Properties of Gases

Goal 1

Describe five macroscopic characteristics of gases.
Properties of Gases

- Gases may be compressed.

A fixed quantity of a gas may be made to occupy a smaller volume by applying pressure.
Properties of Gases

• Gases expand to fill their containers uniformly.

No matter the position of the piston, the gas fills the space.
Properties of Gases

• All gases have low density.
  The density of gaseous air is less than the density of liquid water, which is less than the density of solid iron.
Properties of Gases

• Gases may be mixed.
You can add a gas to a gas already occupying a rigid container of fixed volume.
Properties of Gases

- A confined gas exerts constant pressure on the walls of its container uniformly in all directions.

This is a unique property of a gas, independent of external forces.
Ideal Gas Model

Goal 2

Explain or predict physical phenomena relating to gases in terms of the ideal gas model.
Ideal Gas Model

- Gases consist of particles moving at any given instant in straight lines.
Ideal Gas Model

- Molecules collide with each other and with the container walls without loss of total kinetic energy. 
  \[ E_1 = E_2 = E_3 \]
Ideal Gas Model

- Gas molecules are very widely spaced.
Ideal Gas Model

• The actual volume of molecules is negligible compared to the space they occupy.
Ideal Gas Model

• Gas molecules behave as independent particles; attractive forces between them are negligible.

The large distances between gas particles ensure us that attractions between these molecules are negligible.
Ideal Gas Model

Summary of the Ideal Gas Model:

• Based on kinetic molecular theory (Chapter 2): All matter consists of molecules in constant motion.

• Identical particles

• Particles occupy negligible volume

• Particles exert negligible forces on one another
Gas Measurements

Goal 3

Given a gas pressure in atmospheres, torr, millimeters (or centimeters) of mercury, inches of mercury, pascals, kilopascals, bars, or pounds per square inch, express pressure in each of the other units.

Goal 4

Define pressure and interpret statements in which the term pressure is used.
Gas Measurements

By definition, pressure is the force exerted on a unit area:

\[
\text{Pressure} \equiv \frac{\text{force}}{\text{area}}
\]

\[
P \equiv \frac{F}{A}
\]
Gas Measurements

The Mercury Barometer

The atmospheric pressure, $P_a$, is equal to the pressure of the liquid mercury in the tube, $P_{\text{Hg}}$. 
Gas Measurements

Pressure Units

Barometer-Based

Millimeters of mercury, mm Hg
The height of a column of mercury in a barometer.

Torr, torr
Another name for a millimeter of mercury.

Atmosphere, atm
760 mm Hg
Gas Measurements

Pressure Units

Definition-Based, Metric System

Pascal, Pa
One newton (a unit of force) per square meter (area)
1 atm = $1.013 \times 10^5$ Pa

Kilopascal, kPa
1000 Pa

Bar, bar
1000 kPa
1 atm = 1.013 bar
Gas Measurements

Pressure Units

USCS System

Inch of mercury, in. Hg
(barometer-based)
The height of a column of mercury in a barometer.

Pounds per square inch, psi
(definition-based)
Gas Measurements

Open–End Manometer

Used to measure pressure in the laboratory.

\[ P_g = P_a + P_{Hg} \]
Gas Measurements

The total pressure in the closed leg is \( P_g + P_{Hg} \), which is equal to the atmospheric pressure, \( P_a \). Equating and solving for \( P_g \) yields \( P_g = P_a - P_{Hg} \).
Gas Measurements

Goal 5

Given a temperature in degrees Celsius, convert it to kelvins, and vice versa.
Gas Measurements

Gas temperatures are commonly measured in °C.

In pressure–volume–temperature problems, gas temperatures are expressed in absolute temperature.

**Kelvin (absolute) temperature scale**

The degree on the Kelvin scale is the same size as a Celsius degree, but the lowest temperature, –273°C, is set at zero on the Kelvin scale.

\[ T_K = T_C + 273 \]
Charles’s Law

Goal 6

Describe the relationship between the volume and temperature of a fixed quantity of an ideal gas at constant pressure, and express that relationship as a proportionality, an equation, and a graph.

