Cambridge AS Physics

(Code: 9702)

Chapter 3

Dynamics – explaining motion

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Calculating the acceleration

Figure 3.2a shows how we represent the force which the motors on a train provide to cause it to accelerate. The resultant force is represented by a green arrow. The direction of the arrow shows the direction of the resultant force

$$a = \frac{F}{m} \quad \text{or} \quad F = ma$$

Quantity	Symbol	Unit
resultant force	F	N (newtons)
mass	m	kg (kilograms)
acceleration	a	m s^{-2} (metres per second squared)

Table 3.1 The quantities related by $F = ma$.

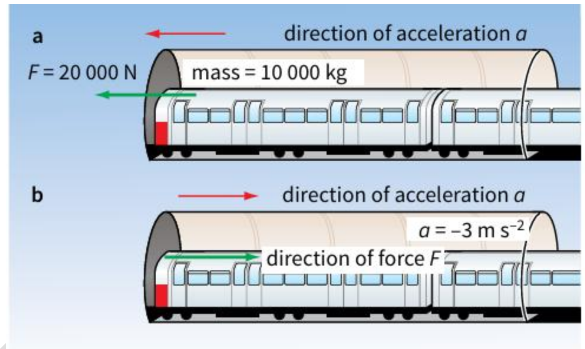


Figure 3.2 A force is needed to make the train **a** accelerate, and **b** decelerate.

Force, mass and acceleration

The equation we used above, F = ma, is a simplified version of Newton's second law of motion. The equation a = F/m relates acceleration, resultant force and mass. In particular, it shows that the bigger the force, the greater the acceleration it produces.

If you push your hardest against a small car (which has a small mass), you will have a greater effect than if you push against a more massive car (Figure 3.3). So, for a constant force, the acceleration is inversely proportional to the mass:

$$a \propto \frac{1}{m}$$

Understanding SI units

Any quantity that we measure or calculate consists of a value and a unit. In physics, we mostly use units from the SI system. These units are all defined with extreme care, and for a good reason. In science and engineering, every measurement must be made on the same basis, so that measurements obtained in different laboratories can be compared. This is important for commercial reasons, too.

Base units, derived units

The metre, kilogram and second are three of the seven SI base units. These are defined with great precision so that every standards laboratory can reproduce them correctly. Other units, such as units of speed (m s^{-1}) and acceleration (m s^{-2}) are known as derived units because they are combinations of base units.

Defining the newton

Isaac Newton (1642–1727) played a significant part in developing the scientific idea of force.

We can use the equation $F = ma$ to define the **newton** (N).

One newton is the force that will give a 1 kg mass an acceleration of $1\,m\,s^{-2}$ in the direction of the force.
$1\,N = 1\,kg \times 1\,m\,s^{-2}$ or $1\,N = 1\,kg\,m\,s^{-2}$

The seven base units

In mechanics (the study of forces and motion), the units we use are based on three base units: the metre, kilogram and second. As we move into studying electricity, we will need to add another base unit, the ampere.

Base unit	Symbol	Base unit
length	*x*, *l*, *s* etc.	m (metre)
mass	*m*	kg (kilogram)
time	*t*	s (second)
electric current	*I*	A (ampere)
thermodynamic temperature	*T*	K (kelvin)
amount of substance	*n*	mol (mole)
luminous intensity	*I*	cd (candela)

Table 3.2 SI base quantities and units. In this course, you will learn about all of these except the candela.

The equations that relate them are the equations that you will learn as you go along (just as F = ma relates the newton to the kilogram, metre and second). The unit of luminous intensity is not part of the A/AS course.

Other SI units

Using only seven base units means that only this number of quantities have to be defined with great precision.

For example, if the density of water were defined as exactly 1 g cm−3, then 1000 cm3 of a sample of water would have a mass of exactly 1 kg.

speed is defined as $\frac{\text{distance}}{\text{time}}$, and so the base units of speed in the SI system are $\mathbf{m\,s^{-1}}$.

