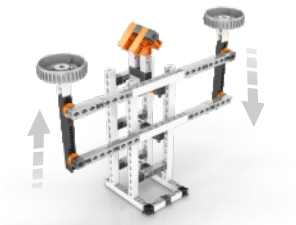
STEM Mechanics Master Set

E97.1 THEORY

The **STEM Mechanics Master set** is the ultimate combination of the main subjects of Simple Machines and Physics, including Levels, Pulleys, Gears, Linkages, Newton's Laws, Energy conversion, Solar Power and Structures. The patented geometry of ENGINO® components allows connectivity to all directions of the 3D space, enabling users to easily create technical models. This unique set enhances creativity and imagination while also teaching a variety of STEM principles. A geared DC motor with a large solar panel is included for animating the ENGINO® builds, converting solar energy to electricity. The set comes with a library of high-precision gears, pulleys and axles for changing speed, force and direction of motion. From this set, besides open projects, students can find digital instructions for 100 working models and amazing animated contraptions such as cars, cranes, bridges!

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Wheels, Axles & Inclined Planes | page 15



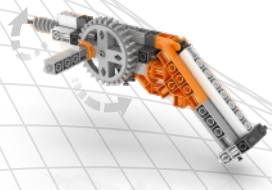
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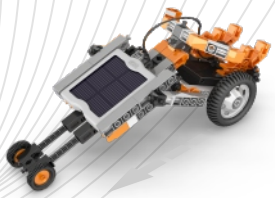
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Engino® EDUCATION

9-12+

Edition: 05/23

Levers & Linkages

What we will learn

I guess you have already been to the playground with your friends and played on the see-saw game! Have you ever wondered how did your light friend manage to lift a heavier kid without a problem? Different types of machines and mechanical systems are all around us today. From a simple clock to a complex rocket, every machine uses energy to perform a certain task. These devices need to be energy efficient and this is made possible with the help of levers and other simple machines. In order to transfer this energy to different parts of a machine and change their motion we can connect many levers together. In this way we create series of levers called "linkages", which are very important in machine design and functionality.



The seesaw works on the principle of levers

This booklet of **Discovering STEM: Levers & Linkages** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about their applications in daily life. Discover all the scientific principles applied through **experimentation**, with step-by-step guides and thought provoking exercises. Follow the **building instructions** to build exciting models such as **a see-saw**, **a movable weight scale, a wheelbarrow**, **a parking gate**, **a toy with moving figures**, **a pantograph, Peaucelier-Lipkin** and **Hart linkages**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.



Pyramids in Egypt

History of levers and linkages

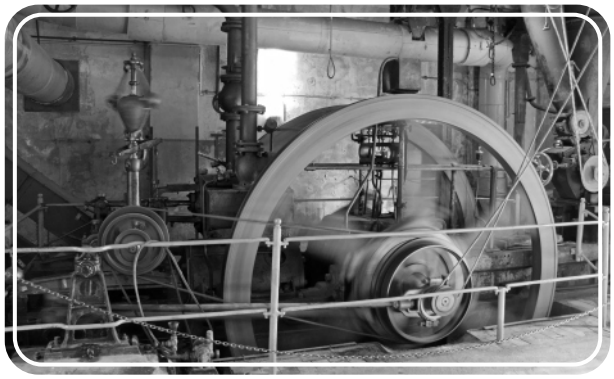
In prehistoric ages, levers were possibly the first tools used by man for moving large objects. During the construction of the Great Pyramid of Giza (about 2500 BC) the builders used "casing stones" (cut blocks of limestone) which weighed 2.5 tons each. In order to move these gigantic blocks, as there weren't any cranes around, ancient tools and methods were used: ramps, slides, boats, ropes and of course levers. The ancient Greek historian Herodotus mentioned that over 100,000 people (slaves) worked on the pyramid's construction for a period of more than 20 years.

Levers are described for the first time in around 260 BC by the ancient Greek mathematician Archimedes. Pappus of Alexandria mentions that Archimedes (287-212 BC) said the following phrase, expressing the mathematical principle that describes the functionality of levers: "Give me a place to stand on and I will move the Earth". The catapult used in ancient times and the trebuchet used in the medieval times also worked on the principle of levers. The latter was a siege engine that utilized gravity to launch projectiles at enemies by placing a large weight on the short end of the trebuchet's lever arm (acting as a counterweight) and then letting it fall.



Models of medieval trebuchets

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A steam engine

Many scientists have been working on the development and practical usage of linkages over the last 200 years. During this period many problems, such as how to create a perfectly straight line with mechanical means were solved. New linkage inventions were essential in cloth making, power conversion and speed regulation. They were also used in many applications such as mechanical computation, typewriting and machining. These applications are the precursor of modern machines and many of them have now been digitalised and replaced by electronic technology.

Did you know?

The Watt's linkage is used in the rear axle of some car suspensions to prevent relative sideways motion between the axle and the body of the car. It consists of two horizontal rods of equal length mounted at each side of the chassis. In between these two rods, a short vertical bar is connected, which moves in an almost straight line. This linkage design is an improvement of the Panhard rod, because it dramatically reduces the sideways component of the axle.



Engino® "Watt's linkage" model

As far as linkages are concerned, even though they are used in almost any machine now, they were not well understood until the 18th century. The Industrial Revolution (between the 18th and the 19th century) proved to be the golden age for the development of linkages. During that time, the Swiss mathematician Leonhard Euler (1707-1783) made the first efforts for understanding linkage synthesis. But it wasn't until James Watt (1736-1819), a Scottish mechanical engineer, started working on the improvement of the Newcomen steam engine, that linkages gained a practical importance. In his double-acting engine he developed a parallel linkage ("Watt's linkage") that was able to cause a steam engine piston to move in an almost straight line.



Mechanical typewriter

Nowadays, we use levers and linkages quite often in combination with other types of simple machines, making our lives much easier. From complex machines like cranes and cars to the most simple of devices like scissors and nail-clippers, almost everything works on the principle of levers and their connections! Furthermore, modern linkage design continues to advance, and ideas that used to take days for an engineer to complete are now calculated by computers within seconds. Nowadays, linkages are used in many machines in a variety of ways, changing the speed, force and motion of different parts, thus increasing machines' efficiency.



Lever crane

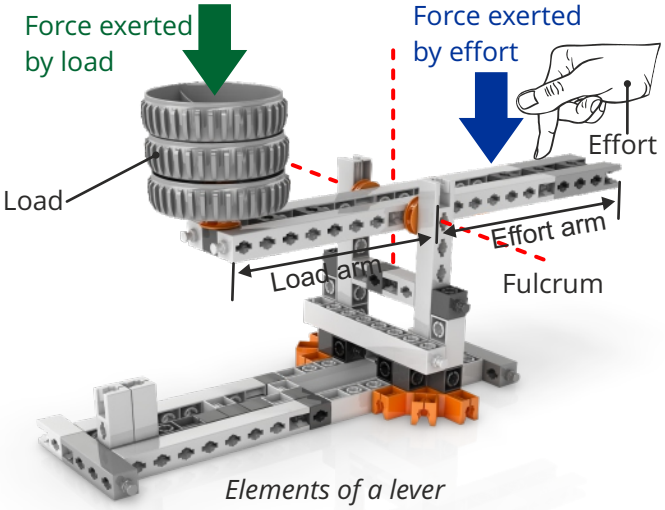
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Definition of lever

A lever is a rigid bar (or rod) pivoted about a fixed axis called fulcrum. Take a look at the next picture. The character is using the lever principle in order to move a heavy object, by placing a wooden board under a small rock. The small rock acts as the **fulcrum** (or pivot), the large object that he is trying to move is the **load**, while the force he applies to move the object is called **effort**. The distance from the fulcrum to the point where the effort is applied is called **effort arm** and the distance from the fulcrum to the load is called **load arm**. You can see all these elements below, as they are applied on an Engino construction.



Archimedes is using a lever to move a boulder!



Elements of a lever

Classes of levers

There are **three classes of levers** and each class depends on the position of the effort (the force we apply), the position of the fulcrum and the position of the load. We are going to learn about each one in the pages that follow.

A linkage is the combination of two or more levers of the same or different class. These are connected together in order to create a mechanism, which can be used for transferring force or motion from one point to another.

Double levers

Two levers can be joined together and make a double lever. Scissors and nutcrackers are examples of such levers. The two lever arms are connected together by a joint, allowing the arms to swivel. In other words, a double lever is considered as a simple form of linkage.



Nutcracker (double)



Pliers (double)

Physical laws

Moment

Now, that we know what a lever looks like, let's see how it works. When we apply a force on a lever away from the fulcrum we get a rotating effect which is called **moment (M).** This rotating effect is the product of the force (F) applied on the lever and the distance (S) between the force and the fulcrum measured in newton metres (Nm).

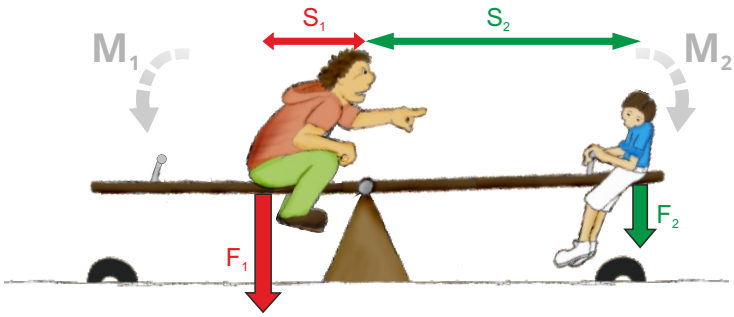
$$M = F \times S$$

Formula for moment (M)

"Moment" is a synonym for "torque", which is a basic concept in Physics and Engineering. Even though both terms express the same rotating effect, engineers use the terms according to the particular application. For example "torque" is usually used to describe a rotational force like a turning screw-driver, while "moment" is often used to describe a bending force on a beam.

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Here is an example of this principle with a boy and a girl playing on a see-saw game. The boy (applying force F_1) is heavier than the little girl (F_2). In order to achieve balance, he sits closer to the center of the see-saw (fulcrum), at a distance S_1, while the girl sits at the edge of see-saw, Both the effort and the load are forces applied on a lever. Therefore, we have two moments: the anticlockwise moment caused by the effort and the clockwise moment caused by the load, at a longer distance S_2.



$$M_1 = M_2 \Longrightarrow F_1 \times S_1 = F_2 \times S_2$$

Balance of moments: the left-side moment is equal to the right-side moment

When the lever is in balance (not moving) the anticlockwise (left-side) moment is equal to the (right-side) clockwise torque ($M_1 = M_2$). Subsequently, the left product $F_1 \times S_1$ is equal to the right product $F_2 \times S_2$. This formula expresses the basic principle of levers and is called **balance of moments**.

Mechanical Advantage (M.A.)

Levers belong in the category of **simple machines**. The ability of a simple machine to output a greater force than the input is called **mechanical advantage** (M.A.). This is calculated by dividing the value of the load to the value of the effort and is measured in pure numbers.

$$M.A. = \frac{\text{Load}}{\text{Effort}}$$

Formula for mechanical advantage

Did you know?

The ancient Egyptians used an innovative version of a lever crane to carry water from rivers to their canals. On one end of a large beam they attached a bucket and on the other they put a counterweight. After the water is lifted, the pole is moved to the other side, so that the water is purred into a channel. It was estimated that one person could lift 2,500 liters of water a day. Without the use of a lever, a person alone wouldn't be able to lift as much water.



Egyptian version of a lever crane

Velocity Ratio (V.R.)

Levers make our lives much easier by changing the way we work. Specifically, levers reduce to a great extent the amount of effort we need to move a load or complete a difficult task. This may create the notion that we gain something out of nothing. Can this be true? Unfortunately not, because as the saying goes "no pain no gain"!

If we observe more closely we will realize that even though a lever may reduce the applied effort, at the same time it increases the distance needed for us to apply the effort. This distance is much bigger than the traveling distance of the load. If we compare the two distances we get the velocity ratio (V.R.). In simple words, the V.R. formula (seen below) states that in order to lift a load 2 times bigger than the effort applied, the effort must cover a distance 2 times bigger than the load.

$$V.R. = \frac{\text{Effort's distance}}{\text{Load's distance}}$$

Formula for velocity ratio

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First-class lever

This is the most common and simple type of lever, in which the support point lies between the two ends. The fulcrum is placed in the middle, while the input effort is on one arm and the output load on the other. You can see all these elements in the next figure. The mechanical advantage of the lever depends on both the distance of the load to the fulcrum and the effort to the fulcrum on the other side (load arm and effort arm). The closer the load is to the fulcrum, or the longer we apply our effort from the fulcrum, the more mechanical advantage is gained.

In the following images you can see some examples of first-class levers. Take a look at the pictures and try to identify where the load, effort and fulcrum are applied in each case.

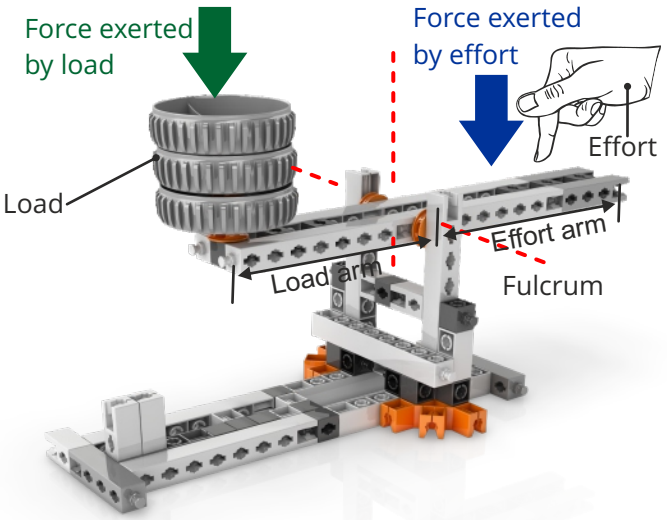


Diagram of first-class lever



Claw hammer



Scissors (double)



Pliers (double)

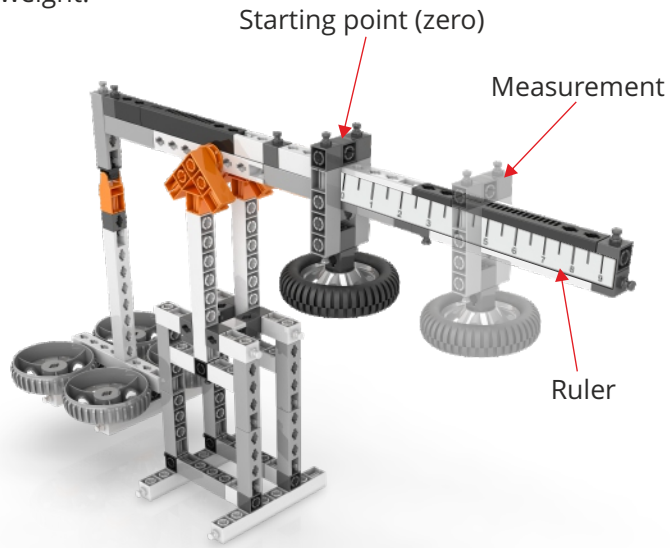
Building Challenge instructions can be found online

Movable weight scale: you can create your own fairly accurate scale with your Engino model! First, balance the beam without any weight. This is the starting point (zero) and it should be about 7 squares from the fulcrum. Then, you will need a small object that you know its exact weight e.g. 100gr. Place it on the loading base and count the squares you need to balance the beam e.g. two more squares after your starting point. Attach a piece of paper on your scale and make a mark at the point of your reference weight.

Then create a ruler by dividing your piece of paper in equal spaces, marking each length according to your previous measurement. In our example, the first square from the starting position would be 100gr, the second 200gr, the third 300gr and so on. You can then divide these in smaller distances for more accuracy.

To use it simply place an unknown weight and balance the scale with the moving part. The indication on the ruler will be the weight of the object.

Build the movable weight scale model and follow the procedure above on how to measure the weight of small objects!



Engino® "movable weight scale" model

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Building Challenge

instructions can be found online

Letter scale: a letter scale is a weight measuring device used for weighing relatively light objects. This type of scale is designed to be very accurate, as it is capable of measuring the slightest change in the weight of an object.

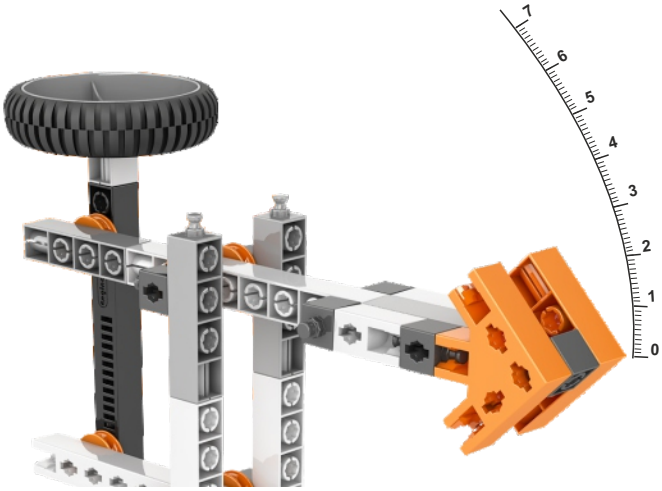
For that reason, the letter scale is used mainly in post offices for measuring the weight of envelopes, small packages or other objects.

Errors in accuracy scales: sometimes mechanical accuracy scales show errors when measuring weights. This is caused mainly by the friction between the different parts, which prevent it from balancing correctly. Errors can also be caused by the following:

- the air of the item is measured as well;
- temperature causes expansion or contraction;
- error in reference weight;
- misallignment over time;
- vibrations and seismic disturbances.



Letter scale



Engino® "letter scale" model

You can create your own Engino letter scale by following the building instructions found online. Use your scale to weigh different light objects, once you create a measuring ruler. Place some light objects on the scale (wheel) and trace the upward movement of the other end with a pencil on a piece of paper. You should end up with an arc shape (part of circle).

Mark the starting position where the scale is balancing without any weight. Place a small item of known weight on your scale and mark the position on the arc. Then create a ruler by dividing the arc in equal distances according to the known weight.

Building Challenge

instructions can be found online

Lever crane: a lever crane is a lifting device that is used mainly in ports for long shoring or in construction sites for moving large and heavy objects. Cranes have a large weight on one side, called counterweight, that helps the crane to balance. Otherwise it would tip over because of the weight difference.

Build the Engino lever crane model and try carrying some loads with it in order to test its strength. As you can observe, the crane can carry various objects using the principle of levers. The fulcrum is placed on two pulleys and the load is wrapped around the rope at the end of the crane. The effort is applied on the other end of the crane (in this case we use our hand). For larger objects, you should add more parts creating a bigger counterweight.



Engino® "lever crane" model

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Second-class lever

In a second-class lever, the fulcrum is placed on one end, the input effort on the other end, while the output load is placed in between. You can see all these elements in the figure on the right. Because the load lies between the fulcrum and the effort, a lower force is needed in order to balance the lever. In this case the principle of the balance of Moments applies, similar to the first-class lever.

Next you can see some examples of second-class levers. Take a look at the pictures and try to find where the load, effort and fulcrum are applied in each case.

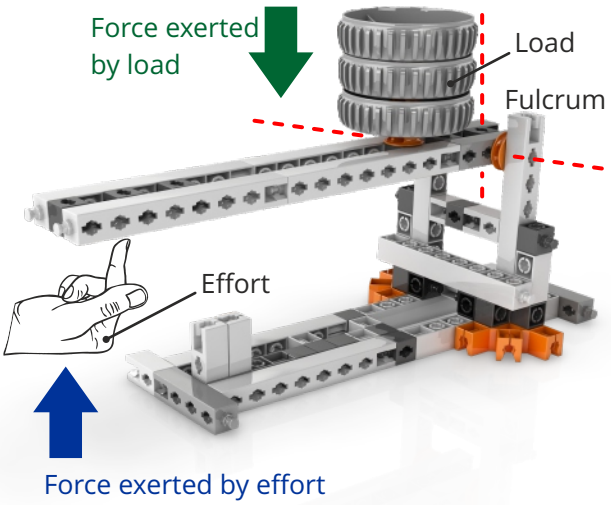


Diagram of second-class lever



Paper guillotine



Nutcracker (double)



Wheelbarrow

Building Challenge

instructions can be found online

Swing: a swing is a sitting construction that hangs from two ropes or chains. When the swing is set into motion it keeps on moving in an oscilating motion until stopped by a person or air friction. A swing can be transformed from a second-class lever to a third-class lever, depending on the position where the effort is applied. If you apply the effort at the lowest part of the swing (using your legs) then the swing will work as a second-class lever. If someone else pushes the swing at the middle then it will work as a third-class lever.

Build the swing model by following the online instructions and use it to change between two classes of levers.



Engino® "swing" model

Did you know?

The Chinese have invented a different version of a wheelbarrow by adding sails! We have records from 550 AD that Gaocang Wushu had invented a "wind-driven carriage" using a mast and a sail, similar to sailing ships, able to carry up to 30 people. From the 16th century onwards, European travelers in China mentioned sailing carriages in their texts, which were basically large wheelbarrows (coaches and wagons) with sails.



Sailing wheelbarrow

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Third-class lever

In a third-class lever, the fulcrum is placed in one end, the output load in the other end, while the input effort is placed in between. You can see all these elements in the figure below. Because the effort is applied between the fulcrum and the load, based on what we have learned on the balance of Moments, a higher effort is needed force to lift the load as compared with the other two types of levers.

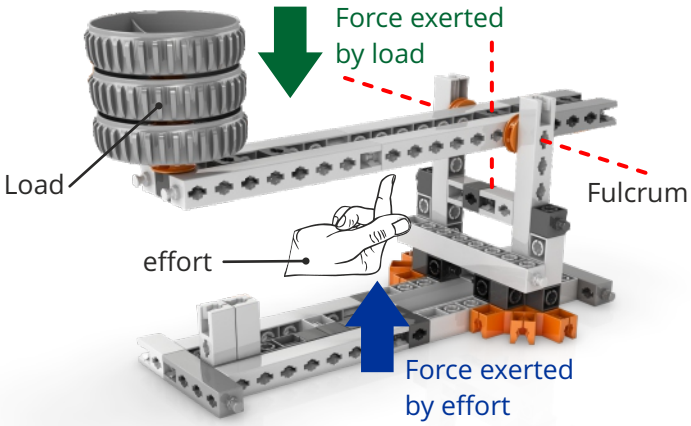


Diagram of third-class lever

Below you can see some examples of third-class levers. Look at the pictures and try to identify where the load, the effort and the fulcrum is applied in each case.



Tweezer (double)



Stapler



Hammer



Golf club

How the human arm works

Our arm works as a third-class lever! When we try to lift an object (for example a ball), that load lies on the palm of our hand. The elbow would be the fulcrum, as it is the point which joints the 2 sections of our arm. The arm swivels up and down from the elbow joint. Finally, the effort is applied from the arm muscle, which lies between the fulcrum and the load, that is our elbow and our palm. Levers can also be found in many other parts of a human body as well as other living creatures.

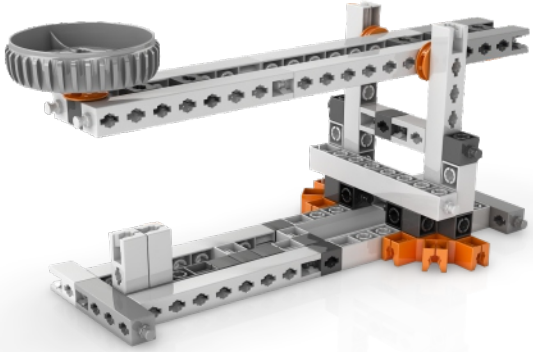


Our arm works as a third-class lever

Building Challenge instructions can be found online

Catapult: the "catapult" is a construction that was invented by the Greeks. Its name comes from the Greek words κατά ("kata") which means "against" and πέλτης ("peltis"), which was a small type of shield. Therefore, the catapult's meaning is "shield piercer". It was perfected by the Romans and used for projecting large arrows, javelins, balls of iron or flammable materials, in distances up to 800 meters.

With the help of the Engino catapult model you can change between all three classes of levers by making some alterations. Once you build it, think about the elements of each class of lever and then make the appropriate changes on the model to create each class.

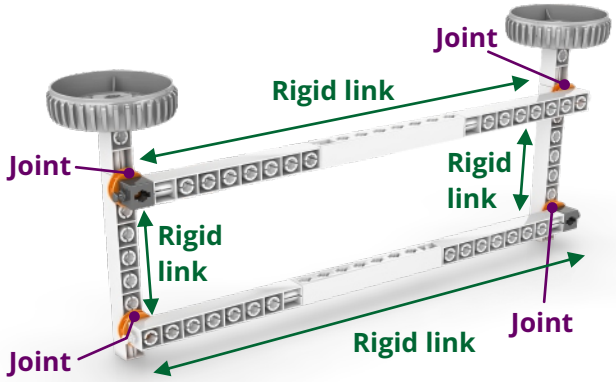


Engino® "catapult" model

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Definition of linkage

In order to create a linkage, two things are needed: **rigid links** (beams or rods) and **joints**. A linkage is a series of rigid links connected with joints to form a closed or open chain. For example, if we take some Engino rods and connect them together with Engino joints (pulley parts) we create an assembly that can behave as a linkage. You can see these elements in the next picture of the Engino scale model. Note that this is a closed chain linkage.



Elements of a linkage



Cargo carriage vehicle

Mechanism

A linkage becomes a **mechanism** when an **input** force is applied at a certain point and produces an **output** force at a different point of the linkage. Output can be a force or a movement. Mechanisms are very important in machines because they allow transfer of motion and force in a controlled way. In short, mechanisms (or movable linkages) are used for:

- changing the direction of a motion;
- changing the size (magnitude) of a force.

Linkages and simple machines

The basic mechanisms used in most mechanical systems are called **simple machines** and there are six types: levers, wheels & axles, pulleys, inclined planes, wedges and screws. As we are going to see next, **linkages can be defined as simple machines connected together**. In order to understand the connection between linkages and simple machines, you can revise levers and how they work.

Disadvantages of linkages

We know that linkages play a very important part in mechanical science and engineering. However, sometimes linkages may not be the appropriate solution for a problem due to the following reasons:

- they need constant maintenance and adjustment (e.g. lubrication);
- the moving parts may cause injuries or other health and safety hazards;
- rigid links and joints wear out with time, so they require replacement;
- better solutions may be available (e.g. electronic computers can be programmed to replace mechanical procedures).

Did you know?

Many courts have a statue of Lady Justice outside their buildings. According to ancient Greek belief, the goddess Themis was the protector of Law and Custom, responsible for keeping the political and social order. She was often represented as a strict woman who was holding two objects: a *sword*, which symbolises the power of Reason and Justice and a *set of scales*, for weighing the facts against or pro a law case. Scales function based on the principles of levers!



Statue of Lady Justice

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Parallel motion linkage

There are several types of linkages that are named after the type of motion they produce. One of them is the **parallel motion linkage** which is based on the *parallelogram* shape. Two lines are parallel if there is no way to intersect, no matter how long they become. In a parallelogram shape, the opposite sites are parallel and stay that way regardless of the movement of the shape. In the example on the right you can see that line AB is parallel to line CD (symbolised AB||CD) and line AC is parallel to line BD (AC||BD). The ENGINO scale model has also such a shape!

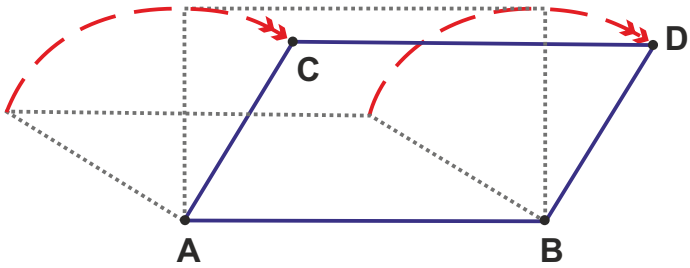


Diagram of parallel motion.

Due to its unique feature, the parallel motion linkage is used in a variety of devices and machines. In a tool box, the linkages make sure that every box is opened in a horizontal position for easy access of the tools. Parallel linkages in an elevator's safety door can save up space by allowing the door to fold. We can also find the parallel linkage in cargo carrier vehicles and in desk laps.



Toolbox



Folding platform



Desk lamp

Building Challenge instructions can be found online

Extendable mechanical arm: an extendable mechanical arm is able to unfold to a maximum or minimum length, for picking up objects, thanks to the parallel linkages.

This Engino model consists of 6 rigid links and 7 joints. You can create a wide grip for holding large objects or a more narrow and pointy grip for lifting small items. You may also extend the arm by using more links and joints.



Engino® "extendable mechanical arm" model.

Building Challenge instructions can be found online

Folding platform: a folding platform is a movable device that is used for lifting personnel or objects of medium weight. Workers are able to reach desired heights with ease.

Build the Engino folding platform model and experiment to see how much load it is able to withstand. Place the model on the floor and unfold it, so that the platform reaches its maximum height. Then put materials until it folds down.



Engino® "folding platform" model

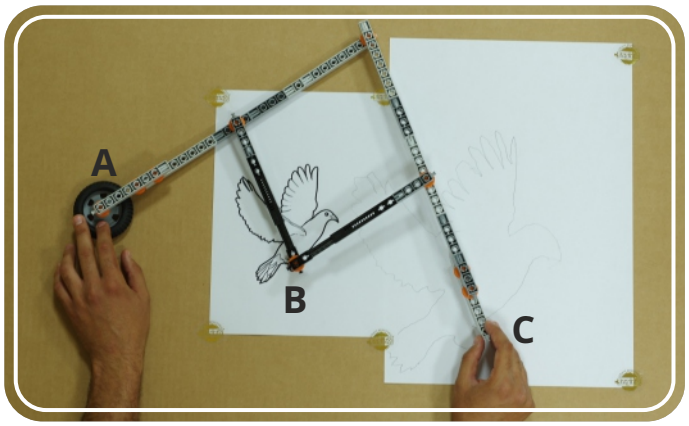
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Pantograph

The pantograph is a mechanism invented in 1630 AD by Christoph Scheiner, based on the principle of **uniform scaling**. It is used mostly by artists and designers for creating a copy of an original image in two ways: either a copy of a larger size than the original image (scale-up) or a copy of a smaller size (scale-down). The pantograph consists of a series of levers that are linked together with joints. Several rods are joined in a special manner, which is based on parallelism.



A beautiful sketch

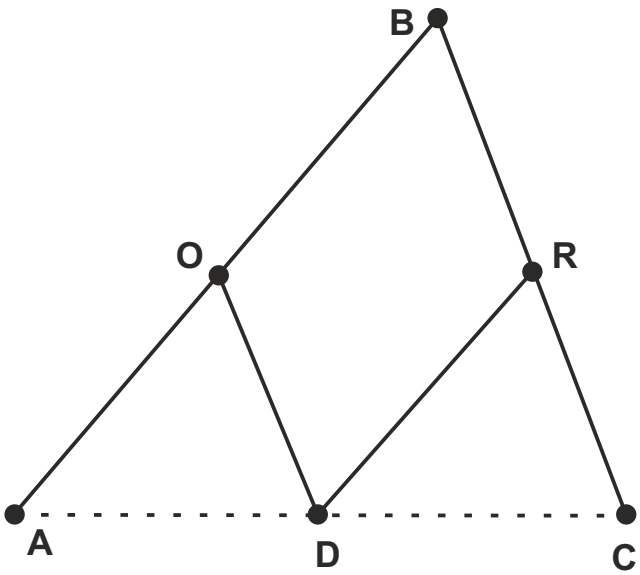


The pantograph in use

A pantograph has three main points, as you can see in the next picture of the Engino model:
- A fixed **point A** which should always be stationary;
- A tracer (small pin) at **point B;**
- A marker or pen at **point C** for drawing copies.

In order to use the pantograph to scale-up an image, you should place your left hand on point A holding it firmly and your right hand on the pencil (point C). While you draw, the tracer on point B should always follow the outline of the original image. If you place the pencil at point B and the tracer at point C you will get a scale-down copy of the original image because the main points will be reversed.

A pantograph works on a mathematical principle called **perspective similarity**. In our pantograph as you can see in the figure below, we have the fixed point **A** and the ratio distance **AB : AO**. This ratio must be equal to the one on the other side of the pantograph **BC : BR**. Since the ratio is always the same and the points move parallel to each other, we can create similar images that are enlarged as many times as the ratio. For example, if the ratio of AB:AO is 3:1 then the copy image will be 3 times larger than the original.



Ratio distances

Did you know?

There was a special type of pantograph used extensively by the third U.S. president Thomas Jefferson called "polygraph". The device had two ink pens and the writer could produce an exact copy of a writing, at the same time while the original was being created, using the principle of parallelism. The president often used the device to produce copies of his numerous writings and letters. In fact, he liked it so much that he called it "the finest invention of the present age".



Thomas Jefferson (1743 - 1826)

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Types of motion

We have already seen that there are different types of linkages named after the type of motion they produce such as the parallel motion linkage. In order to understand how the following linkages work we should first mention a few things about the main types of motion.



Linear motion happens when an object is following a straight line path, e.g. a paper guillotine.

Rotary motion is motion around a fixed point (in a circle), e.g. windmill.



Paper guillotine moving in linear motion

Windmill moving in rotary motion



Oscillating motion is motion backwards and forwards in a circular arc (part of a circle), e.g. swing.

Reciprocating motion is motion forwards and backwards in a straight line, e.g. sewing machine.



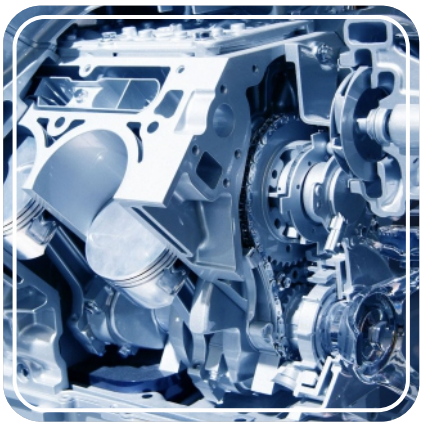
Swing moving in oscillating motion

Sewing machine in reciprocating motion

Other types of linkages

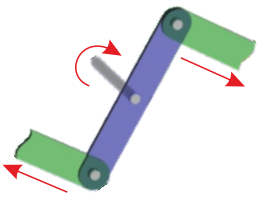
Reverse motion linkage: this type of linkage is used to change the direction of motion. A single lever with a fulcrum at its center reverses the input motion. Examples of reverse motion linkages can be found inside the parts of a car engine.

Bell crank linkage: this type of linkage is also used to change the direction of motion or transfer it around a corner. The mechanism is made out of two links in a bell shape which rotate around the same fulcrum. An example can be found in the brakes of a bike.

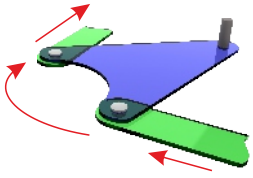


Car's engine parts

Reverse motion



Bell crank linkage





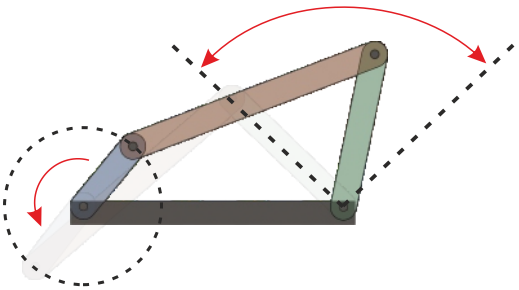
Brakes on a bike

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Sewing machine

Treadle linkage: this type of linkage changes rotary motion into oscillating or the opposite. It can be used to power a rotary machine by working the treadle by foot.

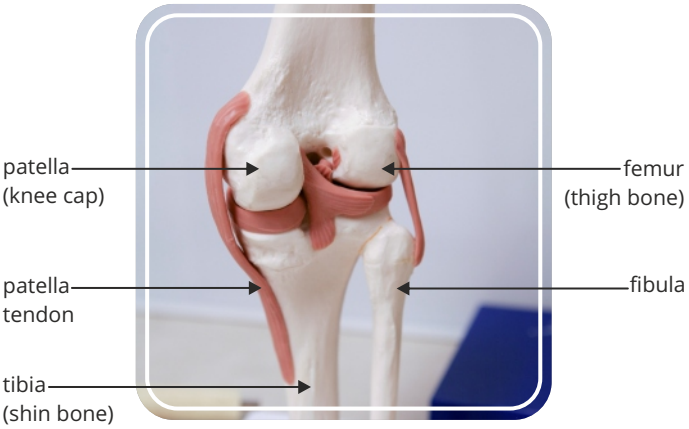


Treadle linkage

Toggle linkage: This is a special type of linkage that is used for securing things in place. It works fast and holds tightly. Toggle clamps and window hooklets are examples of such linkages.



Toggle linkage



Human knee anatomy

Our knee has a special function which works similar to a toggle linkage! The human knee is comprised by four bones, as well as muscles and ligaments that provide support while standing or moving. When you try to stand on one leg, the knee joint is used to lock your foot in position. This is achieved by pushing the knee backwards, like in a locking pliers mechanism, thus locking the rest of the foot from moving forward. Since knees support nearly the entire weight of a human's body, they are vulnerable to injuries. Therefore, you should always take good care of them!

Building Challenge

instructions can be found online

Folding ladder: a folding ladder is a mechanism that is made out of two connected inclined planes with steps. These planes are connected with a certain simple type of linkage, which allow the ladder to fold or open. In this way, we can securely open the ladder and save up storage space when the ladder is not being used.

*Build your own **folding ladder** with Engino parts Play a bit with your model in order to understand how it works. Then, try to change the linkage which connects the two planes together, so that the ladder can open even more. Alternatively, you can try to put a different type of linkage.*



Engino® "folding ladder" model



Folding ladder

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Exact straight line

Peaucellier-Lipkin linkage

After James Watt's discovery of a linkage that produces an almost straighst line in 1784, a race began amongst mathematicians and engineers for discovering a linkage that would produce an exact straight line. The solution was found by two independent scientists: first by Charles-Nicolas Peaucellier in 1864 and then by Yom Tov Lipman Lipkin in 1871. They have created a linkage that was named after both the inventors: **Peaucellier-Lipkin linkage**.

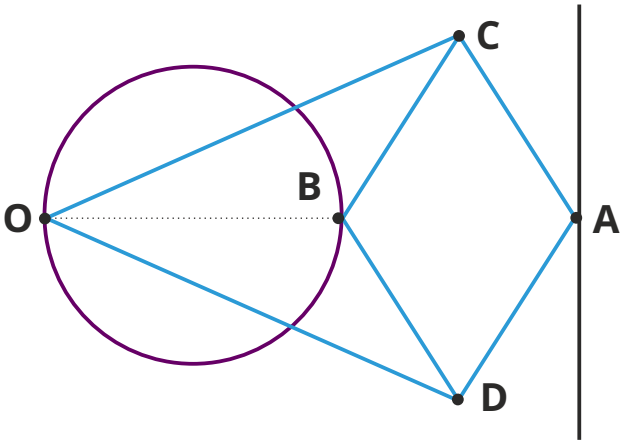
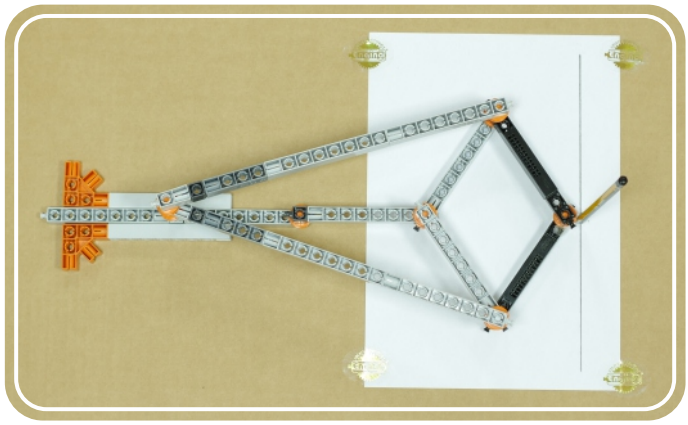


Diagram of the Peaucellier-Lipkin linkage

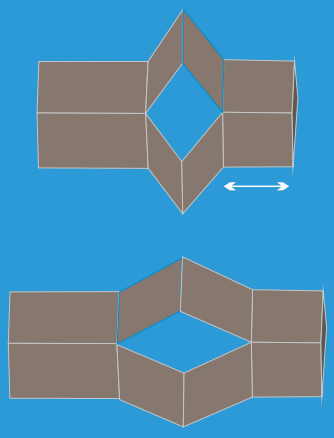


Engino® "Peaucellier-Lipkin linkage" model

The production of an exact straight line is proven mathematically. As a matter of fact, it is so simple in design and theory, that it is remarkable how many years it took until it was invented. If you look at the simplified form of the linkage in the left picture you can see three shapes: **two similar triangles** (COB and DOB) and a **parallelogram** (BCAD). When the line OB is rotated it creates a circle which is basically **inverted** into an exact straight line with the help of the 3 shapes. The inversion of a circle is a mathematical principle where a circle becomes a line, which is considered as a circle with infinitive radius.

