

Momentum conservation, impulse and collision types

Physics grades 11-12 (A Level · IB · Class 11-12) · Lesson

Quick answer: Momentum is the product of mass and velocity, $p = m v$, measured in kg m/s. Impulse is force times time, $F \Delta t$, and equals the change in momentum. Total momentum is conserved in any collision when no external resultant force acts, including two-dimensional collisions.

Level: Physics grades 11-12 (A Level · IB · Class 11-12) · **Curriculum:** IB A.2

What are momentum and impulse?

A heavy lorry and a small car are both hard to stop when they move fast. Momentum measures this. It combines mass and velocity, so it is a vector that points the way the object moves.

Definition

Momentum is mass times velocity, $p = m v$, in kg m/s. **Impulse** is force times the time it acts, $J = F \Delta t$, in N s. The impulse of the net force equals the change in momentum of the object.

Formulae

$$p = m v \text{ and } F = \Delta p \div \Delta t$$

$$\text{Impulse} = F \Delta t = \Delta p = m v - m u$$

p = momentum (kg m/s), m = mass (kg), v = velocity (m/s), F = net force (N), Δt = time (s).

When the force changes during the contact, plot force against time. The area under the graph is the impulse.



The area under a force-time graph is the impulse, equal to the change in momentum.

Worked example 1

Nandi in Durban serves a tennis ball of mass 0.058 kg. The ball leaves her racket at 55 m/s and the contact lasts 4.0 ms.

$$\Delta p = m v - 0 = 0.058 \times 55 = 3.19 \text{ kg m/s.}$$

$$F = \Delta p \div \Delta t = 3.19 \div 0.0040 = \mathbf{8.0 \times 10^2 \text{ N}}$$
 on average.

How do you use force as the rate of change of momentum?

Newton's second law is more general in the form $F = \Delta p / \Delta t$, because it also works when the mass changes or when a stream of particles hits a surface. Spreading the same change of momentum over a longer time lowers the force, which is why a fielder pulls the hands back while catching.

Worked example 2

Hail of total mass 0.30 kg per second hits a flat roof at 20 m/s and stops without bouncing. Momentum lost per second = $0.30 \times 20 = 6.0 \text{ kg m/s per second.}$

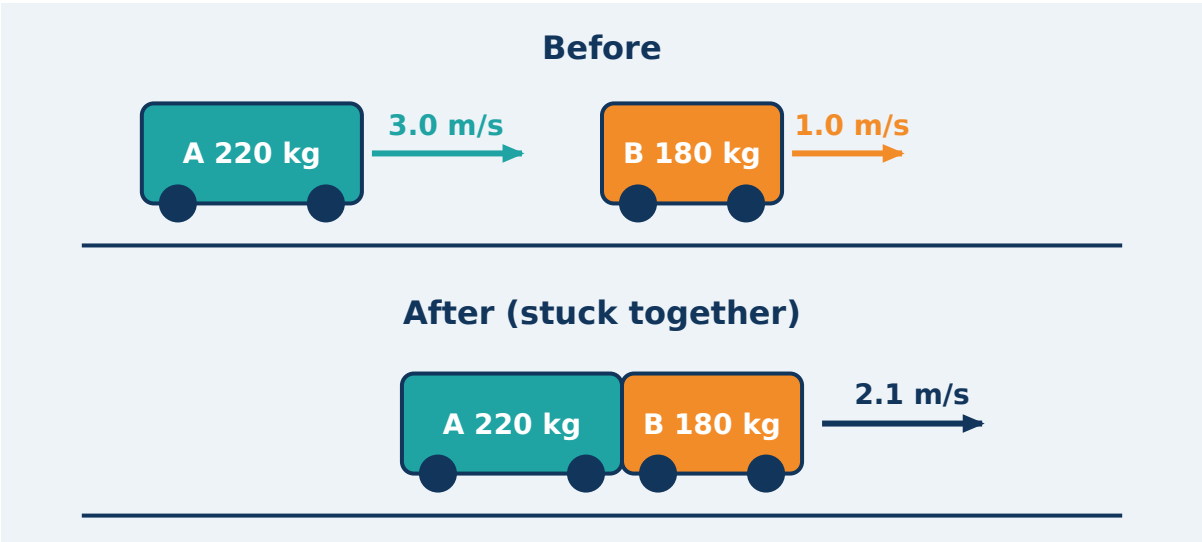
Force on the roof = **6.0 N**.

When is momentum conserved?

Key law

Conservation of momentum: the total momentum of a system is constant if no external resultant force acts on it. In any collision, total momentum before = total momentum after.

Choose a positive direction and give a sign to every velocity. A collision between two cars on a road is a short event, so the friction with the road is negligible compared with the huge forces between the cars.



Momentum before and after: $220 \times 3.0 + 180 \times 1.0 = 400 \times 2.1 = 840 \text{ kg m/s}$.

Worked example 3

In a fairground in Lahore, bumper car A (220 kg, 3.0 m/s) catches car B (180 kg, 1.0 m/s) and they move off together.

