Force, motion and machines

Introduction

This topic explores the key concepts of force, motion and machines as they relate to:

- forces
- motion and inertia
- Newton’s laws of motion
- force and pressure
- energy
- machines.

Key concepts of force, motion and machines

The activities in this topic are designed to explore the following key concepts:

- A force is just a push or a pull.
- Forces always come in pairs and involve two objects. One object applies a force (action force) on another object and, in return, the other object applies an equal and opposite force (reaction force) on the first object.
- Forces can be contact forces involving objects that are in contact.
- Forces can be field forces where one object sets up a force field in the area around it.
- There are different types of forces: for example, tension, compression, friction and normal.
- Multiple forces on an object add up to produce a net force.
- An object with a zero net force on it is either at rest or moving with constant speed.
- Inertia is a property of all objects with mass and represents the resistance of the object to change its motion.
- An object with a non-zero net force will change its motion. This may involve the object speeding up, slowing down and/or changing direction.
- In an interaction between two or more objects the total energy remains the same. Energy may be transferred from one object to another or it may transform from one type of energy into another.
- There are different types of energy: for example, kinetic, gravitational potential, elastic potential, heat and sound.

- A machine is a device that transmits and modifies force. There are different types of machines: for example, incline plane, lever, wheel and axle, pulley and gears.
- A machine gives mechanical advantage, which is equal to the output force (load) divided by the input force (effort).

Students’ alternative conceptions of force, motion and machines

Research into students’ ideas about this topic has identified the following non-scientific conceptions:

Mass, weight and gravity

- A kilogram of iron weighs more than a kilogram of feathers.
- Weight and mass are the same thing; weight is not considered as a gravitational force.
- There must be air for gravity to take effect; therefore, there is no gravity on the moon, nor is there gravity out in space.
- Earth’s magnetism and spin are connected with gravity.
- Things fall naturally without the need for a force.
- Heavier things fall faster than light things.
- Gravity only acts on an object when it begins to fall and when falling. Gravity ceases to act when the object lands on the ground and becomes stationary.
- All objects can be moved with equal ease in the absence of gravity.

Describing motion—kinematics

- Two objects side by side must have the same speed.
- Acceleration and velocity are always in the same direction.
- Velocity is a force.
- If velocity is zero, then acceleration must be zero too.
- Heavier objects fall faster than light ones.
- Acceleration is the same as velocity.
- The acceleration of a falling object depends upon its mass.
- If the speed of an object is increasing, so is its acceleration.
- Velocity is another word for speed. An object’s speed and velocity are always the same.
- Acceleration always means that an object is speeding up. Acceleration is always in a straight line. Acceleration always occurs in the same direction as an object is moving.
- If an object has a speed of zero (even instantaneously), it has no acceleration.

Explaining motion—dynamics

- Forces are only associated with movement.
- Forces get things going rather than making things stop.
- Forces are associated with living things, physical activity and muscular strength.
- Inanimate objects do not apply forces.
- Forces keep objects in motion.
- When an object is moving, there is a force in the direction of its motion.
- A moving object has a force within it which keeps it going.
- Force is a property of a single object rather than a feature of the interaction between two objects.
- f the pushing force ceases there is a force on the moving object which keeps it moving but which gradually gets used up and then the object stops.
- Friction is associated with heat.
- Friction only occurs between solids.
- If an object is at rest, no forces are acting on the object. Only animate objects can exert a force. Thus, if an object is at rest on a table, no forces are acting upon it.
- A force is needed to keep an object moving with a constant speed.
- Action–reaction forces act on the same object.
- Inertia is the force that keeps objects in motion.

Energy

- Energy gets used up or runs out.
- Something not moving does not have energy.
- Gravitational potential energy is the only type of potential energy.
- Energy is only caused by life/animal activity.
- Conservation of energy means that energy should be conserved.
- Energy and force are the same thing.
- Energy is a thing.
- Gravitational potential energy depends only on the height of an object.
- Doubling the speed of a moving object doubles the kinetic energy.
- Energy can be changed completely from one form to another (no energy losses).
- Energy is truly lost in many energy transformations. Things ‘use up’ energy.

Pressure

- Only wind, and not still air, has a pressure.
- Air pressure is a downwards influence.
- A vacuum sucks.
- Pressure is the same as force.

Momentum

- Momentum is the same as force.
- Momentum and kinetic energy are the same thing.

Machines

- Machines must have a motor.
- Machines are only inanimate objects.

Resources

Family science: a SOFweb resource site for science

http://www.sofweb.vic.edu.au/science/famsci/resource/famwebmy.htm
Contains many links to science-related sites.

How Stuff Works

http://www.howstuffworks.com
A comprehensive site that explains how many devices work.

Kid Info: physics

http://www.kidinfo.com/Science/Physics.html
General physics site with lots of information on various topics.

Queensland Museum

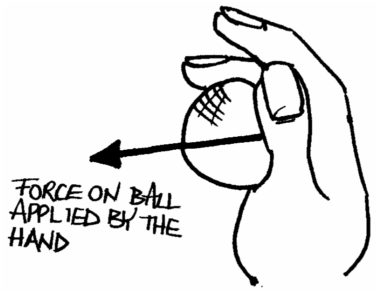
http://www.qmuseum.qld.gov.au/features/
Contains many different topics including links to other major museum centres.

Forces

Forces are just pushes or pulls of one object onto another object. Forces can start things moving, stop them or change their speed or direction. Forces can spin objects or change their size or shape. Forces can also hold things in a stationary state.

Forces always need to be considered in terms of two objects. One object is applying a force (push or pull) on another object. For example, in the act of throwing a ball the hand applies a pushing force onto the ball. The force is represented diagrammatically by an arrow, the length of which is a measure of the strength of the force. The arrowhead gives the direction (refer to Figure 1 below). The convention of drawing forces is that the base of the arrow representing the force is at the point of contact on the object. The diagram that indicates forces on an object is called a force diagram. The unit of force is the newton (N). A 1 kg mass held in the hand applies about 10 N of downwards force on the hand.

FIGURE 1:
FORCE ON A BALL
APPLIED BY A
HAND



Forces can occur in two basic ways: when the two objects are in contact and when they are separated. Forces that occur when objects are in contact are called ‘contact forces’ and when not in contact are called ‘field forces’.

Contact forces

Some examples of contact forces include:

- A tennis racquet applies a contact force (push) to a tennis ball when playing tennis.
- A child drags along a cart by a rope. The rope applies a contact force (pull) to the cart.
- A cyclist applies the brakes and comes to a stop. The brakes apply a contact force (push) onto the wheel.
- A big brother sits on his little brother. The big brother is applying a contact force (push) to his little brother.

Contact forces are always pulls or pushes but are sometimes referred to by various other names depending on the way in which they occur. For example, forces that tend to stretch an object, like pulling on a rope or stretching your leg muscles, are called ‘tension forces’. Forces that tend to squash an object, like a big brother sitting on his little brother, are called ‘compressive forces’. Forces that tend to slow an object down or hold it in place are called ‘friction forces’.

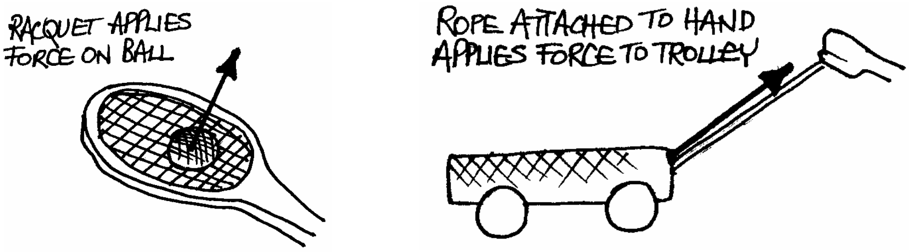
There are several types of friction:

- Static friction prevents a stationary object from moving. When you try to slide a heavy box across a floor, the static frictional force of the floor onto the box opposes your push and the box stays stationary. The more you push, the greater the frictional force until a point is reached when the maximum frictional force is exceeded and the box begins to move. Upon moving, the box encounters other forms of friction which have less strength than static friction. Without static friction we would find it very difficult to walk. If you have ever stood on a banana peel or on ice you will know the importance of friction to walking. In our initial stepping motion we need to grip the ground with our foot to propel us forward. Without this grip, or static friction, your foot slides backwards and you fall.
- Rolling friction and sliding friction are forces that resist the motion of moving objects. These occur when two surfaces rub against each other. Sliding friction is a larger force than rolling friction.
- Fluid friction is encountered by an object that moves through a fluid. Air is considered a fluid and so air resistance is a type of fluid friction. Unlike

rolling friction and sliding friction, fluid friction opposes the motion of the object, and increases with the speed of the object. You notice the effects of air resistance when cycling. The faster you are travelling, the greater the wind resistance. Olympic swimmers, cyclists and track athletes are well aware of the effects of fluid friction and use various methods to limit the fluid friction forces on the body.

Figure 2 shows some force diagrams showing contact forces. Remember that there need to be two objects: one applying the push or pull on the other object.

FIGURE 2: FORCES ON OBJECTS



ACTIVITY: FORCE MEASURERS

You will need:

- **a spring balance**
- **rubber bands or a spring**
- **standard masses**
- **a pencil case**
- **a book**
- **several rolls of sticky tape of different brands.**

Use a force measurer to measure the force needed to apply various forces. Force measurers are devices that involve a spring that stretches when a force is applied (the scale used is in newtons).

Force measurers can be made using rubber bands or springs, and spring balances. Spring balances give a measure of the mass of an object, usually in grams. To convert the spring balance reading from a mass reading to a force reading, use the conversion factor 100 g = 1 N. For example, if the spring balance reads 250 g, this represents a force of 2.50 N.

To make a force measurer out of a rubber band or spring, it needs to be calibrated (that is, to know how much stretch the rubber band has for a range of forces). This is obtained through hanging standard masses on the rubber band/spring and calculating the length of the extension. It is important not to use masses that overstretch the rubber band or spring as it will no longer give consistent readings when stretched with similar forces. The masses, in grams, need to be converted into forces in newtons using the conversion factor 100 g = 1 N.