Did you know?

There is a three-dimensional linkage that also produces an exact straight line! The **Sarrus linkage**, invented in 1853 by Pierre Frédéric Sarrus, is a mechanical linkage which converts circular motion into linear motion. The linkage uses two perpendicular joined rectangular plates positioned parallel over each other and as they extend or shrink, the whole mechanism is moved in an exact straight line forward or backwards.



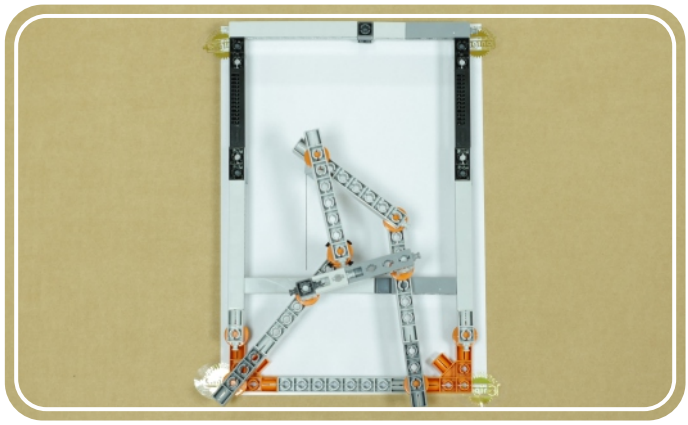
Sarrus Linkage

Building Challenge

instructions can be found online

Hart's A-frame linkage: Hart's A-frame linkage is a mechanism invented by Harry Hart in 1874. It converts rotary motion to a perfect straight line by fixing a point on one short link and driving a point on another link in a circular arc.

Create the Hart's A-frame model with Engino parts and use it to produce an exact straight line. Do not expect the line to be long, as it is limited by the model's parts.



Engino® "Hart's A-frame" model

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Wheels, Axles & Inclined Planes

What we will learn

Wheels can be found everywhere in all kind of sizes and materials! Basically, anything that is circular and capable of rotating is considered to be a *wheel*. What you may not know is that a wheel cannot function without the help of another part: *the axle*. In fact, we wouldn't have cars, bicycles or any other type of vehicle if the wheel and axle weren't joined together! Another simple machine is the *inclined plane*, which can be described as a flat surface tilted at an angle. There is a variety of objects, devices and constructions which work on its principle. Additionally, two more simple machines derive from it: the wedge and the screw. As we will see next, the applications of all these devices have literally changed the world!



Wheels, axles and inclined planes are used everywhere

This booklet of **Discovering STEM: Wheels, Axles & Inclined planes** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about their applications in daily life. Discover all the scientific principles applied through **experimentation** and thought provoking exercises. Follow the **building instructions** to build exciting models such as **a launching platform**, **a door with knob, a well**, **an airport staircase, an experimental ramp** and **a splitting wedge**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.

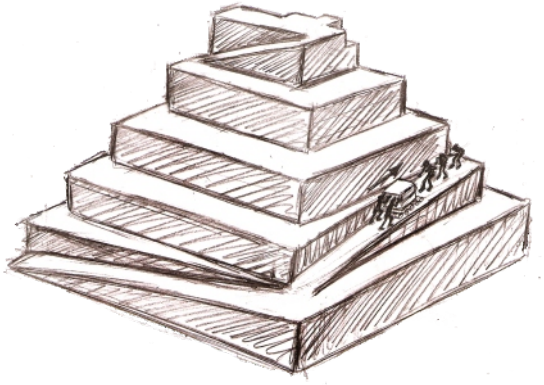


Ancient pot with wheeled carriage

History of wheels, axles and inclined planes

Before the invention of the wheel, people covered long distances either on foot, on floating logs or using slides and canoes. The wheel, however, had potentials that exceeded by far these old techniques. That is why it is considered as one of the most important discoveries of mankind. Historians believe that the ancient Sumerians (southern part of Iraq) were the inventors of the wheel around 4000 BC. The wheel and axle mechanism was first used in pottery, but also in different types of carriages and wagons for transportation.

The inclined plane is one of the simple machines of antiquity and was used extensively by many ancient civilizations. The Egyptians, around 2600 BC, used inclined planes in the form of ramps for raising heavy blocks of rock, in order to build their famous pyramids. It is also believed that the large crosspieces in Stonehenge were elevated in place with the help of inclined planes. The ancient Greek mathematician Archimedes described the inclined plane for the first time around 260 BC. As they take different forms (ramps, slides, ladders etc.) they were used for building early stone constructions like roads and water supplies. The wedge, a transportable inclined plane, was used as a knife or axe for cutting wood, meat or stones.



Pyramids were built using large inclined planes

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Many centuries later Galileo Galilei (1564-1642) used them to explain the properties of forces. His ideas were further developed by Isaac Newton who came up with his famous laws about gravity, mass and acceleration, on which modern understanding of Physics was based.



Evolution of the wheel

The wheel evolved in different forms. The changes aimed in making the wheel lighter and more durable. Wheels with rings were created and the addition of spokes gave extra durability and less weight, as the joints were made out of metal foils. New types of axles and naves reduced friction and vehicles were able to travel longer distances in less time.

In Europe, hundreds of years later, the importance of the wheel was upgraded, because of the industrialisation and the burst of knowledge about mechanisms. In 1816, a German baron by the name *Karl von Drais* came up with the idea of the first bicycle. Some years later, pedals were added on the bike and from then on everything took its course. In 1888, Karl Benz presented his "motorwagen" model in Mannheim, Germany. It was the first practical car with an internal combustion engine running on gasoline. It had three wooden wheels, no gears and could not ascend hills.



Concept of the first bicycle

Did you know?

The oldest real wheel and axle machine ever discovered was the one found in an archaeological site near the city of Ljubljana in Slovenia, Europe. It was made out of ash and oak wood and it is approximately 5150 years old, dated back to 3150 BC. The 72cm in diameter wheel and 124cm long axle were part of a prehistoric two-wheel cart. The mechanism is now exposed in the City Museum of Ljubljana.



The oldest wheel and axle ever found

Since then, the wheel is being used as a tire, which is a material made out of natural rubber filled with air and placed on a metal base (rim). The tire is linked to a suspension (spring) that absorbs the vibrations coming from the road.

Likewise, inclined planes and wedges have also evolved over time and are used daily in a variety of ways. Loading or unloading a truck can be done easily with a portable ramp. Workers use ladders to reach certain heights and slides are capable of lowering objects from high-level to lower-level points with safety. Knives, axes, blades and other similar tools are used for cutting almost everything, from materials (e.g. wood, plastic) to food (e.g. meat, bread, vegetables).



Use of a knife, an example of an inclined plane

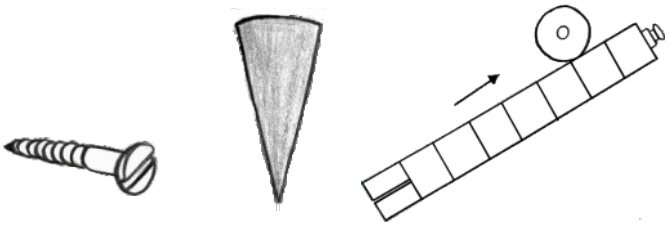
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Definition of wheel and axle

A **wheel** is a circular (round) device that is capable of rotating around itself, or more scientifically is capable of rotating on its axis. The importance of the invention of the wheel, besides its usage on vehicles since ancient times, lies on its ability to be converted to a variety of other forms of similar parts, like pulleys, gears, cams and many more. These parts are vital components in almost every type of machine and mechanism today. An **axle** is a circular shaft (round rod) that fits on a rotating wheel or a gear. It is used for holding the wheel in place and for transferring its force and motion.



Tire fixed on an axle



Screw *Wedge* *Inclined plane*

Wheel and axle as a simple machine

Simple machines are the simplest types of mechanisms that have the ability to multiply the force applied on them. This ability is called **mechanical advantage.** Scientists since antiquity have grouped simple machines in 6 major categories: wheels and axles, levers, pulleys, inclined planes, wedges and screws.

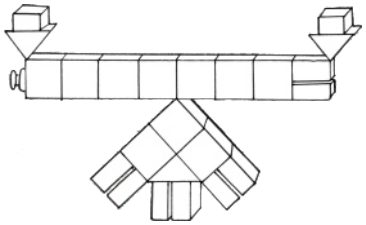
Possibly the most used simple machine is the **wheel and axle** connected together. The wheel does not belong in the "Simple Machines" category on its own, because even though it rotates, we cannot transfer its motion and force in order to gain mechanical advantage. Therefore, a connecting axle is needed for transferring these at any point we want them to go. The wheel and axle, as a mechanism, transfers and multiplies a force, just like a simple machine does. So, next time you are referring to the wheel as a simple machine, remember to add an axle along with it!



Wheel and axle



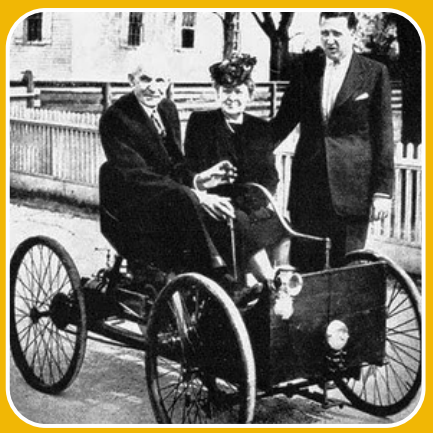
Pulley



Lever

Did you know?

The early automobiles were controlled by a **tiller,** which was a long handle connected directly with the wheels! As you can imagine this steering system had many problems, especially when cars became faster. The version of the **steering wheel** as we know it today was introduced in the late of the 18th century. This controlling system is another mechanism of fixed wheel and axle. The bigger the steering wheel the easier it is to turn the wheels. That is why large vehicles like buses and trucks have bigger steering wheels than regular cars.



Car steered with a tiller

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Types of wheel and axle mechanisms

You might have observed from daily life examples that there are two types of mechanisms of wheel and axle depending on the way that the wheel is rotating with respect to the axle. We shall call these two types as “fixed” and “free rotation”.

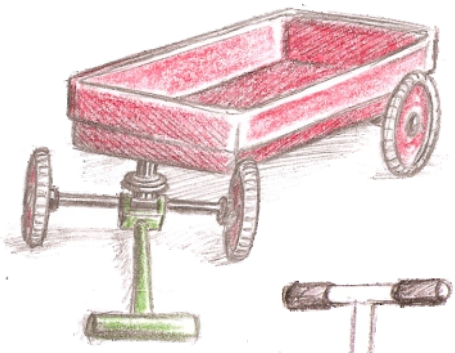
Fixed wheel and axle

This mechanism consists of a large wheel fixed on a wheel of smaller diameter or a rigid axle. When the axle rotates, the wheel is rotating as well. The same applies in reverse. One full rotation of one of the two parts, causes a full rotation of the other part.

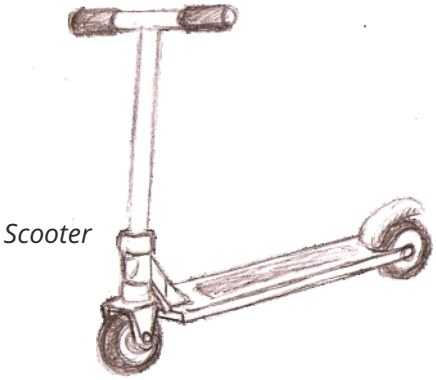
There are many examples of this type of mechanism found in modern cars, motorbikes and almost any form of modern vehicle. Usually, the motion and force is transferred from the engine of the car to the axle and from there to the wheel, which rolls on the road.



Bicycles



Carrying cart



Scooter

Wheel and axle of free rotation

This mechanism consists of a large wheel that is connected with an axle in such a way that the movement of the wheel does not affect the movement of the axle. The axle is firmly fixed on the carriage or vehicle and passes through a hole in the centre of the wheel which rotates freely around the axle. In other words, the wheel is not fixed on the axle moving together as a single entity, but it has the ability to rotate freely while the axle remains fixed and motionless.

This type of mechanism was very common in the past, and is found in wagons, carriages and wheelbarrows. Usually, the motion and force comes from an outside source, like people or horses, which is transferred to the wheel, because of its connectivity with the axle of the vehicle.

Building Challenge instructions can be found online

Car with reverse turning wheels: A steering wheel is used for controlling the direction of the front wheels of a vehicle. If the car moves backwards, the steering wheel works in reverse and the driver should be careful about which side to turn in order to move left or right!

With Engino you can create a model that makes things even more complicated. The strange thing about this model is that the front wheels turn in the opposite direction of the steering wheel, hence its name “car with reverse turning wheels”! It contains two pairs of wheels and axles: front and rear. Both mechanisms are “wheel and axle of free rotation”, as there is no engine to provide power. Build the model of the car with reverse turning wheels and experiment with the different types of wheel and axle mechanisms as well as the direction of motion.



Engino® “car with reverse turning wheels” model.

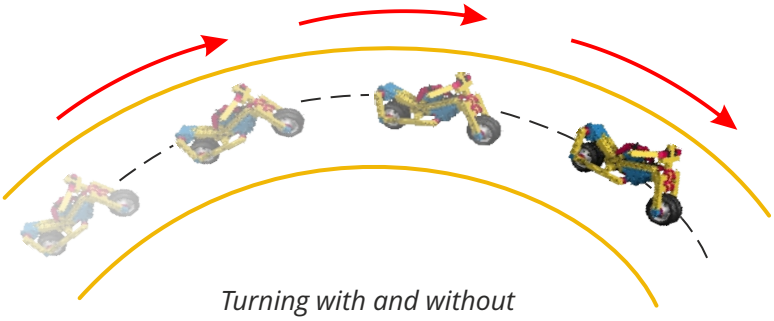
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Motorbike

A motorbike is a two-wheeled vehicle, that has a similar design with the bicycle, and moves on an internal-combustion engine. The first person to build a motorbike was Gottlieb Daimler in 1885, but he only used it for testing engines. The first real type of a motorbike was made by the Werner brothers in 1900 with an internal-combustion engine and a belt for transferring motion (transmission). Some years later, a mixed motion system was built including a belt and a chain. After 1914, the gear box was introduced and in 1923 the chain transmission had prevailed. Nowadays, the belt transmission is back, as well as other designs that make use of axles.



A real motorbike



Turning with and without using the steering handles

This is another use of the "wheel and axle" mechanism. Vehicles are able to turn corners due to the ability of the wheel to follow a circular path without increasing friction.

Building Challenge

instructions can be found online

High speed motorbike: Each motorbike has steering handles. Using the engino model, try to turn around a corner without using the handles at first, just by dragging the motorbike as you can see in the picture above. Feel the amount of effort you apply. Then turn the same corner, by using the steering handles while wheels rotate normally. Can you feel the difference? This is one application of the wheel where friction becomes an ally to aid movement rather than an enemy!

Create your own high speed motorbike and experiment with the steering handles. After you finish, the model would make a wonderful decorating item in your room!



Engino® "high speed motorbike" model.

Did you know?

The motorcycle evolved from a vehicle powered by sheer human energy: the bicycle. French bicycle maker Pierre Michaux and his sons Ernest and Henri first fitted a bicycle with cranks and pedals, precursors to the modern-day motor, in 1861. The Michauxes' velocipede was an instant hit and the family became the largest velo producer in Europe with a large factory at Bar-le-Duc in France. Working with Michaux, L.G. Perreaux devised a steam-powered motorcycle engine, called a velo-a-vapeur, which was patented in 1868.



Vintage motorcycles

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Physical laws

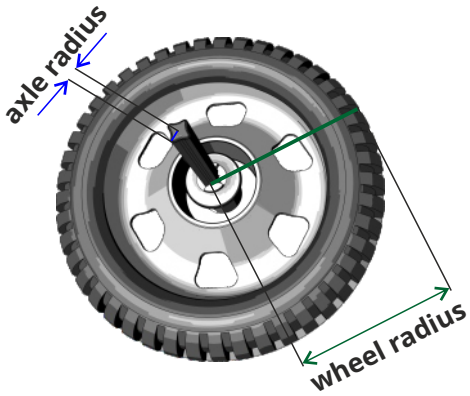
Mechanical Advantage (M.A.)

We have already seen that the "wheel and axle" mechanism belongs in the category of **simple machines**, which are the simplest type of mechanisms that have the ability to multiply the force we put into them. This ability is called **mechanical advantage** and is calculated by dividing the **load** with the **effort.**

$$\text{M.A.} = \frac{\text{Load}}{\text{Effort}}$$

Formula for mechanical advantage (M.A)

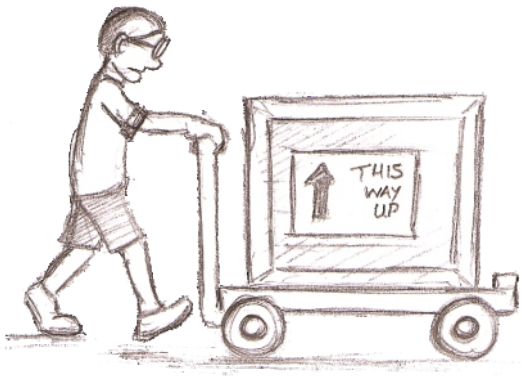
In the case of the "wheel and axle" mechanism, though, we can express this formula in a different way. As both objects are round, we can calculate the mechanical advantage as a ratio of their radii, as displayed in the next formula and picture. In simple words, the mechanical advantage depends on both the radius of the wheel and the radius of the axle.



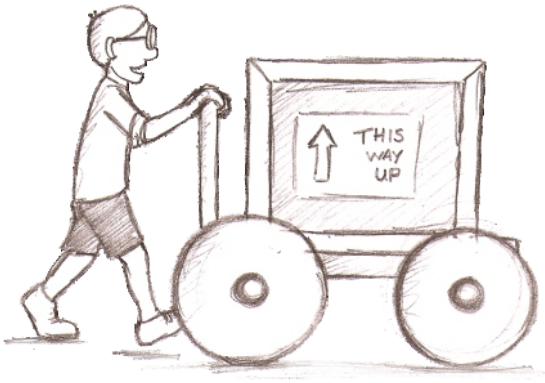
$$\text{M.A.} = \frac{\text{Wheel radius}}{\text{Axle radius}}$$

The M.A. depends on the radii of the wheel and axle

It is obvious that the bigger the wheel is as compared to the axle, the more mechanical advantage is gained. This is also true for situations where an outside source makes an effort for moving a vehicle (e.g. carriage, towed car, carrying cart, wheelbarrow). Thus, according to the ratio between the wheel's and axle's radius, if a bigger wheel is installed, then more mechanical advantage is gained and moving the vehicle becomes a much easier task.



Harder



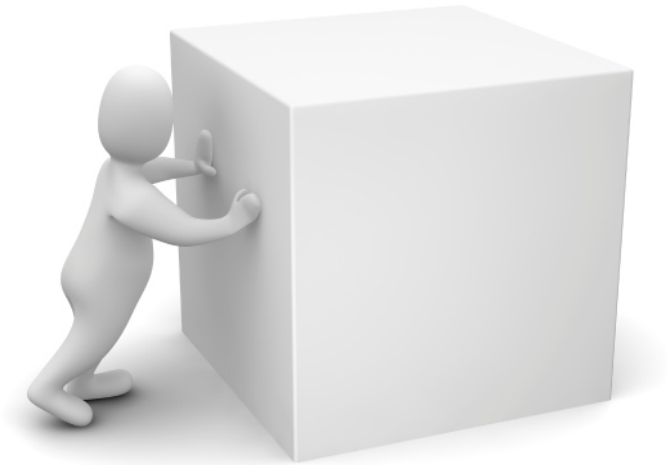
Easier

Bigger wheels offer more mechanical advantage, thus helping us to carry heavier loads

Friction

One of the most important factors that influence the operation and overall efficiency of all machines is **friction**. Friction (f) is the force that resists motion and is created when an object is moving (or someone attempts to move it). There are two types of friction between solid objects, depending on whether the two objects in contact are in motion or not.

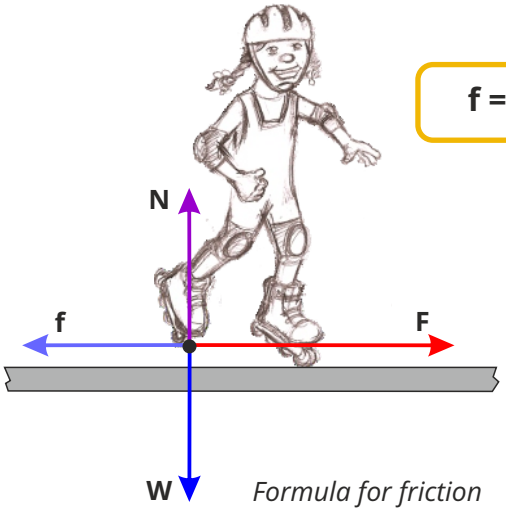
Static friction appears when two objects are in contact, without moving relatively to each other, while an effort is applied in order to move them. For example, when we try to push a box, we have to overcome the static friction between the box and the floor in order for the box to start moving.



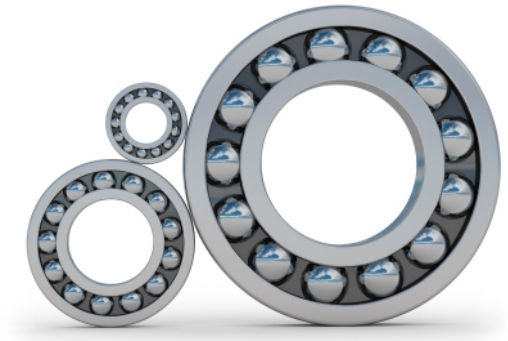
In order to push a box we have to overcome static friction

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Kinetic friction appears when two objects in contact are moving relatively to each other. For example, when you drag a box on the floor you can feel there is another force resisting your effort coming from the ground. This force is called **friction** and depends on the surfaces of the touching materials. Most of the times, friction is wasted energy, converted mostly to heat and sound. Friction also wears out the rubbing surfaces.



Formula for friction



Ball bearings

Coefficient of friction

Different materials and surfaces lead to different frictional forces, even if the same effort is applied. This particular characteristic of connected surfaces is called **coefficient of friction** (symbolised by the Greek letter **μ**). Another factor influencing friction is the weight of the object we are trying to move! It was Isaac Newton in 1687 that said "**for every action there is an equal and opposite reaction**", so when a child for example is roller-skating on the street, her weight pushes the street and the street pushes back on the child! This reaction from the ground is denoted by **N** and friction (**f**) is directly proportional to it.

Ways of reducing friction

Most of the times friction wastes energy and is unwanted. In most machines with moving parts, friction resists and slows down the motion, causing wear and damaging the mechanisms in the long-term. Theoretically, if there was no friction, then we would have been able to move large loads with minimum effort. However, in reality this does not happen, therefore different methods are used for reducing the effects of friction:

- Use of lubricants (grease or animal fat)
- Use of metal axles instead of wooden ones;
- Use of thinner axles (as much as possible);
- Use of ball bearings;
- Use of non-friction materials (bronze rings, nylon).



Lubricants



Wheel marks due to friction

Friction acting as a friend

Many times friction is desirable, acting as a friend. Specifically, when we use the brakes on our bicycle, we manage to reduce the velocity with the help of friction! When we hit the brakes on a car, the wheels stop turning and the car stops due to the force of friction that is created between the road and the wheels. The effects of friction are visible on the wheel marks that are left on the road. Generally, if there was no friction, normal movement of objects could not be achieved (for example driving a car on the road or even walk), as everything would slide!

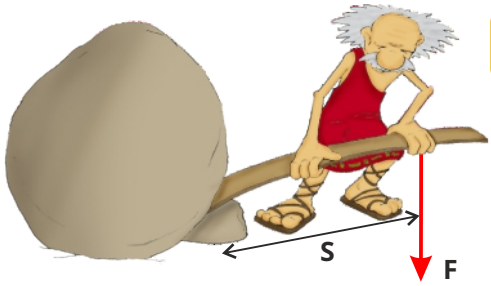
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Wheel and axle as a lever

The wheel and axle mechanism is behaving as a lever capable of rotating 360°. The load and the effort are applied either on the surface of the wheel or on the rotating axle. A lever is a mechanism that pivots around a fixed point, called **fulcrum**, while a force, called **effort**, is applied in order to move a **load** (weight). Levers are divided into three classes depending on the position of the fulcrum, the effort and the load. The distance from the fulcrum to the point where the effort is applied is called **effort arm** and the distance from the fulcrum to the load is called **load arm.** An example of a mechanism that works on the principle of levers is the seesaw game.



The seesaw works on the principle of levers



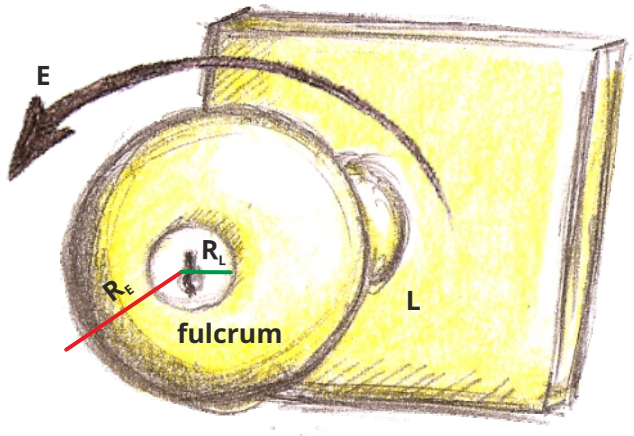
M = F x S

Formula for moment (M)

When a force is applied on a lever, it causes a rotational motion called **Moment** (symbolised with **M**) which is equal to the product of the force (F) times the distance (S) from the fulcrum (M = F x S). When a lever is in balance it means that the clockwise moment is equal to the anti-clockwise moment $M_1 = M_2$, therefore $F_1 \times S_1 = F_2 \times S_2$. This formula expresses the basic principle of levers and is known as **balance of moments**.

Wheel and axle as a first-class lever

The door knob is an example of the wheel and axle functioning as a lever. The load (**L**) is the weight of the whole mechanism (door knob, axle and locking mechanism). The effort (**E**) is applied on the wheel (knob), while the axle plays the part of the fulcrum (**F**). $\mathbf{R_E}$ and $\mathbf{R_L}$ are the radii of the knob and the axle respectively, which represent the effort and load arm. To put it more simply, in the right figure you can see the positions of the force, fulcrum and load, indicating that the door knob functions as a first-class lever (the fulcrum is placed between the effort and the load). If we replace the knob with a handle, we will have the same result.



Forces acting on a door knob mechanism

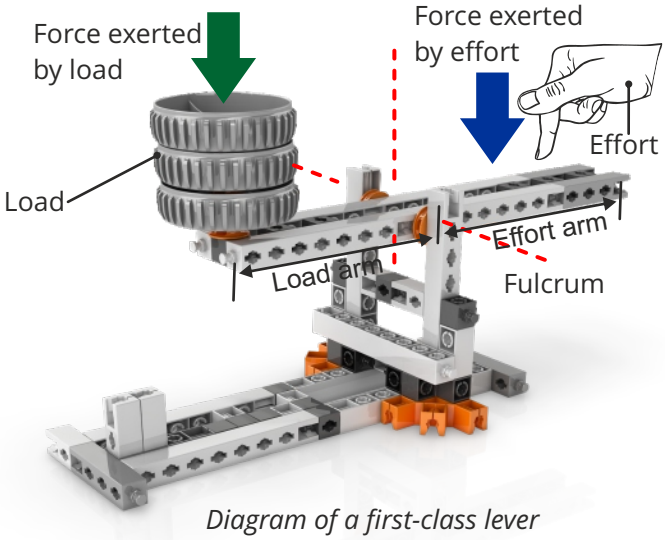


Diagram of a first-class lever

Just before the mechanism is turned, the lever is in balance, meaning that the moment of the effort is equal to the moment of the load:

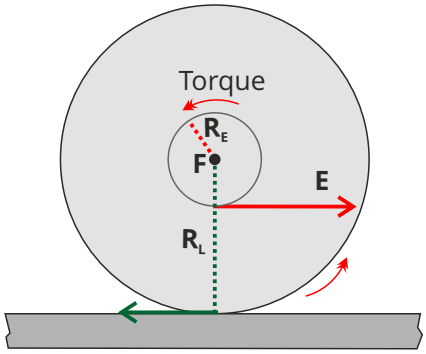
$$M_E = M_L \longrightarrow E \times R_E = L \times R_L$$

If we take a closer look at the formula above, we will notice that because the distance of the effort is longer than the distance of the load, we can overcome the load and turn the mechanism quite easily. In this way, mechanical advantage is gained, meaning that the simple mechanism of the door knob **multiplies** the force we put into it.

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Wheel and axle as a third-class lever

A car's wheel and axle mechanism works also as a lever. In this case, the effort (**E**) is coming from the axle (which is rotated from the car's engine), while the fulcrum (**F**) is the centre (core) of the axle. The load (**L**) is the friction coming from the road, resisting the motion of wheel in the opposite direction. In the next figure you can see the positions of the force (**E**), fulcrum (**F**) and load (**L**), indicating that the wheel of a car functions as a third-class lever (the effort applied between the fulcrum and load).



The wheel and axle as a third class lever

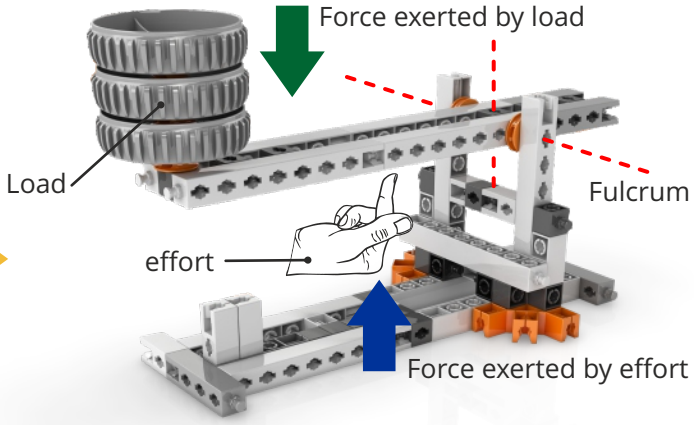


Diagram of a third-class lever

Just before the car is set into motion, the lever is in balance, meaning that the moment of the effort is equal to the moment of the load:

$$M_E = M_L \longrightarrow E \times R_E = L \times R_L$$

If we take a closer look at the formula above, we will notice that the distance of the load (wheel radius, R_L) is longer than the distance of the effort (axle radius, R_E). This means that more effort is needed in order to turn the wheel and move the vehicle. This effort is provided from the engine.

Therefore, we do not have a mechanical advantage as far as the force is concerned. However, whatever is lost in force, is gained in movement. The axle and the wheel make a full rotation simultaneously. As the axle's radius is smaller, it requires less distance in order to rotate. The wheel, on the other hand, has a bigger radius and causes the vehicle to cover a distance equal to its circumference (the line of the circle) in every rotation. In other words, a small rotation of the axle causes a much larger rotation of the wheel.

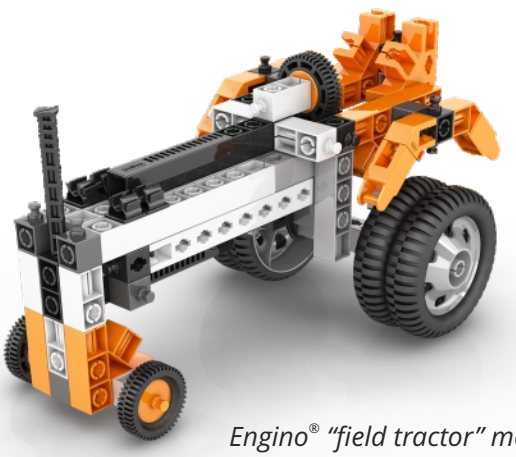


Field tractor

Building Challenge instructions can be found online

Field tractor: Tractors are big tug vehicles which are used mainly for gathering and moving heavy objects. However, tractors are now recognised globally as agricultural machines and offer valuable services in farming, replacing the work of animals. Tractors are so important to mechanical farming that mass food production could not exist without them.

Follow carefully the online instructions in order to make your own **field tractor** model. Observe the pairs of big rear wheels and small front wheels connected with axles. Can you say in which pair we have bigger mechanical advantage? Try different pairs and types of wheels and axles in order to find out the best combination that offers the most mechanical advantage.

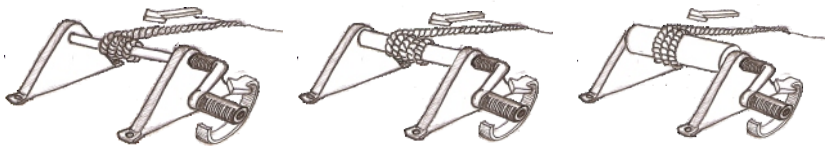


Engino® "field tractor" model

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Axle as a pulley

An axle has the ability to function as a pulley for moving heavy loads. This is done by wrapping a rope around the axle and rotating it. The required effort and speed change depending on the thickness of the axle. Specifically, the thicker the axle, the faster the load is elevated, but the more effort is required. In the pictures below you can see three examples of axles of different thickness (thin, medium and thick) working as pulleys. Note that the wheel has been replaced with a crank that does the same work but in an easier way. In each case the amount of effort and the speed of the pull is different.



Easy on effort
Slow pull

Thin axle

Medium on effort
Quick pull

Medium thickness axle

Hard on effort
Very fast pull

Thick axle



A sailboat winch is a type of axle used as a pulley

This phenomenon can be explained with the help of levers. The radius of the force ($\mathbf{R_E}$) is that of the circle created by the turning crank and is always the same. The longer the radius of the axle, the longer the distance ($\mathbf{R_L}$) of the load from the fulcrum. This creates the need for more effort (**E**) in order for the load (**L**) to move, but this is done faster, because the rope is tied around a larger circumference. But remember, whatever is lost in force is gained in distance and vice versa.

Did you know?

A well is another example of how an axle can be used as a pulley. Since ancient times, wells were used for fetching water. This work was done by sinking a bucket inside the well and bringing it up to the surface using an elevation system. Wells vary in depth and volume, as well as quality of the water. They usually contain more metals (iron, manganese, even arsenic) than the surface water, therefore the pumped water requires a special cleanup.



A well

Screwdriver

A wheel and axle can also be non-circular or round and still be considered as a simple machine! A fine example is the screwdriver, which works on the same principle. The handle with the big radius is the “wheel” and the blade with the smaller radius is the “axle”. As we rotate the handle in order to screw something, we gain mechanical advantage. This can be calculated in the same way from the ratio of the handle’s radius to the blade’s. Generally, anything that rotates and is connected to a smaller rotating part is considered a “wheel and axle” mechanism, even if both parts are not circular.

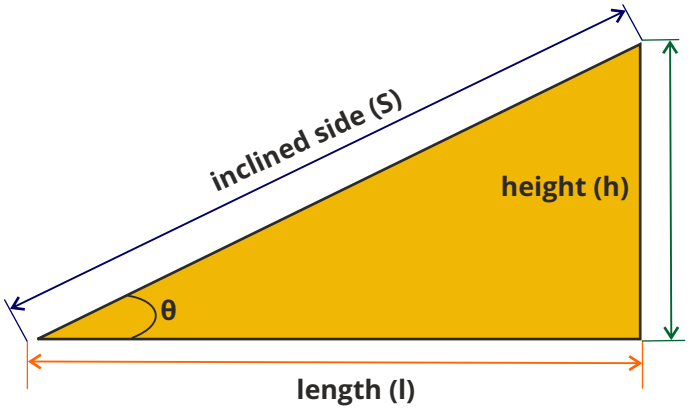


A screwdriver is an example of wheel and axle mechanism

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Definition of inclined plane

The inclined plane, as denoted by its name, in its simplest form is nothing less than a surface - a plane - placed with an inclination (slope or tilt), of an angle less than 90 degrees on a horizontal surface. Basically, if we take a piece of wood and place it at a certain angle then we create an inclined plane, with both ends at different heights.



Elements of an inclined plane



A skater using an inclined plane

One end of the inclined plane starts from the ground (horizontal surface) and the other end is placed at a certain **height**. The actual plane has an **inclined side** and its slope can be found by the **elevation angle (θ)** that is formed between the inclined side and the horizontal surface. The horizontal distance from one side of the plane to the other is the length (l). You can see all these elements in the left picture.

Calculation of slope

The elevation angle or slope of the plane is very important as it shows its steepness, inclination or grade. In order to calculate it, we must first find the ratio of the plane's height (h) to its length (l), thus h/l. Then, the result can be expressed as an angle in degrees or as a percentage by applying different mathematical formulas. For example an angle of 30° is equal to a slope of about 57%.

$$\text{slope} = \frac{\text{height}}{\text{length}} = \frac{h}{l}$$



Indication of slope

Inclined plane as a simple machine

The inclined plane is such a simple invention that some people do not even consider it a machine! However, it belongs in the category of "Simple Machines", which are the simplest type of mechanisms which have the ability to multiply the force we put into them. This ability of simple machines to multiply the input force is called mechanical advantage.

For example, with the help of an inclined plane, the worker in the left picture, manages to transfer a heavy load with relevant ease, in relation to the force needed to lift it directly from the ground to the truck. Of course, the required work remains the same, because whatever is gained in force is lost in distance. This means that the worker needs to carry the load for a longer distance than the distance needed to carry it directly from the ground.



Loading a truck with the help of an inclined plane

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Types of inclined planes

There are many devices that work on the principle of inclined planes. We can distinguish them easily from other simple machines, if we bare in mind that the inclined plane usually does not move (unlike the lever, wheel and axle etc.). Other objects move on an inclined plane, as shown in the following examples:

Ramps

Ramps give access to heights that would be difficult to reach vertically. There are two types of ramps: portable ramps, like the ramps used for loading and unloading heavy objects from a truck, and fixed ramps, for example an inclined pathway for wheelchairs or shopping carts.



Portable ramp on a truck

Chutes

Chutes are inclined planes through which objects move down due to gravity. We can find natural chutes, like channels and river canyons where the water moves downwards through a passage. There are also man-made chutes, usually in buildings, for moving several objects like mail and laundry with safety, from higher floors to lower floors.



River coming down through a chute

Did you know?

The tower of Pisa in Italy is a famous building, which although it was designed to be perfectly vertical, it started to lean during construction since1173. The inclination was caused by the softness of the ground and the building's bad foundations. By 1990, the inclination reached an angle of 5.5 degrees and the building was in danger of falling down entirely. Nowadays, after restoration works, the inclination became safe (3.99 degrees) and the tower is open for public.



