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PHYSICS
FORCE AND MOTION

By Harry Jivenmukta

FORCE

Force is any action that tends to maintain or alter the position of a body or to distort it.

The concept of force is commonly explained in terms of Newton's three laws of motion. Briefly, these are:

- A body that is at rest or moving at a uniform rate in a straight line will remain in that state until some force is applied to it.
- When an external force acts on a body, it produces an acceleration (change in velocity) of the body in the direction of the force.
- When one body exerts a force on another body, the second body exerts an equal force on the first body. This principle of action and reaction explains why a force tends to deform a body (i.e., change its shape) whether or not it causes the body to move.

NB - See page on Newton's laws of motion for further information.

Physicists use the Newton, (N), a unit of the International System, for measuring force. A newton is the force needed to accelerate a body weighing one kilogram by one metre per second per second. The formula F = ma is employed to calculate the number of newtons required to increase or decrease the velocity of a given body. In countries still using the British system of measurement, engineers sometimes still measure force in pounds.

Questions...

1. What is force? Write a short definition.
2. Give examples to illustrate Newton's three laws of motion..
3. Write a short biography of Newton.
4. Explain why things on the moon have a weight 6 times less than their weight on Earth.

WEIGHT

2

Weight is the gravitational force of attraction on an object, caused by the presence of a massive second object, such as the Earth or Moon. Weight is a consequence of the universal law of gravitation:

> **any two objects, because of their masses, attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.**

Bigger objects weigh more in the same location; the further an object is from the Earth, the smaller is its weight. The weight of an object at the Earth's South Pole is slightly more than its weight at the Equator because the polar radius of the Earth is slightly less than the equatorial radius. Though the mass of an object remains constant, its weight varies according to its location. The smaller mass and radius of the Moon compared with those of the Earth combine to make the same object on the Moon's surface weigh one-sixth the value of its weight on Earth.

Weight is the product of an object's mass and either the gravitational field or the acceleration of gravity at the point where the object is located.

Questions...

1. What is weight?
2. How would a non-physicist define weight?
3. Why do things which are further away from Earth weigh less?
4. Explain why things on the moon have a weight 6 times less than their weight on Earth.

FRICTION

Friction is the force that resists the sliding or rolling of one solid object over another.

Friction can be useful - the traction needed to walk without slipping is one example.

Friction can also be disadvantageous - about 20 percent of the engine power of cars is used in overcoming frictional forces in the moving parts.

There are two simple facts that characterize the **friction of sliding solids**:

- the amount of friction is almost independent of the area of contact. If a book is pulled along a table, the frictional force is the same whether the book is lying flat or standing on end,
- friction is proportional to the load or weight that presses the surfaces together. If a pile of three books is pulled along a table, the friction is three times greater than if one book is pulled.

Static friction acts between surfaces at rest with respect to each other. The value of static friction varies between zero and the smallest force needed to start motion. This smallest force required to start motion, or to overcome static friction, is always greater than the force required to continue the motion, or to overcome kinetic friction.

Rolling friction occurs when a wheel, ball, or cylinder rolls freely over a surface, as in ball and roller bearings. The main source of friction in rolling appears to be dissipation of energy involved in deformation of the objects. If a hard ball is rolling on a level surface, the ball is somewhat flattened and the level surface somewhat indented in the regions in contact. The elastic deformation or compression produced at the leading section of the area in contact is a hindrance to motion that is not fully compensated as the substances spring back to normal shape at the trailing section. The internal losses in the two substances are similar to those that keep a ball from bouncing back to the level from which it is dropped.

Questions...

1. What is friction?
2. Why would a book have the same amount of frictional force if it were pulled along a table;
   - on its end,
   - laid flat with all of its area in contact with the table?
3. What is static friction?

TURNING FORCES

4

We use turning forces every day:

- opening a door by turning the handle,
- tightening or opening a tap,
- tightening or loosening a screw-top on a bottle,
- using a screwdriver to join things together, etc.

