IB DP PHYSICS · THEME A SPACE, TIME AND MOTION · A.1 · ~15 MIN READ

A.1 Kinematics

Distance and displacement, speed, velocity and acceleration, motion graphs, the suvat equations, free fall, projectiles launched at any angle, the qualitative effect of air resistance, and the Paper 1B graph skills behind measuring g.

Displacement & velocity | Motion graphs | suvat equations | Free fall | Projectile motion | Fluid resistance | Measuring g & uncertainties

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

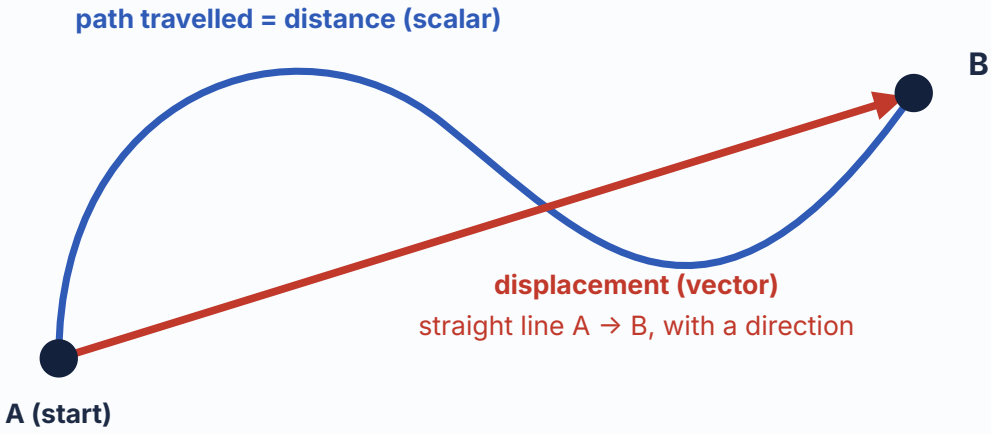
- **Kinematics describes motion** without asking what causes it. Position, velocity and acceleration are vectors: velocity is the rate of change of displacement, acceleration is the rate of change of velocity.
- **Graphs carry the physics:** the gradient of s–t is velocity, the gradient of v–t is acceleration, and the area under v–t is displacement.
- **For constant acceleration** use the four suvat equations from the data booklet. Choose a positive direction and stick to it; in free fall a = −9.8 m s^{-2} if up is positive.
- **A projectile is two motions at once:** constant velocity horizontally, constant acceleration g vertically, linked only by time. Air resistance lowers the height and the range and makes the path lopsided.
- **A.1 is the same at SL and HL.** There is no additional higher level content in this topic.

BY THE END YOU CAN

- Distinguish distance from displacement and speed from velocity, and find average and instantaneous values.
- Draw and interpret displacement–time, velocity–time and acceleration–time graphs, using gradients and areas.
- Choose and apply the equations of motion for uniform acceleration, including free fall.
- Solve projectile problems for launches that are horizontal, above the horizontal and below it.
- Describe qualitatively how fluid resistance changes a projectile's path.
- Linearise $s = \frac{1}{2}gt^2$, find g from a gradient and work out its uncertainty.

1 Describing motion

Distance, displacement, speed and velocity



A full lap of a 400 m track: distance = 400 m, displacement = 0.

Distance follows the path. Displacement only cares where you started and where you ended.

Distance — the total length of the path travelled. A scalar, in m.

Displacement — the change in position: the straight line from start to finish, with a direction. A vector, in m.

Speed — distance ÷ time. A scalar, in m s^{-1}.

Velocity — rate of change of displacement, $v = \Delta s/\Delta t$. A vector, in m s^{-1}.

Acceleration — rate of change of velocity, $a = \Delta v/\Delta t$. A vector, in m s^{-2}. Slowing down is an acceleration opposite to the velocity.