Leaning tower of Pisa in Italy



Slides

Slides work in a similar way as chutes: objects or people move by means of gravity. Examples can be found in playgrounds or waterparks.

Water slide

Uphill roads

Uphill roads have a winding (snake-like) shape because they need to have a mild slope so that the car can actually drive up a steep mountain.



Uphill road

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Forces

We cannot see forces, but we can understand their effects when they are applied. When we pull a rubber band we can see that it stretches. A can is squeezed by the force applied from our hand. Generally, in order to change the shape of an object, temporarily or permanently, a force must be applied on it.

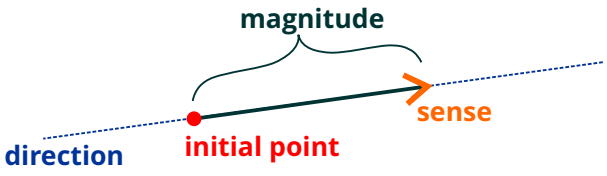
Forces also cause objects to change their motion. In order to make an object move we must apply a force. The same applies if we want to reduce the speed of the object or change its direction of movement.



We can observe the results of a force

Elements of a force

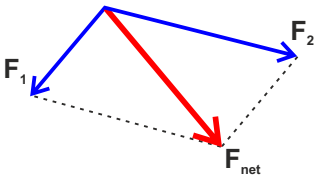
In the diagram below you can see the main elements of a force, as it is represented by an arrow named in scientific terms as "vector".



Elements of a force

Adding forces

In the diagram below you can see how we manage to add two (F_1, F_2) or more forces, called **component** forces, and come up with their **resultant** force F_{net}, by using the parallelogram method.



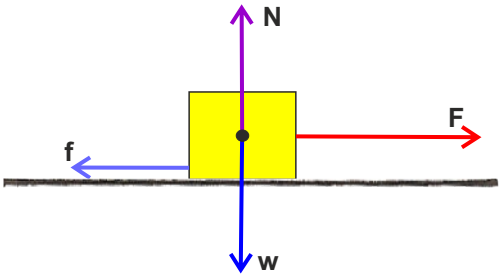
Parallelogram method

Calculation of forces

The calculation of forces in a system is done with the help of simplified diagrams, which usually include a simple design of the object where the applied forces are indicated, represented by vectors (arrows). For practical reasons, the diagram shows only the forces that are necessary for studying a certain phenomenon.

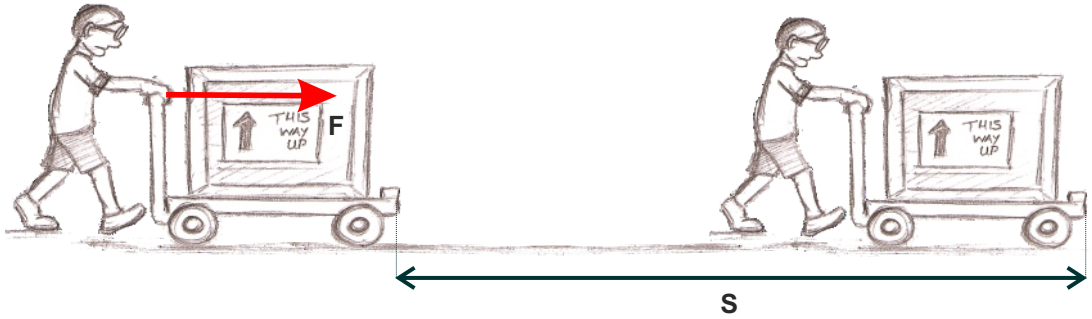
A simple example of calculating forces can be seen next. Here we can see the forces that are applied on an object which lays on the ground, and is moving on the right due to a force (F).

N: normal force applied by the ground to the object (reaction to the weight).
w: the weight of the object
F: the applied force
f : friction between the ground and object



Forces acting on an object moving on the ground.

W = F x S



Work (W)

Work is the energy used for moving an object and depends on the force applied on the object and the distance which the object is moved. Work (W) equals force (F) times the distance of the movement (S).

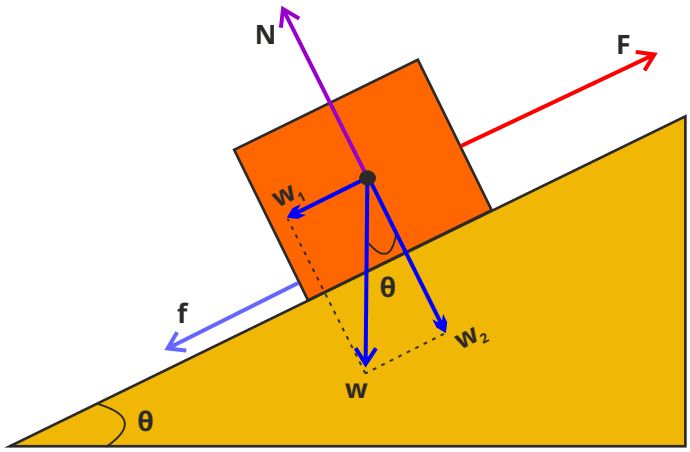
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Calculating forces on an inclined plane

When we have movement on an inclined plane it is necessary to calculate forces in the direction of the motion. The calculation method is the same as the one used in vector addition (parallelogram method). The forces can be calculated either graphically (if the diagrams are drawn by scale) or by doing mathematical calculations using the value of the slope of the inclined plane. For the mathematical minds the analysis that follows may be interesting!

In the example, the force that needs to be calculated is the component of weight ($\mathbf{w_1}$). When the object nearly starts moving, it means that the applied force F is equal to the sum of the component force of the weight $\mathbf{w_1}$ and friction f.

w: the weight of the object.
$\mathbf{w_1}$: the component of the weight resisting the motion.
$\mathbf{w_2}$: the component of the weight perpendicular to the direction of motion.
N: normal force (resistance) applied by the ground equal to w_2.
f: friction between the ground and object equal to the coefficient of friction μ times the normal force N ($f=\mu.N$).
F: the applied force.
θ: angle of elevation of the inclined plane.



Forces acting on an object moving on an inclined plane

Did you know?

Galileo Galilei (1564-1642) supposedly used the inclined tower of Pisa to prove Aristotle (384-322 BC) wrong! One of Aristotle's "laws of nature" disputed that heavier objects fall faster than lighter objects. Galileo believed the opposite. According to legend, he took objects of various weights and sizes to the top of the Piza tower and dropped them at the same time. He noticed they all landed at the base of the building simultaneously, proving that free fall objects fall at the same speed regardless of their weight. This is actually true within a vacuum environment (without air resistance).



Portrait of Galileo Galilei (1564 - 1642)

Frictionless plane

A frictionless plane is simply a plane without friction, as denoted by its name. The ingenious Italian scientist Galileo Galilei (1564-1642) was the first person who used this term in order to describe the movement of an object on an inclined plane. Of course, this type of plane does not exist in reality, because friction is always produced between objects. However, the notion of the frictionless plane is quite useful when we want to calculate with simple maths the forces acting on an object which moves on an inclined plane.

$$F = w_1$$

If we exclude friction in the example above, then **just before the object is going to be moved**, the force F is equal to the force w_1.

In turn, force w_1, as a component of weight, depends on the weight and the ratio of the height to the inclined side, like shown in the next formula.

$$w_1 = w \times \frac{h}{S}$$

$$F = w \times \frac{h}{S}$$

If we combine the two relationships we come up with the leftt formula that applies only for frictionless planes.

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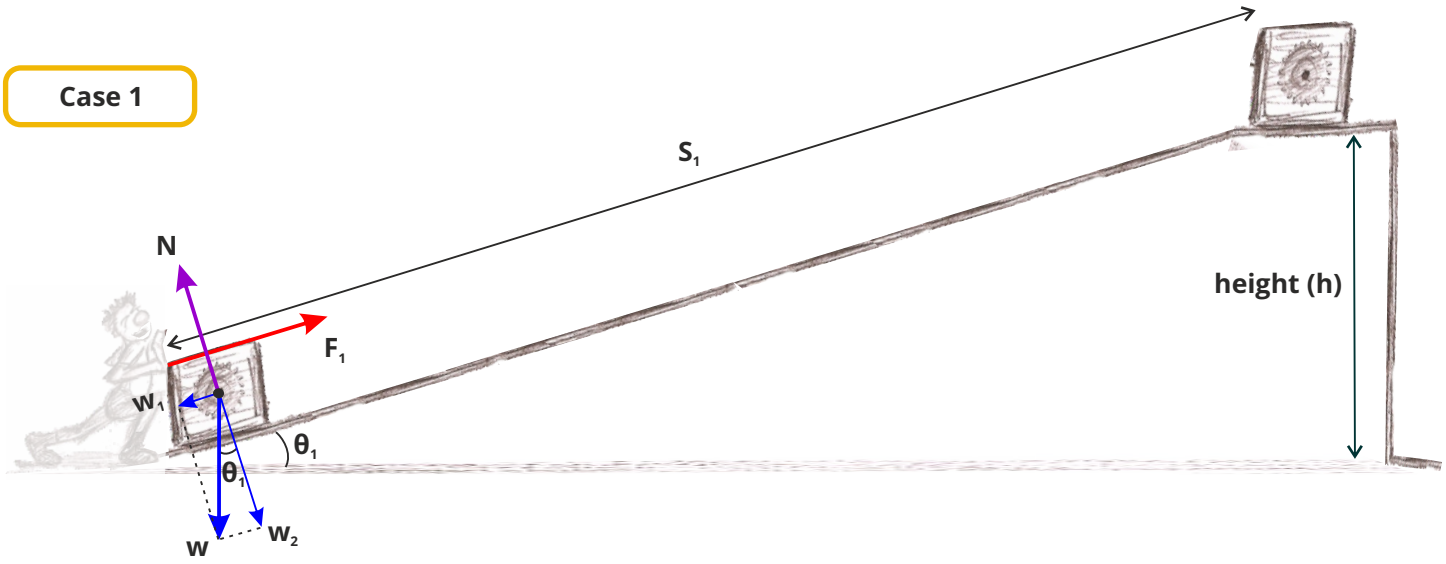
Study of different cases

Next, we are going to examine how the force and the covered distance change according to the slope of the inclined plane. In the following three cases, a worker tries to move a box up to a certain height using a frictionless inclined plane. The weight of the box and the height in all cases stay the same. In case 1, the worker uses a plane with mild slope. In case 2 the plane is steeper and in case 3 there is no ramp and the weight is lifted vertically. The forces applied on the box can be seen in each case: normal force **N**, the force applied from the worker **F** and the weight of the box **w**. In addition the force of the weight is calculated with the parallelogram method into the two component forces ($\mathbf{w}_1$ and $\mathbf{w}_2$).

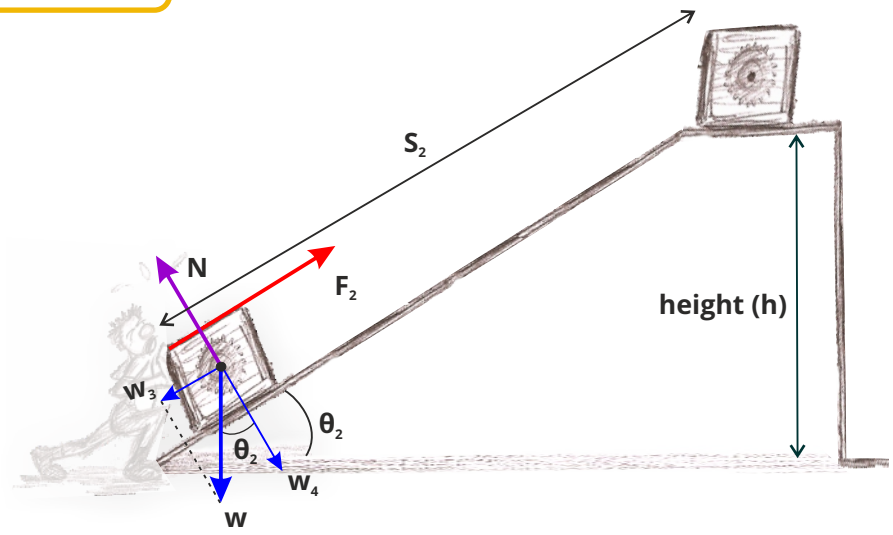


A man running uphill

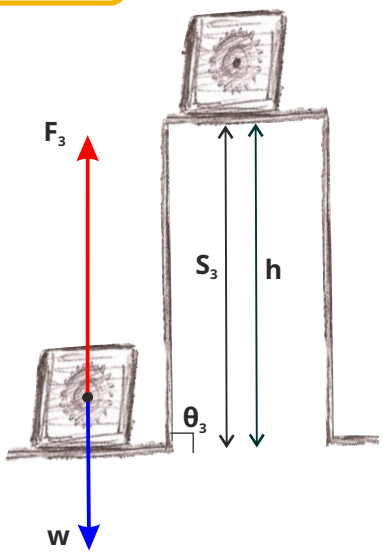
Case 1



Case 2



Case 3



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If we examine the figures in the previous page, it becomes obvious that the carrying distance in case 1 (S_1) is longer that in case 2 (S_2), while the distance S_3 is the shortest. So, we get the next conclusion:

$$S_1 > S_2 > S_3$$

The steeper the inclined plane the shorter the carrying distance

$$F = w \times \frac{h}{S}$$

Formula for calculating the force needed to move an object on a frictionless plane

In order for the object to move, the applied force **F** should at least be equal to the component force of the weight $\mathbf{w_1}$ or $\mathbf{w_2}$. As we have learned in the previous page, this component force is equal to the weight of the box multiplied by the ratio of the height (h) to the covering distance (S). So, force **F** can be calculated with the next formula:

For each case, we have the following calculations:

Case 1: $F_1 = w \times \frac{h}{S_1}$ **Case 2:** $F_1 = w \times \frac{h}{S_2}$

Case 3: $F_3 = w \times \frac{h}{S_3} = w$ (because h = S3)

If we combine these formulas with the conclusion above about the distances, we conclude that in order to move the load in case 1 less force is needed than in case 2, while in case 3 the force needed is the biggest. So, the conclusion below can be extracted:

$$F_1 < F_2 < F_3$$

The steeper the inclined plane the more force is required

Did you know?

Roman soldiers constructed an inclined plane out of soil to conquer the ancient palace in Masada, an area in the south of Israel, during the First Jewish-Roman War. According to the Roman-Jewish historian Josephus, in 72 AD the Roman governor of Ludaea Lucius Flavius Silva marched against Masada and laid siege to its fortress. After several failed attempts, he decided to built a wall around the fortress and then constructed a ramp at one of its sides, using tons of stones and soil. This 114m high assault ramp was completed in 73 AD, allowing the Romans to finally breach the wall of the fortress from above!



Roman ramp made out of soil

Work (W)

It is pointed out that the work (W) remains the same in all three cases, as the total height which the load is elevated is the same. Besides, work is equal to the product of the force (F) times the carrying distance (S), and as the force gets bigger the distance becomes shorter, therefore the product, thus the work, stays the same.

Building Challenge

instructions can be found online

Tow truck: A tow truck is a car with a crane and it is a type of vehicle used for carrying or lifting heavy loads or even other cars. The crane works on the principle of pulleys.

Build the Engino "tow truck" model in order to have a better understanding of inclination and how it helps to lift objects easier. Try to experiment with several small objects and different angles.

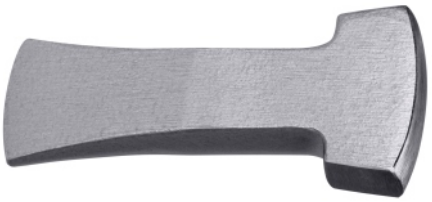


Engino® tow truck model

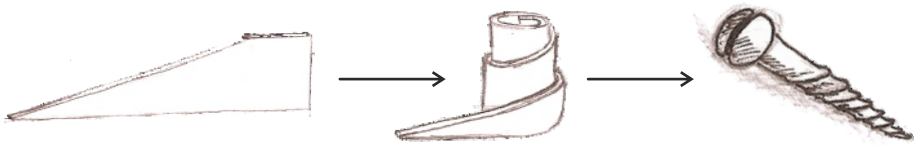
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Definition of wedge

Traditionally, there are six simple machines. The inclined plane is the "creator" of two of them: the wedge and the screw. The wedge is a triangular tool that can be considered as two inclined planes connected back to back. It is in fact a small transportable inclined plane, which functions as a force multiplier in its own way. For that reason, the wedge is another "Simple Machine".



A wedge

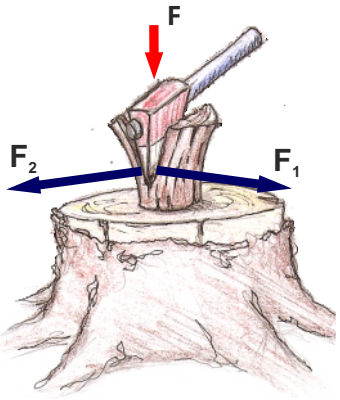


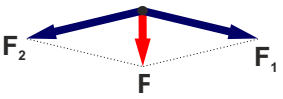
A screw is basically an inclined plane wrapped around a cylinder

The thread of a **screw** is also based on the principle of the inclined plane. When an inclined plane is wrapped around a cylinder, it produces a helix shape, which is the same with the shape of the screw.

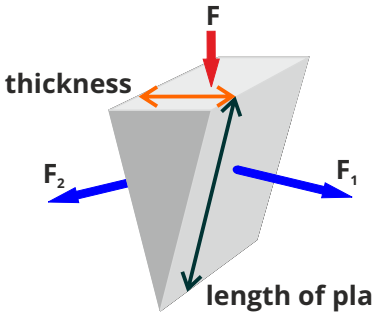
Mechanical Advantage (M.A.)

Even though the wedge has inclined surfaces, it works a bit differently than the inclined plane. In the next figure, we have an example of an axe cutting a piece of wood, by taking advantage of the attributes of the wedge. When the woodcutter hits the piece of wood applying a force (**F**), then the sharp edge of the axe changes the upright force into two almost horizontal component forces ($\mathbf{F_1}$ and $\mathbf{F_2}$ on the right and on the left), which separate the object.





Using the parallelogram method to find the component forces



Calculation of forces acting on a wedge

The force **F** can be expressed by two compronents forces $\mathbf{F_1}$ and $\mathbf{F_2}$ with the help of the parallelogram method. It is obvious that a small force provides two components of big magnitude, because of the inclination of the wedge. That's exactly what gives us the mechanical advantage (M.A.) of the wedge, which all simple machines offer.
Specifically, the M.A. is the ratio of the length of the surface (plane) of the wedge to the wedge's thickness, as denoted by the next formula.

From this formula, the following conclusion can be extracted: **the smaller the angle then the steeper the wedge and the bigger the mechanical advantage it offers.**

$$\text{M.A.} = \frac{\text{length of plane}}{\text{thickness}}$$

Mechanical advantage of a wedge

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Types of wedges

The wedge can be found in a variety of forms. It is actually a very common tool, used quite often for utilising two main tasks: **dividing objects** and **holding objects** or engine parts. Some characteristic examples which function based on the principle of the wedge are shown below:

Blades

Blades are tools (knives, scissors, axes, saws etc.) that have a cutting edge, which allows us to cut, slice, or stub objects. Their sharpness depends on how small the contact area of the blade is and the material to be cut. That's why many blades have "teeth", which make the contact area even smaller.



A sword

Chocks

Chocks are examples of holding objects in place, like doors, cars or airplanes. In the case of a door stop, the force holding the door is that of friction, which is created between the low part of the door and the chock. Again, the same rule applies: the smaller the inclination of the wedge, the more weight can be held.



A door stop

Did you know?

The famous "Gate of Lions" in Mycenae (ancient Greek city) was built in 1250 BC, as the main entrance of the acropolis. What is fascinating about this gate is the large wedge-shape sculpture on the top representing two lions standing opposite to each other. Large stones in the form of a wedge are used in constructions for holding the weight of the roof above doors or large openings. These stones actually work in a reverse way, shifting the weight above the door to the sidewalls.



The Lion's Gate in Mycenae, Greece

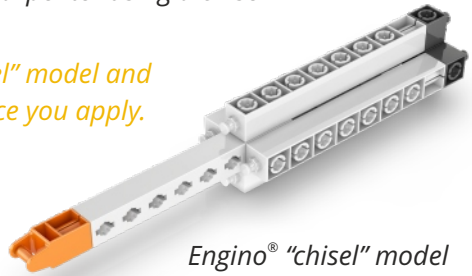
Building Challenge instructions can be found online

Chisel: The chisel is a tool with a cutting edge used for engraving or cutting hard materials like wood, stone or metal. In order for the chisel to work we just need to apply a force directly on the material, either with bare hands or with the help of a hammer.



A carpenter using a chisel

Build the Engino "chisel" model and feel the amount of force you apply.



Engino® "chisel" model

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Pulley Drives

What we will learn

Different types of machines and mechanical systems are all around us today. From a simple clothesline to complex cranes, every machine uses energy to complete a specific task. But, how is this energy transferred to different parts of a machine and how can we control movement? These tasks are made possible by mechanical parts that can transfer motion and change direction, so as to produce work: pulleys! And that's not all! Pulleys have the ability to multiply the applied force by a great amount, gaining huge mechanical advantage. That is why many series of pulley drives are used in a variety of machines that are responsible for lifting enormous weights (usually measured in tons!) such as construction cranes.



A series of wooden pullleys

This booklet of **Discovering STEM: Pulley drives** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about the applications of pulleys in daily life. Discover all the scientific principles applied through **experimentation**, with step-by-step guides and thought provoking exercises. Follow the **building instructions** to build exciting models such as **a material lift**, **a stationary bike, a crane bridge, a blender, a construction crane** and **a windmill**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.



A primitive use of pulleys

History of pulley drives

The need for lifting heavy objects forced people to create the first pulleys. Tree trunks or branches were the ancient pulleys over which a rope was passed in order for a heavy object to be lifted. This primitive type of pulley was probably used before wheels were invented. After the invention of the wheel by the ancient Sumerians (around 4000 BC) and independently by the Chinese (around 2800 BC), the conditions were ideal for the discovery of another simple machine: the pulley. The ingenious addition of a rope around the wheel and axle mechanism led to the creation of some amazing machines that are in use even today !

Archeologists have found objects similar to pulleys, with vines and ropes, used since 1500 BC in Mesopotamia (an area near today's Iraq) for lifting water buckets. However, the Greek scientist Archimedes (287-212 BC) is credited with the discovery of the pulley! According to the historian Plutarch, Archimedes stated to King Hieron that he was able to lift any weight! The king challenged him to move a large ship and pull it on the shore. Archimedes developed a complex system of fixed and movable pulleys, enabling him to pull the rope only with his own strength and move the ship! The king, astonished by Archimedes' achievement, gave him a huge reward and he became famous for his feat.



Archimedes using his invention to pull a ship

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A primitive elevator

During the 12th century AD the building of churches called cathedrals became popular. These buildings were very large, some reaching around 150 metres high. In order for the cathedral builders to lift the huge blocks of stone to build the walls and spires, pulley systems were extensively used. Pulleys were also used for raising the sails of sailing ships as they provided the ability to raise and fold the sails with ease. Such ships were traveling around the world to transfer goods and people. It was with these ships that Columbus discovered America in 1492 while traveling from Spain to be India.

Did you know?

Elevators are more than 2000 years old! When the need for lifting people or goods emerged, the idea of a mechanical lift was born from the Romans and the Egyptians. This idea was refined to the impressive elevators of today. In 1853, American inventor Elisha Otis demonstrated a freight elevator equipped with a safety device to prevent falling. The electrical elevator was built by the German inventor Werner von Siemens in 1880 and in 1883, the first lift was installed in New York City.



A modern elevator

Another application of pulleys was in the mechanism of early elevators. A Roman architect named Vitrius wrote about a primitive type of elevator that included a cab attached to a hemp rope powered by humans or animals. Such type of lifts were also found in the Sinai Monastery in Egypt, where the monks used them in order to reach the monastery built high up on the steep mountain. Elevation platforms with pulleys were also used at the Colosseum in Rome, so that gladiators and wild animals could be lifted to the level of the arena. Scientists today believe that many ancients civilisations from around the world have used pulleys, for a variety of reasons.



Pulleys are used for raising sails

Since then, pulleys have come a long way and have been optimized. Nowadays, pulley systems can be found in a variety of applications helping us achieve important tasks. Construction work sites, factories, cranes, home devices, flag poles, sail boats are just a few examples of the use of the pulley. Practically, every time a rope, chain or belt is used on something, most probably a pulley is the mechanism driving it.

Building Challenge

instructions can be found online

Blender machine: a blender machine is used in the kitchen to mix different ingredients together (eggs, flour, sugar etc). The alternative hand driven blender may seem more exciting, but it requires more time and effort from the cook.

Build the blender machine and observe the increase in speed and the change in direction with the help of pulley drives.



Engino® "blender machine" model

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Definition of pulley drive

A pulley drive is a wheel with a grooved rim, rotating about its center. It is one of the six simple machines among the *lever*, *wheel and axle*, *inclined plane*, *wedge* and *screw*. A rope or a cable runs through the wheel's groove in order to transfer the force from one position to another. By pulling the rope we can lift a heavy object easily, without stressing our back. This means that pulleys can actually use the rope to transfer force from one position to another, that is from our hand to the load.



A pulley hanged from a tree branch



A fishing reel with a crank

When we pull the rope, which passes from a pulley's groove, the force we apply is transferred up to the pulley and down to the load, so that the weight is lifted upwards while we pull downwards. This is best shown in the picture above where a bucket with flowers is raised with the help of a pulley.

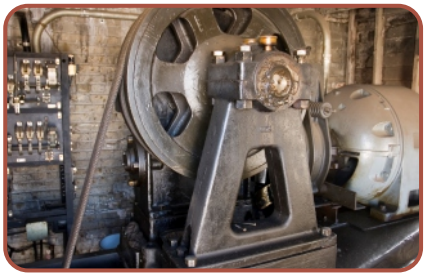
Many times instead of pulling the rope we wrap it around a shaft or an axle which can be turned by a crank more easily, similar to the fishing reel. In the following images you can see some more examples of pulley applications.



Clothesline



Boat winch



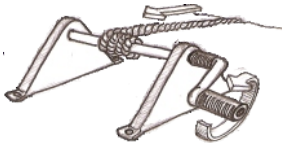
Large pulley used in an elevator

Axle as a pulley

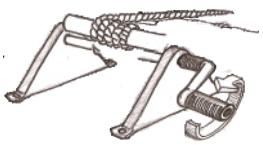
Pulleys can be used in many different ways for a variety of applications. One particular application of pulleys has been in use since ancient times and we can see it in wells and many other machines. To get water out of a deep well, people would lower a bucket and then bring it up to the surface by turning the handle (crank).The required effort and the lifting speed depend on the diameter of the axle. Specifically, the thicker the axle, the **faster the load is lifted,** but **the more effort is required.** In the pictures below you can see three examples of axles of different diameters (thin, medium and thick) working as pulleys.



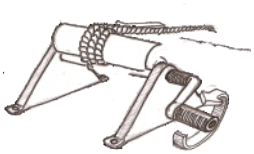
A water well



Easy on effort - Slow pull
Thin axle



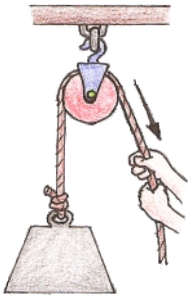
Medium on effort - Quick pull
Medium thickness axle



Hard on effort - Very fast pull
Thick axle

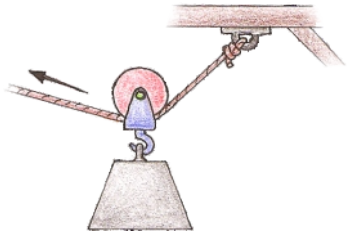
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Types of pulley drives



A fixed pulley

A **fixed pulley** is rotated around a rigid axle which is located at a fixed point. However, fixed pulleys **are not directly attached to the load**. This type of pulley enables us to pull the string downwards in order to lift the load upwards, without any mechanical advantage.

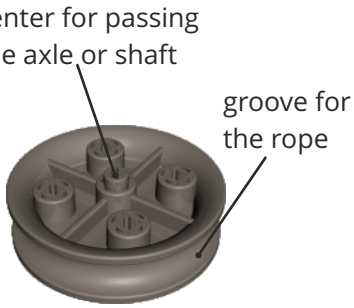


A movable pulley

A **moveable pulley** is **directly connected to the load** and moves simultaneously with it. In order to lift the load, the string should be pulled upwards. This type of pulley offers a mechanical advantage.

Engino pulleys

Among the Engino parts, there are 4 types of Engino pulleys: **1 small pulley** and **3 grey pulleys** (small, medium, large).



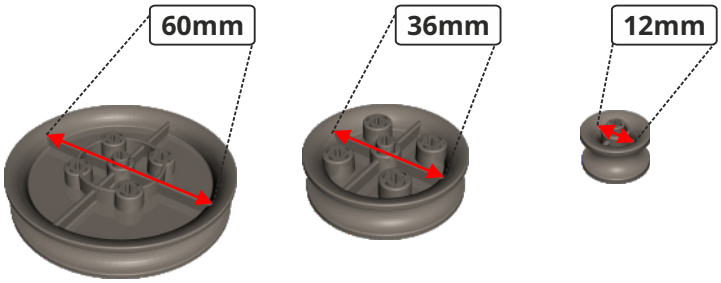
An engino® pulley

The **Engino pulley** (shown at right) incorporates the standard male geometry of Engino plug and can snap-fit on almost all Engino parts. This component has a different "plug" geometry in each side; a cylindrical one, which allows free rotation of the part when connected to others, and an octagonal one for rigid assembly. The advantage of this pulley is that it can be assembled directly on the Engino rods without an extra axle.



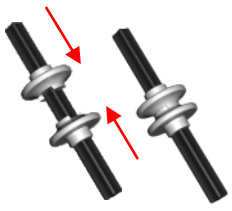
The Engino® orange pulley

The standard Engino pulleys come in 3 different sizes. The common characteristic of them is that they all need an axle to pass through their center in order to be used. If you measure their diameters with the help of a ruler you will find the following numbers. Note that the measurement must be made from the inside surface of the groove where the string touches the pulley and not from the outer rim.



The Engino® grey pulleys which need an axle

Finally, the Engino components offer the opportunity to create **a fifth type** of pulley by connecting two of the light grey spacers back to back as you can see in the picture at right. This type of Engino pulley is the smallest of the Engino set.



The smallest type of Engino® pulleys

Did you know?

Since ancient times, people used bows and arrows to hunt or fight with during war. One interesting adaptation of a bow is the **crossbow** which looks more like a handheld rifle, as in the picture below. Modern day crossbows, and even professional bows have evolved a lot, using better materials. Usually the mechanism involves a compound pulley system which enables archers to easily stretch a bow.



A modern compound crossbow

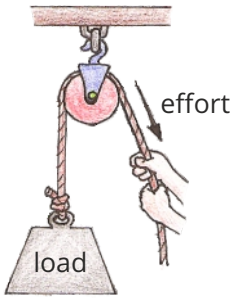
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Mechanical advantage

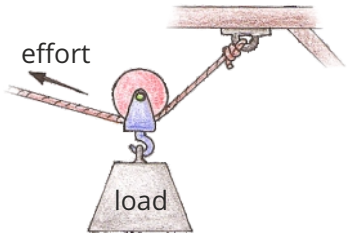
Pulleys like all simple machines, have the ability to multiply the applied force. This is defined as the ratio of the actual **load** we lift and the **effort** we apply. If we can lift more weight than the effort we apply then we have a mechanical advantage.

$$M.A.= \frac{\text{Load}}{\text{Effort}}$$

Formula for mechanical advantage (M.A.)



A fixed pulley



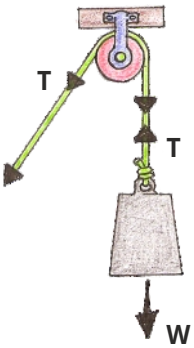
A movable pulley

In the case of the fixed pulley there is no mechanical advantage and the force needed to lift the load is equal to the load. In this case the mechanical advantage is **equal to 1**. The only benefit is the change in the direction of the applied force.

In the case of the movable pulley the mechanical advantage is evident as we need **half the force** to lift the same load. However force is not gained without losing in distance, as we need to pull **twice** the amount of rope!

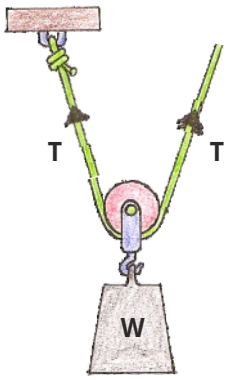
Forces

To understand how pulleys work, it is important to know some information about forces. Forces are depicted as arrows with direction and magnitude. When a rope or string is used, we can safely assume that the same force is applied at any position of the rope as it is always in tension. A system can move only if one force is greater than the others, so when the weight is in balance it means that all forces are equal.



$$T = W$$

In a single fixed pulley system the tension of the rope is equal to the weight



$$T = W/2$$

In a single movable pulley system the tension of the rope equals to half the weight

With a fixed pulley, the tension (T) of the string is constant and equal to the weight (W). With a moveable pulley, the constant tension is the same on both sides of the pulley, so the weight is balanced by twice the tension. The force applied is equal to the tension which means we can apply half the force to lift the weight. This may look as if we gain force out of nothing, however the rope should be pulled twice the distance as compared to the fixed pulley.

Building Challenge

instructions can be found online

Construction crane: a construction crane is a lifting device which is used for the elevation and transfer of large and heavy objects from one place to another.

Build the construction crane model and experiment with different pulley set-ups.



Engino® "construction crane" model



A construction crane

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Compound pulley systems

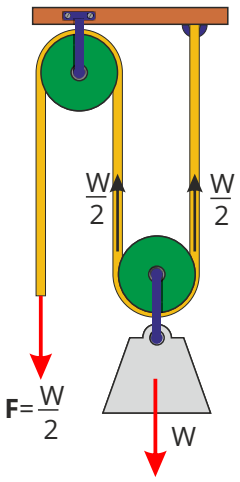
One of the most useful inventions in the field of pulleys came from ancient Greece where the mathematician, engineer and astronomer Archimedes (287-212 BC) invented the **compound pulley system**. Specifically, the compound pulley system comprises of both types of pulleys that were mentioned before: fixed and movable.

There are many different combinations in order to create an effective compound pulley system, as shown in the diagrams below.



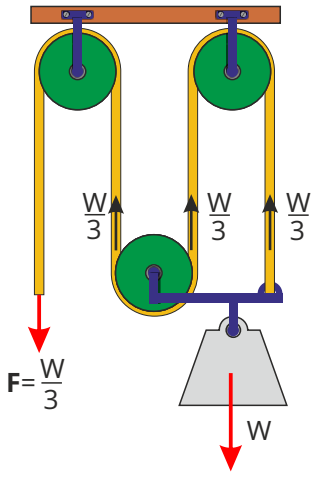
Archimedes depicted in an Italian postage stamp

In case 1, we have only two pulleys, one fixed and one movable. The rope is tied next to or on the fixed pulley. In this case, the force (F) we apply is equal to half of the weight (W).



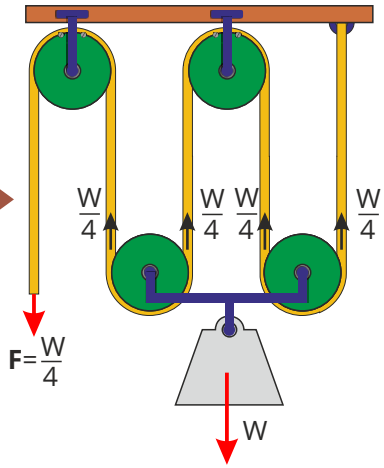
Case 1: two-pulley system

In case 2, we have three pulleys, two fixed and one movable. The rope is tied on the movable pulley. In this case, the force (F) we apply is equal to one third of the weight.



Case 2: three-pulley system

In case 3, we have two fixed pulleys and two movable. The rope is tied next to or on the fixed pulleys. In this case, the force (F) we apply is equal to one quarter of the weight.

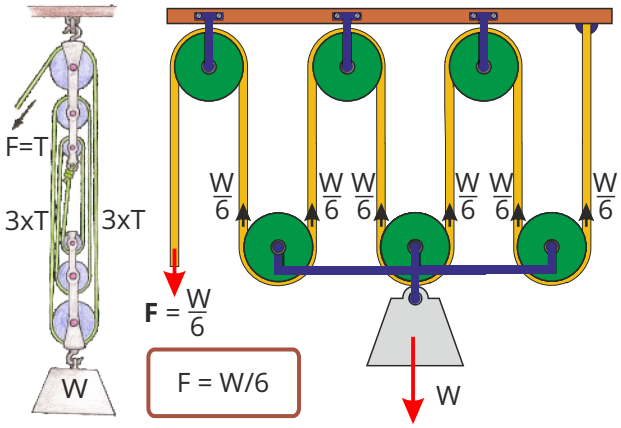


Case 3: four-pulley system

As a general rule, when a compound pulley system is used, we can calculate the force needed to lift the weight by dividing the weight by the total number of pulleys used, both movable and fixed.

$$F = \frac{W}{\text{number of pulleys}}$$

General formula for calculating the force applied in a pulley system



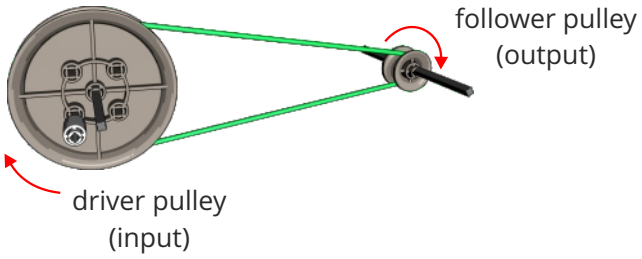
Case 4: six-pulley system

In case 4, we have 3 movable and 3 fixed pulleys, thus decreasing force by 6 times. This set-up is shown both vertically and horizontally. As the **compound pulley system** consists of two or more pulleys, we are able to lift a weight by applying less force, gaining significant **mechanical advantage.** This depends on the number of pulleys used. As mentioned before, the less effort we apply on the rope, the more distance the rope has to travel. In reality, the more pulleys we use the more we increase friction and energy is wasted, so there are limits to how many pulleys we can use and still maintain an effective system.

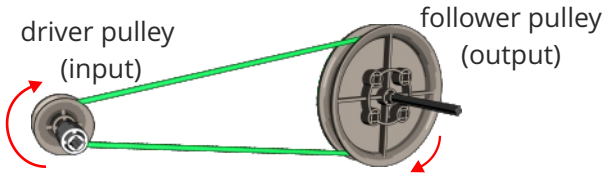
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Changes in speed

In order to increase speed, the **driver** pulley should be bigger than the **follower** pulley. Consider a point on the driver pulley's rim. In one revolution the point will travel distance equal to the circumference of the pulley. The belt is always tight so it will move for a distance equal to the driver's pulleys circumference. The follower pulley will have to rotate enough turns to cover this distance, which means if it has a smaller diameter it will have to turn more **revolutions per minute** (rpm) to do it.



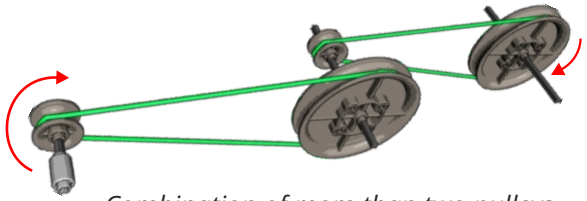
If the driver pulley is bigger than the follower, the speed is increased



If the driver pulley is smaller than the follower, the speed is decreased

In order to reduce the speed of the follower pulley, the driver pulley should have a smaller diameter than the follower pulley. The driver pulley is the **input** of the system because it is the pulley where the power is applied by either a motor or another source. The **output** of the system is the speed and torque of the follower pulley.

