Physics

Big idea (age 11-16)
PFM: Forces and motion

What's the big idea?

Force is a useful idea because it is the key to explaining changes in the motion of an object or in its shape. The motion of an object can be explained or predicted if you know the sizes and directions of all the forces that act on it. Understanding forces helps us to predict and control the physical world around us.

Key concepts

The big idea is developed through a series of key concepts at age 11-16, which have been organised into teaching topics as follows.

11-14:

Topic PFM1
Forces

Key concepts:
- 1.1 What forces do
- 1.2 Describing forces
- 1.3 Balanced and unbalanced forces
- 1.4 Friction
- 1.5 Energy stores and transfers

Topic PFM2
Moving by force

Key concepts:
- 2.1 Describing speed
- 2.2 Motion graphs
- 2.3 Changing motion
- 2.4 Drag

Topic PFM3
More about force

Key concepts:
- 3.1 Mass and weight
- 3.2 Hidden forces
- 3.3 Turning effects

14-16:

Topic PFM4
Measuring and calculating motion

Key concepts:
- 4.1 Velocity
- 4.2 Acceleration
- 4.3 Velocity-time graphs

Topic PFM5
Energy of moving objects

Key concepts:
- 5.1 Energy of moving objects and of springs
- 5.2 Energy of objects in a gravitational field
- 5.3 Energy transfer, conservation and dissipation

Topic PFM6
Forces make things change

Key concepts:
- 6.1 Resultant force in two dimensions
- 6.2 Force, mass and acceleration
- 6.3 Changing momentum

The numbering gives some guidance about teaching order based on research into effective sequencing of key concepts. However, the teaching order can be tailored for different classes as appropriate.

This document last updated: January 2023

Guidance notes

Forces and motion is a topic that students have very strong ideas about, and often with many misconceptions. And because those misconceptions are based on students' interpretations of their own experiences, these are very difficult misconceptions to overcome. This makes forces a difficult topic to teach successfully, and there are often persistent inconsistencies in how individuals think about different situations.

Students often learn the physicist's perspective and apply it to obviously 'physics type' problems whilst interpreting the real world in other ways. Misconceptions can be so strong that students make wrong observations in order to fit in with their view – e.g. in experiments they can convince themselves that they see heavier objects fall faster.

There are additional conceptual loads needed for understanding forces and motion too: vectors and their combinations; and reference frames.

Learning progression

The science story associated with the big idea develops from age 5 to age 16, and could be summarised as follows:

Science story at age 5-11

The basic idea of a force

To start an object moving, something has to push or pull it. When this happens, we say that a force acts on the object. Similarly, to slow down or stop a moving object, or to change the direction in which an object is moving, a force has to act on it.

The motion of objects that are heavier and/or moving faster are harder to change.

A force acting on an object can also change its shape. Two forces acting on an object can hold it in a distorted shape (e.g. by stretching, compressing, or twisting).

We cannot see a force, just its effects. A change in the motion or shape of an object indicates that a force is acting on it.

Science story at age 11-14

Forces and interactions

Forces arise when two objects interact. They may interact by direct contact, or 'at a distance' (for example, two magnets, or electric charges, or masses).

When two objects interact, a force is always exerted on both of them. Object A exerts a force on object B, and object B exerts a force on object A. Forces always arise in pairs. At every instant during the interaction, the force exerted by object A on object B is equal in size and opposite in direction to the force exerted by object B on object A.

Forces arising from direct contact act only while the two objects are touching. 'Action at a distance' forces get weaker, the further the two objects are apart.

Representing and measuring forces

An arrow is a useful way to indicate on a diagram the direction of any force that is acting on an object. The arrowhead shows the direction in which the force acts on the object. The tip or the tail of the arrow shows the point on the object at which the force acts (it does not matter which is used; the meaning is the same).

A force is always exerted by something, and always acts on something. The clearest way to label a force arrow is: force exerted on [object A] by [object B].

The size of a force (in newton, N) can be measured. In everyday situations, this can often be done using a spring balance or a top-pan balance.

Often more than one force acts on an object. The net effect of two forces acting in the same straight line (same direction, or exactly opposite directions) is found by adding them, taking account of their directions.

Identifying and naming the forces acting in everyday situations

In everyday situations, a driving force is needed to start an object moving, and to keep it moving. This can come directly from a person or animal or machine pushing or pulling it, or can arise indirectly through a more complicated set of actions (e.g. pedalling a bicycle; the engine of a car turning the driving wheels; the engine of a boat turning a propeller, etc.).

When a moving object slides over a fixed surface, or is pushed or pulled so that it tends to slide over it, a force of friction acts on the object in the direction opposite to its motion. The friction force is exerted by the surface which the object is sliding (or tending to slide) over.

