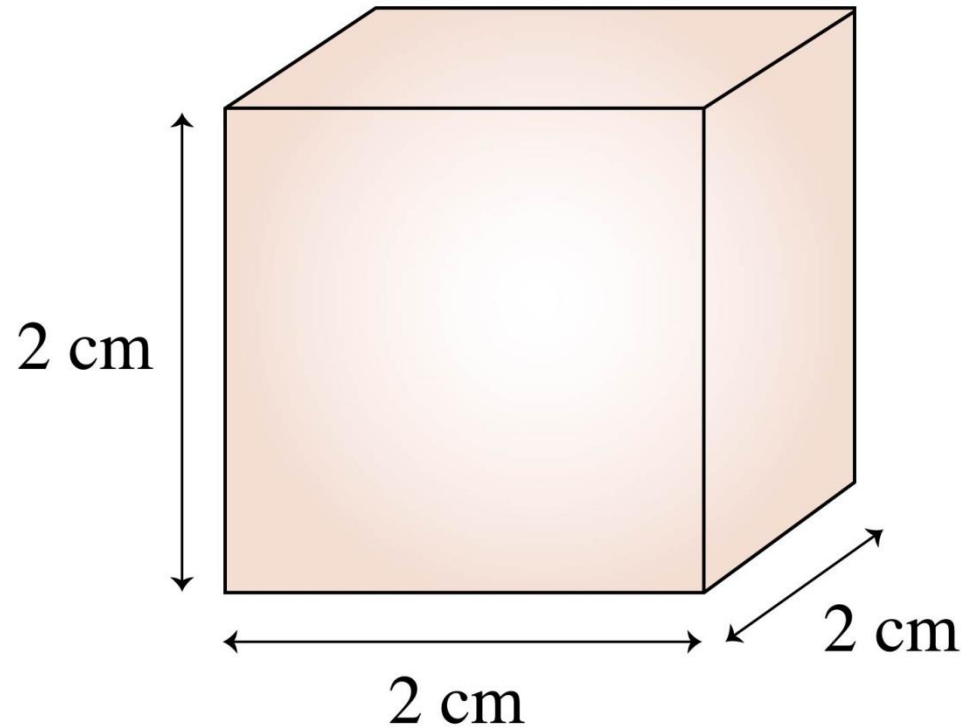# QuickCheck 12.4

The volume of this cube is

   A. $8 \times 10^2 \text{ m}^3$

   B. 8 m^3

   C. $8 \times 10^{-2} \text{ m}^3$

   D. $8 \times 10^{-4} \text{ m}^3$

✔ E. $8 \times 10^{-6} \text{ m}^3$

2 cm

2 cm

2 cm

Section 12.2 The Atomic Model of an Ideal Gas

The Atomic Model of an Ideal Gas

- The temperature of an ideal gas is *directly proportional* to the average kinetic energy per atom K_{avg}:
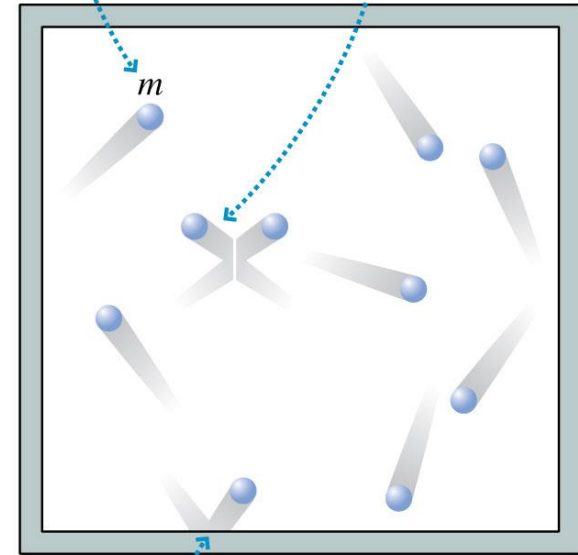
$$T = \frac{2}{3} \frac{K_{avg}}{k_B}$$

- k_B is the **Boltzmann's constant**. Its value is

$$k_B = 1.38 \times 10^{-23} \text{ J/K}$$

1. The gas is made up of a large number N of particles of mass m, each moving randomly.

2. The particles are quite far from each other and interact only rarely when they collide.

m

3. The collisions of the particles with each other (and with walls of the container) are elastic; no energy is lost in these collisions.

The Atomic Model of an Ideal Gas

- The thermal energy of an ideal gas containing N atoms is the sum of the kinetic energies of the individual atoms:

$$E_{th} = NK_{avg} = \frac{3}{2} Nk_B T$$

Thermal energy of an ideal gas of N atoms

- For an ideal gas, **thermal energy is directly proportional to temperature:**

$$\Delta E_{th} = \frac{3}{2} Nk_B \Delta T$$

Example 12.2 Energy need to warm up a room

A large bedroom contains about 1×10^{27} molecules of air. Estimate the energy required to raise the temperature of the air in the room by 5°C.

PREPARE We'll model the air as an ideal gas. Equation 12.6 relates the change in thermal energy of an ideal gas to a change in temperature. The actual temperature of the gas doesn't matter—only the change. The temperature increase is given as 5°C, implying a change in the absolute temperature by the same amount: $\Delta T = 5$ K.

Example 12.2 Energy need to warm up a room (cont.)

SOLVE We can use Equation 12.6 to calculate the amount by which the room's thermal energy must be increased:

$$\Delta E_{\text{th}} = \frac{3}{2} N k_{\text{B}} \Delta T = \frac{3}{2}(1 \times 10^{27})(1.38 \times 10^{-23} \text{ J/K})(5 \text{ K})$$

$$= 1 \times 10^5 \text{ J} = 100 \text{ kJ}$$

This is the energy we would have to supply—probably in the form of heat from a furnace—to raise the temperature.

Example 12.2 Energy need to warm up a room (cont.)

ASSESS 100 kJ isn't that much energy. Table 11.2 showed it to be less than the food energy in a carrot! This seems reasonable because you know that your furnace can quickly warm up the air in a room. Heating up the walls and furnishings is another story.
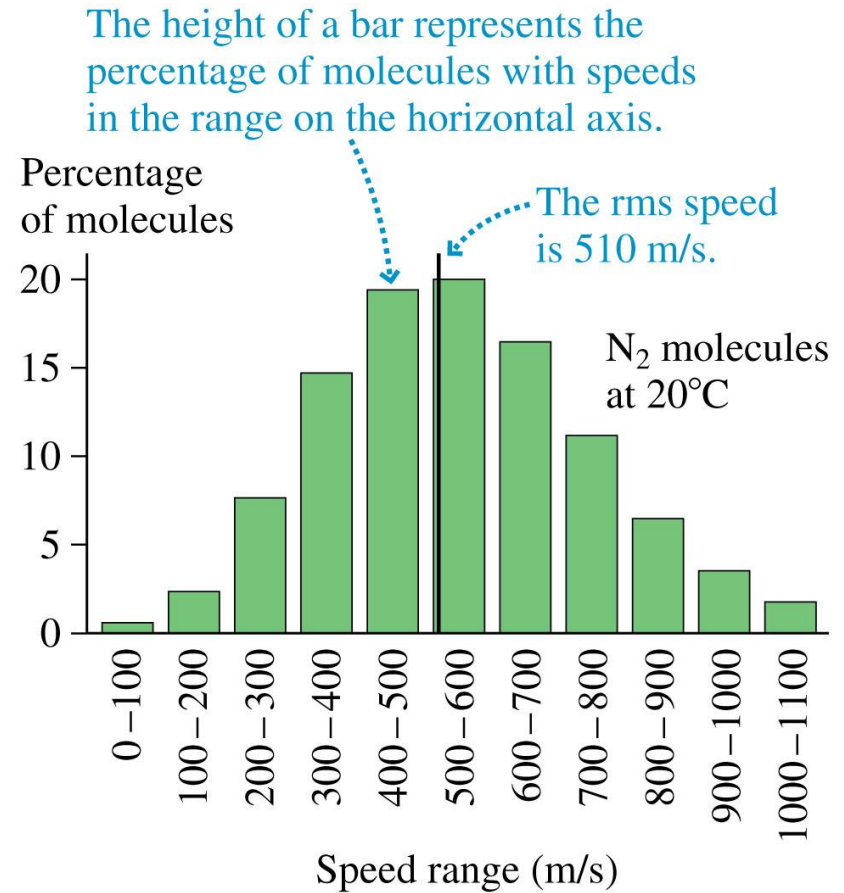
The Atomic Model of an Ideal Gas

- Is it cold in space? The space shuttle orbits in the upper thermosphere, about 300 km above the surface of the earth. There is still a trace of atmosphere left at this altitude, and it has quite a high temperature—over 1000°C. Although the average speed of the air molecules here is high, there are so few air molecules present that the thermal energy is extremely low.

Molecular Speeds and Temperature

- The histogram shows data from an experiment that measures the molecular speeds in nitrogen gas at 20°C.

- Here the most probable speed is 500–600 m/s (1200 mph). Almost 20% of the molecules are moving at that speed.

The height of a bar represents the percentage of molecules with speeds in the range on the horizontal axis.

The rms speed is 510 m/s.

N_2 molecules at 20°C

Percentage of molecules

Speed range (m/s)

Molecular Speeds and Temperature

- Because temperature is proportional to the average kinetic energy of the atoms, it is useful to calculate the average kinetic energy:

$$K_{avg} = \frac{\sum \frac{1}{2}mv^2}{N} = \frac{1}{2}m\frac{\sum v^2}{N} = \frac{1}{2}m(v^2)_{avg}$$

- By definition, this is the average of the *squares* of all the individual speeds.

- The **root-mean-square speed** is the speed of an atom with the average kinetic energy. It is often referred to as the *rms speed* and is calculated as

$$v_{rms} = \sqrt{(v^2)_{avg}} = \text{speed of a typical atom}$$

Molecular Speeds and Temperature

- We can use the expressions for kinetic energy to relate the temperature to the speeds of the atoms:

$$v_{rms} = \sqrt{\frac{3k_B T}{m}}$$

rms speed of an atom of mass m in an ideal gas at temperature T

- Temperature must be in kelvin to compute rms speeds.

Molecular Speeds and Temperature

Square-root relationships

Two quantities are said to have a **square-root relationship** if y is proportional to the square root of x. We write the mathematical relationship as

$$y = A\sqrt{x}$$

y is proportional to the square root of x

The graph of a square-root relationship is a parabola that has been rotated by 90°.

Increasing x by a factor of 4 increases y by a factor of 2.

$y = A\sqrt{x}$

A is the constant of proportionality. It is the value of y when $x = 1$.

SCALING If x has the initial value x_1, then y has the initial value y_1. Changing x from x_1 to x_2 changes y from y_1 to y_2. The ratio of y_2 to y_1 is

$$\frac{y_2}{y_1} = \frac{A\sqrt{x_2}}{A\sqrt{x_1}} = \sqrt{\frac{x_2}{x_1}}$$

which is the square root of the ratio of x_2 to x_1.

- If you increase x by a factor of 4, you increase y by a factor of $\sqrt{4} = 2$.
- If you decrease x by a factor of 9, you decrease y by a factor of $\sqrt{9} = 3$.

These examples illustrate a general rule:

Changing x by a factor of c changes y by a factor of $\sqrt{c}$.
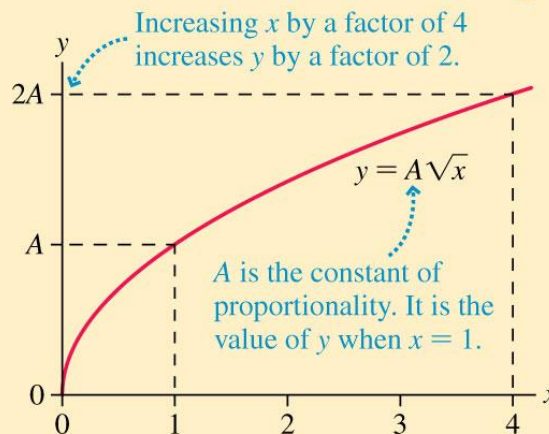
Exercise 13

Text: p. 361

QuickCheck 12.5

A rigid container holds both hydrogen gas (H_2) and nitrogen gas (N_2) at 100°C. Which statement describes their rms speeds?

    A. v_{rms} of H_2 < v_{rms} of N_2

    B. v_{rms} of H_2 = v_{rms} of N_2

    C. v_{rms} of H_2 > v_{rms} of N_2

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✔ C. v_{rms} of $H_2 > v_{rms}$ of N_2

QuickCheck 12.6

An object moving faster than the earth's escape velocity (about 11 km/s) has enough energy to escape the pull of the earth's gravity. Which of the following gas molecules would be most likely to be moving at a speed high enough to escape the earth's atmosphere?

    A. Carbon dioxide

    B. Oxygen

    C. Nitrogen

    D. Water vapor

    E. Hydrogen

QuickCheck 12.6

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    A. Carbon dioxide

    B. Oxygen

    C. Nitrogen

    D. Water vapor

✔   E. Hydrogen

Example 12.3 Speeds of air molecules

Most of the earth's atmosphere is the gas nitrogen, which consists of molecules, N_2. At the coldest temperature ever observed on earth, –129°C, what is the root-mean-square speed of the nitrogen molecules? Does the temperature at the earth's surface ever get high enough that a typical molecule is moving at twice this speed? (The highest temperature ever observed on earth was 57°C.)

Example 12.3 Speeds of air molecules (cont.)

PREPARE You can use the periodic table to determine that the mass of a nitrogen atom is 14 u. A molecule consists of two atoms, so its mass is 28 u. Thus the molecular mass in SI units (i.e., kg) is

$$m = 28 \text{ u} \times \frac{1.66 \times 10^{-27} \text{ kg}}{1 \text{ u}} = 4.6 \times 10^{-26} \text{ kg}$$

Example 12.3 Speeds of air molecules (cont.)

The problem statement gives two temperatures we'll call T_1 and T_2; we need to express these in kelvin. The lowest temperature ever observed on earth is $T_1 = -129 + 273 = 144$ K; the highest temperature is $T_2 = 57 + 273 = 330$ K.

Example 12.3 Speeds of air molecules (cont.)

SOLVE We use Equation 12.11 to find v_{rms} for the nitrogen molecules at T_1:

$$v_{rms} = \sqrt{\frac{3k_B T_1}{m}} = \sqrt{\frac{3(1.38 \times 10^{-23}\,\text{J/K})(144\,\text{K})}{4.6 \times 10^{-26}\,\text{kg}}} = 360\,\text{m/s}$$

Example 12.3 Speeds of air molecules (cont.)

Because the rms speed is proportional to the square root of the temperature, doubling the rms speed would require increasing the temperature by a factor of 4. The ratio of the highest temperature ever recorded to the lowest temperature ever recorded is less than this:

$$v_{\text{rms}} = \sqrt{\frac{3k_{\text{B}}T_1}{m}} = \sqrt{\frac{3(1.38 \times 10^{-23}\,\text{J/K})(144\,\text{K})}{4.6 \times 10^{-26}\,\text{kg}}} = 360\,\text{m/s}$$

The temperature at the earth's surface is never high enough that nitrogen molecules move at twice the computed speed.

Example 12.3 Speeds of air molecules (cont.)

ASSESS We can use the square-root relationship to assess our computed result for the molecular speed. Figure 12.4 shows an rms speed of 510 m/s for nitrogen molecules at 20°C, or 293 K. Temperature T_1 is approximately half of this, so we'd expect to compute a speed that is lower by about $1/\sqrt{2}$, which is what we found.

Pressure

- As particles in the gas move around in a container, they can bounce off the walls, creating a force on the walls.

(a)
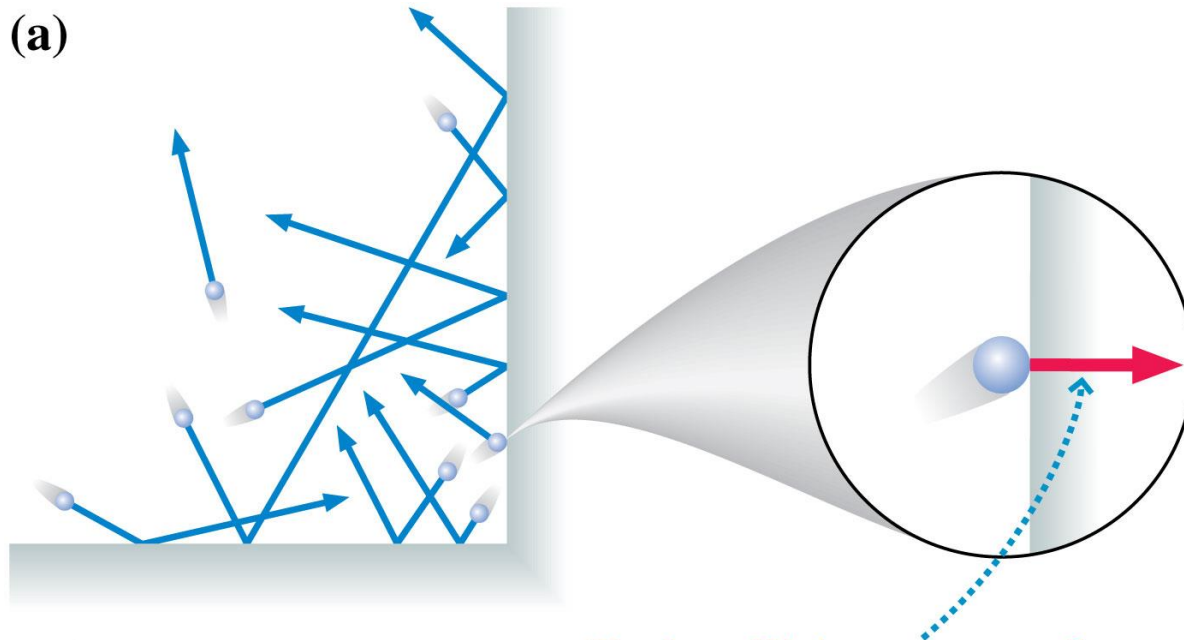
There are an enormous number of collisions of particles against the wall per second.

Each collision exerts a force on the wall. The net force due to all the collisions causes the gas to have a pressure.

Pressure

- The collisions with the wall of the bicycle tire create a force perpendicular to the tire wall. If the patch is doubled, then twice as many particles hit it every second.

(b)

On a macroscopic scale, these microscopic collisions exert a force on an area *A* of the wall that is proportional to *A*.

$\vec{F}$

Area *A*
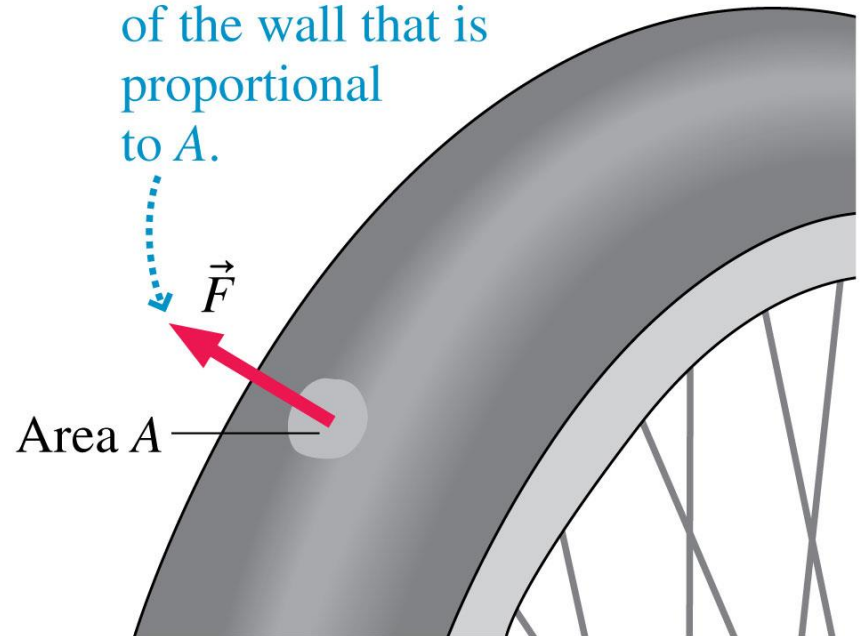
Pressure

- The **pressure** of the gas is the *ratio* of the force to the area:

$$p = \frac{F}{A}$$

Definition of pressure in a gas

- The SI unit of pressure is the **pascal**, defined as

$$1 \text{ pascal} = 1 \text{ Pa} = 1 \frac{\text{N}}{\text{m}^2}$$

- The pressure from the atmosphere at sea level, the *standard atmosphere*, is

    1 standard atmosphere = 1 atm = 101,300 Pa = 101.3 kPa

- In the U.S., pressure is often expressed in pounds per square inch, or psi:

$$1 \text{atm} = 14.7 \text{ psi}$$

Pressure

- The net pressure force is exerted only where there is a pressure *difference* between the two sides of a surface:

$$F_{\text{net}} = F_2 - F_1 = p_2 A - p_1 A$$

$$= A(p_2 - p_1) = A\,\Delta p$$

(a)
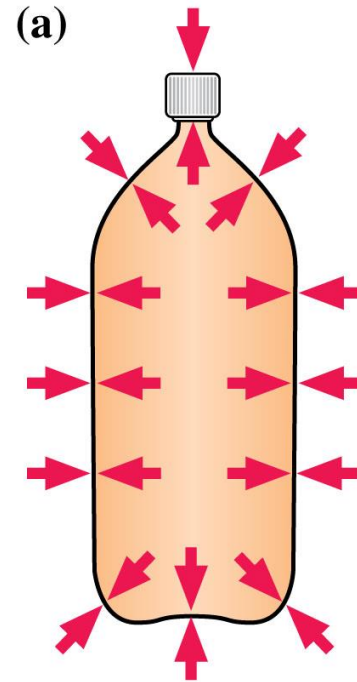
The pressure inside the bottle equals the pressure outside, so there is no net force.

