Lecture PowerPoints

Chapter 13
Physics: Principles with Applications, 7th edition
Giancoli

Chapter 13

Temperature and Kinetic Theory

Contents of Chapter 13

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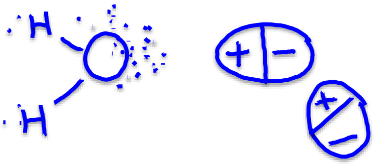
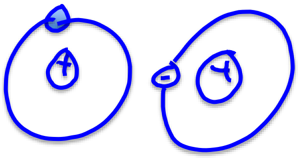
13.1 Atomic Theory

- Element, atom
- Compound, molecule
- Macroscopic, microscopic
  - Molecules attract
  - But too close, repel (electron clouds repel)

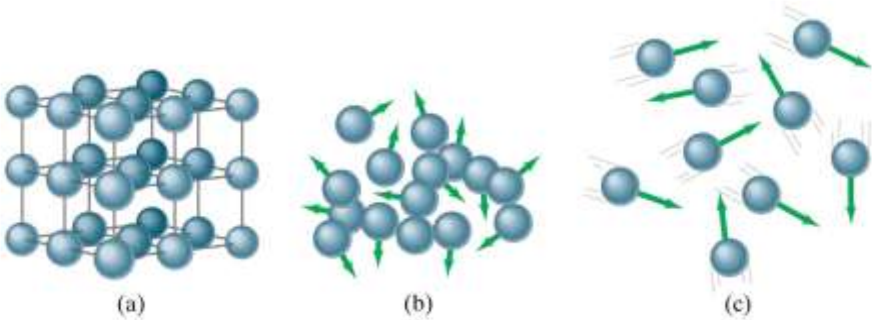




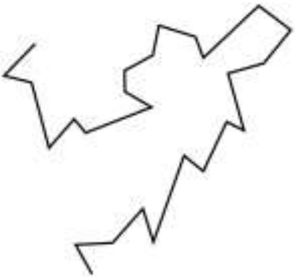
13-1 Atomic Theory of Matter

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

Gas ~ 500 m/s



13-1 Brownian Motio



- 1827 biologist Robert Brown
  - Tiny pollen grains suspended in water
  - Under microscope, moving erratically
  - Why? Water molecules are moving, jostling

- 1905 Albert Einstein theoretically found diameter of atom ~ 10^{-10} m

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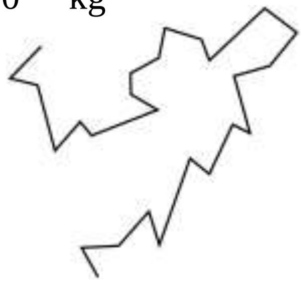
13-1 Atomic Theory of Matter

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.



13-1 Atomic Theory of Matter

- Atomic mass unit (a.m.u.)

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

- Definition: Carbon-12 has 12.0000 amu
  - 6 protons, 6 neutrons = 12 nucleons, (electrons ~ignore)
  - 1 nucleon ~ 1 amu ~ mass of a proton/neutron
- Question:
  - 1 Hydrogen atom ~ 1 a.m.u. (1 proton)
  - 1 Helium atom ~ 4 a.m.u. (2 protons, 2 neutrons)
  - 1 Oxygen atom ~ 16 a.m.u. (8 protons, 8 neutrons)
  - Periodic table in back of book!

13-6, 13-8

- 1 mole = number of atoms in 12 grams of Carbon-12

= N_A particles (Avogadro's Number)

= 6.02 x 10^{23} particles/mole 1 mole ^{12}C

- 1 dozen roses = 12 roses

$N_A \cdot 12$ nucleons = 12 grams

- 1 mole of roses = 6.02 x 10^{23} roses

1 mole of nucleons = 1 gram

$\boxed{1\text{ amu} \leftrightarrow 1\text{ g/mol}}$ $\boxed{N_A\text{ nucleons} = 1\text{ gram}}$

- 1 mol = # particles of substance whose mass in grams is numerically equal to the molecular mass (a.m.u.) of the substance.
  - 1 Carbon atom ~ 12 amu, 1 mole of Carbon~12 grams
  - 1 mole of CO_2= [12 amu + 2 * 16 amu] grams

$1 \text{ amu} \leftrightarrow 1 \frac{g}{mol}$

$\boxed{5C^\circ = 9F^\circ}$

N_A nucleons = 1 gram

$$n \text{ (moles)} = \frac{\text{mass (grams)}}{\text{molecular mass (grams/mol)}}$$

Ⓠ How many moles in 132 grams of CO_2 (44 amu)

$$\frac{132g}{44 g/mol} = \boxed{3 \text{ moles}}$$

6.2 TEMPERATURE

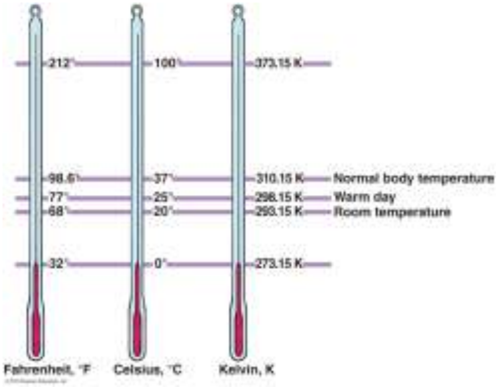
- Can we trust our senses to measure hot and cold?

6.2 TEMPERATURE

- Use a Thermometer to measure temperature.

  0^oC = freezing point of pure water

  100^oC = boiling point of pure water



13-2 Temperature and Thermometers

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

Most materials expand when heated.

