Module 3 Forces & Motion

Unit 4 Newton’s Laws of Motion & Momentum

3.5 Newton’s laws of motion and momentum

This section provides knowledge and understanding of Newton’s laws – fundamental laws that can be used to predict the motion of all colliding or interacting objects in applications such as sport (HSW1, 2). Newton’s law can also be used to understand some of the safety features in cars, such as air bags, and to evaluate the benefits and risks of such features (HSW9). Learners should be aware that the introduction of mandatory safety features in cars is a consequence of the scientific community analysing the forces involved in collisions and investigating potential solutions to reduce the likelihood of personal injury (HSW10, 11, 12).

There are many opportunities for learners to carry out experimental work and analyse data using ICT techniques (HSW3).

Module 2 – Foundations of physics

2.1 Physical quantities and units
2.2 Making measurements and analysing data
2.3 Nature of quantities

Module 3 – Forces and motion

3.1 Motion
3.2 Forces in action
3.3 Work, energy and power
3.4 Materials
3.5 Newton's laws of motion and momentum ← You are here!

Module 4 – Electrons, waves and photons

4.1 Charge and current
4.2 Energy, power and resistance
4.3 Electrical circuits
4.4 Waves
4.5 Quantum physics

3.5 Newton’s Laws of Motion & Momentum

- 3.5.1 Newton’s Laws of Motion
- 3.5.2 Collisions

3.5.1 Newton's Laws of Motion

3.5.1 Newton's laws of motion

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) Newton's three laws of motion

(b) linear momentum; $p = mv$; vector nature of momentum

(c) net force = rate of change of momentum;

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

(d) impulse of a force; impulse = $F\Delta t$

(e) impulse is equal to the area under a force–time graph.

What is Newton’s first law of motion?

Newton's First Law

- An object will remain at rest or continue to move with constant velocity unless acted upon by a resultant force.

- So:
  - If an object is stationary it will remain stationary.
  - If an object is moving at a constant speed in a constant direction (ie constant velocity) it will remain doing so.
  - UNLESS a force acts upon the object.

To summarise:

- A resultant force causes acceleration.
  - A zero resultant force = no acceleration.

- Be careful to talk about constant velocity rather than constant speed!!
  - Why?

What is Newton’s third law of motion?