(b)

Area A

$\vec{F}_1$ $\vec{F}_2$

p_1 $p_2 > p_1$
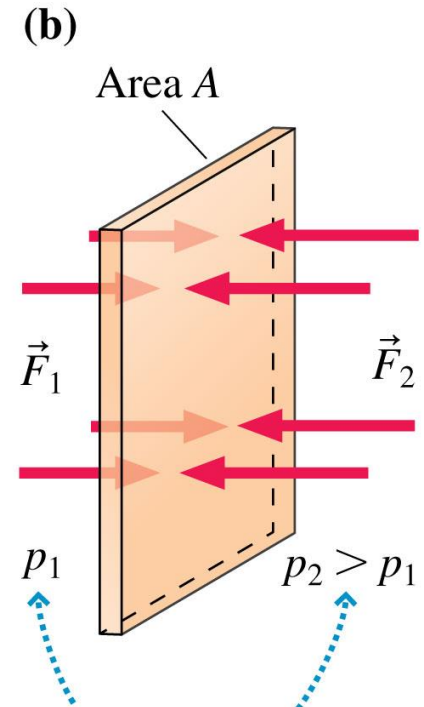
There is a difference in pressure between the two sides.

Pressure

- A **vacuum** is an enclosed space with $p \ll 1$ atm.

- A *perfect vacuum* would be $p = 0$ Pa, but it is impossible to remove every molecule from the container.

- The **gauge pressure** p_g is the *difference* between the actual pressure and the atmospheric pressure.
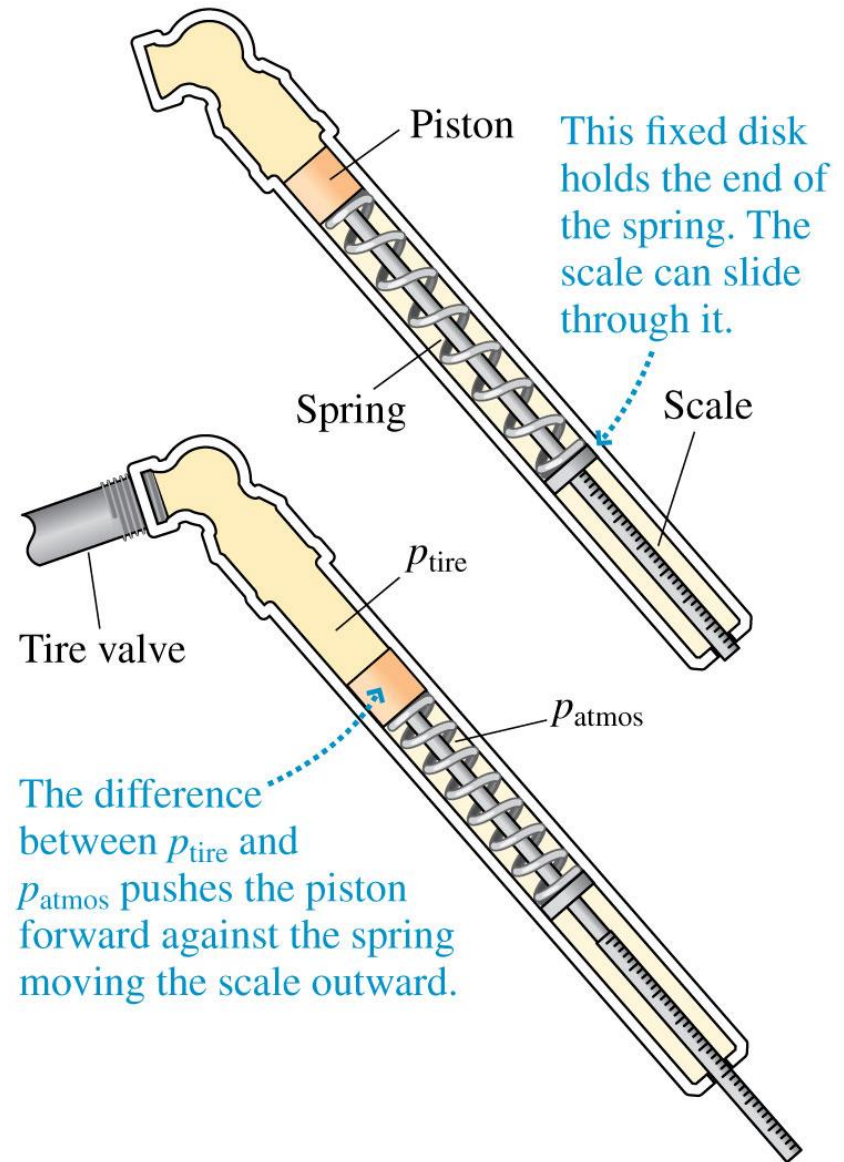
Piston

This fixed disk holds the end of the spring. The scale can slide through it.

Spring

Scale

Tire valve

p_{tire}

p_{atmos}

The difference between p_{tire} and p_{atmos} pushes the piston forward against the spring moving the scale outward.

QuickCheck 12.10

Two identical cylinders, A and B, contain the same type of gas at the same pressure. Cylinder A has twice as much gas as cylinder B. Which is true?

    A. $T_A < T_B$

    B. $T_A = T_B$

    C. $T_A > T_B$

    D.   Not enough information to make a comparison

QuickCheck 12.10

Two identical cylinders, A and B, contain the same type of gas at the same pressure. Cylinder A has twice as much gas as cylinder B. Which is true?

✔ A. $T_A < T_B$

B. $T_A = T_B$

C. $T_A > T_B$

D.   Not enough information to make a comparison

Larger for A, so …

$$pV = nRT$$

Same   Same   … T must be smaller for A.

QuickCheck 12.11

Two cylinders, A and B, contain the same type of gas at the same temperature. Cylinder A has twice the volume as cylinder B and contains half as many molecules as cylinder B. Which is true?

A. $p_A = 4p_B$

B. $p_A = 2p_B$

C. $p_A = p_B$

D. $p_A = ½ p_B$

E. $p_A = ¼ p_B$

QuickCheck 12.11

Two cylinders, A and B, contain the same type of gas at the same temperature. Cylinder A has twice the volume as cylinder B and contains half as many molecules as cylinder B. Which is true?

A. $p_A = 4p_B$

B. $p_A = 2p_B$

C. $p_A = p_B$

D. $p_A = \frac{1}{2} p_B$

✔ E. $p_A = \frac{1}{4} p_B$

$$pV = Nk_BT \implies p = \frac{Nk_BT}{V}$$

Half as large for A
— Same for both
Twice as large for A

Example 12.4 Finding the force due to a pressure difference

Patients suffering from decompression sickness may be treated in a hyperbaric oxygen chamber filled with oxygen at greater than atmospheric pressure. A cylindrical chamber with flat end plates of diameter 0.75 m is filled with oxygen to a gauge pressure of 27 kPa. What is the resulting force on the end plate of the cylinder?

PREPARE There is a force on the end plate because of the pressure *difference* between the inside and outside. 27 kPa is the pressure in excess of 1 atm. If we assume the pressure outside is 1 atm, then 27 kPa is Δp, the pressure difference across the surface.

Example 12.4 Finding the force due to a pressure difference (cont.)

SOLVE The end plate has area A = $\pi(0.75 \text{ m}/2)^2 = 0.442 \text{ m}^2$. The pressure difference results in a net force

$$F_{net} = A\,\Delta p = (0.442 \text{ m}^2)(27{,}000 \text{ Pa}) = 12 \text{ kN}$$

ASSESS The area of the end plate is large, so we expect a large force. Our answer makes sense, although it is remarkable to think that this force results from the collisions of individual molecules with the plate. The large pressure force must be offset with an equally large force to keep the plate in place, so the end plate is fastened with stout bolts.

From Collisions to Pressure and the Ideal-Gas Law
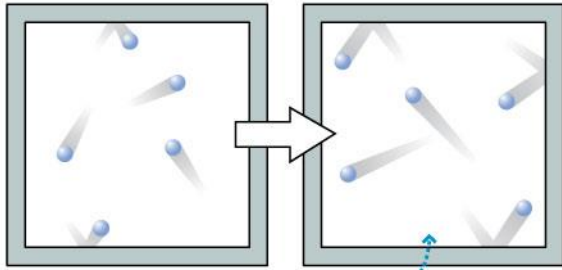
Increasing the temperature of the gas means the particles move at higher speeds. They hit the walls more often and with more force, so there is more pressure.
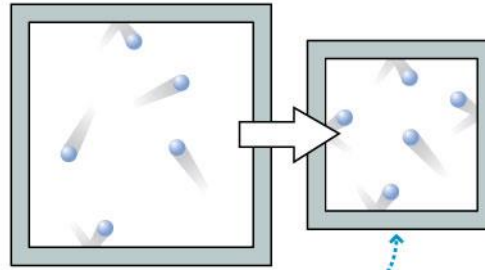
Decreasing the volume of the container means more frequent collisions with the walls of the container, and thus more pressure.
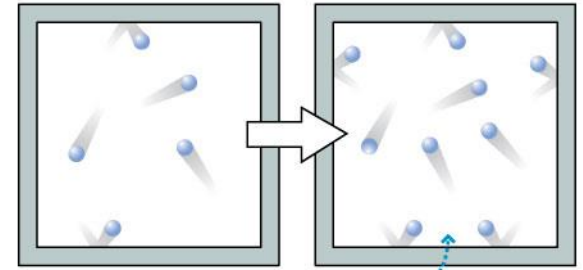
Increasing the number of particles in the container means more frequent collisions with the walls of the container, and thus more pressure.

- Pressure should be proportional to the temperature of the gas: $p \propto T$

- Pressure should be inversely proportional to the volume of the container: $p \propto 1/V$

- Pressure should be proportional to the number of gas particles: $p \propto N$

From Collisions to Pressure and the Ideal-Gas Law

- The **ideal-gas law** relates the pressure, temperature, and volume of an ideal gas:

$$pV = Nk_B T$$

Ideal-gas law, version 1

- The ideal-gas law can also be written:

$$pV = nN_A k_B T = nRT$$

Ideal-gas law, version 2

- The proportionality constant R is known as the *gas constant*:

$$R = N_A k_B = 8.31 \text{ J/mol} \cdot \text{K}$$

From Collisions to Pressure and the Ideal-Gas Law

- Let's review the meaning and the units of the various quantities in the ideal-gas law:

Number of moles in the sample or container of gas

Absolute pressure (Pa)

Gas constant, 8.31 J/mol·K

$$pV = nRT$$

Volume of the sample or container of gas (m³)

Temperature in kelvin (K)

Example 12.5 Finding the volume of a mole

What volume is occupied by 1 mole of an ideal gas at a pressure of 1.00 atm and a temperature of 0°C?

PREPARE The first step in ideal-gas law calculations is to convert all quantities to SI units:

$$p = 1.00 \text{ atm} = 101.3 \times 10^3 \text{ Pa}$$

$$T = 0 + 273 = 273 \text{ K}$$

Example 12.5 Finding the volume of a mole (cont.)

SOLVE We use the ideal-gas law equation to compute

$$V = \frac{nRT}{p} = \frac{(1.00 \text{ mol})(8.31 \text{ J/mol} \cdot \text{K})(273 \text{ K})}{101.3 \times 10^3 \text{ Pa}} = 0.0224 \text{ m}^3$$

We recall from earlier in the chapter that $1.00 \text{ m}^3 = 1000 \text{ L}$, so we can write

$$V = 22.4 \text{ L}$$

Example 12.5 Finding the volume of a mole (cont.)

ASSESS At this temperature and pressure, we find that the volume of 1 mole of a gas is 22.4 L, a result you might recall from chemistry. When we do calculations using gases, it will be useful to keep this volume in mind to see if our answers make physical sense.
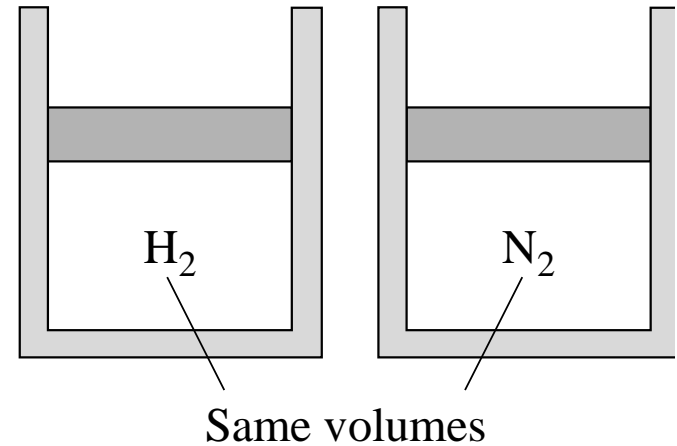
QuickCheck 12.8

The two identical cylinders each have lightweight pistons on top that are free to move, so the pressure inside each cylinder is equal to atmospheric pressure. One cylinder contains hydrogen, the other nitrogen. Both gases are at the same temperature. The number of moles of hydrogen is

H_2 N_2

Same volumes

A. Greater than the number of moles of nitrogen.

B. Equal to the number of moles of nitrogen.

C. Less than the number of moles of nitrogen.

QuickCheck 12.8

The two identical cylinders each have lightweight pistons on top that are free to move, so the pressure inside each cylinder is equal to atmospheric pressure. One cylinder contains hydrogen, the other nitrogen. Both gases are at the same temperature. The number of moles of hydrogen is

H_2 N_2

Same volumes

A. Greater than the number of moles of nitrogen.

✔ B. Equal to the number of moles of nitrogen.

C. Less than the number of moles of nitrogen.

QuickCheck 12.9

The two identical cylinders each have lightweight pistons on top that are free to move, so the pressure inside each cylinder is equal to atmospheric pressure. One cylinder contains hydrogen, the other nitrogen. The mass of gas in each cylinder is the same. The temperature of the hydrogen gas is

H_2

N_2

Same volumes

A. Greater than the temperature of the nitrogen.

B. Equal to the temperature of the nitrogen.

C. Less than the temperature of the nitrogen.

QuickCheck 12.9

The two identical cylinders each have lightweight pistons on top that are free to move, so the pressure inside each cylinder is equal to atmospheric pressure. One cylinder contains hydrogen, the other nitrogen. The mass of gas in each cylinder is the same. The temperature of the hydrogen gas is

H_2 N_2

Same volumes
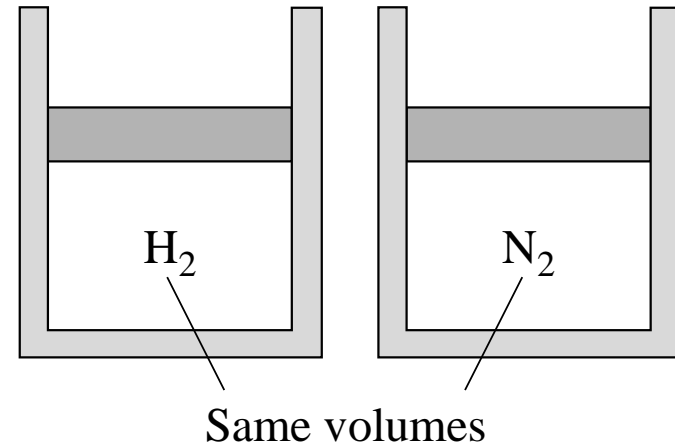
    A. Greater than the temperature of the nitrogen.

✔ B. Equal to the temperature of the nitrogen.

    C. Less than the temperature of the nitrogen.

Section 12.3 Ideal-Gas Processes

Ideal-Gas Processes

- **Ideal-gas processes** have the following properties:
  - The quantity of gas is fixed.
  - There is a well-defined initial state. The initial values of pressure, volume, and temperature will be designated p_i, V_i, and T_i.
  - There is a well-defined final state in which the pressure, volume, and temperature have values p_f, V_f, and T_f.

Ideal-Gas Processes

The values of the variables in the initial and final states are related by

$$\frac{p_f V_f}{T_f} = \frac{p_i V_i}{T_i}$$

Initial and final states for an ideal gas in a sealed container

pV Diagrams

- In a ***pV* diagram**, each point on the graph represents a single, unique state of the gas.

- An ideal-gas process that changes the state of the gas can be represented as a "trajectory."
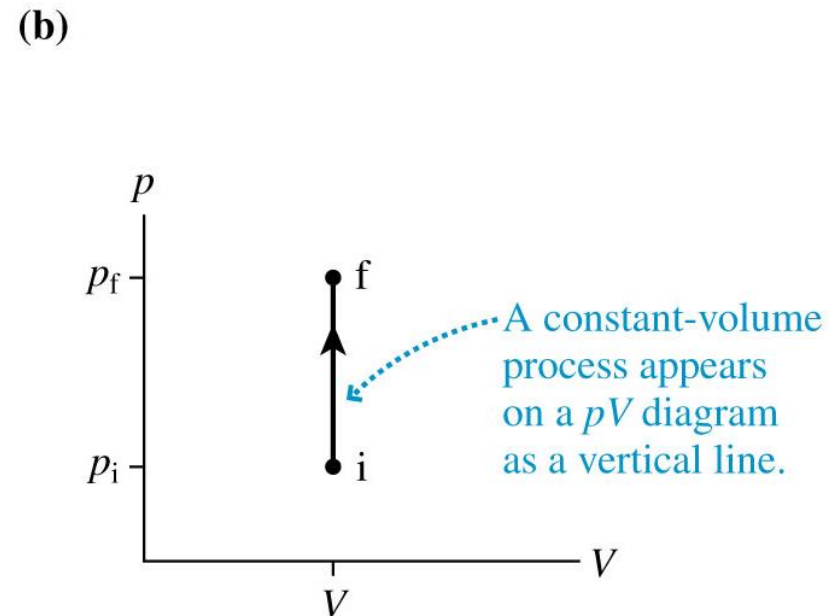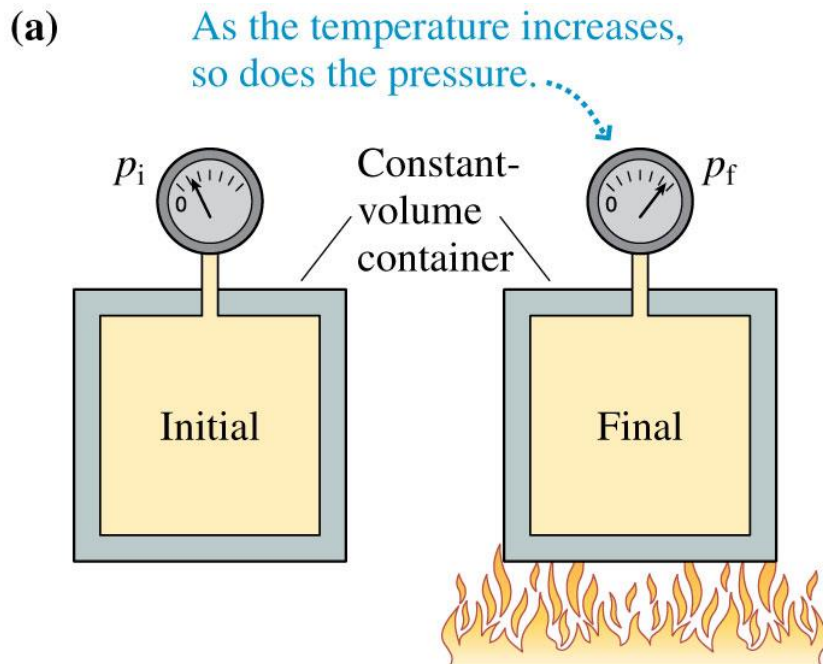

(a) Each state of an ideal gas is represented as a point on a *pV* diagram.

p (kPa)

$n = 1$ mol

2

$T_2 = 3600$ K

1

$T_1 = 900$ K

3

$T_3 = 600$ K

V (m³)
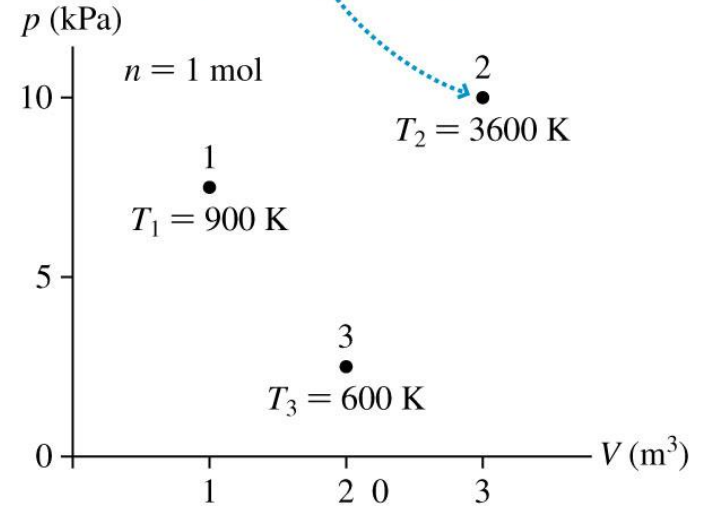
(b) A process that changes the gas from one state to another is represented by a trajectory on a *pV* diagram.

p (kPa)

2

1

3

V (m³)
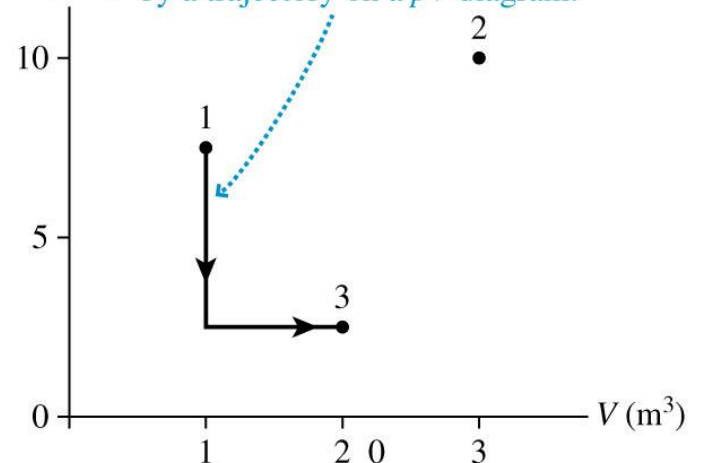
Constant-Volume Processes

- Warming a gas in a closed container will raise the pressure without changing its volume. This is an example of a **constant-volume process**, where $V_f = V_i$.

