Gears model 1 – Beam balance (lever)

To determine the weight of an object, we must know the ratio of the weight to a fixed reference or basic value. The scales shown in this and the next tasks can be used to bring two movable levers into balance. The transformation to the reference weight is then carried out using a suitable scale.

Construction task

Fig. 1 Beam balance

Build the beam balance shown in Fig. 1. It works according to the lever principle: If you increase the weight on the scale pan (in the left image), you must push the movable weight from the four yellow basic building blocks (in the right image) on the beam outward to balance it out so that the indicator (the black axle) points exactly to the tip of the red angle disc.

Cut out the template for the scale and fasten it to the black angle brackets with two S-latches on the right and left. Take a black pen and mark the “zero position” of the weight with a line and a “0” (with the scale pan empty), which is the point at which the tip of the red angle disc under the weight on the scale points.

Topic task

Now the scale still needs to be calibrated. To do so, you must add “unit weights” to the scale pan. If you do not have exact weights available, you can also use basic building blocks as the “unit weight”. (They weigh a little over 5 g.)

Mark the position of the red angle disc under the weight on the scale with a line when the weight is set so that the pointer on the scale points exactly to the lower angle disc. You can complete the scale in this way. Check your calibration to ensure it is correct with objects of different weights whose weights are known to you.

1. What is the distance between two 10 g markings on the scale?
2. What is the maximum weight you can measure using the scale?
3. When the scale is balanced, what physical variables are equal?

Experimental task

1. How can you change the scale so that the measurement range is doubled? Name at least two possibilities.

2. Imagine you want a more precise resolution for the scale. How can you achieve this? (There are also multiple possibilities for this as well.)

Solution sheet Gears model 1 – Beam balance (lever)

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Students receive a copy of the measurement scales to cut out.

Topic task

The beam balance can be calibrated with any “unit weight”. The markings on the scale should be divided into suitable graduation marks.

1. The distance between the graduation marks must be uniform, since the counterweight is pushed in a linear direction to increase the weight in the scale pan. The distance between two 10 g markings should be about 5 cm.

2. The scale can be used to weigh a maximum of a little more than 35 g.

3. When the scale is in balance, meaning that the beam balance is aligned exactly horizontally and the scale indicator points to the tip of the red angle disc, then the torques on the right and left sides of the axle are equal.

Experimental task

1. The measurement range of the scale can be doubled by doubling the length of the right side of the beam balance on the image, or halving the length of the left side. This will double the movable counterweight on the right side of the beam balance.

2. You can achieve a finer resolution for the scale by reducing the counterweight or extending the left side of the beam balance. To retain the measurement range, you must extend the right side of the beam balance accordingly.

Enclosure

Model 1: Building instructions for beam balance, sheet with empty scales to cut out

Gears model 2 – Letter scale (lever)

The following type of mechanical scale would more accurately be called an “inclination balance” and is still used today very broadly as a letter scale.

Construction task

Fig. 1 Letter scale

Build the letter scale shown in Fig. 1. In contrast to a beam balance, it is not necessary to adjust any weights with this scale: The weight placed on the (right) scale pan deflects the left pointer (yellow base module with angle disc on the tip). The scale is in a stable balance.

Cut out the template for the letter scale and fasten it to the yellow, curved angle brackets with two S-latches on the right and left. Take a black pen and mark the “zero position” of the scale with a line and a “0” (with the scale pan empty), which is the point at which the tip of the red angle disc on the scale points.

Topic question

Now this scale still needs to be calibrated. To do so, you must add “unit weights” to the scale pan (see task 1). Make lines to mark the position of the tip of the red angle disc on the scale. Check your calibration to ensure it is correct with objects of different weights whose weights are known to you.

What is the maximum weight you can measure with this scale?

Experimental task

1. How can you increase the measurement range for this scale?

2. How can you refine the measurement for this scale? (Here as well, there are multiple ways to achieve this.)

3. Why are the distances between two 10 g markings, for instance, on the scale smaller as the weight increases?

Solution sheet Gears model 2 – Letter scale (lever)

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Note on technological history: The letter (or hinged lever) scale was invented by *Philipp Matthäus Hahn* (1739-1790), who developed it around 1764-1770. Hahn also developed some of the first mechanical counting machines based on design principles from Leibniz for the calculations of his astronomical clocks and instruments.

Students receive a copy of the measurement scales to cut out.

Topic question

The letter scale can also be calibrated with any “unit weight”. The markings on the scale should be divided into suitable graduation marks; the graduation marks must have less and less distance to the left (as the indicator becomes more deflected).

The maximum weight that can be measured with this scale is a little more than 25 g.

Experimental task

1. The measurement range can be enlarged by increasing the weight of the pointer arm of the scale. This can also be done by extending the pointer.

2. Here as well, the scale can be made more precise by enlarging the right lever, for instance by increasing the distance between the two rotational axes and joints with building blocks, or reducing the weight of the pointer arm of the scale, for instance by replacing building block 30 with static parts. However, this will make the measurement range smaller.

3. The distances between the markings for equal weight differences become smaller because the pointer arm describes a circular movement. The percentage of movement of the pointer that is sideways (and requires little force) becomes smaller, while the percentage of the movement that lifts the pointer increases. Therefore, the deflection angle does not grow in a linear fashion.

(The change can be calculated via the torque: The torques of both sides are always the same – when the scale is swung out.)

Enclosure

Building instructions and templates for the gears and models:

Model 2: Building instructions for letter scale, sheet with empty scales to cut out

Gears Model 3 – Pulley and wheel and axle

The pulley is one of the oldest gearing mechanisms there is. Without it, the impressive stone buildings of the ancient world never would have been built. A pulley amplifies force by dividing stroke over multiple rope slings. The work performed – lifting a weight – remains the same, but the user must pull for a longer period of time (with less force).

Construction task

First, build the simple pulley shown in Fig. 1.

Fig. 1 Pulley with up to four rollers

Topic question

Fig. 2 shows three different rope configurations, which use two, three and four rollers of the pulley respectively. Build these one after the other, and answer the questions below for each one.

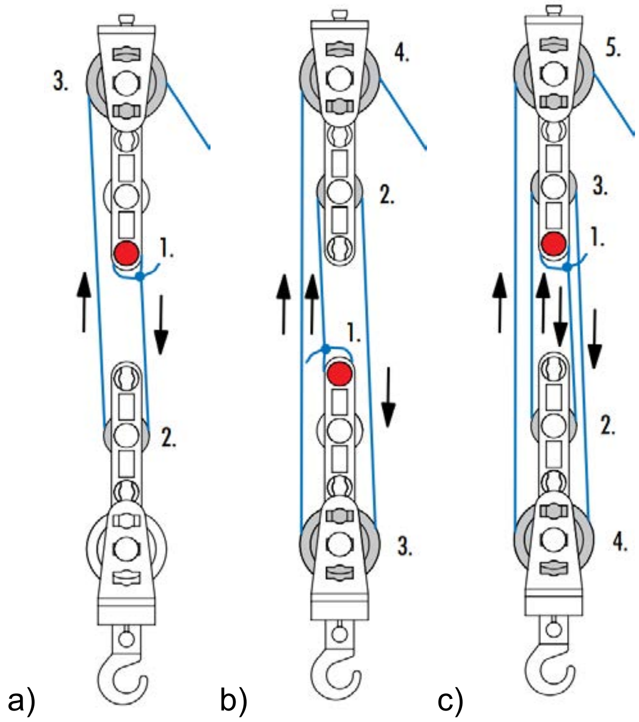


Fig. 2 Three different rope configurations with a) two, b) three and c) four rollers

1. How many crank rotations does the winch need without a pulley, and how many in cases a), b) and c) to lift an object by 10 cm?