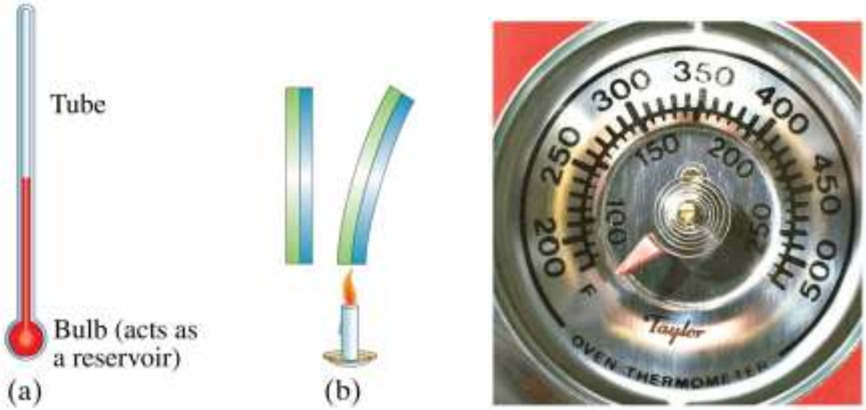
13-2 Temperature and Thermometers

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:

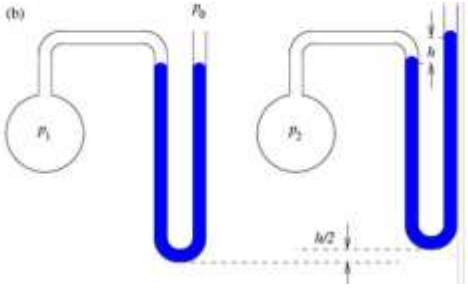
13-2 Temperature and Thermometers

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



Constant Volume Gas Thermometer

- bulb of low pressure gas connected to mercury manometer
- keep volume of gas constant at reference mark by raising/lowering right tube
- T increases → Pbulb increases → right column higher to keep V constant
- For all gases, P decreases to 0, T approaches -273.15^{o}C



Properties that Change with Temperature

- Density decreases, volume increases (except ice water)
  - lakes freeze from top, support life underneath
  - highway expansion joints
- color radiated (iron glows, incandescent tungsten filament, Sun)
- resistance increases

13-3 Thermal Equilibrium and the Zeroth Law of Thermodynamics

Transitive property

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.

13-2 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.

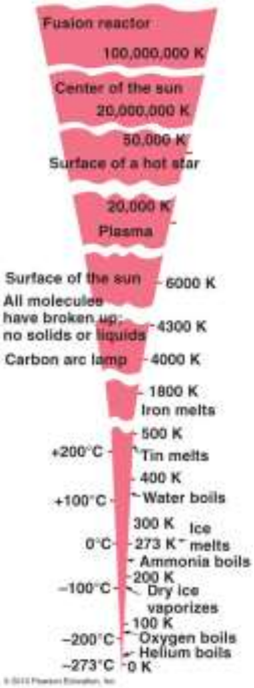
$$°C = \frac{5}{9}(°F - 32)$$

$$K = °C - 273.15$$

6.3 ABSOLUTE ZERO

- How high can temperature go?
- How low can temperature go?

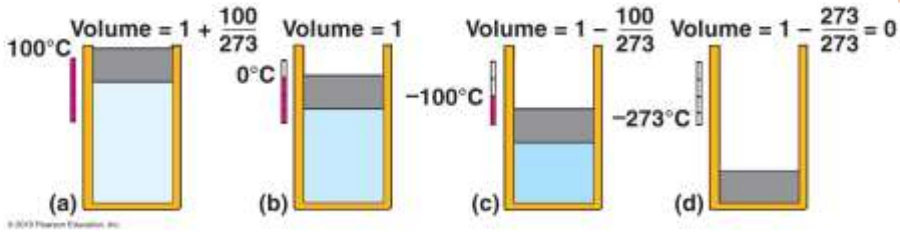
8.3 HOW HOT CAN IT BE?

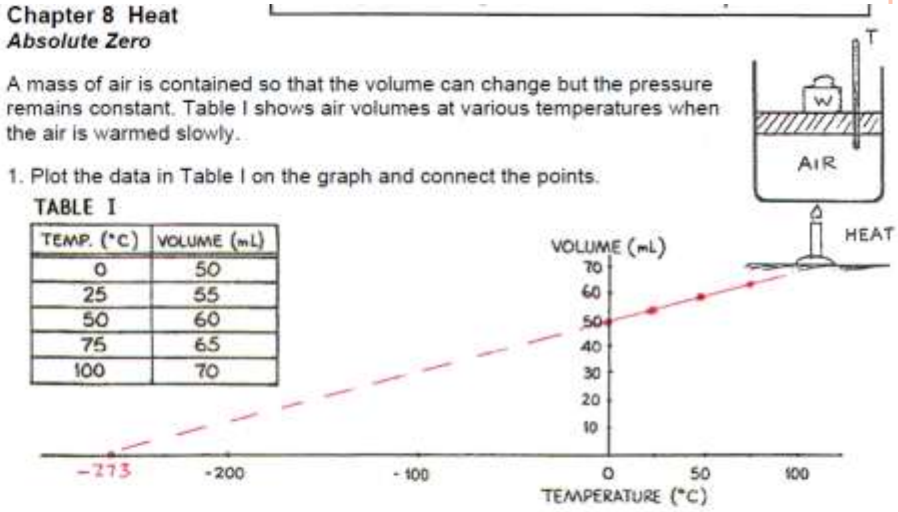


6.3 ABSOLUTE ZERO: HOW COLD CAN IT BE?

How did scientists find absolute zero?

