UNIT 2 | GCSE PHYSICS | 2.2.2

Momentum

- **Momentum** is a property of moving objects.

  p = m × v

  p is the **momentum** in **kilogram metre per second (kg m/s)**.
  m is the **mass** in **kilogram (kg)**.
  v is the **velocity** in **metre per second (m/s)**.

- In a closed system, the total momentum before an event is equal to the total momentum after the event. This is called the **principle of conservation of momentum**.

  Examples of events are **collisions** and **explosions**.

- Evaluate the benefits of **seat belts**, **crumple zones**, **air bags** and **side impact bars** in cars. This should include ideas of both **energy changes** and **momentum changes**.

Momentum

The **momentum** of a moving object is the product of its **mass** and its **velocity**.

MOMENTUM = MASS × VELOCITY

p = m × v

(kg m/s) **(kg)** **(m/s)**

- The **SI unit** of momentum is : **Kilogram metre per second (kg m/s)**
- Momentum is a **vector quantity**, involving both **size** and **direction**.

  So if an object is moving to the **right** and its momentum is conventionally taken as **positive**, then the momentum of an object which is moving to the **left** (i.e. in the opposite direction) is taken as **negative**.

• PRACTICE QUESTIONS (1)

1 Calculate the **momentum** of each of the following :

(a) An Olympic sprinter of mass **86 kg** running at **10. 2 m/s**.

(b) A bullet of mass **8.5 g** fired from a gun with a velocity of **300 m/s**.

(c) A super tanker of mass **200 000 tonnes** (**1 tonne = 1000 kg**) cruising with a velocity of **12 m/s**.

2 A fully-laden, **Boeing-747** jumbo jet is cruising at **275 m/s** during a transatlantic flight. If its momentum at this velocity is **121 000 000 kg m/s**, calculate its **mass**.

3 A male cheetah has an average mass of **64 kg** and its momentum when it is moving at top speed is **1920 kg m/s**. Use this information to calculate its **top speed**.

PRINCIPLE OF CONSERVATION OF MOMENTUM

This principle states that :

In a **closed system**, the **total momentum before** an event* is equal to the **total momentum after** the event*.

- Examples of **events** are :
  - **Collisions** (This could be anything from sub-atomic particles to planets crashing into each other).
  - **Explosions** (This could be a bullet fired from a gun, the ejection of an alpha particle from a nucleus or simply a person stepping out of a boat).
- A **closed system** is one in which **no external forces act** on the objects involved in the event.

Collision Problem

- In this type of problem, so long as no external forces act on the colliding objects :

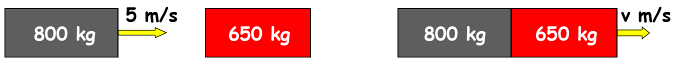
TOTAL MOMENTUM AFTER COLLISION = TOTAL MOMENTUM BEFORE COLLISION

- The best way to understand how this works is to consider an example :

A railway truck of mass **800 kg** moving with a constant velocity of **5 m/s**, collides and couples with another railway truck of mass **650 kg** which is **stationary**. Calculate the **common velocity (v)** with which the coupled trucks move off after the collision.

BEFORE COLLISION

AFTER COLLISION



momentum before collision = momentum after collision

$$(800 \times 5) = (800 + 650) \times v$$

$$4000 = 1450\ v$$

$$v = \frac{4000}{1450}$$

$$v = \boxed{2.76\ \text{m/s}}$$

Explosion Problem

- In this type of problem, so long as no external forces act :

TOTAL MOMENTUM AFTER EXPLOSION = TOTAL MOMENTUM BEFORE EXPLOSION

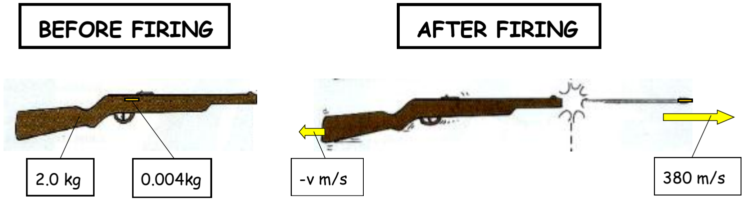
And of course we have to bear in mind that, since nothing is initially moving, the **total momentum before the explosion is zero**.

Momentum is conserved in the explosion which occurs when a gun is fired.