There are two factors which affect the turning process. One is the amount of force applied and the second is the distance from the centre, (axis), that the turning takes place. For example, if you are trying to open a nut on a mechanical construction it will be easier to open if you use a spanner with a long handle; or if you are opening a door, it would be easier if the handle was longer.

The amount of force and the distance which determines the magnitude of the force is called the **moment** of the force and can be defined as:

The moment of a force about a point is the product of the force and the perpendicular distance of its line of action from the point.

In practical terms is it very easy to understand this law. Imagine all the doors in your home had very small handles which did not allow you any leverage. You would have to apply more force on the smaller handle to open the door. If, on the other hand, the handles were long, you would have to move the handle a greater distance but the force required would be less, (in fact the force is the same but feels to be less because it is spread out more). In this way you can see the relationship between the amount of force needed and the amount of leverage or movement available.

Questions...

1. What is a turning force and how does it work?
2. Draw illustrations to show how turning forces help us in our everyday lives.
3. What happens in the force required to open a door if a door handle was:
    - longer
    - laid flat with all of its area in contact with the table?
3. What is static friction?

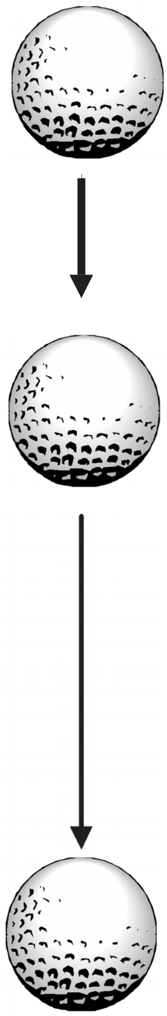
GRAVITY

5

The force that causes things to fall and rivers to run downhill is the same force that holds the Earth in its orbit around the Sun; gravitation.

The first scientific studies of gravity were performed by the Italian astronomer Galileo at the end of the 16th century. Galileo measured the speed of falling objects by timing metal balls rolling down an inclined plane. He concluded that gravity imposes a constant acceleration on all objects. That is, with each second of fall an object acquires a constant additional downward velocity. On Earth this acceleration of gravity is 9.75 meters per second per second. At the end of one second, a falling object is moving at a velocity of 9.75 metres per second and at the end of two seconds, 19.5 meters per second, and so on, before any adjustment for the resistance of the air it passes through.

Galileo found that all objects are accelerated by gravity in the same way. A feather falls more slowly than a rock not because its acceleration from gravity is less but because air resistance slows it more. The force of air resistance varies with the surface area of an object, so that an object that spreads its weight over a greater area suffers more resistance and drops more slowly. This is the principle used in the parachute. If a feather is dropped in a vacuum it will fall at the same speed as a heavier object.



From a position of rest the ball will accelerate in the first second to a speed of 9.75 metres per second.

After two seconds it will be travelling at 19.5 metres per second.

Questions...

1. Explain in your own words what gravity is.
2. Why would a feather take longer to fall to the ground than a stone, in normal circumstances?

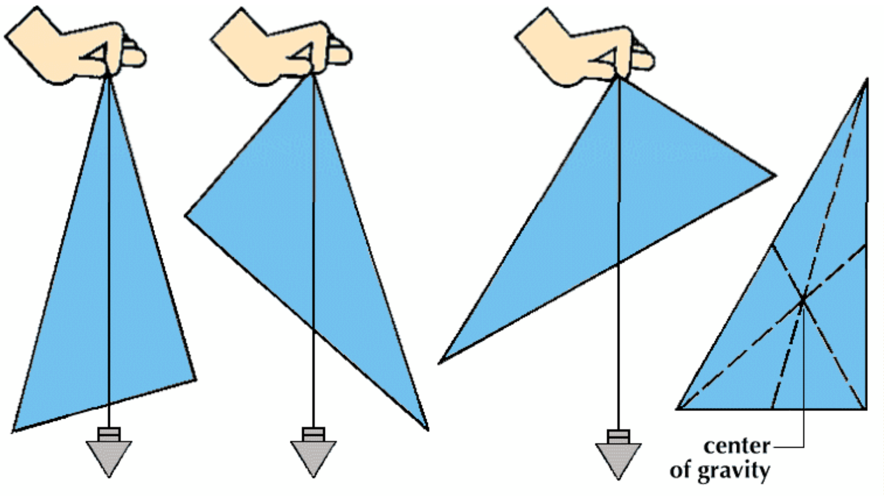
z a rectangle,

z a triangle with three different corner angles,

Earth.

z a random shape.

