

ESAT

Physics

Matter

Free lesson notes

Covers	P5.1 to P5.5
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

Everything around you is made of tiny particles, and almost every property of matter (whether it is hard or runny, light or heavy, whether it pushes on its container) can be explained by how those particles are arranged, how fast they move and how strongly they pull on each other. This topic is a favourite for ESAT because it combines a few short definitions (density, pressure, latent heat) with careful reasoning about units and scaling, and every calculation can be done without a calculator if you set it out calmly.

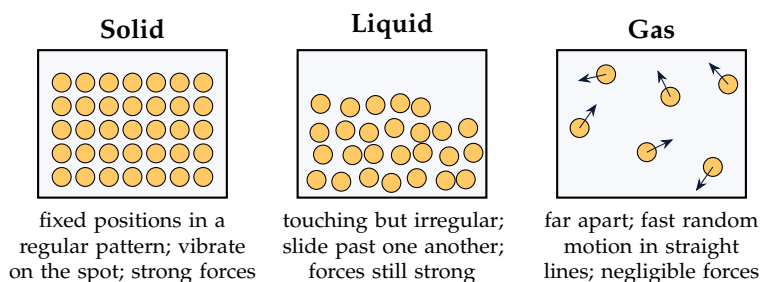
This lesson starts with the particle model of solids, liquids and gases. We then define *density* from scratch and show three experiments for measuring it, define *pressure* and *derive* the formula for pressure in a liquid, explain gas pressure with moving particles and use it to understand why PV is constant at fixed temperature, and finally explain changes of state, internal energy and specific latent heat, including how to combine latent heat with specific heat capacity. Throughout, we use $g = 10 \text{ N/kg}$ and friendly numbers, as in the exam. Specification codes: P5.1 (states and particle models), P5.2 (ideal gas), P5.3 (changes of state and latent heat), P5.4 (density) and P5.5 (pressure).

How to use it. Read each idea, cover the worked example and try it first, and draw a picture for every problem. Finish with the self-check and the practice set.

Heurisco is an independent practice provider and is not affiliated with, endorsed by, or connected to UAT-UK, Pearson VUE, the UCAT Consortium, or any university. All questions are original.

1 States of matter and the particle model

Matter is made of particles. All matter is made of tiny particles (atoms, molecules or ions) that are always in motion and that attract each other when close. A **model** is a simplified picture that explains observations; in the *particle model* we picture each particle as a small sphere. The three common states of matter differ in three things: how the particles are *arranged*, how they *move*, and how strong the *forces* between them are.



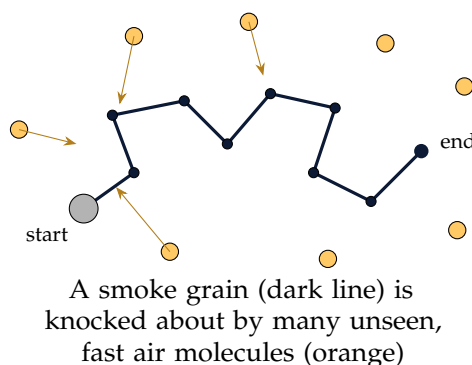
	Solid	Liquid	Gas
Arrangement	regular pattern, touching	irregular, touching	far apart, random
Movement	vibrate about fixed positions	move around, sliding past each other	rapid random motion, straight lines between collisions
Forces	strong	fairly strong	almost none
Shape and volume	fixed shape, fixed volume	takes the shape of container, fixed volume	fills container, no fixed shape or volume
Compressible?	no	hardly	easily

Reading the table. A solid keeps its shape because the strong forces hold every particle in place; it can still be warmed, which makes the particles vibrate more vigorously. A liquid flows because the particles have enough energy to slide past one another, yet they stay in contact, so its *volume* is fixed and it is almost impossible to squash. In a gas the particles are

so far apart (typically about ten particle diameters) that the forces between them are negligible; they travel in straight lines until they collide with each other or a wall. Since there is so much empty space, a gas can be compressed easily.

Why are gases so much less dense than solids? The particles are the same sort of size in all three states, but in a gas they are roughly ten times further apart in each direction, so about a thousand times fewer of them fit in the same volume. That is why a litre of liquid water becomes about 1700 litres of steam.

Evidence: Brownian motion. If you watch smoke particles in air through a microscope you see them jiggle in random zig-zags. The smoke grains are large enough to see, but the air molecules hitting them are not. More molecules happen to hit one side of the grain than the other at any instant, so the grain is pushed in a changing, random direction. This is direct evidence that air molecules exist, move quickly and move randomly.



Worked example: which state is it?

A substance has a fixed volume but takes the shape of its container, and a drop of dye spreads slowly through it. Which state is it, and why does the dye spread?

A fixed volume but variable shape means a **liquid**. The dye spreads because the liquid particles are constantly moving and sliding, so dye particles are carried into the gaps (diffusion). It is slow because the particles are tightly packed and keep colliding.

Common mistakes

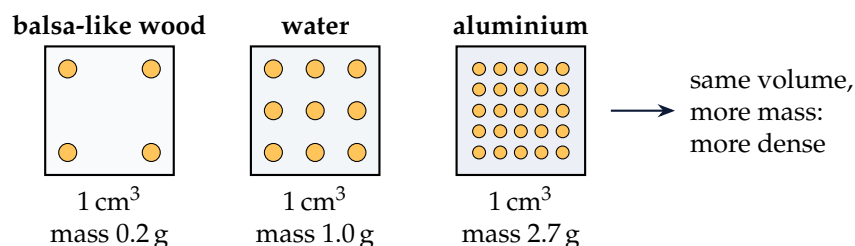
- Drawing the particles in a solid as not moving. They vibrate; they just do not change places.
- Saying particles themselves expand when heated. The particles are the same size; they move faster and (in a gas) further apart.
- Saying there is air between the particles of a gas. There is *nothing* (a vacuum) between them.
- Thinking a liquid has no forces between its particles. The forces are strong; they are just not strong enough to lock the particles in place.