- Increase gas temperature by 1°C → Volume increases by 1/273
- Decrease gas temperature by 1°C → Volume decreases by 1/273
- Decrease gas temperature by 273°C → Volume decreases by 273/273 → 0 Volume!!





Chapter 8 Heat

Absolute Zero

A mass of air is contained so that the volume can change but the pressure remains constant. Table I shows air volumes at various temperatures when the air is warmed slowly.

1. Plot the data in Table I on the graph and connect the points.

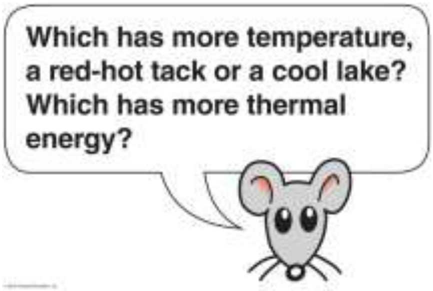
TABLE I

TEMP. (°C)	VOLUME (mL)
0	50
25	55
50	60
75	65
100	70

6.2 TEMPERATURE

- Check Your Thinking (P. 135)

  True or false: Temperature is a measure of the total kinetic energy in a substance.

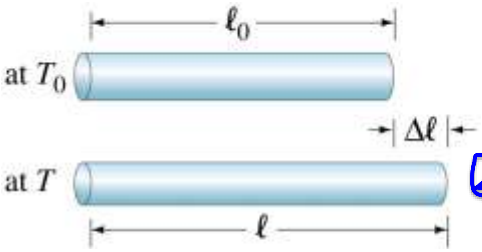
- 

TEMPERATURE CONVERSIONS

$$^{o}F = 9/5 \times {}^{o}C + 32$$

$$^{o}C = K - 273$$

13-4 Thermal Expansion



Linear expansion occurs when an object is heated.

$$\boxed{\Delta \ell = \alpha \ell_0 \Delta T}$$

coefficient of linear expansion $(C^\circ)^{-1}$

$$\ell = \ell_0(1 + \alpha \Delta T), \quad (13\text{-}1b)$$

Here, α is the coefficient of linear expansion.

13-4 Thermal Expansion

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

$$\boxed{\Delta V = \beta V_0 \Delta T,} \quad (13\text{-}2)$$

Here, β is the coefficient of volume expansion.

For uniform solids, $\beta \approx 3^{\alpha}$.

13-4 Thermal Expansion

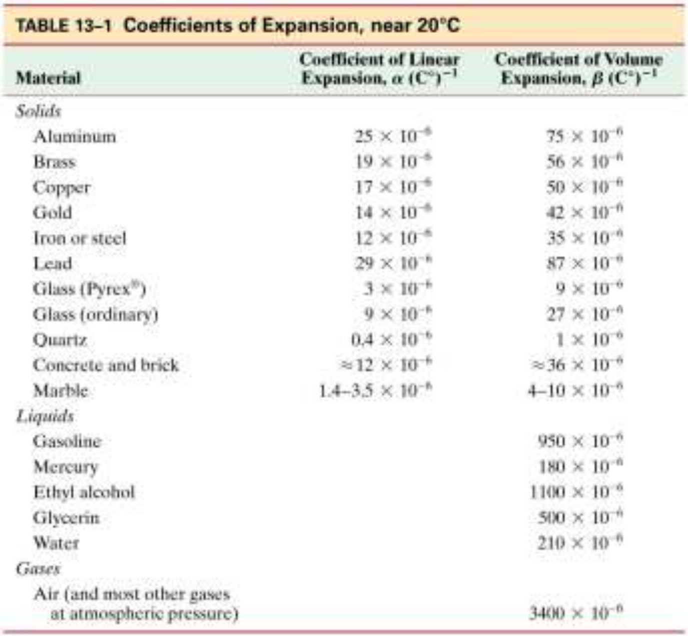
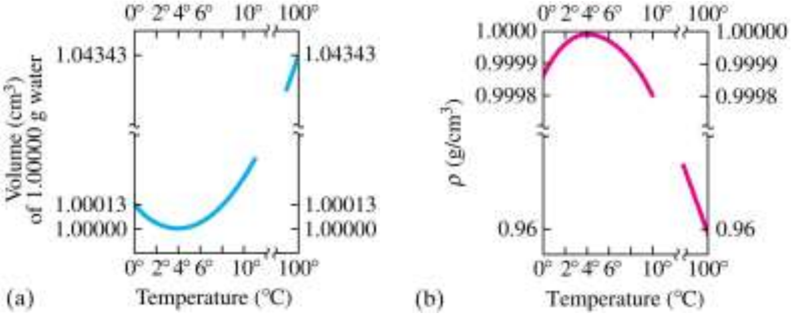


TABLE 13–1 Coefficients of Expansion, near 20°C

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}

13-4 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 has left a bottle in the freezer to cool and then forgets about it can testify.



13-4 Thermal Expansion

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.

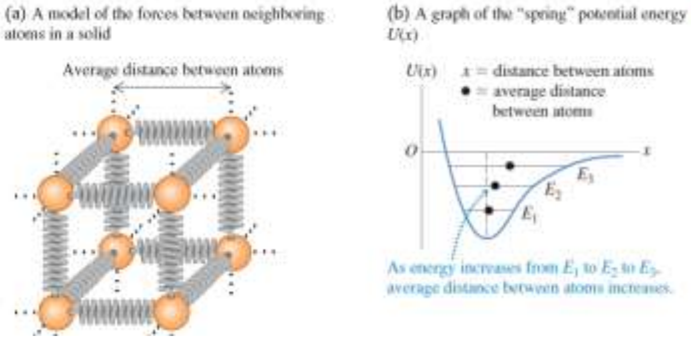
The force required to keep the material from expanding is given by:

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

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

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

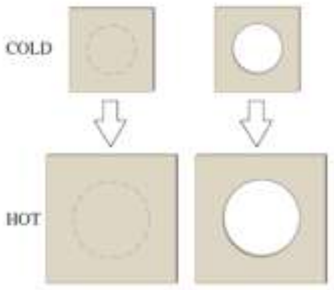
Thermal Expansion



17.9 (a) We can model atom
as being held together by "spri
easier to stretch than to compre
graph of the "spring" potential
versus distance x between neig
atoms is *not* symmetrical (com
14.20b). As the energy increas
atoms oscillate with greater am
average distance increases.

