9 States of Matter

At the top of Mount Everest water boils near $70\,^{\circ}\mathrm{C}$. The water is the same; the air pressing down on it is about a third of what it is at sea level. A boiling point is not a property of the liquid alone, and neither is the volume of a gas. This chapter is about how particles respond to pressure and temperature, and about the attractions between them that decide which state you get. The mock exam gives this chapter 6 of its 70 questions.

9.1 Pressure and the Gas Laws

Pressure
Force per unit area. In a gas it comes from particles striking the walls.

A gas is a collection of particles far apart and moving fast. They fill whatever container they are in, and each time one strikes the wall it pushes on it. **Pressure** is the sum of those pushes spread over the wall's area. The more strikes per second, and the harder each strike, the greater the pressure.

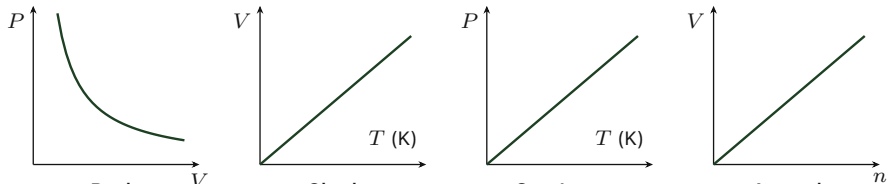
Four quantities describe a gas sample: pressure P, volume V, amount n in moles, and temperature T. Temperature must be in kelvin, $T = t_{^{\circ}\mathrm{C}} + 273.15$. The laws below are proportions, and a proportion only works from a true zero. A gas at $0\,^{\circ}\mathrm{C}$ still has plenty of motion, so doubling $0\,^{\circ}\mathrm{C}$ means nothing.

atm	mmHg or torr	kPa	bar
1	760	101.325	1.01325

Each gas law holds two of the four quantities fixed and shows how the other two move together. The reason is the same picture every time.

- **Boyle's law** (n, T fixed): PV is constant. Squeeze the same particles into half the volume and they strike the wall twice as often, so P doubles.
- **Charles's law** (n, P fixed): V/T is constant. Hotter particles hit harder, so the volume has to grow to keep the pressure the same.
- **Gay-Lussac's law** (n, V fixed): P/T is constant. Hotter particles in a rigid container hit harder and more often.
- **Avogadro's law** (P, T fixed): V/n is constant. More particles at the same pressure need more room. Equal volumes of any gases at the same T and P hold equal numbers of particles.

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Boyle PV constant, n, T fixed

Charles V/T constant, n, P fixed

Gay-Lussac P/T constant, n, V fixed

Avogadro V/n constant, P, T fixed

Most exam questions change two or three variables at once. Combine the laws for a fixed amount of gas:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Pressure and volume may stay in any matching units, because the units cancel in the ratio. Temperature may not. It is always kelvin.

Combined gas law
Use it when the same amount of gas goes from one set of conditions to another.

RULE Convert every temperature to kelvin before you touch a gas law.

EXAMPLE 9.1

A gas occupies $6.20\,\mathrm{L}$ at $745\,\mathrm{mmHg}$ and $18\,^\circ\mathrm{C}$. What volume does it occupy at $0\,^\circ\mathrm{C}$ and $1.00\,\mathrm{atm}$?

What is asked A new volume. The amount of gas does not change.

Convert $T_1 = 18 + 273.15 = 291.15$ K and $T_2 = 273.15$ K. Pressures: $745\,\mathrm{mmHg}$ and 1.00 atm $= 760\,\mathrm{mmHg}$.

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

Substitute $$V_2 = 6.20\,\mathrm{L} \times \frac{745}{760} \times \frac{273.15}{291.15} = 5.70\,\mathrm{L}$$

Check Pressure rose slightly, which shrinks the volume. Temperature fell, which shrinks it again. A smaller answer is right.

Answer **5.70 L**

9.2 The Ideal Gas Law

Put Boyle, Charles and Avogadro together and one equation covers all four variables. A gas that follows it exactly is an **ideal gas**.

$$PV = nRT$$

With $R = 0.082\,06\,\mathrm{L\,atm/(mol\,K)}$, pressure goes in atm, volume in L, and temperature in K. Convert before you substitute. At $0\,^\circ\mathrm{C}$ and $1\,\mathrm{atm}$ (**STP**, standard temperature and pressure) one mole of an ideal gas occupies

$$V = \frac{nRT}{P} = \frac{(1)(0.08206)(273.15)}{1} = 22.41\,\mathrm{L}.$$

Use $22.41\,\mathrm{L/mol}$ only when the stem says STP or gives exactly these conditions. At room temperature a mole takes about $24.5\,\mathrm{L}$.

