Forces, motion and movement

B2 · SL and HL

Can follow-through keep changing a ball after racket separation?

Choose the body, direction and interval

B2 connects Newton's laws, stability, coordinated movement, projectile paths and movement phases.

AHL: collisions, friction, work/power, environmental effects, buoyancy, lift and drag.

All numerical examples and diagrams are invented. Movement after separation cannot supply continued racket–ball contact force.

A complete lap has distance without net displacement

1. **Invented lap.** 400 m in 80 s gives average speed 5 metres per second. Average velocity is zero because displacement is zero.
2. **Practice.** 300 m in 60 s again gives speed 5 and average velocity zero.
3. **Boundary.** Neither path average gives the highest instantaneous speed. Velocity includes direction; acceleration includes direction changes.

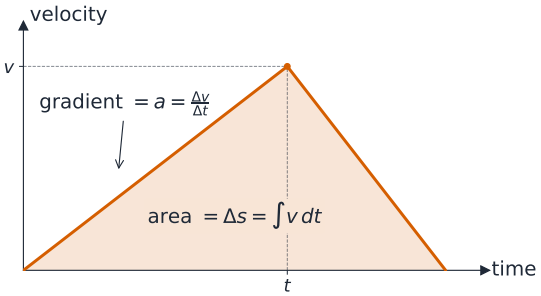
A negative acceleration can accompany increasing speed

1. **Positive movement.** $+1 \to +7$ metres per second over 3 s: acceleration $(7-1)/3 = +2$ metres per second squared.
2. **Negative movement.** $-1 \to -7$ over 3 s: $(-7-(-1))/3 = -2$. Speed increases in the negative direction.
3. **Angular movement.** 1.2 radians in 0.30 s gives average angular velocity 4 radians per second; endpoint speed also depends on radius.

Count frame intervals rather than displayed images

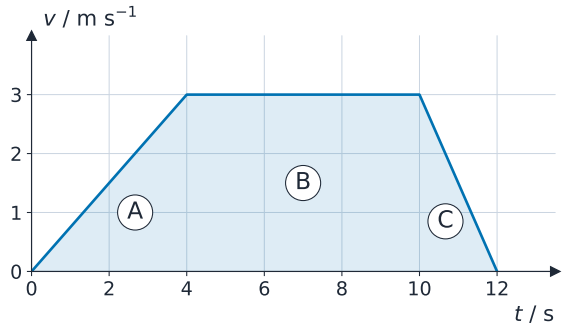
1. **Teaching record.** Frames $10 \rightarrow 25$ contain 15 intervals. At 50 frames per second: 0.30 s. Displacement 0.60 m gives 2.0 metres per second.
2. **Practice.** Frames $12 \rightarrow 20$ at 40 frames per second: $8/40 = 0.20$ s. Displacement $+0.50$ m gives $+2.5$ metres per second.
3. **Measurement.** Calibrate in the movement plane, know frame rate and use consistent landmarks. Perspective and uncertain event frames affect the result.

Reading a velocity–time graph



A triangle: speed up, then slow to rest

Three stages on one graph



Find each acceleration from the gradient and the distance from the area

Keep resultant force distinct from individual interactions

Law	Apply it to a specified body
First	Zero resultant means constant velocity, even when several forces balance
Second	For constant mass, net force $=$ mass $\times$ acceleration
Third	Equal opposite interaction forces act on different bodies

Find the net force, then include resistance

1. **Teaching model.** 60 kg $\times$ 2 metres per second squared $=$ 120 N forward net. With 20 N resistance, driving force is 140 N.
2. **Practice.** 50 kg $\times$ 1.5 $=$ 75 N net. With 15 N resistance, driving force is 90 N.
3. **Boundary.** Whole-body acceleration does not identify one muscle force. Weight is mg: 80 kg at g $=$ 9.81 has weight 784.8 N.

