Space, Time and Motion

IB SL Study Guide

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Aligned to IB Physics 2025 syllabus — Theme A: Space, Time and Motion (first assessment 2025)

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Videos on this page: Watch: Kinematics and SUVAT Equations · Watch: Newton's Laws of Motion

Section 1: Kinematics

Displacement, Velocity, and Acceleration

Kinematics is the study of motion without reference to the forces causing it.

MEMORISE THIS

Key Definitions:

- **Displacement** (s): change in position; a vector quantity, measured in metres (m)
- **Speed**: distance travelled per unit time; a scalar (no direction)
- **Velocity** (v): displacement per unit time; a vector, measured in $\mathrm{m\ s^{-1}}$
- **Acceleration** (a): rate of change of velocity; a vector, measured in $\mathrm{m\ s^{-2}}$

$v = \frac{\Delta s}{\Delta t} \qquad a = \frac{\Delta v}{\Delta t}$

EXAM ALERT

Vector vs Scalar — a guaranteed Paper 1 trap. Displacement, velocity, and acceleration are vectors. Distance and speed are scalars. An object moving in a circle at constant speed has constant speed but changing velocity (direction is changing), so it IS accelerating.

The SUVAT Equations

For uniform (constant) acceleration, the five kinematic variables are linked by the **suvat equations**. These are provided in the IB Physics data booklet.

Symbol	Quantity	Unit
s	displacement	m
u	initial velocity	m s^{-1}
v	final velocity	m s^{-1}
a	acceleration	m s^{-2}
t	time	s

MEMORISE THIS

SUVAT Equations (all in the data booklet):

$v = u + at$

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

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

$s = \frac{1}{2}(u + v)t$

Strategy: identify the three knowns and the one unknown. Choose the equation that contains those four variables.

WORKED EXAMPLE

Worked Example A1 — Braking car:

A car travelling at 24 m s^{-1} applies the brakes and decelerates uniformly at 6.0 m s^{-2}. Find: (a) the time to stop; (b) the stopping distance.

Given: $u = 24 \text{ m s}^{-1}, v = 0, a = -6.0 \text{ m s}^{-2}$

(a) Use $v = u + at$:

$0 = 24 + (-6.0)t \implies t = \frac{24}{6.0} = 4.0 \text{ s}$

(b) Use $v^2 = u^2 + 2as$:

$0 = 24^2 + 2(-6.0)s \implies s = \frac{576}{12} = 48 \text{ m}$

Motion Graphs

Three graph types appear repeatedly in IB exams: displacement-time (s-t), velocity-time (v-t), and acceleration-time (a-t).

Graph	Gradient gives	Area gives
s-t	velocity	—
v-t	acceleration	displacement
a-t	—	change in velocity

⚠ EXAM ALERT

Graph gradients cost marks every session. On a v-t graph, a **negative gradient** means deceleration (acceleration directed opposite to velocity). The area under a v-t graph is displacement — it can be negative if the object moves backward. Always check the sign convention you have set up.

Projectile Motion

A projectile moves under gravity alone after launch. The key insight: **horizontal and vertical motions are independent**.

MEMORISE THIS

Projectile motion rules:

- Horizontal: constant velocity, $a_x = 0$, so $x = u_x t$
- Vertical: constant acceleration downward, $a_y = -g = -9.81\ \text{m s}^{-2}$
- At maximum height: $v_y = 0$
- Range is maximised at a launch angle of 45° (in the absence of air resistance)

WORKED EXAMPLE

Worked Example A2 — Projectile:

A ball is launched horizontally from a cliff of height $45\ \text{m}$ at $20\ \text{m s}^{-1}$. Find the horizontal distance travelled. Take $g = 9.81\ \text{m s}^{-2}$.

Vertical (to find time of flight):

$$s = ut + \frac{1}{2}at^2 \implies 45 = 0 + \frac{1}{2}(9.81)t^2$$

$$t = \sqrt{\frac{2\times 45}{9.81}} = \sqrt{9.17} \approx 3.03\ \text{s}$$

Horizontal:

$$x = u_x t = 20 \times 3.03 \approx 61\ \text{m}$$

IB TIP

Data booklet reference: $g = 9.81\ \text{m s}^{-2}$ (some questions specify $g = 10\ \text{m s}^{-2}$ — use whichever the question states). The suvat equations are in the data booklet under "Mechanics".

