

Force, mass and acceleration

A force is a push or a pull that acts on a body.

The unit of force is the **newton (N)**. It is named in honour of Isaac Newton. Forces can be classified into two categories:

- **contact forces**—these are forces in which there is a direct contact between the force and the body (eg. the tensional force in a rope as it pulls an object along the ground; the frictional forces preventing an object sliding freely over a surface).

surface).

- **field forces**—these are non-contact forces in which a body experiences a force due to its presence in a field (such as a magnetic field, electric field or gravitational field). An iron nail is attracted to a bar magnet owing to the existence of the magnetic field around the magnet.

Balanced and unbalanced forces

In a tug-o-war the centre of the rope does not move if the pulling forces of each team are exactly equal (ie. balanced). This principle is true of all balanced forces. A computer sitting at rest on your desk is acted upon by a set of balanced forces. The force of gravity is pulling the computer downward. This is balanced by the table pushing equally upward on the base of the computer.

Balanced forces do not always imply that the object is stationary. Any object that is travelling at **constant velocity** is also acted

upon by a set of balanced forces. What are these **balanced forces**?

- The force of gravity pulling the car down is balanced by the road pushing up on the car's tyres.
- The force of the engine driving the car forward is balanced by the sum total of all the frictional forces acting backward on the car.

However, for a car to **reach** a constant speed, it must experience an unbalanced force which accelerates it up to the desired speed. Once the desired speed is reached, the accelerator of the car is backed off a little so that the car can cruise under the action of balanced forces.

These observations about motion can be expressed by Newton's first law:

Newton's First Law of Motion: A *body remains at rest or at constant velocity unless acted upon by an unbalanced force.*

Net (unbalanced) forces

A net force is the result of unbalanced forces. In order to make a car move from rest, a sufficient force must be applied to the road in order to overcome frictional forces that hinder movement. Let us examine a simple example.

Example

If a smooth rectangular block of metal (mass = 100 kg) is placed on a smooth, low friction surface (eg. ice) and pulled along by a rope with a constant net force (force = 200 N) the block gains speed as long as the net force acts on it. In this example the block experiences an acceleration of 2 m/s^2 .

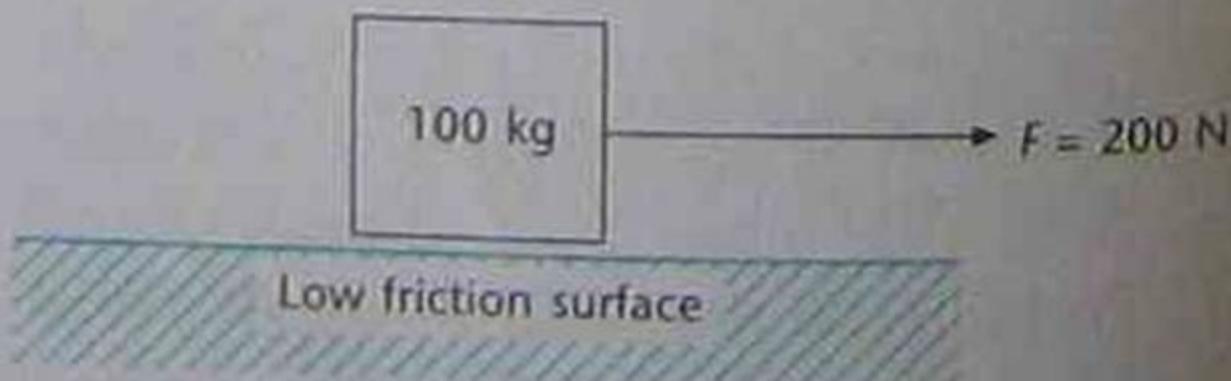


Figure 1.12 Net force acting on a metal block on a low friction surface

- As long as the net force is constant, the block will accelerate uniformly (ie. at 2 m/s^2).
- If the size of the pulling force is reduced (eg. reduced to 100 N) then the acceleration is also reduced proportionally (ie. reduced to 1 m/s^2).
- If the block of metal is replaced by a much heavier block (eg. 200 kg) and the experiment repeated with the same net force (ie. 200 N), the heavier block accelerates less than the lighter block. This lower acceleration is found to be 1 m/s^2 .

The observations described above can be summarised using Newton's second law:

Newton's Second Law of Motion: *The acceleration of a body depends directly on the size of the unbalanced force and inversely on the mass of the body* (ie. the bigger the force the greater is the acceleration, the bigger the mass the smaller is the acceleration).