Third-law partners do not cancel on an athlete's force diagram

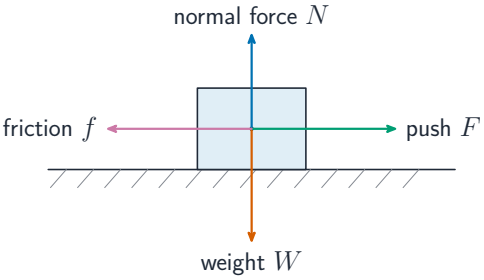
Identify which body each force acts on

Foot pushes ground backwards; ground pushes foot forwards. The pair acts on different bodies.

Weight and support can balance on a stationary athlete, but are not each other's third-law partners.

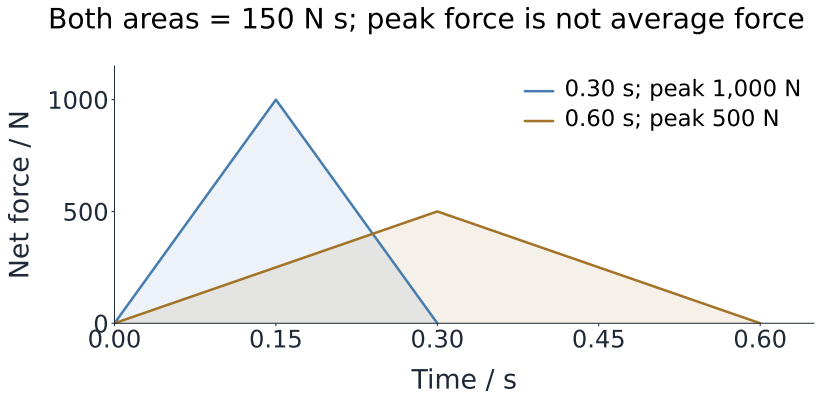
Support need not equal weight during vertical acceleration. Draw the forces acting on the chosen body.

A free-body diagram



Compare opposite pairs to find the resultant

Signed area measures impulse; peak height does not



Equal areas can arise from different durations and peaks.

Do not label a triangular peak as average force

1. **Two teaching curves.** Half $\times$ 0.30 s $\times$ 1,000 N $=$ 150 N s; half $\times$ 0.60 $\times$ 500 $=$ 150 N s.
2. **Averages.** $150/0.30 = 500$ N; $150/0.60 = 250$ N. Each triangular peak is twice its average.
3. **Practice.** 0.40 s with peak 600 N gives **impulse** 120 N s and average 300 N. At 0.80 s, the same triangular impulse needs peak 300 N and average 150 N.

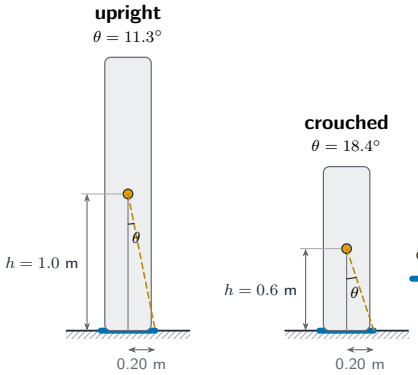
A rebound needs signed velocities, not a difference of speeds

1. **Same direction.** 0.058 kg ball: $+30 \to +20$ metres per second. Momentum change -0.58; over 0.005 s average net force -116 N.
2. **Reverse direction.** $+30 \to -20$: change $= 0.058(-20 - 30) = -2.90$; average net force -580 N.
3. **Practice.** 0.050 kg: $+24 \to -16$ over 0.008 s. Change -2.0 kg metres per second; average resultant -250 N.

Ground reaction must also overcome weight during upward acceleration

1. **Teaching take-off.** 80 kg gains upward momentum 240 over 0.20 s: net upward average 1,200 N; ground reaction $1{,}200 + 784.8 = 1{,}984.8$ N.
2. **Practice.** 60 kg gains upward momentum 120 over 0.25 s: net 480 N; weight 588.6 N; ground reaction 1,068.6 N.
3. **Boundary.** Assume only weight and support vertically. A follow-through after separation cannot add racket contact **impulse** to the released ball.