If we want to decrease the rotational speed even more we can use a third axle and more pulleys, similar to a gear box system. The intermediate axle is driven by the follower pulley, but also includes a smaller pulley which becomes the driver for the pulley of the third axle. The reverse set up will result in a significant increase of the speed.



Combination of more than two pulleys of different diameters for greater speed change

$$\text{V.R.} = \frac{\text{Rotational speed of the driver pulley}}{\text{Rotational speed of the follower pulley}}$$

$$\text{V.R.} = \frac{\text{Diameter of the follower pulley}}{\text{Diameter of the driver pulley}}$$

Formulas for calculating the velocity ratio of a pulley drive system

Velocity ratio (V.R.)

The velocity ratio expresses the relationship between the input speed of the pulley system and the output. It is defined as the ratio of the rotational speed of the driver pulley to the one of the follower pulley. A useful way to calculate the velocity ratio is by using the diameters of the driver and follower pulleys. This is done by dividing the diameter of the follower pulley (output) by the diameter of the driver pulley (input).

Building Challenge instructions can be found online

Windmill: If you visit the Netherlands you will be impressed by the beauty and serenity of the Dutch valleys and their windmills.

Build the windmill model and observe the changes in speed, by making different pulley combinations.



Engino® "windmill" model



A windmill

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Torque

Torque is the tendency of a force to rotate objects. When a **tangential force** (meaning perpendicular to the radius) is applied on a pulley it creates **torque**, which is equal to the force times the distance from the center. In order to rotate an object, we have to apply enough torque to overcome the load. If we apply the force closer to the center, then the radius of the circular motion is smaller and hence a large force is required. If we apply the force further from the center, the radius is bigger and the force required to create the same torque is less.

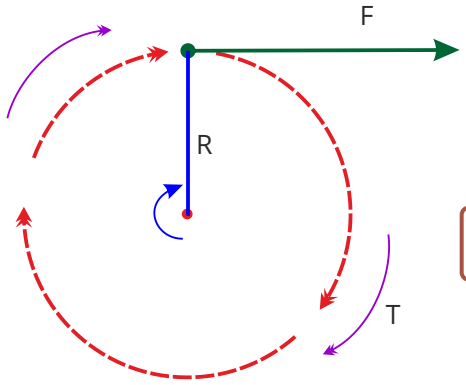
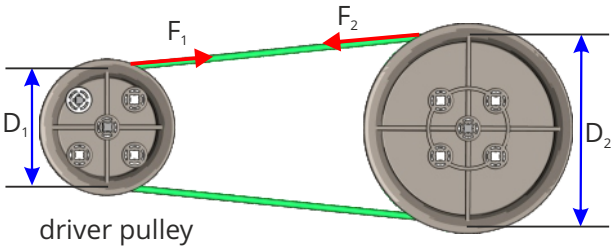


Diagram of forces and formula for calculating Torque



$T_{output} = VR \times T_{input}$

Diagram of forces on a pulley system and formula for calculating the output Torque

In the next figure at right the torque T_1 of the small driver pulley creates a force on the belt (F_1). This force is transferred to the follower pulley (F_2) and creates a torque (T_2). Since the belt is kept stretched, the force on the belt is always the same, therefore F_1=F_2 and the torque of the follower pulley is much higher. The torque (T_2) of the follower pulley is also called output torque (T_{output}) and the torque of the driver pulley input torque (T_{input}). Based on the previous analysis, we can calculate the output torque with the next formula.

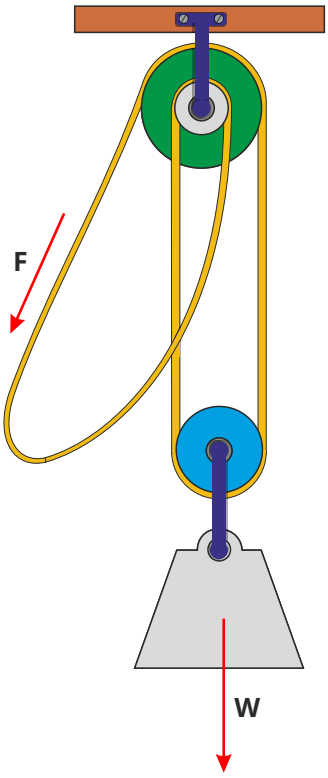
Did you know?

A windmill is a machine that uses sails to convert the energy of wind to rotational motion. The first Greek windmill was designed by Heron of Alexandria in the 1st AD century. In earlier times, windmills were used for grinding wheat and grains and pumping water. A windmill could grind 20-70 kg of grain per hour, depending on the intensity and direction of wind. Nowadays, the power of wind is used to drive the rotating blades of a wind turbine to generate electricity.



A modern wind turbine

The **differential type** is an adaptation of a pulley system. This type is also called "chain hoist" or "chain fall" and it is able to lift very heavy objects for a short distance. An endless rope passes through the fixed pulleys that are of unequal size. These pulleys are connected on the same axle, so that they rotate together. There is also a movable pulley on the load. A product of mechanical advantage is gained, firstly from the compound set-up and secondly from the radius difference of the two fixed pulleys. The two M.A.s are not added but multiplied together, meaning that there is a significant benefit, especially if the fixed pulleys have a big difference in diameter.



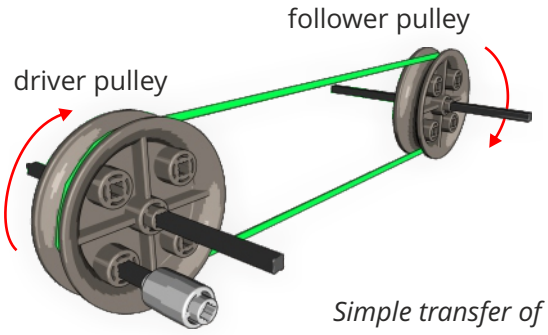
A differential pulley

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Uses of pulley drives

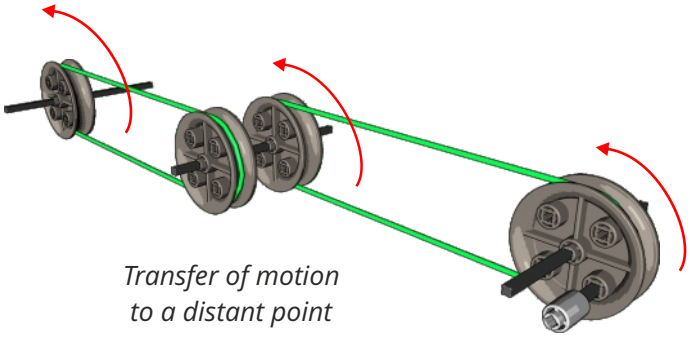
Simple transfer of motion

Pulleys can be appropriate in cases where there is a need to either **transfer rotational motion** or **change the direction** and **speed of rotation.** To do this a belt drive is used instead of a rope, which enables 2 pulleys to work together, with the one driving the other. Usually belt drives are looped flexible ropes set to run tightly in the pulleys' grooves in order to be able to transfer motion from one pulley to the other.



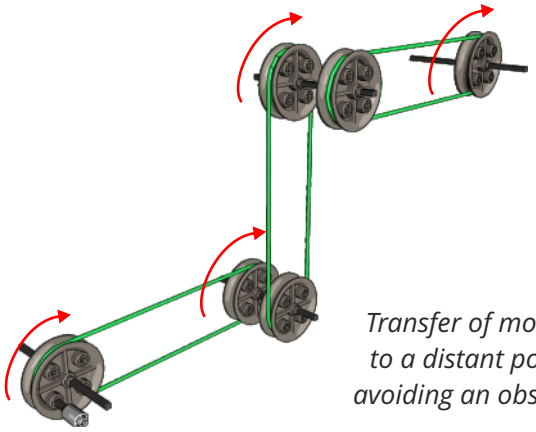
Simple transfer of motion

The pulley which powers the system can be rotated either manually via a crank or mechanically with the help of a motor and it is called the **driver pulley.** The other pulley which is rotated by the belt drive is known as the **follower pulley**. By connecting two pulleys with a rubber band (which acts as the belt drive) we achieve the transfer of the rotational motion from one axle to the other, keeping the original direction of rotation.

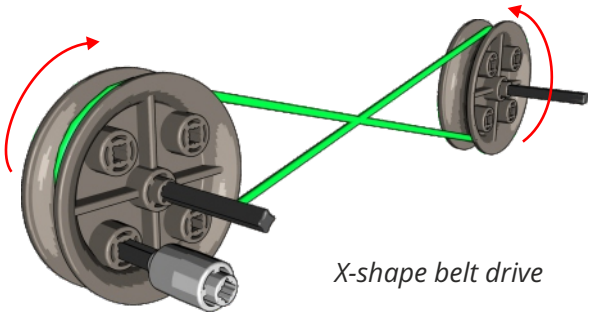


Transfer of motion to a distant point

By adding more pulleys on the same axle, as in the image above, we are able to transfer the rotation to a larger distance, still maintaining the original direction of rotation. Sometimes in a construction, an obstacle needs to be bypassed. Pulleys can help us to achieve this as well. An example of such arrangement can be seen in the next picture. As a result, we manage to avoid the obstacle and transfer the motion to the required position.



Transfer of motion to a distant point, avoiding an obstacle



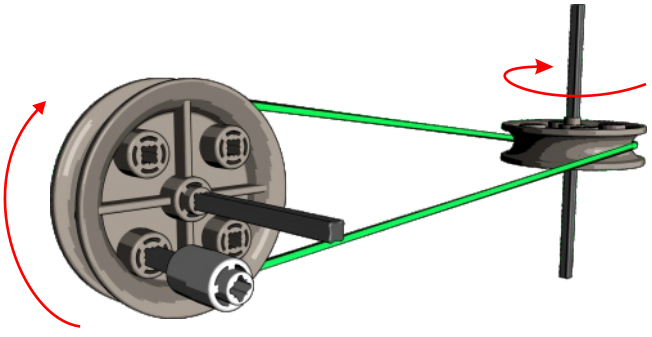
X-shape belt drive

Change in the direction of rotation

In order to change the direction of rotation of a pulley system, we have to change the belt so as to create an X shape. Due to friction such systems lose energy and the belt drive is damaged much faster.

Change in the direction of motion

Due to the flexibility of the belt drive, pulleys are ideal for changing the axle's direction. In fact, the above example of an cross-shaped belt is a change in direction by 180 degrees. In the next picture you can see a change of 90 degrees. As a matter of fact, pulleys can be used for any angle without affecting their performance, something that can not be achieved with a chain drive in a gear set-up.

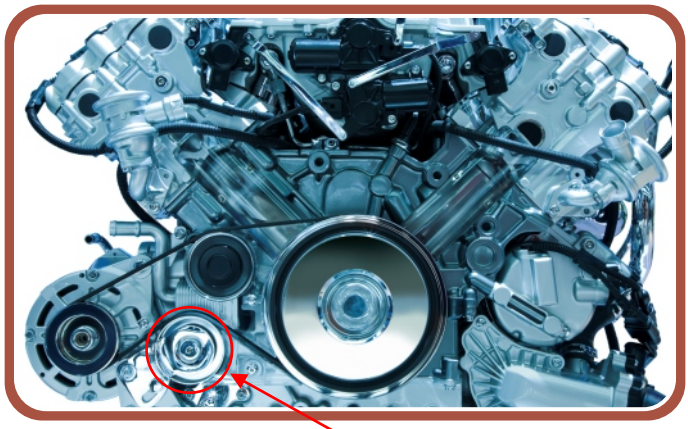


Pulley set-up that allows a 90 degrees change in the direction of motion

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Types of belt drives

Maybe you are more familiar with the chain drive of your bicycle. The belt drive is quite similar, but it is not as rigid as a chain and it is not as strong. However, belt drives are quiet, clean and require low maintenance. They allow misalignment of the rotating shafts and they dampen vibrations and absorb shocks. Due to their elasticity they may slip during rotation or at times of sudden acceleration. In some applications a tensioner is used which is able to maintain the tension in the belt or even change it. This is in fact a third pulley that pushes down on the belt to keep it tight.



Tensioner on an engine



A flat belt used for moving baggage

The **flat belts** are used by the factories to transmit energy and drive the machines or as conveyors in airports and supermarkets.

Vee belts have "V" shape as to solve the problem of flat belt slippage. They require less tension and are used mostly in cars.



A Vee belt on a motor engine



An antique sewing machine

Round belts are circular belts running on pulleys with groove on their rim. They are used for low torque (e.g. sewing machine).

Film belts are very thin belts made more often of plastic used in light-duty operations with low power and high speed. They have long life and are preferred in printers and tapes.



A recording tape with its film belt



A timing belt on toothed pulleys of a car engine

Timing belts are toothed belts that are attached to toothed pulleys (looking more like gears) resulting in no slippage, constant speed and high efficiency. They require the least tension of all other belts.

The **flying rope** can transmit power with high efficiency over a distance without electrical energy (e.g. chair lift or aerial tramway).



A chair lift transfers the skiers on the top of the mountain

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Cams & Cranks

What we will learn

Maybe you have played with wind up toys which make all these funny and strange movements, or even used a pencil sharpener! These smart devices use cams or cranks mechanisms to achieve their motion, but have you ever took time to understand how they actually work? From the most usual devices, such as a pepper grinder to the most complicated ones, such as a fine-tuned car engine, cams and cranks seem to play a vital role in the way these devices work! As we will see next, with the help of a crank we gain mechanical advantage as it has the ability to multiply the force we apply. Combine that with a cam that has the ability to change the direction and even the rate of motion, and you will come up with endless applications.



A coffee grinder

This booklet of **Discovering STEM: Cams & Cranks** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about their applications in daily life. Discover all the scientific principles applied through **experimentation**, with step-by-step guides and thought provoking exercises. Follow the **building instructions** to build exciting models such as **a fishing crane**, **an oil drill**, **a moving figure**, **a flying eagle with flapping wings**, **a sewing machine** and **a moving bridge**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.



An old olive press

History of cams and cranks

Since ancient times the crank was first used as a handle to help rotate things in machine parts. Perhaps the first need arose from the early days of agriculture, when humans had to find a way to grind the wheat grains and create flour for baking bread.

The crank seems to be a much older invention of the cam, which also had many applications. However, the cam mechanism is found from the 3rd century BC in Greece in mechanically water-driven inventions called “automata”.

The eccentrically mounted handle of the rotary handmill appeared in the 5th century BC in Celtiberian Spain and ultimately spread across the Roman Empire. The handmill consists of Quern-stones which are a pair of stone tools for hand grinding not only grain but a variety of material including nuts, seeds, fruit, vegetables, herbs, spices, meat, bark, pigments, temper and clay. The lower, stationary stone is called a quern, whilst the upper, mobile stone is called a handstone and this is considered to be a crank. This type of handmill was used until recently in many parts of the world, but gradually it has been replaced by mechanical mills.



Woman using a handmill

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A water wheel

These historical findings for the connecting rod and crank mechanism indicate that this major machine element of the much later steam engine was known already from ancient times.

In the 12th century the Muslim inventor Al-Jazari used cams in his automated water clocks and water-raising machines. In Europe cams appear in the 14th century and they were used in toys and household objects, mostly for entertainment or other practical reasons. For production purposes, cams were widely spread, like all mechanisms, during the industrial revolution.

Did you know?

One impressive application of the crank is found in the drawing "Anonymous of the Hussite Wars" which shows a boat with a pair of paddle-wheels at each end turned by men operating compound cranks as you can see in the picture. The concept was later improved by the Italian Roberto Valturio in 1463, who designed a boat with five such sets, where the parallel cranks are all joined to a single power source by one connecting-rod.



The crank middle age paddle boat

But the ingenuity of humans did not stop there. Cutting stones or large pieces of timber was a major problem in ancient time. People had to find a way to simulate the saw movement (back and forth) without relying on limited human power, but on the power of flowing or falling water which was much higher. The earliest evidence of water mills that used wheels to harness the power of water date to 3rd century BC in Greece. However, the combination of a crank to a connecting rod, in order to achieve conversion of the rotational motion to a saw-like motion, appears 600 years later in the ruins of the Roman Hierapolis sawmill (from the 3rd century AD.



A drawing of Al-Jazaari

As far as the crank mechanism is concerned, it was not commonly used in Europe until the early 15th century and It was usually used for military applications. Such devices included cranked windlasses (instead of spoke-wheels) for spanning siege crossbows, cranked chain of buckets for water-lifting and cranks fitted to a wheel of bells.

Cranks were very common on many machines in the early 20th century; for example almost all phonographs before the 1930s were powered by cranks, and even the early cars had to be started with the use of a detachable handle. The crank as a handle had and still has many applications, found even today in bikes and fishing rods!



The early car

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Crank as a handle

The earliest and most common application of the crank is that of a handle positioned offset of the axis of rotation in order to help us rotate things. The first machine created by humans was the handmill, and then this technology was applied to wells for lifting water. Nowadays, if you observe carefully you will find many manually driven machines and devices that use the crank in a similar way. Some examples include many of our kitchen grinding machines for coffee or salt or even the mechanical pencil sharpener!



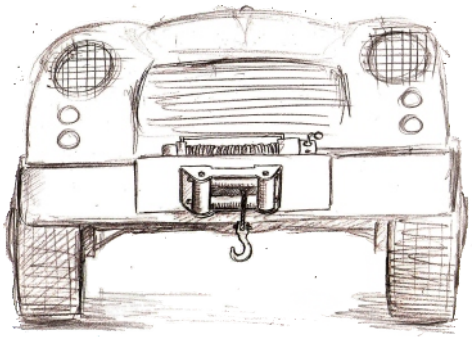
A pepper grinder



A boat winch

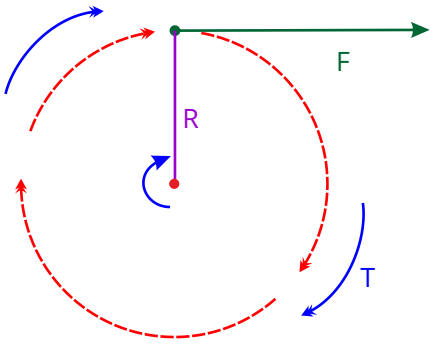
Winch

The crank is also a vital part of the "winch" mechanism which is used to wind up and store rope. Winches are used in sailing ships, cranes, elevators and are frequently elements of backstage mechanics for moving the scenery in large theatrical productions. Specifically, they are part the stage floor and are used to move large set pieces on and off.



Winch on a car

Imagine that you are trying to wind up the rope on a winch that is pulling a car weighing more than a ton! You attempt to turn the crank but it is impossible... the weight is enormous. What can you do? One solution would be to have a crank handle that is not so near to the center of the axle. But why does this work? What is the relationship between input force and the distance of the handle from the axle center? This is explained below with the notion of Torque.



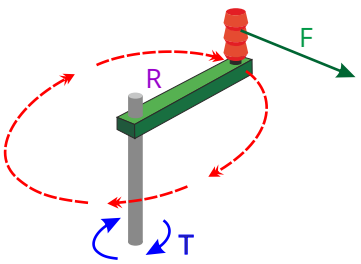
$$T = F \times R$$

Diagram and formula for Torque

Torque

When we apply a tangential force away from the center we create "Moment". If this is applied to rotating parts is called "Torque". We can define Torque in simple terms as a tendency to rotate an object and the higher it is then the easier it will turn. In order to calculate Torque (T) mathematically we need to multiply the tangential Force (F) by the distance of the Force from the center, that is the Radius (R).

For an object to begin rotating we have to apply enough Torque to overcome the load. If we apply the Force closer to the center then the Radius of our circular movement is smaller and hence a bigger force is needed. However, if we apply the Force well away from the center then the Radius is bigger and the Force required to create the same Torque becomes much less than before, but for longer distance.



$$T = F \downarrow \times R \uparrow$$

To achieve the same torque, if the radius increases, the force will decrease

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Crankset

One application of the crank is the bicycle pedals. The pedals are attached on two cranks, one on each side of the bicycle, that are mounted 180 degrees out of phase so that each leg can push down in turn. This combination of cranks and pedals is called **crankset** and it converts the reciprocating motion of our legs (up and down) to rotational. In fact, the first bicycles did not have cranksets and the rider was moving forward by pushing the ground with his legs. In this way it seemed as the bicycle rider was running while sitting!



Bicycle pedals



The Engino® crank

Crank and rod mechanism

We have already learned that the crank can be used as a handle to turn a machine. Now let's reverse this arrangement! Imagine that the wheel is turning on it's own, powered by a motor for example. What used to be the handle now will move in a circular path. What if we attempt to grab the handle as it rotates? Our arm will be forced to move along and what we shall experience is a force pushing and pulling us. Well, maybe this is what inspired the ancient engineers to connect one side of a rod to the handle and the other side to other moving parts, effectively transferring power from the crank. In fact, this connecting rod is often called the "arm" and it converts rotating motion to reciprocal (back and forth).

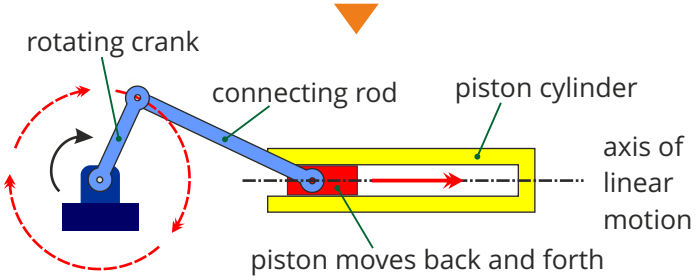


Diagram of the crank and rod mechanism with a piston

Did you know?

The Palace Bridge in Saint Petersburg in Russia is a magnificent moving (bascule) bridge that spans the Neva river between Palace square and Vasilievsky island! The view of the bridge combined with the golden spire of Peter and Paul cathedral is one of the most iconic images of the city. The construction started in 1912 and concluded in 1916, with a length of 260 m and width of 28 m. The bridge allows road and people traffic, while in the night the deck is lifted to allow the passing of ships.



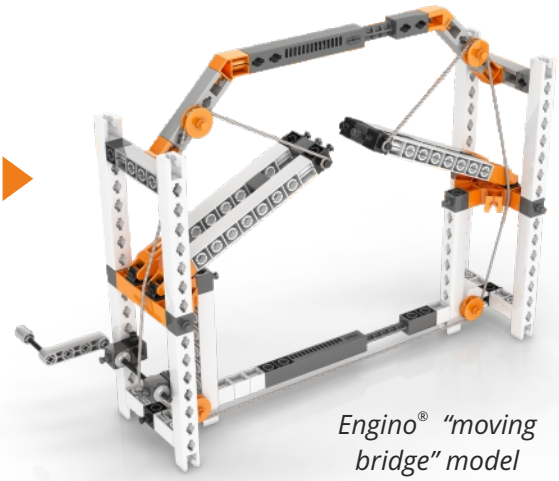
The Palace Bridge in Saint Petersburg

Building Challenge

instructions can be found online

Moving bridge: bridges are used for connecting two sides of a river so that cars and people can move across. In busy rivers it is essential that a bridge can open its "gates" for the large ships to pass.

Build the moving bridge model and simulate the opening of the gates with the help of a crank and pulleys.



Engino® "moving bridge" model

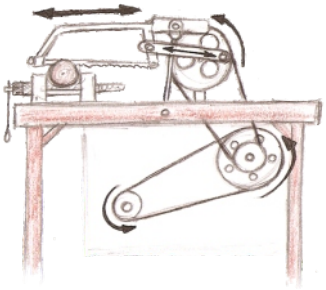
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Applications of crank and rod

The type of motion we achieve from the crank and rod mechanism can be used in so many different applications that it is quite amazing! Look at the picture showing the wheel of a steam engine train. As you can see the rotating wheel has a rod (also called coupling rod) connected off center which powers the wheel. Amazingly, if we were able to pull or push a train with on outside force, the wheels would start turning, rotate the crank and the connecting rod would transfer motion to the engine backwards!



Wheel on a steam train



An automated saw working with a crank.

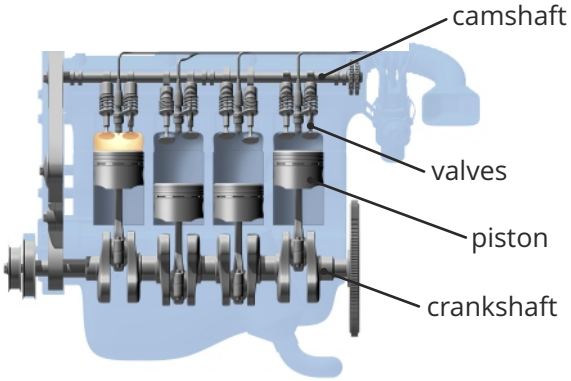
This is one of the greatest advantages of the crank mechanism, that it can work both ways and convert either rotational motion to reciprocal or reciprocal to rotational. Another big advantage is that the crank gets power on both the upward and return strokes. This means that you don't have to rely on gravity which can be a problem with cams (explained later). In addition cranks work in all directions, vertical, horizontal or inclined!



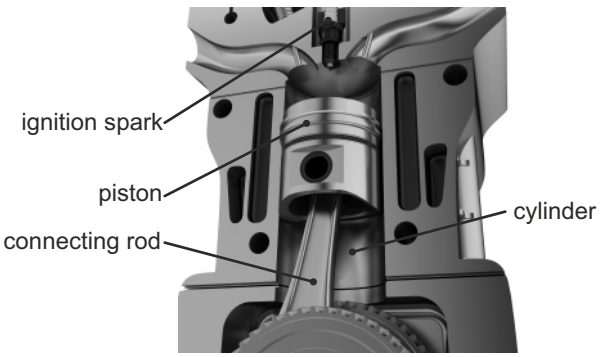
A steam train

Crankshaft

The crude oil pumped from oil wells is processed to create gasoline and petrol, the major fuels that we use in our cars. But how does fuel generate motion? The piston movement is not of constant speed as it is derived from the circular path of the crank. The piston starts from one end and increases its speed. It reaches maximum speed in the middle of its travel, then gradually slows down until it reaches the end of its travel.



The crankshaft connected to the pistons



Engine piston and combustion chamber

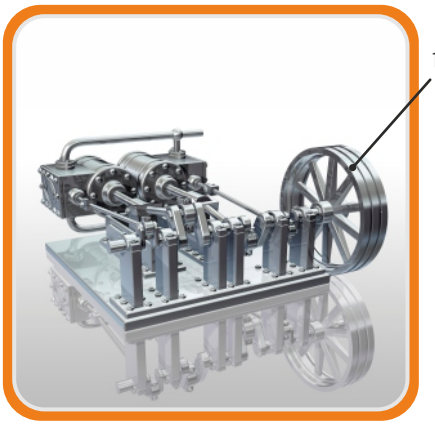
If scientists did not invent the crank, we wouldn't have car engines or any machine that can convert heat energy to kinetic! The car engine is powered by the combustion cylinders. Fuel is injected in the cylinders and the spark ignites the fuel. The explosion pushes the pistons outwards with great force. The pistons are connected via the connecting rods to the crankshaft and the explosion force generates torque that rotates the shaft, which in turn drives the wheels of the car.

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In a car engine where a lot of power is needed one piston is not adequate. How is this problem solved? Engineers discovered that by connecting more than one crank on the same axle, positioned every half rotation (180 degrees out of phase) then you can achieve a smoother rotation with multiplied Torque as each piston will push the crank every half turn. This is what we call **crankshaft** and it is the most vital part of all piston-driven machines. In the right picture you can see a crankshaft with 4 cranks, 2 middle of the same phase and 2 outer 180 degrees out of phase.



Crankshaft



Machine with a flywheel

With each explosion in the combustion chamber the piston pushes the crankshaft. To complete a full rotation without slowing down so that another cycle of combustion is initiated, a special component is needed. This is the **flywheel!** The flywheel is a metallic wheel with a large radius and a lot of dead weight distributed around its circumference. This way it has a very large inertia and once on the move it will not stop easily, dragging along with its momentum the shaft dampening the sudden push of the piston and smoothing the rotational speed of the crank. In the left picture you can see that a flywheel can also become a pulley, transmitting rotation to other places.

Did you know?

The Chinese drilled for oil already from the 3rd century AD and used it as a fuel to evaporate brine and produce salt. In Japan it was known as the "burning water" from the 7th century. In Persia, modern day Iran, oil was found in natural fields without the need of drilling. During the 8th century it was used as tar for paving roads and already from the 9th century it was distilled to create other chemicals such as lamp oil.



Road tar made out of oil

The can engine runs on petrol, a fuel deriving from oil. This was created from the remains of tiny animals (plankton) and plants, that died in ancient seas between 10 million and 600 million years ago! Over the years the remains decayed and without the presence of oxygen, chemical reactions led to the formation of crude oil (petroleum). Unfortunately, because of the great demand for oil in the modern world, it is estimated that reservoirs will not last for long and possibly be depleted within the 21st century. In addition, oil burning causes air pollution and oil spills bring environmental disasters. In recent years, people are becoming more and more aware of the problem and try to develop and use alternative forms of energy, preferably renewable energies, such as solar energy and wind power.

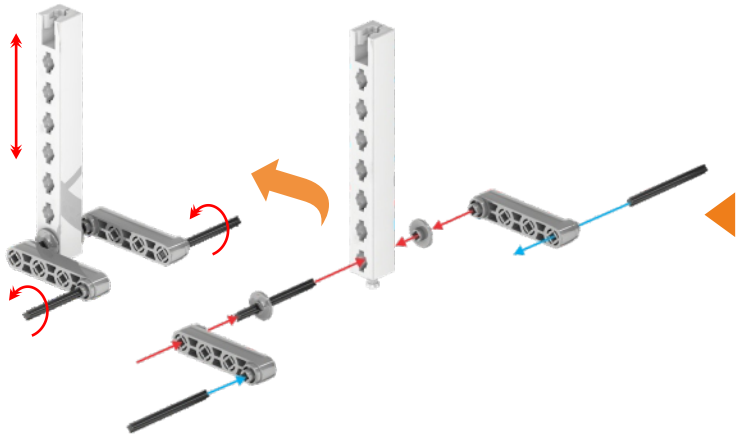


Combination of solar and wind energies

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Engino cranks

Not all cranks are the same; some look more like wheels with an offset connection, some are only rods connected together. With Engino there are many ways to create a crank mechanism and convert rotational motion to reciprocal. Observe below how to create different cranks, build them and study how they work.

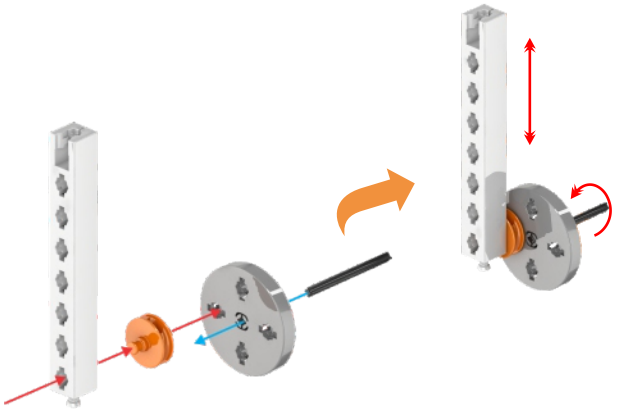


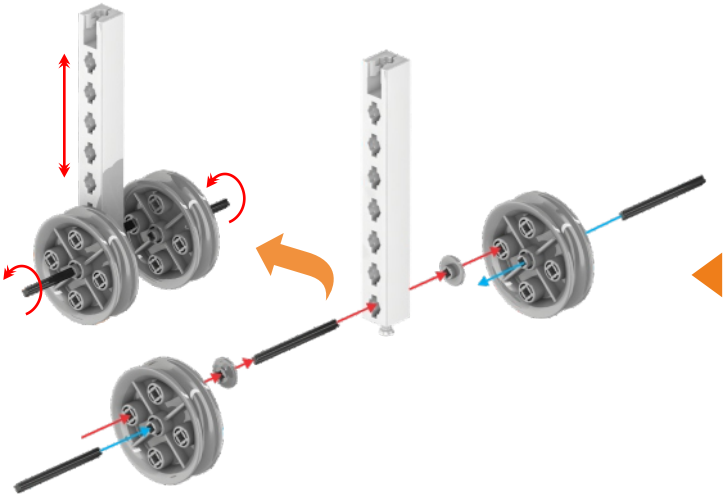
Engino crank 1

A rod is assembled on a central axle and fixed in place by the grey circular spacers. Each side of the central axle connects to a long light grey part at the hole towards one end. At the opposite hole 2 axles are connected in line forming the main shaft.

Engino crank 2

A rod is connected on the red pulley and the red pulley on the offset hole of this light grey circular part. Note this part only connects with the Engino plugs from one side unlike the large gear which connects on either side. The main shaft is the axle that is connected at the center hole of the part.



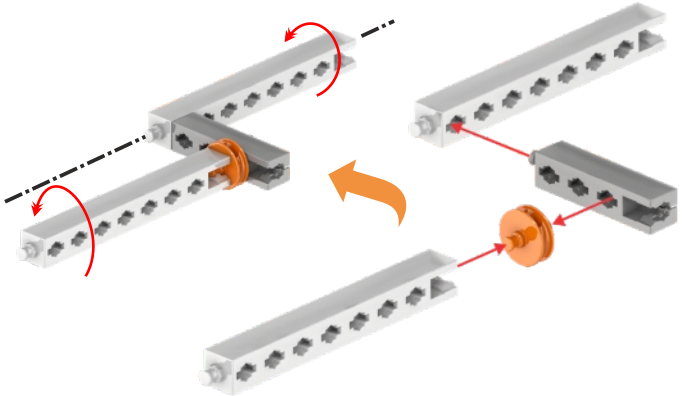


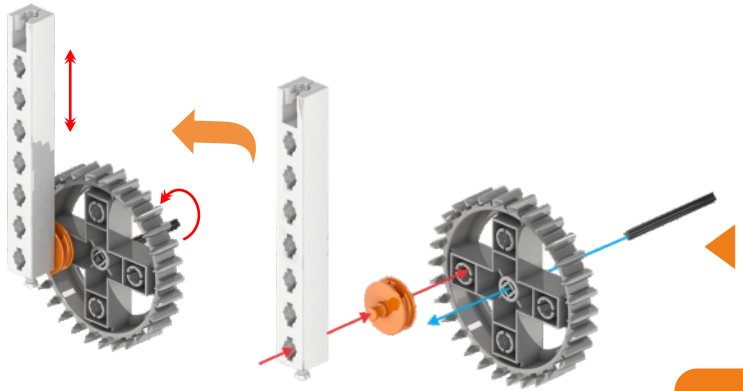
Engino crank 3

A rod is assembled on a central axle and fixed in place by the grey circular spacers. Each side of the center axle connects to the off-center hole of either the medium or large pulley. At the center holes of the pulleys 2 axles are connected in line forming the main shaft. The arrangement would also work if the central axle was positioned at the center hole of the pulleys and the main shaft axles at the offset holes.

Engino crank 4

An orange pulley connects inline with a long rod at the end position and then assembled on a smaller rod vertically. When a third rod is connected vertically to the middle one it can behave as the main shaft.





Engino crank 5

A rod is connected on the red pulley and the red pulley on the offset hole of a large gear (not included in this set). The main shaft is the axle that connects at the center hole of the gear.

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Types of motion

In order to understand the movement of cams we first need to learn about the main types of motion. Also in the next page we will make a revision on pulleys because their properties are used with the Engino parts and are similar to the properties of cams.



Paper guillotine moving in linear motion

Linear motion happens when an object is following a straight line path, e.g. a paper guillotine.

Rotary motion is motion around a fixed point (in a circle), e.g. windmill.



Windmill moving in rotary motion



Swing moving in oscillating motion

Oscillating motion is motion backwards and forwards in a circular arc (part of a circle), e.g. swing.

Reciprocating motion is motion forwards and backwards in a straight line, e.g. sewing machine.



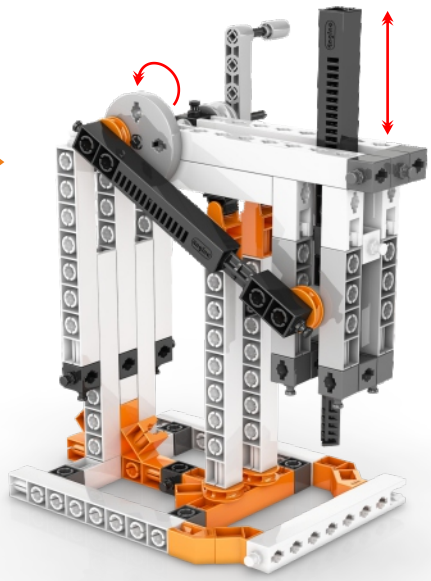
Sewing machine in reciprocating motion

Building Challenge

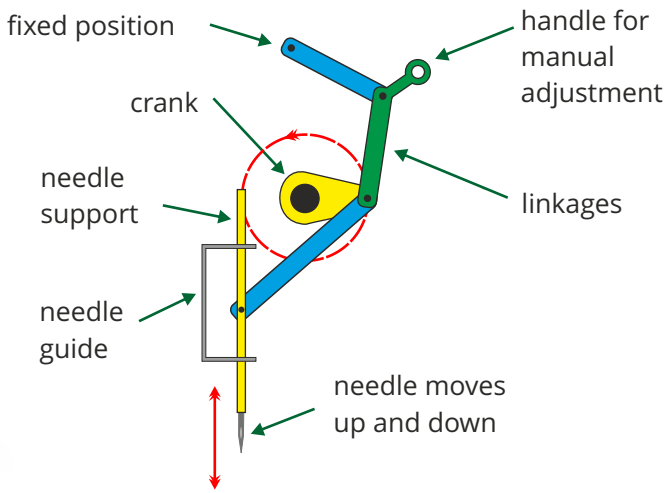
instructions can be found online

Sewing machine: back in the 1850s the demand for sewing machines was so huge that a patent thicket was triggered known as the Sewing Machine War! Below you can observe how the rotational motion of the motor is converted into the reciprocating motion of the needle.

Build the sewing machine and simulate the reciprocating motion of this handy device.



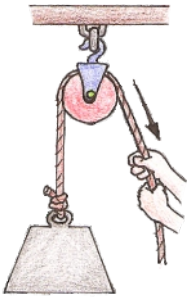
Engino® sewing machine model



A sewing machine needle with a crank

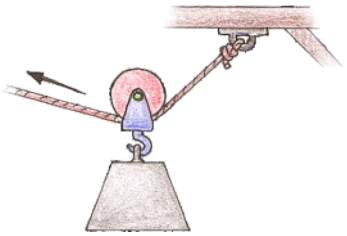
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Revision on pulleys



A fixed pulley

A **fixed pulley** is rotated around a rigid axle which is located at a fixed point in the construction. However, fixed pulleys **are not directly attached to the load**. This type of pulley enables us to pull the string downwards in order to lift the load upwards, without mechanical advantage.

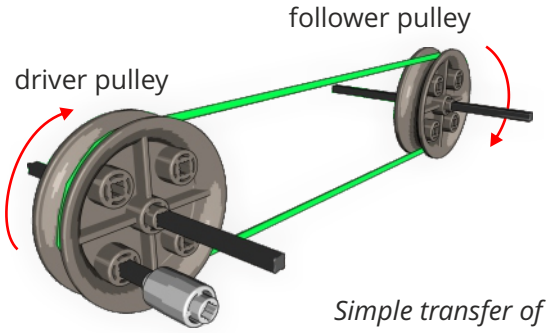


A movable pulley

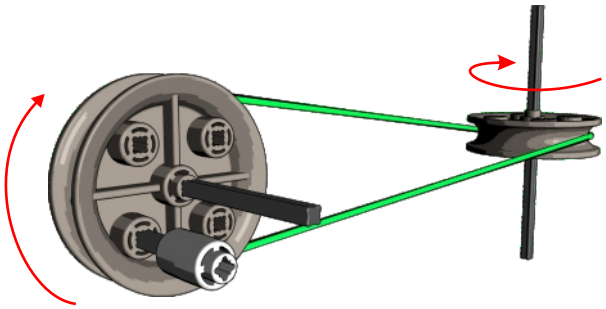
A **moveable pulley** is **directly connected to the load** and moves simultaneously with it. In order to lift the load, the string should be pulled upwards. This type of pulley offers a mechanical advantage.