Since the defining equation for force is F = ma, the base units for force are kg m s^{-2}

When each term in an equation has the same base units the equation is said to be **homogeneous**.

Prefixes

Each unit in the SI system can have **multiples** and **sub multiples** to avoid using very high or low numbers. For example 1 millimetre (mm) is one thousandth of a metre and 1 micrometre (µm) is one millionth of a metre. T h e **prefix** comes before the unit.

Multiples			Sub-multiples		
Multiple	Prefix	Symbol	Multiple	Prefix	Symbol
10^{3}	kilo	k	10^{-1}	deci	d
10^{6}	mega	M	10^{-2}	centi	c
10^{9}	giga	G	10^{-3}	mill	m
10^{12}	tera	T	10^{-6}	micro	µ
10^{15}	peta	P	10^{-9}	nano	n
			10^{-12}	pico	p

Table 3.3 Multiples and sub-multiples.

You must take care when using prefixes.

- Squaring or cubing prefixes – for example:
  $1\,cm = 10^{-2}\,m$
  so $1\,cm^2 = (10^{-2}\,m)^2 = 10^{-4}\,m^2$
  and $1\,cm^3 = (10^{-2}\,m)^3 = 10^{-6}\,m^3$.
- Writing units – for example, you must leave a small space between each unit when writing a speed such as $3\,m\,s^{-1}$, because if you write it as $3\,ms^{-1}$ it would mean 3 millisecond^{-1}.

The pull of gravity

The force which caused the apple to accelerate was the pull of the Earth's gravity. Another name for this force is the **weight** of the apple. The force is shown as an arrow, pulling vertically downwards on the apple (Figure 3.4). It is usual to show the arrow coming from the centre of the apple – its **centre of gravity.**

Large and small

A large rock has a greater weight than a small rock, but if you push both rocks over a cliff at the **same** time, they will fall at the same rate. In other words, they have the same acceleration, regardless of their mass. A feather drifts down to the floor, while a stone falls quickly. However, we are being misled by the presence of **air resistance.**

We can find the force causing this acceleration using F = ma. This force is the object's weight. Hence the weight W of an object is given by: **weight = mass × acceleration** of free fall or **W = mg**

Gravitational field strength

Here is another way to think about the significance of g. This quantity indicates how strong gravity is at a particular place.

So g indicates the strength of the gravitational field at a particular place:

g = gravitational field strength and

weight = mass × gravitational field strength (Gravitational field strength has units of N kg^{-1}. This unit is equivalent to m s^{-2}.)

On the Moon

The Moon is smaller and has less mass than the Earth, and so its gravity is weaker. The acceleration of free fall on the Moon is about one-sixth of that on the Earth:

$$g_{\mathrm{Moon}} = 1.6\,\mathrm{m\,s^{-2}}$$

Mass and weight

We have now considered two related quantities, mass and weight. It is important to distinguish carefully between these (Table 3.4).

However, your moon-buggy will be easier to lift on the Moon, because its weight will be less. From W = mg, since g is less on the Moon, it has a smaller weight than when on the Earth.

Quantity	Symbol	Unit	Comment
mass	*m*	kg	this does not vary from place to place
weight	*mg*	N	this a force – it depends on the strength of gravity

Table 3.4 Distinguishing between mass and weight.

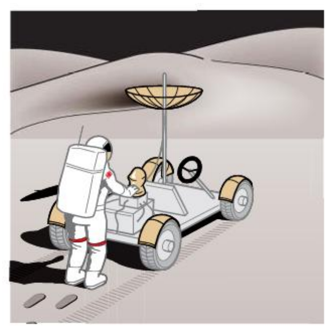


Figure 3.5 The mass of a moon-buggy is the same on the Moon as on the Earth, but its weight is smaller.

