

THEME A · SPACE, TIME AND MOTION

SL & HL ≈ 25 min read

IB Physics A.1 Kinematics — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). A.1 is identical for SL and HL — there is no additional HL content in this sub-topic.



SL A.1 questions



HL A.1 questions



Flashcards



Projectile simulation



Motion graphs simulation

What this page covers

- ✓ Describing motion using position, velocity and acceleration
- ✓ Velocity and acceleration as rates of change; displacement as change in position
- ✓ Distance versus displacement
- ✓ Instantaneous versus average speed, velocity and acceleration — and how to find each
- ✓ The four equations of motion for uniform acceleration
- ✓ Uniform and non-uniform acceleration, and how to analyse each
- ✓ Projectiles with no fluid resistance, using horizontal and vertical components
- ✓ The qualitative effects of fluid resistance, including terminal speed

In one minute

- **Displacement, velocity and acceleration** are vectors; distance and speed are scalars.
- Velocity is the rate of change of displacement; acceleration is the rate of change of velocity.

- On an $s-t$ graph the gradient is velocity. On a $v-t$ graph the gradient is acceleration and the area is displacement.
- The four equations of motion ("suvat") work **only** when acceleration is uniform.
- A projectile's horizontal and vertical motions are independent: constant horizontal velocity, constant downward acceleration g .
- Fluid resistance lowers the maximum height, shortens the range and time of flight, makes the path asymmetric and leads to a terminal speed.

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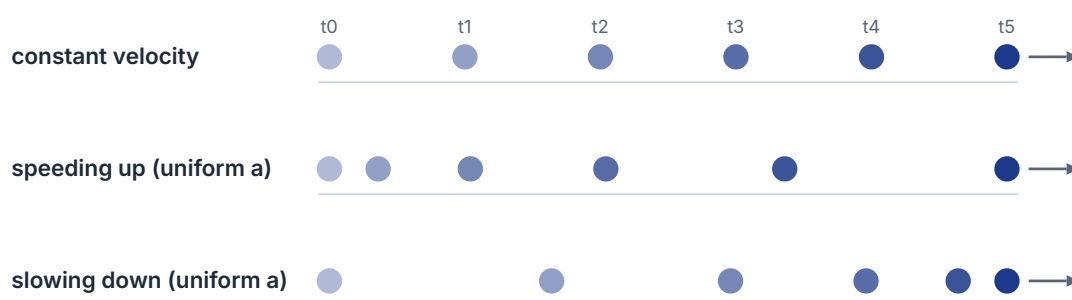
Which quantities are used to describe motion?

Kinematics describes *how* a body moves, without asking *why* (that is A.2, forces). We treat the body as a point particle and track three quantities over time.

Quantity	Symbol	Meaning	SI unit	Type
Position	x	Where the body is, measured from a chosen origin	m	vector
Displacement	s	Change in position	m	vector
Distance	—	Total length of path travelled	m	scalar
Velocity	v	Rate of change of displacement	m s^{-1}	vector
Speed	v	Rate of change of distance (magnitude of velocity)	m s^{-1}	scalar
Acceleration	a	Rate of change of velocity	m s^{-2}	vector

Velocity is the rate of change of displacement: $v = \frac{\Delta s}{\Delta t}$. Acceleration is the rate of change of velocity: $a = \frac{\Delta v}{\Delta t}$.

- In one dimension, the **sign** carries the direction. Choose a positive direction at the start of every problem and keep it.
- A **negative acceleration** does not automatically mean "slowing down". A body slows down when velocity and acceleration have *opposite* signs, and speeds up when they have the *same* sign.



A multiframe picture records the position at equal time intervals. Equal spacing means constant velocity; growing spacing means speeding up; shrinking spacing means slowing down.

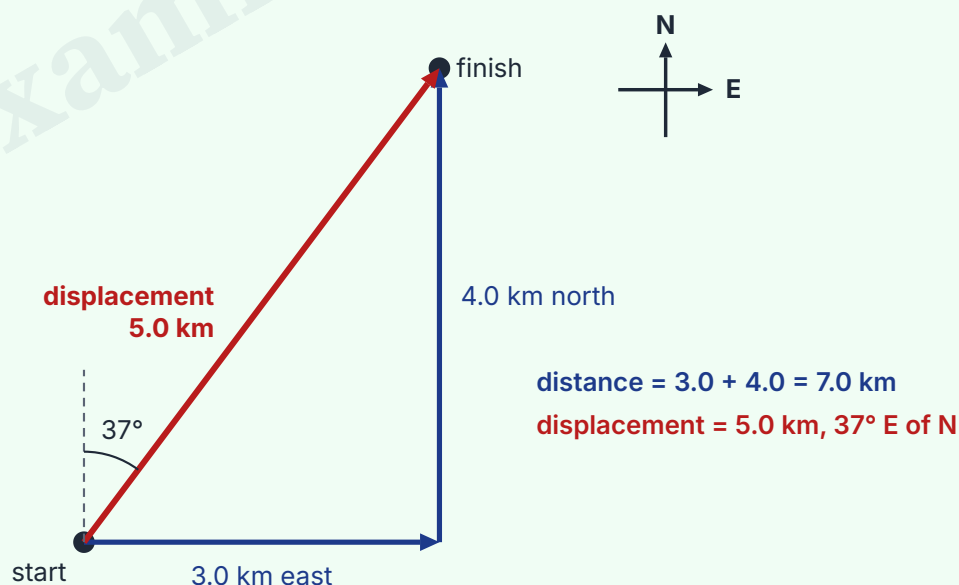
What is the difference between distance and displacement?

Displacement is the change in position of a body — a vector with magnitude and direction. Distance is the total length of the path travelled — a scalar.

- Distance can only increase as a body moves; displacement can increase, decrease or return to zero.
- The two are equal in magnitude only for motion in a straight line **without reversing**.
- For a closed path (returning to the start) the displacement is zero, however far the body travelled.

