2023

PapaCambridge

Dynamics

AS Physics Unit 3

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Newton's Laws of Motion & Momentum

Newton's Laws of Motion

Mass is the property of an object which resists the change in motion.

The First Law

"Every object continues to stay in its state of rest, or with uniform velocity, unless it is acted upon by a resultant force."

This tells us that a **force disturbs the state of rest or velocity of an object, this property of staying in a state of rest or uniform velocity is known as "inertia".**

The Second Law

"For an object of constant mass, its acceleration is directly proportional to the resultant force applied to it."

The second law…

1. Tells us what happens **if a force is exerted on an object which causes the velocity to change.**
   → A force exerted on an object **may increase/decreases its speed or change its direction of motion.**
2. Relates to magnitude of this acceleration to the force applied.

Equations

Word Equation:

$$Resiltant\ Force = Mass \times Acceleration$$

Symbol Equation:

$$F = ma$$

Quantity	Name	Unit
F	Resultant Force	Newtons (n)
m	Mass	Kilograms (kg)
a	Acceleration	Meters/second^2 (ms^{-2})

The Third Law

"Whenever one object exerts a force on another, the second object exerts and equal and opposite force on the first."

As mentioned, when we for example push a trolley, the following happen:

1. We **exert a force on the trolley** (because we push it).
2. The **trolley exerts and equally strong force on us** (as it has mass which resists the change in motion, the friction, etc.).

Momentum (Linear Momentum)

Key Information

→ The momentum of an object is **defined as a product of its mass (m) and velocity (v).**
→ It is a **vector quantity.**
→ Has the **unit of $kgms^{-1}$ or Ns.**

Equations

Word Equation

$$Momentum = Mass \times Velocity$$

Symbol Equation

$$p = mv$$

Quantity	Name	Unit
p	Momentum	$kgms^{-1}$ or Ns
m	Mass	kg
v	Velocity	ms^{-1}

Linear Momentum

Momentum has two types:

1. **Angular Momentum**
2. **Linear Momentum**

In AS Physics, we don't really need to concern ourselves with Angular Momentum so when we talk about **Momentum, we are referring to Linear Momentum.**

By linear momentum we are talking about **the product of an object's mass (m) and velocity (v).**

Linking Momentum and Newton's Laws

The First Law (p = constant)

Newton's first law states **that every object continues in a state of rest, or with uniform velocity unless acted upon by a resultant force.**

1. This in **terms of momentum would mean that if an object maintains a uniform velocity, its momentum does not change.**
2. Same goes for when it is at rest, momentum does not change.

$$p = constant (provided\ there\ is\ no\ external\ resultant\ force)$$

The Second Law ($F = \Delta p/\Delta t$)

We know that **Newton's second law states force as a product of an object's acceleration and mass.**

This concept can be expressed in terms of momentum:

1. As we know, acceleration is the rate of change in velocity.
2. This means that the **product of acceleration and mass, we could also say that it is the product of mass and the rate of change in velocity.**
3. For an object of constant mass, **the force would be the same as the rate of change in** (mass × velocity).
   This gives us the following statement:

"The resultant force acting on an object is proportional to the rate of change in its momentum."

4. This can be rephrased to say that **the force is the rate of change in momentum** (because mass × velocity is the formula of momentum).
   The **constant of proportionality is made to one as talked about earlier,** this gives us the statement:

"The resultant force acting on an object is equal to the rate of change of momentum of that object."

As a formula, we can write:

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

Where:

- F is the resultant force.
- Δp is the change in momentum.
- Δt is the change in time.

The Third Law

We already know that **force is equal to the rate of change in momentum.**

1. This allows us to change the third law to:

"The rate of change of momentum due to the force on one object is equal and opposite to the rate of change of momentum due to the force on other object."