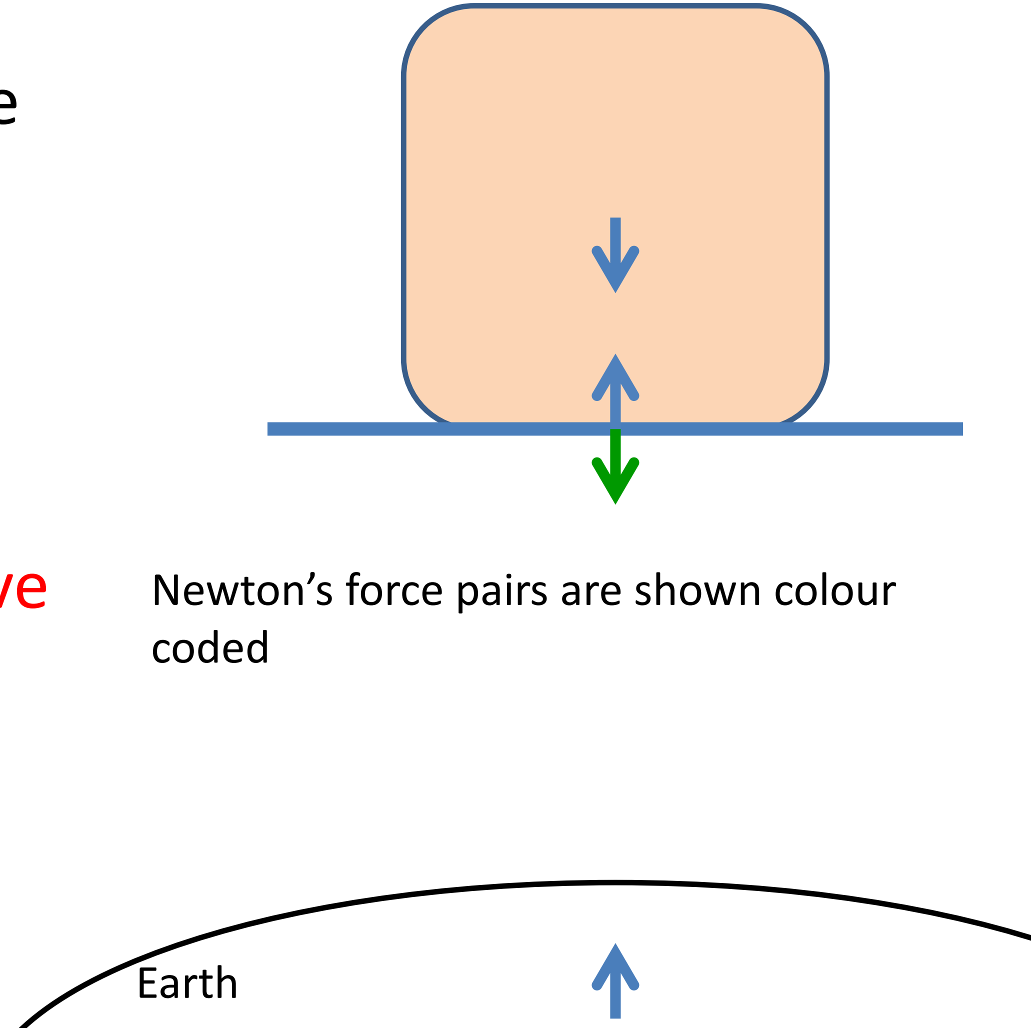
Newton's Third Law

- When two objects interact they exert equal and opposite forces on each other.

- So, When body A exerts a force on body B, then body B will exert a force on body A which is:
  - Equal in magnitude
  - Opposite in direction
  - Of the same type (electrical, magnetic, gravitational, nuclear)

An stationary object on a tabletop…

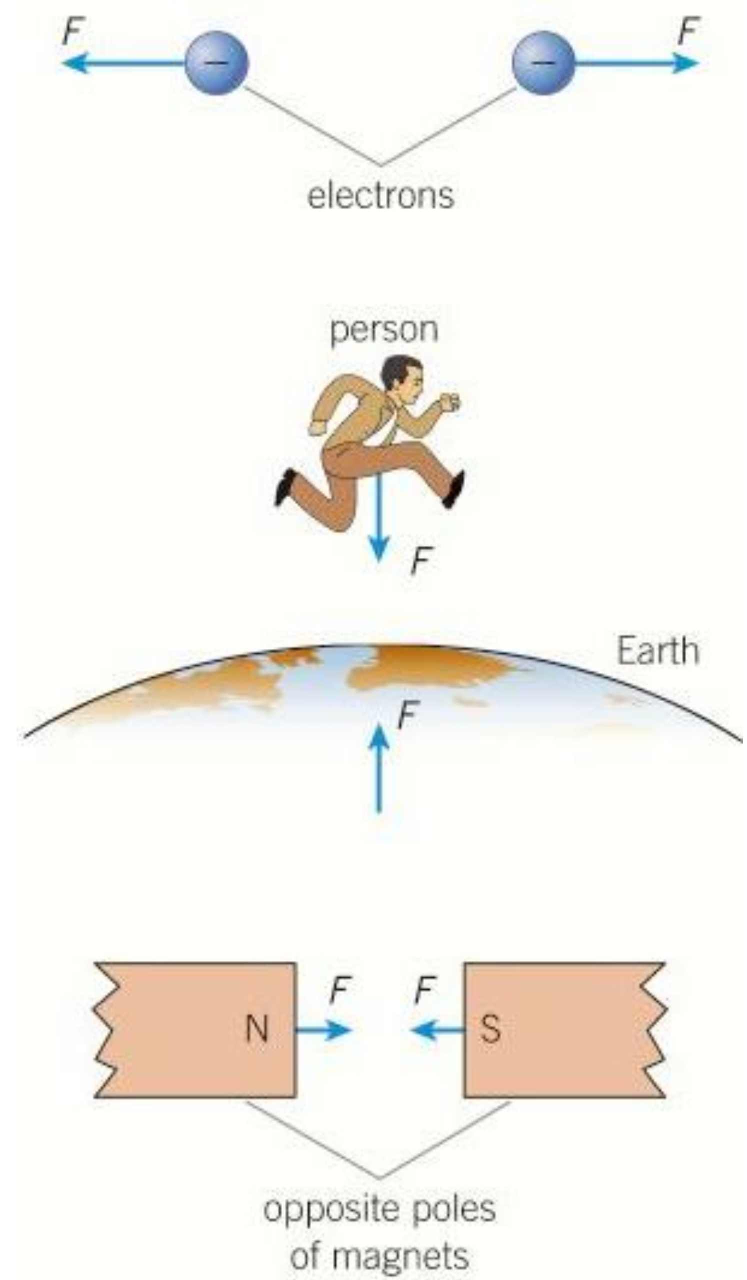
- The weight of the object is equal but opposite to the normal contact force from the table.
- Is this an example of Newton's third law?
- Newton's force pairs have to be of the same type and act on different objects.



