Momentum

A large rugby player running very fast has much more momentum than a skinny one out for a Sunday afternoon stroll. It's something that all moving objects have, so you better get your head around it.

Momentum = Mass × Velocity

Momentum is a property that all moving objects have. (Think of it as how much 'oomph' something has.) It's defined as the product of the object's mass and velocity:

$p = m \times v$ momentum (kg m/s) = mass (kg) × velocity (m/s)

1) The greater the mass of an object, or the greater its velocity, the more momentum the object has.
2) Momentum is a vector quantity — it has size and direction.

EXAMPLE:

A 50 kg cheetah is running at 60 m/s. Calculate its momentum.

$p = m \times v = 50 \times 60$
$= 3000$ kg m/s

EXAMPLE:

A boy has a mass of 30 kg and a momentum of 75 kg m/s. Calculate his velocity.

$v = p \div m = 75 \div 30 = 2.5$ m/s

Total Momentum Before = Total Momentum After

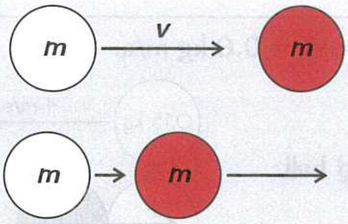
A closed system is just a fancy way of saying that no external forces act.

In a closed system, the total momentum before an event (e.g. a collision) is the same as after the event. This is called conservation of momentum. You can use this to help you calculate things like the velocity or mass of objects in a collision.

In snooker, balls of the same size and mass collide with each other. Each collision is an event where the momentum of each ball changes, but the overall momentum stays the same (momentum is conserved).

Before:

After:



The red ball is stationary, so it has zero momentum. The white ball is moving with a velocity v, so has a momentum of $p = m \times v$.

The white ball hits the red ball, causing it to move. The red ball now has momentum. The white ball continues moving, but at a much smaller velocity (and so a much smaller momentum). The combined momentum of the red and white balls is equal to the original momentum of the white ball, $m \times v$.

EXAMPLE:

A 1500 kg car, travelling at 25 m/s, crashes into the back of a parked car. The parked car has a mass of 1000 kg. The two cars lock together and continue moving in the same direction as the original moving car. Calculate the velocity that the two cars move with.

1) Calculate the momentum before the collision. $p = m \times v = 1500 \times 25 = 37\,500$ kg m/s

Total momentum before = total momentum after

2) Find the combined mass of the cars. New mass of joined cars = 2500 kg = M

3) Rearrange the equation to find the velocity of the cars. $v = p \div M = 37\,500 \div 2500 = 15$ m/s

Learn this stuff — it'll only take a moment... um...

Conservation of momentum is incredibly handy — there's more on using it on the next page.

Q1 Calculate the momentum of a 60 kg woman running at 3 m/s. [2 marks]

Q2 Describe how momentum is conserved by a gun recoiling (moving backwards) as it shoots a bullet. [4 marks]

Changes in Momentum

A force causes the momentum of an object to change. A bigger force makes it change faster.

Forces Cause Changes in Momentum

1) When a resultant force acts on an object for a certain amount of time, it causes a change in momentum. Newton's 2nd Law can explain this:
   - A resultant force on an object causes it to accelerate: force = mass × acceleration (see p.149).
   - Acceleration is just change in velocity over time, so: force $= \frac{\text{mass} \times \text{change in velocity}}{\text{time}}$.
     This means a force applied to an object over any time interval will change the object's velocity.
   - Mass × change in velocity is equal to change in momentum, so you end up with the equation:

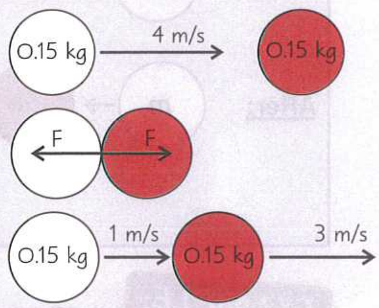
$$\text{force (N)} = \frac{\text{change in momentum (kg m/s)}}{\text{time (s)}} \quad \text{or} \quad F = \frac{(mv - mu)}{t}$$

2) The faster a given change in momentum happens, the bigger the force causing the change must be (i.e. if t gets smaller in the equation above, F gets bigger).
3) So if someone's momentum changes very quickly, like in a car crash, the forces on the body will be very large, and more likely to cause injury. There's more about this on p.149.
4) You can also think of changes in momentum in collisions in terms of acceleration — a change in momentum normally involves a change in velocity, which is what acceleration is (see p.146).
5) As you know, $F = ma$, so the larger the acceleration (or deceleration), the larger the force needed to produce it.

Conservation of Momentum Shows Newton's Third Law

The equation above can help to show Newton's Third Law (reaction forces are equal and opposite). Take the snooker balls from the previous page.

1) Before the collision, the white ball has a momentum of 0.15 × 4 = 0.6 kg m/s. The red ball has a momentum of zero.
2) The total momentum of the system is 0.6 kg m/s.
3) When the balls collide, the white ball exerts a force on the red ball. This force causes the red ball to start moving.
4) Due to Newton's 3rd Law, the red ball also exerts an equal but opposite force on the white ball. This force causes the white ball to slow down.
5) The collision lasts 0.1 s. After the collision, the white ball continues moving at 1 m/s. The red ball begins moving at 3 m/s.