2. This means that **when 2 objects collide/exert force, they experience an equal and opposite force on themselves.**
3. This means that **their changes of momentum are equal & opposite as well.**

Weight

Key Information

1. Weight is the **effect of a gravitational field acting on a mass.**
2. It is equal to the **product of an object's mass & acceleration of free fall.**
3. Has the **unit of Newtons (N).**

$$W = mg \quad \text{or} \quad Weight = Mass \times Acceleration\ of\ free\ fall$$

Note: *If the object is on earth, we take g as* $9.81ms^{-2}$.

Measuring Mass & Weight

Measuring Weight

Weight is usually **measured using a Newton balance.**

1. This is **done by hanging the object to the hook of the balance.**
2. The **weight of the object is balanced out by a force from the spring in the balance.**
3. From a previous calibration, the **force is related to the extension of the spring and shows us the magnitude of the opposing force** which is also the weight of the object.

Measuring Mass

Top-pan Balance

The term **balance refers to the balance of forces.**

Here, the **unknown force (due to the weight) is balanced by a force** which is known through previous calibration of the tool.

Lever Balance

This is **when we have a balance which acts like a seesaw.**

Basically, **we find the mass of the object by balancing its weight using counterweights of known mass/weight.**

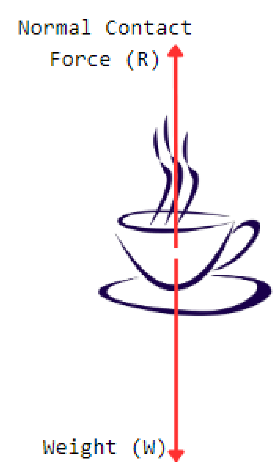
Normal Contact Force

An object **always has weight** even when it **is at rest.**

The reason for this is **related to Newton's first law and means that the resultant force is 0N.**

This means that **there is a force of equal and opposite magnitude on the force** which is exerted on the object by the floor.

This **opposing force is the "normal contact force".**



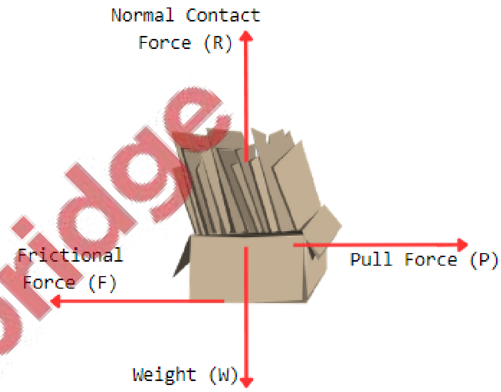
But wait… Isn't This Related to The Third Law?

No, **it is not.**

The reason for this is because the **forces of the third law always act on different bodies rather than the same.**

Here, the **forces act on the same object and is therefore not the case.**

Non-Uniform Motion



Let's saw we pull a box along a surface.

When this happens, there are **four main forces acting on the box:**

1. **Weight** of book (W)
2. **Normal Contact force** (R)
3. **Frictional force** (F)
4. **Pulling force** (P)

The **magnitudes of both forces (P and F) also change the motion of the box:**

1. **P is greater than F:**
   This results in the box accelerating as the force of P overpowers the force of F.
2. **P is equal to F:**
   This results in the object moving at uniform velocity where it neither accelerates nor decelerates.

Viscous/Drag Force

This term is **used to describe the frictional force in a fluid.**

We can find this force **given that we know how viscous the fluid is.**

As the **viscosity of a fluid increases, so does the frictional force** (same goes the other way round).

Terminal Velocity & Air Resistance

If you think about it, **air counts as a fluid and therefore the air resistance is the viscous or drag force.**

Usually, we just **ignore the air resistance** but there are times when it is crucial.