WORKED EXAMPLE 1 Easy · Calculate

A cyclist rides 3.0 km due east and then 4.0 km due north. The whole journey takes 15 minutes.



The blue path is the distance travelled; the red arrow is the displacement from start to finish.

Calculate (a) the distance travelled, (b) the magnitude and direction of the displacement, (c) the average speed and (d) the magnitude of the average velocity.

(a) Distance adds the path lengths: $3.0 + 4.0 = 7.0 \text{ km}$

(b) The two legs are perpendicular, so use Pythagoras: $\sqrt{3.0^2 + 4.0^2} = 5.0 \text{ km}$.

Direction: $\tan^{-1}\left(\frac{3.0}{4.0}\right) = 37^\circ$, so the displacement is **5.0 km at 37° east of north**.

(c) $t = 15 \times 60 = 900 \text{ s}$; average speed $= \frac{7000}{900} = 7.8 \text{ m s}^{-1}$

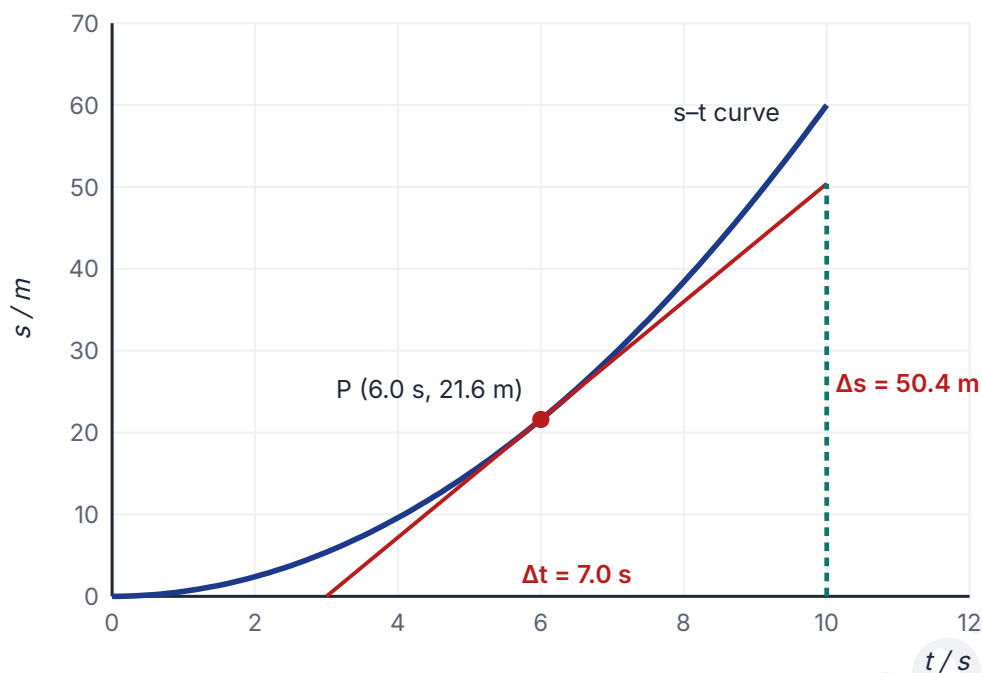
(d) Average velocity $= \frac{5000}{900} = 5.6 \text{ m s}^{-1}$ (in the direction of the displacement)

What is the difference between instantaneous and average values?

An **average** value describes a whole time interval; an **instantaneous** value describes a single moment.

Quantity	Average value	Instantaneous value
Speed	total distance $\div$ total time	magnitude of the instantaneous velocity
Velocity	$\bar{v} = \frac{\Delta s}{\Delta t}$ (total displacement $\div$ total time)	gradient of the tangent to the s - t graph at that instant
Acceleration	$\bar{a} = \frac{\Delta v}{\Delta t}$	gradient of the tangent to the v - t graph at that instant

- For a straight-line graph, the gradient is the same everywhere, so average and instantaneous values are equal.
- For a curve, draw a **tangent** that just touches the curve at the point, then find its gradient using a large triangle.
- Only when acceleration is uniform can you also use $\bar{v} = \frac{u + v}{2}$.



The gradient of the tangent at P gives the instantaneous velocity at $t = 6.0$ s.

WORKED EXAMPLE 2 Medium · Determine

The graph above shows how the displacement s of a car varies with time t as it pulls away from rest with uniform acceleration. A tangent has been drawn at P, where $t = 6.0$ s.

Determine (a) the instantaneous velocity of the car at $t = 6.0$ s and (b) the average velocity of the car over the first 6.0 s.

(a) The tangent passes through (3.0 s, 0 m) and (10.0 s, 50.4 m).

$$v = \text{gradient} = \frac{50.4 - 0}{10.0 - 3.0} = 7.2 \text{ m s}^{-1}$$

(b) Read the displacement at 6.0 s: 21.6 m.

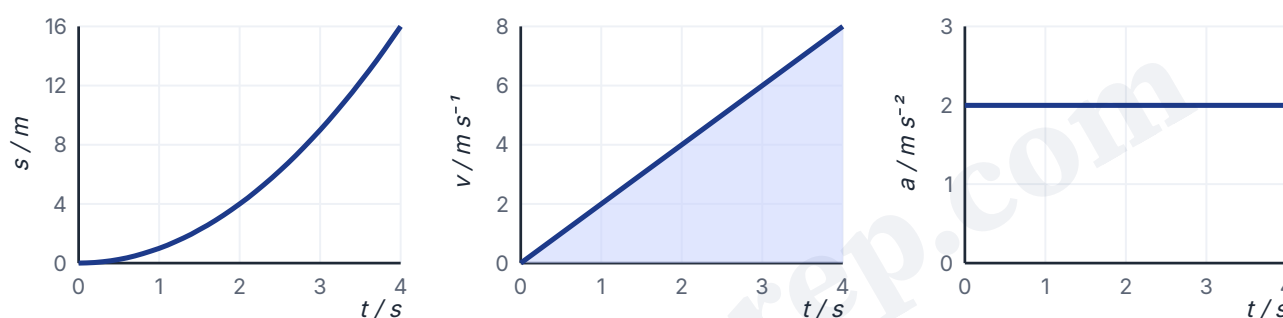
$$\bar{v} = \frac{21.6}{6.0} = 3.6 \text{ m s}^{-1}$$

Check: this car accelerates uniformly from rest, so $\bar{v} = \frac{u+v}{2} = \frac{0+7.2}{2} = 3.6 \text{ m s}^{-1}$. The two methods agree.