▸**Watch: Kinematics and SUVAT Equations** VIDEO

Section 2: Forces and Newton's Laws

Newton's Three Laws

MEMORISE THIS

Newton's Laws (state these precisely in essay-style answers):

1. **First Law (Inertia):** An object remains at rest or moves with constant velocity unless acted upon by a resultant (net) force.
2. **Second Law:** The net force on an object equals the rate of change of momentum. For constant mass: $F_{\text{net}} = ma$
3. **Third Law:** If object A exerts a force on object B, then object B exerts an equal and opposite force on object A.

EXAM ALERT

Newton's Third Law pairs are always on different objects. A common mistake: students say "weight and normal force are a Newton's Third Law pair." They are NOT — they act on the same object (the book/person). The true pair of weight (Earth pulling book) is the book pulling Earth upward by the same magnitude.

Free Body Diagrams

A free body diagram (FBD) shows all forces acting **on a single object**, with arrows indicating direction and relative magnitude.

Common forces:

Force	Symbol	Direction
Weight / gravity	$W = mg$	Vertically downward
Normal (contact) force	N or F_N	Perpendicular to surface
Friction	f or F_f	Parallel to surface, opposing motion
Tension	T	Along string/rope, away from object
Air resistance / drag	F_D	Opposing velocity

IB TIP

Always draw FBDs with a dot representing the object. Arrows should start from the dot. Label each force clearly. IB mark schemes award a mark for each correctly drawn, labelled force.

Friction

There are two types of friction, both opposing relative motion:

$$F_{\text{static, max}} = \mu_s N \qquad F_{\text{dynamic}} = \mu_d N$$

where μ_s (static coefficient) and μ_d (dynamic coefficient) are dimensionless constants, and N is the normal force.

MEMORISE THIS

Key facts about friction:

- Static friction acts on stationary objects; it can have any value from zero up to $\mu_s N$
- Dynamic (kinetic) friction acts on sliding objects and has the fixed value $\mu_d N$
- $\mu_s > \mu_d$ always — it is harder to start an object moving than to keep it moving

WORKED EXAMPLE

Worked Example B1 — Object on a slope:

A 5.0 kg block rests on a slope inclined at 30° to the horizontal. The coefficient of static friction is 0.60. Determine whether the block slides.

Weight components: $W_\parallel = mg\sin 30^\circ = 5.0 \times 9.81 \times 0.50 = 24.5$ N

Normal force: $N = mg\cos 30^\circ = 5.0 \times 9.81 \times 0.866 = 42.5$ N

Maximum static friction: $F_{s,\max} = \mu_s N = 0.60 \times 42.5 = 25.5$ N

Since $W_\parallel = 24.5\text{ N} < F_{s,\max} = 25.5\text{ N}$, the block does **not** slide.

Equilibrium

An object is in **translational equilibrium** when the vector sum of all forces is zero:

$$\sum \vec{F} = 0 \implies F_{\text{net}} = 0$$

This does not mean the object is stationary — it may be moving at constant velocity (Newton's First Law).

EXAM ALERT

Resolving forces into components is essential. For any equilibrium problem, resolve into two perpendicular directions (usually horizontal and vertical) and set each sum equal to zero. Draw the FBD first — every time.

▸**Watch: Newton's Laws of Motion** VIDEO

Section 3: Work, Energy, and Power

Work Done

Work is done when a force causes displacement in the direction of the force.

$$W = Fs\cos\theta$$

where F is the applied force, s is displacement, and θ is the angle between $\vec{F}$ and $\vec{s}$.

MEMORISE THIS

Units: Work is measured in joules (J), where $1 \text{ J} = 1 \text{ N m}$.

- If $\theta = 0^\circ$: $W = Fs$ (maximum — force and displacement in same direction)
- If $\theta = 90^\circ$: $W = 0$ (no work done — e.g. circular motion, normal force on horizontal surface)
- If $\theta = 180^\circ$: $W = -Fs$ (negative work — friction removing energy)

Forms of Mechanical Energy

MEMORISE THIS

Kinetic energy: $E_k = \frac{1}{2}mv^2$

Gravitational potential energy (near Earth's surface): $E_p = mgh$

Elastic potential energy (ideal spring): $E_{el} = \frac{1}{2}kx^2$

where k is the spring constant (N/m) and x is extension or compression from equilibrium.

Conservation of Energy and the Work-Energy Theorem

The **work-energy theorem** states:

$$W_{\text{net}} = \Delta E_k$$

The net work done on an object equals the change in its kinetic energy.