Thermal Expansion

17.10 When an object undergoes thermal expansion, any holes in the object expand as well. (The expansion is exaggerated.)



A plate expands when heated . . .

. . . so a hole cut out of the plate must expand, too.

Thermal Expansion

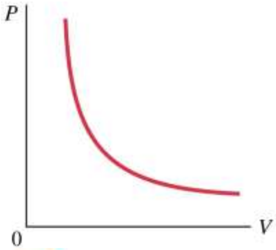
17.11 When this SR-71 aircraft is sitting on the ground, its wing panels fit together so loosely that fuel leaks out of the wings onto the ground. But once it is in flight at over three times the speed of sound, air friction heats the panels so much that they expand to make a perfect fit. (In-flight refueling makes up for the lost fuel.)

13.5~13.7: Ideal Gas Law

- Equilibrium State: after changing P, V, or T, wait long enough for P, V, T to be the same everywhere in the gas
- Ideal Gas
  - Not too dense, Pressure < 1 atm
  - Temperature not too close to liquefaction (boiling)
  - No attraction between molecules

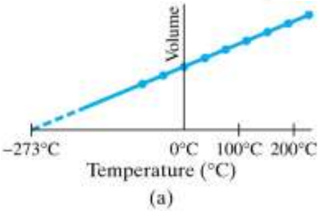
13.5~13.7: Ideal Gas Law

- Toy car analogy?
- Boyle's Law $V \propto 1/P$ (T constant)



- Charles's Law

  $V \propto T.$ (P constant)

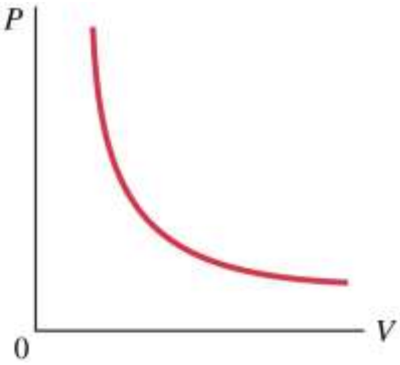


- Gay-Lussac's Law

  $P \propto T.$ (V constant)

13-5 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.

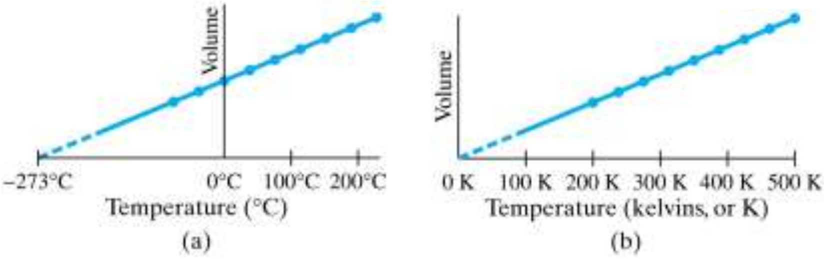
Boyle's Law: the volume of a given amount of gas is inversely proportional to the pressure as long as the temperature is constant.

$$V \propto 1/P$$

13-5 The Gas Laws and Absolute Temperature

The volume is linearly proportional to the temperature, as long as the temperature is somewhat above the condensation point and the pressure is constant: $V \propto T$.

Extrapolating, the volume becomes zero at −273.15°C; this temperature is called absolute zero.



13-5 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: $P \propto T$.

13-6 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:

$PV \propto mT$

13-6 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:

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

13-6 The Ideal Gas Law

We can now write the ideal gas law:

$$PV = nRT, \quad (13\text{-}3)$$

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

$$\begin{aligned} R &= 8.314\ \text{J/(mol}\cdot\text{K)} && \text{[SI units]} \\ &= 0.0821\ \text{(L}\cdot\text{atm)/(mol}\cdot\text{K)} \\ &= 1.99\ \text{calories/(mol}\cdot\text{K)}. \end{aligned}$$

13-7 Problem Solving with the Ideal Gas Law

Useful facts and definitions:

- Standard temperature and pressure (STP)

T = 273 K (0°C)

P = 1.00 atm = 1.013×10^5 N/m^2 = 101.3 kPa

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

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}. \qquad \text{[fixed } n\text{]}$$

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

13-8 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:

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

The number of molecules in a gas is the number of moles times Avogadro's number:

$$N = nN_A$$

13-8 Ideal Gas Law in Terms of Molecules: Avogadro's Number

Therefore we can write:

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

or

$$\boxed{PV = NkT,} \qquad (13\text{-}4)$$

where *k* is called Boltzmann's constant.

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

- Why don't you put a closed glass jar in a campfire?
  - T increasing, V constant, Pressure increases
  - Boom!

