Gear Mechanics

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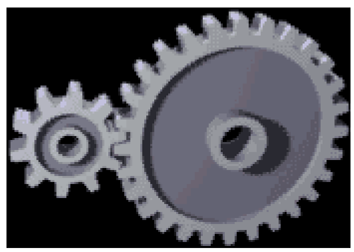
Gear



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.

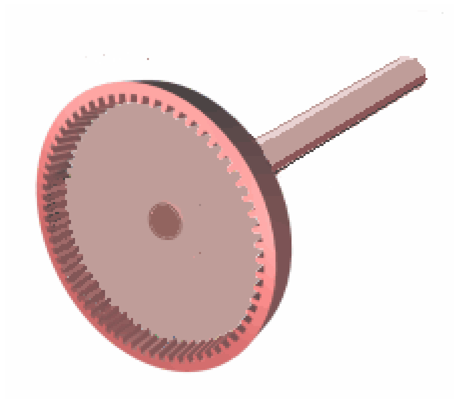
Comparison with other drive mechanisms

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

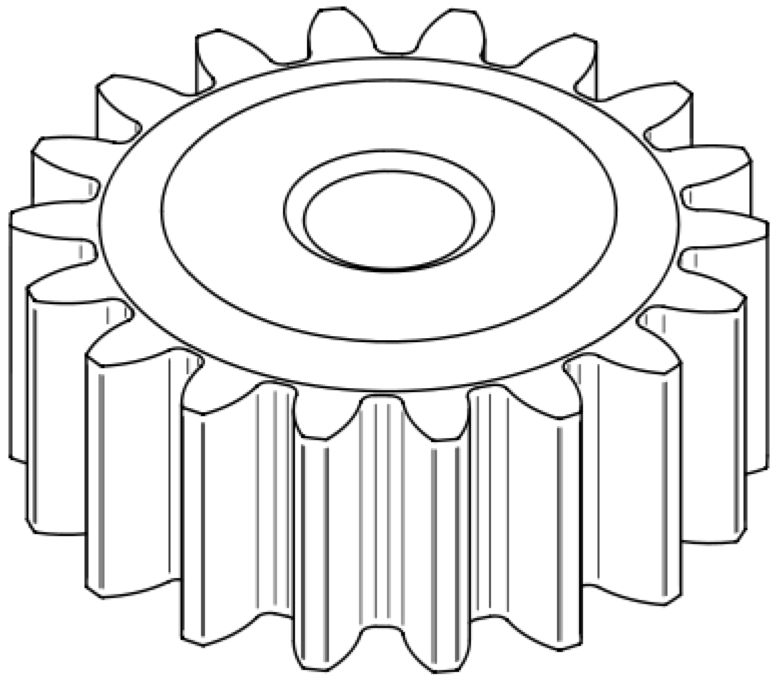
External vs. internal gears



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.

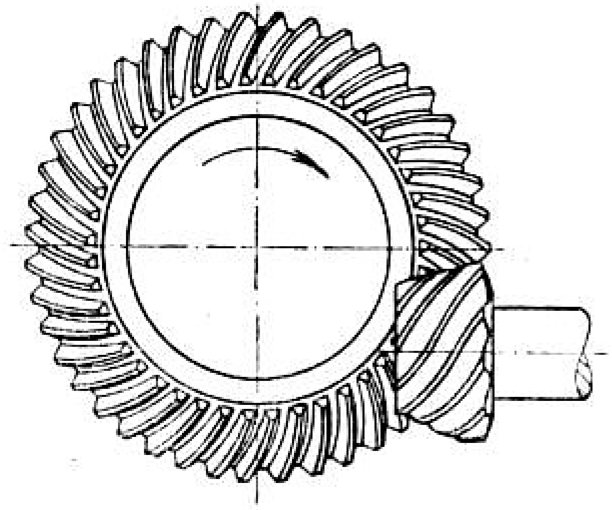
Bevel

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.

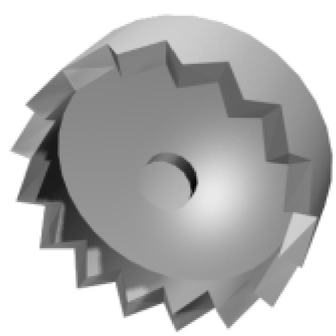
Hypoid



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

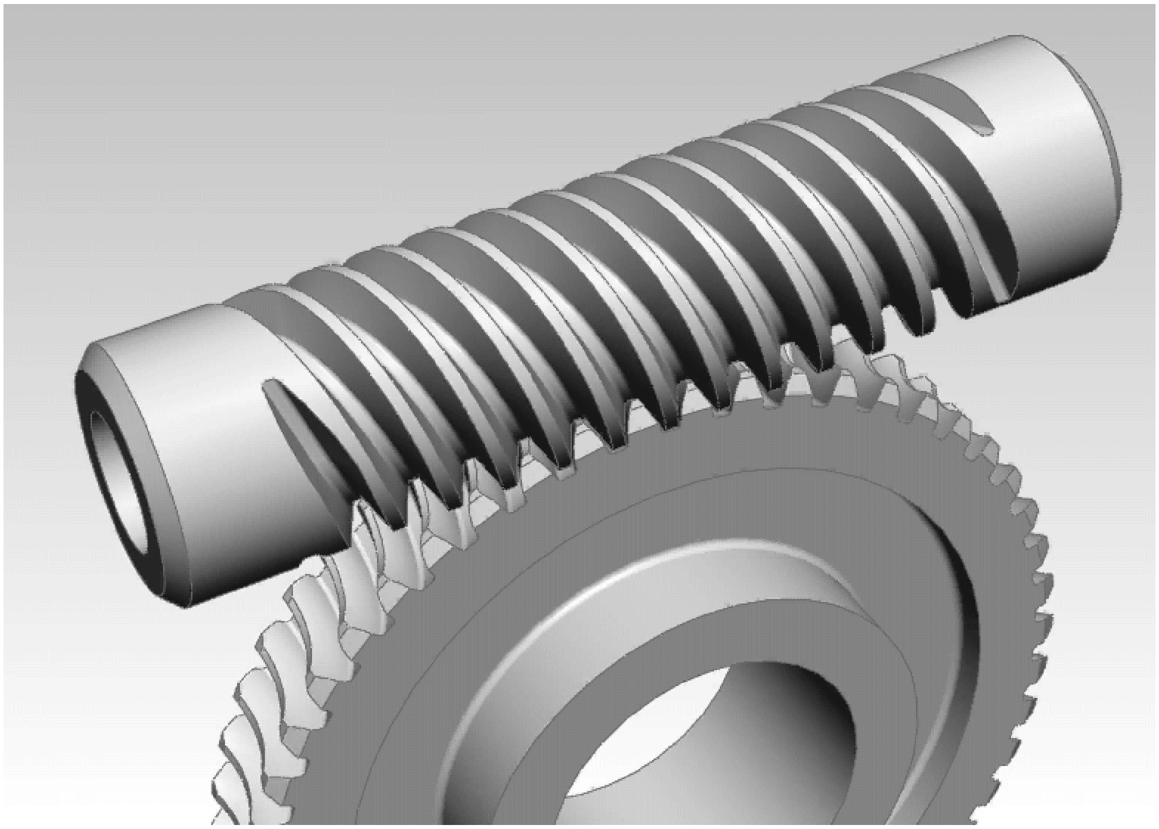


Crown gear

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.

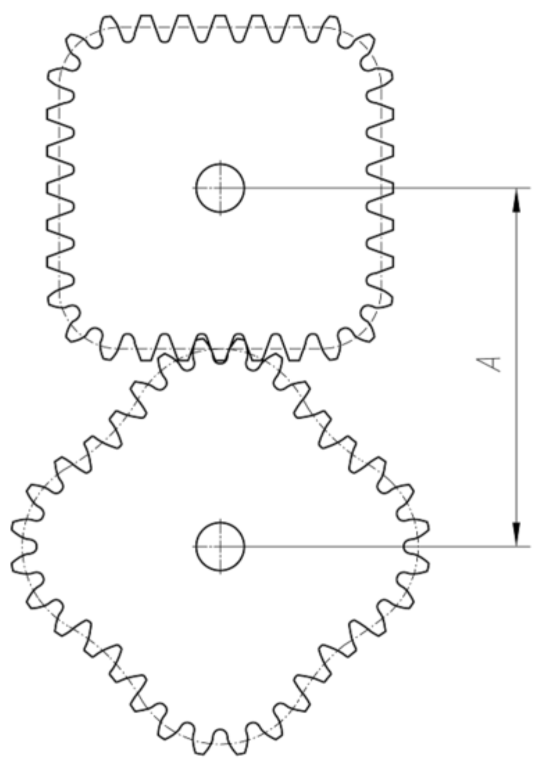
Worm gears can be considered a species of helical gear, but its helix angle is usually somewhat large (close to 90 degrees) and its body is usually fairly long in the axial direction; and it is these attributes which give it its screw like qualities. The distinction between a worm and a helical gear 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.

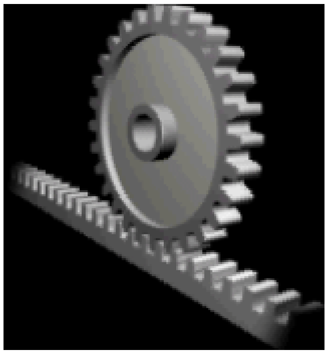
Non-circular



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.

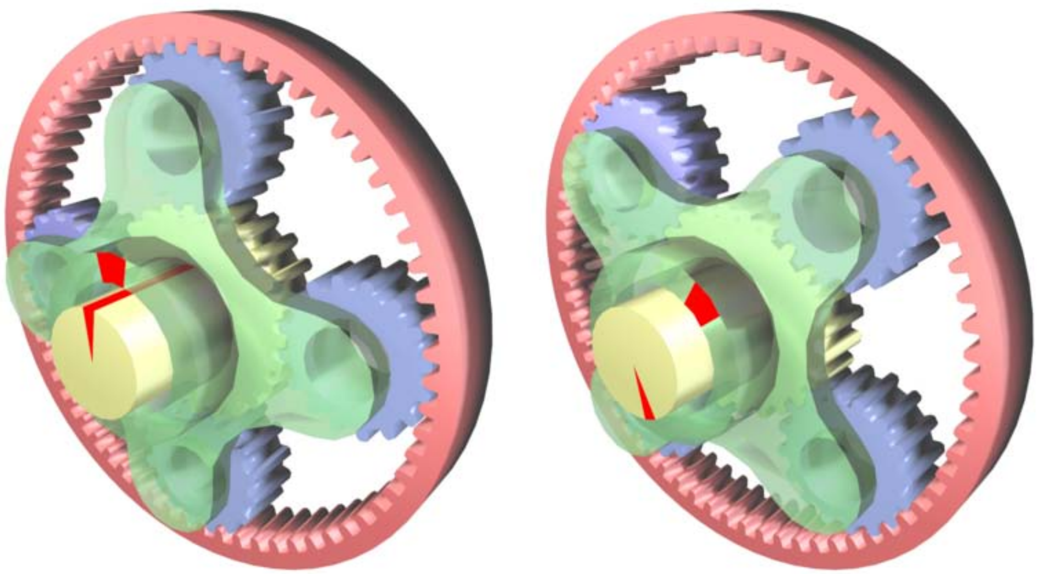
Rack and pinion



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.

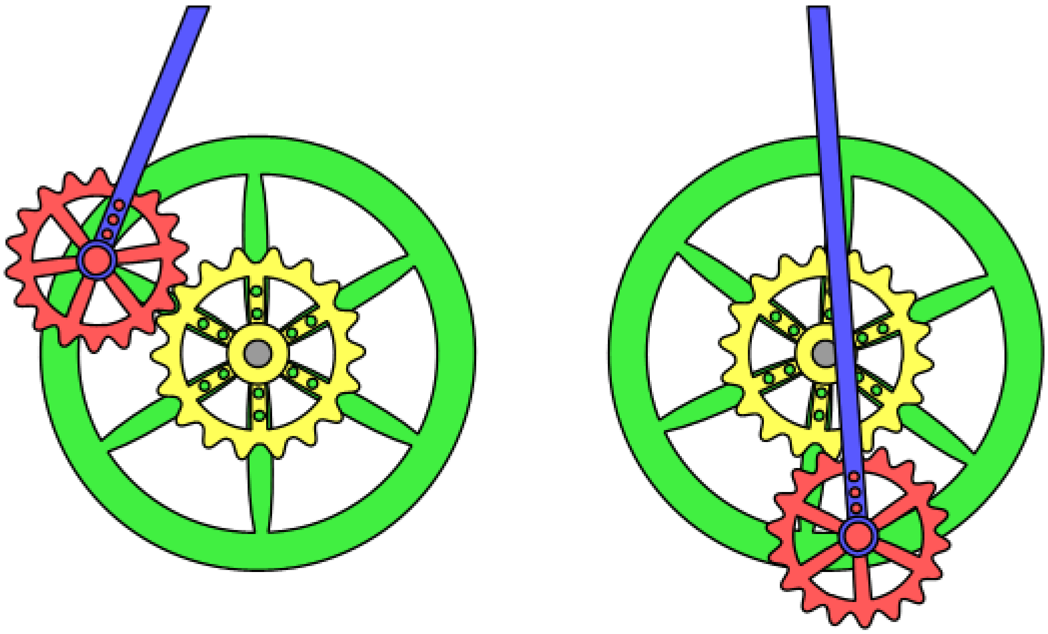
Epicyclic



Epicyclic gearing

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

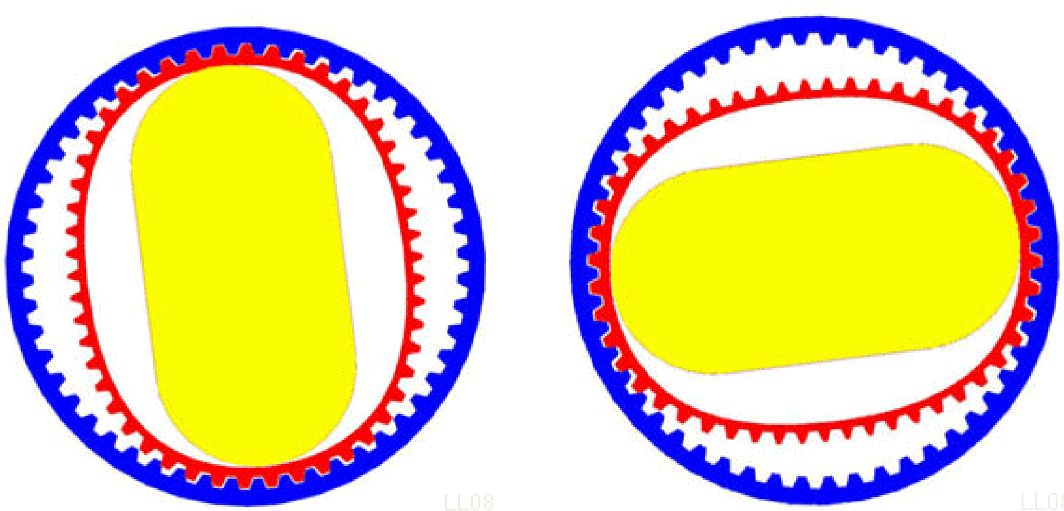
Sun and planet



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.

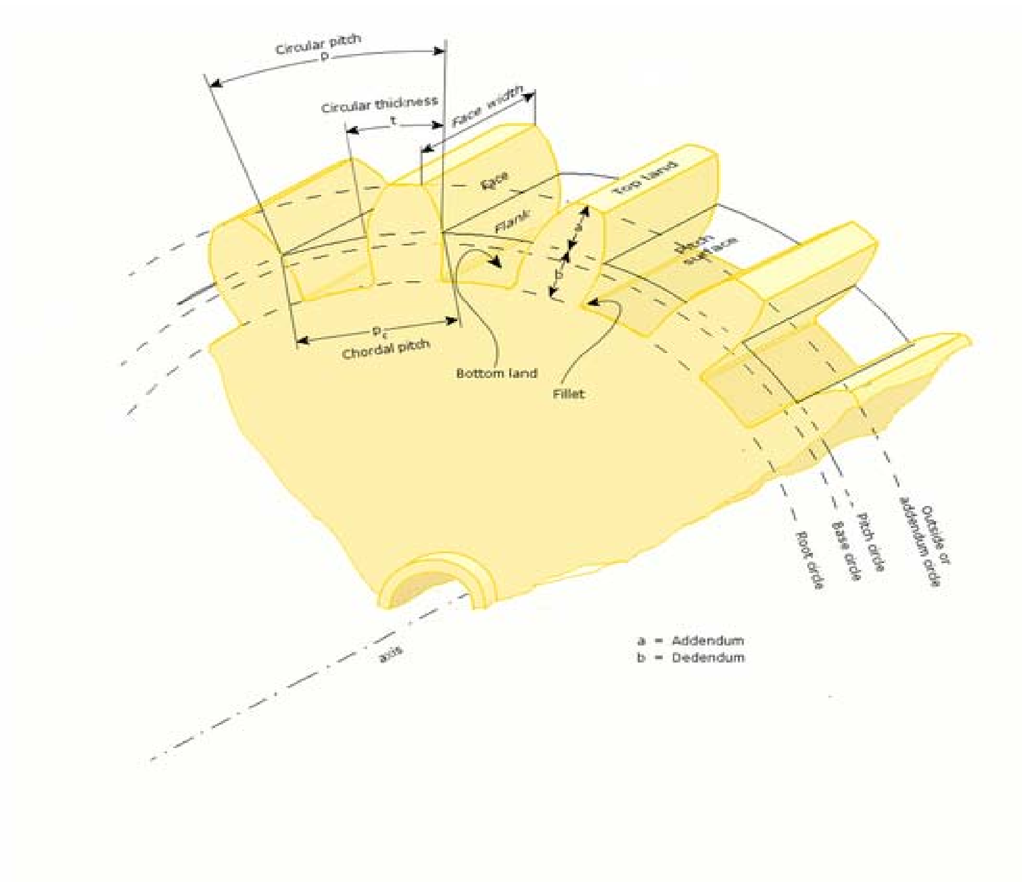
Cage gear

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.

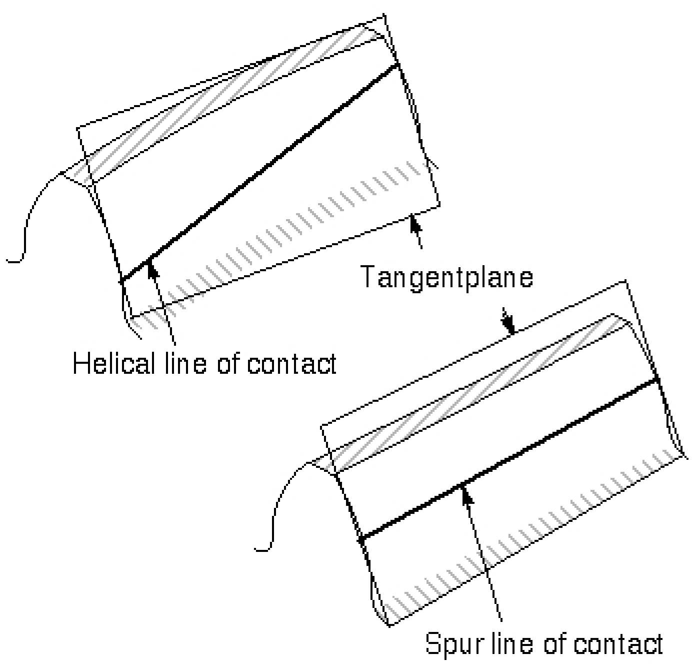
Linear pitch, p
: Distance from any point on a thread to the corresponding point on the adjacent thread, measured parallel to the axis. For a single-thread worm, lead and linear pitch are the same.

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.

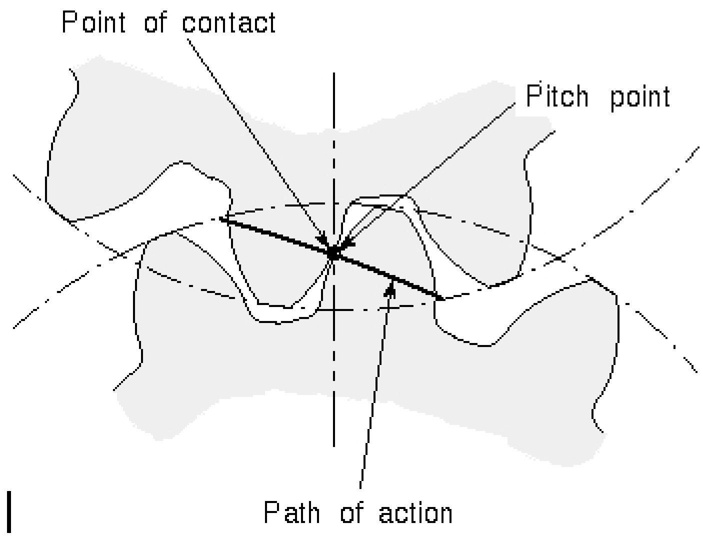
Pitch diameter, d_w
: Same as described earlier in this list. Note that for a worm it is still measured in a plane perpendicular to the gear axis, not a tilted plane.