Simple transfer of motion

Pulleys can be useful in cases where there is a need to either **transfer rotational motion** or **change the direction** and **speed of rotation.** To do this a belt drive is used instead of a rope, which enables 2 pulleys to work together, with the one driving the other. Usually belt drives are looped flexible ropes set to run tightly in the pulleys' grooves in order to be able to transfer motion from one pulley to the other.



Simple transfer of motion



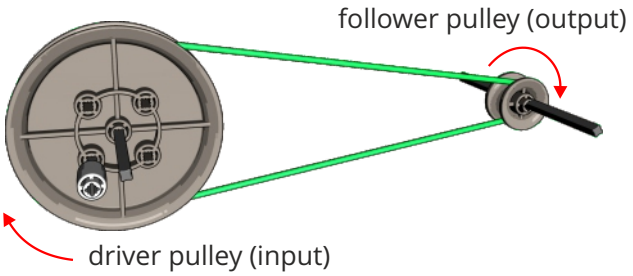
Pulley set-up that allows a 90 degrees change in the direction of motion

Change in the direction of motion

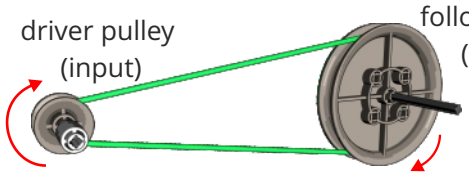
Due to the flexibility of the belt drive, pulleys are ideal for changing the axle's direction. In fact, the above example of an cross-shaped belt is a change in direction by 180 degrees. In the next picture you can see a change of 90 degrees. As a matter of fact, pulleys can be used for any angle without affecting their performance, something that can not be achieved with a chain drive in a gear set-up.

Increase of speed

In order to increase speed, the **driver** pulley should be bigger than the **follower** pulley. Consider a point on the driver pulley's rim. In one revolution the point will travel distance equal to the circumference of the pulley. The belt will move for a distance equal to the driver's pulleys circumference. The follower pulley will have to rotate enough turns to cover this distance, which means if it has a smaller diameter it will have to turn more **revolutions per minute** (rpm) to do it.



If the driver pulley is bigger than the follower, the speed is increased



If the driver pulley is smaller than the follower, the speed is decreased

Decrease of speed

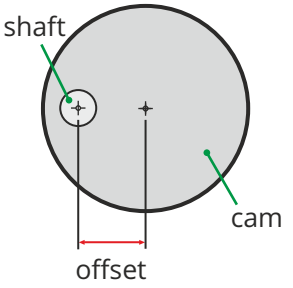
In order to reduce the speed of the follower pulley, the driver pulley should have a smaller diameter than the follower pulley. The driver pulley is the **input** of the system because it is the pulley where the power is applied by either a motor or another source. The **output** of the system is the speed and torque of the follower pulley.

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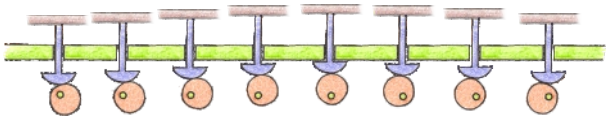
Definition of cam

As we have already discussed, the crank mechanism is able to convert rotational motion to reciprocal and vice-versa.

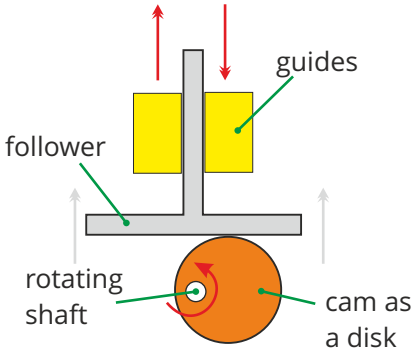
There is another very similar mechanism that can do this but only in one way; this is the **cam**. The greatest advantage of the cam is that it can create almost any type of reciprocal movement with different timings.



*The distance between the center and the rotating shaft is called **offset***



A series of images of the crank and follower as they complete a full cycle (stroke)



The round cam

As you can see in the picture above and on the left, the **cam** in its most basic form is a wheel (disk) that has its rotating shaft positioned eccentrically, that is **off-center**. However, to create output movement another element is required. This is the **follower**, which rests on the cam's profile and is pushed up by the cam's movement and comes down either by gravity or a spring. The follower should always be in contact with the cam's outer surface. The left sketch shows the cam and its follower in different positions as the cam makes a full circle. The follower is actually sliding on the cam's surface which means that friction must be minimized to avoid energy loss and have a more efficient motion.

Did you know?

One of the vital parts of a car engine is the camshaft! This is a rotating shaft with egg shaped cams build into the axle, pushing against the piston valves. The opening and closing of the valves has to be preformed with precision, following the timing of the piston's movement. The valves have elastic springs that enable them to close again. This is a critical job, and if not balanced effectively it can have a huge impact on the engine's performance under different speeds.

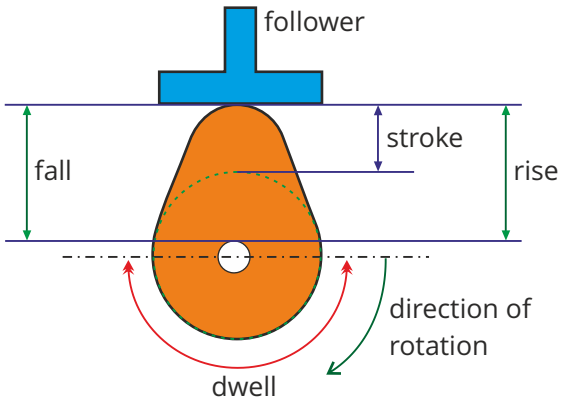


A camshaft

Terminology of cam

In the diagram below you can see the different parts of a cam. When the cam completes a full rotation then it is said to have traveled one **cycle**.

Fall: the part of the cam's profile which causes the follower to drop.
Rise: the part of the cam's profile which causes the follower to go up.
Dwell: the part of the cam's profile which causes the follower to stay idle, that is neither go up or down.
Stroke: the distance between the highest and lowest points of the follower's movement.
Heel: the lowest point of the cam.
Crown: the highest point of the cam.



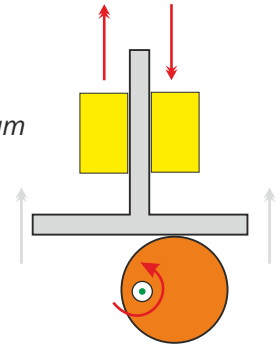
Cam's terminology

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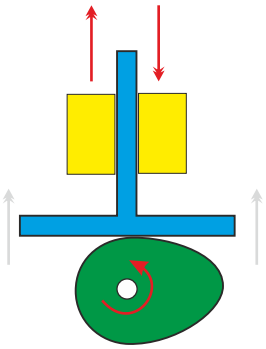
Cam profiles

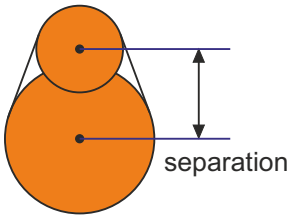
There are many different types of cams depending on the particular application.

Round cam: it has a continuous movement up and down, whose stroke depends on the distance of the shaft from the center, what is called the **offset**.



The round cam

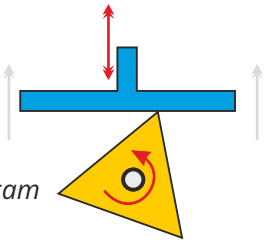




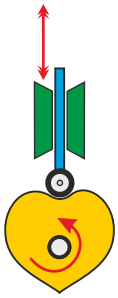
The construction of the pear-shaped cam

Egg-shaped cam: it is also called pear-shaped and the major characteristic of this cam is that its follower rises and falls for part of the cam rotation, followed by a dwell period where the follower is stationary before rising again. This may be particularly useful in machines where timing is important, for example, to open and close valves. The pear-shaped cam is created by a larger and a smaller circle. The distance between their centers is called **separation**.

Triangular cam: a triangular cam produces a continual motion of rise and fall with no dwell period and with a sudden change of direction when each side of the triangle hits the follower.



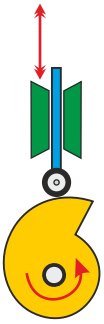
The triangular cam



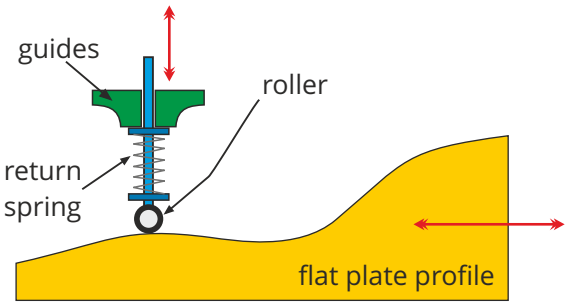
The heart shaped cam

Heart-shaped cam: a heart-shaped cam produces a uniform velocity of the follower in both rise and fall with no abrupt change in its movement. They are used in the cases where we need the follower to move slowly at a constant speed. Such cams are used in the "bobbin winding mechanism" found in sewing machines which leads to even threading.

Drop cam: these cams have a shape that looks very much like a snail and hence it is also called **snail cam**! This is similar to the pear shape, but with an inner step. This step in the profile causes the follower to drop suddenly. This type of cam can work only in one direction as it would jam if rotated against the step.



The drop cam



The linear cam

Linear cam: this cam is quite different, also called flat plate cams. Instead of rotating disks, what pushes the follower up and down is a wedge shape that moves back and forth in a straight line. The inclined surface of the wedge transfers the motion to the follower. Usually the follower of linear cams includes a wheel for using friction as an advantage. In the diagram you can see a spring which assures the follower will keep touching the cam's profile.

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Types of followers

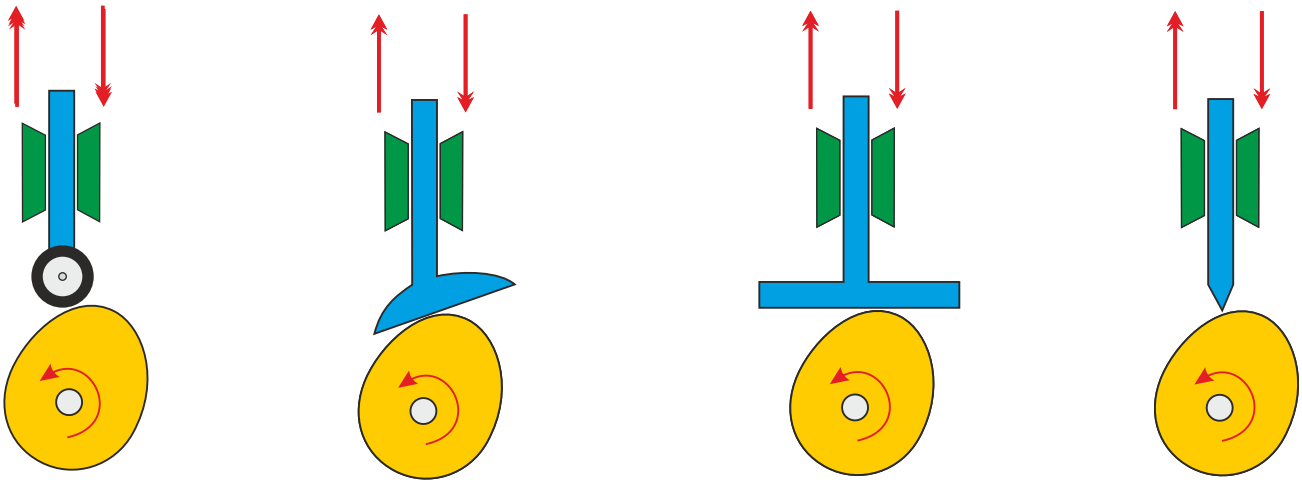
The follower is attached to the cam profile and follows its surface by moving up and down. This element is important as it provides smooth motion transition between the cam and the follower. Below you can see four main types of followers and their characteristics.

Roller: the addition of the wheel enables friction to become an advantage.

Offset: this design has an impact on the contact area.

Flat: this design makes sure that the follower is always touching the cam.

Point/knife: the contact area is limited to minimum.



Four types of followers

Did you know?

Imperial eagles are called this way because of their big size! They can reach a length of almost 1 metre, a wingspan of 2.2 m and a weight of 4.5 kilograms! What is interesting is that females are about a quarter larger than males! The imperial eagles live on the mountains around the Mediterranean sea and they hunt for their food (hares, hamsters, turtles etc). Unfortunately, this amazing bird is in the list of endangered species, as it is threatened with extinction.



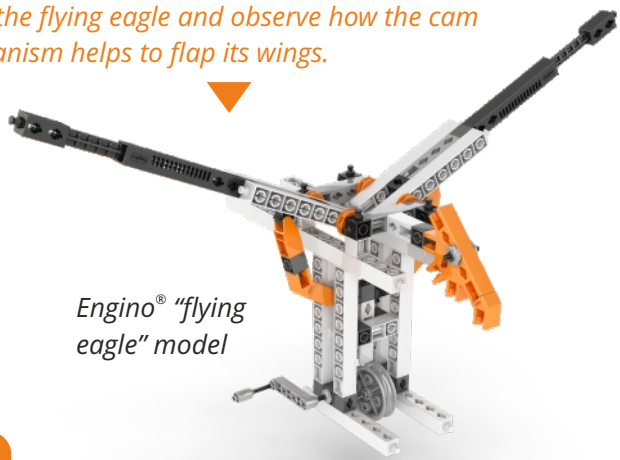
An imperial eagle

Since the cam works by pushing the follower up and down then it is inevitable that there will be friction between the cam's surface and the surface of the follower. There is also friction in the guiding frame where the follower slides. One way to reduce friction is to use lubricants such as oil which flows in between the surfaces and reduces the contact. One way to improve the performance of the cam mechanism is to also change the follower, either by lessening the surface area and hence friction or by using a wheel which takes advantage of friction.

Building Challenge instructions can be found online

Flying eagle with flapping wings: read about this magnificent bird in the "Did you know?" section on the left.

Build the flying eagle and observe how the cam mechanism helps to flap its wings.



Engino® "flying eagle" model

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Gears & Worm Drives

What we will learn

All bicycles have a special mechanism that helps us to transfer power from the pedals to the wheels. Pendulum clocks contain something similar which allows them to tell time with great precision. There are plenty more examples of machines that use gears to decrease or increase force, transfer motion from one position to another or even change speed! In this book we will also examine the screw, another type of simple machine and the worm drive that derives from it. Screws' most common use is to fasten objects together, but we can also found them in huge mechanisms such as dam gates or small tools like the bottle opener (cockscrew). Musicians use worm drives to fine-tune their instruments (guitars or violins).



Close-up of a gear mechanism

This booklet of **Discovering STEM: Gears & Worm drives** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about their applications in daily life. Discover all the scientific principles applied through **experimentation**, with step-by-step guides and thought provoking exercises. Follow the **building instructions** to build exciting models such as **an experimental crane**, **a gearbox, a carousel**, **a helicopter**, **a screw press** and **a crane with rotating arm**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.



Wooden gears of an old windmill

History of gears and worm drives

Large gears were used during ancient times, first by Greeks and then by Romans in their watermills. They consisted mostly of the waterwheel and of toothed gearing which was able to transfer the water power to large machines. Such machines were the saw mills used for cutting huge stones and the trip hammers for crashing, pounding or forging metals and grain mills. Similar mills were also found in China from 30 A.D. Those gears were quite large and powerful. The earliest historic reference of gears dates back to 50 A.D. in the works of the famous inventor Heron of Alexandria.

The Greek philosopher and scientist of the time, Archimedes, designed an ingenious device, the "odometer", which could measure the distance traveled by a carriage based on the wheel's revolutions. Archimedes also used gears in his primitive version of "Planetarium", a mechanism that could predict the movement of the Sun and nearby planets! The "planetarium" up until lately was considered to be a mythical device due to the high level of knowledge and skill that it required. However, the whole world was amazed when a mechanical computer was discovered by some fishermen in 1900s near the Greek island of Antikythera in an ancient shipwreck.



The antikythera mechanism at the museum of Athens

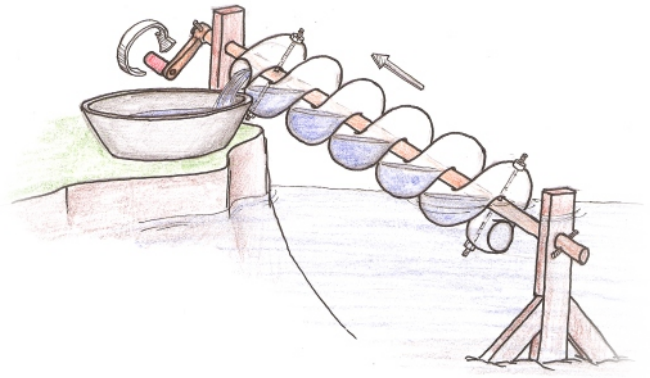
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Model of antikythera mechanism

This “antikythera mechanism” was a very elaborate machine that was able to do calculations of astronomical positions using a complex system of gears. Machines of such complexity were not created again until the 18th century in Europe when pendulum clocks were crafted. The “antikythera mechanism” is being continually studied by expert scientists using X-rays and modern technology to identify markings and mechanical parts. On the 30th of July 2008, scientists reported new findings that showed that the mechanism was able to track the Metonic calendar (it is an extended yearly calendar to cover 6940 days), predicted solar eclipses, and calculated the timing of the Ancient Olympic Games!

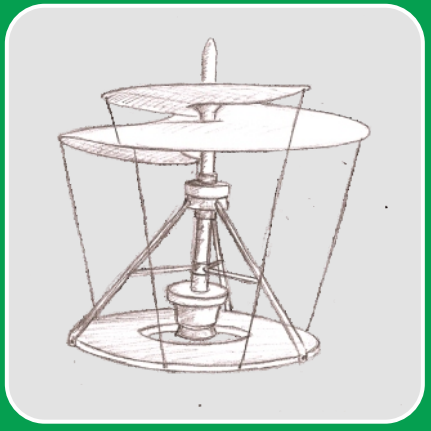
Early wooden screw shaped tools became common in the 1st century BC and were used in wine and olive oil presses. Two centuries earlier, Archimedes designed a machine to pump water from lower ground. This machine, called Archimedes’ screw, was used to lift water from a lower level to a higher one and it was mostly used for draining water out of mines. It consisted of a screw shaped cylinder positioned in a hollow pipe which revolved manually or by a windmill. The bottom end was placed in the water so that with every turn it could scoop up an amount of water.



Archimedes’ screw

Did you know?

Leonardo Da Vinci designed the first helicopter called “Helical Air Screw”. It consisted of a platform with a helical screw in its center and wings, made of a rough cloth, for moving the helicopter in a vertical direction. Da Vinci’s idea was that such a machine could lift a human by screwing through the air, functioning similarly to Archimedes’ screw. Unfortunately, the helicopter was never put in use, but a model has been built at the Museum of Science in Boston.



Leonardo da Vinci’s helicopter

Nowadays, the concept of Archimedes’ invention is applied to high-speed tools and various machines for drainage, irrigation and oil extraction. The Archimedes’ screw model is preferred in screw conveyors as well, which are machines for handling light materials such as grain, sand or ashes, even grapes like in the top picture. Around the 15th century, metal screws were invented and used to fasten two objects together. They were not so common until the end of the 18th century when machine tools for mass production appeared. The first screw-cutting lathe was invented by Jesse Ramsden. Threaded bolts and fasteners are used almost everywhere to hold objects in place!



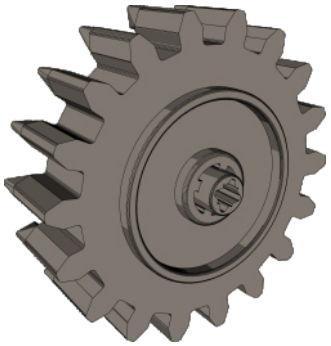
Grapes transferred by a screw

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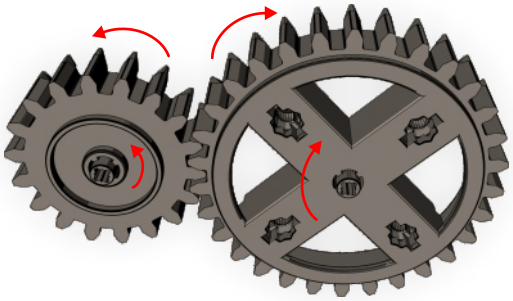
Definition of gear

Gears are wheels with teeth around their circumference, enabling them to mesh with each other. They belong in the category of simple machines which means they can increase the applied force and have a mechanical advantage. Gears can be found in almost all machines that have moving parts and we use them if we want to:

- **transfer** motion from one position to another;
- **reverse** the direction of rotation;
- **increase** or decrease the speed of rotation;
- **change** the axis of rotation;
- **decrease or increase** the force of a machine.



The Engino medium size gear



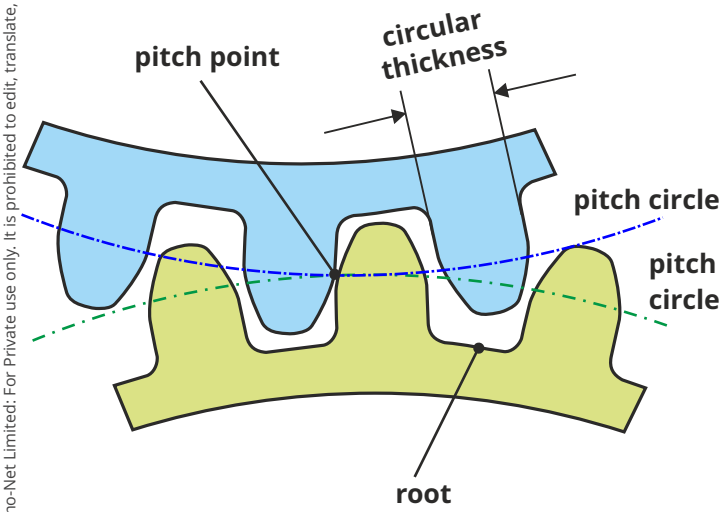
Two gears rotating in reverse

A gear isolated can not really do anything! It has to be connected with other gears in order to transfer power. Gears have teeth that connect them and this type of connection is called **meshing**. The gear that is rotated by a motor or in general by any power source is defined as the "**driver**" gear and the other gear that follows is the "**driven**". If more than two gears mesh in a more complex system this is called **gear train**.

The teeth of the gears are the most essential elements and their design will determine the efficiency of gear transmission. As we have seen in ancient times, gear teeth were made of wooden beams and were big and bulgy. Later on, during the Hellenistic times, when the "antikythera mechanism" was created, gears were made of bronze with high precision. Nowadays, gears have very complex shapes to minimize friction and optimize performance, depending on the application.



A close up of standard gear teeth



A diagram of how two gears with an involute teeth profile mesh

Gear terminology

The ideal profile design allows the teeth to mesh while touching only at a single point. As the gears rotate, the teeth should move as if they were rolling on each other instead of sliding. This rolling motion minimizes friction and wear, making gears the most efficient mechanism for transferring power. The major types of profiles used are the **involute**, **cycloidal** and **circular arc** or **Novikov**. The Engino gear teeth are designed with an **involute profile**.

A common term in all profiles is the **pitch** which refers to the distance between any point on one tooth and the same point on the next tooth. The **pitch circle** is the circle with radius up to around half the teeth's height, where the gear teeth make contact with each other as they rotate. **Pitch point** is the teeth contact point and **root** is the bottom part of the wheel.

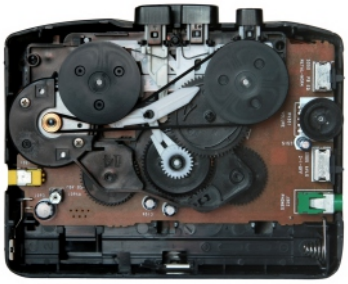
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Examples of gear use

Gears are one of the simple machines which are found in most devices that have movement, from the smallest wrist watch to the biggest train! Below you can see some characteristic examples of gear use. The gearbox of a car allows the driver to change gear depending on the amount of power (first gear) or speed (fifth gear) needed. Plenty devices use gears in order to transfer motion and increase speed (e.g. music player) or to control the rhythm (e.g. wrist watch).



Car gearbox transmission



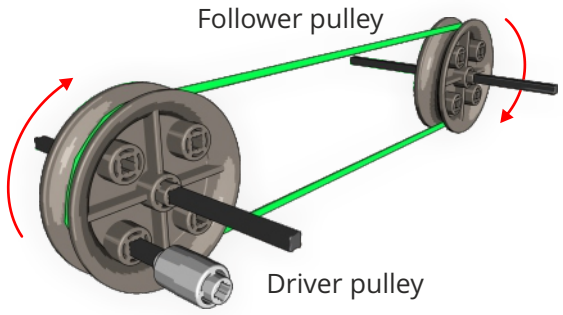
Inside view of a portable music player



Gears in a wrist watch

Chain drive

The gear set-up is very similar to pulley systems, another simple machine. Pulleys also transfer motion and power, but not directly like gears do! The pulleys may be positioned further away between them and have a flexible belt tightly connecting the two, so that if the driver pulley rotates, the other will follow, dragged in motion by the friction force between the belt and the pulley's groove.



Two pulleys rotating in the same direction

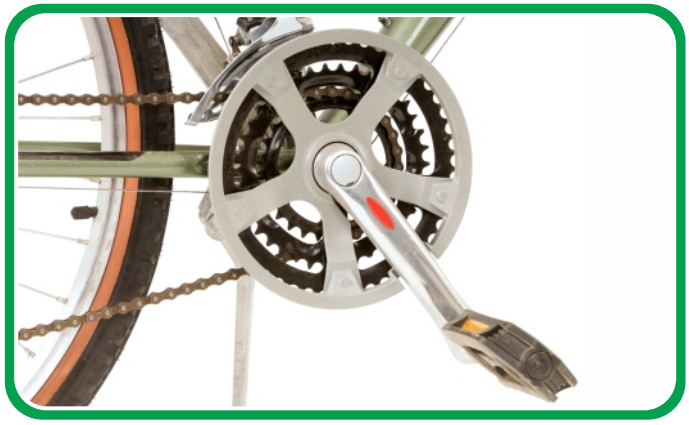
There is another important difference between gears and pulleys. If you look at the red arrows in the pictures of connected gears and pulleys of these pages, you will notice that they have different direction of rotation; two meshed gears rotate in reverse, while two connected pulleys rotate in the same direction. But, there is an easy way to make gears rotate in the same direction by using a **chain drive**. This is made by a series of connected links usually manufactured of metal. The links are connected to each other with metal pins, allowing the interconnecting parts to swivel. The chain is ideal for transferring motion and power from one gear to another as it is strong and does not slip. However, chains have to be lubricated and, unlike pulley's belt drives, they are noisy and do not allow any misalignment of the gear shafts.

Did you know?

The unicycle is a single wheel vehicle that entertains circus audiences and hobbyists. It requires great balancing skills, but it is quite simple in its operation. It started in the 19th century and was based on the early bicycles that had a huge front wheel and a very small back one. Once people realized they could balance on a single wheel the unicycle was created! Nowadays unicycling has evolved to be a competitive sport such as free-style or trials where obstacles are avoided.



Acrobat balancing on a unicycle



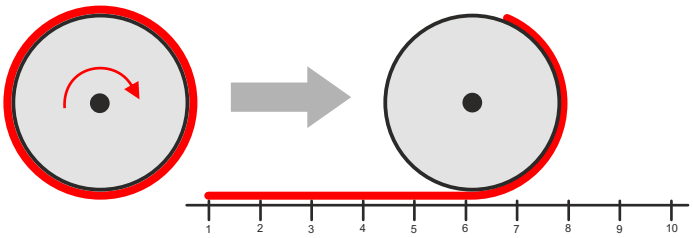
A chain drive on a bicycle

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Physical laws

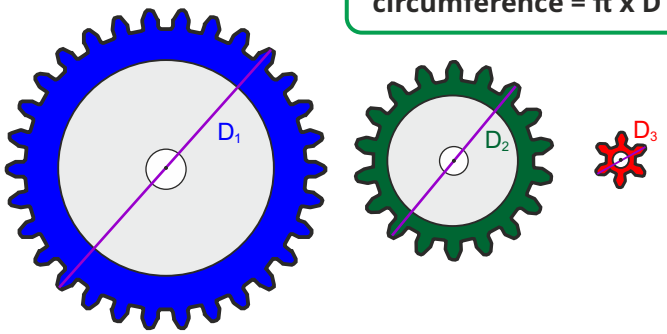
Circumference

In order to calculate the circumference of a circle, we can take a piece of string and wrap it around a gear. The resulting length of the string (measured by a ruler) is the **circumference** of the circle. As an example, we can experiment with the Engino gears. Below you can see the *circumference* (length of string), *diameter* and *number of teeth* of the 3 Engino gears: large, medium and small. We can use these to find the relationships between them.



A wheel's circumference is the length of a line around its rim

circumference = π x D



	large	medium	small
length of string	22cm	14cm	5.4cm
diameter of gear	6.6cm	4.2cm	1.6cm
number of teeth	30	18	6

Calculating the elements of Engino gears

If we divide the length of the surrounding string of each gear with the diameter of the corresponding gear we will find a number between 3 and 4. As a matter of fact if you measure any circle you will always find this same number, which in mathematics is shown with the Greek letter **π** (pronounced as pi) and is approximately 3.14.

When two gears mesh their teeth profile is exactly the same, otherwise they would not be able to mesh! This also means that there is a relationship between the **number of teeth** and the **diameters** of the meshing gears. You can find this yourself. Divide the number of teeth of the large gear with the number of teeth of the medium gear. Repeat this for the large - small and medium - small combinations. Then make exactly the same calculations using the gear diameters. You will see that the ratios are the same in every case.

Velocity ratio

We have found above that a relationship exists between the diameters of the meshing gears, the circumferences of the gears and their number of teeth. When designing machines with gears it is very important to be able to calculate the **speed** and **torque** of the output shaft. Such calculations are based on the **gear ratio** (symbolised with **R**) or as it is more generally called **velocity ratio.**

$$R = \frac{\text{rotational speed of driver gear}}{\text{rotational speed of driven gear}} = \frac{U_{input}}{U_{output}}$$

$$R = \frac{\text{number of teeth of driven gear}}{\text{number of teeth of driver gear}} = \frac{N_{output}}{N_{input}}$$

$$R = \frac{\text{diameter of driven gear}}{\text{diameter of driver gear}} = \frac{D_{output}}{D_{input}}$$

Methods for calculating the velocity ratio of meshing gears

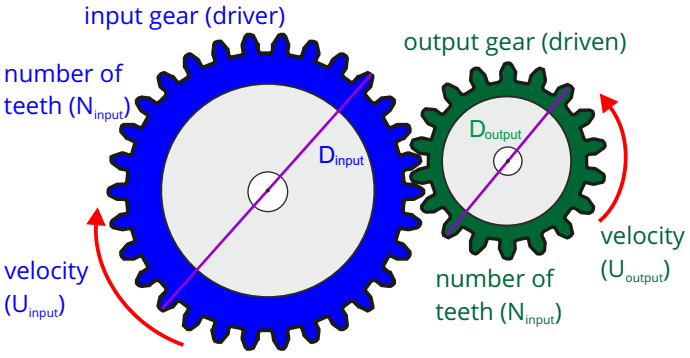


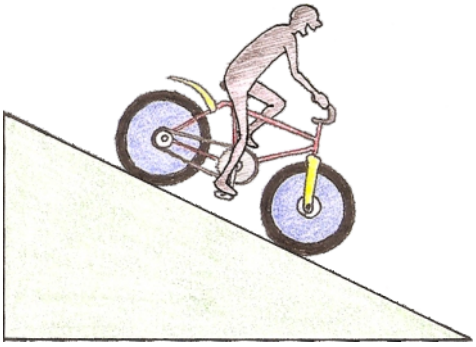
Diagram of meshing gears

The gear ratio can be found by dividing the speed of the driver gear with the speed of the driven gear. Most of the times we only know one speed, that of the driver gear (in rounds per minute, rpm), so we need other ways to calculate the gear ratio. This can be done by finding the ratio of the number of teeth or by calculating the ratio of the diameters of the meshing gears (see formulas on the left). Note that the speed ratio formula is inversed compared to the other two, because the speed of a gear is inversely proportional to the number of teeth and the diameter of the gear.

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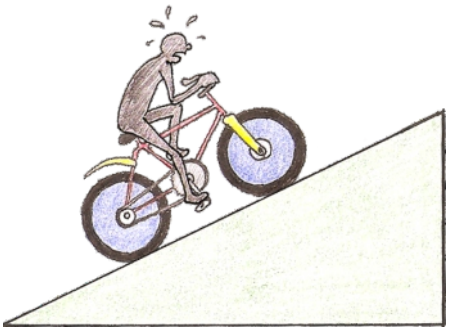
Forces and Torque

All simple machines are power converters, meaning that they transform speed or power accordingly. We can see this with gears if we examine the example of the bicycle. As you know all modern bicycles allow us to change gear and we can either ride fast or slow. When we are driving on a straight road or downhill it is quite easy to move, so we change gear to pedal slower and drive faster. This happens because our weight does not feel very heavy (due to gravity) and all our power is converted to speed.



Cycling downhill is easy and we can drive fast while pedalling slowly

When we are driving uphill our weight feel much heavier and we can not go fast. In fact, if you have experienced this you will know that the only way to move forward is to change gear so that we can pedal faster and move slower! Our power is now converted to torque instead of speed.



Cycling uphill is difficult and we need to drive slowly while pedalling fast

When we connect gears in such a way so as to **increase speed** we are losing torque, which means the ability of a force to rotate an axle. **What we gain in speed we lose in torque**. On the other hand, when we connect gears in such a way so as to **increase torque** and have more strength, we are losing speed. **What we gain in torque we lose in speed.**

Did you know?

The mathematical constant **π** comes from the initial of the Greek word "περίμετρος" which means circumference. Studies on the pyramids of Giza have found that the ratio of a pyramid's perimeter to its height is double π. Egyptologists claim that this was chosen deliberately for reasons we do not understand. In ancient Babylonian texts (1900 B.C), π is estimated within 1% of its real value! The first scientific proof of it's value was made by Archimedes who found a number between $3\frac{10}{71}$ and $3\frac{1}{7}$.

π

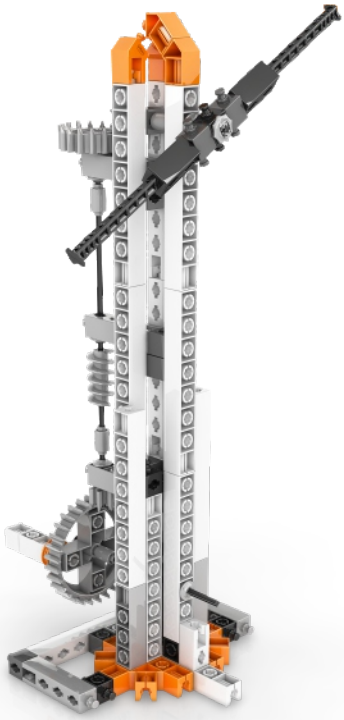
π = 3.141592653589793238 ...

Building Challenge

instructions can be found online

High speed fan: summer for many is the best season of the year with lots of sunlight, swimming in the sea and eating delicious ice-creams. But what happens if the temperature becomes too high and the air-condition is broken? People often use fans in order to cool down.

Build the high speed fan model and learn about the importance of the velocity (gear) ratio. Observe the rotating speed of the input (large gear) and the output (small gear). You can also change the arrangement of the gears and come up with a conclusion through experimentation.



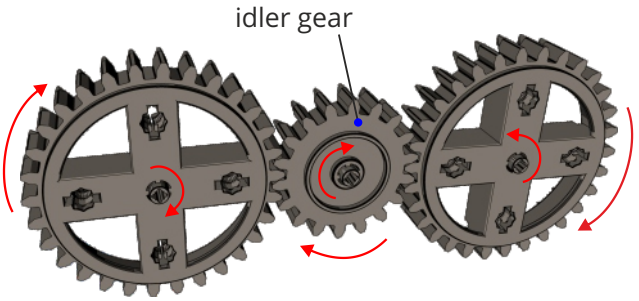
Engino® "high speed fan" model

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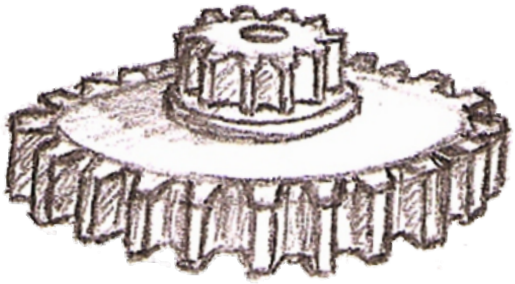
Types of gears

Idler gear

Even without a chain it is still feasible to make the gears rotate in the same direction. What we need to do is to use an intermediate third gear which will connect the two gears, transferring rotation from the driver gear to the follower. This gear is called **idler gear** and is often found in many gear systems where there is a need to re-reverse the direction of rotation or even shift the rotating shafts by a small distance without having to use a chain.



Gears rotating in the same drection because of the intermediate idler gear



A compound gear

Compound gears

When designing a machine engineers need to find ways to make it as small and as efficient as possible. An ingenious set-up to achieve this is by having two or more gears connected on the same axle, turning together as if they were a single block. This is called a **compound gear** and it is a very efficient way to combine gears in order to change speed by a huge amount, while also saving a lot of space! In the sketch you can see a large and a small gear that share the same center, so that a single axle can drive both.

In the picture depicting the inside of a clock mechanism, you see many compound gears connected together creating a large gear train, usually called a **gearbox.** In the case of gear trains with compound gears, we can still calculate the total velocity ratio by multiplying each velocity ratio of each pair of gears that mesh. In the sketch below we can see a compound gear which connects with two more gears, in both input and output directions, in order to change speed by a much higher amount than just 3 single gears connected together.



A gearbox inside a clock

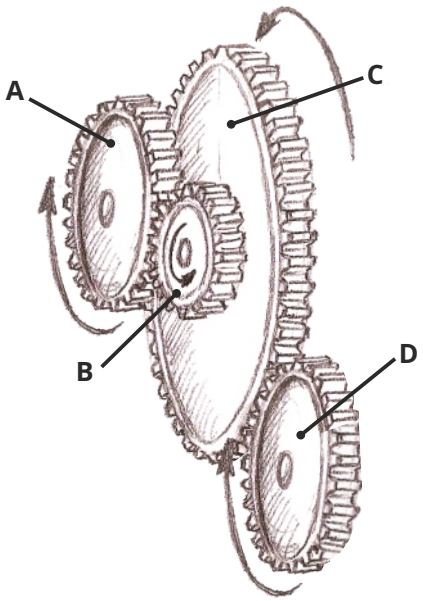


Figure of a gear train with a compound gear

Using this example, we can try to define the velocity ratio of the gear box. Gear **A** is the input (driver) of the train. It drives gear **B** which is fixed with gear **C** which in turn becomes the driver for the gear **D** (output of the gear train). The total velocity ratio (V.R.) should be:

$$V.R._{total} = V.R._{A/B} \times V.R._{C/D}$$

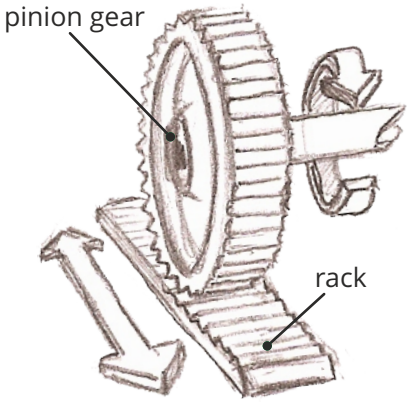
where $V.R._{A/B}$ is the velocity ratio of gear A to gear B
$V.R._{C/D}$ is the velocity ratio of gear C to gear D.

