Newton's First and Second Laws

Prerequisites

The purpose of this chapter is to consolidate your prior knowledge of forces, to introduce you to Newton's first and second laws regarding forces and to practise simple applications of those laws. You should already be familiar with the idea of a force; however, we introduce all these ideas afresh. It is assumed that you are already familiar with the concept of speed and understand acceleration in terms of speeding up or slowing down.

Forces

If someone jumps up into the air the force of *gravity* brings him back down to the earth. In order to get air-born in the first place, the person jumping must exert a force against the surface of the earth that comes from the tension in his muscles. These are common-sense examples of forces. Physicists believe that when the motion of any object changes this is due to the action of a force.

In general, when a force act on an object, it have can have the following effects.

(1) It can cause that object to change its speed
(2) It can cause that object to change its direction
(3) It can cause that object to rotate.

Initially, we do not study the rotational (turning) effect of forces (case 3), but concentrate only on the effect forces have on speed and direction. Regarding direction we are in the first instance concerned only with motion in one dimension – that is along a straight line. We call this *linear motion*. So there is only one possible effect on the direction of an object travelling in a straight line, and that is to reverse the direction. So regarding the ability of forces to make objects change their direction (case 2), we will examine only cases where the direction of motion is either forwards or backwards.

Example (1)

A man throws a stone straight up in the air. Explain the effect of gravity on the motion of this stone. Ignore the effect of air-resistance.

Solution

Since we are told to ignore air-resistance in this question, once the stone has left the man's hand there is only one force acting on the stone, and that is gravity. Initially, the stone is travelling vertically upwards. Gravity is a force that acts on the stone and "pulls" it downwards. Firstly, gravity causes the stone to slow down. It decelerates. Eventually, it comes to a moment of *instantaneous rest* at which point it has reached its maximum height. After that, gravity exerts a downward force on the stone and causes the stone to accelerate towards the ground, vertically downwards.

So in this example we see that a force (gravity) causes an object to change the direction of its motion from vertically upwards to vertically downwards. It also causes it to change its speed – first causing it to decelerate as the stone travels upwards and then causing it to accelerate towards the ground.

Forces are measured in Newtons, symbol N.

Speed is a scalar, velocity is a vector

The motion of an object clearly requires not one but *two* ideas.

(1) The concept of its speed

(2) The concept of the direction in which it is travelling.

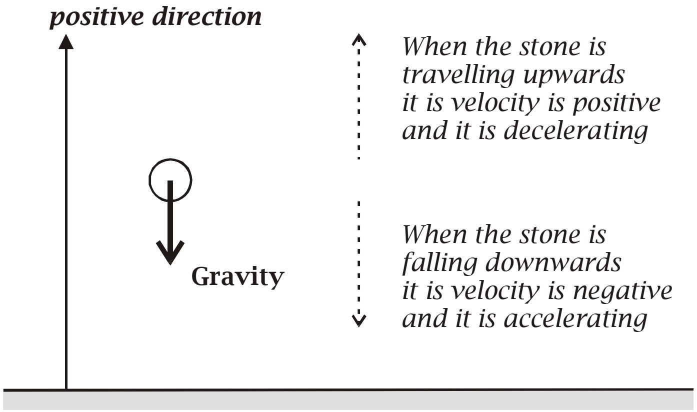
Example (2)

What is the similarity and what is the difference between a stone travelling vertically upwards with a speed of 2 ms^{-1} and the same stone travelling vertically downwards with a speed of 2 ms^{-1}? How might we distinguish between these two cases?

Solution

The similarity is that in both cases the speed is the same; the difference is that when the stone is travelling vertically downwards it is travelling in the *opposite* direction to when it is travelling vertically upwards. We will represent this difference by a *sign*. In both cases the *magnitude* of the speed is the same, 2 ms^{-1}, but if the motion upwards is defined to be positive then the motion downwards is negative. So when the stone is travelling downwards it travels at $-2ms^{-1}$. Note the minus (–) sign in this.

What this example makes clear is that in order to understand motion in a straight line we do need to distinguish between (1) speed as a magnitude and (2) speed in a given direction. The second of these ideas is called *velocity*. Velocity is an example of a *vector*. A vector is any property that has both size (magnitude) *and* direction. By contrast a *scalar* is a property that has just size (or magnitude).



Velocity is a vector

Example (3)

Which of the following are scalars and which are vectors?