WORKED EXAMPLE

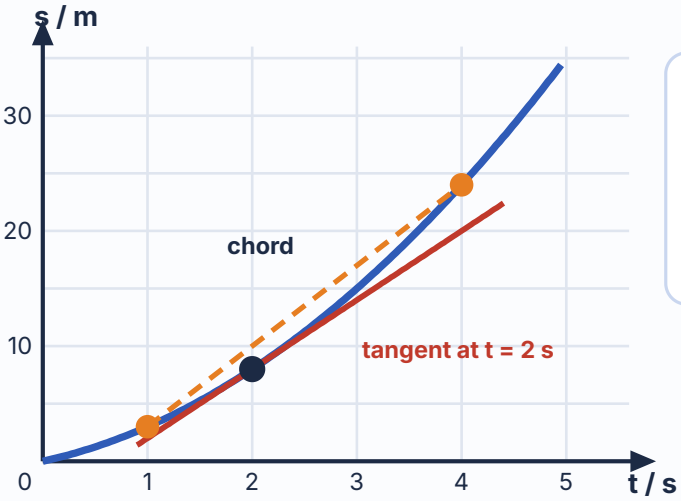
A runner goes 100 m east, then 40 m west, in 20 s. Find the distance, the displacement, the average speed and the average velocity.

1. distance = 100 + 40 = **140 m**
2. displacement = 100 − 40 = **60 m east**
3. average speed = 140/20 = **7.0 m s^{-1}**
4. **average velocity = 60/20 = 3.0 m s^{-1} east**

COMMON MISTAKE

Giving a velocity or displacement without a direction (or a sign). "3.0 m s^{-1}" is a speed; "3.0 m s^{-1} east" or "+3.0 m s^{-1}" is a velocity.

Average and instantaneous values



average velocity,
1 s to 4 s = 21/3 = 7 m s^{-1}
instantaneous velocity
at 2 s = tangent gradient
= 6 m s^{-1}

The chord gives the average velocity over an interval. The tangent gives the velocity at one instant.

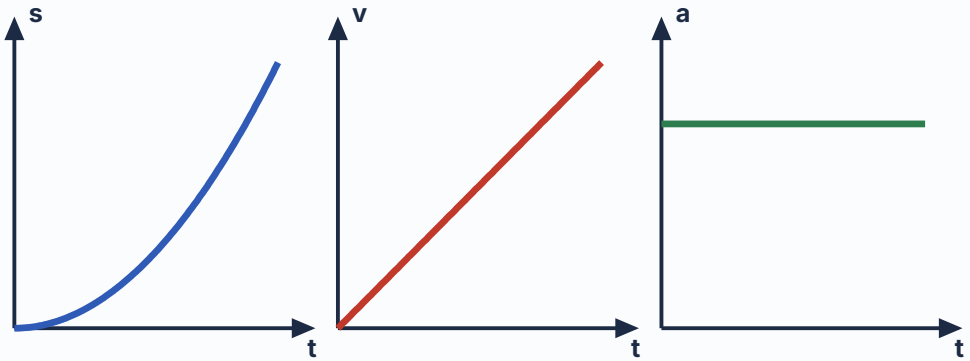
- **Average** velocity = total displacement ÷ total time = gradient of the chord on an s–t graph.
- **Instantaneous** velocity = gradient of the tangent at that instant: v = ds/dt. Likewise a = dv/dt. LEARN IT
- **Drawing a tangent:** use a long ruler, touch the curve at one point and make the line long. A longer triangle gives a smaller percentage uncertainty in the gradient.

LINKING QUESTION

The tangent gradient is exactly the derivative from maths. See IB Maths AA Differentiation for v = ds/dt and a = dv/dt done with calculus.

2 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

One motion, three graphs. Each graph is the gradient of the one before it.