Explaining Terminal Velocity

When an object falls through a resistive fluid, the **velocity of the object doesn't increase forever.**

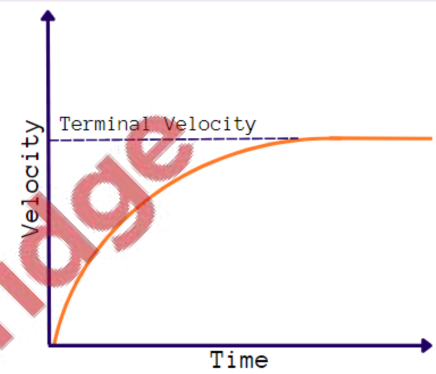
It reaches a **maximum velocity called "terminal velocity".**

This is because, as time goes on, the **drag force increases until eventually the drag force and weight of the object falling balance out** which leaves us with the **object falling at a constant velocity.**

The Graph

As said earlier, as time goes on, the object's acceleration falls due to the increasing drag force until both forces cancel out and we are left with no acceleration meaning uniform velocity (terminal velocity).

On the graph, we would see a curve similar to the one shown on the right.



Immersing an Object into a Fluid

When an object is immersed into a fluid (such as oil), **it experiences three main forces:**

1. The viscous force.
2. The upthrust force.
3. The weight.

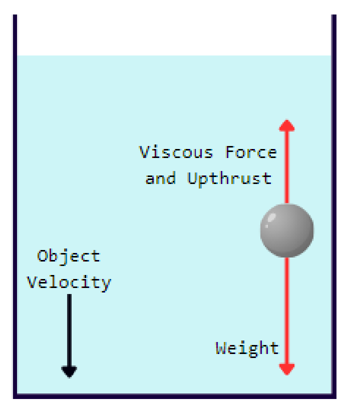
The Upthrust Force

When an object is submerged into a fluid, it **experiences a greater pressure on its bottom surface than on its top surface** which results in an upward force.

The Forces

If we were to drop a ball into a fluid, the forces would act like so:

1. **Viscous force** acting upwards.
2. **Upthrust force** acting upwards.
3. **Weight force** acting downwards.



Reaching Terminal Velocity

As an object falls through a fluid, the **viscous force increases along with the object's velocity.**

The **ends up with the total upwards force balancing with the total downwards force:**

$$Weight = Upthrust + Viscous\ Force$$

This **causes the acceleration to become zero and therefore achieves terminal velocit**y.

Free Body Diagrams

These are **diagrams which shows the object which we care about** and **all the forces which act on it.**

This gives us a clearer picture of the situation and makes it easier for us to find the answer.

Linear Momentum & Its Conservation

Conservation of Momentum

Let's take a system of 2 particles which exert a force on each other:

Let's say that **particle 1 exerts a force *F* on particle 2,** this causes **particle 2 to exert a force *−F* on the first** (due to the third law).

Thinking in terms of momentum:

→ The **change in momentum of the second particle due to the first is equal and opposite to the change in momentum of the first particle.**
→ This is **as a result of the force exerted on the first particle by the second particle.**

This **leads to the changes in momentum of both particles to cancel out** which results in the momentum of the system of these two particles to remain constant **meaning that the particles just "exchanged" momentum.**

As an equation, we would see:

$$p = p_1 + p_2 = constant$$

Where

- P = total momentum.
- P_1 & p_2 = individual momenta.

More General Explanation

"If no external force acts on a system, the total momentum of the system remains constant or is conserved."

The fact that the **total momentum of an isolated system is constant** is the **principle of conservation of momentum** is due to the third law.

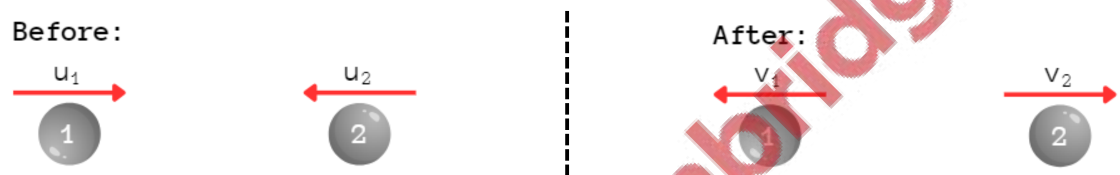
What is an Isolated System?