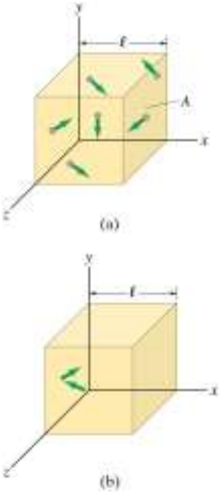
- Hot air balloon. Hot air expands, some air comes out.
  - i) T increases
  - ii) P same! P(Vsame) = (ndecreases)R(Tincreases)
  - iii) density (mass decreases/volume) decreases

13-9 Kinetic Theory and the Molecular Interpretation of Temperature

Assumptions of kinetic theory:

- large number of molecules, moving in random directions with a variety of speeds
- molecules are far apart, on average
- molecules obey laws of classical mechanics and interact only when colliding
- collisions are perfectly elastic

13-9 Kinetic Theory and the Molecular Interpretation of Temperature



The force exerted on the wall by the collision of one molecule is

$$F = \frac{\Delta(mv)}{\Delta t} = \frac{2mv_x}{2\ell/v_x} = \frac{mv_x^2}{\ell}. \qquad \text{[due to one molecule]}$$

Then the force due to all molecules colliding with that wall is

$$F = \frac{m}{\ell} N\overline{v_x^2}. \qquad \textbf{(i)}$$

13-9 Kinetic Theory and the Molecular Interpretation of Temperature

The averages of the squares of the speeds in all three directions are equal:

$$F = \frac{m}{\ell} N \frac{\overline{v^2}}{3}.$$

So the pressure is:

$$P = \frac{F}{A} = \frac{1}{3}\frac{Nm\overline{v^2}}{A\ell}$$

or

$$P = \frac{1}{3}\frac{Nm\overline{v^2}}{V}, \qquad \begin{bmatrix}\text{pressure in an}\\ \text{ideal gas}\end{bmatrix} \qquad (13\text{-}6)$$

13-9 Kinetic Theory and the Molecular Interpretation of Temperature

Rewriting, $PV = \frac{2}{3}N\left(\frac{1}{2}m\overline{v^2}\right).$ (13-7)

so

$$\frac{2}{3}\left(\frac{1}{2}m\overline{v^2}\right) = kT,$$

or

$$\overline{\text{KE}} = \frac{1}{2}m\overline{v^2} = \frac{3}{2}kT. \qquad [\text{ideal gas}] \qquad (13\text{-}8)$$

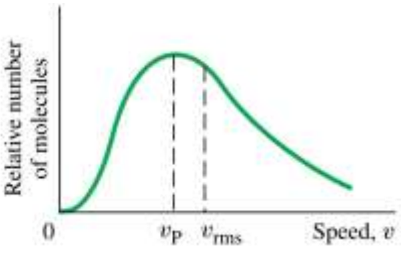
The average translational kinetic energy of the molecules in an ideal gas is directly proportional to the temperature of the gas.

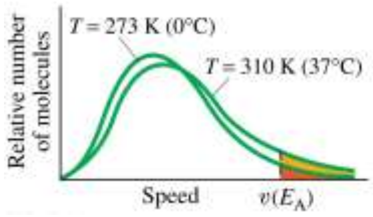
13-9 Kinetic Theory and the Molecular Interpretation of Temperature

We can invert this to find the average speed of molecules in a gas as a function of temperature:

$$v_{\mathrm{rms}} = \sqrt{\overline{v^2}} = \sqrt{\frac{3kT}{m}}. \quad (13\text{-}9)$$

13-10 Distribution of Molecular Speeds

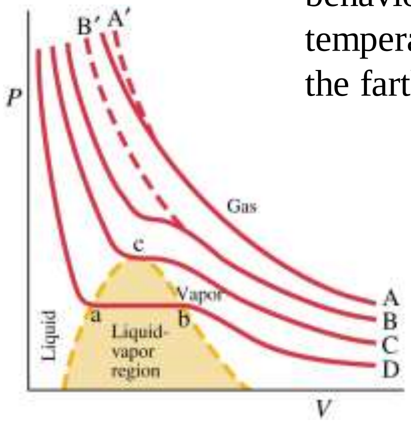




These two graphs show the distribution of speeds of molecules in a gas, as derived by Maxwell. The most probable speed, v_P, is not quite the same as the rms speed.

As expected, the curves shift to the right with temperature.

13-11 Real Gases and Changes of Phase



The curves here represent the behavior of the gas at different temperatures. The cooler it gets, the farther the gas is from ideal.

In curve D, the gas becomes liquid; it begins condensing at (b) and is entirely liquid at (a).

The point (c) is called the critical point.

13-11 Real Gases and Changes of Phase

Below the critical temperature, the gas can liquefy if the pressure is sufficient; above it, no amount of pressure will suffice.

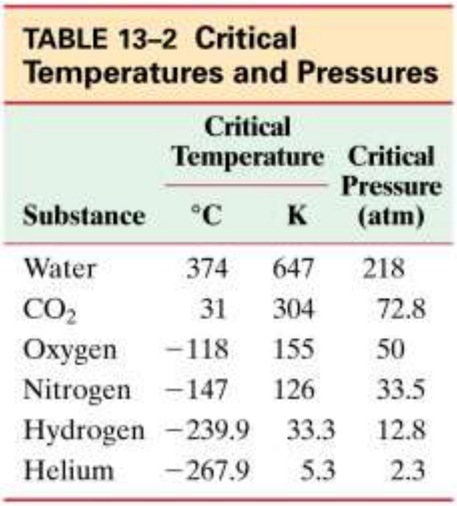
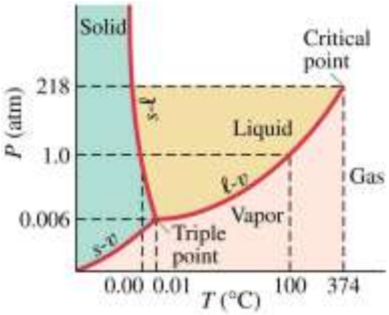