Before the gun is fired, the **total momentum = 0**, since both the gun and the bullet are **stationary**.

Immediately after the gun is fired, in accordance with the **principle of conservation of momentum**, the **total momentum must = 0**. So the bullet and gun have **equal**, but **oppositely directed** momentum.
Since momentum is a vector quantity, if the bullet's momentum is **+ve**, that of the gun will be **-ve** and so they cancel out to give zero total momentum.

A bullet of mass **4.0 g** is fired from a rifle of mass **2.0 kg** with a muzzle velocity of **380 m/s**. What is the **initial recoil velocity** of the rifle ?



momentum before explosion = momentum after explosion

$$0 = (0.004 \times 380) + (2.0 \times -v)$$

$$0 = 1.52 - 2.0v$$

$$v = \frac{1.52}{2.0} = \boxed{0.76 \text{ m/s}}$$

PHYSICS OF CAR SAFETY

Moving cars and the passengers they carry have **kinetic energy** and many of the safety features in all modern cars - **seat belts, crumple zones, air bags and side impact bars** - are designed to reduce injury by **absorbing** much of this kinetic energy in the event of a crash.

The design of these features also ensures that the destructive **forces** which would be exerted on passengers when a collision occurs, are **minimised** as much as possible.

Kinetic energy is absorbed when it is transformed into **work done against resistive forces** in deforming the structure.

kinetic energy lost = work done in plastic deformation

According to **Newton's second law** of motion :

$$\text{FORCE} = \frac{\text{MOMENTUM CHANGE}}{\text{TIME TAKEN}}$$

In any given collision, the **momentum change** experienced by a car has a value which is determined by its **speed** at the moment of impact. So the **size of the force** on the car and passengers depends on the **impact time**. The **greater** the **impact time** is made, the **smaller** the **force** becomes and hence the lower is the risk of injury.

1. Seat Belts

Although a **seat belt** keeps you in your seat during a crash, it does not hold you rigidly in position. The end of the belt is wound over an **inertia reel** which clamps the belt firmly whenever there is a sudden force on it, but allows it to be pulled out slowly when it is being fastened.

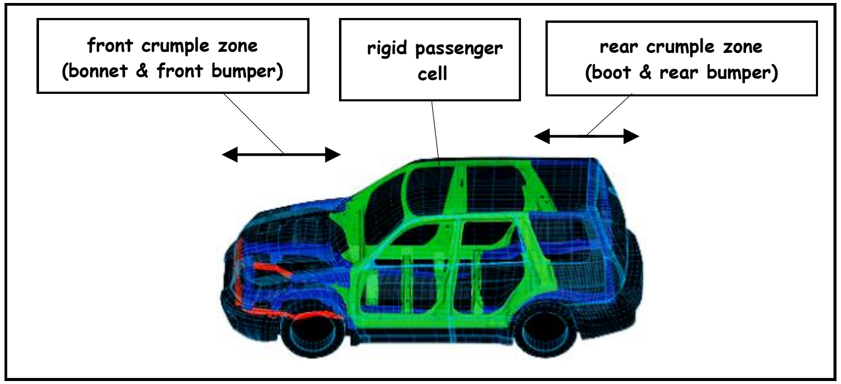
More importantly, the belt is also designed to stretch by about 0.25 m in a crash and this allows the **force** holding you in place to act over a **longer time**. As we have seen from Newton's second law, a **longer time** means a **smaller force**.

Seat belts are also relatively wide so that the **force (F)** acts over a larger **area (A)**, reducing the **pressure** ($p = F/A$) which might otherwise cause injury.

Rear passengers also need to wear seat belts to stop them from becoming lethal projectiles in the event of a crash.

*** Show the very graphic ad for rear seat belts in which an unbelted teenager kills his mother when she brakes suddenly and his forehead crashes into the back of her skull.**

2. Crumple Zones



These are parts of the car at the front and rear, which are designed to **squash or crumple easily** in the event of a crash.

The **kinetic energy** of the moving car is absorbed by the crumpling because **work is done** in causing the metal to deform.

The crumpling also **lengthens** the **impact time** and hence **reduces** the **force** which is transmitted to the passengers.

The area where the passengers are housed is made of much thicker gauge metal which forms a rigid, protective cage around the passengers.