An **isolated system is simply a system on which no external force acts.**

Think of it like a **little box which is not affected by the rest of the universe.**

Collisions

Let's say two balls collide in a closed system:



Where…

→ Ball 1 has:
1. **Mass** m_1.
2. **Initial velocity** (before collision) u_1.
3. **Final velocity** (after collision) $-v_1$.

→ Ball 2 has:
1. **Mass** m_2.
2. **Initial velocity** (before collision) $-u_2$.
3. **Final velocity** (after collision) v_2.

Using the Principal of Conservation of Momentum

Using the principal of conservation of momentum, the **total momentum of the isolated system is constant.**

This concept shows that **we must equate the total momentums before and after the collision:**

Momentum before Collision:

$$m_1u_1 - m_2u_2$$

Momentum after Collision:

$$-m_1v_1 + m_2v_2$$

Total Momentum:

$$m_1u_1 - m_2u_2 = -m_1v_1 + m_2v_2$$

Solving Questions Related to Conservation of Momentum

Questions usually ask us to **find some unknown variable (such as u or v).**

The best way to go around doing this question is:

1. **Draw a diagram** showing the situation before and after the collision with the velocities and their directions.
2. **Obtain an expression** for total momentum before and after the collision.
3. Now we can **equate the momentums** from step 2 and solve to get the unknown variable.

Momentum & Impulse

Impulse is the product of a force acting on an object and the time for which it acts.

This is given by the formula:

$$impulse = F\Delta t$$

Deriving Impulse

If we remember Newton's second law, we know the formula:

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

When we rearrange to make Δp the subject, we get:

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

A Revelation

If we look at the derived formula, we see that $\Delta p = \Delta Ft$.

This **means that the impulse of a force is equal to the change in momentum (Δp).**

Usually, **we are asked for things (such as the value of F) given that we know the other variables.**

This means that we **can equate the change in momentum to impulse** and solve for force.

$$F\Delta t = m_1(u_1 + v_1) - m_2(u_2 + v_2)$$

Elastic & Inelastic Collisions

We decide whether a collision is inelastic or elastic **depending on how much of the kinetic energy was conserved.**

Elastic Collisions

This is when the **total kinetic energy before collision is equal to the total kinetic energy after the collision.**

If we took the figure from the previous section, the equation for kinetic energies would look like so:

$$\frac{1}{2}m_1{u_1}^2 + \frac{1}{2}m_2{u_2}^2 = \frac{1}{2}m_1{v_1}^2 + \frac{1}{2}m_2{u_2}^2$$

For a perfectly elastic collision, we would see that:

$$u_1 + u_2 = v_1 + v_2$$

This **only works when the initial velocity is equal to the final velocity.**

Elastic collisions only work for collisions of molecules or atoms unlike large-scale collisions such as snooker balls.

The **snooker ball collisions can never be elastic because there is a chance some of the energy becomes sound and heat energy.**

However, we **usually just assume that a collision is perfectly elastic.**

Inelastic Collisions

This is when **there is a difference between the initial and final kinetic energies.**

There are a few things we should know:

1. The **total energy remains the same** (due to the conservation of energy).
2. The **kinetic energy changes** as the rest of the energy is transferred into some other energy stores (such as heat or sound).
3. The **momentum remains equal** (due to conservation of energy).

Past Paper Questions

Question 1 [May/June 2009 21]

A ball B of mass 1.2kg travelling at constant velocity collides head-on with a stationary ball S of mass 3.6kg, as shown in Fig. 2.1.