6) The total momentum is (0.15 × 1) + (0.15 × 3) = 0.6 kg m/s. Momentum is conserved.
7) You can calculate the size of the force that caused this change of velocity (and so change of momentum) for each ball:
8) The force exerted on the white ball (by the red ball) is equal and opposite to the force exerted on the red ball (by the white ball). This shows Newton's Third Law.

white ball

$$F = \frac{(mv - mu)}{t} = \frac{(0.15 \times 1) - (0.15 \times 4)}{0.1} = \frac{-0.45}{0.1} = -4.5 \text{ N}$$

red ball

$$F = \frac{(mv - mu)}{t} = \frac{(0.15 \times 3) - (0.15 \times 0)}{0.1} = \frac{0.45}{0.1} = 4.5 \text{ N}$$

Homework this week — play pool to investigate momentum...

Sigh if only. Momentum is a pretty fundamental bit of physics — learn it well. Then have a go at this question.

Q1 Calculate the force a tennis racket needs to apply to a 58 g tennis ball to accelerate it from rest to 34 m/s in 11.6 ms. [3 marks]

Momentum

1 A motorbike is travelling at 25 m/s and has a mass of 220 kg. Grade 4-6

a) State the equation that links momentum, mass and velocity.

....
[1]

b) Calculate the momentum of the motorbike.

Momentum = ... kg m/s
[2]
[Total 3 marks]

2 A car is moving east with a velocity of 15 m/s and momentum 46 000 kg m/s. Grade 4-6

Calculate the mass of the car.

Mass = ... kg
[Total 3 marks]

3 **Figure 1** and **Figure 2** show a Newton's cradle. All of the balls on the cradle have the same mass. Grade 6-7

Figure 1

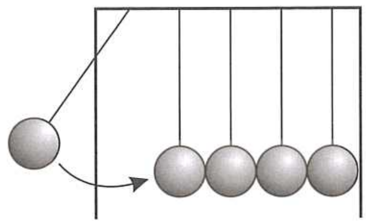
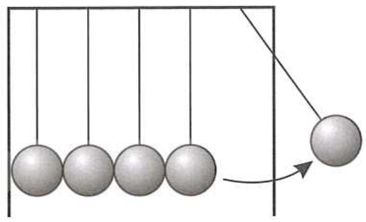


Figure 2



When a ball is lifted and allowed to hit the others as shown in **Figure 1**, it causes the last ball in the line to move outwards, as shown in **Figure 2**. The balls in between appear to remain stationary. Using conservation of momentum, explain this behaviour.

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....
[Total 4 marks]

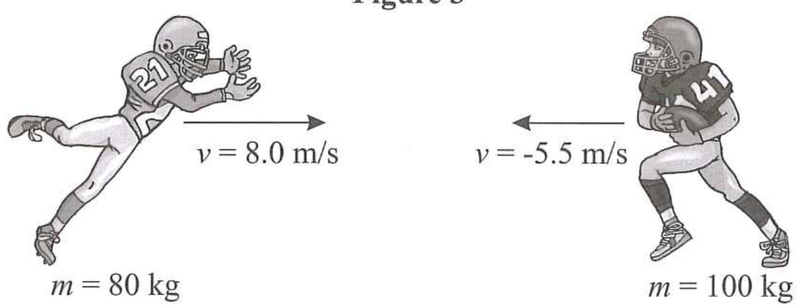
4 A ball moves with an initial velocity of 3 m/s. It comes to rest after 4 seconds due to a constant resistive force of 0.15 N. Calculate the mass of the ball. (Grade 6-7)

Mass = ... kg

[Total 3 marks]

5 **Figure 3** shows two American football players running towards each other. They collide and cling together in a tackle. Calculate the velocity that they move together with once they have collided. (Grade 7-9)

Figure 3



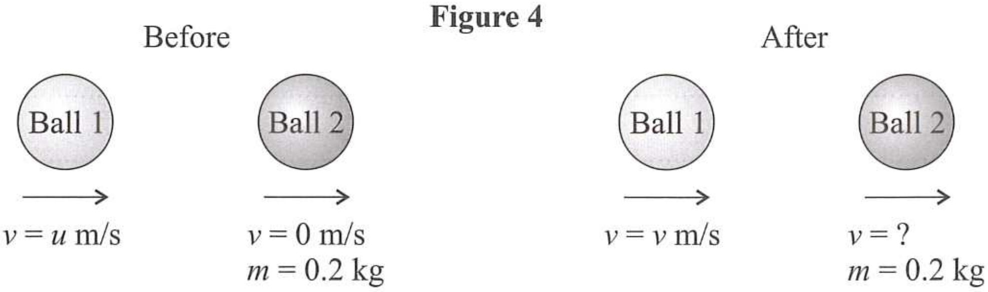
Velocity = ... m/s

[Total 4 marks]

6 **Figure 4** shows balls 1 and 2 before and after a collision. (Grade 7-9)

Ball 1 initially travels with a velocity of u m/s. Ball 2 is stationary and has a mass of 0.2 kg. Ball 1 collides with ball 2 and this collision lasts for 0.1 s. Afterwards, both balls move in the direction of ball 1's initial velocity. Each ball has a different final velocity.

Figure 4



During the collision, a force of –6 N is exerted on ball 1 by ball 2. Calculate the velocity of ball 2 after the collision.

Velocity = ... m/s

[Total 5 marks]