2 Density

The idea. A bucket of iron nails feels much heavier than a bucket of the same size filled with polystyrene beads. We cannot compare masses fairly unless the volumes are the same, so we compare the *mass of one unit of volume*. This quantity is the **density**:

$$\rho = \frac{m}{V} \quad \text{so} \quad m = \rho V \quad \text{and} \quad V = \frac{m}{\rho}.$$

Here ρ (the Greek letter rho) is the density, m the mass and V the volume. The SI unit is kilograms per cubic metre, kg/m^3 . Because a cubic metre is huge, densities are often quoted in g/cm^3 .



Converting between g/cm^3 and kg/m^3 . One cubic metre is $100 \times 100 \times 100 = 10^6 \text{ cm}^3$, and one kilogram is 1000 grams. So $1 \text{ g/cm}^3 = \frac{1 \text{ g}}{1 \text{ cm}^3} = \frac{10^{-3} \text{ kg}}{10^{-6} \text{ m}^3} = 1000 \text{ kg/m}^3$. To go from g/cm^3 to kg/m^3 multiply by 1000. Water is 1.0 g/cm^3 , which is 1000 kg/m^3 : a litre of water ($= 1000 \text{ cm}^3$) has a mass of 1 kg.

material	$\rho \text{ (kg/m}^3\text{)}$	material	$\rho \text{ (kg/m}^3\text{)}$
air (room)	1.2	aluminium	2700
cork	250	iron	7900
ice	920	lead	11 300
water	1000	gold	19 300

Why are solids and liquids of similar density but gases not? In a solid or liquid the particles touch, so a given volume holds roughly the same number of particles; the density then depends mostly on how heavy each atom is (lead atoms are heavy, aluminium atoms light). Gas particles are far apart, so a gas has far fewer particles per cubic metre and a density about a thousand times smaller.

Floating and sinking. A solid object floats in a liquid if it is less dense than the liquid, and sinks if it is more dense. Ice (920 kg/m^3) floats on water (1000 kg/m^3) with most of its volume below the surface; oil (about 800 kg/m^3) floats on water.

Worked example: finding a density

A metal block has a mass of 540 g and a volume of 200 cm^3 . Find its density in g/cm^3 and in kg/m^3 . Could it be aluminium?

$$\rho = \frac{m}{V} = \frac{540}{200} = 2.7 \text{ g/cm}^3 = 2700 \text{ kg/m}^3, \text{ which matches aluminium.}$$

Worked example: using $m = \rho V$

A rectangular tank is $2 \text{ m} \times 1.5 \text{ m} \times 1 \text{ m}$ and is filled with petrol of density 700 kg/m^3 . What is the mass of petrol? $V = 2 \times 1.5 \times 1 = 3 \text{ m}^3$, so $m = \rho V = 700 \times 3 = 2100 \text{ kg}$.

Worked example: a mixture

100 cm^3 of liquid A (1.2 g/cm^3) is mixed with 300 cm^3 of liquid B (0.8 g/cm^3). Assuming the volumes simply add, find the density of the mixture. Never average the densities: always add the *masses* and the *volumes*. $m_A = 1.2 \times 100 = 120 \text{ g}$, $m_B = 0.8 \times 300 = 240 \text{ g}$. Total mass 360 g, total volume 400 cm^3 , so $\rho = \frac{360}{400} = 0.9 \text{ g/cm}^3$ (closer to B because there is more of B).

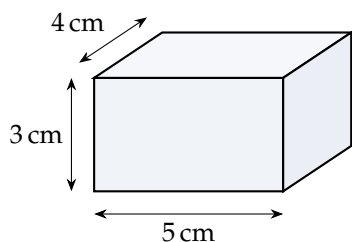
Common mistakes

- Using g with m^3 or kg with cm^3 . Convert *both* mass and volume to a matching pair of units first.
- Thinking 1 m^3 is 100 cm^3 . It is $100^3 = 10^6 \text{ cm}^3$.
- Averaging two densities for a mixture instead of adding masses and volumes.
- Believing heavy objects always sink. An object sinks if its *density* exceeds the liquid's, which is why a steel ship, hollow and full of air, floats.

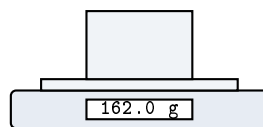
3 Measuring density

To find $\rho = m/V$ we need the mass and the volume of the sample; the mass always comes from a balance, and the method for the volume depends on the shape.

Regular solid. Measure the length, width and height with a ruler (or a micrometer for a small object) and calculate $V = l \times w \times h$ (or $\pi r^2 h$ for a cylinder). Find the mass on a balance. In the figure, $V = 5 \times 4 \times 3 = 60 \text{ cm}^3$ and $m = 162 \text{ g}$, so $\rho = 162/60 = 2.7 \text{ g/cm}^3$.