Graph	Gradient gives	Area under it gives
displacement–time (s–t)	velocity	nothing useful
velocity–time (v–t)	acceleration	displacement
acceleration–time (a–t)	not needed	change in velocity

- **Uniform acceleration:** a straight v–t line. **Non-uniform acceleration:** a curved v–t line. Find the acceleration at a point from a tangent and the displacement by counting squares under the curve.
- **Area below the time axis** counts as **negative** displacement (moving backwards). Distance adds all the areas as positive; displacement adds them with signs.

WORKED EXAMPLE

A car accelerates uniformly from rest to 20 m s^{-1} in 8.0 s, travels at 20 m s^{-1} for 12 s, then brakes uniformly to rest in 5.0 s. Find the total distance and the average speed.

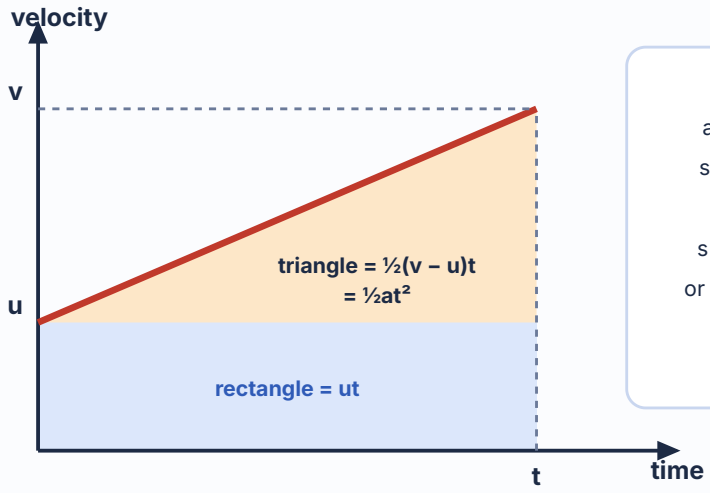
1. area 1 (triangle) = ½ × 8.0 × 20 = 80 m **M1**
2. area 2 (rectangle) = 12 × 20 = 240 m; area 3 (triangle) = ½ × 5.0 × 20 = 50 m
3. total distance = **370 m** **A1**
4. **average speed = 370/25 = 14.8 m s^{-1}** **A1**

COMMON MISTAKE

Reading the displacement off the height of a v–t graph. The height is the velocity. Displacement is the **area**.

3 Equations of motion

Where the suvat equations come from



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.

Gradient and area of a straight v–t line give two equations. The other two follow by algebra.

$v = u + at$ DATA BOOKLET

$s = ut + \frac{1}{2}at^2$ DATA BOOKLET

$v^2 = u^2 + 2as$ DATA BOOKLET

$$s = \frac{(u + v)t}{2}$$ DATA BOOKLET

s displacement, u initial velocity, v final velocity, a acceleration, t time

- **Only for constant acceleration** in a straight line. If a changes, use the graph (gradient and area) instead.
- **Choose the equation that leaves out the quantity you neither know nor need:**

Equation	does not contain
$v = u + at$	s
$s = ut + \frac{1}{2}at^2$	v
$v^2 = u^2 + 2as$	t
$s = \frac{1}{2}(u + v)t$	a

WORKED EXAMPLE

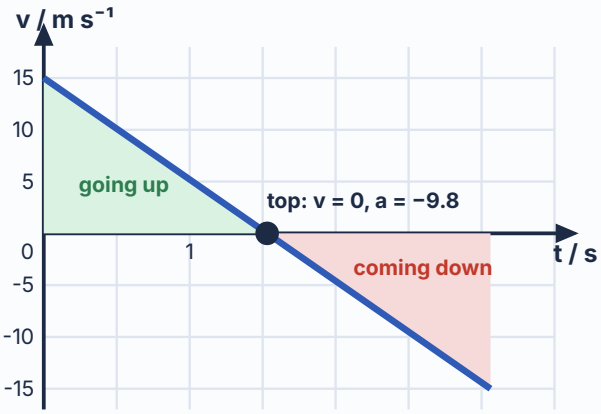
A car travelling at 25 m s^{-1} brakes to rest in 40 m. Find its deceleration and the time taken.