- **A constant-volume process appears on a pV diagram as a vertical line.**

(a) As the temperature increases, so does the pressure.

p_i Constant-volume container p_f

Initial   Final

(b)

p

p_f — f

A constant-volume process appears on a pV diagram as a vertical line.

p_i — i

V

QuickCheck 12.12

The temperature of a rigid (i.e., constant-volume), sealed container of gas increases from 100°C to 200°C. The gas pressure increases by a factor of

A. 2

B. 1.3

C. 1 (the pressure doesn't change)

D. 0.8

E. 0.5

QuickCheck 12.12

The temperature of a rigid (i.e., constant-volume), sealed container of gas increases from 100°C to 200°C. The gas pressure increases by a factor of

A. 2

✔ B. 1.3   Temperatures MUST be in K, not °C, to use the ideal-gas law.

C. 1 (the pressure doesn't change)

D. 0.8

E. 0.5

Example 12.6 Computing the tire pressure on a hot day

The pressure in a car tire is 30.0 psi on a cool morning when the air temperature is 0°C. After the day warms up and bright sun shines on the black tire, the temperature of the air inside the tire reaches 30°C. What is the tire pressure at this temperature?

Example 12.6 Computing the tire pressure on a hot day (cont.)

PREPARE A tire is (to a good approximation) a sealed container with constant volume, so this is a constant-volume process. The measured tire pressure is a gauge pressure, but the ideal-gas law requires an absolute pressure. We must correct for this. The initial pressure is

$$p_i = (p_g)_i + 1.00 \text{ atm} = 30.0 \text{ psi} + 14.7 \text{ psi} = 44.7 \text{ psi}$$

Temperatures must be in kelvin, so we convert:

$$T_i = 0°C + 273 = 273 \text{ K}$$

$$T_f = 30°C + 273 = 303 \text{ K}$$

Example 12.6 Computing the tire pressure on a hot day (cont.)

SOLVE The gas is in a sealed container, so we can use the ideal-gas law as given in Equation 12.16 to solve for the final pressure. In this equation, we divide both sides by V_f, and then cancel the ratio of the two volumes, which is equal to 1 for this constant-volume process:

$$p_f = p_i \, \frac{V_i}{V_f} \frac{T_f}{T_i} = p_i \, \frac{T_f}{T_i}$$

Example 12.6 Computing the tire pressure on a hot day (cont.)

The units for p_f will be the same as those for p_i, so we can keep the initial pressure in psi. The pressure at the higher temperature is

$$p_f = 44.7 \text{ psi} \times \frac{303 \text{ K}}{273 \text{ K}} = 49.6 \text{ psi}$$

Example 12.6 Computing the tire pressure on a hot day (cont.)

This is an absolute pressure, but the problem asks for the measured pressure in the tire—a gauge pressure. Converting to gauge pressure gives

$$(p_\mathrm{g})_\mathrm{f} = p_\mathrm{f} - 1.00 \text{ atm} = 49.6 \text{ psi} - 14.7 \text{ psi} = 34.9 \text{ psi}$$

Example 12.6 Computing the tire pressure on a hot day (cont.)

ASSESS The temperature has changed by 30 K, which is a bit more than 10% of the initial temperature, so we expect a large change in pressure. Our result seems reasonable, and it has practical implications: If you check the pressure in your tires when they are at a particular temperature, don't expect the pressure to be the same when conditions change!

QuickCheck 12.19

A sample of gas is in a cylinder with a moveable piston. The force on the piston can be varied, altering the pressure and volume. A sample of gas is taken from an initial state to a final state following a curve on the pV diagram shown. The final temperature is

A. Higher than the initial temperature.

B. The same as the initial temperature.
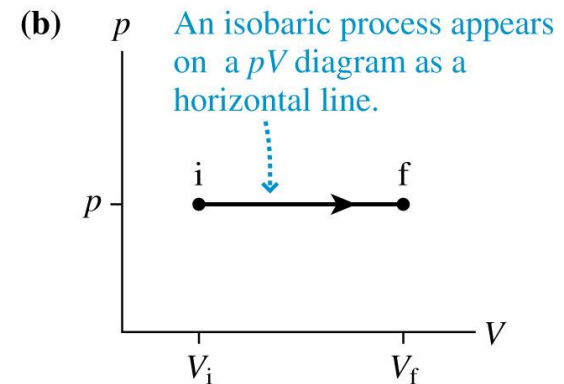
C. Lower than the initial temperature.

p (atm)

End

6

$n = 0.02$ mol

2

Start

V (cm^3)

QuickCheck 12.19

A sample of gas is in a cylinder with a moveable piston. The force on the piston can be varied, altering the pressure and volume. A sample of gas is taken from an initial state to a final state following a curve on the pV diagram shown. The final temperature is
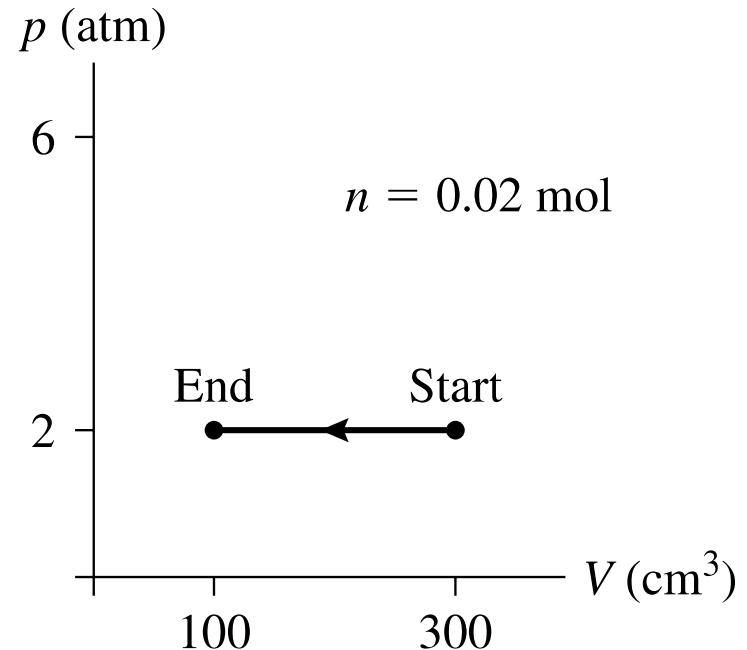
✔ A. Higher than the initial temperature.

B. The same as the initial temperature.

C. Lower than the initial temperature.

p (atm)

End

6

$n = 0.02$ mol

2

Start

V (cm^3)

Constant-Pressure Processes

- An **isobaric process** is a constant-pressure process.

- A piston slides to the position where the external pressure and the gas pressure are equal. As long as the external pressure is constant, so must be the gas pressure.

- **A constant-pressure process appears on a pV diagram as a horizontal line.**

(a) In equilibrium, pressure must be the same on both sides of the piston.

p_{ext}

$\vec{F}_{ext}$

p_{gas}

$\vec{F}_{gas}$

Initial V_i

p_{ext}

p_{gas}

Movable piston

Final V_f
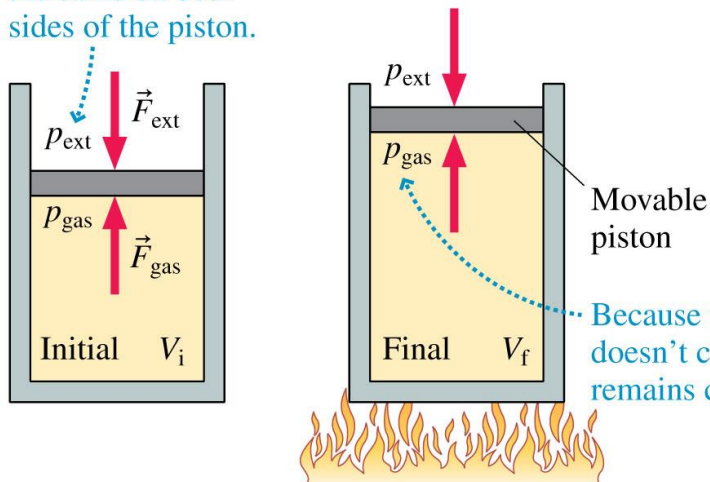
Because the external pressure doesn't change, the gas pressure remains constant as the gas expands.

(b) p An isobaric process appears on a pV diagram as a horizontal line.

p

i   f

V_i V_f V

QuickCheck 12.20

A sample of gas is in a cylinder with a moveable piston. The force on the piston can be varied, altering the pressure and volume. A sample of gas is taken from an initial state to a final state following a curve on the pV diagram shown. The final temperature is

A. Higher than the initial temperature.

B. The same as the initial temperature.
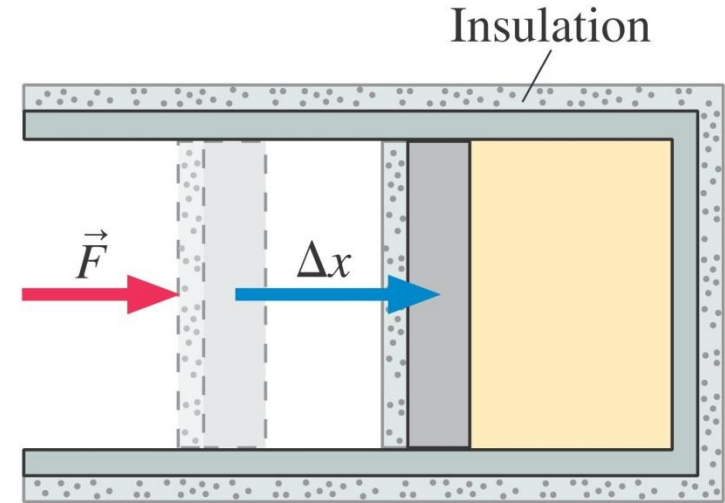
C. Lower than the initial temperature.

QuickCheck 12.20

A sample of gas is in a cylinder with a moveable piston. The force on the piston can be varied, altering the pressure and volume. A sample of gas is taken from an initial state to a final state following a curve on the pV diagram shown. The final temperature is

A. Higher than the initial temperature.

B. The same as the initial temperature.

✔ C. Lower than the initial temperature.

QuickCheck 12.13

A steady force pushes in the piston of a well-insulated cylinder. In this process, the temperature of the gas

Insulation

$\vec{F}$ Δx
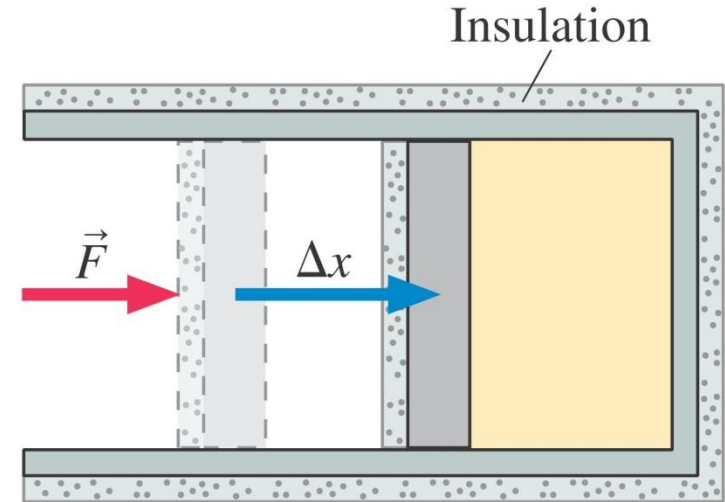
A. Increases.

B. Stays the same.

C. Decreases.

D. There's not enough information to tell.

QuickCheck 12.13

A steady force pushes in the piston of a well-insulated cylinder. In this process, the temperature of the gas

Insulation

$\vec{F}$ Δx

✔ A. Increases.

 B. Stays the same.

 C. Decreases.

 D. There's not enough
    information to tell.

No heat flows (well insulated) ...

... but work is done on the gas.

First law: $Q + W = \Delta E_{th}$

Work increases the gas's thermal energy and with it the temperature.

Example 12.7 A constant-pressure compression

A gas in a cylinder with a movable piston occupies 50.0 cm^3 at 50°C. The gas is cooled at constant pressure until the temperature is 10°C. What is the final volume?

PREPARE This is a sealed container, so we can use Equation 12.16. The pressure of the gas doesn't change, so this is an isobaric process with $p_i/p_f = 1$.

The temperatures must be in kelvin, so we convert:

$$T_i = 50°C + 273 = 323 \text{ K}$$
$$T_f = 10°C + 273 = 283 \text{ K}$$

Example 12.7 A constant-pressure compression (cont.)

SOLVE We can use the ideal-gas law for a sealed container to solve for V_f:

$$V_f = V_i \frac{p_i}{p_f} \frac{T_f}{T_i} = 50.0 \text{ cm}^3 \times 1 \times \frac{283 \text{ K}}{323 \text{ K}} = 43.8 \text{ cm}^3$$

ASSESS In this example and in Example 12.6, we have not converted pressure and volume units because these multiplicative factors cancel. But we did convert temperature to kelvin because this *additive* factor does *not* cancel.

Example Problem

Your lungs have a volume of approximately 4.0 L. While visiting the seaside on a chilly 10°C day, you quickly take a deep breath, all your lungs can hold. The air quickly heats up to your body temperature of 37°C. Assume that you hold the volume of your lungs constant, and that the number of molecules in your lungs stays constant as well. (For a short time, this is a good approximation. Oxygen molecules go out, carbon dioxide go molecules go in, but the net flow is small.) What is the increase in pressure inside your lungs?

Constant-Temperature Processes

- A constant-temperature process is an **isothermal process**.

- A gas cylinder can maintain a constant temperature if submerged in a larger container with a constant temperature.

- Pushing the piston down would be an *isothermal compression*; the reverse would be an *isothermal expansion*.
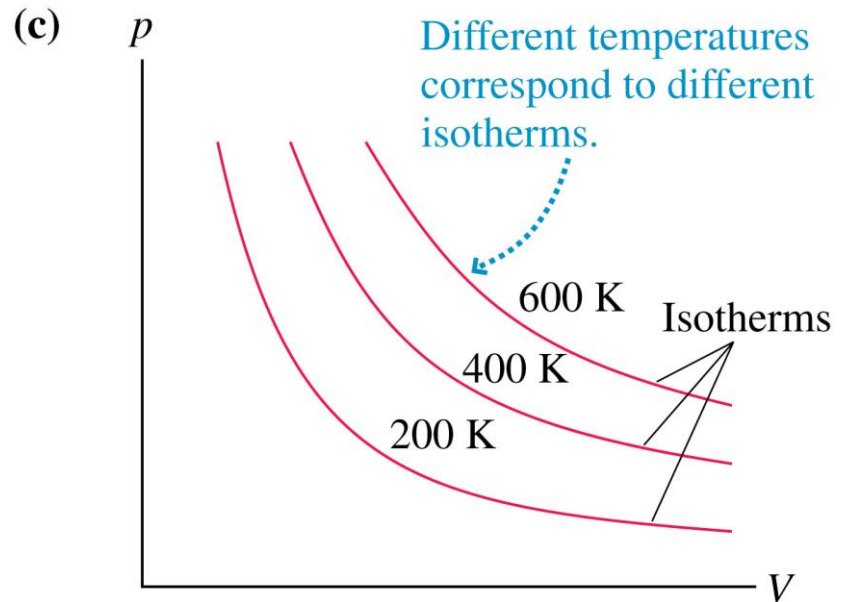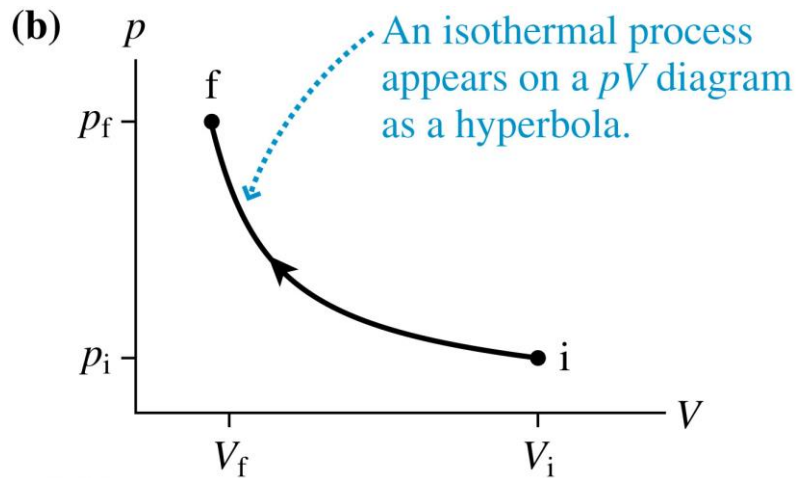

(a)

V_i Initial — Constant T

Push

V_f Final — Constant T
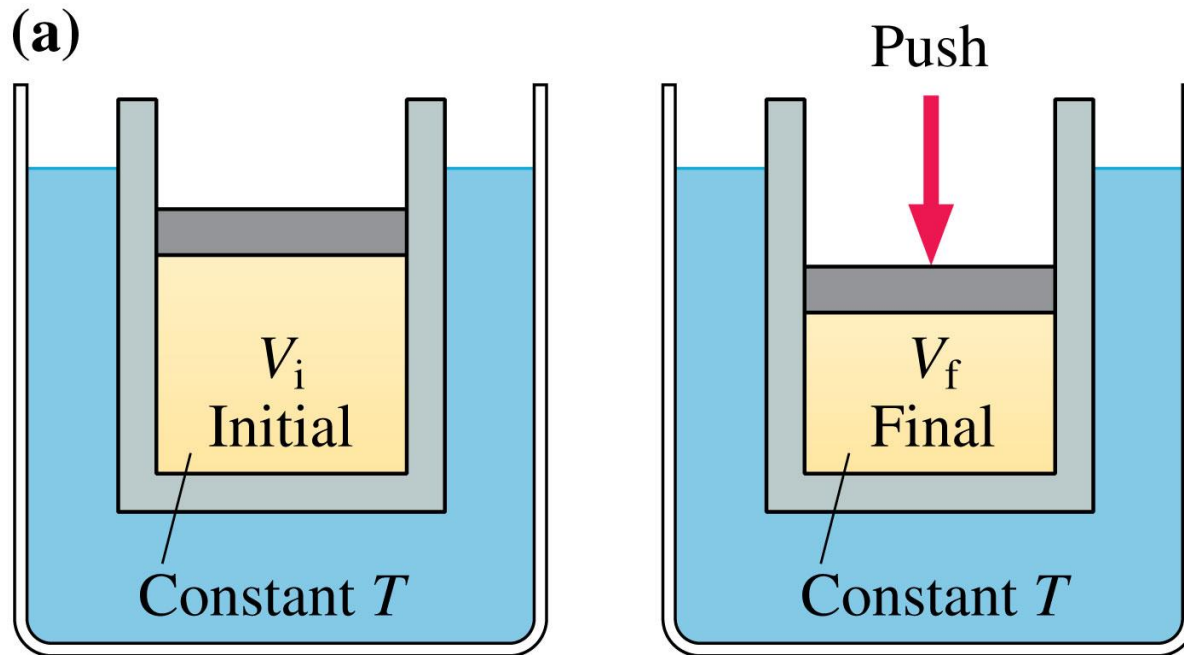
Constant-Temperature Processes

$$p = \frac{nRT}{V} = \frac{\text{constant}}{V}$$

- **Because there is an inverse relationship between p and V, the graph of an isothermal process is a hyperbola.**
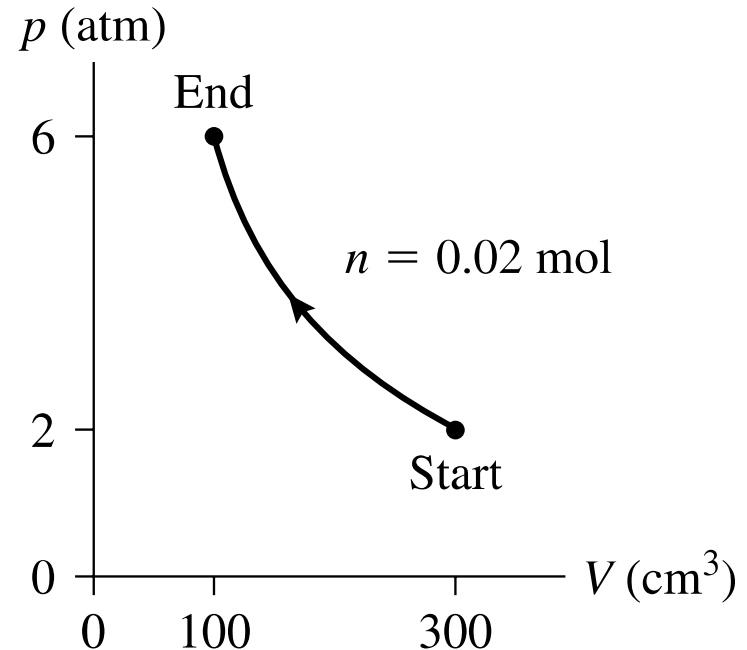

(b) An isothermal process appears on a pV diagram as a hyperbola.