Mass and inertia

It took a long time for scientists to develop correct ideas about forces and motion. We will start by thinking about some wrong ideas, and then consider why Galileo, Newton and others decided new ideas were needed.

Observations and ideas Here are some observations to think about:

■ ■ The large tree trunk shown in Figure 3.6 is being dragged from a forest. The elephant provides the force needed to pull it along. If the elephant stops pulling, the tree trunk will stop moving.

■ ■ A horse is pulling a cart. If the horse stops pulling, the cart soon stops.

■ ■ You are riding a bicycle. If you stop pedalling, the bicycle will come to a halt.

■ ■ You are driving along the road. You must keep your foot on the accelerator pedal, otherwise the car will not keep moving.

■ ■ You kick a football. The ball rolls along the ground and gradually stops.

A moving object needs a force to keep it moving. This might seem a sensible conclusion to draw, but it is wrong. We have not thought about all the forces involved. The missing force is friction.

The idea of inertia

The tendency of a moving object to carry on moving is sometimes known as inertia.

■ ■ An object with a large mass is difficult to stop moving – think about catching a cricket ball, compared with a tennis ball.

■ ■ Similarly, a stationary object with a large mass is difficult to start moving – think about pushing a car to get it started.

■ ■ It is difficult to make a massive object change direction – think about the way a fully laden supermarket trolley tries to keep moving in a straight line.

Here, **uniform motion** means 'moving with constant velocity' or 'moving at a steady speed in a straight line'. Now we can summarise these findings as **Newton's first law of motion.**

An object will remain at rest or in a state of uniform motion unless it is acted on by a resultant force.

Balanced and unbalanced forces

We can calculate the **resultant force** by adding up two (or more) forces which act in the same straight line. We must take account of the direction of each force. In the examples in Figure 3.8, forces to the right are positive and forces to the left are negative.

Free fall

Skydivers (Figure 3.9) are rather like cars – at first, they accelerate freely. Eventually they reach a maximum velocity, known as the **terminal velocity**. At the terminal velocity the air resistance is equal to the weight.

Figure 3.9 A skydiver falling freely.

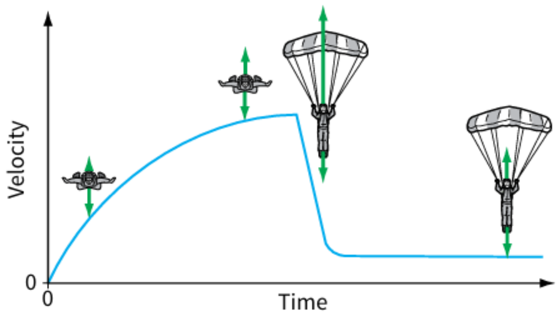
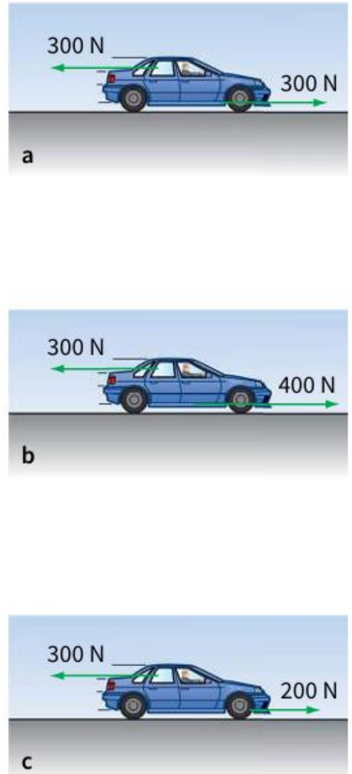


Figure 3.10 The velocity of a parachutist varies during a descent. The force arrows show weight (downwards) and air resistance (upwards).