CENTRE OF GRAVITY



If you want to find the centre of gravity of something, the example above shows a simple way of finding it out. Using a plumb line simply allow the triangle to hang freely from one of its tips and mark the line. Then repeat the exercise on the other two tips. Where all the lines meet is the centre of gravity of the triangle.

It is easy in the example above, but would be harder for a 3 dimensional object. It is very important in some circumstances to know what the centre of gravity of something is. One classic example of getting it wrong is the case of the Mercedes 'A' Class car:

> **The car manufacturer Mercedes designed a small car called the 'A' Class. It was very revolutionary. Unfortunately someone forgot to work out the centre of gravity properly which meant that when the car went around corners, even at fairly sensible speeds, it tipped over. The mistake cost Mercedes £Millions in cancelled orders and redesign costs and even more than that, it dented their pride and made people question the quality of their products.**

1. Why might it be useful to find the centre of gravity of an object?
2. Draw and cut out the following shapes and find the centre of gravity:

SPEED, VELOCITY AND ACCELERATION

7

Speed is the rate of change of distance moved with time.

Calculating speed is often best done by working out an average speed. If you are travelling in a car, the speed may be 30 m.p.h. at one moment and 32 m.p.h. the next. To say that now you are travelling at 30 m.p.h. and a second later at 32 m.p.h. is not very useful from a scientific point of view. In studying the speed of something, it is, therefore, often more useful to work on average speeds.

Average speed is worked out by dividing the distance travelled by the time taken. So, if you travel one hundred miles in four hours you can say the average speed is 25 miles an hour. This type of calculation is of a **scalar** nature. As long as we talk about just the distance travelled all calculations can be called scalar in nature.

In ordinary language we think of speed and velocity to mean the same thing. In physics velocity is:

the rate of change of distance moved with time in a <u>specified direction</u>.

Velocity becomes important when we talk about the direction of travel. If a car travels in a straight line at 30 m.p.h. constantly we can say that the speed and velocity are the same, but if the car then goes around a bend at 30 m.p.h., the speed is still 30 m.p.h., but the velocity keeps changing as the car deals with the force that the bend exerts on the car. Velocity is a **vector** quantity.

Acceleration occurs when the velocity of the object increases:

Acceleration is the rate of change of velocity with time.

If the object is getting faster then acceleration is seen as being positive. If it is getting slower it is seen as being a negative quality. In ordinary language we talk of slowing down not as a negative expression of acceleration but as **deceleration**.

Questions...

1. Write definitions in your own words for:

   - velocity,
   - acceleration.

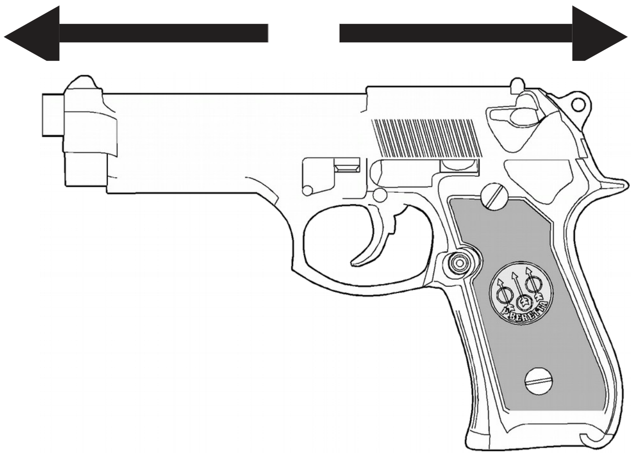
2. What is the difference between speed and velocity?
3. Why would pysicists talk about negative acceleration rather than deceleration?
4. Find out what **scalar** and **vector** mean in relation to speed and velocity.