TABLE 13–2 Critical Temperatures and Pressures

Substance	Critical Temperature °C	Critical Temperature K	Critical Pressure (atm)
Water	374	647	218
CO_2	31	304	72.8
Oxygen	−118	155	50
Nitrogen	−147	126	33.5
Hydrogen	−239.9	33.3	12.8
Helium	−267.9	5.3	2.3

13-11 Real Gases and Changes of Phase

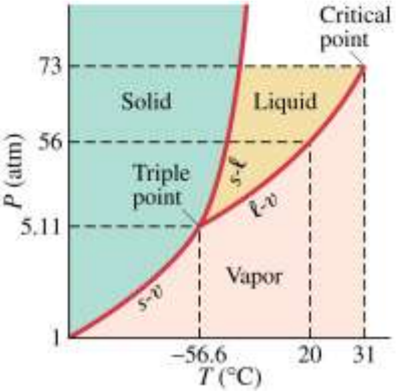
A *PT* diagram is called a phase diagram; it shows all three phases of matter. The solid-liquid transition is melting or freezing; the liquid-vapor one is boiling or condensing; and the solid-vapor one is sublimation.



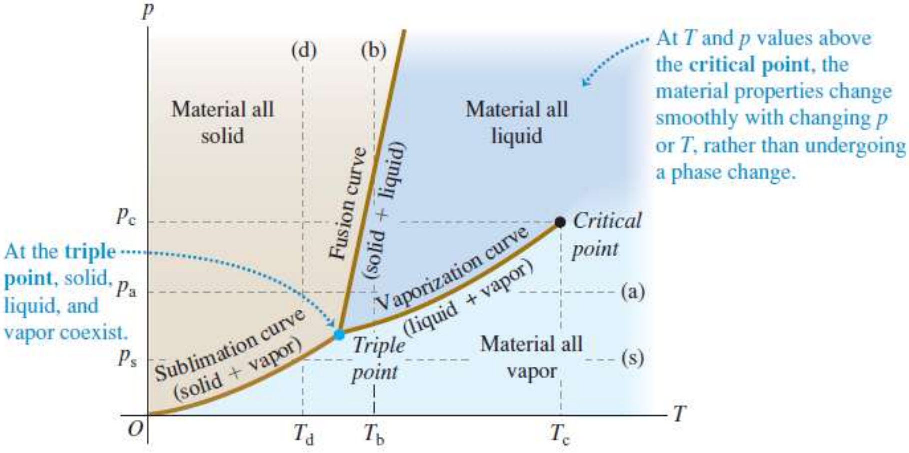
Phase diagram
of water

13-11 Real Gases and Changes of Phase

The triple point is the only point where all three phases can coexist in equilibrium.



Phase diagram
of carbon dioxide

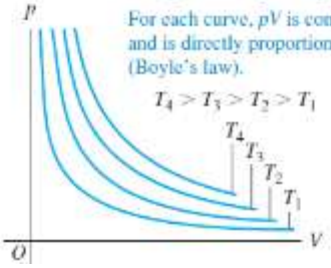


At T and p values above the **critical point**, the material properties change smoothly with changing p or T, rather than undergoing a phase change.

At the **triple point**, solid, liquid, and vapor coexist.

18.6 Isotherms, or constant-temperature curves, for a constant amount of an ideal gas. The highest temperature is T_4; the lowest is T_1. This is a graphical representation of the ideal-gas equation of state.

Each curve represents pressure as a function of volume for an ideal gas at a single temperature.

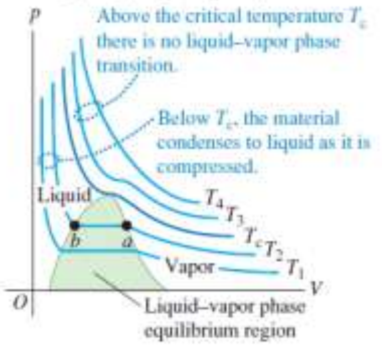


For each curve, pV is constant and is directly proportional to T (Boyle's law).

$T_4 > T_3 > T_2 > T_1$

18.7 A pV-diagram for a nonideal gas, showing isotherms for temperatures above and below the critical temperature T_c. The liquid–vapor equilibrium region is shown as a green shaded area. At still lower temperatures the material might undergo phase transitions from liquid to solid or from gas to solid; these are not shown in this diagram.

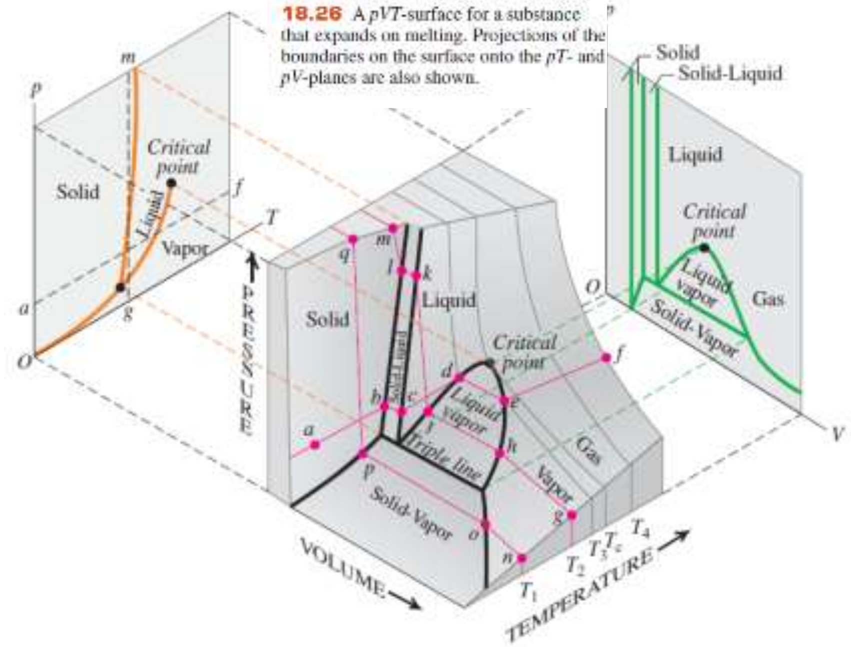
$T_4 > T_3 > T_c > T_2 > T_1$



Above the critical temperature T_c there is no liquid–vapor phase transition.

