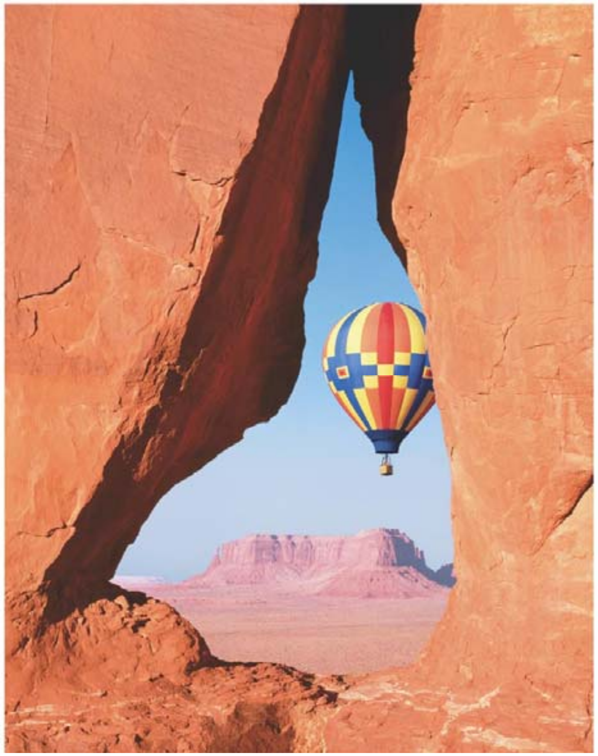
Chapter 17
Temperature, Thermal Expansion, and the Ideal Gas Law



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Units of Chapter 17

- **Atomic Theory of Matter**
- **Temperature and Thermometers**
- **Thermal Equilibrium and the Zeroth Law of Thermodynamics**
- **Thermal Expansion**
- **Thermal Stress**
- **The Gas Laws and Absolute Temperature**
- **The Ideal Gas Law**

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Units of Chapter 17

- Problem Solving with the Ideal Gas Law
- Ideal Gas Law in Terms of Molecules: Avogadro's Number
- Ideal Gas Temperature Scale—a Standard

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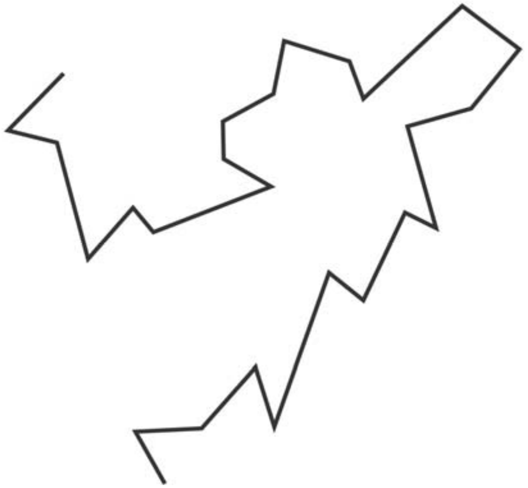
17-1 Atomic Theory of Matter

Atomic and molecular **masses** are measured in unified **atomic mass units** (u). This unit is defined so that the **carbon-12** atom has a mass of exactly **12.0000 u**. Expressed in kilograms:

$$1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg}.$$

Brownian motion is the jittery motion of tiny flecks in water; these are the result of **collisions** with **individual** water molecules.



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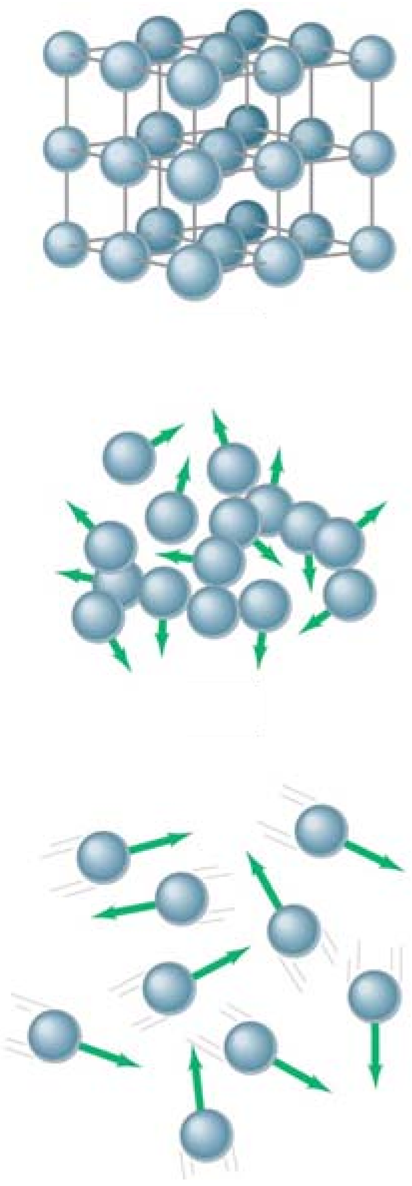
17-1 Atomic Theory of Matter