MOMENTUM

8

A fundamental quality in dynamics is momentum. The momentum of a body is the product of the body's mass times its velocity. Using letters for momentum, mass, and velocity, this relationship can be expressed in the equation $M = mv$. When a moving mass strikes another mass, the total momentum before and after the collision is exactly the same. This principle, the conservation of momentum, is a fundamental law of nature.

Before a gun is fired, there is no motion of either the bullet or the gun, and the total momentum is zero. Firing gives the projectile a large momentum in one direction; the conservation principle requires that the gun receive an equal and opposite momentum, this results in the recoil felt by the shooter. The equal and opposite momenta of the gun and the projectile add to zero, as before firing.



Qu stions...

1. What is momentum?

   z velocity,

   z acceleration.

2. What is the difference between speed and velocity?
3. Why would pysicists talk about negative acceleration rather than deceleration?
4. Find out what **scalar** and **vector** mean in relation to speed and velocity.

GALILEO - A PENDULUM

The most familiar pendulum is the one that controls the escapement that keeps a clock ticking. The study of pendulum motion has given science many important facts about the Earth's movement and the forces that control it.

A simple pendulum consists of a concentrated weight (a metal ball) supported by a thin wire or thread. If the wire is held taut and the ball pulled back and released, the pendulum will swing freely back and forth through an arc. The swing, always in the same plane, is produced because of the force of gravity. As the ball continues to swing, the length of the arc through which it travels becomes shorter. Finally it comes to a complete stop, mainly because of air friction. The period of the swing is the time that it takes the ball to travel through its arc and back again to the starting point. As the arc becomes smaller, the speed also decreases but **the period remains constant**. The period depends only upon the acceleration of gravity and the length of the wire. Since gravity is constant, the period remains the same if the length of the wire does not change. If the wire's length is known and the period is accurately timed, the acceleration of gravity can be calculated.

DRAW AN ILLUSTRATION OF A PENDULUM AND SHOW HOW IT WORKS

Questions...

1. Write a short biography of Galileo.
2. How does a pendulum work?

NEWTON'S LAWS OF MOTION

The three laws of motion were first formulated in the 17th and 18th centuries by Isaac Newton. These principles are known as Newton's laws. The first law describes a fundamental property of matter, called **inertia**, as follows:

- Every body remains in a state of rest or in a state of uniform motion (constant speed in a straight line) unless it is compelled by impressed forces to change that state.

Under this law a moving body is at rest, as far as its own inertia is concerned, as long as its motion continues at the same speed and in the same direction. Therefore, particles (or even worlds) of matter will keep flying through empty space forever, without being driven by any force, until something compels them to change their motion.

Newton's second law describes the manner in which a force compels a change of motion, at a rate of change called acceleration. It can be stated as follows:

- Change of motion is proportional to the impressed force and takes place in the direction of the straight line in which that force is impressed.

This law is often stated in a different manner: the net force acting on a body is equal to the product of the body's mass times the resulting acceleration. It can be stated much more simply as a formula, using letters for force, mass, and acceleration: $F = ma$. The wording of the law, however, makes clear how an impressed force acts. It simply compels a change in the body's motion, its speed or direction, toward the direction in which the force is acting.

Newton's third law may be stated as follows:

- Action and reaction are equal and opposite.

This law is often expressed as "for every action there is an equal and opposite reaction." The law states a fact that can upset many calculations unless it is taken into account.

It explains, for example, the saying that a man cannot literally lift himself by his own bootstraps. As he pulls up on his bootstraps, the bootstraps pull down on him. Action and reaction are equal and opposite. A modern example of action and reaction is jet propulsion.

Questions...

1. In your own words write what you understand each of the three laws of motion to be.

WORK

11

If you walk up a hill you may regard it as work because you exert effort to move your body to a higher level. In this instance, you also do work according to the definition accepted by physicists, because you exert a force to lift yourself over a distance, the distance from the bottom to the top of the hill.