Two equal forces acting in opposite directions cancel each other out. We say they are **balance** The car will continue to move at a steady velocit in a straight line.
resultant force = 0 N

These two forces are unequal, so they do not cancel out. They are **unbalanced**. The car will accelerate.
resultant force
= 400 N – 300
= 100 N to the **right**

Again the forces are unbalanced. This time, the car will slow down o decelerate.
resultant force
= 400 N – 300 N
= 100 N to the **left**

Figure 3.8 Balanced and unbalanced forces.

Moving through fluids

Air resistance is just one example of the resistive or viscous forces which objects experience when they move through a fluid – a liquid or a gas. If you have ever run down the beach and into the sea, or tried to wade quickly through the water of a swimming pool, you will have experienced the force of drag.

Moving through air

We rarely experience drag in air. This is because air is much less dense than water; its density is roughly 1 800 that of water. At typical walking speed, we do not notice the effects of drag.

Identifying forces

It is important to be able to identify the forces which act on an object. When we know what forces are acting, we can predict how it will move. Figure 3.14 shows some important forces, how they arise, and how we represent them in diagrams.

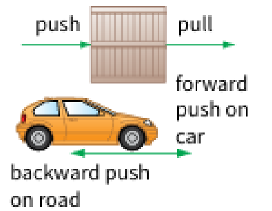
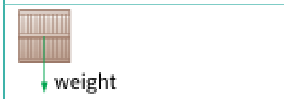
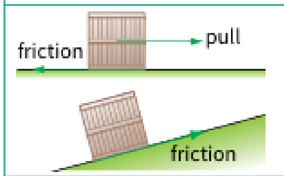
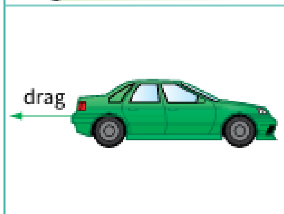
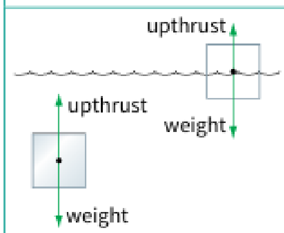
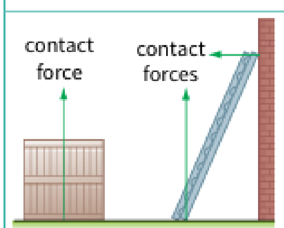
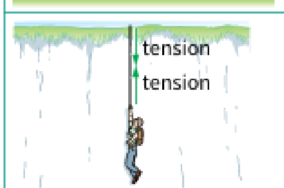
Diagram	Force	Important situations
	**Pushes and pulls.** You can make an object accelerate by pushing and pulling it. Your force is shown by an arrow pushing (or pulling) the object. The engine of a car provides a force to push backwards on the road. Frictional forces from the road on the tyre push the car forwards.	■ pushing and pulling ■ lifting ■ force of car engine ■ attraction and repulsion by magnets and by electric charges
	**Weight.** This is the force of gravity acting on the object. It is usually shown by an arrow pointing vertically downwards from the object's centre of gravity.	■ any object in a gravitational field ■ less on the Moon
	**Friction.** This is the force which arises when two surfaces rub over one another. If an object is sliding along the ground, friction acts in the opposite direction to its motion. If an object is stationary, but tending to slide – perhaps because it is on a slope – the force of friction acts up the slope to stop it from sliding down. Friction always acts along a surface, never at an angle to it.	■ pulling an object along the ground ■ vehicles cornering or skidding ■ sliding down a slope
	**Drag.** This force is similar to friction. When an object moves through air, there is friction between it and the air. Also, the object has to push aside the air as it moves along. Together, these effects make up drag. Similarly, when an object moves through a liquid, it experiences a drag force. Drag acts to oppose the motion of an object; it acts in the opposite direction to the object's velocity. It can be reduced by giving the object a streamlined shape.	■ vehicles moving ■ aircraft flying ■ parachuting ■ objects falling through air or water ■ ships sailing
	**Upthrust.** Any object placed in a fluid such as water or air experiences an upwards force. This is what makes it possible for something to float in water. Upthrust arises from the pressure which a fluid exerts on an object. The deeper you go, the greater the pressure. So there is more pressure on the lower surface of an object than on the upper surface, and this tends to push it upwards. If upthrust is greater than the object's weight, it will float up to the surface.	■ boats and icebergs floating ■ people swimming ■ divers surfacing ■ a hot air balloon rising
	**Contact force.** When you stand on the floor or sit on a chair, there is usually a force which pushes up against your weight, and which supports you so that you do not fall down. The contact force is sometimes known as the normal reaction of the floor or chair. (In this context, normal means 'perpendicular'.) The contact force always acts at right angles to the surface which produces it. The floor pushes straight upwards; if you lean against a wall, it pushes back against you horizontally.	■ standing on the ground ■ one object sitting on top of another ■ leaning against a wall ■ one object bouncing off another
	**Tension.** This is the force in a rope or string when it is stretched. If you pull on the ends of a string, it tends to stretch. The tension in the string pulls back against you. It tries to shorten the string. Tension can also act in springs. If you stretch a spring, the tension pulls back to try to shorten the spring. If you squash (compress) the spring, the tension acts to expand the spring.	■ pulling with a rope ■ squashing or stretching a spring