How do you read motion graphs?

Many kinematics marks on Papers 1A, 1B and 2 come from interpreting graphs. Learn what the gradient and the area mean for each graph.

Graph	Gradient gives	Area under the graph gives
displacement–time (s – t)	velocity	no physical meaning
velocity–time (v – t)	acceleration	displacement
acceleration–time (a – t)	not required	change in velocity



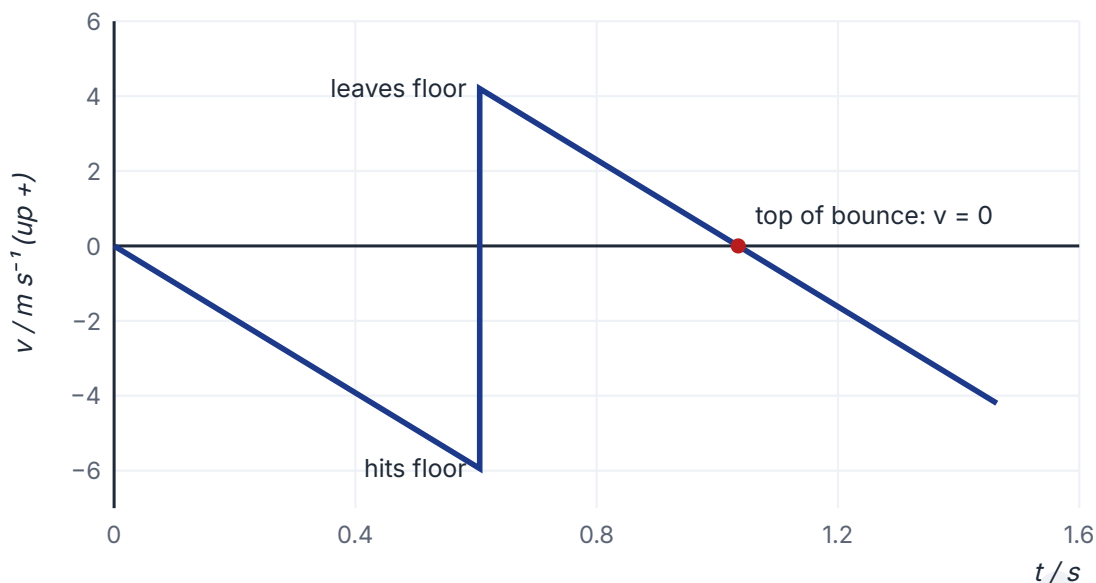
Uniform acceleration from rest: a parabola on the s – t graph, a straight line through the origin on the v – t graph, and a horizontal line on the a – t graph. The shaded area (16 m) equals the final displacement.

- Area **below** the time axis on a v – t graph is negative displacement (motion in the negative direction).
- Total **distance** = sum of the magnitudes of all areas. Total **displacement** = areas above minus areas below.
- Count the shape carefully: triangles $\frac{1}{2}bh$, trapezia $\frac{1}{2}(a + b)h$, or count squares for curves.

TRY IT YOURSELF

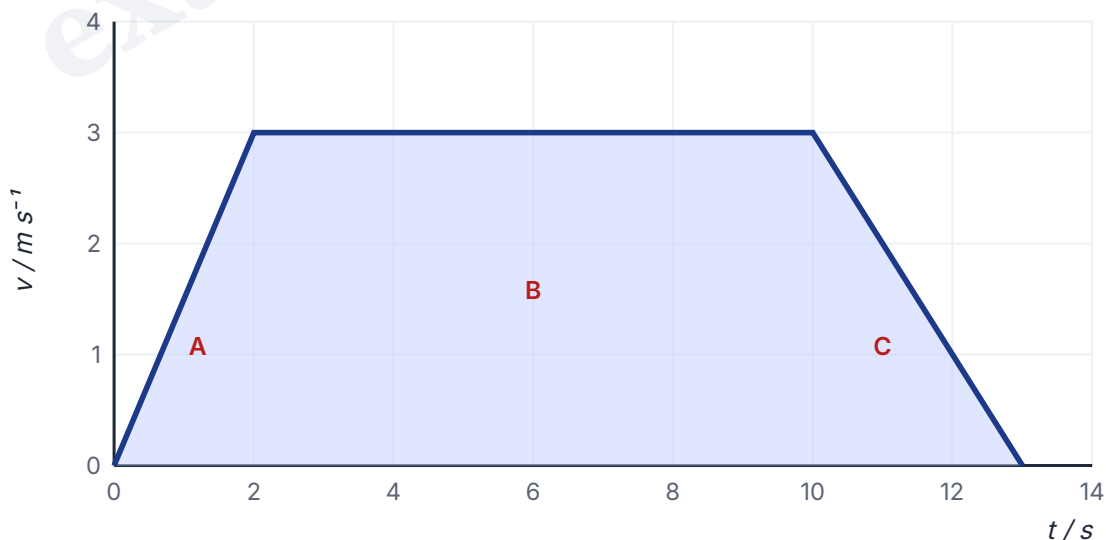
A.1 Motion Graphs simulation: move an object and watch its displacement–time and velocity–time graphs build up together — gradients and areas live.

A ball that is dropped and bounces



Upward is taken as positive. Both straight sections have the same gradient, -9.8 m s^{-2} , because the acceleration in flight is always g downward. The vertical jump is the very short contact with the floor.