However, if you stand without moving with a heavy weight in your outstretched arms, you are not doing any work as physicists define work. You are exerting a force that keeps the heavy weight from falling to the floor, but the position of the weight remains unchanged. It is not moved any distance by the force. You are, of course, exerting a lot of muscular effort to prevent the dropping of the weight, and the average person would say that he or she is working very hard. But you would not be doing any work according to the definition accepted in physics.

You might think that pushing hard against a wall is work. You can get very tired using a lot of effort. But if the wall doesn't move, according to physics you haven't done any work!

Questions...

1. What is work as defined by physics?
2. What do you define as work?
3. How is a physics definition of work important in studying **force** and **distance**?
4. Make a list of activities which would be considered work in the normal sense, but is not work if we use a physics definition. List the activities in the first box and say why it is not work according to the physics definition in the second box.

WORK IN THE NORMAL SENSE	WHY IT IS NOT WORK IN THE PHYSICS DEFINITION

ENERGY

12

A roof slate falling from the roof is different from the slates which are in place. The person who gets up in the morning, full of energy, is different from the tired person who is lethargic. A glowing heater is different from the same heater when the electricity, (or gas), is switched off. In each case, an agent of change has acted upon them. That agent is energy.

Energy is one of the most basic ideas of science. All occurrences in the universe can be explained in terms of energy and matter. But the definition of energy is not at all simple since energy occurs in many different forms, and it is not always easy to tell how these forms are related to one another and what they have in common. One of the best-known definitions of energy is the classical definition used in physics:

Energy is the ability to do work.

Energy can often be seen as a chain which transfers many times into other forms of energy as it is used to help humans to live comfortably.

The Sun gives energy to plants and helps growth → Plants grow and become food for animals and humans → The worker eats the food and goes to work → The worker produces things for use by others

In the example above light and heat energy help the plants to grow. Plants turn the Sun's energy into chemical energy. The plant is consumed by the worker who also turns the energy into chemical energy useful to humans. The work energy is kinetic energy.

Questions...

1. What is energy?
2. Make a list of the types of energy referred to in physics.

or part of larger machines.

3. What is the difference between **Prime Movers** and **Operators**?

- how coal becomes electrical energy,
- how the wind becomes a power generator,
- how water becomes electrical power to run a mill or machines.

MACHINES

13

Machines are devices that have a particular purpose, that aids or replaces human or animal effort for the accomplishment of physical tasks. This category includes such simple devices as:

- the lever,
- wedge,
- wheel and axle,
- pulley,
- screw.

Most machines are more complicated than these basic devices and make use of two or more of these individual features.

The operation of a machine may involve the transformation of chemical, thermal, electrical, or nuclear energy into mechanical energy, or vice versa, or it may simply transmit forces and motions. All machines have an input, an output, and a transforming or modifying effect.

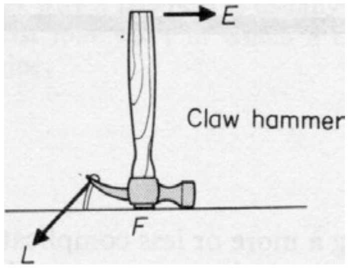
Machines that receive their input energy from a natural source, (air, petrol, water, etc.), are known as **prime movers**. Windmills, waterwheels, turbines, steam engines, and internal-combustion engines are prime movers. In these machines the inputs vary; the outputs are usually rotating shafts capable of being used as inputs to other machines, such as electric generators, hydraulic pumps, or air compressors. All three of the latter devices may be classified as **generators**; their outputs of electrical, hydraulic, and pneumatic energy can be used as inputs to electric, hydraulic, or air motors. These motors can be used to drive machines with a variety of outputs, (electrical appliances, machines in factories, etc.). All machines that are neither prime movers, generators, or motors can be classified as **operators**. This category also includes manually operated instruments of all kinds, such as calculating machines and typewriters.

1. What is the main function of a machine?
2. Give examples of how the devices listed at the top of the page are used as machines themselves

LEVERS

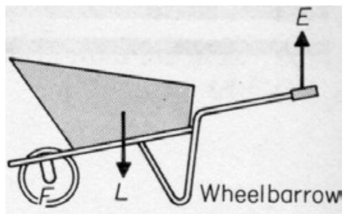
The simplest lever is the crowbar, which is a length of steel rod.