Additional content—Mathematical extension:

Another way of describing Newton's second law is in algebraic terms:

$$F = ma$$

Example:

- Q If a net force of 1000 N acts on a 200 kg body, what is its acceleration?

A $F = 1000 \text{ N}$

$$m = 200 \text{ kg}$$

$$F = ma$$

$$1000 = 200a$$

$$a = 5 \text{ m/s}^2$$

Action and reaction forces

Newton discovered that forces always occur in pairs. They are called action-reaction pairs. This idea is expressed in Newton's third law:

Newton's Third Law of Motion: *To every action there is an equal and opposite reaction.*

Example 1: Rolling a ball

Example 1. Ball fired from a cannon

A ball can be projected from a cannon by igniting gunpowder to produce an explosive force. This explosive force is the action force which acts on the ball. At the same time the ball exerts an equal and opposite reaction force on the cannon. Because a net force acts on the ball, it accelerates forward out of the cannon. Because of the reaction force acting backward on the cannon, the cannon recoils.

Example 2. Sprinting from rest in a 100 m race

The muscles in the runner's legs and feet exert an action force (backward) on the track. At the same time the track exerts an equal and opposite reaction force on the runner. Because a net force acts on the runner, he will accelerate out of the blocks and along the track. At each contact with the ground the same thing happens. Note that the action force applied to the track is actually applied to the whole Earth, which is so massive that its acceleration is essentially unobservable.

Distance, speed and time

The average speed of a moving body can be calculated by measuring the total distance travelled and the time taken to travel that distance.

Average speed = distance moved/time taken

Example

Q Calculate the average speed for a 150 km journey which takes 2 h 45 min.

A Distance = 150 km

Time = 2.75 h

$$\text{Average speed} = 150/2.75 = 54.6 \text{ km/h}$$

The speedometer in a car does not measure the average speed. It measures the

instantaneous speed. This is the speed of the car at a particular moment of time. The instantaneous speed may be higher or lower than the average speed for a whole trip. When slowing down near traffic lights a car's instantaneous speed will drop below its average speed for the journey. Along an open section of road the car can travel above the average speed according to the speed limits of the road.

Velocity

it is useful to distinguish between the terms **speed** and **velocity**. Velocity is a term used by physicists to measure the change in motion of an object along a straight line in a particular direction. The speed of a body is independent of direction.

Example

Consider a straight road running east–west. A car travels along the road at a constant speed of 40 km/h. When it is travelling east, its velocity is said to be 40 km/h east. When it is travelling at the same speed west, its velocity is said to be 40 km/h west.

Acceleration

Whenever the velocity of an object changes by changing its speed and/or changing its direction, it is said to **accelerate**. The extent of this acceleration depends on the mass of the object and the size of the net force as described by Newton's second law.

The acceleration of an object often changes throughout its motion and so it is often useful to calculate the **average acceleration**.

$$\text{Average acceleration} = \frac{\text{change in velocity}}{\text{time taken}}$$

Example

Q A car starts from rest and reaches a velocity of 15 m/s in 5 seconds. Calculate its average acceleration.

A Initial velocity = 0 m/s (ie, at rest).

Final velocity = 15 m/s.

Change in velocity

$$= \text{final velocity} - \text{initial velocity}$$

$$= 15 - 0 = 15 \text{ m/s.}$$

Time taken = 5 s.

Average acceleration = $15/5 = 3 \text{ m/s}^2$.

Deceleration

If an object such as a car loses speed we say it is **decelerating**. This can happen when a motorist puts his foot on the brake.

Example

Q A car is travelling at 18 m/s, the brakes are applied and it comes to a stop in 4 seconds. Calculate its average deceleration.

A Initial velocity = 18 m/s.

Final velocity = 0 m/s (ie. at rest).

Change in velocity = final velocity – initial velocity = $0 - 18 = -18 \text{ m/s}$.

Time taken = 4 s.

Average acceleration = $-18/4 = -4.5 \text{ m/s}^2$.

The negative sign indicates that the acceleration is negative. That is, the car is decelerating with an average deceleration of 4.5 m/s^2 .

Uniform acceleration

An object will undergo **uniform acceleration** if a constant net force acts on it. The size of this uniform acceleration can be calculated using Newton's second law or from a knowledge of the initial and final velocities and the time it takes to change the velocity.