On a **microscopic** scale, the arrangements of molecules in **solids** (a), **liquids** (b), and **gases** (c) are quite different.



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17-1 Atomic Theory of Matter

Example 17-1: Distance between atoms.

The density of copper is 8.9×10^3 kg/m^3, and each copper atom has a mass of 63 u. Estimate the average distance between the centers of neighboring copper atoms.

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17-2 Temperature and Thermometers

Temperature is a measure of how hot or cold something is.

Most materials **expand** when heated.

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17-2 Temperature and Thermometers

Thermometers are instruments designed to measure temperature. In order to do this, they take advantage of some **property** of matter that **changes** with temperature.

Early thermometers:

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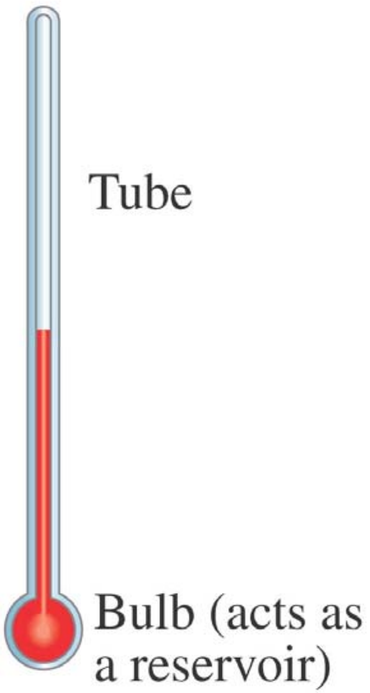
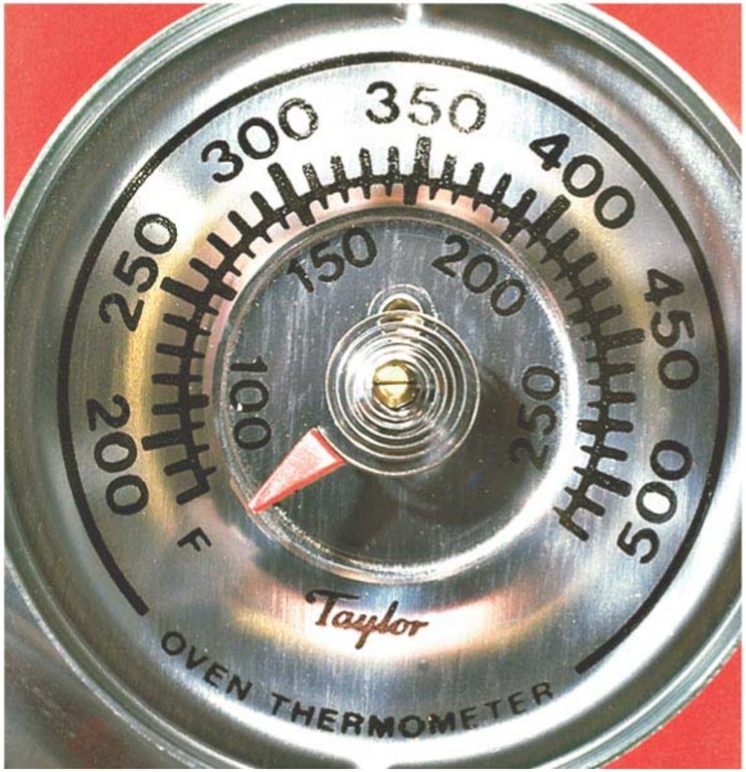
17-2 Temperature and Thermometers

Common thermometers used today include the **liquid-in-glass** type and the **bimetallic strip**.