The purpose of any lever is simply to use the advantage of length to reduce the amount of force required to do something, (actually the force is the same but seems less because it is spread out over a greater area or distance). A simple example is if you try to pull a nail out of a piece of wood. If you use a claw hammer it is very easy because the hammer can be used as a lever. The amount of movement is greater than pulling the nail straight out upwards but the amount of effort in using the lever of the hammer is negligible for most people.



There are many other examples of the use of levers in everyday life:

- using a knife to cut up food,
- pliers and similar tools,
- scissors,
- using a wheelbarrow.



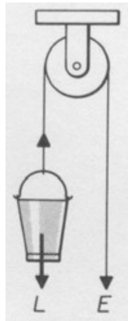
KEY
E = EFFORT
L = LOAD
F = FORCE

Questions...

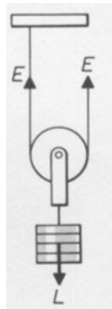
1. Describe how a lever works.
2. Explain how a wheelbarrow construction makes use of leverage.
3. Make a list of levers used in your home.

PULLEYS

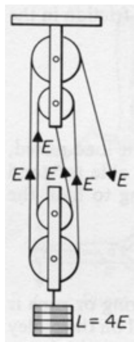
A pulley is a wheel with a grooved rim in which a rope can be passed. An example of a simple pulley is when builders use buckets full of materials which are passed up to where people are working. The pulley is at a high point of the building and a rope hangs down both sides. The bucket is filled and someone stands at the bottom pulling the rope down and raising the bucket higher. This type of pulley does not give any work advantage but is simply convenient.



Some pulleys give actual work advantage, that is they make the work easier to do. In a single moving pulley a weight is suspended from the pulley. If the weight of the object was 4kg then each string is holding 2kg of force each. The string has to be moved twice as far to raise the weight the same distance if it were on a single string, but the effort is halved. In this way a weight which would be otherwise difficult to move can be more easily moved. Like the lever, the pulley works by lengthening the amount of movement and so reducing the amount of effort, (spreading the effort over a longer distance).



The third illustration is of a block and tackle type of pulley arrangement. The block and tackle is used for lifting heavy weights like car engines. In the illustration the mechanical advantage is four. This means that the rope has to be pulled four times as far as the weight would be lifted. Pulling the rope so far would not exhaust the workers whereas lifting the weight directly would. So we can say that the mechanical advantage is four because the rope passes through four pulleys and the rope has to be pulled four times the distance of the weight lifted.



These are simple examples, but sometimes pulleys are more complicated and the calculations required to work out the mechanical advantage are more difficult. For example we have to take friction into account.

KEY

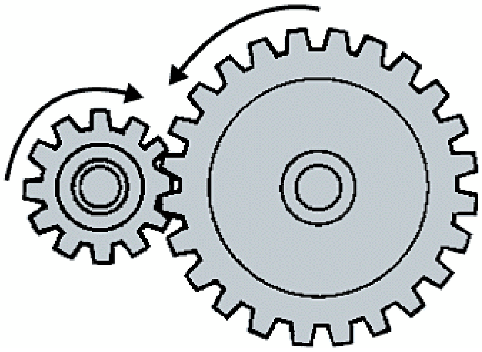
E = EFFORT

L = LOAD

Questions...

1. What is a pulley?
2. How can we increase mechanical advantage by using pulley arrangements? Give examples.
3. How do pulleys differ from levers?

GEARS



Gears are an important way to vary output between mechanical advantage and speed.

- If a gear is large it gives a greater mechanical advantage but less speed.
- A small gear gives more speed but less mechanical advantage.

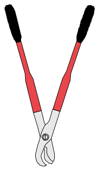
An easy way to understand gears is to look at the bicycle. When you are going uphill you need a big gear. First gear is the largest gear physically. This means that you have to pedal more but you will not travel as far as when you are in a smaller gear. Although you travel less far, you can progress without too much effort. When you are on a flat road you need less effort to progress so you can choose a smaller gear, your top gears. These need more effort but make you go faster.