When an object moves through a fluid (a liquid or a gas), a drag force acts on it in the direction opposite to its motion. If the driving force acting on an object stops, friction and/or drag forces will make it slow down until it stops.

In everyday situations, a downward force acts on every object, due to the gravitational attraction of the Earth. This is called its weight. It can be measured (in N) using a spring (or top-pan) balance.

If an object is immersed in, or floats on, a fluid, the fluid exerts an upward force on the object which is called upthrust.

Describing motion: Distance and speed

If we want to explain why objects move as they do, we first need to be able to describe motion clearly and accurately.

One useful measure is the distance an object has travelled since a chosen starting moment.

Another is the speed of an object. The speed of an object is a measure of how far it moves in a given time interval. An object's speed might change during a given time interval, so what we measure is really its average speed during that time interval. Average speed is defined as: distance travelled/time taken.

To find the speed of an object at a particular moment in time (its instantaneous speed), we measure its average speed over a very short time interval around that moment.

Motion graphs

Information on the motion of an object can be summarised in a distance-time graph (showing the distance the object has travelled from its starting point at a given time). The slope (or gradient) of the graph at a given time indicates the speed of the object at that time.

Information on the motion of an object can also be summarised in a speed-time graph (showing the instantaneous speed of the object at a given time). The slope of the graph at a given time indicates the rate at which the speed is changing (its acceleration if it is moving in a straight line) at that time.

The speed of an object depends on the frame of reference in which it is measured. So, for example, a book on the table of a moving train might have a speed of 20 m/s if measured by a person on the platform (one frame of reference), but a speed of zero if measured by someone on the train (another frame of reference). The speed of object A relative to B is the speed of object A that would be measured by an observer moving along with object B. For two objects travelling in the same straight line, the speed of one object relative to the other (their relative speed) is the sum of their speeds (if they are moving in opposite directions) or the difference between their speeds (if they are travelling in the same direction).

The link between force and motion

To explain the motion of an object, it is essential first to identify all the forces acting on that object. From this, we can then work out the net force acting horizontally and/or vertically on the object.

Stationary objects: If an object is not moving (stationary), the net force acting on it is zero. Usually this is because several forces act on it, which add to zero (they cancel each other out).

So, for example, if an object is being pushed, but is not moving, the friction force is equal to the applied push. If an object is sitting on a level surface, the normal reaction of the surface is equal to its weight. If an object is hanging from a string, the tension of the string is equal to its weight. If an object is floating on a liquid, the upthrust is equal to its weight.

Changing motion: If a non-zero net force acts on a stationary object, the object will start to move in the direction of the force and its speed will steadily increase.

If a non-zero net force acts on a moving object in the same direction as its motion, the speed of the object will steadily increase.

If a non-zero net force acts on a moving object in the opposite direction to its motion, the speed of the object will steadily decrease. If its speed falls to zero, and the force continues to act, the object will then start to move in the direction of the force, with a steadily increasing speed.

In all cases, the bigger the net force, the greater the rate of change of motion (for a given object). And the bigger the object, the smaller the rate of change of motion.

Uniform motion: If an object is moving at a steady speed in a straight line, the net force acting on it is zero. A net force is needed to change the motion of an object, but not to maintain motion at a uniform speed.

Friction and drag

The friction force acting an object is caused by the unevenness at a microscopic level of the surfaces in contact. This leads to a force along the line of the interface, when an applied force makes an object slide (or tend to slide) over another object. Friction can be reduced by using a liquid (a lubricant) to fill the tiny surface irregularities.

For a given object on a given surface, the friction force balances (cancels) the applied force that is trying to slide one object over the other, up to a limit (which depends on the weight of the object and on the surfaces in contact). If the applied force exceeds this limit, the object will start to move.

Once an object starts to slide, the friction force acting on it remains the same size, regardless of its speed. The drag force on an object moving through a fluid increases with its speed. The size of the drag force can be reduced by giving the moving object a streamlined shape.

Mass and weight

Mass can be thought of as the amount of matter in an object – the sum of all the atoms that make it up. Mass is measured in kilograms. The mass of an object is always the same, no matter where the object is.

The weight of an object (the downward force acting on it due to the gravitational attraction of the Earth) is proportional to its mass. Near the Earth's surface, the weight of a 1 kg object is roughly 10 N. The Earth's gravitational field strength is therefore 10 N/kg.

More generally, the gravitational force of attraction between any two objects is proportional to the masses of each of them, and decreases with the distance between them. So the weight of an object will get less with distance from the centre of the Earth, and would be different on another planet or on the Moon.

The mass of an object is also a measure of its resistance to any change in its motion. For a given force, the larger its mass, the smaller the change of motion that results.

