A LEVEL PHYSICS 9702 · AS LEVEL · TOPIC 2 · ~9 MIN READ

Kinematics

Displacement, velocity and acceleration, motion graphs, deriving the equations of uniformly accelerated motion, free fall and measuring g, and projectiles with uniform velocity in one direction and uniform acceleration in the other.

Distance & displacement | Speed & velocity | Acceleration | Motion graphs | Deriving suvat | Free fall | Measuring g | Projectiles

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Paper tag = **where it is examined** DATA & FORMULAE given in the exam C1 A1 B1 how marks are awarded

highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **Displacement, velocity and acceleration are vectors;** distance and speed are scalars. Choose a positive direction and keep the signs.
- **Gradient of s–t = velocity. Gradient of v–t = acceleration. Area under v–t = displacement.**
- **The suvat equations** follow from the definitions of velocity and acceleration, but only for **constant** acceleration.
- **Free fall** near Earth: a = g = 9.81 m s^{-2} downwards, if air resistance is negligible.
- **Projectiles:** treat horizontal and vertical motion separately. Horizontal velocity is constant; vertical acceleration is g. Time links the two.

BY THE END YOU CAN

- Define and use displacement, speed, velocity and acceleration.
- Interpret s–t and v–t graphs using gradients and areas.
- Derive and use the equations of uniformly accelerated motion.
- Describe an experiment to measure g.
- Solve projectile problems by resolving into horizontal and vertical motion.

1 Definitions and graphs

Key definitions

Displacement — distance in a stated direction from a fixed point (vector).

Speed — distance travelled per unit time (scalar).

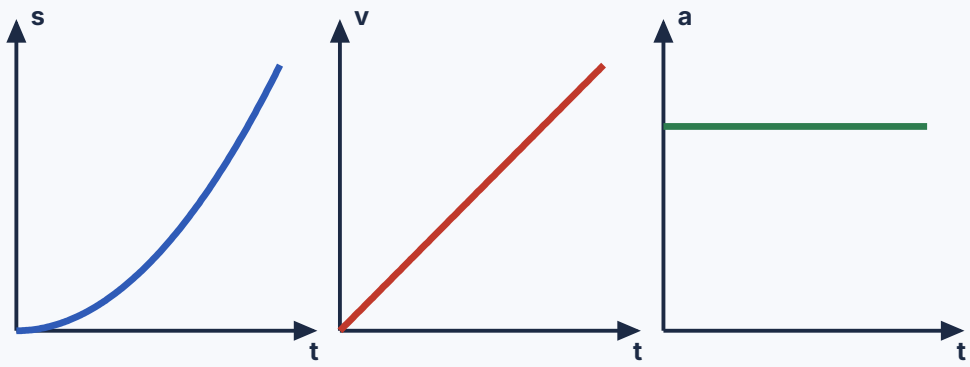
Velocity — rate of change of displacement, v = Δs/Δt (vector).

Acceleration — rate of change of velocity, a = Δv/Δt (vector).

- **"Rate of change"** always means "per unit time". Definitions in words must be dimensionally correct: "velocity is displacement per unit time", not "displacement over time taken".

Motion graphs

Uniform acceleration from rest: the same motion, three graphs



s–t: a curve
gradient = velocity

v–t: a straight line
gradient = acceleration
area = displacement

a–t: flat line
area = change in velocity

The same uniformly accelerated motion on s–t, v–t and a–t graphs.

Graph	Gradient gives	Area gives
displacement–time	velocity	(nothing useful)
velocity–time	acceleration	displacement
acceleration–time	(nothing useful)	change in velocity

- **Instantaneous value from a curve:** draw a tangent at the point and find its gradient with a large triangle. In 2024 many candidates calculated an average acceleration instead of the gradient at the given time.
- **Area below the time axis** on a v–t graph is a displacement in the negative direction.

WORKED EXAMPLE

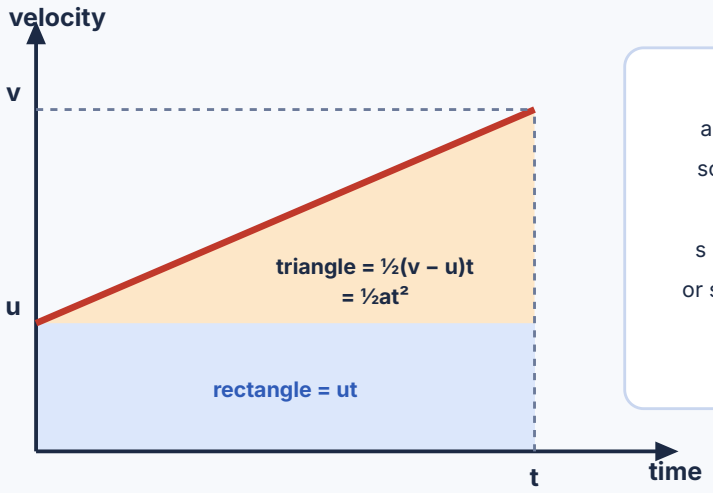
A train accelerates uniformly from rest to 8.0 m s^{-1} in 4.0 s, travels at constant speed for 6.0 s, then decelerates uniformly to rest in 2.0 s. Find the total distance.