(c) Different temperatures correspond to different isotherms.

600 K
400 K
200 K
Isotherms
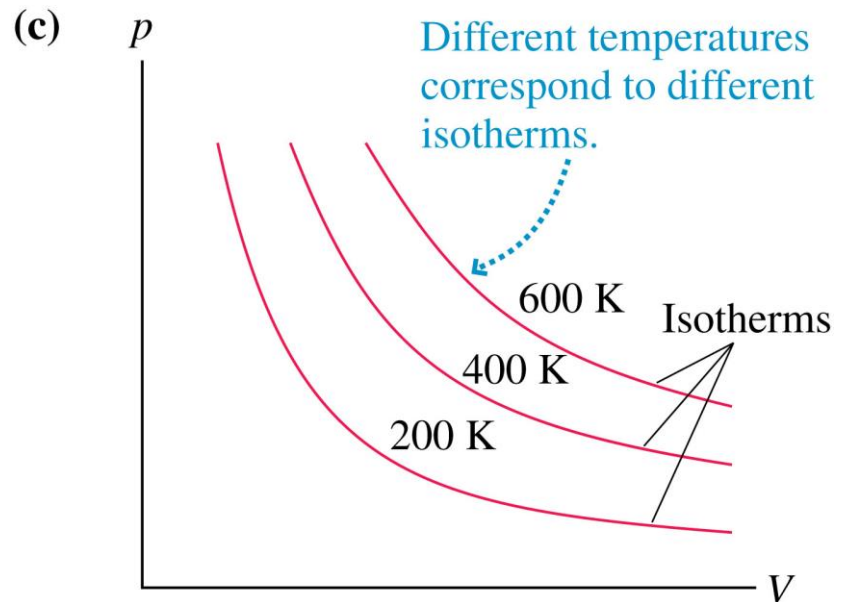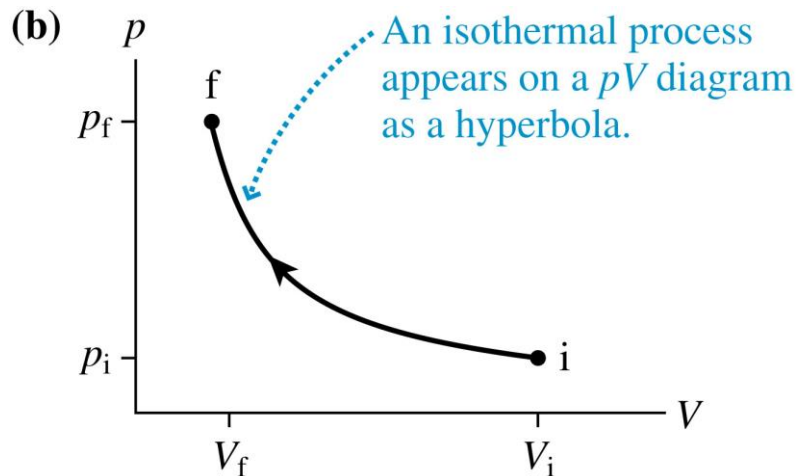
Constant-Temperature Processes

- An **isotherm** is a graph of an isothermal process.

- The location of the isotherm depends on temperature. The direction along the isotherm depends on the process.

(b) p

f

An isothermal process appears on a pV diagram as a hyperbola.

p_f

p_i

i

V_f V_i

V

(c) p

Different temperatures correspond to different isotherms.

600 K

400 K

200 K

Isotherms

V

QuickCheck 12.21

A sample of gas is in a cylinder with a moveable piston. The force on the piston can be varied, altering the pressure and volume. A sample of gas is taken from an initial state to a final state following a curve on the pV diagram shown. The final temperature is

A. Higher than the initial temperature.

B. The same as the initial temperature.

C. Lower than the initial temperature.

p (atm)

End

6

$n = 0.02$ mol

2

Start

0

0   100   300

V (cm^3)

QuickCheck 12.21

A sample of gas is in a cylinder with a moveable piston. The force on the piston can be varied, altering the pressure and volume. A sample of gas is taken from an initial state to a final state following a curve on the pV diagram shown. The final temperature is

A. Higher than the initial temperature.

✔ B. The same as the initial temperature.

C. Lower than the initial temperature.

p (atm)

End

6

$n = 0.02$ mol

2

Start

0

0   100   300

V (cm^3)

Example 12.8 Compression air in the lungs

A snorkeler takes a deep breath at the surface, filling his lungs with 4.0 L of air. He then descends to a depth of 5.0 m, where the pressure is 0.50 atm higher than at the surface. At this depth, what is the volume of air in the snorkeler's lungs?

PREPARE At the surface, the pressure of the air inside the snorkeler's lungs is 1.0 atm—it's atmospheric pressure at sea level. As he descends, the pressure inside his lungs must rise to match the pressure of the surrounding water, because the body can't sustain large pressure differences between inside and out. Further, the air stays at body temperature, making this an isothermal process with $T_f = T_i$.

Example 12.8 Compression air in the lungs (cont.)

SOLVE The ideal-gas law for a sealed container (the lungs) gives

$$V_f = V_i \frac{p_i}{p_f} \frac{T_f}{T_i} = 4.0 \text{ L} \times \frac{1.0 \text{ atm}}{1.5 \text{ atm}} = 2.7 \text{ L}$$

Notice that we didn't need to convert pressure to SI units. As long as the units are the same in the numerator and the denominator, they cancel.

ASSESS The air has a smaller volume at the higher pressure, as we would expect. The air inside your lungs does compress—significantly!—when you dive below the surface.

Thermodynamics of Ideal-Gas Processes

- When gases expand, they do work on the piston.

- If the gas expands under constant pressure, pushing the piston (with area A) from x_i to x_f a distance $d = x_f - x_i$, then the work done is

$$W_{gas} = F_{gas} d = (pA)(x_f - x_i)$$
$$= p(x_f A - x_i A)$$

This can be written as

$$W_{gas} = p(V_f - V_i) = p \Delta V$$

Work done by a gas in an isobaric process

The gas pushes on the piston with force $\vec{F}_{gas}$.

(a)

To keep the piston in place, an external force must be equal and opposite to $\vec{F}_{gas}$.

Pressure p

$\vec{F}_{gas}$ $\vec{F}_{ext}$

(b)

As the piston moves a distance d, the gas does work $F_{gas}d$.

Piston area A

d

0 x_i x_f x

The gas volume changes by $\Delta V = dA$.
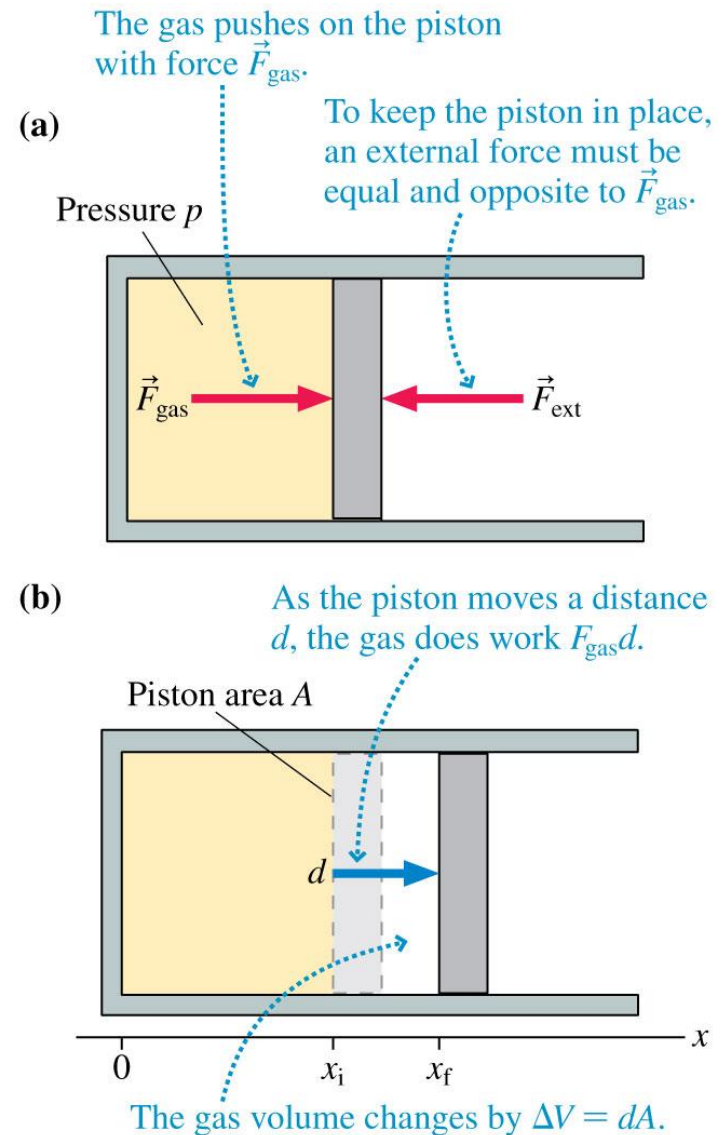
Thermodynamics of Ideal-Gas Processes

- For all ideal-gas processes, the work is the area under the pV graph between V_i and V_f.

(a)

For an *isobaric* process, the area under the graph $p\Delta V$ is the work done by the gas as it expands from V_i to V_f.

(b)

In general, the work done by a gas is the area under the graph between V_i and V_f.

W_{gas} = area
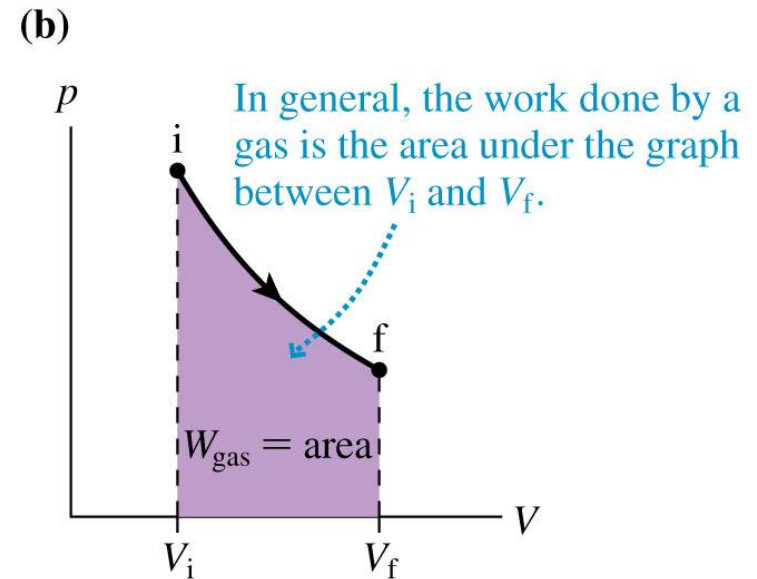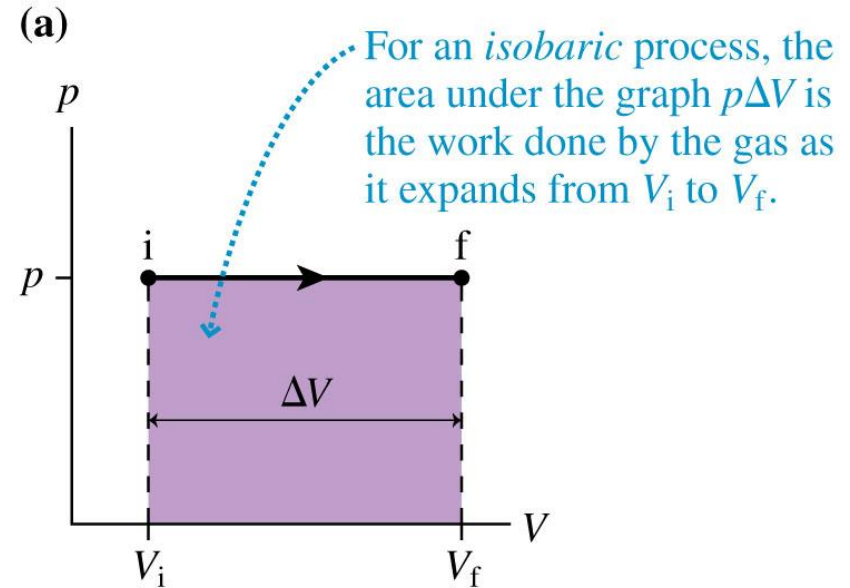
Thermodynamics of Ideal-Gas Processes

- In order for the gas to do work, its volume must change. No work is done in a constant-volume process.

- The simple relationship of Equation 12.18 applies only to constant-pressure processes. For any other ideal-gas process, you must use the geometry of the pV diagram to calculate the area under the graph.

- To calculate work, pressure must be in Pa and volume in m^3. The product of Pa (which is N/m^2) and m^3 is $N \cdot m$. But $1 \ N \cdot m$ is J—the unit of work and energy.

Thermodynamics of Ideal-Gas Processes (cont.)

- W_{gas} is positive if the gas expands ($\Delta V > 0$). The gas does work by pushing against the piston. In this case, the work done is energy transferred out of the system, and the energy of the gas decreases. W_{gas} is negative if the piston compresses the gas ($\Delta V < 0$) because the force $\vec{F}_{gas}$ is opposite the displacement of the piston. Energy is transferred into the system as work, and the energy of the gas increases. We often say "work is done *on* the gas," but this just means that W_{gas} is negative.

Thermodynamics of Ideal-Gas Processes

- The first law of thermodynamics can be written

$$\Delta E_{\text{th}} = Q - W_{\text{gas}}$$

- Because the thermal energy only depends on its temperature, we can also write the change in thermal energy of an ideal gas as

$$\Delta E_{\text{th}} = \frac{3}{2} N k_{\text{B}} \, \Delta T = \frac{3}{2} n R \, \Delta T$$

Adiabatic Processes

- **Adiabatic processes** are processes during which heat is not transferred. In these processes, $Q = 0$.

- **An adiabatic expansion lowers the temperature of a gas.**

- **An adiabatic compression raises the temperature of a gas.**

- Adiabatic processes allow you to use work, rather than heat, to change the temperature of the gas.

QuickCheck 12.14

A cylinder of gas has a frictionless but tightly sealed piston of mass M. A small flame heats the cylinder, causing the piston to slowly move upward. For the gas inside the cylinder, what kind of process is this?

A. Isochoric
B. Isobaric
C. Isothermal
D. Adiabatic
E. None of the above

QuickCheck 12.14

A cylinder of gas has a frictionless but tightly sealed piston of mass M. A small flame heats the cylinder, causing the piston to slowly move upward. For the gas inside the cylinder, what kind of process is this?

A. Isochoric

✔ B. Isobaric

C. Isothermal

D. Adiabatic

E. None of the above

QuickCheck 12.15

A cylinder of gas has a frictionless but tightly sealed piston of mass M. The gas temperature is increased from an initial 27°C to a final 127°C. What is the final-to-initial volume ratio V_f / V_i?

A. 1.50

B. 1.33

C. 1.25

D. 1.00

E. Not enough information to tell

QuickCheck 12.15

A cylinder of gas has a frictionless but tightly sealed piston of mass M. The gas temperature is increased from an initial 27°C to a final 127°C. What is the final-to-initial volume ratio V_f / V_i?

A. 1.50

✔ B. 1.33

C. 1.25

D. 1.00

E. Not enough information to tell

Isobaric, so

$$\frac{V_f}{V_f} = \frac{T_f}{T_f} = \frac{400 \text{ K}}{300 \text{ K}}$$

QuickCheck 12.16

A cylinder of gas floats in a large tank of water. It has a frictionless but tightly sealed piston of mass M. Small masses are slowly placed onto the top of the piston, causing it to slowly move downward. For the gas inside the cylinder, what kind of process is this?

A. Isochoric

B. Isobaric

C. Isothermal

D. Adibatic
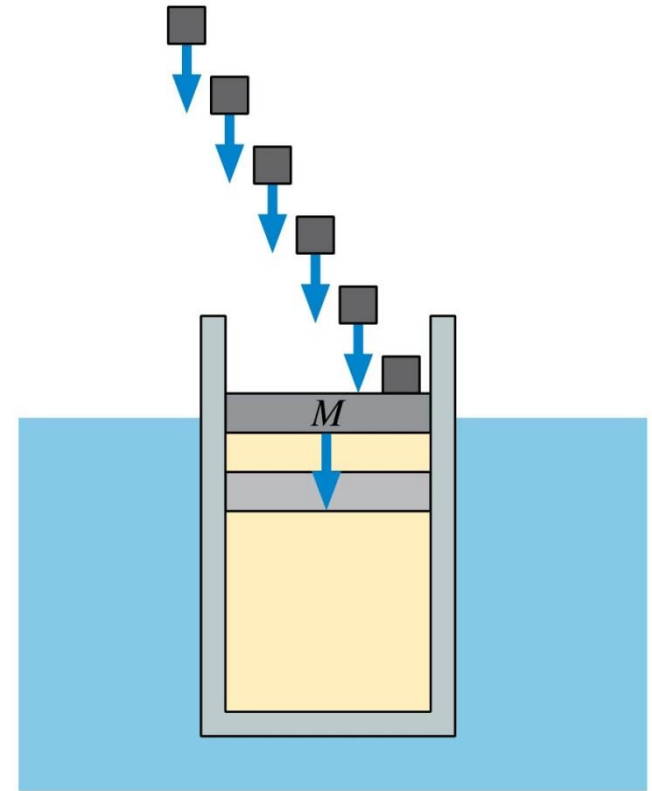
E. None of the above

QuickCheck 12.16

A cylinder of gas floats in a large tank of water. It has a frictionless but tightly sealed piston of mass M. Small masses are slowly placed onto the top of the piston, causing it to slowly move downward. For the gas inside the cylinder, what kind of process is this?

A. Isochoric

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D. Adibatic
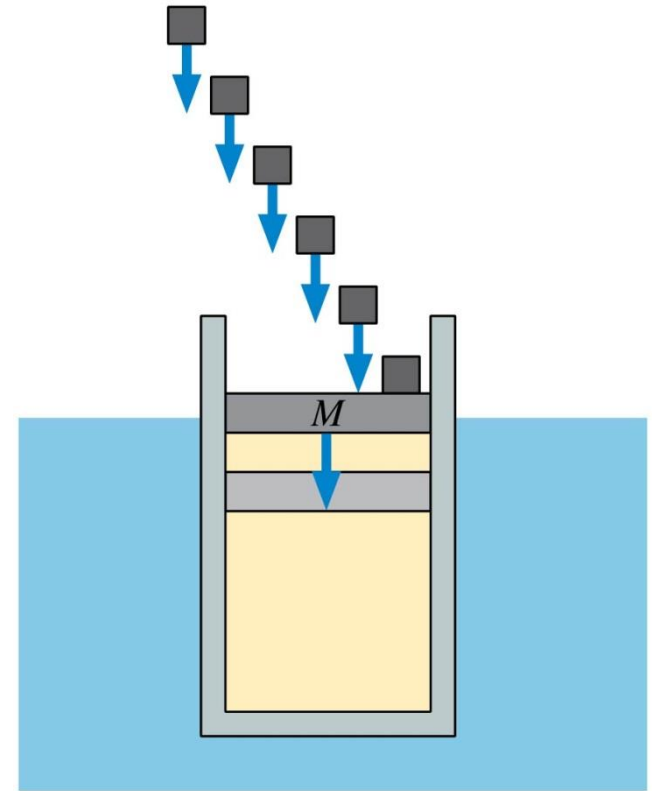
E. None of the above

# Conceptual Example 12.10 Adiabatic curves on a pV diagram

FIGURE 12.17 shows the *pV* diagram of a gas undergoing an isothermal compression from point 1 to point 2. Sketch how the *pV* diagram would look if the gas were compressed from point 1 to the same final pressure by a rapid adiabatic compression.