Conservation of mechanical energy applies when only conservative forces do work (no friction, no air resistance):

$$E_k + E_p = \text{constant}$$

WORKED EXAMPLE

Worked Example C1 — Roller-coaster loop:

A roller-coaster car of mass 800 kg starts from rest at a height of 40 m. Assuming no friction, find the speed at the bottom of the drop.

Using conservation of energy:

$$mgh = \frac{1}{2}mv^2$$

$$v = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 40} = \sqrt{784.8} \approx 28 \text{ m s}^{-1}$$

⚠ EXAM ALERT

IB frequently asks for "explain why the actual speed would be less." Always state: friction and air resistance convert some mechanical energy into thermal energy (internal energy of the system), so less kinetic energy is available at the bottom.

Power and Efficiency

$P = \frac{W}{t} = Fv$

$\text{efficiency} = \frac{P_{\text{useful output}}}{P_{\text{total input}}} \times 100\%$

IB TIP

Data booklet reference: $W = Fs\cos\theta$, $E_k = \frac{1}{2}mv^2$, $E_p = mgh$, $E_{el} = \frac{1}{2}kx^2$, $P = \frac{W}{t}$ are all in the data booklet. $P = Fv$ can be derived from these.

Section 4: Momentum and Impulse

Momentum

Linear momentum is a vector quantity:

$p = mv$

SI unit: kg m s^{-1}, equivalent to N s.

Newton's Second Law — Impulse Form

$F_{\text{net}} = \frac{\Delta p}{\Delta t} \implies F\Delta t = \Delta p = \text{Impulse}$

Impulse (J or $F\Delta t$) equals the change in momentum. On a force-time graph, the area under the curve gives the impulse.

MEMORISE THIS

Impulse-momentum theorem:

$\text{Impulse} = \Delta p = mv - mu$

The longer the contact time for a given change in momentum, the smaller the average force. This is the physics behind crash helmets, crumple zones, and catching a ball by "giving" with your hands.

Conservation of Momentum

In a closed system (no external forces), total momentum is conserved:

$\sum p_{\text{before}} = \sum p_{\text{after}}$

MEMORISE THIS

Types of collision:

Type	Kinetic energy	Momentum
Elastic	Conserved	Conserved
Inelastic	Not conserved (some converted to thermal/sound)	Conserved
Perfectly inelastic	Maximum loss (objects stick together)	Conserved

Momentum is conserved in ALL collisions. Kinetic energy is conserved only in elastic collisions.

WORKED EXAMPLE

Worked Example D1 — Perfectly inelastic collision:

A 3.0 kg trolley moving at 4.0 m s^{-1} collides with a stationary 2.0 kg trolley and they stick together. Find the velocity after the collision.

$$m_1 u_1 + m_2 u_2 = (m_1 + m_2)v$$

$$3.0 \times 4.0 + 2.0 \times 0 = 5.0 \times v$$

$$v = \frac{12.0}{5.0} = 2.4 \text{ m s}^{-1}$$

Check kinetic energy change:

$$E_{k,\text{before}} = \frac{1}{2}(3.0)(4.0)^2 = 24 \text{ J}$$

$$E_{k,\text{after}} = \frac{1}{2}(5.0)(2.4)^2 = 14.4 \text{ J}$$

Energy lost = 9.6 J (converted to thermal and sound energy — inelastic collision confirmed).

WORKED EXAMPLE

Worked Example D2 — Explosion (recoil):

A stationary rifle of mass 3.5 kg fires a bullet of mass 0.010 kg at 400 m s^{-1}. Find the recoil velocity of the rifle.

Initial total momentum = 0 (system at rest).

$$0 = m_{\text{bullet}} v_{\text{bullet}} + m_{\text{rifle}} v_{\text{rifle}}$$

$$0 = 0.010 \times 400 + 3.5 \times v_{\text{rifle}}$$

$$v_{\text{rifle}} = -\frac{4.0}{3.5} \approx -1.1 \text{ m s}^{-1}$$

The negative sign means the rifle recoils in the opposite direction to the bullet.

⚠ **EXAM ALERT**

Sign conventions in momentum questions: establish a positive direction at the start and stick to it. Objects moving in the negative direction get a negative velocity. A common error is forgetting to negate the velocity of one object in a head-on collision.

IB TIP

Data booklet reference: $p = mv$ and $F = \frac{\Delta p}{\Delta t}$ are both in the data booklet. The conservation of momentum principle itself is not a formula — it must be stated as a principle.