Place your mass values, force conversions and extension readings in a table like that shown below.

Mass (g)	**Extension (cm)**	**Force (N)**

Construct a graph of force (N) [vertical axis] versus extension (cm) [horizontal axis] and draw a line of best fit. Use the graph to convert extension measurements of the rubber band or spring to force measurements.

Explanatory note: The graph produces a straight line if the rubber band does not get overstretched. Older students may be able to determine the equations, or formula, for the line of best fit. The formula can then be used when using the device.

Determine the force needed to:

- **lift a pencil case**
- **drag a book along a table**
- **lift different types of sticky tape from different surfaces**
- **open a door.**

ACTIVITY: MEASURING FRICTION FORCES

You will need:

- **a wooden block with a hook attached**
- **other wooden blocks or weights**
- **a force measurer (refer to the figure *Force measurer*).**
- **a variety of surfaces.**

Investigate one or more of the following questions:

How does the size of the maximum static frictional forces (this is equivalent to the maximum stretch in the force measurer to begin the object moving) depend on the mass of the block?

How does the maximum static friction on the block compare with the sliding friction force?

How does the sliding friction force vary with the mass of the block?

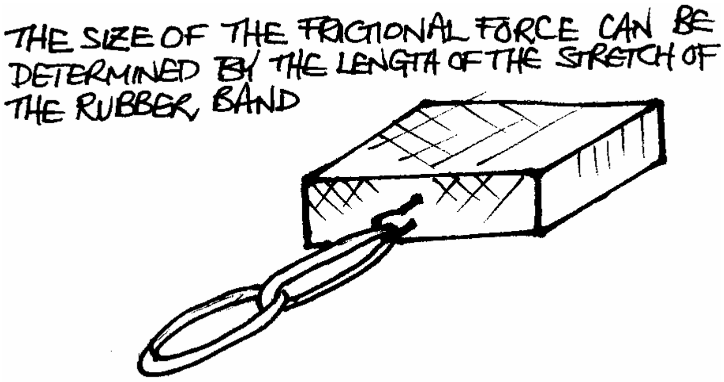
Does the sliding friction depend on the speed of the block? (Ensure that the block is pulled along with a steady speed each time.)

Does the area of surface contact affect the size of:

- **the maximum static friction force**
- **the sliding friction force?**

Investigate the size of the friction forces on different surfaces, for example, carpet, vinyl, grass, dirt, etc.

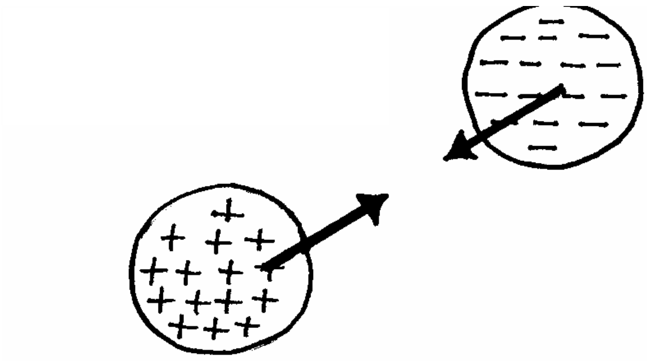
FIGURE: MEASURING FRICTION FORCES



Field forces

Field forces occur at a distance. One object sets up a force field in the space around it. If another object comes into that space it will have a force applied to it. For example, in the topic ‘Electricity’ we have learned that a negatively charged object applies an attractive, or pulling, force on an object that is positively charged. In this circumstance the positively charged object sets up a force field around it. A negatively charged object that is brought nearby will have a force applied to it. The force diagram is shown in Figure 3 below. There is no direct point of contact on the negatively charged object. The whole of the object is in the force field and so the force is simultaneously applied to all parts of the object. This is represented in Figure 3 as the force applied to the centre of the object.

FIGURE 3: ELECTRIC FIELD FORCE ON CHARGED OBJECTS



There are different types of field forces, as these examples illustrate:

- Earth sets up a gravitational force field around it, so if a piece of matter were to come nearby, a pulling force would be applied to it directed to the centre of Earth. Such forces are called gravitational forces.
- An electric charged object sets up an electric force field around it, so that if the same type of charged object were in the vicinity, a pushing force would be applied to it. If an oppositely charged object were to come in the vicinity, then a pulling force would be applied to it. Such forces are called electric forces.
- A magnet and a current-carrying wire set up magnetic fields that push or pull on other magnets and current-carrying wires in the vicinity. Such forces are called magnetic forces.

The nuclei of atoms, which contain protons and neutrons, are held together by very strong pulling forces called ‘nuclear forces’. As protons are positively charged, they tend to repel each other. Therefore, as the nucleus remains intact, nuclear forces are greater than the repulsive electric field forces.

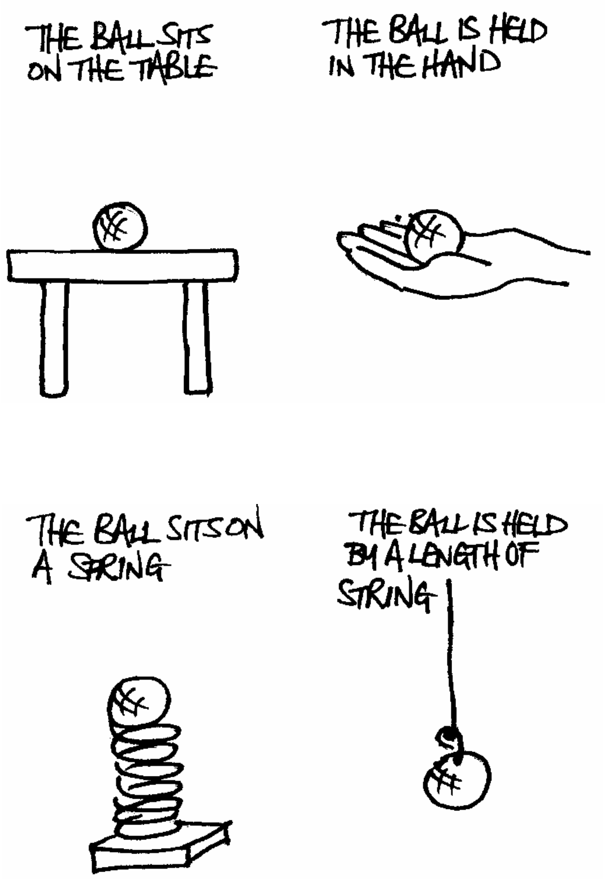
People quite often forget that there are always two objects involved in field forces as the force is applied at a distance. One of the objects sets up a force field that applies a force to the object that comes within that force field. To think otherwise can create problems in understanding forces. Consider the following example about the famous English physicist Sir Isaac Newton.

It has been purported (although it is probably not true) that Isaac Newton discovered gravity when an apple fell on his head when he was sitting in a garden. Newton did not discover gravity (it had been known since cave-dwelling days) but he held the view that Earth interacts with objects such as apples in such a way that they have an attractive force applied to them because both Earth and the apple have mass.

ACTIVITY: DRAWING FORCE DIAGRAMS

Draw in all the forces acting on the ball in the diagrams in the figure *Find the forces on the ball*. Remember, forces are drawn as arrows with the tail at the point of contact on the object if it is a contact force and in the centre if a field force is applied. The length of the arrows that represent the forces give a measure of their strength. If you feel that two forces are acting on the object and one is larger than the other, then draw a force arrow larger than the other. Label each of your forces.

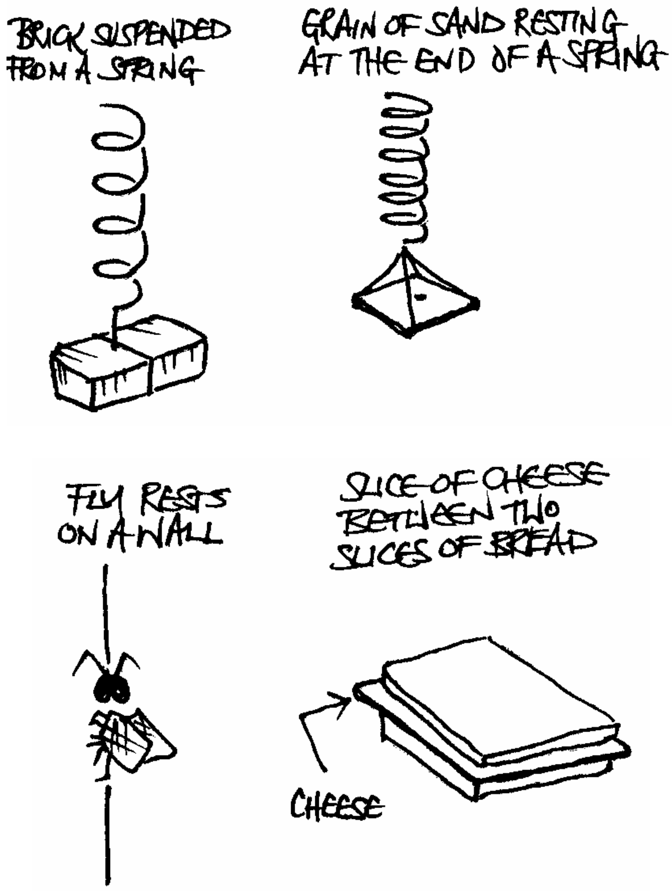
FIGURE: FIND THE FORCES ON THE BALL



Explanatory note: For each of the situations shown in the next figure there are two forces operating. One of the forces is the gravitational force and is directed downwards. The other force is a contact force from the table or hand or spring or string and is directed upwards. The ball is at rest and remains so. Therefore, the two forces are of equal strength but in opposite direction.

Draw a force diagram (that is, draw in all the forces acting on the object and label them) for each of the specified objects in each situation shown in the figure below.