Below T_c, the material condenses to liquid as it is compressed.

Liquid–vapor phase equilibrium region

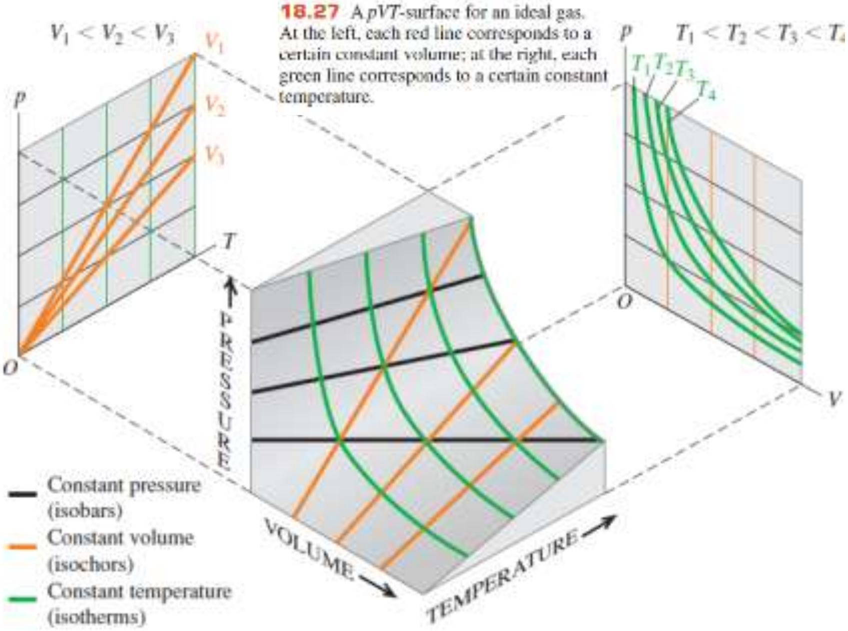


18.26 A *pVT*-surface for a substance that expands on melting. Projections of the boundaries on the surface onto the *pT*- and *pV*-planes are also shown.

pVT-Surfaces

We remarked in Section 18.1 that the equation of state of any material can be represented graphically as a surface in a three-dimensional space with coordinates *p*, *V*, and *T*. Visualizing such a surface can add to our understanding of the behavior of materials at various temperatures and pressures. Figure 18.26 shows a typical *pVT*-surface. The light lines represent *pV*-isotherms; projecting them onto the *pV*-plane gives a diagram similar to Fig. 18.7. The *pV*-isotherms represent contour lines on the *pVT*-surface, just as contour lines on a topographic map represent the elevation (the third dimension) at each point. The projections of the edges of the surface onto the *pT*-plane give the *pT* phase diagram of Fig. 18.24.

Line *abcdef* in Fig. 18.26 represents constant-pressure heating, with melting along *bc* and vaporization along *de*. Note the volume changes that occur as *T* increases along this line. Line *ghjklm* corresponds to an isothermal (constant temperature) compression, with liquefaction along *hj* and solidification along *kl*. Between these, segments *gh* and *jk* represent isothermal compression with increase in pressure; the pressure increases are much greater in the liquid region *jk* and the solid region *lm* than in the vapor region *gh*. Finally, line *nopq* represents isothermal solidification directly from vapor, as in the formation of snowflakes or frost.



18.27 A pVT-surface for an ideal gas. At the left, each red line corresponds to a certain constant volume; at the right, each green line corresponds to a certain constant temperature.

13-12 Vapor Pressure and Humidity

An open container of water can evaporate, rather than boil, away. The fastest molecules are escaping from the water's surface, so evaporation is a cooling process as well.

The inverse process is called condensation.

When the evaporation and condensation processes are in equilibrium, the vapor just above the liquid is said to be saturated, and its pressure is the saturated vapor pressure.

13-12 Vapor Pressure and Humidity

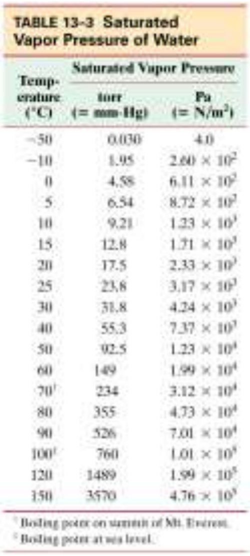


TABLE 13-3 Saturated Vapor Pressure of Water

Temperature (°C)	Saturated Vapor Pressure torr (= mm-Hg)	Pa (= N/m²)
−50	0.030	4.0
−10	1.95	2.60×10^2
0	4.58	6.11×10^2
5	6.54	8.72×10^2
10	9.21	1.23×10^3
15	12.8	1.71×10^3
20	17.5	2.33×10^3
25	23.8	3.17×10^3
30	31.8	4.24×10^3
40	55.3	7.37×10^3
50	92.5	1.23×10^4
60	149	1.99×10^4
70[1]	234	3.12×10^4
80	355	4.73×10^4
90	526	7.01×10^4
100[2]	760	1.01×10^5
120	1489	1.99×10^5
150	3570	4.76×10^5

[1] Boiling point on summit of Mt. Everest.