In general, the total velocity ratio is the product of the individual velocity ratios of each gear combination that mesh (not the ratio of compound gears e.g. B:C).

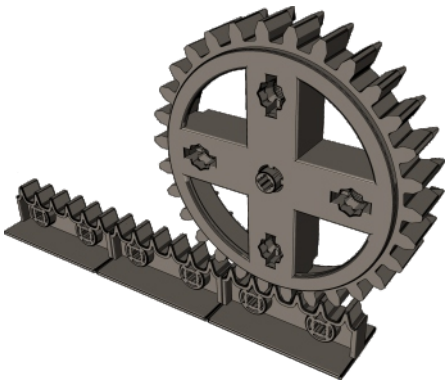
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Rack and pinion

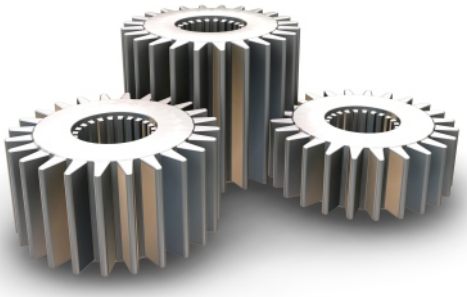
In many machines there is a need to convert rotational motion to linear, that is in a straight line movement. Other machines can do this as well such as the crank or the cam, even linkages, however, gears can do it with precision allowing full control at any position! These gears are called **rack and pinion**.



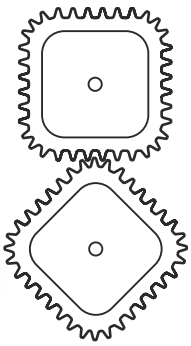
The rack and pinion gear system



The Engino rack and pinion gear system



Spur gears



Non-circular gears

Other types

There are more types of gears, each one developed for a particular application. So, we can have standard **spur** gear, the **bevel** gear (explained in the next page), the **crown** gear and the **worm** gear. The spur gear's teeth can be modified for maximum performance and such designs are known as **helical** gears because their teeth are curved. We can even find gears that do not have the usual circular shape, used when speed variations are needed or axle oscillations such as in textile machines.

Did you know?

Another gear set-up that can have special applications is the **planetary gearing**, also called **epileptic gearing**. This is a complex set-up of gears that consists of one or more outer gears (called planet gears), revolving about a central gear (called sun). If you see in the picture below there is also an outer ring gear (called annulus) which meshes with the planet gears. A great advantage of this type of gearing is that it is compact and can transfer big loads.



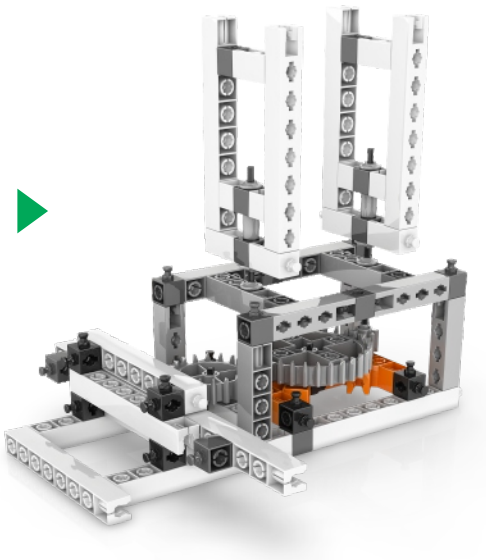
A planetary gear system

Building Challenge

instructions can be found online

Rotating sign post: a sign post can have multiple advertisements in one place. This is made possible by having long cuboids that contain a part of an ad on each rectangular face. When the cuboids rotate they synchronise their faces in order to show the next ad.

Build the rotating sign post model and learn how the rack and pinion works, transforming linear motion into rotating motion. You can observe also the interchanging of advertisements and maybe you can put some interesting ads yourself!

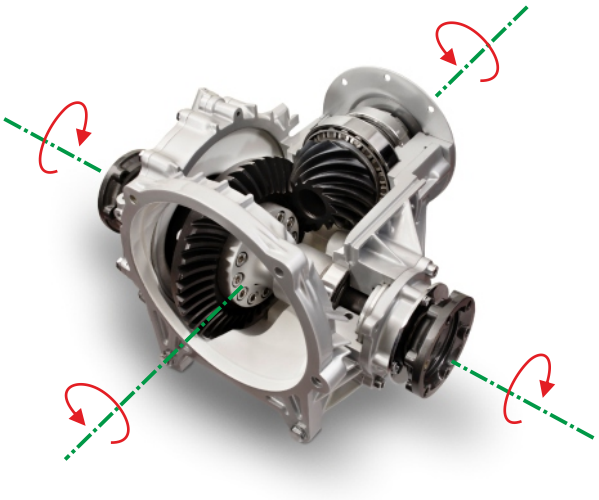


Engino® "rotating sign post" model

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Changing axle's direction

In most machines the output direction of movement is not the same as the input direction. This is yet another feature of simple machines: the ability to change direction of motion. An ideal mechanism for this is linkages. However, when high speed is required with high precession, gears offer the best solution. How should the gear's shape be modified to effectively transfer rotation in a 90 degree angle?



The inside of a motor transmission with bevel gears of more efficient design

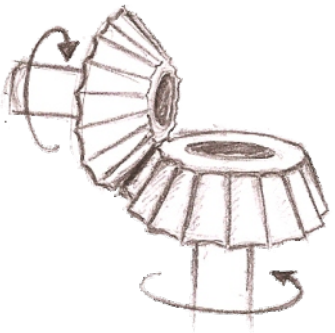
The standard gears that mesh next to each other are called spur gears. However, the Engino gears are also able to transfer rotation in a 90 degrees angle, like bevel gears do. This type of gear is similar to peg gears used in mills in older times because it was easy to be manufactured from wood. Nowadays, such gears can be made with precession but they are inferior to bevel gears as they have more energy loss due to friction. But, like all machine elements every design has its purpose. The Engino gears belong in the category of **crown gears** because of their special shape.

Building Challenge

instructions can be found online

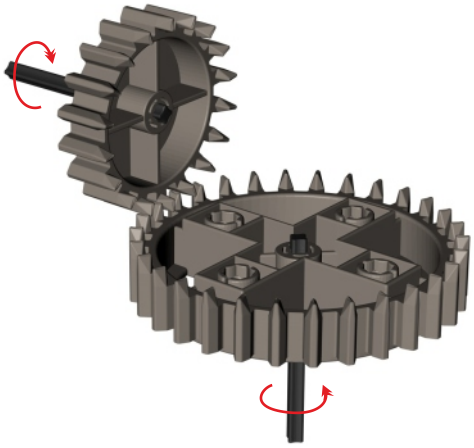
Hand blender: who wouldn't like a nice chocolate cake? Cooks use hand blenders with bevel gears, in order to mix different ingredients (eggs, flour, sugar, milk etc) creating delicious cakes. By hand they are able to control the placement of the blender as compared with the electrical one.

Build the hand blender model and find out how bevel gears work in order to change the direction of motion, while gaining speed from the gear's arrangement.

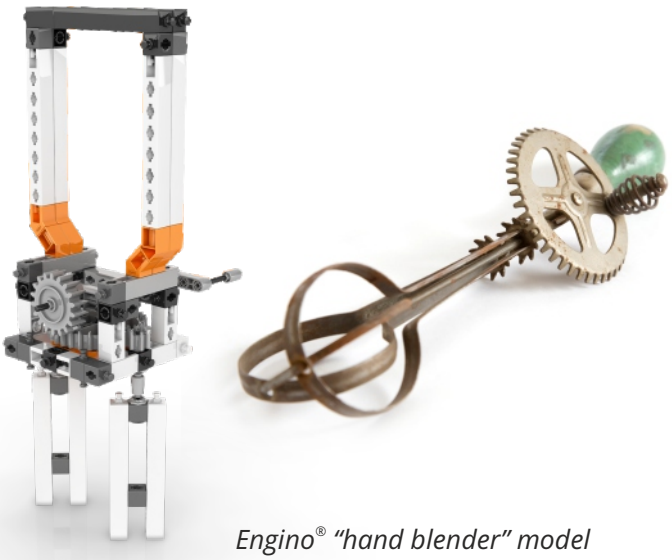


Gears transferring rotation in a 90 degree angle

The common characteristic of the left and top picture is the shape of the teeth. This is a V shape which enables gears to mesh effectively when perpendicular to each other; that is when being at a 90 degree angle. This type of V-shaped gear is called **bevel gear** and it is one of the most useful type of gears as it has numerous applications. Take for example the traditional hand drill. This type of gear enables us to turn the crank in a direction that is easy for us. Do you notice also the difference in the diameter of the two bevel gears? Why do you think the hand drill gears are not of the same size?



The Engino® crown gears

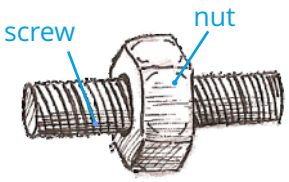


Engino® "hand blender" model and a real hand blender

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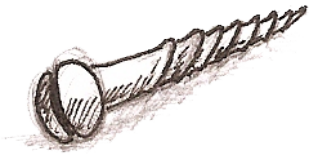
Definition of screw

A screw is simply a cylinder with a thread at its outer surface, also called a helical ridge. Screws can have a flat or a pointed end, and are categorized according to their application. The most common use of screws is as **fasteners**, enabling connection of different materials.



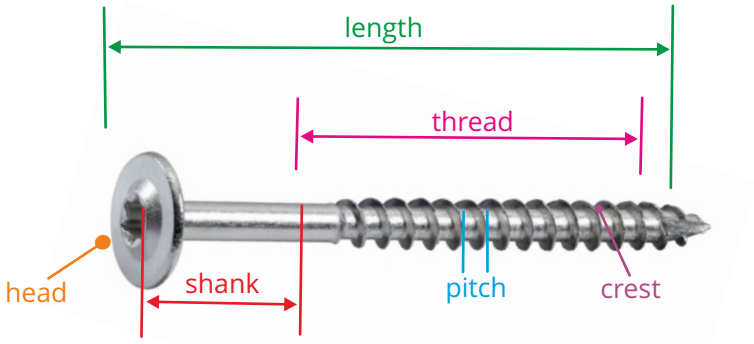
A flat end screw with a nut

Screw **threads** convert rotational motion or force to linear when the screw is driven on a material. Common screws have a **head** that does not allow them to be driven deeper than their length. **Screw length** depends on the head type; flat head screws are measured from the top of the head up to the bottom; but, round head screws are measured from beneath the head up to the bottom. The portion between the screw head and the point where the thread begins is known as **shank**. The distance between any **crest** of the thread to the next one is called **pitch**.



A screw with a pointed end

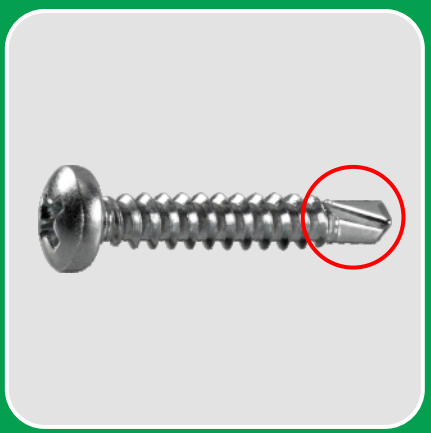
However, screws can also be used in conjunction with a **nut** or a tapped hole. When the screw rotates, it moves through the nut which has the same internal threading, converting the rotational motion to linear, that is in a straight line. Screws are the basis of worm drives which we will examine later on.



The basic parts of a screw

Did you know?

Throughout the centuries, hand drills have been improved in order to become more user friendly. The ancient Indians and Egyptians used "anchor drills" to pierce gemstones. Nowadays, electric hand drills offer accuracy and speed. When fastening thin metal plates there is no need to make a hole first and then pass the screw. This is done at the same time as engineers had the innovative idea to combine drill bits and screws, creating an invention called **self-tapping screw.**



A self tapping screw with a drill-shaped edge

Building Challenge

instructions can be found online

Folding platform with screw: cleaning the windows or installing posters on tall buildings can be very dangerous tasks! These jobs can be achieved a lot easier by using a folding platform. The device uses parallel linkages and gear-screw mechanisms to raise its platform at a desired height.

Build the folding platform model and combine linkages with screws. Set the platform on any height and try to push down with your hand in order to discover a feature of the screw. You can also find the relation between the number of crank rotations and the travelled distance of the nut.



Engino® "folding platform" model

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Types of screws



A standard screw

Standard screw with a sharp end point. This type is mostly used to fasten a plate of metal or other material on a wooden article. This plate usually has a hole which allows the screw to pass through.

The **screw** with a flat end point that is combined **with a nut.** This is usually used to secure heavy objects together or metal sheets. These materials have aligned holes.



Screws with nuts on a water pipe



A set screw

The **set screw** is similar to the nut type but without the head. It is used to secure one inner object relative to the outer. The outer object has a threaded hole and the set screw passes through and is tightened against the inner object

The **drill bit** is a type of screw that, instead of fastening objects together, it creates a cylindrical hole in the material.



Drill bits of different sizes

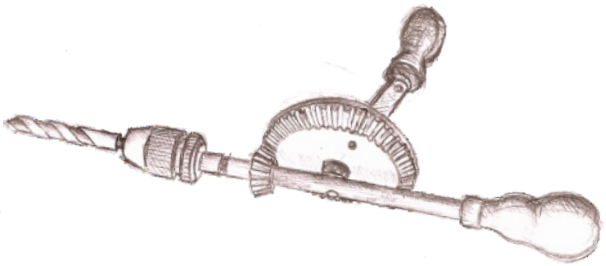
Building Challenge instructions can be found online

Hand dril: the drill is a tool with a sharp screw (bits) that rotates in order to open holes on various materials. We can find hand drills, similar to the one in the next picture, for piercing soft materials (eg. wood) and electric drills which can open holes in iron or even granite.

Build the hand drill model and observe how the gear-screw combination works. You can use it to make holes in soft sand or paper if you wish.



Engino "hand drill" model



Manual hand drill

Size of screw pitch

The size of a screw pitch differs from screw to screw. The larger the distance between crests, the faster the screw will move inwards. Faster movement means that a higher force will be required for screwing, therefore screws with a large pitch are appropriate for soft materials such as wood screws or chipboard screws. A good example of a screw with very wide threading is the **corkscrew,** used for opening wine bottles.



The bottle opener is actually a screw!

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Head shape

If you pay a visit at a DIY store you will see many different types of screws, of different sizes, threading and also types of head! A well known type of screw head is the Phillip's screw with a **cross-shaped** recess like the plus sign (+). This enables us to apply force with a screw driver without any slippage.



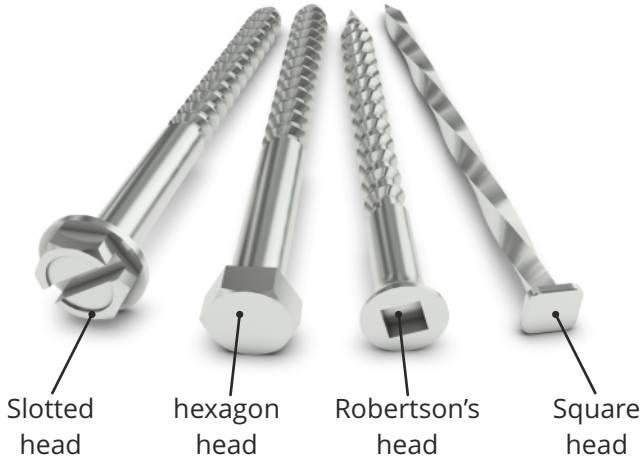
A slotted head screw

Square head screws consist of two types, depending on the position of the shape. One type has an external square-shaped head while the other one, known as **Robertson screw**, has a head with a square hole. A similar type is the **hexagon head** and this can also be seen in two types, **internal and external.** The hexacon external shape is used for larger screws for which a big force is needed to screw them, for example to connect together two large beams of wood.



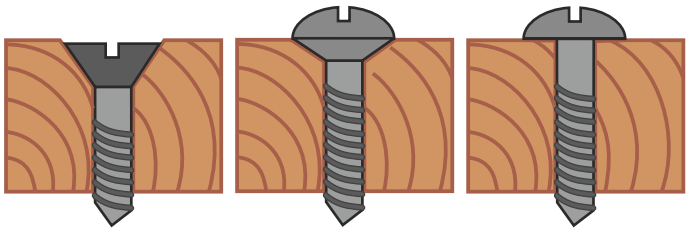
A cross-shaped head screw

Another very common type of screw is the **slotted head screw** which has a straight recess, same as the minus sign (-). This type has a disadvantage over the cross head as the screw driver may slip easily but it requires less head thickness and looks nice on decorative elements.



Square and hexagonal head types

The type of head also depends on whether we want the head to protrude or not from the fastened materials. For example when a metal sheet is screwed, the screw head can not sink in the thin metal, therefore a head with a flat profile is needed. On the other hand, when fastening a wooden piece which is relatively soft, then a screw with a tapered head can be used, which will allow the screw to completely sink in the material. Of course, sometimes we want screws to look nice, for example those supporting mirrors, so as decorative elements they are designed with more rounded heads.



A countersunk head screw sunk in wood

A raised head screw

A round head screw

Did you know?

The ship's propeller is actually a screw! Up to the 18th century all ships were powered by paddles and sails. In 1775, David Bushnell invented the submarine called **Turtle** and he was the first to use hand-powered screws for vertical and horizontal propulsion. However, the first practicable screw propeller was not invented until 1827 by the engineer Josef Ressel. James Watt combined them with steam engines on ships and until the 20th century they completely replaced paddles and sales.



Screw propeller on a boat

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Tools for screws

Many different tools were designed in order to help people fasten materials, depending on the shape of recess on the head and the shape of the head itself. The most known tool is the **screwdriver** which can be used for both slot and cross-head screws. Screwdrivers can be manually driven, such as those in the pictures at right, or electrically. In fact, nowadays electric drills come with several drill bits and replaceable screw drivers, enabling us to use a single machine tool for a variety of applications. All the screws that can be screwed with a screwdriver, electric or manual, are usually small.



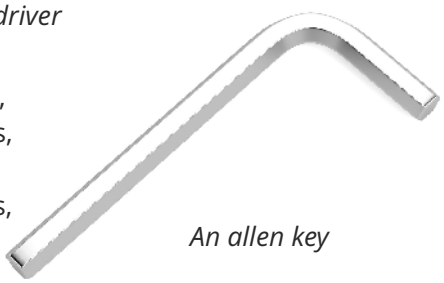
A cross head screwdriver

A slot head screwdriver



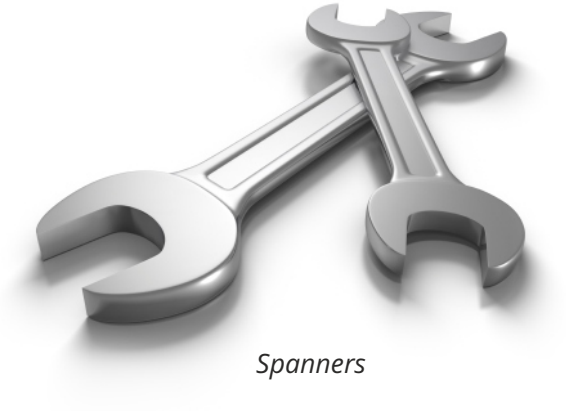
A battery operated screw driver

Medium size screws, especially set screws, are tightened using hexagonal wrenches, most commonly called **allen keys**.



An allen key

For larger screws where a bigger force is required, we need to use different tools that work as levers. Slotted heads or even cross shaped ones do not have enough surface to allow large forces to act. This is when the screws with square shaped heads are needed! Or, better yet, the more common hexagonal shaped heads. The tool that can tighten these screws is called **spanner** and like allen keys and screw drives, it comes in many different sizes. Spanners also tighten the nuts which also have a hexagonal shape. In the case of a bolt and a nut, two spanners are needed to tighten the screw. One is holding the head and the other is rotating the nut in the opposite direction.



Spanners

Engineers have also devised two very useful wrenches that make the job of screwing much easier. The first one is the **adjustable wrench.** This tool has an adjustable mouth that can open and close to fit the heads of a big range of screws. The tool is functioning based on the principles of screws, utilizing a worm drive mechanism!



An adjustable wrench

The other ingenious tool is the **socket wrench**, which is more commonly called a **ratchet.** This tool uses separate, removable sockets to fit many different sizes of nuts and bolds! It was invented in 1863 by the American J.J. Richardson and it has been refined today to be one of the most used tools. Another innovation of the socket wrench, is that it is using a ratchet mechanism (discussed later on) to enable continual screwing, unlike standard wrenches that have to be repositioned after every turn to give us good leverage.



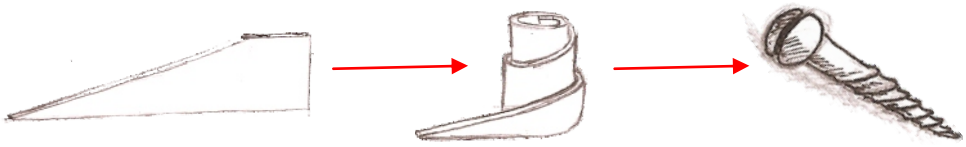
A rachet

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Mechanical advantage

Screw as an inclined plane

Screws can be considered as a modified version of an inclined plane as their threads are a spiraling inclined plane around a cylinder.



A screw is basically an inclined plane wrapped around a cylinder

$$M.A. = \frac{S}{h} \qquad M.A. = \frac{\text{effort's distance}}{\text{load's distance}}$$

Formulas to calculate the M.A. of an inclined plane

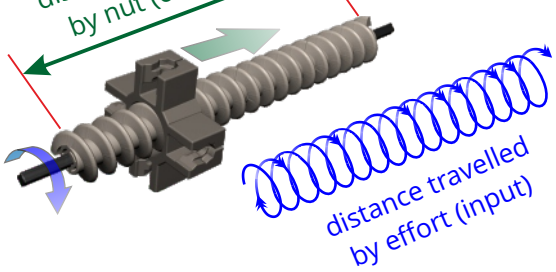
M.A. of the inclined plane

The mechanical advantage indicates the extend at which a simple machine can multiply our input force. In the case of inclined planes, the M.A. is defined as the ratio of the length of the plane to its height or generally the ratio of the output force to the input force.

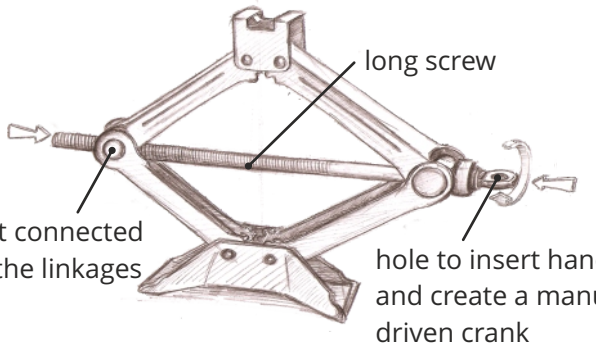
M.A. of the screw

We can apply the formulas above to find the M.A. of the screw. The less steep an inclined plane is, the more dense the threads will be when it is wrapped around a cylinder. The **pitch**, that is the distance between two crests, is important to the function of the screw and to it's ability to convert motion and force. As it is not always convenient to measure the threaded length of the screw, we can calculate the M.A. by measuring only the diameter of the screw and the pitch as shown here.

$$M.A. = \frac{\text{circumference}}{\text{pitch}}$$



Mechanical advantage of the screw



A car jack

One of the most important features of screws is that they can offer a big M.A. without occupying too much space. We can find many small machines that provide incredible output forces, such as the car jack. This particular machine is operated by a manual crank and enables us to lift an entire car in order to change the flat tire! The more dense the threads of the screw, the bigger the M.A.

Building Challenge

instructions can be found online

Vice: The clamp or vice is an essential tool used to hold or secure objects tightly together, preventing movement or separation. It is often used on workbenches and it works with a screw that rotates until desired height is reached.

Build the vice model and use it to secure light objects in place. Observe how the screw and nut mechanism works, by preventing the securing part to move back.



Engino® "vice" model



A G-type clamp

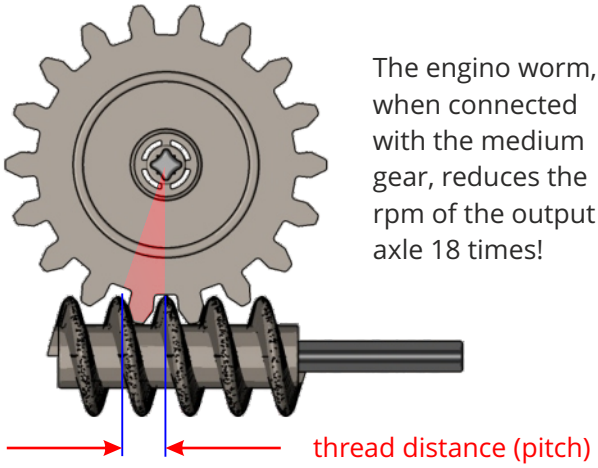
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Worm drives

The Engino screw can have two functions, one in combination with a nut as a screw, and the other in combination with ordinary gears as a **worm**. The combination of a worm and a gear is called a **worm drive** and this setup, as compared to standard gearboxes, takes much less space, increases torque and also changes the direction of the rotating axis by 90 degrees. Generally, by using a worm drive we can lower speed to a great extent while increasing the output force.



A worm drive of an old shipyard crane



The engino worm, when connected with the medium gear, reduces the rpm of the output axle 18 times!

The Engino worm connected with the medium gear

The mechanical advantage, as defined in the previous chapter, is the factor by which the output force is increased. There is another term widely used with gears, and this is the **gear ratio**. The gear ratio, expresses the amount of speed decrease (or increase) of the driven gear as compared to the input shaft. This is in fact the same as the mechanical advantage, but the term gear ratio emphasizes on speed, while the mechanical advantage on force. In general, for the worm wheel to rotate one full revolution, the worm has to rotate as many turns as the number of the wheel's teeth.

Worm drives have many applications where speed reduction by a great extent is required (for example in motor gearboxes). One significant advantage of worm drives is that they only operate in one direction, that of the worm. If you attempt to turn it the other way, the worm wheel will lock and not move at all! This can be very useful in certain applications where we need a safe one-way operation, for example in cranes where we do not want the load to drop by its own weight. On the other hand, worm drives have the disadvantage of increased friction so they require continuous lubrication.



An old worm drive used on a machine

Did you know?

Another application of worm screws is that of being the tuning mechanism for many musical instruments, including guitars, double-basses, mandolins and bouzoukis. The ability to reduce movement by a great extent, enables musicians to fine-tune their instruments. This is made possible because even a large movement by the musician's hand translates to a minimal increase or decrease of the string's tension.

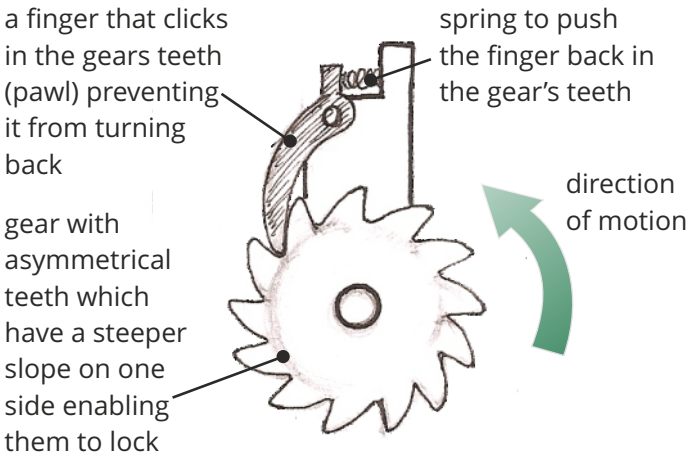


Worm drives on a guitar's headstock

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Rachet mechanism

On the Engino "crane with rotating arm" model (experiment page 24) there is a pivoted part that meshes into the teeth of the rotating gear, preventing it from returning back under the pull of the load. This assembly is a simulation of the **ratchet mechanism** which is used in machines where movement in one direction is needed. Similar to the worm drive that locks and does not allow reverse input motion, the ratchet mechanism also works in one way. In the right figure you can see the three main elements of the ratchet mechanism: the spring and the pawl that meshes on a gear with asymmetrical teeth.



The rachet mechanism

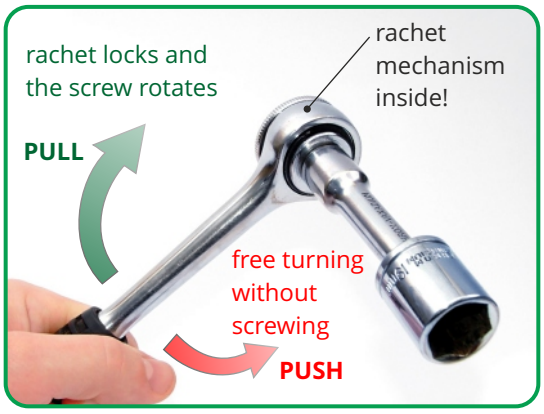


A miniature ratchet mechanism

The pawl easily slides up and over the gently sloped edges of the teeth, with a spring forcing it into the depression between the teeth as it passes the tip of each tooth. When the teeth move in the opposite (backward) direction, the pawl will catch against the steeply sloped edge of the first tooth it encounters, thereby locking it against the tooth and preventing any further motion in that direction.

This is a valuable feature especially when safety is involved, as in the example of raising a heavy load that would drop if not held in place by the ratchet.

The rachet is also a very useful mechanism in many tools such as the **socket wrench**, allowing us to continually turn a screw in one direction. How? By continually pulling and pushing the handle without having to re-grip the head of the screw. With every pull the ratchet locks and applies force tightening the screw; the ratchet's handle moves freely until our hand is again in a convenient pulling position. Another clever feature of the socket wrench is that you can reverse the ratchet locking direction enabling you to unscrew the screw, applying force in the pushing direction instead of the pulling direction!



The socket wrench in operation

Building Challenge instructions can be found online

Crane with moving arm: cranes are used in construction sites where there is a need to lift and move heavy objects. Usually the rotating mechanism contains gears, while the lifting arm contains pulleys to maximise the mechanical advantage.

Build the crane with moving arm model and try to add a rachet mechanism, similar to the rotating arm model. Note that this works with the use of crank, worm drive and gear.



Engino® "crane with moving arm" model and a real crane

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Structures

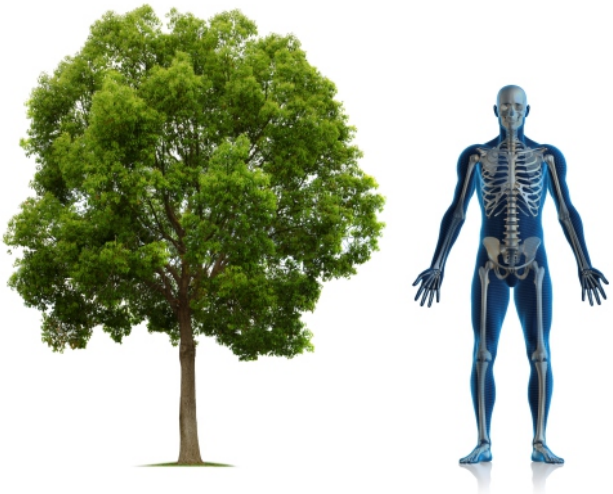
What we will learn

Have you ever been across a bridge? Maybe you crossed the Rio-Antirion bridge in Greece or the Tower Bridge in London. What about other famous landmarks? Maybe you have been inside the Colosseum in Rome or on top of the Eiffel tower in Paris. But, do you know what does your school, a tree log, a cave and your house have in common? They are all structures! Almost everything that is around you right now is a structure; even your body is supported by one! Not only people build structures. Animals also create their own things to cover whatever needs they might have, such as a bee-hive for the queen bee! Moreover, natural occurrences too result into structures as we will see next.



The Colosseum in Rome, Italy

This booklet of **Discovering STEM: Buildings & Bridges** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about their applications in daily life. Discover all the scientific principles applied through **experimentation**, with step-by-step guides and thought provoking exercises. Follow the **building instructions** to build exciting models such as **a house, a truss bridge, a lower truss bridge, an arch bridge**, **a cable-stayed bridge** and **a suspension bridge**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.



Tree logs and skeletons are natural structures

History of buildings & bridges

Buildings and bridges belong in the general category of structures, so it is necessary to make a broader reference to them throughout the booklet. Structures have existed for as long as life itself. Every living thing needs a structure to support its weight. A tree log, with its branches, is a natural structure that supports the leaves and fruits of the tree; your skeleton supports your muscles, nerves and everything else in your body, therefore is also a structure. Besides natural makings there are also man-made constructions that existed since people became aware of how to build, using primitive materials.

Possibly the first structure ever built by man is a bridge; and by bridge we do not mean a big and fancy suspension bridge like the Golden Gate Bridge in the USA. A bridge can be also a log over a stream or a river. Something as simple as that is called a beam bridge. Early humans probably used them to cross narrow streams and canyons long before they built houses or settlements.

As humans started settling in different places for agricultural purposes, people needed to built residences to live. These were small round or square houses made out of stone, wood or brick.



Boy using a natural bridge

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Pyramid of Kukulcan El Castillo in Mexico

A building shape favoured by almost all ancient civilisations was the pyramid. People wanted to reach as high as possible and make magnificent creations to praise their gods or bury their kings. They understood that a practical way to achieve this is by starting with a large base and moving upwards by adding less and less materials, converting on a single point at the top, hence the pyramid shape. These structures can be found all over the world in different periods of time: from Asia (China, India) to Africa (Egypt, Mesopotamia, Nigeria) to Europe (Greece, Spain, Italy) to Central America (Mexico) and South America (Peru)!

It should not come as a surprise that the tallest structure in the world for more than 3800 years was the Great Pyramid of Giza. Completed in 2560 BC at a height of 146.5 meters, it is the biggest and oldest of the three pyramids at the Giza Necropolis. Its record was surpassed by the Lincoln Cathedral, in Lincoln, England, with a height of 160 meters, in 1300 AD. The title was then won by a skyscraper in 1930, by the Chrysler building, with a height of 319 meters, although its record was short-lived (only 11 months) when it was overtaken by the Empire State Building in 1931 of 443 meters.



The Great Pyramid of Giza

Did you know?

One of the world's most famous cultural monuments, the Parthenon in Athens (Greece), makes of a great optical illusion! Its columns are supposed to lean outwards, but they actually lean slightly inwards! This ingenious parabolic design was mostly intended to reinforce the building against earthquakes. The Parthenon was built during 447-438 BC on the top of the Athenian Acropolis and served as a temple dedicated to the Greek goddess Athena.



Parthenon in Athens, Greece

Advancements in all fields and population growth worldwide created the need for bigger and stronger structures. As technology progressed, better materials became available, like concrete and steel, helping humankind to create skyscrapers, bridges, monuments and almost everything else you see around you! For example, the tallest skyscraper in the world (until 2015 at least) the Burj Khalifa in Dubai, has an extraordinary height of 828 meters! It also holds the record for the tallest man-made structure ever! That is why it is called as "the vertical city"! Besides building all across Earth's land, people have managed to create structures inside the sea, flying in the air or even wandering in space. The next big step will be the creation of structures in other planets, where people will finally be able to inhabit!



The Burj Khalifa skyscraper in Dubai

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Definition of structure

A structure is any configuration, natural or man-made, that supports a weight. You may think that almost everything falls into this broad definition, because all constructions support something, even if it is simply their own weight! However, not all structures are the same as they are divided in many categories. Next we will examine three basic distinctions between them: 1) whether structures are built by man or whether they are natural, 2) their profile, meaning in what way they are actually built and how they support the weight and 3) whether they are designed for people to live in them or not.



Steel structure made to support a roof



Eggs are natural structures

Natural structures are those which occur naturally, or weren't built by man. Examples of these are the tree log we discussed previously, the egg, our skeleton and many more.

Man-made structures are those which are built by man. These are the structures you see around you, live in them, you move with them and you admire them! It is your house, your parent's car or a skyscraper.



Man-made skyscraper



A termite hill is a structure made by insects

An interesting combination of the two categories is structures built by animals. Anthills, termite hills and beaver dams are perfect examples of this, since they are not naturally occurring structures, but they are also built by someone other than humans. In fact, most of our structures are based on designs taken from these animal-built ones. Scientists study the way animals' and insects' creations withstand weather conditions and how they are used for utilising their purpose. An example is a spider's web, that has a special shape, colour and texture in order to catch pray and warn the spider about it.

Frame structures are structures that consist of many pieces connected together, called **members.** They can be both natural and man-made. The triangle, square and arch shapes are parts of a frame structure. Engineers prefer mostly the triangle shapes, as they are more stable than square shapes. The reason for this is the fact that any force that is applied on a triangle is transferred to its corners, which are its strongest points. The arch consists of small wedged-shaped elements. It is built in a way that transfers all the force and pressure on the base of the arch, thus once the arch is completed it becomes very stable.



Frame structure used while building a house

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A car hood is a shell structure

Shell structures are structures that consist of a solid unit that supports weight from the outside. This means the load is in the inside of the structure. A great example of this structure is the egg shell, which supports the chick from the outside. Shell structures tend to be lighter than frame structures. There are also many examples of structures that are a combination of shell and frame ones, like the hood of the car, which is a shell structure but has a frame underneath it to provide greater strength.

The final category is that of **buildings** and **nonbuildings**. A building is any structure in which people can live in (hotels, houses, etc), while a nonbuilding is a structure in which people don't live continuously (like cars, bridge, cranes, etc). However some structures, like lighthouses and power stations, which are not continuously occupied, are classified as buildings for safety purposes.

The most important elements of structures are the materials that they are made out of. When we build our houses and skyscrapers we want them to be strong under all types of forces. These are explained in the next page.



A house is a building, while a bridge is not

Did you know?

Some materials are **elastic,** which means they can change their shape temporarily, without permanent damage. A great example of this is rubber which bends and changes its shape without breaking, unlike wood, which when bent will break apart. Of course, there is a limit; if enough force is exerted on them, even the most elastic materials will eventually deform and finally break. Other examples are springs, used in cases that temporary deformation is needed (e.g. car suspensions).



Springs are elastic

Building Challenge

instructions can be found online

Pyramid: we have already examined how important the pyramid shape was for ancient civilisations. Nowadays, this design is not preferred anymore as it is impractical. However, there are several examples of modern pyramid structures around the world such as the glass pyramid outside the museum of Louvre in Paris, the Luxor Hotel in Las Vegas (USA) and the Transamerica Pyramid in San Francisco (California, USA).

Build the Engino pyramid model and use it as a lovely decorative piece. You can also modify your model according to different pyramid designs that you like. A good example would be the Pyramid of Kukulcan El Castillo with the square top and stairs on its sides.