Section 5: Circular Motion

Uniform Circular Motion

An object moving in a circle at constant speed is **not** in equilibrium — its velocity direction is continuously changing, so it has an acceleration.

Centripetal acceleration is directed toward the centre of the circle:

$$a_c = \frac{v^2}{r} = \omega^2 r$$

where ω is the angular velocity in radians per second (rad s^{-1}).

Centripetal force — the net force required to maintain circular motion:

$$F_c = ma_c = \frac{mv^2}{r} = m\omega^2 r$$

⚠ **EXAM ALERT**

"Centripetal force" is NOT a new type of force. It is the label for whatever force (gravity, tension, friction, normal force) is providing the inward acceleration. In a banked curve question, state: "the horizontal component of the normal force provides the centripetal force."

MEMORISE THIS

Useful circular motion relationships:

- Period: $T = \frac{2\pi r}{v} = \frac{2\pi}{\omega}$
- Frequency: $f = \frac{1}{T}$
- Angular velocity: $\omega = 2\pi f = \frac{2\pi}{T}$

Banked Curves

On a banked road inclined at angle θ, at the design speed no friction is needed:

$$\tan\theta = \frac{v^2}{rg}$$

WORKED EXAMPLE

Worked Example E1 — Banked curve:

A road is banked at 15° for a curve of radius $80\ \mathrm{m}$. Find the design speed.

$v = \sqrt{rg\tan\theta} = \sqrt{80 \times 9.81 \times \tan 15^\circ}$

$v = \sqrt{80 \times 9.81 \times 0.268} = \sqrt{210.4} \approx 14.5\ \mathrm{m\ s^{-1}}$

Vertical Circles

In a vertical circle, the centripetal acceleration changes at each point because the contribution from gravity varies.

At the top of a loop (minimum speed condition — $N = 0$):

$mg = \frac{mv_{\text{min}}^2}{r} \implies v_{\text{min}} = \sqrt{gr}$

At the bottom of a loop (normal force is maximum):

$N - mg = \frac{mv^2}{r} \implies N = mg + \frac{mv^2}{r}$

IB TIP

Data booklet reference: $a = \frac{v^2}{r}$, $F = \frac{mv^2}{r}$, and $\omega = \frac{v}{r}$ are all in the data booklet under "Circular motion."

Section 6: Gravitational Fields

Newton's Law of Universal Gravitation

Any two masses attract each other with a gravitational force:

$F_g = \frac{Gm_1m_2}{r^2}$

where $G = 6.67 \times 10^{-11}\ \mathrm{N\ m^2\ kg^{-2}}$ is the universal gravitational constant, and r is the distance between the centres of the masses.

EXAM ALERT

r is centre-to-centre, not surface-to-surface. For a satellite orbiting at height h above a planet of radius R, use $r = R + h$. This is a very common error in Paper 2 calculations.

Gravitational Field Strength

The gravitational field strength g at distance r from a mass M:

$g = \frac{GM}{r^2}$

Near Earth's surface, $g \approx 9.81 \text{ m s}^{-2}$.

The gravitational field strength is identical numerically to the gravitational acceleration experienced by a test mass.

Orbital Mechanics

For a satellite in a circular orbit of radius r around a planet of mass M, the gravitational force provides the centripetal force:

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

Solving for orbital speed:

$$v = \sqrt{\frac{GM}{r}}$$

Orbital period (from $v = \frac{2\pi r}{T}$):

$$T^2 = \frac{4\pi^2 r^3}{GM}$$

This is **Kepler's Third Law** for circular orbits.

MEMORISE THIS

Geostationary orbit: a satellite with orbital period = 24 hours (same as Earth's rotation) appears stationary above a fixed point on the equator. Used for telecommunications and weather satellites. Altitude $\approx 36{,}000$ km above Earth's surface.

Escape Velocity

The minimum launch speed needed to escape a planet's gravitational field (reaching $r \to \infty$ with zero velocity):

$$v_{\text{esc}} = \sqrt{\frac{2GM}{R}}$$

where R is the planet's radius.

WORKED EXAMPLE

Worked Example F1 — Orbital speed:

Find the orbital speed of the International Space Station (ISS), orbiting at 400 km above Earth's surface.