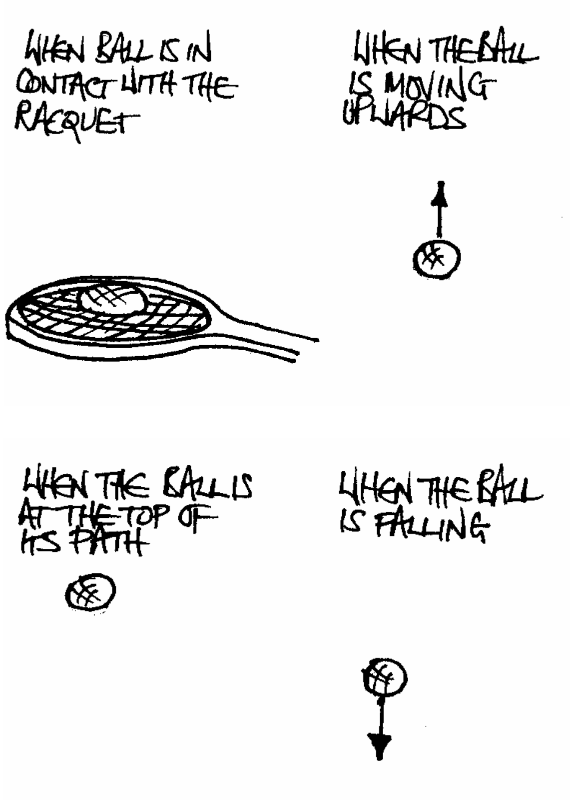
FIGURE: DRAW FORCE DIAGRAMS FOR EACH OBJECT STATED



Explanatory note: Each object is at rest and remains so. Therefore, all the forces on each object must cancel out. This means that all the total of all the downward forces must equal the total of all the upward forces. For the brick, the gravitational force is equal in strength but opposite in direction to the upwards contact force (tension force) of the string. The downward gravitational force on the fly is offset by an upward contact force (friction force) by the wall. The cheese has a gravitational force and a contact force (compression force) from the top bread layer. These two forces when added together are offset by an upward contact force (compression force) by the lower bread layer; in this situation the push up from the lower bread layer is greater in strength than the push down by the upper bread layer.

For each situation of the ball in the figure below, draw a force diagram.

FIGURE:
DRAW FORCE
DIAGRAMS FOR
THE BALL

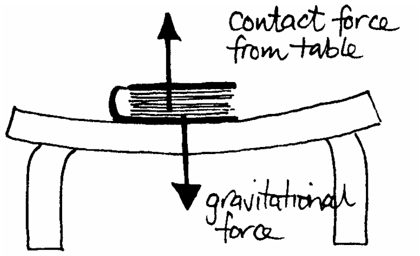


Explanatory note: When the ball is in contact with the racquet, it gets squashed—the upwards contact force from the racquet is greater than the downwards gravitational force. This means that the ball will soon rise into the air. When moving upwards the ball has two downward forces on it: air resistance and gravitational force. The two forces combine to slow the ball down. At the top of its path the ball is momentarily stationary (that is, if it was hit vertically) and the only force on it is a gravitational force. This will result in the ball dropping to the ground. When falling there are two forces on the ball: a downwards gravitational force and an upwards air resistance force. The gravitational force is usually greater than the air resistance force, which results in the ball accelerating to the ground.

Some common misconceptions about forces

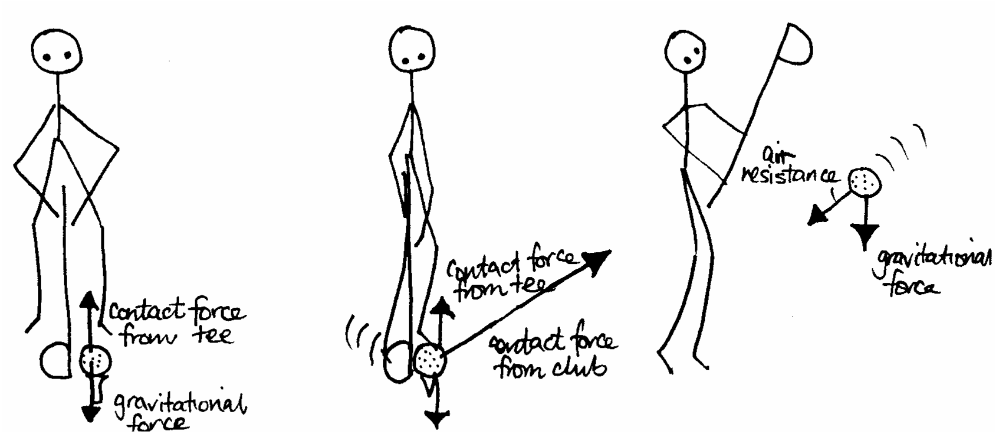
People often believe that only humans, compressed springs and stretched rubber bands can apply contact forces and objects like tables and the ground cannot. But from a scientific perspective this is not true. We can feel the force of our hand pushing up on an object such as a ball. If the ball is a shot-put we know the push from our hand must be great, whereas a grain of sand requires very little push. We can also see directly the stretch or compression in the rubber band or spring when applying a force to an object. However, we don't see the compression in a table, say, when a book rests on it but it is still applying an upward force on the book. What we need to picture microscopically is that the table is bending to support the book. Figure 4 shows this on an exaggerated scale. Therefore, despite there not being any obvious bending or stretching in the object, this does not mean that it is not applying a force.

FIGURE 4: FORCE DIAGRAM OF A BOOK RESTING ON A TABLE



Another common misconception relating to an object such as a golf ball is that it retains the force that was applied by the club even though the club may no longer be in contact with the ball. In Figure 5, in the action of hitting the ball, the ball has a contact force applied from the golf club. It also has a gravitational field force. When the ball leaves the club, the club is no longer in contact with the ball, therefore the contact force can no longer apply (there is no contact!). However, the ball will feel the contact of the wind trying to slow it down and so, when moving in the air, a frictional contact force applies. This slows the ball down. When in the air the gravitational force still applies as it is a force field and the golf ball is within the force field set up by Earth.

FIGURE 5: FORCES ON A GOLF BALL

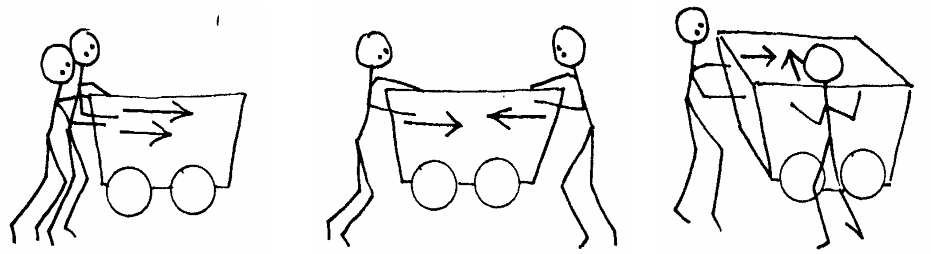


Adding forces

When an object has two or more forces the combined effect may vary depending on the size and direction of the individual forces. For example, consider two students pushing on a trolley with equal force. If the two students push in the same direction the trolley will move in the direction of the pushes. However, if the two students push on the trolley from opposite directions then the trolley will not move. What do you think would happen to the trolley if the students push from adjacent sides?

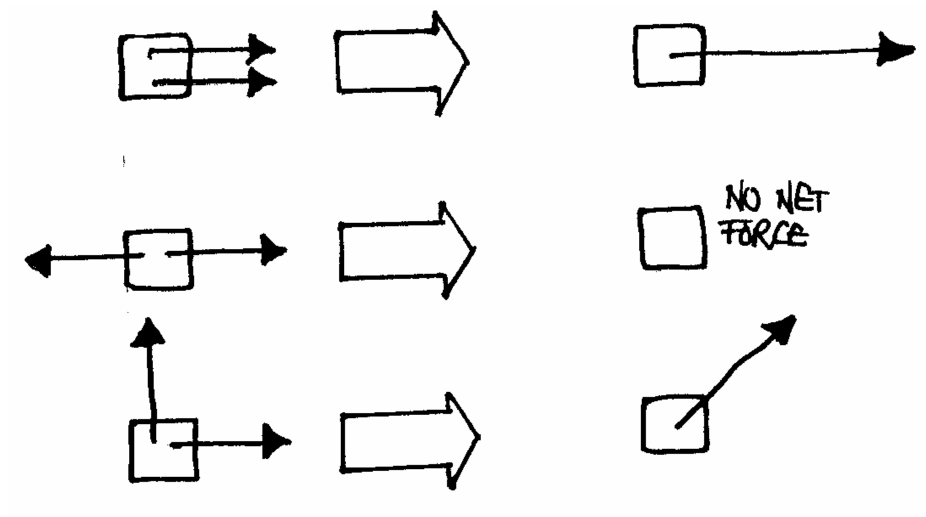
FIGURE 6: FORCES ON A TROLLEY

Forces in the same direction	Forces in opposite directions	Forces in different directions



These situations can be understood in terms of one equivalent force that we call the net force. This net force is found by adding the individual forces. Where the two forces are in the same direction this is equivalent to one force twice the size of each individual force and in the same direction. Where the two forces are in opposite direction this is equivalent to zero net force, as the trolley does not move. In this circumstance the two individual forces cancel each other out. Where the two forces are at right angles the net force is in an entirely different direction with a size that is bigger than any individual force but less than double any individual force. The addition of forces is shown in Figure 7 below.

FIGURE 7: ADDITION OF FORCES

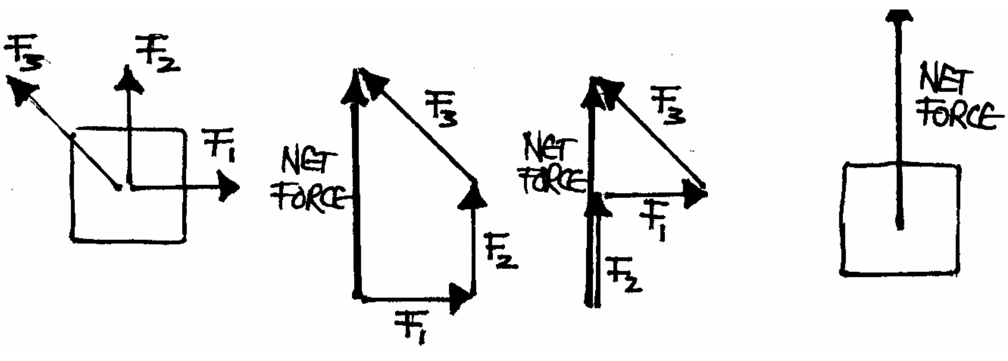


A general rule for adding forces is as follows:

- select one force as a starting point
- add the next force to the first by placing the tail of this force to the head of the first
- add the next force by placing the tail of the third force on the head of the second force
- add any remaining forces in the same manner as the previous two points.