1. u = 25, v = 0, s = 40; t is not needed, so use $v^2 = u^2 + 2as$ M1
2. $0 = 625 + 80a \Rightarrow a = -7.8$ m s^{-2} (deceleration **7.8 m s^{-2}**) A1
3. **$v = u + at \Rightarrow t = 25/7.81 = 3.2$ s** A1

Free fall and the sign convention



green area = red area:
back to the start



gradient = −9.8 m s^{-2} everywhere, even at the top

The v–t line keeps the same gradient the whole time, through the top and on the way down.

$g = 9.8\ \text{m s}^{-2}$ DATA BOOKLET

acceleration of free fall near Earth's surface, always directed downwards

- **Pick a positive direction** at the start and write it down ("up is +"). Then $a = -9.8\ \text{m s}^{-2}$, velocities going down are negative, and points below the launch have negative s.

WORKED EXAMPLE

A ball is thrown vertically upwards at 15 m s^{-1} from 1.5 m above the ground. Find its maximum height above the ground and the time it takes to hit the ground.

1. up is +, $a = -9.8\ \text{m s}^{-2}$
2. at the top $v = 0$: $0 = 15^2 - 2(9.8)s \Rightarrow s = 11.5$ m, so **13.0 m above the ground** M1 A1
3. it hits the ground at $s = -1.5$ m: $-1.5 = 15t - 4.9t^2$ M1
4. $4.9t^2 - 15t - 1.5 = 0 \Rightarrow t = \dfrac{15 + \sqrt{(225 + 29.4)}}{9.8}$ **= 3.16 s (reject the negative root)** A1

COMMON MISTAKE

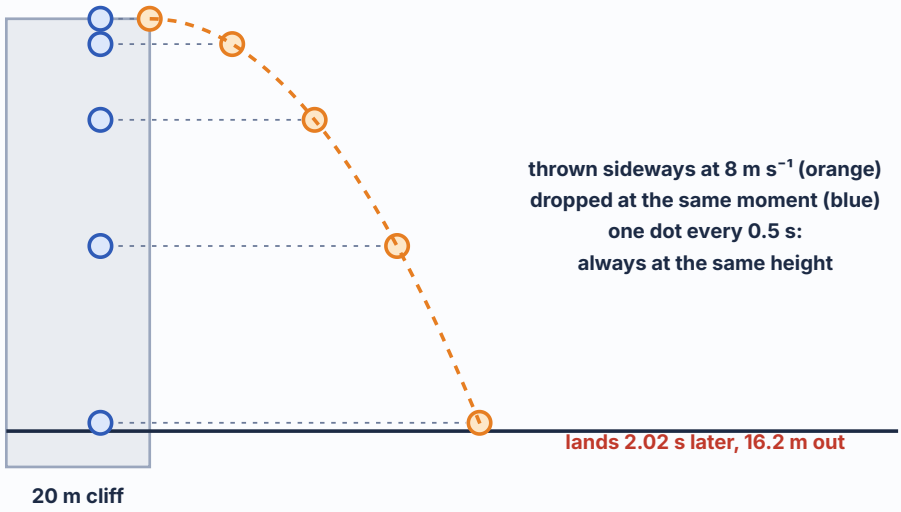
Saying the acceleration is zero at the top. Only the **velocity** is zero there. The acceleration is still 9.8 m s^{-2} downwards, which is why the ball comes back.

EXAM TIP

A height question with no time in it is a $v^2 = u^2 + 2as$ question. A "when does it land" question usually becomes a quadratic in t: keep the positive root.

4 Projectile motion

Two independent motions



The thrown ball moves sideways at a steady rate, but its fall matches the dropped ball exactly.

