Dynamics

Mass and weight, F = ma, momentum, force as rate of change of momentum, Newton's laws, drag and terminal velocity, conservation of momentum, and elastic and inelastic collisions.

Momentum and Newton's laws of motion

Mass, weight and momentum

Mass is the property of an object that resists a change in its motion. It is a scalar, measured in kg.

Weight is the effect of a gravitational field on a mass. It is a force: $W = mg$. Your mass is the same on the Moon, but your weight is less.

Linear momentum is mass × velocity, $p = mv$. It is a vector, measured in kg m/s or N s.

Newton's laws

1. **First law:** an object stays at rest or moves with constant velocity unless a resultant force acts on it.
2. **Second law:** the resultant force on an object is proportional to its rate of change of momentum, and acts in the same direction.
3. **Third law:** if body A exerts a force on body B, then B exerts a force on A that is equal in size and opposite in direction, of the same type.

The second law gives $F = \frac{\Delta p}{\Delta t}$. When the mass is constant this becomes $F = ma$, and the acceleration is always in the direction of the resultant force.

Third-law pairs act on different bodies and are the same type of force. A book's weight and the table's push on it both act on the book, so they are not a third-law pair. The partner of the book's weight is the book's gravitational pull on the Earth.

TRY IT

A 0.15 kg ball hits a wall at 20 m/s and rebounds at 15 m/s. The contact lasts 0.010 s. Find the average force on the ball. Taking the rebound direction as positive, $\Delta p = 0.15(15) - 0.15(-20) = 5.25$ N s. $F = 5.25/0.010 = 525$ N, away from the wall.

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Non-uniform motion

Friction and drag

Friction acts between surfaces, opposing relative motion. **Drag** (viscous force) acts on an object moving through a fluid, and air resistance is drag in air. Drag acts opposite to the velocity and **increases with speed**.

Terminal velocity

An object falling through air:

1. Starts with only its weight acting, so its acceleration is g.
2. As speed rises, drag rises, so the resultant force and the acceleration fall.
3. When drag equals the weight, the resultant force is zero. It then falls at a constant **terminal velocity**.

The velocity–time graph starts with gradient g and its gradient falls to zero. If a skydiver opens a parachute, drag suddenly exceeds the weight, so they decelerate to a new, lower terminal velocity.

Linear momentum and its conservation

Conservation of momentum

> **The total momentum of a system of interacting bodies stays constant, provided no resultant external force acts on the system.**

Remember momentum is a vector: choose a positive direction, and an object moving the other way has negative momentum.

> TRY IT
>
> **A 2.0 kg trolley moving at 3.0 m/s hits a stationary 1.0 kg trolley and they stick together. Find their velocity.** $2.0 \times 3.0 = 3.0 \times v$, so $v = 2.0$ m/s.

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Elastic and inelastic collisions

	Momentum	Kinetic energy
Elastic collision	conserved	conserved
Inelastic collision	conserved	**not** conserved (some goes to heat, sound or deformation)

Total energy is always conserved. It is only the *kinetic* energy that may change. In the trolley example, the kinetic energy falls from 9 J to 6 J.

For an elastic collision, there is a useful result:

$$\text{relative speed of approach} = \text{relative speed of separation}$$

TRY IT

A 1.0 kg ball at 4.0 m/s collides elastically head-on with a stationary 3.0 kg ball. Find both final velocities. Momentum: $4 = v_1 + 3v_2$. Relative speeds: $4 = v_2 - v_1$. Adding gives $8 = 4v_2$, so $v_2 = 2.0$ m/s and $v_1 = -2.0$ m/s: the lighter ball bounces back.

Collisions in two dimensions

Momentum is conserved **separately in each of two perpendicular directions**. Resolve each velocity into components along those directions, then write one conservation equation for each. A vector triangle of the momenta works too, because the initial and final total momentum vectors must be equal.

NOTE

Exam tip: when two objects fly apart from rest, as in an explosion, the total momentum stays zero, so they have equal and opposite momenta. The lighter one moves faster and gets more of the kinetic energy.

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