Forces exerted by surfaces and strings

If a force is exerted on a spring (or a springy object), which is fixed at its other end, to stretch or compress it, the spring/object exerts a force of the same size in the opposite direction on whatever is doing the stretching or compressing.

In fact all materials are springy or stretchy, at the microscopic level. An object sitting on, or pressing against, another one (e.g. the floor) compresses it a little, and an object hanging from another one (e.g. a string) stretches it a little. So both objects experience a force.

The force exerted by a hard surface on an object sitting (or pressing) on it is called the normal reaction of the surface. ('Normal' here means 'at right angles to the surface.) The force exerted by a string on an object that is stretching it is called the tension of the string.

Springs and elastic materials

The extension (increase in length) of a spring that is held fixed at its top end is directly proportional to the load (in kg) that is hung from it, provided the load is small. (This is called Hooke's Law.) More generally, the extension or compression of a spring, held fixed at one end, is proportional to the force applied at the other end along the line of the spring. Many elastic materials (though not all of them) behave in the same way.

If the applied force exceeds a limit (which depends on the object or material), the extension is no longer proportional to the applied force, and the object or material does not return to its original length when the force is removed.

The amount of distortion of a material when a force is applied depends on the size of the applied force and the area over which it acts. The larger the quantity force/area, the bigger the distortion. This quantity is often called 'pressure '.

Turning effects

If a rigid object is pivoted at a fixed point, a force acting on it at any other point will make it rotate. The turning effect of a force is called the moment of the force. It is defined as: force x perpendicular distance from the pivot to the line of action of the force

If an object is stationary, the sum of the moments of all the forces turning it in a clockwise direction is equal to the sum of the moments of all the forces turning it in an anticlockwise direction.

Science story at age 14-16

Describing motion

Displacement and velocity are vector quantities and give a direction to the motion of an object. Displacement-time and velocity-time graphs describe the motion of an object moving in one-dimension over time.

A vector has both a magnitude and a direction. Distance and speed are scalar quantities because they have a magnitude, but no direction.

Displacement tells us both how far an object has moved from its starting point, and in what direction. As an object moves, the change in the displacement is the arrow that joins the starting point of the motion to the end point. The displacement arrow has a magnitude and a direction, and its magnitude is most often different to the distance travelled.

Velocity and acceleration are measured indirectly and calculated:

- Velocity = change of displacement/change of time
- Acceleration = change of velocity/change of time

Velocity, like speed, is measured in metres per second (m/s), but average velocity is rarely equal to average speed because displacement usually has a different magnitude to the distance travelled.

Instantaneous velocity, the velocity at an instant of time, is the same as the instantaneous speed and its direction is the same as the object at that instant.

The change of velocity of an object is the difference between the instantaneous velocity of the object at two different times. Change of velocity is a vector.

Acceleration is measured in metres per second – per second (m/s^2). Acceleration is a vector.

Acceleration of an object is in the direction of the resultant force acting on the object.

Forces

The weight of an object is lower when it is immersed in a fluid (liquid or gas) because the pressure of the fluid increases with depth and pushes harder on the bottom of the object. The upthrust caused by this is equal to the weight of the fluid displaced.

An object will float in a liquid if it is less dense than the liquid. When it is floating the upthrust is equal to its weight.

Free-body diagrams can be used to show all the forces acting on an object. Scale drawings of the forces can be used to work out the direction and size of the resultant force on an object.

Newton's Laws of motion

Newton's Laws of motion explain the motion of stationary objects, objects moving with uniform velocity, and those that are accelerating.

Inertia is the tendency of objects to maintain their current motion (or lack of motion) that depends on their mass.

The quantitative relationship between resultant force, mass and acceleration of an object can be calculated:

- Resultant force = mass x acceleration

In freefall the resultant force and acceleration change as an object increases its speed. As it falls faster, air resistance increasingly opposes the gravitational force. When these two forces are equal, the object falls at a steady terminal velocity. Releasing a parachute increases the air resistance and the resulting opposing force creates a negative acceleration that creates a new slower terminal velocity.

The momentum of an object is conserved when objects spring apart or collide. It can be calculated:

- momentum = mass x velocity

Changing momentum more quickly requires a bigger force. The quantitative relationship between momentum and force can be calculated:

- Force = change in momentum/time

Work done by a force

When a force causes an object to move through a distance work is done on the object. So a force does work on an object when the force causes a displacement of the object.

The work done by a force on an object can be calculated:

- work done = force × distance moved (along the line of action of the force)

Power

Doing work leads to a transfer of energy. Power is a measure of the rate at which energy is transferred. It can be calculated:

- power = energy transferred/time taken

Power is measured in Watts (W) and 1 W is equal to 1 J/s.