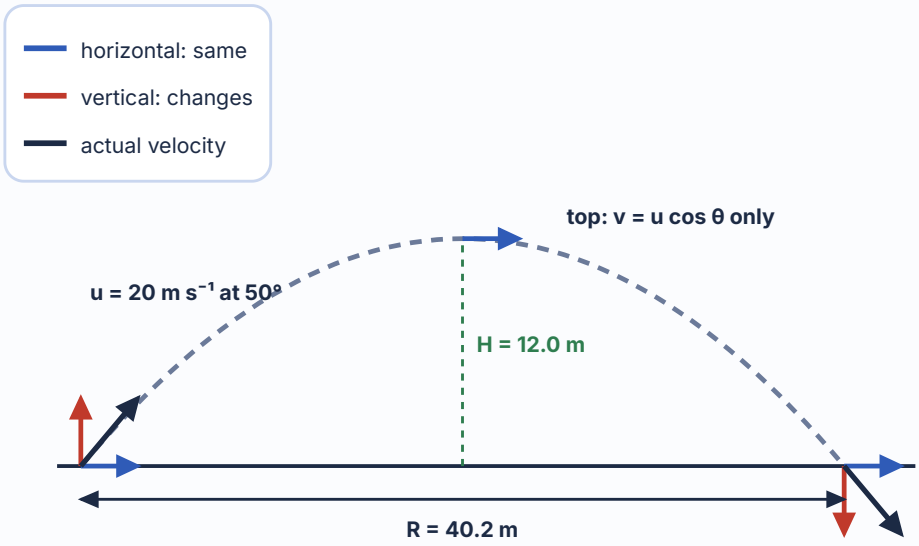
- **Horizontal:** no force (without air resistance), so **constant velocity**: $x = u_x t$.
- **Vertical:** constant acceleration g downwards, so use suvat with u_y.
- **Time links them.** Find t from one direction, then use it in the other.
- Launch at speed u and angle θ above the horizontal: **$u_x = u\cos\theta$** and **$u_y = u\sin\theta$**.

WORKED EXAMPLE

A ball rolls off a 20 m high cliff at 8.0 m s^{-1}. Find how far out it lands and its velocity on impact.

1. vertical: $u_y = 0$, s = 20 m down: $20 = \frac{1}{2}(9.8)t^2 \Rightarrow t = 2.02$ s M1 A1
2. horizontal: $x = 8.0 \times 2.02 =$ **16.2 m** A1
3. at impact $v_y = 9.8 \times 2.02 = 19.8$ m s^{-1} down and $v_x = 8.0$ m s^{-1} M1
4. **speed = $\sqrt{(8.0^2 + 19.8^2)} = 21.4$ m s^{-1}, at $\arctan(19.8/8.0) = 68°$ below the horizontal** A1

Launched at an angle



The horizontal arrow never changes. The vertical arrow shrinks to zero at the top and grows again downwards.

WORKED EXAMPLE

A ball is kicked at 20 m s^{-1} at 50° above the horizontal on level ground. Find the maximum height, the time of flight and the range.

1. $u_x = 20 \cos 50° = 12.9$ m s^{-1}; $u_y = 20 \sin 50° = 15.3$ m s^{-1} M1
2. top: $0 = 15.3^2 - 2(9.8)H \Rightarrow$ **H = 12.0 m** A1
3. time to top = 15.3/9.8 = 1.56 s, so time of flight = **3.13 s** (symmetric path) A1
4. **range = 12.9 × 3.13 = 40.2 m** A1

WORKED EXAMPLE

A stone is thrown from the top of a 30 m tower at 10 m s^{-1} at 20° below the horizontal. How far from the tower does it land?