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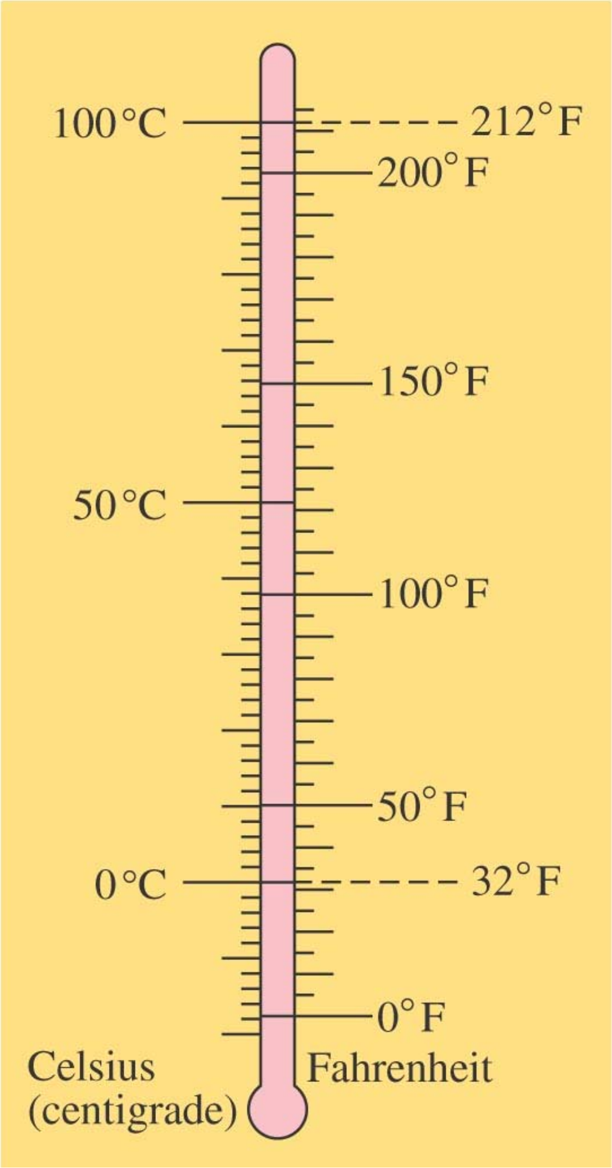
17-2 Temperature and Thermometers



Temperature is generally measured using either the **Fahrenheit** or the **Celsius** scale.

The **freezing** point of water is **0°C**, or **32°F**; the **boiling** point of water is **100°C**, or **212°F**.

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17-2 Temperature and Thermometers

Example 17-2: Taking your temperature.

Normal body temperature is 98.6°F. What is this on the Celsius scale?

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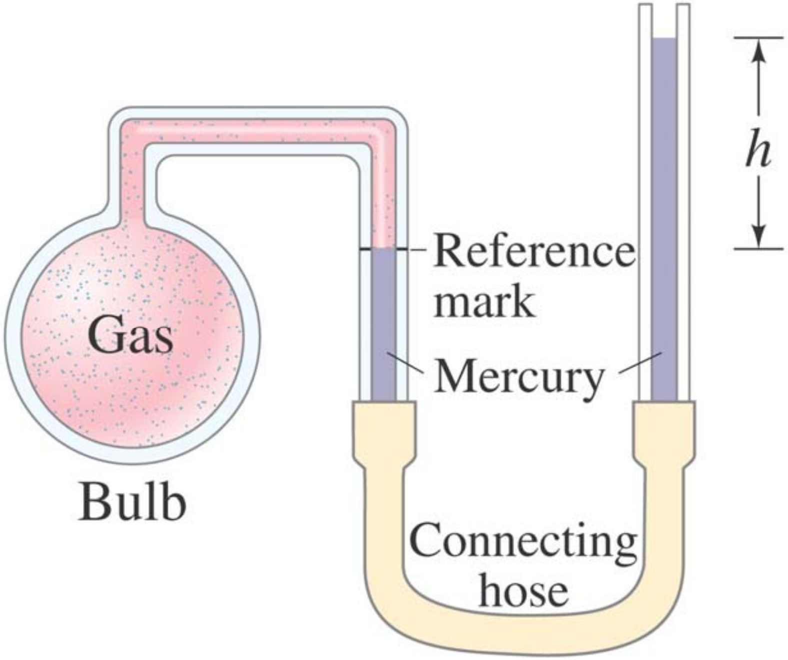
17-2 Temperature and Thermometers

A constant-volume gas thermometer depends only on the properties of an ideal gas, which do not change over a wide variety of temperatures. Therefore, it is used to calibrate thermometers based on other materials.



