Topic A.2

FORCES & MOMENTUM

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

Topics Covered

Newton's Laws & Free-Body Diagrams
Contact Forces (friction, Hooke, drag)
Field Forces (grav., electric, magnetic)
Momentum, Impulse & Collisions
Circular Motion

Exam Relevance

P1 & P2 (with & without GDC)
4–15 marks per question
Momentum conservation (Sec. A & B)
Vertical loops & conical pendulum
2-D momentum (HL)

The Big Picture — How A.2 Fits Together

FORCES & MOMENTUM
every question is a force balance or a momentum balance

- **Newton's Laws**: $F = ma = \frac{\Delta p}{\Delta t}$; 1st: inertia; 3rd: pairs
- **Types of Force**: contact: N, F_f, T, Hooke, drag, buoyancy; field: mg, qE, qvB
- **Momentum**: $p = mv$; Impulse $J = F\Delta t = \Delta p$
- **Collisions**: p always conserved; KE: elastic only; + explosions
- **Circular Motion**: $F_c = \frac{mv^2}{r}$; a *real* force supplies it

§1 — Newton's Three Laws

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Newton's Three Laws

1st Law (Inertia): An object remains at rest or in uniform motion unless a net external force acts on it.
2nd Law: $\vec{F}_{\text{net}} = \frac{\Delta \vec{p}}{\Delta t} = m\vec{a}$ (constant mass). Net force equals rate of change of momentum.
3rd Law (Action–Reaction): $\vec{F}_{AB} = -\vec{F}_{BA}$. Forces act on **different** bodies, same type, equal magnitude.

TRAP N3L pairs act on DIFFERENT bodies. Weight and normal force on the same block are NOT an N3L pair.

TRICK For N3L pairs: same magnitude, opposite direction, same force type, act simultaneously on different objects.

TRICK **Two forms of N2L:** use $F = ma$ when mass is constant (blocks, inclines); use $F = \Delta p/\Delta t$ for varying mass (rockets, jets) or impacts over a time Δt.

Translational equilibrium: $\sum \vec{F} = 0 \Rightarrow$ at rest or constant velocity

NOTE A force is a push/pull (unit N) — the cause of a deformation or an acceleration. Forces add as **vectors**: draw them tip-to-tail, and a **closed** triangle means equilibrium. Tilted string: $T\cos\theta = mg$, $T\sin\theta = P$.

FROM THE PHOTON QUESTION BANK
Examiners reward a precise law statement, resolving to the **resultant** before $F = ma$, and naming N3L pairs (two bodies, same force type). "Constant velocity" = zero resultant — don't invent a net forward force.

§2 — Contact Forces

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Normal force (horizontal): $F_N = mg$

Normal force (incline at angle θ): $F_N = mg\cos\theta$

Static friction: $F_f \le \mu_s F_N$ (inequality — up to max)

Dynamic friction: $F_f = \mu_d F_N \quad (\mu_d < \mu_s)$

Hooke's Law: $F_H = -kx$ (restoring, opposes displacement)

Stokes' drag: $F_d = 6\pi\eta r v$

Buoyancy (Archimedes): $F_b = \rho_{\text{fluid}} V g$

Incline Decomposition

On an incline at angle θ:
$\parallel$ slope: $F_{\text{net}} = F_{\text{app}} - mg\sin\theta \mp F_f$
$\perp$ slope: $F_N = mg\cos\theta$
Weight component down slope: $mg\sin\theta$. Normal: $mg\cos\theta$.

TRAP Static friction is NOT always $\mu_s F_N$ — it takes any value $\leq \mu_s F_N$ as needed.

NOTE Terminal velocity: $mg = F_b + 6\pi\eta r v_T$ so $v_T = \dfrac{mg - \rho_f V g}{6\pi\eta r} = \dfrac{2r^2(\rho_s - \rho_f)g}{9\eta}$.

NOTE Viscosity $\eta = \dfrac{\text{tangential stress}}{\text{velocity gradient}} = \dfrac{F/A}{\Delta v/\Delta y}$ (units Pa s). Friction rises to match the push up to $F_{\text{max}} = \mu_s F_N$, then **drops** to $\mu_d F_N$ once sliding starts.

§3 — Field Forces

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Gravitational (weight): $F_g = mg, \quad g = 9.81\,\text{m/s}^2$

Electric force: $F_e = qE$ (in uniform field; direction depends on sign of q)

Magnetic force: $F_m = qvB\sin\theta$ (perpendicular to v, does no work)

TRICK Electric field $E = V/d$ between parallel plates. Balance: $qE = mg$ gives $q = mgd/V$.