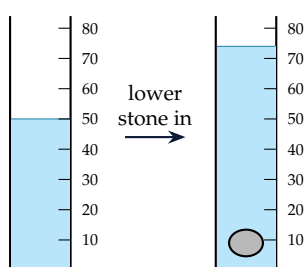


measure length, width and height
with a ruler: $V = l \times w \times h$



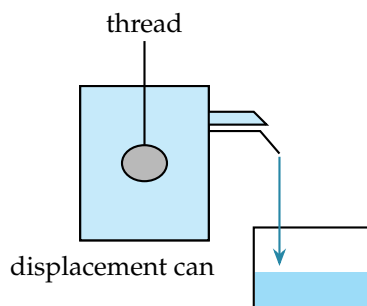
mass from a balance

Irregular solid (displacement). A stone has no formula for its volume, but when it is fully submerged it pushes aside a volume of water exactly equal to its own. Either read the water level in a measuring cylinder before and after lowering the stone in on a thread (the rise is the volume), or use a *displacement (eureka) can* filled to the spout and collect the overflow in a measuring cylinder. The method needs the stone to sink (use a sinker for a floating object) and not to absorb water.



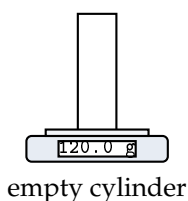
water: 50 cm^3 with stone: 74 cm^3

volume of stone
 $= 74 - 50 = 24 \text{ cm}^3$
(use a thread to
lower the stone gently)

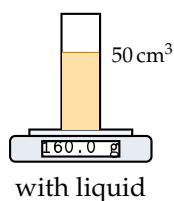


overflow collects in a
beaker: its volume is the
volume of the stone

Liquid. Put an empty measuring cylinder on the balance and note its mass (or press “tare” to zero the balance). Add the liquid, read the volume at the bottom of the curved surface (the *meniscus*) with your eye level with it, and read the new mass. The mass of liquid is the *difference*.



empty cylinder



with liquid

mass of liquid $= 160 - 120 = 40 \text{ g}$
density $= \frac{40}{50} = 0.8 \text{ g/cm}^3$

Reducing error. Read the scale at eye level (to avoid parallax), repeat the measurements and average, use a large enough sample for the volume reading to be a decent fraction of the scale, and make sure the object is dry when weighed.

Worked example: a pebble

A pebble of mass 65 g raises the water level in a measuring cylinder from 40 cm^3 to 65 cm^3 . Find its density and decide whether it would float on water.

$V = 65 - 40 = 25 \text{ cm}^3$, so $\rho = \frac{65}{25} = 2.6 \text{ g/cm}^3$. This is more than 1.0 g/cm^3 , so it sinks.

Common mistakes

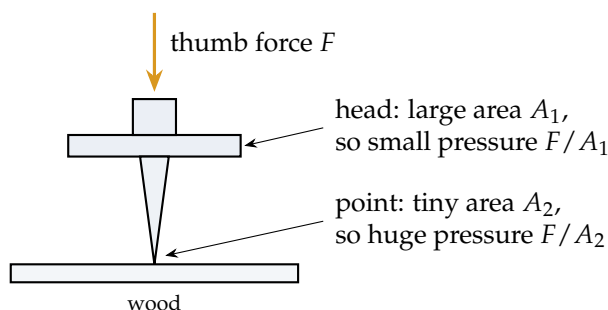
- Subtracting the wrong way, or using the final reading as the volume of the stone. It is the *change* in reading.
- Forgetting to subtract the mass of the container when finding the mass of a liquid.
- Using a floating object in the displacement method without a sinker. It displaces only the volume that is submerged.

4 Pressure

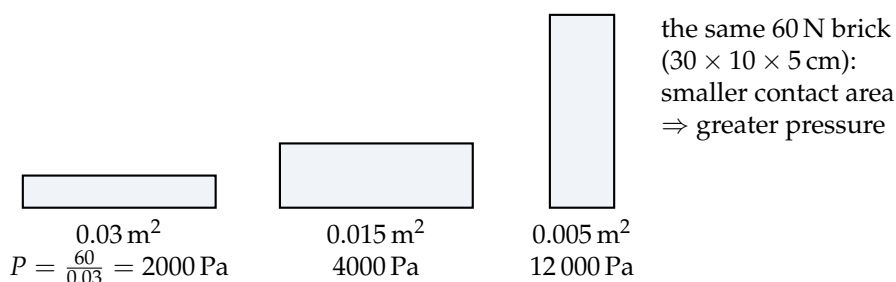
The idea. A force pushing on a surface has a different effect depending on how much area it is spread over. A person on skis does not sink into snow but the same person in walking boots does; a sharp knife cuts but a blunt one does not, with the same push. The quantity that measures this is the **pressure**: the force acting *at right angles* to a surface per unit area of the surface.

$$P = \frac{F}{A} \quad \text{so} \quad F = PA \quad \text{and} \quad A = \frac{F}{P}.$$

The SI unit is the pascal: $1 \text{ Pa} = 1 \text{ N/m}^2$. One pascal is a tiny pressure (about the pressure of a sheet of paper lying on a table), so kPa and MPa are common.



Doing the sums. Always convert areas to square metres. Remember that $1 \text{ m}^2 = 10^4 \text{ cm}^2$ (since 100×100), so 50 cm^2 is 0.005 m^2 . The pressure goes up when the force goes up, or when the area goes down. Halve the area and you double the pressure.



Everyday uses. To *reduce* pressure we spread the force: skis, snowshoes, caterpillar tracks, wide tractor tyres, a broad base on a building. To *increase* pressure we shrink the area: nails, needles, knife edges, high-heeled shoes (a 600 N person on one stiletto heel of area 1 cm^2 gives $600/10^{-4} = 6 \times 10^6 \text{ Pa}$, far more than the pressure of an elephant's foot).

Worked example: pressure from a person

A person of mass 60 kg stands on two shoes each of area 150 cm^2 . Find the pressure on the ground. ($g = 10 \text{ N/kg}$)
 Force = $W = mg = 60 \times 10 = 600 \text{ N}$. Total area = $2 \times 150 = 300 \text{ cm}^2 = 0.03 \text{ m}^2$. $P = \frac{600}{0.03} = 20000 \text{ Pa}$. On one foot the area halves and the pressure doubles to 40000 Pa .