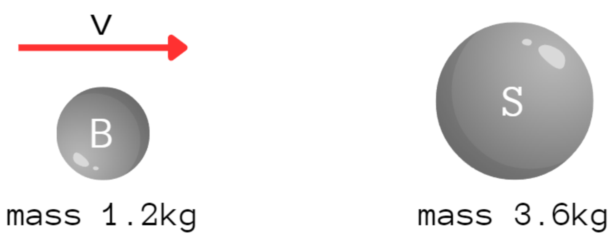
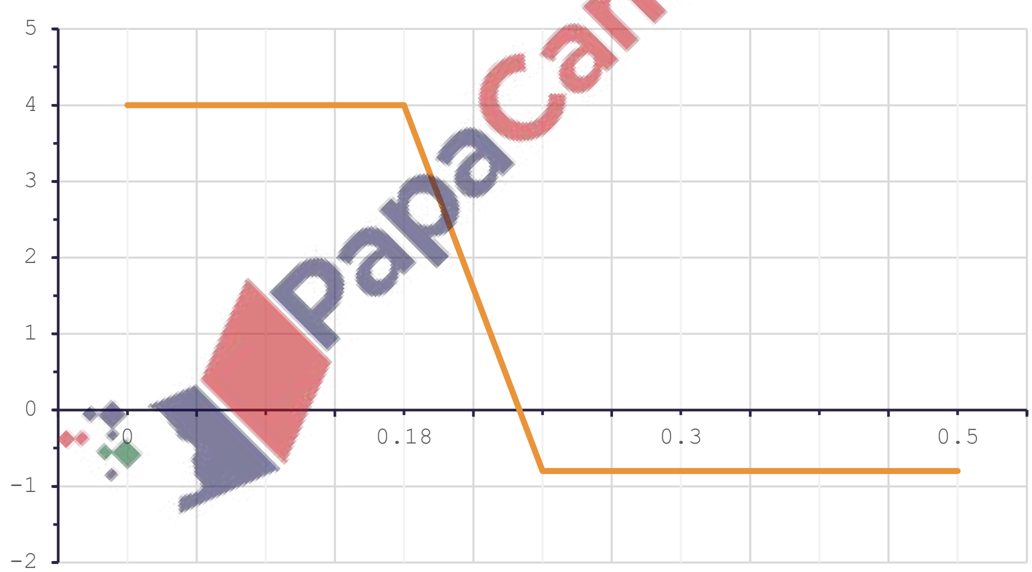


Fig. 2.1

Frictional forces are negligible.

The variation with time t of the velocity v of ball B before, during and after colliding with ball S is shown in Fig 2.2.

Fig. 2.2



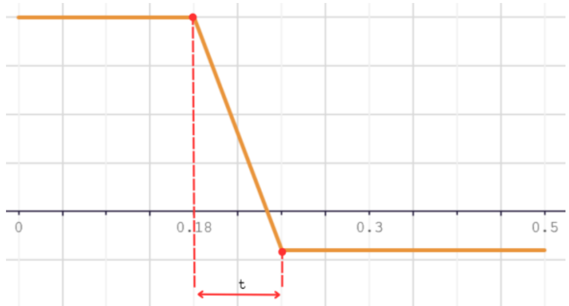
1. **State the significance of positive and negative values for v in Fig 2.2.**
   It indicates that the ball is moving in the negative direction.
2. **Use Fig. 2.2 to determine, for ball B during the collision with ball S.**
   a. **The change in momentum of ball B.**
      We can take the values of the highest and lowest values in fig 2.2 and put that into the formula for change in momentum:

$$1.2(4+0.8) = 1.2(4.8) = 5.76\ Ns$$

b. The magnitude of the force acting on ball B.

Here we can use the formula $Ft = \Delta p$.

Where Δp is 5.76 and t is 0.08 (The x-axis distance for the fall):



Now, we can put these values into the formula and make F the subject:

$$F = \frac{\Delta p}{t} = \frac{5.76}{0.08} = 72N$$

3. Calculate the speed of ball S after the collision.

One key thing to remember is that Δp before the collision is going to be equal to Δp after the collision.

$$5.76 = 3.6 \times v$$

$$v = \frac{5.76}{3.6} = 1.6\, ms^{-1}$$

4. Using your answer to (3) and information from Fig 2.2, deduce the quantitively whether the collision is elastic or inelastic.