Newton's force pairs are shown colour coded

Newtons pairs

- For each diagram:
  - What are the types of forces?
  - What objects are they acting on?



What is Newton’s second law of motion?

Before we answer this...

- We need to look at the idea of momentum.

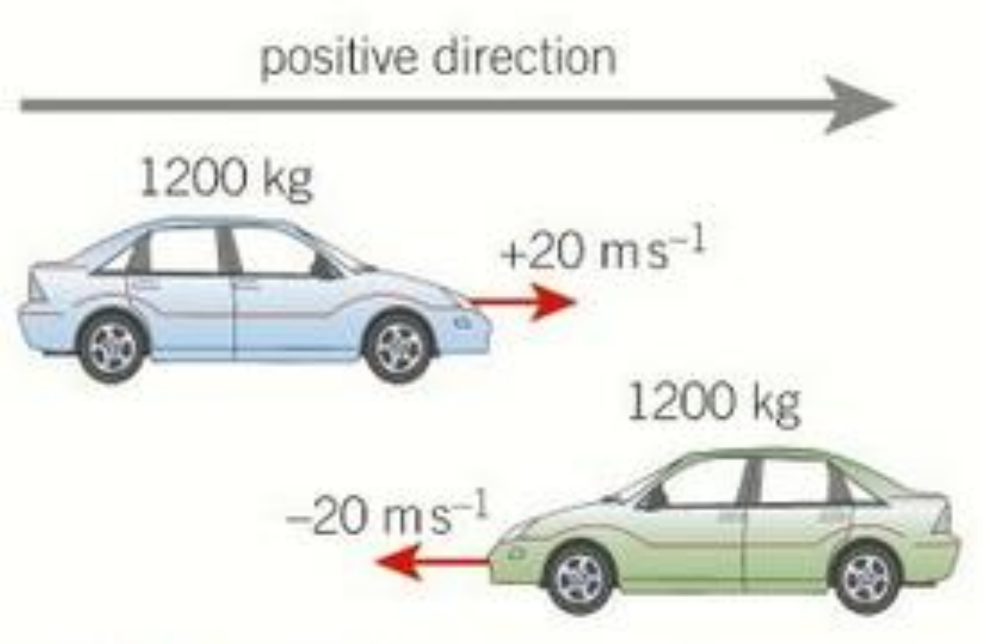
Momentum

- Linear momentum = Mass x Velocity

  (momentum in a straight line)

- Momentum is a vector quantity
- Its symbol is p.
- It has the unit of $kgms^{-1}$
- **p = mv**

- **What is the momentum of these cars?**



Blue car: $p = mv = 1200x20 = 24000kgms^{-1}$

Green car: $p = mv = 1200x\text{-}20 = -24000kgms^{-1}$

The Principle of Conservation of Momentum

- For a system of interacting objects, the total momentum in a specified direction remains constant as long as no external forces act on the system.

- Colliding objects transfer momentum between them but the total momentum does not change.

What does this mean?

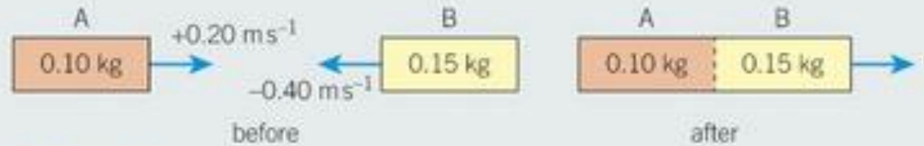
- When objects collide, the total momentum before and after the collision remains the same.

Worked example, p.103.

Worked example: Air track collision

Two gliders are on a linear air track. Glider **A** is travelling at $0.20\,\mathrm{m\,s^{-1}}$ and has mass 0.10 kg. It is hit by glider **B** of mass 0.15 kg travelling at $0.40\,\mathrm{m\,s^{-1}}$ in the opposite direction. They stick together. Calculate their new velocity *v*.