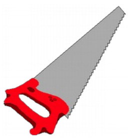
Sometimes it is difficult to understand gears because when we speak of a lower gear you might imagine a smaller gear. But this is not the case. A lower gear is physically bigger, and a higher gear is physically smaller. The highest gear on a bicycle is the smallest one on the rear wheel. The lowest gear is the biggest gear on the rear wheel.

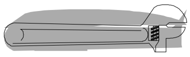
Questions...

1. What is a gear?
2. In your own words write how the gears of a bicycle work:
   - when you go up a steep hill,
   - when you are on a flat road and want to go fast.
3. Make a list of other uses of gears not including bicycles.

Consider the following objects. Explain in physics terms how they work and how their design maximises their performance.







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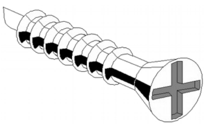
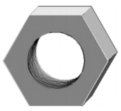
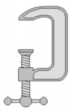






WEIGHTS AND MEASURES

The term weights and measures signifies standard quantities by which comparisons are achieved. Standard quantities may be established by reference to some universal constant. Standards for different kinds of quantities may develop separately or may be integrated into logical systems of units. Originally there were four types of standard measures:

- mass (weight),
- volume (liquid or dry measure),
- length,
- area.

As science and society developed others were added: standard measurements of temperature, luminosity, pressure, electric current, and others.

The earliest standard measurements appeared in the ancient cultures and were based on parts of the body, or on calculations of what humans or animals could haul, or on the volume of containers or the area of fields in common use. The **Egyptian cubit** is generally recognized to have been the most widespread unit of measurement in the ancient world. It came into use around 3000 BC and was based on the length of the arm from the elbow to the extended finger tips. It was standardized by a royal master cubit of black granite, against which all cubit sticks in Egypt were regularly checked. One of the earliest known weight measures was the **Babylonian mina**. Two surviving examples vary widely, one weighs 640 g (about 1.4 pounds), the other 978 g (about 2.15 pounds).

The terms ounce, inch, pound, and mile come from the Roman adoption of earlier Greek measuring units. The **Roman system** of measurement lasted into the Middle Ages in Europe, but there was great diversity of standards. From the Middle Ages onwards, various national governments made efforts to standardize their systems, producing many often confusing units and standards. The **British Imperial** and US Customary are two of the most elaborate such systems.

Questions...

1. Trace how the units of weight and measurement have changed with time.
2. Find out about and list the Imperial Measurements used by Britain up to 1970.

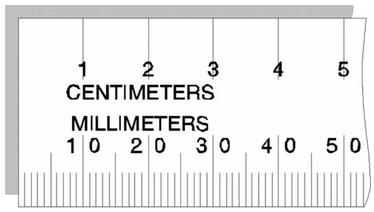
MEASUREMENT

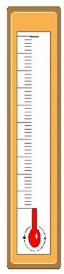
20

The first proposal for what would later become the **metric system** was made by a French clergyman, Gabriel Mouton, around 1670. He suggested a standard linear measurement based on the length of the arc of one minute of longitude on the Earth's surface and divided decimally. In 1795 France officially adopted the metric system. Its spread throughout the rest of Europe was accelerated by the military successes of the French Revolution and Napoleon, but in many places it took a long time to overcome the customary systems of weights and measures that had been used for centuries.

Now the standard system in most nations, the metric system, has been modernized to take into account 20th-century technological advances. In Paris in 1960 an international convention agreed on a new metric-based system of units. This was the Système Internationale (SI). Six base units were adopted:

- the metre (length),
- the kilogram (mass),
- the second (time),
- the ampere (electric current),
- the degree Kelvin (temperature),
- the candela (luminosity).





Questions...

1. Why is a metric system seen to be the most desirable one today?
2. Find out and write short descriptions of the following:
   - the ampere,
   - the degree Kelvin,
   - the candela.