- Falling: velocity becomes more negative at a steady rate.
- Bounce: velocity changes from negative to positive almost instantly. The rebound speed is smaller because energy is dissipated in the collision.
- Rising: velocity decreases to zero at the top of the bounce — but the gradient (acceleration) is unchanged.



Velocity–time graph for a lift travelling upwards between two floors.

WORKED EXAMPLE 3 Medium · Determine

The graph shows the velocity of a lift as it travels upwards between two floors.

(a) Determine the acceleration during stages A and C. (b) Determine the height between the two floors. (c) Calculate the average velocity for the whole journey.

(a) Stage A: $a = \frac{3.0 - 0}{2.0} = 1.5 \text{ m s}^{-2}$. Stage C: $a = \frac{0 - 3.0}{13.0 - 10.0} = -1.0 \text{ m s}^{-2}$ (the lift is slowing down).

(b) Height = area under the graph = $\frac{1}{2}(2.0)(3.0) + (8.0)(3.0) + \frac{1}{2}(3.0)(3.0) = 3.0 + 24 + 4.5 = 31.5 \text{ m} \approx 32 \text{ m}$

The area of the trapezium $\frac{1}{2}(8.0 + 13.0)(3.0) = 31.5 \text{ m}$ gives the same answer in one step.

(c) $\bar{v} = \frac{31.5}{13.0} = 2.4 \text{ m s}^{-1}$ upwards

What are the equations of motion and when can you use them?

For motion in a straight line with **uniform (constant) acceleration**, five quantities are linked by four equations. All four are in the Physics data booklet.

$$s = \frac{u + v}{2} t \quad v = u + at \quad s = ut + \frac{1}{2}at^2 \quad v^2 = u^2 + 2as$$

- s = displacement (m)
- u = initial velocity (m s^{-1})
- v = final velocity (m s^{-1})
- a = acceleration (m s^{-2}), constant
- t = time taken (s)

Where do they come from?

- The v - t graph for uniform acceleration is a straight line. Its gradient is $a = \frac{v-u}{t}$, which rearranges to $v = u + at$.

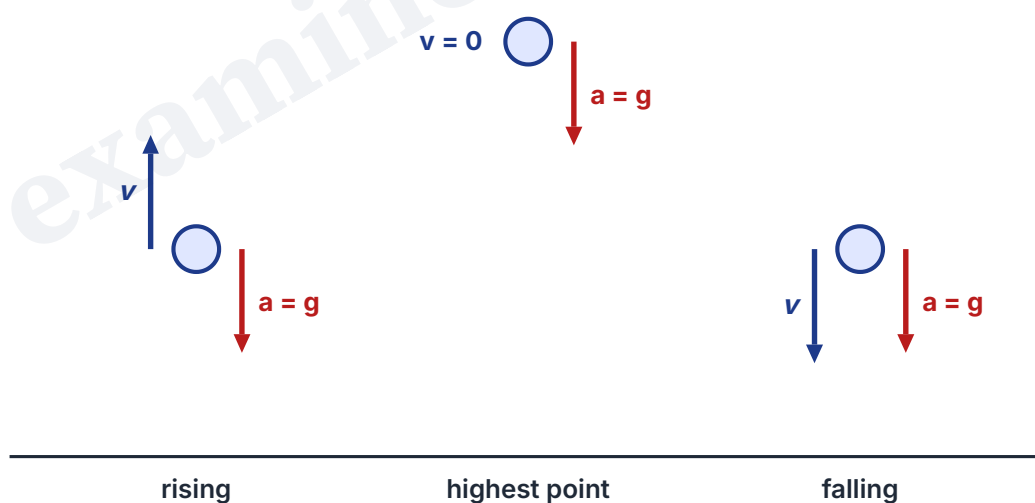
- The area under it is a trapezium: $s = \frac{u+v}{2}t$.
- Substituting one equation into the other removes v or t and gives the remaining two.

A reliable method

1. Choose a positive direction and write it down.
2. List s, u, v, a, t with signs; mark the unknown you want and the one you neither know nor need.
3. Pick the equation that does *not* contain the quantity you neither know nor need.
4. Substitute with units, then round only at the end.

For free fall near the Earth's surface, $a = g = 9.8 \text{ m s}^{-2}$ downwards (data booklet value). If you take up as positive, $a = -9.8 \text{ m s}^{-2}$.

Up taken as positive: $v > 0$ rising, $v = 0$ at the top, $v < 0$ falling; $a = -9.8 \text{ m s}^{-2}$ throughout



A ball thrown upwards: the velocity changes size and direction, but the acceleration is the same at every moment — including at the top.

WORKED EXAMPLE 4 Medium · Show that / Calculate

A train travelling at 27.8 m s^{-1} brakes with uniform deceleration and comes to rest in a distance of 640 m.

(a) Show that the magnitude of the deceleration is about 0.60 m s^{-2} . (b) Calculate the time taken to stop.

(a) Known: $u = 27.8$, $v = 0$, $s = 640$; t not needed, so use $v^2 = u^2 + 2as$:
 $0 = 27.8^2 + 2a(640) \Rightarrow a = -\frac{772.8}{1280} = -0.604 \text{ m s}^{-2}$, magnitude $\approx 0.60 \text{ m s}^{-2}$.

(b) Use $s = \frac{u+v}{2}t$, which needs only the original data: $t = \frac{2 \times 640}{27.8 + 0} = 46 \text{ s}$

Using $v = u + at$ with $a = -0.604$ gives the same 46.0 s .

EXAM TIP — "SHOW THAT"

In a "show that" question the answer is given, so the marks are for the working. Write the equation, show the substitution, and give your result to **one more significant figure** than the value in the question (here 0.604 , not 0.60). Simply writing " 0.60 " earns nothing.

What changes when acceleration is non-uniform?

With uniform acceleration the v - t graph is a straight line. With non-uniform acceleration it is curved, and the equations of motion cannot be used.