Worked example: force from a pressure

The atmosphere exerts a pressure of about $1.0 \times 10^5 \text{ Pa}$. What force does it exert on a window of area 0.5 m^2 ? Why does the window not break?

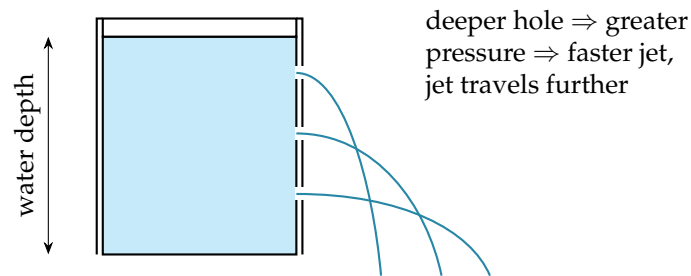
$F = PA = 10^5 \times 0.5 = 50\,000\text{ N}$. The window is not crushed because air on the *other* side pushes the opposite way with an equal force, so the resultant force is nearly zero.

Common mistakes

- Using area in cm^2 with force in newtons and calling the answer pascals. Convert to m^2 .
- Using the *mass* instead of the weight as the force. Multiply by g first.
- Using a wrong face of the object: the area is the area in *contact* with the surface.

5 Pressure in liquids and the atmosphere

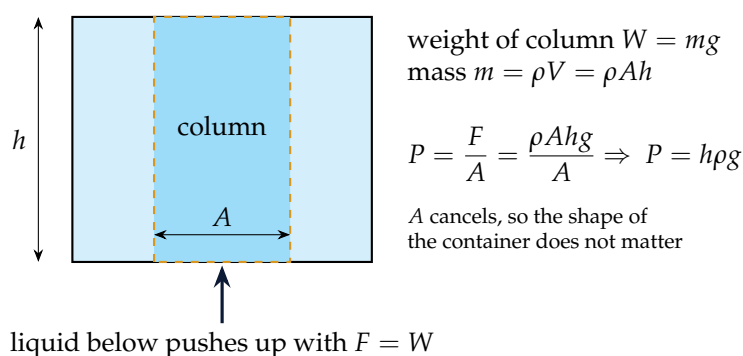
What a liquid does. The particles of a liquid are in constant motion and collide with the walls and with any object in the liquid. A liquid at rest pushes on every surface in contact with it, at right angles to that surface, and the pressure at one point is the same in every direction. We also observe that pressure *increases with depth*: the deeper you dive, the more it squeezes your ears, and a hole near the bottom of a bottle squirts water much further than a hole near the top.



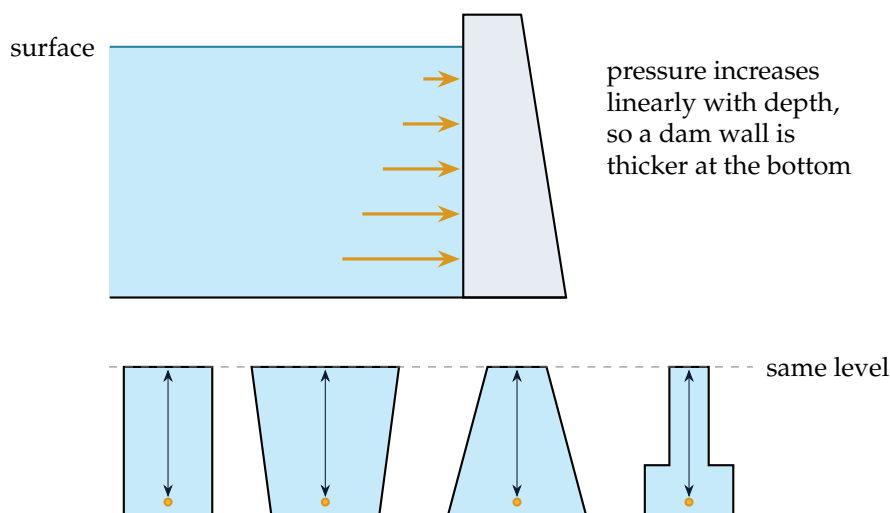
Deriving the formula. Why does depth matter? At depth h in a liquid of density ρ , imagine a vertical column of liquid of cross-section area A reaching up to the surface. The volume of the column is $V = Ah$, so its mass is $m = \rho V = \rho Ah$, and its weight is $W = mg = \rho Ahg$. The liquid below must hold this column up, so it pushes upwards on the base of the column with force $F = W$. The pressure at the base is therefore

$$P = \frac{F}{A} = \frac{\rho Ahg}{A} = h\rho g.$$

The area cancels. So the pressure due to a liquid depends only on the *depth* h , the *density* ρ and the field strength g .



Consequences. (1) Pressure is proportional to depth: twice as deep, twice the pressure, so dam walls are thicker at the bottom. (2) Pressure depends on the *vertical* depth, not on the width, shape or total amount of liquid: all the points at the same depth below the surface in the same liquid are at the same pressure, whatever the container. (3) A denser liquid gives a greater pressure at the same depth.