Goal 7

Given the initial volume (or temperature) and the initial and final temperatures (or volumes) of a fixed quantity of gas at constant pressure,
Charles’s Law

**a**
- Thermometer
- Rubber band
- Capillary
- Mercury plug
- Height \( \propto V \)

**b**

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>50</td>
</tr>
<tr>
<td>75</td>
<td>22</td>
</tr>
<tr>
<td>69</td>
<td>0</td>
</tr>
<tr>
<td>66</td>
<td>-15</td>
</tr>
</tbody>
</table>

**c**

- Graph showing volume vs. temperature
- Volume \( \propto \) height
- Temperature range from -300 to 100 kelvins
- Temperature range from 0 to 300
Charles’s Law

All graphs of gas volume versus absolute temperature are straight lines that pass through the origin. This indicates that they are graphs of a direct proportionality:

\[ V \propto T \]

By inserting a proportionality constant, \( k \), the proportionality can be changed to an equation:

\[ V = k \times T \]
Charles’s Law

The volume ($V$) of a fixed quantity of gas at constant pressure is directly proportional to absolute temperature ($T$):

$$V \propto T$$
Charles’s Law

For a fixed quantity of gas at constant pressure,

\[ V \propto T \]

\[ V = k \times T \]

Divide both sides of the equation by \( T \):

\[ \frac{V}{T} = \frac{V_1}{T_1} = \frac{V_2}{T_2} = k = \frac{V_1}{T_1} \frac{V_2}{T_2} = k = \]
Charles’s Law

Applying Charles’s Law

A fixed quantity of gas in a flexible-walled container is cooled from 44°C to 21°C. If the initial volume of the container is 3.20 L, what is the final volume?

\[
\frac{V_1}{T_1} = \frac{V_2}{T_2}
\]

\[
V_2 = V_1 \times \frac{T_2}{T_1} = 3.20 \text{ L} \times \frac{21 + 273}{44 + 273} \text{ K} = 2.97 \text{ L}
\]
Charles’s Law

• The volume of a certain gas sample is 235 mL at a temperature of 25 °C. At what temperature would that same gas sample have a volume of 310. mL, if the pressure and mass of gas were held constant?
Boyle’s Law

Goal 8

Describe the relationship between the volume and pressure of a fixed quantity of an ideal gas at constant temperature, and express that relationship as a proportionality, an equation, and a graph.

Goal 9

Given the initial volume (or pressure) and initial and final pressures (or volumes) of a fixed quantity of gas at constant temperature, calculate the final volume (or pressure).
Boyle’s Law

Pressure–Volume Data

<table>
<thead>
<tr>
<th>Pressure (torr)</th>
<th>Volume (mL)</th>
<th>$P \times V$ (torr)(mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>12.6</td>
<td>$6.93 \times 10^3$</td>
</tr>
<tr>
<td>668</td>
<td>10.3</td>
<td>$6.88 \times 10^3$</td>
</tr>
<tr>
<td>753</td>
<td>9.19</td>
<td>$6.92 \times 10^3$</td>
</tr>
<tr>
<td>842</td>
<td>8.17</td>
<td>$6.88 \times 10^3$</td>
</tr>
<tr>
<td>917</td>
<td>7.46</td>
<td>$6.84 \times 10^3$</td>
</tr>
</tbody>
</table>

Diagram a: Gas chamber with movable and fixed legs, labeled with pressure readings.

Diagram b: Pressure–Volume data table.

