States of matter

The origin of gas pressure, ideal and real gases and pV = nRT, and giant ionic, molecular, covalent and metallic structures with their physical properties.

4.1 The gaseous state: ideal and real gases and pV = nRT

Gas pressure comes from the **collisions of gas molecules with the walls** of the container. Each collision exerts a force, and many collisions every second give a steady pressure.

An **ideal gas** has particles of **zero volume** and **no intermolecular forces**. It obeys

$$pV = nRT$$

with p in Pa, V in m³, T in K and $R = 8.31$ J K⁻¹ mol⁻¹. (1 dm³ = 10^{-3} m³ and 1 kPa = 10^{3} Pa.) With $n = m/M_r$ it gives $M_r = \dfrac{mRT}{pV}$.

> **TRY IT**
>
> 0.250 g of a gas occupies 100 cm³ at 300 K and 101 kPa. Find M_r.

$$M_r = \frac{0.250 \times 8.31 \times 300}{101\,000 \times 1.00 \times 10^{-4}} = 61.7.$$

Real gases deviate from ideal behaviour at **high pressure** (the volume of the particles is no longer negligible) and at **low temperature** (intermolecular forces matter). They are closest to ideal at **low pressure and high temperature**.

Explaining the gas laws with particles

At constant volume, warming a gas increases the mean kinetic energy of its molecules. They strike the walls more frequently and transfer more momentum in each collision, increasing pressure. At constant temperature, compressing the same gas increases the number of particles per unit volume, so wall collisions become more frequent. The temperature has not changed, so do not claim the molecules have become faster merely because the pressure rose.

The ideal-gas model assumes negligible particle volume, negligible attractions between particles and elastic collisions. Molecules move continually in random directions. Their mean kinetic energy depends on absolute temperature, so 0 °C does **not** mean zero kinetic energy. Use $T/\mathrm{K} = \theta/^{\circ}\mathrm{C} + 273$ for syllabus calculations.

At low temperature, attractive forces have a greater influence relative to kinetic energy; real gases may eventually condense. At high pressure, the molecules occupy an appreciable fraction of the container

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volume. These are different reasons for non-ideal behaviour. Explaining both is more precise than stating that "the particles collide more".

Units and rearrangements of pV = nRT

Choose one consistent set of units before substituting. With $R = 8.31$ J K^{-1} mol^{-1}, pressure is Pa and volume is m³. The useful conversions are $1\ \text{cm}^3 = 10^{-6}\ \text{m}^3$ and $1\ \text{dm}^3 = 10^{-3}\ \text{m}^3$. A volume of 250 cm³ is 2.50×10^{-4} m³, not 0.250 m³. Write the conversion explicitly rather than hiding it in a calculator entry.

Worked example: find the volume of 0.0200 mol gas at 27 °C and 100 kPa. First $T = 300$ K and $p = 1.00 \times 10^5$ Pa. Then $V = nRT/p = 0.0200(8.31)(300)/(1.00 \times 10^5) = 4.99 \times 10^{-4}$ m³, or **499 cm³**. This is close to the room-temperature molar-volume estimate, providing a useful scale check.

For a fixed quantity of ideal gas, pV/T is constant. Thus $p_1V_1/T_1 = p_2V_2/T_2$ compares two states without knowing the number of moles. This relationship assumes no gas has escaped or reacted. If mass and density are supplied, combining $pV = nRT$ with $n = m/M$ and $\rho = m/V$ gives $M = \rho RT/p$, provided mass units are consistent.

> **TRY IT**
>
> A sealed rigid container holds gas at 100 kPa and 300 K. What is its pressure at 360 K? State one assumption.

Answer: $p_2 = 100(360/300) = 120$ kPa. Assume fixed gas amount and volume and approximately ideal behaviour. Do not use temperatures in Celsius in the ratio.

> **TRY IT**
>
> 0.440 g of a gas occupies 250 cm³ at 300 K and 100 kPa. Find its molar mass.

Answer: $n = pV/RT = (100000)(2.50 \times 10^{-4})/(8.31 \times 300) = 0.0100$ mol approximately. $M = 0.440/n = 43.9$ g mol^{-1}. Use the unrounded mole value for the final calculation.

4.2 Bonding and structure

Structure	Particles and forces	Examples
Giant ionic	Ions held in a lattice by strong electrostatic attraction	NaCl, MgO
Simple molecular	Molecules held by weak intermolecular forces	I_2, ice, C_{60}
Giant molecular	Atoms joined by covalent bonds in a network	SiO_2, diamond, graphite
Giant metallic	Metal ions in a sea of delocalised electrons	Cu