Step 1: Write down the information given for each glider before and after the collision. Alternatively, you can do a quick sketch to help you to visualise the problem, as shown in Figure 3.



▲ **Figure 3** *Before and after sketches*

The velocity, and therefore momentum, of one glider must be negative because of its direction of travel.

Step 2: Write an equation for this collision using the principle of conservation of momentum.

total momentum before = total momentum after

$$(0.10 \times 0.20) + (0.15 \times -0.40) = (0.10 + 0.15)v$$

Step 3: Solve this equation to calculate *v*.

$$0.020 - 0.060 = 0.25v$$

$$-0.040 = 0.25v$$

$$v = \frac{-0.040}{0.25} = -0.16\,\mathrm{m\,s^{-1}}$$

The velocity of the joined gliders is $-0.16\,\mathrm{m\,s^{-1}}$.

Note: The negative sign shows that the gliders move in the direction in which glider **B** was originally travelling.

But why is momentum conserved?

- Newton's 3rd Law states that two interacting objects experience equal but opposite forces.

- The net force acting on both objects is therefore zero.
  (F + -F = 0)
- Newton's 2nd Law shows that the total change in momentum of these two objects must also be zero:

$$F_{net} = \frac{\Delta p}{\Delta t} = 0$$

Momentum and Newton's 3rd Law

- The total momentum of these examples is zero. Explain:
  - **The recoil of a gun as a bullet is fired.**

  - **An exploding firework.**
  - **A rocket launch.**

Types of collisions

- Whenever two objects collide they transfer momentum and energy between them.
  - The total energy and total momentum is always conserved during a collision.
  - However, kinetic energy is often transformed into other energy types (eg. heat, sound).
- Elastic Collisions
  - Conserve kinetic energy
  - The combined speeds of the objects before the collision equals that after the collision.
  - Eg. Colliding electrons.
- Inelastic Collisions
  - Do not conserve kinetic energy.
  - Some kinetic energy is transformed into sound/heat.
  - Eg. Colliding cars.

Newton’s Second Law

The rate of change of momentum on an object is proportional to the resultant force acting upon it.

$$F \propto \frac{\Delta p}{\Delta t}$$

This can be written as an equation if we include a constant.

$$F = \frac{k\Delta p}{\Delta t}$$

Using SI units, the k equals 1 so:

$$\boxed{F = \frac{\Delta p}{\Delta t}}$$

Newton's 2nd Law with Constant Mass

- If the mass of an object doesn't change as it accelerates:

$$F = \frac{\Delta p}{\Delta t} = \frac{mv - mu}{t} = m\left(\frac{v - u}{t}\right) = ma$$

$$F = ma$$

This is a special case of Newton's 2nd Law which applies only when mass remains constant during acceleration. SO BE CAREFUL!!!

What is meant by the impulse of a force?

Impulse of a Force

- Forces act over a period of time.
  - A quick kick of a ball sees the foot in contact with the ball for a few milliseconds.

According to Newton:

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

This is called the impulse of a force

Rearranging gives:

$$F\Delta t = \Delta p$$

So, the product of force and time equals the change in momentum

Impulse of a force = Change in Momentum

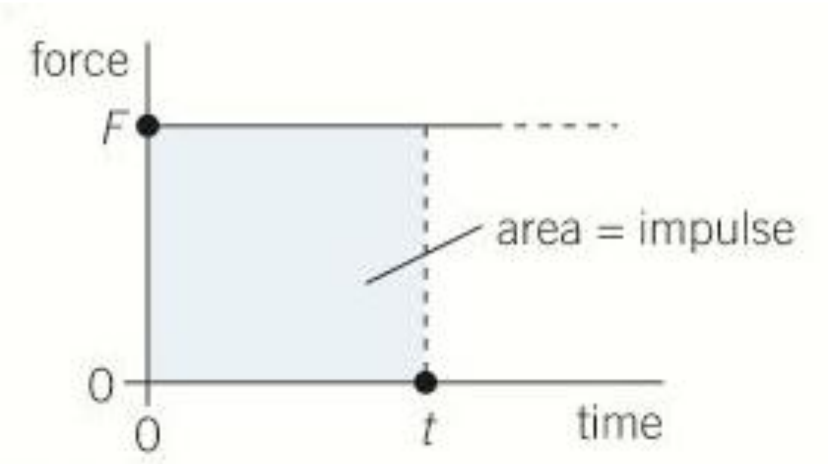
What is the unit of impulse?

$$F\Delta t = \Delta p$$

- Impulse has a units of :
  - Ns or $kgms^{-1}$
  - Can you show why these units are homogenous?

