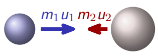
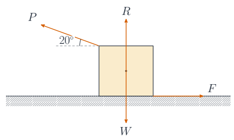
Dynamics

AS Physics ▪ Topic 3

A-Level Physics



What we will cover



1 Momentum and force

Mass and momentum

- **mass** – how hard it is to change motion (a scalar, kg)
- **linear momentum** 动量 $p = mv$ – a vector, along the velocity

Unit of p: $\mathrm{kg\,m\,s^{-1}} = \mathrm{N\,s}$.

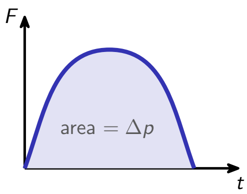
Skydiver terminal

Force is the rate of change of momentum

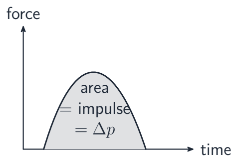
Newton's second law, general form:

$$F = \frac{\Delta p}{\Delta t} \xrightarrow{\text{constant } m} F = ma.$$

> **Impulse** 冲量 $= F\Delta t = \Delta p$ – the area under a force–time graph.



Impulse is the area under the force



$F\Delta t = \Delta p$: a small force for a long time changes momentum as much as a large force for a short one – which is what a crumple zone trades.

> Impulse $= F\Delta t =$ the area under a force–time graph, and it equals the change in momentum. A soft landing spreads the same impulse over a longer time, so the force is smaller.

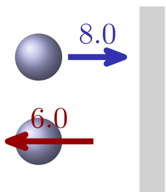
Worked example – ball bouncing off a wall

$m = 0.20\,\mathrm{kg}$: hits at 8.0, rebounds at $6.0\,\mathrm{m\,s^{-1}}$, contact $0.050\,\mathrm{s}$

Rebound direction $+$, so $u = -8.0$, $v = +6.0$:

$$\Delta p = m(v-u) = 0.20(6.0+8.0) = 2.8\,\mathrm{kg\,m\,s^{-1}}$$

$$F = \frac{\Delta p}{\Delta t} = \frac{2.8}{0.050} = 56\,\mathrm{N}.$$

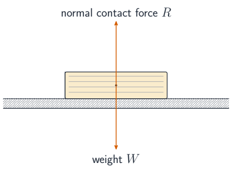


2 Newton's laws

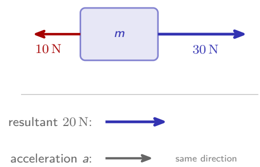
Newton's first law

An object stays at rest, or moves at constant velocity, unless a resultant **external force** 外力 acts.

> Zero resultant force $\Leftrightarrow$ zero acceleration. This is **inertia**.



Newton's second law



Resultant force = rate of change of momentum:

$$F = \frac{\Delta p}{\Delta t} = ma.$$

> Acceleration points the same way as the resultant force.

Add forces as vectors to get the resultant first.

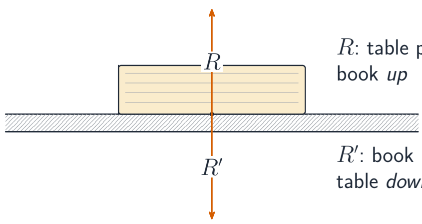
Newton's third law

A on B $\Rightarrow$ B on A: equal and opposite. The pair:

- act on different objects
- are the same type – both gravitational, both contact, both **electrostatic** 静电
- equal size, opposite direction

> A book's **weight** 重力 and the table's **normal contact force** 支持力 are not a pair – same object, different types. The weight's partner is the pull the book makes on the Earth.

Newton's third law, in detail



R: table pushes the book *up*

R': book pushes the table *down*

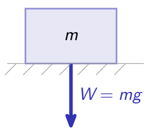
> A on B $\Rightarrow$ B on A: equal and opposite.

Weight – a gravitational force

Weight 重力 is the pull of a **gravitational field** 重力场:

$$W = mg, \qquad g \approx 9.81\,\mathrm{m\,s^{-2}}.$$

> Mass is the same everywhere; weight changes with place.

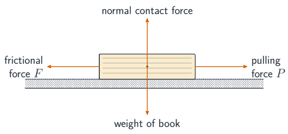


3 Friction, drag & terminal velocity

Friction and drag

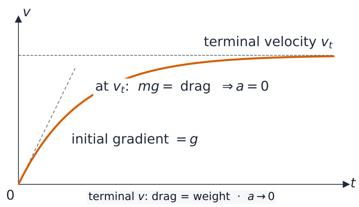
- **friction** 摩擦力 – between solid surfaces, opposes sliding
- **drag** 阻力 (viscous) – from a **fluid** 流体 on a moving object

> Drag grows with speed; at zero speed the drag is zero. No **coefficient** 系数 of friction or viscosity is needed in this syllabus.



Falling through air – terminal velocity

1. only weight → speeds up at g
2. drag grows → acceleration shrinks
3. drag = weight → **terminal velocity** 收尾速度 (constant)

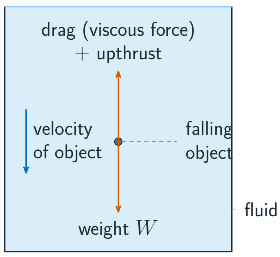


Cyclist or car at constant speed

A vehicle at constant speed on a flat road has zero resultant force.