[2] Boiling point at sea level.

The saturated vapor pressure increases with temperature.

13-12 Vapor Pressure and Humidity

A liquid boils when its saturated vapor pressure equals the external pressure.

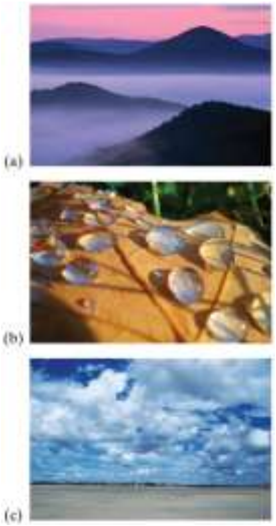
13-12 Vapor Pressure and Humidity

Partial pressure is the pressure each component of a mixture of gases would exert if it were the only gas present. The partial pressure of water in the air can be as low as zero, and as high as the saturated vapor pressure at that temperature.

Relative humidity is a measure of the saturation of the air.

$$\text{Relative humidity} = \frac{\text{partial pressure of } H_2O}{\text{saturated vapor pressure of } H_2O} \times 100\%.$$

13-12 Vapor Pressure and Humidity



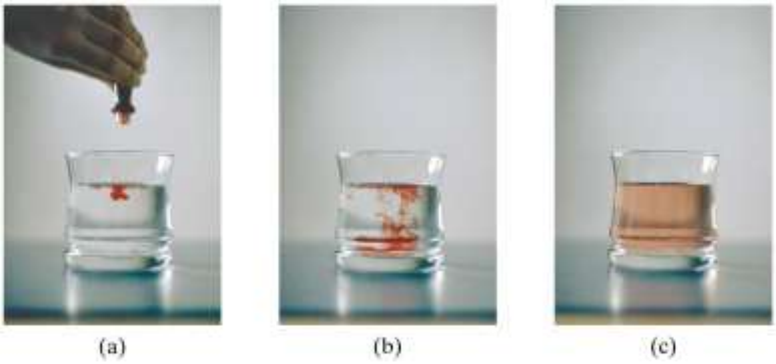
When the humidity is high, it feels muggy; it is hard for any more water to evaporate.

The dew point is the temperature at which the air would be saturated with water.

If the temperature goes below the dew point, dew, fog, or even rain may occur.

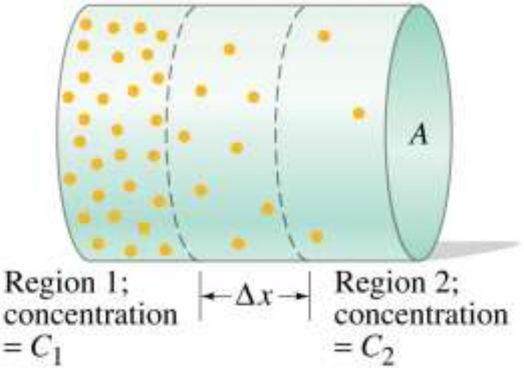
13-13 Diffusion

Even without stirring, a few drops of dye in water will gradually spread throughout. This process is called diffusion.



13-13 Diffusion

Diffusion occurs from a region of high concentration towards a region of lower concentration.



13-13 Diffusion

The rate of diffusion is given by:

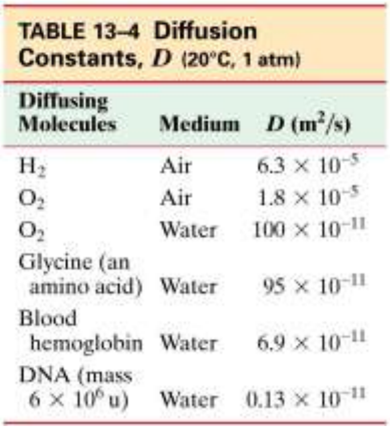


TABLE 13–4 Diffusion Constants, D (20°C, 1 atm)

Diffusing Molecules	Medium	D (m^2/s)
H_2	Air	6.3×10^{-5}
O_2	Air	1.8×10^{-5}
O_2	Water	100×10^{-11}
Glycine (an amino acid)	Water	95×10^{-11}
Blood hemoglobin	Water	6.9×10^{-11}
DNA (mass 6×10^6 u)	Water	0.13×10^{-11}

$$J = DA\frac{C_1 - C_2}{\Delta x}. \quad (13\text{-}10)$$

In this equation, *D* is the diffusion constant.

Summary of Chapter 13

- 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.

Summary of Chapter 13

- 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.

Summary of Chapter 13

- The average kinetic energy of molecules in a gas is proportional to the temperature:

$$\tfrac{2}{3}\left(\tfrac{1}{2}m\overline{v^2}\right) = kT,$$

or

$$\mathrm{KE} = \tfrac{1}{2}m\overline{v^2} = \tfrac{3}{2}kT. \qquad \text{[ideal gas]} \quad (13\text{-}8)$$

- Below the critical temperature, a gas can liquefy if the pressure is high enough.
- At the triple point, all three phases are in equilibrium.
- Evaporation occurs when the fastest moving molecules escape from the surface of a liquid.

Summary of Chapter 13

- Saturated vapor pressure occurs when the two phases are in equilibrium.
- Relative humidity is the ratio of the actual vapor pressure to the saturated vapor pressure.
- Diffusion is the process whereby the concentration of a substance becomes uniform.