We know that the initial velocity is 4 ms^{-1} and the velocity at separation is 2.4 ms^{-1} (0.8 + 1.6).

Since there is a difference between the two, we can say that collision is inelastic as the velocities are not equal (they would be equal if the collision was elastic).

Question 2 [May/June 2020 13]

A ball of mass m travels vertically downwards and then hits a horizontal floor at speed u.

It rebounds vertically upwards with speed v.

The collision lasts a time Δt.

What is the average resultant force exerted on the ball during the collision?

A	B	C	D
$\frac{mv - mu}{\Delta t}$	$\frac{mv - mu}{\Delta t}$	$\frac{mv + mu}{\Delta t}$	$\frac{mv + mu}{\Delta t}$
Downwards	Upwards	Downwards	Upwards

Explanation:

We are asked for the resultant force therefore we use $Ft = \Delta p$.

Rearranging this we get $F = \frac{mv-(-mu)}{\Delta t} = \frac{mv+mu}{\Delta t}$ (assuming upwards is positive).

Since we know that we must find the force acting on the ball, we can say that it acts upwards (as it rebounds).

Question 3 [May/June 2020 21]

1. **Define Velocity**
   Velocity is a vector quantity which measures the rate of change in displacement.
2. **A rock of mass 7.5kg is projected vertically upwards from the surface of a planet. The rock leaves the planet's surface with a speed of 4.0 ms^{-1} at time t = 0. The variation with time t of the velocity v of the rock is shown in Fig. 1.1.**

Fig. 1.1

Assume that the planet does not have an atmosphere and that the viscous force acting on the rock is always zero.

a. **Determine the height of the rock above the surface of the planet at time t = 4.0s.**
   Let's split this up into 2 sections:
   1. Finding maximum height.
   2. Subtracting the distance at t = 4 from the maximum point.

   Part 1:
   Here, we can simply find the <u>area under the graph in positive area:</u>

$$s_{max} = {}^{1}/_{2} \times 4 \times 2.5 = 5m$$

   Part 2:
   This is when we find the <u>area above the gradient in the negative direction</u>:

$$s_{negative} = {}^{1}/_{2} \times 2.4 \times 1.5 = 1.8m$$

   Now, we can subtract these two values to give us the height at t = 4:

$$s_{height} = 5 - 1.8 = 3.2m$$

b. Determine the change in momentum of the rock from time *t* = 0 to time *t* = 4.0s.

Simply use $\Delta p = m(v-u)$ like so:

$$\Delta p = 7.5(-4-2.4) = 48\ Ns$$

c. Determine the weight *W* of the rock on this planet.

To find weight, we can use the formula $F\Delta t = \Delta p$.

In this equation, we can replace F with W which gives us:

$$W\Delta t = \Delta p$$

We now simply rearrange and substitute the values in:

$$W = \frac{\Delta p}{\Delta t} \qquad W = \frac{48}{4} = 12N$$

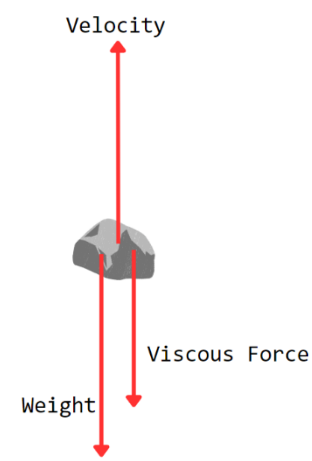
3. In practice, the planet in (2) does have an atmosphere that causes a viscous force to act on the moving rock.
State and explain the variation, if any, in the resultant force acting on the rock as it moves upwards.

As the rock moves upwards, the velocity decreases.
As the velocity falls, so does the viscous force.
This causes the resultant force to reduce as well.