REASON An adiabatic compression increases the temperature of the gas as the work done on the gas is transformed into thermal energy. Consequently, as seen in FIGURE 12.18, the curve of the adiabatic compression cuts across the isotherms to end on a higher-temperature isotherm when the gas pressure reaches p_2.
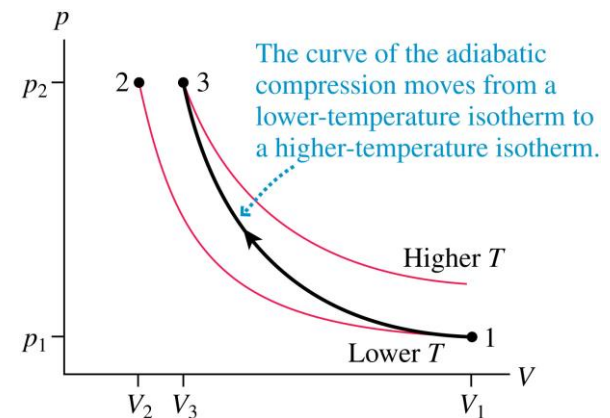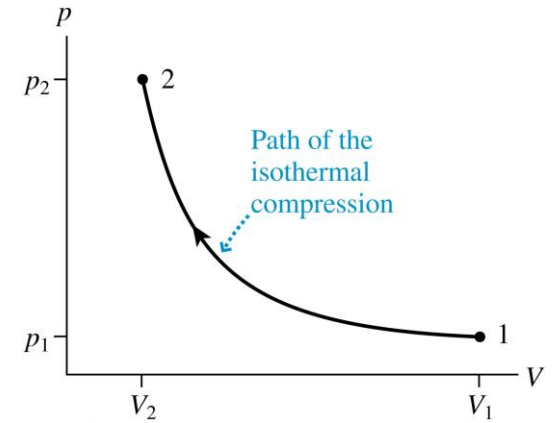
# Conceptual Example 12.10 Adiabatic curves on a pV diagram (cont.)

ASSESS In an isothermal compression, heat energy is transferred out of the gas so that the gas temperature stays the same. This heat transfer doesn't happen in an adiabatic compression, so we'd expect the gas to have a higher final temperature. In general, the temperature at the final point of an adiabatic compression is higher than at the starting point. Similarly, an adiabatic expansion ends on a lower-temperature isotherm.
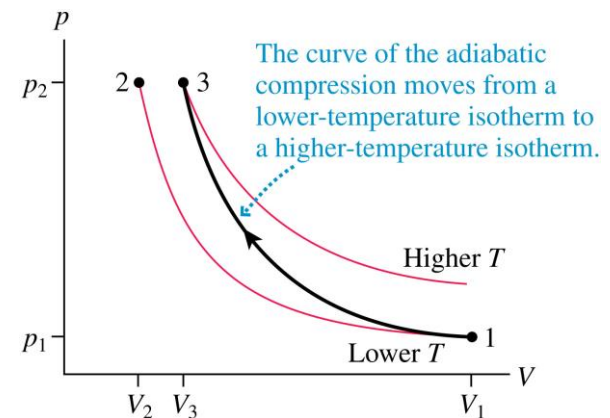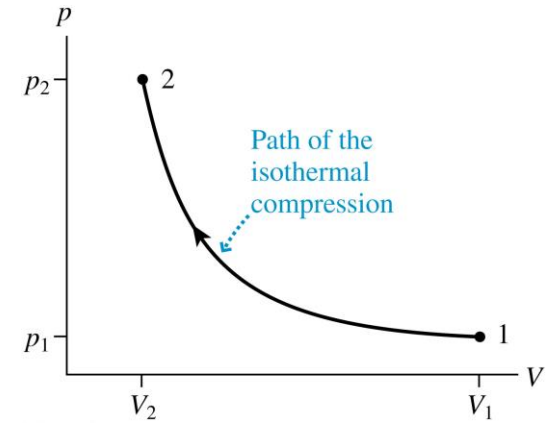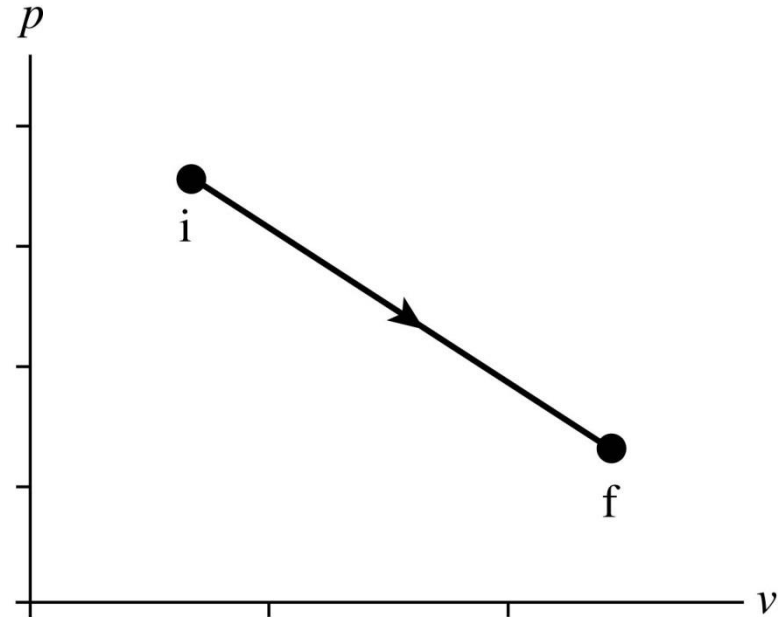
QuickCheck 12.17

What type of gas process is this?

A. Isochoric

B. Isobaric

C. Isothermal

D. Adiabatic
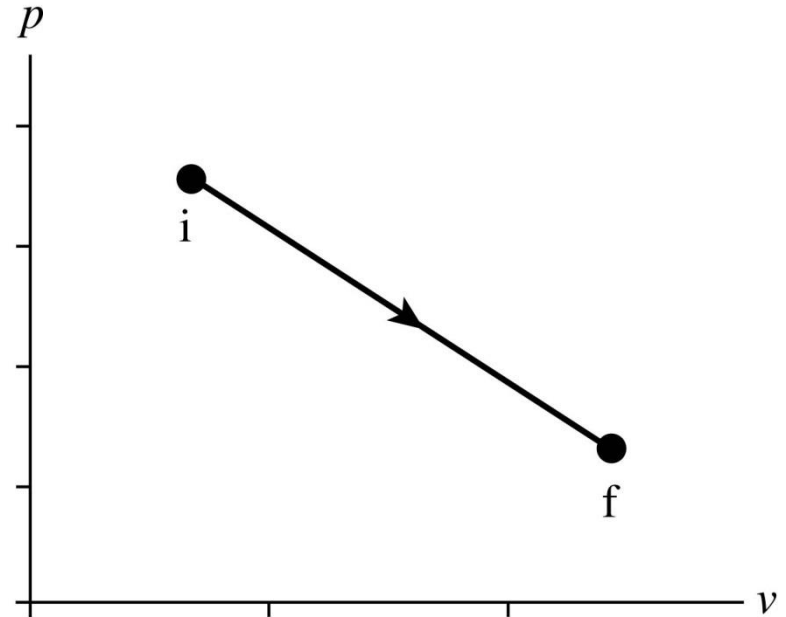
E. None of the above
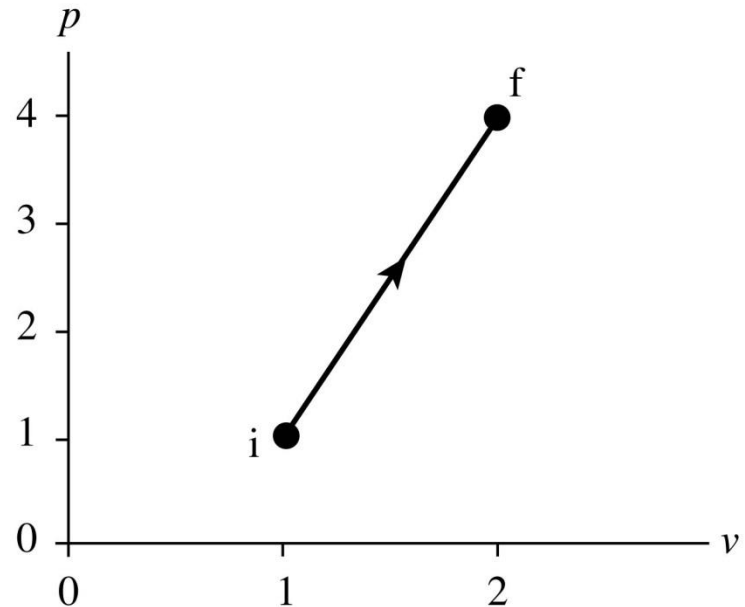
QuickCheck 12.17

What type of gas process is this?

A. Isochoric

B. Isobaric

C. Isothermal

D. Adiabatic

✔ E. None of the above

QuickCheck 12.18

A gas follows the process shown. What is the final-to-initial temperature ratio T_f / T_i?

A. 2

B. 4

C. 8

D. 16

E. Not enough information
   to tell

QuickCheck 12.18

A gas follows the process shown. What is the final-to-initial temperature ratio T_f / T_i?
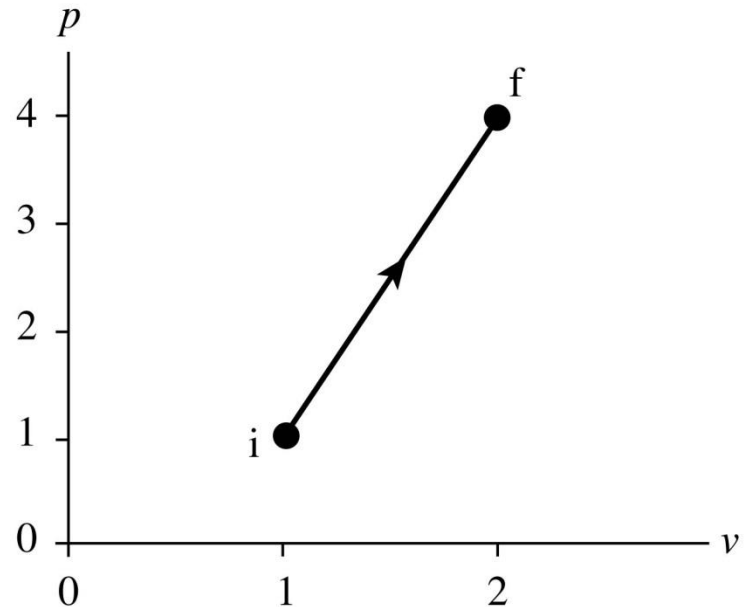
A. 2

B. 4

✔ C. 8 $\dfrac{T_f}{T_i} = \dfrac{p_f V_f}{p_i V_i} = 4 \cdot 2 = 8$

D. 16

E. Not enough information to tell

QuickCheck 12.7

If the volume of a sealed container of gas is decreased, the gas temperature

   A. Increases.
   B. Stays the same.
   C. Decreases.
   D. Not enough information to tell.

QuickCheck 12.7

If the volume of a sealed container of gas is decreased, the gas temperature

 A. Increases.
 B. Stays the same.
 C. Decreases.
✔ D. Not enough information to tell.

$$pV = nRT \implies T = \frac{pV}{nR}$$

V decreases but …

… we don't know anything about *p*.

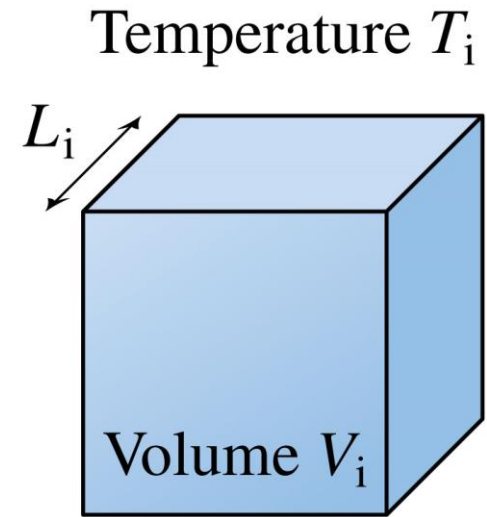# Section 12.4 Thermal Expansion

Thermal Expansion

- **Thermal expansion** is the expansion of a material (including solids) when heated.

- Volume thermal expansion is

$$\Delta V = \beta V_i \Delta T$$

Volume thermal expansion

(a) Temperature T_i

L_i

Volume V_i

- The constant β is the **coefficient of volume expansion.** Its value depends on the material of the object and has units of K^{-1}.
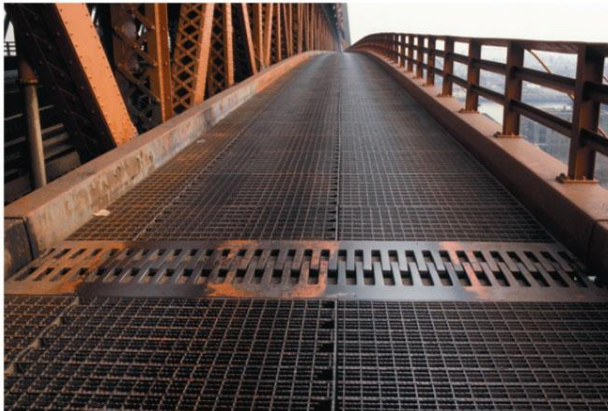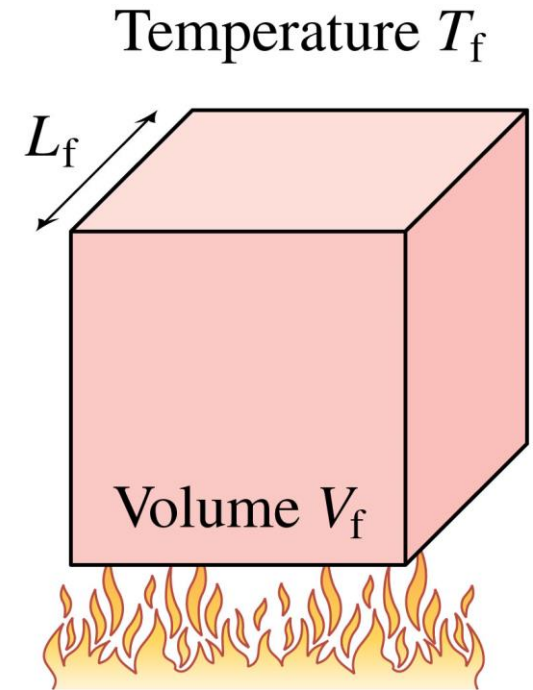
Thermal Expansion

- Linear thermal expansion is

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

  Linear thermal expansion

- The constant α is the **coefficient of linear expansion.** Its value depends on the material of the object and has units of K^{-1}.

(b) Temperature T_f

L_f

Volume V_f

Expanding spans: A long steel bridge will slightly increase in length on a hot day and decrease on a cold day. Thermal expansion joints let the bridge's length change without causing the roadway to buckle.

Thermal Expansion

TABLE 12.3 Coefficients of linear and volume thermal expansion at $20°C$

Substance	Linear α (K^{-1})	Volume β (K^{-1})
Aluminum	23×10^{-6}	69×10^{-6}
Glass	9×10^{-6}	27×10^{-6}
Iron or steel	12×10^{-6}	36×10^{-6}
Concrete	12×10^{-6}	36×10^{-6}
Ethyl alcohol		1100×10^{-6}
Water		210×10^{-6}
Air (and other gases)		3400×10^{-6}

Thermal Expansion

- The expressions for thermal expansions are **empirical formulas;** they are a good fit to data, but not all materials follow the equations for volume and linear thermal expansions. Water at low temperatures is one example.

QuickCheck 12.22

Two rods are precisely 10.000 cm long. Rod 1 is made of aluminum, with a coefficient of linear expansion $\alpha = 24 \times 10^{-6}$ /K. Rod 2 is made of steel, and has $\alpha = 12 \times 10^{-6}$ /K. Rod 1 is heated by 10°C while rod 2 is heated by 20°C. After heating, which rod is longer?

    A. Rod 1

    B. Rod 2

    C. Both rods have the same length.

QuickCheck 12.22

Two rods are precisely 10.000 cm long. Rod 1 is made of aluminum, with a coefficient of linear expansion $\alpha = 24 \times 10^{-6}$ /K. Rod 2 is made of steel, and has $\alpha = 12 \times 10^{-6}$ /K. Rod 1 is heated by 10°C while rod 2 is heated by 20°C. After heating, which rod is longer?

   A. Rod 1

   B. Rod 2

✔ C. Both rods have the same length.

QuickCheck 12.23

Aluminum rod 1 is 10.000 cm long, while aluminum rod 2 is 20.000 cm long. Both rods are heated by 20°C. After heating, which rod has undergone the greatest change in length?

    A. Rod 1

    B. Rod 2

    C. The lengths of both rods have changed by the same amount.

QuickCheck 12.23

Aluminum rod 1 is 10.000 cm long, while aluminum rod 2 is 20.000 cm long. Both rods are heated by 20°C. After heating, which rod has undergone the greatest change in length?

A. Rod 1

✔ B. Rod 2

C. The lengths of both rods have changed by the same amount.

Example Problem

In the United States, railroad cars ride on steel rails. Until the mid-1900s, most track consisted of 11.9 m lengths connected with expansion joints that allowed for the rails to expand and contract with temperature. If a section of rail is exactly 11.900 m long on a hot, sunny day when it warms up to 50°C, how long will it be on a cold −10°C winter morning?

Try It Yourself: Thermal Expansion to the Rescue

If you have a stubborn lid on a glass jar, try this: Put the lid under very hot water for a short time. Heating the lid and the jar makes them both expand, but, as you can see from the data in Table 12.3, the steel lid—and the opening in the lid that fits over the glass jar— expands by more than the glass jar. The jar lid is now looser and can be more easily removed.
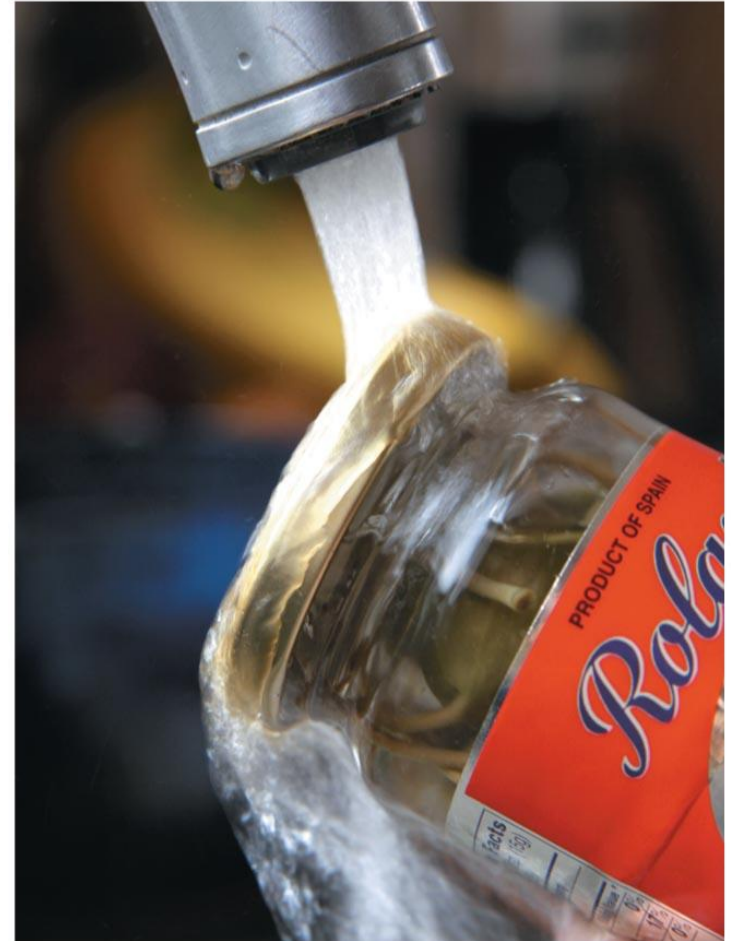
Example 12.11 How much closer to space?

The height of the Space Needle, a steel observation tower in Seattle, is 180 meters on a 0°C winter day. How much taller is it on a hot summer day when the temperature is 30°C?

PREPARE The steel expands because of an increase in temperature, which is

$$\Delta T = T_f - T_i = 30°C - 0°C = 30°C = 30 \text{ K}$$

Example 12.11 How much closer to space? (cont.)