Engino® "pyramid" model

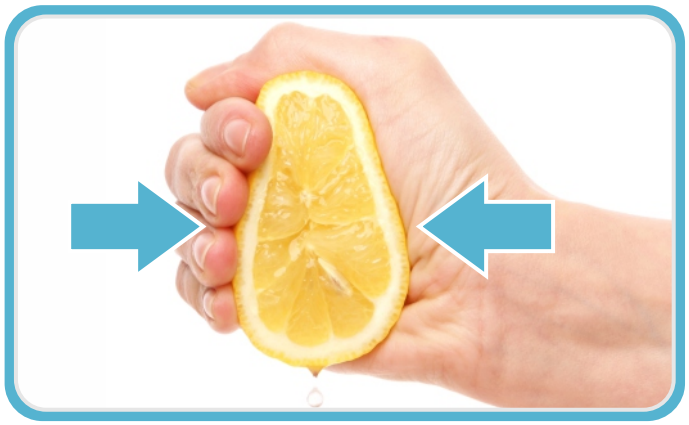
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Types of forces

We cannot see forces, but we can understand their effects when they are applied. When we pull a rubber band we can see that it stretches. A can is squeezed by the force applied from our hand. Generally, in order to change the shape or the motion of an object, a force must be applied on it. But not all forces have the same effect. Some cause the body to be pulled apart and therefore make it longer; others shrink it, while others break it apart. It all depends on the direction the force is applied and on the properties and strength of the material as explained below.

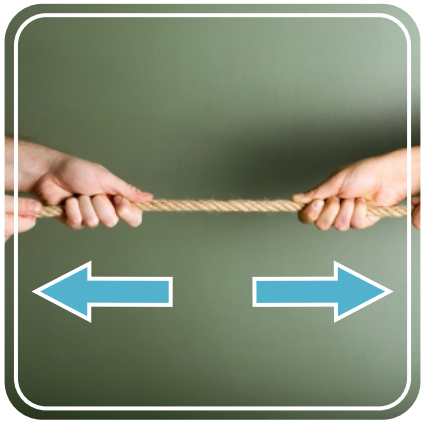


We can observe the results of a force



Compression forces on a lemon

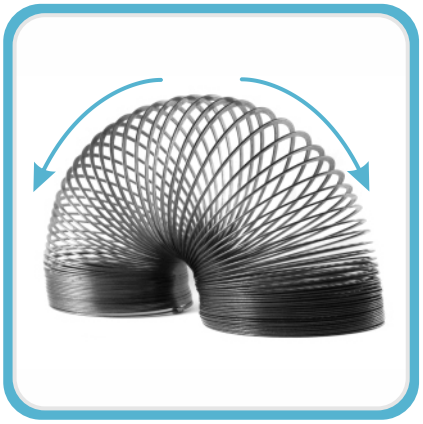
Compression is the force that squeezes a material. If the material is elastic it will shrink. The direction of the forces is inwards, along the axis of the body. Example of compression can be the squeezing of a lemon or pushing of a metal spring. The latter is also a great example of a material that changes its behavior when its shape is different. A straight metal rod is very strong under compression, with almost no visible change in its length. However, when it is shaped like a spring, it is not as strong under compression, but still returns to its original shape when we stop applying the force. Materials strong under compression are wood, steel, reinforced concrete etc.



Tension forces in a tug-of-war game

Tension is the force that pulls a material apart. It is the opposite of compression, since the direction of the force is outwards. Materials that are strong under tension are wood, rope, steel, cables etc.

Bending is the force that bends a material, basically a combination of the two forces mentioned above. When an object is bent down, its top side is under tension and its bottom under compression



Bending forces on a spring



Shear forces on a ribbon

Shear is the force that tears a body. The direction of the two forces is opposite to each other, which causes parts of the body to move in opposite directions, and thus break it apart.

Torsion is the force that twists a body. It is similar to shear, but now we have parts of the body doing circular motion, but in opposite directions. Eventually, the body will break apart, as with the shear force.



Torsion forces on a bag

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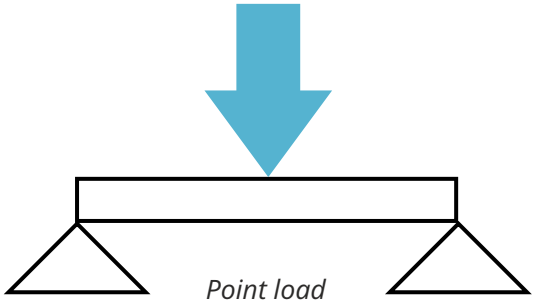
Types of loads

We have learned earlier that a structure is anything that supports a weight. The weight is also called a **load.** Basically, a load is **any force that acts on a structure,** being the weight of a car, a train, the force of the wind or the water (in case of a bridge), even the weight of the structure itself. But there are many different types of loads, depending on lots of things: who exerts the force, where the force is exerted and what kind of force is it.



A person carrying a box is basically carrying a load, since the weight of the box is applied on the person!

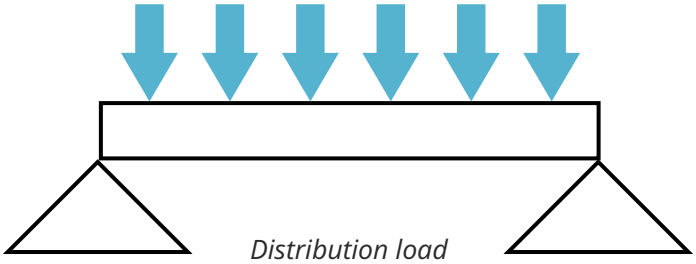
Loads can be either **static** or **dynamic,** depending on whether the force acting on the structure is constant, or changing slowly, or dynamically (changing fast).



Point load

If the force is exerted at just a point of the bridge, then that load is called a **point load.** Realistically, this is not possible since perfect points do not exist in real life! However, if any load is exerted in a relatively small area of the structure, then it behaves as point load.

If now the force is not applied at a single point but over a wide area of the structure it is called a **distribution load.** The force of the point load and the distribution load can have the same value but because the point load is only exerted at one point of the structure, meaning that all the force is concentrated at one point, the structure can fail.



Distribution load



Working load is the weight of the bridge and the cars on it

Dead Load is the weight of the structure itself, thus it is constant over time. In this aspect, the dead load needs to be as small as possible, so that the structure is lighter and more cost-efficient.

Live Load is any weight that is exerted on the structure that is not permanent. This includes people, animals, cars and anything else that will exert a force on the structure for a short period of time.

The combination of the dead load and the live load is called **working load.**

Shock Load is the load exerted by heavy and fast-moving objects. These objects produce a force called shock, which adds up to their weight and increases their total load. For example, when a train crosses a bridge its shock load is very big, sometimes bigger than most bridges can handle.

Environmental Load is the load that is exerted by any natural phenomenon. Examples for this are the wind, rain, snow, earthquakes and many more. For this, engineers must consider the location of the bridge, the weather conditions in the area, any history of seismic activity, the currents of the waters etc.



Environmental load: a bridge covered in snow

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Types of bridges

Any structure that is designed to provide passage over any kind of obstacle (rivers, canyons, even seas) can be called a **bridge.** Bridges come in all shapes and sizes. From the big and complex, to the simplest types of bridges, they are all part of our lives in many ways. Travelling long distances is made easy with them, as well as overcoming any obstacles in the way. They have been created even by ancient civilizations and they are probably the first man-made structures ever built. There are many different types of them, each with its own characteristics, advantages and disadvantages.



The Newport bridge in Rhode Island, USA



A beam bridge connecting a highway road

Beam bridge

A **beam bridge** is the simplest type of bridge. It consists of a number of **vertical supports** (pillars or piers), which hold a beam (the **deck** of the bridge). The weight of the bridge, as well as any load, is entirely supported by the pillars. The deck of a beam bridge is susceptible to bending, so the **span** of it (the distance between two successive piers) has a limit of how long it can be. One way to reduce bending is to increase the thickness of the deck, but this increases the weight. For these reasons, beam bridges are used to span relatively small gaps.

Truss bridge

A **truss Bridge** is similar to a beam bridge but with one very important difference: the deck of the bridge is supported from above or below with triangular and rectangular elements. This way, the deck doesn't bend. Again, the weight of the bridge, and any load, are supported by the piers, but now the triangular shaped elements are under tension and compression instead of bending, offering rigidity to the bridge and the deck. The materials used for this structure are wood and steel, keeping it relatively light and cheap.



A truss bridge supported with trusses from above



A stone arch bridge

Arch bridge

An **arch Bridge**, as the name denotes, is built with an arch to support the weight of the bridge. It can contain one or more arches, where each arch can be built either under the deck, over the deck or even with the deck passing through it. Arch bridges are very stable once they are completed and can support a lot of weight, although they are quite heavy and cannot span over large distances. Arch bridges made out of stone, were the most common bridges in ancient and medieval times.

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An arch consists of wedge-shaped blocks (usually stones or bricks) put next to each other to form an arch shape. The top block of the arch is called the **keystone** and it supports the weight of the whole bridge. It is the most important piece of the arch, providing stability. The load on the bridge is transferred to the bottom of the arch to the ground and back, whereas three forces are applied on it: compression on the top of the bridge, tension on the bottom (although the tension on an arch bridge is negligible) of the bridge and a shear force at the two ends of the bridge.



The Ponte Vecchio bridge in Florence, Italy



A series of keystones

To counter-balance this, huge structures need to be placed on either end to exert a force opposite to the shear, so that the arch won't open. These structures are called **abutments,** and they are as important as the arch itself since they stop the arch from collapsing, thus providing stability.

A great example of an arch bridge is the famous "Ponte Vecchio Bridge" in Florence, Italy. Its name means "old bridge" in Italian and it was built during the medieval times, spanning the Arno river. A fascinating fact is that the bridge has shops along its deck that are still in use today by artists and jewellers!

Did you know?

The oldest arch bridge in the world is Arkadiko Bridge, at Arkadiko, Greece. It was build somewhere around 1200-1300 BC by the Mycenaeans, to be used as a chariot road. What is amazing is the fact that the bridge is still in use today by the locals! It has a span of only 1 meter, which is a long way short of the record for the longest arch bridge, which is held by the Chaotianmen Bridge in China. This bridge has a total length of 1.7 km, with a span of 552 meters!!



Chaotianmen Bridge in China

Cantilever bridge

A **cantilever bridge** is a type of a beam bridge where the beam is supported at only one place. Usually this is somewhere in the middle, so that opposite forces balance the beam. There is also a middle span (not supported by a pier) which connects the cantilevers. For the structure to be stable, usually there is a counterweight at the end of each pier so that the cantilevers balance.

One of the most famous cantilever bridges is the Forth Rail Bridge in Scotland, which was built in 1890. This bridge is a combination of a cantilever and a truss bridge since the deck is also supported by trusses.



The Forth Rail Bridge in Edinburgh, Scotland

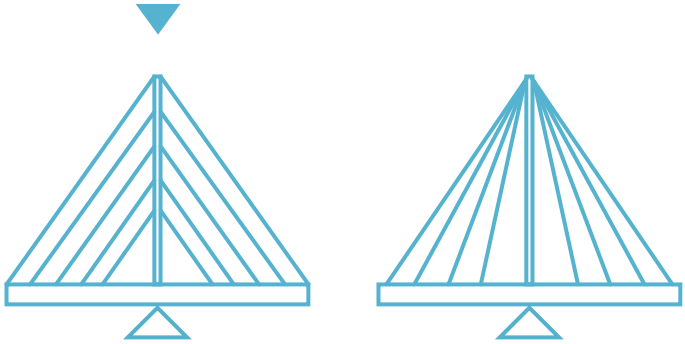
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Cable bridges

Cable-stayed bridge

In a **cable-stayed bridge** the deck is connected with cables to the tower directly. Steel cables are used to support the weight of the bridge and are very strong under tensile forces. There are two types of designs, depicted in the next picture, depending on where the cables are attached to the tower.

In the **harp** design, the cables on each side are almost parallel to each other because they are connected at different points on the tower and the deck.



Harp design *Fan design*



A cable-stayed bridge in the USA

In the **fan** design, the cables are all connected at the top of the bridge, or pass through the top to connect to the deck on the other side of the tower. The cables are constantly under tension, supporting the weight of the deck and any load on it, and as a result the deck on cable-stayed bridges is not completely straight due to those tensile forces.

The advantage of this type of bridge is that it can span at longer lengths than any other type of bridge we have seen so far, but less than the suspension bridge we will examine next.

A famous example of a cable-stayed bridge is the Rio-Antirion Bridge in Greece, which spans the Gulf of Corinth. The bridge has unique engineering features, required for the special conditions that exist in the area (water attrition, earthquakes etc). The pillars of the bridge are not buried in the sea floor, but rather they are rested on a bed of gravel which allows some movement. The Rio-Antirio bridge has a length of 560 metres and a width of 27 metres. It was opened for public use in August 2004, just one week before the Olympic Games in Athens. Olympic torchbearers were the first to officially cross its length!



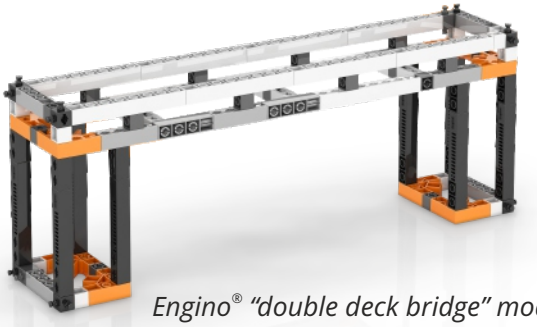
The Rio-Antirion bridge in Greece

Building Challenge

instructions can be found online

Double deck bridge: bridges can change type through specific modifications. This can be simulated with the Engino system in an easy way. For example you can transform a single beam bridge into a double deck bridge and this into a cable-stayed bridge (using the string accordingly).

Build the Engino double deck bridge model and try the challenge described above. Before each transformation check the rigidity of the bridge by pushing down on the deck and pillars. You can also combine other features of bridges to make it as strong as possible such as trusses and arches.



Engino® "double deck bridge" model

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Suspension bridge with anchors in Moscow, Russia

Suspension bridges have many advantages over other types of bridges: they require less material, and therefore are cheaper, and can span longer lengths than any other bridge. Also they are less rigid than most bridges and can better withstand strong earthquakes. However, due to that lack of rigidity, they are more susceptible to environmental loads (especially wind) and need to be specifically designed to withstand them. The most famous example of a suspension bridge is the Golden Gate Bridge in San Francisco, USA, which was also declared one of the Modern Wonders of the World.

Did you know?

There are many bridges that are combinations of different types! One fascinating example is the Sydney Harbour Bridge in Australia, which is a combination of an arch and a truss bridge. The Tower Bridge in London (England) is also very famous. It consists of two large towers with two beam passages, which support two smaller suspension bridges on each side. The main deck can be lifted to allow clearance for ships making the bridge a bascule type as well!



The Tower Bridge in London (England)

Suspension bridge

A **suspension Bridge** has a different setup. Two **main cables** connect the two towers and smaller cables (called **hangers**) vertically connect those main cables with the deck. Again, all the cables are under tension, with the suspension cables transferring the weight of the deck and the traffic on it to the towers. In this case, the deck of the bridge can bend a little due to the tension from the hangers. Suspension bridges also need **anchors,** to support the towers so that they won't collapse inwards due to the tensile forces of the main cables. These anchors are usually the main cables that run past the towers and into the ground.



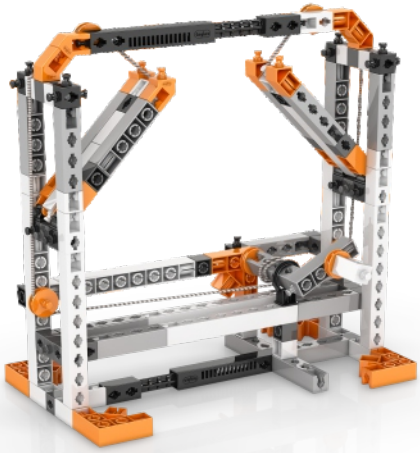
The Golden Gate bridge in San Francisco

Building Challenge

instructions can be found online

Bascule bridge: Some bridges can move their deck allowing ships to pass. These are special type of bridges called *Bascule*, deriving from the French word for "balance". There can be different variations of them either in the number of rising decks (single-leaf or double-leaf) or in the way the deck is lifted and the counterweights used (e.g. rotating around a large axle).

Build the Engino bascule bridge model and observe how the decks are lifted with the help of the string and crank. Modify your bridge in order to create the single-leaf type or add more counterweight to decrease effort.



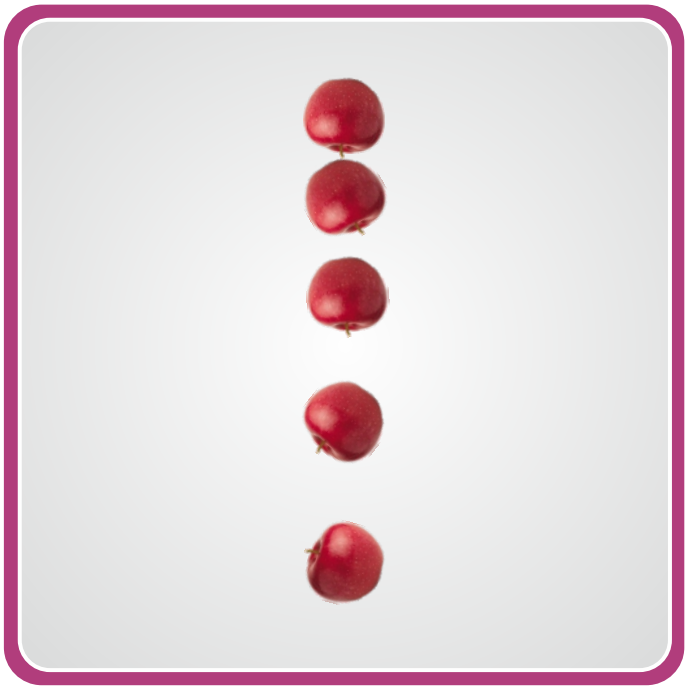
Engino® "bascule bridge" model

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Newton's Laws

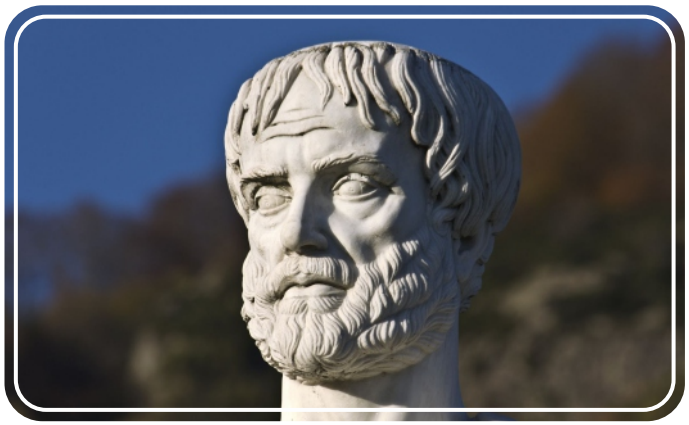
What we will learn

Things that move have been studied for millennia, from the motion of the planets to the movement of a pendulum. Even today you may ask: "how do the stars, the Moon and our Sun move in space?"; "what are the factors which influence the speed of an object and how can we make it move faster or come to a halt?"; "what is Momentum and why do car passengers get thrown off their seats when it crashes?"; "how can the kinetic energy of the wind be harnessed and converted into other forms?"; "which are the forms of potential energy and how can they power our machines?". These questions can be answered if we apply the three laws of motion expressed by one of the greatest scientists of all times: Sir Isaac Newton.



An apple accelerates while falling to the ground

This booklet of **Discovering STEM: Newton's laws** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about their applications in daily life. Discover all the scientific principles applied through **experimentation**, with step-by-step guides and thought provoking exercises. Follow the **building instructions** to build exciting models such as **a moving cabin**, **a ballistic catapult**, **a collision car**, **a balloon powered plane**, **a gravity fan** and **a dragster**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.

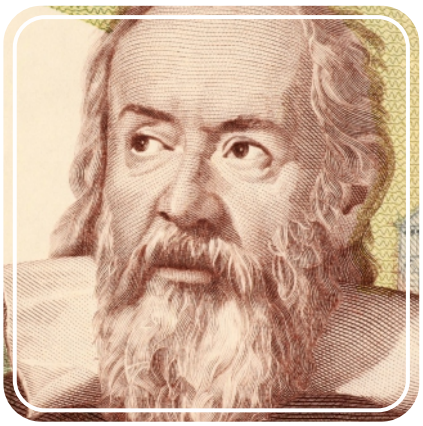


Aristotle (384 - 322 BC)

History of Newton's laws

Since ancient times questions about how objects move have been challenging the minds of philosophers and scientists. The ancient Greek philosopher Aristotle thought that all objects have a natural place in the universe: heavy objects (such as rocks) wanted to be at rest on the Earth and that light objects like smoke wanted to be at rest in the sky and the stars wanted to remain in the heavens. He first thought that a body was in its natural state when it was at rest and for the body to move in a straight line at a constant speed an external agent was needed continually to propel it, otherwise it would stop moving.

The understanding of acceleration was due to the work of the Italian physicist Galileo Galilei (1564–1642). During the late sixteenth and early seventeenth centuries, Galileo first observed the motion of objects rolling down an inclined plane. He wrote mathematical equations that showed how the velocities of these objects increased as they rolled down the planes. These equations first described the idea of accelerated motion. Newton later explained the observations made by Galileo. For example, in the case of a ball rolling down a plane, the force driving down the ball is the force of gravity.



Galileo Galilei (1564 - 1642)

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Sir Isaac Newton (1642 - 1727)

Sir Isaac Newton (1642-1727) was a mathematician and physicist, one of the foremost scientific intellects of all time. Newton was born near Grantham in Lincolnshire from a farming family. When he was 17, his mother insisted that he returned from school to run the farm! Thankfully, Newton was a bad farmer and not long afterwards, his uncle successfully persuaded his mother to let him attend Trinity College in Cambridge instead. After some time he was elected a Fellow of Trinity College in 1667, and Lucasian Professor of Mathematics in 1669. He remained at the university, lecturing in most years, until 1696.

During his time at Cambridge, he was at the height of his creative power. According to the well-known story (probably untrue!), it was on seeing an apple fall in his orchard at some time during 1665 or 1666 that Newton conceived that the same force governed the motion of the Moon, planets and the apple. He calculated the force needed to hold the Moon in its orbit, as compared with the force pulling an object to the ground. After three years of intense work, Newton prepared a book named "Philosophiae Naturalis Principia Mathematica" commonly known as the "Principia".



The Moon is pulled by Earth's gravitational force

His work though was not published until many years later in 1687. The "Principia" lays the foundations of the science of mechanics (things that move), and explains the "three laws of motion":

1st law: Every object remains at rest or continues to move at a constant velocity, unless acted upon by an external force.

2nd law: The sum of forces **F** acting on an object is equal to the mass **m** of the object multiplied by the acceleration **a** of the object (F = m.a) .

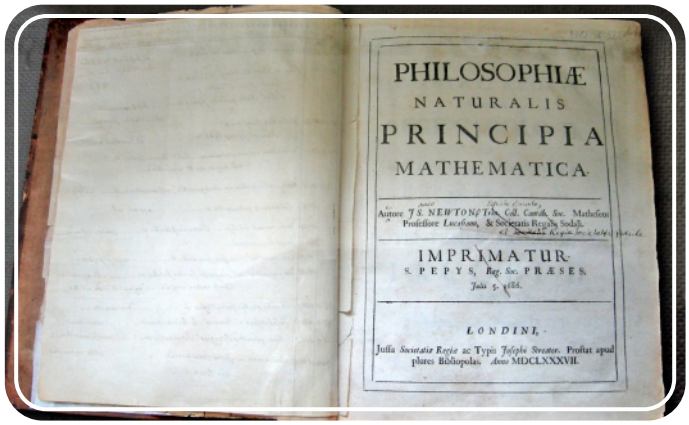
3rd law: For every action there is an equal and opposite reaction.

Did you know?

There's no doubt that Newton was brilliant, but what is not commonly known was that the majority of Newton's discoveries were made between his twenty-first and twenty-seventh birthday. Yet, he didn't tell anyone about his discoveries until years later. He was interested in a variety of scientific fields such as Mathematics, Geometry, Physics, Optics, Astronomy (Gravity) and Alchemy. He also expressed his views on religion and philosophy in general.



Newton was interested in planetary motion



Newton's own copy of Principia with handwritten notes

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Forces and Work

We cannot see forces, but we can understand their effects when they are applied. When we pull a rubber band we can see that it stretches. A can is squeezed by the force applied from our hand. Generally, in order to change the shape of an object, temporarily or permanently, a force must be applied on it.

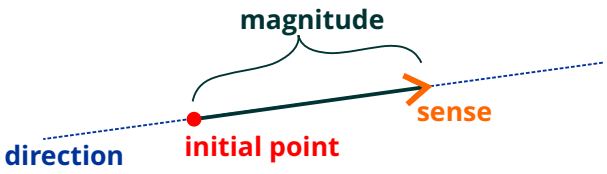
Forces also cause objects to change their motion. In order to make an object move we must apply a force. The same applies if we want to reduce the speed of an object or change its direction of movement.



We can observe the results of a force

Elements of a force

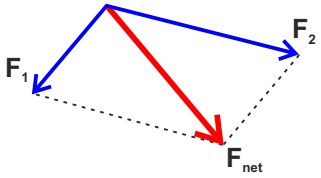
In the diagram below you can see the main elements of a force. It is represented by an arrow named in scientific terms as "vector".



Elements of a force

Adding forces

In the right diagram you can see how we manage to add two (F_1, F_2) or more forces, called **component** forces, and come up with their **resultant** force F_{net}, by using the parallelogram method.



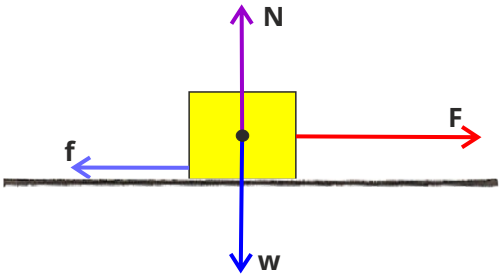
Parallelogram method

Calculation of forces

The calculation of forces in a system is done with the help of simplified diagrams, which usually include a simple design of the object where the applied forces are indicated, represented by vectors (arrows). For practical reasons, the diagram shows only the forces that are necessary for studying a certain phenomenon.

A simple example of calculating forces can be seen next. Here we can see the forces that are applied on an object which lays on the ground, and is moving on the right due to a force **(**F).

N: normal force applied by the ground to the object (reaction to the weight).
w: the weight of the object
F: the applied force
f : friction between the ground and object

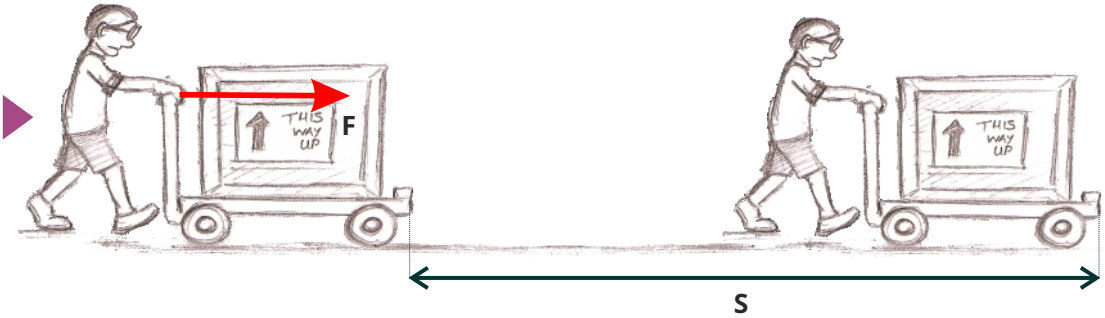


Forces acting on an object moving on the ground.

Work (W)

Work is the energy used for moving an object and depends on the force applied on the object and the distance which the object is moved. Work (W) equals force (F) times the distance of the movement (S).

$$W = F \times S$$



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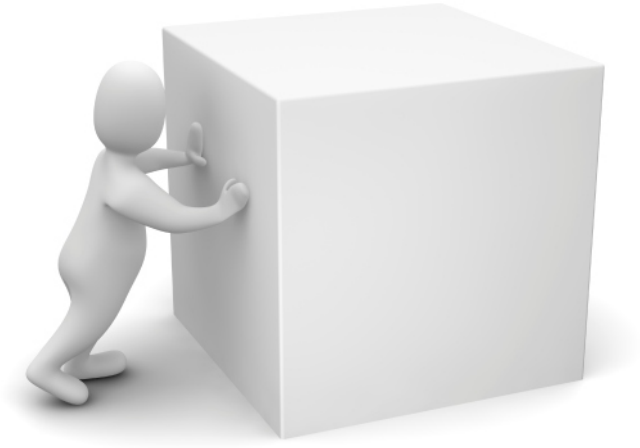
Friction

One of the most important phenomena that influence the operation and overall efficiency of all machines is **friction**. Friction (f) is the force that resists motion and is created when an object is moving (or someone attempts to move it) . There are two types of friction depending if the connected objects are moving or not.

Static friction: this appears when two objects are in contact, without moving relatively to each other and an effort is applied in order to move them. For example, when we try to push a box, we have to overcome the static friction between the box and the floor in order for the box to start moving.



Ball bearings



In order to push a box we have to overcome static friction

Kinetic friction appears when two objects in contact are moving relatively to each other. For example, when you drag a box on the floor you can feel there is another force resisting your effort coming from the ground. This force is called **friction** and depends on the surfaces of the touching materials. Most of the times, friction is wasted energy, converted mostly to heat and sound. Special objects (like ball bearings) reduce this effect. Friction also wears out the surfaces.

Did you know?

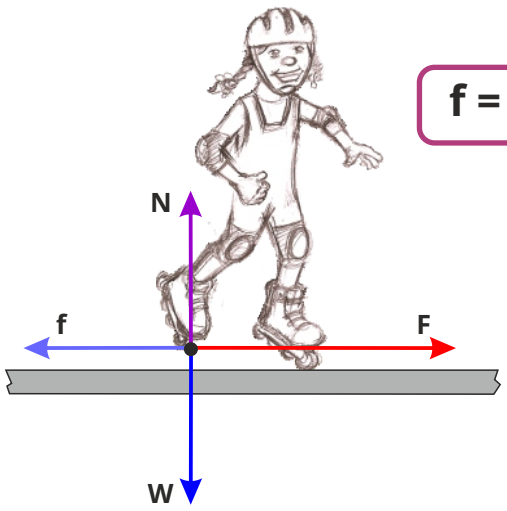
Many times friction is desirable, acting as a friend. Specifically, when we use the brakes on our bicycle, we manage to reduce velocity with the help of friction! When we hit the brakes on a car, the wheels stop turning due to the force of friction created between the road and the wheels. The effects of friction are visible on the wheel marks that are left on the road. Generally, if there was no friction, normal movement of objects could not be achieved because everything would slide!



Wheel marks due to friction

Coefficient of friction

Different materials and surfaces lead to different frictional forces, even if the same effort is applied. This characteristic of connected surfaces is called **coefficient of friction** and is symbolized by the Greek letter **μ**. Another factor influencing friction is the weight of the object we are trying to move! It was Isaac Newton in 1687 that said "**for every action there is an equal and opposite reaction"**, so when a child for example is roller-skating on the street, her weight pushes the street and the street pushes back on the child! This reaction from the ground is denoted by **N** and is directly proportional to friction (**f**).



Formula for friction

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Newton’s 1st law of motion

Newton's First law of motion states that **every object remains at rest or continues to move at a constant velocity, unless acted upon by an external force**. More simply, in order to alter an object’s velocity, a force should be applied. If the force is in the same direction of movement, then the object will accelerate. If it is in the opposite direction, the object will decelerate. If the force is applied at an angle then the object will turn! Newton’s first law is also called **Law of Inertia** (explained below) and it is more observable in objects with big mass (e.g. a big ship).



A big ship has a lot of inertia



If we stop pedaling, the bicycle will eventually stop!

Sometimes we observe the opposite effect, for example if we are on a bicycle and gain some speed, once we stop pedaling (meaning that we stop acting force) then pretty soon the bicycle will stop on its own. This is caused by friction. You may not see friction or realize it but it is always present, and unless we counterbalance friction by an opposite force the object will inevitably stop. In fact, the bicycle stops instead of keep moving because Newton’s 1st law is in effect! Air resistance and friction between rotating parts are acting opposite to the direction of motion and decelerate the bicycle.

Inertia

The ability of a bicycle to keep moving even after we stop pedaling, is called **Inertia.** It is defined as the **property of objects to resist any change in their motion**. If an object is moving, then it will “want” to continue moving; if it is idle then it will “want” to remain idle. This “unwillingness” of objects to move is what we call Inertia.

What if instead of a bicycle we had a car, or even a truck! The latter would be more difficult to start moving or stop. Inertia depends on the mass of an object, **the bigger the mass the higher the inertia**. This is what you feel when you are in a car and the driver applies the brakes or what pushes you back to the seat of the plane when it takes off! Therefore you must always wear your seatbelt when you are in a car or a plane, as to avoid the risk of injury.

Building Challenge

instructions can be found online

Dragster: when a driver tries to change the velocity of a car too fast, inertia causes the wheels to spin.

Observe the inertia phenomenon using the dragster model !



Engino® “dragster” model

Did you know?

The fastest animal on the planet is the cheetah, which can reach a velocity of up to 120 kilometers per hour (Km/h)! This means that if cheetahs could run the same way for a full hour, they would cover a distance of 120 Km! Of course, cheetahs get tired very fast and can only run at these speeds for one minute. If within that minute they do not succeed in capturing their pray, they stop and wait for a long time to regain their strength to make another sprint.



The cheetah is the fastest animal on earth

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Newton’s 2nd law of motion

Newton's Second Law states that **the sum of forces (F) acting on an object is equal to the mass m of the object multiplied by the acceleration a of the object (F = m x a) .**

This law takes up where the first law ends, introducing a fundamental concept: **mass**. Newton used the word “mass” as a way to say “quantity of matter” or "how much there is of something". Today, we more precisely define **mass as a quantity of the inertia of a body.**

$$F = m \times a$$

F = force
m = mass
a = acceleration

Formula for Newton’s second law



A car has big mass, so it needs a large force to move

From the formula is obvious that force, mass and acceleration are interrelated! As a matter of fact, force is directly proportional to mass and acceleration. Therefore, we could state the relationship in two ways: (a) for the same mass, **the bigger the force the bigger the acceleration** and (b) to achieve the same acceleration, **the bigger the mass the more force is needed.**

In the left picture you can see a man pushing a car. As the car has big mass, the man needs to apply a big force in order to achieve movement and acceleration.

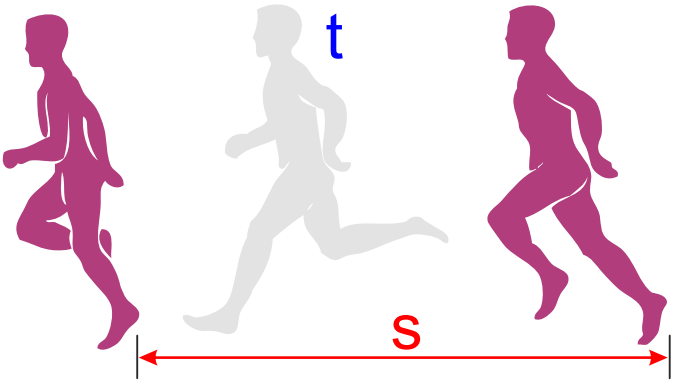
Velocity

We have already covered the concepts of force and mass. But what about acceleration? For this we need to understand the notion of velocity first.

Velocity is the change in distance over time and is denoted by its initial letter (v). In simple terms, if you are able to cover more distance in less time then you have a higher velocity. Many times velocity is referred to as speed. In reality speed is just the magnitude of it. Like a force, velocity is a vector and has also initial point, direction and sense.



Velocity is the change in distance over time



The athlete covers a distance S in a time t

To calculate the velocity of the athlete (as seen in the next picture), all we have to do is measure the distance covered and the time it took to do it! Then, if we divide distance (s) by time (t) we get velocity. Its unit of measurement is **meter per second (m/s)**.

$$v = \frac{S}{t}$$

Formula for calculating velocity

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Acceleration

Acceleration (a) is the change in velocity of an object, from slow to fast or from fast to slow. Acceleration is to velocity what velocity is to distance. Since velocity is a vector quantity, acceleration is also a vector quantity, and its unit is the meter per second squared (m/s^2). One meter per second squared is defined as the acceleration which can increase the speed of an object by 1 meter per second every second. The formula can be seen on the right.

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

a = acceleration
v = velocity
t = time

Formula for calculating acceleration



The boy has acceleration as from zero speed he gains velocity (due to pedaling)

A more accurate formula would indicate velocity as **Δv** which means difference in velocity (final velocity minus the initial velocity) and time as Δt which means difference in time.

As an example we can study the case of a young boy that learns how to ride a bicycle with his dad. At first, the velocity of the bicycle is zero, as the boy is not applying any force. His father gives him a push to increase the bicycle's velocity. After 10 seconds the boy reaches a steady velocity of 7 m/s, which means that every second he will travel 7 meters. So, The boy has accelerated with $0.7 m/s^2$ (a=7/10)!

Now, if they boy does not know how to pedal and the father stops pushing, then the bicycle will gradually come to a halt. This is called **deceleration** and it is actually negative acceleration! Both acceleration and deceleration require a force to be applied. Without the action of a force and as per Newton's 1st law, the objects would just continue with the same speed. The force that decelerates the bike is friction.

We can observe the effect of deceleration in the example of the picture below: a biker hits the brakes so fast that the back of the bike is lifting up! According to the first law, the bike is unwilling to make such sudden change of motion, so it keeps moving forward.



A biker decelerating too fast

Did you know?

All objects (stars, planets, galaxies) attract each other because of gravity, which depends on the mass of the objects. Small objects (people, furniture etc) also attract each other, but the force is so weak due to the small amount of mass, that it has no effect. The gravitational acceleration of earth (denoted with the letter g) is what causes us to have weight. In space, astronauts feel weightless because of the lack of gravity, while in larger planets they would weigh much more than in earth.

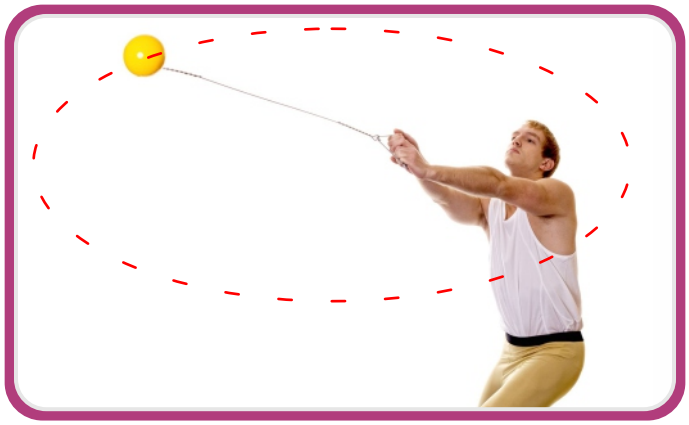


An astronaut weightless in space

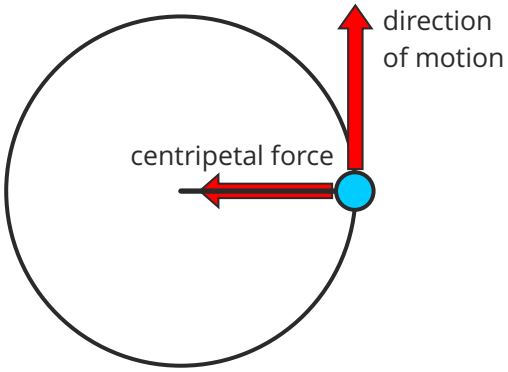
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Circular acceleration

So far we have only studied **linear acceleration.** There is another form called **circular acceleration** or sometimes called **circular motion.** This is defined as the rotation about a point following a circular path or a circular orbit. It can be uniform, that is with constant angular rate of rotation, or non-uniform, that is with a changing rate of rotation. Whatever the object, if it moves in a circular path, there is some force acting on it causing it to change from its straight-line path, accelerate inwards and move along a circular path.