Explanation:

To make life easier, we first make a little drawing.
This helps us visualize the forces:

1. Velocity: acting upwards (as it was thrown).
2. Weight: Acts down (naturally).
3. Viscous Force: Acts down (opposite to velocity).



Obviously, the rock decelerates as it goes up and therefore velocity decreases.
Since velocity falls, the viscous force also decreases as it is dependent on the velocity.
Since the viscous force is acting downwards, it causes the resultant force to decrease.

Question 4 [Feb/Mar 2023 12]

Which expression defines force?

A $(mass \times change\ in\ speed) \times time\ taken$

B $\dfrac{mass \times change\ in\ speed}{time\ taken}$

C $(change\ of\ momentum) \times time\ taken$

D $\dfrac{change\ of\ momentum}{time\ taken}$

Explanation:

We know that the formula of F in terms of momentum is:

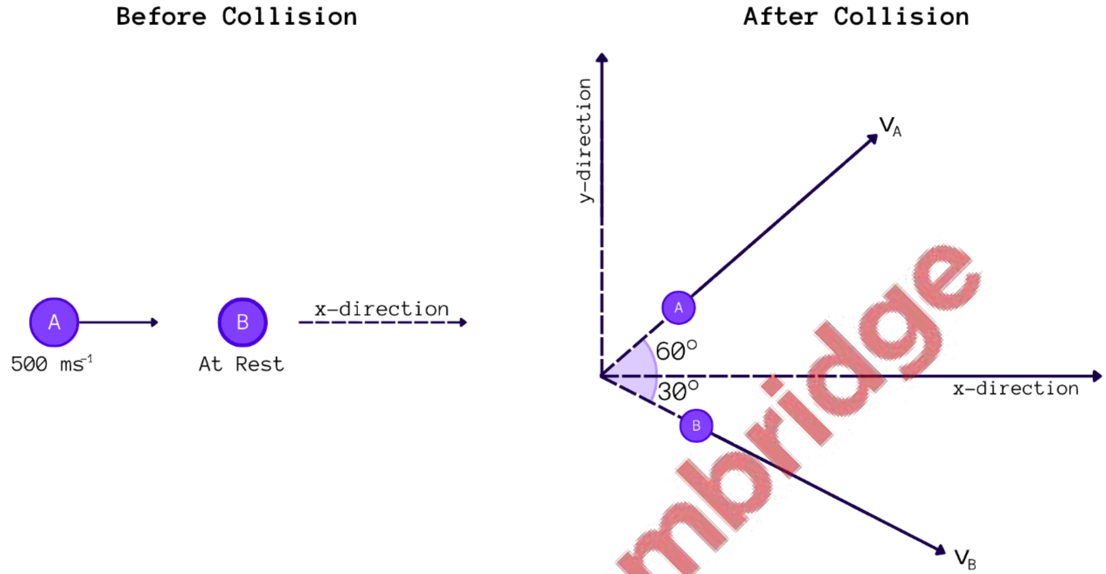
$$F\Delta t = \Delta p$$

Therefore, the answer is:

$$Force = \frac{change\ of\ momentum}{time\ taken}$$

Question 5 [May/June 2016 23]

1. **State the law of conservation of momentum.**
   The total momentum of a system stays constant given that it is a closed or isolated system.
2. **Two particles A and B collide elastically, as shown in the figure below:**



The initial velocity of A is 500 ms^{-1} in the x-direction & B is at rest.

The velocity of A after the collision is v_A at 60° to the x-axis. The velocity of B after the collision in v_B at 30° to the x-axis.