- If we take F = ma which has units of N and $kgms^{-2}$ respectively.
- Multiply both sides by time and we get units of Ns and $kgms^{-1}$

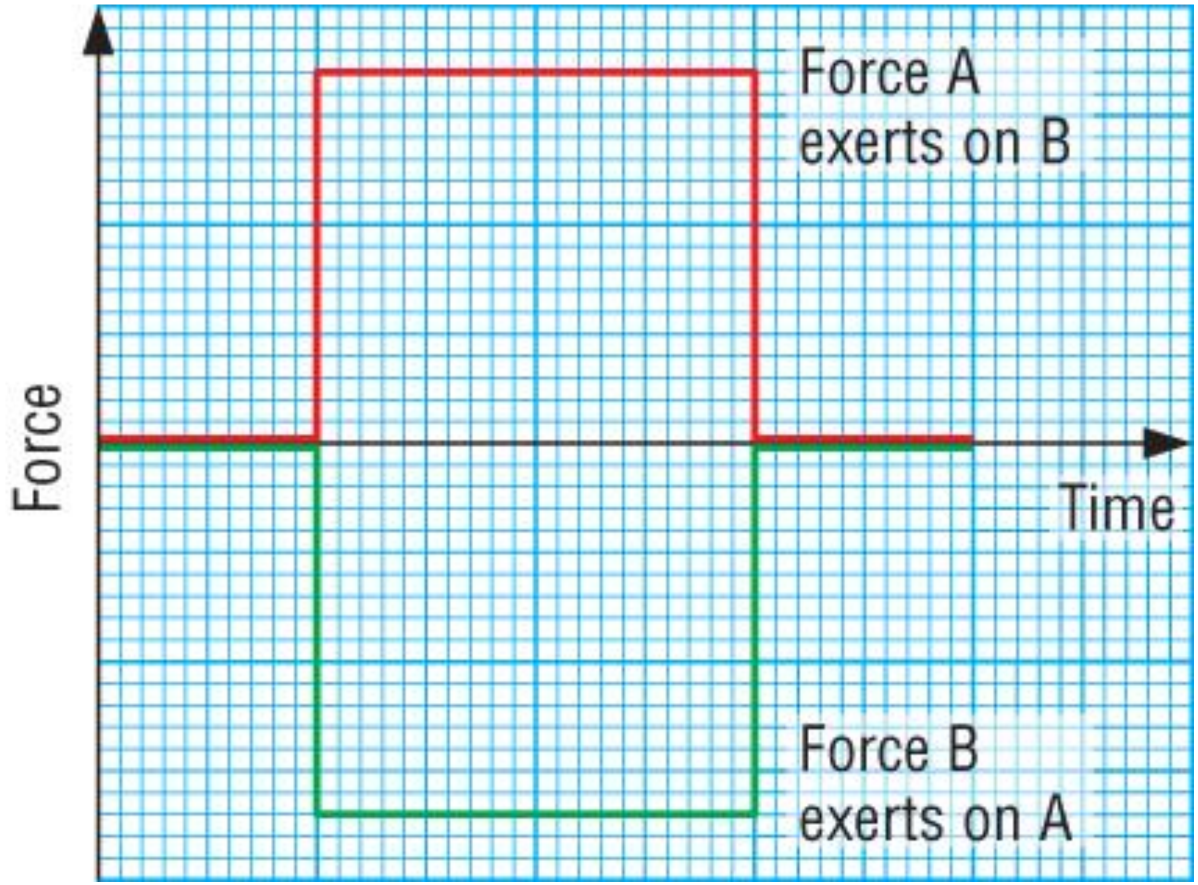
Force – Time graphs



- The area under a force-time graph is equal to Ft, which is the impulse of the force (Δp).
- This even applies when the force changes over time.

Going back to Newton's 3rd Law:

- Remember Δp=force x time.
- Each time an object gains momentum, another object must lose the same amount.