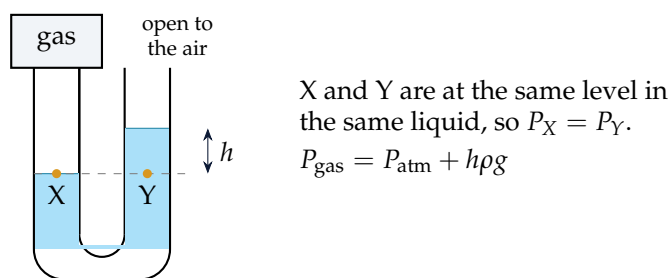
same liquid, same depth $h \Rightarrow$ same pressure $P = h\rho g$ at the dots (the amount of liquid does not matter)

Atmospheric pressure. We live at the bottom of an ocean of air, whose weight presses on everything. At sea level the atmospheric pressure is about $P_{\text{atm}} = 1.0 \times 10^5 \text{ Pa}$. (Air has thinned out by the time you reach a mountain top, so P_{atm} is smaller there: the column of air above you is shorter.) At depth h under water, the total pressure is the atmosphere pressing on the surface *plus* that due to the water:

$$P_{\text{total}} = P_{\text{atm}} + h\rho g.$$

Ten metres of water give $10 \times 1000 \times 10 = 10^5 \text{ Pa}$, which is a whole extra atmosphere. So every ten metres of depth in water adds about one atmosphere.

The U-tube (manometer). A U-tube partly filled with liquid is used to compare pressures. If both arms are open to the air the liquid surfaces are level. Connect one arm to a gas supply and the liquid is pushed down on that side. The key rule: two points *at the same level in the same liquid* that are connected by the liquid are at the same pressure. In the figure, point X (level with the surface in the left arm) has pressure equal to the gas pressure; point Y, at the same level in the right arm, has pressure equal to P_{atm} plus the pressure of the extra liquid column of height h above it. Hence $P_{\text{gas}} = P_{\text{atm}} + h\rho g$.



Worked example: pressure on a diver

A diver is at a depth of 30 m in a lake (water density 1000 kg/m^3 , $g = 10 \text{ N/kg}$, atmospheric pressure $1.0 \times 10^5 \text{ Pa}$). Find the pressure due to the water and the total pressure.

$P = h\rho g = 30 \times 1000 \times 10 = 3.0 \times 10^5 \text{ Pa}$. Total $= 1.0 \times 10^5 + 3.0 \times 10^5 = 4.0 \times 10^5 \text{ Pa}$ (4 atmospheres).

Worked example: two liquids

A U-tube contains water. Oil of density 800 kg/m^3 is poured into the right arm until the oil column is 25 cm high. How high is the water column above the oil–water boundary level in the left arm?

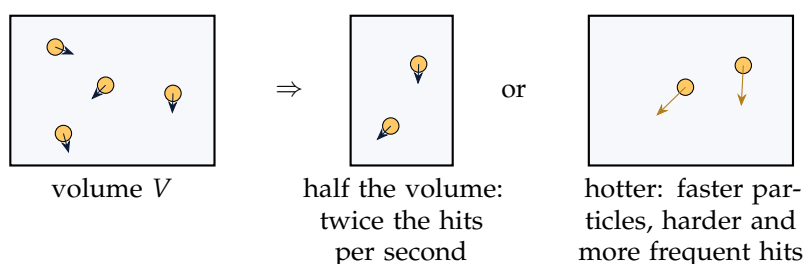
The boundary level in the right arm (point on the boundary) and the point at the same level in the left arm are at the same pressure: $h_w \rho_w g = h_o \rho_o g$. So $h_w = \frac{800}{1000} \times 25 = 20 \text{ cm}$. The oil surface stands 5 cm higher than the water surface, because oil is less dense.

Common mistakes

- Measuring h along a sloping tube or from the bottom of the container. It must be the *vertical* depth below the surface.
- Thinking a wider container (more water) gives a greater pressure at the same depth. The area cancels.
- Forgetting to add atmospheric pressure when the question asks for the *total* pressure.
- Using g/cm^3 in $h\rho g$ without converting: the density must be in kg/m^3 and h in metres to get pascals.

6 Gases: pressure, volume and temperature

What causes gas pressure? The particles of a gas move at hundreds of metres per second and collide with the walls of the container. Each collision gives the wall a tiny push (the particle bounces back, so its momentum changes). There are about 10^{27} collisions per square metre every second, so the pushes add up to a steady force, and the force per unit area is the gas pressure. A large *ideal gas* is a simple model: particles with negligible size, no forces except in collisions, and perfectly elastic collisions. Real gases behave almost like this at everyday conditions.

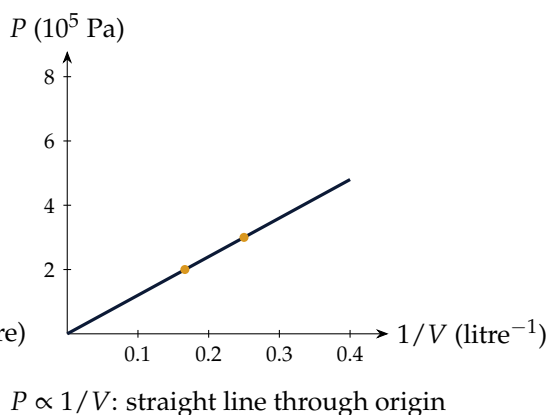
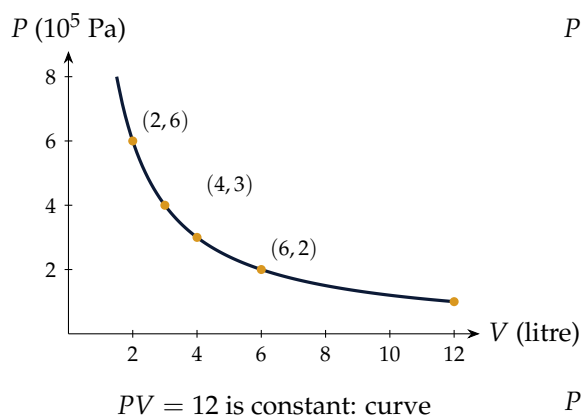


Temperature and particle energy. The *temperature* of a gas is a measure of the average kinetic energy of its particles. Heating a gas makes the particles move faster on average. In a fixed volume this has two effects: they hit the walls *more often* and *harder*. Hence the pressure rises. So for a fixed mass of gas in a rigid container: **higher temperature means higher pressure**.