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17-3 Thermal Equilibrium and the Zeroth Law of Thermodynamics

Two objects placed in **thermal contact** will eventually come to the **same** temperature. When they do, we say they are in **thermal equilibrium**.

The **zeroth** law of thermodynamics says that if two objects are each in equilibrium with a **third** object, they are also in thermal equilibrium with each other.

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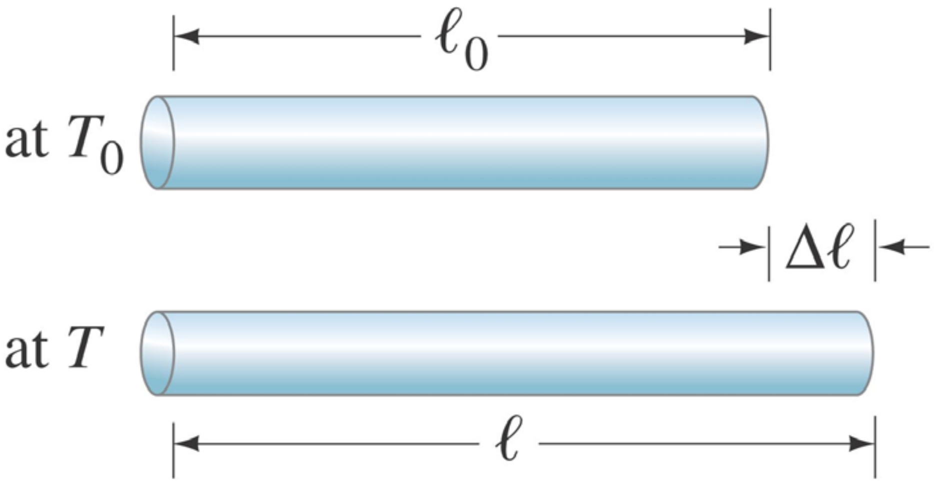
17-4 Thermal Expansion



Linear expansion occurs when an object is heated.

$$\ell = \ell_0(1 + \alpha\,\Delta T)$$

Here, α is the **coefficient of linear expansion**.

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17-4 Thermal Expansion

TABLE 17–1 Coefficients of Expansion, near 20°C

Material	Coefficient of Linear Expansion, α $(C°)^{-1}$	Coefficient of Volume Expansion, β $(C°)^{-1}$
Solids		
Aluminum	25×10^{-6}	75×10^{-6}
Brass	19×10^{-6}	56×10^{-6}
Copper	17×10^{-6}	50×10^{-6}
Gold	14×10^{-6}	42×10^{-6}
Iron or steel	12×10^{-6}	35×10^{-6}
Lead	29×10^{-6}	87×10^{-6}
Glass (Pyrex®)	3×10^{-6}	9×10^{-6}
Glass (ordinary)	9×10^{-6}	27×10^{-6}
Quartz	0.4×10^{-6}	1×10^{-6}
Concrete and brick	$\approx 12 \times 10^{-6}$	$\approx 36 \times 10^{-6}$
Marble	$1.4\text{–}3.5 \times 10^{-6}$	$4\text{–}10 \times 10^{-6}$
Liquids		
Gasoline		950×10^{-6}
Mercury		180×10^{-6}
Ethyl alcohol		1100×10^{-6}
Glycerin		500×10^{-6}
Water		210×10^{-6}
Gases		
Air (and most other gases at atmospheric pressure)		3400×10^{-6}

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17-4 Thermal Expansion

Example 17-3: Bridge expansion.

The steel bed of a suspension bridge is 200 m long at 20°C. If the extremes of temperature to which it might be exposed are -30°C to +40°C, how much will it contract and expand?