2. What force amplification is delivered by the three pulley versions a), b) and c) in contrast to a rope hoist without a pulley?

3. Why is this type of pulley called a block and tackle?

Experimental task

Now, add a wheel and axle to the pulley as shown in Fig. 3.

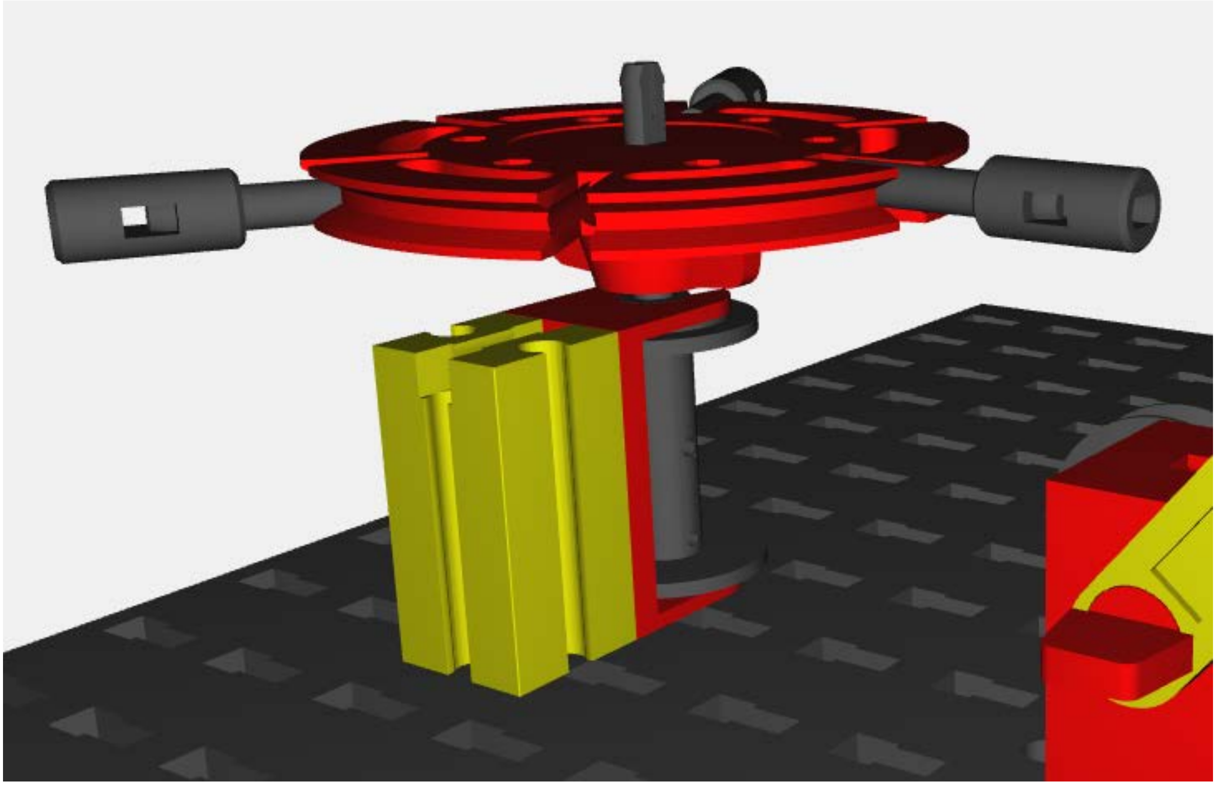


Fig. 3 Wheel and axle with pulley

You can understand the effect of the wheel and axle by imaging it as a lever: You can convert the force acting on the centre of the snap-on adapter into the force of the rope drum acting on the rope.

1. What force amplification is provided by the wheel and axle with a) a clip axle 30 and b) a clip axle 45 as the lever?

2. What "price" do you pay for using a wheel and axle for force amplification?

3. What force amplification is easier to generate – that on the wheel and axle or that on the pulley? Name different advantages and disadvantages of the two options for force amplification.

Solution sheet Gears Model 3 – Pulley and wheel and axle

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Note on technological history: When the pulley was invented is not known. The oldest known descriptions of pulleys come from the Roman author *Marcus Vitruvius Pollo* (approx. 80-15 BC), who described the engineering knowledge of the day in his “Ten books about architecture”. These books included the wheel and axle, which was used in Roman building cranes.

Topic question

1. The exact number of crank revolutions depends on the thickness of the rope drum, or the amount of rope that has already been wound. Without a pulley, this will be a full three rotations, in case a) around six and a half, in case b) around 10 and in case c) 13.

2. The force amplification is inversely proportional to the required rope length. Case a) doubles the force, case b) triples it and case c) quadruples it. The force amplification can be counted based on the number of rope loops.

3. This is called a “factor”: The number of rollers used is the factor by which force is amplified.

Experimental task

1. The force amplification of the wheel and axle corresponds to the ratio between the long lever and the radius of the rope drum. If the rope is wound directly onto the drum (diameter 0.7 cm), and if a hand grips the centre of the snap-on adapter, then the amplification in case a) is $4.5/0.35 \approx 12.85$ and in case b) $6/0.35 \approx 17.14$.

As the quantity of rope wound increases, the radius of the rope drum also increases, and the force amplification is reduced. However, when comparing the wheel and axle with the crank, it should be noted that the crank itself amplifies force by around a factor of $1.2/0.35 \approx 3.42$.

2. The path length that must be completed when turning the wheel and axle increases proportional to the force amplification. (It is easy to check the plausibility of this, since the circumference is $U = 2 \pi r$; multiplying the radius by the same factor is used to calculate the circumference.)

3. It is relatively easy to generate a high force amplification on a wheel and axle. The pulley requires a large number of additional rollers to do the same thing. If the rollers of the pulley are arranged one on top of the other, the stroke length is shortened. However, this can be avoided by arranging the rollers in parallel. The additional rope

length required must, however, fit on the rope drum. The advantage of this is that the weight to be lifted is distributed over the rope slings; a more stable tow rope is not required for a higher weight.

The lever on the wheel and axle and tow rope, in contrast, must absorb the entire increased force or the weight to be lifted, and must be stronger in order to handle the greater weight. A longer lever on the wheel and axle also requires a larger, round running surface around the wheel and axle. Since the tensile force on the rope drum increases with the increase in weight lifted, a wheel and axle should also have a pawl.

Enclosure

Building instructions and templates for the gears and models:

Model 3: Building instructions pulley with cable winch, building instructions pulley with wheel and axle

Tasks Gears Model 4 (with variants) – Crank rocker arm, crankshafts and scissors lift

Generally, input shafts generate a rotational movement. However, a back and forth movement is often required for the output drive. This is achieved using crank rocker arms, a crankshaft and a scissors lift. Crankshafts play a central role in combustion engines. They convert the pushing movement of the piston rod into a rotational movement of the output shaft.

Construction task

The gearing mechanism shown in Fig. 1 is a “crank rocker arm”: It converts a circular movement (that of the eccentric disc) into an oscillation movement. The axle at the top end of the flexibly mounted basic building block moves along an arc. One typical application for a crank rocker arm is a simple windscreen wiper.

Fig. 1 Crank rocker arm

Expand the crank rocker arm to make it a windscreen wiper by adding two separated wiper blades. (You can simulate the wiper blades by static struts attached to the basic building block with an S latch.)

Experimental task

1. A gearing mechanism that is very similar to the crank rocker arm is the “crankshaft” shown in Fig. 2. In contrast to a crank rocker arm, the circular movement of the eccentric disc here is not converted into an oscillating but rather into a pushing movement: The guide from the metal axle ensures that building block 15 with drill hole moves back and forth on a straight line.