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

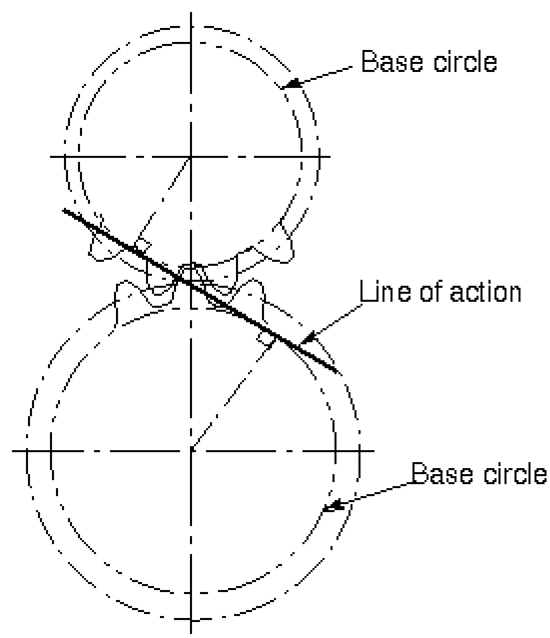
Tooth contact nomenclature



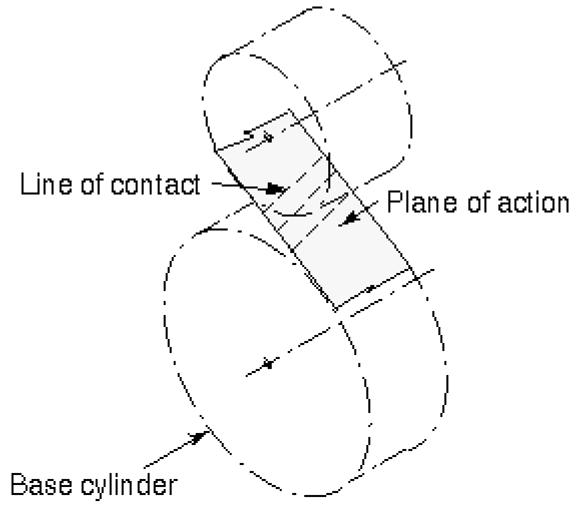
Line of contact



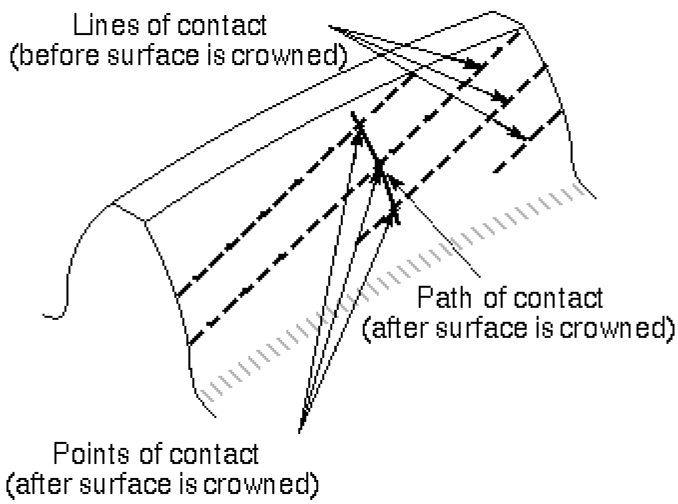
Path of action



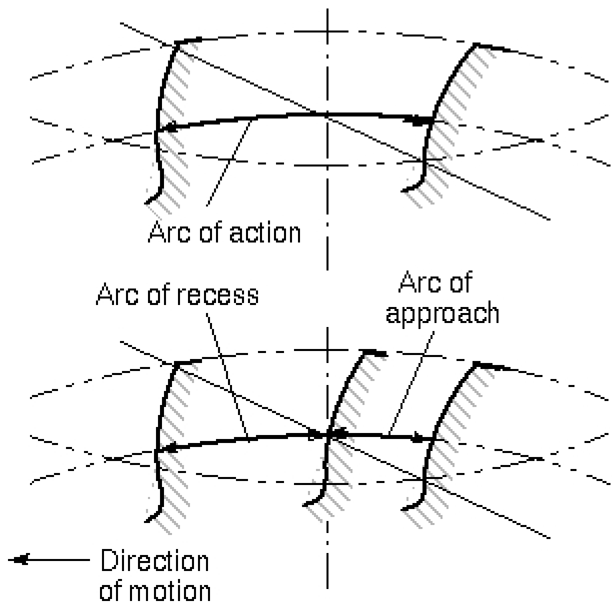
Line of action



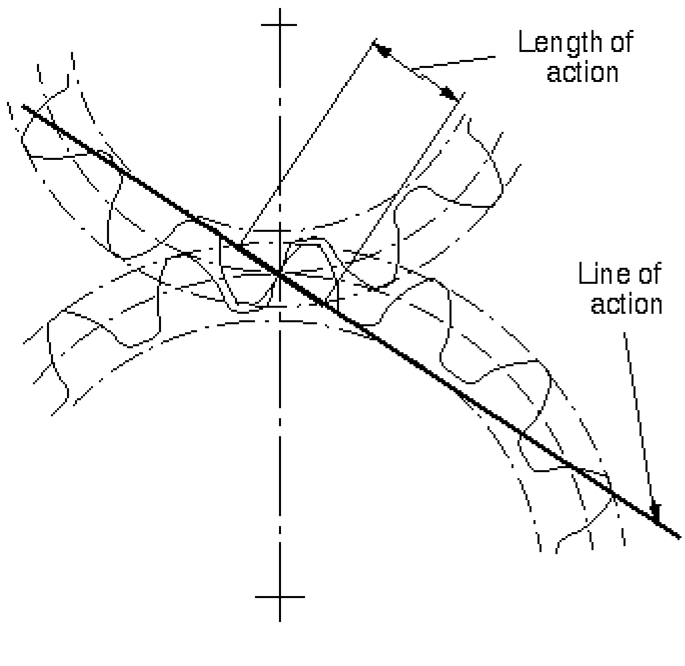
Plane of action



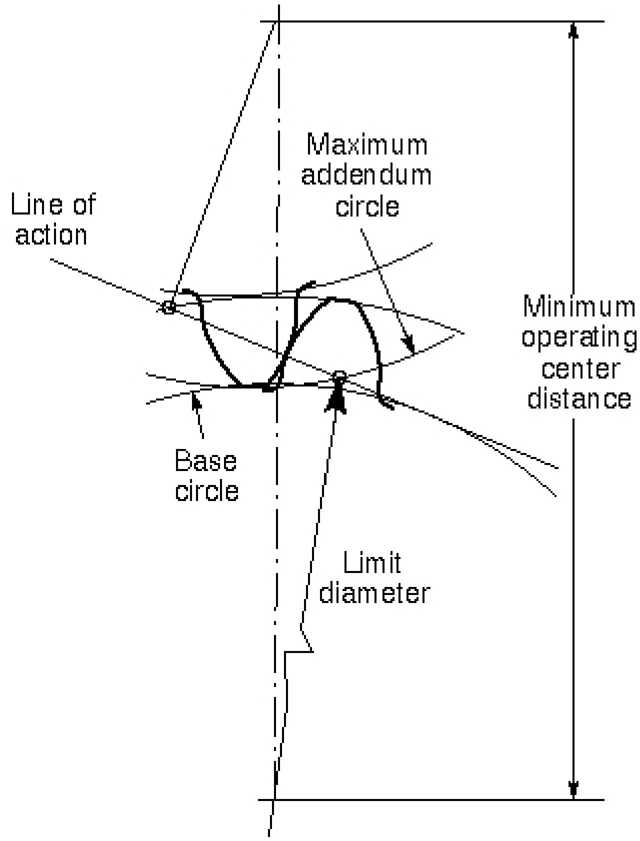
Lines of contact (helical gear)



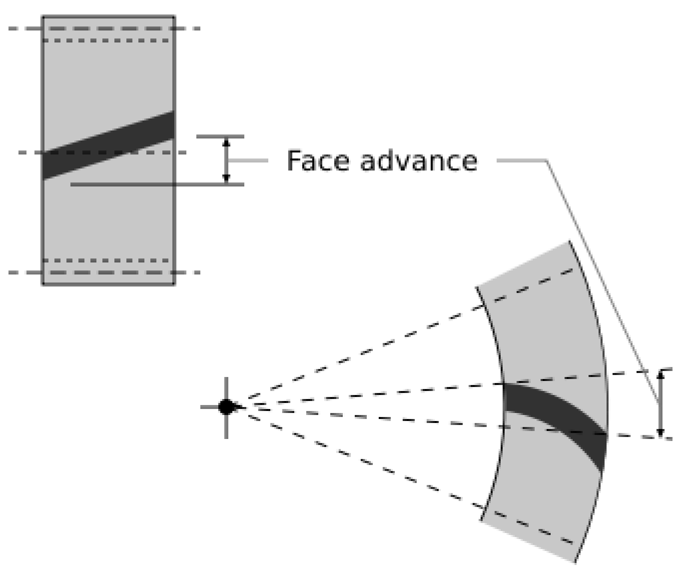
Arc of action



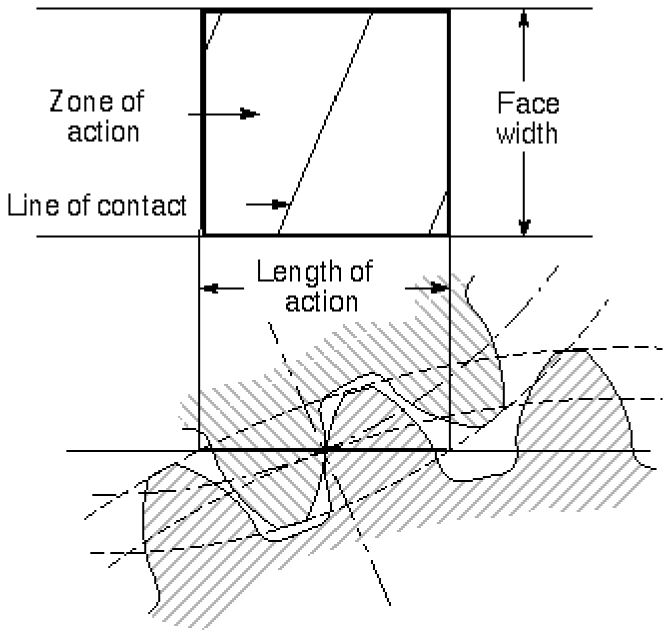
Length of action



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.

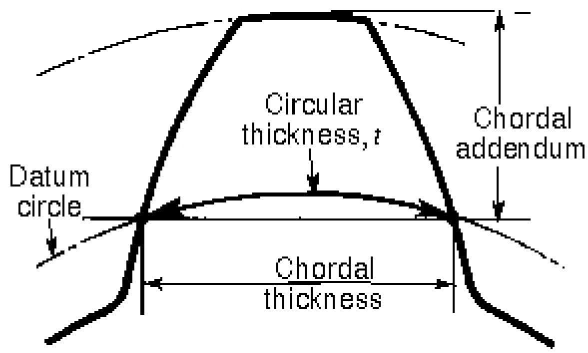
Start of active profile (SAP)

Intersection of the limit diameter and the involute profile.

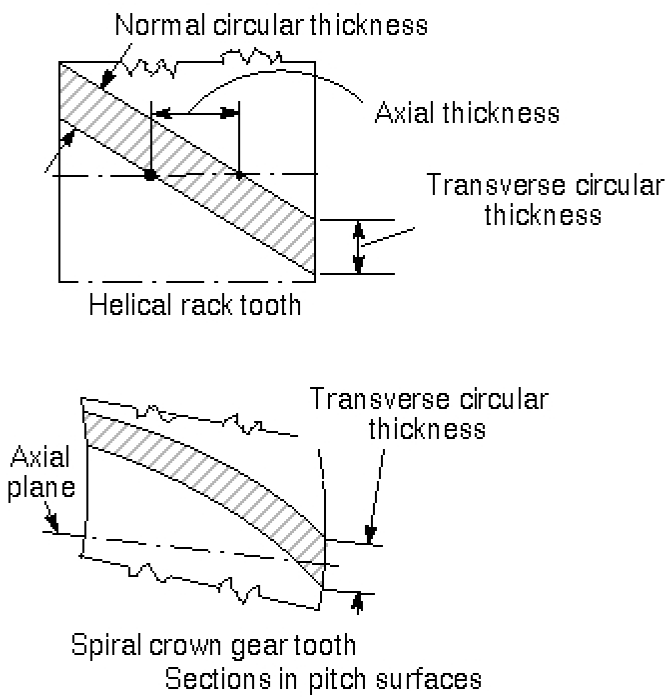
Face advance

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.

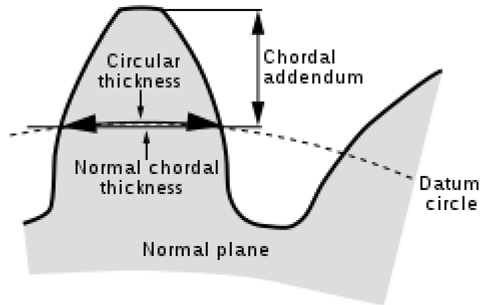
Tooth thickness nomeclature



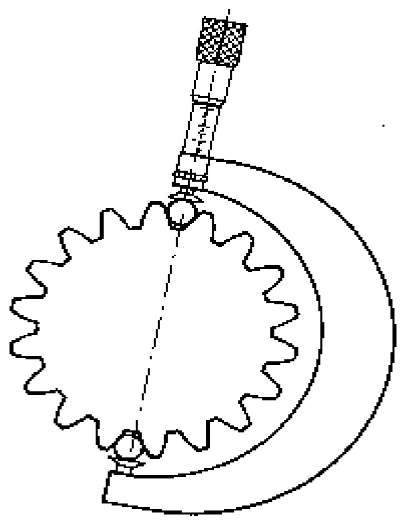
Tooth thickness



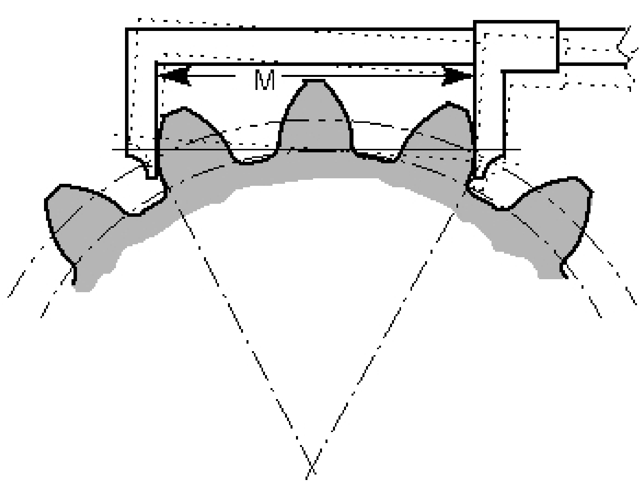
Thickness relationships



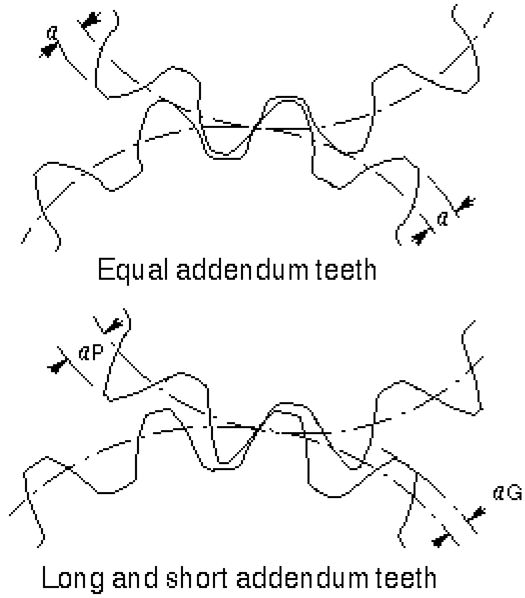
Chordal thickness



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

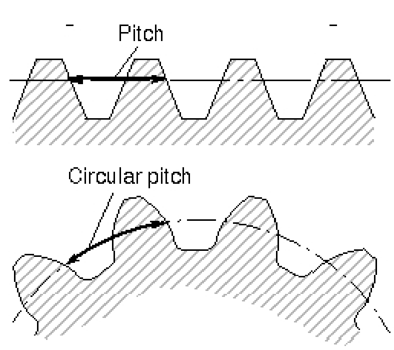
Teeth in which two engaging gears have equal addendums.

Long and short-addendum teeth

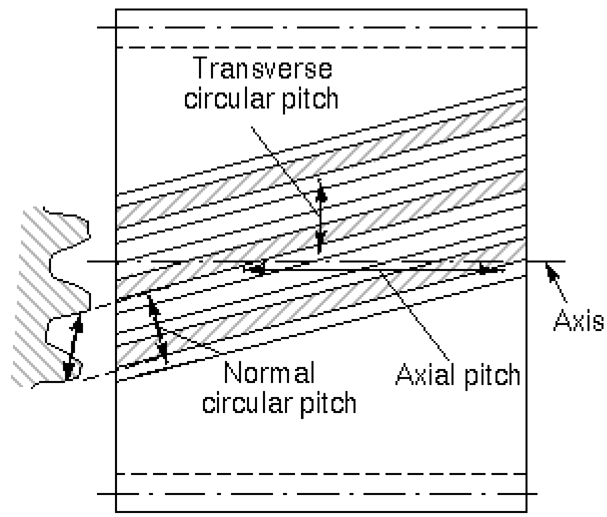
Teeth in which the addendums of two engaging gears are unequal.

Pitch nomenclature

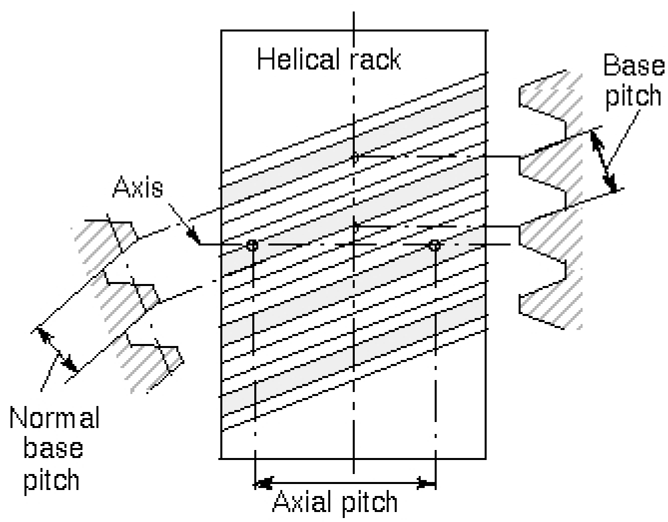
Pitch is the distance between a point on one tooth and the corresponding point on an adjacent tooth. It is a dimension measured along a line or curve in the transverse, normal, or axial directions. The use of the single word *pitch* without qualification may be ambiguous, and for this reason it is preferable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



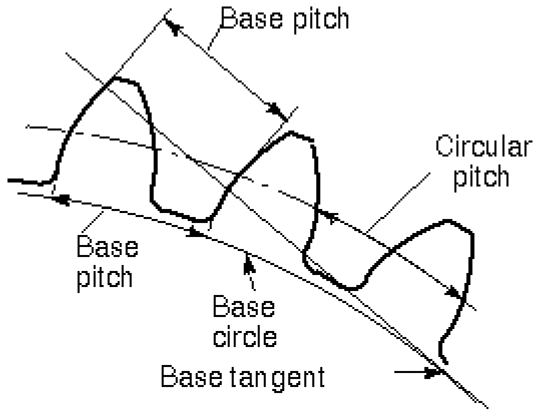
Pitch



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.