Example

Q A 10 kg mass, initially moving along a flat surface at 10 m/s is uniformly accelerated for 3 seconds until its velocity is 16 m/s. Calculate its uniform acceleration.

A Initial velocity = 10 m/s.
Final velocity = 16 m/s.

Change in velocity = final velocity
– initial velocity = $16 - 10 = 6 \text{ m/s}$.

Time taken = 3 s.

Uniform acceleration = $6/3 = 2 \text{ m/s}^2$.

Accelerating by changing direction

Acceleration can also be due to changes in direction rather than changes in speed. A car that is travelling at a constant velocity of 10 m/s north turns a corner and continues to travel at a constant velocity of 10 m/s towards the west. At all times its speed has stayed constant at 10 m/s but due to its change in direction the car must have experienced a net force. Consequently it must have accelerated to turn the corner. This example illustrates Newton's first and second laws. The first law tells us that the car will travel in a straight line at constant velocity unless acted upon by a force. As the car does not continue in a straight line, a net force has operated on the car. The second law tells us that net forces cause an object to accelerate (in this case to change direction).

Analysing motion

Analyse each of the following motion examples.

Example 1. Motion of a car along a straight road

A 1000 m straight road runs east–west.

The most westerly point is labelled A and the most easterly point is labelled B. A car starts from rest at the mid-point (M) of the road AB and initially travels east. (Figure 1.13).

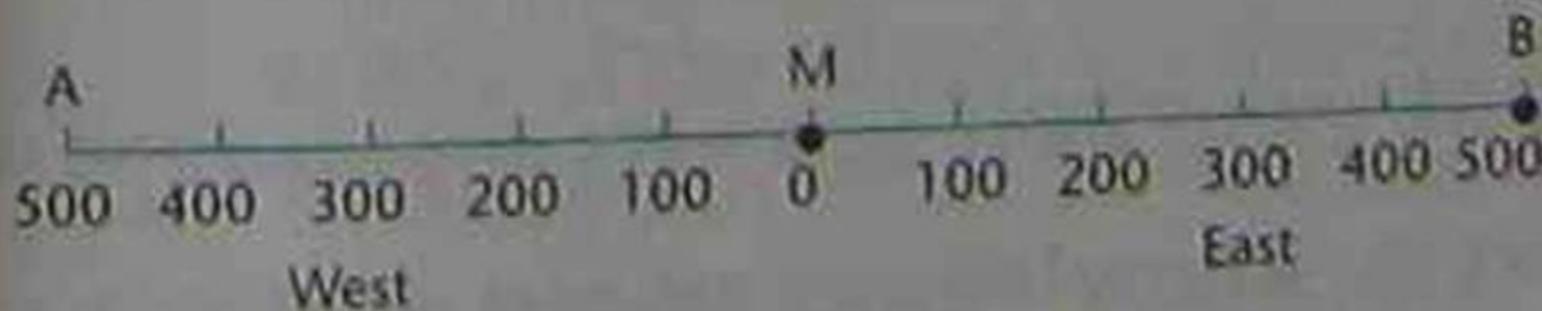


Figure 1.13 Motion of a car along the road AB

Table 1.5 shows the position of the car measured from the starting line (M) over a period of time.

Table 1.5 Data for the motion of a car along the road AB

Time (s)	Position of car relative to M (metres)
0	at M
10	100 east
20	200 east
30	300 east
40	500 east
50	500 east
60	300 east
70	100 east
80	100 west
90	200 west
100	250 west
110	250 west

- Q** Use the data in Table 1.5 to
- Plot the data points and join the points to form a line graph of position versus time.
 - Discuss the motion of the car in relation to the shape of the graph.

- A** Answer
- Figure 1.14 shows the line graph of these data.
 - Between 0 and 30 seconds the car is travelling east at a constant speed as