The mass of each particle is 1.67×10^{-27} kg.

a. **Explain what is meant by the particles colliding elastically.**
   The total kinetic energy before the collision is equal to the total kinetic energy after the collision.

b. **Calculate the total initial momentum of A and B.**

$$Momentum = mass \times Velocity$$
$$Momentum = (1.67 \times 10^{-27}) \times 500$$
$$Momentum = 8 \times 10^{-25}\ Ns$$

3. **State an expression in terms of m, velocities v_A and v_B for the total momentum after the collision.**

   a. **In the x-direction,**

$$mv_A \cos(60°) + mv_B \cos(30°)$$

Explanation:

Here, we use basic trigonometry where we take the hypotenuse as the momentum for both speeds and use cos to find the length of the horizontal direction (adjacent).

For example, for v_A:

$$momentum\ of\ A = m \times v_A$$
$$hyp = mv_A\ and\ \theta = 60°$$
$$\cos(60°) = \frac{adj}{mv_A}$$
$$mv_A \cos(60°) = adj$$

Similarly, we do the same for v_B and then add with the adjacent value of v_B.

   b. **In the y-direction,**

$$mv_A \sin(60°) + mv_B \sin(30°)$$

Explanation:

Similar to part a, we use the trigonometric functions except we find the opposite (vertical direction) rather than the adjacent.

For example, if we wish to find the vertical of v_B:

$$Momentum\ of\ B = mv_B$$
$$hyp = mv_B\ and\ \theta = 30°$$
$$\sin(30°) = \frac{opp}{mv_B}$$
$$mv_B \sin(30°) = opp$$

Again, we use mv_A to find the momentum of mv_A in the y-direction and add to the momentum we calculated from mv_B.

4. Calculate the magnitudes of the velocities v_A and v_B after the collision.

Here, apply the conservation of momentum:

$$Initial\ Momentum = Final\ Momentum$$

Therefore, we can equate the y and x components before and after the collision:

$$8 \times 10^{-25} = mv_A \cos(60°) + mv_B \cos(30°)$$
$$0 = mv_A \sin(60°) + mv_B \sin(30°)$$

Let's start with simplifying the x-component:

$$8 \times 10^{-25} = mv_A \cos(60°) + mv_B \cos(30°)$$

→ Remove the mass values which leaves us with just the speeds:

$$500 = v_A \cos(60°) + v_B \cos(30°)$$

→ Simplify the equation:

$$500 = \frac{v_A}{2} + \frac{v_B\sqrt{3}}{2}$$
$$1000 = v_A + v_B\sqrt{3}$$

Now, we simplify the y-component:

$$0 = mv_A \sin(60°) + mv_B \sin(30°)$$

→ Now, divide by m which would give us 0 on the other side:

$$0 = v_A \sin(60°) + v_B \sin(30°)$$
$$0 = \frac{v_A \times \sqrt{3}}{2} - \frac{v_B}{2}$$

→ We subtract v_A from v_B as they act in opposite directions.
Now we keep on simplifying and the make one of the velocities as the subject:

$$0 = \sqrt{3}\, v_A - v_B$$
$$v_B = \sqrt{3}\, v_A$$

Now, we can substitute v_B into the x-component equation:

For v_A:

$$1000 = v_A + (\sqrt{3}\, v_A)\sqrt{3}$$
$$1000 = v_A + 3\, v_A$$
$$1000 = 4\, v_A$$
$$250 = v_A$$

For v_B:

$$v_B = \sqrt{3} \times 250$$
$$v_B = 433.01$$

Therefore:

v_A = 250 ms^{-1}

v_B = 433.01 ms^{-1}

Sources (and Resources) Used

Most of the information has come from the **AS & A Level Physics Student Book by Hodder Education**.

Other resources/tools have also been used and are listed below:

Name	Link	Use
Save My Exams	**LINK**	Mainly understanding concepts to make them simpler
ZNotes	**LINK**	
Canva	**LINK**	Designing of figures and diagrams
Geogebra	**LINK**	Vector diagrams
Papa Cambridge	**LINK**	Topical Questions
AS/A Level Syllabus	**LINK**	Checking syllabus
Word 2010	**LINK**	Creating the notes
Word 365	**LINK**	Exporting and stuff

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Dynamics

AS Physics Unit 3