- Instead, use the graph: instantaneous acceleration = gradient of the tangent; displacement = area under the curve (counting squares or splitting into strips).
- Typical examples: a car whose engine force varies, a body falling through air, a skydiver opening a parachute, a mass on a spring.
- You can sometimes apply the equations of motion to *separate stages* of a journey, provided the acceleration is constant within each stage (as in the lift example).

How do you analyse projectile motion?

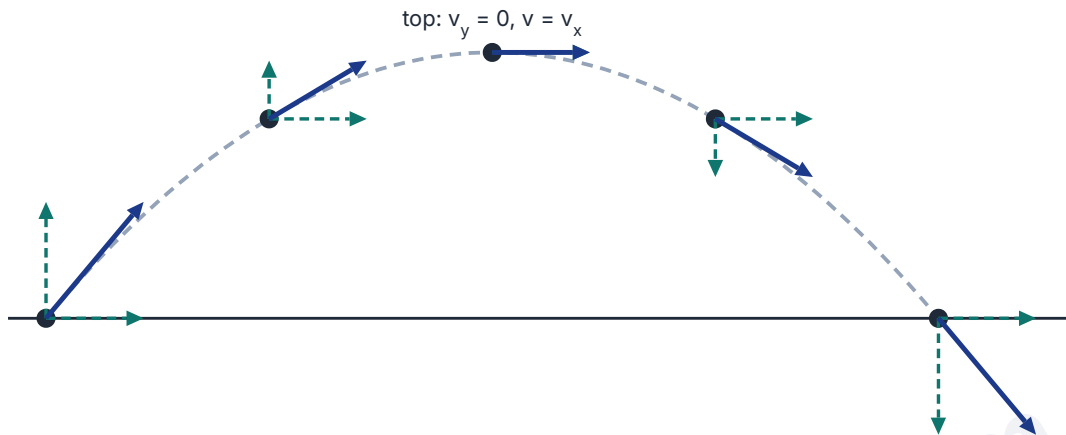
A projectile is a body moving freely under gravity after launch. With no fluid resistance, the only force is its weight, so the acceleration is g vertically downwards at every point — including the highest point.

The horizontal and vertical motions of a projectile are independent. Horizontally the velocity is constant; vertically the acceleration is constant and equal to g downwards.

	Horizontal	Vertical (up positive)
Initial velocity	$u_x = u \cos \theta$	$u_y = u \sin \theta$
Acceleration	0	$-g$
Velocity at time t	u_x (constant)	$v_y = u_y - gt$
Displacement at time t	$x = u_x t$	$y = u_y t - \frac{1}{2}gt^2$

- **Time links the two directions.** Usually you find the time from the vertical motion and then use it horizontally.
- At the highest point $v_y = 0$, so the velocity is horizontal and equal to u_x . The speed there is a minimum, not zero (unless launched vertically).
- The velocity at any point is tangent to the path: magnitude $\sqrt{v_x^2 + v_y^2}$, angle below or above the horizontal $\tan^{-1}(v_y/v_x)$.
- The path is a **parabola** (you do not need its equation).
- If it lands at its launch height, the path is symmetric: time up = time down, and it lands with the same speed it was launched with.

— velocity v (tangent to path)
 - - components v_x (constant) and v_y (changes by 9.8 m s^{-1} every second)



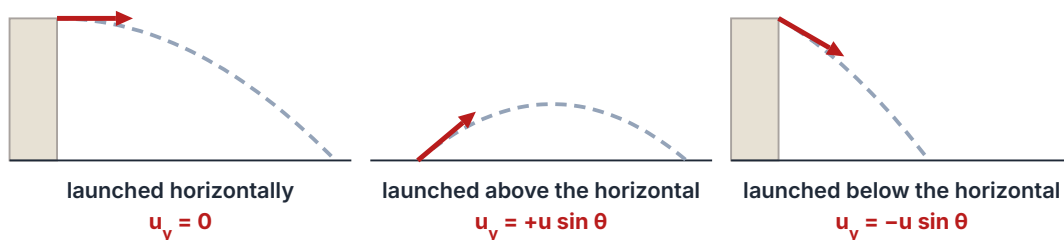
Along the path the horizontal component stays the same while the vertical component decreases steadily, passes through zero at the top, then grows downwards.

TRY IT YOURSELF

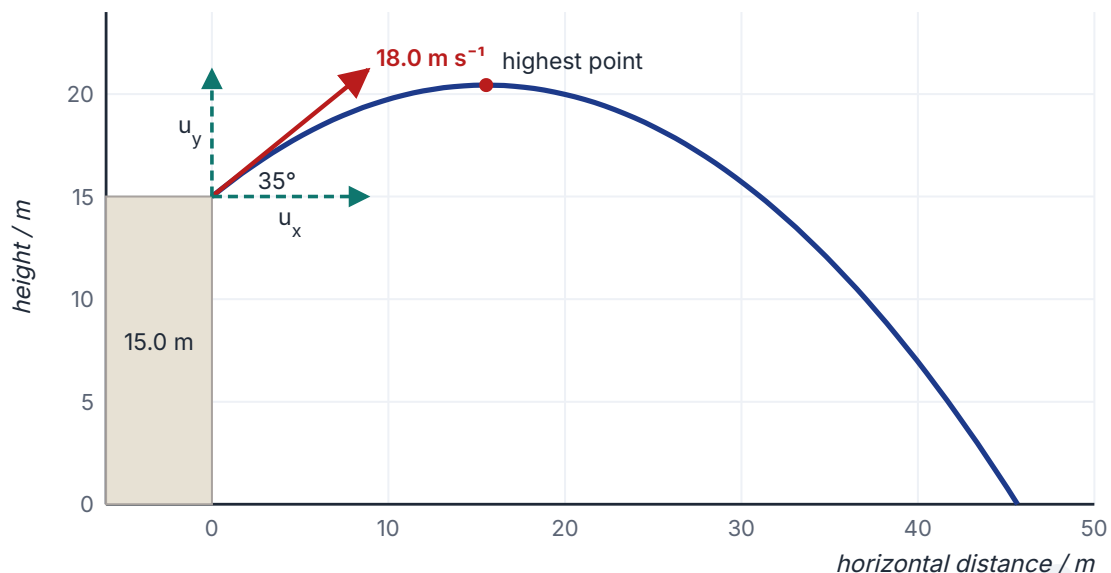
A.1 Projectile Motion simulation: change the launch angle, speed and height and watch the components and the range respond.

