

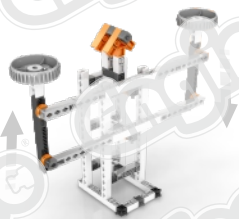
# STEM Mechanics Master Set

## E97.1 THEORY

The **STEM Mechanics Master set** is the ultimate combination of the main subjects of Simple Machines and Physics, including Levers, 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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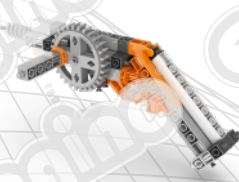
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# Levers & Linkages

## 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.

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**, **Peaucellier-Lipkin** and **Hart linkages**. A lot more models are available online! Finally, take the revision quiz to test your newly acquired knowledge.



*The seesaw works on the principle of levers*

## 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.



*Pyramids in Egypt*

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*





*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.

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*



## 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*

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*

## 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.

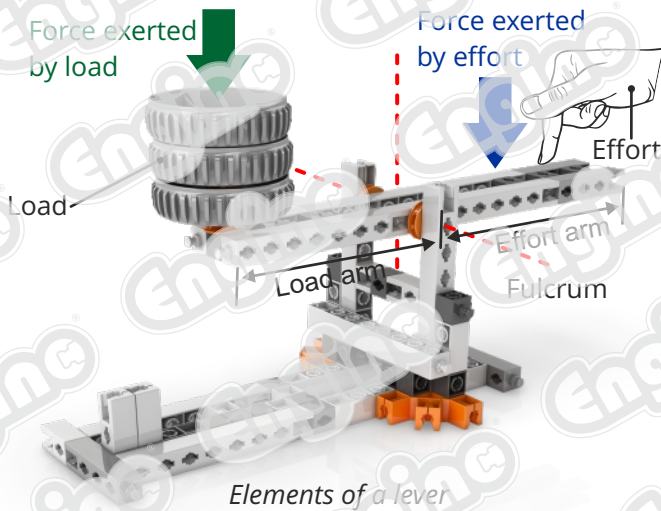


Archimedes is using a lever to move a boulder!

## 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.



## 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).

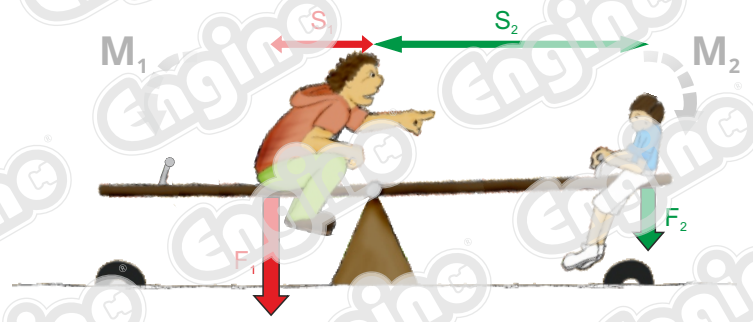
$$M = F \times S$$

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.



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  $S_2$ .



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

*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*

### 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*



### 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 poured 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*

## 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.

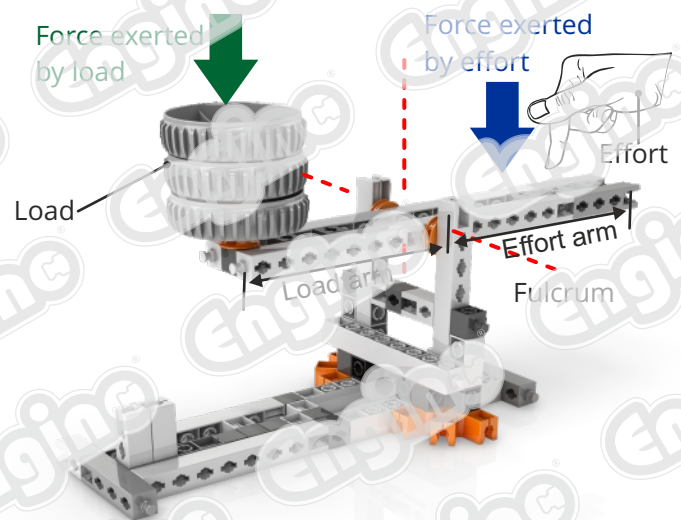


Diagram of first-class lever



Claw hammer



Scissors (double)



Pliers (double)

### Building Challenge



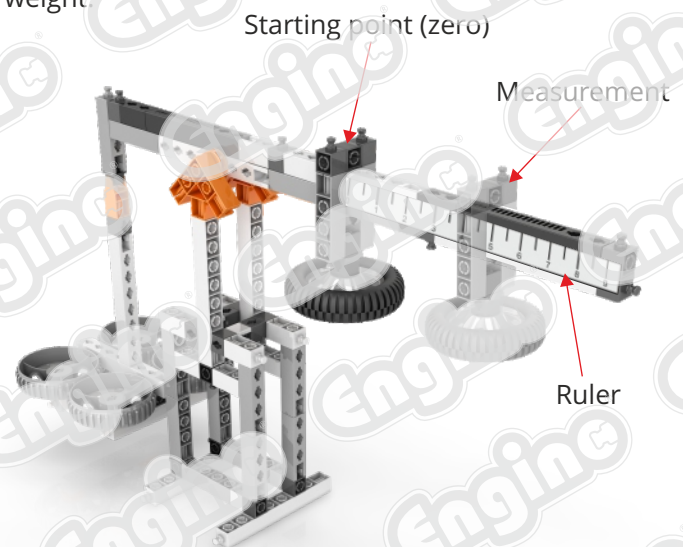
instructions can be found online

**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



## 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;
- misalignment 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