Volume and pressure. Suppose the temperature is constant, so the particles' speeds do not change. Compress the gas into half the volume. The particles are now closer to the walls, so they travel a shorter distance between hits and hit each wall twice as often, while the area of the walls is also smaller. The pressure doubles. This is **Boyle's law**: for a fixed mass of gas at constant temperature,

$$PV = \text{constant}, \quad \text{or} \quad P_1 V_1 = P_2 V_2.$$

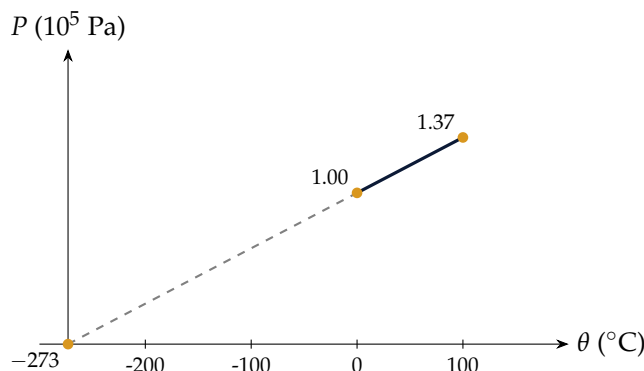
Halve the volume and the pressure doubles; triple the volume and the pressure falls to a third. The graph of P against V is a curve (a hyperbola), while the graph of P against $1/V$ is a straight line through the origin.



Pressure and temperature, and the kelvin scale. In a sealed rigid container the pressure rises steadily with temperature. If we plot pressure against temperature in $^{\circ}\text{C}$ we get a straight line that does not pass through the origin, but when it is extended backwards it reaches $P = 0$ at about -273°C . There the particles would have almost no kinetic energy and would not push on the walls: this is **absolute zero**, the lowest possible temperature. The **kelvin scale** starts from this point:

$$T(\text{K}) = \theta(^{\circ}\text{C}) + 273.$$

Water freezes at 273 K and boils at 373 K; a change of 1 K is the same size as a change of 1 °C. Because the average kinetic energy of the particles is proportional to the kelvin temperature, the pressure of a fixed mass of gas at constant volume is proportional to it as well: $\frac{P}{T} = \text{constant}$, i.e. $\frac{P_1}{T_1} = \frac{P_2}{T_2}$. *Always convert to kelvin*: doubling the Celsius temperature does not double the pressure.



measured readings (solid) extended
back (dashed) reach $P = 0$ at -273°C

Worked example: Boyle's law

A bicycle pump contains 600 cm^3 of air at $1.0 \times 10^5\text{ Pa}$. The outlet is blocked and the piston is pushed in slowly so the temperature stays the same, until the volume is 150 cm^3 . Find the new pressure.

$P_1 V_1 = P_2 V_2$: $1.0 \times 10^5 \times 600 = P_2 \times 150$, so $P_2 = \frac{600}{150} \times 10^5 = 4.0 \times 10^5\text{ Pa}$. (The volume fell to a quarter, so the pressure rose four times.)

Worked example: heating a sealed can

A sealed can of gas at 27°C has a pressure of $2.0 \times 10^5\text{ Pa}$. It is heated to 327°C . Find the new pressure (the volume does not change).

Convert: $T_1 = 27 + 273 = 300\text{ K}$, $T_2 = 327 + 273 = 600\text{ K}$. The kelvin temperature has doubled, so the pressure doubles: $4.0 \times 10^5\text{ Pa}$. (Using Celsius would suggest a factor of 12, which is absurd.)

Exam tip

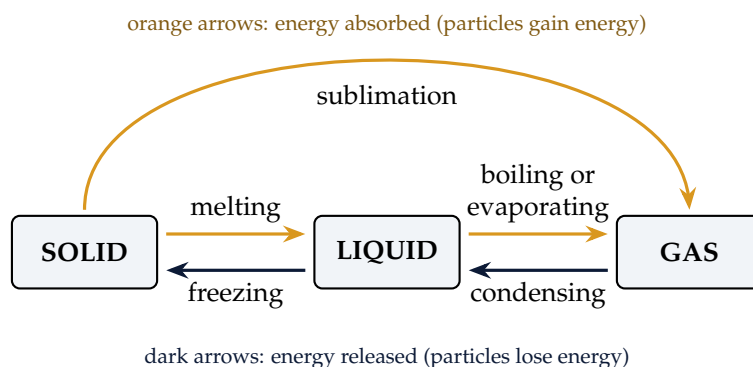
Decide first which of P , V , T is fixed. Fixed T : $P_1 V_1 = P_2 V_2$. Fixed V : $P_1/T_1 = P_2/T_2$ with T in kelvin. Then sanity-check the direction of the change with the particle picture (smaller volume means more frequent hits, so higher pressure).

Common mistakes

- Using Celsius in $P/T = \text{constant}$.
- Saying the pressure rises with temperature because the particles "expand" or "collide more with each other". It is the faster collisions with the *walls*.
- Saying a gas particle loses speed after hitting a wall. In an ideal gas collisions are elastic, so the speed is unchanged on average.
- Forgetting that Boyle's law needs a fixed mass of gas and a constant temperature.