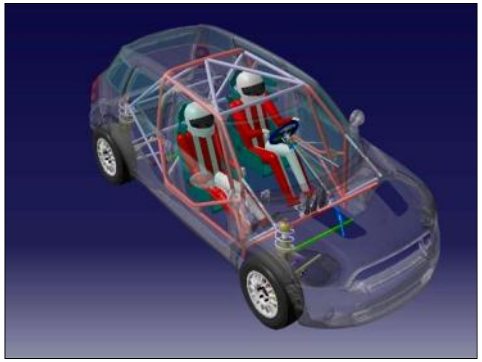
3. Air Bags

The purpose of an **air-bag** is to provide a soft, yielding cushion between the person's upper body (mainly the head) and the steering wheel or dashboard.

The injuries (mainly to the face and chest) which could result in the event of a crash are virtually eliminated by the deployment of an air-bag. This is because :

- The moving person's **kinetic energy** is absorbed as a result of the **work done in deformation** of the bag.
- The **impact time** is **increased** with a subsequent **decrease** in the size of the **impact force**.

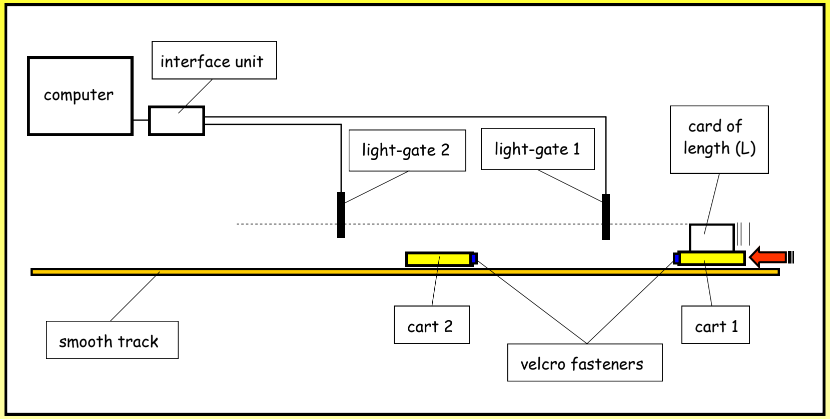
4. Side Impact Bars



These lessen the amount of bodywork distortion produced inside the passenger compartment during a crash.

The side impact bars cause the energy created during a collision to be directed to the floor, bulkhead, sills, roof etc. These structures **absorb** the **energy** and so **reduce damage and intrusion** to the passenger compartment and so protect the passengers from severe injuries.

PRACTICAL WORK : THE PRINCIPLE OF CONSERVATION OF MOMENTUM



- The apparatus shown above can be used to test the validity of the **principle of conservation of momentum**.
- **Cart 1** is pushed towards **stationary cart 2** and as it passes through **light-gate 1** the computer automatically calculates its speed **(v_1)**.

$$v_1 = \frac{\text{length of card passing through the light-gate}}{\text{time taken for card to pass through light-gate}} = \frac{L}{t}$$

- When **cart 1** collides with **cart 2**, the velcro fasteners cause the carts to stick together.
- The two carts then pass through **light-gate 2** and their common speed **(v_2)** is also calculated by the computer.
- The **mass** of each cart is measured using an electronic balance.

RESULTS

Mass of cart 1, m_1 = kg

Mass of cart 2, m_2 = kg

Speed of cart 1 before collision, v_1 = m/s

Speed of carts (1 + 2) after collision, v_2 = m/s

CALCULATIONS

Momentum before collision = $m_1 v_1$ = x = kg m s^{-1}

Momentum after collision = $(m_1 + m_2)\, v_2$ = x = kg m s^{-1}

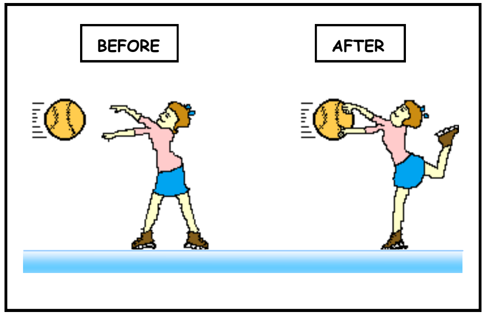
SOME QUESTIONS

- Is the **total momentum after the collision** equal to the **total momentum before the collision** ?
- Has the **principle of conservation of momentum** been verified ?
- Did any **external force** act on the system of colliding carts ? If so, **name** the external force.