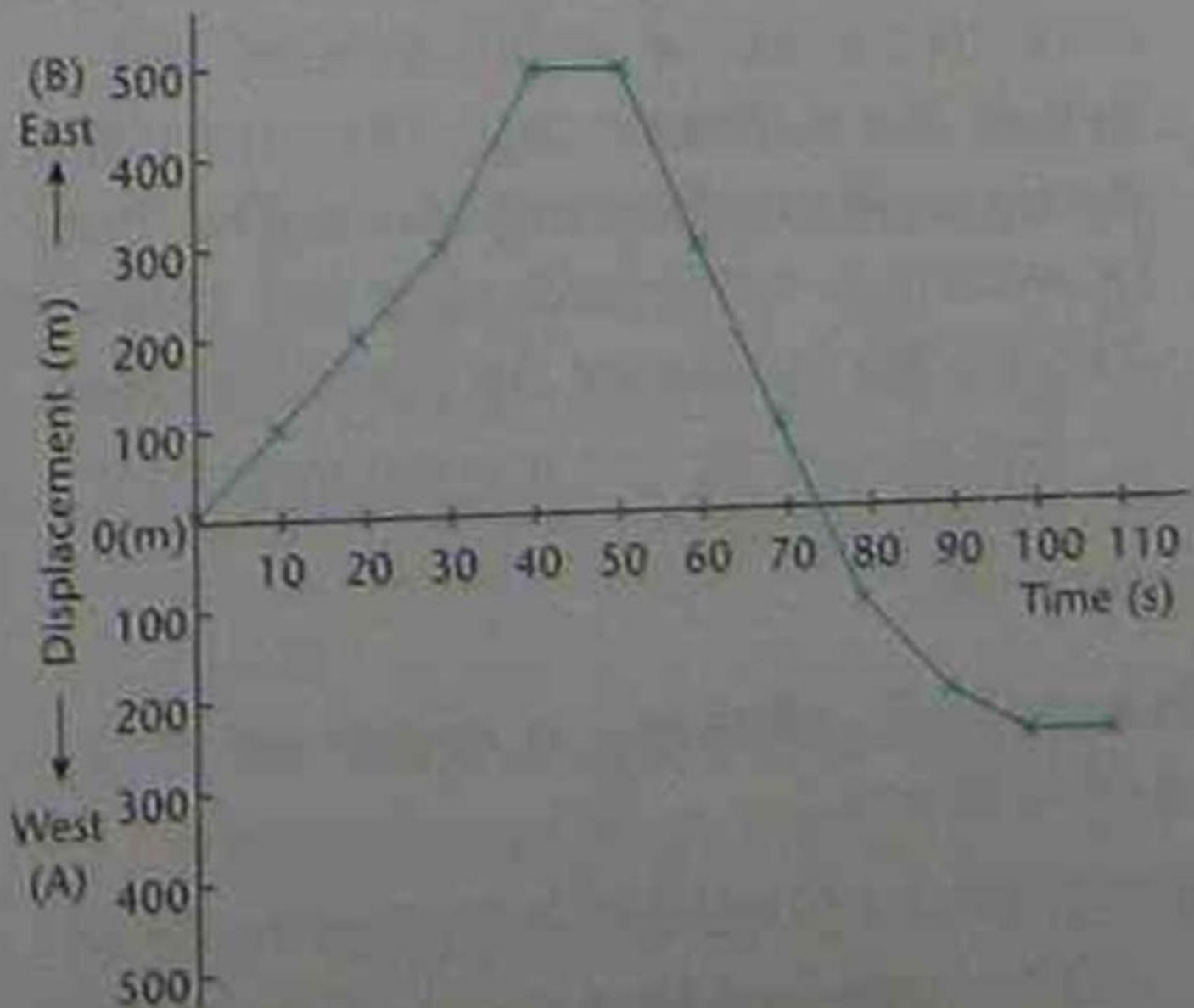


Figure 1.14 Line graph of data

it covers equal distances in equal time intervals (shown by the straight line in the graph).

After 30 seconds the car speeds up and travels at a higher speed in an easterly direction than before. By 40 seconds it has reached the end of the road at B (after 500 m). It remains stationary at B for 10 seconds.

It remains stationary at S for 10 seconds.

Between 50 and 80 seconds after the start, the car travels west at a constant speed. It passes through M on the journey west.

Between 80 and 100 seconds the car gradually slows down until at 100 seconds it reaches a point 250 m west of M. It remains stationary at this point for 10 seconds.

this point for 10 seconds.

Example 2. Emergency stop of a bus

- Q Consider a bus containing seated and standing passengers that is forced to make a sudden emergency stop as a dog runs across the road. Explain what happens to the standing passengers in terms of Newton's first law.

- A The standing passengers fall forward as the bus comes to a sudden stop. This is explained by Newton's first law which states that a body will continue in uniform motion unless acted upon by a net force. In this case the passengers are not attached to the bus and so continue on with the same speed as they did before the sudden stop. They do not experience the braking force. The bus, however, is subjected to a net force and its velocity suddenly decreases to zero.