(*a*) The number of passengers on an aeroplane.
(*b*) The height (altitude) of the plane above sea level.
(*c*) The thrust of the plane's engines.
(*d*) The volume of fuel in the plane's tank.
(*e*) The direction and distance of the plane from Paris.
(*f*) The resistance of the wind striking the plane.
(*g*) The acceleration of the plane.

Solution

(*a*) Number is a scalar.
(*b*) Altitude is a scalar.
(*c*) Thrust is a force, and forces act in given directions, so are vectors.
(*d*) Volume is a scalar.
(*e*) Direction plus distance is *displacement* – it is a vector.
(*f*) Resistance is a force, so is a vector.
(*g*) Acceleration is speeding up or slowing down, so involves a change of direction. Acceleration may also result in a change of bearing, which is clearly a change of direction. Hence, acceleration is a vector.

In the last example we introduce *acceleration*. Acceleration is a change of speed or a change of direction or both. In other words, acceleration is a change in velocity.

Example (4)

A car travelling at 10 ms^{-1} accelerates to 30 ms^{-1} in 5 seconds. What is its acceleration?

Solution

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

In symbols

$$a = \frac{\Delta v}{\Delta t}$$

where the symbol Δ (pronounced "delta") stands for "change in".

Here $\Delta v = 30 - 10 = 20\ \text{ms}^{-1}$ and $\Delta t = 5\ \text{s}$. Hence

$$a = \frac{\Delta v}{\Delta t} = \frac{20}{5} = 4\ \text{ms}^{-2}$$

Resultant forces

Forces can cause objects to speed up or slow down, and to change direction. However, just because a force is acting on an object it does not necessarily mean that the object will speed up or slow down.

Example (5)

Two teams of men are engaged in a tug-of-war competition. On the rope a red ribbon has been tied. For five minutes the ribbon does not move. Explain why.

Solution

The two teams of men are pulling with exactly the same force in opposite directions. The force exerted by one team exactly cancels out the force exerted by the other. The *resultant* force is zero.

As the example makes clear, we need to introduce the concept of a *resultant* force. When forces cancel out the resultant is zero and no change of motion is produced. When the resultant is not zero then an object will speed up or slow down.

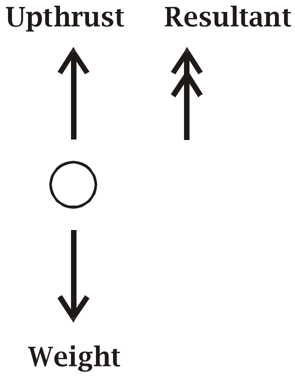
Example (6)

A man is riding in a balloon. Despite the effect of gravity acting on the man and the balloon, the balloon is rising. Draw a diagram to explain why.

Solution

The balloon together with the man experience an upthrust, (This is in fact because the gas inside the balloon, for example helium, is less dense than the surrounding air.) The upthrust is greater than the weight (force due to gravity) of the man and balloon combined. So the resultant force acts upwards.

In making a diagram we shall now introduce the convention that the man and balloon combined may be represented as a single object, so we will not attempt to draw the balloon (or the man).

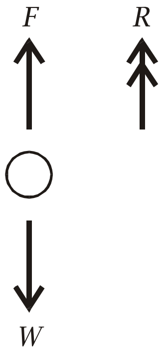


In this diagram the resultant is *not a new force* but is the difference between the upthrust of the balloon and the weight. It is added to the diagram to make it clear that the upthrust is a bigger force upwards than the weight is a force downwards. To make it clear that it is not an additional force we mark it with a double arrow.

Example (6) continued

Add symbols to the above diagram as follows. Let the magnitude of the upthrust be F, the magnitude of the weight be W, and let the resultant be R. Form an equation involving these three terms to illustrate the idea that the upthrust is greater than the weight.

Solution



The equation is

$R = F - W$

This equation captures also the idea that forces are vectors. The reason why it does is because the fact that the weight (W) acts downwards is represented by the minus (–) sign. We could write this equation as

$(+R) = (+F) + (-W)$

which shows that we are *adding* a force in the positive direction to a force in negative direction. The overall resultant is a force in the positive direction. So *subtracting* a force is the same as *adding a negative* force. We do not usually write plus (+) symbols in front of positive numbers. So $+F = F$.

Example (7)

A car is travelling along a straight track on level ground. The thrust of the engine is 150 N and the combined resistance of the track and air is 175 N. What is the resultant force acting on the car? Is the car accelerating, decelerating, or travelling with uniform speed?