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

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

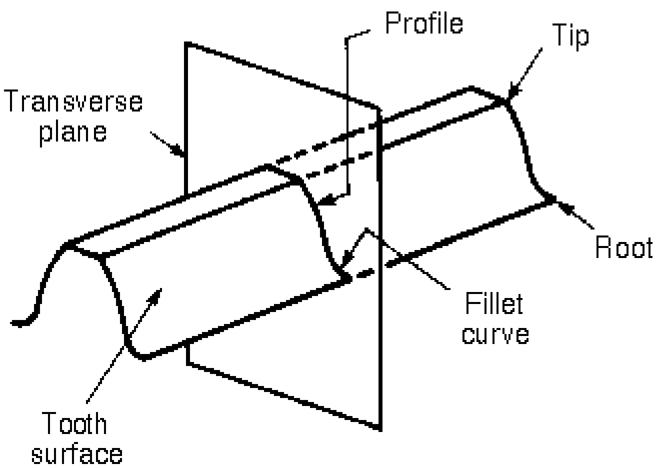
In some machines (e.g., automobiles) it is necessary to alter the gear ratio to suit the task. There are several methods of accomplishing this. For example:

- 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)

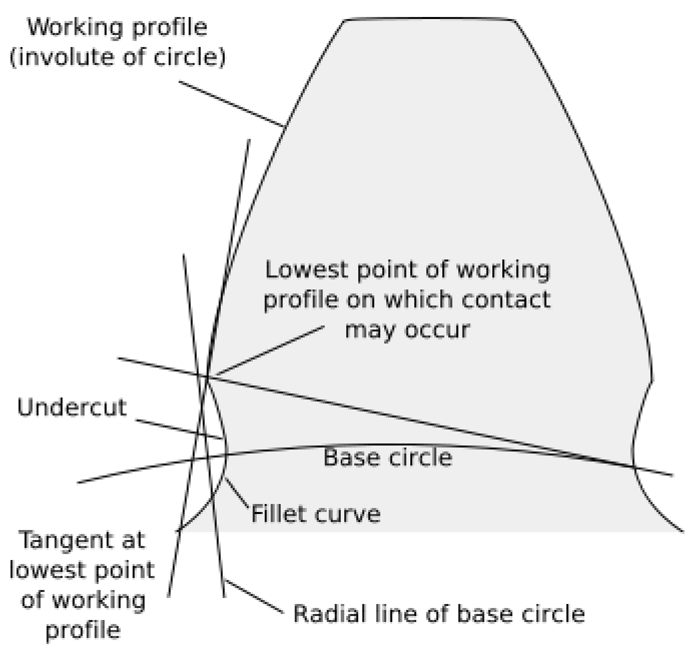
There are several outcomes of gear shifting in motor vehicles. In the case of vehicle noise emissions, there are higher sound levels emitted when the vehicle is engaged in lower gears. The design life of the lower ratio gears is shorter so cheaper gears may be used (i.e.

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

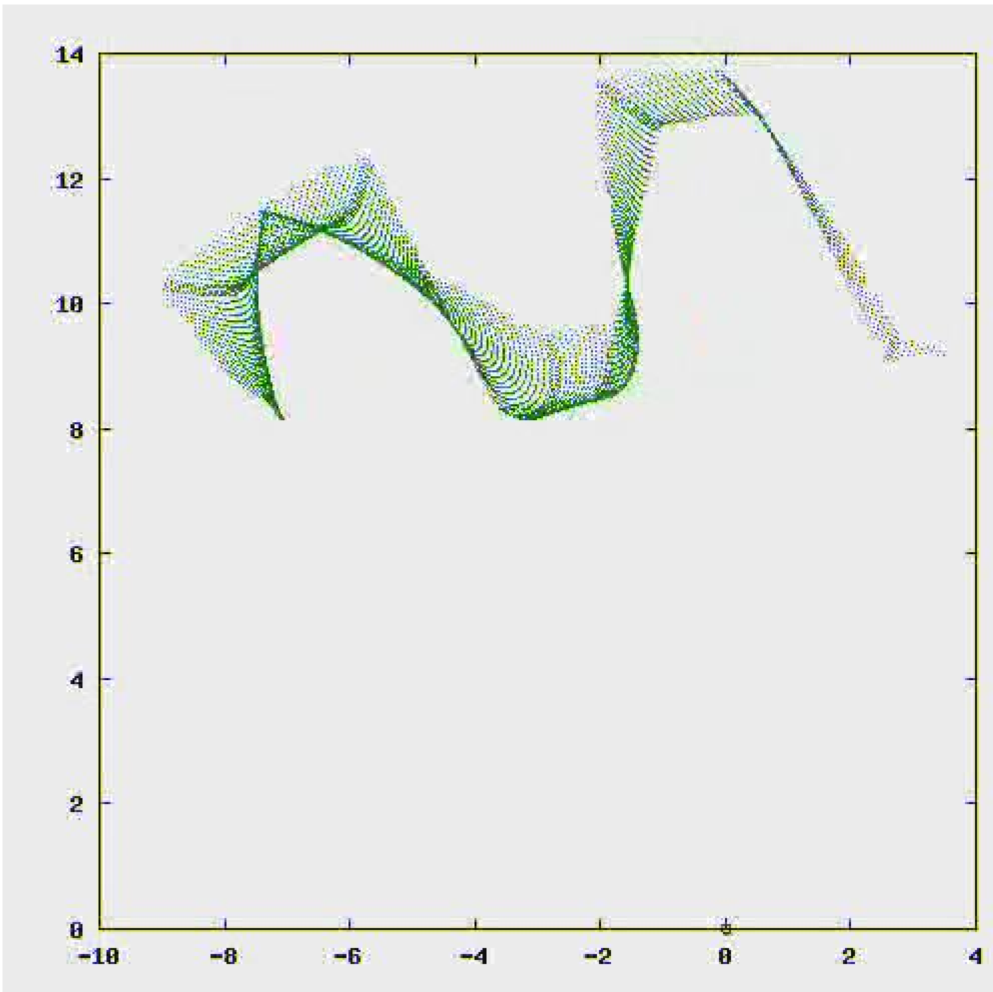
Wooden gears of a historic windmill

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.

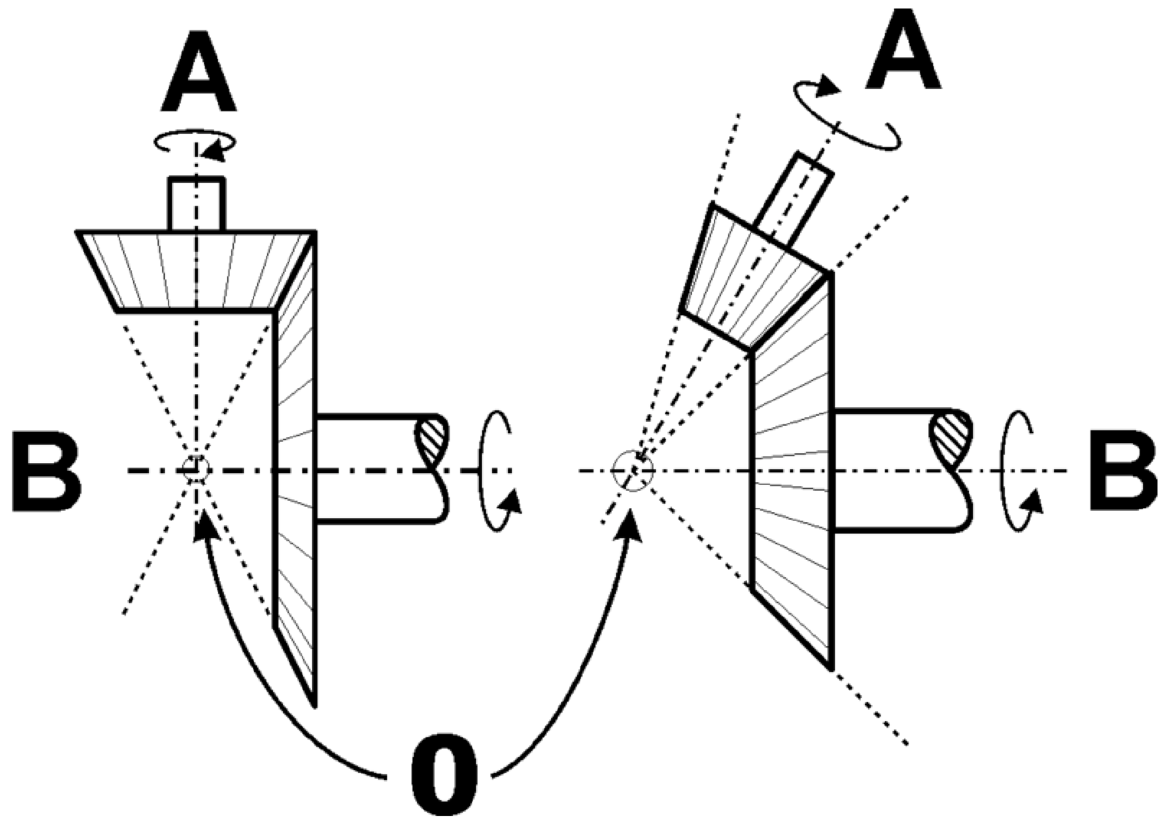
The Three Wave Hypothesis compares the wave–particle duality to a bevel gear.

Chapter 2

Bevel Gear

Bevel gears are gears where the axes of the two shafts intersect and the tooth-bearing faces of the gears themselves are conically shaped. Bevel gears are most often mounted on shafts that are 90 degrees apart, but can be designed to work at other angles as well. The pitch surface of bevel gears is a cone.

Bevel gear on roller shutter door.



Independently from the operating angle, the gear axes must intersect (at the point O)

Bevel gear lifts floodgate by means of central screw.

Bevel ring gear on the rear wheel of a shaft-driven bicycle

Spiral bevel gear - ZF Friedrichshafen

Introduction

Two important concepts in gearing are **pitch surface** and **pitch angle**. The pitch surface of a gear is the imaginary toothless surface that you would have by averaging out the peaks and valleys of the individual teeth. The pitch surface of an ordinary gear is the shape of a cylinder. The pitch angle of a gear is the angle between the face of the pitch surface and the axis.

The most familiar kinds of bevel gears have pitch angles of less than 90 degrees and therefore are cone-shaped. This type of bevel gear is called **external** because the gear teeth point outward. The pitch surfaces of meshed external bevel gears are coaxial with the gear shafts; the apexes of the two surfaces are at the point of intersection of the shaft axes.

Bevel gears that have pitch angles of greater than ninety degrees have teeth that point inward and are called **internal** bevel gears.

Bevel gears that have pitch angles of exactly 90 degrees have teeth that point outward parallel with the axis and resemble the points on a crown. That's why this type of bevel gear is called a **crown** gear.

Miter gears are mating bevel gears with equal numbers of teeth and with axes at right angles.

Skew bevel gears are those for which the corresponding crown gear has teeth that are straight and oblique.

Teeth

There are two issues regarding tooth shape. One is the cross-sectional profile of the individual tooth. The other is the line or curve on which the tooth is set on the face of the gear: in other words the line or curve along which the cross-sectional profile is projected to form the actual three-dimensional shape of the tooth. The primary effect of both the cross-sectional profile and the tooth line or curve is on the smoothness of operation of the gears. Some result in a smoother gear action than others.

Tooth line

The teeth on bevel gears can be straight, spiral or "zero".

Straight tooth lines

In **straight bevel gears** the teeth are straight and parallel to the generators of the cone. This is the simplest form of bevel gear. It resembles a spur gear, only conical rather than cylindrical. The gears in the floodgate picture are straight bevel gears. In straight, when each tooth engages it impacts the corresponding tooth and simply curving the gear teeth can solve the problem.

Spiral tooth lines

Spiral bevel gears have their teeth formed along spiral lines. They are somewhat analogous to cylindrical type helical gears in that the teeth are angled; however with spiral gears the teeth are also curved.

The advantage of the spiral tooth over the straight tooth is that they engage more gradually. The contact between the teeth starts at one end of the gear and then spreads across the whole tooth. This results in a less abrupt transfer of force when a new pair of teeth come in to play. With straight bevel gears, the abrupt tooth engagement causes noise, especially at high speeds, and impact stress on the teeth which makes them unable to take heavy loads at high speeds without breaking. For these reasons straight bevel gears are generally limited to use at linear speeds less than 1000 feet/min; or, for small gears, under 1000 r.p.m.

Zero tooth lines

Zero bevel gears are an intermediate type between straight and spiral bevel gears. Their teeth are curved, but not angled.

Applications

The bevel gear has many diverse applications such as locomotives, marine applications, automobiles, printing presses, cooling towers, power plants, steel plants, railway track inspection machines, etc.

For examples :

- Bevel gears are used in **differential drives**, which can transmit power to two axles spinning at different speeds, such as those on a cornering automobile.

- Bevel gears are used as the main mechanism for a **hand drill**. As the handle of the drill is turned in a vertical direction, the bevel gears change the rotation of the chuck to a horizontal rotation. The bevel gears in a hand drill have the added advantage of increasing the speed of rotation of the chuck and this makes it possible to drill a range of materials.

- The gears in a **bevel gear planer** permit minor adjustment during assembly and allow for some displacement due to deflection under operating loads without concentrating the load on the end of the tooth.

- Spiral bevel gears are important components on **rotorcraft** drive systems. These components are required to operate at high speeds, high loads, and for a large number of load cycles. In this application, spiral bevel gears are used to redirect the shaft from the horizontal gas turbine engine to the vertical rotor.

Bevel gears on grain mill at Dordrecht. Note wooden teeth inserts on one of the gears.

Advantages

- This gear makes it possible to change the operating angle.
- Differing of the number of teeth (effectively diameter) on each wheel allows mechanical advantage to be changed. By increasing or decreasing the ratio of teeth between the drive and driven wheels one may change the ratio of rotations between the two, meaning that the rotational drive and torque of the second wheel can be changed in relation to the first, with speed increasing and torque decreasing, or speed decreasing and torque increasing.

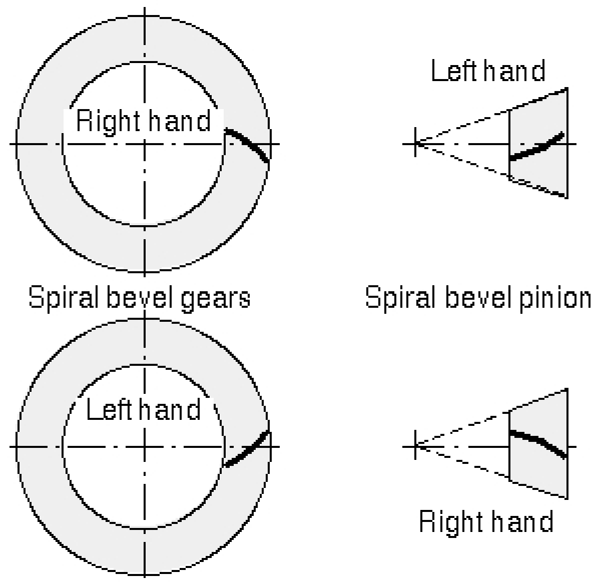
Disadvantages

- One wheel of such gear is designed to work with its complementary wheel and no other.
- Must be precisely mounted.
- The axes must be capable of supporting significant forces.

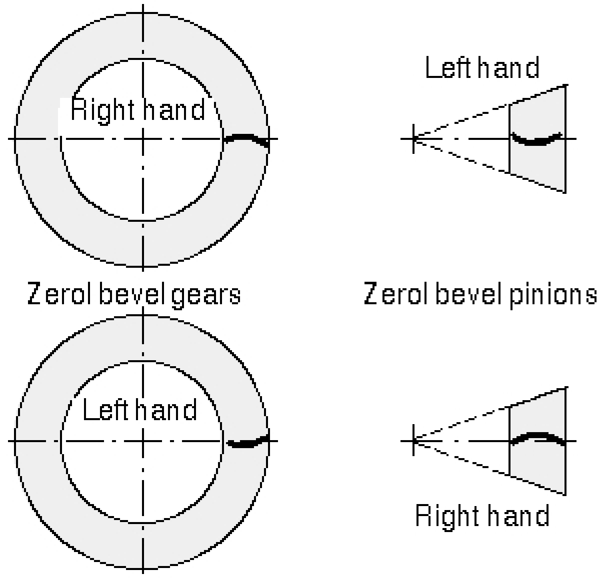
Chapter 3

Spiral Bevel Gear and Herringbone Gear

Spiral bevel gear



Spiral bevel handedness



Zerol handedness

A **spiral bevel gear** is a bevel gear with helical teeth. The main application of this is in a vehicle differential, where the direction of drive from the drive shaft must be turned 90 degrees to drive the wheels. The helical design produces less vibration and noise than conventional straight-cut or spur-cut gear with straight teeth.

A spiral bevel gear set should always be replaced in pairs i.e. both the left hand and right hand gears should be replaced together since the gears are manufactured and lapped in pairs.

Handedness

A **right hand** spiral bevel gear is one in which the outer half of a tooth is inclined in the clockwise direction from the axial plane through the midpoint of the tooth as viewed by an observer looking at the face of the gear.

A **left hand** spiral bevel gear is one in which the outer half of a tooth is inclined in the counterclockwise direction from the axial plane through the midpoint of the tooth as viewed by an observer looking at the face of the gear.

Note that a spiral bevel gear and pinion are always of opposite hand, including the case when the gear is internal.

Also note that the designations right hand and left hand are applied similarly to other types of bevel gear, hypoid gears, and oblique tooth face gears.

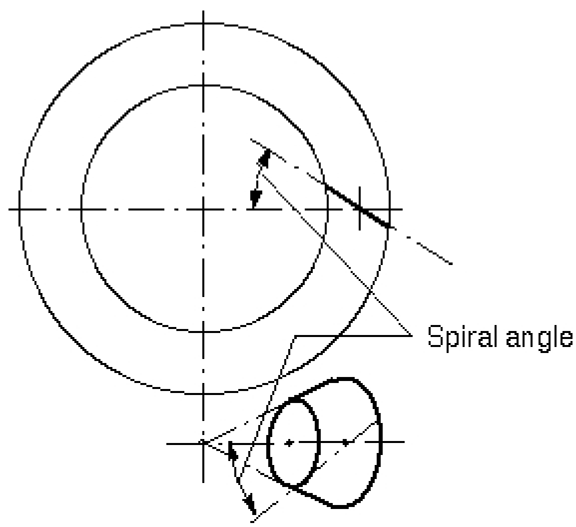
Hypoid gears

A **hypoid** is a type of spiral bevel gear whose axis does not intersect with the axis of the meshing gear. The shape of a hypoid gear is a revolved hyperboloid (that is, the pitch surface of the hypoid gear is a hyperbolic surface), whereas the shape of a spiral bevel gear is normally conical. The hypoid gear places the pinion off-axis to the crown wheel (ring gear) which allows the pinion to be larger in diameter and have more contact area. In hypoid gear design, the pinion and gear are practically always of opposite hand, and the spiral angle of the pinion is usually larger than that of the gear. The hypoid pinion is then larger in diameter than an equivalent bevel pinion.

A hypoid gear incorporates some sliding and can be considered halfway between a straight-cut gear and a worm gear. Special gear oils are required for hypoid gears because the sliding action requires effective lubrication under extreme pressure between the teeth.

Hypoid gearings are used in power transmission products that are more efficient than conventional worm gearing.

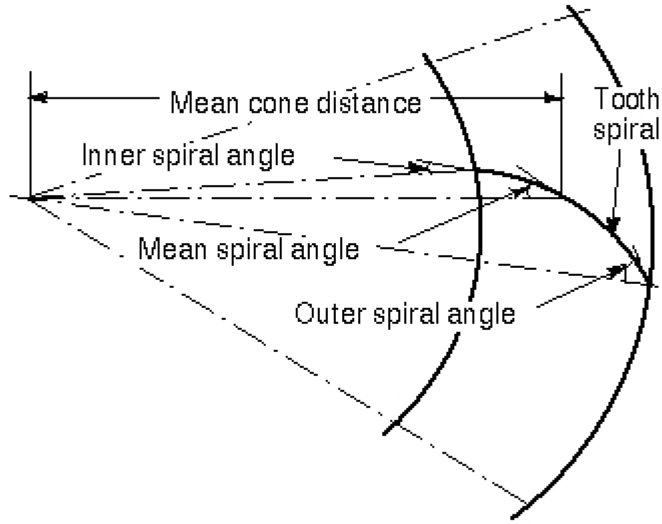
Spiral angle



Spiral angle

The spiral angle in a spiral bevel gear is the angle between the tooth trace and an element of the pitch cone, and corresponds to the helix angle in helical teeth. Unless otherwise specified, the term spiral angle is understood to be the mean spiral angle.

- Mean spiral angle is the specific designation for the spiral angle at the mean cone distance in a bevel gear.
- Outer spiral angle is the spiral angle of a bevel gear at the outer cone distance.
- Inner spiral angle is the spiral angle of a bevel gear at the inner cone distance.