SOLVE The coefficient of linear expansion is given in Table 12.3; we can use this value in Equation 12.22 to compute the increase in height:
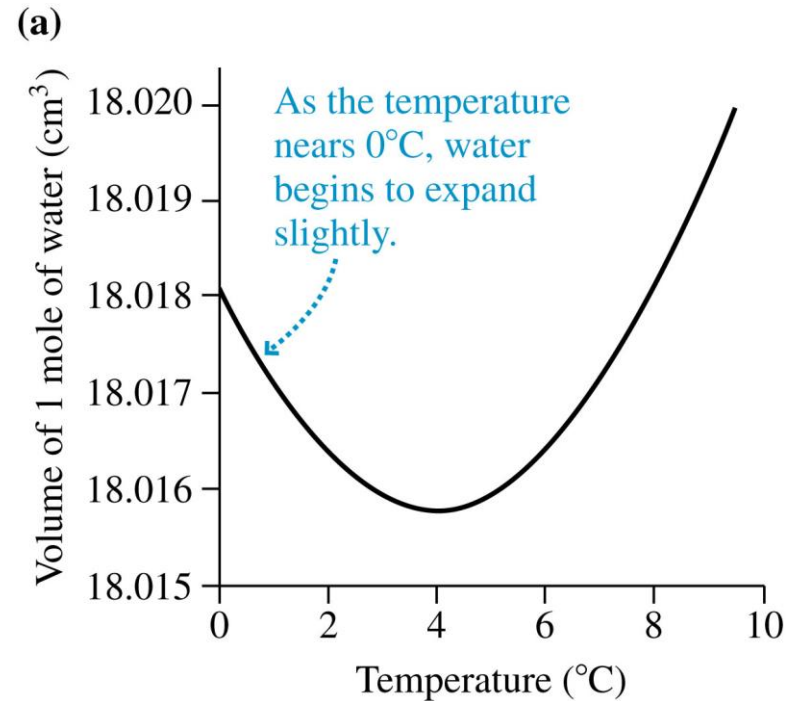
$$\Delta L = \alpha L_i \, \Delta T = (12 \times 10^{-6} \text{ K}^{-1})(180 \text{ m})(30 \text{ K}) = 0.065 \text{ m}$$

Example 12.11 How much closer to space? (cont.)

ASSESS You don't notice buildings getting taller on hot days, so we expect the final answer to be small. The change is a small fraction of the height of the tower, as we expect. Our answer makes physical sense. Compared to 180 m, an expansion of 6.5 cm is not something you would easily notice—but it isn't negligible. The thermal expansion of structural elements in towers and bridges must be accounted for in the design to avoid damaging stresses. When designers failed to properly account for thermal stresses in the marble panels cladding the Amoco Building in Chicago, all 43,000 panels had to be replaced, at great cost.

Special Properties of Water and Ice

- Water differs from other liquids at colder temperatures.

- Instead of decreasing volume with decreasing temperature, water increases in volume at temperatures below 4°C.

- This happens at lower temperatures because the water molecules form clusters that are more strongly bound but are located farther apart.

(a)

As the temperature nears 0°C, water begins to expand slightly.

Volume of 1 mole of water (cm^3): 18.015, 18.016, 18.017, 18.018, 18.019, 18.020

Temperature (°C): 0, 2, 4, 6, 8, 10

Special Properties of Water and Ice

- Freezing the water results in an even greater increase in volume.

- Because water *expands* as it freezes, ice is less dense than liquid water and floats.

(b)

Water expands significantly when making a transition from liquid to solid.

Solid | Liquid
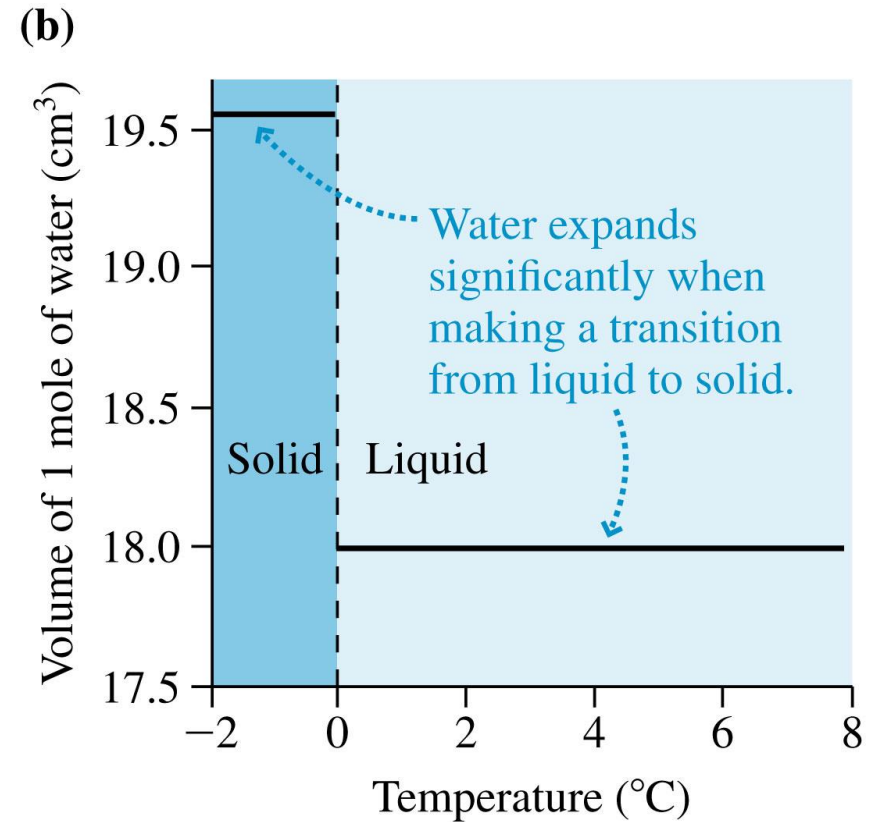
Section 12.5 Specific Heat and Heat of Transformation

Specific Heat

- The **specific heat** of a substance is the amount of heat that raises the temperature of 1kg of that substance by 1 K.

- The symbol for specific heat is c:

$$Q = Mc\,\Delta T$$

Heat needed to produce a temperature change ΔT for mass M with specific heat c

Specific Heat

TABLE 12.4 Specific heats of solids and liquids

Substance	$c \, (\text{J/kg} \cdot \text{K})$
Solids	
Lead	128
Gold	129
Copper	385
Iron	449
Aluminum	900
Water ice	2090
Mammalian body	3400
Liquids	
Mercury	140
Ethyl alcohol	2400
Water	4190

Specific Heat

- Substances with a large specific heat, like water, are slow to warm up and slow to cool down.

- Such substances are also described as having a large thermal inertia.

Temperate lakes: At night, the large specific heat of water prevents the temperature of a body of water from dropping nearly as much as that of the surrounding air. Early in the morning, water vapor evaporating from a warm lake quickly condenses in the colder air above, forming mist. During the day, the opposite happens: The air becomes much warmer than the water.

QuickCheck 12.24

Two liquids, A and B, have equal masses and equal initial temperatures. Each is heated for the same length of time over identical burners. Afterward, liquid A is hotter than liquid B. Which has the larger specific heat?

    A. Liquid A

    B. Liquid B

    C. There's not enough information to tell.

QuickCheck 12.24

Two liquids, A and B, have equal masses and equal initial temperatures. Each is heated for the same length of time over identical burners. Afterward, liquid A is hotter than liquid B. Which has the larger specific heat?

  A. Liquid A
✔ B. Liquid B
  C. There's not enough information to tell.

$$\Delta T = \frac{Q}{mc} \quad \text{so larger } c \text{ gives smaller } \Delta T$$

Example 12.13 Energy to run a fever

A 70 kg student catches the flu, and his body temperature increases from 37.0°C (98.6°F) to 39.0°C (102.2°F). How much energy is required to raise his body's temperature?

PREPARE The increase in temperature requires the addition of energy. The change in temperature ΔT is 2.0°C, or 2.0 K.

Example 12.13 Energy to run a fever (cont.)

SOLVE Raising the temperature of the body uses energy supplied internally from the chemical reactions of the body's metabolism, which transfer heat to the body. The specific heat of the body is given in Table 12.4 as 3400 J/kg · K. We can use Equation 12.23 to find the necessary heat energy:

$$Q = Mc\,\Delta T = (70\text{ kg})(3400\text{ J/kg} \cdot \text{K})(2.0\text{ K}) = 4.8 \times 10^5\text{ J}$$

Example 12.13 Energy to run a fever (cont.)

ASSESS The body is mostly water, with a large specific heat, and the mass of the body is large, so we'd expect a large amount of energy to be necessary. Looking back to Chapter 11, we see that this is approximately the energy in a large apple, or the amount of energy required to walk 1 mile.

QuickCheck 12.25

1 kg of silver ($c = 234$ J/kg K) is heated to 100°C. It is then dropped into 1 kg of water ($c = 4190$ J/kg K) at 0°C in an insulated beaker. After a short while, the common temperature of the water and silver is

   A. 0°C

   B. Between 0°C and 50°C

   C. 50°C

   D. Between 50°C and 100°C

   E. 100°C

QuickCheck 12.25

1 kg of silver (c = 234 J/kg K) is heated to 100°C. It is then dropped into 1 kg of water (c = 4190 J/kg K) at 0°C in an insulated beaker. After a short while, the common temperature of the water and silver is

    A. 0°C

✔ B. Between 0°C and 50°C

    C. 50°C

    D. Between 50°C and 100°C

    E. 100°C

Phase Changes

- If you place ice cubes in a sealed container and heat the container, the ice will warm without melting until the temperature reaches 0°C. As it melts, the temperature of the ice and liquid remain at 0°C. The temperature does not begin to rise again until all of the ice is melted. The process is repeated as the liquid warms and evaporates into steam.
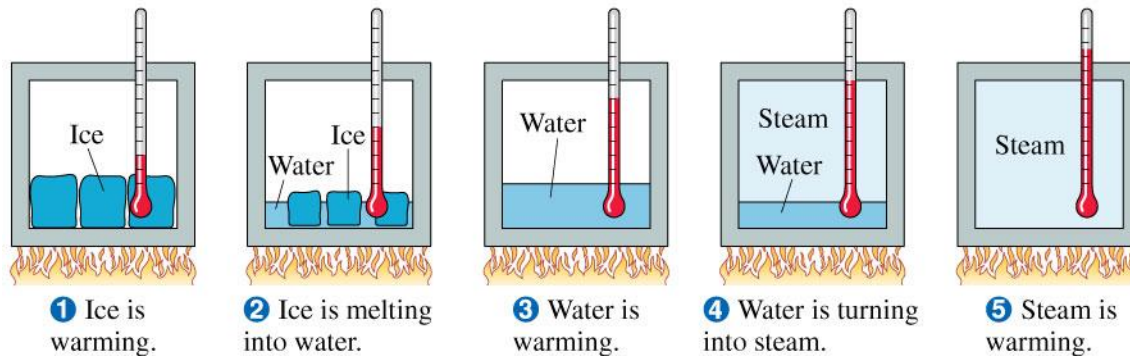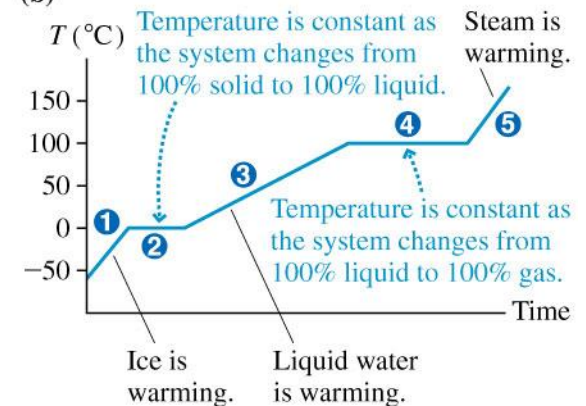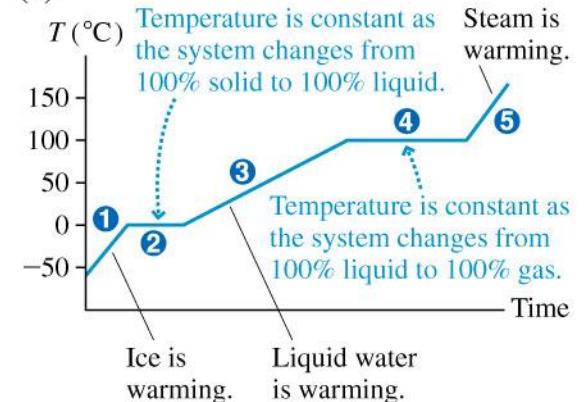
Phase Changes

- As you heat the solid, the thermal energy gets so large the the molecular bonds begin to break, allowing the atoms to move around; the solid begins to melt.

- The temperature does not rise until all of the bonds are broken.
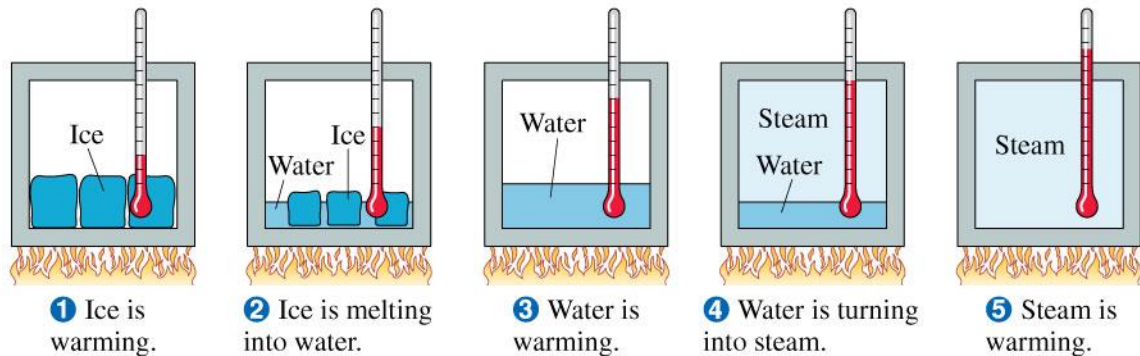
Phase Changes

- The temperature at which a solid becomes a liquid is the **melting point.**

- The temperature at which a liquid becomes a solid is the **freezing point.**

- Melting and freezing are *phase changes*. A system at the melting point is in **phase equilibrium.**

- The temperature at which a gas becomes a liquid is the **condensation point.**

- The temperature at which a liquid becomes a gas is the **boiling point.**

Conceptual Example 12.14 Strategy for cooling a drink

If you have a warm soda that you wish to cool, is it more effective to add 25 g of liquid water at 0°C or 25 g of water ice at 0°C?

REASON If you add liquid water at 0°C, heat will be transferred from the soda to the water, raising the temperature of the water and lowering that of the soda. If you add water ice at 0°C, heat first will be transferred from the soda to the ice to melt it, transforming the 0°C ice to 0°C liquid water, then will be transferred to the liquid water to raise its temperature. Thus more thermal energy will be removed from the soda, giving it a lower final temperature, if ice is used rather than liquid water.

ASSESS This makes sense because you know that this is what you do in practice. To cool a drink, you drop in an ice cube.

Heat of Transformation

- **A phase change is characterized by a change in thermal energy without a change in temperature.**

- The amount of heat energy that causes 1kg of a substance to undergo a phase change is called the **heat of transformation** (*L*).

Lava—molten rock—undergoes a phase change from liquid to sold when it contacts liquid water; the transfer of heat to the water causes the water to undergo a phase change from liquid to gas.

Heat of Transformation

- The **heat of fusion** L_f is the heat of transformation between a solid and a liquid.

- The **heat of vaporization** L_v is the heat of transformation between a liquid and a gas.

- The heat needed for these phase changes is

$$Q = \begin{cases} \pm ML_f & \text{Heat needed to melt/freeze mass } M \\ \pm ML_v & \text{Heat needed to boil/condense mass } M \end{cases}$$

- **You must explicitly include the minus sign when it is needed.**

Heat of Transformation

TABLE 12.5 Melting and boiling temperatures and heats of transformation at standard atmospheric pressure

Substance	T_m (°C)	L_f (J/kg)	T_b (°C)	L_v (J/kg)
Nitrogen (N_2)	−210	0.26×10^5	−196	1.99×10^5
Ethyl alcohol	−114	1.09×10^5	78	8.79×10^5
Mercury	−39	0.11×10^5	357	2.96×10^5
Water	0	3.33×10^5	100	22.6×10^5
Lead	328	0.25×10^5	1750	8.58×10^5

QuickCheck 12.26

If you heat a substance in an insulated container, is it possible that the temperature of the substance remains unchanged?

A. Yes

B. No

QuickCheck 12.26

If you heat a substance in an insulated container, is it possible that the temperature of the substance remains unchanged?

✔ A. Yes   If there's a phase change.
   B. No

Example 12.16 Melting a popsicle

A girl eats a 45 g frozen popsicle that was taken out of a −10°C freezer. How much energy does her body use to bring the popsicle up to body temperature?

PREPARE We can assume that the popsicle is pure water. Normal body temperature is 37°C. The specific heats of ice and liquid water are given in Table 12.4; the heat of fusion of water is given in Table 12.5.

Example 12.16 Melting a popsicle (cont.)

SOLVE There are three parts to the problem, corresponding to stages 1–3 in Figure 12.22: The popsicle must be warmed to 0°C, then melted, and then the resulting water must be warmed to body temperature. The heat needed to warm the frozen water by $\Delta T = 10°C = 10\ \text{K}$ to the melting point is

$$Q_1 = Mc_{\text{ice}}\ \Delta T = (0.045\ \text{kg})(2090\ \text{J/kg} \cdot \text{K})(10\ \text{K}) = 940\ \text{J}$$

Example 12.16 Melting a popsicle (cont.)

Note that we use the specific heat of water ice, not liquid water, in this equation. Melting 45 g of ice requires heat

$$Q_2 = ML_f = (0.045 \text{ kg})(3.33 \times 105 \text{ J/kg}) = 15{,}000 \text{ J}$$

The liquid water must now be warmed to body temperature; this requires heat

$$Q_3 = Mc_{\text{water}} \Delta T = (0.045 \text{ kg})(4190 \text{ J/kg} \cdot \text{K})(37 \text{ K})$$

$$= 7000 \text{ J}$$

The total energy is the sum of these three values:

$$Q_{\text{total}} = 23{,}000 \text{ J}.$$

Example 12.16 Melting a popsicle (cont.)

ASSESS More energy is needed to melt the ice than to warm the water, as we would expect. A commercial popsicle has 40 Calories, which is about 170 kJ. Roughly 15% of the chemical energy in this frozen treat is used to bring it up to body temperature!

Example Problem

On a hot summer day, a cup of flavored shaved ice can be a welcome treat. Suppose you ignore the obvious "brain freeze" danger and eat an 8 oz (0.22 kg) cup of ice rather quickly. How much heat is needed to melt this ice and warm it to your 37°C body temperature?

Evaporation

- **Evaporation** is the process of some molecules moving from the liquid to gas phase at lower temperatures than the boiling point.

- At any temperature, some molecules are moving fast enough to go into the gas phase, carrying away thermal energy and reducing the average kinetic energy (and temperature) of the liquid.

Keeping your cool: Humans (and cattle and horses) have sweat glands, so we can perspire to moisten our skin, allowing evaporation to cool our bodies. Animals that do not perspire can also use evaporation to keep cool. Dogs, goats, rabbits, and even birds pant, evaporating water from their respiratory passages. Elephants spray water on their skin; other animals may lick their fur.

QuickCheck 12.27

50 g of ice at 0°C is added to 50 g of liquid water at 0°C in a well-insulated container, also at 0°C. After a while, the container will hold

    A. All ice.

    B. > 50 g of ice, < 50 g of liquid water.

    C. 50 g of ice, 50 g of liquid water.

    D. < 50 g of ice, > 50 g of liquid water.

    E. All liquid water.

QuickCheck 12.27

50 g of ice at 0°C is added to 50 g of liquid water at 0°C in a well-insulated container, also at 0°C. After a while, the container will hold

   A. All ice.

   B. > 50 g of ice, < 50 g of liquid water.

✔ C. 50 g of ice, 50 g of liquid water.

   D. < 50 g of ice, > 50 g of liquid water.

   E. All liquid water.

Example 12.17 Computing heat loss by perspiration

The human body can produce approximately 30 g of perspiration per minute. At what rate is it possible to exhaust heat by the evaporation of perspiration?

SOLVE The evaporation of 30 g of perspiration at normal body temperature requires heat energy

$$Q = ML_v = (0.030 \text{ kg})(24 \times 10^5 \text{ J/kg}) = 7.2 \times 10^4 \text{ J}$$

This is the heat lost per minute; the rate of heat loss is

$$\frac{Q}{\Delta t} = \frac{7.2 \times 10^4 \text{ J}}{60 \text{ s}} = 1200 \text{ W}$$

Example 12.17 Computing heat loss by perspiration (cont.)

ASSESS Given the metabolic power required for different activities, as listed in Chapter 11, this rate of heat removal is sufficient to keep the body cool even when exercising in hot weather—as long as the person drinks enough water to keep up this rate of perspiration.

Example Problem

Jason, a 60 kg cyclist, is pedaling his bike at a good clip, using a total energy of 400 W. As he exercises, his body will start to warm up, and he will perspire to keep himself cool.

1) Assuming Jason's pedaling has a typical 25% efficiency, by how much would his body temperature rise during 1.0 h of cycling if he had no means of exhausting excess thermal energy?

2) Assume that the only means by which his body cools itself is evaporation. To keep his body temperature constant, what mass of water must be evaporated during a 1.0 h ride? What volume of water must he drink each hour to keep from becoming dehydrated? (1.0 kg of water has a volume of 1.0 L.)