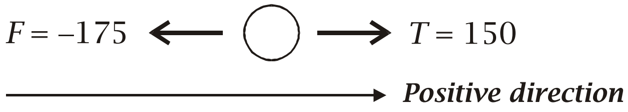
Solution

Let the thrust of the car's engine be T.

Let the frictional resistance be F.

Let the resultant force be R.

Let the positive direction be defined by the following diagram.



Then

$$
\begin{aligned}
R &= T + F \\
&= 150 - 175 \\
&= -25\text{N}
\end{aligned}
$$

The resultant force has a magnitude of 25 Newtons and as the minus sign indicates it acts in a direction opposite to the motion of the car and the thrust of the engine; so the car is decelerating.

Newton's first law

In life the pure effect of forces is often very difficult to experience or study – this is because there are only rare situations in which an object is subject to *just one force*.

Example (8)
An ice-skater is at a very large ice-rink. A friend pushes the skater and skater just glides across the ice without making any further effort. The skater does not reach the barriers of the ice-rink, but even so the skater eventually comes to a halt. Explain why.

Solution
The one word answer to this question is *friction*. Here friction is a force that impedes motion and eventually brings the skater to a halt.

Example (7) continued
Suppose in the above example, (*a*) the ice-rink was infinite in dimension and (*b*) the contact between the ice-skater and the ice-rink was *frictionless*. What would happen to the ice-skater?

Solution
The ice-skater would carry on moving forever in a straight line at the same speed.

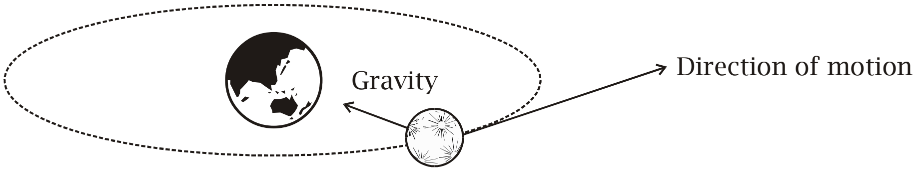
Such an ice-rink would be impossible to make. There is no place in the universe where there are no forces. However, it is possible to make some environments *almost* frictionless. An air-track is an example of this. The answer to example (4) is a version of *Newton's first law of motion*.

Newton's first law
Every object remains at rest or in uniform velocity unless acted upon by a resultant force.

Example (9)

What would happen to the Moon if the Earth (and Sun) suddenly ceased to exist?

Solution



If it were not for gravity exerted by the Earth on the Moon, the Moon would carry on in a straight line. This is in accordance with Newton's first law. The effect of the gravitational attraction of the Earth is to bend the motion of the Moon into an (approximately) circular orbit.

Newton's second law

We saw above that acceleration is change of speed, or change of direction or both. When forces cancel out there is no acceleration and the object remains a rest or travelling in a straight line at the same speed forever. This is the content of Newton's first law. Newton's second law answers the question: what do (resultant) forces produce?

Newton's Second Law[1]
The (resultant) force applied to an object is proportional to its acceleration.

This definition is given for completeness. In practice you will remember this law as the equation

$F = ma$
Force = mass × acceleration.

This equation introduces the concept of *mass*. Mass represents the notion of the *amount of substance.*

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[1] This is a simplified version of the law. The more general statement is: *the change in momentum of a body is proportional to the applied force and the momentum change takes place in the direction of the force.*

Example (10)

A collector of strange objects has two spheres each of exactly the same size (volume) but one is made of wood and the other is made of lead. Explain why one of these objects has more mass than the other. Which of the two spheres is easier to throw and why?

Solution

In some ways this is a "trick" question because the concept of mass is indefinable! The question invites us to say that the wooden sphere has less substance than the sphere made of lead and that lead is a more *dense* material, but you really learn the meaning of substance and hence the meaning of *mass* from experience and specifically from experiment. The wooden sphere is easier to throw because it has less mass than the lead sphere, so you have to exert a smaller force to make it go the same distance.

Example (10) continued

What is the difference between mass and weight? Why is it *wrong* to say, "The weight of the lead sphere is 3 kg"?

Solution

Weight is actually a force – it is the force produced by gravity on objects that have mass. Mass is amount of substance and is measured in kilograms. Since weight is a force it is measured in Newtons, which are the units of force. Because weight is a force it depends on the force of gravity. Thus, if a 3 kg ball is taken from the Earth to the Moon its weight will change – it is lighter on the Moon than it is on the Earth because the Moon's gravity is less than the Earth's gravity. However, the mass of the ball does not change. It always remains 3 kg. Furthermore, because the mass of the ball does not change it would be just as hard to make the ball accelerate on the Moon as it would be on the Earth.