The net force (equivalent force) now extends from the tail of the first force to the head of the last force that was added. This is shown in Figure 8.

FIGURE 8 ADDITION OF FORCES TO OBTAIN THE NET FORCE

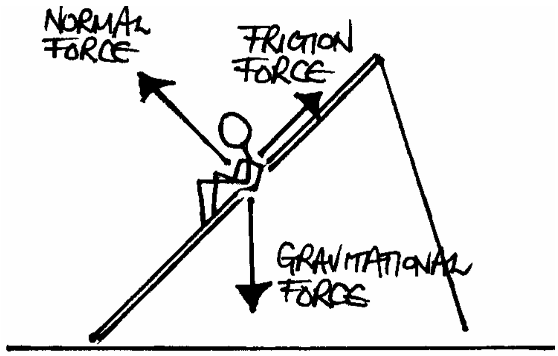


Forces and stationary objects

As all objects on Earth are within Earth's gravitational force field, then each object must have at least one force acting on it: the gravitational force. From a scientific perspective, if an object is at rest then the net force acting on the object is zero. In other words, all the forces add together to give no force at all. If each object has a gravitational force, then when an object is at rest it must have forces that oppose the gravitational force. For example, consider a book resting on a table. There are two forces acting on the book. The gravitational force pulling on the book towards Earth and a contact force pushing up on the book by the table (remember the table has microscopic bending). The net force will be zero.

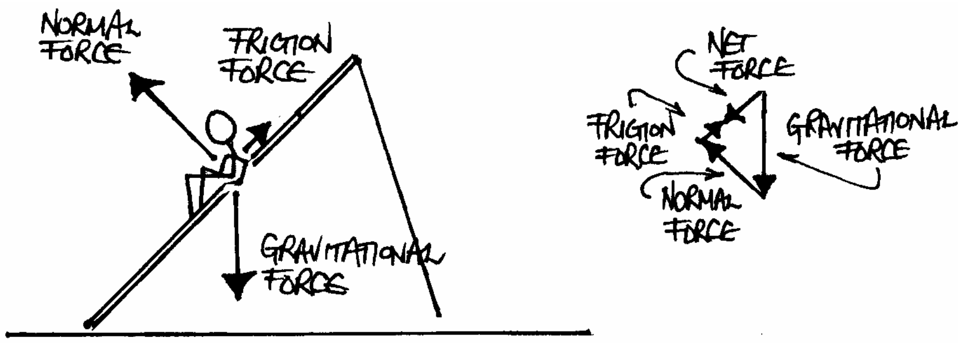
The contact force from a flat surface like the table or ground is called the normal force and is always directed perpendicularly to the surface of the object resting on the surface. Consider now the situation where a child is at rest halfway down a slide (see Figure 9). She must use her rubber shoes on the surface of the slide to be able to remain stationary. In this circumstance three forces are acting: the gravitational force from Earth, the normal force from the slide and the frictional force of the slide to provide the grip on the child's shoes. Our scientific requirement is that the net force must be zero as the child is stationary.

FIGURE 9: CHILD AT REST HALFWAY DOWN THE SLIDE



Adding the forces together will result in a zero net force. If the child takes off her shoes or doesn't use them for gripping the surface of the slide then she will slip down the slide. This can be explained by a much smaller friction force. The net force on the girl will now be in a direction down the slide. This is shown in Figure 10.

FIGURE 10: CHILD MOVING DOWN A SLIDE



Motion and inertia

To understand the concept of inertia, undertake the following activity.

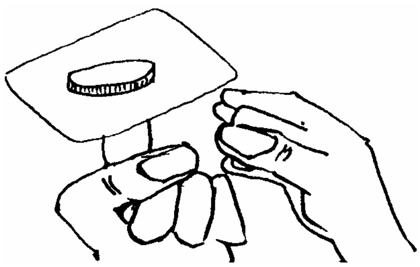
ACTIVITY:
CARD FLICK

You will need:

- **a large coin**
- **a playing card in good condition.**

Balance a large coin in the middle of a playing card on top of your index finger. Having achieved this balance, use your other hand to flick the card horizontally off your finger. The coin stays in place!

FIGURE:
CARD FLICK



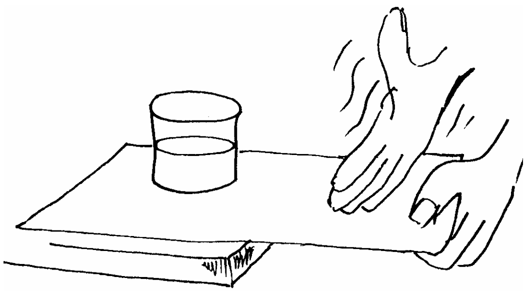
ACTIVITY:
REMOVING THE TABLE CLOTH

You will need:

- **an A4 (or larger) piece of paper**
- **a glass of water**
- **a table with a smooth surface and edge.**

Place the glass of water with a strip of paper under it projecting out from the table. For this trick the table and the paper must be dry. Hold the other end of the paper with one hand, and bring your other hand down on the paper in a karate chop motion to pull the paper out from under the glass.

FIGURE:
REMOVING THE TABLECLOTH



Inertia

The inertia of an object is the property of an object to resist changes in its motion. The inertia of an object depends only on its mass. For example, an adult on a playground swing is more difficult to move than a small child. The only way to change the motion of an object is to apply a non-zero net force on it.

In the previous activities, the coin and the glass of water remain stationary as they have inertia. The friction force caused by moving the card or paper quickly will not be large enough to move the objects. However, if the movement of the card or paper is slow, the friction force will be sufficiently large to move the coin or glass.

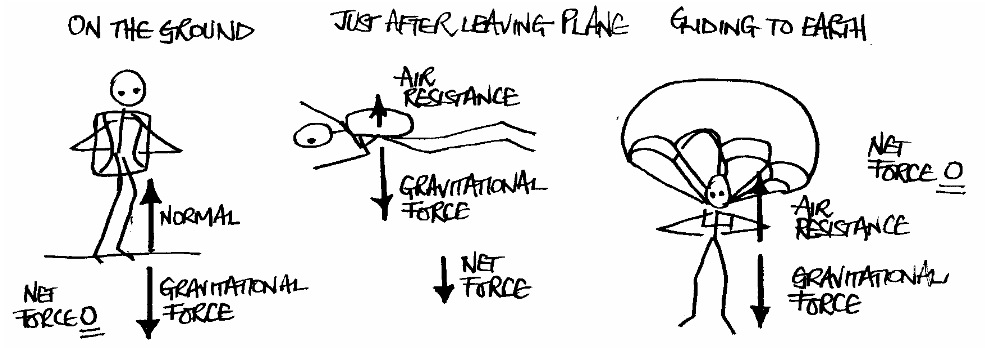
The inertia of objects also refers to objects that are set in motion. For example, consider the passenger in a moving car not wearing a seatbelt. If the car suddenly comes to a stop, the passenger will continue to move forward with speed. The passenger will continue their motion unless acted on by a stopping force. This usually occurs when the passenger's head hits the windscreen. The inertia of the passenger made them continue moving. A passenger's inertia is also evident when a car moves quickly forwards. The passenger is pushed forward by the seat. However, if there are not any properly mounted headrests then the head of the passenger will want to stay where it is when the rest of their body moves forwards. Whiplash!

The inertia of a body implies that if the net force on an object is zero then the object can be either stationary or moving with constant speed. An object at constant speed, or stationary, will continue to remain in that state unless a non-zero net force acts on it. This idea appears odd to our everyday thinking. For example, we know that to keep a trolley moving we need to push it continually. This is because there is a friction force on the trolley that opposes our push. If the trolley is moving at constant speed then the friction force equals the pushing force. When we let the trolley go, it slows down to rest as there is a non-zero net force from friction. If there was no friction, then the initial push on the trolley would be enough to set it in motion. The trolley would continue in that motion despite no longer being pushed. There are very few places on Earth where we can remove the effects of friction. However, the effect can be imagined in space. A good approximation occurs on a slippery surface like ice. However, the ice still applies friction forces; therefore, the trolley will eventually stop.

Net force of zero

If the net force on an object is zero then its natural state is at rest or moving with constant speed. This natural state will only change when a non-zero net force acts on the object. As an example, consider a parachutist standing on the ground. The net force on the parachutist is zero. There are two forces operating: a gravitational field force and a contact normal force. Both these forces are of equal strength but in different directions so that when they are added they amount to a zero net force. When the parachutist jumps out of a plane, there will be two forces acting on them. These are the gravitational field force and an air resistance contact force. Initially the air resistance is not large and so the net force is non-zero and points towards the ground. This will result in the parachutist accelerating to the ground. However, as the parachutist gets faster, and opens their parachute, the air resistance becomes greater until it becomes equal to the gravitational force (hopefully this occurs when the parachutist is still in the air!). At this point the net force becomes zero and the parachutist completes their fall to the ground at constant speed.

FIGURE 11: FORCES ON A PARACHUTIST

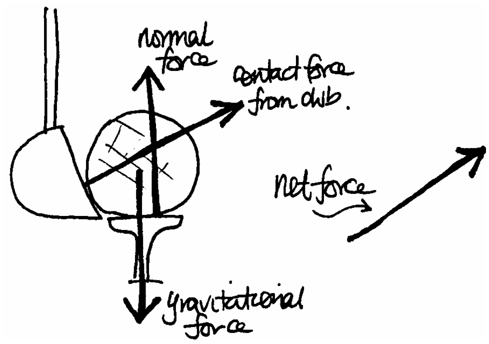


Net force and change in motion

If an object has a non-zero net force it will change the state that it is in. This does not mean that a new force acts on the object. It could be that one of the forces already acting on the object changes in size or direction. The net force is not a single force but the sum of all the forces acting on an object.