NOTE Mass (kg) is invariant; weight $W = mg$ (N) depends on g ($\approx 10\,\text{N/kg}$ Earth, $\approx 1.6\,\text{N/kg}$ Moon). Scale reading (apparent weight) $= m(g \pm a)$ in an accelerating lift.

§4 — Linear Momentum & Impulse

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Linear momentum: $\vec{p} = m\vec{v}$ [kg m/s]

Newton's 2nd law: $\vec{F} = \dfrac{\Delta\vec{p}}{\Delta t}$

Impulse: $\vec{J} = \vec{F}\,\Delta t = \Delta\vec{p}$ [N s]

Conservation of momentum: $\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$ (no net ext. force)

NOTE On a force–time graph: area under curve $= J = \Delta p$.

TRICK **Two ways to find impulse:** $J = F\Delta t$ for a constant/average force, OR the *area under the F–t graph* for a varying force. Both equal Δp — longer Δt means smaller peak force (airbags, crumple zones).

TRAP When a ball bounces: $\Delta p = m(-v_f) - m(v_i) = -m(v_f + v_i)$. Magnitude $= m(v_f + v_i)$, NOT $m(v_f - v_i)$.

FROM THE PHOTON QUESTION BANK

Examiners test the impulse–momentum theorem, the **area** under an F–t graph, and average impact force $F = \Delta p/\Delta t$. Assign a direction first; a drop-and-stop uses $v = \sqrt{2gh}$ then $\Delta p/\Delta t$ (airbags stretch Δt to cut F).

§5 — Collisions & Explosions

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Types of Collision

Type	Momentum	Kinetic Energy
Elastic	Conserved	Conserved
Inelastic	Conserved	Not conserved (decreases)
Perfectly inelastic	Conserved	Maximum loss; objects stick
Explosion	Conserved	Increases (from stored energy)

Perfectly inelastic: $m_1 v_{1i} + m_2 v_{2i} = (m_1 + m_2) v_f$

Explosion (initially at rest): $0 = m_1 v_1 + m_2 v_2 \Rightarrow m_1|v_1| = m_2|v_2|$

KE loss (perfectly inelastic): $\Delta E_k = \dfrac{m_1 m_2}{2(m_1+m_2)}(v_{1i} - v_{2i})^2$

TRICK In an explosion: both fragments have equal and opposite momenta. Lighter fragment always has MORE kinetic energy ($E_k = p^2/2m$, smaller m gives larger E_k).

TRICK **Which is conserved?** Momentum is conserved in *every* collision — always your first equation. Only write the KE equation if the question says "elastic". Objects stick together $\Rightarrow$ perfectly inelastic (max KE lost).

§6 — Circular Motion

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Angular velocity: $\omega = \dfrac{2\pi}{T} = 2\pi f$ [rad/s]

Linear speed: $v = \omega r = \dfrac{2\pi r}{T}$

Centripetal acceleration: $a_c = \dfrac{v^2}{r} = \omega^2 r = \dfrac{4\pi^2 r}{T^2}$

Centripetal force: $F_c = \dfrac{mv^2}{r} = m\omega^2 r = \dfrac{4\pi^2 mr}{T^2}$

Key Circular Motion Scenarios

Conical pendulum (string at θ from vertical):
$T\cos\theta = mg$, $T\sin\theta = m\omega^2 r$, $\tan\theta = \omega^2 r/g$
Vertical circle — bottom: $N - mg = mv^2/r$ (N increases)
Vertical circle — top: $N + mg = mv^2/r$ (N decreases)
Min speed at top of loop: $v_{\text{min}} = \sqrt{gr}$ (when $N = 0$)
Inside cylinder wall: $N = mv^2/r$ (centripetal); $\mu_d N = mg$ (supports weight)

TRAP Centripetal force is NOT a new force. It is provided by existing forces (tension, gravity, normal, friction). Never draw it on a free-body diagram as a separate arrow.

TRICK **Two steps every time:** (1) name the *real* force pointing to the centre (tension / gravity / normal / friction); (2) set it equal to mv^2/r. Step 1 is where the marks are.

TRICK ω doubles $\Rightarrow F_c$ quadruples. r doubles $\Rightarrow F_c$ doubles (at same ω). Remember: $F_c \propto \omega^2 r$.

NOTE Centripetal force is always perpendicular to velocity. It changes direction, not speed. Work done by centripetal force = 0.

FROM THE PHOTON QUESTION BANK

Examiners want you to **name the real force** supplying F_c (tension / gravity / normal / friction) and set it equal to mv^2/r. Flat bend: $v_{\text{max}} = \sqrt{\mu_s g r}$. Conical pendulum / bowl: resolve so vertical balances mg and horizontal $= mv^2/r$.