Figure 3.14 Some important forces.

Contact forces and upthrust

We will now think about the forces which act when two objects are in contact with each other. When two objects touch each other, each exerts a force on the other. These are called contact forces

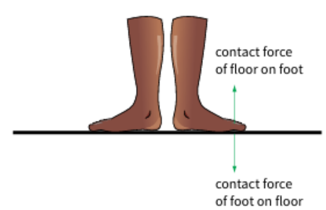


Figure 3.15 Equal and opposite contact forces act when you stand on the floor.

When an object is immersed in a fluid (a liquid or a gas), it experiences an upward force called **upthrust**. It is the upthrust of water which keeps a boat floating (Figure 3.16) and the upthrust of air which lifts a hot air balloon upwards.

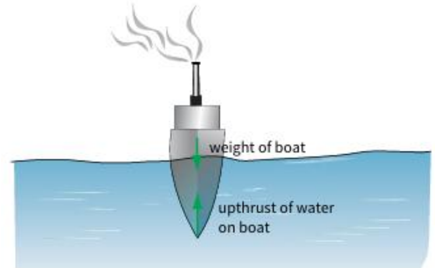


Figure 3.16 Without sufficient upthrust from the water, the boat would sink.

The upthrust of water on a boat can be thought of as the contact force of the water on the boat. It is caused by the pressure of the water pushing upwards on the boat. Pressure arises from the motion of the water molecules colliding with the boat and the net effect of all these collisions is an upward force.

Newton's third law of motion

For completeness, we should now consider **Newton's third law of motion**. (There is more about this in Chapter 6.) When two objects interact, each exerts a force on the other.

When two bodies interact, the forces they exert on each other are equal in magnitude and opposite in direction.

(These two forces are sometimes described as **action** and **reaction**, but this is misleading as it sounds as though one force arises as a consequence of the other

The two forces which make up a 'Newton's third law pair' have the following characteristics:

■ ■ They act on different objects.

■ ■ They are equal in magnitude.

■ ■ They are opposite in direction.

■ ■ They are forces of the same type.

What does it mean to say that the forces are 'of the same type'? We need to think about the type of interaction which causes the forces to appear.

■ ■ Two objects may attract each other because of the gravity of their masses – these are gravitational forces.

■ ■ Two objects may attract or repel because of their electrical charges – electrical forces.

■ ■ Two objects may touch – contact forces.

■ ■ Two objects may be attached by a string and pull on each other – tension forces.

■ ■ Two objects may attract or repel because of their magnetic fields – magnetic forces.