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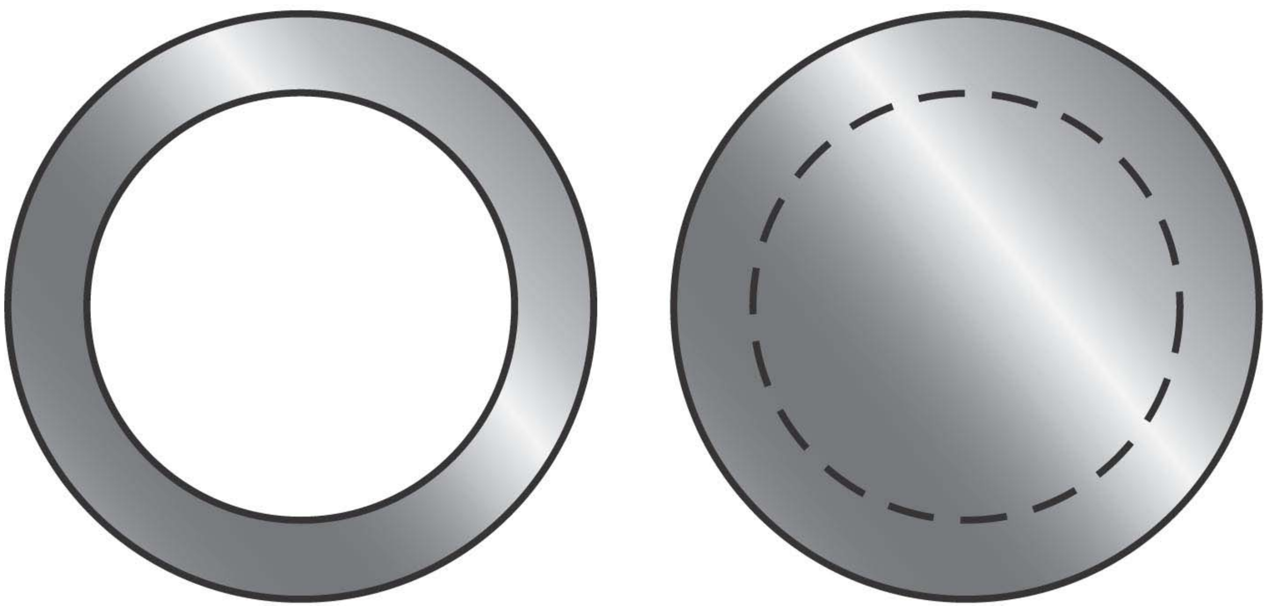
17-4 Thermal Expansion

Conceptual Example 17-4: Do holes expand or contract?

If you heat a thin, circular ring in the oven, does the ring's hole get larger or smaller?



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17-4 Thermal Expansion

Example 17-5: Ring on a rod.

An iron ring is to fit snugly on a cylindrical iron rod. At 20°C, the diameter of the rod is 6.445 cm and the inside diameter of the ring is 6.420 cm. To slip over the rod, the ring must be slightly larger than the rod diameter by about 0.008 cm. To what temperature must the ring be brought if its hole is to be large enough so it will slip over the rod?

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17-4 Thermal Expansion

Conceptual Example 17-6: Opening a tight jar lid.

When the lid of a glass jar is tight, holding the lid under hot water for a short time will often make it easier to open. Why?

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17-4 Thermal Expansion

Volume expansion is similar, except that it is relevant for **liquids** and **gases** as well as solids:

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

Here, β is the coefficient of **volume** expansion.

For **uniform** solids, $\beta \approx 3\alpha$.

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17-4 Thermal Expansion

Example 17-7: Gas tank in the Sun.

The 70-liter (L) steel gas tank of a car is filled to the top with gasoline at 20°C. The car sits in the Sun and the tank reaches a temperature of 40°C (104°F). How much gasoline do you expect to overflow from the tank?