Three launch types you must handle

- **Horizontal launch:** $u_y = 0$; the fall time depends only on the height: $h = \frac{1}{2}gt^2$.
- **Above the horizontal:** $u_y = +u \sin \theta$; the body rises first.
- **Below the horizontal:** $u_y = -u \sin \theta$ (up positive); the body is already moving down at launch.



The red arrow is the launch velocity. The only thing that changes between the three cases is the sign (or absence) of the initial vertical component.



A ball kicked at 18.0 m s^{-1} at 35° above the horizontal from a 15.0 m cliff. The dashed arrows are the horizontal and vertical components of the launch velocity.

WORKED EXAMPLE 5 Hard · Determine

A ball is kicked from the edge of a cliff 15.0 m above level ground. It leaves the foot at 18.0 m s^{-1} at 35° above the horizontal. Fluid resistance is negligible.

Determine (a) the maximum height of the ball above the ground, (b) the time of flight, (c) the horizontal distance from the cliff where the ball lands and (d) the speed of the ball just before it lands.

Components: $u_x = 18.0 \cos 35^\circ = 14.74 \text{ m s}^{-1}$; $u_y = 18.0 \sin 35^\circ = 10.32 \text{ m s}^{-1}$. Carry these unrounded values through, and round only the final answers.

(a) At the top $v_y = 0$: $0 = 10.32^2 - 2(9.8)h \Rightarrow h = 5.43 \text{ m}$ above the cliff.
Height above ground = $15.0 + 5.43 = \mathbf{20.4 \text{ m}}$

(b) Up positive, landing at $y = -15.0 \text{ m}$: $-15.0 = 10.32t - 4.9t^2$.
Rearrange: $4.9t^2 - 10.32t - 15.0 = 0$. The positive root is $\mathbf{t = 3.1 \text{ s}}$ (3.095 s).

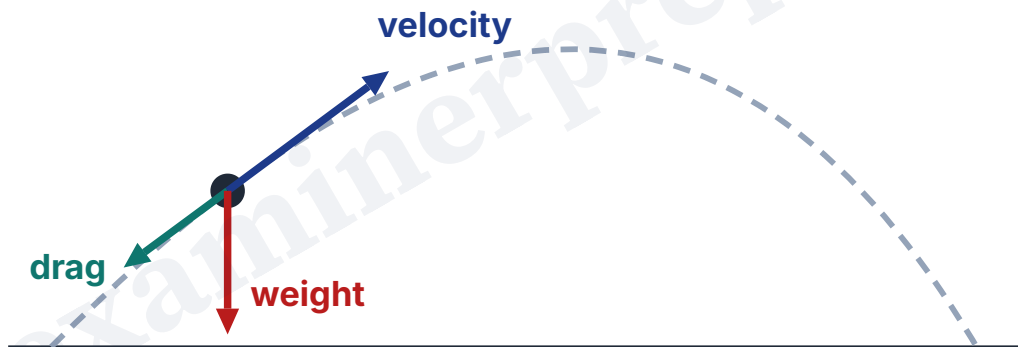
(c) $x = u_x t = 14.74 \times 3.095 = \mathbf{46 \text{ m}}$ (45.6 m)

(d) $v_y = 10.32 - 9.8(3.095) = -20.01 \text{ m s}^{-1}$; $v = \sqrt{14.74^2 + 20.01^2} = \mathbf{24.9 \text{ m s}^{-1}}$, at 54° below the horizontal.

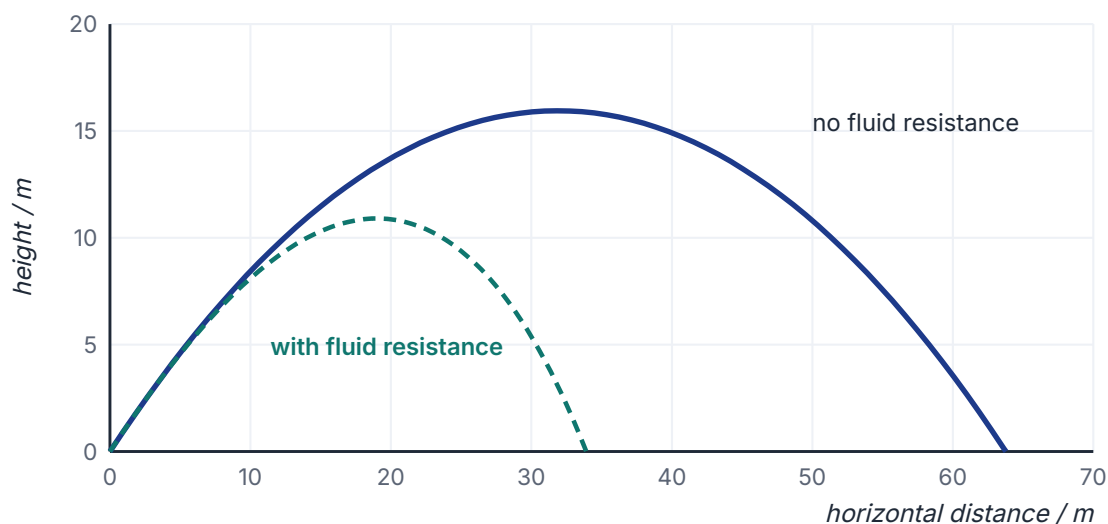
Faster route for (d), using energy (A.3): $\frac{1}{2}mv^2 = \frac{1}{2}mu^2 + mgh \Rightarrow v = \sqrt{18.0^2 + 2(9.8)(15.0)} = 24.9 \text{ m s}^{-1}$. Mass cancels and no time is needed.