Diagram c: Graph showing the relationship between pressure (torr) and volume (mL) with data points and a curve fitting the data.
Boyle’s Law

Graphs of gas pressure versus volume for a fixed quantity of gas at constant temperature indicate an inverse proportionality between the variables. This is verified when pressure (P) versus the inverse of volume (1/V) is graphed, yielding a direct proportionality:

\[ P \propto \frac{1}{V} \]
Boyle’s law

\[ P \propto \frac{1}{V} \]

\[ P = k \times \frac{1}{V} \]

Multiplying both sides of the equation by \( V \) yields:

\[ PV = k \]

\[ P_1 V_1 = k \quad P_2 V_2 = k \]

\[ P_1 V_1 = k = P_2 V_2 \]

For a fixed quantity of gas at constant temperature,

\[ P_1 V_1 = P_2 V_2 \]
Boyle’s Law

Applying Boyle’s Law

A fixed quantity of gas in a flexible-walled container is initially at 729 torr and a volume of 0.993 L. The temperature is kept constant as the volume of the container is reduced to 0.720 L. What is the resulting pressure at this volume?

\[
\frac{P_1 V_1}{V_2} = P_2
\]

\[
P_2 = P_1 \times \frac{V_1}{V_2} = 729 \text{ torr} \times \frac{0.993 \text{ L}}{0.720 \text{ L}} = 1.01 \times 10^3 \text{ torr}
\]
Boyle’s Law

• A sample of a certain gas has a volume of 222 mL at 695 mm Hg and 0 °C. What would be the volume of this same sample of gas if it were measured at 333 mm Hg and 0 °C?
The Combined Gas Law

Goal 10

For a fixed quantity of a confined gas, given the initial volume, pressure, and temperature and the final values of any two variables, calculate the final value of the third variable.

Goal 11

State the values associated with standard temperature and pressure (STP) for gases.
The Combined Gas Law

Charles’s Law: \[ V \propto T \]

Boyle’s Law: \[ P \propto \frac{1}{V} \]

Rearranging Boyle’s Law:

Combining the two proportionalities:

Inserting a proportionality constant:

\[ V = k \times \frac{P}{T} \times \frac{1}{PV} \]

\[ V = k \times T \times \frac{1}{P} \]
The Combined Gas Law

\[
\frac{PV}{T} = k
\]

\[
\frac{P_1 V_1}{T_1} = k = \frac{P_2 V_2}{T_2}
\]

This is the Combined Gas Law:
The Combined Gas Law

Standard Temperature and Pressure (STP) for gases:

0°C (273 K) and 1 atm

To two significant figures, 1.0 bar = 1.0 atm,

so STP is also 0°C and 1 bar
if measured quantities are limited
The Combined Gas Law

Applying the Combined Gas Law

What is the STP volume of a sample of argon gas which had an initial volume of 729 mL when at 44°C and 881 mm Hg?

\[
\frac{P_1}{T_1} \cdot \frac{V_1}{T_1} = \frac{P_2}{T_2} \cdot \frac{V_2}{T_2}
\]

Cross multiplying, \( P_1 V_1 T_2 = P_2 V_2 T_1 \)

\[
\frac{760 \text{ mm Hg}}{881 \text{ mm Hg}} = \frac{(0 + 273) \text{ K}}{(44 + 273) \text{ K}}
\]

\( V_2 = V_1 \times \frac{P_1}{P_2} \times \frac{T_2}{T_1} \)

\( V_2 = 729 \text{ mL} \times \frac{760}{881} \times \frac{667}{44} \)

\( V_2 = 728 \text{ mL} \)

Check: Pressure down, volume up, pressure fraction > 1, OK.
Combined Gas Law

• A gas at 25 °C in a 10.0 L tank has a pressure of 1.00 atm. The gas is transferred to a 20.0 L tank at 0 °C. What is the pressure of the gas after transfer?
The Combined Gas Law

The Combined Gas Law can be used to derive Boyle’s and Charles’s Laws

\[ \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \]

If \( T \) is constant, \( T_1 = T_2 \), so if you multiply each side by \( T \):

\[ P_1V_1 = P_2V_2 \quad \text{(constant } T) \text{Boyle’s Law} \]

\[ \frac{V_1}{T_1}P \text{ is constant, } P_1 = P_2, \text{ so if you divide each side} \]

\[ \frac{V_1}{T_1} = \frac{V_2}{T_2} \]