Try this:

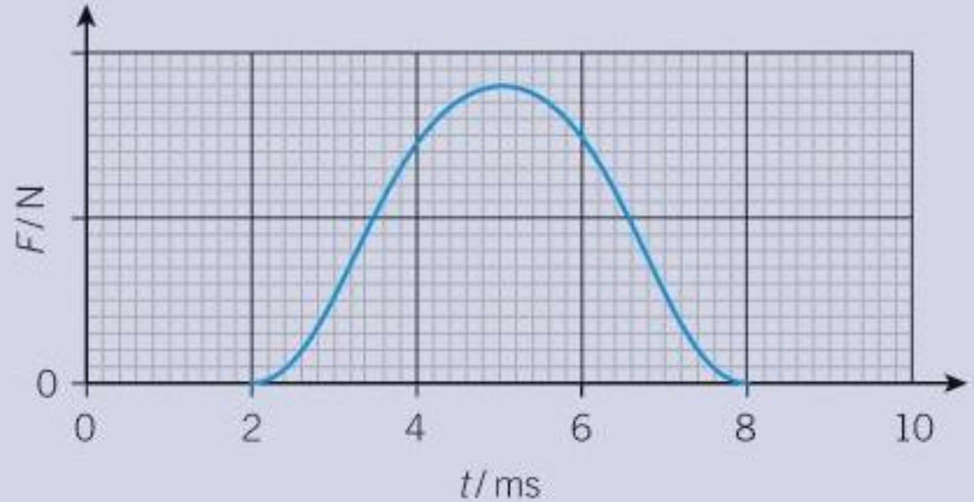
i) To calculate final velocity we need the impulse.

How can we get this?

We could count squares

Or we could draw a triangle and calculate its area.

b A stationary tennis ball of mass 60 g is hit with a racquet. Figure 1 shows a graph of force *F* on the ball against time *t* of impact between the racquet and the ball.



▲ **Figure 1**

(i) Calculate the final velocity of the ball. *(3 marks)*

(ii) Show that the maximum force acting on the ball is about 1 kN. *(3 marks)*

3.5.1 Newton's Laws of Motion (review)

3.5.1 Newton's laws of motion

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(a)	Newton's three laws of motion
(b)	linear momentum; $p = mv$; vector nature of momentum
(c)	net force = rate of change of momentum; $F = \frac{\Delta p}{\Delta t}$
(d)	impulse of a force; impulse = $F\Delta t$
(e)	impulse is equal to the area under a force–time graph.

3.5.2 Collisions

3.5.2 Collisions

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) the principle of conservation of momentum

(b) collisions and interaction of bodies in one dimension and in two dimensions

(c) perfectly elastic collision and inelastic collision.

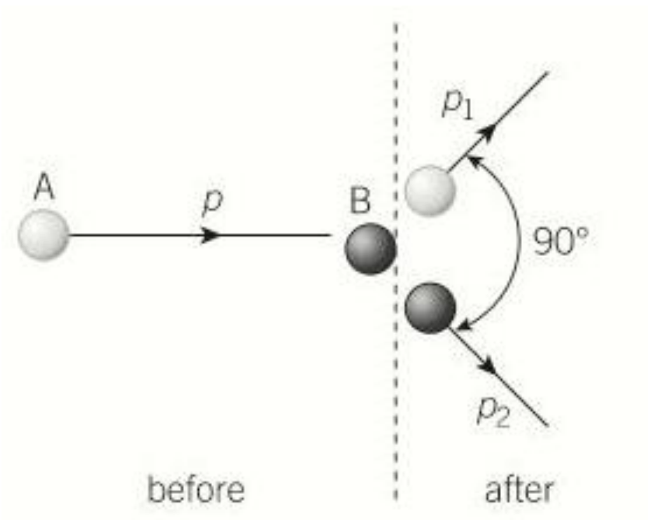
How can we calculate the momentum of objects after a collision?

Collisions

- When any object collides with another object the total momentum of the two objects is conserved.
- This applies whether the collisions are in:
  - One dimention
    - Eg. The linear air track, or cars rolling down a ramp.
  - Two dimensions
    - Eg. Balls on a snooker table
  - Three dimensions
    - Eg. Air molecules in a room

Calculating Momentum in a Two-Dimensional Collision

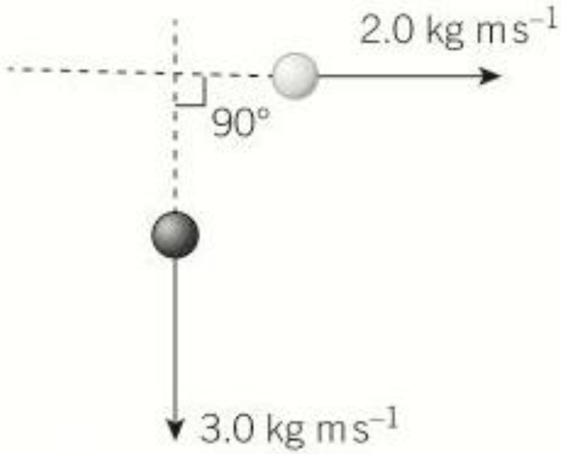
- If we view momentum as a vector, we can use the vector addition/resolution rules and trigonometry to calculate momenta.