1. area = ½ × 4.0 × 8.0 + 6.0 × 8.0 + ½ × 2.0 × 8.0 C1
2. **= 16 + 48 + 8 = 72 m** A1

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2 The equations of uniformly accelerated motion

Deriving them



gradient:
a = (v − u)/t
so v = u + at
area:
s = ut + ½at²
or s = ½(u + v)t

Both suvat results come straight from the v–t graph. Only for constant acceleration.

The v–t graph for constant acceleration gives every equation.

- **From the definition of acceleration:** a = (v − u)/t ⇒ **v = u + at**.
- **Displacement = average velocity × time** (area of the trapezium under the v–t graph): **s = ½(u + v)t**.
- **Substitute v = u + at:** s = ½(u + u + at)t ⇒ **s = ut + ½at²**.
- **Eliminate t** using t = (v − u)/a: s = ½(u + v)(v − u)/a ⇒ **v² = u² + 2as**.

$v = u + at$; $s = ut + \frac{1}{2}at^2$; $v^2 = u^2 + 2as$ DATA & FORMULAE

s = ½(u + v)t must be recalled; all four need constant acceleration

COMMON MISTAKE

Using suvat when acceleration changes, for example with air resistance or a spring. The equations are only valid for constant acceleration.

Using them

- **List s, u, v, a, t,** fill in the three you know, choose the equation without the one you don't need.
- **Sign convention:** decide which direction is positive. For something thrown upwards, if up is positive then a = −9.81 m s^{-2}.

WORKED EXAMPLE

A car accelerates uniformly from 12 m s^{-1} to 30 m s^{-1} in 6.0 s. Find its acceleration and the distance travelled.

1. a = (30 − 12)/6.0 = **3.0 m s^{-2}** A1
2. **s = ½(12 + 30) × 6.0 = 126 m** C1 A1

WORKED EXAMPLE

A ball is thrown vertically upwards at 15 m s^{-1} from a point 1.2 m above the ground. Find its maximum height above the ground and the time until it hits the ground.

1. at the top v = 0: $0 = 15^2 - 2 \times 9.81 \times s \Rightarrow s = 11.5$ m, so height = 11.5 + 1.2 = **12.7 m** C1 A1
2. ground is s = −1.2 m (up positive): $-1.2 = 15t - 4.905t^2$ C1
3. **$4.905t^2 - 15t - 1.2 = 0 \Rightarrow t = 3.1$ s (positive root)** A1

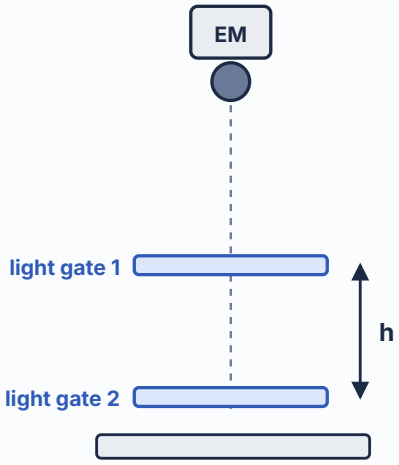
COMMON MISTAKE

Forgetting the release height, or giving g the wrong sign. Both were common in 2024 Paper 2.

3 Free fall and measuring g

The acceleration of free fall

- **Without air resistance,** all objects near Earth's surface fall with the same acceleration g ≈ 9.81 m s^{-2}, whatever their mass.



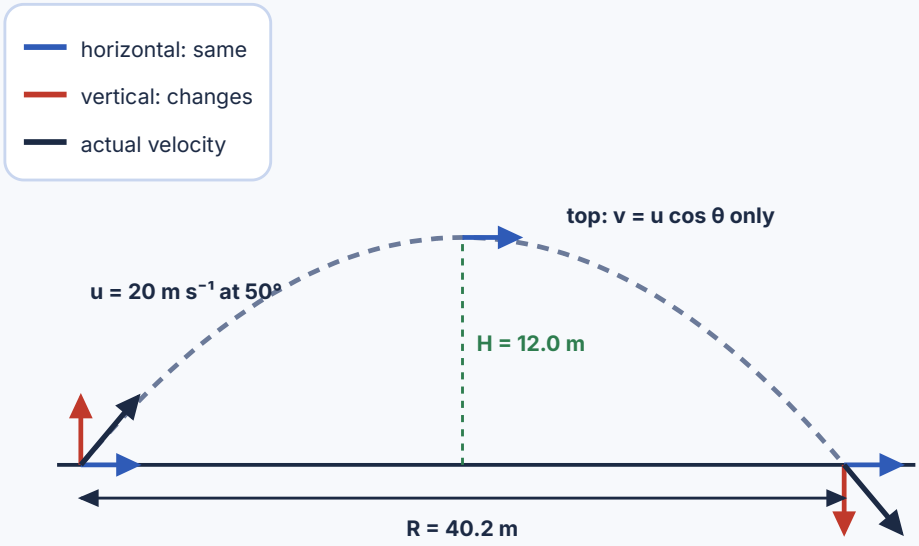
Measure the time t to fall from rest through height h (or between two gates).
$s = ut + \frac{1}{2}at^2$ with u = 0
$\Rightarrow h = \frac{1}{2}gt^2$
plot h against t^2:
gradient = g/2