## 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.

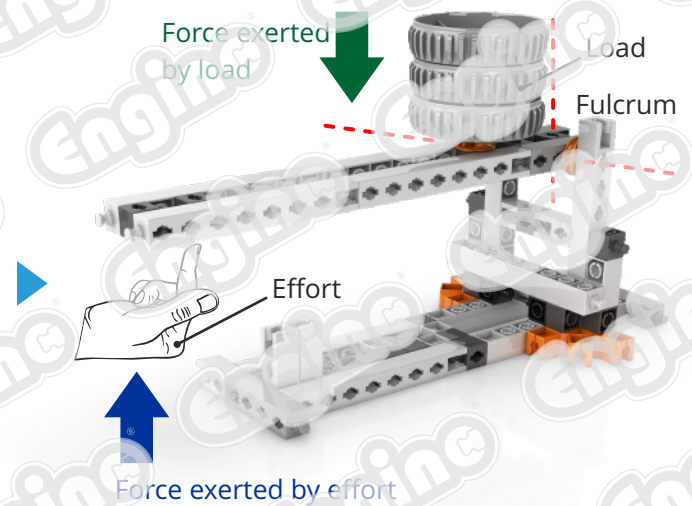


Diagram of second-class lever



Paper guillotine



Nutcracker (double)



Wheelbarrow

### Building Challenge



**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 oscillating 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.



LEGO® "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 Gaochang 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.



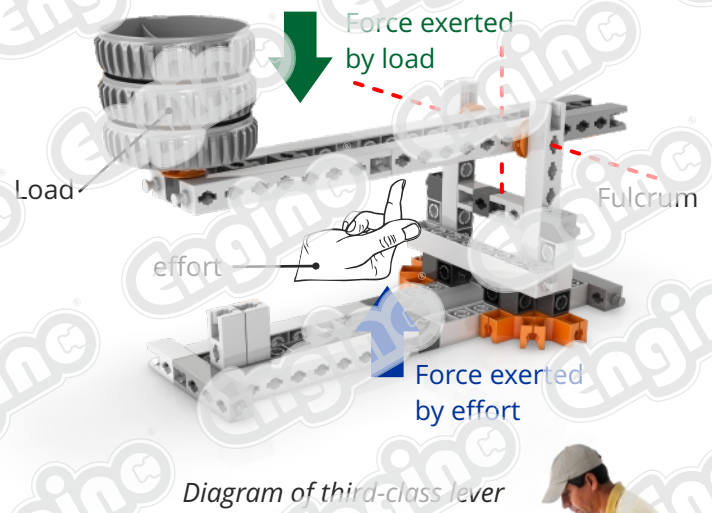
Sailing wheelbarrow



## 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.

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.



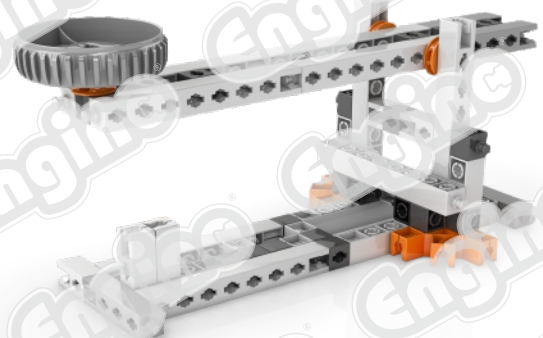
Our arm works as a third-class lever

## Building Challenge



**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.

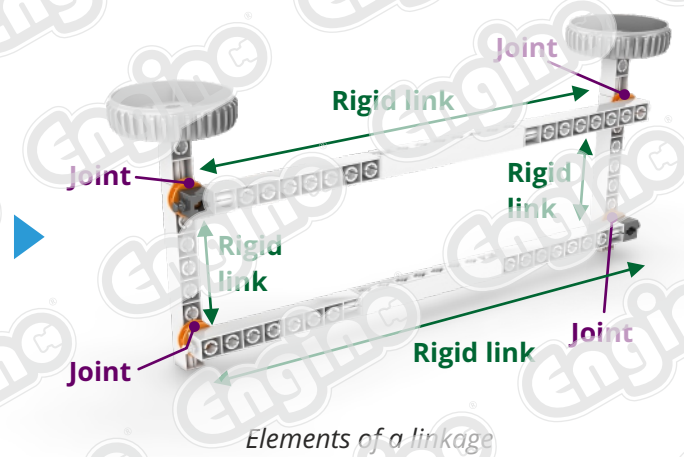


Engino “catapult” model



## 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.



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



## 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  $AB \parallel CD$ ) and line AC is parallel to line BD ( $AC \parallel BD$ ). The ENGINO scale model has also such a shape!

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 lamps.

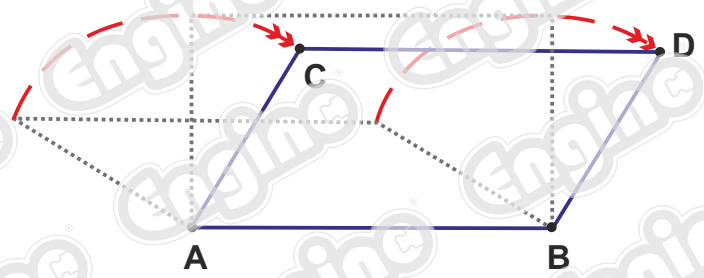


Diagram of parallel motion.



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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