Spiral angle relationships

Comparison of spiral bevel gears to hypoid gears

Hypoid gears are stronger, operate more quietly and can be used for higher reduction ratios, however they also have some sliding action along the teeth, which reduces mechanical efficiency, the energy losses being in the form of heat produced in the gear surfaces and the lubricating fluid.

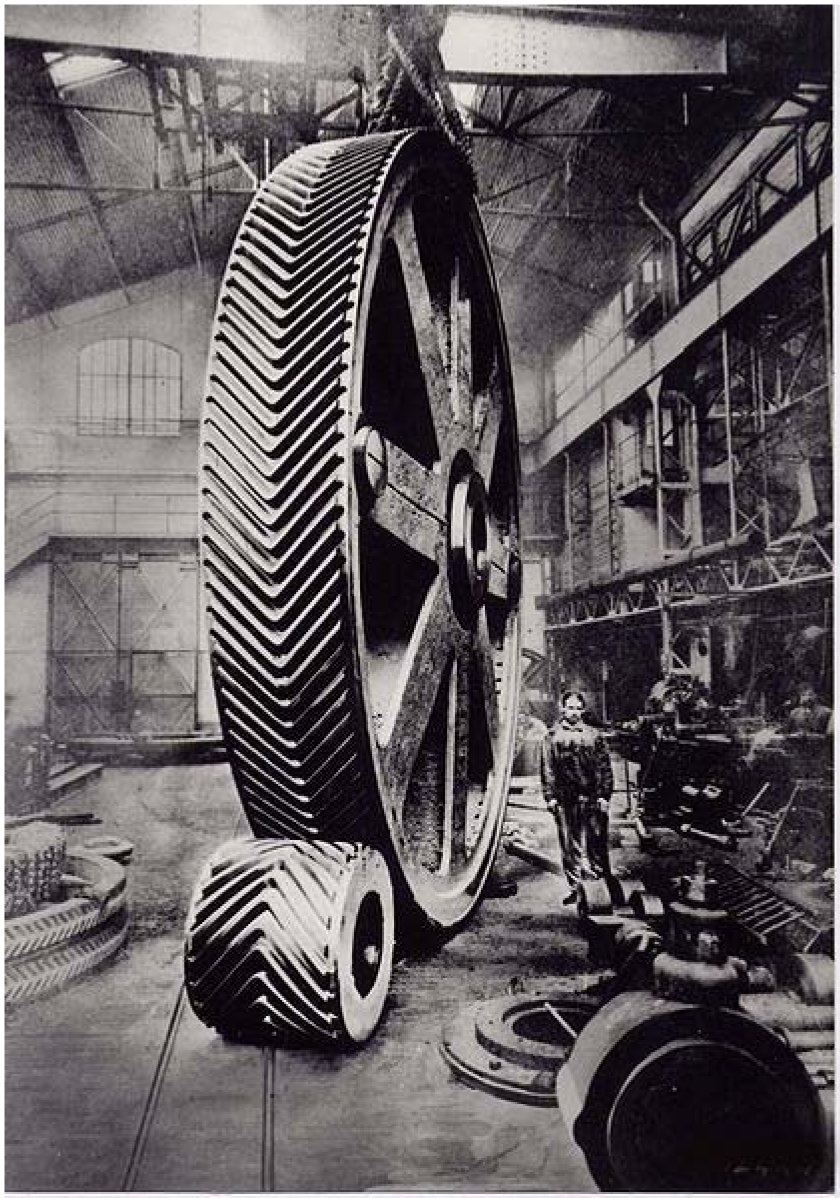
In older automotive designs, hypoid gears were typically used in rear-drive automobile drivetrains, but modern designs have tended to substitute spiral bevel gears to increase driving efficiency.

Hypoid gears are still common in larger trucks because they can transmit higher torque. A higher hypoid offset allows the gear to transmit higher torque. However increasing the hypoid offset results in reduction of mechanical efficiency and a consequent reduction in fuel economy. For practical purposes, it is often impossible to replace low efficiency hypoid gears with more efficient spiral bevel gears in automotive use because the spiral bevel gear would need a much larger diameter to transmit the same torque. Increasing the size of the drive axle gear would require an increase of the size of the gear housing and a reduction in the ground clearance.

Another advantage of hypoid gear is that the ring gear of the differential and the input pinion gear are both hypoid. In most passenger cars this allows the pinion to be offset to the bottom of the crown wheel. This provides for longer tooth contact and allows the shaft that drives the pinion to be lowered, reducing the "hump" intrusion in the passenger compartment floor. However, the greater the displacement of the input shaft axis from the crown wheel axis, the lower the mechanical efficiency.

Hypoid gear in a differential

Herringbone gear



A **herringbone gear**, also known as a **double helical gear**, is a special type of gear which is a side to side (not face to face) combination of two helical gears of opposite hands. Unlike helical gears they can sustain axial load smoothly. From the top the helical grooves of this gear looks like letter V.

Like helical gears, they have the advantage of transferring power smoothly as multiple gear teeth engage and disengage simultaneously. Their advantage over the helical gears is that the side-thrust of one half is balanced by that of the other half. This means that herringbone gears can be used in torque gearboxes without requiring a substantial thrust bearing. Because of this herringbone gears were an important step in the introduction of the steam turbine to marine propulsion.

Precision herringbone gears are more difficult to manufacture than equivalent spur or helical gears and consequently are more expensive. They are used in heavy machinery.

Where the oppositely angled teeth meet in the middle of a herringbone gear, the alignment may be such that tooth tip meets tooth tip, or the alignment may be staggered, so that tooth tip meets tooth trough. The latter alignment is the unique defining characteristic of a Wuest type herringbone gear, named after its inventor.

With the older method of fabrication, herringbone gears had a central channel separating the two oppositely-angled courses of teeth. This was necessary to permit the shaving tool to run out of the groove. The development of the Sykes gear shaper made it possible to have continuous teeth, with no central gap. After the W.E. Sykes and Farrel Gear Machine companies dissolved in 1983-84 there are no current production machines that have this ability. It is standard industry practice to obtain an older machine and rebuild it if necessary to create this unique type of gear. A disadvantage of the herringbone gear is that it cannot be cut by simple gear hobbing machines, as the cutter would run into the other half of the gear. Solutions to this have included assembling small gears by stacking two helical gears together, cutting the gears with a central groove to provide clearance, and (particularly in the early days) by casting the gears to an accurate pattern and without further machining.

The logo of the car maker Citroën is a graphic representation of a herringbone gear, it comes from Andre Citroën's early involvement in the manufacture of these gears.

Chapter 4

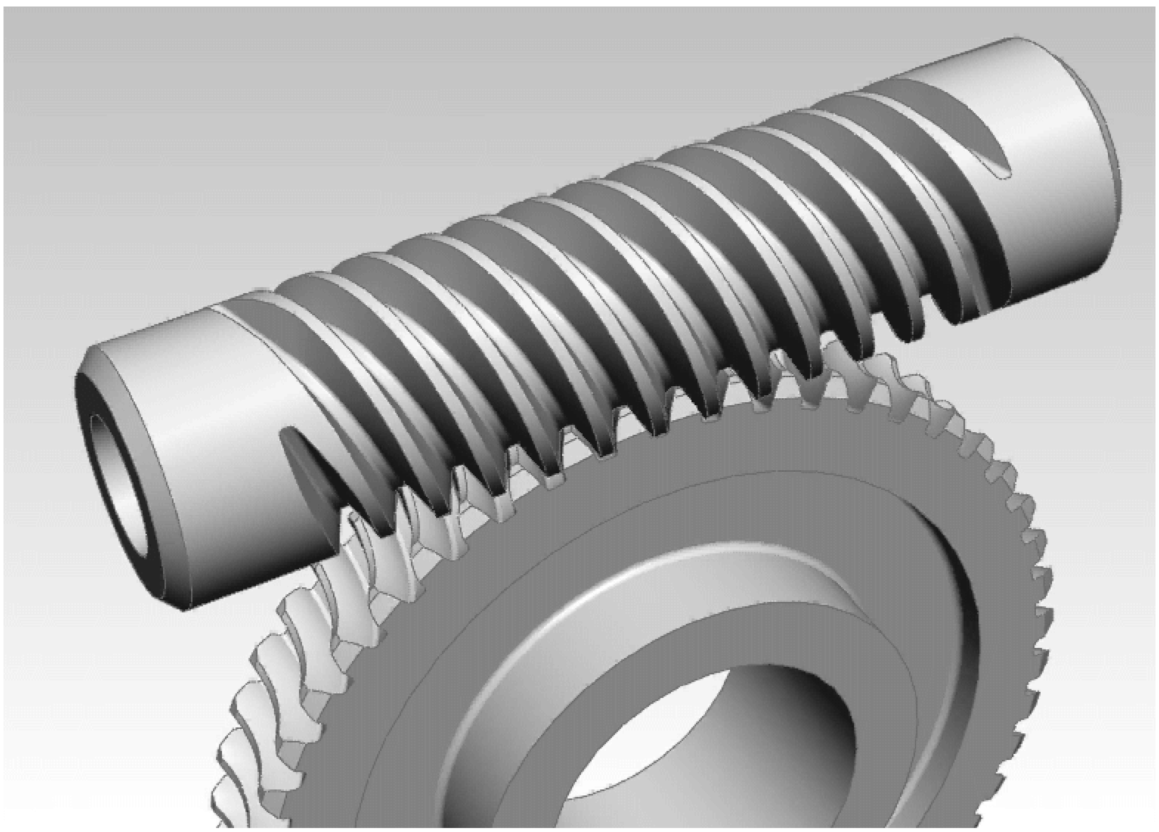
Worm Drive

Worm and worm gear

A **worm drive** is a gear arrangement in which a **worm** (which is a gear in the form of a screw) meshes with a **worm gear** (which is similar in appearance to a spur gear, and is also called a **worm wheel**). The terminology is often confused by imprecise use of the term *worm gear* to refer to the worm, the worm gear, or the worm drive as a unit.

Like other gear arrangements, a worm drive can reduce rotational speed or allow higher torque to be transmitted. The image shows a section of a gear box with a worm gear being driven by a worm. A worm is an example of a screw, one of the six simple machines.

Explanation



Worm gear with 4-start worm

A gearbox designed using a worm and worm-wheel will be considerably smaller than one made from plain spur gears and has its drive axes at 90° to each other. With a *single start* worm, for each 360° turn of the worm, the worm-gear advances only one tooth of the gear. Therefore, regardless of the worm's size (sensible engineering limits notwithstanding), the gear ratio is the *"size of the worm gear - to - 1"*. Given a single start worm, a 20 tooth worm gear will reduce the speed by the ratio of 20:1. With spur gears, a gear of 12 teeth (the smallest size permissible, if designed to good engineering practices) would have to be matched with a 240 tooth gear to achieve the same ratio of 20:1. Therefore, if the diametrical pitch (DP) of each gear was the same, then, in terms of the physical size of the 240 tooth gear to that of the 20 tooth gear, the worm arrangement is considerably smaller in volume.

A double bass features worm gears as tuning mechanisms

Types

There are three different types of gears that can go in a worm drive.

The first are *non-throated* worm gears. These don't have a *throat*, or groove, machined around the circumference around either the worm or worm wheel. The second are single-throated worm gears,in which the worm wheel is throated. The final type are double-throated worm gears, which have both gears throated. This type of gearing can support the highest loading.

An enveloping (hourglass) worm has one or more teeth and increases in diameter from its middle portion toward both ends.

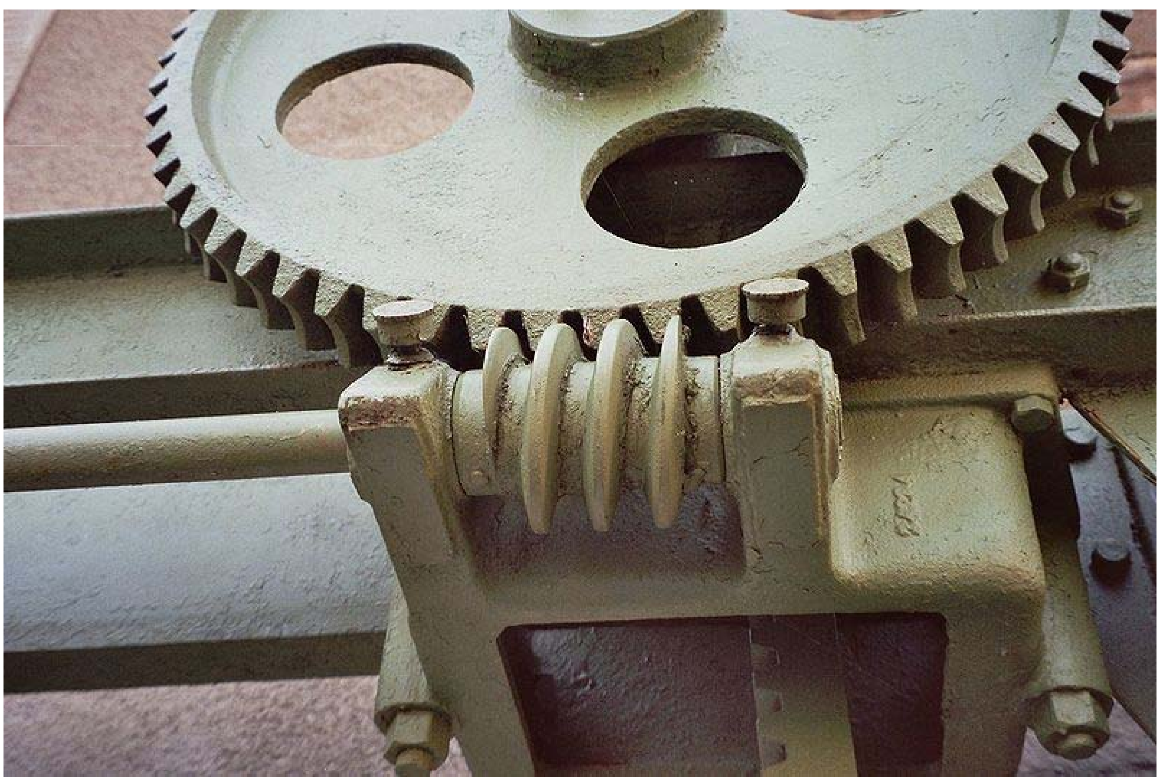
Double-enveloping wormgearing comprises enveloping worms mated with fully enveloping wormgears. It is also known as globoidal wormgearing.

Direction of transmission

Unlike with ordinary gear trains, the direction of transmission (input shaft vs output shaft) is not reversible when using large reduction ratios, due to the greater friction involved between the worm and worm-wheel, when usually a single start (one spiral) worm is used. This can be an advantage when it is desired to eliminate any possibility of the output driving the input. If a multistart worm (multiple spirals) then the ratio reduces accordingly and the *braking effect* of a worm and worm-gear may need to be discounted as the gear may be able to drive the worm.

Worm gear configurations in which the gear can not drive the worm are said to be *self-locking*. Whether a worm and gear will be self-locking depends on the lead angle, the pressure angle, and the coefficient of friction; however, it is approximately correct to say that a worm and gear will be self-locking if the tangent of the lead angle is less than the coefficient of friction.

Applications



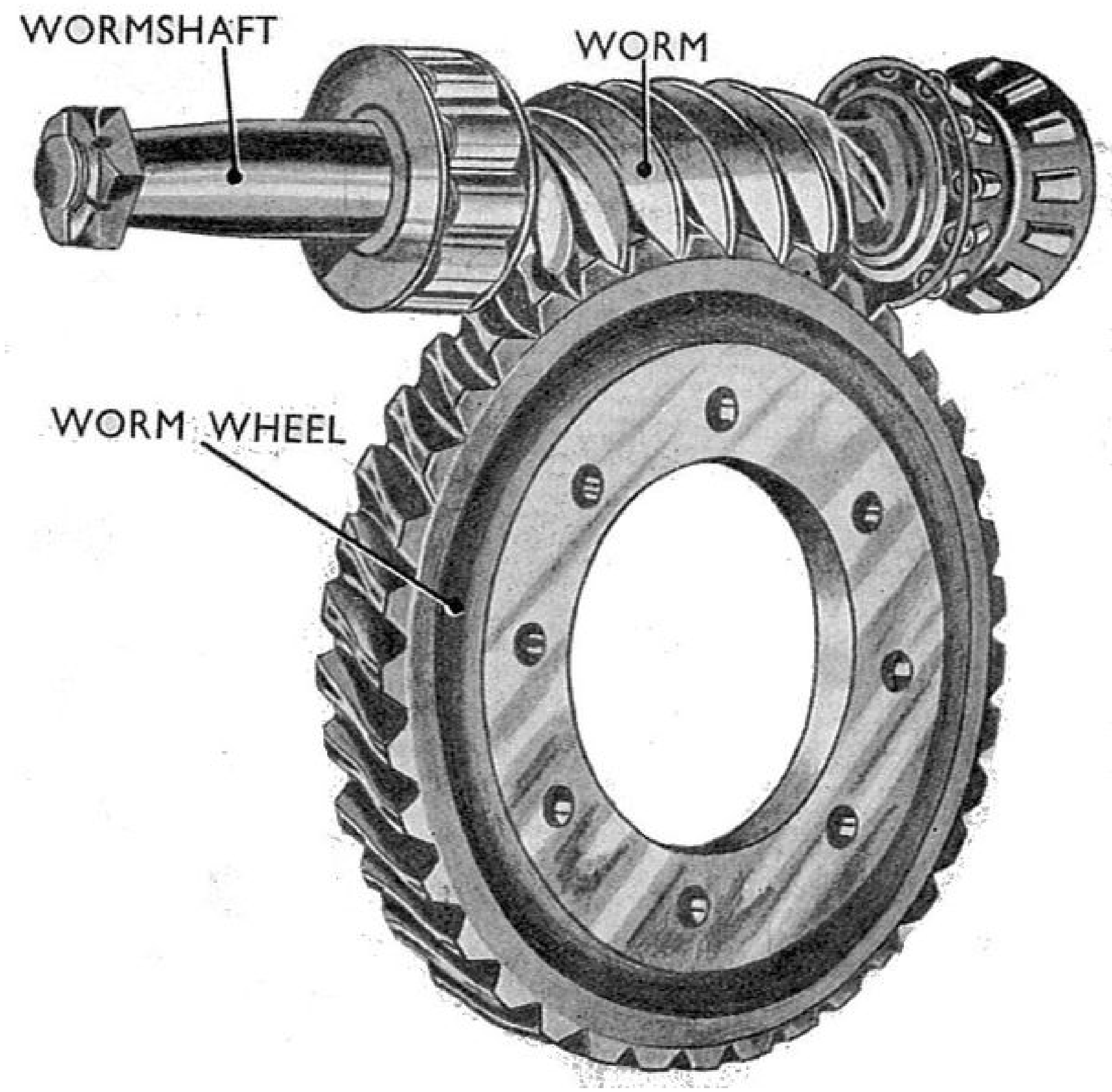
A worm drive controlling a gate. The position of the gate will not change after being set

In early 20th century automobiles prior to the introduction of power steering, the effect of a flat or blowout on one of the front wheels will tend to pull the steering mechanism toward the side with the flat tire. The employment of a worm screw reduced this effect. Further development of the worm drive employs recirculating ball bearings to reduce frictional forces, allowing some of the steering force to be felt in the wheel as an aid to vehicle control and greatly reducing wear, which leads to difficulties in steering precisely.

Worm drives are a compact means of substantially decreasing speed and increasing torque. Small electric motors are generally high-speed and low-torque; the addition of a worm drive increases the range of applications that it may be suitable for, especially when the worm drive's compactness is considered.

Worm drives are used in presses, in rolling mills, in conveying engineering, in mining industry machines, and on rudders. In addition, milling heads and rotary tables are positioned using high-precision duplex worm drives with adjustable backlash. Worm gears are used on many lift- (in US English known as elevator) and escalator-drive applications due to their compact size and the non-reversibility of the gear.

In the era of sailing ships, the introduction of a worm drive to control the rudder was a significant advance. Prior to its introduction, a rope drum drive was used to control the rudder, and rough seas could cause substantial force to be applied to the rudder, often requiring several men to steer the vessel, with some drives having two large-diameter wheels to allow up to four crewmen to operate the rudder.