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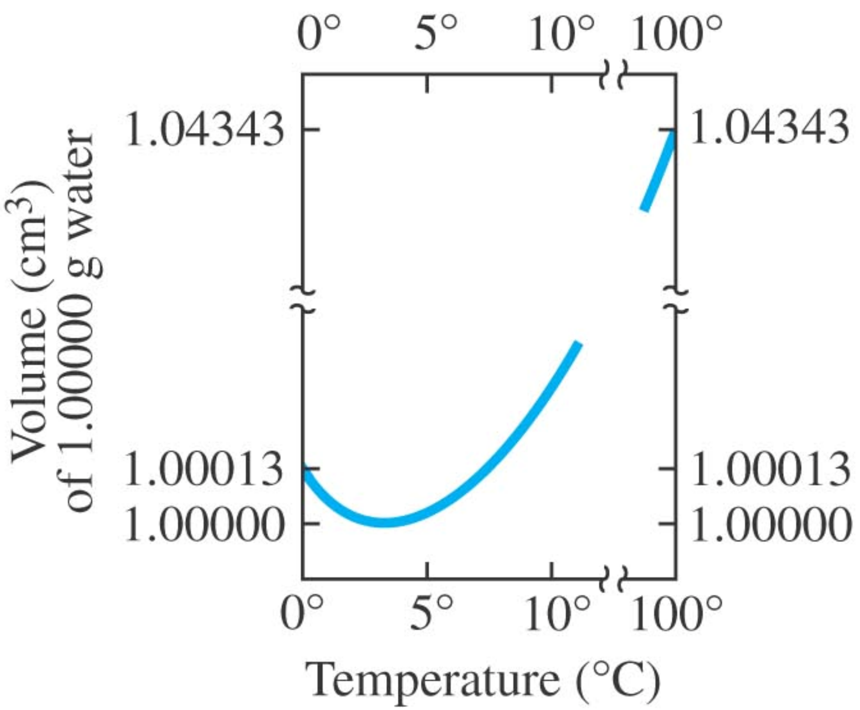
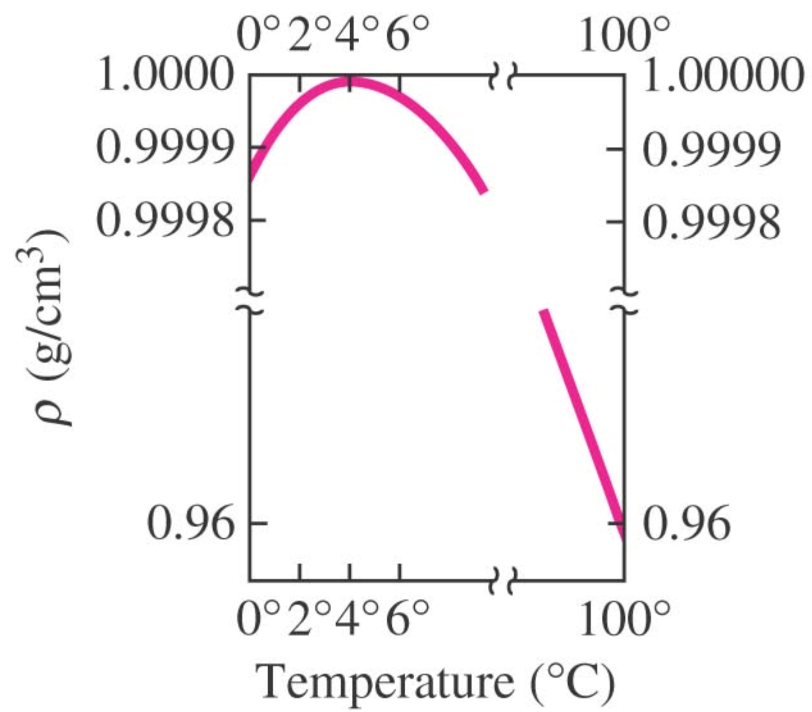
17-4 Thermal Expansion

Water behaves differently from most other solids—its **minimum** volume occurs when its temperature is 4°C. As it cools further, it **expands**, as anyone who leaves a bottle in the freezer to cool and then forgets about it can testify.





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17-5 Thermal Stresses

A material may be **fixed** at its ends and therefore be unable to expand when the temperature changes. It will then experience large **compressive** or **tensile stress—thermal stress**—when its temperature changes. The **force** required to keep the material from expanding is found from:

$$\Delta\ell = \frac{1}{E}\frac{F}{A}\ell_0 ,$$

where E is the Young's modulus of the material. Therefore, the **stress** is:

$$\frac{F}{A} = \alpha E \, \Delta T.$$

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17-5 Thermal Stresses

Example 17-8: Stress in concrete on a hot day.

A highway is to be made of blocks of concrete 10 m long placed end to end with no space between them to allow for expansion. If the blocks were placed at a temperature of 10°C, what compressive stress would occur if the temperature reached 40°C? The contact area between each block is 0.20 m^2. Will fracture occur?