The change of state of an object due to a non-zero net force can occur in a number of ways. If an object is initially stationary, such as a golf ball, then if a non-zero net force operates such as when the ball is hit by a club, the object will begin to move in the direction of the net force (see Figure 12).

FIGURE 12: FORCES ON A GOLF BALL



If the object is initially moving at constant speed (a situation where the net force on it is zero) and the non-zero net force is applied in the same direction of motion, then the object will move faster in the direction of the net force. For example, in some team cycle races, team-mates can give pushes to cyclists already on the move.

If the object is initially moving at constant speed and a non-zero net force occurs in the opposite direction to the object's motion then it will slow down. For example, a baseballer sliding in to home base has an opposing friction force. In this situation the friction force decreases to zero as the baseballer comes to a stop. If the opposing force is maintained then the object comes to a stop and then speeds up in the opposite direction. An example of this is a baseball hit. In the action of hitting the ball the non-zero net force is at first opposite to the motion of the ball and then in the same direction as the ball. At the point where the ball is stationary some people believe that the net force comes to zero. If this were the case then inertia of the ball would mean that it would not move any more. However, we know that it does and so while the ball is instantaneously stopped it still has a non-zero net force acting on it.

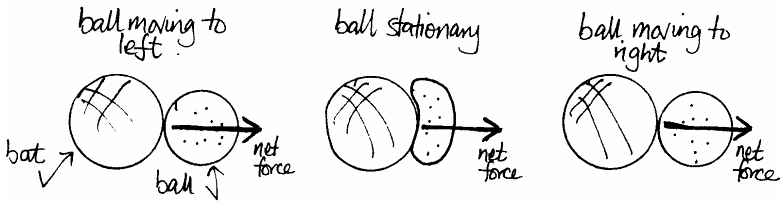


FIGURE 13: FORCES ON A BASEBALL

If the object is moving at constant speed and a sideways non-zero net force acts then the object will swerve in that direction. For example, a ball is thrown at an angle to the wall. When the ball hits the wall, a normal contact force is applied to the ball. This changes the direction of the ball. If you set an object in motion so it is moving at constant speed and then apply a constant sideways force, this will constantly change the direction of the ball. At just the right amount of sideways force the ball will travel in a circle. Have you ever wondered why the Moon does not fall into Earth? Isaac Newton did. He believed that all objects with mass attract each other and so Earth applies a gravitational field force on the Moon and as this force is pulling sideways on the Moon's motion it moves in a circle instead of crashing into Earth. However, if the Moon were to slow down, it would spiral into Earth. But as there is no air resistance on the Moon, it remains at the same speed and distance from Earth.

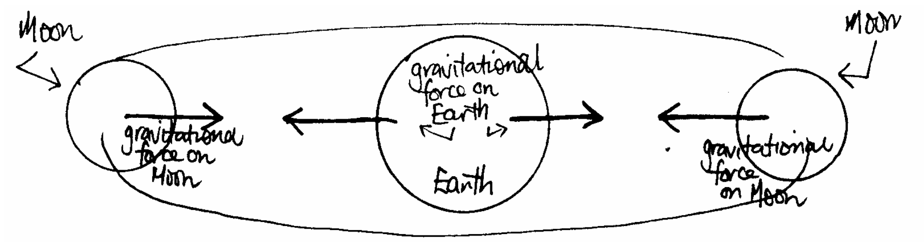


FIGURE 14: GRAVITATIONAL FORCES ON THE MOON AND EARTH

ACTIVITY: PAPER DROP

You will need:

- **two sheets of A4 paper**
- **an A4-sized book.**

For the following experiments make predictions about what you think will happen, giving your reasons. Then undertake the experiments and record your observations. Determine if the observations are consistent with your predictions. If not, try to explain why.

Hold two sheets of A4 paper at an equal height above the floor. Hold one parallel to the floor and the other perpendicular. Drop the two at the same time. Which do you think will hit the ground first? Why?

Screw up one of the sheets of A4 paper and repeat the above experiment. Which one will reach the floor first this time? Why?

Take one A4 sheet of paper and an A4-sized book. Hold both parallel to the floor at the same height and drop them simultaneously. Which one will land first? Why?

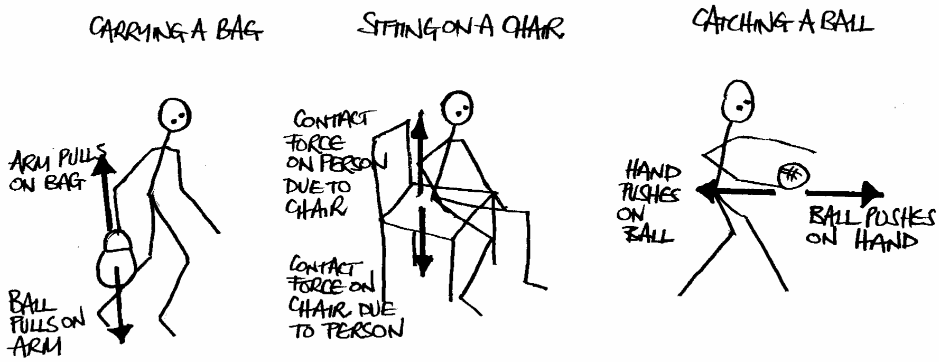
Now, put the A4 sheet of paper *under* the book and drop them together. What will happen? Why?

Put the A4 sheet of paper *on top* of the book and drop them together. What do you think will happen here? Why?

Forces are always in pairs

We have already come to an understanding that two objects are needed for a force to be applied. One of the objects applies a contact or field force to the other object. However, forces always occur in pairs. This means that as the first object is applying a force to the second object, the second object is applying an equally sized force in the opposite direction to the first object. For example, if you lift a bag, the bag will pull down on your arm at the same time that your arm is pulling up the bag. As you sit on a chair, you are pushing down on the chair and at the same time you can feel the chair pushing up on you. As you catch a ball, your hand pushes on the ball to stop it and at the same time you can feel the ball pushing on your hand.

FIGURE 15: FORCES ACT IN PAIRS



We can now extend our rule concerning forces. This can be understood as ‘forces always occur in pairs involving two objects: one object applies a force on the other object and the other object applies an equal and opposite force in return’. The force that is applied to another object is sometimes referred to as the ‘action force’ and the opposing force from the other object that is induced by the applied force is called the ‘reaction force’. The rule of pairs of forces is sometimes described as ‘for every action force there is always an equal and opposite reaction force’. In the examples given above, the action force of the hand lifting the bag induced a reaction force of the bag pulling back on the hand. The action force of the hand pushing on the ball induced a reaction force of the ball pushing on the hand. This force pair may be considered as the action force of the ball pushing on the hand induces a reaction force of the hand on the ball.

These pairs of forces cannot act on the same object because if they did then the net force would always be zero and no object would change state.

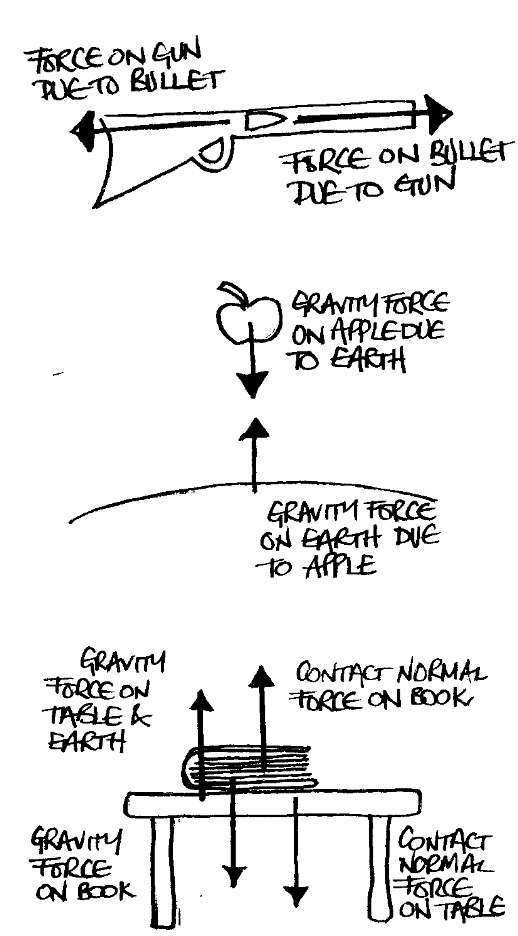
Consider the following examples to illustrate the point that forces act in pairs:

- A rifle is fired. The rifle applies an action force to the bullet that speeds out of the barrel. At the same time the bullet applies a reaction force to the rifle which makes a movement backwards. This can be felt in the shoulder of the shooter. The size of the force on the bullet is the same as that of the gun. The reason that the gun does not move as fast is that it has a lot more inertia, because of its mass, and is therefore harder to move.
- An apple falls to Earth. The gravitational field force on the apple from Earth is equal to the size of the gravitational field force of Earth on the apple. The size of the field force is determined by the combined mass of both Earth and the apple. Why doesn’t Earth rise up to the apple as the apple falls to Earth?

The reason is the same as that in the last example. As Earth has a lot more inertia due to its mass, it is more difficult to move. Do you know why the Moon moves around Earth? What if Earth and the Moon were the same size—would they move around each other?

- A book rests on the table. There are two pairs of forces here: one pair relates to the gravitational field forces and the other pair relates to the normal contact forces. The book applies a contact (action) force on the table and in return the table applies a contact (reaction) force on the book. In addition, the book applies a gravitational field (action) force on Earth and in return Earth applies a gravitational field (reaction) force on the book. A misconception of many students is that the two forces on the book (gravitational and contact) make up the pair of action and reaction forces. However, this cannot be: firstly because they are different types of forces (gravitational versus contact) and, secondly, both forces act on the one object. The action and reaction forces must be of the same type and be applied to different objects.