Truck final drive of the 1930s

Worm drives have been used in a few automotive rear-axle final drives (although not the differential itself at this time). They took advantage of the location of the gear being at either the very top or very bottom of the differential crown wheel. In the 1910s they were common on trucks; to gain the most clearance on muddy roads the worm gear was placed on top. In the 1920s the Stutz firm used them on its cars; to have a lower floor than its competitors, the gear was located on the bottom. An example from around 1960 was the Peugeot 404. The worm gear carries the differential gearing, which protects the vehicle against rollback. This ability has largely fallen from favour due to the higher-than-necessary reduction ratios.

A more recent exception to this is the Torsen differential, which uses worms and planetary worm gears in place of the bevel gearing of conventional open differentials. Torsen differentials are most prominently featured in the HMMWV and some commercial Hummer vehicles, and as a center differential in some all wheel drive systems, such as Audi's quattro. Very heavy trucks, such as those used to carry aggregates, often use a worm gear differential for strength. The worm drive is not as efficient as a hypoid gear, and such trucks invariably have a very large differential housing, with a correspondingly large volume of gear oil, to absorb and dissipate the heat created.

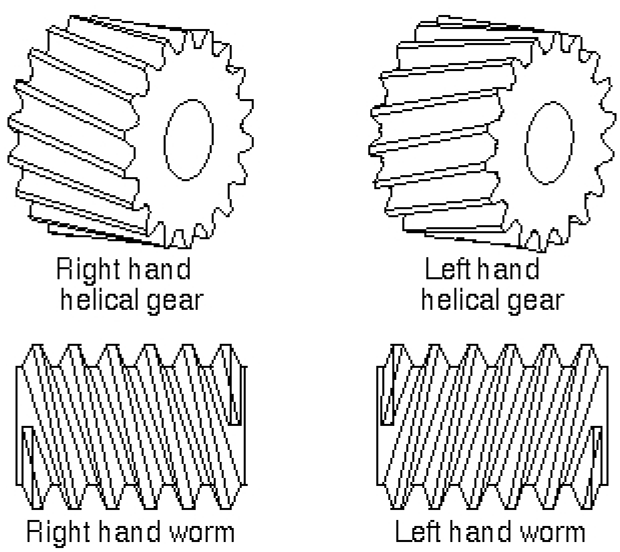
Worm drives are used as the tuning mechanism for many musical instruments, including guitars, double-basses, mandolins and bouzoukis, although not banjos, which use planetary gears or friction pegs. A worm drive tuning device is called a machine head.

Plastic worm drives are often used on small battery-operated electric motors, to provide an output with a lower angular velocity (fewer revolutions per minute) than that of the motor, which operates best at a fairly high speed. This motor-worm-gear drive system is often used in toys and other small electrical devices.

A worm drive is used on jubilee-type hose clamps or jubilee clamps; the tightening screw has a worm thread which engages with the slots on the clamp band.

Occasionally a worm gear is designed to be run in reverse, resulting in the output shaft turning much faster than the input. Examples of this may be seen in some hand-cranked centrifuges or the wind governor in a musical box.

Left hand and right hand worm



Helical and worm handedness

A right hand helical gear or right hand worm is one in which the teeth twist clockwise as they recede from an observer looking along the axis. The designations, right hand and left hand, are the same as in the long established practice for screw threads, both external and internal. Two external helical gears operating on parallel axes must be of opposite hand. An internal helical gear and its pinion must be of the same hand.

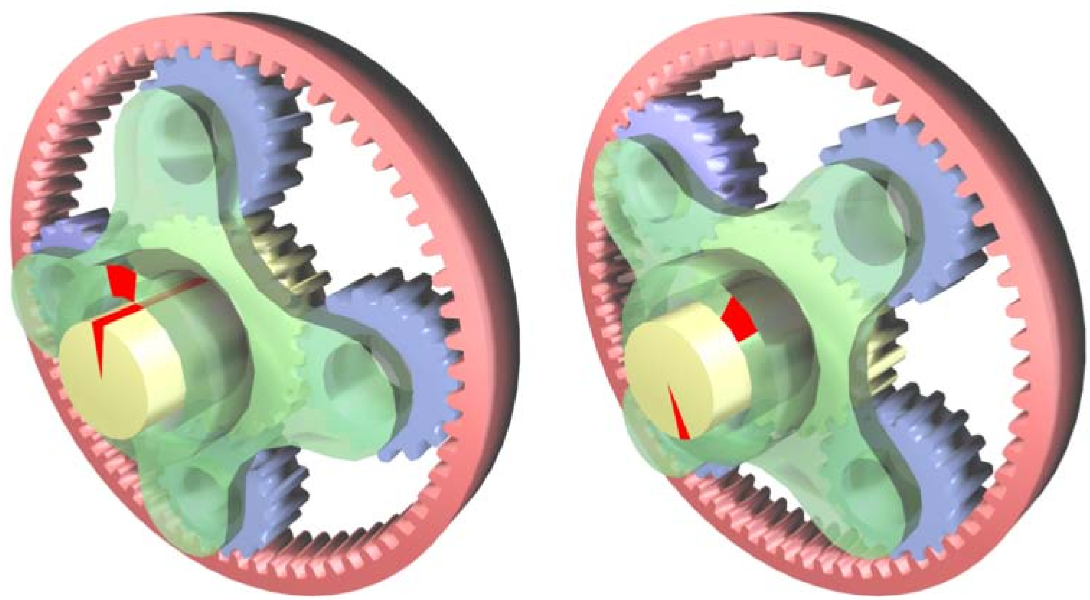
A left hand helical gear or left hand worm is one in which the teeth twist counterclockwise as they recede from an observer looking along the axis.

Manufacture

Worm wheels are first gashed to rough out the teeth and then hobbed to the final dimensions.

Chapter 5

Epicyclic Gearing

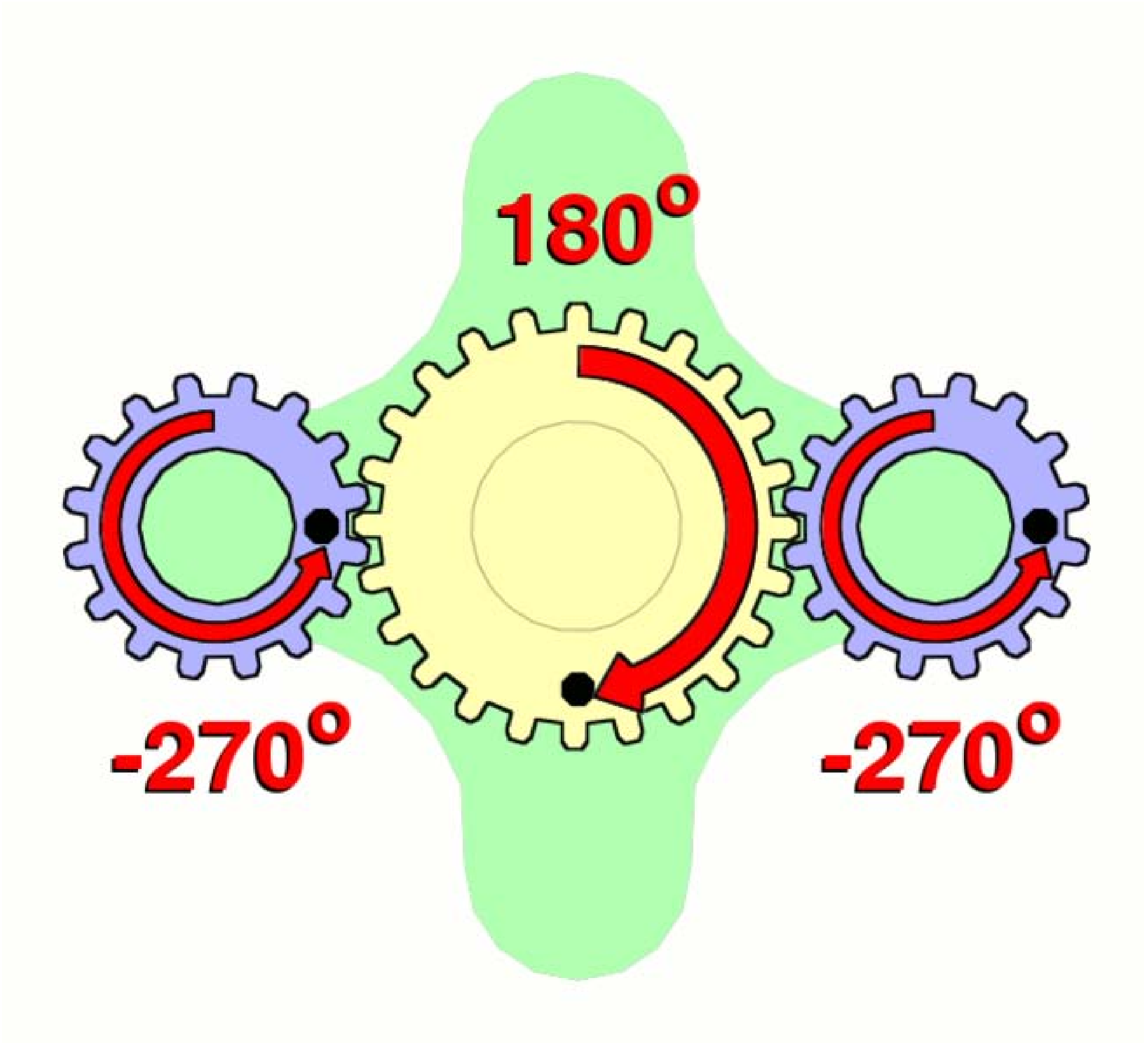


Epicyclic gearing is used here for increasing output speed. The planet gear carrier (green) is driven by an input torque. The sun gear (yellow) provides the output torque, while the ring gear (red) is fixed. Note the red marks both before and after the input drive is rotated 45° clockwise.

Epicyclic gearing or **planetary gearing** is a gear system consisting of one or more outer gears, or *planet* gears, revolving about a central, or *sun* gear. Typically, the planet gears are mounted on a movable arm or *carrier* which itself may rotate relative to the sun gear. Epicyclic gearing systems also incorporate the use of an outer ring gear or *annulus*, which meshes with the planet gears.

The axes of all gears are usually parallel, but for special cases like pencil sharpeners they can be placed at an angle, introducing elements of bevel gear (see below). Further, the sun, planet carrier and annulus axes are usually concentric.

Gear ratio



In this example, the carrier (green) is held stationary while the sun gear (yellow) is used as input. The planet gears (blue) turn in a ratio determined by the number of teeth in each gear. Here, the ratio is -24/16, or -3/2; each planet gear turns at 3/2 the rate of the sun gear, in the opposite direction.

Reduction gears on Pratt & Whitney Canada PT6 gas turbine engine.

The gear ratio in an epicyclic gearing system is somewhat non-intuitive, particularly because there are several ways in which an input rotation can be converted into an output rotation. The three basic components of the epicyclic gear are:

- *Sun*: The central gear
- *Planet carrier*: Holds one or more peripheral *planet* gears, all of the same size, meshed with the sun gear
- *Annulus*: An outer ring with inward-facing teeth that mesh with the planet gear or gears

In many epicyclic gearing systems, one of these three basic components is held stationary; one of the two remaining components is an *input*, providing power to the system, while the last component is an *output*, receiving power from the system. The ratio of input rotation to output rotation is dependent upon the number of teeth in each gear, and upon which component is held stationary.

In other systems, such as hybrid vehicle transmissions, two of the components are used as *inputs* with the third providing *output* relative to the two inputs.

One situation is when the planetary carrier is held stationary, and the sun gear is used as input. In this case, the planetary gears simply rotate about their own axes at a rate determined by the number of teeth in each gear. If the sun gear has *Ns* teeth, and each planet gear has *Np* teeth, then the ratio is equal to -*Ns*/*Np*. For instance, if the sun gear has 24 teeth, and each planet has 16 teeth, then the ratio is -24/16, or -3/2; this means that one clockwise turn of the sun gear produces 1.5 *counterclockwise* turns of each of the planet gear(s) about its axis.

This rotation of the planet gears can in turn drive the annulus, in a corresponding ratio. If the annulus has *Na* teeth, then the annulus will rotate by *Np*/*Na* turns for each turn of the planet gears. For instance, if the annulus has 64 teeth, and the planets 16, one clockwise turn of a planet gear results in 16/64, or 1/4 clockwise turns of the annulus. Extending this case from the one above:

- One turn of the sun gear results in $-Ns / Np$ turns of the planets
- One turn of a planet gear results in Np / Na turns of the annulus

So, with the planetary carrier locked, one turn of the sun gear results in $-Ns / Na$ turns of the annulus.

The annulus may also be held fixed, with input provided to the planetary gear carrier; output rotation is then produced from the sun gear. This configuration will produce an increase in gear ratio, equal to 1+*Na*/*Ns*.

These are all described by the equation:

$$(2 + n)\omega_a + n\omega_s - 2(1 + n)\omega_c = 0$$

where n is the form factor of the planetary gear, defined by:

$$n = Ns / Np$$

If the annulus is held stationary and the sun gear is used as the input, the planet carrier will be the output. The gear ratio in this case will be 1/(1+*Na*/*Ns*). This is the lowest gear ratio attainable with an epicyclic gear train. This type of gearing is sometimes used in tractors and construction equipment to provide high torque to the drive wheels.

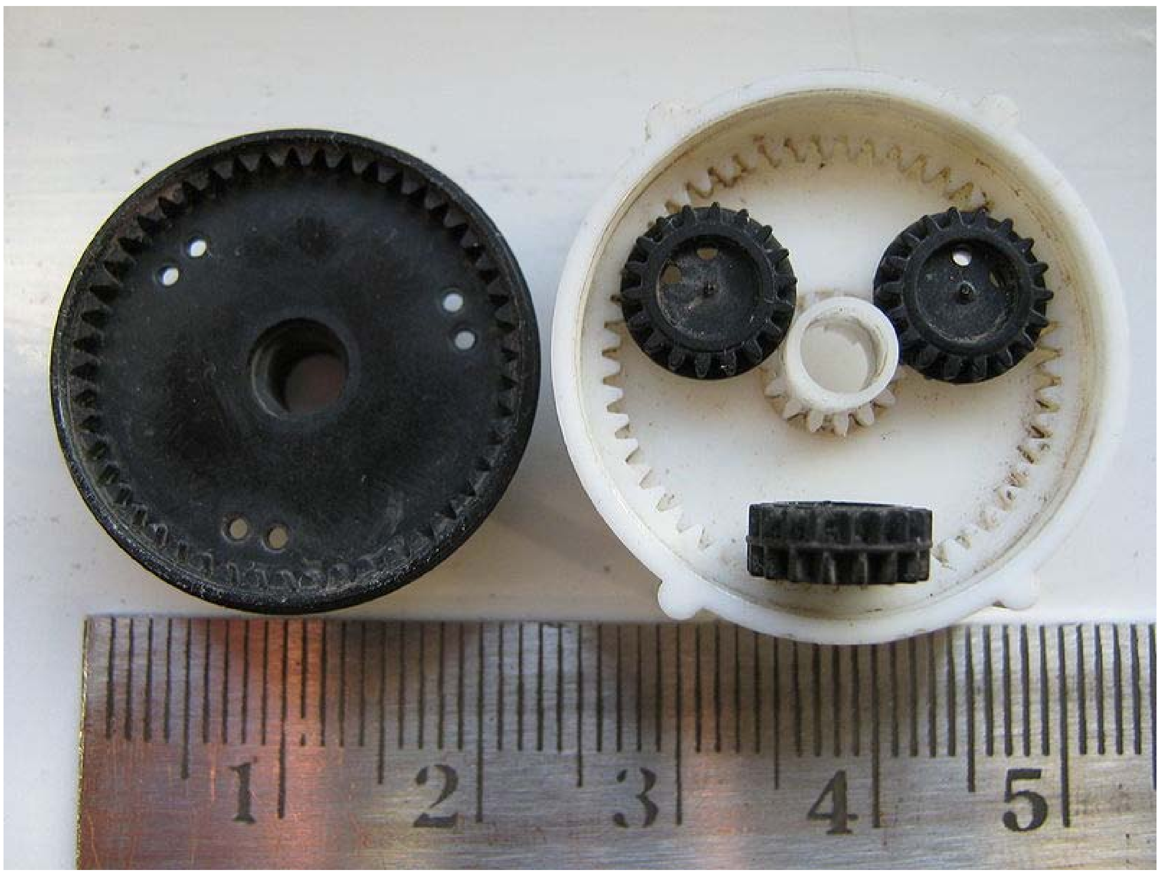
In bicycle hub gears, the sun is usually stationary, being keyed to the axle or even machined directly onto it. The planetary gear carrier is used as input. In this case the gear ratio is simply given by (*Ns*+*Na*)/*Na*. The number of teeth in the planet gear is irrelevant.

Compound planets of a Sturmey-Archer AM bicycle hub (gear ring removed)

Some designs use "compound planets" which have two differently-sized gears on either end of a common casting. The large end engages the sun, while the small end engages the annulus. This may be necessary to achieve smaller step changes in gear ratio when the overall package size is limited. Compound planets have "timing marks" and must be assembled in the correct initial orientation relative to each other, or their teeth will not simultaneously engage the sun and annulus at opposite ends of the planet, leading to very rough running and short life. The use of compound planets is like increasing the size of the annulus; for example, compound planets with teeth in a 2:1 ratio with a 50T annulus would give the same effect as a 100T annulus, but with half the actual diameter.

More planet and sun gear units can be placed in series in the same annulus housing (where the output shaft of the first stage becomes the input shaft of the next stage) providing a larger (or smaller) gear ratio. This is the way some automatic transmissions work.

During World War II, a special variation of epicyclic gearing was developed for portable radar gear, where a very high reduction ratio in a small package was needed. This had two outer annular gears, each half the thickness of the other gears. One of these two annular gears was held fixed and had one tooth fewer than did the other. Therefore, several turns of the "sun" gear made the "planet" gears complete a single revolution, which in turn made the rotating annular gear rotate by a single tooth.



Split annulus, compound planet, epicyclic gears of a car rear-view mirror positioner

The mechanism of a pencil sharpener with stationary annulus and rotating planet carrier as input. Planet gears are extended into cylindric cutters, rotating around the pencil that is placed on the sun axis. The axis of planetary gears join at pencil sharpening angle.

Calculating the output from the input

It is first drawn simplified as the sun, a single planet, the annulus, and an arm holding the planet. Any gear can be the input or output, including the arm.

Now, put in the known values and solve for ω_{ring}:

$$\frac{N_{\mathbf{sun}}}{N_{\mathbf{ring}}} = \frac{\omega_{\mathbf{arm}} - \omega_{\mathbf{ring}}}{\omega_{\mathbf{sun}} - \omega_{\mathbf{arm}}}$$

or you can use the other form of this equation:

$$N_{\mathbf{sun}} \cdot \omega_{\mathbf{sun}} + N_{\mathbf{ring}} \cdot \omega_{\mathbf{ring}} = (N_{\mathbf{ring}} + N_{\mathbf{sun}}) \cdot \omega_{\mathbf{arm}}$$

where N is the number of teeth, ω is angular velocity of the element (sun, arm, or ring). Since the angular velocity and rpm are directly proportional, you can use rpm instead.

However, if the arm is the input or output, say the ring is the output/input instead and reverse the direction (since if the arm moves a certain speed relative to the ring, the ring moves that same speed the other way relative to the arm, and obviously the arm does not have a tooth count to plug in)

To derive this, just imagine the arm is locked, and calculate the gear ratio $\omega_{\text{ring}} / \omega_{\text{sun}} = N_{\text{sun}} / N_{\text{ring}}$, then unlock the arm. From the arms reference frame the ratio is always $N_{\text{sun}}/N_{\text{ring}}$, but from your frame all the speeds are increased by the angular velocity of the arm. So to write this relative relationship, you arrive at the equation from above.

Also, make sure $N_{\text{sun}}+2N_{\text{planet}}=N_{\text{ring}}$ where N is the number of teeth. This simply says that the gears will fit, since N is directly proportional to diameter.

Advantages and disadvantages

Advantages of planetary gears over parallel axis gears include high power density, large reduction in a small volume, multiple kinematic combinations, pure torsional reactions, and coaxial shafting. Disadvantages include high bearing loads, inaccessibility, and design complexity. The planetary gearbox arrangement is an engineering design that offers many advantages over traditional gearbox arrangements. One advantage is its unique combination of both compactness and outstanding power transmission efficiencies. A typical efficiency loss in a planetary gearbox arrangement is only 3% per stage. This type of efficiency ensures that a high proportion of the energy being input is transmitted through the gearbox, rather than being wasted on mechanical losses inside the gearbox.