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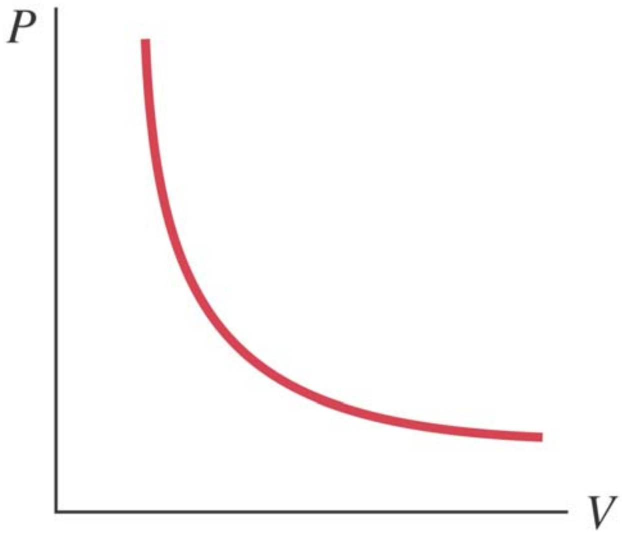
17-6 The Gas Laws and Absolute Temperature

The relationship between the volume, pressure, temperature, and mass of a gas is called an **equation of state**.

We will deal here with gases that are not too dense.



Boyle's law: the **volume** of a given amount of gas is inversely proportional to the **pressure** as long as the **temperature** is constant.

$$V \propto \frac{1}{P}$$

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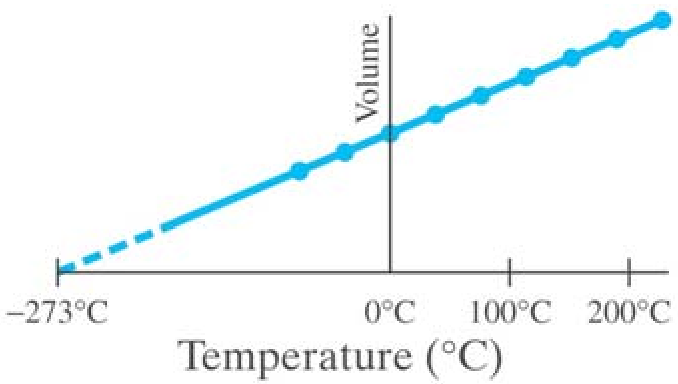
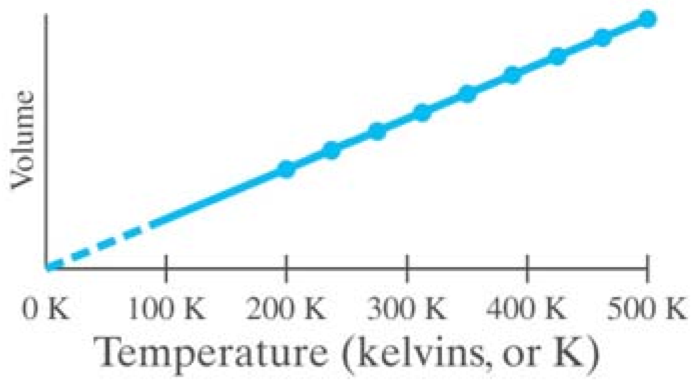
17-6 The Gas Laws and Absolute Temperature





$$V \propto T$$

The **volume** is linearly proportional to the **temperature**, as long as the temperature is somewhat above the **condensation point** and the **pressure** is constant. Extrapolating, the volume becomes zero at −273.15°C; this temperature is called **absolute zero**.

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17-6 The Gas Laws and Absolute Temperature

The concept of absolute zero allows us to define a third temperature scale—the absolute, or **Kelvin**, scale. This scale starts with **0 K** at **absolute zero**, but otherwise is the same as the Celsius scale. Therefore, the **freezing** point of water is 273.15 K, and the **boiling** point is 373.15 K.

Finally, when the **volume** is constant, the **pressure** is directly proportional to the **temperature**.

$$P \propto T$$

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17-6 The Gas Laws and Absolute Temperature

Conceptual Example 17-9: Why you should not throw a closed glass jar into a campfire.

What can happen if you did throw an empty glass jar, with the lid on tight, into a fire, and why?

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17-7 The Ideal Gas Law

We can combine the three relations just derived into a **single** relation:

$$PV \propto T.$$

What about the **amount** of gas present? If the **temperature** and **pressure** are constant, the **volume** is proportional to the **amount** of gas:

$$PV \propto mT.$$

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17-7 The Ideal Gas Law

A **mole** (mol) is defined as the number of **grams** of a substance that is numerically equal to the **molecular mass** of the substance:

1 mol H_2 has a mass of 2 g.