In addition to the function already indicated as a crankshaft in vehicle engines, there are other useful applications for this – for instance as “feed drives”.

Expand the crankshaft to make one such feed drive that pushes a sheet of paper on the base plate evenly by a defined distance. Demonstrate the function.

Fig. 2 Crankshafts

2. Fig. 3 shows a jack with scissors lift that is lifted using a worm gear. The gear is self-locking, meaning the jack remains stable in the position set using the worm gear.

Fig. 3 Jack with scissors lift and worm gear

Build the jack according to the figure. You will find that the jack lifts up surprisingly high. Consider: How can the stroke be increased even further? Name multiple possibilities, and compare them.

Solution sheet Gears Model 4 (with variants) – Crank rocker arm, crankshafts and scissors lift

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Note on technological history: Crankshafts have been employed since antiquity to make use of the rotational movement of a waterwheel for masonry saws. They have been found as far back as the 3rd century A.D. With the development of the steam machine to the “steam engine” by *James Watt* (1736-1819), they became centrally important at the end of the 18th century for vehicles.

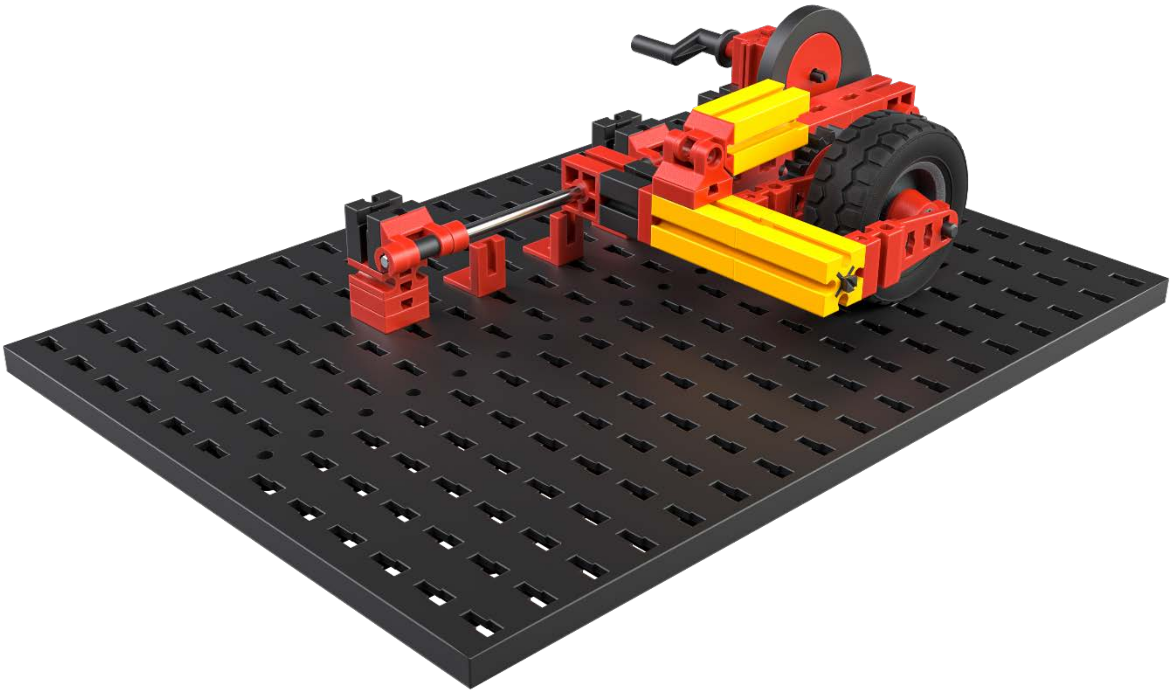
Construction task

One possible way to construct a windscreen wiper.

A larger or smaller lever underneath the connection between the two swing arms can reduce or increase the side deflection of the wiper blades.

Experimental task

1. The feed drive requires a wheel with a safety catch so that it only rolls in one direction, while being blocked in the other, and therefore able to “pull” a piece of paper underneath it.



The feed is determined by the cam used; in this design this is around 4.75 cm.

2. The stroke of the jack can be increased by extending the worm gear or by adding additional pairs of struts to extend the scissors lift. In the first solution, the length of the gear increases. The length of the struts should also be increased to the same extent so that the scissors lift is not too narrow and becomes statically unstable. In the second solution, more force is required for the same stroke, since the distance which the nut is moved remains the same. The force amplification of the lift gear is reduced.

Enclosure

Building instructions and templates for the gears and models:

Model 4: Building instructions for crank rocker arm, Building instructions for windscreen wiper, Building instructions for crankshaft, Building instructions for feed gear, Building instructions for jack/scissors lift

Tasks Gears Model 5 – Cardan shaft

Sometimes, the input and output shafts of a gear drive are neither in line nor parallel with one another; instead, they intersect with one another at an obtuse angle. Then the direction of motion of the shaft must be changed. This is done using a cardan drive, also called a universal joint or cardan joint.

Construction task

Build the cardan joint shown in Fig. 1. What is the angle between the input and output axles?

Fig. 1 Cardan joint

If you drive the input shaft using the crank, you will see that the output shaft does not move in the same even manner. It sometimes turns faster and sometimes slower than the input shaft. This effect is called “cardan error”.

Topic task

Now, extend the input shaft with a snap-on coupling and a snap-on axle 45, and the output shaft by replacing the snap-on axle 30 with a snap-on axle 45. Add a hub 60 to the input shaft with a flat hub so that the hub nut points towards the cardan joint, and add a second bearing before inserting the snap-on crank once again. Replace the wheel with a second hub 60 with flat hub; the hub nut in this case must point away from the cardan joint. Finally, extend the bearing of the input shaft and output shaft with a module 15 with attached 60° angle module, to be able to better read the angle disc (see Fig. 2).

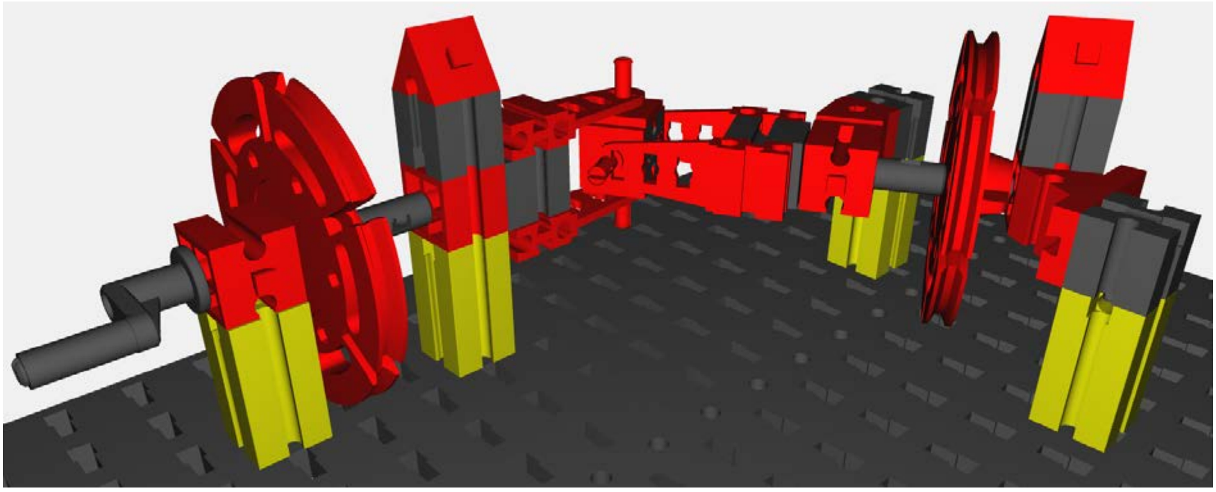


Fig. 2 Adding two protractors to the cardan shaft.

Cut out the two angle discs (Fig. 3), cut a hole in the middle and push them onto the two axles in front of the hubs so that they are clamped on the input axle between the crank and hub and on the output axle between the snap-on coupling and hub. You can also attach them to the hub using transparent tape.

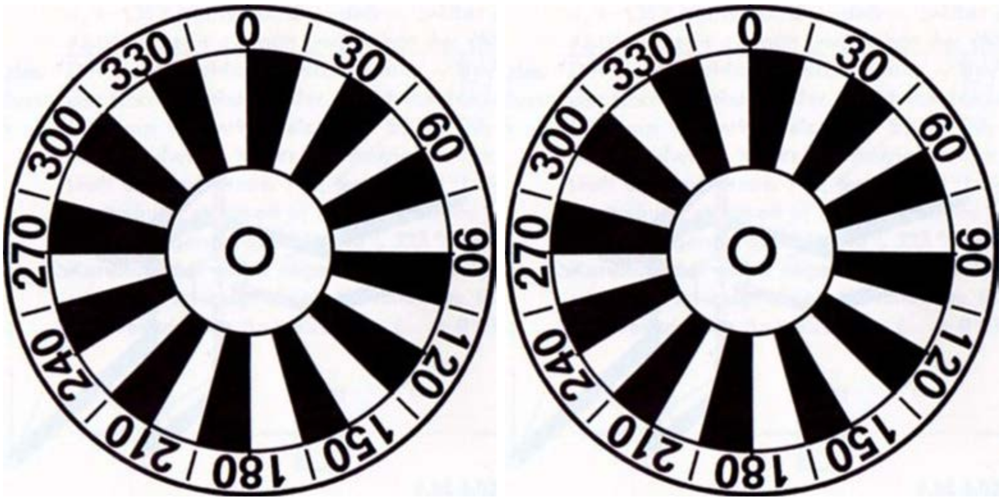


Fig. 3 Disc with graduation as protractor

Bring the cardan shaft to the same position as shown in Fig. 2 and align the two protractors so that the tips of the red angle disc are “flush” with the 0° indicator. Now, turn the crank in 15° steps from 0° to 180° and note the angle values indicated on the second protractor on the output axle.

Enter the measurement results and respective deviation between the input and output axles (“delta”) into the following table.

Rotational angle input	Rotational angle output	Δ	Rotational angle input	Rotational angle output	Δ
0°	0°	0°	**90°**	90°	0°
15°			**105°**		
30°			**120°**		
45°			**135°**		
60°			**150°**		
75°			**165°**		
90°	90°	0°	**180°**	180°	0°

Experimental task

As you have seen, the cardan error of a cardan shaft can be significant. The greater the angle by which the shaft is deflected, the greater the error.

However, there is one interesting point to note: If we "connect" two cardan joints to a cardan shaft one after the other so that the input and output shafts are parallel, then the cardan errors of the two cardan joints cancel one another out. Therefore, cardan joints in even drives are generally only used with a low deflection, or used in pairs when designing a cardan shaft.

Fig. 4 Cardan shaft with two cardan joints

Fig. 4 shows one such cardan shaft. Build this shaft, and use it to solve the following tasks.

1. What is the maximum angle at which the two cardan joints still turn "cleanly"?

2. Mount the two protractors on the input and output shafts of the cardan shaft, and check to see whether the cardan error has really been eliminated.

3. What other gearing mechanisms can you think of that can achieve the kind of offset between input and output that we see with a cardan shaft? What are their advantages and disadvantages, compared to a cardan shaft?

Solution sheet Gears Model 5 – Cardan shaft

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Note on technological history: The name “cardan joint” comes from the Italian scholar and mathematician *Gerolamo Cardano* (1501-1576), who described what would later be called “cardan suspension” in 1550 in “De Subtilitate”. Actually, this type of suspension, also called a “gimbal suspension” had already been described as early as 230 BC by Philo of Byzantium, and was drawn many times by *Leonardo da Vinci* (1452-1519) around 1500. There is no known publication by Cardano of a universal or cardan joint based on the cardan suspension. The oldest known description of the cardan joint comes from *Caspar Schott* (1608-1666) in his book “Technica Curiosa” from 1664.

The correction of the cardan error in a cardan shaft was discovered by English physicist *Robert Hooke* (1635-1703) in 1683.

Students receive a copy of the protractors to cut out.

Construction task

The input and output axles meet at an angle of about 119°.

Topic task

Rotational angle input	Rotational angle output	Δ	Rotational angle input	Rotational angle output	Δ
0°	0°	0°	**90°**	90°	0°
15°	17°	2°	**105°**	95°	-10°
30°	42.5°	12.5°	**120°**	102.5°	-17.5°
45°	57.5°	12.5°	**135°**	115°	-20°
60°	70°	10°	**150°**	125°	-25°
75°	77.5°	2.5°	**165°**	150°	-15°
90°	90°	0°	**180°**	180°	0°

Experimental task

1. The maximum adjustable angle of the cardan joint (smallest angle between the input and centre portion of the cardan shaft) is approx. 117°.

3. Alternative gearing mechanisms include, for instance, a spur gear drive (two toothed gears of the same size on the input and output axle, with any toothed gear between them so that there is no reversal of direction), a chain or belt drive. The disadvantage of a spur gear drive is a loss in efficiency (up to 10%); the disadvantage of a belt drive is the force-locking connection. Chain drives have a significantly lower maximum speed than a spur gear drive (factor of 10 to 30).

Enclosure

Building instructions and templates for the gears and models:

Model 5: Cardan joint building instructions, page with protractors for the cardan joint to cut out, cardan joint building instructions with protractors

Tasks Gears Model 6 – Control gears

Gears with a changeable gearing ratio are called control gears. Control gears are required in vehicles with combustion engines, since these engines generate a high level of effectiveness only within a relatively narrow speed range. The control gear can translate the rotational speed of the input axle to different rotational speeds of the output axle.

Construction task

Control gears are usually built using toothed gears. The following section differentiates between the toothed gears in use, based on their number of teeth: A toothed gear with 30 teeth is called a Z30, one with ten teeth a Z10, etc.

Fig. 1 shows a drivetrain (with crank, front) and an output shaft (with wheel, rear right on the image). Between them is an (empty) gear axle that can be moved horizontally via a lever (right).

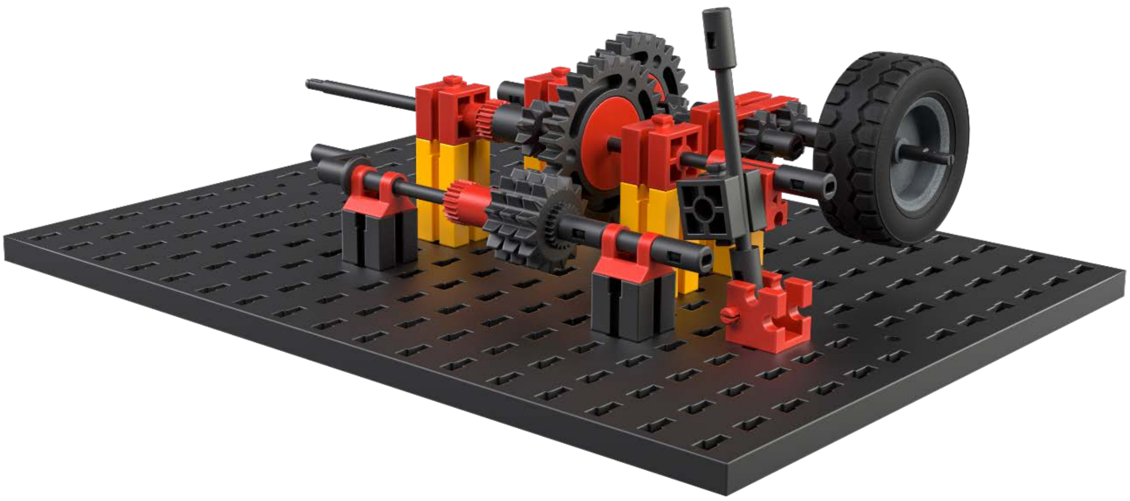


Fig. 1 Control gear – Basic construction

Expand this initial construction to create a control gear that can be used to choose between two different gearing ratios (or “gears”).

Topic task

1. What gearing ratios does your gear have? How great is the difference in the rotational speeds of the output axle (with input axle running at the same speed) in the two gears?

2. Your control gear is one of many that can be built with the toothed gears provided (Z10, Z15, Z20, Z30, Z40). What other two-speed control gears could you create with these toothed gears (and if necessary other distances between the gear axles)?

Experimental task

1. Expand your two-speed control gear to create a three-speed control gear. What gearing ratios does your gear have? Are other designs possible?

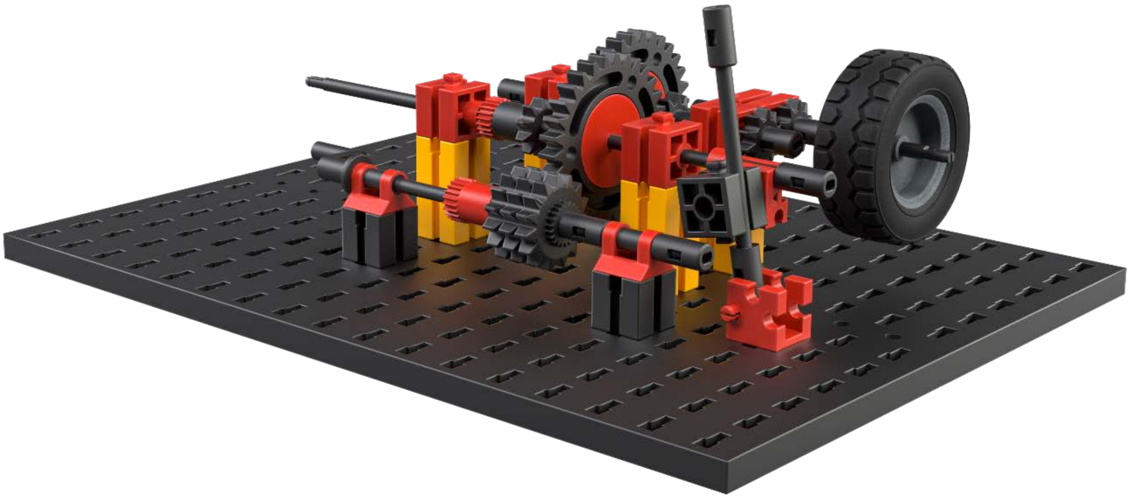
2. Add a reverse gear to your three-speed gear.

Solution sheet Gears Model 6 – Control gears

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Students receive the building instructions for the base construction of the control gears.

Construction task



Topic task

1. The switching shaft in the figure gears down at a 1:3 ratio or gears up at a 3:1 ratio. The drive shaft gears down to the switching shaft at a ratio of 1:2. In the first gear, the control gear therefore gears down at a ratio of 1:6, and in the second gear it gears up at a ratio of 3:2. The rotational speed of the output axle differs by a factor of 9 in both gears.

2. There are a large number of alternative construction options:

Two Z20s can be used to replace one of the two gear ratios of the switching shaft with a 1:1 ratio. In this case, the rotational speed of the output axle in both speeds will differ by a factor of 3.

Two Z10s and two Z40s can be used to achieve a 1:4 with a 4:1 ratio (up or down); the rotational speeds will then differ by a factor of 16.

If we replace one of the two pairs of sprockets in the latter control gear with two Z30s, then we can replace the 1:4 or 4:1 ratio with a 1:1 ratio. The rotational speeds of the output axles will then differ only by a factor of 4.

We can use two Z15s and two Z30s or two Z10s and two Z20s to build a gearing with a 1:2 and a 2:1 ratio; the rotational speeds of the output axles will also differ by a factor of 4 with this gearing.

A gearing with two Z15s and two Z10s would result in the ratios 3:2 and 2:3; the difference in the rotational speeds of the output axles in this design would be 9:4 (of a factor of 2.25).

Two Z15s and two Z20s would result in a 3:4 and a 4:3 ratio; the difference in rotational speeds in this gearing would be a factor of 16:9 (or around 1.8).

Two Z15s and two Z40s would result in a 3:8 and a 8:3 ratio; the difference in the rotational speeds of the output axles would be a factor of 64:9 (or around 7.1).

Experimental task

1. The following three-speed gearbox (with two Z30s, two Z20s and two Z10s) results in ratios of 1:3, 1:1 and 3:1.

Two Z40s, two Z30s and two Z20s can be used to achieve ratios of 1:2, 1:1 and 2:1.

The same gearing ratios can also be achieved (in a much more compact manner) with two Z10s, two Z15s and two Z20s.

2. The three snap-in Z10s at the left of the image provide the reverse gear (directional change!) with a 1:1 ratio. The centre sprocket can be replaced by any other sprocket and placed higher or lower to connect the two outer snap-in Z10s.

Note: Changing the ratio of the output to the change shaft and the final ratio to the output axle (constant 1:1 in the gearing examples above) makes it possible to dimension a complete gearbox.

If the optimal speed range for the motor and the speed range to be covered are known, then the required total ratio for the gearbox can be calculated accordingly, and the gear mechanism can be designed to match.

Enclosure

Building instructions and templates for the gears and models:

Model 6: Building instructions for basic gearbox construction, building instructions for two-speed gearbox, building instructions for three-speed gearbox, building instructions for three-speed gearbox with reverse

Tasks Gears Model 7 – Clock gears

Construction task

One of the most refined technical details of a clock is that multiple hands – at least the hour and minute hands – speed on the same axle at different speeds.

This is achieved using a “freewheel hub”: The minute hand is driven by the metal axle in Fig. 1, while hub 60 placed loose on the same axle with the black freewheel hub is moved by the Z40 behind it.

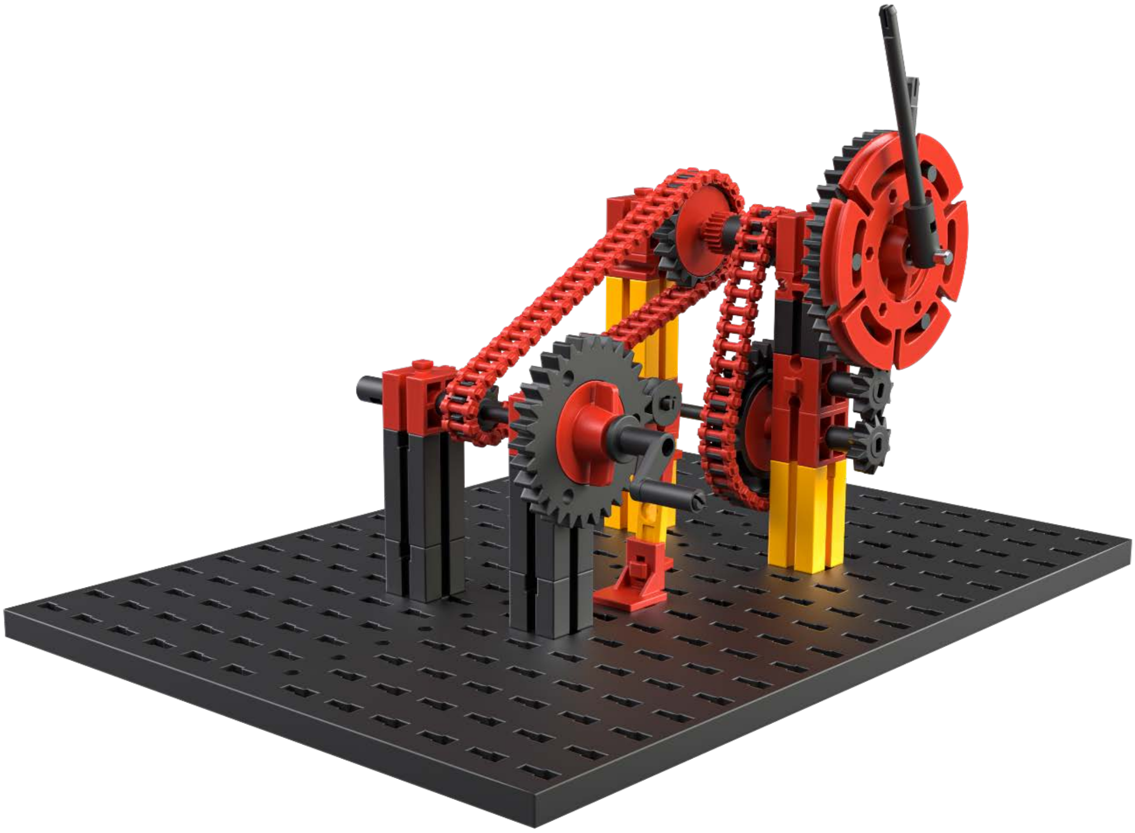


Fig. 1 Clock gears – Base construction

The clock should be operated with a single input shaft: the axle on which the minute hand sits. If the hour hand (hub 60 or Z40) should turn depending on this shaft: What gear ratio would then be required between the minute hand and hub 60?

Topic task

Now, build the gear to drive the hour hand based on the hand shaft as the input shaft.

To do so, proceed "backwards": Look at the Z10 below the Z40. What is the gear ratio here between the shaft of the Z10 and hub 60? What gear ratio is required between the shaft of the Z10 and that of the minute hand?

Now, ask yourself what toothed gears you could use to create this gear ratio, then build the gear ratio so that it connects the minute pointer shaft with the Z10 under hub 60.

Experimental task

1. Clock faces normally show 12 hours, but this is not always the case. It would be more natural to show all 24 hours of the day in one rotation, dividing the clock face into 24 hours. What would a gear used for this purpose look like? Can you build one?

2. We are still missing an input shaft for the clock. We want to create one using a crank.

Build a crank drive to the side of the clock with a toothed gear with catch, so that each time the catch "clicks" (on each tooth of the toothed gear), the clock hands move exactly one minute forward.

Solution sheet Gears Model 7 – Clock gear

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Note on technological history: Astronomical clocks were one of the earliest applications for spur gears. The oldest known spur gear is the so-called "Antikythera mechanism" from the 2nd century BC, an astronomical clock that could be used to predict eclipses of the moon and sun. The first mechanical clocks used to display time were church tower clocks. They were invented in the 14th century AD.

Construction task

A gearing ratio of 1:12 is required, gearing down for the gearing ratio between the minute shaft and hour hand. After exactly 12 rotations of the minute hand, the hour hand must have turned exactly once.

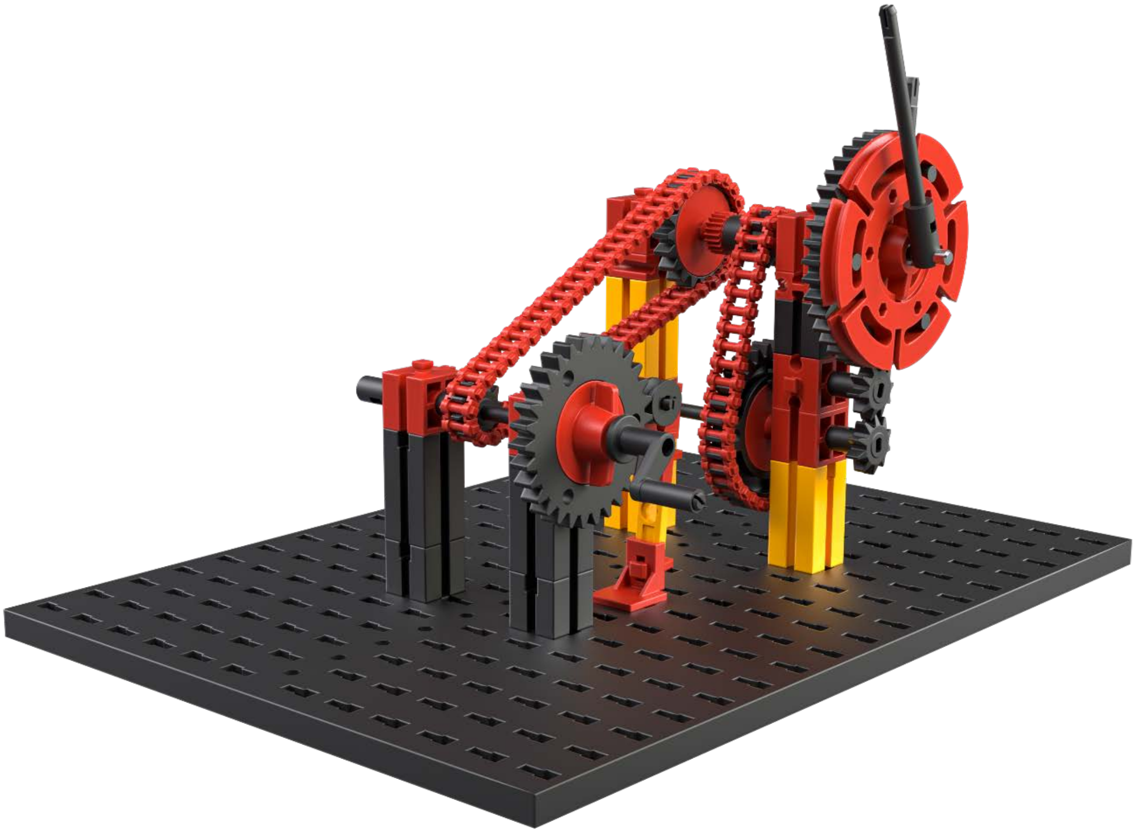
Topic task

There are multiple possible solutions for the gearing mechanism; the following is one of them. In addition to the gearing ratio 1:4 (that of the snap-on Z10 on the Z40), we also need a gearing ratio of 1:3. We must note the direction of rotation in particular: It is retained in chain drives; the two snap-on Z10s reverses it twice.

Experimental task

Clock gears with an unconventional 24 hour display: We will add a 1:2 gear ratio, gearing down to the mechanism. Replacing the chain drive with two spur gears (1:3 and 1:2) keeps the same direction of rotation.

Crank drive with "minute scale": a Z30 and a gearing ratio of 1:2 gearing down ensures that each tooth of the Z30 moves the minute hand 1/60th of a rotation further.



Enclosure

Building instructions and templates for the gears and models:

Model 7: Building instructions for base construction of clock gear hand, Building instructions for clock gear, (Building instructions for clock gear with 24h display), Building instructions for clock gear with crank drive

Tasks Gears Model 8 – Planetary gear

Gears in which the change in motion is coaxial are particularly well-suited for many practical applications. In these gears, the input and output shafts are in line with one another. They are compact, easy to construct, and simple to combine with one another.

Construction task

Fig. 1 shows a coaxial gear mechanism with bevel gears. Build this gear mechanism. What change in motion does it generate?

Fig. 1 Coaxial bevel gear

A coaxial gear can also have a gearing ratio. The gearing mechanism in Fig. 2 uses a crown wheel. Build this mechanism. What is the gearing ratio?

Fig. 2 Coaxial step-up gear unit with crown wheel

Topic task

Planetary gears are a special type of coaxial step-up gear units. They are generally constructed as spur gears, meaning that the teeth of the sprockets are vertical to the axle (shaft). Planetary gears consist of

- a “sun gear” (a toothed gear in the centre).
- multiple “planetary gears” that “revolve” around the sun gear, with shafts connected to one another via a carrier, and
- a “ring gear” into the internal teeth of which the teeth of the planetary gears interlock.

Planetary gears can be constructed to be very compact. Depending on which of the three shafts of the planetary gear – the shaft of the sun gear, that of the carrier or that of the ring gear – is fixed, the gearing ratio will change.

First, observe and build the following planetary gear with fixed carrier and the sun gear on the drive shaft (Fig. 3):

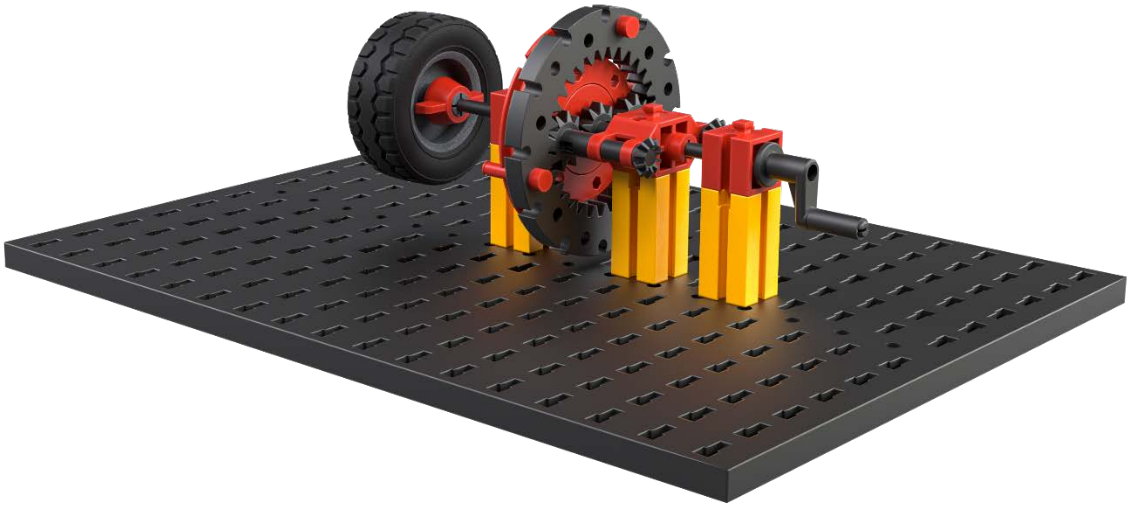


Fig. 3 Planetary gear with fixed planetary gear carrier and sun gear input shaft

The gearing ratio of the planetary gear is identical to that of the following simple spur gear (Fig. 4):

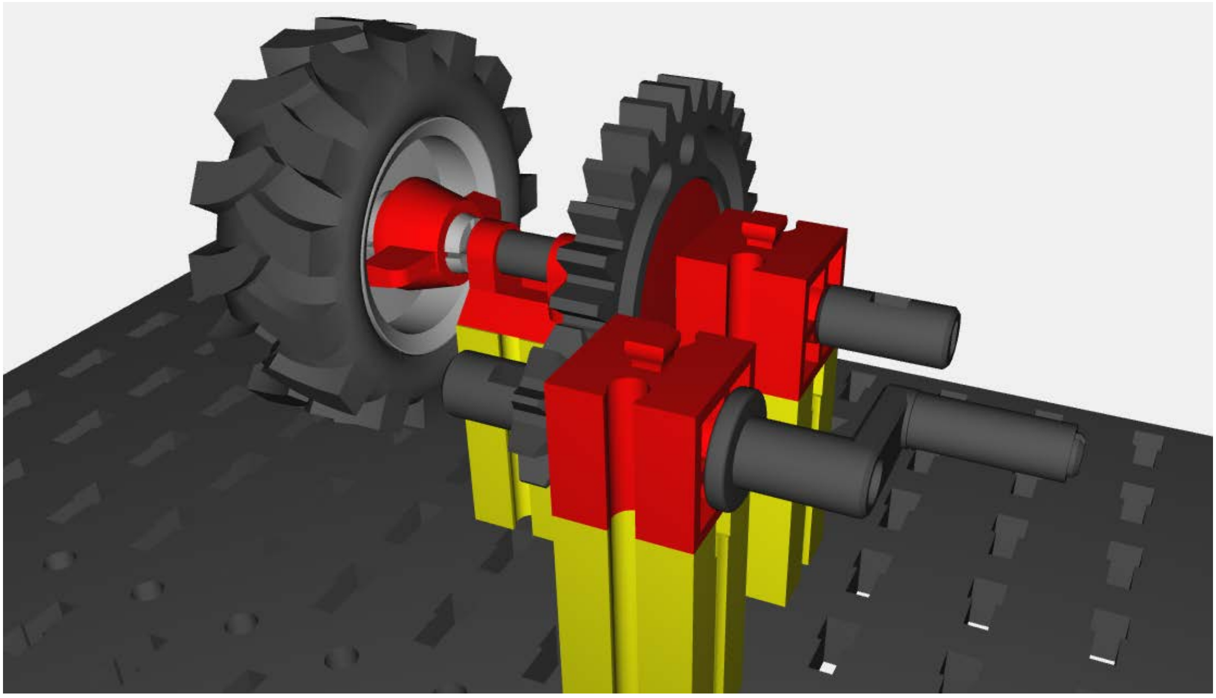


Fig. 4 Spur gear equivalent to the planetary gear

Why is this? Please explain. What is the gearing ratio of the planetary gear with fixed carrier and sun gear as the input?

Experimental task

1. The carrier in the planetary gear in Fig. 3 is fixed. Build another planetary guild where either the sun gear or the ring gear is fixed.

2. What gearing ratios can be achieved with fischertechnik spur planetary gears with internal gear Z30? Complete the following table:

Fixed	Input	Output	Gearing ratio	Change in direction
Carrier	Sun gear	Ring gear		yes/no
Carrier	Ring gear	Sun gear		yes/no
Ring gear	Sun gear	Carrier		yes/no
Ring gear	Carrier	Sun gear		yes/no
Sun gear	Carrier	Ring gear		yes/no
Sun gear	Ring gear	Carrier		yes/no

As you have seen, some of these gearing mechanisms reverse the direction. We use a minus symbol ("-") to designate these in the gearing ratio equation.

3. Connecting multiple planetary gears in a series can be used to create high gearing ratios. Observe the three different planetary gears. Which two (different) gears would you connect to implement the greatest gearing down?

Solution sheet Gears Model 8 – Planetary gear

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Note on technological history: In 1780, *James Pickard* received a patent for a crankshaft drive, although such drives has already been in use for at least 1500 years. He attempted to use it to blackmail *James Watt* (1736-1819), who was close to completing his first “steam engine”. Afterwards, Watt's congenial assistant *William Murdoch* (1754-1839) quickly invented an epicyclic gear consisting of two coupled toothed gears, of which one revolves like a “planet” around the other (the “sun”), in order to circumvent Pickard’s patent. Watt then received his own patent for this alongside his expansion steam engine in 1781 (patent no. GB 1321).

Students receive the building instructions for the planetary gear with fixed carrier.

Construction task

The coaxial bevel gear reverses the direction of rotation.

The coaxial crown wheel results in a gearing down of 1:3.2.

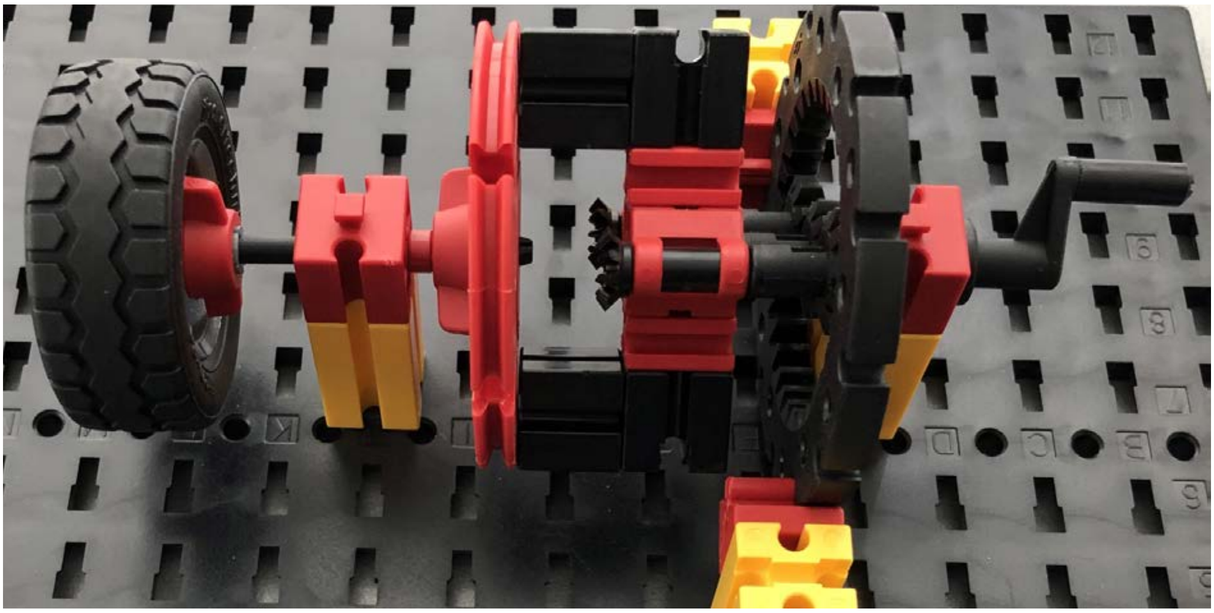
Topic task

The two gearing mechanisms are identical, since both the internal and external gears have 30 teeth. In the planetary gearing mechanism, the two planetary gears reverse the direction (the rotational direction remains the same for the internal gear). In a simple spur gear, the transition from Z10 to Z30 results in a reversal of direction.

The planetary gear with fixed carrier and sun gear on the input shaft, therefore, results in a gearing ratio of 1:3, gearing down with a change of direction.

Experimental task

1. The fischertechnik Z30 internal gear can be used to construct the following two other planetary gears: a) planetary gear with fixed ring gear:



Interesting variant of this gearing mechanism: The shaft of a planetary gear as output is provided by a stirrer:

b) Planetary gear with fixed sun gear:

2. These fischertechnik planetary gears can be used to implement the following gearing ratios:

Fixed	Input	Output	Gearing ratio	Change in direction
Carrier	Sun gear	Ring gear	-3	yes
Carrier	Ring gear	Sun gear	-0.33	yes
Ring gear	Sun gear	Carrier	4	no
Ring gear	Carrier	Sun gear	0.25	no
Sun gear	Carrier	Ring gear	0.75	no
Sun gear	Ring gear	Carrier	1.33	no

3. You can achieve the greatest gearing down by coupling the first (in the table) and third gears. This results in a gearing ratio (with change in direction) of -12.

Enclosure

Building instructions and templates for the gears and models:

Model 8: Building instructions for planetary gear with fixed carrier, building instructions for planetary gear with fixed ring gear, building instructions for planetary gear with fixed sun gear.

Tasks Gears Model 9 – Differential gear

Without differential gears, no car could drive around a tight curve – differential gears allow the wheels of a driven rigid axle to turn at different speeds.

Construction task

The differential gear is one special type of planetary gear: It is a planetary gear made of cone gear wheels.

Fig. 1 Differential gear

Build the differential shown in Fig. 1. What happens when a vehicle driven by this kind of differential gear drives around a tight curve?

Topic task

1. What change in direction does the differential gear achieve?

2. Simulate one wheel being blocked (for instance during braking) by holding it still. Describe what happens.

Experimental task

1. What happens if one of the wheels, for instance, spins in a sandy surface or on the ice?

2. Off-road vehicles have a “differential lock” to handle spinning wheels, which essentially “bypasses” the differential. How could you add something like this to your differential gear?

Solution sheet Gears Model 9 – Differential gear

Students are supported in constructing and solving some of the tasks with provided building instructions (see attachment). This is indicated at the start of the solution sheet in tasks where appropriate.

Note on technological history: The differential gear was patented in 1828 by *Onésiphore Pecqueur* (1792–1852) as a key element of his steam automobile. However, it is very similar to the “dynamometer” publicised by *James White* in 1822. The differential gear may have already been known to the Chinese in the 3rd century B.C. Engineer *Ma Jun* (200-265) probably used one to build a mechanical “south-pointing chariot” that always pointed towards the same direction.

Students receive the building instructions for the construction of the differential gear.

Construction task

When a vehicle is travelling around a curve, the inner wheel turns more slowly, while the outer wheel turns more quickly in the same ratio. The input speed, therefore, is divided between the two wheels.

Topic task

1. The differential gear transmits the rotation of the input axle with a crown wheel on an output axle turned by 90°, thereby achieving a gearing ratio of 1:3.2, gearing down.

2. If one wheel is blocked, the other turns at twice the speed of the input axle.

Experimental task

1. If one wheel spins, the other remains stopped because the differential transmits the drive to the axle with the lowest resistance.

2. A differential lock can be created, for instance, using a second axle parallel to the output axle which is connected on each side of the differential to the output axle with a toothed gear or chain drive, so that the two side axles have to turn at the same speed.

Enclosure

Building instructions and templates for the gears and models:

Model 9: Building instructions for differential gear

Gears – Tasks Secondary level I+II

Topic

The central topic is changing the torque using a gear, and thereby using it as a “force amplifier”. Gearing mechanisms such as pulleys, cardan shafts and planetary gears with important practical roles are introduced, built and calculated.

Learning objective

- Understanding of the fundamental principles and applications of gears as “force amplifiers”
- Calculating gearing ratios, gearing up and down
- Designing gearing mechanisms to change the speed of movement and torque

Time required

Constructing each of the gearing mechanisms should not take more than 10-20 minutes – if students already have a little bit of experience building with the fischertechnik system. The estimated time required to handle the topic task is 10-20 minutes. The tasks are all suitable for use as group work. Then, the results should be briefly evaluated and discussed (5-10 minutes). Therefore, generally each of the tasks should be able to be dealt with in the course of a class period – as long as students have a basic knowledge of gearing mechanisms (see primary level classroom set).

The experimental tasks deepen student knowledge of the topic. They are designed either as expansions of the topic (time required: about one additional class period), or can be provided to students who finish the topic task early.