Given: $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, $M_E = 5.97 \times 10^{24}$ kg, $R_E = 6.37 \times 10^6$ m

$r = R_E + h = 6.37 \times 10^6 + 4.00 \times 10^5 = 6.77 \times 10^6$ m

$v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67\times10^{-11}\times5.97\times10^{24}}{6.77\times10^6}}$

$v = \sqrt{\frac{3.98\times10^{14}}{6.77\times10^6}} = \sqrt{5.88 \times 10^7} \approx 7670$ m s^{-1} ≈ 7.7 km s^{-1}

Gravitational Potential Energy (Extended)

The gravitational potential energy of a mass m at distance r from mass M (taking $E_p = 0$ at $r \to \infty$):

$E_p = -\frac{GMm}{r}$

The negative sign reflects the fact that the field is attractive — you must do work to pull objects apart.

EXAM ALERT

Near-surface vs universal formula: $E_p = mgh$ is only valid near Earth's surface where g is approximately constant. For large distances from Earth (or other planets), you must use $E_p = -\frac{GMm}{r}$. Confusing these two is a recurring HL Paper 2 error.

IB TIP

Data booklet reference: $F = \frac{Gm_1m_2}{r^2}$, $g = \frac{GM}{r^2}$, $T^2 = \frac{4\pi^2r^3}{GM}$, $v = \sqrt{\frac{GM}{r}}$, $v_{esc} = \sqrt{\frac{2GM}{R}}$, $E_p = -\frac{GMm}{r}$ are all in the data booklet.

Exam-Style Practice Questions

The questions below are styled to match IB Paper 1 (MCQ) and Paper 2 (structured response) format.

Paper 1 Style (MCQ)

Q1. A ball is thrown vertically upward and returns to its starting point. Which of the following correctly describes the acceleration of the ball throughout the motion?

A. Upward during ascent, downward during descent

B. Downward throughout, magnitude g

C. Zero at the highest point, downward elsewhere

D. Upward throughout

▶ Answer

Q2. A trolley of mass 2.0 kg moving at $3.0\ \mathrm{m\ s^{-1}}$ to the right collides with a stationary trolley of mass 4.0 kg. After the collision, the first trolley moves at $1.0\ \mathrm{m\ s^{-1}}$ to the left. What is the speed of the second trolley after the collision?

A. $0.50\ \mathrm{m\ s^{-1}}$

B. $1.0\ \mathrm{m\ s^{-1}}$

C. $1.5\ \mathrm{m\ s^{-1}}$

D. $2.0\ \mathrm{m\ s^{-1}}$

▶ Answer

Q3. A satellite is in a circular orbit at radius r from the centre of a planet. The orbital period is T. The satellite moves to a new circular orbit of radius $4r$. What is the new period?

A. $\frac{T}{8}$

B. $\frac{T}{2}$

C. $4T$

D. $8T$

▶ Answer

Paper 2 Style (Structured Response)

Q4. A skier of mass 70 kg starts from rest at the top of a slope of vertical height 50 m and length 120 m.

(a) Calculate the gravitational potential energy lost by the skier as they descend the full slope. [1]

(b) The skier reaches the bottom of the slope with a speed of $24\ \mathrm{m\ s^{-1}}$. Calculate the work done against friction. [2]

(c) Determine the average friction force on the skier during the descent. [1]

(d) On the graph axes, sketch the shape of the velocity-time graph for the skier during the descent, assuming friction is constant. Explain the shape. [2]

▶ Mark-scheme answers

Q5. A planet of mass $M = 6.0 \times 10^{24}$ kg and radius $R = 6.4 \times 10^{6}$ m has a moon orbiting at distance $r = 3.8 \times 10^{8}$ m from the planet's centre.

(a) Show that the orbital speed of the moon is approximately $1.0\ \text{km s}^{-1}$. [2]

(b) Calculate the orbital period in days. [2]

(c) Explain why the gravitational potential energy of the moon is negative. [2]

▶ Mark-scheme answers

⚠ **EXAM ALERT**

Common Theme A errors that cost marks:

1. Forgetting to convert km to m, or hours to seconds — always check units before substituting.
2. Using $g = 10\ \text{m s}^{-2}$ when the question specifies $9.81\ \text{m s}^{-2}$ (or vice versa).
3. Treating speed and velocity as interchangeable — they are not.
4. Forgetting to include the direction (sign) in momentum calculations.
5. Using $E_p = mgh$ for problems at large distances from Earth — use $E_p = -\frac{GMm}{r}$ instead.
6. Not squaring correctly in $v^2 = u^2 + 2as$ — write out every step.