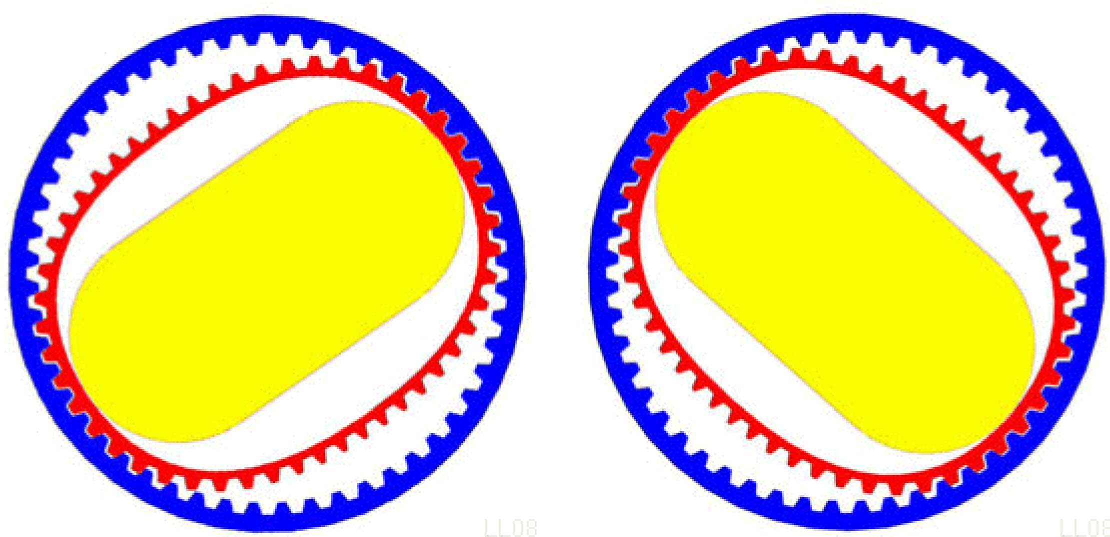
Another advantage of the planetary gearbox arrangement is load distribution. Because the load being transmitted is shared between multiple planets, torque capability is greatly increased. The more planets in the system, the greater load ability and the higher the torque density.

The planetary gearbox arrangement also creates greater stability due to the even distribution of mass and increased rotational stiffness.

Chapter 6

Harmonic Drive and Non-Circular Gear

Harmonic drive



Harmonic drive

A **Harmonic Drive** (also known as "Strain Wave Gearing") is a special type of mechanical gear system that can improve certain characteristics compared to traditional gearing systems (such as Helical Gears or Planetary Gears). It was invented in 1957 and is now produced by Harmonic Drive LLC. The advantages include: no backlash, compactness and light weight, high gear ratios, reconfigurable ratios within a standard housing, good resolution and repeatability when repositioning inertial loads, high torque capability, and coaxial input and output shafts. High gear reduction ratios are possible in a small volume (a ratio of 100:1 is possible in the same space in which planetary gears typically only produce a 10:1 ratio).

Disadvantages include a tendency for 'wind-up' (a torsional spring rate) and potential degradation over time from mechanical shocks and environment.

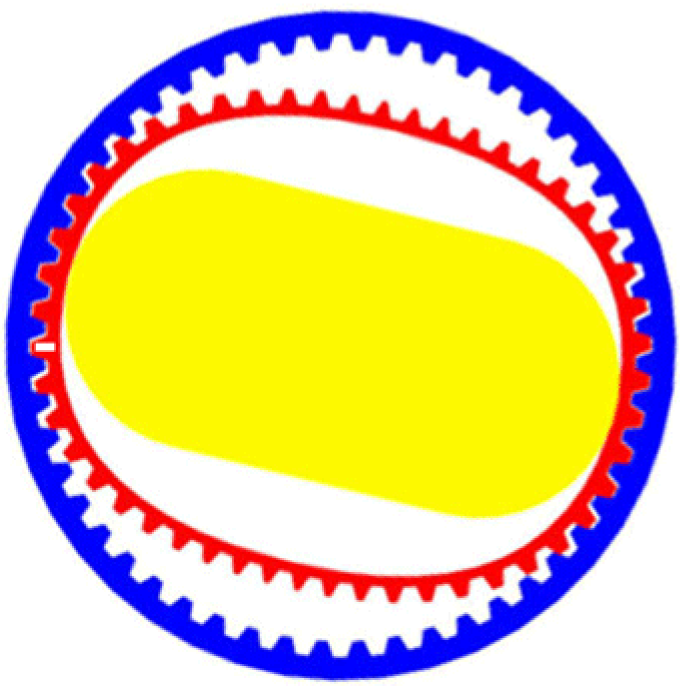
They are typically used in industrial motion control, robotics and aerospace, for gear reduction but may also be used to increase rotational speed, or for differential gearing.

History

The basic concept of Strain Wave Gearing (SWG) was introduced by C.W. Musser in his 1957 patent. It was first used successfully in 1964 by Hasegawa Gear Works, Ltd. and USM Co., Ltd. Later, Hasegawa Gear Works, Ltd. became Harmonic Drive Systems Inc. located in Japan and USM Co., Ltd. Harmonic Drive division became Harmonic Drive Technologies Inc.

On January 1, 2006, Harmonic Drive Technologies/Nabtesco of Peabody, MA and HD Systems of Hauppauge, NY, merged to form a new joint venture, Harmonic Drive LLC. HD Systems, Inc. was a subsidiary company of Harmonic Drive System, Inc. Offices are maintained in both Peabody and Hauppauge.

Mechanics



Cross-section of a Strain Wave Gearing.
A: circular spline (fixed)
B: flex spline (attached to output shaft, not shown)
C: wave generator (attached to input shaft, not shown)

The Strain Wave Gearing theory is based on elastic dynamics and utilizes the flexibility of metal. The mechanism has three basic components: a wave generator, a flex spline, and a circular spline. More complex versions have a fourth component normally used to shorten the overall length or to increase the gear reduction within a smaller diameter, but still follow the same basic principles.

The wave generator is made up of two separate parts: an elliptical disk called a *wave generator plug* and an outer ball bearing. The gear plug is inserted into the bearing, giving the bearing an elliptical shape as well.

The flex spline is like a shallow cup. The sides of the spline are very thin, but the bottom is thick and rigid. This results in significant flexibility of the walls at the open end due to the thin wall, but in the closed side being quite rigid and able to be tightly secured (to a shaft, for example). Teeth are positioned radially around the outside of the flex spline. The flex spline fits tightly over the wave generator, so that when the wave generator plug is rotated, the flex spline deforms to the shape of a rotating ellipse but does not rotate with the wave generator.

The circular spline is a rigid circular ring with teeth on the inside. The flex spline and wave generator are placed inside the circular spline, meshing the teeth of the flex spline and the circular spline. Because the flex spline has an elliptical shape, its teeth only actually mesh with the teeth of the circular spline in two regions on opposite sides of the flex spline, along the major axis of the ellipse.

Assume that the wave generator is the input rotation. As the wave generator plug rotates, the flex spline teeth which are meshed with those of the circular spline change. The major axis of the flex spline actually rotates with wave generator, so the points where the teeth mesh revolve around the center point at the same rate as the wave generator. The key to the design of the harmonic drive is that there are fewer teeth (for example two fewer) on the flex spline than there are on the circular spline. This means that for every full rotation of the wave generator, the flex spline would be required to rotate a slight amount (two teeth, for example) backward relative to the circular spline. Thus the rotation action of the wave generator results in a much slower rotation of the flex spline *in the opposite direction*.

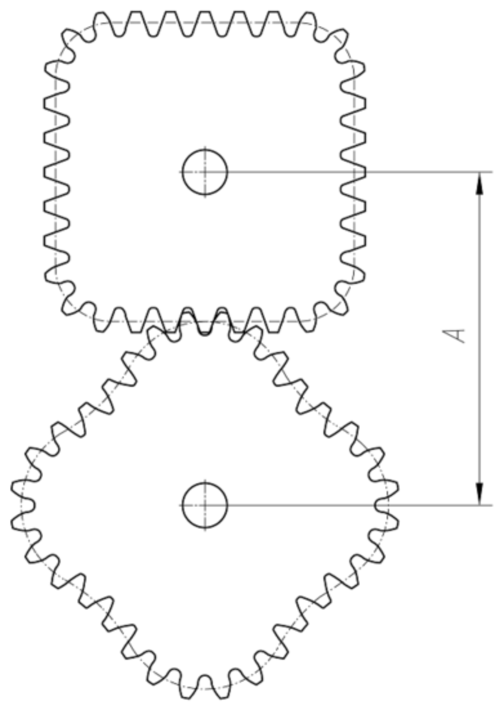
For a Strain Wave Gearing mechanism, the gearing reduction ratio can be calculated from the number of teeth on each gear:

$$\text{reduction ratio} = \frac{\text{flex spline teeth} - \text{circular spline teeth}}{\text{flex spline teeth}}$$

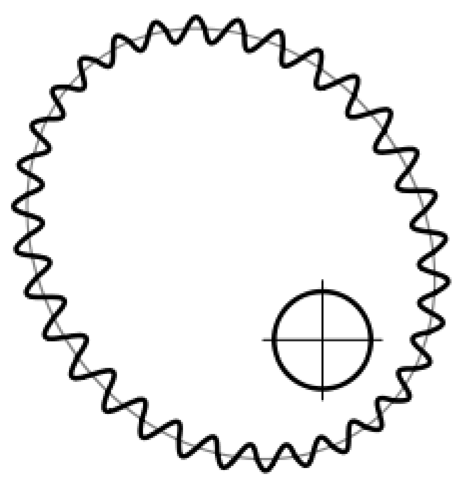
For example, if there are 202 teeth on the circular spline and 200 on the flex spline, the reduction ratio is $(200 - 202)/200 = -0.01$

Thus the flex spline spins at 1/100 the speed of the wave generator plug and in the opposite direction. This allows different reduction ratios to be set without changing the mechanism's shape, increasing its weight, or adding stages. The range of possible gear ratios is limited by teeth size limits for a given configuration.

Non-Circular gear



Non-circular gear example



Another non-circular gear

A **non-circular gear** (**NCG**) is a special gear design with special characteristics and purpose. While a regular gear is optimized to transmit torque to another engaged member with minimum noise and wear and with 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 CVTs (continuously variable transmissions). Many bicycles have an elliptical gear, see, eg., Biopace.

A regular gear pair can be represented as two circles rolling together without slip. In the case of non-circular gears, those circles are replaced with anything different from a circle. This is also the reason NCG in most cases is not round, however round NCGs looking like regular gears are possible too (small ratio variations result from meshing area modifications).

Generally NCG should meet all the requirements of regular gearing, but in some cases, for example variable axle distance, could prove impossible to support and such gears require very tight manufacturing tolerances and assembling problems arise. Because of complicated geometry, NCGs are most likely spur gears and molding or electrical discharge machining technology is used instead of generation.

Mathematical description

Ignoring the gear teeth for the moment (i.e. assuming the gear teeth are very small), let $r_1(\theta_1)$ be the radius of the first gear wheel as a function of angle from the axis of rotation θ_1, and let $r_2(\theta_2)$ be the radius of the second gear wheel as a function of angle from its axis of rotation θ_2. If the axles remain fixed, the distance between the axles is also fixed:

$$r_1(\theta_1) + r_2(\theta_2) = a$$

Assuming that the point of contact lies on the line connecting the axles, in order for the gears to touch without slipping, the velocity of each wheel must be equal at the point of contact and perpendicular to the line connecting the axles, which implies that:

$$r_1\, d\theta_1 = r_2\, d\theta_2$$

Of course, each wheel must be cyclic in its angular coordinates. If the shape of the first wheel is known, the shape of the second can often be found using the above equations. If the relationship between the angles is specified, the shapes of both wheels can often be determined analytically as well.

It is more convenient to use the circular variable $z = e^{i\theta}$ when analyzing this problem. Assuming the radius of the first gear wheel is known as a function of z, and using the relationship $dz = iz\, d\theta$, the above two equations can be combined to yield the differential equation:

$$\frac{dz_2}{z_2} = \frac{r_1(z_1)}{a - r_1(z_1)}\, \frac{dz_1}{z_1}$$

where z_1 and z_2 describe the rotation of the first and second gears respectively. This equation can be formally solved as:

$$\ln(z_2) = \ln(K) + \int \frac{r_1(z_1)}{a - r_1(z_1)} \frac{dz_1}{z_1}$$

where $\ln(K)$ is a constant of integration.

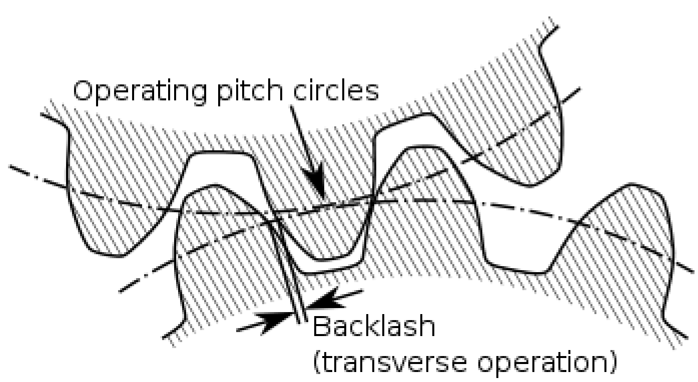
Chapter 7

Backlash (Engineering)

In mechanical engineering, **backlash**, sometimes called **lash** or **play**, is clearance between mating components, sometimes described as the amount of lost motion due to clearance or slackness when movement is reversed and contact is re-established. For example, in a pair of gears, backlash is the amount of clearance between mated gear teeth.

Theoretically, the backlash should be zero, but in actual practice some backlash must be allowed to prevent jamming. It is unavoidable for nearly all reversing mechanical couplings, although its effects can be negated. Depending on the application it may or may not be desirable. Reasons for requiring backlash include allowing for lubrication, manufacturing errors, deflection under load and thermal expansion.

Gears



Backlash

Factors affecting the amount backlash required in a gear train include errors in profile, pitch, tooth thickness, helix angle and center distance, and runout. The greater the accuracy the smaller the backlash needed. Backlash is most commonly created by cutting the teeth deeper into the gears than the ideal depth. Another way of introducing backlash is by increasing the center distances between the gears.

Backlash due to tooth thickness changes is typically measured along the pitch circle and is defined by:

$$b_t = t_i - t_a$$

where:

b_t = backlash due to tooth thickness modifications
t_i = tooth thickness on the pitch circle for ideal gearing (no backlash)
t_a = actual tooth thickness

Backlash, measured on the pitch circle, due to operating center modifications is defined by:

$$b_c = 2\,(\Delta c)\tan\phi$$

where:

b_c = backlash due to operating center distance modifications
Δc = difference between actual and ideal operating center distances
ϕ = pressure angle

Standard practice is to make allowance for half the backlash in the tooth thickness of each gear. However, if the pinion (the smaller of the two gears) is significantly smaller than the gear it is meshing with then it is common practice to account for all of the backlash in the larger gear. This maintains as much strength as possible in the pinion's teeth. The amount of additional material removed when making the gears depends on the pressure angle of the teeth. For a 14.5° pressure angle the extra distance the cutting tool is moved in equals the amount of backlash desired. For a 20° pressure angle the distance equals 0.73 times the amount of backlash desired.

As a rule of thumb the average backlash is defined as 0.04 divided by the diametral pitch; the minimum being 0.03 and the maximum 0.05.

In a gear train, backlash is cumulative. When a gear-train is reversed the driving gear is turned a short distance, equal to the total of all the backlashes, before the final driven gear begins to rotate. At low power outputs, backlash results in inaccurate calculation from the small errors introduced at each change of direction; at large power outputs backlash sends shocks through the whole system and can damage teeth and other components.

Anti-backlash designs

In certain applications, backlash is an undesirable characteristic and should be minimized; for example, a radio tuning dial where one may make precise tuning movements both forwards and backwards. Specialised gear designs allow this. One of the more common designs splits the gear into two gears, each half the thickness of the original. One half of the gear is fixed to its shaft while the other half of the gear is allowed to turn on the shaft, but pre-loaded in rotation by small coil springs that rotate the free gear relative to the fixed gear. In this way, the spring tension rotates the free gear until all of the backlash in the system has been taken out; the teeth of the fixed gear press against one side of the teeth of the pinion while the teeth of the free gear press against the other side of the teeth on the pinion. Loads smaller than the force of the springs do not compress the springs and with no gaps between the teeth to be taken up, backlash is eliminated.

High-precision main drives and positioning drives of CNC machine tools use duplex worm gear sets for backlash adjustment.

In mechanical computers a more complex solution is required, namely a frontlash gearbox. This works by turning slightly faster when the direction is reversed to 'use up' the backlash slack.

Some motion controllers include backlash compensation. Compensation may be achieved by simply adding extra compensating motion or by sensing the load's position in a closed loop control scheme.The dynamic response of backlash itself, essentially a delay, makes the position loop less stable and prone to oscillation.

Minimum backlash

Minimum backlash is the minimum transverse backlash at the operating pitch circle allowable when the gear tooth with the greatest allowable functional tooth thickness is in mesh with the pinion tooth having its greatest allowable functional tooth thickness, at the tightest allowable center distance, under static conditions.

Difference between the maximum and minimum backlash occurring in a whole revolution of the larger of a pair of mating gears.

Applications

Gear couplings use backlash to allow for angular misalignment.

Backlash is undesirable in precision positioning applications such as machine tool tables. It can be minimized by tighter design features such as ball screws instead of leadscrews, and by using preloaded bearings. A preloaded bearing uses a spring or other compressive force to maintain bearing surfaces in contact despite reversal of direction.

There can be significant backlash in unsynchronized transmissions because of the intentional gap between dog gears (also known as dog clutches). The gap is necessary so that the driver or electronics can engage the gears easily while synchronizing the engine speed with the driveshaft speed. If there was a small clearance, it would be nearly impossible to engage the gears because the teeth would interfere with each other in most configurations. In synchronized transmissions, synchromesh solves this problem.

Chapter 8

Derailleur Gears

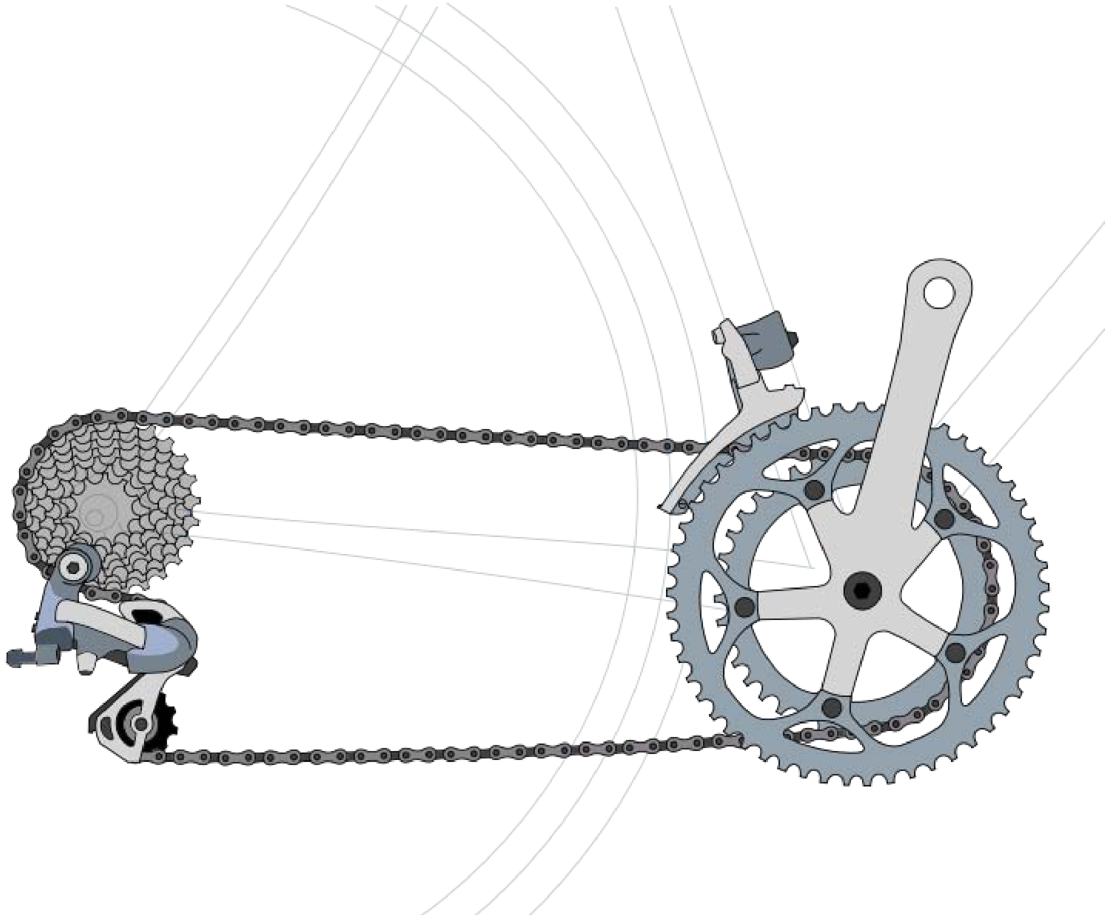
Derailleur gears are a variable-ratio transmission system commonly used on bicycles, consisting of a chain, multiple **sprockets** of different sizes, and a mechanism to move the chain from one sprocket to another. Although referred to as *gears* in the bike world, these bicycle *gears*, unlike the gears in an internally-geared hub, are technically *sprockets* since they drive or are driven by a chain, and are not driven by one another.