1. down is +: $u_y = 10 \sin 20° = 3.42$ m s^{-1}, a = 9.8 m s^{-2}, s = 30 m M1
2. $30 = 3.42t + 4.9t^2 \Rightarrow t = 2.15$ s A1
3. $u_x = 10 \cos 20° = 9.40$ m s^{-1}
4. **x = 9.40 × 2.15 = 20.2 m** A1

- **At the top** the velocity is horizontal, v = u cos θ, not zero.
- **On level ground** without air resistance, the path is symmetric and the range is greatest at **45°**. Angles that add to 90° (30° and 60°) give equal ranges.
- **The trajectory is a parabola.** You do not need its equation, and the range formula R = u^2 sin 2θ / g is not in the data booklet: derive the range from u_x × time of flight.

COMMON MISTAKE

Using u instead of u cos θ for the horizontal motion, or forgetting that u_y is negative (or positive, if down is +) for a launch below the horizontal.

Fluid resistance (qualitative)



The red path is not a parabola. You only need to describe it, not calculate it.

Air resistance grows with speed and always acts against the velocity, so it slows the horizontal motion as well as the vertical one.

- **What changes with air resistance:** lower maximum height; shorter range; the horizontal velocity decreases instead of staying constant; the path is no longer symmetric and comes down more steeply; the way down takes longer than the way up; the best launch angle for range is less than 45°.
- **Falling objects** reach a terminal speed when the drag force equals the weight, so the acceleration falls to zero. The forces are covered in A.2.

COMMON MISTAKE

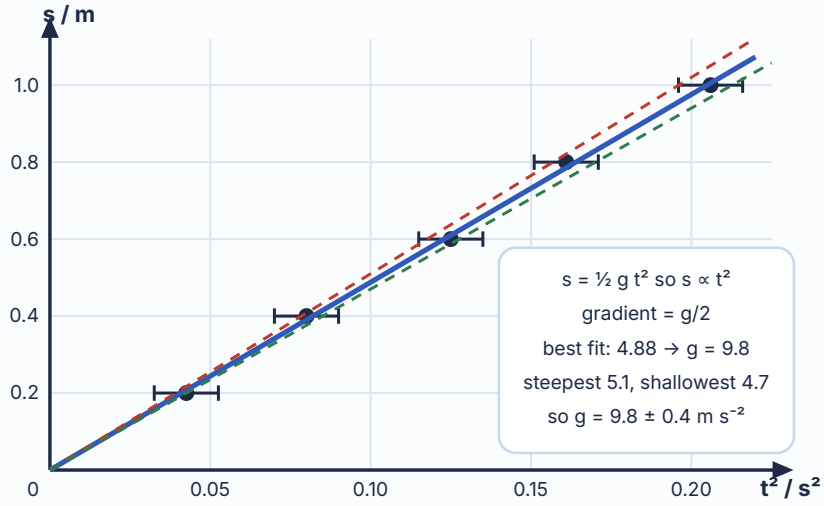
Saying air resistance acts only horizontally, or only upwards. It acts **opposite to the velocity**, so its direction changes along the path.

EXAM TIP

Exam questions on this point ask you to **sketch** the new path on the same axes and **describe** the changes. No calculation is expected. Draw it lower, shorter and steeper at the end.

5 Data skills for Paper 1B

Measuring g with a straight-line graph



Error bars show the uncertainty in t^2. Draw the best line and the steepest and shallowest lines through all bars.

Plotting s against t^2 turns the curve $s = \frac{1}{2}gt^2$ into a straight line through the origin with gradient g/2.

- **Linearise:** compare $s = \frac{1}{2}gt^2$ with $y = mx$. Plot **y = s** and **$x = t^2$**, so the gradient $m = g/2$ and **g = 2 × gradient**.
- **Error bars:** if t has an uncertainty, t^2 has **twice the percentage uncertainty**. Draw the best-fit line, then the steepest and the shallowest lines that pass through every error bar.
- **Uncertainty in g:** $\Delta g \approx \frac{1}{2}(g_{max} - g_{min})$, using the gradients of the steepest and shallowest lines.

WORKED EXAMPLE

A ball falls 1.20 ± 0.01 m in 0.50 ± 0.01 s from rest. Find g and its uncertainty.