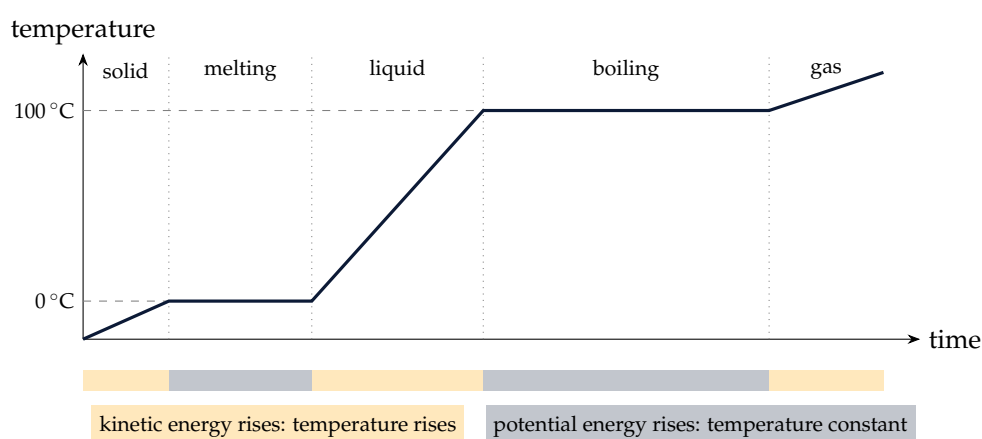
7 Changes of state and internal energy

Changes of state. When a substance is heated or cooled it can change state. The names are shown below. These are *physical* changes: the particles are the same, only their arrangement and energy change, and a substance returns to its original form when the change is reversed. Mass is conserved in every change of state.



Internal energy. The particles of a substance have two kinds of energy: **kinetic energy** because they move (or vibrate), and **potential energy** stored in the forces between them (separating attracting particles takes energy, like pulling two magnets apart). The **internal energy** is the total of both kinds, summed over all the particles. Heating a substance increases its internal energy.

Heating curves. Heat a solid steadily and record its temperature. The graph below has sloping sections and flat sections. *Sloping sections* (the temperature is rising): the energy supplied increases the particles' *kinetic* energy, and temperature measures the average kinetic energy. *Flat sections* (melting and boiling): the temperature stays constant even though the heater is still supplying energy. The kinetic energy is not changing; the energy goes into increasing the *potential* energy by pulling the particles away from their neighbours (melting loosens the regular pattern; boiling separates the particles completely against the strong forces). During the flat section the substance is a mixture of the two states, and the temperature only starts to rise again once the change is complete.



Cooling is the same graph run backwards: the flat sections occur at the freezing and condensing temperatures, where energy is *released* as the particles bond again.

Evaporation versus boiling. Evaporation happens at the surface of a liquid at *any* temperature: the fastest particles near the surface have enough kinetic energy to escape, so the liquid left behind has a lower average kinetic energy and cools (which is why sweating cools you). Boiling happens throughout the liquid at one particular temperature, the boiling point, when bubbles of vapour form inside it. Evaporation is faster when the liquid is warmer, has a bigger surface area, and when moving air carries the vapour away.

Gas to solid directly. In sublimation (for example dry ice, solid carbon dioxide, at atmospheric pressure) a solid turns straight into a gas without passing through the liquid state.

Worked example: explaining a flat section

A solid is heated by a heater of constant power and its temperature stops rising at 80 °C for several minutes before rising again. Explain what is happening.

The solid is melting at its melting point. The energy supplied is used to break the bonds holding the particles in a fixed pattern (increasing their potential energy), not to speed them up, so the average kinetic energy and hence the temperature stay constant. When all the solid has melted, the energy again goes into kinetic energy and the temperature rises.

Common mistakes

- Saying the energy “disappears” or “the heater stops working” during the flat section. Energy is still being transferred.
- Writing that the substance is all liquid in the melting section. It is a *mixture* of solid and liquid.
- Confusing heat and temperature. Temperature is about average kinetic energy; the total internal energy depends on the mass as well.
- Thinking evaporation only occurs at the boiling point.

8 Specific latent heat

Definition. The energy needed to melt or boil a substance depends on how much of it there is. For a given substance, the energy needed to change the state of 1 kg *without changing the temperature* is called its **specific latent heat** L . For a mass m :

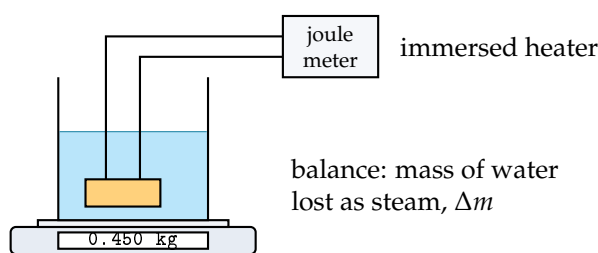
$$E = mL \quad \text{so} \quad L = \frac{E}{m}.$$

The unit is J/kg. There are two values for every substance: the **specific latent heat of fusion** L_f (solid $\leftrightarrow$ liquid) and the **specific latent heat of vaporisation** L_v (liquid $\leftrightarrow$ gas). For water, $L_f \approx 3.3 \times 10^5$ J/kg and $L_v \approx 2.3 \times 10^6$ J/kg. The same energy is *released* when the substance changes back (freezing or condensing).

Why is L_v so much bigger than L_f ? Melting only loosens the particles so they can slide, while boiling pulls each particle completely away from all its neighbours and also pushes back the atmosphere to make room for the vapour. That is why steam at 100 °C burns you far worse than water at 100 °C: as it condenses on your skin it releases the whole L_v on top of the energy from cooling.