Compare the margin in the direction of the disturbance



$$\tan\theta = \frac{0.20}{h}$$

the body must tilt by θ before its line of gravity reaches the edge of the base: a lower centre of mass gives a larger margin

centre of mass

base of support

A lower **centre of mass** can increase the geometric toppling margin.

Static toppling is a useful model, not a complete model of running

Relate the line of gravity to the supporting contacts

Wider base and lower centre of mass can improve the margin; the disturbance direction matters.

Weight can produce a toppling moment after its line passes an edge. A step or other action can change the base.

Mass affects inertia and weight moments, but geometry, friction and task also matter. Dynamic balance includes changing contacts.

A throwing sequence is more than adding isolated muscle forces

Identify timing, segment interactions and turning effects

Legs, trunk, shoulder, elbow and wrist can contribute in a coordinated sequence. Task and timing affect endpoint motion.

Torque is force $\times$ perpendicular lever arm. An off-centre force can change angular and linear motion.

A force through the centre of mass has no moment about that centre; a larger isolated muscle force does not guarantee a better throw.

Reducing moment of inertia can raise angular velocity

1. **Teaching airborne model.** $I = 0.80$ kg square metres and angular velocity 4 radians per second: angular momentum 3.2. At $I = 0.40$, angular velocity is 8.
2. **Practice.** $I = 0.60$ and angular velocity 5 gives angular momentum 3.0; at $I = 0.30$, angular velocity is 10.
3. **Condition.** Net external **torque** about the axis is negligible. Gravity through the **centre of mass** can still act; taking off or landing can add external torque.

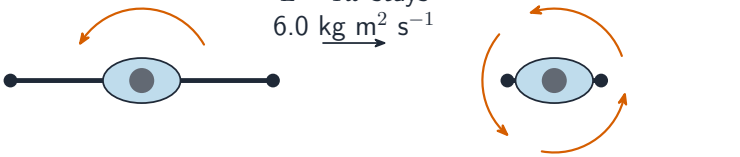
Angular momentum is conserved

arms out

arms pulled in

$L = I\omega$ stays

6.0 kg m^2 s^{-1}

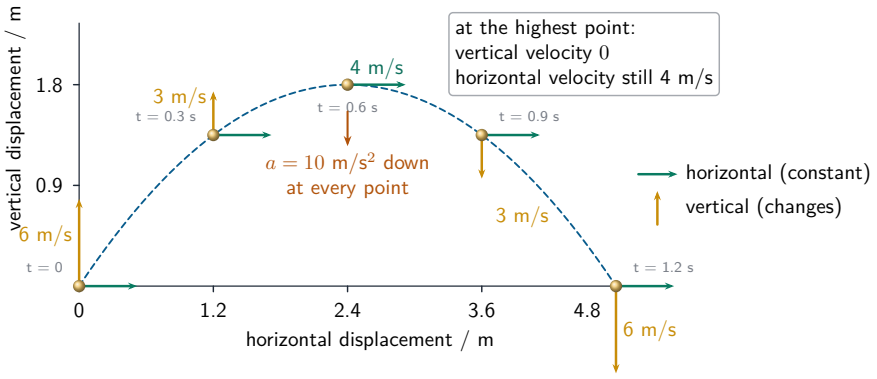


$I = 3.0$ kg m^2, $\omega = 2.0$ rad s^{-1}

$I = 1.0$ kg m^2, $\omega = 6.0$ rad s^{-1}

$I\omega$ stays 6.0

At the apex, horizontal velocity and gravity remain



Zero vertical velocity at the apex does not mean zero acceleration.

State release height and the no-drag assumption

1. **Teaching model.** Horizontal component 4, vertical component 6 metres per second; downward acceleration 10. Equal-height flight time is 1.20 s; range 4.8 m.
2. **Practice.** Supplied horizontal speed 5 and flight time 0.80 s give range 4.0 m.
3. **Boundary.** Release direction, speed and relative target height affect the path. A 45-degree release is not universally optimal; light broad objects can be strongly affected by drag.