Modern front and rear derailleurs typically consist of a moveable chain-guide that is operated remotely by a Bowden cable attached to a shift lever mounted on the down tube, handlebar stem, or handlebar. When a rider operates the lever while pedalling, the change in cable tension moves the chain-guide from side to side, "derailing" the chain onto different sprockets.

History

Various derailleur systems were designed and built in the late 1800s. The French bicycle tourist, writer and cycling promoter Paul de Vivie (1853–1930), who wrote under the name *Velocio*, invented a two speed rear derailleur in 1905 which he used on forays into the Alps. Some early designs used rods to move the chain onto various gears. 1928 saw the introduction of the "Super Champion Gear" (or "Osgear") from the company founded by champion cyclist Oscar Egg, and the Vittoria Margherita; both employed chainstay mounted 'paddles' and single lever chain tensioners mounted near or on the downtube. However, these systems, along with the rod-operated Campagnolo Cambio Corsa were eventually superseded by *parallelogram derailleurs*. In 1937, the derailleur system was introduced to the Tour de France, allowing riders to change gears without having to remove wheels. Previously, riders would have to dismount in order to change their wheel from downhill to uphill mode. Derailleurs did not become common road racing equipment until 1938 when Simplex introduced a cable-shifted derailleur.

In 1949 Campagnolo introduced the Gran Sport, a refined version of less commercially successful cable-operated parallelogram rear derailleurs already existing.



A modern road bicycle drivetrain with front and rear derailleurs

In 1964, Suntour invented the *slant-parallelogram* rear derailleur, which let the jockey pulley maintain a more constant distance from the different sized sprockets, resulting in easier shifting. Once the patents expired, other manufacturers adopted this design, at least for their better models, and the "slant parallelogram" remains the current rear derailleur pattern.

Before the 1990s many manufacturers made derailleurs, including Simplex, Huret, Galli, Mavic, Gipiemme, Zeus, Suntour, and Shimano. However, the successful introduction and promotion of indexed shifting by Shimano in 1985 required a compatible system of shift levers, derailleur, cogset, chainrings, chain, shift cable, and shift housing. This need for compatibility increased the use of groupsets made by one company, and was one of the factors that drove the other manufacturers out of the market. Today Campagnolo and Shimano are the two main manufacturers of derailleurs, with Campagnolo only making road cycling derailleurs and Shimano making both road and offroad. American manufacturer SRAM has been an important third, specializing in derailleurs for mountain bikes, and in 2006 they introduced a drivetrain system for road bicycles.

Modern derailleur types

The major innovations since then have been the switch from friction to indexed shifting and the gradual increase in the number of gears. With friction shifting, the rider first moves the lever enough for the chain to jump to the next sprocket, and then adjusts the lever a slight amount to center the chain on that sprocket. An indexed shifter has a detent or ratchet mechanism which stops the gear lever, and hence the cable and the derailleur, after moving a specific distances with each press or pull. Indexed shifters require re-calibration when cables stretch and parts get damaged or swapped out. On racing bicycles, 10-gear rear cassettes appeared in 2000, and 11-gear cassettes appeared in 2009. Most current mountain bicycles have three front chainrings; while road bicycles may have two or three.

Rear derailleurs

Campagnolo Super Record rear derailleur from 1983.

Shimano XT rear derailleur on a mountain bike

The rear derailleur serves double duty: moving the chain between rear sprockets and taking up chain slack caused by moving to a smaller sprocket at the rear or a smaller chainring by the front derailleur. In order to accomplish this second task, it is positioned in the path of the bottom, slack portion of chain.

Construction

Although variations exist, as noted below, most rear derailleurs have several components in common. They have a **cage** that holds two pulleys that guide the chain in an S-shaped pattern. The pulleys are known as the **jockey pulley** or **guide pulley** (top) and the **tension pulley** (bottom). The cage rotates in its plane and is spring-loaded to take up chain slack. The cage is positioned under the desired sprocket by an arm that can swing back and forth under the sprockets. The arm is usually implemented with a parallelogram mechanism to keep the cage properly aligned with the chain as it swings back and forth. The other end of the arm mounts to a pivot point attached to the bicycle frame. The arm pivots about this point to maintain the cage at a nearly constant distance from the different sized sprockets. There may be one or more adjustment screws that control the amount of lateral travel allowed and the spring tension.

The components may be constructed of aluminum alloy, steel, plastic, or carbon fiber composite. The pivot points may be bushings or ball bearings. These will require moderate lubrication.

Relaxed position

High normal or **top normal** rear derailleurs return the chain to the smallest sprocket on the cassette when no cable tension is applied. This is the regular pattern used on most Shimano mountain, all Shimano road, and all SRAM and Campagnolo derailleurs. In this condition, spring pressure takes care of the easier change to smaller sprockets. In road racing the swiftest gear changes are required on the sprints to the finish line, hence **high-normal** types, which allow a quick change to a higher gear, remain the preference.

Low normal or **rapid rise** rear derailleurs return the chain to the largest sprocket on the cassette when no cable tension is applied. While this was once a common design for rear derailleurs, it is relatively uncommon today. In mountain biking and off-road cycling, the most critical gear changes occur on uphill sections, where riders must cope with obstacles and difficult turns while pedaling under heavy load. This derailleur type provides an advantage over high normal derailleurs because gear changes to lower gears occur in the direction of the loaded spring, making these shifts easier during high load pedaling.

Cage length

The distance between the upper and lower pulleys of a rear derailleur is known as the **cage length**. Cage length determines the capacity of a derailleur to take up chain slack. Cage length determines the **total capacity** of the derailleur, that is the size difference between the largest and smallest chainrings, and the size difference between the largest and smallest sprockets on the cogset added together. A larger sum requires a longer cage length. Typical cross country mountain bikes with three front chainrings will use a long cage rear derailleur. A road bike with only two front chainrings and close ratio sprockets can operate with either a short or long cage derailleur, but will work better with a short cage.

Manufacturer stated derailleur capacities are as follows: Shimano long = 45T; medium = 33T SRAM long = 43T; medium = 37T; short = 30T

Benefits of a shorter cage length:

- more positive gear-changing due to less flex in the parallelogram
- better gear-changing with good cable leverage
- better obstruction clearance
- less danger of catching spokes.
- slight weight savings.

Cage positioning

There are at least two methods employed by rear derailleurs to maintain the appropriate gap between the upper jockey wheel and the rear sprockets as the derailleur moves between the large sprockets and the small sprockets.

- One method, used by Shimano, is to use chain tension to pivot the cage. This has the advantage of working with most sets of sprockets, if the chain has the proper length. A disadvantage is that rapid shifts from small sprockets to large over multiple sprockets at once can cause the cage to strike the sprockets before the chain moves onto the larger sprockets and pivots the cage as necessary.
- Another method, used by SRAM, is to design the spacing into the parallelogram mechanism of the derailleur itself. The advantage is that no amount of rapid, multi-sprocket shifting can cause the cage to strike the sprockets. The disadvantage is that there are limited options for sprocket sizes that can be used with a particular derailleur.

Actuation ratio

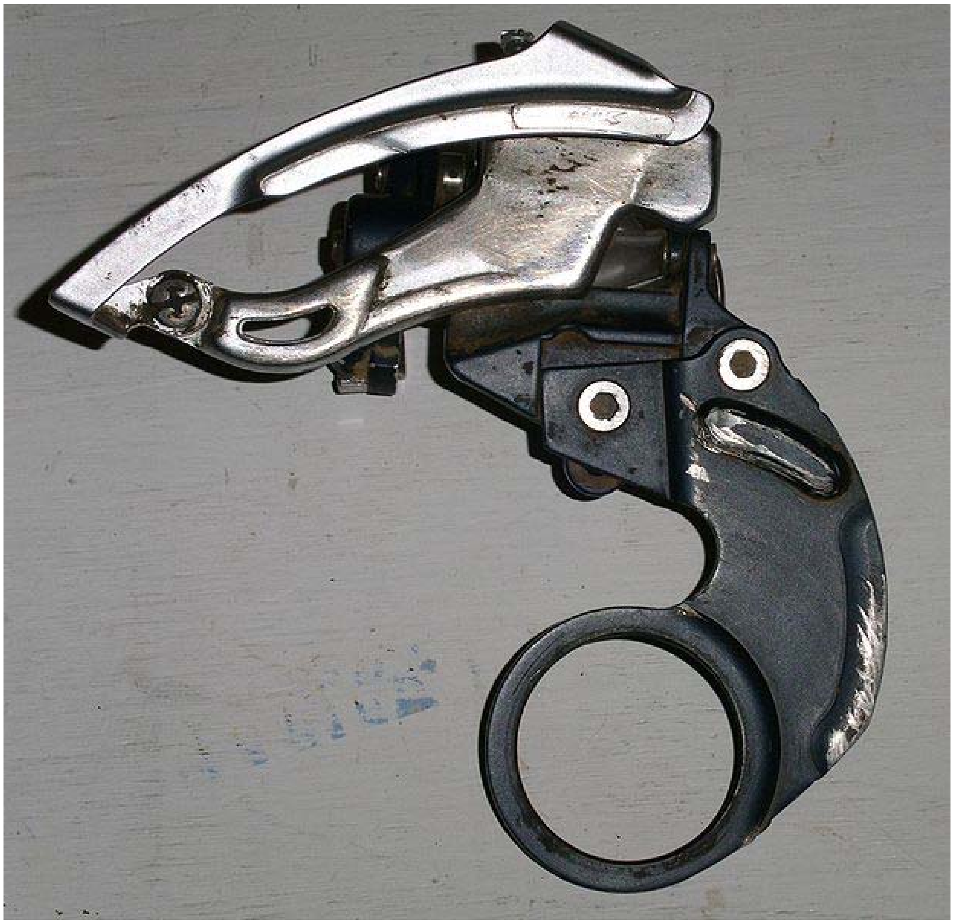
Currently there are multiple conventions for the relationship between shifter travel and rear derailleur travel, known as **actuation ratios**. The ratios, when given, are nominal, and do not represent an exact ratio.

- One convention, used by Shimano, is one-to-two (1:2). A unit of cable moved in causes about twice as much movement of the derailleur.
- Another convention, used by SRAM mountain bike rear derailleurs, is one-to-one (1:1). A unit of cable moved in the shifter causes about an equal amount to be moved in the derailleur. SRAM claims that this makes their systems more robust: more accepting of contamination.
- Exact Actuation, used by SRAM road bike rear derailleurs, similar but different from the mountain ratio.
- Campagnolo convention.
- Suntour's convention.

Shifters employing one convention are generally not compatible with derailleurs employing the other, although exceptions exist.

Front derailleurs

Shimano XT front derailleur (top pull, bottom swing, triple cage) on a mountain bike



Shimano E-type front derailleur (top pull, top swing, triple cage)

The front derailleur only has to move the chain side to side between the front chainrings, but it has to do this with the top, taut portion of the chain. It also needs to accommodate large differences in chainring size: from as many as 53 teeth to as few as 20 teeth.

Construction

As with the rear derailleur, the front derailleur has a **cage** through which the chain passes. On a properly adjusted derailleur, the chain will only touch the cage while shifting. The cage is held in place by a movable arm which is usually implemented with a parallelogram mechanism to keep the cage properly aligned with the chain as it swings back and forth. There are usually two adjustment screws controlling the limits of lateral travel allowed.

The components may be constructed of aluminum alloy, steel, plastic, or carbon fiber composite. The pivot points are usually bushings, and these will require lubrication.

Cable pull types

bottom pull

Commonly used on road and touring bikes, this type of derailleur is actuated by a cable pulling downwards. The cable is often routed beneath the bottom bracket shell on a plastic guide, which redirects the cable up the lower edge of the frame's down tube. Full-suspension mountain bikes often have bottom pull routing as the rear suspension prevents routing via the top tube .

top pull

This type is more commonly seen on mountain bikes without rear-suspension. The derailleur is actuated by a cable pulling upwards, which is usually routed along the frame's top tube, using cable stops and a short length of housing to change the cable's direction. This arrangement keeps the cable away from the underside of the bottom bracket/down tube which get pelted with dirt when off-road.

combination of both (dual pull)

There are some derailleurs available that have provisions for either top pull or bottom pull, and can be used in either application.

Cage types

double **(Standard)**

These are intended to be used with cranksets having two chainrings. When viewed from the side of the bicycle, the inner and outer plates of the cage have roughly the same profile.

triple **(Alpine)**

Derailleurs designed to be used with cranksets having three chainrings, or with two chainrings that differ greatly in size. When viewed from the side of the bicycle, the inner cage plate extends further towards the bottom bracket's center of rotation than the outer cage plate does. This is to help shift the chain from the smallest ring onto the middle ring more easily.

Swing types

bottom swing

The derailleur cage is mounted to the bottom of the four-bar linkage that carries it. This is the most common type of derailleur.

top swing

The derailleur cage is mounted to the top of the four-bar linkage that carries it. This alternate arrangement was created as a way to get the frame clamp of the derailleur closer to the bottom bracket to be able to clear larger suspension components and allow different frame shapes. The compact construction of a top swing derailleur can cause it to be less robust than its bottom swing counterpart. Top swing derailleurs are typically only used in applications where a bottom swing derailleur will not fit. An alternate solution would be to use an E-type front derailleur, which does not clamp around the seat tube at all.

Mount types

clamp
: The vast majority of front derailleurs are mounted to the frame by a clamp around the frame's seat tube. Derailleurs are available with several different clamp diameters designed to fit different types of frame tubing. Recently, there has been a trend to make derailleurs with only one diameter clamp, and several sets of shims are included to space the clamp down to the appropriate size.

braze-on
: An alternative to the clamp is the braze-on derailleur hanger, where the derailleur is mounted by bolting a tab on the derailleur to a corresponding tab on the frame's seat tube. This avoids any clamp size issues, but requires either a frame with the appropriate braze-on, or an adapter clamp that simulates a braze-on derailleur tab.

E-type
: This type front derailleurs do not clamp around the frame's seat tube, but instead are attached to the frame by a plate mounted under the drive side bottom bracket cup and a screw threaded into a boss on the seat tube. These derailleurs are usually found on mountain bikes with rear suspension components that do not allow space for a normal derailleur's clamp to go around the seat tube.

DMD
: Direct-Mount-Derailleur - Initiated by Specialized Bicycles, this type of derailleur is bolted directly to bosses on the chainstay of the bike. They are mostly used on dual suspension mountain bikes, where suspension movement causes changes to the chain angle as it enters the front derailleur cage. By utilizing a DMD system, the chain and derailleur move together, allowing for better shifting when the suspension is active. A DMD derailleur should not be confused with Shimano's Direct Mount, which uses a different mounting system. However, SRAM's direct mount front derailleurs are compatible with DMD, and certain Shimano E-type derailleurs can be used with DMD if the e-type plate is removed.

Add-ons

Because of the possibility of the chain shifting past the smallest inner chainring, especially when the inner chainring is very small, even on bikes adjusted by professional race mechanics, and the problems such misshifts can cause, a small after-market of add-on products, called **chain deflectors**, exists to help prevent them from occurring. Some clamp around the seat tube, below the front derailleur, and at least one attaches to the front derailleur mount.

Use of derailleurs

Derailleurs require the chain to be in movement, the rider pedalling, in order to change ratio. This requires foresight in regular road-usage and commuting, changing down (while still pedalling) on approaching a junction.

Chain-drive systems such as the derailleur systems work best if the chain is in line with the sprockets, especially avoiding the biggest drive sprocket running with the biggest driven sprocket (or the smallest with the smallest). The diagonal chain run produced by these practices is less efficient and shortens the life of all components, with no advantage from the middle of the range ratio obtained.

Hence, the change down should be one or two sprockets at the rear derailleur, followed by a change at the front derailleur, followed by further changes at the rear. This advice does not apply when forced to slow down quickly, when it is more convenient to change down at the front derailleur first, getting a bigger difference in the easier direction, the chain forced off a larger sprocket onto a smaller one.

Electronic gear-shifting system

Electrically actuated front derailleur

An **electronic gear-shifting system** is a derailleur system that uses electric motors controlled by switches in place of traditional lever-and-cable actuation.

Chapter 9

Hub Gear

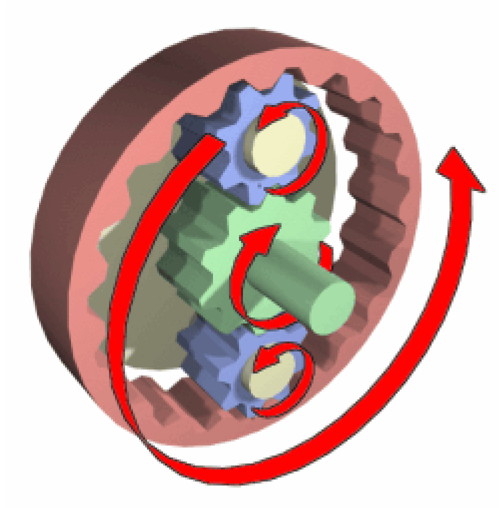
Hub gears or **internal-gear hubs** are gear ratio changing systems commonly used on bicycles. Hub gear systems generally have a long and largely maintenance-free life though some are not suitable for high-stress use in competitions or hilly, off-road conditions.

Many commuter or urban cycles such as European city bikes are now commonly fitted with 7-speed gear-hubs and 8-speed systems are becoming increasingly available. Older or less costly utility bicycles often use 3-speed gear-hubs, e.g. the public bicycle rental programmes in Paris, Montreal, Lyon, London, and Washington, DC (Vélib', Bixi, Vélo'v, Barclays Cycle Hire, and Capital Bikeshare). Many folding bicycles use 3-speed gear-hubs. Modern developments with up to 14 gear ratios are available.

Gear-hubs use internal planetary or epicyclic gearing. Unlike derailleur gears, where the gears and mechanism are exposed to the elements, hub gears and lubricants are sealed within the hub-shell of the bicycle's rear wheel.

Changing the gear ratio was traditionally accomplished by a lever connected to the hub. Twist-grip style shifters have become general.

History



In this simple epicyclic gear mechanism, the inner gear or "sun gear" (green) provides the input rotation. The two "planet gears" (blue) rotate freely about the planet gear carrier (yellow) which is fixed. As the planet gears rotate about the sun gear, they propel the outer ring gear or "annulus" (red), which provides the output rotation

Before epicyclic gears were used in bicycle hubs, they were used on tricycles. Patents for epicyclic hubs date from the mid-1880s. The first patent for a compact epicyclic hub gear was granted in 1895 to the American machinist Seward Thomas Johnson of Noblesville, Indiana, U.S.A. This was a 2-speed but was not commercially successful.

In 1896 William Reilly of Salford, England patented a 2-speed hub which went into production in 1898 as 'The Hub'. It was a great success, remaining in production for a decade. It rapidly established the practicality of compact epicyclic hub gears.

By 1902 Reilly had designed a 3-speed hub gear. He parted company with the manufacturer of 'The Hub' but had signed away to them the intellectual rights to his future gear designs. To circumvent this problem, the patents for Reilly's 3-speed were obtained in the name of his colleague, James Archer. Meanwhile, well-known English journalist and inventor Henry Sturmey had also invented a 3-speed hub. In 1903 Frank Bowden, head of the Raleigh cycle company, formed The Three-Speed Gear Syndicate, having obtained the rights to both the Reilly/Archer and Sturmey 3-speeds. Reilly's hub went into production as the first Sturmey Archer 3-speed.

In 1902 Mikael Pedersen (who also produced the Dursley Pedersen bicycle) patented a 3-speed hub gear and this was produced in 1903. This was said to be based on the "counter shaft" principle but was arguably an unusual epicyclic gear, in which a second sun was used in place of an annulus. In 1904 the Fichtel & Sachs company (Germany, Schweinfurt) produced a hub gear under license to Wanderer, and by 1909 there were 14 different 3-speed hub gears on the British market.