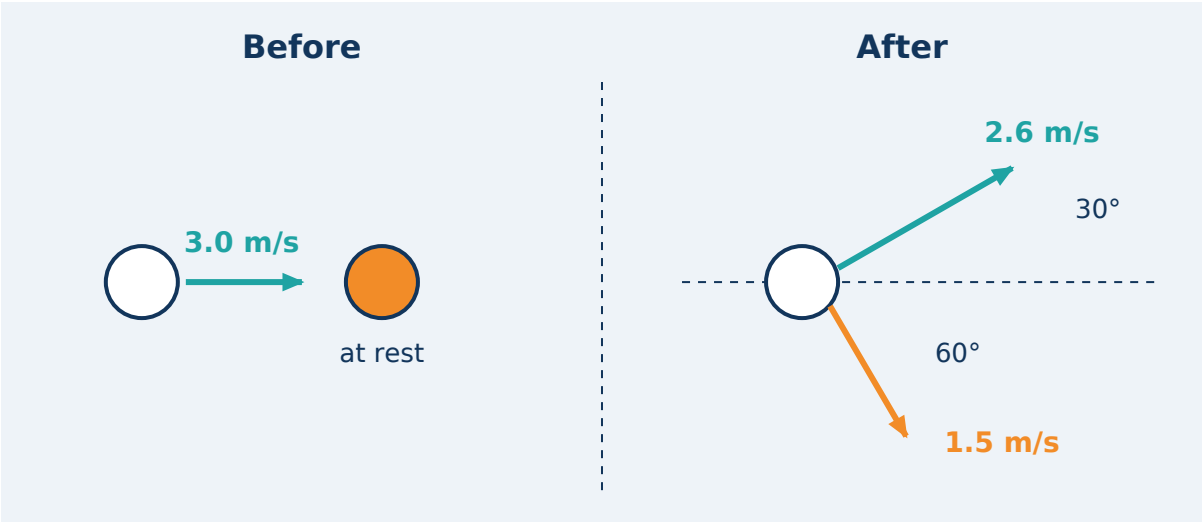
$220 \times 3.0 + 180 \times 1.0 = (220 + 180) v$, so $v = 840 \div 400 = \mathbf{2.1 \text{ m/s}}$.

KE before = $\frac{1}{2} \times 220 \times 9.0 + \frac{1}{2} \times 180 \times 1.0 = 990 + 90 = 1080 \text{ J}$; after = $\frac{1}{2} \times 400 \times 2.1^2 = 882 \text{ J}$. The loss of **198 J** became thermal energy and sound.

Collision type	Momentum	Kinetic energy	Separation rule
Elastic	conserved	conserved	relative speed of separation = approach
Inelastic	conserved	some lost	separate slower than approach
Perfectly inelastic	conserved	maximum lost	objects stick together

How do two-dimensional collisions work?

Momentum is a vector, so it is conserved separately in every direction. Choose x and y axes, resolve each velocity into components, and write one equation for each axis.



Resolve momentum along x and y separately: the y -components cancel because the total was zero before.

Worked example 4

A cue ball of mass 0.17 kg moves at 3.0 m/s and strikes an identical stationary ball. The cue ball leaves at 2.6 m/s at 30° above the original line.

x : $3.0 = 2.6 \cos 30^\circ + v \cos \phi$, so $v \cos \phi = 0.75$.

y : $0 = 2.6 \sin 30^\circ - v \sin \phi$, so $v \sin \phi = 1.3$.

$v = \sqrt{(0.75^2 + 1.3^2)} = \mathbf{1.5 \text{ m/s}}$ at $\phi = \tan^{-1}(1.3 \div 0.75) = \mathbf{60^\circ}$ below the line.

Common mistake

Students add speeds instead of velocities, or forget that a bounce reverses the sign. If a ball hits a wall at 5.0 m/s and rebounds at 3.0 m/s, the change in velocity is 8.0 m/s, not 2.0 m/s. Always set a positive direction first.

Lina's tip

Draw a before and after sketch and write the momentum of each object under it with signs. Then the conservation equation is just "sum before = sum after", and you cannot lose a minus sign.

Key points to remember

- Momentum $p = m v$ is a vector in kg m/s; impulse $J = F \Delta t = \Delta p$ in N s.
- Newton's second law: $F = \Delta p / \Delta t$; the area under a force-time graph is the impulse.
- Momentum is conserved in all collisions if no external resultant force acts.
- Elastic collisions also conserve kinetic energy; relative speed of approach equals that of separation.
- In two dimensions conserve momentum separately along x and y .

Momentum conservation, impulse and collision types: frequently asked questions

What is the difference between momentum and impulse?

Momentum is a property of a moving object, $p = m v$. Impulse is a quantity delivered by a force over time, $J = F \Delta t$, and it equals the change in momentum. Both are in the same units, since $1 \text{ N s} = 1 \text{ kg m/s}$.

Why is momentum conserved but kinetic energy is not always?

The forces between colliding objects are equal and opposite for the same time, so the momentum changes cancel. Kinetic energy can be turned into thermal energy, sound or deformation, so it is conserved only in elastic collisions.

Why do crumple zones and airbags save lives?

They lengthen the time over which the passenger's momentum changes. For the same change

in momentum, $F = \Delta p / \Delta t$ gives a much smaller average force over a longer time.

How does a rocket accelerate in empty space?

The rocket pushes exhaust gas backwards, so by conservation of momentum the rocket gains forward momentum. It does not need air to push against.

How do you recognise a perfectly inelastic collision?

The objects move together after impact with a common velocity. Momentum is conserved, but the loss of kinetic energy is as large as it can be.