Define the event that separates movement phases

Phase	Operational description
Preparation	Positions body and implement for the task
Force production	Develops movement leading towards the critical event
Critical instant	Named event such as last contact/release; not the entire force-production phase
Follow-through / recovery	Subsequent control for a discrete action / preparation for the next continuous cycle

Use movement analysis to evaluate a defined adjustment

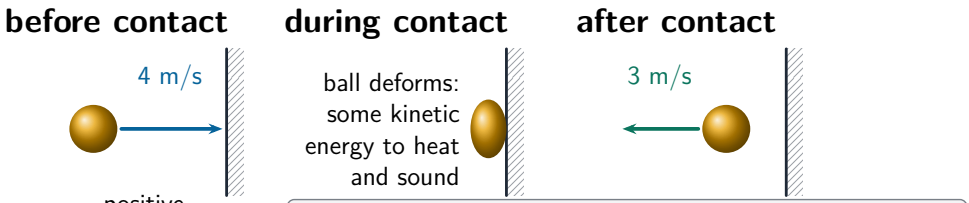
Matched recordings help compare like with like

Keep camera geometry, task, landmarks and phase definitions consistent. A timing difference needs context such as stroke rate.

Moving an invented target closer can reduce required reach; test the adjustment with intended users.

Video can support accessibility or rehabilitation assessment, but one view does not diagnose an injury. Class work can use supplied low-risk records.

AHL: Compare approach and separation speeds



$$e = \frac{\text{relative speed of separation}}{\text{relative speed of approach}} = \frac{3}{4} = 0.75$$

velocities $+4$ and -3 m/s: use the positive speeds, not $-3/4$

Restitution is a relative-speed ratio, not generally an energy percentage.

AHL: A fixed-surface bounce has different speed and energy ratios

1. **Teaching bounce.** Approach speed 4, rebound speed 3: $e = 0.75$; same-mass translational energy fraction e squared $= 0.5625$, or 56.25%.
2. **Practice.** Approach 5, rebound 4: $e = 0.80$; retained translational fraction 64%.
3. **Boundary.** Use positive relative speeds along the collision line. Material, temperature, speed and surface can affect restitution; ordinary passive-collision e lies from zero to one.

AHL: Two moving bodies need momentum and restitution together

1. **Teaching collision.** Equal masses, initial $+4$ and 0, $e = 0.50$. Momentum: $v1 + v2 = 4$. Restitution: $v2 - v1 = 2$. Final velocities $+1$ and $+3$.
2. **Energy.** For mass 0.20 kg each: initial 1.6 J, final 1.0 J; 0.6 J or 37.5% leaves translational kinetic energy.
3. **Practice and system.** Initial $+6$ and 0 with $e = 0.50$ gives final $+1.5$ and $+4.5$. Momentum conservation requires negligible external **impulse** on the chosen two-body system.

AHL: Static friction adjusts up to a limit

1. **Teaching contact.** $N = 500$ N; static coefficient 0.60 gives limit 300 N. Actual static friction balancing a 100 N push is only 100 N.
2. **Sliding model.** Coefficient 0.40 gives friction 200 N. Over 2 m, its work on the sliding object is -400 J.
3. **Practice.** $N = 400$, static coefficient 0.50: limit 200 N, balancing an 80 N push requires 80 N. Sliding coefficient 0.30 gives 120 N; over 3 m, work is -360 J.

AHL: Mechanical power is transferred work per time

1. **Teaching model.** Parallel 300 N force through 0.40 m: work 120 J; over 0.50 s: average power 240 W.
2. **Practice.** 250 N through 0.60 m gives 150 J; over 0.75 s gives 200 W.
3. **Limits.** An isometric hold uses metabolic energy despite zero external work on a stationary load. Normal force need not equal weight; traction and equipment need task-specific evaluation.