Release the ball from rest with an electromagnet; repeat each height and average t.

Measuring g: time a ball falling from rest through a measured height.

- **Method:** a steel ball is held by an electromagnet and released from rest; a timer starts when the current is switched off and stops when the ball passes a light gate (or opens a trapdoor). Measure the height h with a metre rule.
- **Analysis:** with u = 0, $h = \frac{1}{2}gt^2$. Repeat for several heights. Plot h against t^2: a straight line through the origin with **gradient g/2**.
- **Improving accuracy:** repeat each timing and average; use a dense, small ball to reduce air resistance; use light gates instead of a hand-held stopwatch to remove reaction time; measure h to the bottom of the ball.

Horizontal and vertical are independent



Horizontal velocity stays constant; vertical velocity changes at g.

	Horizontal	Vertical
Initial velocity	u cos θ	u sin θ
Acceleration	0	−g (up positive)
Equation	x = (u cos θ)t	y = (u sin θ)t − ½gt²

- **Time is the link.** Find the time from the vertical motion, then use it horizontally.
- **Never put horizontal and vertical values into one suvat equation,** and never use suvat with a horizontal acceleration that isn't there. These were 2024 Paper 2 errors.

WORKED EXAMPLE

A ball is kicked horizontally at 12 m s^{-1} from the top of a cliff 20 m high. Find the time of flight, the horizontal distance and the speed on landing.

1. vertical: 20 = ½ × 9.81 × t² ⇒ t = **2.0 s** C1 A1
2. horizontal: x = 12 × 2.02 = **24 m** A1
3. **vertical speed = 9.81 × 2.02 = 19.8 m s^{-1}; v = √(12² + 19.8²) = 23 m s^{-1}** C1 A1 **(at 59° below the horizontal)**

WORKED EXAMPLE

A ball is projected at 25 m s^{-1} at 40° above the horizontal from level ground. Find the maximum height and the range.

1. u_x = 25 cos 40° = 19.2 m s^{-1}; u_y = 25 sin 40° = 16.1 m s^{-1} C1
2. max height: 0 = 16.1² − 2 × 9.81 × h ⇒ **h = 13.2 m** A1
3. **time of flight = 2 × 16.1/9.81 = 3.28 s; range = 19.2 × 3.28 = 63 m** C1 A1

- **With air resistance (qualitatively):** the range and maximum height are smaller, the path is no longer symmetrical, and the descent is steeper than the ascent.

LINKING QUESTION

Forces cause the accelerations in Dynamics; air resistance and terminal velocity are in the same note; and the energy approach to falling objects is in Work, energy and power.

Test yourself — cover the answers first

QUICK CHECK

1. Define acceleration.
2. What does the area under a velocity–time graph represent?
3. State the condition for using the suvat equations.
4. A stone is dropped from a bridge and hits the water 2.4 s later. How high is the bridge?
5. What is the horizontal acceleration of a projectile (no air resistance)?

EXAM-STYLE

6. Derive $v^2 = u^2 + 2as$ from $v = u + at$ and $s = \frac{1}{2}(u + v)t$.
7. A student drops a ball from heights h and records the fall time t. A graph of h against t^2 is a straight line through the origin with gradient 4.85 m s^{-2}. Find g and suggest why it is less than 9.81 m s^{-2}.
8. A ball is thrown at 20 m s^{-1} at 30° above the horizontal from a cliff 15 m high. Find the time for it to reach the sea below.

Show answers

1. rate of change of velocity
2. displacement
3. constant (uniform) acceleration
4. $\frac{1}{2} \times 9.81 \times 2.4^2 = 28$ m
5. zero
6. $t = (v - u)/a$; $s = \frac{1}{2}(u + v)(v - u)/a = (v^2 - u^2)/(2a) \Rightarrow v^2 = u^2 + 2as$
7. $g = 2 \times 4.85 = 9.7$ m s^{-2}; air resistance, or a delay in the release mechanism (the electromagnet takes time to release the ball)
8. $-15 = 10t - 4.905t^2 \Rightarrow 4.905t^2 - 10t - 15 = 0 \Rightarrow t = 3.0$ s

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