FIGURE 16:
PAIRS OF FORCES



What force is responsible for moving a car or a body forward? Commonsense tells us it is the force of the engine on the wheels that makes the car go forward, and for body motion it is the muscles in our legs that allow us to move forward. However, from a scientific perspective this is not true. The ground pushes on both the car and the person to allow both to move forwards. These contact forces from the ground are in reaction to the wheels or feet pushing the ground. When we walk, we apply an action force to the ground. In return the ground applies a reaction force to the foot making it move forward. In the cases of both the car and the walker, the type of contact force is friction. If the maximum friction force is exceeded by the push from the foot or wheel then the foot will slip backwards and the wheel will spin. Such occurrences can occur on icy surfaces or in sand. If an object is stationary then commonsense tells us that if we apply a non-zero net force then the object will move in that direction. Therefore, if we push on the ground in a backwards direction to move forwards, it seems illogical that this backwards force is responsible for the forward motion.

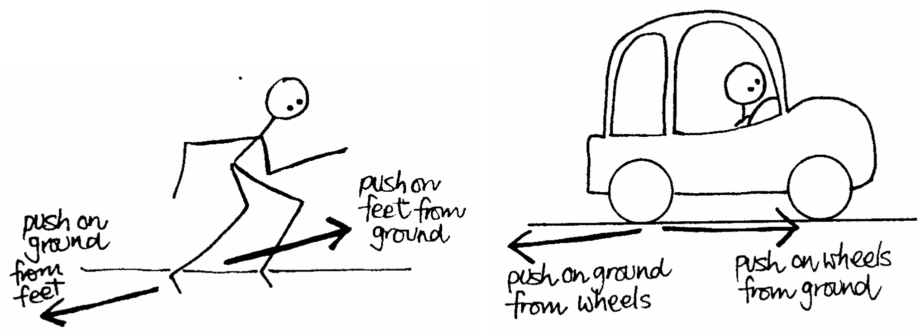


FIGURE 17:
PAIRS OF FORCES

Newton’s laws of motion

The previous sections on forces and motion are summarised in Newton’s laws of motion. They are summarised as follows:

- First law of motion: If no net force acts on an object it will continue in its current state of motion (this may be at rest or constant speed and direction).
- Second law of motion: If a net force acts on an object it will accelerate (it will change either or both of its speed and direction). The size of the acceleration depends on the mass of the object.
- Third law of motion: Forces occur when two objects A and B interact. For the force that object A exerts on object B there is an equal and opposite force that object B exerts on object A.

Force and pressure

Pressure is a quantity that is related to force but it is not the same thing. For example, a 100 kg male wearing flat-soled shoes walking on a wooden floor will not damage the floor, but a 50 kg female wearing stiletto-heeled shoes may very well damage the floor. Whereas the male exerts twice the contact force on the floor than the female, the male’s shoes exert less pressure on the floor than the female’s. Riding over the flat end of a tack will not puncture a tyre but riding over the sharp end of the tack surely will. Once again, the force on the tack is the same but the pressure exerted on the tyre is different.

Pressure is defined as the amount of force applied to an object per unit area of application. Therefore, a unit of pressure is newton’s per square metre ($N/m^{2)}$. This is given another name: pascal (Pa). A pressure of 10 N/m^2 is the same as 10 Pa. Daily weather forecasts give the atmospheric pressure in hectopascals (hPa), where each hectopascal is equivalent to 100 Pa. Atmospheric pressure at Earth's surface is around 1000 hectopascals, which represents 100 000 Pa.

The extent of injuries incurred in a car accident depends on a number of factors that include the size of the stopping force and where that stopping force is applied. Seatbelts and airbags ensure that the stopping force is spread over a larger part of the body; less pressure is applied to stop the passenger. Have you ever wondered how Indian mystics can sleep on beds of nails? Can anybody do this?

Air pressure

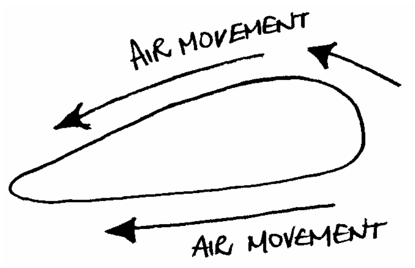
We know that air is a gas made up of fast-moving particles. These particles collide with objects in the air, applying forces. As objects are surrounded by air they receive forces on all sides and thus pressure is applied to all sides of the body. We call this pressure 'air pressure'. Normally the pressure is the same on all sides of a stationary object and all the forces from the individual collisions of the particles amount to a net force of zero. However, if the pressure on one side of an object is greater than that on another side then there will be the equivalent of a force being applied to an object. From a particle model we can imagine a high air pressure as many particles colliding with an object (creating a large force) and low air pressure as few particles hitting an object (creating a small force). Therefore, an object will tend to move in a direction to a low-pressure region.

We can understand air flight in terms of pressure differences acting on the wings of a plane. The wings are in the shape of an air foil. The basic shape is shown in Figure 18. As the plane moves forward, air rushes over the top and bottom of the air foil. As the air has a longer distance to travel over the top, it is more spread out than underneath the air foil. Therefore, a low-pressure region occurs at the top of the air foil and a high-pressure region occurs at the bottom. This pressure difference creates a lifting force on the plane.

The sails on yachts and sailboards create air foil shapes as they move through the air. The pressure differences on the sail allow the sailor or sailboarder to travel in most directions.

If the fluid is moving faster on one side of an object than on another, then a pressure difference will be created. The faster moving fluid has less pressure as the particles are more spread out. Consider the *Friendly cans* and W*ater lift* activities below.

FIGURE 18:
AIR FOIL



ACTIVITY::
THE BLOCKED FUNNEL

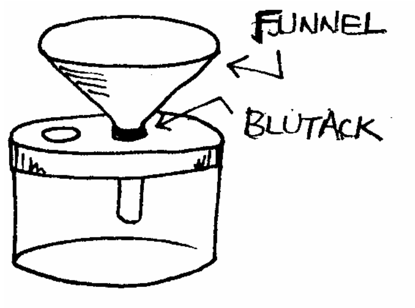
You will need:

- **a container with a metal or plastic lid**
- **Blu-Tack or plasticine**
- **a small plastic funnel.**

Create two holes in the lids of the container. Put the lid onto the container and seal airtight using Blu-Tack or plasticine. Insert the funnel into one of the two holes in the lid and seal with Blu-Tack or plasticine. Look through the funnel stuck in the lid. Is it blocked or clear?

Put your finger on the other hole and pour some water into the funnel. Can you explain what you observe? What will happen if you take your finger off the hole? Why?

FIGURE:
BLOCKED FUNNEL



ACTIVITY:
SUCKING UP A BALLOON

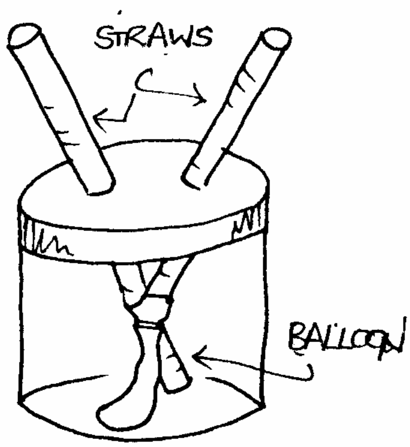
You will need:

- **an airtight container with a lid**
- **plastic tubes or straws**
- **a balloon.**

Assemble the above items as shown in the figure *Sucking up a balloon*.

What do you think will happen to the balloon if you blow in the different tubes? What do you think will happen if you suck through each of the tubes? What do you think will happen if you suck or blow through one tube while closing the other tube with your finger? Check your predictions. Can you explain what you see?

FIGURE:
SUCKING UP A BALLOON



ACTIVITY: FRIENDLY CANS

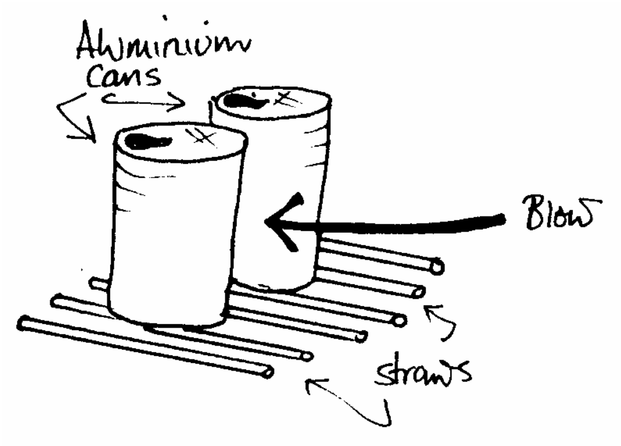
You will need:

- **two aluminium cans**
- **a number of straws.**

Place two empty cans about 3 cm apart on a set of plastic straws placed parallel so they can roll easily toward or away from each other. Blow gently between them.

What do you observe? Can you explain your observation?

FIGURE: FRIENDLY CANS



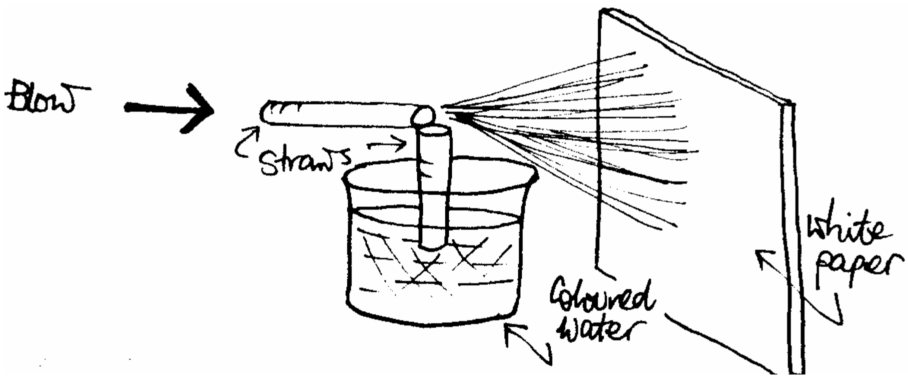
ACTIVITY: WATER LIFT

You will need:

- **a glass of water**
- **a straw**
- **scissors.**

Cut a straw in two. Place one half in a glass of water as shown in the figure *Water lift* (coloured water is more dramatic) and use the other straw to blow a stream of air across the top of the vertical straw. If you get it right, you will have quite an effective spray device.