The more mass an object has the harder it is to make it accelerate. This is the content of the equation $F = ma$.

Example (11)

A girl kicked a ball of mass 3 kg, and it accelerated by 6 m/s.

(*a*) What was the force of the girl's kick?

(*b*) If the girl had kicked a ball of mass 1 kg with the same force, what would have been the acceleration?

Solution

(a) Force = mass × acceleration

That is

$F = m \times a$

Here

$m = 3,\ a = 6$

Therefore

$F = 3 \times 6 = 18N$

(b) Substituting $F = 18,\ m = 1$ into $F = ma$

$18 = 1 \times a$

$a = 18\ \text{ms}^{-1}$

The equation $F = ma$ can be rearranged to give

$$a = \frac{F}{m}$$

and also

$$m = \frac{F}{a}$$

Example (12)

In the gym a boxer struck a punch bag of mass 50 kg with a force of 120 N. What was the acceleration of the punch bag?

Solution

$F = ma$

$$a = \frac{F}{m}$$

On substituting $F = 120,\ m = 50$

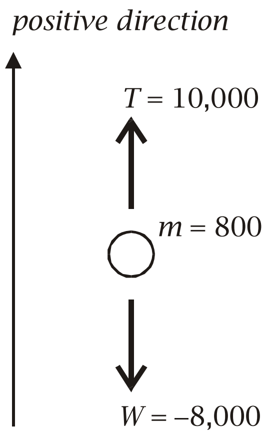
$$a = \frac{F}{m} = \frac{120}{50} = 2.4\ \text{ms}^{-2}$$

Example (12)

A lift has mass 800 kg and weight 8,000N. The tension in the supporting cable is 10,000 *N*. Find the acceleration of the lift.

Solution

Let the positive direction be defined as in the diagram. Let the tension be $T = 10{,}000$ N. Let the weight be $W = -8{,}000$ N. Let the mass be $m = 800\,\text{kg}$.



Then the resultant is

$$\begin{aligned} R &= T + W \\ &= 10000 - 8000 \\ &= 2000 \text{ N} \end{aligned}$$

The acceleration is

$$a = \frac{R}{m} = \frac{2000}{800} = 2.5 \text{ ms}^{-2}$$

The lift is accelerating upwards.

Example (13)

A car of mass 200 kg accelerates from a speed of 10 ms^{-1} to a speed of 50 ms^{-1} in 5 seconds. The motion of the car is resisted by a constant force of 500 N owing to friction between the car and the road. There is also a force due to the wind. If the thrust of the engine is 2000 N, determine whether the car is being assisted or resisted by the wind. Find also the magnitude of the force exerted by the wind.

Solution

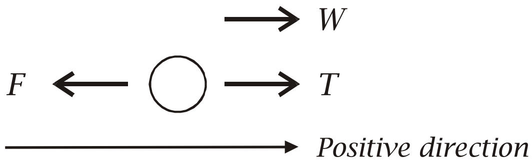
The acceleration of the car is given by

$$a = \frac{\Delta v}{\Delta t} = \frac{50 - 10}{5} = 8 \text{ ms}^{-2}$$

The *resultant force*, *R* is

$$\begin{aligned} R &= ma \\ &= 200 \times 8 \\ &= 1600 \text{ N} \end{aligned}$$

This resultant force is the sum of three forces – the thrust of the engine (*T*), the frictional resistance of the road (*F*) and the force of the wind (*W*). Let us draw a diagram to show these three forces.



This diagram indicates that we have chosen to define the positive direction as being the same direction as the thrust of the car's engine and the motion of the car. The force of the wind (*W*) is shown as acting in that direction, but if in fact it is opposing the motion then it will come out as a negative number, so the direction of the arrow is actually irrelevant to the solution, as is the direction of the arrow representing the friction (*F*) provided we remember to substitute a negative value for it, as it acts in the direction opposite to the motion. Thus the resultant is

$R = T + F + W$

On substituting

$R = 1600$
$T = 2000$
$F = -500$

we obtain

$1600 = 2000 - 500 + W$
$W = 100 \text{ N}$

So the force due to the wind is 100 Newtons and acts in the same direction as the thrust of the engine; the car is being assisted by the wind.