AHL: State which conditions are held fixed

Condition	Relevant change and boundary
Air	Temperature, pressure, altitude and humidity affect density; warmer or humid air is less dense at matched other conditions
Wind	Aerodynamic forces depend on air-relative velocity, not only ground speed
Water	Temperature and salinity can affect density and other properties; greater density raises buoyancy at fixed displaced volume

AHL: Headwind and tailwind change relative flow

1. **Teaching runner.** Ground speed 6 metres per second; headwind 2 gives relative speed 8; tailwind 2 gives 4.
2. **Squared-speed model.** Compared with no wind: ratios $(8/6)$ squared ≈ 1.78 and $(4/6)$ squared ≈ 0.44.
3. **Practice and limit.** Ground speed 8 with headwind 2 gives relative speed 10; drag ratio $(10/8)$ squared $= 1.5625$. The model does not directly predict race time or metabolic cost.

AHL: Use displaced submerged volume for buoyancy

1. **Teaching model.** Density 1,000 kg per cubic metre $\times$ displaced volume 0.060 cubic metres $\times$ g 9.81 $=$ 588.6 N.
2. **Weight comparison.** A 60 kg body weighs 588.6 N. A 65 kg body with the same submerged volume has net 49.05 N downwards before other forces.
3. **Practice.** Displaced volume 0.050 cubic metres gives 490.5 N. Denser saline water gives greater buoyancy at the same volume.

Headwind and tailwind



air speed relative to runner $6 + 2 = 8$ m/s
drag $\approx (8/6)^2 = 1.78\times$ still air

air speed relative to runner $6 - 2 = 4$ m/s
drag $\approx (4/6)^2 = 0.44\times$ still air

> Drag grows with the square of the air speed

AHL: Different resistance mechanisms need different explanations

Drag type	**Physical feature**
Surface	Shear at the moving object's surface
Form	Pressure differences and flow separation
Wave	Wave generation near a water surface

AHL: Lift is perpendicular to relative flow, not always upwards

Flow, orientation and spin affect the force

Angle of attack changes orientation to incoming flow; increasing it can lead to separation/stall rather than ever-increasing useful lift.

Bernoulli relates pressure and speed along suitable streamlines in an idealized flow. Equal transit times on opposite sides are not required.

Magnus force involves spin-altered flow. Conventional topspin commonly adds downward force and backspin upward force for a ball moving horizontally; flow regime and surface matter.

AHL: A measured benefit does not automatically justify equipment use

Evaluate a bounded sporting claim

Alignment, area, surface and depth can alter different drag contributions. Doubling relative speed can quadruple drag in a simple unchanged-condition model: 6 N $\rightarrow$ 24 N.

Consider measured effects, safety, user fit, access and cost.

Competition rules can change; assess the applicable rules before claiming that an imagined design or named product is permitted.

Practise with a defined system and signs

Show quantities and interpret the result

Use motion measurements, Newton's laws, force-time area, signed momentum change, ground reaction and angular momentum.

Explain stability, projectile assumptions and operational movement phases.

AHL: combine collision conditions and evaluate friction, work/power, relative flow, buoyancy and equipment claims.

Check the shared calculations before interpreting performance

1. **Motion and force.** Lap: speed 5, average velocity zero. Acceleration $+2$ and -2. Video: 0.20 s, $+2.5$ metres per second. Net 75 N; driving 90 N.
2. **Impulse.** Triangular **impulse** 120 N s; average 300 N. Rebound change -2.0 and average resultant -250 N. Ground reaction 1,068.6 N.
3. **Angular and projectile models.** Angular momentum 3.0; final angular velocity 10. Range 4.0 m. Each numerical result depends on its stated model.

Check yourself

Separate signs, force boundaries and model assumptions

Count frame intervals. Average and peak force differ. Net force is not ground reaction; third-law partners act on different bodies.

Conserved angular momentum requires negligible external torque. Gravity remains at a projectile's apex, and follow-through cannot keep pushing after separation.

AHL: restitution uses relative speeds, static friction adjusts, buoyancy uses displaced volume and aerodynamic comparisons use relative flow. Mechanical power differs from metabolic cost.