1. $g = 2s/t^2 = 2(1.20)/0.50^2 = 9.6\ m\ s^{-2}$ A1
2. % uncertainty: s gives 0.83 %, t^2 gives 2 × 2.0 % = 4.0 % M1
3. total = 4.8 %, and 4.8 % of 9.6 is 0.46
4. **$g = 9.6 \pm 0.5\ m\ s^{-2}$** A1

- **Systematic error:** a line that misses the origin points to one. A positive intercept on the t^2 axis (every time too long) often comes from reaction time, or a delay in the release mechanism. Random errors scatter the points; systematic errors shift them all.
- **Nature of science:** Galileo slowed free fall down on a gentle ramp so that he could time it, and found that distance grows with time squared. Linearising data the same way is still how physicists test a model.

IDEA FOR YOUR IA / EXPLORATION

Measure how the range of a small ball depends on launch angle with a simple launcher and phone video (Tracker is free). Compare your best angle with the 45° prediction and use air resistance to explain the difference.

LINKING QUESTION

For a falling object, $v^2 = u^2 + 2as$ and conservation of energy (A.3) give the same speed: $\frac{1}{2}mv^2 = \frac{1}{2}mu^2 + mgh$. Which approach still works if the path is curved?

Test yourself — cover the answers first

QUICK CHECK

1. A runner completes one lap of a 400 m track. Give the distance and the displacement.
2. What does the gradient of a velocity–time graph represent?
3. A car accelerates uniformly from 4.0 m s^{-1} to 16 m s^{-1} in 6.0 s. Find a and the distance travelled.
4. What are the velocity and the acceleration of a ball at the top of a vertical throw?
5. Without air resistance, what happens to a projectile's horizontal velocity?
6. One ball is dropped and another is thrown horizontally from the same height at the same moment. Which lands first?
7. Which launch angle gives the greatest range on level ground without air resistance?
8. How does air resistance change the maximum height and the range?

EXAM-STYLE

9. A stone is thrown at 12 m s^{-1} at 35° above the horizontal from the edge of a 25 m cliff. Find the time of flight and how far from the foot of the cliff it lands.
10. A lift starts from rest, accelerates at 1.2 m s^{-2} for 2.5 s, moves at constant velocity for 6.0 s, then decelerates uniformly to rest in 2.0 s. Find the total distance.
11. A student plots s against t^2 for a falling ball and gets a best-fit gradient of 4.85 m s^{-2}, with steepest and shallowest gradients of 5.05 and 4.65 m s^{-2}. Find g with its uncertainty.

Show answers

1. 400 m and 0
2. acceleration
3. $a = 2.0\ m\ s^{-2}$; $s = \frac{1}{2}(4.0 + 16)(6.0) = 60\ m$
4. $v = 0$; $a = 9.8\ m\ s^{-2}$ downwards
5. it stays constant
6. both together: their vertical motions are identical
7. 45°
8. both decrease
9. $u_y = 12 \sin 35° = 6.88\ m\ s^{-1}$ up; $u_x = 12 \cos 35° = 9.83\ m\ s^{-1}$

   up is +: $-25 = 6.88t - 4.9t^2$

   $t = \frac{6.88 + \sqrt{(6.88^2 + 490)}}{9.8}$ = **3.07 s**

   $x = 9.83 \times 3.07$ = **30.2 m**
10. top speed = $1.2 \times 2.5 = 3.0\ m\ s^{-1}$

    areas: $\frac{1}{2}(2.5)(3.0) + 6.0(3.0) + \frac{1}{2}(2.0)(3.0) = 3.75 + 18 + 3.0$

    total = **24.8 m** (25 m)
11. $g = 2 \times 4.85 = 9.7\ m\ s^{-2}$

    $\Delta g = \frac{1}{2}(10.1 - 9.3) = 0.4$

    $g = 9.7 \pm 0.4\ m\ s^{-2}$

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