1 mol Ne has a mass of 20 g.

1 mol CO_2 has a mass of 44 g.

The number of moles in a certain mass of material:

$$n\,(\text{mole}) = \frac{\text{mass (grams)}}{\text{molecular mass (g/mol)}}.$$

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17-7 The Ideal Gas Law

We can now write the **ideal gas law**:

$$PV = nRT,$$

where n is the number of **moles** and R is the **universal gas constant**.

$$\begin{aligned} R &= 8.314\,\mathrm{J/(mol\cdot K)} \\ &= 0.0821\,\mathrm{(L\cdot atm)/(mol\cdot K)} \\ &= 1.99\,\mathrm{calories/(mol\cdot K)}. \end{aligned}$$

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17-8 Problem Solving with the Ideal Gas Law

Standard temperature and pressure (STP):

$$T = 273\ \text{K}\ (0°\text{C})$$

$$P = 1.00\ \text{atm} = 1.013\ \text{N/m}^2 = 101.3\ \text{kPa}.$$

Example 17-10: Volume of one mole at STP.

Determine the volume of 1.00 mol of any gas, assuming it behaves like an ideal gas, at STP.

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17-8 Problem Solving with the Ideal Gas Law

Example 17-11: Helium balloon.

A helium party balloon, assumed to be a perfect sphere, has a radius of 18.0 cm. At room temperature (20°C), its internal pressure is 1.05 atm. Find the number of moles of helium in the balloon and the mass of helium needed to inflate the balloon to these values.

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17-8 Problem Solving with the Ideal Gas Law

Example 17-12: Mass of air in a room.

Estimate the mass of air in a room whose dimensions are 5 m x 3 m x 2.5 m high, at STP.

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17-8 Problem Solving with the Ideal Gas Law

- **Volume** of 1 mol of an ideal gas is **22.4 L**
- If the amount of gas does not change:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}.$$

- Always measure *T* in **kelvins**
- *P* must be the **absolute** pressure

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17-8 Problem Solving with the Ideal Gas Law

Example 17-13: Check tires cold.

An automobile tire is filled to a gauge pressure of 200 kPa at 10°C. After a drive of 100 km, the temperature within the tire rises to 40°C. What is the pressure within the tire now?

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17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Since the gas constant is **universal**, the **number** of molecules in one mole is the same for all gases. That number is called **Avogadro's number**:

$$N_A = 6.02 \times 10^{23}.$$

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17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Therefore we can write:

$$PV = nRT = \frac{N}{N_A}RT,$$

or

$$\boxed{PV = NkT,}$$

where k is called **Boltzmann's constant**.

$$k = \frac{R}{N_A} = \frac{8.314\ \mathrm{J/mol \cdot K}}{6.02 \times 10^{23}/\mathrm{mol}} = 1.38 \times 10^{-23}\ \mathrm{J/K}.$$

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17-9 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Example 17-14: Hydrogen atom mass.

Use Avogadro's number to determine the mass of a hydrogen atom.

Example 17-15: How many molecules in one breath?

Estimate how many molecules you breathe in with a 1.0-L breath of air.

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17-10 Ideal Gas Temperature Scale—a Standard

This standard uses the constant-volume gas thermometer and the ideal gas law. There are two fixed points:

Absolute zero—the pressure is zero here

The triple point of water (where all three phases coexist), defined to be 273.16 K—the pressure here is 4.58 torr.

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17-10 Ideal Gas Temperature Scale—a Standard

Then the temperature is defined as:

$$T = (273.16\,\mathrm{K})\left(\frac{P}{P_{\mathrm{tp}}}\right).$$

In order to determine temperature using a real gas, the pressure must be as low as possible.

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Summary of Chapter 17

- All matter is made of atoms.
- Atomic and molecular masses are measured in atomic mass units, u.
- Temperature is a measure of how hot or cold something is, and is measured by thermometers.
- There are three temperature scales in use: Celsius, Fahrenheit, and Kelvin.
- When heated, a solid will get longer by a fraction given by the coefficient of linear expansion.

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Summary of Chapter 17

- The fractional change in volume of gases, liquids, and solids is given by the coefficient of volume expansion.
- Ideal gas law: $PV = nRT$.
- One mole of a substance is the number of grams equal to the atomic or molecular mass.
- Each mole contains Avogadro’s number of atoms or molecules.

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