FIGURE: WATER LIFT



Explanatory note: Air has a pressure and so it will take up space. Moving air has less pressure than stationary air, so if one side of an object has moving air passing over it and the other side has stationary air, then the side with stationary air will have more pressure applied to it. This means that for equal areas on each side the side that has stationary air will have a greater force applied—this may result in the object moving in that direction.

Energy

Much has been already been said about different types of energy. The change in motion of an object, attributable to the application of a non-zero net force, can result in a number of energy changes of the object. The total energy of all the objects in the interaction remains constant. Energy may be transferred from one object to another or it may transform into other types of energy, but it is never lost!

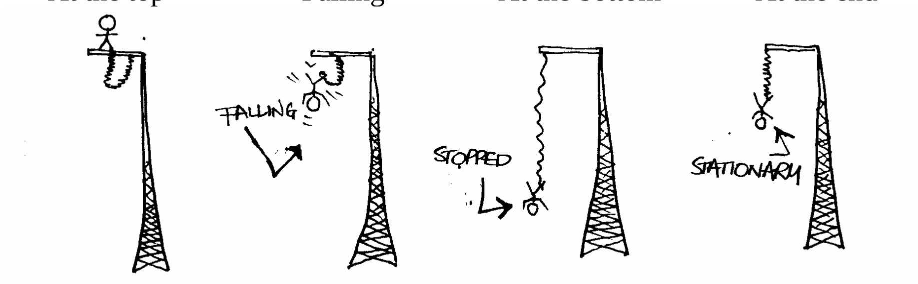
The following energies need to be considered when objects interact with other objects:

- Kinetic energy: an object that moves has kinetic energy. Kinetic energy is not only related to the speed of the object but also its mass. Therefore, a semitrailer moving at 100 km/h has more kinetic energy than a car travelling at the same speed.
- Gravitational potential energy: an object that is higher in the air than another object has more potential energy. This is because if both objects were let go then the higher object would achieve more kinetic energy in falling.
- Elastic potential energy: a flexible object (like a tennis ball) that is squashed or an arrow in a stretched bow has elastic potential energy. In both cases, the ball and arrow will receive kinetic energy if they are let go.
- Heat energy: in many interactions that involve rolling, sliding or fluid friction kinetic energy or potential energy will convert into heat energy. The objects involved in the interaction will rise in temperature.
- Sound energy: in any interaction that involves sound (e.g. a bat hits a ball) there is some kinetic or potential energy conversion into sound energy.

Consider the energy changes in the following interactions:

- Baseball: a baseballer slides in to base. In this situation the baseballer initially has kinetic energy. As they slide into base this energy is being converted into heat energy within their clothes and shoes. Their clothes and shoes will rise in temperature slightly.
- Bungee jumping: the bungee jumper initially has gravitational potential energy. This is converted to kinetic energy as they fall. However, after falling some distance they stretch the bungee cord and so kinetic energy is converted onto elastic potential energy. At the bottom of the fall they rise, converting elastic potential energy into both kinetic energy and gravitational potential energy. As there are frictional forces occurring in falling through the air and within the bungee cord, there is always energy converted to heat energy in the person and the bungee cord. Therefore, the bungee jumper finally comes to rest with less gravitational potential energy than they had at the start but the jumper and the bungee cord have increased slightly in temperature. The total energy of the bungee jumper and cord remain the same throughout the jump. However, different types of energy may make up this total.

FIGURE 19: ENERGY CHANGES IN A BUNGEE JUMP



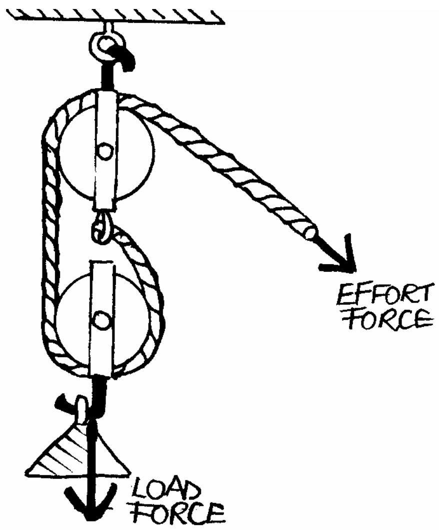
At the top	Falling	At the bottom	At the end
Gravitational potential energy	Gravitational potential energy	Gravitational potential energy	Gravitational potential energy
	Elastic potential energy	Elastic potential energy	Elastic potential energy
	Heat energy	Heat energy	Heat energy
	Kinetic energy		

Machines

Machines are all around us. Cars, cranes, dishwashers, computers and power saws are all examples of complex machines and all make a particular task easier to complete. However, these complex machines are made up of a number of simpler machines. Almost all machines used in our daily lives are made up of a combination of some simpler machines that are described as lever, wheel and axle, inclined plane, gears, and pulleys.

From a scientific perspective, a machine is a device that transmits and modifies forces. For example, Figure 20 illustrates a simple machine called a ‘pulley’. By pulling on the rope, a large mass can be lifted. By applying a force on one part of the pulley (machine), a force is applied at another point and so the pulley transmits a force. In addition, the pulling force on the rope creates a greater lifting force at the other point in the pulley and so the machine modifies, and in most cases, increases the applied force. The input force to the machine is called the ‘effort force’ and the output force of the machine is called the ‘load force’.

FIGURE 20: FORCES IN A PULLEY



Machines first appear to be able to get extra force for little input force by the operator of the machine. However, there is a trade-off. In the example of the pulley the effort force must be applied over a longer distance, called the 'effort distance', than the distance the load force is applied (called the 'load distance'). For a smaller effort force than a load force, the effort force must be applied over a longer distance than the effort force. This can be very simply stated as a rule:

effort force × effort distance = load force × load distance.

For the pulley system shown in the Figure 20, notice that if you pull on the rope, say 10 cm, the load will rise only half this value, 5 cm. If the load force needed to lift the mass is 100 N then the effort force required will only need to be 50 N. Applying the rule above:

effort force × effort distance = load force × load distance

(50 N × 10 cm = 500) = (100 N × 5 cm = 500).

In describing different machines, a quantity called 'mechanical advantage' is used. The mechanical advantage of a machine is equal to the load force divided by the effort force. In the example of the pulley, the mechanical advantage of the pulley was 100 N divided by 50 N, which is 2.

We will consider very simple machines such as incline planes, pulleys, wheels and axles, and levers. The everyday names given to these machines include bottle opener, wheelbarrow, doorhandle, light switch, scissors, screwdriver, stairs, car ramp, key and nutcracker.

ACTIVITY: INCLINE PLANES

You will need:

- **a flat board**
- **some bricks**
- **a trolley**
- **a spring balance, force measurer or rubber bands**
- **a measuring tape or ruler.**

Place one brick under one end of the board. Attach your spring balance or force measurer (the amount of stretch on a rubber band gives a good measure of the size of force) and determine the force required to roll the trolley along the board so the trolley is raised the vertical height of one brick. Find the distance travelled by the trolley along the board.

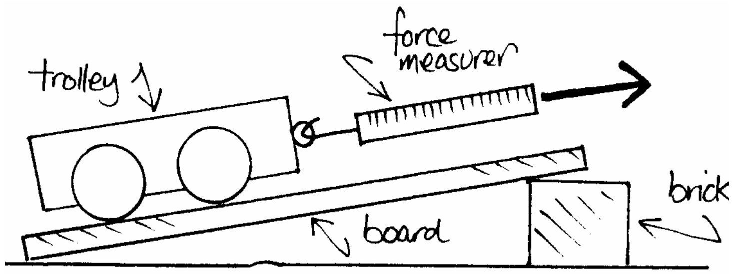
Now raise the end of the board to two bricks high. Find the force needed to roll the trolley so that it is raised only one brick high (this will occur before the end of the board).

Find the length travelled by the trolley along the board to raise it a vertical height of one brick.

Continue raising the end of the trolley with more bricks and each time find the force required to raise the trolley one brick high and the distance travelled along the pulley to achieve this. Tabulate all your results.

How does the force change when the incline angle is increased? How does the distance along the board change as the incline angle is increased?

FIGURE: LIFTING A LOAD ON AN INCLINE



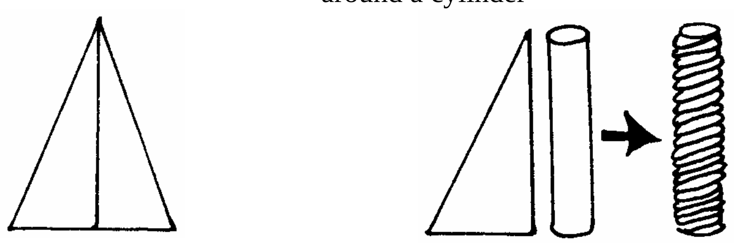
Incline planes are very simple machines that raise an object a vertical distance. An inclined plank is frequently used for wheeling loads onto trucks. Stairs and ramps are much easier to climb than ladders. However, while the effort force required to move an object along an incline is less than the load force to raise it vertically, the effort distance travelled along the incline is longer than the vertical distance, which represents the load distance.

Other types of incline planes are the screw thread and the wedge. Figure 21 indicates that the wedge can be considered to be two inclined planes whereas the screw thread is an incline plane wound around a cylinder or a cone. Sharp instruments such as knives and axes act as wedges. By applying an effort force on the blade over a certain distance, a load force is applied perpendicularly to the blade movement. Screw threads are found in screws, bolts, drill bits, car jacks and engines. The greater number of threads means that a bigger mechanical advantage is achieved but more turns are required.