PRACTICE QUESTIONS (2)

1 A medicine ball of mass **12 kg** is thrown at a velocity of **5.5 m/s** to a person of mass **60kg** who is standing **at rest** on ice.
The person catches the ball and then slides with the ball across the ice.

Calculate the **velocity** of the person and the ball after the collision.



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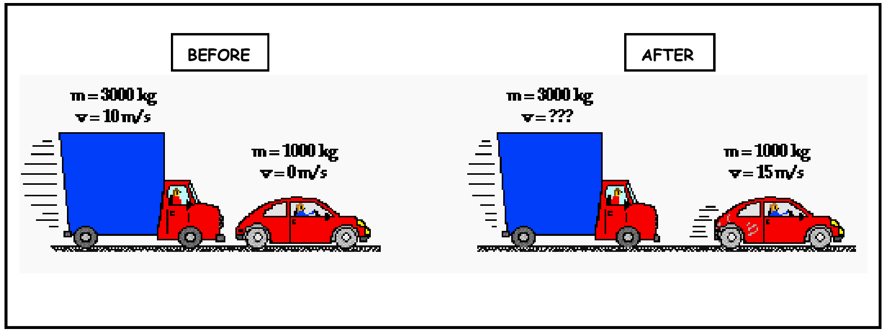
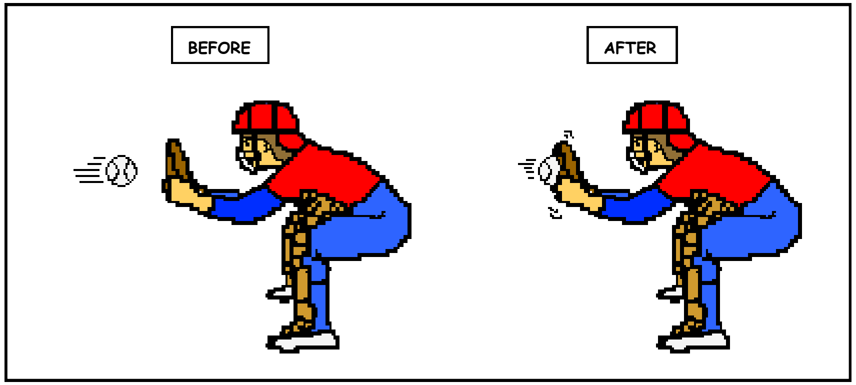


A truck of mass **3000 kg** moving with a velocity of **10 m/s** collides with a stationary car of mass **1000 kg**. The impact causes the car to move off with an initial velocity **15 m/s**.

Assuming that momentum is conserved during the collision, determine the **velocity of the truck** immediately after the collision.

3

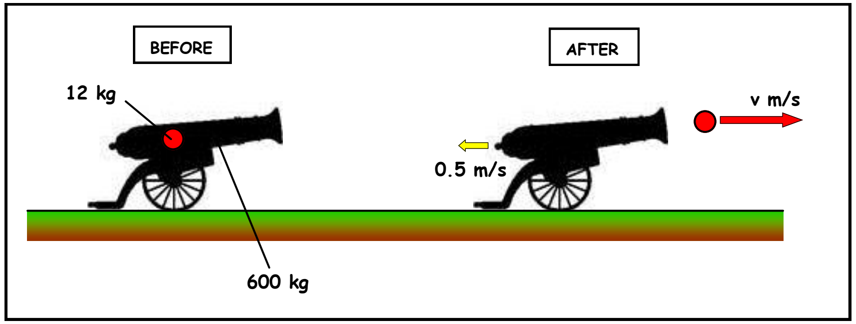


A baseball of mass **0.15 kg** moving at a speed of **35.0 m/s** crosses the plate and strikes the catcher's mitt which has a mass of **0.25 kg** and originally at rest.
The catcher's mitt immediately recoils backwards (at the same speed as the ball) before the catcher applies an external force to stop its momentum.

If the catcher's hand is in a relaxed state at the time of the collision, it can be assumed that no net external force exists and the **law of momentum conservation applies** to the baseball-catcher's mitt collision.

Calculate the **velocity** of the mitt and ball immediately after the collision..

4



A cannon of mass **600 kg** recoils at a speed of **0.5 m/s** when a cannon ball of mass **12 kg** is fired from it.

Calculate the **velocity of the cannon ball** as it leaves the cannon.