How does fluid resistance affect motion?

Fluid resistance (drag) is the force exerted by a gas or liquid on a body moving through it. It acts **opposite to the velocity** and **increases with speed**. At IB level, the effect on projectiles is **qualitative only** — you will not be asked to calculate a path with drag.



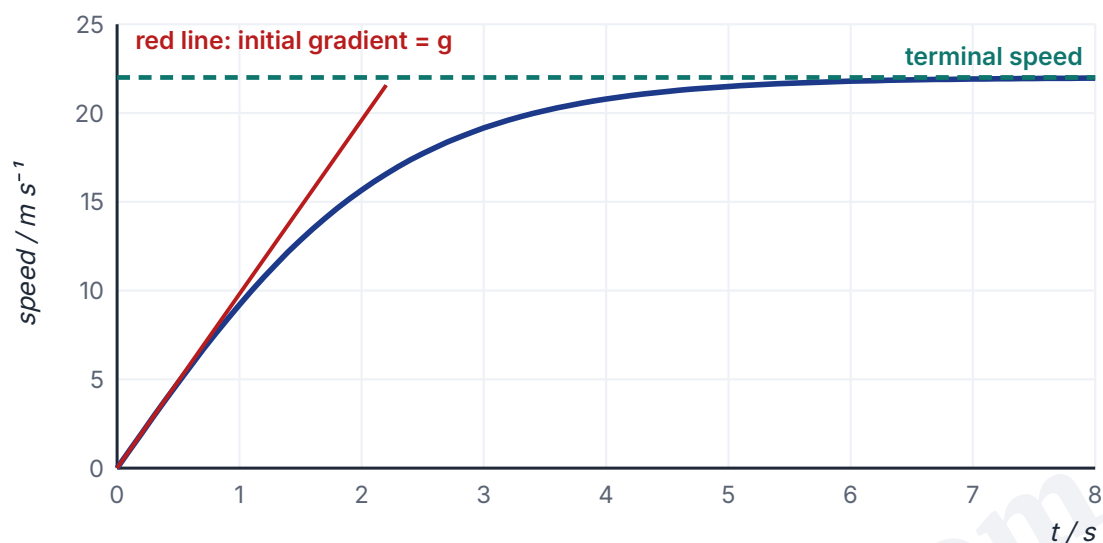
On the way up, drag acts backwards along the path, so it has a downward component that adds to the weight. On the way down it has an upward component.



The same launch (25 m s^{-1} at 45°) with and without fluid resistance. With drag the path is lower, shorter and steeper on the way down.

Feature	Effect of fluid resistance	Reason
Maximum height	lower	drag adds to weight on the way up, so the vertical velocity falls to zero sooner
Range	shorter	horizontal velocity decreases throughout the flight
Time of flight	shorter overall; the descent takes longer than the ascent	drag opposes weight on the way down, reducing the downward acceleration
Trajectory	no longer a symmetric parabola; descends more steeply	horizontal velocity has decreased by the time the body descends
Velocity	smaller at every point; lands with a lower speed than it was launched with	drag does negative work, transferring mechanical energy (kinetic plus gravitational potential) to internal energy of the fluid and body
Acceleration	no longer constant or exactly vertical; its vertical component is greater than g on the way up and less than g on the way down	the drag force changes in size and direction as the velocity changes

Terminal speed

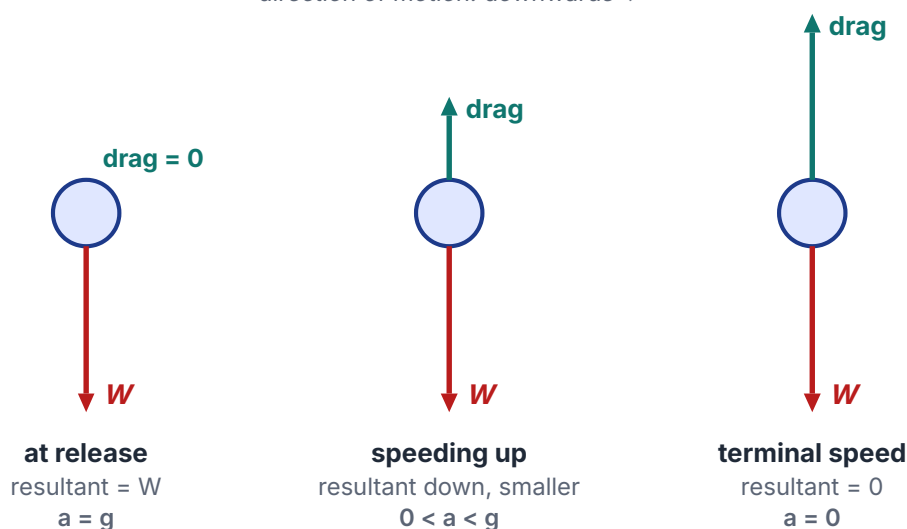


Speed-time graph for a body released from rest in air. The gradient starts at g and decreases to zero as the speed approaches the terminal speed.

- At release the speed is zero, so drag is zero and the acceleration is g .
- As speed increases, drag increases, so the resultant force — and the acceleration — decrease.
- When the upward forces (drag, plus buoyancy if significant) equal the weight, the resultant force is zero: the body moves at constant **terminal speed** with zero acceleration.

Terminal speed is reached when the drag force (plus any buoyancy) balances the weight, so the resultant force and the acceleration are zero.

direction of motion: downwards ↓



Free-body diagrams for a body falling from rest. Drag grows with speed until it balances the weight.

TRY IT YOURSELF

A.2 Terminal Velocity simulation: drop objects of different mass and shape and watch drag grow until it balances the weight.

Exam tips for A.1

EXAM TIP 1 — ARROWS ON A TRAJECTORY

When asked to draw the velocity of a projectile at a point, draw the arrow along the **tangent to the path**, starting at the point and pointing in the direction of motion. With no fluid resistance, the acceleration arrow is always **vertically downwards**, at every point including the top.