By the 1930s hub gears were used on bicycles all over the world. They were particularly popular in the UK, The Netherlands, the German speaking countries and Scandinavia. Since the 1970s, they have become much less common in the English-speaking countries. But in many parts of northern Europe, where bicycles are regularly used as daily transport rather than merely for sport or leisure, hub gears are still widely used. The cheaper and stronger (but less reliable) derailleur system now started to appear and offer a wider gear range.

By 1987 Sturmey-Archer made only 3- and 5-speed hubs, and Fichtel & Sachs and Shimano made only 2- and 3-speed hubs. In that year the first book (apart from service manuals) for some 80 years dealing solely with epicyclic bicycle gears was published. Since then there has been a slow but steady increase in interest in hub gears, reflected in the wider range of products now available.

In 1995 Sachs introduced the Elan, the first hub gear with more than 12 speeds, and an overall range of 339%. Three years later Rohloff came out with the Speedhub 500/14, a gear hub with 14 speeds and a range of 526%, comparable to that of a 27 speed derailleur gear system, and also sufficiently robust and light weight for mountain biking. In 2007 NuVinci started manufacturing stepless ∞-speed (CVT) hubs for commuter bicycles, with a range of about 350%.

As of 2008, Sturmey-Archer makes 3-, 5- and 8-speed hubs, SRAM (successor to Fichtel & Sachs) make 3-, 5-, 7- and 9-speeds and Shimano make 3-, 7- and 8-speeds. In february 2010 Shimano announced the introduction of the Shimano Alfine 700, an 11-speed model.

Though most hub gear systems use one rear sprocket, SRAM's DualDrive system combines an epicyclic hub with a multi-speed rear derailleur system to provide a wide-ranging drivetrain concentrated at the rear wheel. In 2010 Canyon introduced the 144^2, a hybrid hub which uses a similar epicyclical/derailleur combination.

Brompton Bicycle have their own design, with a two-speed derailleur coupled to a special three-speed wide-ratio Sturmey-Archer hub, the "BWR" (Brompton Wide Ratio). The system is useful for folding bicycles (where a multiple front chainset could foul the bike's folding mechanism) and in recumbent bicycles and freight bicycles (where small wheels and/or increased weight require a wider range of gears with smaller steps). Hub gears have in the past also been used on motorcycles, although this is now rare.

Principle of operation

The simplest 3-speed hubs use a single planetary epicyclic gearset. The sun gear is mounted solidly to the axle and is thus fixed. In low gear, the sprocket drives the annulus, while the planet carrier drives the hub, giving a gear reduction. In mid gear, the annulus is connected to both the sprocket and hub, giving a direct drive. The planets cycle freely. In high gear, the sprocket is switched to drive the planets, while the annulus remains connected to the hub, giving an overdrive gear.

The hub axle of a hub-gear (unlike that of a derailleur system) must be securely braced against rotation. While anti-rotation washers between the dropout and axle nut have often proved adequate, better quality modern systems use a reaction arm affixed to the chain stay. Rear wheels with drum brakes (another feature of better quality commuter bicycles) require a reaction arm anyway.

Advantages

This belt-drive on a Trek Soho is fitted with a sprocket too.

- Hub-gear systems can change gear ratios when the rear wheel is stationary. This can be useful for commuter cycling with frequent stops and for mountain biking in rough terrain.
- Hub-gear systems are simple to use for inexperienced riders, because there is generally only a single shifter to operate and there are no overlapping gear ratios. By contrast, modern derailleur systems often have two shifters, and require some forethought to avoid problematic gear combinations.
- The mechanism is sealed within the hub and bathed in a lubricant. This protects it from water and grit.
- The single chainline allows for a full chain enclosure chain guard, so the chain is also protected from water and grit.

- The single chainline does not require the chain to bend or twist. As a result, the chain can be constructed differently, with parallel pins instead of barrel-shaped ones. Line-contact between the bearing surfaces, instead the point-contact of a derailleur chain, greatly extends the working life of all components.
- The single external sprocket means that the wheel can be built with less dish making it stronger than a similar wheel dished to accommodate multiple sprockets.
- Hub gears completely avoid the danger of collision with the spokes and wheel-collapse that derailleur systems can suffer.
- Hub gears provide a means for shifting gear ratios on drivetrains incompatible with external deraileurs such as belt drives and shaft drives.

Disadvantages

- Hub-gears are typically more expensive than derailleur systems.
- Gear-hubs with a large number of speeds will tend to be less efficient than a properly lubricated and adjusted derailleur system in new condition. However, less sophisticated gear-hubs such as the 3-speed hub (with only a single epicyclic stage per high/low gear, and direct drive in second gear), when run-in and properly lubricated, can match the efficiency of similar quality derailleur systems, because the hub-gear chain runs in a straight line and does not run through the jockey wheels of a chain tensioner.
- Gear-hubs will tend to be heavier than equivalent derailleur systems, and the additional weight is concentrated at the back wheel. On rear-suspension bicycles in sporting use this unsprung weight will adversely affect traction and braking.
- Gear-hubs are complex and virtually impossible for the ordinary rider to repair - most certainly not as a side-of-the-road procedure. However, failures generally give plenty of warning and repair may be an option.
- Gear-hubs systems are generally incompatible with quick release mechanisms/skewer axles.
- The gear-hub is an integral part of the wheel and it is not possible to change the wheel without also changing the hub.

Hub-gears in everyday use

Traditional lever change, 3-speed.

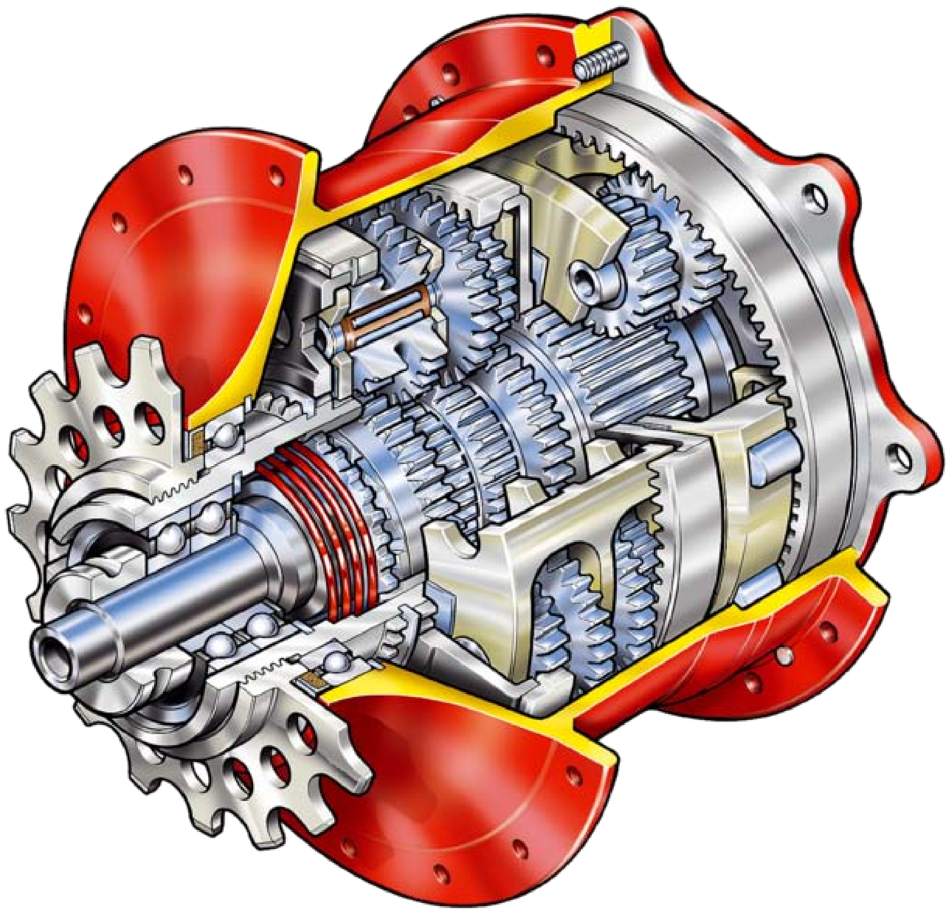
A modern twist-style seven-speed indexed shifter uses the same bowden cable as the older lever.

- Traditional hub gears are indexed at the shifter making operation dependent on correct cable tension (and lubrication thereof). In practice, gear-jumping and consequent internal damage are unusual except in high-mileage units. Modern hub gear-units incorporate the indexing in the unit itself and are therefore unaffected by shifting malfunctions caused in this way.
- The Sturmey Archer and Fichtel & Sachs 'Torpedo' systems defaulted to top gear at slack-cable, which could make the bicycle usable for long distance travel in flat terrain even if a fault developed in the change mechanism (rather like a derailleur system, which can be manually set to a high gear in case of a similar fault). Some modern hub gear systems (eg 7-speed Shimano) default to bottom gear and are thus more dependent on the (generally) very reliable cable-pull.

Hybrid gearing with derailleurs

Some systems have combined internally-geared hubs with derailleurs. A freewheeling hub with a sprocket suitable for narrow chain can be used with a double or triple crankset and front derailleur, in order to give a wider range and closer gear spacing. A chain tensioner (or a rear derailleur fixed in one position) is needed to take up the slack, and care is needed not to over-torque the hub by using too small a chain ring/sprocket ratio. Alternatively, two drive sprockets can be selected with a rear derailleur and careful sprocket selection means the gears of one sprocket fall half-way between those of the other, giving half-step gearing, as on the Brompton 6-speed folding bicycle. This concept is used and extended in SRAM's 'dualdrive' system. When both front and rear derailleurs are used with a geared hub, the result is a very wide-ranging drivetrain, at the expense of increased weight and complexity.

Latest developments



14-speed hub cutaway diagram

Rohloff 14 speed internally-geared rear hub

Hubs with higher numbers of gears use multiple epicyclic gears driven by each other, their ratios chosen to give evenly spaced gears. The operating principle is the same. An exception is the older style of Sturmey-Archer 5-speed, which used a second shift lever to change between close and wide-range sun gears, effectively giving two 3-speed hubs in one unit. The middle gear in both ranges was direct drive, so there were 5 distinct gears.

The latest 14-ratio hub-gear systems have a 5 to 1 range and are now directly comparable to "27-speed" derailleur systems, since the latter have 3 overlapping ranges with no more than about 15 distinct gears. The hub-gear system is much easier and more intuitive to operate while suffering little from loss of mechanical efficiency.

List of multispeed hub gears

- Rohloff Speedhub 500/14
- Shimano Alfine SG-700
- Shimano Alfine SG-500
- Shimano Nexus Inter-8
- Shimano Nexus Inter-7
- Sachs Elan
- SRAM i-Motion 9
- SRAM Spectro S7
- Sturmey Archer XRF-8 (XRF,XRD,XRR,XRK)

Chapter 10

Manual Transmission

A floor-mounted gear shift lever in a modern passenger car with a manual transmission

A **manual transmission**, also known as a **manual gearbox** or **standard transmission** (informally, a "manual", "straight shift", "stick (shift)" (US), or "straight drive") is a type of transmission used in motor vehicle applications. It generally uses a driver-operated clutch, typically operated by a pedal or lever, for regulating torque transfer from the internal combustion engine to the transmission, and a gear stick, either operated by hand (as in a car) or by foot (as on a motorcycle).

A conventional manual transmission is frequently the base equipment in a car; other options include automated transmissions such as an automatic transmission (often a manumatic), a semi-automatic transmission, or a continuously variable transmission (CVT).

Overview

Manual transmissions often feature a driver-operated clutch and a movable gear stick. Most automobile manual transmissions allow the driver to select any forward gear ratio ("gear") at any time, but some, such as those commonly mounted on motorcycles and some types of racing cars, only allow the driver to select the next-higher or next-lower gear. This type of transmission is sometimes called a sequential manual transmission. Sequential transmissions are commonly used in auto racing for their ability to make quick shifts.

Manual transmissions are characterized by gear ratios that are selectable by locking selected gear pairs to the output shaft inside the transmission. Conversely, most automatic transmissions feature epicyclic (planetary) gearing controlled by brake bands and/or clutch packs to select gear ratio. Automatic transmissions that allow the driver to manually select the current gear are called Manumatics. A manual-style transmission operated by computer is often called an *automated* transmission rather than an *automatic*.

Contemporary automobile manual transmissions typically use four to six forward gears and one reverse gear, although automobile manual transmissions have been built with as few as two and as many as eight gears. Transmission for heavy trucks and other heavy equipment usually have at least 9 gears so the transmission can offer both a wide range of gears and close gear ratios to keep the engine running in the power band. Some heavy vehicle transmissions have dozens of gears, but many are duplicates, introduced as an accident of combining gear sets, or introduced to simplify shifting. Some manuals are referred to by the number of forward gears they offer (e.g., 5-speed) as a way of distinguishing between automatic or other available manual transmissions. Similarly, a 5-speed automatic transmission is referred to as a "5-speed automatic."

Unsynchronized transmission

The earliest form of a manual transmission is thought to have been invented by Louis-René Panhard and Emile Levassor in the late 19th century. This type of transmission offered multiple gear ratios and, in most cases, reverse. The gears were typically engaged by sliding them on their shafts (hence the phrase *shifting gears*), which required a lot of careful timing and throttle manipulation when shifting, so that the gears would be spinning at roughly the same speed when engaged; otherwise, the teeth would refuse to mesh. These transmissions are called *sliding mesh* transmissions and sometimes called a crash box, because of the difficulty in changing gears and the loud grinding sound that often accompanied. Newer manual transmissions on cars, instead have all gears mesh at all times; these are referred to as *constant-mesh* transmissions, with "synchro-mesh" being a further refinement of the constant mesh principle.

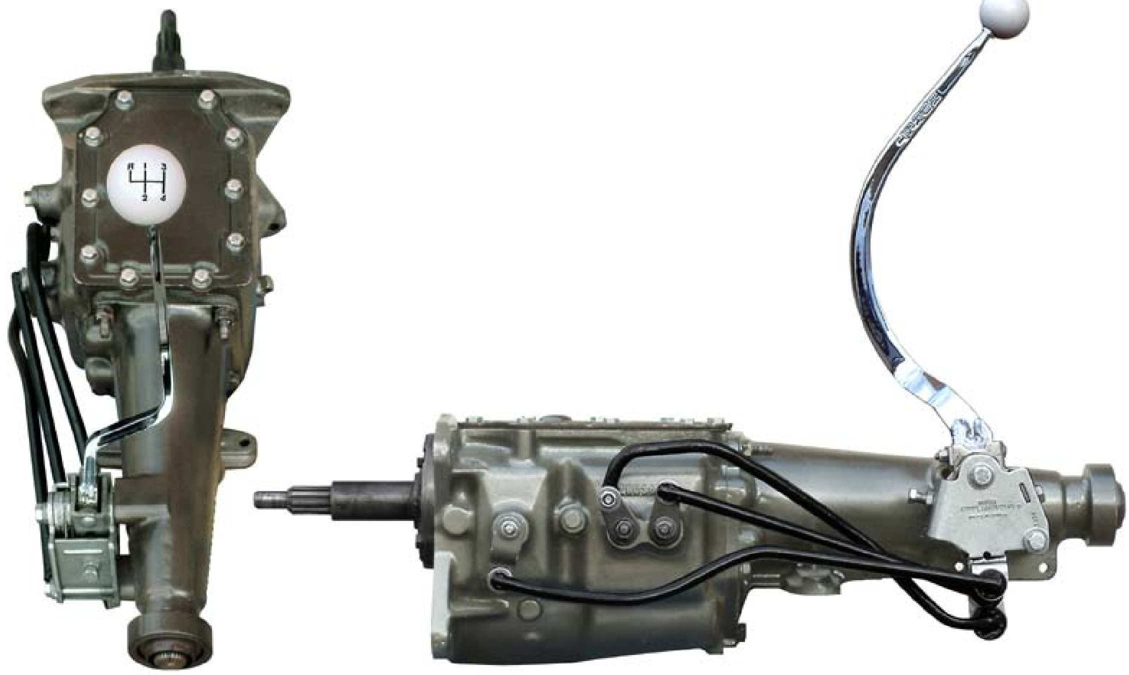
In both types, a particular gear combination can only be engaged when the two parts to engage (either gears or clutches) are at the same speed. To shift to a higher gear, the transmission is put in neutral and the engine allowed to slow down until the transmission parts for the next gear are at a proper speed to engage. The vehicle also slows while in neutral and that slows other transmission parts, so the time in neutral depends on the grade, wind, and other such factors. To shift to a lower gear, the transmission is put in neutral and the throttle is used to speed up the engine and thus the relevant transmission parts, to match speeds for engaging the next lower gear. For both upshifts and downshifts, the clutch is released (engaged) while in neutral. Some drivers use the clutch only for starting from a stop, and shifts are done without the clutch. Other drivers will depress (disengage) the clutch, shift to neutral, then engage the clutch momentarily to force transmission parts to match the engine speed, then depress the clutch again to shift to the next gear, a process called double clutching. Double clutching is easier to get smooth, as speeds that are close but not quite matched need to speed up or slow down only transmission parts, whereas with the clutch engaged to the engine, mismatched speeds are fighting the rotational inertia and power of the engine.

Even though automobile and light truck transmissions are now almost universally synchronised, transmissions for heavy trucks and machinery, motorcycles, and for dedicated racing are usually not. Non-synchronized transmission designs are used for several reasons. The friction material, such as brass, in synchronizers is more prone to wear and breakage than gears, which are forged steel, and the simplicity of the mechanism improves reliability and reduces cost. In addition, the process of shifting a synchromesh transmission is slower than that of shifting a non-synchromesh transmission. For racing of production-based transmissions, sometimes half the teeth (or *dogs*) on the synchros are removed to speed the shifting process, at the expense of greater wear.

Heavy duty trucks often use unsynchronized transmissions. Military trucks usually have synchronized transmissions, allowing untrained personnel to operate them in emergencies. In the United States, traffic safety rules refer to non-synchronous transmissions in classes of larger commercial motor vehicles. In Europe, heavy duty trucks use synchronized gearboxes as standard.

Similarly, most modern motorcycles use unsynchronized transmissions as synchronizers are generally not necessary or desirable. Their low gear inertias and higher strengths mean that forcing the gears to alter speed is not damaging, and the pedal operated selector on modern motorcycles is not conducive to having the long shift time of a synchronized gearbox. Because of this, it is necessary to synchronize gear speeds by blipping the throttle when shifting into a lower gear on a motorcycle.

Synchronised transmission



Top and side view of a typical manual transmission, in this case a Ford Toploader, used in cars with external floor shifters.

Most modern cars are fitted with a synchronised gear box. Transmission gears are always in mesh and rotating, but gears on one shaft can freely rotate or be locked to the shaft. The locking mechanism for a gear consists of a collar (or *dog collar*) on the shaft which is able to slide sideways so that teeth (or *dogs*) on its inner surface bridge two circular rings with teeth on their outer circumference: one attached to the gear, one to the shaft. When the rings are bridged by the collar, that particular gear is rotationally locked to the shaft and determines the output speed of the transmission. The gearshift lever manipulates the collars using a set of linkages, so arranged so that one collar may be permitted to lock only one gear at any one time; when "shifting gears," the locking collar from one gear is disengaged before that of another engaged. One collar often serves for two gears; sliding in one direction selects one transmission speed, in the other direction selects another.

In a synchromesh gearbox, to correctly match the speed of the gear to that of the shaft as the gear is engaged, the collar initially applies a force to a cone-shaped brass clutch attached to the gear, which brings the speeds to match prior to the collar locking into place. The collar is prevented from bridging the locking rings when the speeds are mismatched by synchro rings (also called blocker rings or baulk rings, with the latter being spelt *balk* in the U.S.). The synchro ring rotates slightly due to the frictional torque from the cone clutch. In this position, the dog clutch is prevented from engaging. The brass clutch ring gradually causes parts to spin at the same speed. When they do spin the same speed, there is no more torque from the cone clutch, and the dog clutch is allowed to fall in to engagement. In a modern gearbox, the action of all of these components is so smooth and fast it is hardly noticed.

The modern cone system was developed by Porsche and introduced in the 1952 Porsche 356; cone synchronisers were called *Porsche-type* for many years after this. In the early 1950s, only the second-third shift was synchromesh in most cars, requiring only a single synchro and a simple linkage; drivers' manuals in cars suggested that if the driver needed to shift from second to first, it was best to come to a complete stop then shift into first and start up again. With continuing sophistication of mechanical development, however, fully synchromesh transmissions with three speeds, then four speeds, and then five speeds, became universal by the 1980s. