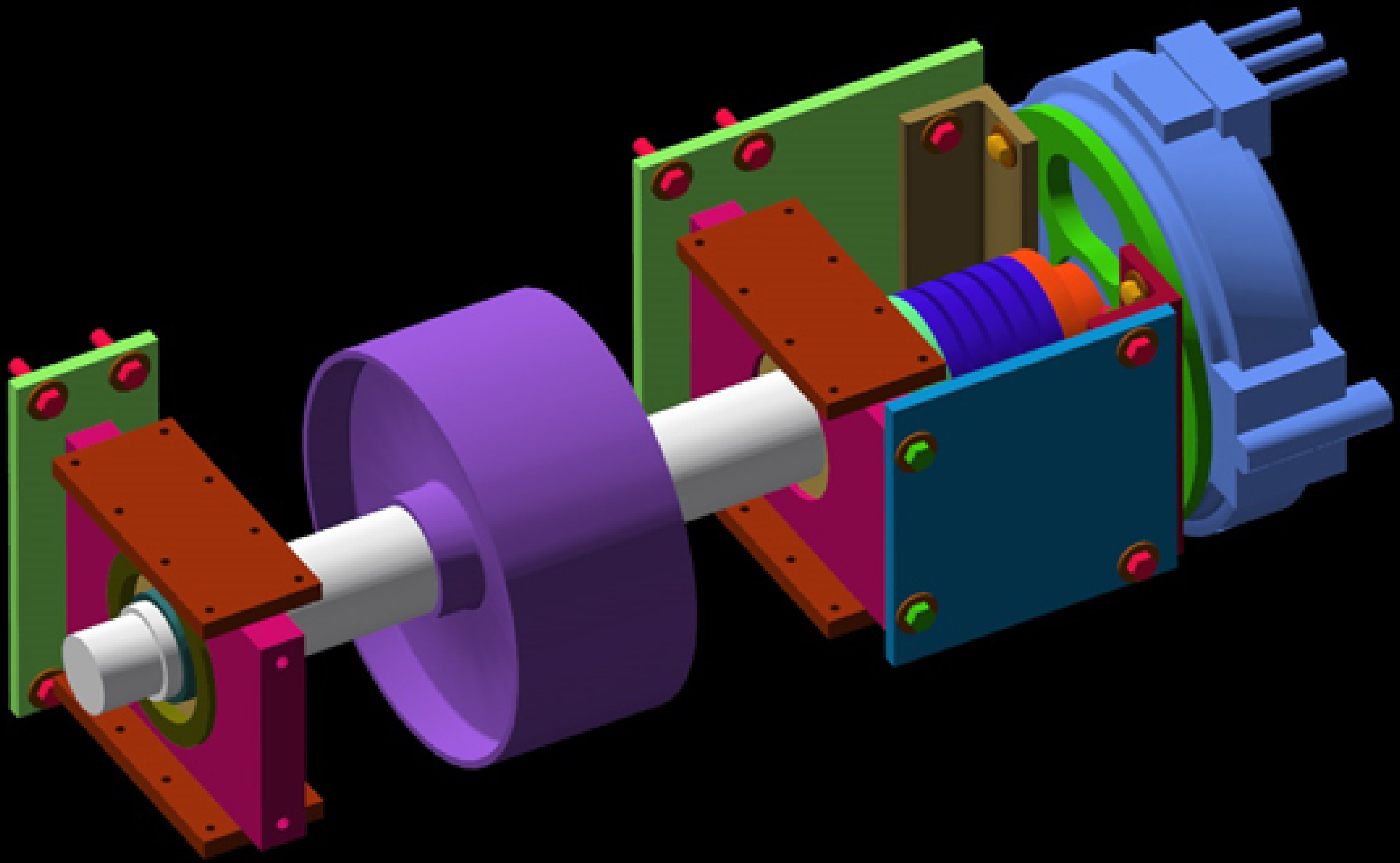
Simple and Rotating Machines Handbook



Keli Gaskin
Rueben Ayala

First Edition, 2012

ISBN 978-81-323-0985-7

Published by:
Academic Studio
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

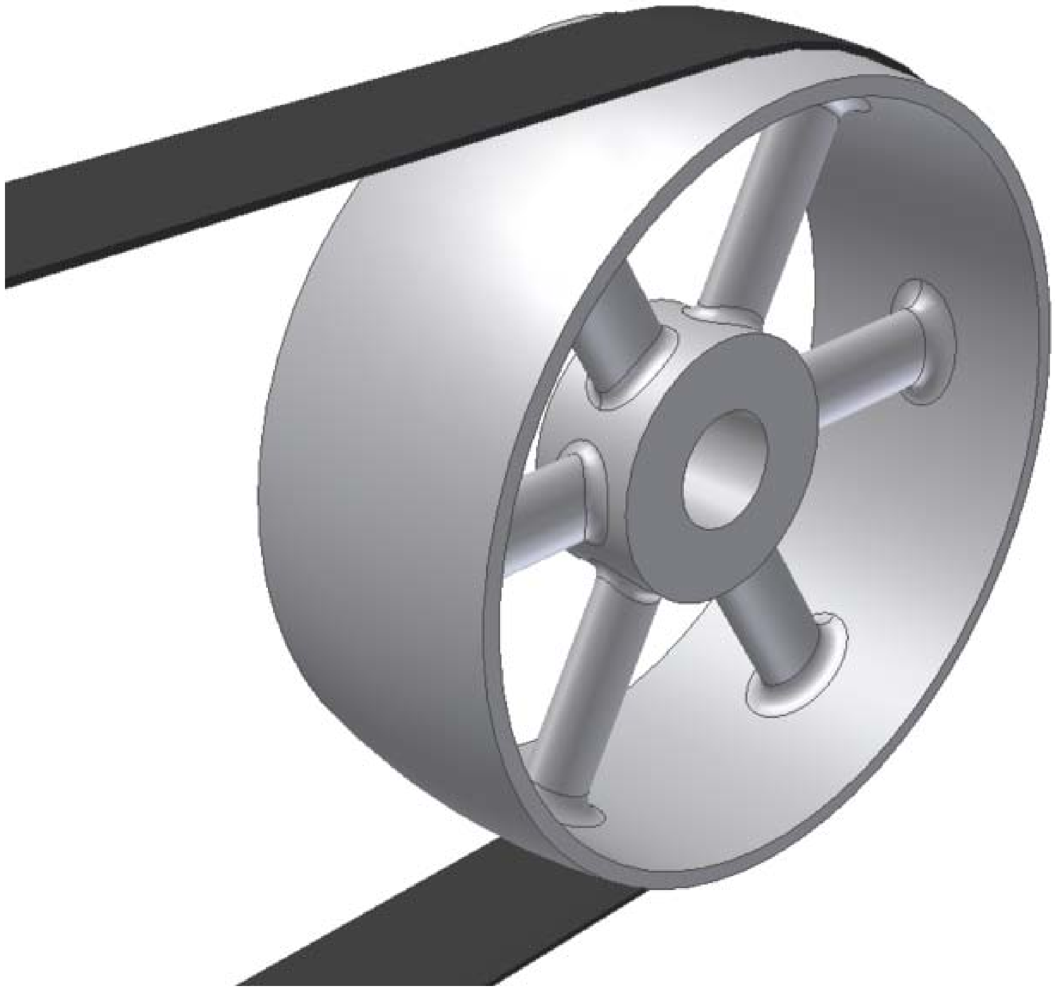
Chapter 1

Pulley

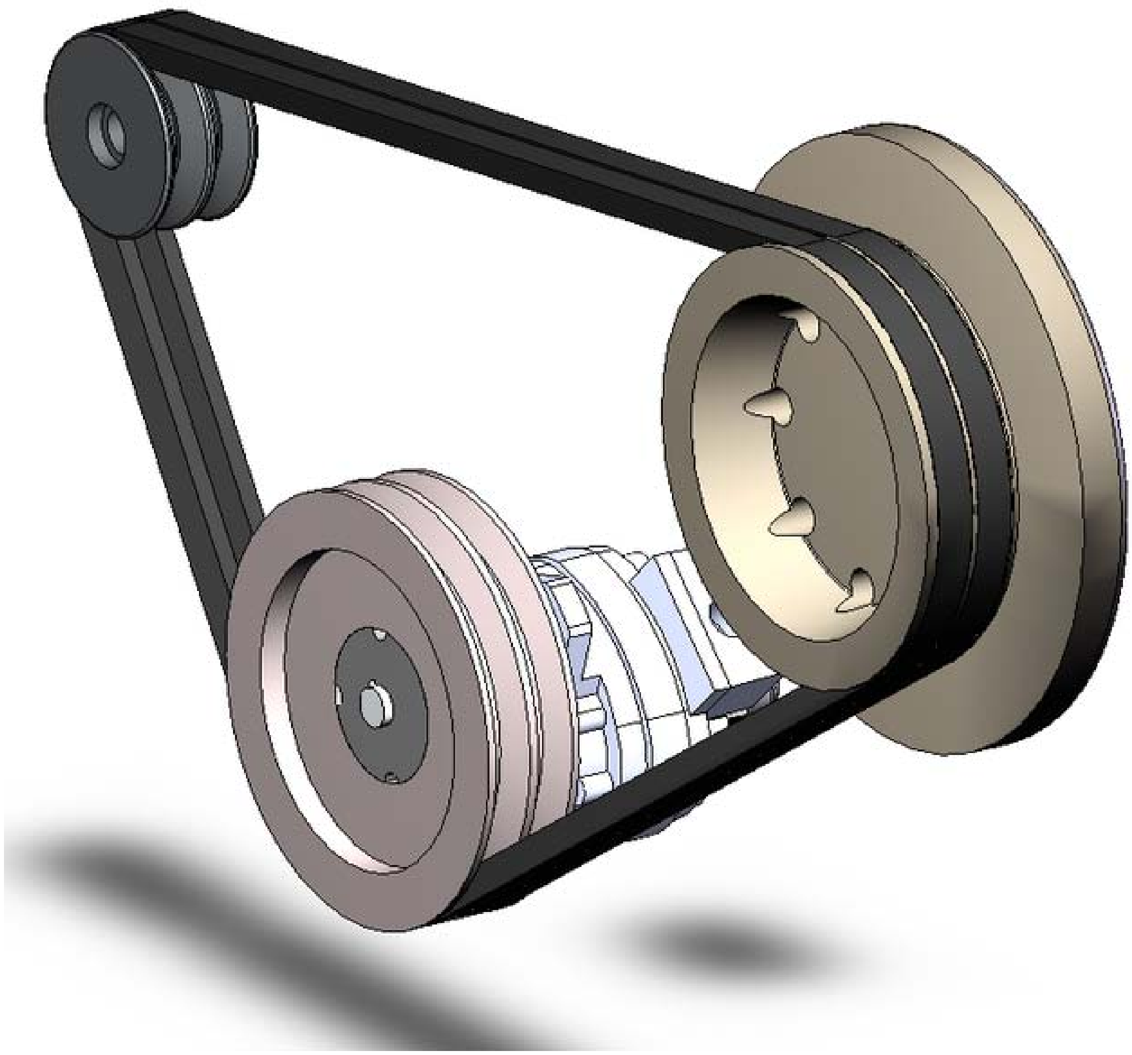
Pulley

Pulleys on a ship. In this context, pulleys are usually known as blocks.

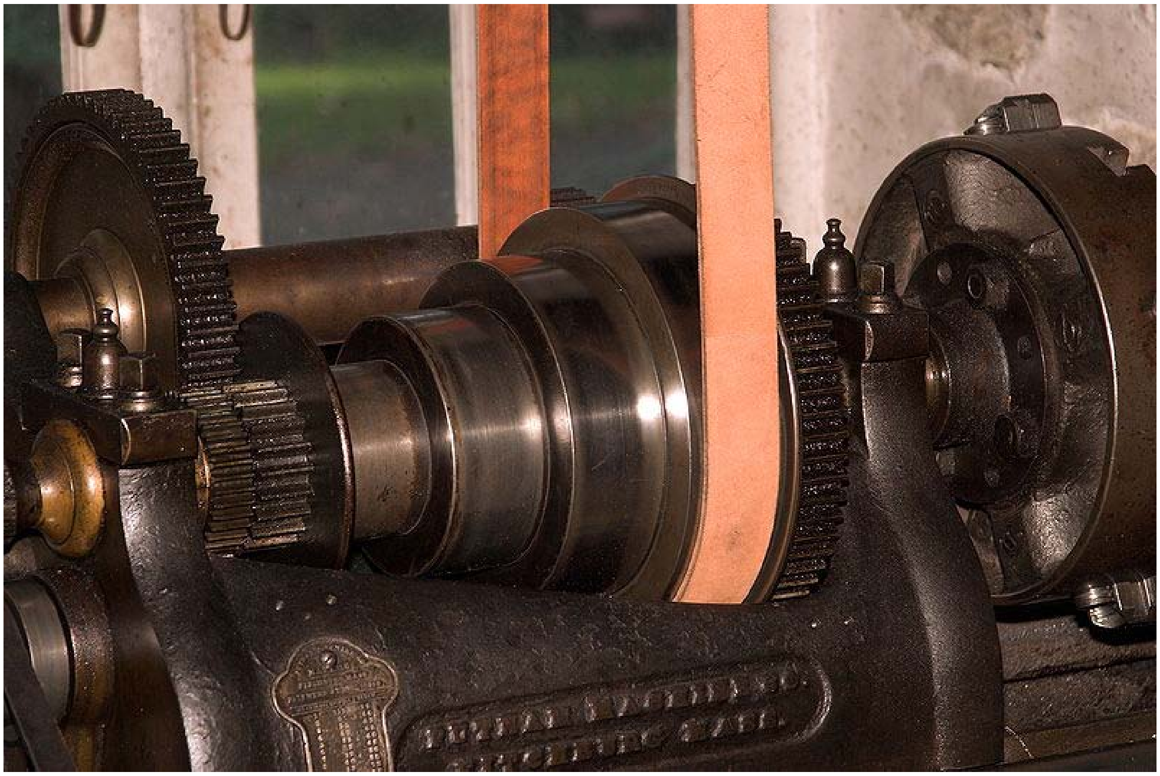
Classification	Simple machine
Industry	Construction, transportation
Powered	No
Wheels	1
Axles	1



Flat belt on a drum



Belt and pulley system



Cone pulley driven from above by a line shaft.

Cone pulley driven from below by an electric motor.

A **pulley**, also called a sheave or a drum, is a mechanism composed of a wheel on an axle or shaft that may have a groove between two flanges around its circumference. A rope, cable, belt, or chain usually runs over the wheel and inside the groove, if present. Pulleys are used to change the direction of an applied force, transmit rotational motion, or realize a mechanical advantage in either a linear or rotational system of motion. It is one of the six simple machines. Two or more pulleys together are called a block and tackle.

Belt and pulley systems

A belt and pulley system is characterized by two or more pulleys in common to a belt. This allows for mechanical power, torque, and speed to be transmitted across axles and, if the pulleys are of differing diameters, a mechanical advantage to be realized.

A belt drive is analogous to that of a chain drive, however a belt sheave may be smooth (devoid of discrete interlocking members as would be found on a chain sprocket, spur gear, or timing belt) so that the mechanical advantage is approximately given by the ratio of the pitch diameter of the sheaves only, not fixed exactly by the ratio of teeth as with gears and sprockets.

In the case of a drum-style pulley, without a groove or flanges, the pulley often is slightly convex to keep the flat belt centered. It is sometimes referred to as a crowned pulley. Though once widely used in factory line shafts, this type of pulley is still found driving the rotating brush in upright vacuum cleaners.

Rope and pulley systems

Also called block and tackles, rope and pulley systems (the rope may be a light line or a strong cable) are characterized by the use of one rope transmitting a linear motive force (in tension) to a load through one or more pulleys for the purpose of pulling the load (often against gravity.) They are often included in lists of simple machines.

In a system of a single rope and pulleys, when friction is neglected, the mechanical advantage gained can be calculated by counting the number of rope lengths exerting force on the load. Since the tension in each rope length is equal to the force exerted on the free end of the rope, the mechanical advantage is simply equal to the number of ropes pulling on the load. For example, in Diagram 3 below, there is one rope attached to the load, and 2 rope lengths extending from the pulley attached to the load, for a total of 3 ropes supporting it. If the force applied to the free end of the rope is 10 lb, each of these rope lengths will exert a force of 10 lb. on the load, for a total of 30 lb. So the mechanical advantage is 3.

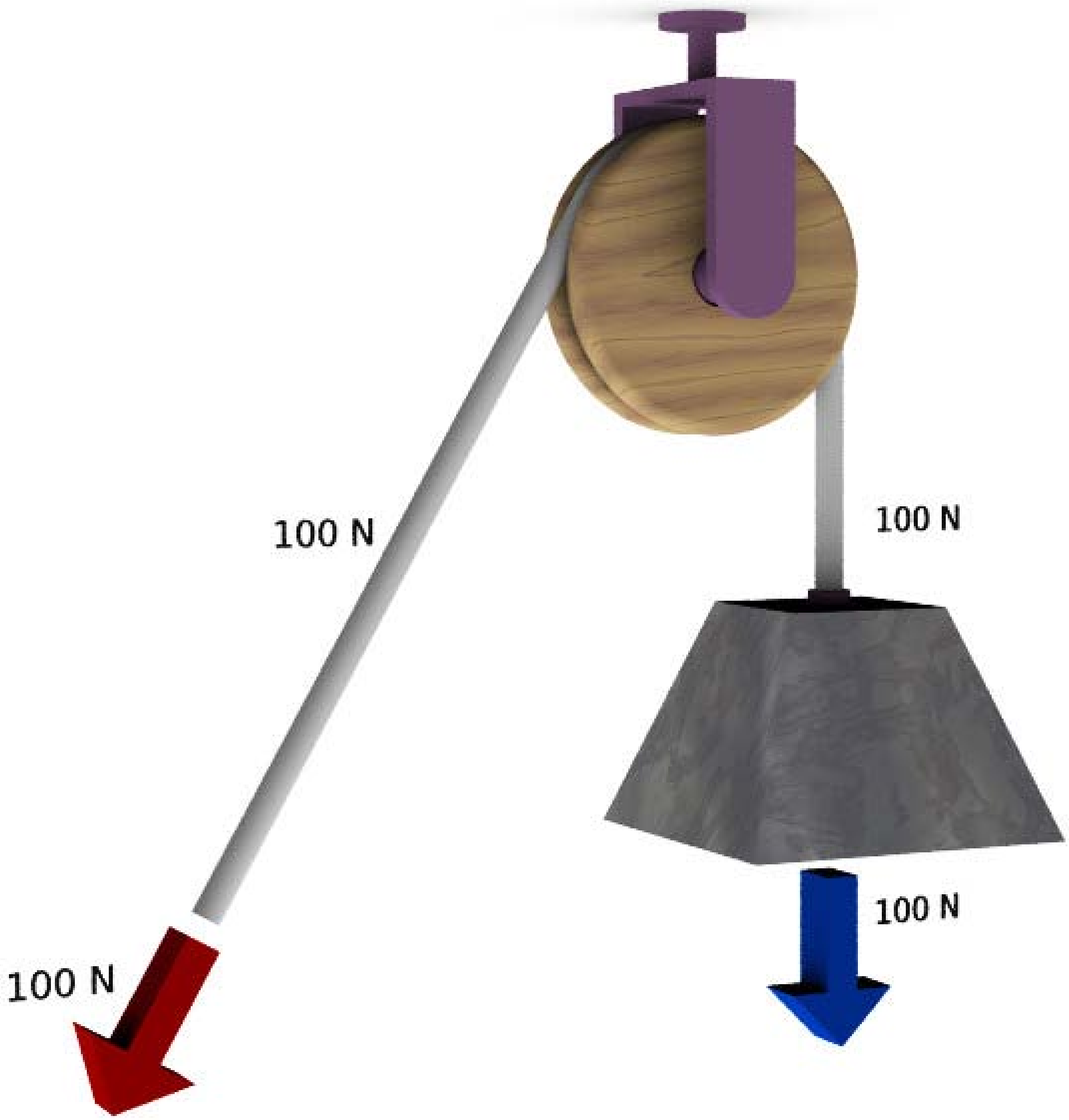
The force on the load is increased by the mechanical advantage; however the distance the load moves, compared to the length the free end of the rope moves, is decreased in the same proportion. Since a slender cable is more easily managed than a fat one (albeit shorter and stronger), pulley systems are often the preferred method of applying mechanical advantage to the pulling force of a winch (as can be found in a lift crane).

Pulley systems are the only simple machines in which the possible values of mechanical advantage are limited to whole numbers.

In practice, the more pulleys there are, the less efficient a system is. This is due to sliding friction in the system where cable meets pulley and in the rotational mechanism of each pulley.

It is not recorded when or by whom the pulley was first developed. It is believed however that Archimedes developed the first documented block and tackle pulley system, as recorded by Plutarch. Plutarch reported that Archimedes moved an entire warship, laden with men, using compound pulleys and his own strength.

Types of systems



Fixed pulley

Movable pulley

These are different types of pulley systems:

- **Fixed** A *fixed* or *class 1* pulley has a fixed axle. That is, the axle is "fixed" or anchored in place. A fixed pulley is used to change the direction of the force on a rope (called a belt). A fixed pulley has a mechanical advantage of 1. A mechanical advantage of one means that the force is equal on both sides of the pulley and there is no multiplication of force.
- **Movable** A *movable* or *class 2* pulley has a free axle. That is, the axle is "free" to move in space. A movable pulley is used to multiply forces. A movable pulley has a mechanical advantage of 2. That is, if one end of the rope is anchored, pulling

on the other end of the rope will apply a doubled force to the object attached to the pulley.

- **Compound** A *compound pulley* is a combination of a fixed and a movable pulley system.
    - **Block and tackle** - A *block and tackle* is a type of compound pulley where several pulleys are mounted on each axle, further increasing the mechanical advantage. Block and tackles usually lift objects with a mechanical advantage greater than 2.

How it works

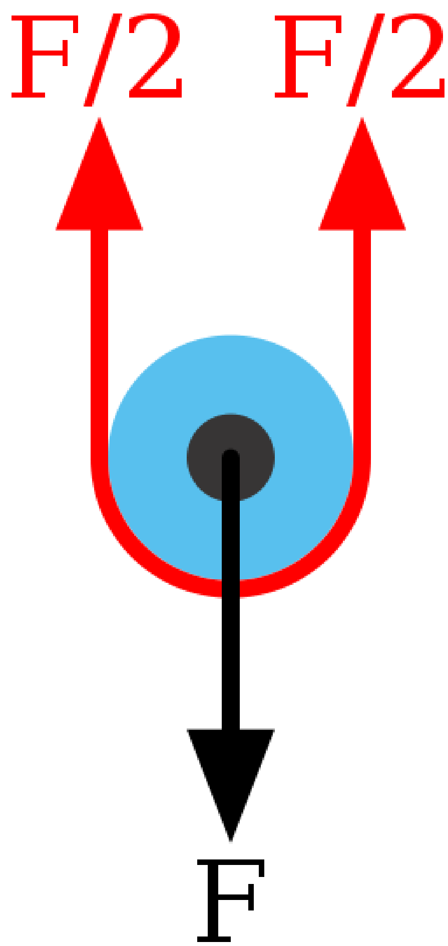


Diagram 1 - A basic equation for a pulley: In equilibrium, the force *F* on the pulley axle is equal and opposite to the sum of the tensions in each line leaving the pulley, and these tensions are equal.

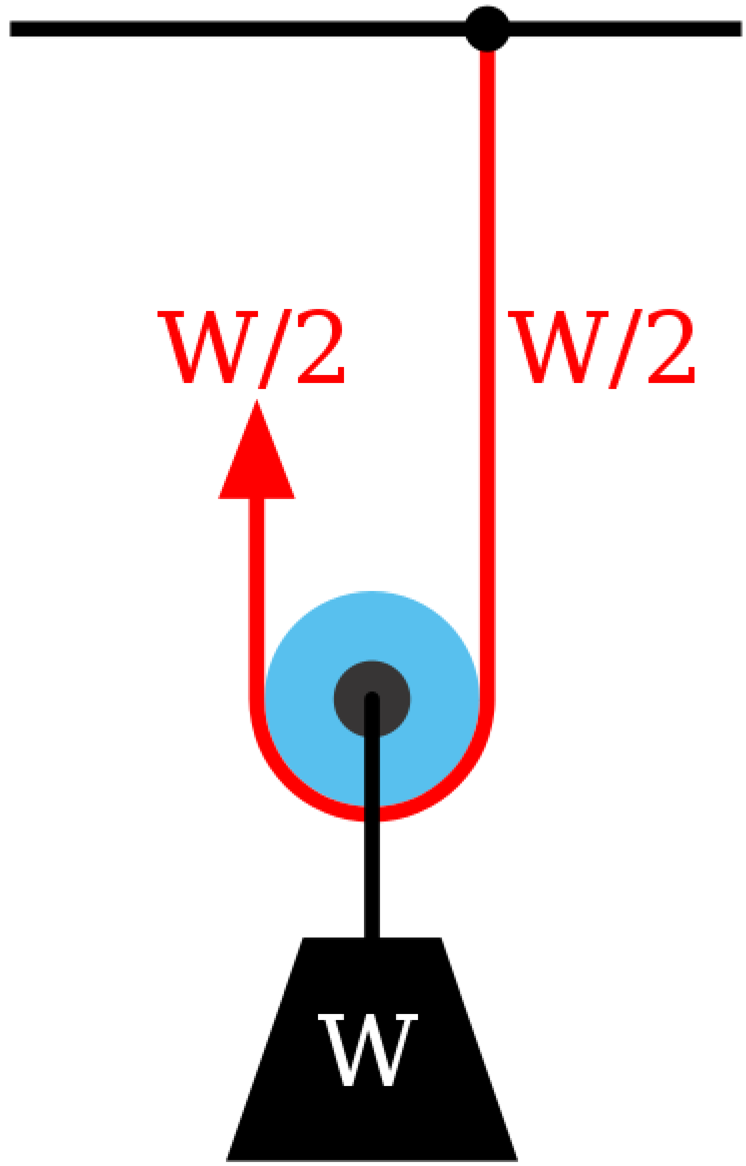


Diagram 2 - A simple pulley system - a single movable pulley lifting weight *W*. The tension in each line is *W/2*, yielding an advantage of 2.

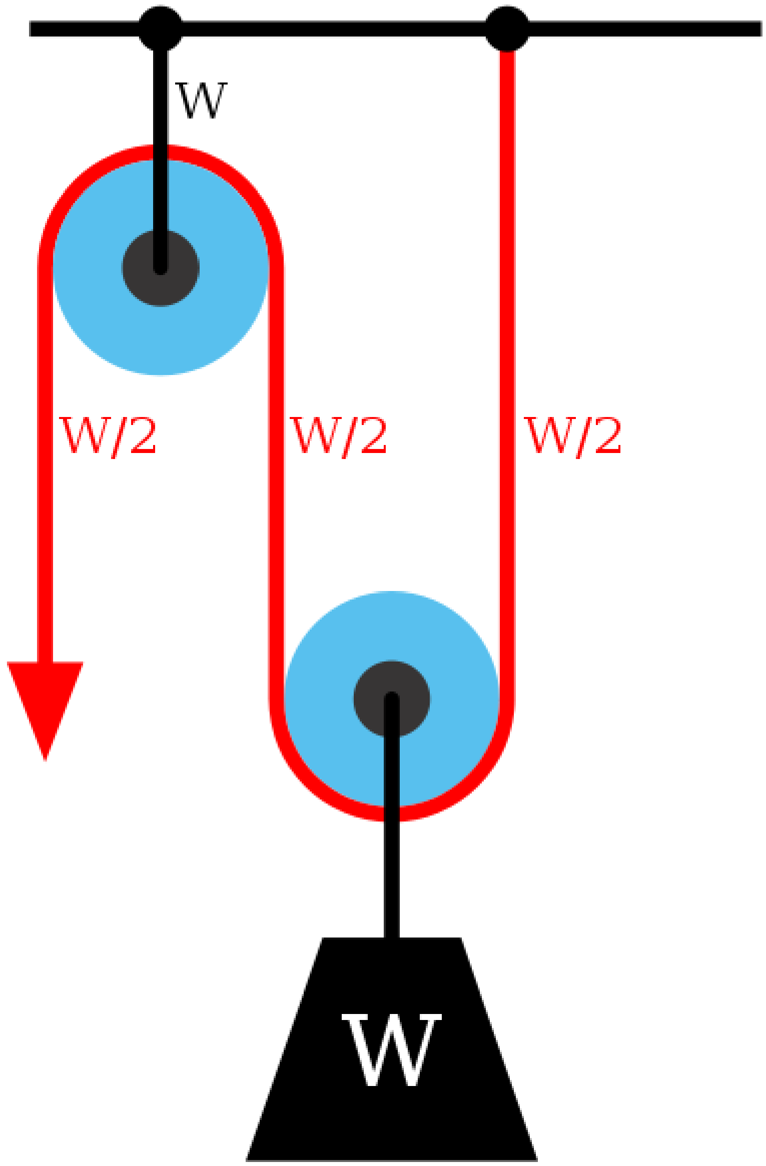
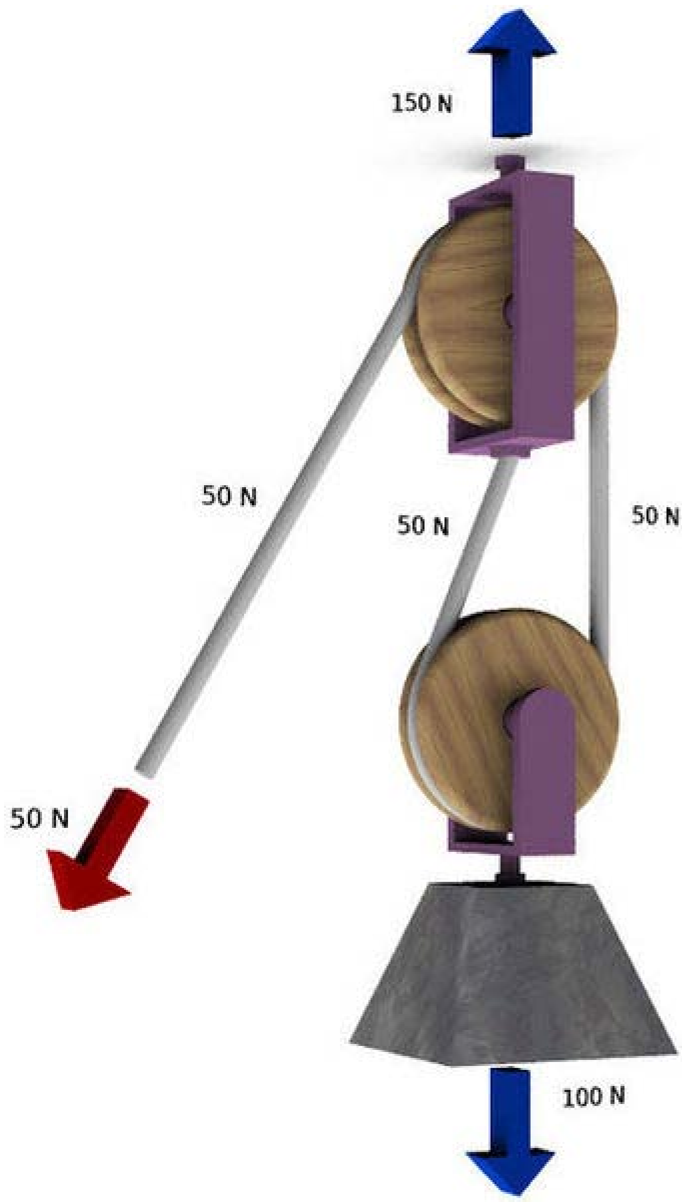


Diagram 2a - Another simple pulley system similar to diagram 2, but in which the lifting force is redirected downward.



A practical compound pulley corresponding to diagram 2a.

The simplest theory of operation for a pulley system assumes that the pulleys and lines are weightless, and that there is no energy loss due to friction. It is also assumed that the lines do not stretch.

A crane using the compound pulley system yielding an advantage of 4. The single fixed pulley is installed on the crane. The two movable pulleys (joined together) are attached to the hook. One end of the rope is attached to the crane frame, another - to the winch.

In equilibrium, the total force on the pulley must be zero. This means that the force on the axle of the pulley is shared equally by the two lines looping through the pulley. The situation is schematically illustrated in diagram 1. For the case where the lines are not parallel, the tensions in each line are still equal, but now the vector sum of all forces is zero.

A second basic equation for the pulley follows from the conservation of energy: The product of the weight lifted times the distance it is moved is equal to the product of the lifting force (the tension in the lifting line) times the distance the lifting line is moved.

The weight lifted divided by the lifting force is defined as the **advantage** of the pulley system.

It is important to notice that a system of pulleys does not change the amount of work done. The work is given by the force times the distance moved. The pulley simply allows trading force for distance: you pull with less force, but over a longer distance.

In diagram 2, a single movable pulley allows weight *W* to be lifted with only half the force needed to lift the weight without assistance. The total force needed is divided between the lifting force (red arrow) and the "ceiling" which is some immovable object (such as the earth). In this simple system, the lifting force is directed in the same direction as the movement of the weight. The advantage of this system is 2. Although the force needed to lift the weight is only *W/2*, we will need to draw a length of rope that is twice the distance that the weight is lifted, so that the total amount of work done (Force x distance) remains the same.

A second pulley may be added as in diagram 2a, which simply serves to redirect the lifting force downward; it does not change the advantage of the system.

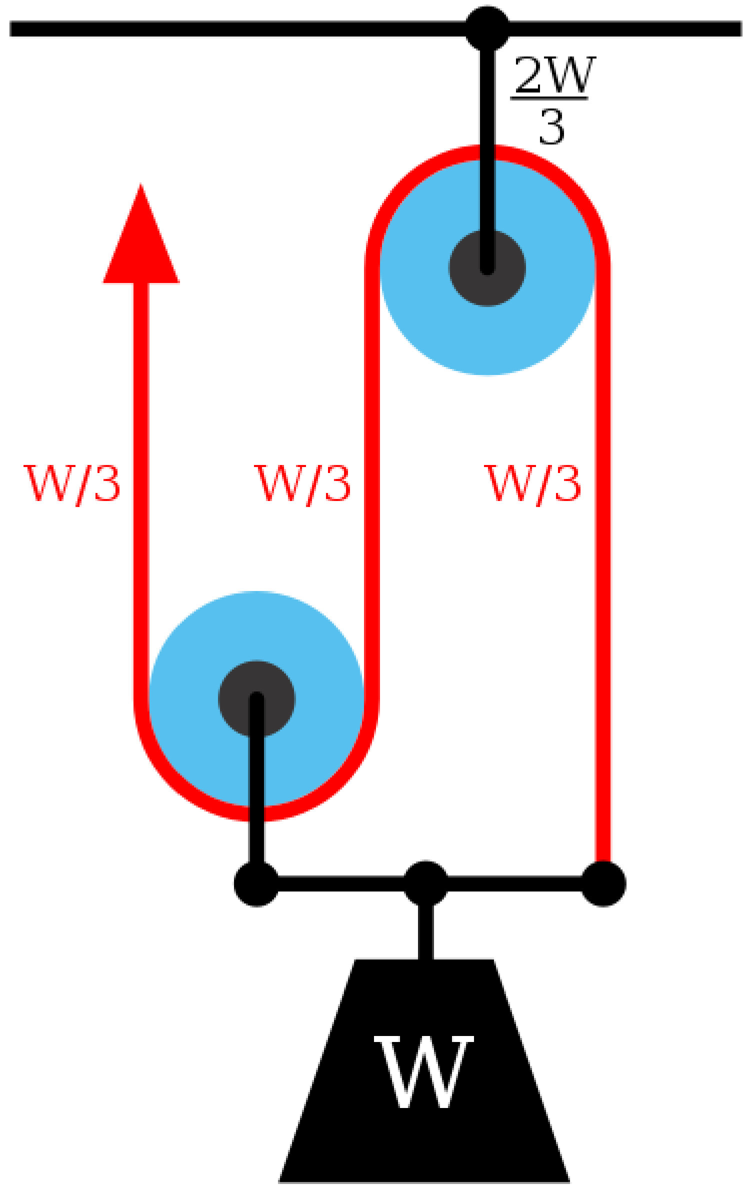


Diagram 3 - A simple compound pulley system: a movable pulley and a fixed pulley lifting weight *W*. The tension in each line is *W/3*, yielding an advantage of 3.

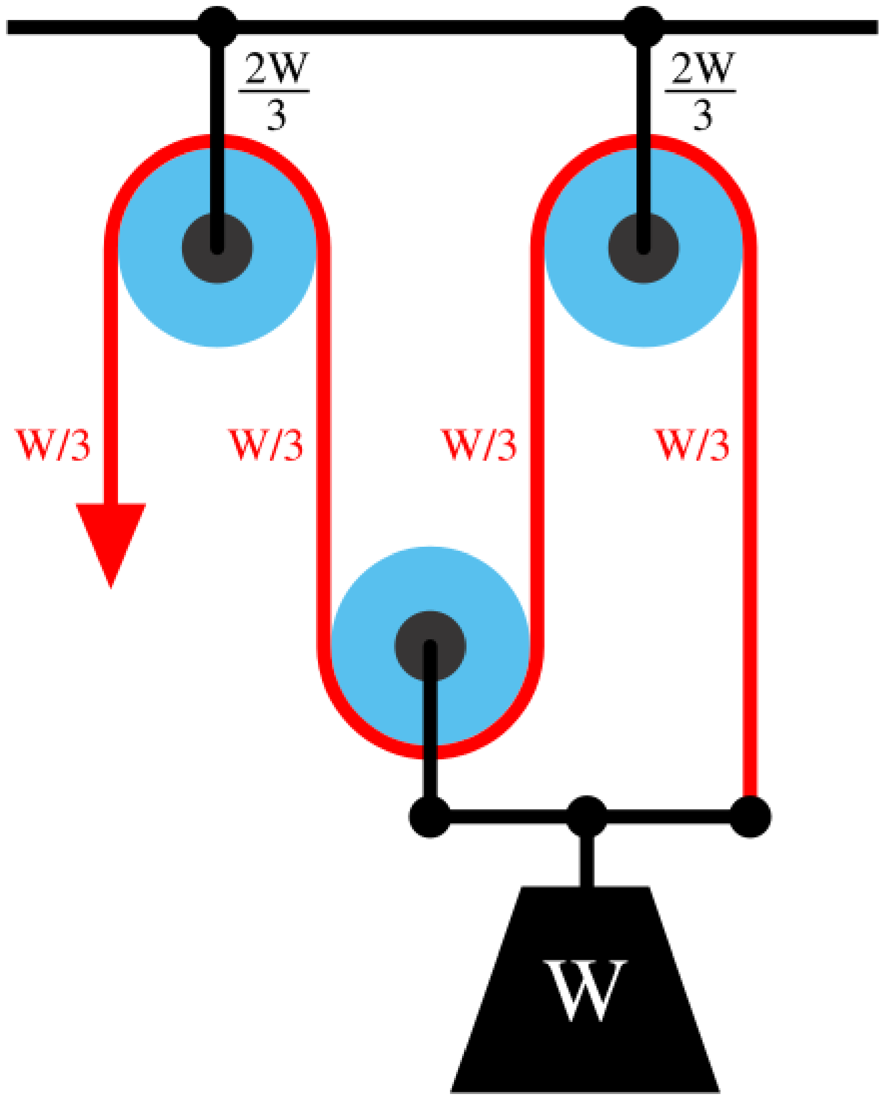


Diagram 3a - A simple compound pulley system: a movable pulley and a fixed pulley lifting weight *W*, with an additional pulley redirecting the lifting force downward. The tension in each line is *W/3*, yielding an advantage of 3.

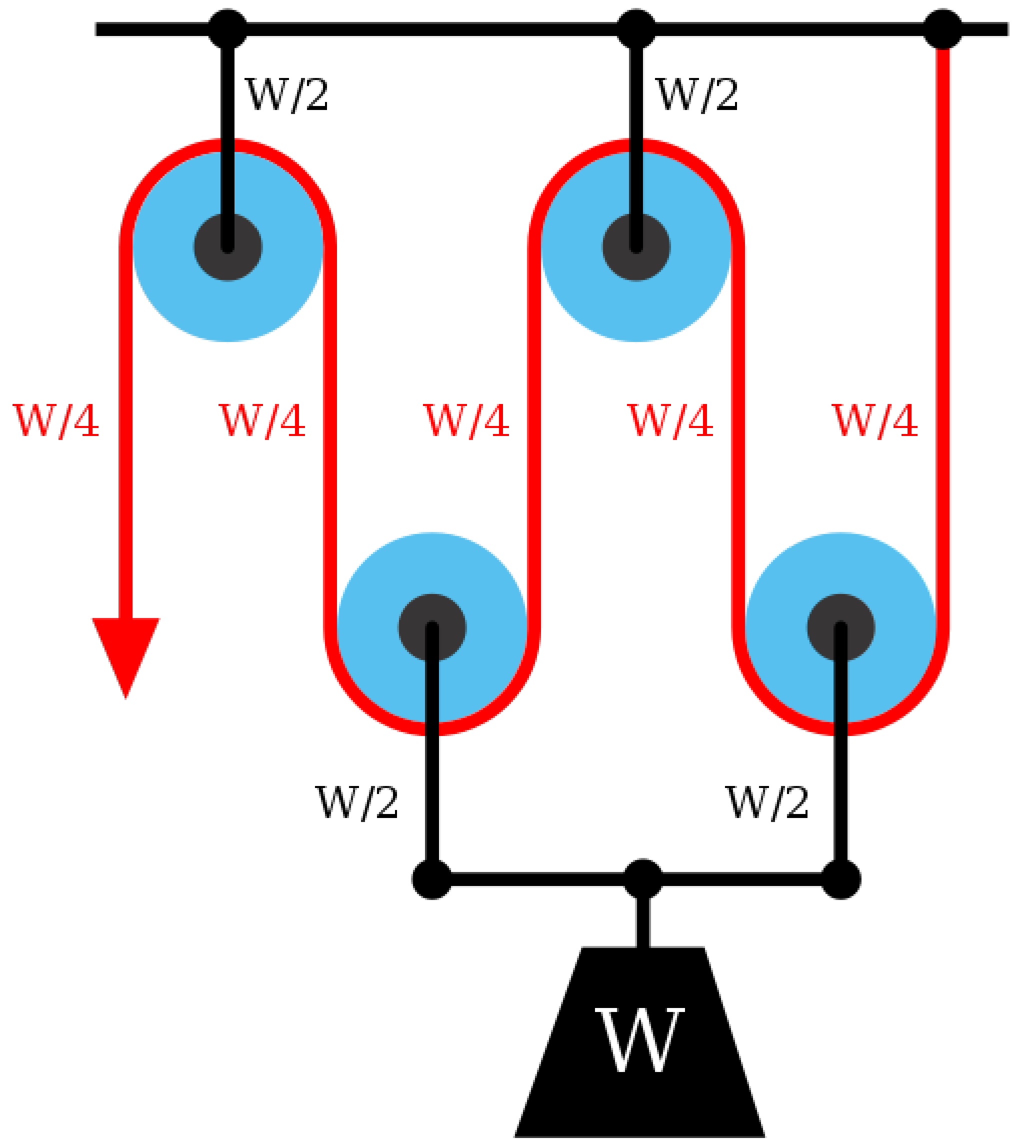


Diagram 4a - A more complicated compound pulley system. The tension in each line is *W/4*, yielding an advantage of 4. An additional pulley redirecting the lifting force has been added.

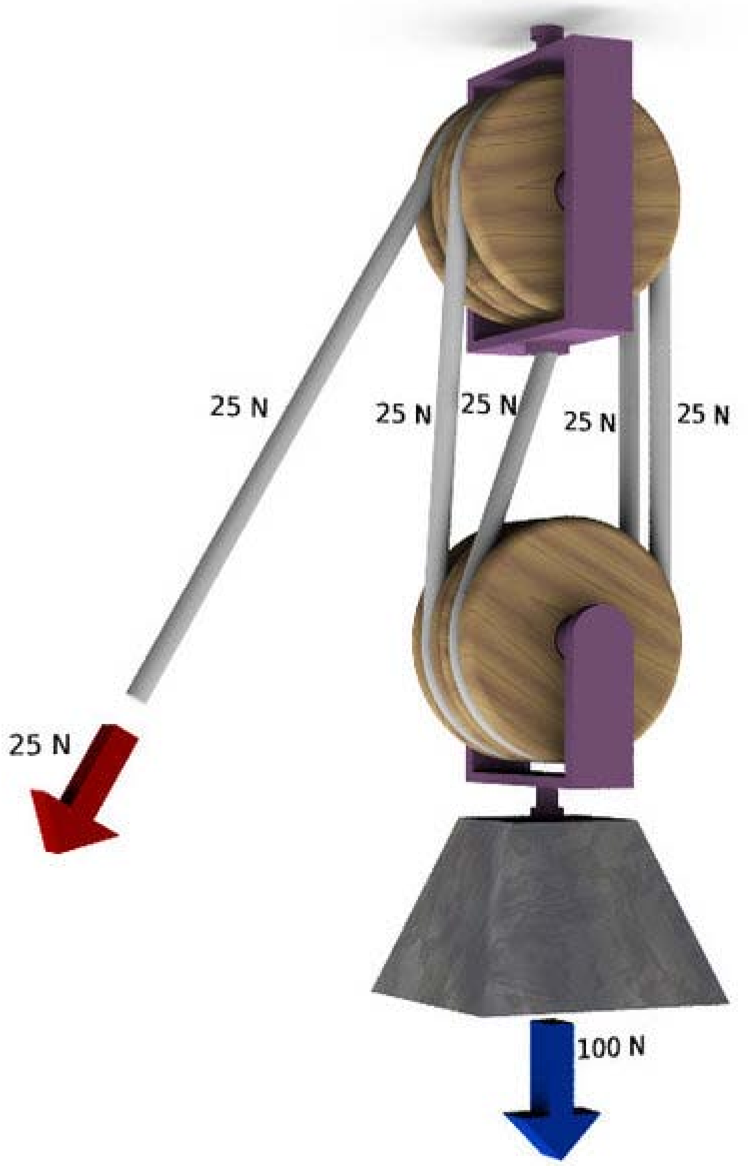


Figure 4b - A practical block and tackle pulley system corresponding to diagram 4a. Note that the axles of the fixed and movable pulleys have been combined.

The addition of a fixed pulley to the single pulley system can yield an increase of advantage. In diagram 3, the addition of a fixed pulley yields a lifting advantage of 3. The tension in each line is *W/3*, and the force on the axles of each pulley is *2W/3*. As in the case of diagram 2a, another pulley may be added to reverse the direction of the lifting force, but with no increase in advantage. This situation is shown in diagram 3a.

This process can be continued indefinitely for ideal pulleys with each additional pulley yielding a unit increase in advantage. For real pulleys friction among rope and pulleys will increase as more pulleys are added to the point that no advantage is possible. It puts a limit for the number of pulleys usable in practice. The above pulley systems are known collectively as block and tackle pulley systems. In diagram 4a, a block and tackle system with advantage 4 is shown. A practical implementation in which the connection to the ceiling is combined and the fixed and movable pulleys are encased in single housings is shown in figure 4b.

Other pulley systems are possible, and some can deliver an increased advantage with fewer pulleys than the block and tackle system. The advantage of the block and tackle system is that each pulley and line is subjected to equal tensions and forces. Efficient design dictates that each line and pulley be capable of handling its load, and no more. Other pulley designs will require different strengths of line and pulleys depending on their position in the system, but a block and tackle system can use the same line size throughout, and can mount the fixed and movable pulleys on a common axle.

Chapter 2

Inclined Plane

Inclined plane

Roman soldiers constructed an inclined plane out of earth to lay siege to the Masada during the First Jewish-Roman War in 73 CE.

Classification	Simple machine
Industry	Construction

The **inclined plane** is one of the original six simple machines; as the name suggests, it is a flat surface whose endpoints are at different heights. By moving an object up an inclined plane rather than completely vertical, the amount of force required is reduced, at the expense of increasing the distance the object must travel. The mechanical advantage of an inclined plane is the ratio of the length of the sloped surface to the height it spans; this may also be expressed as the cosecant of the angle between the plane and the horizontal. Note that due to the conservation of energy, the same amount of mechanical energy is required to lift a given object by a given distance, except for losses from friction, but the inclined plane allows the same work to be done with a smaller force exerted over a greater distance.

Ramps, chutes and slides

An inclined plane is a simple machine that does not move. Many devices based on the principles of the inclined plane allow expending less force to achieve a task. Ramps enable accessing heights that would be too difficult to scale vertically. Ramps allow heavy objects to ascend to, and descend safely from, a high-level bridge. Portable ramps allow easy loading and unloading of high-decked trucks. Siege ramps gave ancient armies the ability to walk up bringing heavy equipment to the tops of high walls. Chutes and slides allow fragile objects, including humans, to be safely lowered from a vertical rise by countering gravitational force with the normal force provided by a stiff surface at an angle to the gravitational vector. Airplane rescue slides allow people to quickly reach the ground safely, without the danger of jumping from a height. The addition of the normal force and gravity vectors causes the sliding object to move parallel to surface of the slide, so a slide can be used to move objects through a distribution system from one area to another. Hoppers and funnels are formed by planes shaped into an inverted pyramid or cone shape to concentrate granular or fluid material at the apex.

Eliminating friction from a slide increases the maximum speed at which an object can move down the slide, while the acceleration of the moving object can be controlled to any degree by varying the angle of the slide. Because of this, slides are one of the most common and popular forms of entertainment. A well-polished slide can allow a human to move at a high speed with no effort, even experience near free-fall acceleration, yet arrive on the ground safely because the angle of slide can be varied along its length to end up parallel to the ground, so the forward motion of the slider can be slowly arrested by friction. The metal slide is a popular piece of playground equipment, and towering water slides employ liquid lubrication to reduce friction even further. Wheeled cars of roller coasters roll down inclined tracks to achieve high speeds. In the sports of luge, bobsled, sledding, and skiing, participants accelerate to extremely high speeds utilizing only the inclined plane, whether a mountain slope provided by nature, or a chute lined with near-frictionless ice. Mountains are another example of an inclined plane.

Blades, wedges, and foils

The blade is a compound inclined plane, consisting of two inclined planes placed so that the planes meet at one edge. The edge where the two planes meet is pushed into a solid or fluid substance and overcomes the resistance of materials to separate by transferring the force exerted against the material into two opposing forces normal to the faces of the blade. First known to be used by humans in the knife to separate animal tissue, the blade allowed humans to separate meat, fibers, and other plant and animal materials, with much less force than it would take to tear them by simply pulling them apart. Blades can separate solid material, as with plows that separate soil particles, scissors and shears to cut flexible materials, axes to separate wood fibers, and chisels and planes to remove precise portions of wood.

Wedges, saws and chisels can separate thick and hard materials, such as wood, including solid stone and hard metals, with much less force, less waste of material, and more precision, than crushing. Saws have many chisel-like "teeth" along their cutting surface to transfer linear or circular motion to counteract the normal force of the surface to be cut. Crushing, the overcoming of material bonds by transferring momentum to a material through the normal force of another, harder, object was the only way to cut through a hard material before saws, and the materials to make them, were developed.

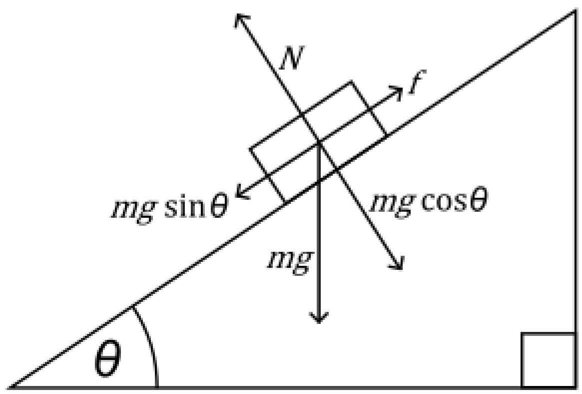
Drills produce circular holes in solids by rotating a chisel around its center, with the edge is sharpened at opposing angles on either side of the rotation axis, so as to cut in the direction of rotation. Twist drills provide one or more heliacally twisted chisels formed out of grooves cut along the side of the bit, to help evacuate cuttings from the drill hole, by using the same inclined plane principle as the archimedean screw. The water screw, though most likely preexisting Archimedes, has been used since ancient times to pump water, and is now also used to move granulated and ground materials, such as wheat, coal, and meat. Screws also join pieces of wood or metal together, by using a helical plane, usually formed by cutting a helical groove into a rod, so that the rod can force itself into the material when it is rotated.

The ancient water wheel uses inclined planes mounted around a rotating wheel to transform the momentum of moving water into a torque that can turn a shaft and do work. Sails extract the momentum of moving air to drive a vehicle, and windmills extend the principle to move a balanced set of sails around a shaft to perform work. Although known for thousands of years, these devices for extracting work from a moving fluid were always limited in efficiency by the drag-inducing vortices caused when a fluid is separated. Foils are specialized blades, shaped to allow the most efficient movement of fluid over their surfaces, to minimize the turbulence caused by these vortices. Rotating vortices dissipate the momentum of the fluid as heat, reducing the amount of energy available to do useful work.

Foils have many different designs, depending on the viscosity, velocity, and pressure of the fluid they will operate in, and their intended purpose. Aircraft wings and helicopter rotors counteract gravity by redirecting momentum generated from lateral movement, as with fixed-wing aircraft, or from rotating airfoils around a shaft, as with helicopters, so that separated air flows over the top of the foil faster than it flows over the bottom. This difference in velocity causes the pressure to decrease on the top surface, generating a lifting force, through what is known as Bernoulli's Principle. The resulting decrease in pressure across the upper surface provides up to 65% of the lift of the airfoil. The same principle in reverse allows an automotive spoiler to keep a car firmly in contact with the road.

Airplane and marine propellers use the same principle to drive vehicles though a fluid along the direction of the torque applied to the propeller shaft. Nautical propellers are often called screws. Rotating impeller blades increase the pressure difference between the inlet and outlet of a pump to force fluids through pipes. Turbines capture momentum from fast-moving fluid at high efficiency to a torque vector along the direction of the turbine's axis of rotation, while compressors use rotational motion to increase the pressure in a fast-moving fluid. Rotary fans move air, and can harness the reaction force of the moving air to drive a limo. .

Calculation of forces acting on an object on an inclined plane



Key:
N = Normal force that is perpendicular to the plane
m = Mass of object
g = Acceleration due to gravity
θ (theta) = Angle of elevation of the plane, measured from the horizontal
f = frictional force of the inclined plane

To calculate the forces on an object placed on an inclined plane, consider the three forces acting on it.

1. The normal force (*N*) exerted on the body by the plane due to the force of gravity i.e. mg cos θ
2. the force due to gravity (*mg*, acting vertically downwards) and
3. the frictional force (*f*) acting parallel to the plane.

We can decompose the gravitational force into two vectors, one perpendicular to the plane and one parallel to the plane. Since there is no movement perpendicular to the plane, the component of the gravitational force in this direction ($mg \cos \theta$) must be equal and opposite to normal force exerted by the plane, *N*. If the remaining component of the gravitational force parallel to the surface ($mg \sin \theta$) is greater than the static frictional force f_s – then the body will slide down the inclined plane with acceleration ($g \sin \theta - f_k/m$), where f_k is the kinetic friction force – otherwise it will remain stationary.

When the slope angle (θ) is zero, $\sin \theta$ is also zero so the body does not move.

The MA or Mechanical advantage(ratio of load to effort) of the inclined plane equals to length of the plane over the height of the plane, in an ideal case where efficiency is 100%.

To calculate the MA (Mechanical Advantage) of an inclined plane, divide the length by the height of the ramp.

Example: The height of the ramp = 1 meter The length of the ramp = 5 meters Divide 5 by 1=5 **ma= 5**

Chapter 3

Lever & Wheel and Axle

Lever

Lever

Levers can be used to exert a large force over a small distance at one end by exerting only a small force over a greater distance at the other.

Classification	Simple machine
Industry	Construction

In physics, a **lever** (from French *lever*, "to raise", c.f. a *levant*) is a rigid object that is used with an appropriate fulcrum or pivot point to either multiply the mechanical force (effort) that can be applied to another object or resistance force (load), or multiply the distance and speed at which the opposite end of the rigid object travels. This **leverage** is also termed mechanical advantage, and is one example of the principle of moments. A lever is one of the six simple machines.

Early use

The earliest remaining writings regarding levers date from the 3rd century BC and were provided by Archimedes. "*Give me a place to stand, and I shall move the earth with a lever*" is a remark of Archimedes who formally stated the correct mathematical principle of levers (quoted by Pappus of Alexandria).

It is assumed that in ancient Egypt, constructors used the lever to move and uplift obelisks weighting more than 100 tons.

Force and levers

The force applied (at end points of the lever) is proportional to the ratio of the length of the lever arm measured between the fulcrum (pivoting point) and application point of the force applied at each end of the lever.

Mathematically, this is expressed by $M = Fd$, where F is the force, d is the perpendicular distance between the force and the fulcrum, and M is the turning force known as the moment or torque.

Classes

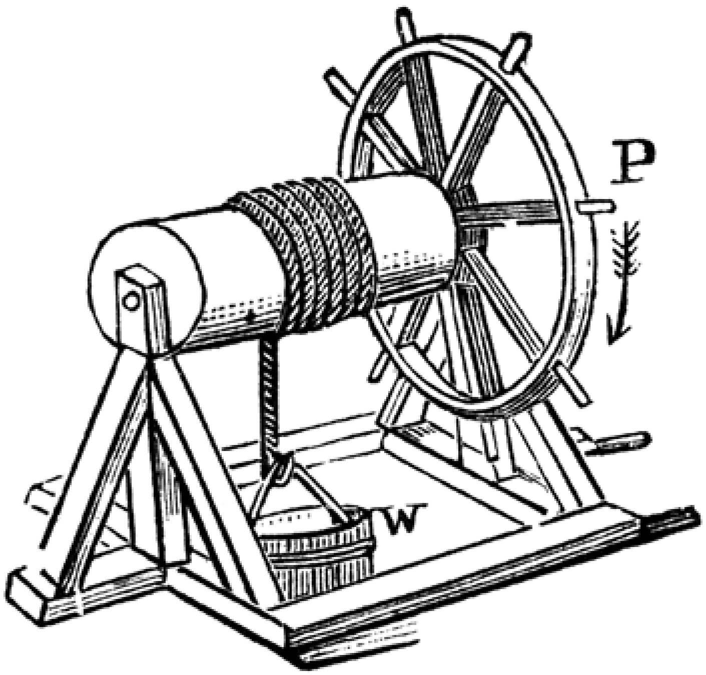
There are three classes of levers representing variations in the relative locations of the fulcrum, the load and the force:

- Class 1: The fulcrum is located between the applied force and the load, for example, a crowbar or a pair of scissors or a seesaw.
- Class 2: The load is situated between the fulcrum and the force, for example, a wheelbarrow or a nutcracker.
- Class 3: The force is applied between the fulcrum and the load, for example, a pair of tweezers or the human mandible.

In the real world

For the classical mechanics formulas to work, or to be a good approximation of real world applications, the lever must be made from a combination of rigid bodies, (*i.e.*, a beam) and a rigid fulcrum. Any bending or other deformation must be negligible.

Wheel and Axle



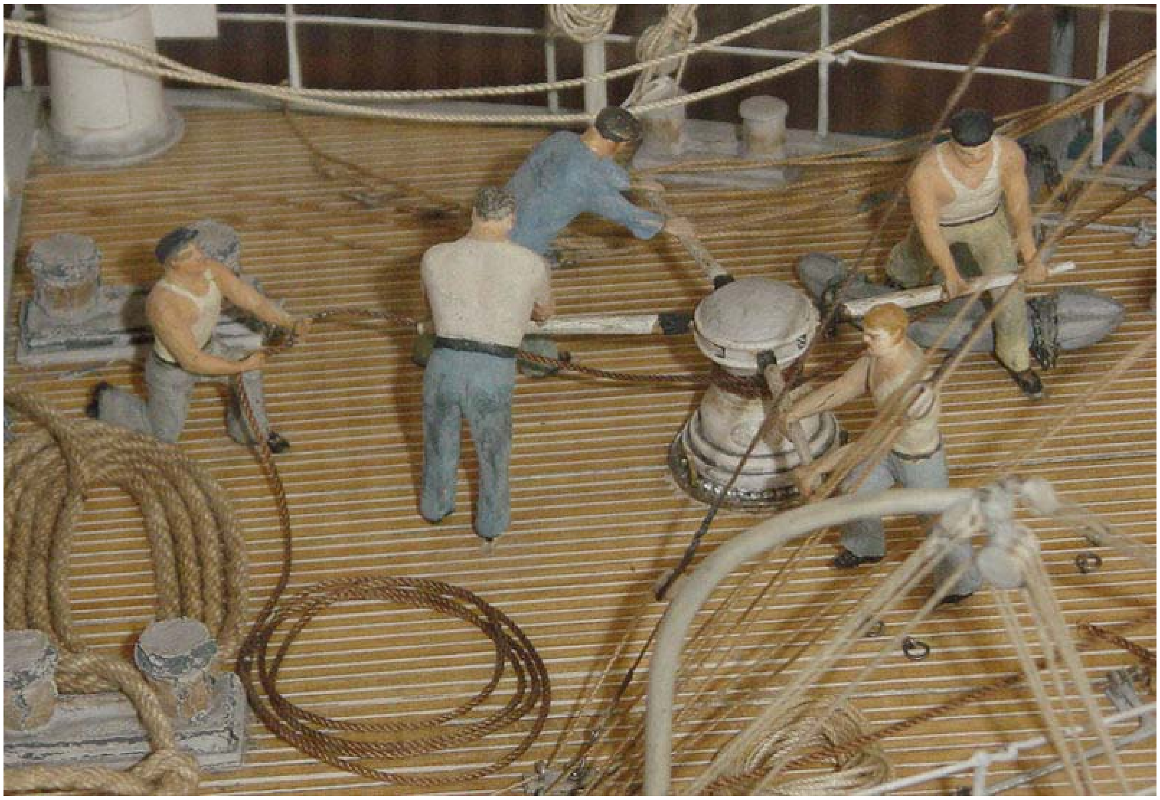
A well known application of the wheel and axle.

The wheel and axle is one of six simple machines developed in ancient times and is in the category of a first-class lever. In its simplest form it consists of a rod attached to a wheel so that their movements are coupled when one of the parts is turned. The wheel and axle is used either as a force multiplier (such as a doorknob, steering wheel or fishing reel) or as a distance multiplier (such as on a bicycle or the driven wheels of a car). In the first kind of application, the larger wheel is used to create more torque (in the axle) with less force. In the second kind of application, when the axle is turned, the outside of the wheel turns at a greater linear speed that is proportional to the ratio of the radii of the wheel and axle. For example, if a bike wheel has a gear that turns eight inches in one second, and the wheel circumference is eighty inches, the wheel rotates through a distance ten times greater than the gear (and reducing the number of rotations of the pedals required). By varying the radii of the axle and/or wheel, any amount of mechanical advantage may be gained.

Turning a doorknob creates torque with little force required.

Description

The wheel and axle is a simple machine that is generally classified as a lever and provides mechanical advantage. The mechanical advantage is the ratio of the resistance to the effort. It consists of a rod attached to a wheel so that their movements are coupled when one of the parts is turned. When the axle is turned, the outside of the wheel turns at a greater linear speed because the rotational speed is the same. This principle is used in cars to gain more distance by applying a large torque (from the engine) to the axle, causing the wheels, which have a much larger radius, to turn. In the reverse case, when a force is applied to the wheel, more torque is created with less force. The result is proportional to the ratio of the radii. For example, if a sailor is pushing a capstan bar, pushing closer to the center is harder because he makes use of the wheel and axle as if it were a lever. Because the longer a lever is, the less force you have to use, the longer the bar the less effort is required.



A ship's crew creates a wheel and axle when they insert capstan bars into the capstan – this reduces the effort required to lift the anchor.

History

It is not known for certain who created the wheel and axle, it is known that it was used in ancient times. The oldest wheel publicized by archaeologists was found in 2002 in Ljubljana. Austrian experts established that the wheel is between 5,100 and 5,350 years old and is therefore at least a century older than those found in Switzerland and southern Germany. The wheel was made of ash and oak and had a radius of 70 cm. The axle is 120 cm long and made of oak.

Uses/Examples

The wheel and axle has many uses on many size scales and there are many examples. Common examples include the lift mechanism on a well, doorknob, a rotary telephone dial, a rotary egg beater, faucet handles, a wheel on which torque acts in a car, a fishing reel, a screw driver, a steering wheel, and even a simple top. In a top, the highest part of the top is spun so that the edge turns rapidly and keeps it upright. These examples are simple applications of a wheel and axle, yet they are great innovations.

Misconceptions

One misconception about the wheel and axle is that any wheel on a cylinder is a wheel and axle. This is not so. To be a true wheel and axle, the wheel must be firmly attached to the axle so that if one is turned the other turns with it.

Calculating mechanical advantage

The mechanical advantage of a simple machine like the wheel and axle is computed as the ratio of the resistance to the effort. The larger the ratio the greater the multiplication of force (torque) created or distance achieved. By varying the radii of the axle and/or wheel, any amount of mechanical advantage may be gained. In this manner, the size of the wheel may be increased to an inconvenient extent. In this case a system or combination of wheels (often toothed, that is, gears) are used. As a wheel and axle is a type of lever, a system of wheels and axles is like a compound lever.

Ideal mechanical advantage

The ideal mechanical advantage of a wheel and axle is calculated with the following formula:

$$I.M.A. = \frac{Radius_{Wheel}}{Radius_{Axle}}$$

Actual mechanical advantage

The actual mechanical advantage of a wheel and axle is calculated with the following formula:

$$A.M.A. = \frac{R}{E_{actual}}$$

where

R = resistance force, i.e. the weight of the bucket in this example.
E_{actual} = actual effort force, the force required to turn the wheel.

More Examples

- Doorknobs are similar to the water well, as the mechanism uses the axle as a pinion to withdraw the latch.
- With a simple chain fall, the user pulls on the wheel using the input chain, so the input motion is actually linear.
- Screwdrivers - an example of the rotational form. The diameter of the handle gives a mechanical advantage.

- Gears
- Bicycle wheels
- Ferris wheels
- automobiles
- blenders
- clocks
- escalators
- golf carts
- helicopters
- jet
- lawn mowers
- microwaves
- propellers
- unicycles
- Zambonis

Chapter 4

Wedge (Mechanical Device) and Screw (Simple Machine)

Wedge

A wood splitting wedge

A **wedge** is a triangular shaped tool, a compound and portable inclined plane, and one of the six classical simple machines. It can be used to separate two objects or portions of an object, lift an object, or hold an object in place. It functions by converting a force applied to its blunt end into forces perpendicular (normal) to its inclined surfaces. The mechanical advantage of a wedge is given by the ratio of the length of its slope to its width. Although a short wedge with a wide angle may do a job faster, it requires more force than a long wedge with a narrow angle.

History

The origin of the wedge is unknown likely because it has been in use for over 9000 years. In ancient Egyptian quarries, bronze wedges were used to break away blocks of stone used in construction. Wooden wedges, that swelled after being saturated with water, were also used. Some indigenous peoples of the Americas used antler wedges for splitting and working wood to make canoes, dwellings and other objects.

Examples for lifting and separating

Wedges can be used to lift heavy objects, separating them from the surface upon which they rest. They can also be used to separate objects, such as blocks of cut stone. Splitting mauls and splitting wedges are used to split wood along the grain. A narrow wedge with a relatively long taper used to finely adjust the distance between objects is called a shim, and is commonly used in carpentry.

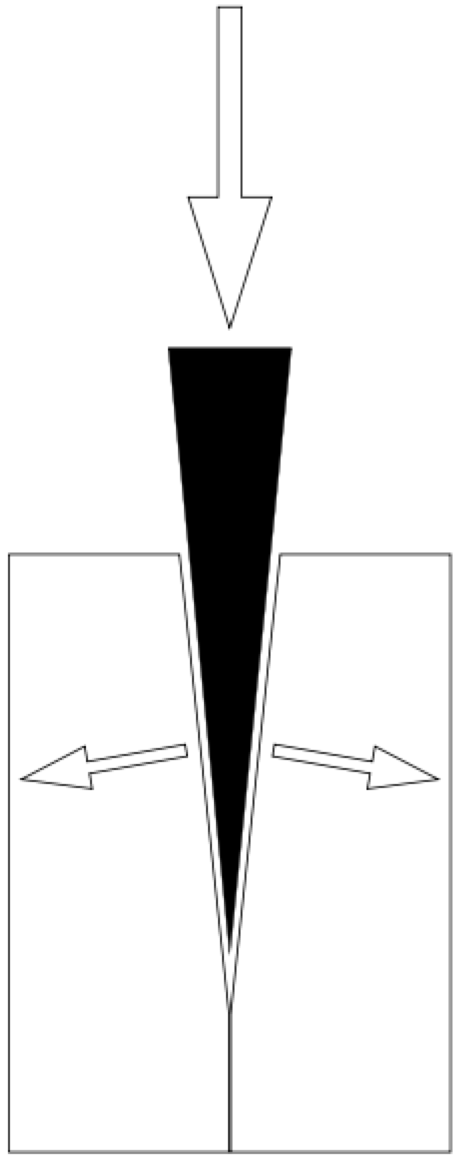
The tips of forks and nails are also wedges, as they split and separate the material into which they are pushed or driven; the shafts may then hold fast due to friction.

Examples for holding fast

Wedges can also be used to hold objects in place, such as engine parts (poppet valves), bicycle parts (stems and eccentric bottom brackets), and doors.

A wedge-type door stop (door wedge) functions largely because of the friction generated between the bottom of the door and the wedge, and the wedge and the floor (or other surface).

Mechanical advantage



Cross-section of a splitting wedge with its length oriented vertically. A downward force produces forces perpendicular to its inclined surfaces.

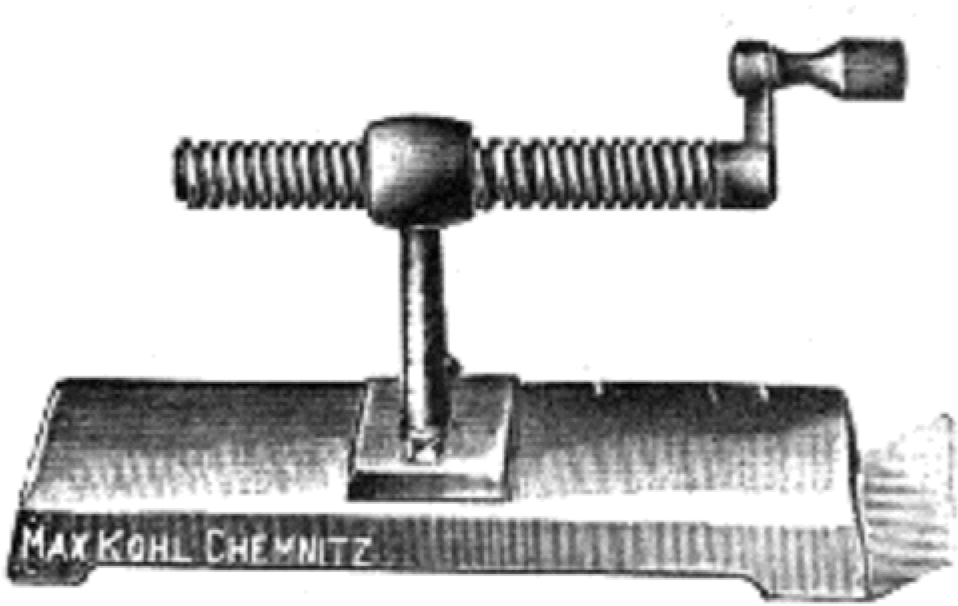
The mechanical advantage of a wedge can be calculated by dividing the length of the slope by the wedge's width:

$$MA = \frac{S}{W}$$

The more acute, or narrow, the angle of a wedge, the greater the ratio of the length of its slope to its width, and thus the more mechanical advantage it will yield.

However, in an elastic material such as wood, friction may bind a narrow wedge more easily than a wide one. This is why the head of a splitting maul has a much wider angle than that of an axe.

Screw



A machine used to demonstrate the action of a screw, 1912. It consists of a threaded shaft through a hole in a stationary mount. When the crank on the right is turned, the shaft moves horizontally through the hole.

A **screw** is one of the six classical simple machines. It can convert a rotational motion to a linear motion, and a torque (rotational force) to a linear force. The most common form consists of a cylindrical shaft with helical grooves or ridges called threads around the outside. The screw passes through a hole in another object or medium, with stationary threads on the inside of the hole. When the shaft of the screw is rotated relative to the stationary threads, the screw moves along its axis relative to the medium surrounding it; for example rotating a woodscrew forces it into wood. Geometrically, a screw can be viewed as a narrow inclined plane wrapped around a shaft.

Other mechanisms that use the same principle, also called screws, don't necessarily have a shaft or threads. For example, an Archimedes' screw is a water pump that uses a rotating helical chamber to move water uphill. The common principle of all screws is that a rotating helix can cause linear motion.

Lead and pitch

A screw's *lead* is defined as the linear distance the screw travels in one revolution (360°). The lead determines the mechanical advantage of the screw; the smaller the lead, the higher the mechanical advantage. The *pitch* of a screw is defined as the distance between adjacent threads. In most screws, called "*single start*" screws, which have a single helical thread, the lead and pitch are equal. They only differ in "*multiple start*" screws, which have several intertwined threads. In these screws the lead is equal to the pitch multiplied by the number of *starts*.

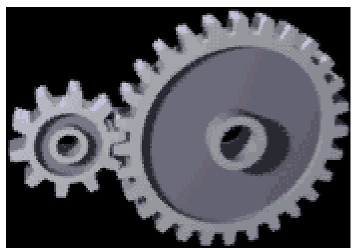
Uses

Practical screw devices may or may not have a shaft around which the thread is wrapped; the propeller blade, for example, does not. Uses include:

- the bolt, used as a fastener together with a nut or tapped hole with mating thread
- the metal woodscrew, a fastener with a thread sharp enough to cut its way through wood, forming a thread in the wood, driving the screw in, and holding it in place
- the screw top, to hold the lid of a bottle or jar tightly in place
- the lathe screw, which uses rotation of a knob by hand to make much smaller, precisely controlled linear movements
- the similar worm gear, to drive a perpendicular gear with increased mechanical advantage
- the lead screw, ball screw and roller screw, which convert screw rotation to linear movement of a shaft
- the corkscrew
- the micrometer, essentially a calibrated, precise screw used for measuring linear distances
- the propeller blade to move a water- or aircraft, an example of a screw of less than one turn which is not required to move a shaft
- the electric fan blade, a fixed propeller which moves the air
- the helical twist drill bit, an Archimedean screw used to remove swarf from a hole being drilled
- the screw conveyor, closely related to the Archimedean screw

Chapter 5

Gear



Two meshing gears transmitting rotational motion. Note that the smaller gear is rotating faster. Although the larger gear is rotating less quickly, its torque is proportionally greater.

A **gear** or more correctly a "gear wheel" is a rotating machine part having cut *teeth*, or *cogs*, which *mesh* with another toothed part in order to transmit torque. Two or more gears working in tandem are called a *transmission* and can produce a mechanical advantage through a gear ratio and thus may be considered a simple machine. Geared devices can change the speed, magnitude, and direction of a power source. The most common situation is for a gear to mesh with another gear, however a gear can also mesh a non-rotating toothed part, called a rack, thereby producing translation instead of rotation.

The gears in a transmission are analogous to the wheels in a pulley. An advantage of gears is that the teeth of a gear prevent slipping.

When two gears of unequal number of teeth are combined a mechanical advantage is produced, with both the rotational speeds and the torques of the two gears differing in a simple relationship.

In transmissions which offer multiple gear ratios, such as bicycles and cars, the term **gear**, as in *first gear*, refers to a gear ratio rather than an actual physical gear. The term is used to describe similar devices even when gear ratio is continuous rather than discrete, or when the device does not actually contain any gears, as in a continuously variable transmission.

The earliest known reference to gears was circa A.D. 50 by Hero of Alexandria, but they can be traced back to the Greek mechanics of the Alexandrian school in the 3rd century B.C. and were greatly developed by the Greek polymath Archimedes (287–212 B.C.). The Antikythera mechanism is an example of a very early and intricate geared device, designed to calculate astronomical positions. Its time of construction is now estimated between 150 and 100 BC.

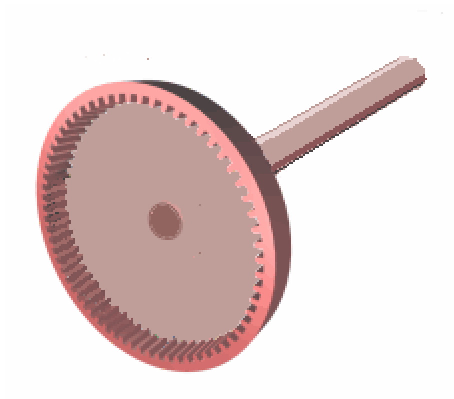
Comparison with other drive mechanisms

The definite velocity ratio which results from having teeth gives gears an advantage over other drives (such as traction drives and V-belts) in precision machines such as watches that depend upon an exact velocity ratio. In cases where driver and follower are in close proximity gears also have an advantage over other drives in the reduced number of parts required; the downside is that gears are more expensive to manufacture and their lubrication requirements may impose a higher operating cost.

The automobile transmission allows selection between gears to give various mechanical advantages.

Types

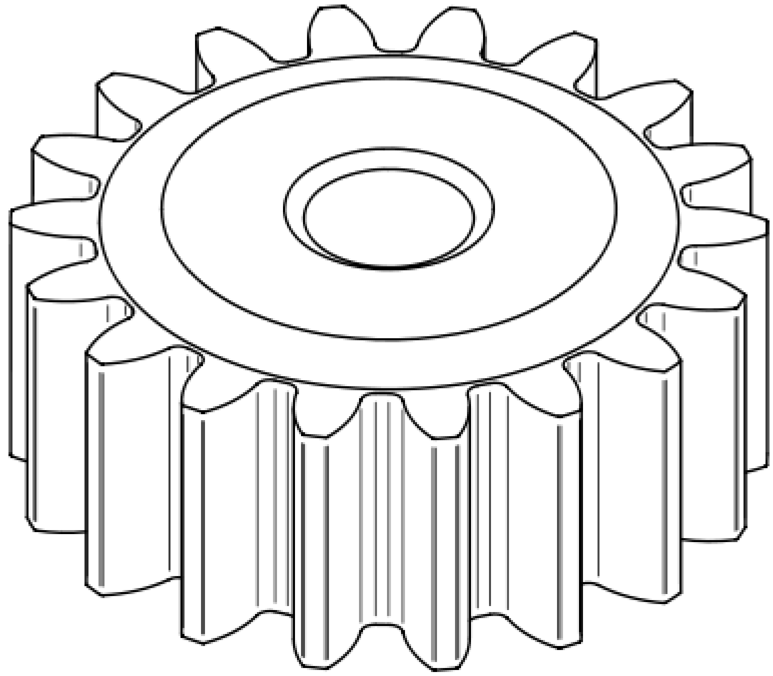
External vs. internal gears



Internal gear

An *external gear* is one with the teeth formed on the outer surface of a cylinder or cone. Conversely, an *internal gear* is one with the teeth formed on the inner surface of a cylinder or cone. For bevel gears, an internal gear is one with the pitch angle exceeding 90 degrees. Internal gears do not cause direction reversal.

Spur



Spur gear

Spur gears or *straight-cut gears* are the simplest type of gear. They consist of a cylinder or disk with the teeth projecting radially, and although they are not straight-sided in form, the edge of each tooth is straight and aligned parallel to the axis of rotation. These gears can be meshed together correctly only if they are fitted to parallel shafts.

Helical

Helical gears
Top: parallel configuration
Bottom: crossed configuration

Helical gears offer a refinement over spur gears. The leading edges of the teeth are not parallel to the axis of rotation, but are set at an angle. Since the gear is curved, this angling causes the tooth shape to be a segment of a helix. Helical gears can be meshed in a *parallel* or *crossed* orientations. The former refers to when the shafts are parallel to each other; this is the most common orientation. In the latter, the shafts are non-parallel, and in this configuration are sometimes known as "skew gears".

The angled teeth engage more gradually than do spur gear teeth causing them to run more smoothly and quietly. With parallel helical gears, each pair of teeth first make contact at a single point at one side of the gear wheel; a moving curve of contact then grows gradually across the tooth face to a maximum then recedes until the teeth break contact at a single point on the opposite side. In spur gears teeth suddenly meet at a line contact across their entire width causing stress and noise. Spur gears make a characteristic whine at high speeds and can not take as much torque as helical gears. Whereas spur gears are used for low speed applications and those situations where noise control is not a problem, the use of helical gears is indicated when the application involves high speeds, large power transmission, or where noise abatement is important. The speed is considered to be high when the pitch line velocity exceeds 25 m/s.

A disadvantage of helical gears is a resultant thrust along the axis of the gear, which needs to be accommodated by appropriate thrust bearings, and a greater degree of sliding friction between the meshing teeth, often addressed with additives in the lubricant.

For a crossed configuration the gears must have the same pressure angle and normal pitch, however the helix angle and handedness can be different. The relationship between the two shafts is actually defined by the helix angle(s) of the two shafts and the handedness, as defined:

$E = \beta_1 + \beta_2$ for gears of the same handedness
$E = \beta_1 - \beta_2$ for gears of opposite handedness

Where β is the helix angle for the gear. The crossed configuration is less mechanically sound because there is only a point contact between the gears, whereas in the parallel configuration there is a line contact.

Quite commonly helical gears are used with the helix angle of one having the negative of the helix angle of the other; such a pair might also be referred to as having a right-handed helix and a left-handed helix of equal angles. The two equal but opposite angles add to zero: the angle between shafts is zero – that is, the shafts are *parallel*. Where the sum or the difference (as described in the equations above) is not zero the shafts are *crossed*. For shafts *crossed* at right angles the helix angles are of the same hand because they must add to 90 degrees.

Double helical

Double helical gears

Double helical gears, or *herringbone gear*, overcome the problem of axial thrust presented by "single" helical gears by having two sets of teeth that are set in a V shape. Each gear in a double helical gear can be thought of as two standard mirror image helical gears stacked. This cancels out the thrust since each half of the gear thrusts in the opposite direction. Double helical gears are more difficult to manufacture due to their more complicated shape.

For each possible direction of rotation, there are two possible arrangements of two oppositely-oriented helical gears or gear faces. In one possible orientation, the helical gear faces are oriented so that the axial force generated by each is in the axial direction away from the center of the gear; this arrangement is unstable. In the second possible orientation, which is stable, the helical gear faces are oriented so that each axial force is toward the mid-line of the gear. In both arrangements, when the gears are aligned correctly, the total (or *net*) axial force on each gear is zero. If the gears become misaligned in the axial direction, the unstable arrangement generates a net force for disassembly of the gear train, while the stable arrangement generates a net corrective force. If the direction of rotation is reversed, the direction of the axial thrusts is reversed, a stable configuration becomes unstable, and *vice versa*.

Stable double helical gears can be directly interchanged with spur gears without any need for different bearings.

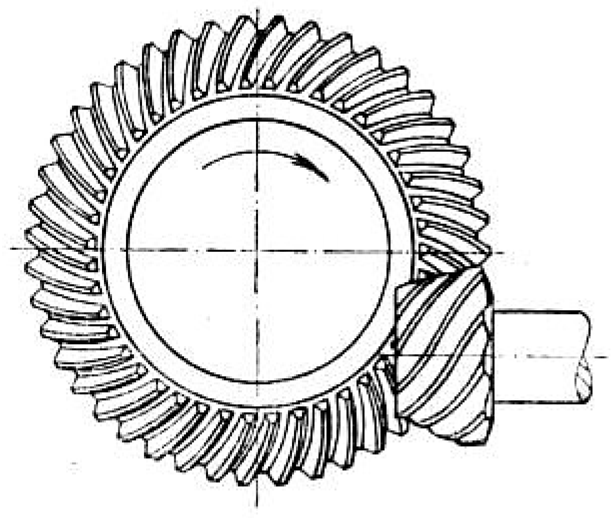
Bevel

Bevel gear

A bevel gear is shaped like a right circular cone with most of its tip cut off. When two bevel gears mesh their imaginary vertices must occupy the same point. Their shaft axes also intersect at this point, forming an arbitrary non-straight angle between the shafts. The angle between the shafts can be anything except zero or 180 degrees. Bevel gears with equal numbers of teeth and shaft axes at 90 degrees are called *miter gears*.

The teeth of a bevel gear may be straight-cut as with spur gears, or they may be cut in a variety of other shapes. *Spiral bevel gear* teeth are curved along the tooth's length and set at an angle, analogously to the way helical gear teeth are set at an angle compared to spur gear teeth. *Zerol bevel gears* have teeth which are curved along their length, but not angled. Spiral bevel gears have the same advantages and disadvantages relative to their straight-cut cousins as helical gears do to spur gears. Straight bevel gears are generally used only at speeds below 5 m/s (1000 ft/min), or, for small gears, 1000 r.p.m.

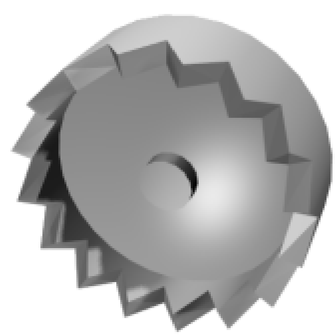
Hypoid



Hypoid gear

Hypoid gears resemble spiral bevel gears except the shaft axes do not intersect. The pitch surfaces appear conical but, to compensate for the offset shaft, are in fact hyperboloids of revolution. Hypoid gears are almost always designed to operate with shafts at 90 degrees. Depending on which side the shaft is offset to, relative to the angling of the teeth, contact between hypoid gear teeth may be even smoother and more gradual than with spiral bevel gear teeth. Also, the pinion can be designed with fewer teeth than a spiral bevel pinion, with the result that gear ratios of 60:1 and higher are feasible using a single set of hypoid gears. This style of gear is most commonly found driving mechanical differentials; which are normally straight cut bevel gears; in motor vehicle axles.

Crown

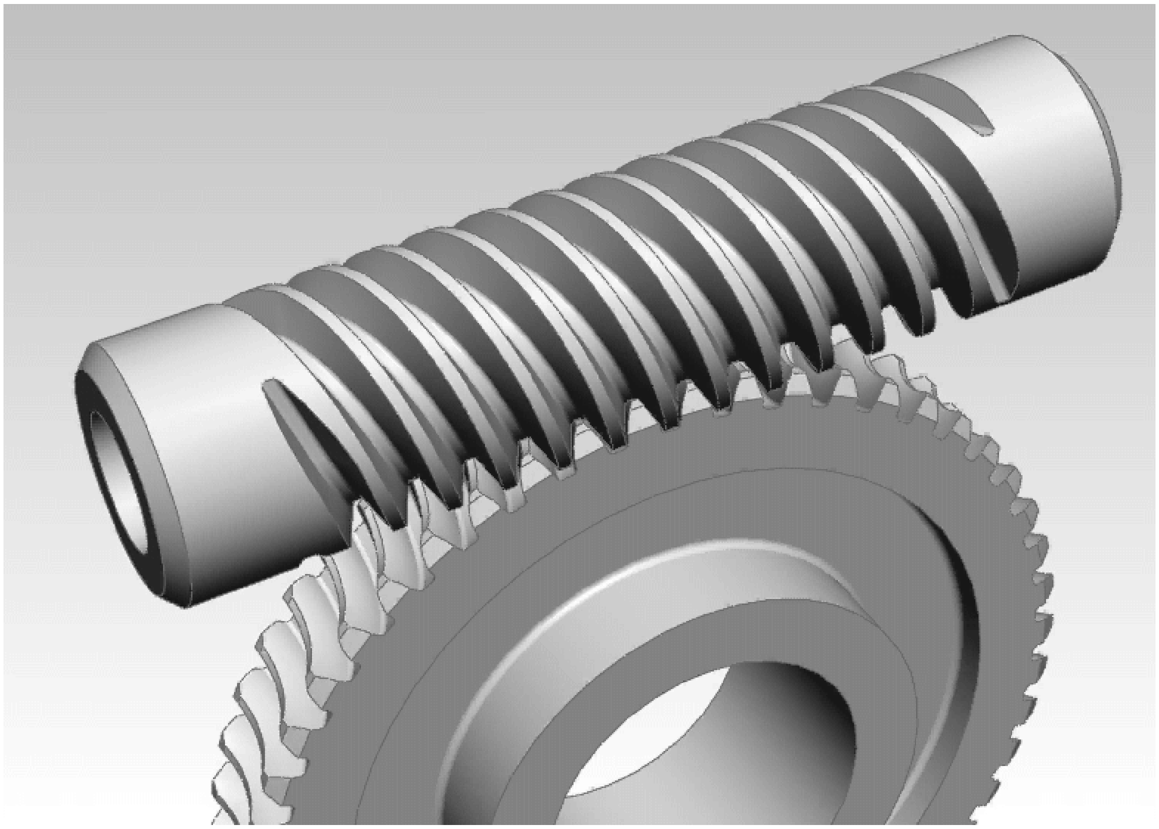


Crown gear

Crown gears or *contrate gears* are a particular form of bevel gear whose teeth project at right angles to the plane of the wheel; in their orientation the teeth resemble the points on a crown. A crown gear can only mesh accurately with another bevel gear, although crown gears are sometimes seen meshing with spur gears. A crown gear is also sometimes meshed with an escapement such as found in mechanical clocks.

Worm

Worm gear



4-start worm and wheel

Worm gears resemble screws. A worm gear is usually meshed with an ordinary looking, disk-shaped gear, which is called the *gear*, *wheel*, or *worm wheel*.

Worm-and-gear sets are a simple and compact way to achieve a high torque, low speed gear ratio. For example, helical gears are normally limited to gear ratios of less than 10:1 while worm-and-gear sets vary from 10:1 to 500:1. A disadvantage is the potential for considerable sliding action, leading to low efficiency.

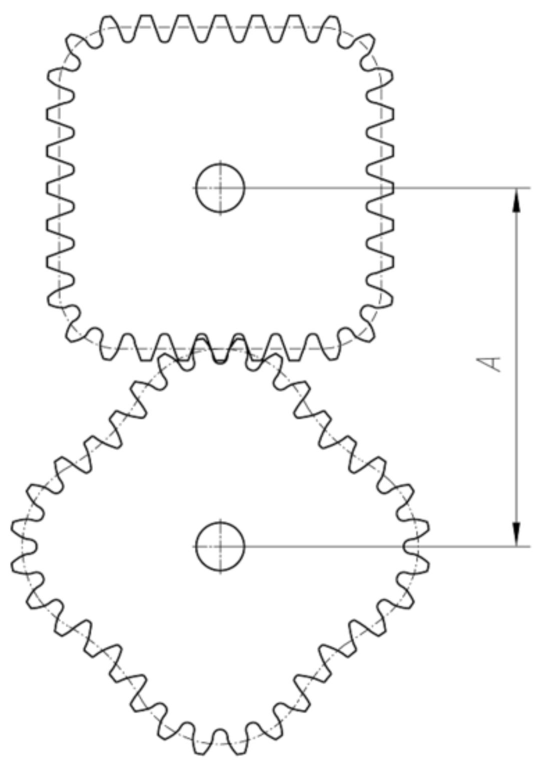
Worm gears can be considered a species of helical gear, but its helix angle is usually somewhat large (close to 90 degrees) and its body is usually fairly long in the axial direction; and it is these attributes which give it its screw like qualities. The distinction between a worm and a helical gear is made when at least one tooth persists for a full rotation around the helix. If this occurs, it is a 'worm'; if not, it is a 'helical gear'. A worm may have as few as one tooth. If that tooth persists for several turns around the helix, the worm will appear, superficially, to have more than one tooth, but what one in fact sees is the same tooth reappearing at intervals along the length of the worm. The usual screw nomenclature applies: a one-toothed worm is called *single thread* or *single start*; a worm with more than one tooth is called *multiple thread* or *multiple start*. The helix angle of a worm is not usually specified. Instead, the lead angle, which is equal to 90 degrees minus the helix angle, is given.

In a worm-and-gear set, the worm can always drive the gear. However, if the gear attempts to drive the worm, it may or may not succeed. Particularly if the lead angle is small, the gear's teeth may simply lock against the worm's teeth, because the force component circumferential to the worm is not sufficient to overcome friction. Worm-and-gear sets that do lock are called **self locking**, which can be used to advantage, as for instance when it is desired to set the position of a mechanism by turning the worm and then have the mechanism hold that position. An example is the machine head found on some types of stringed instruments.

If the gear in a worm-and-gear set is an ordinary helical gear only a single point of contact will be achieved. If medium to high power transmission is desired, the tooth shape of the gear is modified to achieve more intimate contact by making both gears partially envelop each other. This is done by making both concave and joining them at a saddle point; this is called a **cone-drive**.

Worm gears can be right or left-handed following the long established practice for screw threads.

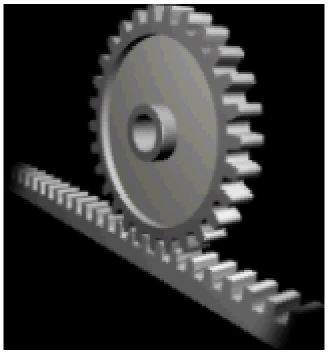
Non-circular



Non-circular gears

Non-circular gears are designed for special purposes. While a regular gear is optimized to transmit torque to another engaged member with minimum noise and wear and maximum efficiency, a non-circular gear's main objective might be ratio variations, axle displacement oscillations and more. Common applications include textile machines, potentiometers and continuously variable transmissions.

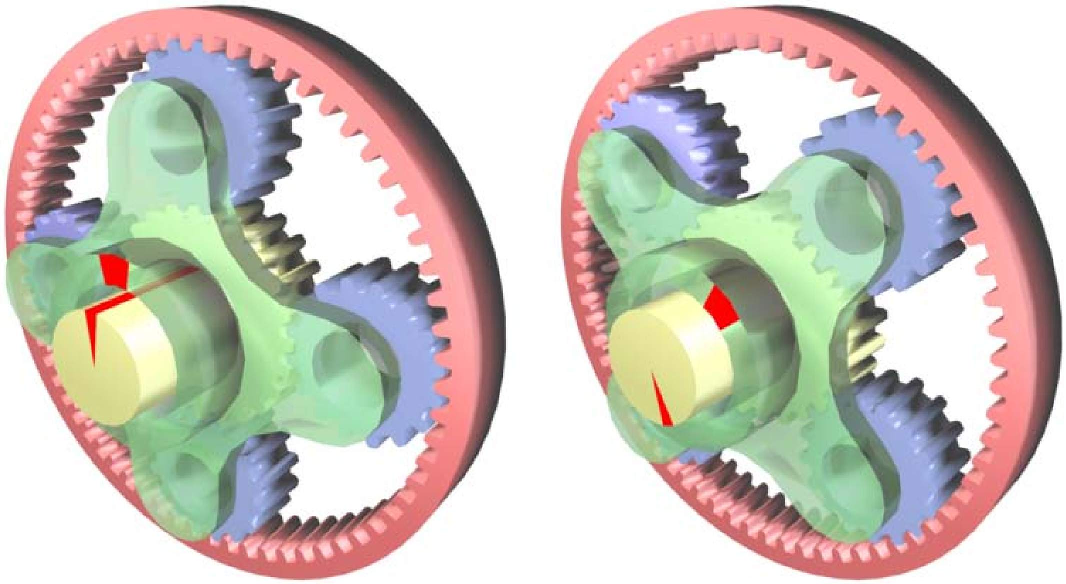
Rack and pinion



Rack and pinion gearing

A rack is a toothed bar or rod that can be thought of as a sector gear with an infinitely large radius of curvature. Torque can be converted to linear force by meshing a rack with a pinion: the pinion turns; the rack moves in a straight line. Such a mechanism is used in automobiles to convert the rotation of the steering wheel into the left-to-right motion of the tie rod(s). Racks also feature in the theory of gear geometry, where, for instance, the tooth shape of an interchangeable set of gears may be specified for the rack (infinite radius), and the tooth shapes for gears of particular actual radii then derived from that. The rack and pinion gear type is employed in a rack railway.

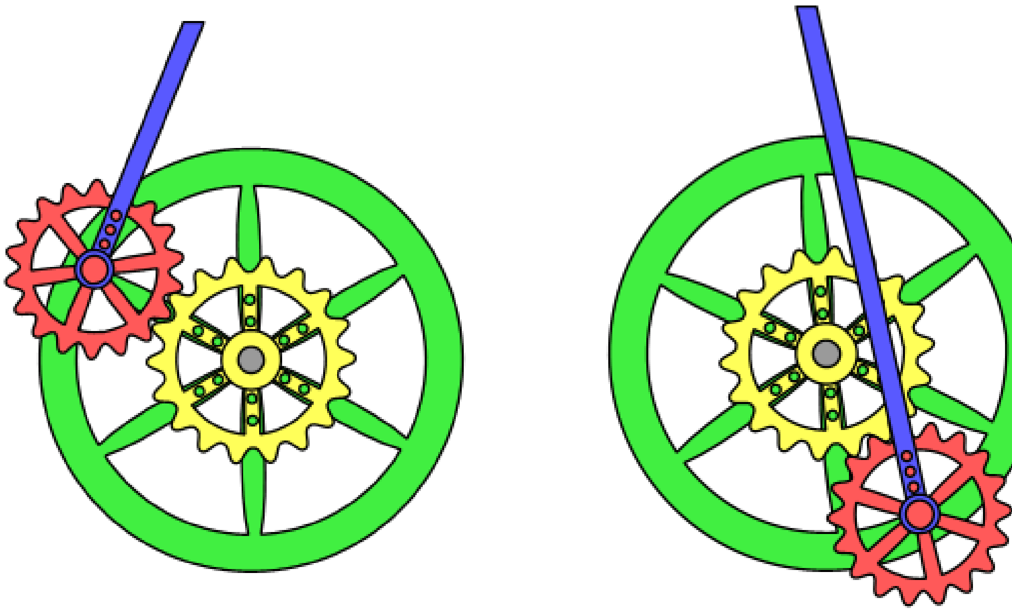
Epicyclic



Epicyclic gearing

In epicyclic gearing one or more of the gear axes moves. Examples are sun and planet gearing and mechanical differentials.

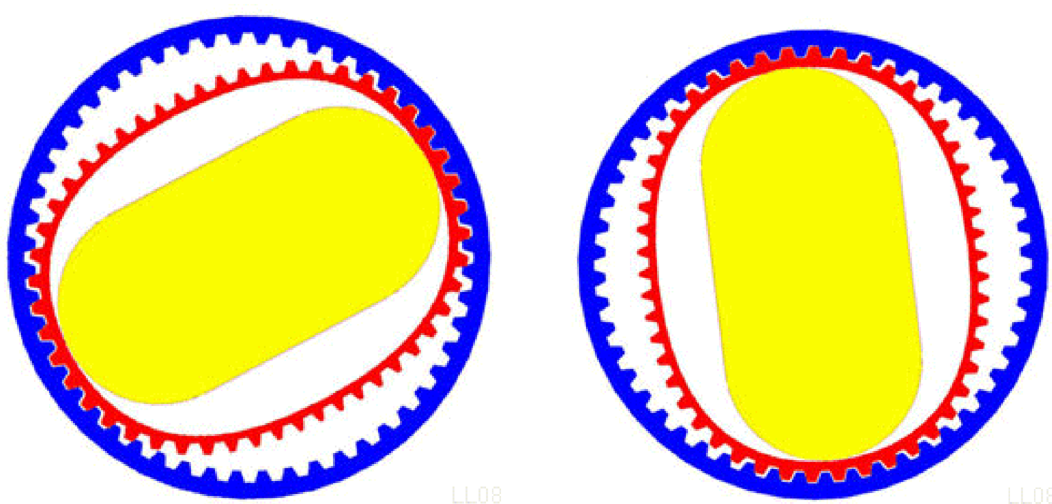
Sun and planet



Sun (yellow) and planet (red) gearing

Sun and planet gearing was a method of converting reciprocal motion into rotary motion in steam engines. It played an important role in the Industrial Revolution. The Sun is yellow, the planet red, the reciprocating crank is blue, the flywheel is green and the driveshaft is grey.

Harmonic drive



Harmonic drive gearing

A *harmonic drive* is a specialized proprietary gearing mechanism.

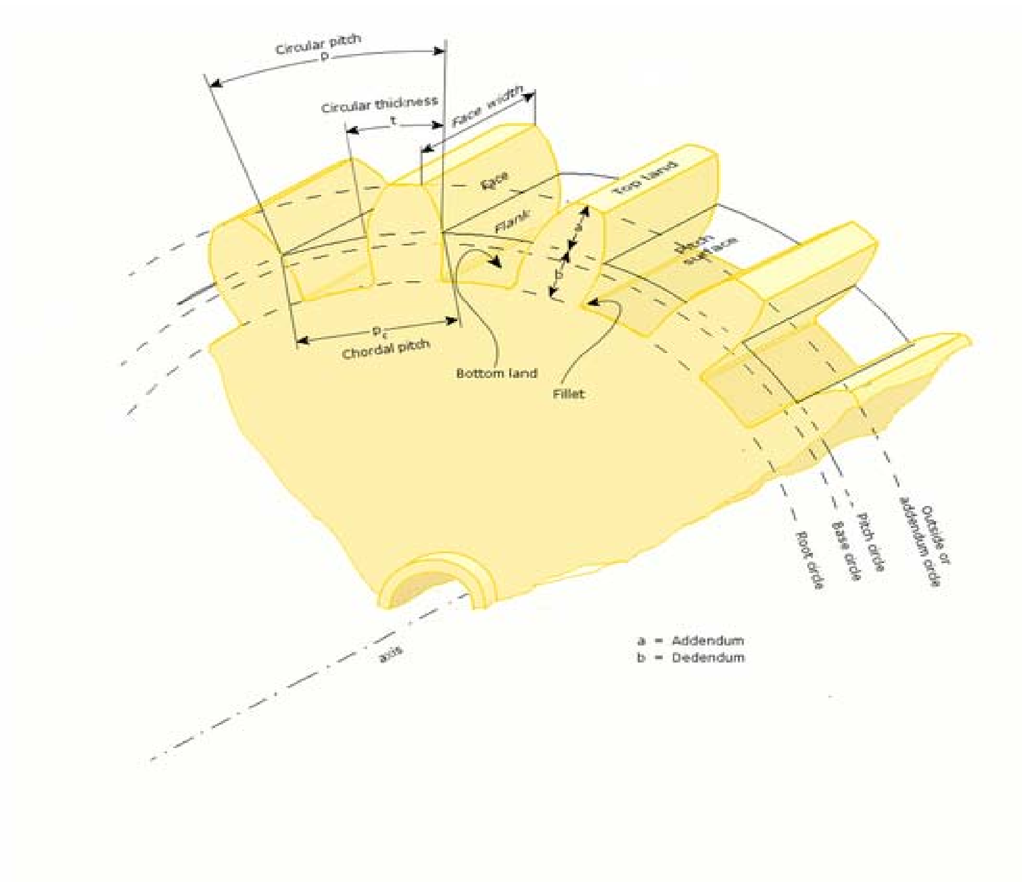
Cage gear

Cage gear in Pantigo Windmill, Long Island

A *cage gear*, also called a *lantern gear* or *lantern pinion* has cylindrical rods for teeth, parallel to the axle and arranged in a circle around it, much as the bars on a round bird cage or lantern. The assembly is held together by disks at either end into which the tooth rods and axle are set.

Nomenclature

General nomenclature



Rotational frequency, n

Measured in rotation over time, such as RPM.

Angular frequency, ω

Measured in radians per second. $1 RPM = \pi / 30$ rad/second

Number of teeth, N

How many teeth a gear has, an integer. In the case of worms, it is the number of thread starts that the worm has.

Gear, wheel

The larger of two interacting gears or a gear on its own.

Pinion

The smaller of two interacting gears.

Path of contact

Path followed by the point of contact between two meshing gear teeth.

Line of action, pressure line

Line along which the force between two meshing gear teeth is directed. It has the same direction as the force vector. In general, the line of action changes from moment to moment during the period of engagement of a pair of teeth. For involute gears, however, the tooth-to-tooth force is always directed along the same line—that is, the line of action is constant. This implies that for involute gears the path of contact is also a straight line, coincident with the line of action—as is indeed the case.

Axis

Axis of revolution of the gear; center line of the shaft.

Pitch point, p

Point where the line of action crosses a line joining the two gear axes.

Pitch circle, pitch line

Circle centered on and perpendicular to the axis, and passing through the pitch point. A predefined diametral position on the gear where the circular tooth thickness, pressure angle and helix angles are defined.

Pitch diameter, d

A predefined diametral position on the gear where the circular tooth thickness, pressure angle and helix angles are defined. The standard pitch diameter is a basic dimension and cannot be measured, but is a location where other measurements are made. Its value is based on the number of teeth, the normal module (or normal diametral pitch), and the helix angle. It is calculated as:

$d = \frac{Nm_n}{cos\psi}$ in metric units or $d = \frac{N}{P_d cos\psi}$ in imperial units.

Module, m

A scaling factor used in metric gears with units in millimeters who's effect is to enlarge the gear tooth size as the module increases and reduce the size as the module decreases. Module can be defined in the normal (m_n), the transverse (m_t), or the axial planes (m_a) depending on the design approach employed and the type of gear being designed. Module is typically an input value into the gear design and is seldom calculated.

Operating pitch diameters

Diameters determined from the number of teeth and the center distance at which gears operate. Example for pinion:

$$d_w = \frac{2a}{u+1} = \frac{2a}{\frac{z_2}{z_1}+1}.$$

Pitch surface

In cylindrical gears, cylinder formed by projecting a pitch circle in the axial direction. More generally, the surface formed by the sum of all the pitch circles as one moves along the axis. For bevel gears it is a cone.

Angle of action

Angle with vertex at the gear center, one leg on the point where mating teeth first make contact, the other leg on the point where they disengage.

Arc of action

Segment of a pitch circle subtended by the angle of action.

Pressure angle, θ
: The complement of the angle between the direction that the teeth exert force on each other, and the line joining the centers of the two gears. For involute gears, the teeth always exert force along the line of action, which, for involute gears, is a straight line; and thus, for involute gears, the pressure angle is constant.

Outside diameter, D_o
: Diameter of the gear, measured from the tops of the teeth.

Root diameter
: Diameter of the gear, measured at the base of the tooth.

Addendum, a
: Radial distance from the pitch surface to the outermost point of the tooth. $a = (D_o - D) / 2$

Dedendum, b
: Radial distance from the depth of the tooth trough to the pitch surface. $b = (D - rootdiameter) / 2$

Whole depth, h_t
: The distance from the top of the tooth to the root; it is equal to addendum plus dedendum or to working depth plus clearance.

Clearance
: Distance between the root circle of a gear and the addendum circle of its mate.

Working depth
: Depth of engagement of two gears, that is, the sum of their operating addendums.

Circular pitch, p
: Distance from one face of a tooth to the corresponding face of an adjacent tooth on the same gear, measured along the pitch circle.

Diametral pitch, p_d
: Ratio of the number of teeth to the pitch diameter. Could be measured in teeth per inch or teeth per centimeter.

Base circle
: In involute gears, where the tooth profile is the involute of the base circle. The radius of the base circle is somewhat smaller than that of the pitch circle.

Base pitch, normal pitch, p_b
: In involute gears, distance from one face of a tooth to the corresponding face of an adjacent tooth on the same gear, measured along the base circle.

Interference
: Contact between teeth other than at the intended parts of their surfaces.

Interchangeable set
: A set of gears, any of which will mate properly with any other.

Helical gear nomenclature

Helix angle, ψ
: Angle between a tangent to the helix and the gear axis. It is zero in the limiting case of a spur gear, albeit it can considered as the hypotenuse angle as well.

Normal circular pitch, p_n
: Circular pitch in the plane normal to the teeth.

Transverse circular pitch, p

Circular pitch in the plane of rotation of the gear. Sometimes just called "circular pitch". $p_n = p\cos(\psi)$

Several other helix parameters can be viewed either in the normal or transverse planes. The subscript n usually indicates the normal.

Worm gear nomenclature

Lead
: Distance from any point on a thread to the corresponding point on the next turn of the same thread, measured parallel to the axis.

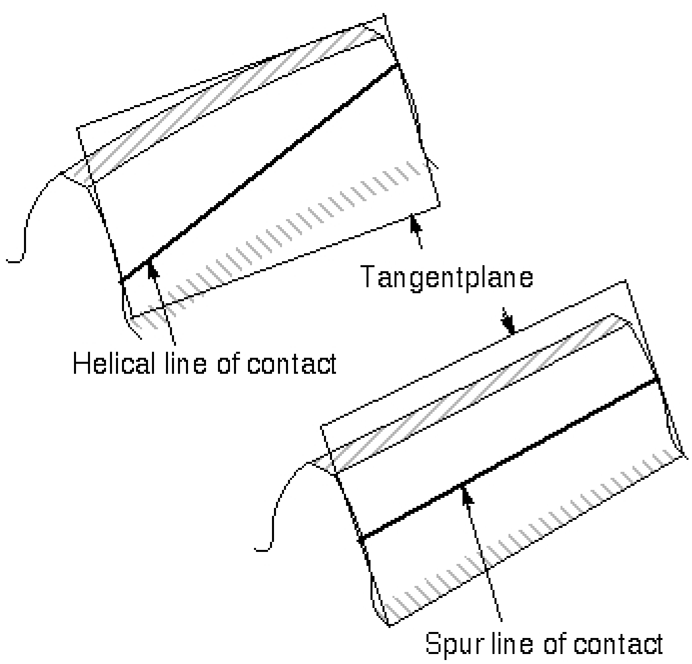
Linear pitch, p
: Distance from any point on a thread to the corresponding point on the adjacent thread, measured parallel to the axis. For a single-thread worm, lead and linear pitch are the same.

Lead angle, λ
: Angle between a tangent to the helix and a plane perpendicular to the axis. Note that it is the complement of the helix angle which is usually given for helical gears.

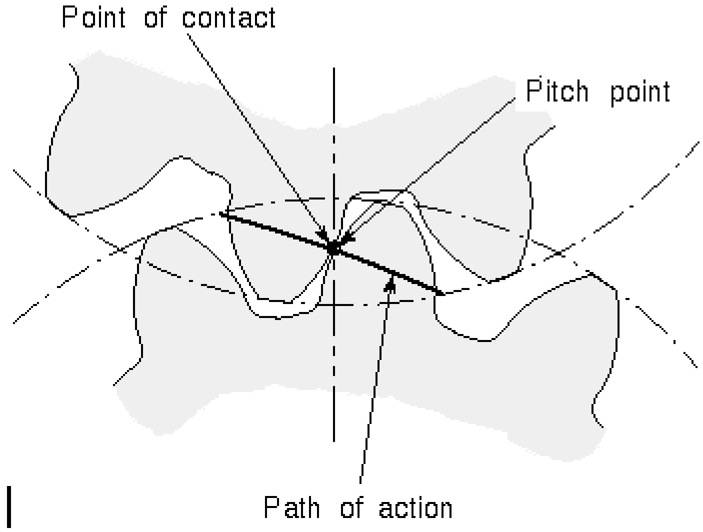
Pitch diameter, d_w
: Same as described earlier in this list. Note that for a worm it is still measured in a plane perpendicular to the gear axis, not a tilted plane.

Subscript w denotes the worm, subscript g denotes the gear.

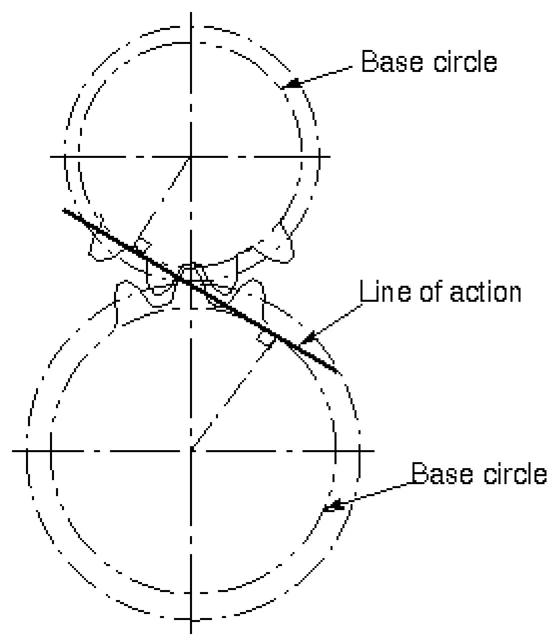
Tooth contact nomenclature



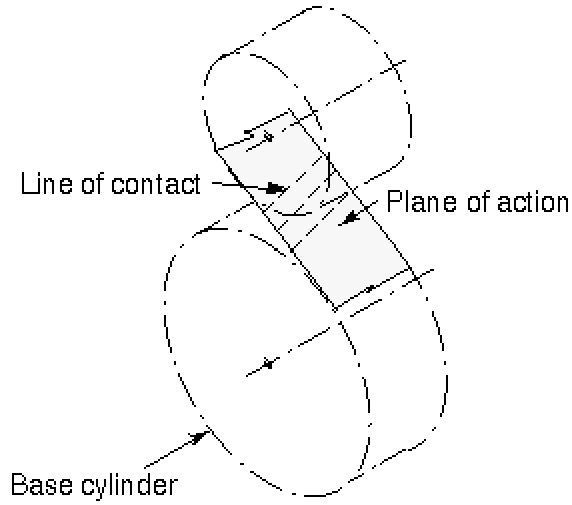
Line of contact



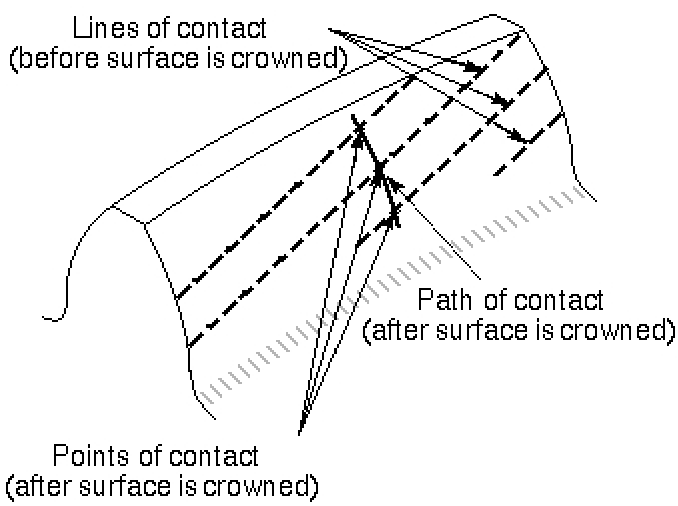
Path of action



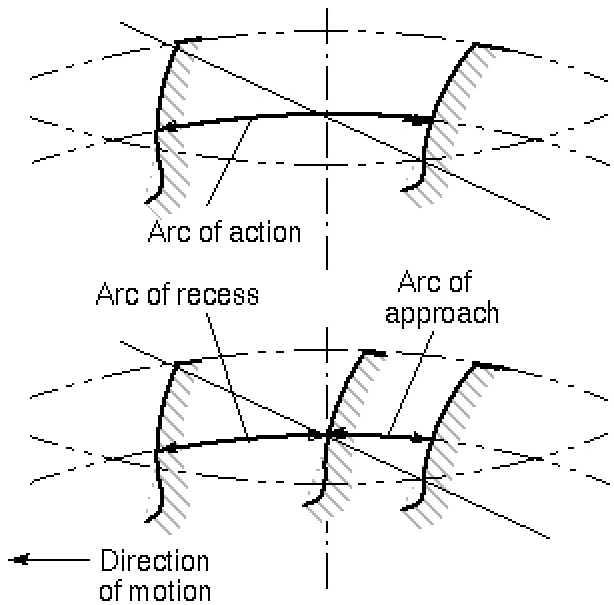
Line of action



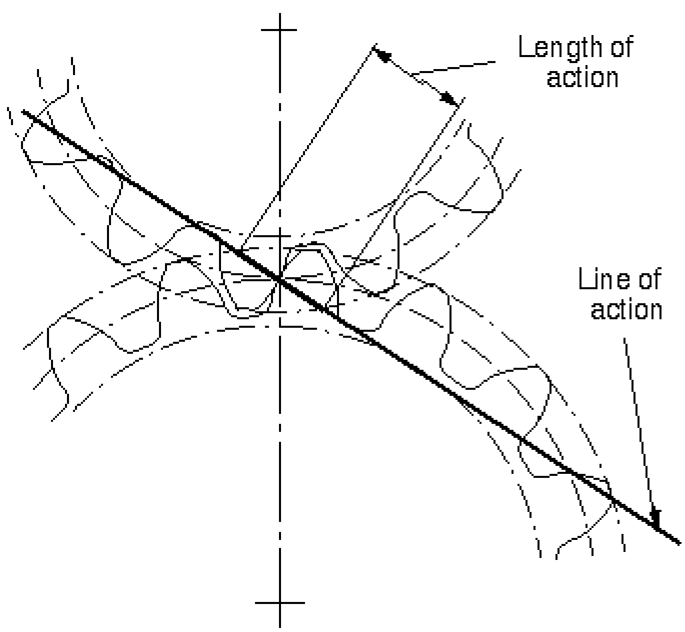
Plane of action



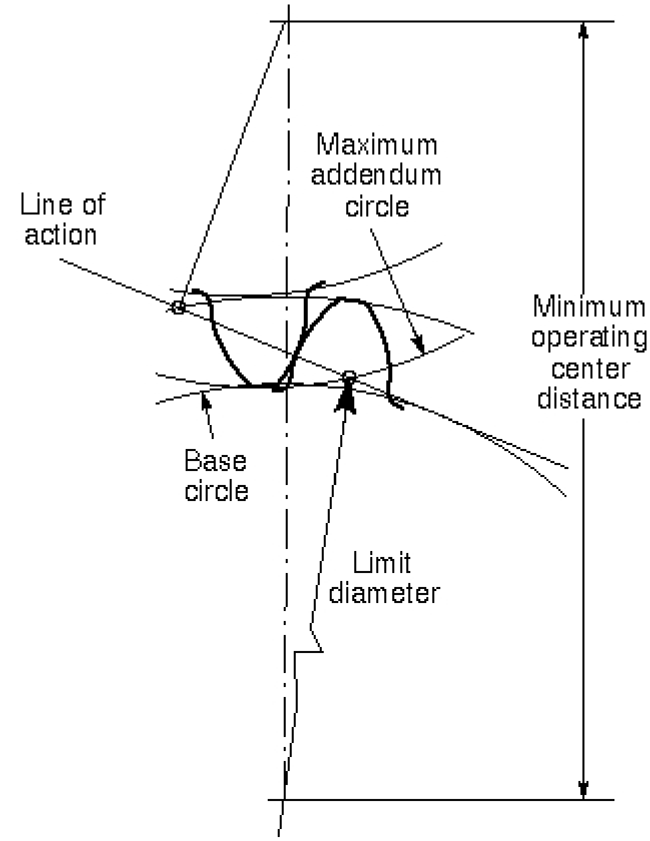
Lines of contact (helical gear)



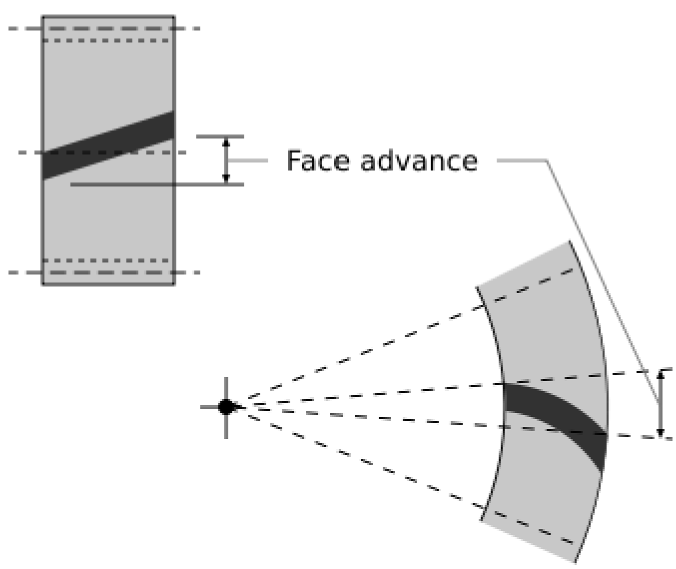
Arc of action



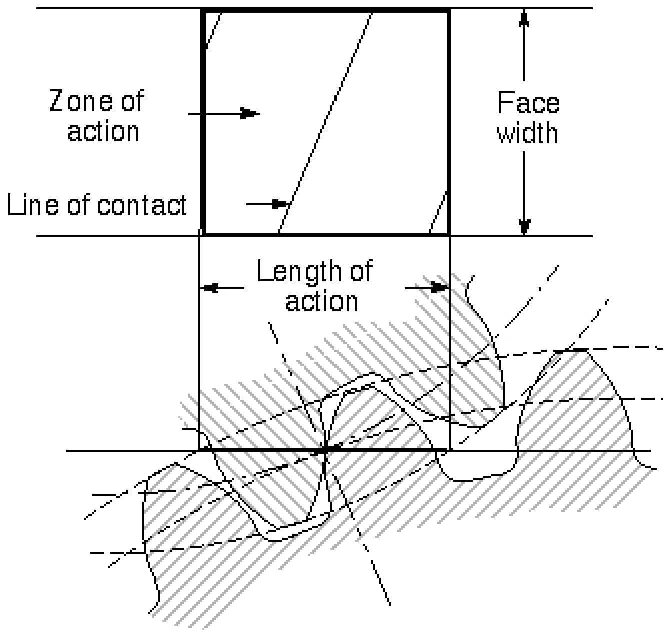
Length of action



Limit diameter



Face advance



Zone of action

Point of contact
: Any point at which two tooth profiles touch each other.

Line of contact
: A line or curve along which two tooth surfaces are tangent to each other.

Path of action
: The locus of successive contact points between a pair of gear teeth, during the phase of engagement. For conjugate gear teeth, the path of action passes through the pitch point. It is the trace of the surface of action in the plane of rotation.

Line of action
: The path of action for involute gears. It is the straight line passing through the pitch point and tangent to both base circles.

Surface of action
: The imaginary surface in which contact occurs between two engaging tooth surfaces. It is the summation of the paths of action in all sections of the engaging teeth.

Plane of action
: The surface of action for involute, parallel axis gears with either spur or helical teeth. It is tangent to the base cylinders.

Zone of action (contact zone)
: For involute, parallel-axis gears with either spur or helical teeth, is the rectangular area in the plane of action bounded by the length of action and the effective face width.

Path of contact
: The curve on either tooth surface along which theoretical single point contact occurs during the engagement of gears with crowned tooth surfaces or gears that normally engage with only single point contact.

Length of action

The distance on the line of action through which the point of contact moves during the action of the tooth profile.

Arc of action, Q_t

The arc of the pitch circle through which a tooth profile moves from the beginning to the end of contact with a mating profile.

Arc of approach, Q_a

The arc of the pitch circle through which a tooth profile moves from its beginning of contact until the point of contact arrives at the pitch point.

Arc of recess, Q_r

The arc of the pitch circle through which a tooth profile moves from contact at the pitch point until contact ends.

Contact ratio, m_c, ε

The number of angular pitches through which a tooth surface rotates from the beginning to the end of contact.In a simple way, it can be defined as a measure of the average number of teeth in contact during the period in which a tooth comes and goes out of contact with the mating gear.

Transverse contact ratio, m_p, ε_α

The contact ratio in a transverse plane. It is the ratio of the angle of action to the angular pitch. For involute gears it is most directly obtained as the ratio of the length of action to the base pitch.

Face contact ratio, m_F, ε_β

The contact ratio in an axial plane, or the ratio of the face width to the axial pitch. For bevel and hypoid gears it is the ratio of face advance to circular pitch.

Total contact ratio, m_t, ε_γ

The sum of the transverse contact ratio and the face contact ratio.

$\varepsilon_\gamma = \varepsilon_\alpha + \varepsilon_\beta$

$m_t = m_p + m_F$

Modified contact ratio, m_o

For bevel gears, the square root of the sum of the squares of the transverse and face contact ratios.

$$m_o = (m_p^2 + m_F^2)^{0.5}$$

Limit diameter

Diameter on a gear at which the line of action intersects the maximum (or minimum for internal pinion) addendum circle of the mating gear. This is also referred to as the start of active profile, the start of contact, the end of contact, or the end of active profile.

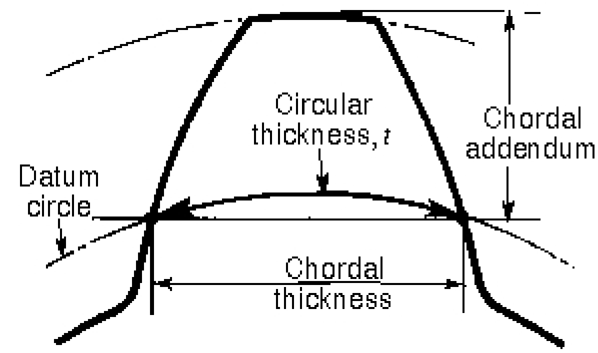
Start of active profile (SAP)

Intersection of the limit diameter and the involute profile.

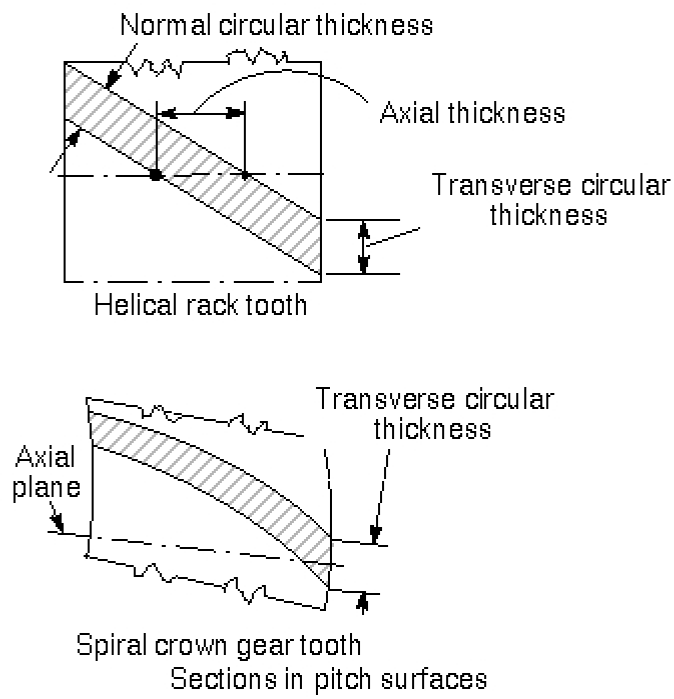
Face advance

Distance on a pitch circle through which a helical or spiral tooth moves from the position at which contact begins at one end of the tooth trace on the pitch surface to the position where contact ceases at the other end.

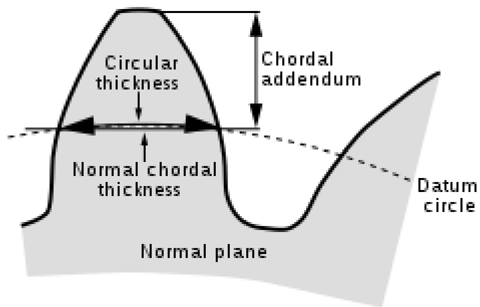
Tooth thickness nomeclature



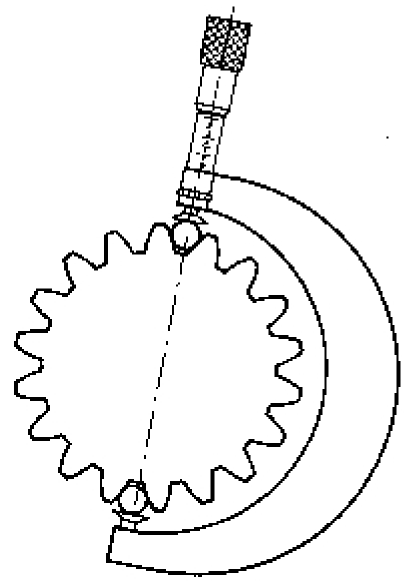
Tooth thickness



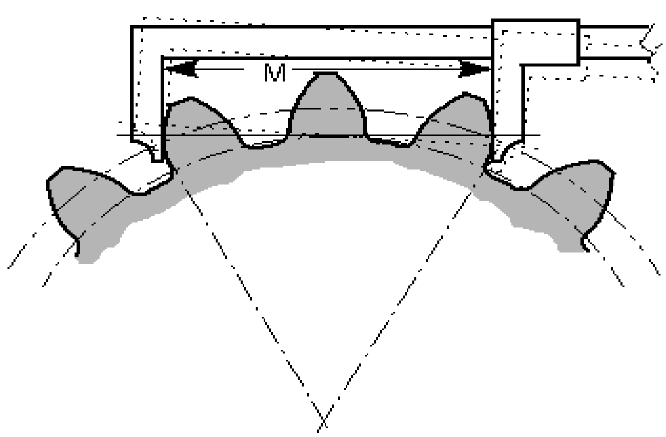
Thickness relationships



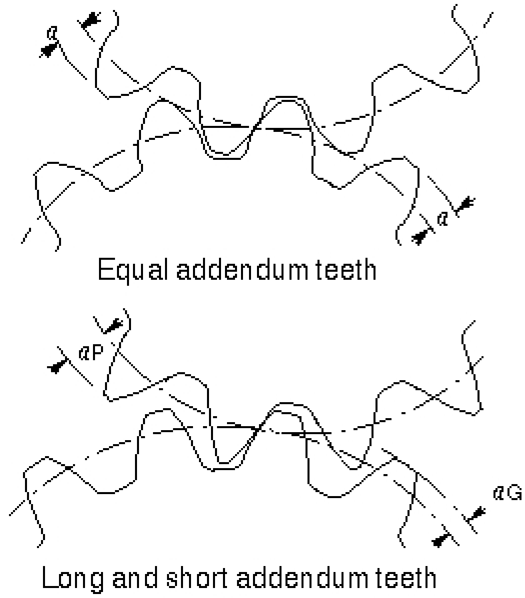
Chordal thickness



Tooth thickness measurement over pins



Span measurement



Long and short addendum teeth

Circular thickness

Length of arc between the two sides of a gear tooth, on the specified datum circle.

Transverse circular thickness

Circular thickness in the transverse plane.

Normal circular thickness

Circular thickness in the normal plane. In a helical gear it may be considered as the length of arc along a normal helix.

Axial thickness

In helical gears and worms, tooth thickness in an axial cross section at the standard pitch diameter.

Base circular thickness

In involute teeth, length of arc on the base circle between the two involute curves forming the profile of a tooth.

Normal chordal thickness

Length of the chord that subtends a circular thickness arc in the plane normal to the pitch helix. Any convenient measuring diameter may be selected, not necessarily the standard pitch diameter.

Chordal addendum (chordal height)

Height from the top of the tooth to the chord subtending the circular thickness arc. Any convenient measuring diameter may be selected, not necessarily the standard pitch diameter.

Profile shift

Displacement of the basic rack datum line from the reference cylinder, made non-dimensional by dividing by the normal module. It is used to specify the tooth thickness, often for zero backlash.

Rack shift

Displacement of the tool datum line from the reference cylinder, made non-dimensional by dividing by the normal module. It is used to specify the tooth thickness.

Measurement over pins

Measurement of the distance taken over a pin positioned in a tooth space and a reference surface. The reference surface may be the reference axis of the gear, a datum surface or either one or two pins positioned in the tooth space or spaces opposite the first. This measurement is used to determine tooth thickness.

Span measurement

Measurement of the distance across several teeth in a normal plane. As long as the measuring device has parallel measuring surfaces that contact on an unmodified portion of the involute, the measurement will be along a line tangent to the base cylinder. It is used to determine tooth thickness.

Modified addendum teeth

Teeth of engaging gears, one or both of which have non-standard addendum.

Full-depth teeth

Teeth in which the working depth equals 2.000 divided by the normal diametral pitch.

Stub teeth

Teeth in which the working depth is less than 2.000 divided by the normal diametral pitch.

Equal addendum teeth

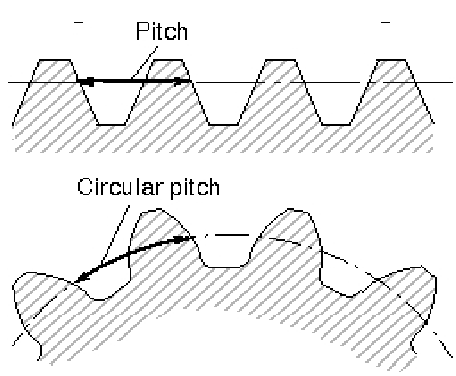
Teeth in which two engaging gears have equal addendums.

Long and short-addendum teeth

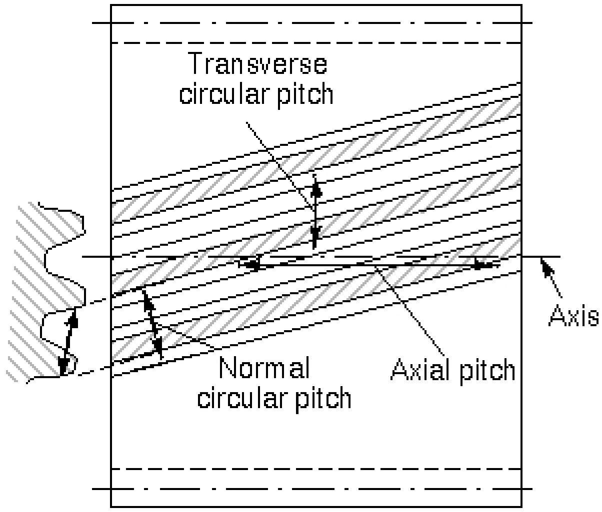
Teeth in which the addendums of two engaging gears are unequal.

Pitch nomenclature

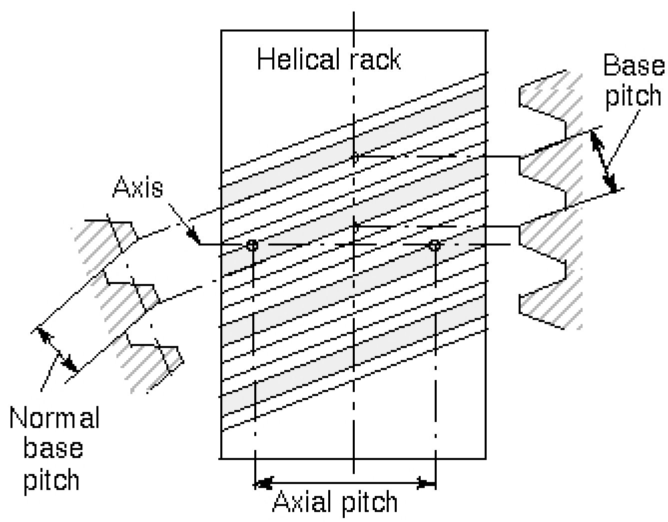
Pitch is the distance between a point on one tooth and the corresponding point on an adjacent tooth. It is a dimension measured along a line or curve in the transverse, normal, or axial directions. The use of the single word *pitch* without qualification may be ambiguous, and for this reason it is preferable to use specific designations such as transverse circular pitch, normal base pitch, axial pitch.



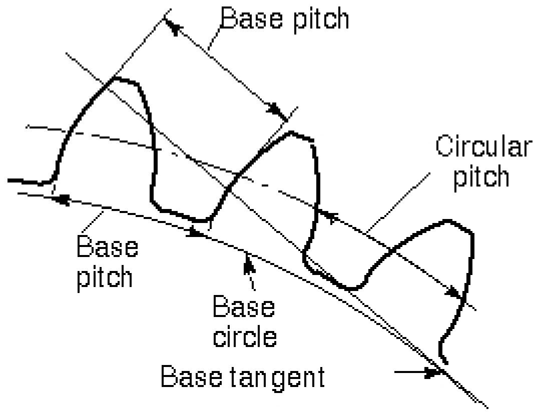
Pitch



Tooth pitch



Base pitch relationships



Principal pitches

Circular pitch, p

Arc distance along a specified pitch circle or pitch line between corresponding profiles of adjacent teeth.

Transverse circular pitch, p_t

Circular pitch in the transverse plane.

Normal circular pitch, p_n, p_e

Circular pitch in the normal plane, and also the length of the arc along the normal pitch helix between helical teeth or threads.

Axial pitch, p_x

Linear pitch in an axial plane and in a pitch surface. In helical gears and worms, axial pitch has the same value at all diameters. In gearing of other types, axial pitch may be confined to the pitch surface and may be a circular measurement. The term axial pitch is preferred to the term linear pitch. The axial pitch of a helical worm and the circular pitch of its worm gear are the same.

Normal base pitch, p_N, p_{bn}

An involute helical gear is the base pitch in the normal plane. It is the normal distance between parallel helical involute surfaces on the plane of action in the normal plane, or is the length of arc on the normal base helix. It is a constant distance in any helical involute gear.

Transverse base pitch, p_b, p_{bt}

In an involute gear, the pitch on the base circle or along the line of action. Corresponding sides of involute gear teeth are parallel curves, and the base pitch is the constant and fundamental distance between them along a common normal in a transverse plane.

Diametral pitch (transverse), P_d

Ratio of the number of teeth to the standard pitch diameter in inches.

$$P_{\mathrm{d}} = \frac{N}{d} = \frac{25.4}{m} = \frac{\pi}{p}$$

Normal diametral pitch, P_{nd}

Value of diametral pitch in a normal plane of a helical gear or worm.

$$P_{\mathrm{nd}} = \frac{P_{\mathrm{d}}}{\cos\psi}$$

Angular pitch, θ_N, τ

Angle subtended by the circular pitch, usually expressed in radians.

$\tau = \frac{360}{z}$ degrees or $\frac{2\pi}{z}$ radians

Backlash

Backlash is the error in motion that occurs when gears change direction. It exists because there is always some gap between the trailing face of the driving tooth and the leading face of the tooth behind it on the driven gear, and that gap must be closed before force can be transferred in the new direction. The term "backlash" can also be used to refer to the size of the gap, not just the phenomenon it causes; thus, one could speak of a pair of gears as having, for example, "0.1 mm of backlash." A pair of gears could be designed to have zero backlash, but this would presuppose perfection in manufacturing, uniform thermal expansion characteristics throughout the system, and no lubricant. Therefore, gear pairs are designed to have some backlash. It is usually provided by reducing the tooth thickness of each gear by half the desired gap distance. In the case of a large gear and a small pinion, however, the backlash is usually taken entirely off the gear and the pinion is given full sized teeth. Backlash can also be provided by moving the gears farther apart.

For situations, such as instrumentation and control, where precision is important, backlash can be minimised through one of several techniques. For instance, the gear can be split along a plane perpendicular to the axis, one half fixed to the shaft in the usual manner, the other half placed alongside it, free to rotate about the shaft, but with springs between the two halves providing relative torque between them, so that one achieves, in effect, a single gear with expanding teeth. Another method involves tapering the teeth in the axial direction and providing for the gear to be slid in the axial direction to take up slack.

Shifting of gears

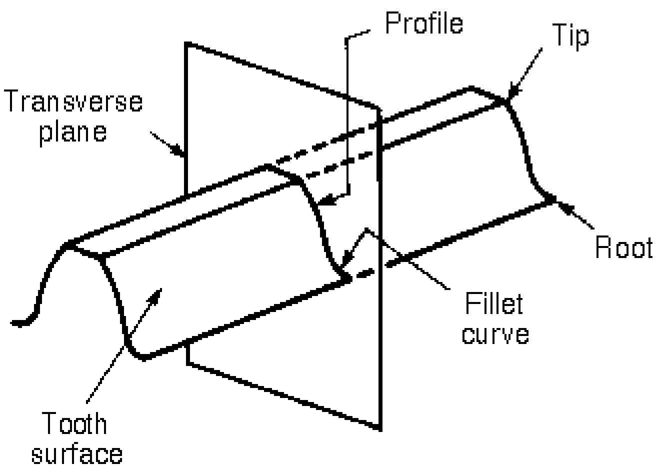
In some machines (e.g., automobiles) it is necessary to alter the gear ratio to suit the task. There are several methods of accomplishing this. For example:

- Manual transmission
- Automatic transmission
- Derailleur gears which are actually sprockets in combination with a roller chain
- Hub gears (also called epicyclic gearing or sun-and-planet gears)

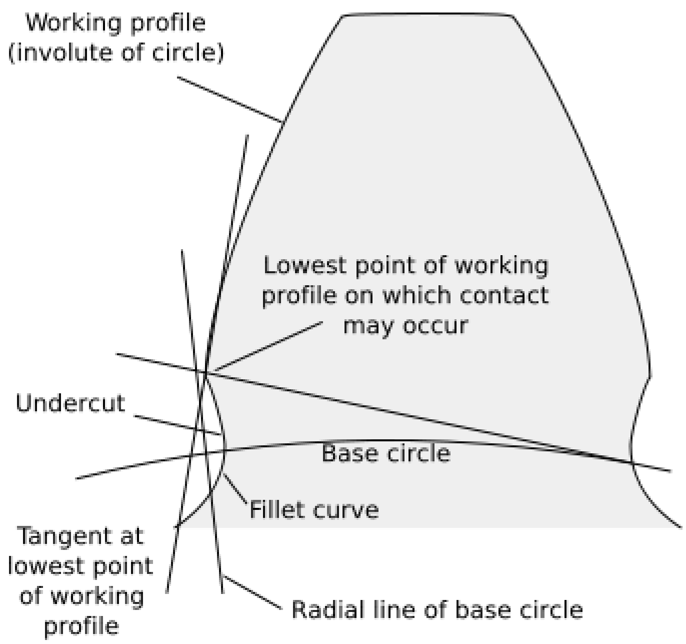
There are several outcomes of gear shifting in motor vehicles. In the case of vehicle noise emissions, there are higher sound levels emitted when the vehicle is engaged in lower gears. The design life of the lower ratio gears is shorter so cheaper gears may be used (i.e.

spur for 1st and reverse) which tends to generate more noise due to smaller overlap ratio and a lower mesh stiffness etc than the helical gears used for the high ratios. This fact has been utilized in analyzing vehicle generated sound since the late 1960s, and has been incorporated into the simulation of urban roadway noise and corresponding design of urban noise barriers along roadways.

Tooth profile



Profile of a spur gear



Undercut

A profile is one side of a tooth in a cross section between the outside circle and the root circle. Usually a profile is the curve of intersection of a tooth surface and a plane or surface normal to the pitch surface, such as the transverse, normal, or axial plane.

The fillet curve (root fillet) is the concave portion of the tooth profile where it joins the bottom of the tooth space.[2]

As mentioned in the beginning, the attainment of a non fluctuating velocity ratio is dependent on the profile of the teeth. Friction and wear between two gears is also dependent on the tooth profile. There are a great many tooth profiles that will give a constant velocity ratio, and in many cases, given an arbitrary tooth shape, it is possible to develop a tooth profile for the mating gear that will give a constant velocity ratio. However, two constant velocity tooth profiles have been by far the most commonly used in modern times. They are the cycloid and the involute. The cycloid was more common until the late 1800s; since then the involute has largely superseded it, particularly in drive train applications. The cycloid is in some ways the more interesting and flexible shape; however the involute has two advantages: it is easier to manufacture, and it permits the center to center spacing of the gears to vary over some range without ruining the constancy of the velocity ratio. Cycloidal gears only work properly if the center spacing is exactly right. Cycloidal gears are still used in mechanical clocks.

An undercut is a condition in generated gear teeth when any part of the fillet curve lies inside of a line drawn tangent to the working profile at its point of juncture with the fillet. Undercut may be deliberately introduced to facilitate finishing operations. With undercut the fillet curve intersects the working profile. Without undercut the fillet curve and the working profile have a common tangent.

Gear materials

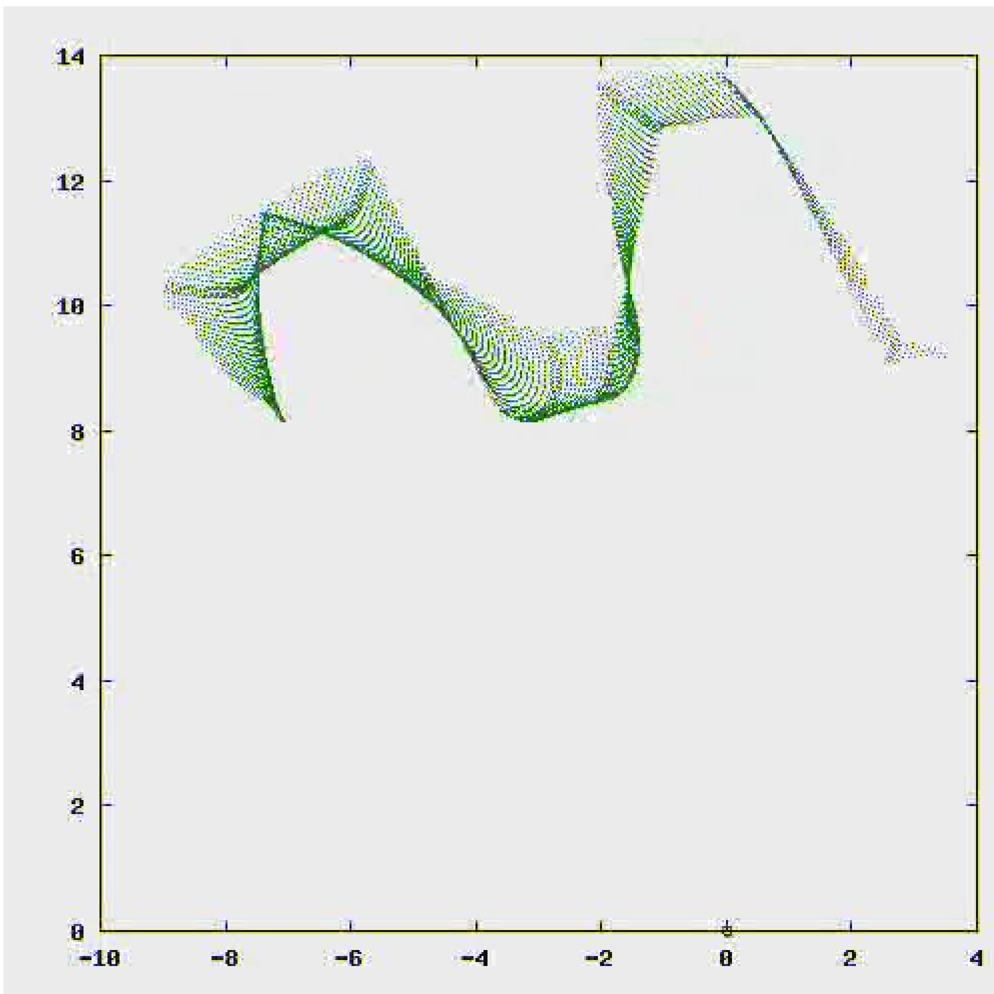
Wooden gears of a historic windmill

Numerous nonferrous alloys, cast irons, powder-metallurgy and even plastics are used in the manufacture of gears. However steels are most commonly used because of their high strength to weight ratio and low cost. Plastic is commonly used where cost or weight is a concern. A properly designed plastic gear can replace steel in many cases because it has many desirable properties, including dirt tolerance, low speed meshing, and the ability to "skip" quite well. Manufacturers have employed plastic gears to make consumer items affordable in items like copy machines, optical storage devices, VCRs, cheap dynamos, consumer audio equipment, servo motors, and printers.

The module system

Countries which have adopted the metric system generally use the module system. As a result, the term module is usually understood to mean the pitch diameter in millimeters divided by the number of teeth. When the module is based upon inch measurements, it is known as the *English module* to avoid confusion with the metric module. Module is a direct dimension, whereas diametral pitch is an inverse dimension (like "threads per inch"). Thus, if the pitch diameter of a gear is 40 mm and the number of teeth 20, the module is 2, which means that there are 2 mm of pitch diameter for each tooth.

Manufacture



Gear Cutting simulation faster, high bitrate version.

Gears are most commonly produced via hobbing, but they are also shaped, broached, cast, and in the case of plastic gears, injection molded. For metal gears the teeth are usually heat treated to make them hard and more wear resistant while leaving the core soft and tough. For large gears that are prone to warp a quench press is used.

Inspection

Gear geometry can be inspected and verified using various methods such as industrial CT scanning, coordinate-measuring machines, white light scanner or laser scanning. Particularly useful for plastic gears, industrial CT scanning can inspect internal geometry and imperfections such as porosity.

Gear model in modern physics

Modern physics adopted the gear model in different ways. In the nineteenth century, James Clerk Maxwell developed a model of electromagnetism in which magnetic field lines were rotating tubes of incompressible fluid. Maxwell used a gear wheel and called it an "idle wheel" to explain the electrical current as a rotation of particles in opposite directions to that of the rotating field lines.

More recently, quantum physics uses "quantum gears" in their model. A group of gears can serve as a model for several different systems, such as an artificially constructed nanomechanical device or a group of ring molecules.

The Three Wave Hypothesis compares the wave–particle duality to a bevel gear.

Chapter 6

Screw

Screws come in a variety of shapes and sizes for different purposes. U.S. quarter coin (diameter 24 mm) shown for scale.

A **screw**, or **bolt**, is a type of fastener characterized by a helical ridge, known as an *external thread* or just *thread*, wrapped around a cylinder. Some screw threads are designed to mate with a complementary thread, known as an *internal thread*, often in the form of a nut or an object that has the internal thread formed into it. Other screw threads are designed to cut a helical groove in a softer material as the screw is inserted. The most common uses of screws are to hold objects together and to position objects.

Often screws have a *head*, which is a specially formed section on one end of the screw that allows it to be turned, or *driven*. Common tools for driving screws include screwdrivers and wrenches. The head is usually larger than the body of the screw, which keeps the screw from being driven deeper than the length of the screw and to provide a *bearing surface*. There are exceptions; for instance, carriage bolts have a domed head that is not designed to be driven; set screws have a head smaller than the outer diameter of the screw; J-bolts have a J-shaped head which is not designed to be driven, but rather is usually sunk into concrete allowing it to be used as an anchor bolt. The cylindrical portion of the screw from the underside of the head to the tip is known as the *shank*; it may be fully threaded or partially threaded.

The majority of screws are tightened by clockwise rotation, which is termed a *right-hand thread*. Screws with left-hand threads are used in exceptional cases. For example, when the screw will be subject to anticlockwise forces (which would work to undo a right-hand thread), a left-hand-threaded screw would be an appropriate choice. The left side pedal of a bicycle has a left-hand thread.

Differentiation between bolt and screw

A carriage bolt with square nut

A structural bolt with a nut and washer

There is no universally accepted distinction between a screw and a bolt. The *Machinery's Handbook* describes the distinction as follows:

A bolt is an externally threaded fastener designed for insertion through holes in assembled parts, and is normally intended to be tightened or released by torquing a nut. A screw is an externally threaded fastener capable of being inserted into holes in assembled parts, of mating with a preformed internal thread or forming its own thread, and of being tightened or released by torquing the head. An externally threaded fastener which is prevented from being turned during assembly and which can be tightened or released only by torquing a nut is a bolt. (Example: round head bolts, track bolts, plow bolts.) An externally threaded fastener that has thread form which prohibits assembly with a nut having a straight thread of multiple pitch length is a screw. (Example: wood screws, tapping screws.)

This distinction is consistent with ASME B18.2.1 and some dictionary definitions for *screw* and *bolt*.

The issue of what is a screw and what is a bolt is not completely resolved with *Machinery's Handbook* distinction, however, because of confounding terms, the ambiguous nature of some parts of the distinction, and usage variations. Some of these issues are discussed below:

Machine screws

ASME standards specify a variety of "Machine Screws" in diameters ranging up to 0.75 in (19.05 mm). These fasteners are often used with nuts as well as often driven into tapped holes. They might be considered a screw or a bolt based on the *Machinery's Handbook* distinction. In practice, they tend to be mostly available in smaller sizes and the smaller sizes are referred to as screws or less ambiguously as machine screws, although some kinds of machine screws can be referred to as stove bolts.

Hex cap screws

ASME standard B18.2.1 -1996 specifies Hex Cap Screws that range in size from 0.25–3 in (6.35–76.20 mm) in diameter. These fasteners are very similar to hex bolts. They differ mostly in that they are manufactured to tighter tolerances than the corresponding bolts. The *Machinery's Handbook* refers parenthetically to these fasteners as "Finished Hex Bolts". Reasonably, these fasteners might be referred to as bolts but based on the US government document, Distinguishing Bolts from Screws, the US government might classify them as screws because of the tighter tolerance. In 1991 responding to an influx of counterfeit fasteners Congress passed PL 101-592 "Fastener Quality Act" This resulted in the rewriting of specifications by the ASME B18 committee. B18.2.1 was re-written and as a result they eliminated the "Finished Hex Bolts" and renamed them the "Hex Cap Screw".

Lug bolts & head bolts

These terms refer to fasteners that are designed to be threaded into a tapped hole that is in part of the assembly and so based on the *Machinery's Handbook* distinction they would be screws. Here common terms are at variance with *Machinery's Handbook* distinction.

Lag bolt

Lag bolts : These are clearly screws based on the *Machinery's Handbook* distinction. The term has been replaced by "Lag Screw" in the *Machinery's Handbook*

Government standards

The US government made an effort to formalize the difference between a bolt and a screw because different tariffs apply to each. The document seems to have no significant effect on common usage and does not eliminate the ambiguous nature of the distinction between screws and bolts for some threaded fasteners.

Historical issue

Old USS and SAE standards defined cap screws as fasteners with shanks that were threaded to the head and bolts as fasteners with shanks that were partially unthreaded. This is now an obsolete distinction.

Controlled vocabulary versus natural language

The distinctions delineated above are enforced in the controlled vocabulary of standards organizations. Nevertheless, there are sometimes differences between the controlled vocabulary and the natural-language usage of the words among machinists, auto mechanics, and other workers. These differences reflect linguistic evolution shaped by the changing of technology over centuries. The words *bolt* and *screw* have both existed since before today's modern mix of fastener types existed, and the natural usage of those words has evolved retronymously in response to the technological change. (That is, the use of words as names for objects changes as the objects themselves change.) Nonthreaded fasteners predominated in fastening technology until the advent of practical, inexpensive screw-cutting in the early 19th century. The basic meaning of the word *screw* has long involved the idea of a helical screw thread, but the Archimedes screw and the screw gimlet (like a corkscrew) preceded the fastener.

> The word *bolt* is also a very old word, and it was used for centuries to refer to metal rods that passed through the substrate to be fastened on the other side, often via nonthreaded means (clinching, forge welding, pinning, wedging, etc.). The connection of this sense to the sense of a door bolt or the crossbow bolt is apparent. In the 19th century, bolts fastened via screw threads were often called *screw bolts* in contradistinction to *clench bolts*.
>
> In common usage, the distinction is often that screws are smaller than bolts, and that screws are generally tapered and bolts are not. This distinction is not rigorous.

Other distinctions

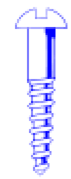
> Bolts have been defined as headed fasteners having external threads that meet an exacting, uniform bolt thread specification (such as M, MJ, UN, UNR, and UNJ) such that they can accept a nontapered nut. Screws are then defined as headed, externally threaded fasteners that do not meet the above definition of bolts. These definitions of screw and bolt eliminate the ambiguity of the *Machinery's handbook* distinction. And it is for that reason, perhaps, that some people favor them. However, they are neither compliant with common usage of the two words nor are they compliant with formal specifications.

Types of screws and bolts

Threaded fasteners either have a tapered shank or a non-tapered shank. Fasteners with tapered shanks are designed to either be driven into a substrate directly or into a pilot hole in a substrate. Mating threads are formed in the substrate as these fasteners are driven in. Fasteners with a non-tapered shank are designed to mate with a nut or to be driven into a tapped hole.

Fasteners with a tapered shank (self-threading screws)

A Phillips wood screw being driven into a board with a driver.



Wood screw

A **wood screw** is defined as a male screw made of a metal with a slotted head and sharp point. A wood screw is commonly furnished with a flat, round or oval-head. A wood screw generally has an unthreaded shank below the head. It is designed to attach two pieces of wood together.

Twinfast screw

A Twinfast screw : is a type of wood screw with two threads (i.e. a lead of 2), so that it can be driven twice as fast.

Coach screw (UK) or lag screw/bolt (US)

Coach screw or lag screw/bolt is similar to a wood screw except that it is generally much larger running to lengths up to 15 in (381 mm) with diameters from 0.25–0.5 in (6.35–12.70 mm) in commonly available (hardware store) sizes (not counting larger mining and civil engineering lags and lag bolts) and it generally has a hexagonal drive head. Lag bolts are designed for securely fastening heavy timbers (post and beams, timber railway trestles and bridges) to one another, or to fasten wood to masonry or concrete.

> Lag bolts are usually used with an expanding insert called a lag in masonry or concrete walls, the lag manufactured with a hard metal jacket that bites into the sides of the drilled hole, and the inner metal in the lag being a softer alloy of lead, or zinc alloyed with soft iron. The coarse thread of a lag bolt and lag mesh and deform slightly making a secure near water tight anti-corroding mechanically strong fastening.

Sheet metal screw

A Sheet metal screw (self-tapping screw, thread cutting screws) has sharp threads that cut into a material such as sheet metal, plastic or wood. They are sometimes notched at the tip to aid in chip removal during thread cutting. The shank is usually threaded up to the head. Sheet metal screws make excellent fasteners for attaching metal hardware to wood because the fully threaded shank provides good retention in wood.

Concrete screw

A concrete screw is a stainless or carbon steel screw for fastening wood, metal, or other materials into concrete or masonry. Concrete screws are commonly blue in color, with or without corrosion coating. They may either have a Phillips flat head or a slotted hex washer head. Heads sizes range from 0.1875 to 0.375 in (4.763 to 9.525 mm) and lengths from 1.25 to 5 in (32 to 127 mm).

> Typically an installer uses a hammer drill to make a pilot hole for each concrete screw.
> In the United States, concrete screws are commonly called *Tapcons* which refers to the brand name created from the definition of "an anchor that taps its own threads into concrete." Other commercial names for the fastener are *masonry screw*, *confast screw*, *blue screw*, *self-tapping screw*, and *Titen*.

Drywall screw

A drywall screw is a specialized screw with a bugle head that is designed to attach drywall to wood or metal studs, however it is a versatile construction fastener with many uses. The diameter of drywall screw threads is larger than the shaft diameter.

Particle board screw (chipboard screw)

A particle board screw is similar to a drywall screw except that it has a thinner shaft and provides better resistance to pull-out in particle board, while offset against a lower shear strength. The threads on particle board screws are asymmetrical.

Deck screw

A deck screw is similar to drywall screw except that it has improved corrosion resistance and is generally supplied in a larger gauge. Most deck screws have a type-17 (auger type) thread cutting tip for installation into decking materials.

Double ended screw (dowel screw)

A double ended screw (dowel screw) is similar to a wood screw but with two pointed ends and no head, used for making hidden joints between two pieces of wood.

Screw eye (eye screw)

A screw eye (eye screw) is a screw with a looped head. Larger ones are sometimes call lag eye screws. Designed to be used as attachment point, particularly for something that is hung from it.

Mirror screws

Mirror screws are flat head wood screws with a tapped hole in the head, which is designed to receive a separate screw-in chrome-plated cover. They are usually used to mount mirrors.

Thread rolling screws

Thread rolling screws have a lobed (usually triangular) cross-section. They form threads in a pre-drilled hole in the mating workpiece by pushing the material outward during installation.

Self-drilling screw (Teks screw)

A self-drilling screw is similar to a sheet metal screw, but it has a drill-shaped point to cut through the substrate to eliminate the need for drilling a pilot hole. Designed for use in soft steel or other metals. The points are numbered from 1 through 5, the larger the number, the thicker metal it can go through without a pilot hole. A 5 point can drill a 0.5 in (12.7 mm) of steel, for example.

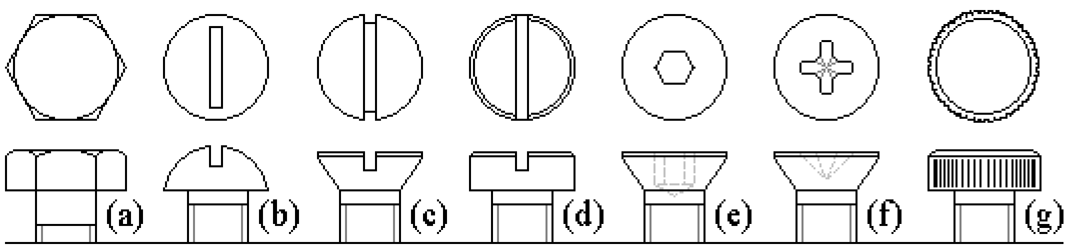
Fasteners with a non-tapered shank

Breakaway bolt

A Breakaway bolt is a bolt with a hollow threaded shank, which is designed to break away upon impact. Typically used to fasten fire hydrants, so they will *break away* when hit by a car. Also used in aircraft to reduce weight.

Cap screw

The term *cap screw* refers to many different things at different times and places. Currently, it most narrowly refers to a style of head. More broadly, and more commonly, it refers to the group of screws: shoulder screws, hex heads, counter-sunk heads, button heads, and fillister heads. In the US, cap screws are defined by ASME B18.6.2 and ASME B18.3. In the past, the term *cap screw*, in general, referred to screws that were supposed to be used in applications where a nut was not used, however the characteristics that differentiated it from a bolt vary over time. In 1910, Anthony defined it as screw with a hex head that was thicker than a bolt head, but the distance across the flats was less than a bolt's. In 1913, Woolley and Meredith defined them like Anthony, but gave the following dimensions: hex head cap screws up to and including $^7/_{16}$ inches (11.1125 mm) have a head that is $^3/_{16}$ inches (4.7625 mm) larger than the shank diameter; screws greater than $^1/_2$ inches (12.7 mm) in diameter have a head that is $^1/_4$ inches (6.35 mm) larger than the shank. Square head cap screws up to and including $^3/_4$ inches (19.05 mm) have a head $^1/_8$ inches (3.175 mm) larger than the shank; screws larger than $^3/_4$ inches (19.05 mm) have a head $^1/_4$ inches (6.35 mm) larger than the shank. In 1919, Dyke defined them as screws that are threaded all the way to the head.



Cap screws (wide definition)

Hex cap screw

A hex cap screw is a cap screw with a hexagonal head, designed to be driven by a wrench (spanner). An ASME B18.2.1 compliant cap screw has somewhat tighter tolerances than a hex bolt for the head height and the shank length. The nature of the tolerance difference allows an ASME B18.2.1 hex cap screw to always fit where a hex bolt is installed but a hex bolt could be slightly too large to be used where a hex cap screw is designed in.

Hex bolt

At times the term *hex bolt* is used interchangeably with *hex cap screw*. An ASME B18.2.1 compliant hex bolt is built to different tolerances than a hex cap screw.

Socket cap screw

A socket cap screw, also known as a *socket head cap screw*, *socket screw* or *Allen bolt*, this is a type of cap screw with a hexagonal recessed drive. The most common types in use have a cylindrical head whose diameter is nominally 1.5 times (1960 series design) that of the screw shank (major) diameter. Counterbored holes in parts allow the screw head to be flush with the surface or recessed. Other head designs include *button* head and *flat* head, the latter designed to be seated into countersunk holes. A hex key (sometimes referred to as an *Allen wrench* or *Allen key*) or *hex driver* is required to tighten or loosen a socket screw. Socket screws are commonly used in assemblies that do not provide sufficient clearance for a conventional wrench or socket.

Machine screw

A machine screw is generally a smaller fastener (less than ¼ inches (6.35 mm) in diameter) threaded the entire length of its shank that usually has a recessed drive type (slotted, Phillips, etc.). Machine screws are also made with socket heads, in which case they may be referred to as socket head machine screws.

Self-tapping machine screw

A self-tapping machine screw is similar to a machine screw except the lower part of the shank is designed to cut threads as the screw is driven into an untapped hole. The advantage of this screw type over a self-tapping screw is that, if the screw is reinstalled, new threads are not cut as the screw is driven.

Set screw

A set screw (grub screw) is generally a headless screw but can be any screw used to fix a rotating part to a shaft. The set screw is driven through a threaded hole in the rotating part until it is tight against the shaft. The most often used type is the socket set screw, which is tightened or loosened with a hex key.

Set bolt

A set bolt (tap bolt) is a bolt that is threaded all the way to the head. An ASME B18.2.1 compliant set/tap bolt has the same tolerances as an ASME B18.2.1 compliant hex cap screw.

Stud

Studs (threaded rods) are head-less screws. They may be threaded at both ends and unthreaded in the middle or completely threaded; the latter is usually referred to as a threaded rod, especially when it has a large aspect ratio (that is, quite long compared to diameter). Completely threaded round stock is available in bar stock form and is then usually referred to as "all-thread".

Eye bolt

An eye bolt is a bolt with a looped head.

Toggle bolt

A toggle bolt is a bolt with a special nut known as a wing. It is designed to be used where there is no access to side of the material where the nut is located. Usually the wing is spring loaded and expands after being inserted into the hole.

Carriage bolt

A carriage bolt (coach bolt) has a domed or countersunk head, and the shank is topped by a short square section under the head. The square section grips into the part being fixed (typically wood), preventing the bolt from turning when the nut is tightened. A rib neck carriage bolt has several longitudinal ribs instead of the square section, to grip into a metal part being fixed.

Elevator bolt

An elevator bolt is a bolt similar to a carriage bolt, except the head is thin and flat. There are many variations. Some do not have a square base, but rather triangular sections of the flat head are folded down to form "fangs" that cut into wood and hold it secure.

Stove bolt

A stove bolt is a type of machine screw that has a round or flat head and is threaded to the head. They are usually made of low grade steel, have a slot or Phillips drive, and are used to join sheet metal parts using a hex or square nut.

Shoulder screw

A shoulder screw (stripper bolt) differs from machine screws in that the shank is ground to a precise diameter, known as the *shoulder*, and the threaded portion is smaller in diameter than the shoulder. Shoulder bolt specifications call out the shoulder diameter, shoulder length, and threaded diameter; the threaded length is fixed, based on the threaded diameter, and usually quite short. It is usually used for revolving joints in mechanisms and linkages; when used as a guide for the stripper plate in a die set its called a stripper bolt.

Thumb screw

A thumb screw is a threaded fastener designed to be twisted into a tapped hole by hand without the use of tools.

Security screw

A security screw is similar to a standard screw except that once inserted it cannot be easily removed.

Tension control bolt

A tension control bolt (TC bolt) is a heavy duty bolt used in steel frame construction. The head is usually domed and is not designed to be driven. The end of the shank has a spline on it which is engaged by a special power wrench which prevents the bolt from turning while the nut is tightened. When the appropriate torque is reached the spline shears off.

Plow bolt

A plow bolt is bolt similar to a carriage bolt, except the head is flat or concave, and the underside of the head is a cone designed to fit in a countersunk recess. There are many variations, with some not using a square base, but rather a key, a locking slot, or other means. The recess in the mating part must be designed to accept the particular plow bolt.

Spring bolt

A spring bolt is a bolt which must be pulled back and which is brought back into place by the spring when the pressure is released. Spring bolts are used in Rubik's Snakes, for example, the wedges of which are pulled apart slightly when twisted and are pulled back together by the spring bolt when shifted back into position.

Other threaded fasteners

Superbolt, or multi-jackbolt tensioner

A superbolt, or multi-jackbolt tensioner is an alternative type of fastener that retrofits or replaces existing nuts, bolts, or studs. Tension in the bolt is developed by torquing individual jackbolts, which are threaded through the body of the nut and push against a hardened washer. Because of this, the amount of torque required to achieve a given preload is reduced. Installation and removal of any size tensioner is achieved with hand tools, which can be advantageous when dealing with large diameter bolting applications.

Hanger screw

A hanger screw is a headless fastener that has machine screw threads on one end and self-tapping threads on the other designed to be driven into wood or another soft substrate. Often used for mounting legs on tables.

Materials

Screws and bolts are made from a wide range of materials, with steel being perhaps the most common, in many varieties. Where great resistance to weather or corrosion is required, stainless steel, titanium, brass (steel screws can discolor oak and other woods), bronze, monel or silicon bronze may be used, or a coating such as brass, zinc or chromium applied. Electrolytic action from dissimilar metals can be prevented with aluminium screws for double-glazing tracks, for example. Some types of plastic, such as nylon or polytetrafluoroethylene (PTFE), can be threaded and used for fastening requiring moderate strength and great resistance to corrosion or for the purpose of electrical insulation.

Bolted joints

Rusty hexagonal bolt heads

The American Institute of Steel Construction (AISC) 13th Edition Steel Design Manual section 16.1 chapter J-3 specifies the requirements for bolted structural connections. Structural bolts replaced rivets due to decreasing cost and increasing strength of structural bolts in the 20th century. Connections are formed with two types of joints: slip-critical connections and bearing connections. In slip-critical connections, movement of the connected parts is a serviceability condition and bolts are tightened to a minimum required pretension. Slip is prevented through friction of the "faying" surface, that is the plane of shear for the bolt and where two members make contact. Because friction is proportional to the normal force, connections must be sized with bolts numerous and large enough to provide the required load capacity. However, this greatly decreases the shear capacity of each bolt in the connection. The second type and more common connection is a bearing connection. In this type of connection the bolts carry the load through shear and are only tightened to a "snug-fit." These connections require fewer bolts than slip-critical connections and therefore are a less expensive alternative. Slip-critical connections are more common on flange plates for beam and column splices and moment critical connections. Bearing type connections are used in light weight structures and in member connections where slip is not important and prevention of structural failure is the design constraint. Common bearing type connections include: shear tabs, beam supports, gusset plates in trusses.

Mechanical classifications

The numbers stamped on the head of the bolt are referred to the grade of the bolt used in certain application with the strength of a bolt. High-strength steel bolts usually have a hexagonal head with an ISO strength rating (called *property class*) stamped on the head. And the absence of marking/number indicates a lower grade bolt with low strength. The property classes most often used are 5.8, 8.8, and 10.9. The number before the point is the tensile ultimate strength in MPa divided by 100. The number after the point is 10 times the ratio of tensile yield strength to tensile ultimate strength. For example, a property class 5.8 bolt has a nominal (minimum) tensile ultimate strength of 500 MPa, and a tensile yield strength of 0.8 times tensile ultimate strength or 0.8(500) = 400 MPa.

Tensile ultimate strength is the stress at which the bolt fails. Tensile yield strength is the stress at which the bolt will receive a permanent set (an elongation from which it will not recover when the force is removed) of 0.2 % offset strain. When elongating a fastener prior to reaching the yield point, the fastener is said to be operating in the elastic region; whereas elongation beyond the yield point is referred to as operating in the plastic region, since the fastener has suffered permanent plastic deformation.

Mild steel bolts have property class 4.6. High-strength steel bolts have property class 8.8 or above.

The same type of screw or bolt can be made in many different grades of material. For critical high-tensile-strength applications, low-grade bolts may fail, resulting in damage or injury. On SAE-standard bolts, a distinctive pattern of marking is impressed on the heads to allow inspection and validation of the strength of the bolt. However, low-cost counterfeit fasteners may be found with actual strength far less than indicated by the markings. Such inferior fasteners are a danger to life and property when used in aircraft, automobiles, heavy trucks, and similar critical applications.

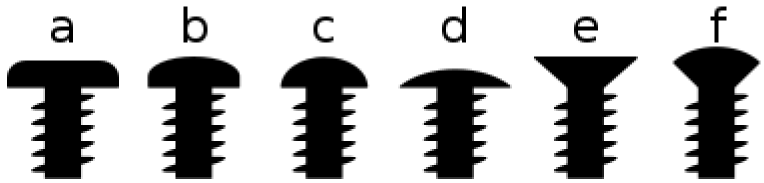
Inch

SAE J429 defines the bolt grades for inch-system sized bolts and screws. It defines them by *grade*, which ranges from 0 to 8, with 8 being the strongest. Higher grades do not exist within the specification. SAE grades 5 and 8 are the most common.

Metric

The international standard for metric screws is defined by ISO 898, specifically ISO 898-1. SAE J1199 and ASTM F568M are two North American metric standards that closely mimic the ISO standard. In case of inch sizes the grade is dictated by the number of radial shapes plus a value of two. Inch-system bolts use integer values to indicate grades but metric bolts use numbers with one decimal. The two North American standards use the same property class markings as defined by ISO 898. The ASTM standard only includes the following property classes from the ISO standard: 4.6, 4.8, 5.8, 8.8, 9.8, 10.9, and 12.9; it also includes two extra property classes: 8.8.3 and 10.9.3. ASTM property classes are to be stamped on the top of screws and it is preferred that the marking is raised.

Screw head shapes



(a) pan, (b) button, (c) round, (d) truss, (e) flat (countersunk), (f) oval

Combination flanged-hex/Phillips-head screw used in computers

Pan head

A low disc with chamfered outer edge

Button or dome head

Cylindrical with a rounded top

Round head

A dome-shaped head used for decoration.

Truss head

Lower-profile dome designed to prevent tampering

Countersunk or flat head

Conical, with flat outer face and tapering inner face allowing it to sink into the material. The *angle* of the screw is measured as the full angle of the cone.

Oval or raised head

A decorative screw head with a countersunk bottom and rounded top.

Bugle head

Similar to countersunk, but there is a smooth progression from the shank to the angle of the head, similar to the bell of a bugle

Cheese head

Disc with cylindrical outer edge, height approximately half the head diameter

Fillister head

Cylindrical, but with a slightly convex top surface. Height to diameter ratio is larger than cheese head.

Flanged head

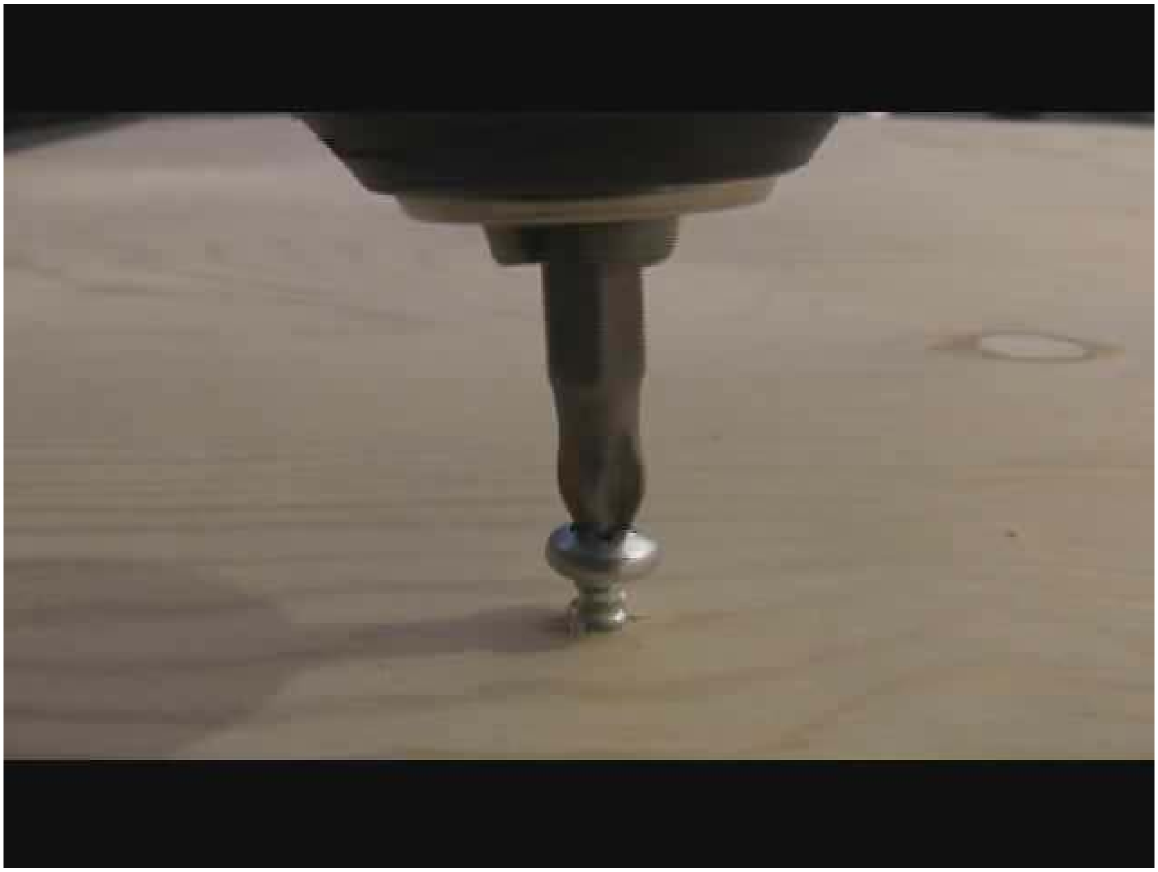
A flanged head can be any of the above head styles with the addition of an integrated flange at the base of the head. This eliminates the need for a flat washer.

Some varieties of screw are manufactured with a break-away head, which snaps off when adequate torque is applied. This prevents tampering and also provides an easily inspectable joint to guarantee proper assembly. An example of this is the shear bolts used on vehicle steering columns, to secure the ignition switch.

Types of screw drives

Modern screws employ a wide variety of drive designs, each requiring a different kind of tool to drive in or extract them. The most common screw drives are the slotted and Phillips; hex, Robertson, and torx are also common in some applications. Some types of drive are intended for automatic assembly in mass-production of such items as automobiles. More exotic screw drive types may be used in situations where tampering is undesirable, such as in electronic appliances that should not be serviced by the home repair person.

Tools



An electric driver screws a self-tapping phillips head screw into wood

The hand tool used to drive in most screws is called a *screwdriver*. A power tool that does the same job is a *power screwdriver*; power drills may also be used with screw-driving attachments. Where the holding power of the screwed joint is critical, torque-measuring and *torque-limiting screwdrivers* are used to ensure sufficient but not excessive force is developed by the screw. The hand tool for driving hex head threaded fasteners is a *spanner* (UK usage) or *wrench* (US usage).

Thread standards

There are many systems for specifying the dimensions of screws, but in much of the world the ISO metric screw thread preferred series has displaced the many older systems. Other relatively common systems include the British Standard Whitworth, BA system (British Association), and the Unified Thread Standard.

ISO metric screw thread

The basic principles of the ISO metric screw thread are defined in international standard ISO 68-1 and preferred combinations of diameter and pitch are listed in ISO 261. The smaller subset of diameter and pitch combinations commonly used in screws, nuts and bolts is given in ISO 262. The most commonly used pitch value for each diameter is the *coarse pitch*. For some diameters, one or two additional *fine pitch* variants are also specified, for special applications such as threads in thin-walled pipes. ISO metric screw threads are designated by the letter **M** followed by the major diameter of the thread in millimeters (e.g., *M8*). If the thread does not use the normal *coarse pitch* (e.g., 1.25 mm in the case of M8), then the pitch in millimeters is also appended with a multiplication sign (e.g. "M8×1" if the screw thread has an outer diameter of 8 mm and advances by 1 mm per 360° rotation).

The nominal diameter of a metric screw is the outer diameter of the thread. The tapped hole (or nut) into which the screw fits, has an internal diameter which is the size of the screw minus the pitch of the thread. Thus, an M6 screw, which has a pitch of 1 mm, is made by threading a 6 mm shank, and the nut or threaded hole is made by tapping threads into a hole of 5 mm diameter (6 mm - 1 mm).

Metric hexagon bolts, screws and nuts are specified, for example, in British Standard BS 4190 (general purpose screws) and BS 3692 (precision screws). The following table lists the relationship given in these standards between the thread size and the maximal width across the hexagonal flats (wrench size):

ISO metric thread	M1.6	M2	M2.5	M3	M4	M5	M6	M8	M10	M12	M16	M20	M24	M30	M36	M42	M48	M56	M64
Wrench size (mm)	3.2	4	5	5.5	7	8	10	13	17	19	24	30	36	46	55	65	75	85	95

In addition, the following non-preferred intermediate sizes are specified:

ISO metric thread	M7	M14	M18	M22	M27	M33	M39	M45	M52	M60	M68
Wrench size (mm)	11	22	27	32	41	50	60	70	80	90	100

Whitworth

The first person to create a standard (in about 1841) was the English engineer Sir Joseph Whitworth. Whitworth screw sizes are still used, both for repairing old machinery and where a coarser thread than the metric fastener thread is required. Whitworth became *British Standard Whitworth*, abbreviated to BSW (BS 84:1956) and the *British Standard Fine* (BSF) thread was introduced in 1908 because the Whitworth thread was too coarse for some applications. The thread angle was 55° and a depth and pitch of thread that varied with the diameter of the thread (i.e., the bigger the bolt, the coarser the thread). The spanner size is determined by the size of the bolt, not the distance between the flats.

The most common use of a Whitworth pitch nowadays is in all UK scaffolding. Additionally, the standard photographic tripod thread, which for small cameras is 1/4" Whitworth (20 tpi) and for medium/large format cameras is 3/8" Whitworth (16 tpi). It is also used for microphone stands and their appropriate clips, again in both sizes, along with "thread adapters" to allow the smaller size to attach to items requiring the larger thread.

British Association screw thread

A later standard established in the United Kingdom was the British Association (BA) screw threads, named after the British Association for Advancement of Science. Screws were described as "2BA", "4BA" etc., the odd numbers being rarely used, except in equipment made prior to the 1970s for telephone exchanges in the UK. This equipment made extensive use of odd-numbered BA screws, in order—it may be suspected—to reduce theft. BA threads are specified by British Standard BS 93:1951 "Specification for British Association (B.A.) screw threads with tolerances for sizes 0 B.A. to 16 B.A."

While not related to ISO metric screws, the sizes were actually defined in metric terms, a 0BA thread having a 6 mm diameter and 1 mm pitch. Other threads in the BA series are related to 0BA in a geometric series with the common factors 0.9 and 1.2. For example, a 4BA thread has pitch $p=0.9^4$ mm (0.65mm) and diameter $6p^{1.2}$ mm (3.62mm). Although 0BA has the same diameter and pitch as ISO M6, the threads have different forms and are not compatible.

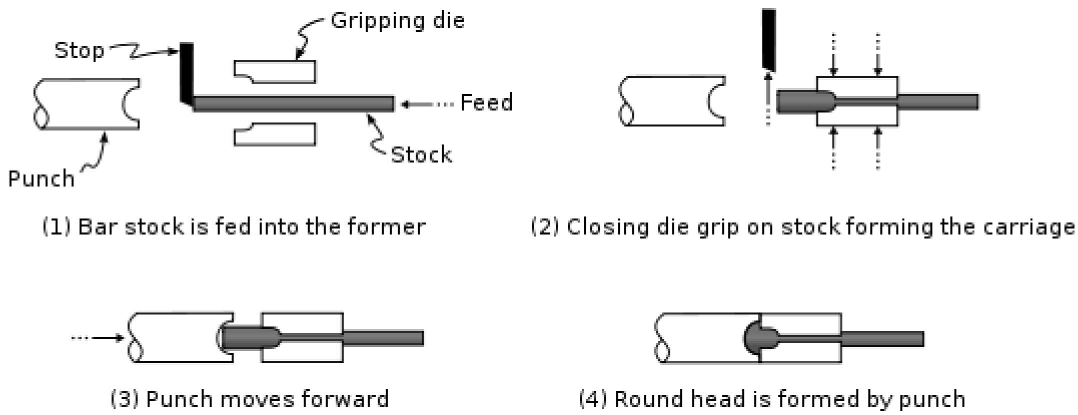
BA threads are still common in some niche applications. Certain types of fine machinery, such as moving-coil meters and clocks, tend to have BA threads wherever they are manufactured. BA sizes were also used extensively in aircraft, especially those manufactured in the United Kingdom. BA sizing is still used in railway signalling, mainly for the termination of electrical equipment and cabling.

BA threads are extensively used in Model Engineering where the smaller hex head sizes make scale fastenings easier to represent. As a result many UK Model Engineering suppliers still carry stocks of BA fasteners up to typically 8BA and 10BA. 5BA is also commonly used as it can be threaded onto 1/8 rod.

Unified Thread Standard

The Unified Thread Standard (UTS) is most commonly used in the United States of America, but is also extensively used in Canada and occasionally in other countries. The size of a UTS screw is described using the following format: **X-Y**, where **X** is the nominal size (the hole or slot size in standard manufacturing practice through which the shaft of the screw can easily be pushed) and **Y** is the threads per inch (TPI). For sizes ¼ inch and larger the size is given as a fraction; for sizes less than this an integer is used, ranging from 0 to 16. For most size screws there are multiple TPI available, with the most common being designated a Unified Coarse Thread (UNC or UN) and Unified Fine Thread (UNF or UF).

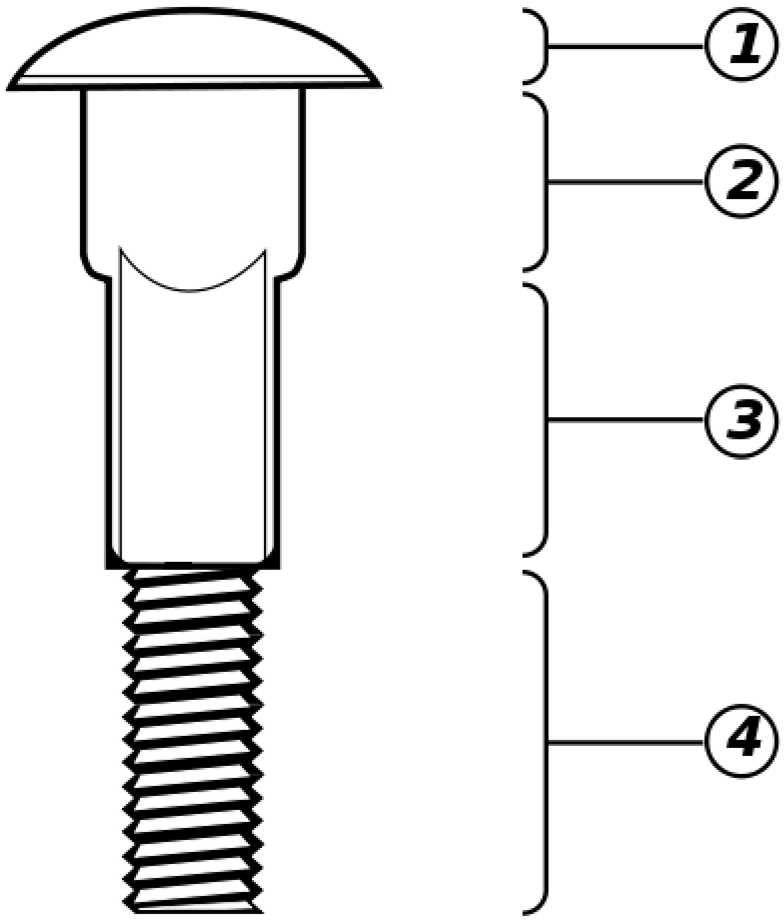
Manufacture



A schematic of the heading process

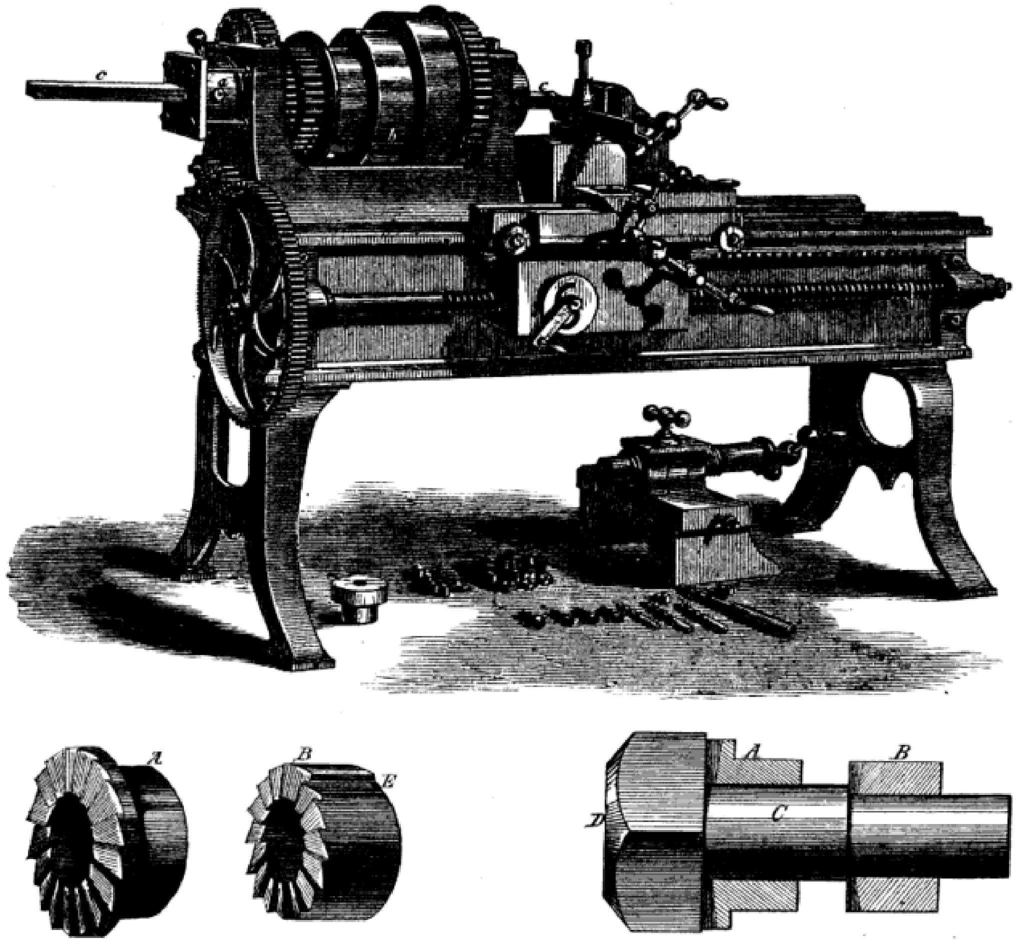
There are three steps in manufacturing a screw: *heading*, *thread rolling*, and *coating*. Screws are normally made from wire, which is supplied in large coils, or round bar stock for larger screws. The wire or rod is then cut to the proper length for the type of screw being made; this workpiece is known as a *blank*. It is then cold headed, which is a cold working process. Heading produces the *head* of the screw. The shape of the die in the machine dictates what features are pressed into the screw head; for example a flat head screw uses a flat die. For more complicated shapes two heading processes are required to get all of the features into the screw head. This production method is used because heading has a very high production rate, and produces virtually no waste material. Slotted head screws require an extra step to cut the slot in the head; this is done on a *slotting machine*. These machines are essentially stripped down milling machines designed to process as many blanks as possible.

The blanks are then polished again prior to threading. The threads are usually produced via thread rolling, however some are cut. The workpiece is then tumble finished with wood and leather media to do final cleaning and polishing. For most screws a coating, such as hot-dip galvanizing or blackening, is applied to prevent corrosion.

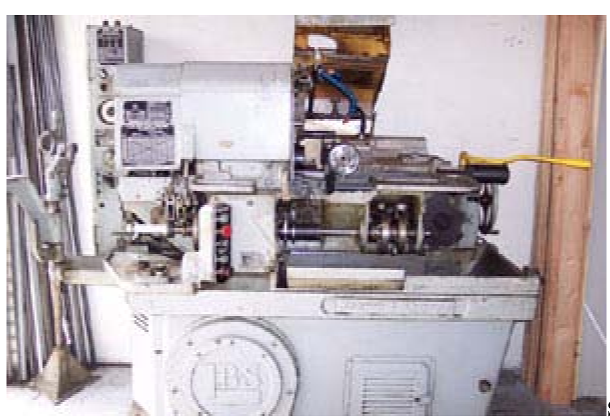


Different bolt sections

History



A lathe of 1871, equipped with leadscrew and change gears for single-point screw-cutting.


s

A Brown & Sharpe single-spindle screw machine.

While a recent hypothesis attributes the Archimedes' screw to Sennacherib, King of Assyria, archaeological finds and pictorial evidence only appear in the Hellenistic period and the standard view holds the device to be a Greek invention, most probably by the 3rd century BC polymath Archimedes himself.

The screw was later described by the Greek mathematician Archytas of Tarentum (428 – 350 BC). By the 1st century BC, wooden screws were commonly used throughout the Mediterranean world in devices such as oil and wine presses. Metal screws used as fasteners did not appear in Europe until the 15th century.

In 1744, the flat-bladed bit for the carpenter's brace was invented, the precursor to the first simple screwdriver. Handheld screwdrivers first appeared after 1800.

Prior to the mid-19th century, cotter pins or pin bolts, and "clinch bolts" (now called rivets), were used in shipbuilding.

The metal screw did not become a common fastener until machine tools for mass production were developed at the end of the 18th century. In the 1770s, English instrument maker Jesse Ramsden (1735–1800) invented the first satisfactory screw-cutting lathe. The British engineer Henry Maudslay (1771–1831) patented a screw-cutting lathe in 1797; a similar device was patented by David Wilkinson in the United States in 1798. These developments caused great increase in the use of threaded fasteners. Standardization of threadforms began almost immediately, but it was not quickly completed; it has been an evolving process ever since.

The development of the turret lathe (1840s) and of the screw machine (1870s) drastically reduced the unit cost of threaded fasteners by increasingly automating the machine tool control. This cost reduction spurred ever greater use of screws.

Throughout the 19th century, the most commonly used forms of screw head (drive) were simple internal-wrenching slots and external-wrenching squares and hexagons. These were easy to machine and served most applications adequately. The 20th century saw the development of many other types of drive. In 1908, Canadian P. L. Robertson invented the internal-wrenching square drive. The internal-wrenching hexagon drive (hex socket) shortly followed in 1911. In the early 1930s, the Phillips-head screw was invented by Henry F. Phillips.

Threadform standardization further improved in the late 1940s, when the ISO metric screw thread and the Unified Thread Standard were defined.

Other fastening methods

Alternative fastening methods are nails, rivets, roll pins, pinned shafts, welding, soldering, brazing, and gluing (including taping), and clinch fastening.

Chapter 7

Engine

An **engine** or **motor** is a machine designed to convert energy into useful mechanical motion.

Motors converting heat energy into motion are usually referred to as *engines*, which come in many types. A common type is a heat engine such as an internal combustion engine which typically burns a fuel with air and uses the hot gases for generating power. External combustion engines such as steam engines use heat to generate motion via a separate working fluid.

Another common type of motor is the electric motor. This takes electrical energy and generates mechanical motion via varying electromagnetic fields.

Other motors including pneumatic motors that are driven by compressed air, and motors can be driven by elastic energy, such as springs. Some motors are driven by non combustive chemical reactions.

Terminology

Originally an engine was a mechanical device that converted force into motion. Military devices such as catapults, trebuchets and battering rams are referred to as *siege engines*. The term "gin" as in cotton gin is recognised as a short form of the Old French word *engin*, in turn from the Latin *ingenium*, related to *ingenious*. Most devices used in the industrial revolution were referred to as engines, and this is where the steam engine gained its name.

In modern usage, the term is used to describe devices capable of performing mechanical work, as in the original steam engine. In most cases the work is produced by exerting a torque or linear force, which is used to operate other machinery which can generate electricity, pump water, or compress gas. In the context of propulsion systems, an air-breathing engine is one that uses atmospheric air to oxidise the fuel carried rather than supplying an independent oxidizer, as in a rocket.

In common usage, an *engine* burns or otherwise consumes fuel, and is differentiated from an electric machine (i.e., electric motor) that derives power without changing the composition of matter. A heat engine may also serve as a *prime mover*, a component that transforms the flow or changes in pressure of a fluid into mechanical energy. An automobile powered by an internal combustion engine may make use of various motors and pumps, but ultimately all such devices derive their power from the engine.

The term *motor* was originally used to distinguish the new internal combustion engine-powered vehicles from earlier vehicles powered by steam engines, such as the steam roller and motor roller, but may be used to refer to any engine.

History of engines

Antiquity

Simple machines, such as the club and oar (examples of the lever), are prehistoric. More complex engines using human power, animal power, water power, wind power and even steam power date back to antiquity. Human power was focused by the use of simple engines, such as the capstan, windlass or treadmill, and with ropes, pulleys, and block and tackle arrangements; this power was transmitted usually with the forces multiplied and the speed reduced. These were used in cranes and aboard ships in Ancient Greece, as well as in mines, water pumps and siege engines in Ancient Rome. The writers of those times, including Vitruvius, Frontinus and Pliny the Elder, treat these engines as commonplace, so their invention may be far more ancient. By the 1st century AD, various breeds of cattle and horses were used in mills, driving machines similar to those powered by humans in earlier times.

According to Strabo, a water powered mill was built in Kaberia of the kingdom of Mithridates during the 1st century BC. Use of water wheels in mills spread throughout the Roman Empire over the next few centuries. Some were quite complex, with aqueducts, dams, and sluices to maintain and channel the water, along with systems of gears, or toothed-wheels made of wood and metal to regulate the speed of rotation. In a poem by Ausonius in the 4th century AD, he mentions a stone-cutting saw powered by water. Hero of Alexandria is credited with many such wind and steam powered machines in the 1st century AD, including the Aeolipile, but it is not known if any of these were put to practical use.

Medieval

During the Muslim Agricultural Revolution from the 9th to 13th centuries, Muslim engineers developed numerous innovative industrial uses of hydropower, early industrial uses of tidal power, wind power, and fossil fuels such as petroleum, together with the earliest large factory complexes (*tiraz* in Arabic). The industrial uses of watermills in the Islamic world date back to the 7th century, whereas horizontal-wheeled and vertical-wheeled water mills were both in widespread use since at least the 9th century. A variety of industrial mills were invented in the Islamic world, including fulling mills, hullers, steel mills, sugar refineries, and windmills. By the 11th century, every province throughout the Islamic world had these industrial mills in operation, from the Middle East and Central Asia to al-Andalus and North Africa.

Roman engineers invented water turbines in the 4th century AD, Muslim engineers employed gears in mills and water-raising machines, and pioneered the use of dams as a source of water power to provide additional power to watermills and water-raising machines. Such advances made it possible for many industrial tasks that were previously driven by manual labour to be mechanized and driven by machinery to some extent in the medieval Islamic world.

In 1206, al-Jazari employed a crank-connecting rod system for two of his water-raising machines. A similar steam turbine later appeared in Europe a century later, which eventually led to the steam engine and Industrial Revolution in 18th century Europe.

Industrial revolution

English inventor Sir Samuel Morland allegedly used gunpowder to drive water pumps in the 17th century. For more conventional, reciprocating internal combustion engines, the fundamental theory for two-stroke engines was established by Sadi Carnot, France, 1824, whilst the American Samuel Morey received a patent on April 1, 1826. Sir Dugald Clark (1854–1932) designed the first two-stroke engine in 1878 and patented it in England in 1881. Automotive engines have used a range of energy-conversion systems. These include electric, steam, solar, turbine, rotary, piston-type internal combustion engine.

Karl Benz was one of the leaders in the development of new engines. In 1878 he began to work on new designs. He concentrated his efforts on creating a reliable gas two-stroke engine that was more powerful, based on Nikolaus Otto's design of the four-stroke engine. Karl Benz showed his real genius, however, through his successive inventions registered while designing what would become the production standard for his two-stroke engine. Benz was granted a patent for it in 1879.

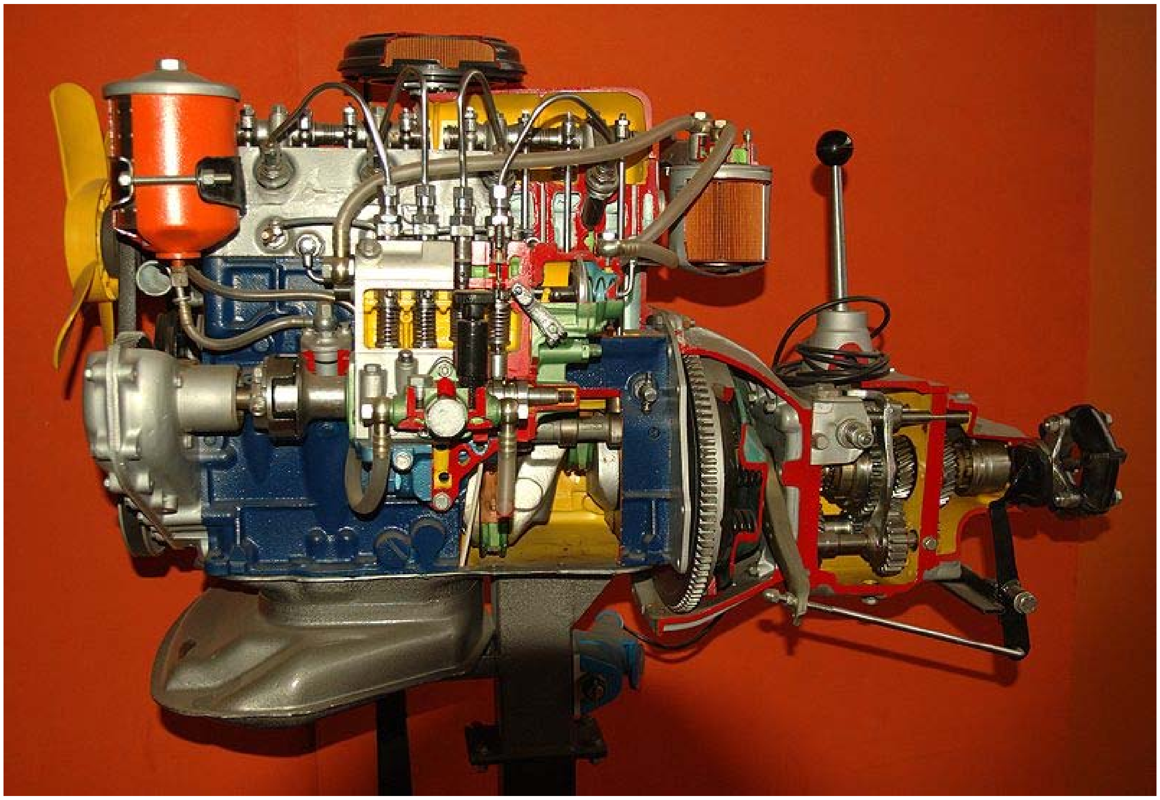
The lightweight petrol internal combustion engine, operating on a four-stroke Otto cycle, has been the most successful for automobiles, while the more efficient diesel engine is used for trucks and buses.

Horizontally opposed pistons

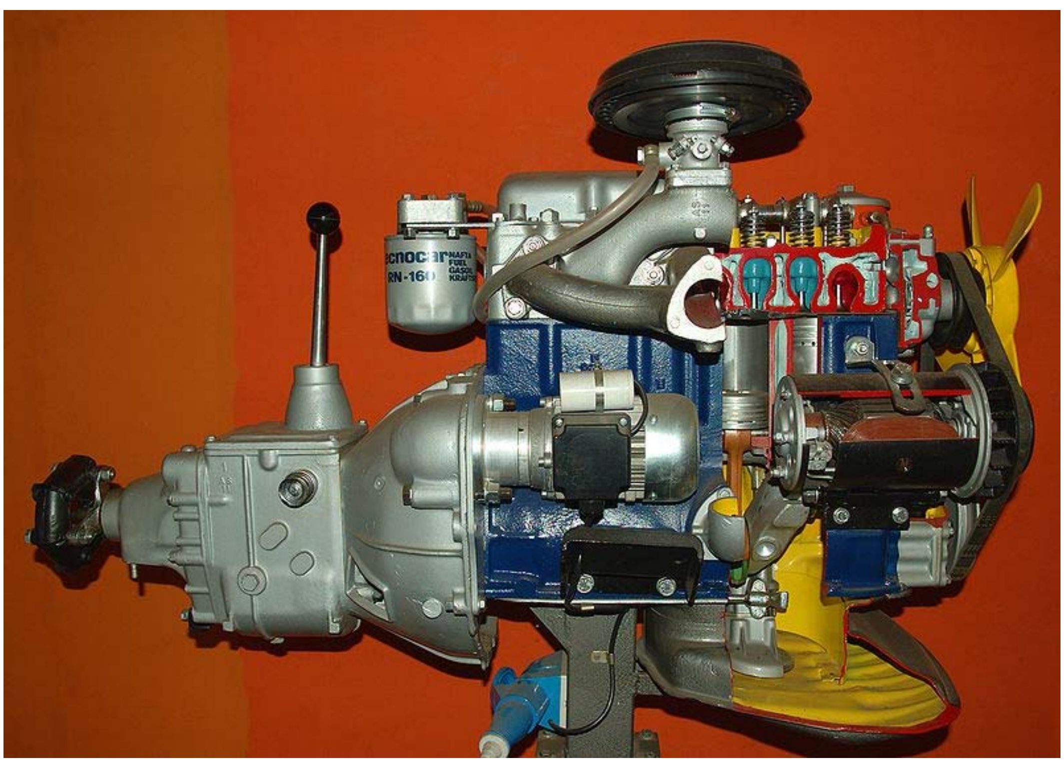
In 1896, Karl Benz was granted a patent for his design of the first engine with horizontally opposed pistons. Many BMW motorcycles use this engine type. His design created an engine in which the corresponding pistons move in horizontal cylinders and reach top dead center simultaneously, thus automatically balancing each other with respect to their individual momentums. Engines of this design are often referred to as flat engines because of their shape and lower profile. They must have an even number of cylinders and six, four or two cylinder flat engines have all been common. The most well-known engine of this type is probably the Volkswagen Beetle engine. Engines of this type continue to be a common design principle for high performance aero engines (for propeller driven aircraft) and, engines used by automobile producers such as Porsche and Subaru.

Advancement

Mercedes V6 engine in 1996



School model of engine



School model of an engine

Continuance of the use of the internal combustion engine for automobiles is partly due to the improvement of engine control systems (onboard computers providing engine management processes, and electronically controlled fuel injection). Forced air induction by turbocharging and supercharging have increased power outputs and engine efficiencies. Similar changes have been applied to smaller diesel engines giving them almost the same power characteristics as petrol engines. This is especially evident with the popularity of smaller diesel engine propelled cars in Europe. Larger diesel engines are still often used in trucks and heavy machinery. They do not burn as clean as gasoline engines, however they have far more torque. The internal combustion engine was originally selected for the automobile due to its flexibility over a wide range of speeds. Also, the power developed for a given weight engine was reasonable; it could be produced by economical mass-production methods; and it used a readily available, moderately priced fuel - petrol.

Increasing power

The first half of the 20th century saw a trend to increasing engine power, particularly in the American models. Design changes incorporated all known methods of raising engine capacity, including increasing the pressure in the cylinders to improve efficiency, increasing the size of the engine, and increasing the speed at which power is generated. The higher forces and pressures created by these changes created engine vibration and size problems that led to stiffer, more compact engines with V and opposed cylinder layouts replacing longer straight-line arrangements.

Combustion efficiency

The design principles favoured in Europe, because of economic and other restraints such as smaller and twistier roads, leant toward smaller cars and corresponding to the design principles that concentrated on increasing the combustion efficiency of smaller engines. This produced more economical engines with earlier four-cylinder designs rated at 40 horsepower (30 kW) and six-cylinder designs rated as low as 80 horsepower (60 kW), compared with the large volume V-8 American engines with power ratings in the range from 250 to 350 hp (190 to 260 kW).

Engine configuration

Earlier automobile engine development produced a much larger range of engines than is in common use today. Engines have ranged from 1 to 16 cylinder designs with corresponding differences in overall size, weight, piston displacement, and cylinder bores. Four cylinders and power ratings from 19 to 120 hp (14 to 90 kW) were followed in a majority of the models. Several three-cylinder, two-stroke-cycle models were built while most engines had straight or in-line cylinders. There were several V-type models and horizontally opposed two- and four-cylinder makes too. Overhead camshafts were frequently employed. The smaller engines were commonly air-cooled and located at the rear of the vehicle; compression ratios were relatively low. The 1970s and '80s saw an increased interest in improved fuel economy which brought in a return to smaller V-6 and four-cylinder layouts, with as many as five valves per cylinder to improve efficiency. The Bugatti Veyron 16.4 operates with a W16 engine meaning that two V8 cylinder layouts are positioned next to each other to create the W shape.

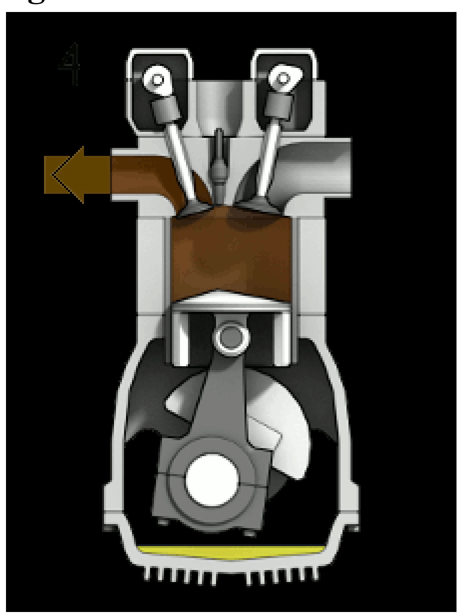
The largest internal combustion engine ever built is the Wärtsilä-Sulzer RTA96-C, a 14-cylinder, 2-stroke turbocharged diesel engine that was designed to power the Emma Maersk, the largest container ship in the world. This engine weighs 2300 tons, and when running at 102 RPM produces 109,000 bhp (80,080 kW) consuming some 13.7 tons of fuel each hour.

Heat engine

Combustion engine

Combustion engines are heat engines driven by the heat of a combustion process.

Internal combustion engine



the four stages of the 4-stroke combustion engine cycle:
1. Induction *(Fuel enters)*
2. Compression
3. Ignition *(Fuel is burnt)*
4. Emission *(Exhaust out)*

The **internal combustion engine** is an engine in which the combustion of a fuel (generally, fossil fuel) occurs with an oxidizer (usually air) in a combustion chamber. In an internal combustion engine the expansion of the high temperature and high pressure gases, which are produced by the combustion, directly applies force to components of the engine, such as the pistons or turbine blades or a nozzle, and by moving it over a distance, generates useful mechanical energy.

External combustion engine

An **external combustion engine** (EC engine) is a heat engine where an internal working fluid is heated by combustion of an external source, through the engine wall or a heat exchanger. The fluid then, by expanding and acting on the mechanism of the engine produces motion and usable work. The fluid is then cooled, compressed and reused (closed cycle), or (less commonly) dumped, and cool fluid pulled in (open cycle air engine).

"Combustion" refers to burning fuel with an oxidizer, to supply the heat. Engines of similar (or even identical) configuration and operation may use a supply of heat from other sources such as nuclear, solar, geothermal or exothermic reactions not involving combustion; but are not then strictly classed as external combustion engines, but as external thermal engines.

The working fluid can be a gas as in a Stirling engine, or steam as in a steam engine or an organic liquid such as n-pentane in an Organic Rankine Cycle. The fluid can be of any composition; gas is by far the most common, although even single-phase liquid is sometimes used. In the case of the steam engine, the fluid changes phases between liquid and gas...

Gas turbine

A gas turbine is internal combustion is the sense that the combustion takes place in the working fluid, but external combustion in the sense that the combustion is not fully closed in and is outside the actual moving turbine section. Traditionally, "internal combustion" usually excludes gas turbines, jets and rockets.

Air-breathing combustion engines

Air-breathing engines are combustion engines that use the oxygen in atmospheric air to oxidise ('burn') the fuel carried, rather than carrying an oxidiser, as in a rocket. Theoretically, this should result in a better specific impulse than for rocket engines.

A continuous stream of air flows through the Air-breathing engine. This air is compressed, mixed with fuel, ignited and expelled as the exhaust gas. Thrust produced by a typical air-breathing engine is about eight times greater than its weight. The maximum velocity of Air-breathing engines is limited to 1–3 km/s due to extreme temperature and dissociation of the exhaust gas; however, the maximum velocity of a hydrogen-breathing engine of the same design is about 4 times higher.

Examples

Typical air-breathing engines include:

- Reciprocating engine

- Steam engine
- Gas turbine

    duct jet engine
    Turbo-propeller engine

- IRIS engine
- Pulse detonation engine
- Pulse jet
- Ramjet
- Scramjet
- Liquid air cycle engine/Reaction Engines SABRE

Environmental effects

Operation of engines typically has a negative impact upon air quality and ambient sound levels. There has been a growing emphasis on the pollution producing features of automotive power systems. This has created new interest in alternate power sources and internal-combustion engine refinements. Although a few limited-production battery-powered electric vehicles have appeared, they have not proved to be competitive owing to costs and operating characteristics. In the 21st century the diesel engine has been increasing in popularity with automobile owners. However, the gasoline engine, with its new emission-control devices to improve emission performance, has not yet been significantly challenged.

Air quality

Exhaust from a spark ignition engine consists of the following: nitrogen 70 to 75% (by volume), water vapor 10 to 12%, carbon dioxide 10 to 13.5%, hydrogen 0.5 to 2%, oxygen 0.2 to 2%, carbon monoxide: 0.1 to 6%, unburnt hydrocarbons and partial oxidation products (e.g. aldehydes) 0.5 to 1%, nitrogen monoxide 0.01 to 0.4%, nitrous oxide <100 ppm, sulfur dioxide 15 to 60 ppm, traces of other compounds such as fuel additives and lubricants, also halogen and metallic compounds, and other particles. Carbon monoxide is highly toxic, and can cause carbon monoxide poisoning, so it is important to avoid any build-up of the gas in a confined space. Catalytic converters can reduce toxic emissions, but not completely eliminate them. Also, resulting greenhouse gas emissions, chiefly carbon dioxide, from the widespread use of engines in the modern industrialized world is contributing to the global greenhouse effect – a primary concern regarding global warming.

Non combustive heat engines

Some engines convert heat from non combustive processes into mechanical work, for example a nuclear power plant uses the heat from the nuclear reaction to produce steam and drive a steam engine, or a gas turbine in a rocket engine may be driven by decomposing hydrogen peroxide. Apart from the different energy source, the engine is often engineered much the same as an internal or external combustion engine.

Non thermal chemically powered motor

Non thermal motors usually are powered by a chemical reaction, but are not heat engines. Examples include:

- Molecular motor - motors found in living things
- Synthetic molecular motor

Electric motor

An **electric motor** uses electrical energy to produce mechanical energy, usually through the interaction of magnetic fields and current-carrying conductors. The reverse process, producing electrical energy from mechanical energy, is accomplished by a generator or dynamo. Traction motors used on vehicles often perform both tasks. Electric motors can be run as generators and vice versa, although this is not always practical. Electric motors are ubiquitous, being found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives. They may be powered by direct current (for example a battery powered portable device or motor vehicle), or by alternating current from a central electrical distribution grid. The smallest motors may be found in electric wristwatches. Medium-size motors of highly standardized dimensions and characteristics provide convenient mechanical power for industrial uses. The very largest electric motors are used for propulsion of large ships, and for such purposes as pipeline compressors, with ratings in the thousands of kilowatts. Electric motors may be classified by the source of electric power, by their internal construction, and by their application.

The physical principle of production of mechanical force by the interactions of an electric current and a magnetic field was known as early as 1821. Electric motors of increasing efficiency were constructed throughout the 19th century, but commercial exploitation of electric motors on a large scale required efficient electrical generators and electrical distribution networks.

By convention, *electric engine* refers to a railroad electric locomotive, rather than an electric motor.

Physically powered engine

Some engines are powered by potential energy, for example some clocks have a weight that falls under gravity. Other forms of potential energy include compressed gases (such as pneumatic motors), springs and elastic bands.

Historic military siege engines included large catapults, trebuchets, and (to some extent) battering rams were powered by potential energy.

Pneumatic motor

A **pneumatic motor** is a machine which converts potential energy in the form of compressed air into mechanical work. Pneumatic motors generally convert the compressed air to mechanical work though either linear or rotary motion. Linear motion can come from either a diaphragm or piston actuator, while rotary motion is supplied by either a vane type air motor or piston air motor. Pneumatic motors have found widespread success in the hand-held tool industry and continual attempts are being made to expand their use to the transportation industry. However, pneumatic motors must overcome efficiency deficiencies before being seen as a viable option in the transportation industry.

Hydraulic engine

A **hydraulic engine** one that derives its power from a pressurized fluid. This type of engine can be used to move heavy loads or produce motion.

Sound levels

In the case of sound levels, engine operation is of greatest impact with respect to mobile sources such as automobiles and trucks. Engine noise is a particularly large component of mobile source noise for vehicles operating at lower speeds, where aerodynamic and tyre noise is less significant. Petrol and diesel engines are fitted with mufflers (silencers) to reduce noise.

Engine efficiency

Depending on the type of engine employed, different rates of efficiency are attained.

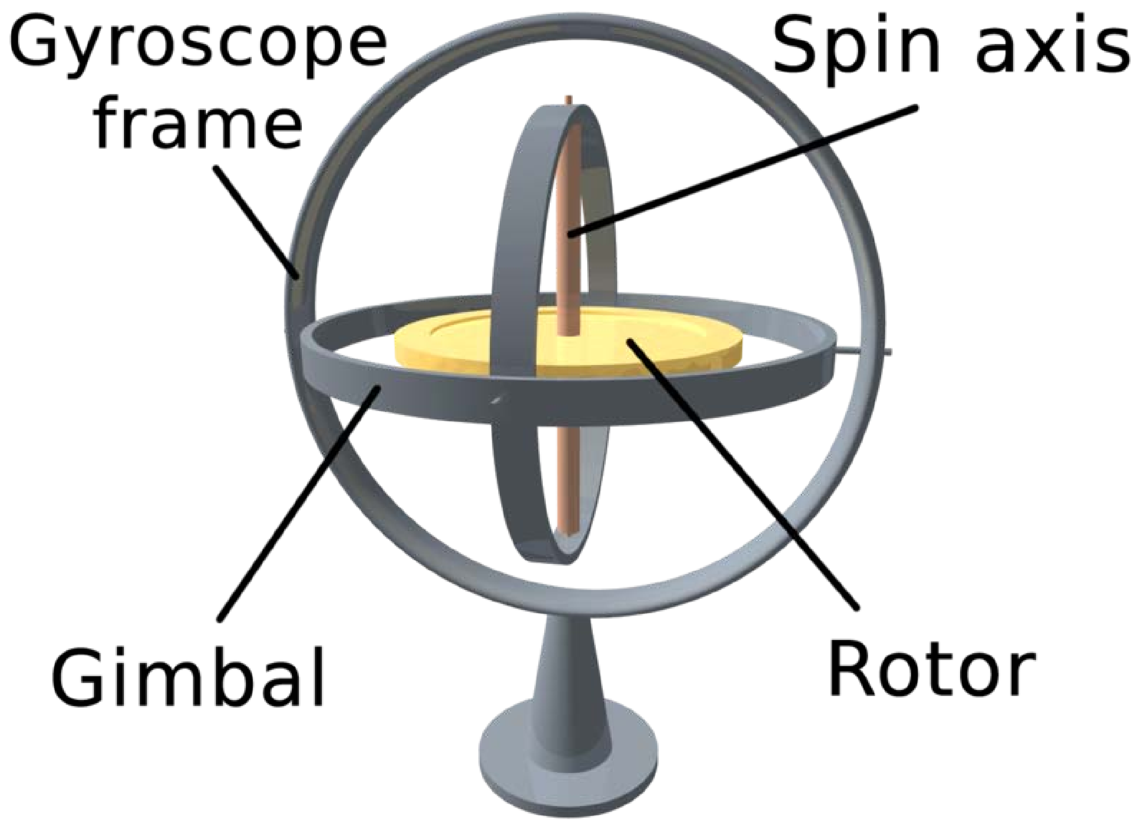
Engines by use

Particularly notable kinds of engines include:

- Aircraft engine
- Automobile engine
- model engine
- Motorcycle engine
- Marine propulsion engines such as Outboard motor
- Railway locomotive engine
- Spacecraft propulsion engines such as Rocket engine
- Traction engine

Chapter 8

Gyroscope



A gyroscope

A **gyroscope** is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum. A mechanical gyroscope is essentially a spinning wheel or disk whose axle is free to take any orientation. This orientation changes much less in response to a given external torque than it would without the large angular momentum associated with the gyroscope's high rate of spin. Since external torque is minimized by mounting the device in gimbals, its orientation remains nearly fixed, regardless of any motion of the platform on which it is mounted.

Gyroscopes based on other operating principles also exist, such as the electronic, microchip-packaged MEMS gyroscope devices found in consumer electronic devices, solid state ring lasers, fibre optic gyroscopes and the extremely sensitive quantum gyroscope.

Applications of gyroscopes include navigation (INS) when magnetic compasses do not work (as in the Hubble telescope) or are not precise enough (as in ICBMs) or for the stabilization of flying vehicles like radio-controlled helicopters or UAVs. Due to their high precision, gyroscopes are also used to maintain direction in tunnel mining.

Description and diagram

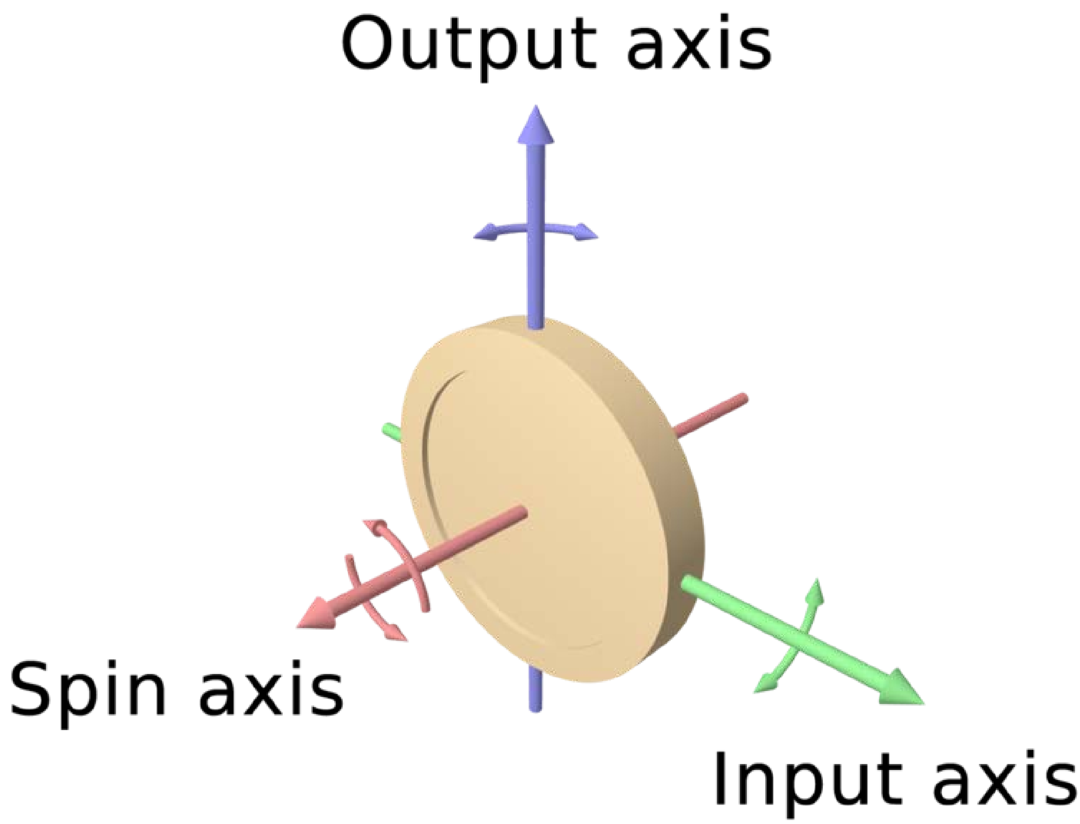


Diagram of a gyro wheel. Reaction arrows about the output axis (blue) correspond to forces applied about the input axis (green), and vice versa.

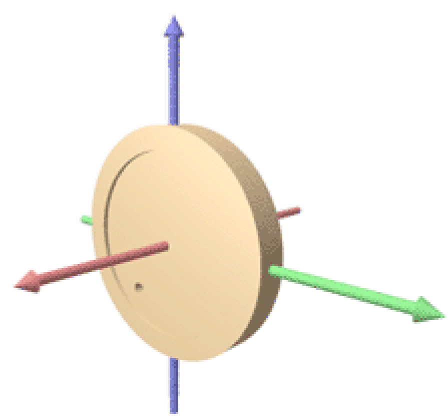
Within mechanical systems or devices, a conventional *gyroscope* is a mechanism comprising a rotor journalled to spin about one axis, the journals of the rotor being mounted in an inner gimbal or ring, the inner gimbal is journalled for oscillation in an outer gimbal which is journalled in another gimbal for a total of three gimbals.

The **outer gimbal** or ring which is the gyroscope frame is mounted so as to pivot about an axis in its own plane determined by the support. This outer gimbal possesses one degree of rotational freedom and its axis possesses none. The next **inner gimbal** is mounted in the gyroscope frame (outer gimbal) so as to pivot about an axis in its own plane that is always perpendicular to the pivotal axis of the gyroscope frame (outer gimbal). This inner gimbal has two degrees of rotational freedom. Similarly, next **innermost gimbal** is attached to the inner gimbal which has three degrees of rotational freedom and its axis possesses two.

The axle of the spinning wheel defines the spin axis. The rotor is journaled to spin about an axis which is always perpendicular to the axis of the innermost gimbal. So, the rotor possesses four degrees of rotational freedom and its axis possesses three. The wheel responds to a force applied about the input axis by a reaction force about the output axis.

The behaviour of a gyroscope can be most easily appreciated by consideration of the front wheel of a bicycle. If the wheel is leaned away from the vertical so that the top of the wheel moves to the left, the forward rim of the wheel also turns to the left. In other words, rotation on one axis of the turning wheel produces rotation of the third axis.

A **gyroscope flywheel** will roll or resist about the output axis depending upon whether the output gimbals are of a free- or fixed- configuration. Examples of some free-output-gimbal devices would be the attitude reference gyroscopes used to sense or measure the pitch, roll and yaw attitude angles in a spacecraft or aircraft.



Gyro wheel in action

The centre of gravity of the rotor can be in a fixed position. The rotor simultaneously spins about one axis and is capable of oscillating about the two other axes, and thus, except for its inherent resistance due to rotor spin, it is free to turn in any direction about the fixed point. Some gyroscopes have mechanical equivalents substituted for one or more of the elements, e.g., the spinning rotor may be suspended in a fluid, instead of being pivotally mounted in gimbals. A control moment gyroscope (CMG) is an example of a fixed-output-gimbal device that is used on spacecraft to hold or maintain a desired attitude angle or pointing direction using the gyroscopic resistance force.

In some special cases, the outer gimbal (or its equivalent) may be omitted so that the rotor has only two degrees of freedom. In other cases, the centre of gravity of the rotor may be offset from the axis of oscillation and thus the centre of gravity of the rotor and the centre of suspension of the rotor may not coincide.

History

Gyroscope invented by Léon Foucault in 1852. Replica built by Dumoulin-Froment for the Exposition universelle in 1867. National Conservatory of Arts and Crafts museum, Paris.

The earliest known gyroscope-like instrument was made by German Johann Bohnenberger, who first wrote about it in 1817. At first he called it the "Machine". Bohnenberger's machine was based on a rotating massive sphere. In 1832, American Walter R. Johnson developed a similar device that was based on a rotating disk. The French mathematician Pierre-Simon Laplace, working at the École Polytechnique in Paris, recommended the machine for use as a teaching aid, and thus it came to the attention of Léon Foucault. In 1852, Foucault used it in an experiment involving the rotation of the Earth. It was Foucault who gave the device its modern name, in an experiment to see the Earth's rotation (Greek *gyros*, circle or rotation), which was visible in the 8 to 10 minutes before friction slowed the spinning rotor.

In the 1860s, the advent of electric motors made it possible for a gyroscope to spin indefinitely; this lead to the first prototype gyrocompasses. The first functional marine gyrocompass was patented in 1907 by German inventor Hermann Anschütz-Kaempfe. The American Elmer Sperry followed with his own design later that year, and other nations soon realized the military importance of the invention—in an age in which naval prowess was the most significant measure of military power—and created their own gyroscope industries. The Sperry Gyroscope Company quickly expanded to provide aircraft and naval stabilizers as well, and other gyroscope developers followed suit.

In 1917, the Chandler Company of Indianapolis, Indiana, created the "Chandler gyroscope", a toy gyroscope with a pull string and pedestal. Chandler continued to produce the toy until the company was purchased by TEDCO inc. in 1982. The chandler toy is still produced by TEDCO today.

In the first several decades of the 20th century, other inventors attempted (unsuccessfully) to use gyroscopes as the basis for early black box navigational systems by creating a stable platform from which accurate acceleration measurements could be performed (in order to bypass the need for star sightings to calculate position). Similar principles were later employed in the development of inertial guidance systems for ballistic missiles.

During World War Two, the gyroscope became the prime component for aircraft and anti-aircraft gun sights.

Properties

A gyroscope in operation with freedom in all three axes. The rotor will maintain its spin axis direction regardless of the orientation of the outer frame.

A gyroscope exhibits a number of behaviours including precession and nutation. Gyroscopes can be used to construct gyrocompasses which complement or replace magnetic compasses (in ships, aircraft and spacecraft, vehicles in general), to assist in stability (Hubble Space Telescope, bicycles, motorcycles, and ships) or be used as part of an inertial guidance system. Gyroscopic effects are used in tops, boomerangs, yo-yos, and Powerballs. Many other rotating devices, such as flywheels, behave gyroscopically although the gyroscopic effect is not being used.

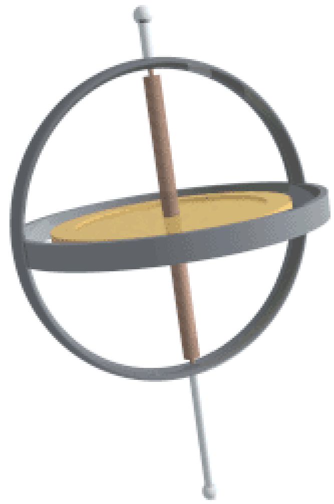
The fundamental equation describing the behavior of the gyroscope is:

$$\boldsymbol{\tau} = \frac{d\mathbf{L}}{dt} = \frac{d(I\boldsymbol{\omega})}{dt} = I\boldsymbol{\alpha}$$

where the vectors $\boldsymbol{\tau}$ and $\mathbf{L}$ are, respectively, the torque on the gyroscope and its angular momentum, the scalar I is its moment of inertia, the vector $\boldsymbol{\omega}$ is its angular velocity, and the vector $\boldsymbol{\alpha}$ is its angular acceleration.

It follows from this that a torque $\boldsymbol{\tau}$ applied perpendicular to the axis of rotation, and therefore perpendicular to $\mathbf{L}$, results in a rotation about an axis perpendicular to both $\boldsymbol{\tau}$ and $\mathbf{L}$. This motion is called *precession*. The angular velocity of precession $\boldsymbol{\Omega}_P$ is given by the cross product:

$$\boldsymbol{\tau} = \boldsymbol{\Omega}_{\mathrm{P}} \times \mathbf{L}.$$



Precession on a gyroscope

Precession can be demonstrated by placing a spinning gyroscope with its axis horizontal and supported loosely (frictionless toward precession) at one end. Instead of falling, as might be expected, the gyroscope appears to defy gravity by remaining with its axis horizontal, when the other end of the axis is left unsupported and the free end of the axis slowly describes a circle in a horizontal plane, the resulting precession turning. This effect is explained by the above equations. The torque on the gyroscope is supplied by a couple of forces: gravity acting downwards on the device's centre of mass, and an equal force acting upwards to support one end of the device. The rotation resulting from this torque is not downwards, as might be intuitively expected, causing the device to fall, but perpendicular to both the gravitational torque (horizontal and perpendicular to the axis of rotation) and the axis of rotation (horizontal and outwards from the point of support), i.e. about a vertical axis, causing the device to rotate slowly about the supporting point.

Under a constant torque of magnitude τ, the gyroscope's speed of precession Ω_{P} is inversely proportional to L, the magnitude of its angular momentum:

$$\tau = \Omega_{\mathrm{P}} L \sin\theta,$$

where θ is the angle between the vectors $\mathbf{\Omega}_{\mathrm{P}}$ and $\mathbf{L}$. Thus if the gyroscope's spin slows down (for example, due to friction), its angular momentum decreases and so the rate of precession increases. This continues until the device is unable to rotate fast enough to support its own weight, when it stops precessing and falls off its support, mostly because friction against precession cause another precession that goes to cause the fall.

By convention, these three vectors, torque, spin, and precession, are all oriented with respect to each other according to the right-hand rule.

To easily ascertain the direction of gyro effect, simply remember that a rolling wheel tends, when it leans to the side, to turn in the direction of the lean.

Variations

Gyrostat

A **gyrostat** is a variant of the gyroscope. It consists of a massive flywheel concealed in a solid casing. Its behaviour on a table, or with various modes of suspension or support, serves to illustrate the curious reversal of the ordinary laws of static equilibrium due to the gyrostatic behaviour of the interior invisible flywheel when rotated rapidly. The first gyrostat was designed by Lord Kelvin to illustrate the more complicated state of motion of a spinning body when free to wander about on a horizontal plane, like a top spun on the pavement, or a hoop or bicycle on the road.

MEMS

A MEMS gyroscope takes the idea of the Foucault pendulum and uses a vibrating element, known as a MEMS (Micro Electro-Mechanical System). The MEMS-based gyro was initially made practical and producible by Systron Donner Inertial (SDI). Today, SDI is a large manufacturer of MEMS gyroscopes.

FOG

A fiber optic gyroscope (FOG) is a gyroscope that uses the interference of light to detect mechanical rotation. The sensor is a coil of as much as 5 km of optical fiber. The development of low loss single mode optical fiber in the early 1970s for the telecommunications industry enabled the development of Sagnac effect fiber optic gyros.

VSG or CVG

A vibrating structure gyroscope (VSG), also called a **coriolis vibratory gyroscope** (CVG), uses a resonator made of different metallic alloys. It takes a position between the low accuracy, low cost MEMS gyroscope and the higher accuracy and higher cost fiber optic gyroscope (FOG). Accuracy parameters are increased by using low intrinsic damping materials, resonator vacuumization, and digital electronics to reduce temperature dependent drift and instability of control signals.

High-Q Wine-Glass Resonators for precise sensors like HRG or CRG are based on Bryan's "wave inertia effect". They are made from high-purity quartz glass or from single-crystalline sapphire.

DTG

A dynamically tuned gyroscope (DTG) is a rotor suspended by a universal joint with flexure pivots. The flexure spring stiffness is independent of spin rate. However, the dynamic inertia (from the gyroscopic reaction effect) from the gimbal provides negative spring stiffness proportional to the square of the spin speed (Howe and Savet, 1964; Lawrence, 1998). Therefore, at a particular speed, called the tuning speed, the two moments cancel each other, freeing the rotor from torque, a necessary condition for an ideal gyroscope.

London moment

A London moment gyroscope relies on the quantum-mechanical phenomenon whereby a

spinning superconductor generates a magnetic field whose axis lines up exactly with the spin axis of the gyroscopic rotor. A magnetometer determines the orientation of the generated field, which is interpolated to determine the axis of rotation. Gyroscopes of this type can be extremely accurate and stable, for example those used in the Gravity Probe B experiment measured changes in gyroscope spin axis orientation to better than 0.5 milliarcseconds (1.4×10^{-7} degrees) over a one-year period. This is equivalent to an angular separation the width of a human hair viewed from 32 kilometers (20 miles) away.

The GP-B gyro consists of a nearly-perfect spherical rotating mass made of fused quartz which provides a dielectric support for a thin layer of niobium superconducting material. To eliminate friction found in conventional mechanical bearings, the rotor assembly is suspended by six electromagnets that form a magnetic bearing. After the initial spin-up by a jet of helium brings the rotor to 4,000 RPM, the polished gyroscope housing is evacuated to a ultra-high vacuum to further reduce drag on the rotor. Provided the suspension electronics remain powered, the extreme rotational symmetry, lack of friction, and low drag will allow the angular momentum of the rotor to keep it spinning for about 15,000 years.

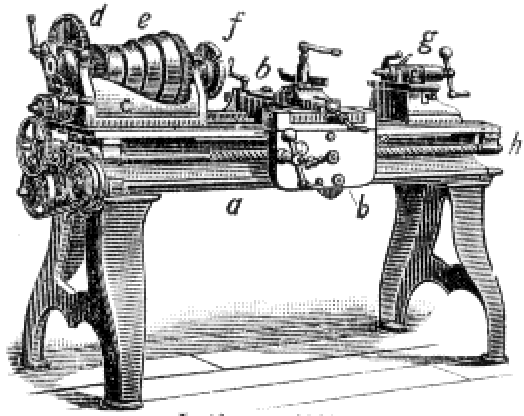
A sensitive DC SQUID magnetometer able to discriminate changes as small as one quantum, or about 2×10^{-15} Wb, is used to monitor the gyroscope. A precesses, or tilt, in the orientation of the rotor causes the London moment magnetic field to shift relative to the housing. The moving field passes through a superconducting pickup loop fixed to the housing, inducing a small electric current. The current produces a voltage across a shunt resistance, which is resolved to spherical coordinates by a microprocessor. The system is designed to minimize Lorentz torque on the rotor.

Modern uses

In addition to being used in compasses, aircraft, computer pointing devices, etc., gyroscopes have been introduced into consumer electronics. Since the gyroscope allows the calculation of orientation and rotation, designers have incorporated them into modern technology. The integration of the gyroscope has allowed for more accurate recognition of movement within a 3D space than the previous lone accelerometer within a number of smartphones. Scott Steinberg, known for his critiques on newly released technology, says that the new addition of the gyroscope in the iPhone 4 may "completely redefine the way we interact with downloadable apps".

Chapter 9

Lathe



Lathe, p. 1218.

A metalworking lathe from 1911 showing component parts.
a = bed, b = carriage (with cross-slide and toolpost), c = headstock, d = back gear (other geartrain nearby below drives leadscrew), e = cone pulley for belt drive from an external power source, f = faceplate mounted on spindle, g = tailstock. h = leadscrew.

A **lathe** is a machine tool which rotates the workpiece on its axis to perform various operations such as cutting, sanding, knurling, drilling, or deformation with tools that are applied to the workpiece to create an object which has symmetry about an axis of rotation.

Lathes are used in woodturning, metalworking, metal spinning, and glassworking. Lathes can be used to shape pottery, the best-known design being the potter's wheel. Most suitably equipped metalworking lathes can also be used to produce most solids of revolution, plane surfaces and screw threads or helices. Ornamental lathes can produce three-dimensional solids of incredible complexity. The material can be held in place by either one or two *centers*, at least one of which can be moved horizontally to accommodate varying material lengths. Other workholding methods include clamping the work about the axis of rotation using a chuck or collet, or to a faceplate, using clamps or dogs.

Examples of objects that can be produced on a lathe include candlestick holders, cue sticks, table legs, bowls, baseball bats, musical instruments (especially woodwind instruments), crankshafts and camshafts.

History

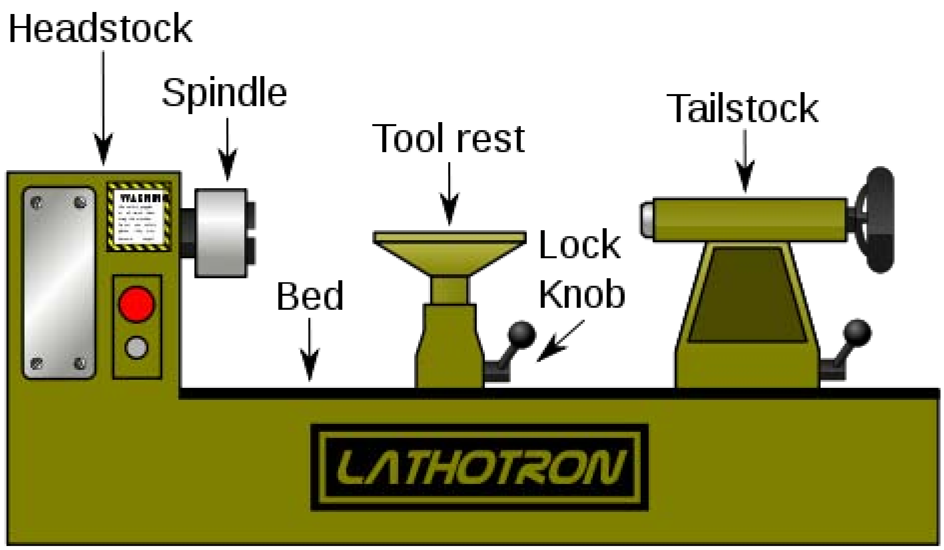
The lathe is an ancient tool, dating at least to ancient Egypt and known and used in Assyria, ancient Greece, and the Roman and Byzantine Empires.

The origin of turning dates to around 1300 BC when the Egyptians first developed a two-person lathe. One person would turn the wood work piece with a rope while the other used a sharp tool to cut shapes in the wood. The Romans improved the Egyptian design with the addition of a turning bow. Early bow lathes were also developed and used in Germany, France and Britain. In the Middle Ages a pedal replaced hand-operated turning, freeing both the craftsman's hands to hold the woodturning tools. The pedal was usually connected to a pole, often a straight-grained sapling. The system today is called the "spring pole" lathe. Spring pole lathes were in common use into the early 20th century. A two-person lathe, called a "great lathe", allowed a piece to turn continuously (like today's power lathes). A master would cut the wood while an apprentice turned the crank.

During the Industrial Revolution, mechanized power generated by water wheels or steam engines was transmitted to the lathe via line shafting, allowing faster and easier work. The design of lathes diverged between woodworking and metalworking to a greater extent than in previous centuries. Metalworking lathes evolved into heavier machines with thicker, more rigid parts. The application of leadscrews, slide rests, and gearing produced commercially practical screw-cutting lathes. Between the late 19th and mid-20th centuries, individual electric motors at each lathe replaced line shafting as the power source. Beginning in the 1950s, servomechanisms were applied to the control of lathes and other machine tools via numerical control (NC), which often was coupled with computers to yield computerized numerical control (CNC). Today manually controlled and CNC lathes coexist in the manufacturing industries.

Description

Parts



Parts of a wood lathe

A lathe may or may not have a **stand** (or **legs**), which sits on the floor and elevates the lathe bed to a working height. Some lathes are small and sit on a **workbench** or **table**, and do not have a stand.

Almost all lathes have a **bed**, which is (almost always) a horizontal beam (although some CNC lathes have a vertical beam for a bed to ensure that swarf, or chips, falls free of the bed). A notable exception is the Hegner VB36 Master Bowlturner, a woodturning lathe designed for turning large bowls, which in its basic configuration is little more than a very large floor-standing headstock.

At one end of the bed (almost always the left, as the operator faces the lathe) is a **headstock**. The headstock contains high-precision spinning bearings. Rotating within the bearings is a horizontal axle, with an axis parallel to the bed, called the **spindle**. Spindles are often hollow, and have exterior threads and/or an interior Morse taper on the "inboard" (i.e., facing to the right / towards the bed) by which workholding accessories may be mounted to the spindle. Spindles may also have exterior threads and/or an interior taper at their "outboard" (i.e., facing away from the bed) end, and/or may have a handwheel or other accessory mechanism on their outboard end. Spindles are powered, and impart motion to the workpiece.

The spindle is driven, either by foot power from a treadle and flywheel or by a belt or gear drive to a **power source**. In most modern lathes this power source is an integral electric motor, often either in the headstock, to the left of the headstock, or beneath the headstock, concealed in the stand.

In addition to the spindle and its bearings, the headstock often contains parts to convert the motor speed into various spindle speeds. Various types of **speed-changing mechanism** achieve this, from a cone pulley or step pulley, to a cone pulley with back gear (which is essentially a low range, similar in net effect to the two-speed rear of a truck), to an entire gear train similar to that of a manual-shift auto transmission. Some motors have electronic rheostat-type speed controls, which obviates cone pulleys or gears.

The counterpoint to the headstock is the **tailstock**, sometimes referred to as the loose head, as it can be positioned at any convenient point on the bed, by undoing a locking nut, sliding it to the required area, and then relocking it. The tailstock contains a barrel which does not rotate, but can slide in and out parallel to the axis of the bed, and directly in line with the headstock spindle. The barrel is hollow, and usually contains a taper to facilitate the gripping of various type of tooling. Its most common uses are to hold a hardened steel centre, which is used to support long thin shafts while turning, or to hold drill bits for drilling axial holes in the work piece. Many other uses are possible.

Metalworking lathes have a **carriage** (comprising a **saddle** and **apron**) topped with a **cross-slide**, which is a flat piece that sits crosswise on the bed, and can be cranked at right angles to the bed. Sitting atop the cross slide is usually another slide called a **compound rest**, which provides 2 additional axes of motion, rotary and linear. Atop that sits a **toolpost**, which holds a **cutting tool** which removes material from the workpiece. There may or may not be a **leadscrew**, which moves the cross-slide along the bed.

Woodturning and metal spinning lathes do not have cross-slides, but rather have **banjos**, which are flat pieces that sit crosswise on the bed. The position of a banjo can be adjusted by hand; no gearing is involved. Ascending vertically from the banjo is a toolpost, at the top of which is a horizontal **toolrest**. In woodturning, hand tools are braced against the tool rest and levered into the workpiece. In metal spinning, the further pin ascends vertically from the tool rest, and serves as a fulcrum against which tools may be levered into the workpiece.

Accessories

A steady rest

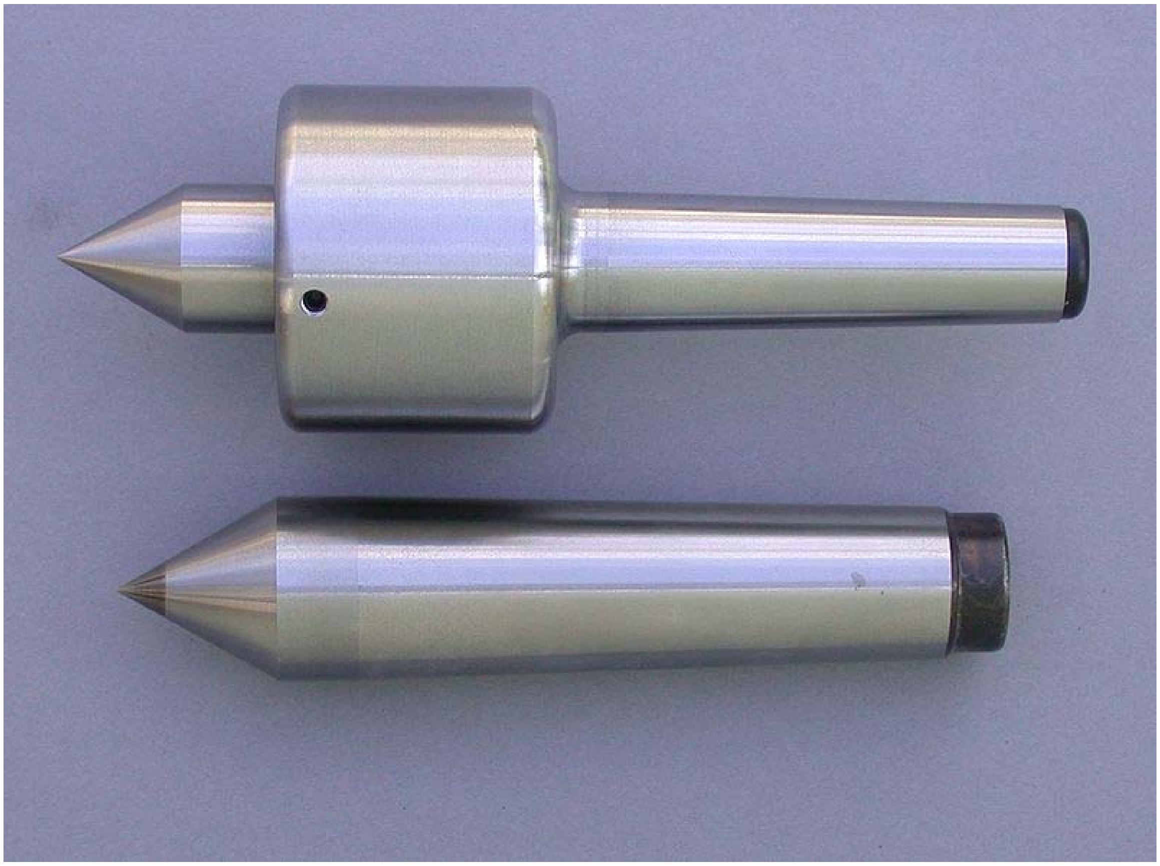
Unless a workpiece has a taper machined onto it which perfectly matches the internal taper in the spindle, or has threads which perfectly match the external threads on the spindle (two conditions which rarely exist), an accessory must be used to mount a workpiece to the spindle.

A workpiece may be bolted or screwed to a faceplate, a large, flat disk that mounts to the spindle. In the alternative, faceplate dogs may be used to secure the work to the faceplate.

A workpiece may be mounted on a mandrel, or circular work clamped in a three- or four-jaw chuck. For irregular shaped workpieces it is usual to use a four jaw (independent moving jaws) chuck. These holding devices mount directly to the Lathe headstock spindle.

In precision work, and in some classes of repetition work, cylindrical workpieces are usually held in a collet inserted into the spindle and secured either by a drawbar, or by a collet closing cap on the spindle. Suitable collets may also be used to mount square or hexagonal workpieces. In precision toolmaking work such collets are usually of the draw-in variety, where, as the collet is tightened, the workpiece moves slightly back into the headstock, whereas for most repetition work the dead length variety is preferred, as this ensures that the position of the workpiece does not move as the collet is tightened.

A soft workpiece (wooden) may be pinched between centers by using a spur drive at the headstock, which bites into the wood and imparts torque to it.



Live center (top); dead center (bottom)

A soft dead center is used in the headstock spindle as the work rotates with the centre. Because the centre is soft it can be trued in place before use. The included angle is 60°. Traditionally, a hard dead center is used together with suitable lubricant in the tailstock to support the workpiece. In modern practice the dead center is frequently replaced by a live center, as it turns freely with the workpiece — usually on ball bearings — reducing the frictional heat, especially important at high speeds. When clear facing a long length of material it must be supported at both ends. This can be achieved by the use of a travelling or fixed steady. If a steady is not available, the end face being worked on may be supported by a dead (stationary) half centre. A half centre has a flat surface machined across a broad section of half of its diameter at the pointed end. A small section of the tip of the dead centre is retained to ensure concentricity. Lubrication must be applied at this point of contact and tail stock pressure reduced. A lathe carrier or lathe dog may also be employed when turning between two centers.

In woodturning, one variation of a live center is a cup center, which is a cone of metal surrounded by an annular ring of metal that decreases the chances of the workpiece splitting.

A circular metal plate with even spaced holes around the periphery, mounted to the spindle, is called an "index plate". It can be used to rotate the spindle to a precise angle, then lock it in place, facilitating repeated auxiliary operations done to the workpiece.

Other accessories, including items such as taper turning attachments, knurling tools, vertical slides, fixed and traveling steadies, etc., increase the versatility of a lathe and the range of work it may perform.

Modes of use

When a workpiece is fixed between the headstock and the tailstock, it is said to be "between centers". When a workpiece is supported at both ends, it is more stable, and more force may be applied to the workpiece, via tools, at a right angle to the axis of rotation, without fear that the workpiece may break loose.

When a workpiece is fixed only to the spindle at the headstock end, the work is said to be "face work". When a workpiece is supported in this manner, less force may be applied to the workpiece, via tools, at a right angle to the axis of rotation, lest the workpiece rip free. Thus, most work must be done axially, towards the headstock, or at right angles, but gently.

When a workpiece is mounted with a certain axis of rotation, worked, then remounted with a new axis of rotation, this is referred to as "eccentric turning" or "multi axis turning". The result is that various cross sections of the workpiece are rotationally symmetric, but the workpiece as a whole is not rotationally symmetric. This technique is used for camshafts, various types of chair legs.

Varieties

The smallest lathes are "jewelers lathes" or "watchmaker lathes", which are small enough that they may be held in one hand. The workpieces machined on a jeweler's lathes are metal, jeweler's lathes can be used with hand-held "graver" tools or with compound rests that attach to the lathe bed. Graver tools are generally supported by a T-rest, not fixed to a cross slide or compound rest. The work is usually held in a collet. Common spindle bore sizes are 6 mm, 8 mm and 10 mm. The term W/W refers to the Webster/Whitcomb collet and lathe, invented by the American Watch Tool Company of Waltham, Massachusetts. Most lathes commonly referred to as watchmakers lathes are of this design. In 1909, the American Watch Tool company introduced the Magnus type collet (a 10-mm body size collet) using a lathe of the same basic design, the Webster/Whitcomb Magnus. (F.W.Derbyshire, Inc. retains the trade names Webster/Whitcomb and Magnus and still produces these collets.) Two bed patterns are common: the WW (Webster Whitcomb) bed, a truncated triangular prism (found only on 8 and 10 mm watchmakers' lathes); and the continental D-style bar bed (used on both 6 mm and 8 mm lathes by firms such as Lorch and Star). Other bed designs have been used, such a triangular prism on some Boley 6.5 mm lathes, and a V-edged bed on IME's 8 mm lathes.

Smaller metalworking lathes that are larger than jewelers' lathes and can sit on a bench or table, but offer such features as tool holders and a screw-cutting gear train are called hobby lathes, and larger versions, "bench lathes". Even larger lathes offering similar features for producing or modifying individual parts are called "engine lathes". Lathes of these types do not have additional integral features for repetitive production, but rather are used for individual part production or modification as the primary role.

Lathes of this size that are designed for mass manufacture, but not offering the versatile screw-cutting capabilities of the engine or bench lathe, are referred to as "second operation" lathes.

Lathes with a very large spindle bore and a chuck on both ends of the spindle are called "oil field lathes".

Fully automatic mechanical lathes, employing cams and gear trains for controlled movement, are called screw machines.

Lathes that are controlled by a computer are CNC lathes.

Lathes with the spindle mounted in a vertical configuration, instead of horizontal configuration, are called vertical lathes or vertical boring machines. They are used where very large diameters must be turned, and the workpiece (comparatively) is not very long.

A lathe with a cylindrical tailstock that can rotate around a vertical axis, so as to present different tools towards the headstock (and the workpiece) are turret lathes.

A lathe equipped with indexing plates, profile cutters, spiral or helical guides, etc., so as to enable ornamental turning is an ornamental lathe.

Various combinations are possible: for example, a vertical lathe have CNC as well (such as a CNC VTL).

Lathes can be combined with other machine tools, such as a drill press or vertical milling machine. These are usually referred to as combination lathes.

Major categories

Woodworking lathes

A modern woodworking lathe.

Woodworking lathes are the oldest variety. All other varieties are descended from these simple lathes. An adjustable horizontal metal rail - the tool rest - between the material and the operator accommodates the positioning of shaping tools, which are usually hand-held. With wood, it is common practice to press and slide sandpaper against the still-spinning object after shaping to smooth the surface made with the metal shaping tools.

There are also woodworking lathes for making bowls and plates, which have no horizontal metal rail, as the bowl or plate needs only to be held by one side from a metal face plate. Without this rail, there is very little restriction to the width of the piece being turned. Further detail can be found on the woodturning page.

Metalworking lathes

A metalworking lathe

In a metalworking lathe, metal is removed from the workpiece using a hardened cutting tool, which is usually fixed to a solid moveable mounting, either a toolpost or a turret, which is then moved against the workpiece using handwheels and/or computer controlled motors. These (cutting) tools come in a wide range of sizes and shapes depending upon their application. Some common styles are diamond, round, square and triangular.

The toolpost is operated by leadscrews that can accurately position the tool in a variety of planes. The toolpost may be driven manually or automatically to produce the roughing and finishing cuts required to *turn* the workpiece to the desired shape and dimensions, or for cutting threads, worm gears, etc. Cutting fluid may also be pumped to the cutting site to provide cooling, lubrication and clearing of swarf from the workpiece. Some lathes may be operated under control of a computer for mass production of parts.

Manually controlled metalworking lathes are commonly provided with a variable ratio gear train to drive the main leadscrew. This enables different thread pitches to be cut. On some older lathes or more affordable new lathes, the gear trains are changed by swapping gears with various numbers of teeth onto or off of the shafts, while more modern or expensive manually controlled lathes have a **quick change box** to provide commonly used ratios by the operation of a lever. CNC lathes use computers and servomechanisms to regulate the rates of movement.

On manually controlled lathes, the thread pitches that can be cut are, in some ways, determined by the pitch of the leadscrew: A lathe with a metric leadscrew will readily cut metric threads (including BA), while one with an imperial leadscrew will readily cut imperial unit based threads such as BSW or UTS (UNF,UNC). This limitation is not insurmountable, because a 127-tooth gear, called a transposing gear, is used to translate between metric and inch thread pitches. However, this is optional equipment that many lathe owners do not own. It is also a larger changewheel than the others, and on some lathes may be larger than the changewheel mounting banjo is capable of mounting.

The workpiece may be supported between a pair of points called centres, or it may be bolted to a faceplate or held in a chuck. A chuck has movable jaws that can grip the workpiece securely.

There are some effects on material properties when using a metalworking lathe. There are few chemical or physical effects, but there are many mechanical effects, which include residual stress, microcracks, workhardening, and tempering in hardened materials.

Cue lathes

Cue lathes function similar to turning and spinning lathes allowing for a perfectly radially-symmetrical cut for billiard cues. They can also be used to refinish cues that have been worn over the years.

Glassworking lathes

Glassworking lathes are similar in design to other lathes, but differ markedly in how the workpiece is modified. Glassworking lathes slowly rotate a hollow glass vessel over a fixed or variable temperature flame. The source of the flame may be either hand-held, or mounted to a banjo/cross slide that can be moved along the lathe bed. The flame serves to soften the glass being worked, so that the glass in a specific area of the workpiece becomes malleable, and subject to forming either by inflation ("glassblowing"), or by deformation with a heat resistant tool. Such lathes usually have two headstocks with chucks holding the work, arranged so that they both rotate together in unison. Air can be introduced through the headstock chuck spindle for glassblowing. The tools to deform the glass and tubes to blow (inflate) the glass are usually handheld.

In diamond turning, a computer-controlled lathe with a diamond-tipped tool is used to make precision optical surfaces in glass or other optical materials. Unlike conventional optical grinding, complex aspheric surfaces can be machined easily. Instead of the dovetailed ways used on the tool slide of a metal turning lathe, the ways typically float on air bearings and the position of the tool is measured by optical interferometry to achieve the necessary standard of precision for optical work. The finished work piece usually requires a small amount subsequent polishing by conventional techniques to achieve a finished surface suitably smooth for use in a lens, but the rough grinding time is significantly reduced for complex lenses.

Metal spinning lathes

In metal spinning, a disk of sheet metal is held perpendicularly to the main axis of the lathe, and tools with polished tips (*spoons*) are hand held, but levered by hand against fixed posts, to develop large amounts of torque/pressure that deform the spinning sheet of metal.

Metal spinning lathes are almost as simple as woodturning lathes (and, at this point, lathes being used for metal spinning almost always *are* woodworking lathes). Typically, metal spinning lathes require a user-supplied rotationally symmetric mandrel, usually made of wood, which serves as a template onto which the workpiece is moulded (non-symmetric shapes *can* be done, but it is a very advanced technique). For example, if you want to make a sheet metal bowl, you need a solid chunk of wood in the shape of the bowl; if you want to make a vase, you need a solid template of a vase, etc.

Given the advent of high speed, high pressure, industrial die forming, metal spinning is less common now than it once was, but still a valuable technique for producing one-off prototypes or small batches where die forming would be uneconomical.

Ornamental turning lathes

The ornamental turning lathe was developed around the same time as the industrial screwcutting lathe in the nineteenth century. It was used not for making practical objects, but for decorative work - *ornamental turning*. By using accessories such as the horizontal and vertical cutting frames, eccentric chuck and elliptical chuck, solids of extraordinary complexity may be produced by various generative procedures.

A special purpose lathe, the Rose engine lathe is also used for ornamental turning, in particular for engine turning, typically in precious metals, for example to decorate pocket watch cases. As well as a wide range of accessories, these lathes usually have complex dividing arrangements to allow the exact rotation of the mandrel. Cutting is usually carried out by rotating cutters, rather than directly by the rotation of the work itself. Because of the difficulty of polishing such work, the materials turned, such as wood or ivory, are usually quite soft, and the cutter has to be exceptionally sharp. The finest ornamental lathes are generally considered to be those made by Holtzapffel around the turn of the 19th century.

Reducing lathe

Many types of lathes can be equipped with accessory components to allow them to reproduce an item: the original item is mounted on one spindle, the blank is mounted on another, and as both turn in synchronized manner, one end of an arm "reads" the original and the other end of the arm "carves" the duplicate.

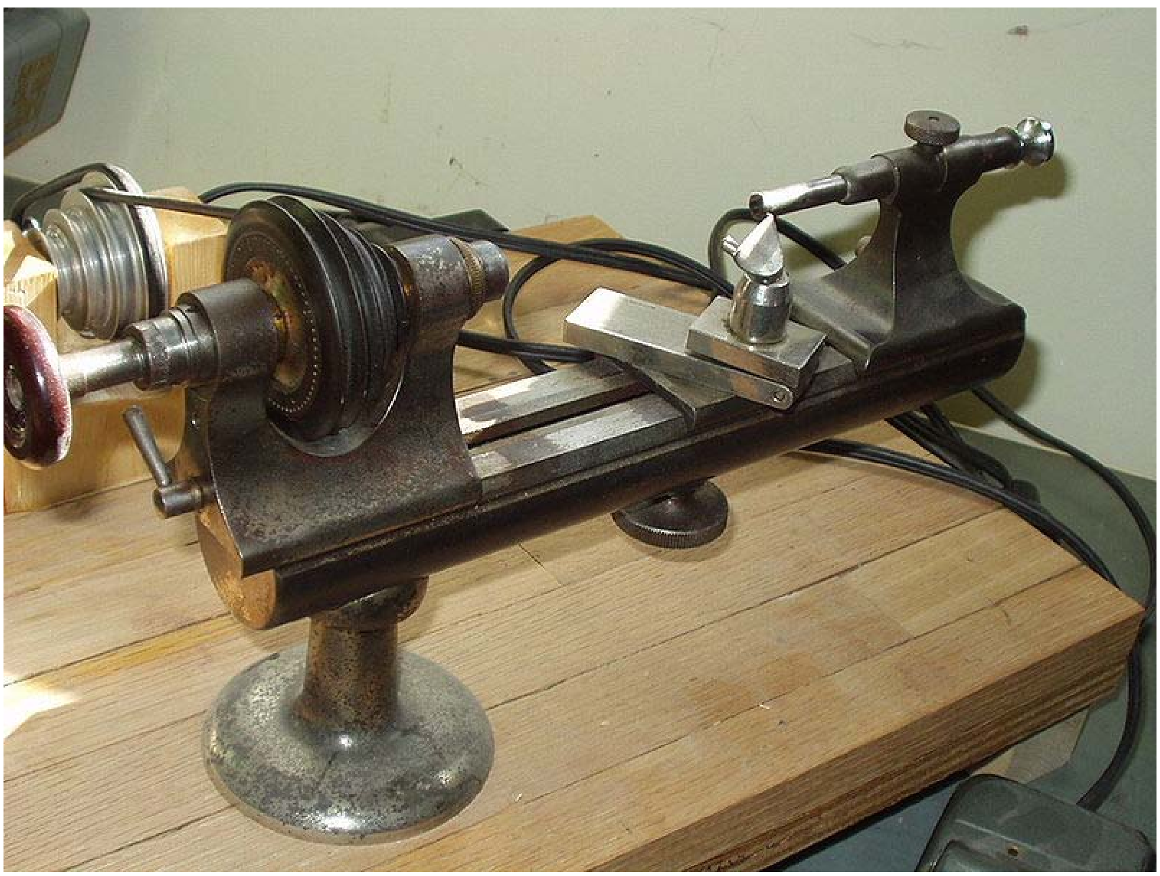
A **reducing lathe** is a specialized lathe that is designed with this feature, and which incorporates a mechanism similar to a pantograph, so that when the "reading" end of the arm reads a detail that measures one inch (for example), the cutting end of the arm creates an analogous detail that is (for example) one quarter of an inch (a 4:1 reduction, although given appropriate machinery and appropriate settings, any reduction ratio is possible).

Reducing lathes are used in coin-making, where a plaster original (or an epoxy master made from the plaster original, or a copper shelled master made from the plaster original, etc.) is duplicated and reduced on the reducing lathe, generating a master die.

Rotary lathes

A lathe in which softwood, like spruce or pine, or hardwood, like birch, logs are turned against a very sharp blade and peeled off in one continuous or semi-continuous roll. Invented by Immanuel Nobel (father of the more famous Alfred Nobel). The first such lathes were set up in the United States in the mid-19th century. The product is called wood veneer and it is used for finishing chipboard objects and making plywood.

Watchmaker's lathes



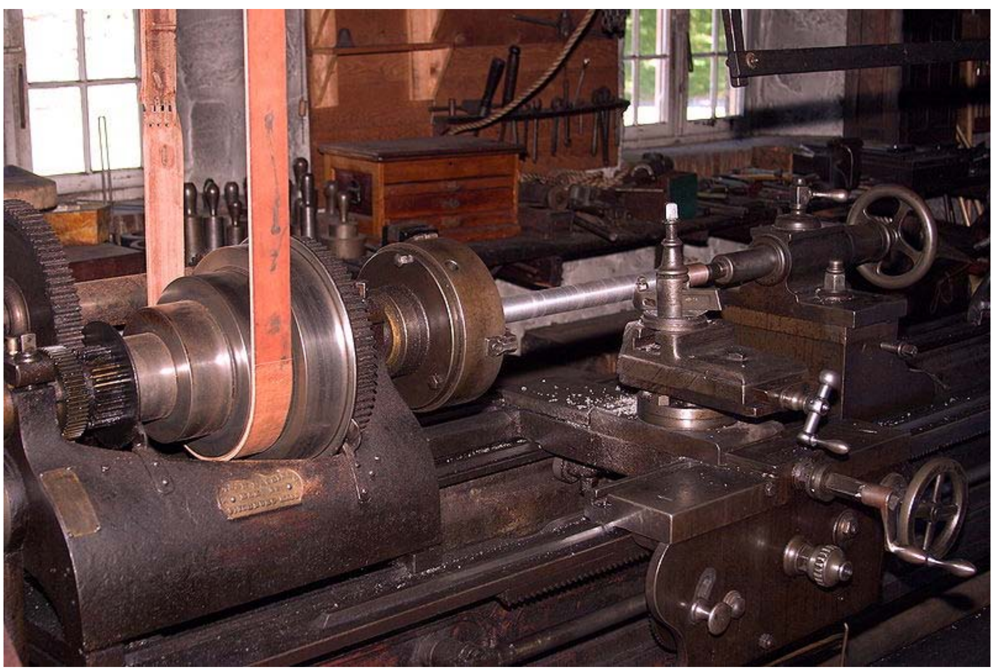
Watchmaker's lathe

Watchmakers lathes are delicate but precise metalworking lathes, usually without provision for screwcutting, and are still used by horologists for work such as the turning of balance shafts. A handheld tool called a graver is often used in preference to a slide mounted tool. The original watchmaker's turns was a simple dead-centre lathe with a moveable rest and two loose headstocks. The workpiece would be rotated by a bow, typically of horsehair, wrapped around it.

Examples of lathes

Small metalworking lathe

Large old lathe



Belt-driven metalworking lathe in the machine shop at Hagley Museum

Examples of work produced from a lathe

Lathe exercise

Turned chess pieces

Chapter 10

Propeller

Rotating the Hamilton Standard 54H60 propeller on a US Navy EP-3E Orion's number four engine as part of pre-flight checks

A **propeller** is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the airfoil-shaped blade, and air or water is accelerated behind the blade. Propeller dynamics can be modeled by both Bernoulli's principle and Newton's third law. A propeller is often colloquially known as **screw** both in aviation and maritime.

History

Ship propeller from 1843. Designed by C F Wahlgren based on one of John Ericsson propellers. It was fitted to the steam ship s/s *Flygfisken* built at the Motala dockyard.

The principle employed in using a screw propeller is used in sculling. It is part of the skill of propelling a Venetian gondola but was used in a less refined way in other parts of

Europe and probably elsewhere. For example, propelling a canoe with a single paddle using a "j-stroke" involves a related but not identical technique. In China, sculling, called "lu", was also used by the 3rd century AD.

In sculling, a single blade is moved through an arc, from side to side taking care to keep presenting the blade to the water at the effective angle. The innovation introduced with the screw propeller was the extension of that arc through more than 360° by attaching the blade to a rotating shaft. Propellers can have a single blade, but in practice there are nearly always more than one so as to balance the forces involved.

The origin of the actual screw propeller starts with Archimedes, who used a screw to lift water for irrigation and bailing boats, so famously that it became known as Archimedes' screw. It was probably an application of spiral movement in space (spirals were a special study of Archimedes) to a hollow segmented water-wheel used for irrigation by Egyptians for centuries. Leonardo da Vinci adopted the principle to drive his theoretical helicopter, sketches of which involved a large canvas screw overhead.

In 1784, J. P. Paucton proposed a gyrocopter-like aircraft using similar screws for both lift and propulsion. At about the same time, James Watt proposed using screws to propel boats, although he did not use them for his steam engines. This was not his own invention, though; Toogood and Hays had patented it a century earlier, and it had become a common use as a means of propelling boats since that time.

By 1827, Czech constructor Josef Ressel had invented a screw propeller which had multiple blades fastened around a conical base; this new method of propulsion allowed steam ships to travel at much greater speeds without using sails thereby making ocean travel faster (first tests with the Austro-Hungarian Navy).

John Patch, a mariner in Yarmouth, Nova Scotia developed a two-bladed, fan-shaped propeller in 1832 and publicly demonstrated it in 1833, propelling a row boat across Yarmouth Harbour and a small coastal schooner at Saint John, New Brunswick, but his patent application in the United States was rejected until 1849 because he was not American citizen His efficient design drew praise in American scientific circles but by this time there were multiple competing versions of the marine propeller.

In 1835, when Francis Pettit Smith discovered a new way of building propellers. Up to that time, propellers were literally screws, of considerable length. But during the testing of a boat propelled by one, the screw snapped off, leaving a fragment shaped much like a modern boat propeller. The boat moved faster with the broken propeller. At about the same time, Frédéric Sauvage and John Ericsson applied for patents on vaguely similar, although less efficient shortened-screw propellers, leading to an apparently permanent controversy as to who the official inventor is among those three men. Ericsson became widely famous when he built the *Monitor*, an armoured battleship that in 1862 fought the Confederate States' *Virginia* in an American Civil War sea battle.

The first screw propeller to be powered by a gasoline engine, fitted to a small boat (now known as a powerboat) was installed by Frederick Lanchester, also from Birmingham. This was tested in Oxford. The first 'real-world' use of a propeller was by David Bushnell, who used hand-powered screw propellers to navigate his submarine "Turtle" in 1776.

The superiority of screw against paddles was taken up by navies. Trials with Smith's SS *Archimedes*, the first steam driven screw, led to the famous tug-of-war competition in 1845 between the screw-driven HMS *Rattler* and the paddle steamer HMS *Alecto*; the former pulling the latter backward.

In the second half of the nineteenth century, several theories were developed. The momentum theory or Disk actuator theory—a theory describing a mathematical model of an ideal propeller—was developed by W.J.M. Rankine (1865), Alfred George Greenhill (1888) and R.E. Froude (1889). The propeller is modeled as an infinitely thin disc, inducing a constant velocity along the axis of rotation. This disc creates a flow around the propeller. Under certain mathematical premises of the fluid, there can be extracted a mathematical connection between power, radius of the propeller, torque and induced velocity. Friction is not included.

The blade element theory (BET) is a mathematical process originally designed by William Froude (1878), David W. Taylor (1893) and Stefan Drzewiecki to determine the behavior of propellers. It involves breaking an airfoil down into several small parts then determining the forces on them. These forces are then converted into accelerations, which can be integrated into velocities and positions.

A World War I wooden aircraft propeller on a workbench.

The twisted airfoil (aerofoil) shape of modern aircraft propellers was pioneered by the Wright brothers. While both the blade element theory and the momentum theory had their supporters, the Wright brothers were able to combine both theories. They found that a propeller is essentially the same as a wing and so were able to use data collated from their earlier wind tunnel experiments on wings. They also found that the relative angle of attack from the forward movement of the aircraft was different for all points along the length of the blade, thus it was necessary to introduce a twist along its length. Their original propeller blades are only about 5% less efficient than the modern equivalent, some 100 years later.

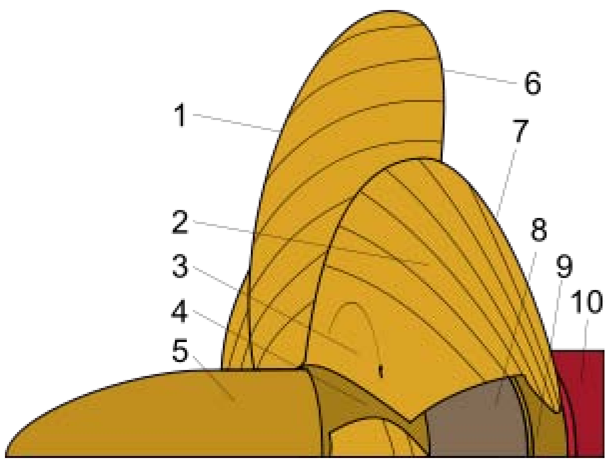
Alberto Santos Dumont was another early pioneer, having designed propellers before the Wright Brothers (albeit not as efficient) for his airships. He applied the knowledge he gained from experiences with airships to make a propeller with a steel shaft and aluminium blades for his 14 bis biplane. Some of his designs used a bent aluminium sheet for blades, thus creating an airfoil shape. These are heavily undercambered because of this and combined with the lack of a lengthwise twist made them less efficient than the Wright propellers. Even so, this was perhaps the first use of aluminium in the construction of an airscrew.

Aviation

Aircraft propellers convert rotary motion from piston engines or turboprops to provide propulsive force. They may be fixed or variable pitch. Early aircraft propellers were carved by hand from solid or laminated wood with later propellers being constructed from metal. The most modern propeller designs use high-technology composite materials.

Marine

Marine propeller nomenclature



1) Trailing edge	6) Leading edge
2) Face	7) Back
3) Fillet area	8) Propeller shaft
4) Hub or Boss	9) Stern tube bearing
5) Hub or Boss Cap	10) Stern tube

A propeller is the most common propulsor on ships, imparting momentum to a fluid which causes a force to act on the ship.

The ideal efficiency of any size propeller (free-tip) is that of an actuator disc in an ideal fluid. An actual marine propeller is made up of sections of helicoidal surfaces which act together 'screwing' through the water (hence the common reference to marine propellers as "screws"). Three, four, or five blades are most common in marine propellers, although designs which are intended to operate at reduced noise will have more blades. The blades are attached to a *boss* (hub), which should be as small as the needs of strength allow - with fixed pitch propellers the blades and boss are usually a single casting.

An alternative design is the controllable pitch propeller (CPP, or CRP for controllable-reversible pitch), where the blades are rotated normal to the drive shaft by additional machinery - usually hydraulics - at the hub and control linkages running down the shaft. This allows the drive machinery to operate at a constant speed while the propeller loading is changed to match operating conditions. It also eliminates the need for a reversing gear and allows for more rapid change to thrust, as the revolutions are constant. This type of propeller is most common on ships such as tugs where there can be enormous differences in propeller loading when towing compared to running free, a change which could cause conventional propellers to lock up as insufficient torque is generated. The downsides of a CPP/CRP include: the large hub which decreases the torque required to cause cavitation, the mechanical complexity which limits transmission power and the extra blade shaping requirements forced upon the propeller designer.

For smaller motors there are self-pitching propellers. The blades freely move through an entire circle on an axis at right angles to the shaft. This allows hydrodynamic and centrifugal forces to 'set' the angle the blades reach and so the pitch of the propeller.

A propeller that turns clockwise to produce forward thrust, when viewed from aft, is called right-handed. One that turns anticlockwise is said to be left-handed. Larger vessels often have twin screws to reduce *heeling torque*, counter-rotating propellers, the starboard screw is usually right-handed and the port left-handed, this is called outward turning. The opposite case is called inward turning. Another possibility is contra-rotating propellers, where two propellers rotate in opposing directions on a single shaft, or on separate shafts on nearly the same axis. One example of the latter is the CRP Azipod by the ABB Group. Contra-rotating propellers offer increased efficiency by capturing the energy lost in the tangential velocities imparted to the fluid by the forward propeller (known as "propeller swirl"). The flow field behind the aft propeller of a contra-rotating set has very little "swirl", and this reduction in energy loss is seen as an increased efficiency of the aft propeller.

Additional designs

An azimuthing propeller is a vertical axis propeller.

The blade outline is defined either by a projection on a plane normal to the propeller shaft (*projected outline*) or by setting the circumferential chord across the blade at a given radius against radius (*developed outline*). The outline is usually symmetrical about a given radial line termed the *median*. If the median is curved back relative to the direction of rotation the propeller is said to have *skew back*. The skew is expressed in terms of circumferential displacement at the blade tips. If the blade face in profile is not normal to the axis it is termed *raked*, expressed as a percentage of total diameter.

Each blade's pitch and thickness varies with radius, early blades had a flat face and an arced back (sometimes called a circular back as the arc was part of a circle), modern propeller blades have aerofoil sections. The *camber line* is the line through the mid-thickness of a single blade. The *camber* is the maximum difference between the camber line and the *chord* joining the trailing and leading edges. The camber is expressed as a percentage of the chord.

The radius of maximum thickness is usually forward of the mid-chord point with the blades thinning to a minimum at the tips. The thickness is set by the demands of strength and the ratio of thickness to total diameter is called *blade thickness fraction.*

The ratio of pitch to diameter is called *pitch ratio*. Due to the complexities of modern propellers a nominal pitch is given, usually a radius of 70% of the total is used.

Blade area is given as a ratio of the total area of the propeller disc, either as *developed blade area ratio* or *projected blade area ratio*.

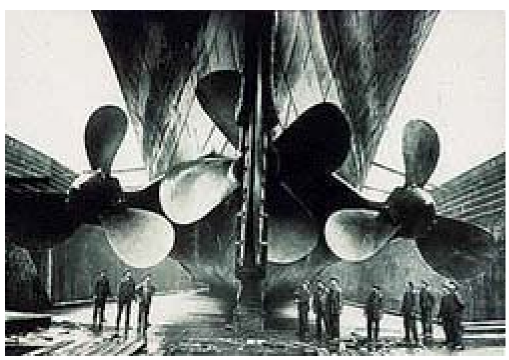
Transverse axis propellers

Most propellers have their axis of rotation parallel to the fluid flow. There have however been some attempts to power vehicles with the same principles behind vertical axis wind turbines, where the rotation is perpendicular to fluid flow. Most attempts have been unsuccessful. Blades that can vary their angle of attack during rotation have aerodynamics similar to flapping flight. Flapping flight is still poorly understood and almost never seriously used in engineering because of the strong coupling of lift, thrust and control forces.

The fanwing is one of the few types that has actually flown. It takes advantage of the trailing edge of an airfoil to help encourage the circulation necessary for lift.

The Voith-Schneider propeller pictured below is another successful example, operating in water.

History of ship and submarine screw propellers



Propellers of the *Titanic*: 2 triple-blade and 1 quadruple-blade at center

A propeller from the *Lusitania*

Propeller on a modern mid-sized merchant vessel

James Watt of Scotland is generally credited with applying the first screw propeller to an engine, an early steam engine, beginning the use of an hydrodynamic screw for propulsion.

Mechanical ship propulsion began with the steam ship. The first successful ship of this type is a matter of debate; candidate inventors of the 18th century include William Symington, the Marquis de Jouffroy, John Fitch and Robert Fulton, however William

Symington's ship the *Charlotte Dundas* is regarded as the world's "first practical steamboat". Paddlewheels as the main motive source became standard on these early vessels. Robert Fulton had tested, and rejected, the screw propeller.

Sketch of hand-cranked vertical and horizontal screws used in Bushnell's *Turtle*, 1775

The screw (as opposed to paddlewheels) was introduced in the latter half of the 18th century. David Bushnell's invention of the submarine (Turtle) in 1775 used hand-powered screws for vertical and horizontal propulsion. The Bohemian engineer Josef Ressel designed and patented the first practicable screw propeller in 1827. Francis Pettit Smith tested a similar one in 1836. In 1839, John Ericsson introduced practical screw propulsion into the United States. Mixed paddle and propeller designs were still being used at this time (*vide* the 1858 *SS Great Eastern*).

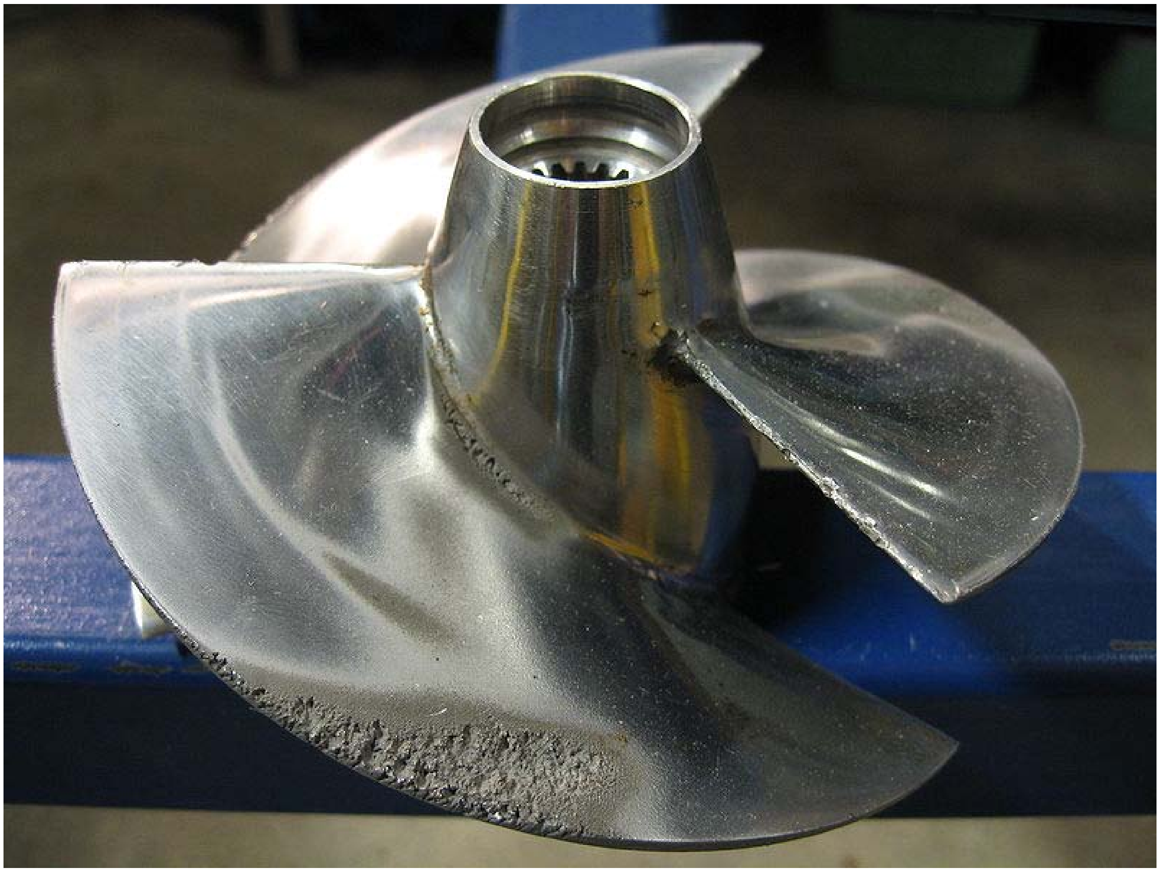
In 1848 the British Admiralty held a tug of war contest between a propeller driven ship, *Rattler*, and a paddle wheel ship, *Alecto*. *Rattler* won, towing *Alecto* astern at 2.5 knots (4.6 km/h), but it was not until the early 20th century that paddle propelled vessels were entirely superseded. The screw propeller replaced the paddles owing to its greater efficiency, compactness, less complex power transmission system, and reduced susceptibility to damage (especially in battle)

Voith-Schneider propeller

Initial designs owed much to the ordinary screw from which their name derived - early propellers consisted of only two blades and matched in profile the length of a single screw rotation. This design was common, but inventors endlessly experimented with different profiles and greater numbers of blades. The propeller screw design stabilized by the 1880s.

In the early days of steam power for ships, when both paddle wheels and screws were in use, ships were often characterized by their type of propellers, leading to terms like screw steamer or screw sloop.

Propellers are referred to as "lift" devices, while paddles are "drag" devices.



Cavitation damage evident on the propeller of a personal watercraft.

Marine propeller cavitation

Cavitation can occur if an attempt is made to transmit too much power through the screw, or if the propeller is operating at a very high speed. Cavitation can occur in many ways on a propeller. The two most common types of propeller cavitation are suction side surface cavitation and tip vortex cavitation.

Suction side surface cavitation forms when the propeller is operating at high rotational speeds or under heavy load (high blade lift coefficient). The pressure on the upstream surface of the blade (the "suction side") can drop below the vapour pressure of the water, resulting in the formation of a pocket of vapour. Under such conditions, the change in pressure between the downstream surface of the blade (the "pressure side") and the suction side is limited, and eventually reduced as the extent of cavitation is increased. When most of the blade surface is covered by cavitation, the pressure difference between the pressure side and suction side of the blade drops considerably, and thrust produced by the propeller drops. This condition is called "thrust breakdown". This effect wastes energy, makes the propeller "noisy" as the vapour bubbles collapse, and most seriously, erodes the screw's surface due to localized shock waves against the blade surface.

Tip vortex cavitation is caused by the extremely low pressures formed at the core of the tip vortex. The tip vortex is caused by fluid wrapping around the tip of the propeller; from the pressure side to the suction side. This video demonstrates tip vortex cavitation well. Tip vortex cavitation typically occurs before suction side surface cavitation and is less damaging to the blade, since this type of cavitation doesn't collapse on the blade, but some distance downstream.

Cavitation can be used as an advantage in design of very high performance propellers, in form of the supercavitating propeller. In this case, the blade section is designed such that the pressure side stays wetted while the suction side is completely covered by cavitation vapor. Because the suction side is covered with vapor instead of water it encounters very low viscous friction, making the supercavitating (SC) propeller comparably efficient at high speed. The shaping of SC blade sections however, make it inefficient at low speeds, when the suction side of the blade is wetted.

A similar, but quite separate issue, is *ventilation,* which occurs when a propeller operating near the surface draws air into the blades, causing a similar loss of power and shaft vibration, but without the related potential blade surface damage caused by cavitation. Both effects can be mitigated by increasing the submerged depth of the propeller: cavitation is reduced because the hydrostatic pressure increases the margin to the vapor pressure, and ventilation because it is further from surface waves and other air pockets that might be drawn into the slipstream.

14-ton propeller from *Voroshilov* a Kirov class cruiser on display in Sevastopol

Forces acting on an aerofoil

The force (F) experienced by an aerofoil blade is determined by its area (A), chord (c), velocity (V) and the angle of the aerofoil to the flow, called *angle of attack* (α), where:

$$\frac{F}{\rho A V^2} = f(R_n, \alpha)$$

The force has two parts - that normal to the direction of flow is *lift* (L) and that in the direction of flow is *drag* (D). Both are expressed non-dimensionally as:

$$C_L = \frac{L}{\frac{1}{2}\rho A V^2} \text{ and } C_D = \frac{D}{\frac{1}{2}\rho A V^2}$$

Each coefficient is a function of the angle of attack and Reynolds' number. As the angle of attack increases lift rises rapidly from the *no lift angle* before slowing its increase and then decreasing, with a sharp drop as the *stall angle* is reached and flow is disrupted. Drag rises slowly at first and as the rate of increase in lift falls and the angle of attack increases drag increases more sharply.

For a given strength of circulation (τ), Lift = $L = \rho V \tau$. The effect of the flow over and the circulation around the aerofoil is to reduce the velocity over the face and increase it over the back of the blade. If the reduction in pressure is too much in relation to the ambient pressure of the fluid, *cavitation* occurs, bubbles form in the low pressure area and are moved towards the blade's trailing edge where they collapse as the pressure increases, this reduces propeller efficiency and increases noise. The forces generated by the bubble collapse can cause permanent damage to the surfaces of the blade.

Propeller thrust

Single blade

Taking an arbitrary radial section of a blade at *r*, if revolutions are *N* then the rotational velocity is $2\pi N r$. If the blade was a complete screw it would advance through a solid at the rate of *NP*, where *P* is the pitch of the blade. In water the advance speed is rather lower, V_a, the difference, or *slip ratio*, is:

$$\text{Slip} = \frac{NP - V_a}{NP} = 1 - \frac{J}{p}$$

where $J = \frac{V_a}{ND}$ is the *advance coefficient*, and $p = \frac{P}{D}$ is the *pitch ratio*.

The forces of lift and drag on the blade, *dA*, where force normal to the surface is *dL*:

$$\mathrm{d}L = \frac{1}{2}\rho V_1^2 C_L dA = \frac{1}{2}\rho C_L [V_a^2(1+a)^2 + 4\pi^2 r^2 (1-a')^2] b\mathrm{d}r$$

where:

$$V_1^2 = V_a^2(1+a)^2 + 4\pi^2 r^2 (1-a')^2$$
$$\mathrm{d}D = \frac{1}{2}\rho V_1^2 C_D \mathrm{d}A = \frac{1}{2}\rho C_D [V_a^2(1+a)^2 + 4\pi^2 r^2 (1-a')^2] b\mathrm{d}r$$

These forces contribute to thrust, *T*, on the blade:

$$\mathrm{d}T = \mathrm{d}L\cos\varphi - \mathrm{d}D\sin\varphi = \mathrm{d}L(\cos\varphi - \frac{\mathrm{d}D}{\mathrm{d}L}\sin\varphi)$$

where:

$$tan\beta = \frac{\mathrm{d}D}{\mathrm{d}L} = \frac{C_D}{C_L}$$
$$= \frac{1}{2}\rho V_1^2 C_L \frac{\cos(\varphi+\beta)}{\cos\beta} b\mathrm{d}r$$

As $V_1 = \frac{V_a(1+a)}{\sin\varphi}$,

$$\mathrm{d}T = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\cos(\varphi+\beta)}{\sin^2\varphi\cos\beta} b\mathrm{d}r$$

From this total thrust can be obtained by integrating this expression along the blade. The transverse force is found in a similar manner:

$$\mathrm{d}M = \mathrm{d}L\sin\varphi + \mathrm{d}D\cos\varphi$$
$$= \mathrm{d}L(\sin\varphi + \frac{\mathrm{d}D}{\mathrm{d}L}\cos\varphi)$$
$$= \frac{1}{2}\rho V_1^2 C_L \frac{\sin(\varphi+\beta)}{\cos\varphi} b\mathrm{d}r$$

Substituting for $V_1$and multiplying by *r*, gives torque as:

$$\mathrm{d}Q = r\mathrm{d}M = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\sin(\varphi+\beta)}{\sin^2\varphi\cos\beta} br\mathrm{d}r$$

which can be integrated as before.

The total thrust power of the propeller is proportional to $TV_a$and the shaft power to $2\pi NQ$. So efficiency is $\frac{TV_a}{2\pi NQ}$. The blade efficiency is in the ratio between thrust and torque:

$$\text{blade element efficiency} = \frac{V_a}{2\pi Nr} \cdot \frac{1}{\tan(\varphi + \beta)}$$

showing that the blade efficiency is determined by its momentum and its qualities in the form of angles $\varphi$and β, where $\beta$is the ratio of the drag and lift coefficients.

This analysis is simplified and ignores a number of significant factors including interference between the blades and the influence of tip vortices.

Thrust and torque

The thrust, T, and torque, Q, depend on the propeller's diameter, D, revolutions, N, and rate of advance, V_a, together with the character of the fluid in which the propeller is operating and gravity. These factors create the following non-dimensional relationship:

$$T = \rho V^2 D^2 [f_1(\frac{ND}{V_a}), f_2(\frac{v}{V_a D}), f_3(\frac{gD}{V_a^2})]$$

where f_1 is a function of the advance coefficient, f_2 is a function of the Reynolds' number, and f_3 is a function of the Froude number. Both f_2 and f_3 are likely to be small in comparison to f_1 under normal operating conditions, so the expression can be reduced to:

$$T = \rho V_a^2 D^2 \times f_r(\frac{ND}{V_a})$$

For two identical propellers the expression for both will be the same. So with the propellers T_1,T_2, and using the same subscripts to indicate each propeller:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{V_{a1}^2}{V_{a2}^2} \times \frac{D_1^2}{D_2^2}$$

For both Froude number and advance coefficient:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{D_1^3}{D_2^3} = \frac{\rho_1}{\rho_2} \lambda^3$$

where λ is the ratio of the linear dimensions.

Thrust and velocity, at the same Froude number, give thrust power:

$$\frac{P_{T1}}{P_{T2}} = \frac{\rho_1}{\rho_2}\lambda^{3.5}$$

For torque:

$$Q = \rho V_a^2 D^3 \times f_q\left(\frac{ND}{V_a}\right)$$

...

Actual performance

When a propeller is added to a ship its performance is altered; there is the mechanical losses in the transmission of power; a general increase in total resistance; and the hull also impedes and renders non-uniform the flow through the propeller. The ratio between a propeller's efficiency attached to a ship (P_D) and in open water (P'_D) is termed *relative rotative efficiency.*

The *overall propulsive efficiency* (an extension of *effective power* (P_E)) is developed from the *propulsive coefficient* (PC), which is derived from the installed shaft power (P_S) modified by the effective power for the hull with appendages (P'_E), the propeller's thrust power (P_T), and the relative rotative efficiency.

P'_E/P_T = hull efficiency = η_H
P_T/P'_D = propeller efficiency = η_O
P'_D/P_D = relative rotative efficiency = η_R
P_D/P_S = shaft transmission efficiency

Producing the following:

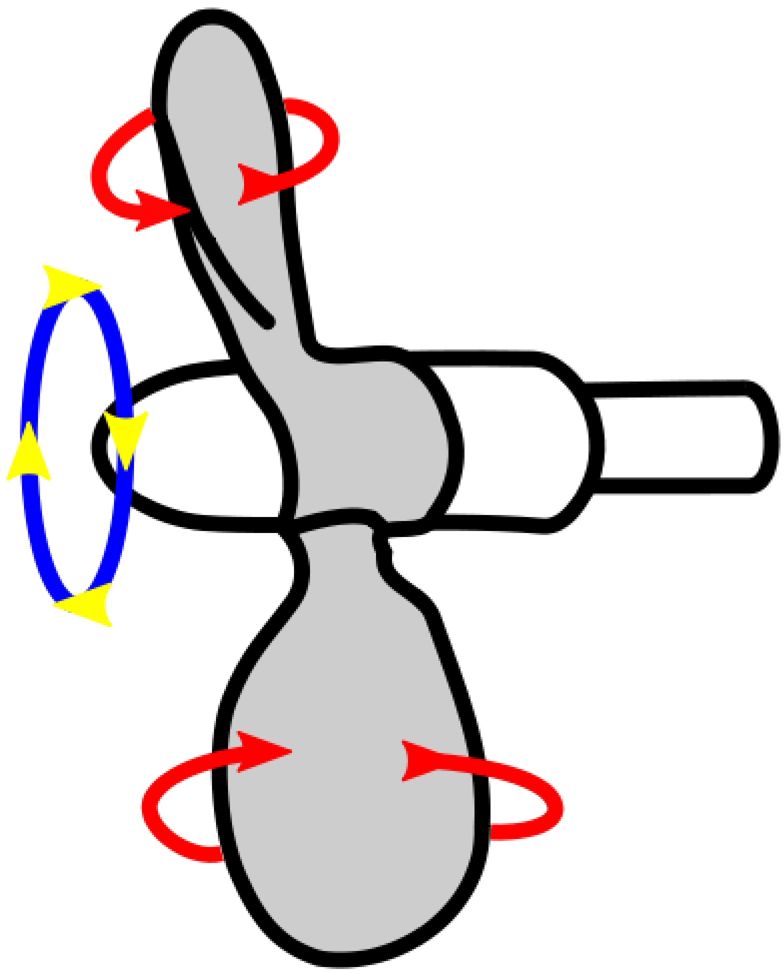
$$PC = \left(\frac{\eta_H \cdot \eta_O \cdot \eta_R}{\text{appendage coefficient}}\right) \cdot \text{transmission efficiency}$$

The terms contained within the brackets are commonly grouped as the *quasi-propulsive coefficient* (QPC, η_D). The $QPC$is produced from small-scale experiments and is modified with a load factor for full size ships.

Wake is the interaction between the ship and the water with its own velocity relative to the ship. The wake has three parts: the velocity of the water around the hull; the boundary layer between the water dragged by the hull and the surrounding flow; and the waves created by the movement of the ship. The first two parts will reduce the velocity of water into the propeller, the third will either increase or decrease the velocity depending on whether the waves create a crest or trough at the propeller.

Types of marine propellers

Controllable pitch propeller



A controllable pitch propeller

At present, one of the newest and best type of propeller is the controllable pitch propeller. This propeller has several advantages with ships. These advantages include: the least drag depending on the speed used, the ability to move the sea vessel backwards, and the ability to use the "vane"-stance, which gives the least water resistance when not using the propeller (e.g. when the sails are used instead).

Skewback propeller

An advanced type of propeller used on German Type 212 submarines is called a **skewback propeller**. As in the scimitar blades used on some aircraft, the blade tips of a skewback propeller are swept back against the direction of rotation. In addition, the blades are tilted rearward along the longitudinal axis, giving the propeller an overall cup-shaped appearance. This design preserves thrust efficiency while reducing cavitation, and thus makes for a quiet, stealthy design.

Modular propeller

A modular propeller provides more control over the boats performance. There is no need to change an entire prop, when there is an opportunity to only change the pitch or the damaged blades. Being able to adjust pitch will allow for boaters to have better performance while in different altitudes, water sports, and/or cruising.

Protection of small engines

A failed rubber bushing in an outboard's propeller

For smaller engines, such as outboards, where the propeller is exposed to the risk of collision with heavy objects, the propeller often includes a device which is designed to fail when over loaded; the device or the whole propeller is sacrificed so that the more expensive transmission and engine are not damaged.

Typically in smaller (less than 10 hp/7.5 kW) and older engines, a narrow shear pin through the drive shaft and propeller hub transmits the power of the engine at normal loads. The pin is designed to shear when the propeller is put under a load that could damage the engine. After the pin is sheared the engine is unable to provide propulsive power to the boat until an undamaged shear pin is fitted. Note that some shear pins used to have shear grooves machined into them. Nowadays the grooves tend to be omitted. The result of this oversight is that the torque required to shear the pin rises as the cutting edges of the propeller bushing and shaft become blunted. Eventually the gears will strip instead.

In larger and more modern engines, a rubber bushing transmits the torque of the drive shaft to the propeller's hub. Under a damaging load the friction of the bushing in the hub is overcome and the rotating propeller slips on the shaft preventing overloading of the engine's components. After such an event the rubber bushing itself may be damaged. If so, it may continue to transmit reduced power at low revolutions but may provide no power, due to reduced friction, at high revolutions. Also the rubber bushing may perish over time leading to its failure under loads below its designed failure load.

Whether a rubber bushing can be replaced or repaired depends upon the propeller; some cannot. Some can but need special equipment to insert the oversized bushing for an interference fit. Others can be replaced easily.

The "special equipment" usually consists of a tapered funnel, some kind of press and rubber lubricant (soap). Often the bushing can be drawn into place with nothing more complex than a couple of nuts, washers and "allscrew" (threaded bar). If one does not have access to a lathe an improvised funnel can be made from steel tube and car body filler! (as the filler is only subject to compressive forces it is able to do a good job) A more serious problem with this type of propeller is a "frozen-on" spline bushing which makes propeller removal impossible. In such cases the propeller has to be heated in order to deliberately destroy the rubber insert. Once the propeller proper is removed, the splined tube can be cut away with a grinder. A new spline bushing is of course required. To prevent the problem recurring the splines can be coated with anti-seize anti-corrosion compound.

In some modern propellers, a hard polymer insert called a *drive sleeve* replaces the rubber bushing. The splined or other non-circular cross section of the sleeve inserted between the shaft and propeller hub transmits the engine torque to the propeller, rather than friction. The polymer is weaker than the components of the propeller and engine so it fails before they do when the propeller is overloaded. This fails completely under excessive load but can easily be replaced.

Chapter 11

Turbine

A steam turbine with the case opened.

A **turbine** is a rotary engine that extracts energy from a fluid flow and converts it into useful work.

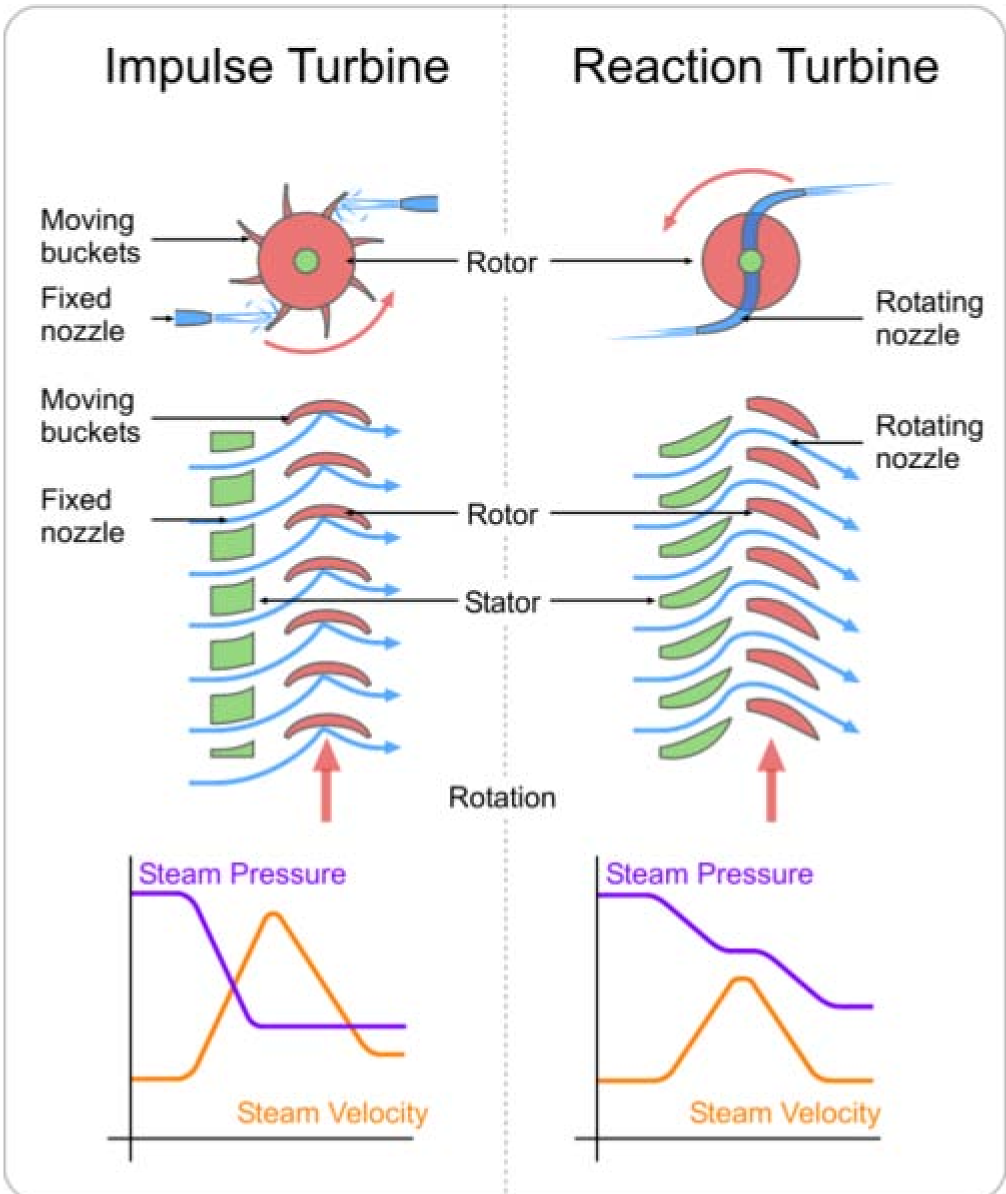
The simplest turbines have one moving part, a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades, or the blades react to the flow, so that they move and impart rotational energy to the rotor. Early turbine examples are windmills and water wheels.

Gas, steam, and water turbines usually have a casing around the blades that contains and controls the working fluid. Credit for invention of the steam turbine is given both to the British engineer Sir Charles Parsons (1854–1931), for invention of the reaction turbine and to Swedish engineer Gustaf de Laval (1845–1913), for invention of the impulse turbine. Modern steam turbines frequently employ both reaction and impulse in the same unit, typically varying the degree of reaction and impulse from the blade root to its periphery.

A device similar to a turbine but operating in reverse, i.e., driven, is a compressor or pump. The axial compressor in many gas turbine engines is a common example. Here again, both reaction and impulse are employed and again, in modern axial compressors, the degree of reaction and impulse will typically vary from the blade root to its periphery.

Claude Burdin coined the term from the Latin *turbo*, or vortex, during an 1828 engineering competition. Benoit Fourneyron, a student of Claude Burdin, built the first practical water turbine.

Theory of operation



A working fluid contains potential energy (pressure head) and kinetic energy (velocity head). The fluid may be compressible or incompressible. Several physical principles are employed by turbines to collect this energy:

Impulse turbines

These turbines change the direction of flow of a high velocity fluid or gas jet. The resulting impulse spins the turbine and leaves the fluid flow with diminished kinetic energy. There is no pressure change of the fluid or gas in the turbine rotor blades (the moving blades), as in the case of a steam or gas turbine, all the pressure drop takes place in the stationary blades (the nozzles).

Before reaching the turbine, the fluid's *pressure head* is changed to *velocity head* by accelerating the fluid with a nozzle. Pelton wheels and de Laval turbines use this process exclusively. Impulse turbines do not require a pressure casement around the rotor since the fluid jet is created by the nozzle prior to reaching the blading on the rotor. Newton's second law describes the transfer of energy for impulse turbines.

Reaction turbines

> These turbines develop torque by reacting to the gas or fluid's pressure or mass. The pressure of the gas or fluid changes as it passes through the turbine rotor blades. A pressure casement is needed to contain the working fluid as it acts on the turbine stage(s) or the turbine must be fully immersed in the fluid flow (such as with wind turbines). The casing contains and directs the working fluid and, for water turbines, maintains the suction imparted by the draft tube. Francis turbines and most steam turbines use this concept. For compressible working fluids, multiple turbine stages are usually used to harness the expanding gas efficiently. Newton's third law describes the transfer of energy for reaction turbines.

In the case of steam turbines, such as would be used for marine applications or for land-based electricity generation, a Parsons type reaction turbine would require approximately double the number of blade rows as a de Laval type impulse turbine, for the same degree of thermal energy conversion. Whilst this makes the Parsons turbine much longer and heavier, the overall efficiency of a reaction turbine is slightly higher than the equivalent impulse turbine for the same thermal energy conversion.

Steam turbines and later, gas turbines developed continually during the 20th Century, continue to do so and in practice, modern turbine designs will use both reaction and impulse concepts to varying degrees whenever possible. Wind turbines use an airfoil to generate lift from the moving fluid and impart it to the rotor (this is a form of reaction). Wind turbines also gain some energy from the impulse of the wind, by deflecting it at an angle. Crossflow turbines are designed as an impulse machine, with a nozzle, but in low head applications maintain some efficiency through reaction, like a traditional water wheel. Turbines with multiple stages may utilize either reaction or impulse blading at high pressure. Steam Turbines were traditionally more impulse but continue to move towards reaction designs similar to those used in Gas Turbines. At low pressure the operating fluid medium expands in volume for small reductions in pressure. Under these conditions (termed Low Pressure Turbines) blading becomes strictly a reaction type design with the base of the blade solely impulse. The reason is due to the effect of the rotation speed for each blade. As the volume increases, the blade height increases, and the base of the blade spins at a slower speed relative to the tip. This change in speed forces a designer to change from impulse at the base, to a high reaction style tip.

Classical turbine design methods were developed in the mid 19th century. Vector analysis related the fluid flow with turbine shape and rotation. Graphical calculation methods were used at first. Formulae for the basic dimensions of turbine parts are well documented and a highly efficient machine can be reliably designed for any fluid flow condition. Some of the calculations are empirical or 'rule of thumb' formulae, and others are based on classical mechanics. As with most engineering calculations, simplifying assumptions were made.

Velocity triangles can be used to calculate the basic performance of a turbine stage. Gas exits the stationary turbine nozzle guide vanes at absolute velocity V_{a1}. The rotor rotates at velocity U. Relative to the rotor, the velocity of the gas as it impinges on the rotor entrance is V_{r1}. The gas is turned by the rotor and exits, relative to the rotor, at velocity V_{r2}. However, in absolute terms the rotor exit velocity is V_{a2}. The velocity triangles are constructed using these various velocity vectors. Velocity triangles can be constructed at any section through the blading (for example: hub , tip, midsection and so on) but are usually shown at the mean stage radius. Mean performance for the stage can be calculated from the velocity triangles, at this radius, using the Euler equation:

$$\Delta\, h = u \cdot \Delta\, v_w$$

Hence:

$$\left(\frac{\Delta\, h}{T}\right) = \left(\frac{u}{\sqrt{T}}\right) \cdot \left(\frac{\Delta\, v_w}{\sqrt{T}}\right)$$

where:

$\Delta\, h =$specific enthalpy drop across stage
$T =$turbine entry total (or stagnation) temperature
$u =$turbine rotor peripheral velocity
$\Delta\, v_w =$change in whirl velocity

The turbine pressure ratio is a function of $\left(\frac{\Delta\, H}{T}\right)$ and the turbine efficiency.

Modern turbine design carries the calculations further. Computational fluid dynamics dispenses with many of the simplifying assumptions used to derive classical formulas and computer software facilitates optimization. These tools have led to steady improvements in turbine design over the last forty years.

The primary numerical classification of a turbine is its ***specific speed***. This number describes the speed of the turbine at its maximum efficiency with respect to the power and flow rate. The specific speed is derived to be independent of turbine size. Given the fluid flow conditions and the desired shaft output speed, the specific speed can be calculated and an appropriate turbine design selected.

The specific speed, along with some fundamental formulas can be used to reliably scale an existing design of known performance to a new size with corresponding performance.

Off-design performance is normally displayed as a turbine map or characteristic.

Types of turbines

- Steam turbines are used for the generation of electricity in thermal power plants, such as plants using coal, fuel oil or nuclear power. They were once used to directly drive mechanical devices such as ships' propellors (eg the Turbinia), but most such applications now use reduction gears or an intermediate electrical step, where the turbine is used to generate electricity, which then powers an electric motor connected to the mechanical load. Turbo electric ship machinery was particularly popular in the period immediately before and during WWII, primarily due to a lack of sufficient gear-cutting facilities in US and UK shipyards.

- Gas turbines are sometimes referred to as turbine engines. Such engines usually feature an inlet, fan, compressor, combustor and nozzle (possibly other assemblies) in addition to one or more turbines.
- Transonic turbine. The gasflow in most turbines employed in gas turbine engines remains subsonic throughout the expansion process. In a transonic turbine the gasflow becomes supersonic as it exits the nozzle guide vanes, although the downstream velocities normally become subsonic. Transonic turbines operate at a higher pressure ratio than normal but are usually less efficient and uncommon.

- Contra-rotating turbines. With axial turbines, some efficiency advantage can be obtained if a downstream turbine rotates in the opposite direction to an upstream unit. However, the complication can be counter-productive. A contra-rotating steam turbine, usually known as the Ljungström turbine, was originally invented by Swedish Engineer Fredrik Ljungström (1875–1964), in Stockholm and in partnership with his brother Birger Ljungström he obtained a patent in 1894. The design is essentially a multi-stage radial turbine (or pair of 'nested' turbine rotors) offering great efficiency, four times as large heat drop per stage as in the reaction (Parsons) turbine, extremely compact design and the type met particular success in backpressure power plants. However, contrary to other designs, large steam volumes are handled with difficulty and only a combination with axial flow turbines (DUREX) admits the turbine to be built for power greater than ca 50 MW. In marine applications only about 50 turbo-electric units were ordered (of which a considerable amount were finally sold to land plants) during 1917-19, and during 1920-22 a few turbo-mechanic not very successful units were sold. Only a few turbo-electric marine plants were still in use in the late 1960s (ss Ragne, ss Regin) while most land plants remain in use 2010.

- Statorless turbine. Multi-stage turbines have a set of static (meaning stationary) inlet guide vanes that direct the gasflow onto the rotating rotor blades. In a statorless turbine the gasflow exiting an upstream rotor impinges onto a downstream rotor without an intermediate set of stator vanes (that rearrange the pressure/velocity energy levels of the flow) being encountered.

- Ceramic turbine. Conventional high-pressure turbine blades (and vanes) are made from nickel based alloys and often utilise intricate internal air-cooling passages to prevent the metal from overheating. In recent years, experimental ceramic blades have been manufactured and tested in gas turbines, with a view to increasing Rotor Inlet Temperatures and/or, possibly, eliminating aircooling. Ceramic blades are more brittle than their metallic counterparts, and carry a greater risk of catastrophic blade failure. This has tended to limit their use in jet engines and gas turbines, to the stator (stationary) blades.

- Shrouded turbine. Many turbine rotor blades have shrouding at the top, which interlocks with that of adjacent blades, to increase damping and thereby reduce blade flutter. In large land-based electricity generation steam turbines, the shrouding is often complemented, especially in the long blades of a low-pressure turbine, with lacing wires. These are wires which pass through holes drilled in the blades at suitable distances from the blade root and the wires are usually brazed to the blades at the point where they pass through. The lacing wires are designed to reduce blade flutter in the central part of the blades. The introduction of lacing wires substantially reduces the instances of blade failure in large or low-pressure turbines.

- Shroudless turbine. Modern practice is, wherever possible, to eliminate the rotor shrouding, thus reducing the centrifugal load on the blade and the cooling requirements.
- Bladeless turbine uses the boundary layer effect and not a fluid impinging upon the blades as in a conventional turbine.
- Water turbines
  - Pelton turbine, a type of impulse water turbine.
  - Francis turbine, a type of widely used water turbine.
  - Kaplan turbine, a variation of the Francis Turbine.
- Wind turbine. These normally operate as a single stage without nozzle and interstage guide vanes. An exception is the Éolienne Bollée, which has a stator and a rotor, thus being a true turbine.

Other

- Velocity compound "Curtis". Curtis combined the de Laval and Parsons turbine by using a set of fixed nozzles on the first stage or stator and then a rank of fixed and rotating blade rows, as in the Parsons or de Laval, typically up to ten compared with up to a hundred stages of a Parsons design. The overall efficiency of a Curtis design is less than that of either the Parsons or de Laval designs, but it can be satisfactorily operated through a much wider range of speeds, including successful operation at low speeds and at lower pressures, which made it ideal for use in ships' powerplant. In a Curtis arrangement, the entire heat drop in the steam takes place in the initial nozzle row and both the subsequent moving blade rows and stationary blade rows merely change the direction of the steam. Use of a small section of a Curtis arrangement, typically one nozzle section and two or three rows of moving blades, is usually termed a Curtis 'Wheel' and in this form, the Curtis found widespread use at sea as a 'governing stage' on many reaction and impulse turbines and turbine sets. This practice is still commonplace today in marine steam plant.

- Pressure Compound Multistage Impulse or Rateau. The Rateau employs simple Impulse rotors separated by a nozzle diaphragm. The diaphragm is essentially a partition wall in the turbine with a series of tunnels cut into it, funnel shaped with the broad end facing the previous stage and the narrow the next they are also angled to direct the steam jets onto the impulse rotor.

- Positive displacement hydraulic devices. In a turbine, the fluid's own pressure accelerates it and the momentum and kinetic energy of the moving fluid do the mechanical work. An alternative is the reverse of a positive displacement pump, in which the pressure of the fluid does work directly on moving surfaces. As with pumps such as superchargers, these devices tend to have much wider speed and pressure ranges than turbines do, but they are larger and less efficient at high power. These are common, for example, in the power steering of cars.

Uses of turbines

Almost all electrical power on Earth is produced with a turbine of some type. Very high efficiency steam turbines harness about 40% of the thermal energy, with the rest exhausted as waste heat.

Most jet engines rely on turbines to supply mechanical work from their working fluid and fuel as do all nuclear ships and power plants.

Turbines are often part of a larger machine. A gas turbine, for example, may refer to an internal combustion machine that contains a turbine, ducts, compressor, combustor, heat-exchanger, fan and (in the case of one designed to produce electricity) an alternator. Combustion turbines and steam turbines may be connected to machinery such as pumps and compressors, or may be used for propulsion of ships, usually through an intermediate gearbox to reduce rotary speed.

Reciprocating piston engines such as aircraft engines can use a turbine powered by their exhaust to drive an intake-air compressor, a configuration known as a turbocharger (turbine supercharger) or, colloquially, a "turbo".

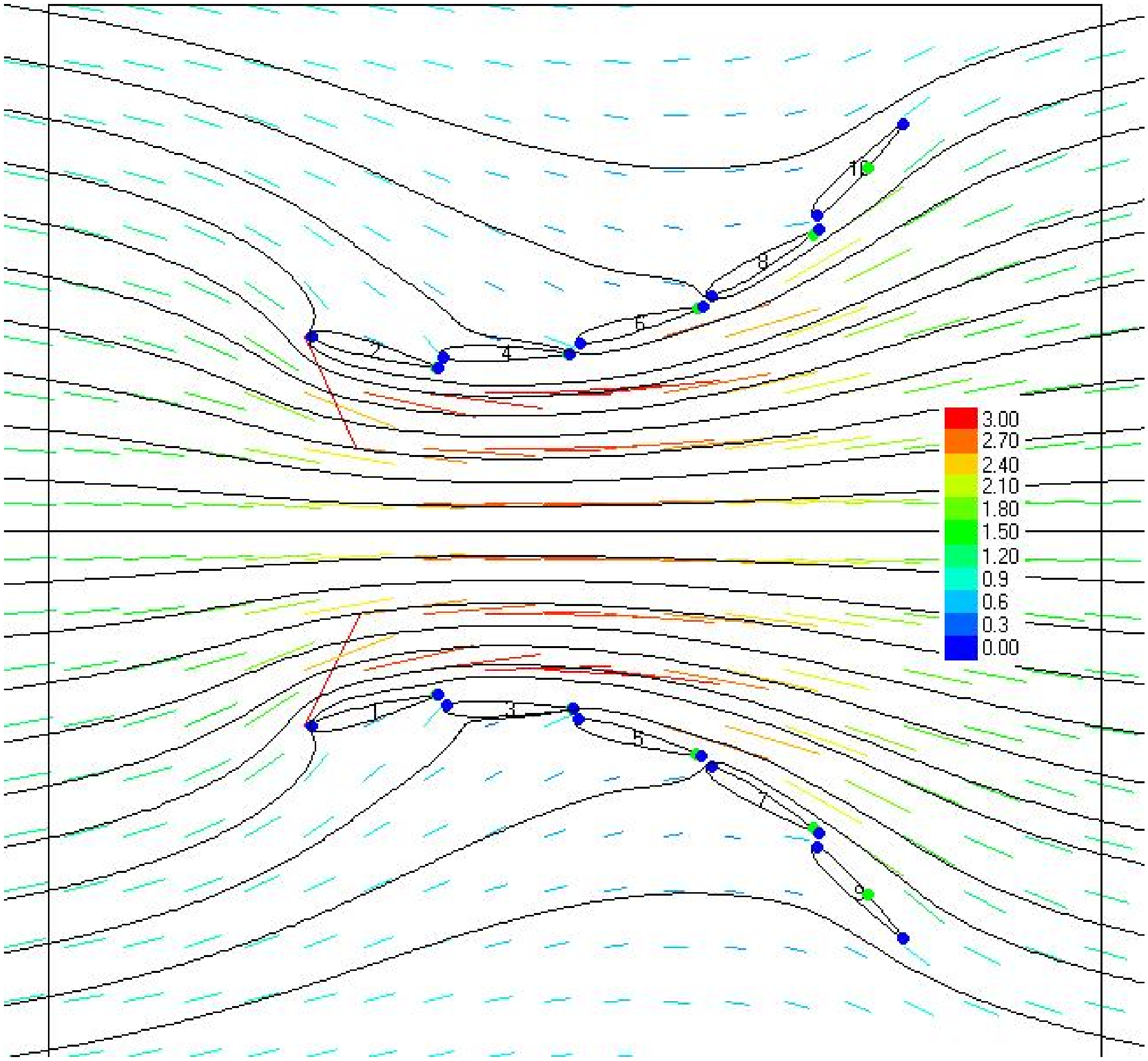
Turbines can have very high power density (ie the ratio of power to weight, or power to volume). This is because of their ability to operate at very high speeds. The Space Shuttle's main engines use turbopumps (machines consisting of a pump driven by a turbine engine) to feed the propellants (liquid oxygen and liquid hydrogen) into the engine's combustion chamber. The liquid hydrogen turbopump is slightly larger than an automobile engine (weighing approximately 700 lb) and produces nearly 70,000 hp (52.2 MW).

Turboexpanders are widely used as sources of refrigeration in industrial processes.

Shrouded tidal turbines

An emerging renewable energy technology is the shrouded tidal turbine enclosed in a venturi shaped shroud or duct producing a sub atmosphere of low pressure behind the turbine. It is often claimed that this allows the turbine to operate at higher efficiency (than the Betz limit of 59.3%) because the turbine can typically produce 3 times more power than a turbine of the same size in free stream. This, however, is something of a misconception because the area presented to the flow is that of the largest duct cross-section. If this area is used for the calculation, it will be seen that the turbine still cannot exceed the Betz limit. Further, due to frictional losses in the duct, it is unlikely that the turbine will be able to produce as much power as a free-stream turbine with the same radius as the duct.

Although situating the rotor in the throat of the duct allows the blades to be supported at their tips (thus reducing bending stress from hydrodynamic thrust) the financial impact of the large amount of steel in the duct must not be omitted from any energy cost calculations.



Asymmetric airfoil

As shown in the CFD generated figure, it can be seen that a down stream low pressure (shown by the gradient lines) draws upstream flow into the inlet of the shroud from well outside the inlet of the shroud. This flow is drawn into the shroud and concentrated (as seen by the red coloured zone). This augmentation of flow velocity corresponds to a 3-4 times increase in energy available to the turbine. Therefore a turbine located in the throat of the shroud is then able to achieve higher efficiency, and an output 3-4 times the energy the turbine would be capable of if it were in open or free stream. However, as mentioned above, it is not correct to conclude that this circumvents the Betz limit. The figure shows only the near-field flow, which is accelerated through the duct. A far-field image would show a more complete picture of how the free-stream flow is affected by the obstruction.

Considerable commercial interest has been shown in recent times in shrouded tidal turbines as it allows a smaller turbine to be used at sites where large turbines are restricted. Arrayed across a seaway or in fast flowing rivers shrouded tidal turbines are easily cabled to a terrestrial base and connected to a grid or remote community.

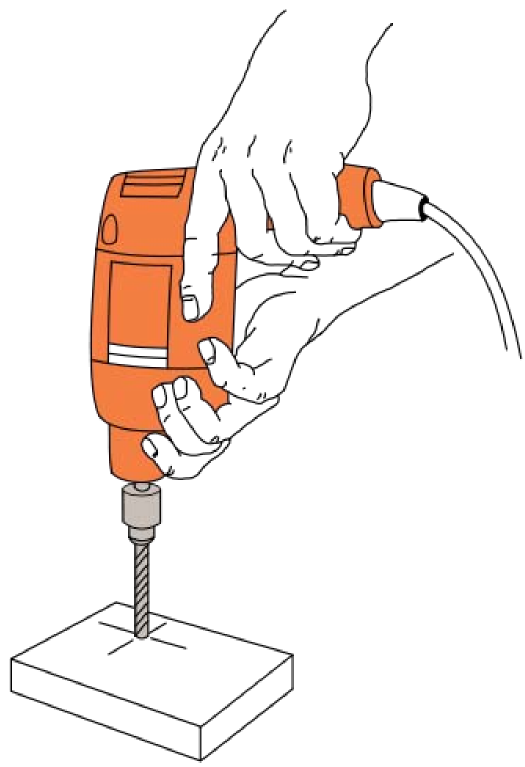
Alternatively the property of the shroud that produces an accelerated flow velocity across the turbine allows tidal flows formerly too slow for commercial use to be utilised for commercial energy production.

While the shroud may not be practical in wind, as a tidal turbine it is gaining more popularity and commercial use. A non-symmetrical shrouded tidal turbine (the type discussed above) is mono directional and constantly needs to face upstream in order to operate. It can be floated under a pontoon on a swing mooring, fixed to the seabed on a mono pile and yawed like a wind sock to continually face upstream. A shroud can also be built into a tidal fence increasing the performance of the turbines. Several companies (for example, Lunar Energy) are proposing bi-directional ducts that would not be required to turn to face the oncoming tide every six hours.

Cabled to the mainland they can be grid connected or can be scaled down to provide energy to remote communities where large civil infrastructures are not viable. Similarly to tidal stream open turbines they have little if any environmental or visual amenity impact.

Chapter 12

Drill



Drill scheme

A **drill** or **drill motor** is a tool fitted with a cutting tool attachment or driving tool attachment, usually a drill bit or driver bit, used for drilling holes in various materials or fastening various materials together with the use of fasteners. The attachment is gripped by a chuck at one end of the drill and rotated while pressed against the target material.

The tip, and sometimes edges, of the cutting tool does the work of cutting into the target material. This may be slicing off thin shavings (twist drills or auger bits), grinding off small particles (oil drilling), crushing and removing pieces of the workpiece (SDS masonry drill), countersinking, counterboring, or other operations.

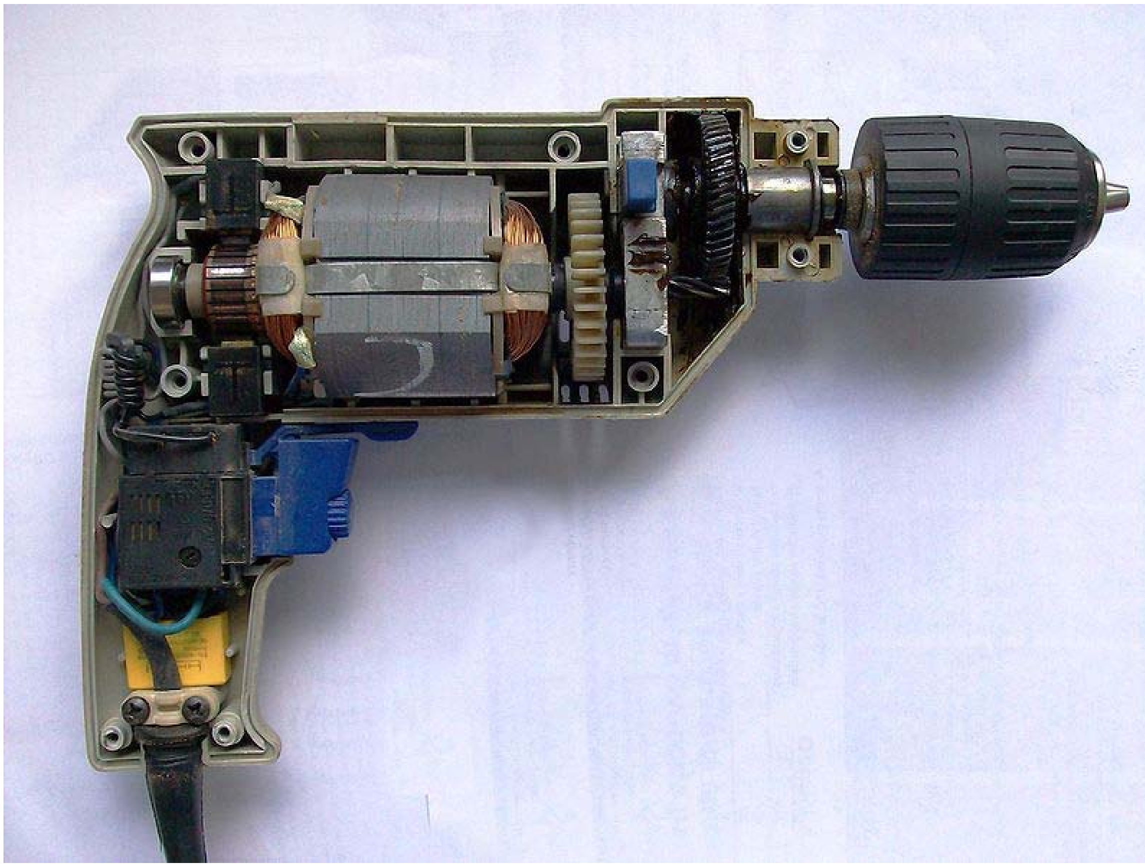
Drills are commonly used in woodworking, metalworking, construction and do-it-yourself projects. Specially designed drills are also used in medicine, space missions and other applications.

History

A wooden drill handle and other carpentry tools found on board the 16th century carrack *Mary Rose*.

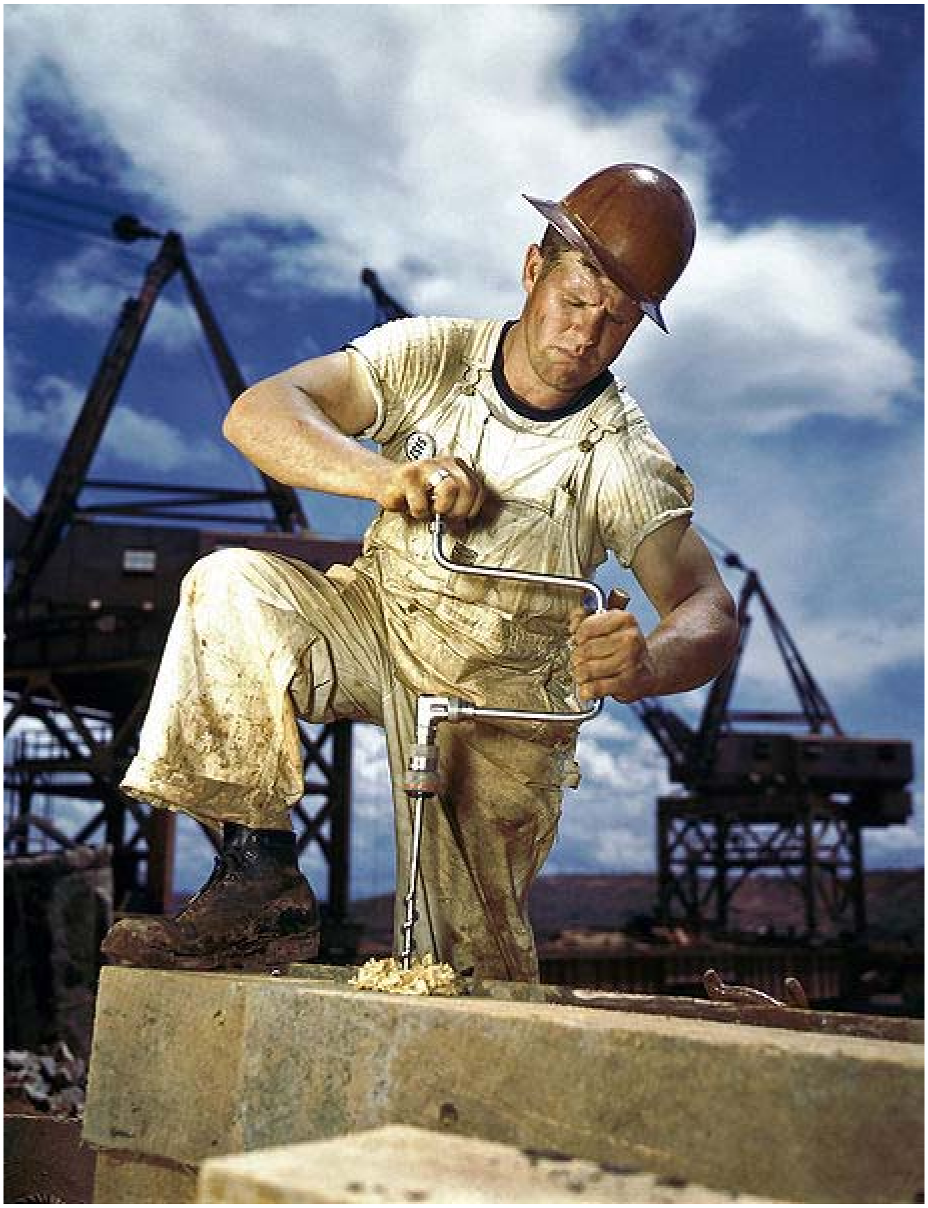
The earliest drills were bow drills which date back to the ancient Harappans and Egyptians. The drill press as a machine tool evolved from the bow drill and is many centuries old. It was powered by various power sources over the centuries, such as human effort, water wheels, and windmills, often with the use of belts. With the coming of the electric motor in the late 19th century, there was a great rush to power machine tools with such motors, and drills were among them. The invention of the first electric drill is credited to Arthur James Arnot and William Blanch Brain , in 1889, at Melbourne, Australia. Wilhelm Fein invented the portable electric drill in 1895, at Stuttgart, Germany. In 1917, Black & Decker patented a trigger-like switch mounted on a pistol-grip handle.

Types



Inside an electric drill

There are many types of drills: some are powered manually, others use electricity (electric drill) or compressed air (*pneumatic drill*) as the motive power, and a minority are driven by an internal combustion engine (for example, earth drilling augers). Drills with a percussive action (hammer drills) are mostly used in hard materials such as masonry (brick, concrete and stone) or rock. Drilling rigs are used to bore holes in the earth to obtain water or oil. Oil wells, water wells, or holes for geothermal heating are created with large drilling rigs. Some types of hand-held drills are also used to drive screws and other fasteners. Some small appliances that have no motor of their own may be drill-powered, such as small pumps, grinders, etc.



Carpenter using a crank-powered brace to drill a hole

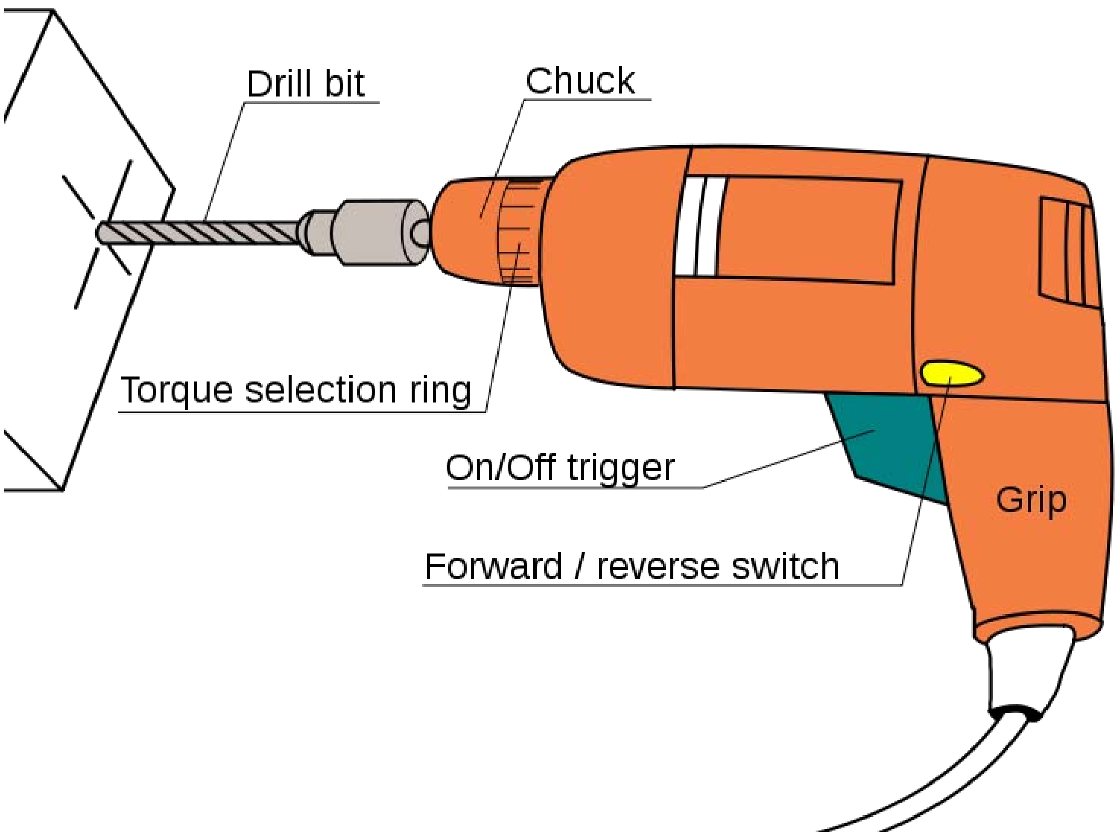
Hand tools

A variety of hand-powered drills have been employed over the centuries. Here are a few, starting with approximately the oldest:

- Bow drill
- Brace and bit
- Gimlet
- Breast drill, also known as "eggbeater" drill
- Push drill, a tool using a spiral ratchet mechanism
- Pin chuck, a small hand-held jewellers drill

An old hand drill or "eggbeater" drill. The hollow wooden handle, with screw-on cap, is used to store drill bits

Pistol-grip (corded) drill



Anatomy of a pistol-grip corded drill.

Drills with pistol grips are the most common type in use today, and are available in a huge variety of subtypes. A less common type is the right-angle drill, a special tool used by tradesmen such as plumbers and electricians.

For much of the 20th century, many attachments could commonly be purchased to convert corded electric hand drills into a range of other power tools, such as orbital sanders and power saws, more cheaply than purchasing conventional, self-contained versions of those tools (the greatest saving being the lack of an additional electric motor for each device). As the prices of power tools and suitable electric motors have fallen, however, such attachments have become much less common. A similar practice is currently employed for cordless tools where the battery, the most expensive component, is shared between various motorised devices, as opposed to a single electric motor being shared between mechanical attachments.

Hammer drill

The **hammer drill** is similar to a standard electric drill, with the exception that it is provided with a hammer action for drilling masonry. The hammer action may be engaged or disengaged as required. Most electric hammer drills are rated (input power) at between 600 and 1100 watts. The efficiency is usually 50-60% i.e. 1000 watts of input is converted into 500-600 watts of output (rotation of the drill and hammering action).

The hammer action is provided by two cam plates that make the chuck rapidly pulse forward and backward as the drill spins on its axis. This pulsing (hammering) action is measured in Blows Per Minute (BPM) with 10,000 or more BPMs being common. Because the combined mass of the chuck and bit is comparable to that of the body of the drill, the energy transfer is inefficient and can sometimes make it difficult for larger bits to penetrate harder materials such as poured concrete. The operator experiences considerable vibration, and the cams are generally made from hardened steel to avoid them wearing out quickly. In practice, drills are restricted to standard masonry bits up to 13 mm (1/2 inch) in diameter. A typical application for a hammer drill is installing electrical boxes, conduit straps or shelves in concrete.

In contrast to the cam-type hammer drill, a rotary/pneumatic hammer drill accelerates only the bit. This is accomplished through a piston design, rather than a spinning cam. Rotary hammers have much less vibration and penetrate most building materials. They can also be used as "drill only" or as "hammer only" which extends their usefulness for tasks such as chipping brick or concrete. Hole drilling progress is greatly superior to cam-type hammer drills, and these drills are generally used for holes of 19 mm (3/4 inch) or greater in size. A typical application for a rotary hammer drill is boring large holes for lag bolts in foundations, or installing large lead anchors in concrete for handrails or benches.

A standard hammer drill accepts 6 mm (1/4 inch) and 13 mm (1/2 inch) drill bits, while a rotary hammer uses SDS or Spline Shank bits. These heavy bits are adept at pulverising the masonry and drill into this hard material with relative ease.

However, there is a big difference in cost. In the UK a cam hammer typically costs £12 or more, while a rotary/pneumatic costs £35 or more. In the US a typical hammer drill costs between $70 and $120, and a rotary hammer between $150 and $500 (depending on bit size). For DIY use or to drill holes less than 13 mm (1/2 inch) in size, the hammer drill is most commonly used.

Rotary hammer drill

A rotary hammer drill used in construction

The rotary hammer drill (also known as a rotary hammer, roto hammer drill or masonry drill) combines a primary dedicated hammer mechanism with a separate rotation mechanism, and is used for more substantial material such as masonry or concrete. Generally, standard chucks and drills are inadequate and chucks such as SDS and carbide drills that have been designed to withstand the percussive forces are used. Some styles of this tool are intended for masonry drilling only and the hammer action cannot be disengaged. Other styles allow the drill to be used without the hammer action for normal drilling, or hammering to be used without rotation for chiselling.

Cordless drills

A cordless drill with clutch

A cordless drill is an electric drill which uses rechargeable batteries. These drills are available with similar features to an AC mains-powered drill. They are available in the hammer drill configuration and most have a clutch, which aids in driving screws into various substrates while not damaging them. Also available are right angle drills, which allow a worker to drive screws in a tight space. While 21st century battery innovations allow significantly more drilling, large diameter holes (typically 12–25 mm (0.5–1.0 in) or larger) may drain current cordless drills quickly.

For continuous use, a worker will have one or more spare battery packs charging while drilling, and quickly swap them instead of having to wait an hour or more for recharging, although there are now Rapid Charge Batteries that can charge in 10–15 minutes.

Early cordless drills used interchangeable 7.2 V battery packs, and over the years available battery voltages have increased, with 18 V drills being most common, and higher voltage drills, such as 24V, 28V, and 36V, are made also. This allows these tools to produce as much torque as some mains-powered drills. The drawback of most current models is the use of nickel-cadmium (NiCd) batteries, which have limited life, self-discharging and eventually internally short circuiting due to dendrite growth. This severely limits battery life, and poses a hazardous materials disposal problem.

Lithium ion batteries are becoming more common because of their short charging time, longer life, and low weight. Instead of charging a tool for an hour to get 20 minutes of use, 20 minutes of charge can run the tool for an hour. Lithium-ion batteries also have a constant discharge rate. The power output remains constant until the battery is depleted, something that nickel-cadmium batteries also lack, and which makes the tool much more versatile. Lithium-ion batteries also hold a charge for a significantly longer time than nickel-cadmium batteries, about two years if not used, vs. 1 to 4 months for a nickel-cadmium battery. There are three major drawbacks to Lithium Ion batteries. 1. They do not perform well in low temperatures 2. The batteries are very expensive to replace. 3. The overall batteries can only handle about 1/3 of the recharges over a lifetime as a NiCad or NiMH battery. NiCad batteries can also be rebuilt or upgraded, diminishing the benefits of Li-ion batteries.

A cordless drill with a high torque (in excess of 30 Nm) works well as a screw driver even if working on a hardwood. In drilling the high torque is needed when the diameter of the drill is large.

The handles of cordless drills are usually made from polyurethane which is easy and quick to mold to a comfortable shape for holding. The main body of the drill is usually made from polyethylene as it is able to withstand the high temperatures which the drill reaches.

Drill press

A drill press

A drill press (also known as pedestal drill, pillar drill, or bench drill) is a fixed style of drill that may be mounted on a stand or bolted to the floor or workbench. A drill press consists of a base, column (or pillar), table, spindle (or quill), and drill head, usually driven by an induction motor. The head has a set of handles (usually 3) radiating from a central hub that, when turned, move the spindle and chuck vertically, parallel to the axis of the column. The table can be adjusted vertically and is generally moved by a rack and pinion; however, some older models rely on the operator to lift and reclamp the table in position. The table may also be offset from the spindle's axis and in some cases rotated to a position perpendicular to the column. The size of a drill press is typically measured in terms of *swing*. Swing is defined as twice the *throat distance*, which is the distance from the center of the spindle to the closest edge of the pillar. For example, a 16-inch (410 mm) drill press will have an 8-inch (200 mm) throat distance.

Old industrial drill press designed to be driven from the power source by a flat belt

A drill press has a number of advantages over a hand-held drill:

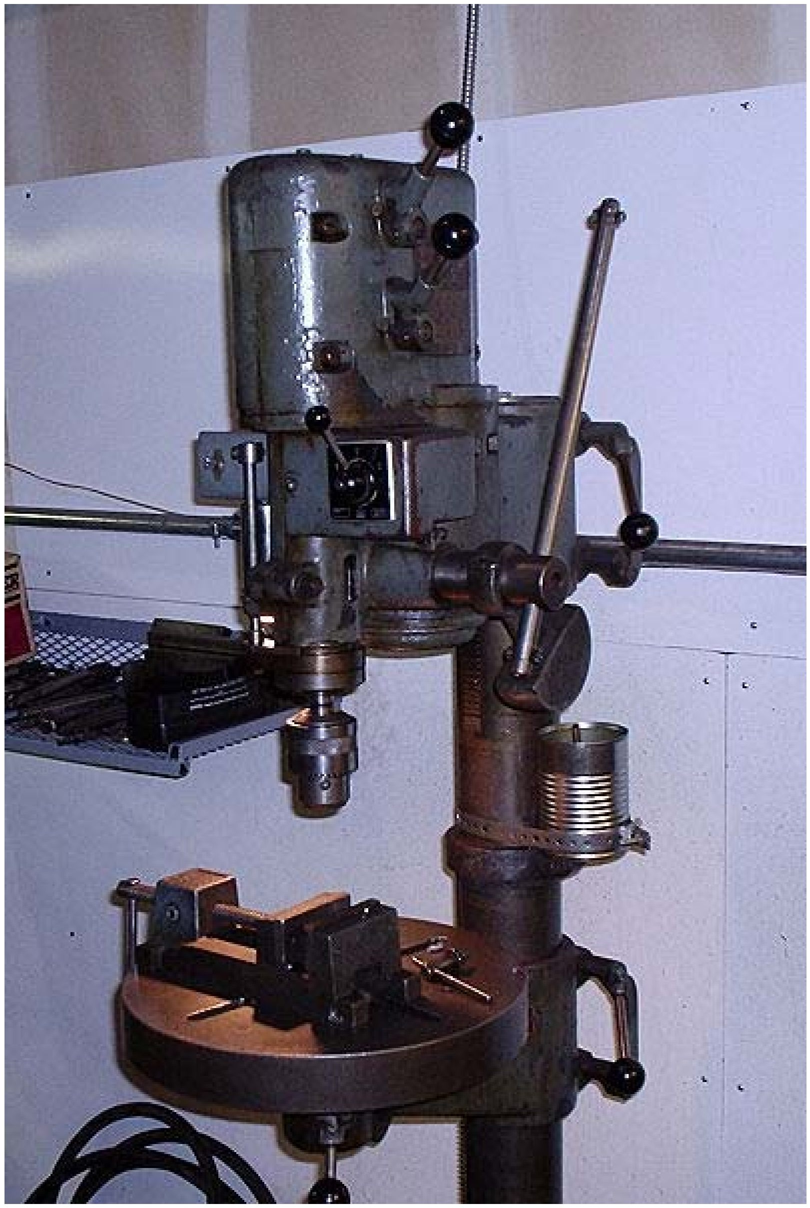
- Less effort is required to apply the drill to the workpiece. The movement of the chuck and spindle is by a lever working on a rack and pinion, which gives the operator considerable mechanical advantage
- The table allows a vise or clamp to be used to position and restrain the work, making the operation much more secure
- The angle of the spindle is fixed relative to the table, allowing holes to be drilled accurately and consistently

- Drill presses are almost always equipped with more powerful motors compared to hand-held drills. This enables larger drill bits to be used and also speeds up drilling with smaller bits.

Speed change is achieved by manually moving a belt across a stepped pulley arrangement. Some drill presses add a third stepped pulley to increase the speed range. Modern drill presses can, however, use a variable-speed motor in conjunction with the stepped-pulley system. Some machine shop (tool room) drill presses are equipped with a continuously variable transmission, giving a wide speed range, as well as the ability to change speed while the machine is running.

Drill presses are often used for miscellaneous workshop tasks such as sanding, honing or polishing, by mounting sanding drums, honing wheels and various other rotating accessories in the chuck. This can be unsafe in some cases, as the chuck arbor, which may be retained in the spindle solely by the friction of a taper fit, may dislodge during operation.

Geared head drill press



Geared head drill press. Shift levers on the head and a two speed motor control immediately in front of the quill handle select one of eight possible speeds

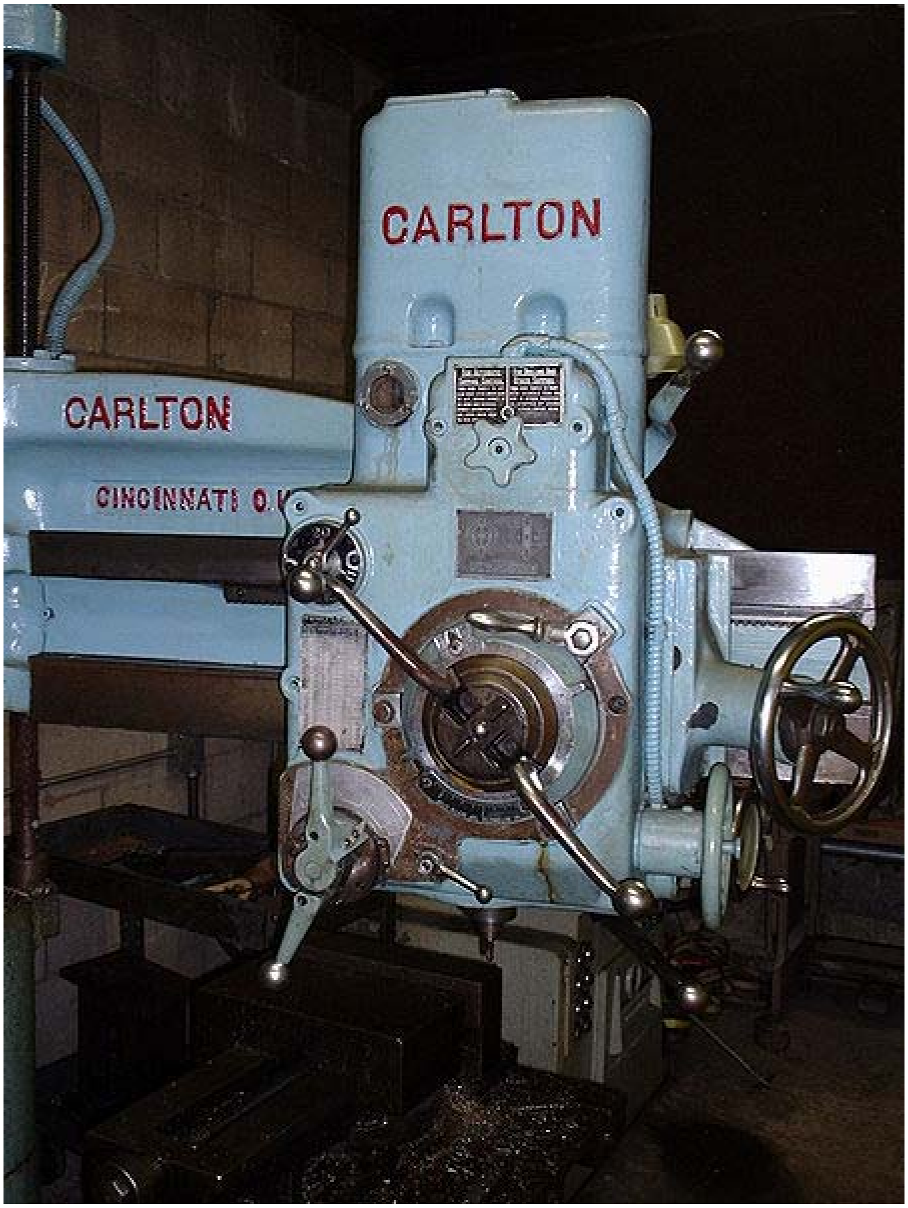
A geared head drill press is a drill press in which power transmission from the motor to the spindle is achieved solely through spur gearing inside the machine's head. No friction elements (e.g., belts) of any kind are used, which assures a positive drive at all times and minimizes maintenance requirements.

Levers attached to one side of the head are used to select different gear ratios to change the spindle speed, usually in conjunction with a two- or three-speed motor. Most machines of this type are designed to be operated on three phase power and are generally of more rugged construction than equivalent sized belt-driven units. Virtually all examples have geared racks for adjusting the table and head position on the column.

Geared head drill presses are commonly found in tool rooms and other commercial environments where a heavy duty machine capable of production drilling and quick setup changes is required. In most cases, the spindle is machined to accept Morse taper tooling for greater flexibility. Larger geared head drill presses are frequently fitted with power feed on the quill mechanism, with an arrangement to disengage the feed when a certain drill depth has been achieved or in the event of excessive travel. Some gear-head drill presses have the ability to perform tapping operations--a reversing mechanism drives the tap into the part under power and then backs it out of the threaded hole once the proper depth is reached. Coolant systems are also common on these machines to prolong tool life under production conditions.

Radial arm drill press.

Radial arm drill press



Radial arm drill press controls

A radial arm drill press is a large geared head drill press in which the head can be moved along an arm that radiates from the machine's column. As it is possible to swing the arm relative to the machine's base, a radial arm drill press is able to operate over a large area without having to reposition the workpiece. The size of work that can be handled may be considerable, as the arm can swing out of the way of the table, allowing an overhead crane or derrick to place a bulky piece on the table or base. A vise may be used with a radial arm drill press, but more often the workpiece is secured directly to the table or base, or is held in a fixture. Power spindle feed is nearly universal with these machines and coolant systems are common. The biggest radial arm drill presses are able to drill holes as large as four inches (101.6 millimeters) diameter in solid steel or cast iron.

Mill drill

Mill drills are a lighter alternative to a milling machine. They combine a drill press (belt driven) with the X/Y coordinate abilities of the milling machine's table and a locking collet that ensures that the cutting tool will not fall from the spindle when lateral forces are experienced against the bit. Although they are light in construction, they have the advantages of being space-saving and versatile as well as inexpensive, being suitable for light machining that may otherwise not be affordable.

Unusual Uses

- A household drill was used to save a boy's life in Australia. The boy suffered from potentially fatal bleeding within the brain after a fall from his bike. Having no proper medical tools, the attending doctor decided to use a household drill stored in the hospital maintenance room to remove a clot. This was done in order to relieve the blood pressure in the boy's brain. If this had not been done, the boy would have died in minutes. The doctor performed the procedure and was guided by a neurosurgeon over the phone. The boy was later airlifted to a larger hospital and recovered within days.
- Paul Gilbert and Billy Sheehan of Mr. Big use a cordless drill for the solo of Daddy, Brother, Lover, Little Boy commonly known as "The Electric Drill Song". This was done by using 3.3mm plectrums on a wooden dowel.

Other perforation tools

- Milling machines, metal lathes and routers are also often used for drilling.