Do not confuse L with c . Specific heat capacity c (J/(kg · °C)) is for changes that *do* change the temperature: $E = mc\Delta\theta$. Specific latent heat L is for changes of state at *constant* temperature: $E = mL$. A problem that takes a substance from a cold solid to a hot vapour needs both, in stages: warm the solid ($mc\Delta\theta$), melt it (mL_f), warm the liquid ($mc\Delta\theta$), boil it (mL_v), warm the vapour. Add up the stages.

Measuring L_v . Bring water to the boil in a beaker on a balance with an electric heater connected to a joule meter. Record the energy supplied and the loss of mass (the water carried away as steam) over a few minutes. Then $L_v = E/\Delta m$. The result is a little too high in practice because some of the energy is lost to the surroundings. For L_f , use a heater in a funnel full of crushed ice, collect the melted water and compare with a control funnel to correct for melting from the room’s warmth.



$$L_v = \frac{E}{\Delta m} \quad (\text{water already boiling})$$

Worked example: energy to melt

How much energy is needed to melt 0.6 kg of ice at 0 °C? ($L_f = 3.3 \times 10^5$ J/kg.) How long would a 900 W heater take if all its energy went into the ice?

$$E = mL_f = 0.6 \times 3.3 \times 10^5 = 1.98 \times 10^5 \text{ J. The time is } t = E/P = \frac{198\,000}{900} = 220 \text{ s.}$$

Worked example: a heating curve with a heater

A 0.5 kg block of solid is heated by a 500 W heater. Its temperature stays at 60 °C for 300 s, the whole of the time it is melting. Find L_f .

$$\text{Energy supplied while melting } E = Pt = 500 \times 300 = 1.5 \times 10^5 \text{ J. } L_f = \frac{E}{m} = \frac{150\,000}{0.5} = 3.0 \times 10^5 \text{ J/kg.}$$

Worked example: two stages

How much energy is needed to turn 0.2 kg of water at 20 °C into steam at 100 °C? ($c = 4200 \text{ J}/(\text{kg} \cdot ^\circ\text{C})$, $L_v = 2.2 \times 10^6 \text{ J/kg}$.)

Stage 1: warm to 100 °C: $E_1 = mc\Delta\theta = 0.2 \times 4200 \times 80 = 67\,200 \text{ J}$. Stage 2: boil: $E_2 = mL_v = 0.2 \times 2.2 \times 10^6 = 440\,000 \text{ J}$. Total = $507\,200 \text{ J} \approx 5.1 \times 10^5 \text{ J}$. Note that boiling needs nearly seven times as much energy as heating to the boil.

Worked example: mixing ice and water

0.05 kg of ice at 0 °C is dropped into warm water and the final temperature of everything is 20 °C. How much energy must the ice absorb? ($L_f = 3.36 \times 10^5 \text{ J/kg}$, $c = 4200 \text{ J}/(\text{kg} \cdot ^\circ\text{C})$.)

First the ice melts: $0.05 \times 336\,000 = 16\,800 \text{ J}$. Then the melt-water warms from 0 °C to 20 °C: $0.05 \times 4200 \times 20 = 4200 \text{ J}$. Total 21 000 J, taken from the warm water.

Exam tip

For a problem with several stages, sketch the heating curve first and label each section “ $mc\Delta\theta$ ” or “ mL ”. Latent heat sections are the flat ones. Check that every mass is in kilograms and every energy in joules before you add.

Common mistakes

- Using $E = mc\Delta\theta$ for a change of state, or $E = mL$ for a temperature rise.
- Forgetting that melted ice is then water that still has to be warmed.
- Leaving mass in grams: L and c are per *kilogram*.
- Using L_f for boiling, or the other way round.

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. Describe the arrangement and movement of the particles in a gas, and explain why a gas is easy to compress.
2. A block has a mass of 480 g and a volume of 60 cm^3 . Find its density in kg/m^3 .
3. A force of 240 N acts on an area of 80 cm^2 . What is the pressure?
4. Find the pressure due to the water at the bottom of a 5 m deep tank of water ($\rho = 1000 \text{ kg}/\text{m}^3$, $g = 10 \text{ N/kg}$).
5. Air at $1.0 \times 10^5 \text{ Pa}$ in a 3 L syringe is squashed slowly (constant temperature) to 1 L. What is the new pressure?
6. A sealed rigid tank of gas is at 27 °C. Roughly what Celsius temperature would double the pressure?
7. Why does the temperature stay constant while ice is melting although a heater is supplying energy?
8. How much energy is needed to boil away 0.1 kg of water already at 100 °C? ($L_v = 2.3 \times 10^6 \text{ J/kg}$)

Answers to the self-check

1. The particles are far apart and move randomly and quickly. Compressing a gas just reduces the large gaps, with almost no resistance from forces between the particles.
2. $\rho = 480/60 = 8 \text{ g/cm}^3 = 8000 \text{ kg/m}^3$.
3. $A = 0.008 \text{ m}^2$, so $P = 240/0.008 = 30\,000 \text{ Pa}$.
4. $h\rho g = 5 \times 1000 \times 10 = 50\,000 \text{ Pa}$.
5. $P_1 V_1 = P_2 V_2$; $P_2 = 3 \times 10^5 \text{ Pa}$.
6. The kelvin temperature must double: $300 \rightarrow 600 \text{ K}$, i.e. 327°C .
7. The energy increases the potential energy of the particles as the bonds in the solid pattern break; their kinetic energy (and hence the temperature) is unchanged.
8. $E = mL = 0.1 \times 2.3 \times 10^6 = 2.3 \times 10^5 \text{ J}$.

Next step

Heurisco's *ESAT Physics: Matter Practice Set* has twenty original exam-style questions on this lesson, with diagrams and graphs, in order of difficulty, with a full worked solution for each.