If momentum is to be conserved, $p = p_1 + p_2$

A vector triangle allows us to calculate the momenta

You try:



▲ Figure 7

- Shows the momenta of 2 particles after a collision. What was the initial momentum of the colliding particle before the collision?
- Shows a collision. The two particles stick together as they collide. What is the final velocity of the 2 particles after the collision?

The initial momentum must equal the final momentum. The final momentum is the vector sum of the two momentums. [1]

Therefore

initial momentum = $\sqrt{3.0^2 + 2.0^2}$ [1]

initial momentum = $3.6\,\text{kg m s}^{-1}$ (2 s.f.) [1]

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final momentum = total initial momentum [1]

final momentum = $\sqrt{(0.250 \times 3.0)^2 \times (0.150 \times 4.0)^2}$ [1]

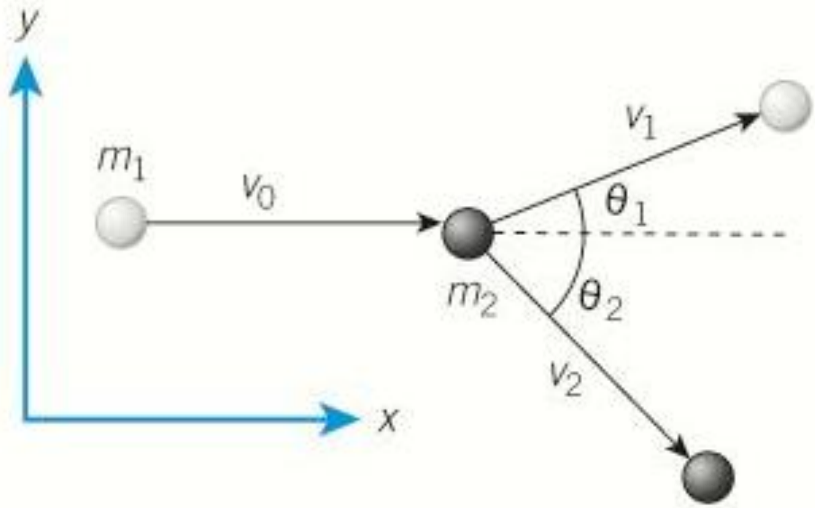
final momentum = $0.96\ldots\,\text{kg m s}^{-1}$ [1]

final velocity $v = \dfrac{0.96\ldots}{0.400} = 2.4\,\text{m s}^{-1}$ (2 s.f.) [1]

What about when the angles are not 90^{o}?

- Just remember that momentum in any direction must be conserved.

- So we can resolve all vectors into x and y directions.
  - We need to ensure total momentum in the x direction is conserved.
  - And total momentum in the y direction is conserved.



▲ **Figure 5** *The white object is originally moving in the x direction, so after the collision, the total momentum in the y direction must be zero*

For example:

Beware:

You could be asked to calculate final or initial velocities or momenta or even the angles or the masses.

The momentum in any direction must be conserved. In this case, the momentum must remain the same in the x direction and y direction.

x direction: total initial momentum = total final momentum

$$m_1 v_0 = m_1 v_1 \cos\theta_1 + m_2 v_2 \cos\theta_2$$

y direction: total initial momentum = total final momentum

$$0 = m_1 v_1 \sin\theta_1 + m_2 v_2 \sin\theta_2$$

Calculating Momentum in 3 Dimensions

- The collision of 2 air particles in 3 dimensional space when one of the particles is initially stationary will always occur on a plane.

- So the maths required is no more than that for 2D collisions.

- Things become tricky with moving particles.
  - We do not need to concern ourselves with these.

3.5.2 Collisions (review)

3.5.2 Collisions

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

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(b) collisions and interaction of bodies in one dimension and in two dimensions

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Complete! → 3.5

Module 4 – Electrons, waves and photons

- 4.1 Charge and current
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