Section 12.6 Calorimetry

Calorimetry

- **Calorimetry** is the quantitative measurement of the heat transferred between systems or evolved in reactions.

Heat
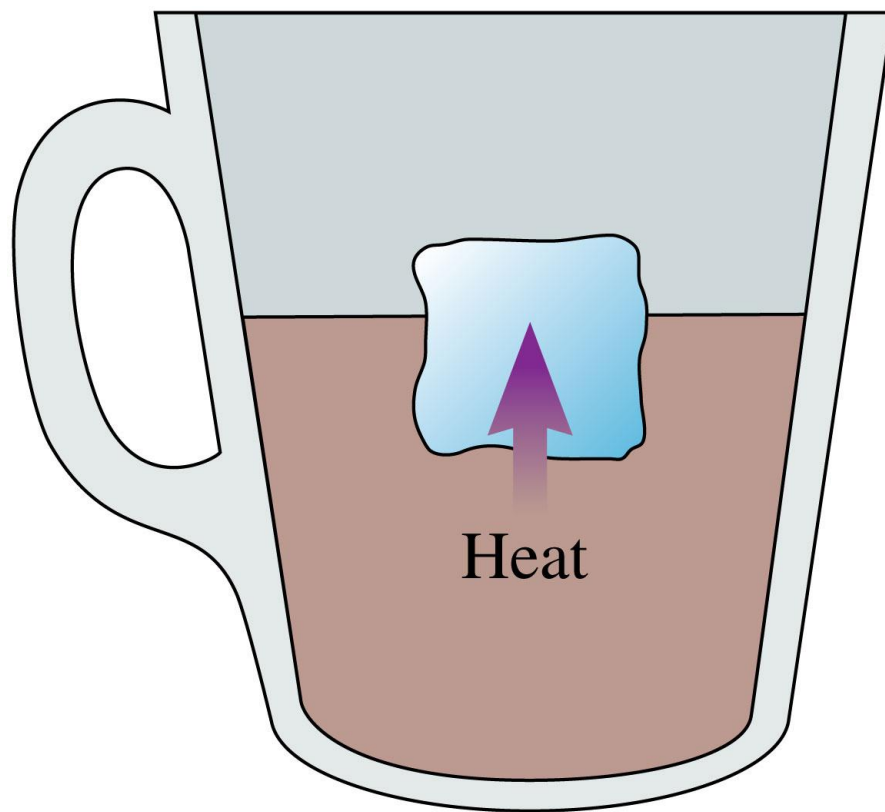
Calorimetry

- In an insulated environment, the energy transferred to system 1 (Q_1) is positive if energy *enters* system 1, negative if energy *leaves* system 1. Q_2 is the energy transferred to system 2.

- The relationship can be written

$$Q_{net} = Q_1 + Q_2 = 0$$

The magnitude $|Q_1|$ of the heat leaving system 1 equals the magnitude $|Q_2|$ of the heat entering system 2.

| System 1 | Q_2 | System 2 |
| T_1 | Q_1 | T_2 |
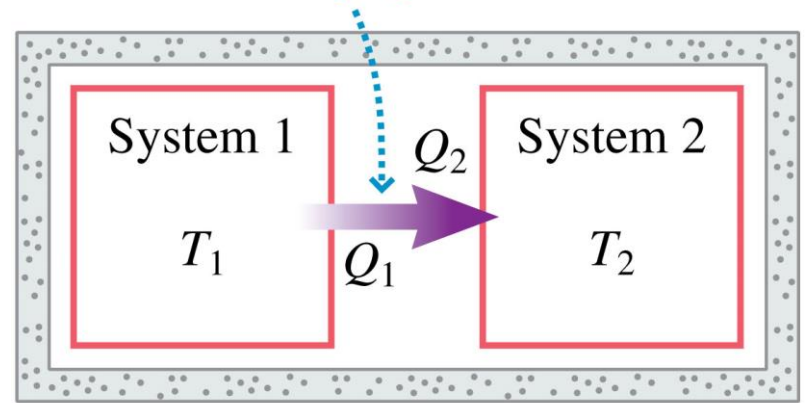
Opposite signs mean that $Q_{net} = Q_1 + Q_2 = 0$

Calorimetry

PROBLEM-SOLVING STRATEGY 12.1 — Calorimetry problems

MP

When two systems are brought into thermal contact, we use calorimetry to find the heat transferred between them and their final equilibrium temperature.

PREPARE Identify the individual interacting systems. Assume that they are isolated from the environment. List the known information and identify what you need to find. Convert all quantities to SI units.

SOLVE The statement of energy conservation is

$$Q_{net} = Q_1 + Q_2 + \cdots = 0$$

- For systems that undergo a temperature change, $Q_{\Delta T} = Mc(T_f - T_i)$. Be sure to have the temperatures T_i and T_f in the correct order.
- For systems that undergo a phase change, $Q_{phase} = \pm ML$. Supply the correct sign by observing whether energy enters or leaves the system during the transition.
- Some systems may undergo a temperature change *and* a phase change. Treat the changes separately. The heat energy is $Q = Q_{\Delta T} + Q_{phase}$.

ASSESS The final temperature should be between the initial temperatures. A T_f that is higher or lower than all initial temperatures is an indication that something is wrong, usually a sign error.

Text: p. 151

Example 12.18 Using calorimetry to identify a metal

200 g of an unknown metal is heated to 90.0°C, then dropped into 50.0 g of water at 20.0°C in an insulated container. The water temperature rises within a few seconds to 27.7°C, then changes no further. Identify the metal.

PREPARE The metal and the water interact thermally; there are no phase changes. We know all the initial and final temperatures. We will label the temperatures as follows: The initial temperature of the metal is T_m; the initial temperature of the water is T_w. The common final temperature is T_f. For water, $c_w = 4190$ J/kg $\cdot$ K is known from Table 12.4. Only the specific heat c_m of the metal is unknown.

Example 12.18 Using calorimetry to identify a metal (cont.)

SOLVE Energy conservation requires that $Q_w + Q_m = 0$. Using $Q = Mc(T_f - T_i)$ for each, we have

$$Q_w + Q_m = M_w\, c_w\, (T_f - T_w) + M_m\, c_m\, (T_f - T_m) = 0$$

This is solved for the unknown specific heat:

$$
\begin{aligned}
c_m &= \frac{-M_w c_w (T_f - T_w)}{M_m (T_f - T_m)} \\[2mm]
&= \frac{-(0.0500\ \text{kg})(4190\ \text{J/kg} \cdot \text{K})(27.7^\circ\text{C} - 20.0^\circ\text{C})}{(0.200\ \text{kg})(27.7^\circ\text{C} - 90.0^\circ\text{C})} \\[2mm]
&= 129\ \text{J/kg} \cdot \text{K}
\end{aligned}
$$

Example 12.18 Using calorimetry to identify a metal (cont.)

Referring to Table 12.4, we find we have either 200 g of gold or, if we made an ever-so-slight experimental error, 200 g of lead!

ASSESS The temperature of the unknown metal changed much more than the temperature of the water. This means that the specific heat of the metal must be much less than that of water, which is exactly what we found.

Section 12.7 Specific Heat of Gases

Specific Heats of Gases

- The temperature change in a gas depends on the heating process.

- Constant-volume processes require *less* heat than constant-pressure processes because work is not done in the constant-volume process.
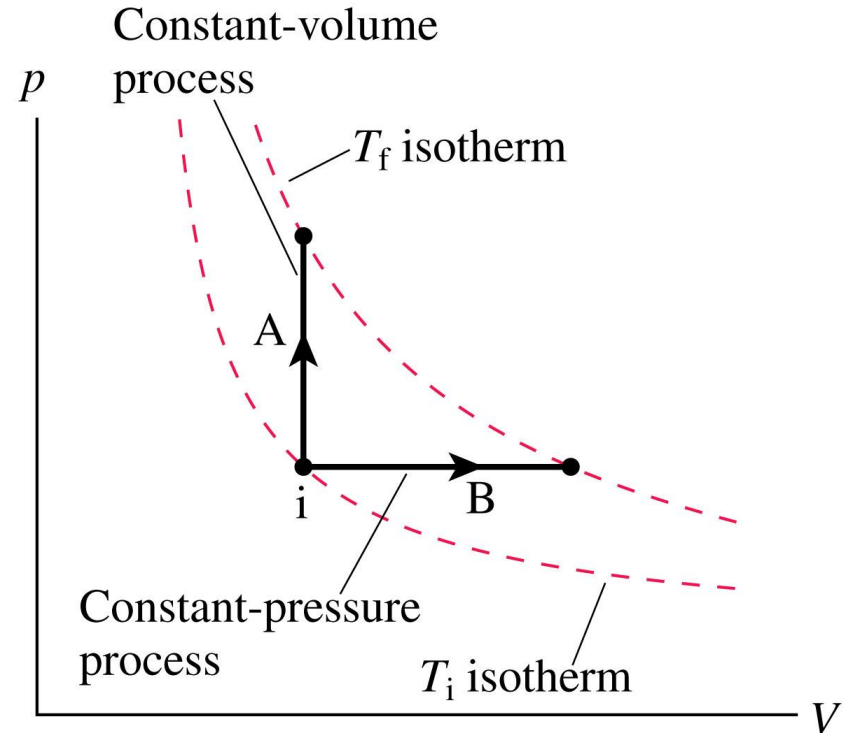
Specific Heats of Gases

- We define two different versions of specific heat of gases.
- The quantity of heat needed to change the temperature of n moles of gas for a constant-volume processes is

$$Q = nC_V\Delta T$$

- For a constant-pressure process, the quantity is

$$Q = nC_P\Delta T$$

- C_V is the **molar specific heat at a constant volume.**
- C_P is the **molar specific heat at a constant pressure.**

Specific Heats of Gases

- The monatomic gases have the same specific heats because they are close to ideal.

- The molar specific heats at constant pressure are higher because work is done during those processes.

TABLE 12.6 Molar specific heats of gases (J/mol · K) at 20°C

Gas	C_P	C_V
Monatomic Gases		
He	20.8	12.5
Ne	20.8	12.5
Ar	20.8	12.5
Diatomic Gases		
H_2	28.7	20.4
N_2	29.1	20.8
O_2	29.2	20.9
Triatomic Gas		
Water vapor	33.3	25.0

Specific Heats of Gases

- The diatomic gases have higher modal specific heats than the monatomic gases.

- For monatomic gases, the thermal energy is exclusively translational kinetic energy (atoms move faster).

- For diatomic gases, the molecules also rotate. Some energy must go into the rotational kinetic energy.

The thermal energy of a diatomic gas is the sum of the translational kinetic energy of the molecules . . .

$\vec{v}$
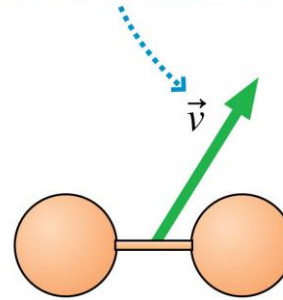
. . . and the rotational kinetic energy of the molecules.
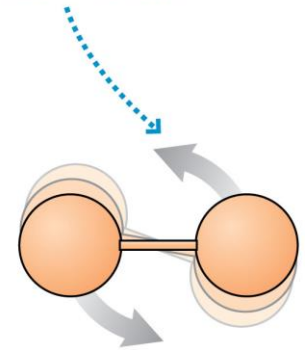
QuickCheck 12.28

Suppose you have a sample of gas at 10°C that you need to warm up to 20°C. Which will take more heat energy: raising the temperature while keep the pressure constant or raising the temperature while keeping the volume constant?

A. It takes more energy to raise the temperature while keeping the volume constant.

B. It takes more energy to raise the temperature while keeping the pressure constant.

C. The heat energy is the same in both cases.

QuickCheck 12.28

Suppose you have a sample of gas at 10°C that you need to warm up to 20°C. Which will take more heat energy: raising the temperature while keep the pressure constant or raising the temperature while keeping the volume constant?

   A. It takes more energy to raise the temperature while keeping the volume constant.

✔ B. It takes more energy to raise the temperature while keeping the pressure constant.

   C. The heat energy is the same in both cases.

Example 12.20 Work done by an expanding gas

A typical weather balloon is made of a thin latex envelope that takes relatively little force to stretch, so the pressure inside the balloon is approximately equal to atmospheric pressure. The balloon is filled with a gas that is less dense than air, typically hydrogen or helium. Suppose a weather balloon filled with 180 mol of helium is waiting for launch on a cold morning at a high-altitude station. The balloon warms in the sun, which raises the temperature of the gas from 0°C to 30°C. As the balloon expands, how much work is done by the expanding gas?

Example 12.20 Work done by an expanding gas (cont.)

PREPARE The work done is equal to $p\Delta V$, but we don't know the pressure (it's not sea level and we don't know the altitude) and we don't know the volume of the balloon. Instead, we'll use the first law of thermodynamics. We can rewrite Equation 12.19 as

$$W_{gas} = Q - \Delta E_{th}$$

Example 12.20 Work done by an expanding gas (cont.)

The change in temperature of the gas is 30°C, so $\Delta T = 30$ K. We can compute how much heat energy is transferred to the balloon as it warms because this is a temperature change at constant pressure, and we can compute how much the thermal energy of the gas increases because we know ΔT.

Example 12.20 Work done by an expanding gas (cont.)

SOLVE The heat required to increase the temperature of the gas is given by Equation 12.28:

$$Q = nC_P \Delta T = (180 \text{ mol})(20.8 \text{ J/mol} \cdot \text{K})(30 \text{ K}) = 112 \text{ kJ}$$

The change in thermal energy depends on the change in temperature according to Equation 12.20:

$$\Delta E_{\text{th}} = \frac{3}{2}nR\Delta T = \frac{3}{2}(180 \text{ mol})(8.31 \text{ J/mol} \cdot \text{K})(30 \text{ K})$$
$$= 67.3 \text{ kJ}$$

Example 12.20 Work done by an expanding gas (cont.)

The work done by the expanding balloon is just the difference between these two values:

$$W_{gas} = Q - \Delta E_{th} = 112 \text{ kJ} - 67.3 \text{ kJ} = 45 \text{ kJ}$$

ASSESS The numbers are large—it's a lot of heat and a large change in thermal energy—but it's a big balloon with a lot of gas, so this seems reasonable.

Section 12.8 Heat Transfer

Heat Transfer

- There are four basic mechanisms by which objects exchange heat with other objects or their surroundings.
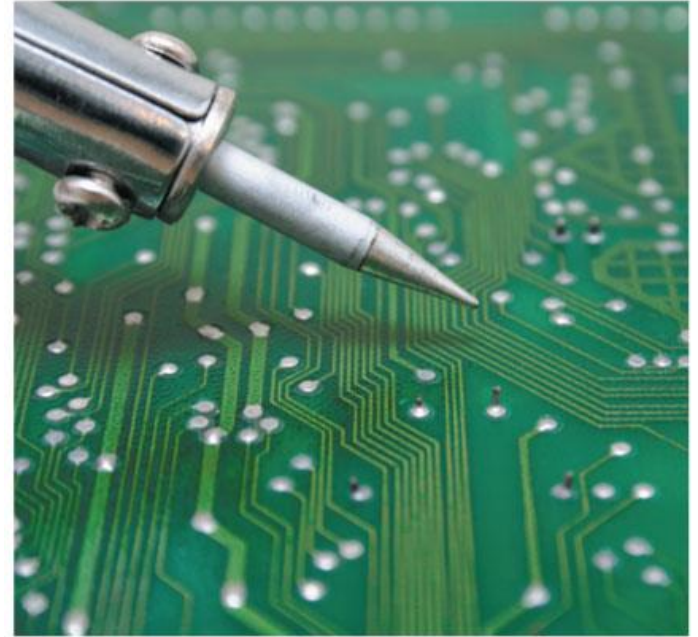
When two objects are in direct physical contact, such as the soldering iron and the circuit board, heat is transferred by *conduction*. **Energy is transferred by direct contact.**

Heat Transfer

• There are four basic mechanisms by which objects exchange heat with other objects or their surroundings.
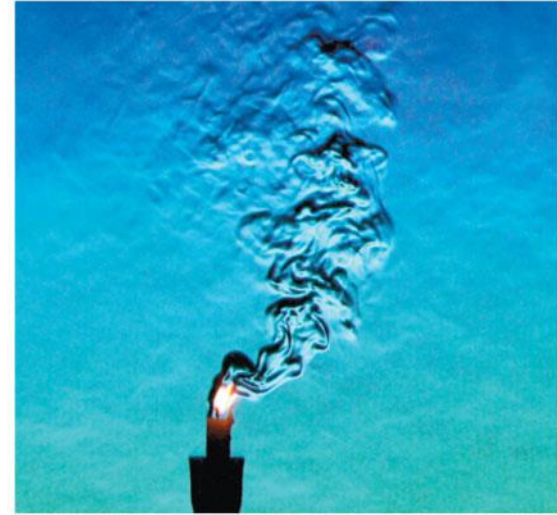
This special photograph shows air currents near a warm glass of water. Air near the glass is warmed and rises, taking thermal energy with it in a process known as *convection*. **Energy is transferred by the bulk motion of molecules with high thermal energy.**

Heat Transfer

- There are four basic mechanisms by which objects exchange heat with other objects or their surroundings.

The lamp shines on the lambs huddled below, warming them. The energy is transferred by infrared *radiation,* a form of electromagnetic waves. **Energy is transferred by electromagnetic waves.**

Heat Transfer

- There are four basic mechanisms by which objects exchange heat with other objects or their surroundings.

As we saw in an earlier section, the *evaporation* of liquid can carry away significant quantities of thermal energy. When you blow on a cup of cocoa, this increases the rate of evaporation, rapidly cooling it. **Energy is transferred by the removal of molecules with high thermal energy.**

Conduction

- **Conduction** is the transfer of thermal energy directly through a physical material.
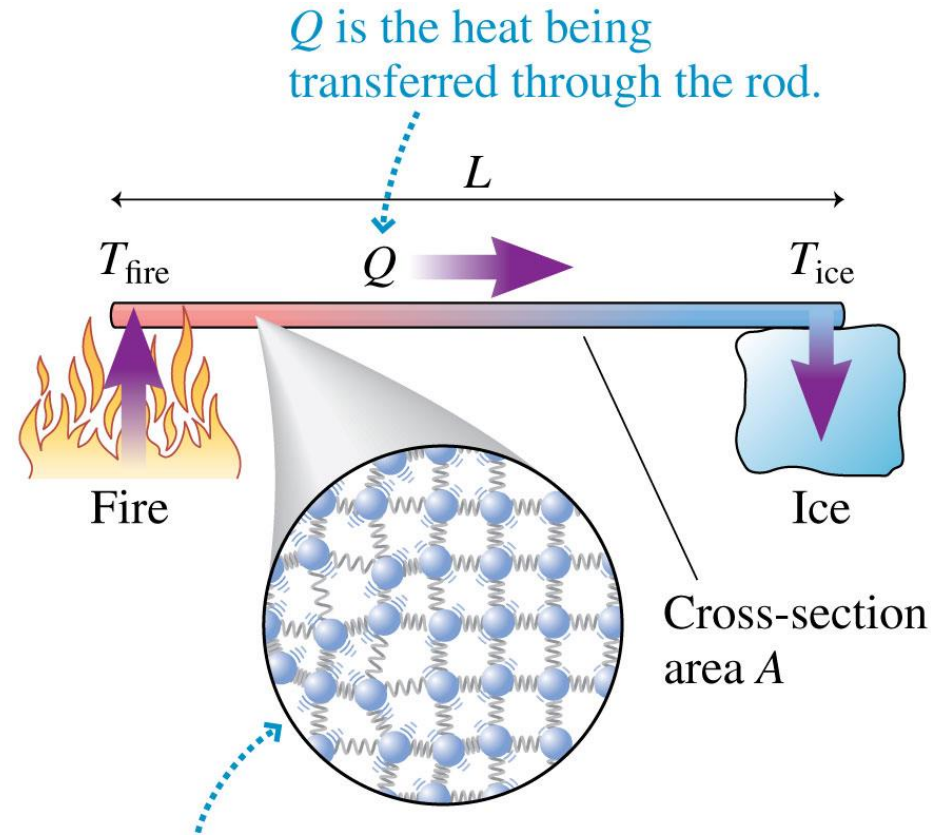
Q is the heat being transferred through the rod.

L

T_{fire} Q → T_{ice}

Fire

Ice

Cross-section area A

The particles on the left side of the rod are vibrating more vigorously than the particles on the right. The particles on the left transfer energy to the particles on the right via the bonds connecting them.

Conduction

- *Q* increases if the temperature difference ΔT between the hot end and the cold end is increased.

- *Q* increases if the cross-section area *A* of the rod is increased.

- *Q* decreases if the length *L* of the rod is increased.

- Some materials (such as metals) transfer heat quite readily. Other materials (such as wood) transfer very little heat.

Q is the heat being transferred through the rod.

L

T_{fire} Q T_{ice}

Fire

Ice

Cross-section area *A*

The particles on the left side of the rod are vibrating more vigorously than the particles on the right. The particles on the left transfer energy to the particles on the right via the bonds connecting them.
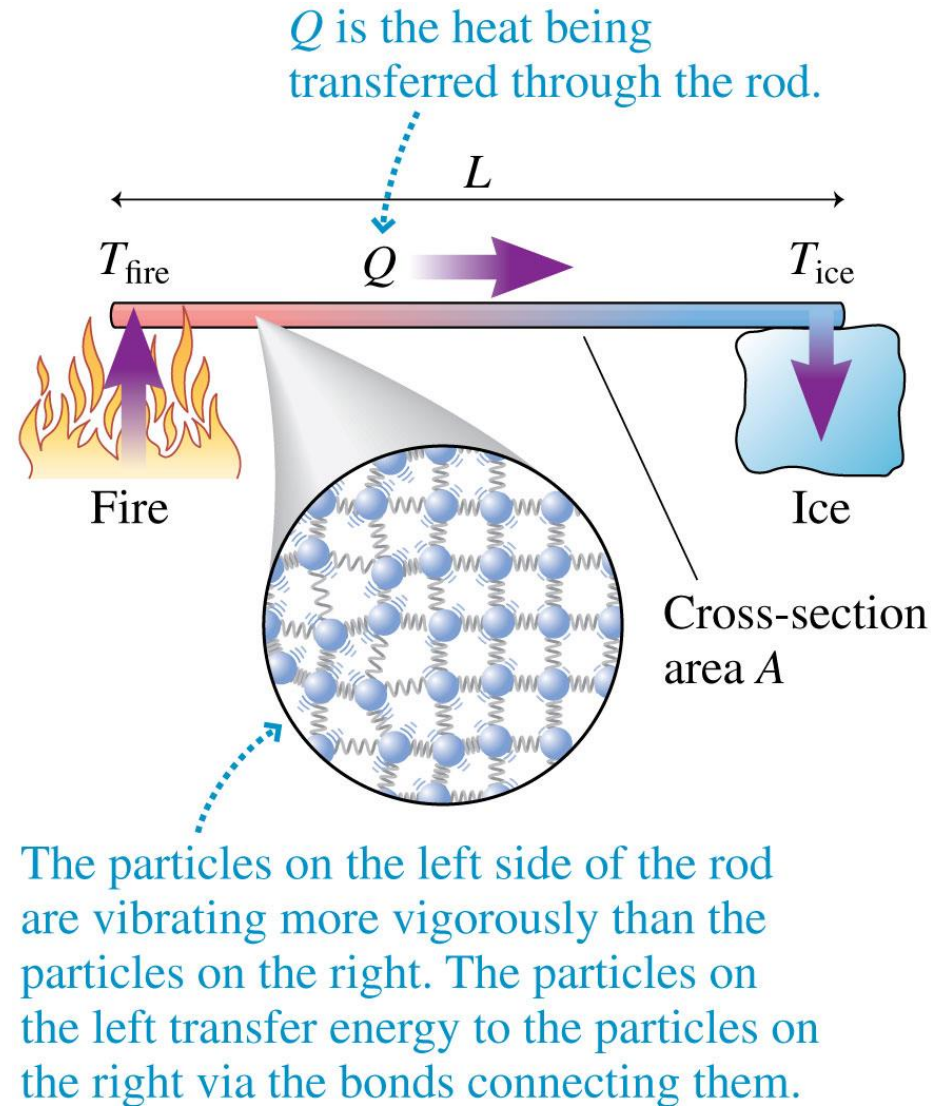
Conduction

- The *rate* of heat transfer for a material of cross-section area *A* and length *L* is

$$\frac{Q}{\Delta t} = \left(\frac{kA}{L}\right)\Delta T$$

Rate of conduction of heat across a temperature difference

- *k* is the **thermal conductivity** of the material and characterizes whether the material is a good or poor conductor of heat. The units of *k* are W/m · K.

Conduction

TABLE 12.7 Thermal conductivity values (measured at 20°C)

Material	k (W/m · K)	Material	k (W/m · K)
Diamond	1000	Skin	0.50
Silver	420	Muscle	0.46
Copper	400	Fat	0.21
Iron	72	Wood	0.2
Stainless steel	14	Carpet	0.04
Ice	1.7	Fur, feathers	0.02–0.06
Concrete	0.8	Air (27°C, 100 kPa)	0.026
Plate glass	0.75		

Convection

- **Convection** is the transfer of thermal energy by the motion of a fluid.

- When you boil water, the heated water on the bottom expands, becomes less dense and rises, while the cooler, denser water sinks.

- Convection is responsible for making the wind blow and the ocean currents circulate.

Radiation

- **Radiation** consists of electromagnetic waves that transfer energy from the object that emits the radiation to the object that absorbs it.

Radiation

- The rate of heat transfer by radiation is

$$\frac{Q}{\Delta t} = e\sigma A T^4$$

Rate of heat transfer by radiation at temperature T (Stefan's law)

- e is the **emissivity** of a surface, a measure of the effectiveness of radiation. The value of e ranges from 0 to 1. Human skin is a very effective radiator at body temperature, with $e = 0.97$.

- T is the absolute temperature in kelvin.

- A is the surface area in m^2.

- σ is a constant known as the Stefan-Boltzmann constant, with the value $\sigma = 5.67 \times 10^{-8}$ W/m$^2 \cdot$ K^4.

Example 12.22 Determining energy loss by radiation for the body

A person with a skin temperature of 33°C is in a room at 24°C. What is the net rate of heat transfer by radiation?

PREPARE Body temperature is $T = 33 + 273 = 306$ K; the temperature of the room is $T_0 = 24 + 273 = 297$ K.
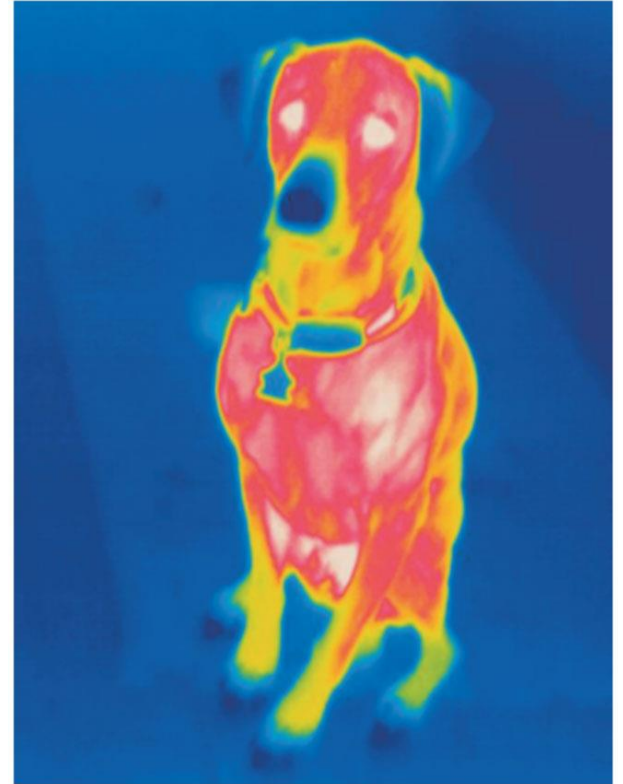
Example 12.22 Determining energy loss by radiation for the body (cont.)

SOLVE The net radiation rate, given by Equation 12.36, is

$$\frac{Q_{net}}{\Delta t} = e\sigma A(T^4 - T_0^4)$$

$$= (0.97)\left(5.67 \times 10^{-8}\,\frac{W}{m^2 \cdot K^4}\right)(1.8\text{ m}^2)\left[(306\text{ K})^4 - (297\text{ K})^4\right] = 98\text{ W}$$
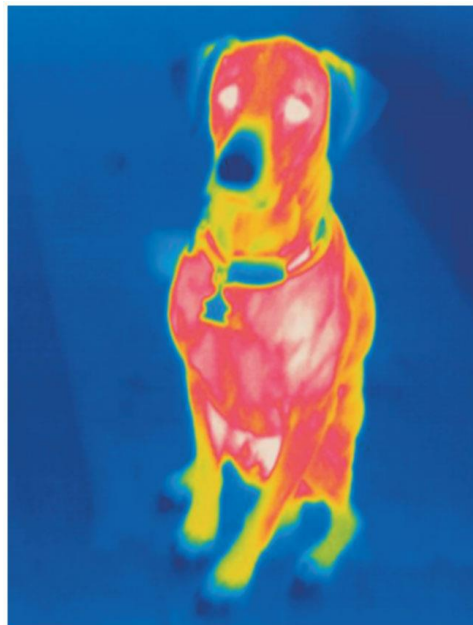
Example 12.22 Determining energy loss by radiation for the body (cont.)

ASSESS This is a reasonable value, roughly matching your resting metabolic power. When you are dressed (little convection) and sitting on wood or plastic (little conduction), radiation is your body's primary mechanism for dissipating the excess thermal energy of metabolism.
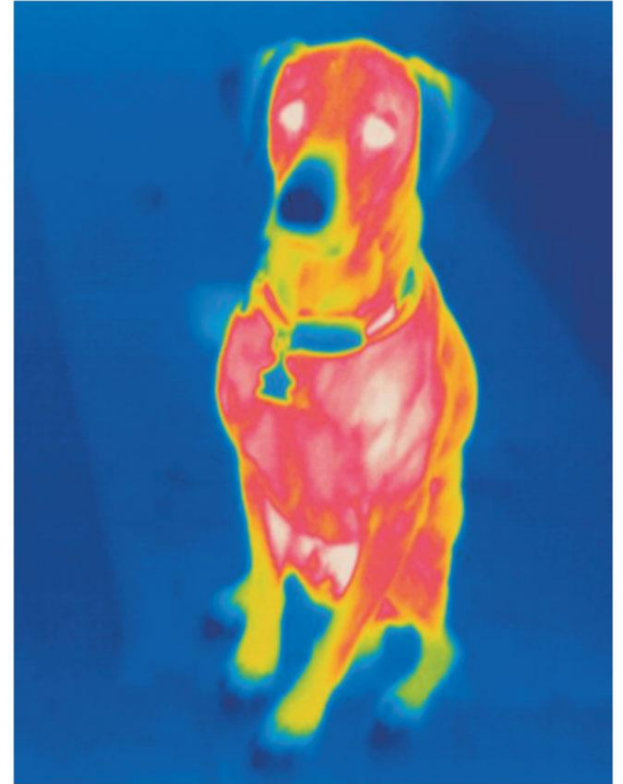
Summary: General Principles

Atomic Model

We model matter as being made of simple basic particles. The relationship of these particles to each other defines the phase.

Gas   Liquid   Solid
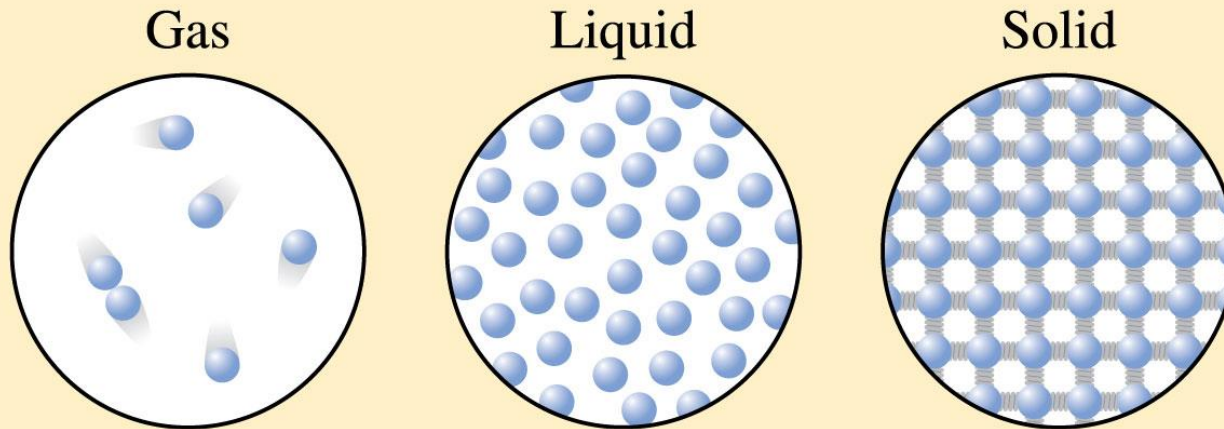
The atomic model explains thermal expansion, specific heat, and heat transfer.

Text: p. 389

Summary: General Principles

Atomic Model of a Gas

Macroscopic properties of gases can be explained in terms of the atomic model of the gas. The speed of the particles is related to the temperature:

$$v_{rms} = \sqrt{\frac{3k_B T}{m}}$$

The collisions of particles with each other and with the walls of the container determine the pressure.

p, V, T
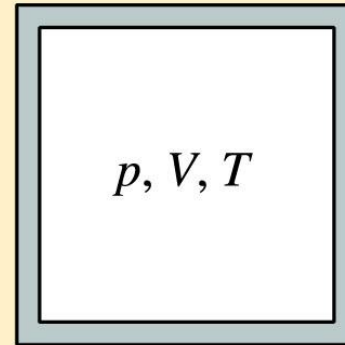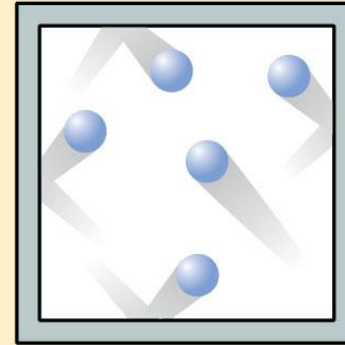
Text: p. 389

Summary: General Principles

Ideal-Gas Law

The ideal-gas law relates the pressure, volume, and temperature in a sample of gas. We can express the law in terms of the number of atoms or the number of moles in the sample:

$$pV = Nk_{B}T$$

$$pV = nRT$$

For a gas process in a sealed container,

$$\frac{p_i V_i}{T_i} = \frac{p_f V_f}{T_f}$$

Text: p. 389

Summary: Important Concepts

Effects of heat transfer

A system that is heated can either change temperature or change phase.

The **specific heat** c of a material is the heat required to raise 1 kg by 1 K.

$$Q = Mc\,\Delta T$$

The **heat of transformation** is the energy necessary to change the phase of 1 kg of a substance. Heat is added to change a solid to a liquid or a liquid to a gas; heat is removed to reverse these changes.

$$Q = \begin{cases} \pm ML_f & \text{(melt/freeze)} \\ \pm ML_v & \text{(boil/condense)} \end{cases}$$

The **molar specific heat** of a gas depends on the process.

$$\begin{cases} \text{For a constant-volume process:} & Q = nC_V\,\Delta T \\ \text{For a constant-pressure process:} & Q = nC_P\,\Delta T \end{cases}$$
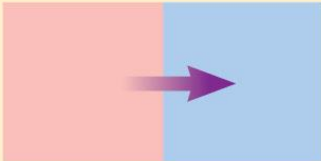
Text: p. 389

Summary: Important Concepts

Mechanisms of heat transfer

An object can transfer heat to other objects or to its environment:
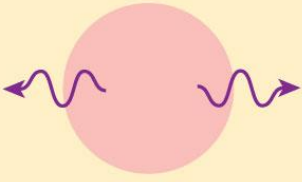
Conduction is the transfer of heat by direct physical contact.

$$\frac{Q}{\Delta t} = \left(\frac{kA}{L}\right)\Delta T$$

Convection is the transfer of heat by the motion of a fluid.
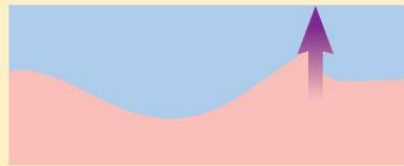
Radiation is the transfer of heat by electromagnetic waves.

$$\frac{Q}{\Delta t} = e\sigma AT^4$$

Text: p. 389

Summary: Important Concepts

A *pV* (pressure-volume) diagram is a useful means of looking at a process involving a gas.

A **constant-volume** process has no change in volume.	An **isobaric** process happens at a constant pressure.	An **isothermal** process happens at a constant temperature.	An **adiabatic** process involves no transfer of heat; the temperature changes.	The work done by a gas is the area under the graph.
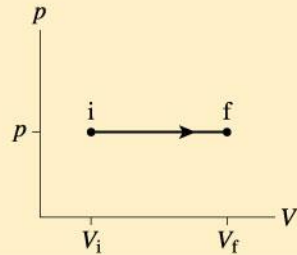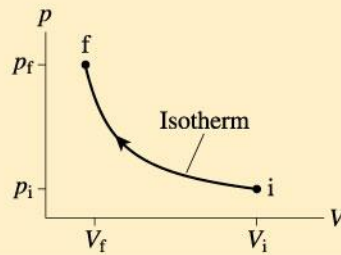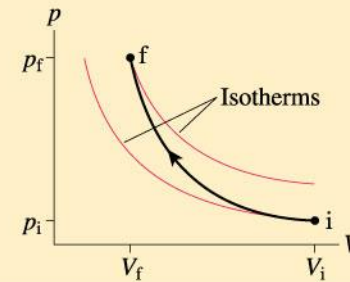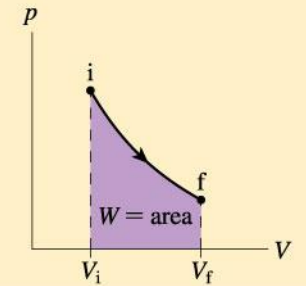
Text: p. 389

Summary: Applications

Thermal expansion Objects experience an increase in volume and an increase in length when their temperature changes:

$$\Delta V = \beta V_i \, \Delta T \qquad \Delta L = \alpha L_i \, \Delta T$$

Text: p. 389

Summary: Applications

Calorimetry When two or more systems interact thermally, they come to a common final temperature determined by

$$Q_{net} = Q_1 + Q_2 + Q_3 + \cdots = 0$$

Text: p. 389

Summary: Applications

The number of **moles** is

$$n = \frac{M \text{ (in grams)}}{M_{\text{mol}}}$$

Text: p. 389

Summary

GENERAL PRINCIPLES

Atomic Model

We model matter as being made of simple basic particles. The relationship of these particles to each other defines the phase.

Gas   Liquid   Solid
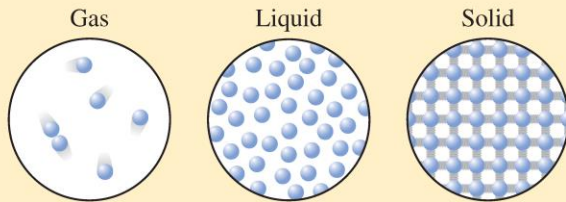
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Text: p. 389

Summary

IMPORTANT CONCEPTS

Effects of heat transfer

A system that is heated can either change temperature or change phase.

The **specific heat** c of a material is the heat required to raise 1 kg by 1 K.

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The **heat of transformation** is the energy necessary to change the phase of 1 kg of a substance. Heat is added to change a solid to a liquid or a liquid to a gas; heat is removed to reverse these changes.

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The **molar specific heat** of a gas depends on the process.

For a constant-volume process: $Q = nC_V\,\Delta T$

For a constant-pressure process: $Q = nC_P\,\Delta T$

Mechanisms of heat transfer

An object can transfer heat to other objects or to its environment:

Conduction is the transfer of heat by direct physical contact.

$$\frac{Q}{\Delta t} = \left(\frac{kA}{L}\right)\Delta T$$

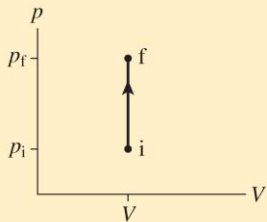**Convection** is the transfer of heat by the motion of a fluid.

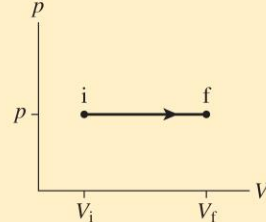**Radiation** is the transfer of heat by electromagnetic waves.

$$\frac{Q}{\Delta t} = e\sigma A T^4$$

A pV **(pressure-volume) diagram** is a useful means of looking at a process involving a gas.
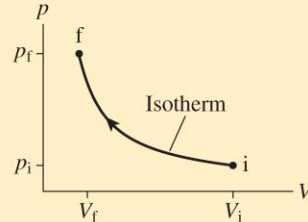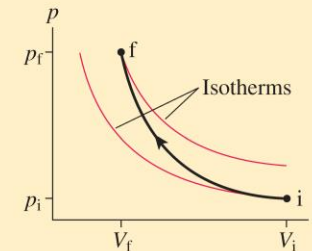
A **constant-volume** process has no change in volume.

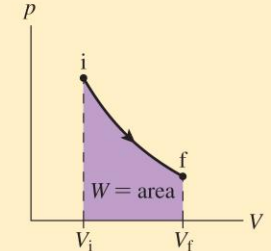An **isobaric** process happens at a constant pressure.

An **isothermal** process happens at a constant temperature.

An **adiabatic** process involves no transfer of heat; the temperature changes.

The work done by a gas is the area under the graph.

Text: p. 389

Summary

APPLICATIONS

Thermal expansion Objects experience an increase in volume and an increase in length when their temperature changes:

$$\Delta V = \beta V_i \, \Delta T \qquad \Delta L = \alpha L_i \, \Delta T$$

Calorimetry When two or more systems interact thermally, they come to a common final temperature determined by

$$Q_{net} = Q_1 + Q_2 + Q_3 + \cdots = 0$$

The number of **moles** is

$$n = \frac{M \text{ (in grams)}}{M_{mol}}$$

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