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Properties

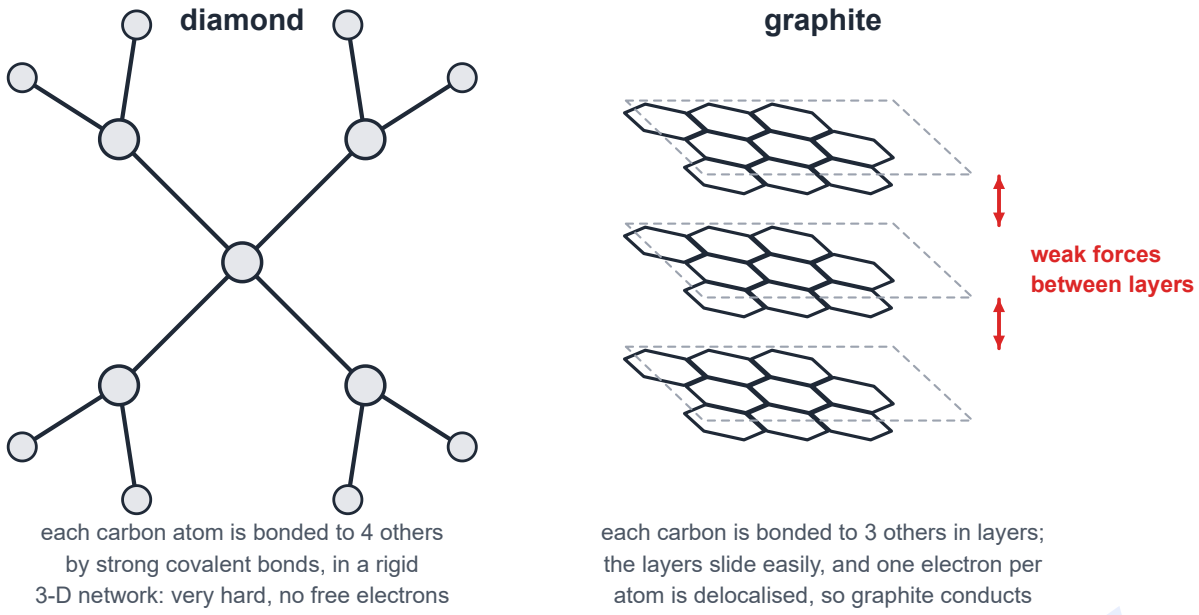
- **Giant ionic:** high melting and boiling points, hard but brittle. They do not conduct when solid (the ions are fixed) but conduct when **molten or in solution**. Many dissolve in water.
- **Simple molecular:** low melting and boiling points, because only weak forces are overcome. They do not conduct and tend to dissolve in non-polar solvents. I_2 is a dark solid that sublimes. Ice is an open hydrogen-bonded lattice. C_{60} (buckminsterfullerene) is a molecular cage of 60 carbon atoms.
- **Giant molecular:** very high melting points. In **diamond** each C is bonded to four others (tetrahedral); it is very hard and, with no free electrons, an insulator. In **graphite** there are layers of hexagonal rings with each C bonded to three others and delocalised electrons between the layers, so it **conducts**, and the layers slide because the forces between them are weak. In SiO_2 each Si is bonded to four O; it is hard, has a high melting point and is an insulator.
- **Giant metallic:** conducts when solid and molten (mobile electrons), is malleable and ductile (layers of ions slide while the electron sea holds them), and has a high melting point.

To deduce a structure from data: low melting point and non-conducting means simple molecular; high melting point that conducts only when molten means giant ionic; high melting point that conducts when solid means metallic (or graphite); very high melting point and no conductivity means giant molecular.

Structure–property explanations that earn the marks

Separate three questions: what are the particles, what holds them together, and what changes during the process? Melting an ionic solid overcomes attractions between ions; melting a molecular solid mainly overcomes attractions **between molecules**. The covalent bonds inside those molecules normally survive. A substance with strong covalent bonds can therefore have a low boiling point if it consists of small, weakly attracting molecules.

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Graphite's delocalised electrons move mainly **along its layers**; they are not simply a pool between layers. Each carbon contributes an electron to the delocalised system after making three sigma bonds. The weaker interlayer attractions allow layers to slide. Diamond has four covalent bonds per carbon in a three-dimensional network, giving hardness and no comparable mobile-electron system.

In silicon dioxide, each silicon bonds to four oxygens and each oxygen to two silicons; this sharing gives the overall formula SiO_2. There are no separate SiO_2 molecules in the giant network. In C_{60}, by contrast, strong bonds hold each cage together but weaker forces act between cages. A molecular cage and a giant covalent network are different structural categories even though both contain covalent bonds.

Interpreting unfamiliar evidence

Worked example: solid X melts at a high temperature, does not conduct as a solid, and conducts when molten. The combination supports an ionic lattice: ions are fixed in the solid and mobile in the melt. Conductivity alone does not identify a particular formula, and a high melting point alone would not distinguish ionic, metallic and giant covalent structures.

Solubility is supporting evidence, not an absolute rule. Some ionic compounds are sparingly soluble in water; some molecular compounds dissolve because they form favourable interactions with the solvent. Avoid writing that every ionic compound dissolves or every molecular compound is insoluble.

> **TRY IT**
>
> Two substances conduct when solid. One is malleable; the other is brittle and has a layered structure. Suggest their structural types and explain the charge carriers.

Answer: The malleable material is consistent with a metal; the layered brittle material may be graphite. Both conduct through mobile delocalised electrons. The observations do not support describing either as

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a solid ionic conductor.

Chapter check: use gas laws with absolute temperatures and consistent units. For solids, distinguish particles, bonds and mobile charge carriers. Link numerical work to **stoichiometry** and property explanations to **chemical bonding**.

References and further reading

Scope follows section 4 of the **Cambridge 9701 syllabus for 2025–2027**. **Chemguide's Cambridge topic index** links to alternative explanations. The worked exercises and added diagrams are original teaching examples; numerical examples are illustrative unless a specific source is identified.

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