Gas constant
$R = 0.082\,06\,\mathrm{L\,atm/(mol\,K)} = 8.314\,\mathrm{J/(mol\,K)}$. Pick the value whose units match your P and V.

Three slips cause most wrong answers with this equation.

– Leaving the temperature in $^\circ\mathrm{C}$. T is always kelvin.

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– Pairing the wrong R with the units. $R = 0.082\,06\ \mathrm{L\,atm/(mol\,K)}$ needs pressure in atm, so convert mmHg or kPa first.
– Using $22.41\ \mathrm{L/mol}$ away from STP. A warmer gas takes more room per mole.

Density and molar mass

The number of moles is mass over molar mass, $n = m/M$. Put that into $PV = nRT$ and divide by V:

$$d = \frac{PM}{RT} \qquad \text{or} \qquad M = \frac{dRT}{P}$$

The reason a gas's density depends on conditions is that the same mass spreads over more volume when it is hotter or at lower pressure. At the same T and P, the gas with the larger molar mass is the denser one. Measure a gas's density at a known T and P and this equation gives its molar mass.

Density
Mass per unit volume. For a gas it is usually g/L.

EXAMPLE 9.2

A gas has a density of $2.59\ \mathrm{g/L}$ at $0.940\ \mathrm{atm}$ and $40\ ^\circ\mathrm{C}$. What is its molar mass?

What is asked Molar mass in g/mol, from density, P and T.

Convert $T = 40 + 273.15 = 313.15$ K.

Choose $M = dRT/P$. Density already contains the mass and the volume.

Substitute
$$M = \frac{(2.59)(0.08206)(313.15)}{0.940} = 70.8\ \mathrm{g/mol}$$

Check Density in g/L times RT/P in L/mol gives g/mol. The value is close to Cl_2, $70.90\ \mathrm{g/mol}$.

Answer **70.8 g/mol**

Gas stoichiometry

The balanced equation talks in moles, never in liters or grams. So a gas problem is a mole problem with one extra step at the start or the end. Convert whatever you are given into moles of that substance, cross the equation with the mole ratio, then turn moles of the gas you want into volume with $PV = nRT$ at the conditions the stem gives. Do not use $22.41\ \mathrm{L/mol}$ unless the gas is at STP.

Mole ratio
The ratio of coefficients in the balanced equation. It is the only bridge between substances.

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PRACTICE SET 9A 12 questions · 18 minutes · calculator

1. A barometer reads $735\,\text{mmHg}$. What is this pressure in kPa?

(A) $98.0\,\text{kPa}$ **(B)** $0.967\,\text{kPa}$
(C) $5.51 \times 10^{3}\,\text{kPa}$ **(D)** $7.45 \times 10^{4}\,\text{kPa}$

2. A gas at $2.40\,\text{atm}$ occupies $5.00\,\text{L}$. The pressure is lowered to $1.50\,\text{atm}$ at constant temperature. What is the new volume?

(A) $3.13\,\text{L}$ **(B)** $5.00\,\text{L}$
(C) $7.50\,\text{L}$ **(D)** $8.00\,\text{L}$

3. A $4.00\,\text{L}$ sample of gas at $27\,^{\circ}\text{C}$ is heated to $127\,^{\circ}\text{C}$ at constant pressure. What is the final volume?

(A) $3.00\,\text{L}$ **(B)** $5.33\,\text{L}$
(C) $18.8\,\text{L}$ **(D)** $59.3\,\text{L}$

4. A rigid can of gas at $80\,^{\circ}\text{C}$ has a pressure of $2.00\,\text{atm}$. It is cooled to $20\,^{\circ}\text{C}$. What is the final pressure?

(A) $1.66\,\text{atm}$ **(B)** $2.00\,\text{atm}$
(C) $2.41\,\text{atm}$ **(D)** $8.00\,\text{atm}$

5. What volume do $12.0\,\text{g}$ of CH_4 occupy at STP? Take STP as $0\,^{\circ}\text{C}$ and $1\,\text{atm}$, where one mole of gas occupies $22.41\,\text{L}$.

(A) $269\,\text{L}$ **(B)** $18.3\,\text{L}$
(C) $16.8\,\text{L}$ **(D)** $0.536\,\text{L}$

6. At constant temperature and pressure, $6.0\,\text{L}$ of H_2 react completely with excess N_2: $\text{N}_2 + 3\,\text{H}_2 \longrightarrow 2\,\text{NH}_3$. What volume of NH_3 forms?

(A) $2.0\,\text{L}$ **(B)** $6.0\,\text{L}$
(C) $9.0\,\text{L}$ **(D)** $4.0\,\text{L}$

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