FIGURE 21: INCLINE PLANES

Wedge is two inclined planes

A screw has an inclined plane wrapped around a cylinder



The mechanical advantage of the inclined plane can be determined by knowing the length of the incline and the height:

mechanical advantage = length of incline ÷ the height.

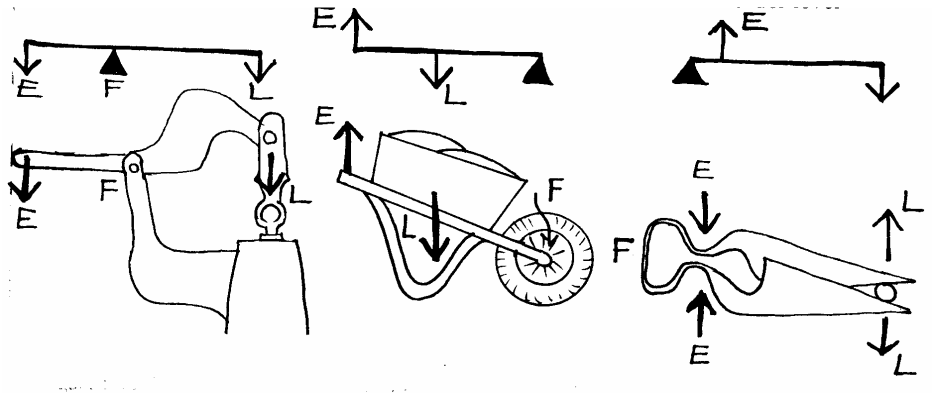
Levers

A lever is a rigid bar, not necessarily straight, which can rotate about a fixed point. This fixed point is called a ‘pivot of fulcrum’. Some examples of machines that are levers are scissors, nutcrackers, shears, pump handles and wheelbarrows. The human body has a number of levers where muscles, bones and joints are used to create movement.

Levers are classified as first, second or third order according to the arrangement of the effort force, the load force and the fulcrum. A first-order lever, such as a pump handle, has the fulcrum between the load force and the effort force. A second-order lever, such as a wheelbarrow, has the load force separating the fulcrum and the effort force. A third-order lever, such as a pair of shears, has the effort force between the fulcrum and the load force.

FIGURE 22: ORDER OF LEVERS

First-order lever Second-order lever Third-order lever

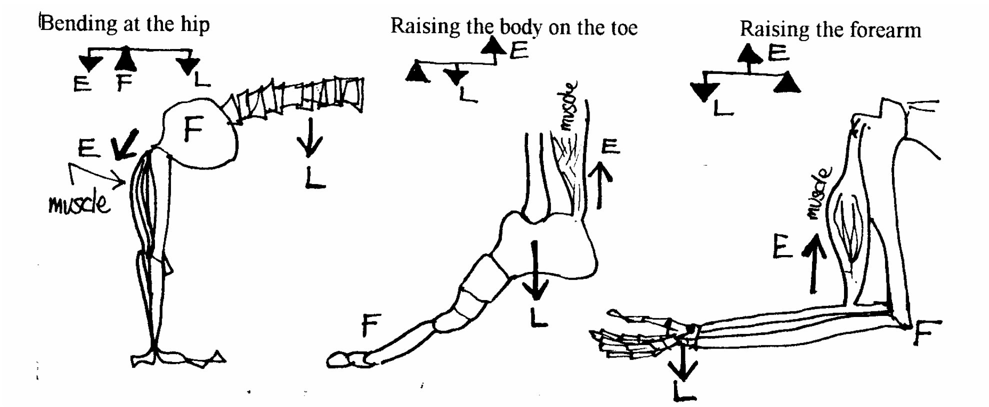


(Martin & O'Connor 1968, p. 119)

All orders of levers are found in the human body (see Figure 23).

FIGURE 23: EXAMPLES OF HUMAN LEVERS

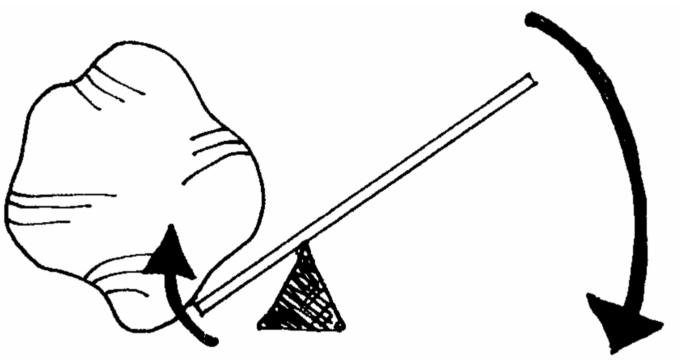
First-order lever Second-order lever Third-order lever



(Martin & O'Connor 1968, p. 120)

In the lever system a large rotation by the effort force about the fulcrum creates a small rotation at the load force. The greater the difference in the rotations, the greater the mechanical advantage.

FIGURE 24: THE LEVER



Wheels and axles

Cars, trains, bicycles and trucks all contain wheels and axles. A doorhandle is a wheel and an axle. The wheel has a larger radius than the axle so the effort force again moves further than the load force. The mechanical advantage of a wheel and axle is equal to the radius of the wheel divided by the radius of the axle. The greater the difference between the wheel radius and the axle radius, the greater the mechanical advantage. Other machines that can be described as a wheel and axle are screwdrivers and spinning wheels.

ACTIVITY: PULLEYS

You will need:

- **two strong rods, for example, two cricket stumps**
- **a piece of cord at least 3 m long (sash cord is suitable).**

Choose two strong people to hold the rods. Tie one end of the piece of cord to one of the rods. Ask one person to hold the rod horizontally by placing their hands at each end of the rod. Ask a second person to hold the other rod in the same way, but parallel to and about 20 cm from the first rod. Now wind the rope six times round the two rods as shown in the figure *Tug of war*. Ask your assistants to try to hold the rods apart while you try to move the rods closer together by pulling the free end of the cord toward you. What do you find?

FIGURE: TUG OF WAR

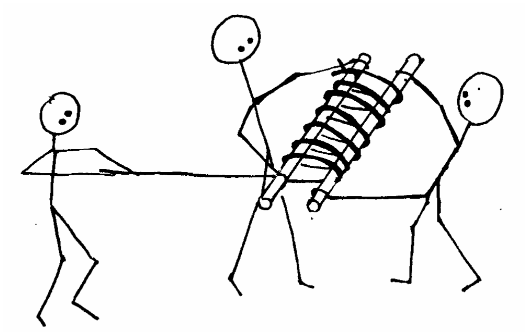
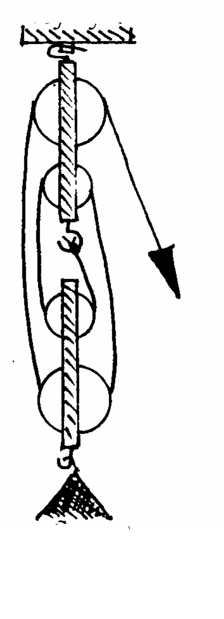


Figure 25 represents a pulley being used to lift up an engine. The wheels of the pulley block are drawn above the other to show how the rope is fixed, but the pulleys need to be side by side. The mechanical advantage of a set of pulleys is about equal to the number of ropes between the pulleys. In the figure the mechanical advantage is 4.

FIGURE 25: PULLEY SYSTEM



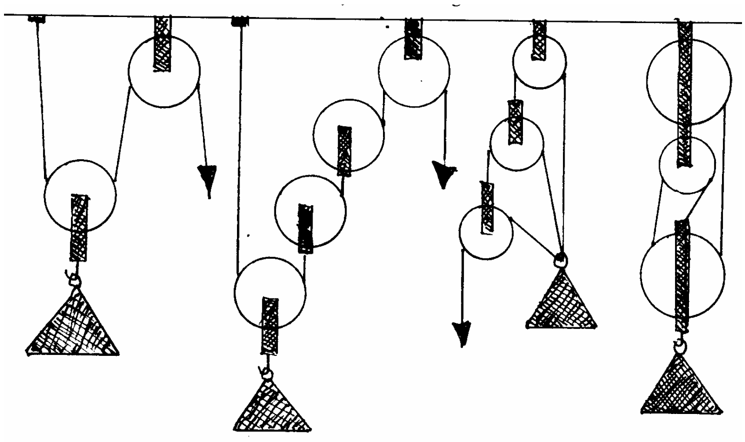
ACTIVITY: PULLEY SYSTEM

You will need:

- **a number of pulleys.**

If you can get access to a number of pulleys, try some of the pulley systems as shown in the figure *Example of a pulley system*. Which provide the best mechanical advantage? Try some of your own designs.

FIGURE: EXAMPLE OF A PULLEY SYSTEM

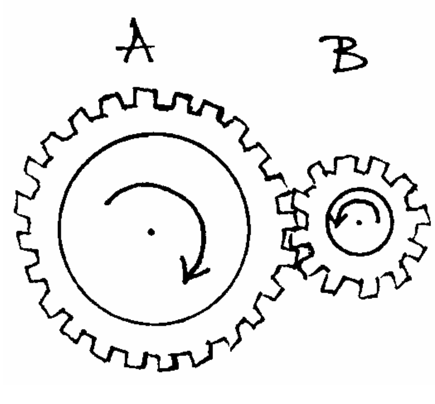


Gears

Gear systems consist of rotating wheels, called cogs, with teeth attached to shafts. Rotating one of the wheels will rotate another. Gears are commonly used when shafts are required to rotate at different speeds, for example when riding a bicycle. In Figure 26, wheel A has more teeth than wheel B. Rotating wheel A in a clockwise direction will rotate wheel B in an anticlockwise direction. In addition, the rotation rate of wheel A will be slower than wheel B as it has more teeth.

Rotating the smaller cog with a twisting effort force will create a larger twisting load force in the larger cog. The smaller cog will make more complete rotations than the larger cog.

FIGURE 26: GEARS



References

Martin, SL & O'Connor, AK 1968, *Basic physics I*, Whitcombe & Tombs, Sydney.