EXAM TIP 2 — "DECREASES" IS NOT ENOUGH

For "state how the acceleration changes" for a body approaching terminal speed, write that the acceleration **decreases to zero**. A bare "decreases" describes the trend but not the outcome, and it may not be credited.

EXAM TIP 3 — TIME COMES FROM THE VERTICAL

In a horizontal launch, the time in the air is set **only** by the height. A common error is to use the horizontal distance to find the time and then carry that wrong time into later parts.

EXAM TIP 4 — SHOW EVERY SUBSTITUTION

Later parts often use earlier answers. If your earlier value is wrong but you use it correctly, you can still earn the later marks through “error carried forward” — but only if your substitution is visible. A bare final number leaves nothing to credit.

EXAM TIP 5 — TANGENTS AND TRIANGLES

When finding a gradient from a curve, draw a tangent that touches (not cuts) the curve at the required point, and use a **large** triangle — at least half the graph width. Read coordinates from the tangent line, not from the curve.

Common misconceptions

Misconception	Why it is wrong	Correct idea
At the top of its flight a ball has zero acceleration.	Only the vertical velocity is zero there; the weight still acts.	Acceleration is g downwards throughout (no drag).
The horizontal velocity of a projectile decreases.	With no fluid resistance, no horizontal force acts.	u_x stays constant for the whole flight.
A heavier object falls faster.	All bodies have the same acceleration g in the absence of drag.	Mass matters only when fluid resistance is significant.
Negative acceleration means slowing down.	The sign depends on your chosen positive direction.	A body slows down when v and a have opposite signs.
Area under a v - t graph is always the distance.	Area below the axis is negative displacement.	Net area = displacement; sum of magnitudes = distance.
$\bar{v} = \frac{u+v}{2}$ works for any motion.	It relies on a straight-line v - t graph.	Use it only for uniform acceleration; otherwise $\bar{v} = \Delta s / \Delta t$.

How this topic connects

Projectiles by energy: finding a speed at a given height without the suvat equations

Whenever the question asks for a **speed** at a given height and fluid resistance is negligible. Kinetic plus gravitational potential energy is conserved, so $v = \sqrt{u^2 + 2gh}$ whatever the launch angle, where h is the vertical distance fallen below the launch point. Energy cannot give the direction of the velocity or any time, so for those you still need components and kinematics (see worked example 5).

Same method, different field: falling masses and charges in uniform fields

Both experience a constant force in a uniform field, so both have constant acceleration in one direction and constant velocity at right angles to it. If the initial velocity has a component perpendicular to the field, both follow parabolic paths, and both are analysed with the same component method. The difference is the source of the acceleration: g is the same for all masses, while for a charge $a = qE/m$ depends on the particle's charge-to-mass ratio (D.2, D.3).

Reading gradients and areas: what else a motion graph can tell you

Gradients and areas turn one measured relationship into another quantity: velocity from an $s-t$ graph, acceleration and displacement from a $v-t$ graph. Linearising a relationship makes this precise. For example, plotting s against t^2 for a body falling from rest gives a straight line through the origin with gradient $g/2$.

Tools & inquiry — measuring motion in the lab

- Hand timing has a reaction-time uncertainty of roughly 0.1–0.2 s, which is large for short falls. Light gates, data loggers or **video analysis** with a timer and a ruler in the frame reduce it dramatically.
- For a free-fall investigation, plot s against t^2 ; $g = 2 \times \text{gradient}$. A non-zero intercept points to a systematic error, such as a delay in release.
- In video analysis, keep the camera perpendicular to the plane of motion and far from it to reduce parallax.

Key equations

Equation	Use	In data booklet?
$v = \frac{\Delta s}{\Delta t}, a = \frac{\Delta v}{\Delta t}$	definitions; average values	no — learn them
$s = \frac{u + v}{2}t$	uniform a , when a is not needed	yes
$v = u + at$	uniform a , when s is not needed	yes
$s = ut + \frac{1}{2}at^2$	uniform a , when v is not needed	yes
$v^2 = u^2 + 2as$	uniform a , when t is not needed	yes
$u_x = u \cos \theta, u_y = u \sin \theta$	resolving a launch velocity	no — learn them

Check your understanding

1. A ball is thrown vertically upwards. State its velocity and its acceleration at the highest point.

Velocity: zero. Acceleration: 9.8 m s^{-2} vertically downwards — gravity still acts.

2. A runner completes one lap of a 400 m track in 80 s. Calculate the average speed and the average velocity.

Average speed = $400/80 = 5.0 \text{ m s}^{-1}$. Average velocity = 0, because the displacement after a full lap is zero.

3. A stone is dropped from rest and falls for 2.5 s. Calculate the distance fallen and its final speed. Ignore fluid resistance.

$s = \frac{1}{2}(9.8)(2.5)^2 = 31 \text{ m}$ (30.6 m); $v = 9.8 \times 2.5 = 25 \text{ m s}^{-1}$ (24.5 m s^{-1}).

4. A marble rolls off a table 1.25 m high at 3.0 m s^{-1} . How far from the table does it land?

Time from the vertical: $t = \sqrt{2(1.25)/9.8} = 0.51$ s. Horizontal distance = $3.0 \times 0.51 = 1.5$ m.

5. A body has a negative velocity and a positive acceleration. Is it speeding up or slowing down?

Slowing down — velocity and acceleration have opposite signs, so the magnitude of the velocity decreases.

Practise A.1 with exam-style questions

Original Paper 1A, 1B and 2 questions on kinematics, with full mark schemes. Tick the questions you want and print them as your own test.

SL A.1 questions

HL A.1 questions

Revise and explore

- Flashcards — choose IB Physics and filter to A.1 Kinematics. Free, no sign-up.
- A.1 Projectile Motion simulation
- A.1 Motion Graphs simulation
- A.2 Terminal Velocity simulation
- Full IB Physics question bank (all sub-topics, SL & HL)

Next: A.2 Forces and momentum →