> The forward driving force is equal and opposite to the total resistive force (friction, air resistance, and rolling resistance).

Forces and energy in a fall



At terminal velocity the **parachutist** 跳伞者 has constant kinetic energy.

> The lost **gravitational potential energy** 重力势能 becomes thermal energy of the air – *not* extra kinetic energy.

A car at constant speed: driving force = resistive force; faster ⇒ more **power** 功率.

4 Conservation of momentum

Conservation of linear momentum

With no external resultant force, total momentum stays constant.

> Holds in collisions, **explosions** 爆炸 and **recoil** 反冲. In 2-D, it holds along *each* direction.

The principle

For a system with no resultant external force, the total momentum stays constant.

> This is **conservation of momentum 动量守恒**.

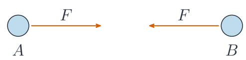
Worked example – spring release (recoil)

From rest: the $2.0\,\mathrm{kg}$ trolley leaves at $6.0\,\mathrm{m\,s^{-1}}$ – how fast is the $3.0\,\mathrm{kg}$?

Total momentum stays zero:

$$0 = (2.0)(6.0) + (3.0)(-v)$$

$$v = \frac{12}{3.0} = 4.0\,\mathrm{m\,s^{-1}} \text{ (opposite way).}$$



equal size, opposite direction
(forces act on different objects)

> Newton's third law in an isolated two-particle system: equal and opposite forces

Elastic vs inelastic

Momentum is always conserved. Kinetic energy is the difference:

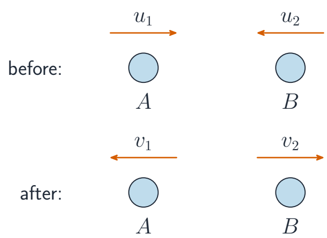
Elastic collision 弹性碰撞

kinetic energy also conserved
relative speed of approach = relative speed of separation

Inelastic collision 非弹性碰撞

kinetic energy falls (heat, sound, **deformation** 形变)
if they stick: perfectly inelastic

Head-on collisions: pick one positive direction



Momentum along that direction is conserved:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2.$$

> Every velocity carries a sign: one to the left is negative. Choose the direction once and keep it.

An elastic collision gives you a second equation

Momentum alone leaves two unknowns. If the collision is elastic, kinetic energy is conserved as well:

$$\tfrac{1}{2}m_1u_1^2 + \tfrac{1}{2}m_2u_2^2 = \tfrac{1}{2}m_1v_1^2 + \tfrac{1}{2}m_2v_2^2$$

which is quadratic, so use the equivalent form instead:

$$\boxed{u_1 - u_2 = -(v_1 - v_2)}$$

Relative speed 相对速率 of approach = relative speed of separation. Now two linear equations for two unknowns.

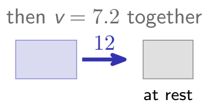
Worked example – cars lock together

$1500\,\mathrm{kg}$ at $12\,\mathrm{m\,s^{-1}}$ hits a stationary $1000\,\mathrm{kg}$; they stick

$$1500(12) + 1000(0) = (1500 + 1000)\,v$$

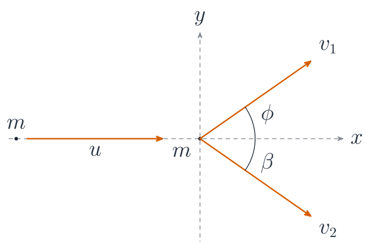
$$v = \frac{18\,000}{2500} = 7.2\,\mathrm{m\,s^{-1}}.$$

Perfectly inelastic – kinetic energy is lost.



Collisions in two dimensions

Resolve into **perpendicular** 垂直 **components** 分量, then conserve momentum along each axis. Choose one axis along the incoming motion, one across it.



Rocket – pushing out mass

Gas leaves at speed u with **mass-flow rate** 质量流率 $\dot{m}$:

$$F = \dot{m}\,u.$$

From $F = \Delta p/\Delta t$ – the momentum given to the gas each second equals the thrust on the rocket (Newton's third law).

Exam tips

- **Newton's second law is** $F = \Delta p/\Delta t$ (rate of change of momentum); $F = ma$ is the special case for constant mass.
- Identify **third-law pairs** correctly: the same type of force, acting on **two different bodies** – not the balanced forces on one body.
- **Momentum is conserved** in every collision; kinetic energy is conserved only in an **elastic** collision.
- For **terminal velocity**, explain that drag rises with speed until drag = weight, so the acceleration becomes zero.

5 Recap

Topic 3 – key takeaways

1 Momentum

$p = mv$; $F = \Delta p / \Delta t = ma$

2 Three laws

inertia; $F = ma$; equal-and-opposite pairs

3 Terminal velocity

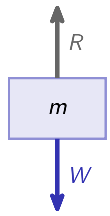
drag grows until it balances weight

4 Conservation

total momentum constant with no external force

Check yourself

1. Units of momentum, in terms of N?
2. Are a book's weight and the table's push a third-law pair?
3. At terminal velocity, what is the resultant force?
4. Two trolleys stick on collision – which quantity is conserved?



Answers **1.** $\mathrm{N\,s}$ **2.** no (same object, different types) **3.** zero **4.** momentum