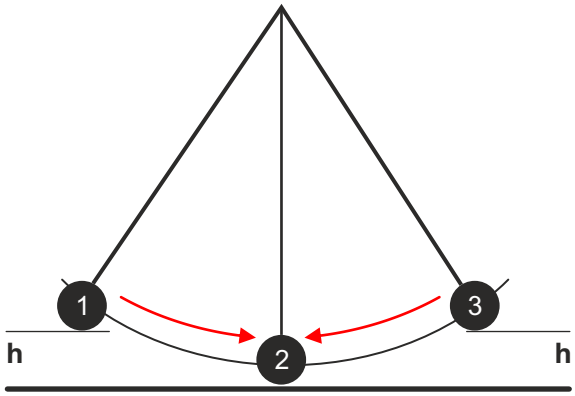
Hammer throw involves circular acceleration



A ball being spun around with a string attached to it.

Circular motion brings a new kind of force called **centripetal Force.** Any object moving in a circle experiences a centripetal force. That is, there is some force pushing or pulling the object towards the centre of the circle, the point about which it is rotating. We are not really introducing a new type of force, but rather describing the direction of the net force acting on the object that moves along a circular path. When for example we continually pull the string that drives the ball in a circle we apply a centripetal force towards the center.

The pendulum, a mechanism found in old wall clocks, is an example of circular acceleration and deceleration, even if it makes part of a circle. A chain or rod holds a heavy piece of metal vertical to the ground. The centripetal force causes it to move on a circular path up to a certain point. As a matter of fact there is a continuous conversion from one form of energy to another, as the Potential Energy at the highest points (1 and 3) is converted to Kinetic, and the Kinetic energy at the fastest point (2) is converted to Potential. We will discuss more about Energy in the last pages of the theoretical section.



A swinging pendulum

More examples of circular motion include an artificial satellite orbiting the Earth in geosynchronous orbit, a stone which is tied to a rope and is being swung in circles (e.g. hammer throw), a race car turning through a curve in a race track, an electron moving perpendicular to a uniform magnetic field and a gear rotating inside a mechanism.



Gears rotating inside an engine



A satellite orbiting the earth



Driving a race car on a track

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Momentum

Every object has Inertia which depends on mass and exists whether the object is at rest or moving. When an object has speed then inertia generates **Momentum**; the higher the speed of the object the higher the momentum. It was introduced by the French scientist and philosopher Descartes. Momentum (p) is the product of mass (m) and velocity (v) of an object.

$$p = m \times v$$

p = momentum
m = mass
v = velocity

Formula for calculating Momentum



René Descartes (1596 - 1650)



Momentum transfer from the cue ball to the other balls

Conservation of Momentum

One of the most important physics laws is the **conservation of momentum**. This means that in a closed system, when objects collide with each other the total momentum remains unchanged! The only thing that happens is a transfer of momentum from one object to the other and the momentum lost by one object is gained by the other one. A game of billiard is a fine example. When the cue ball (white colour) hits another ball, we observe that the second ball moves, while the cue loses velocity.

For calculating reasons think about someone weighing about 45 kg, sitting motionless on high quality (frictionless) skate board on a level smooth floor. A 5 kg ball is thrown directly at him by someone standing in front of him, at 5 m/s and only a short distance away, so that the ball is moving perfectly horizontal. He catches and holds the ball, and because of its impact he begins to roll backwards. From this we can calculate the momentum of the ball and person, before and after he catches the ball.

Sketch of a boy catching a ball

$$p_{ball} = 5 \times 5 = 25 \text{ Kg.m/s}$$

$$p_{person} = 45 \times 0 = 0 \text{ Kg.m/s}$$

Momentum of the ball and person BEFORE the person catches the ball

What could have been observed if we were to carry out this experiment is that after the person catches the ball, the person and the ball roll backwards at much smaller speed than what the ball had before hitting the person. This is expected as the mass of the person is much higher, so by the principle of momentum's conservation, the total momentum of the system will remain unchanged.

$$p_{before} = p_{after} \qquad p_{person+ball} = p_{person} + p_{ball}$$

$$p_{person+ball} = (45 + 5) \times v \Rightarrow v = 25/50 = 0.5 \text{ m/s}$$

Momentum of the ball and person AFTER the person catches the ball

Therefore, the "new" combination object of person and ball together will have the same momentum as before the collision and their speed will be reduced to balance out the increase of mass. We can use the equation of Momentum to calculate the new velocity (v) to 0.5 m/s as you can see on the left.

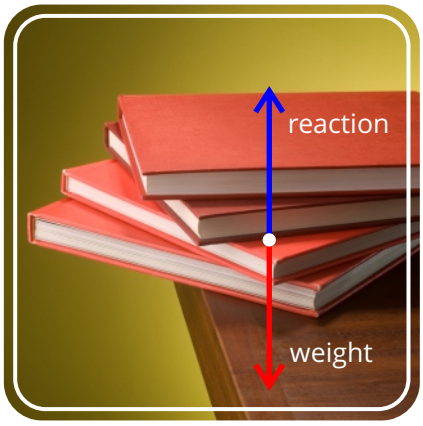
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Newton's 3rd law of motion

The forces which arise from the interaction of two or more objects are called **action and reaction** forces and are the subject of Newton's third law of motion. Simply put, **Newton's Third law** states that **for every action, there is an equal and opposite reaction.** This statement means that in every interaction, there is a pair of forces acting on the two interacting objects. The magnitude of the force on the first object equals the magnitude of the force on the second object.



The boy pushes the wall and the wall pushes back the boy



The table pushes back the pile of books

All objects on Earth are being pulled down by the force of gravity. So, what causes a pile of books to stay on a table higher than the Earth's surface? Why the books do not simply fall down? This is explained by the first law; a body at rest means that there is no force acting on it. Since gravity is still there, there must be another force which cancels out gravity. This is what Newton called "reaction" and it is equal and opposite to the gravitational pull on the books! In simple words, the books remain on the table because a reaction force is acted by the table to the books!

Did you know?

The action and reaction law is what led Newton to the discovery of the conservation of Momentum law! An example to understand this is the recoil of riffle when a bullet is fired from a it! The gases from gunpowder push the bullet out of the barrel in very high velocity, as it has very small mass. The momentum of the bullet is equal and opposite to the momentum of the rifle, but because the rifle has more mass it recoils at much lower velocity!



When the bullet is fired, the riffle recoils

Space exploration

Space exploration is made possible thanks to Newton's third law! Earth's gravity pulls back anything that tries to escape from Earth. This force is so strong that the velocity needed to escape Earth's gravitational pull is about 40000 km/h! Therefore, space scientists had to invent special propulsion methods that would achieve these speeds. The rocket uses liquid fuel that releases extremely high energy gases that push the ground with a huge force. According to the third law, the ground pushes the rocket back with equally huge force resulting in moving the rocket upwards in a very high velocity.



Space shuttle launch

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Properties of Energy

Energy is a physical quantity with 3 main properties:

1) Energy is conserved over time and cannot be created anew or destroyed.

2) Energy can be stored and transferred from one object to another through the interaction of forces between the objects.

3) Energy comes in a variety of forms (kinetic, potential, sound, heat etc.) and it is converted from one form into the other.



Pendulums transfer energy to the clock's mechanism



Food contains chemical energy

The law of **conservation of energy** states that the total amount of energy in an isolated system remains constant over time. Energy can only be converted from one form to another. When we eat food our body converts the chemical energy into mechanical or thermal energy. Wind turbines use wind energy and convert it into kinetic energy of the blades, which is then converted to electrical energy. Solar panels convert solar energy into electrical energy. Nuclear power plants convert nuclear energy into electrical.



Wind energy transforms to kinetic



Solar power to electrical



Nuclear power to electrical

Energy conversion efficiency



Engines need to be as much efficient as possible

During any kind of energy conversion, some energy is lost to the surroundings. "Lost" does not mean 'disappeared', just that some of the energy has been wasted unintentionally to something else, such as heat and sound. As a result of this loss, no machine could ever be 100% efficient. The **"energy conversion efficiency"** is how well a machine or system can convert from one form of energy to another. All systems have different energy conversion efficiencies. Water turbines, for instance, have an extremely high energy conversion efficiency of nearly 90%. Combustion engines in cars, trucks and motorbikes have conversion efficiencies from 10% to 50%.

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Main forms of Energy

Kinetic Energy

We have learned at the beginning of this book that forces perform work when they move an object. However, to be able to perform work, energy is required! Energy comes in many forms; we can see or feel energy in nature such as in winds, waves and sunlight or we can chemically produce it using for example fuels and batteries. One of the most common forms of Energy is the kinetic energy which is the energy of any object in motion.



The ball has no Kinetic Energy until it is hit

$$KE = \frac{1}{2} m \times v^2$$

KE = Kinetic Energy
m = mass of the object
v = velocity of the object

Formula for calculating Kinetic Energy

The word "kinetic" comes from the greek word "κίνησις" (kinisis) which means movement. From the analysis of Newton's laws, we now understand that a big mass will have more inertia and objects with higher velocity will have more momentum. It would therefore be expected that the bigger the mass of a moving object and the higher its velocity, the more energy it will have. The equation to calculate Kinetic Energy (KE) is shown on the left.

Potential Energy

Even an object that is not moving may still have the potential to do something! This "stored" energy is known as potential energy (PE). There are various forms of potential energy, the most obvious one is the one caused by Earth's gravitational pull. If you hold up some objects e.g. books and let them go, then they will drop down! The following equation shows how to calculate the potential energy of objects at a height.



If you let go of the books, they will fall as they have Potential Energy due to their position (height)

$$PE = m \times g \times h$$

PE = Potential Energy
m = mass of the object
g = gravitational acceleration
h = height of the object

Formula for calculating Potential Energy

The equation shows that all the factors governing the object's potential energy are directly proportional to it. Gravitational acceleration (g) is about 10 m/s^2 on the Earth's surface, but it is different on other planets, so the potential energy of the same object on the Moon is much less than on Earth and much greater in huge planets. The other factors are mass and height, the higher the object is positioned the more potential energy it has!



There are some other forms of energy that are considered as subcategories of potential energy. One example is **elastic energy**, found usually in easily deformed objects such as stretched rubber bands, squashed springs and inflated balloons. All these objects contain stored energy when they are deformed which affects their surrounding environment once released. In the left picture you can see one example of elastic energy, the stretch of a bow.

A stretched bow has elastic energy

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Solar Power

What we will learn

We use energy for just about everything. Think of every single action you took this morning until you left the house. From switching on the lights, keeping food fresh in the refrigerator, to the car or bus you took to school. Global warming and climate change urge scientists to take action and save our planet by reducing carbon emission (the gasses released from the burning of fossils fuels and petrol). The solution can be found in the use of renewable energiessuch as solar power! Our sun can provide free energy for all our necessities, however, we need to convert it to a useful form. One of the most modern technologies to harness solar power is the use of photovoltaic cells, converting solar energy to electricity.



Global warming causes glaciers to melt

This booklet of **Discovering STEM: Solar power** contains a comprehensive **theoretical section** with building challenges and interesting facts, so that you learn all about the applications of energy in daily life. Discover all the scientific principles applied through **experimentation**, with step-by-step guides and thought provoking exercises. Follow the **building instructions** to build exciting solar-powered models such as a **solar chopper car, solar fan, solar plane, solar robot, solar tractor** and **solar winch crane**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.



The oculus in the dome of the Pantheon in Rome, Italy

History of renewable energies

The use of renewable energy resources started when humans learned to control fire which was so important for light, protection and warmth. Apart from burning wood and other flammable materials, they took advantage of natural resources like water, wind, sun and even geothermal energy. People were aware of the properties of these resources even if they could not understand how they work scientifically. In the famous Pantheon, built by ancient Romans in the 2nd century AD, an oculus was created on the top of the dome to act as the only source of valuable natural light.

All ancient civilisations knew that the most important source of energy on earth comes from outside; the sun. People worshipped the sun as a God and planned all their activities according to the different seasons (farming, organising athletic games and even warfare). In ancient Greece, they believed that all things in the world were made out of five elements: earth, water, air, fire and aether (a material that fills the area above ground). The elements had specific qualities (e.g. hot, wet, cold etc). Lucian of Samosa in the 2nd century AD wrote about the Siege of Syracuse (3rd century BC), where Archimedes prevented the Roman attack with a burning-glass, using the solar power.



Creating the element of fire using sunlight

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Boats use wind energy to move

Besides sun, there are other renewable sources of energies used since the ancient times. For example wind power was used for propelling ships and rotating windmills. The earliest records of wind use date back as early as 5000 BC, when simple sails were employed to transport boats along the Nile River. As people invented other ways to harness wind and water, the hard work of grinding grain to make flour was replaced. This technological achievement dates back at least as early as 200 B.C. in Persia and the Middle East.

Geothermal energy (coming from earth's core) was also exploited by Romans for heating bathing pools.

By the late 19th century, the electrical generator was developed and attached to water based systems. The growing demand for power during the Industrial Revolution drove its development as well. At the beginning of the 20th century, many small hydroelectric power plants were being constructed by commercial companies in mountains near built up areas. By 1920, as 40% of the power produced in the United States was hydroelectric, the Federal Power Act was enacted into law. As the power plants became larger, their associated dams developed additional purposes to include flood control, irrigation and navigation.



The generators inside the Hoover Dam

Hydroelectric power plants continued to become larger in the 20th century. Hydropower was referred to as 'white coal' because of its usage and abundance. The Hoover Dam built in 1936 was the world's largest hydroelectric power plant with production capacity of 1,345 MW. Today, the Three Gorges Dam in China is the world's largest power station in terms of installed capacity, with a production capacity of 22,500 MW. Hydroelectricity eventually began suppling some countries, including Norway, Democratic Republic of the Congo, Paraguay and Brazil, with over 85% of their electricity. The United States currently has over 2,000 hydroelectric power plants which supply 49% of its renewable electricity. Tidal power is another form of hydropower which uses the energy of tides to create electricity.

Did you know?

In 1878 the world's first hydroelectric power scheme was developed by William George Armstrong in England. The set up was used to power a single arc lamp in his art gallery! The first Edison hydroelectric power plant, the Vulcan Street Plant, began operating on September 30, 1882, in Wisconsin, with an output of about 12.5 kilowatts. For comparison, this is as much power output as that generated by a scooter, but for its time, that was a great achievement !



Ruins of an old hydroelectric power plant



The Three Gorges Dam in China

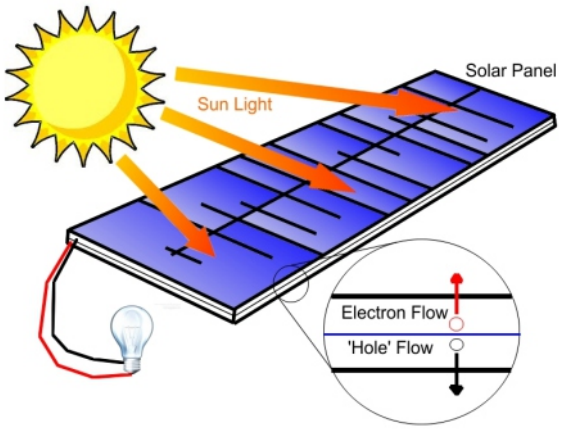
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Solar power

Solar power is energy which comes from the sun. This energy is very powerful and reaches the earth non-stop. Even the tiny percentage of sunlight that touches the earth is more than enough to meet the energy needs of the entire human population by more than 8,500 times over. Solar energy is produced by the **nuclear fusion** of hydrogen into helium. The core of the sun is full of hydrogen gas which gets compressed to such an extent that eventually causes nuclear fusion. The slight difference in mass converts into huge amounts of energy (heat and light).



Our beautiful and powerful star: the Sun!



A solar panel converts solar power to electricity

Solar cells

These should really be called "photovoltaic", "PV" or "photoelectric" cells. They convert light directly into electricity. In a sunny climate, you can get enough power to run a 100W light bulb from just one square metre of solar panel. The technology was originally developed in order to provide electricity for satellites, as there is no other available power source in space. These days, people are increasingly installing PV panels on their roof tops for heating up water or powering the house. If you notice, even portable calculators are powered by solar cells!

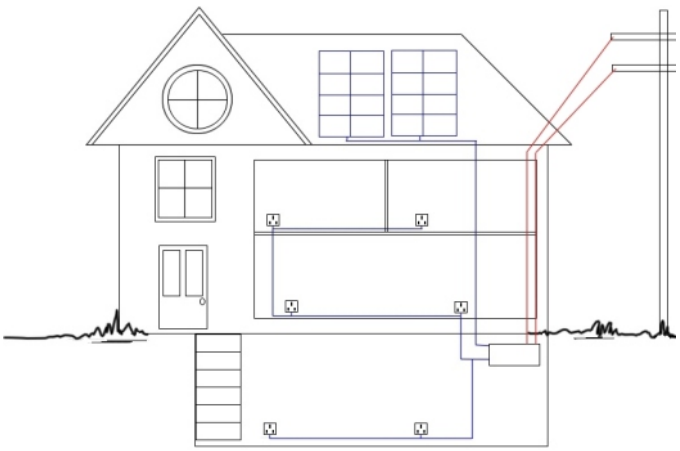
Living off-grid

The applications of solar power are vast and varied. One example is living off-grid, which means living in a location that is not serviced by the main electric utility grid. Remote homes and cabins benefit quite a bit from solar power systems. No longer is it necessary to pay huge fees for the installation of electric utility poles and cabling from the nearest main grid access point. A solar electric system is potentially less expensive and can provide power for up to 30 years if properly maintained.



Solar panels can be quite beneficial for remote houses

Besides the fact that solar panels make it possible to live off-grid, perhaps the greatest benefit is that solar power is a clean and a renewable source of energy. Solar panels have no moving parts and require little maintenance.



Connection between the solar panel and the grid

They are ruggedly built and can last for decades. For grid-tie solar power system owners, the benefits begin from the moment the system comes online, potentially eliminating monthly electricity bills or, and this is the best part, actually earning the system's owner additional income by selling energy to the electric company!

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Effects of solar power

Advantages

- Solar panels give off no pollution and produce electricity silently, unlike other sources.
- It can generate electricity in remote locations that are not linked to a national grid and can be used by a large area of the globe.
- Solar panels can be installed on top of many rooftops, solving the problem of setup space.
- Although the initial investment of solar cells might be high, it will pay off in the long-term.



Air pollution affects solar panels' efficiency



A modern solar car

Disadvantages

- High initial cost of solar panels.
- Solar energy is only able to generate electricity during daylight hours. This means for around half of each day, solar panels are not producing energy for your home.
- Weather conditions can affect the efficiency of solar cells (for example mist, dust, clouds etc).
- Pollution can also become a problem for solar cells' efficiency. Businesses or factories wishing to harness solar energy in heavily polluted areas need to consider this factor.
- Large areas of land are required to capture sufficient energy.

Did you know?

During the summer of 1990 the solar powered airplane Sunseeker successfully flew across the USA. It used a small battery charged by solar cells on the wing to drive a propeller for takeoff and then flew on direct solar power. It was piloted by Eric Diamond, who was taking advantage of beneficial conditions when possible. Several versions of the plane followed after with more powerful motor, larger wings, lithium battery packs and updated control electronics.



The Sunseeker solar powered plane

Building Challenge

instructions can be found online

Solar robot: technological advancements in solar panels and innovations about harnessing as much energy as possible have led to the creation of numerous solar powered machines. A solar car, for example, has panels that are connected to an electric battery, enabling it to carry at least one person on the road. Within the same principle we can find solar powered planes (e.g. "the Sunseeker airplane") or even solar robots like the Opportunity rover sent by NASA to explore the planet of Mars!

Build the solar robot model and learn how solar energy can be harvested and used to power an electric motor. Imitate the change between daylight and night by placing your model in sunny and shady spots.



Engino® "solar robot" model

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Solar thermal power stations

Solar thermal power plants use the rays of the sun to heat a liquid to very high temperatures. The liquid is then circulated through pipes so it can transfer its heat to water for producing steam. The steam, in turn, is converted into mechanical energy in a turbine and into electricity by a conventional generator coupled to the turbine. Most power stations are usually designed to operate at full power using solar energy alone, given sufficient solar energy. However, sometimes fossil fuel combustion can be used to supplement the solar output during periods of low solar energy, such as in cloudy days, but doing so adds to the pollution problem.

Parabolic troughs

A parabolic trough collector has a long parabolic-shaped reflector that focuses the sun's rays on a receiver pipe located at the focus of the parabola. The collector tilts with the sun as the sun moves from east to west during the day to ensure that the sun is continuously focussed on the receiver. Because of its parabolic shape, a trough can focus the sun at 30 to 100 times its normal intensity (concentration ratio) on the receiver pipe located along the focal line of the trough, achieving operating temperatures over 400°C.

Parabolic troughs are used in the largest solar power facility in the world located in the Mojave Desert at Kramer Junction, California.

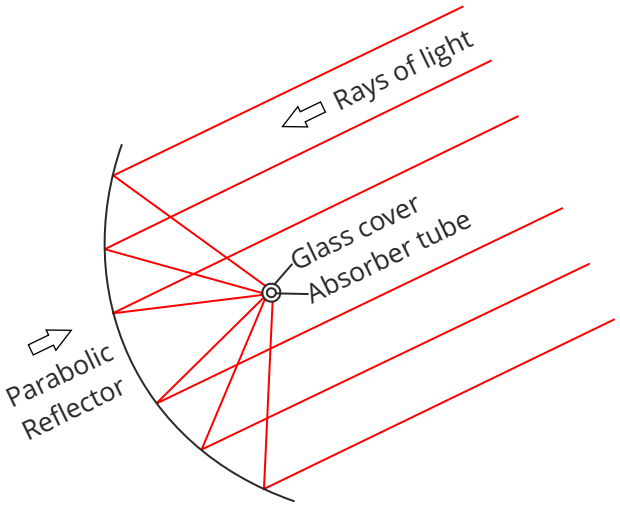


Diagram of a parabolic trough



A solar field in a desert in the USA

The "solar field" has many parallel rows of solar parabolic trough collectors aligned on a north-south horizontal axis. A liquid is heated as it passes through the receiver pipes and returns to a series of "heat exchangers" at a central location. Here, the liquid circulates through pipes so it can transfer its heat to water to generate high-pressure, superheated steam. The steam is then sent to a conventional steam turbine and generator to produce electricity. When the hot liquid passes through the heat exchangers, it cools down, and is then recirculated through the solar field to heat up again.

Solar dish

A solar dish/engine system uses concentrating solar collectors that follow the sun, so they always point straight at the sun and concentrate the solar energy at the focal point of the dish. A solar dish's concentration ratio is much higher than a solar trough's, typically by over 2,000, with a liquid temperature over 750°C. The power-generating equipment used with a solar dish can be mounted at the focal point of the dish, making it well suited for remote operations or, as with the solar trough, the energy may be collected from a number of installations and converted to electricity at a central point.



A parabolic solar collector used for cooking

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The engine in a solar dish/engine system converts heat to mechanical power by compressing the air or helium. This gas is then expanded through a turbine or by using a piston (Stirling engine) to produce electricity. The engine is mounted at the focal point of the dish, so that sunlight can heat it as much as possible. The basic energy transformation happens on the electric generator, which converts mechanical power to electric power. The Stirling engine is preferred compared to steam engines, as it is known for high efficiency, quiet operation, and its ability to use almost any heat source.



A solar dish with a Stirling engine



A solar power tower in Spain

Solar power tower

A solar power tower or central receiver generates electricity from sunlight by focusing concentrated solar energy on a tower-mounted heat exchanger (receiver). This system uses hundreds to thousands of flat sun-tracking mirrors called heliostats to reflect and concentrate the sun's energy onto a central receiver tower. The energy can be concentrated as much as 1,500 times that of the energy coming in from the sun. Power towers must be large to be economical. This is a promising technology for large-scale grid-connected power plants.



A series of heliostat mirrors

Did you know?

Besides offering warmth and light, the importance of the Sun for sustaining life on Earth is observable in plants! Specifically, green plants use solar energy, in a process called ***photosynthesis***, to transform carbon dioxide into oxygen and glucose (sugar). This has two enormous effects for life on earth: a) the atmosphere is constantly cleaned from toxic carbon and refilled with oxygen and b) plants produce food for their own, maintaining the food chain for the other organisms.



Green plants produce their own food!

Building Challenge instructions can be found online

Solar winch crane:

build the solar winch crane model and maximise its efficiency by creating a parabolic shape out of aluminium foil to concentrate sunlight on the solar panel.



Engino® "solar winch crane" model

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Wind power

The windmill's modern equivalent - the wind turbine - uses the wind's energy to generate electricity. Wind turbines are mounted on a tower to capture the maximum amount of energy. At 30 meters or more above the ground, they can take advantage of the faster and less turbulent wind. Turbines catch the wind's energy with their propeller-like blades. Usually, two or three blades are mounted on a shaft to form a rotor. When the wind blows it forces the blades to start rotating caused by a combination of lift and drag on the blades. The blades are attached on a turning shaft that spins a generator to produce electricity.



An old corn mill



A group of wind turbines, also called "wind farm"

The idea behind generating electricity from wind is quite simple. Wind is the motion of air molecules in the atmosphere. In order to use this kinetic energy, all that we have to do is to have the wind hit a surface that is allowed to move. This will cause the kinetic energy of the wind to be converted to the kinetic energy of the moving object. Anyone who has ever been outside on a very windy day understands this concept. The hard part about generating electricity from wind is doing it cheaply. To do this, a more fundamental knowledge about wind is needed.

Wind creation

The driving force behind wind is sunlight. Materials in the atmosphere absorb some of the energy from the Sun, causing the surface to increase its temperature. The hotter air expands, resulting in a reduction of the density of the air, causing it to rise as it becomes more buoyant. The air that rises takes a great deal of mass with it. Without the weight of the air pressing down in this area, the air pressure is reduced. The resulting pressure difference causes the surrounding air to rush towards the lower air pressure, giving us surface winds. This part of the process is known as **advection**.



Warm air causes the balloon to rise up



Mountains affect wind creation

Surface winds can also be affected by changes in the temperature between land and water. As water has a heat capacity nearly 8 times that of soil and rock, it means the soil increases its temperature 8 times faster. So, the air that is over the land will get hotter and rise faster. This creates an air flow from the sea onto the land during the day and from land to sea during the night. Mountains play an important role in creating and modifying the wind too. For instance, a mountain chain becomes a "wall" to airflow. The air can also be "squeezed", resulting in high wind speeds in mountain passes and low wind speeds in valleys.

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Wind turbine operation

A wind turbine converts the movement of the wind past its blades into rotary motion. The energy from the rotating blades is transferred down a shaft to a gear box which transfers it to the electrical generator. All these pieces are contained in the top of the turbine in a housing called a 'nacelle'. The direction of the nacelle is governed by a wind vain. A computer decides which direction the wind turbine should be facing, by instructing a 'yaw' motor to turn placing the nacelle towards the wind.



Wind turbine section







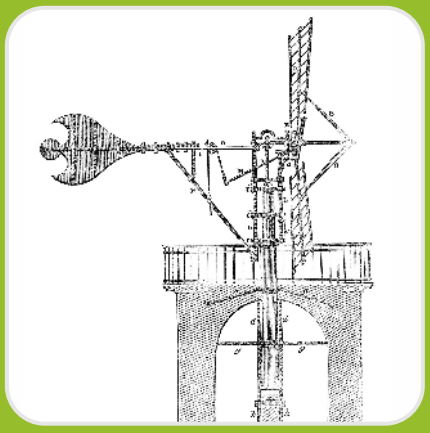
Examples of vertical wind turbine designs

Blade design and materials

There are many different designs that have been created over the years. Most wind turbines have 3 blades and sit on a tower. However, there are also vertical blade designs that work with the same efficiency. The blades need to be very light and strong, so they are constructed out of aluminium, carbon, kevlar or glass reinforced plastics.

Did you know?

The term "turbine" derives from the Greek word "τύρβη" (tyrbe) which means "turbulence". Early turbine examples are windmills and waterwheels. The first power generating turbine was constructed in Cleveland, America in 1889 by Charles F. Brush; an inventor, entrepreneur and philanthropist. It was 60 feet (18 m) tall, weighed 4 tons (3.6 metric tonnes) and powered a 12 kW generator. It had one-hundred and forty-four blades, and was used to charge batteries.



Old illustration of a windmill

Effects of wind power

Wind power is free and available around the globe. It does not generate "pollution", or radioactive waste as there is no need for burning fossil fuels. It is a form of renewable energy with no hidden costs.

On the other hand, power production is not stable as wind speeds change all the time. The towers and blades require constant maintenance as they can be damaged from weather (e.g. lightening) and friction, as well as birds which can be in danger as they fly between the blades. There is a limitation of space for wind power plants, so they are either built in remote areas or even inside the sea, but this comes with a much higher cost.



Wind power station located in the sea

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Hydroelectric power

Hydroelectricity is the electricity created through the use of the gravity causing the falling or flowing of water. It is the most widely used form of renewable energy. Once a hydroelectric power station is constructed, the dam produces no direct waste, and has a considerably lower output level of the greenhouse gas carbon dioxide (CO_2) than fossil fuel powered energy plants. Worldwide, an installed capacity of 1,010 Giga Watts (this is enough to power 20 cities the size of London) was supplied by hydroelectricity in 2010. This was approximately 16% of the world's electricity and accounts for about 76% of all electricity from renewable sources.



A water wheel powering a corn mill in England

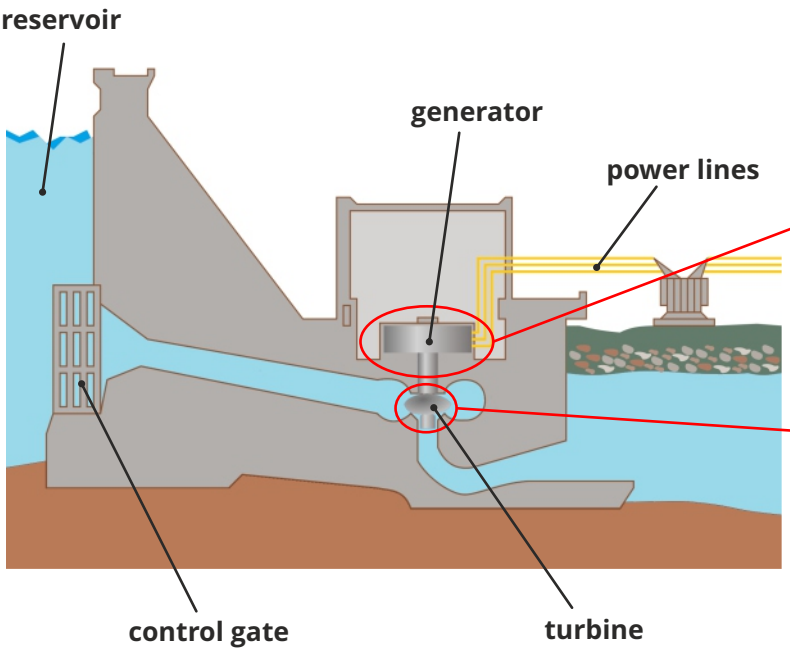


A dam used for producing hydroelectric power

Types of hydroelectric power production

Dams: most hydroelectric power comes from the potential energy of dammed water that drives a water turbine and generator. The power extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the “head”. The amount of potential energy in water is proportional to the head. Existing dams, used for saving water or for eliminating the danger of flooding, can easily be transformed into hydroelectric power plants.

Below you can observe a diagram of the basic layout of a hydroelectric power station, as well as a more detailed look of a water turbine and generator. The water is concentrated in a dam and channelled through a control gate with high pressure into the power station’s turbine. The potential gravitational energy of the water is turned into kinetic energy, rotating the blades. As the turbine is connected to the generator, the kinetic energy is transformed into electric energy, which is then transferred by the power lines.



The basic layout of a hydroelectric dam power station

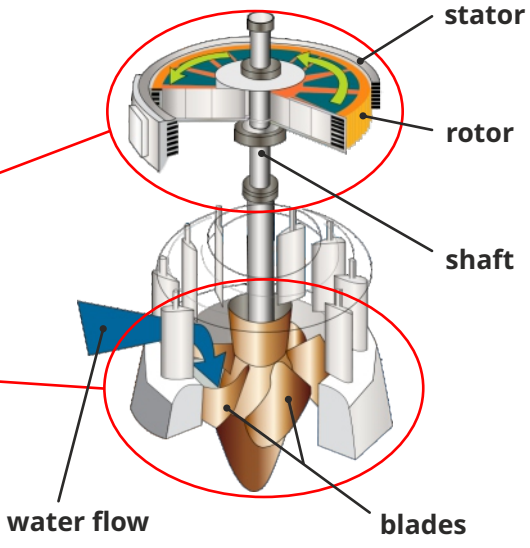


Diagram of a turbine and generator

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Pumping water between reservoirs

Pumped-storage method produces electricity to supply high peak demands by moving water between reservoirs at different elevations.

Run-of-the-river stations are those with small or no reservoir capacity, so that the water coming from upstream must be used for generation at that moment, or must be allowed to bypass the dam.



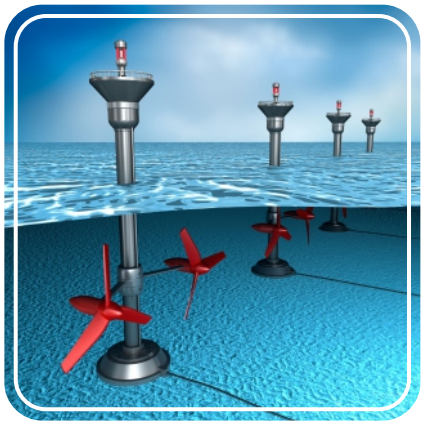
Small reservoir



Wave energy

Wave energy is produced when electricity generators are placed on the surface of the ocean. Energy output is determined by wave height, speed, length and density.

A **tidal power** plant makes use of the daily rise and fall of ocean water due to tides; such events are highly predictable providing power even in high demand periods.



Tidal power

Advantages of hydroelectric power

- The cost of operating a hydroelectric plant is minimal compared to fossil fuels.
- Hydroelectric plants have long economic lives, with some plants still in service after 50–100 years.
- Operating labour costs is also usually low, as plants are automated and have few personnel on site during normal operation.
- Hydroelectricity produces the least amount of greenhouse gases out of any other energy source.
- Large hydro dams can control floods, which would otherwise affect people living downstream of the dam.



Hydroelectric plants are largely automated



Mud in the water can cause dam failure

Disadvantages of hydroelectric power

- Changes in the amount of river flow will affect the amount of energy produced by a dam. This can result in power shortages for dependable areas.
- Reservoirs of power plants in tropical regions may produce substantial amounts of methane due to rotting plants in flooded areas.
- Mud can fill a reservoir and reduce its capacity to control floods or even fail completely.
- Often, people have to be relocated in order for the area to be flatted. Up to 2008 it was estimated that 40-80 million people worldwide were moved due to dams.

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Geothermal power

The word geothermal comes from the Greek words "γαία" (geo which means earth) and "θέρμος" (thermos which means heat). So, geothermal energy is heat from within the Earth. It is considered to be a renewable energy source because the heat is continuously produced inside the Earth and will practically never stop. Geothermal energy is generated in the Earth's core. Temperatures hotter than the sun's surface are continuously produced inside the Earth by the slow decay of radioactive particles. But from where does all this energy comes from? To answer this we need to learn more about Earth's interior.



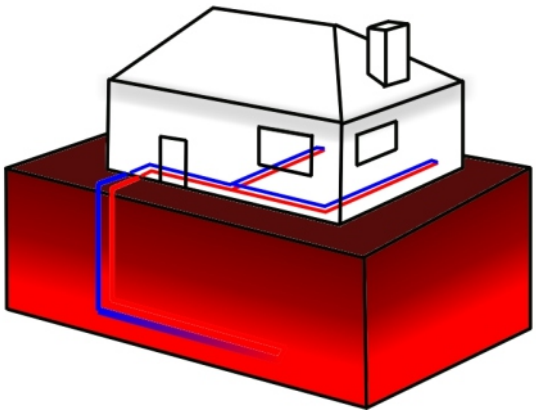
A diagram view of Earth's interior



Volcanic eruptions produce lava

The Earth has a number of different layers: 1) The **core** (in the middle) itself has two layers: a solid iron core and an outer core made of very hot melted rock, called magma. 2) The **mantle** surrounds the core and is about 1,800 miles thick. It is made of magma and rock. 3) The **crust** is the outermost layer of the Earth, the land that forms the continents and ocean floors. It can be 3 to 5 miles thick under the oceans and 15 to 25 miles thick on the continents. The crust is broken into pieces called plates. Magma comes close to the Earth's surface near the edges of these plates. This is where volcanoes burst and lava is expelled.

Geothermal power stations work on a simple set of principles. First you drill holes where there are hot rocks near the Earths surface. Then, pump water down one of the holes you drilled. When the water in the hole gets really hot it can come back up the other hole as steam. This steam is then used to drive an electric generator. The remaining hot water can then be either used again or sent to houses to heat them in winter. People around the world use geothermal energy to heat their homes and to produce electricity by digging deep wells and pumping the heated underground water or steam to the surface.



Geothermal energy is used to heat houses



Hot waters in Iceland

Effects of geothermal power

Geothermal energy is a pure source, with very low toxic emissions (e.g. sulfur). The Earth's interior is in a constant state of producing the same amount of heat for the next 4 billion years! Unlike other renewable sources, it does not rely on weather to generate power, so it will work all day regardless of the season. However, scientists fear that too much exploitation will have many negative effects, such as changes in Earth's tectonic movement (earthquakes). Also, very few countries make use of this technology, making it hard to find qualified personnel to do the job at a low cost.

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Biofuels



Wheat is used to produce biofuel

Biofuels are any liquid, solid or gaseous fuels produced from organic materials. These materials can be: starch and sugary plants such as corn, wheat or sugar cane; oily plants such as rape seed, soya beans or jatropha; vegetable oils and animal fats; wood and straw; algae, organic waste and others. Biofuels are not a new idea and have a long history in the motor industry, reaching back to the development of the combustion engines of the 1800s. Rudolf Diesel designed his compression engine to run on peanut oil, while Nicolaus Otto's spark-ignition engine was running on ethanol (alcohol).

1st generation biofuels

The most common 1st generation biofuel are bioethanol from starch or sugar crops and biodiesel from oil-rich plants. Bioethanol in particular was promoted by Henry Ford who had a vision to "build a vehicle affordable to the working family and powered by a fuel that would boost the rural farm economy". His famous Model T Ford car first ran on bioethanol. These fuels are primarily derived from crops which are also used as food for animals and humans. They were criticised for wasting food by "feeding" it to an engine.



The Model T Ford was designed to run on biofuel

2nd generation biofuels

Second generation biofuels are biofuel technologies that are still in the research and development stage. The Biofuel Research Centre focuses on 2nd Generation biofuels produced by microbial fermentation of non-food crops. These carbon-rich lignocellulosic materials (the things we don't eat and what the farmers throw away) are renewable and widely available. Sources include agricultural waste such as corn stover, straw and bagasse; industrial waste such as sawdust and paper pulp; woody biomass from forestry; Domestic waste including household food, garden waste and paper products.

Did you know?

Normal cars use fuels that produce dangerous carbon emissions, which cause global warming. On the other hand, green cars use alternative fuels that have zero carbon emissions. Brazil is an excellent example on the matter being the leading country in ethanol usage, a biofuel produced from sugar cane. Other types of environmentally friendly fuels include hydrogen, made out of methane or water electrolysis and biodiesel, made out of vegetable oil or animal fat.



A sugar cane plantation

Building Challenge

instructions can be found online

Solar tractor:

build the solar tractor model and combine two renewable energies: solar (to move the model) and biofuel (from harvesting the crops).



Engino® "solar tractor" model

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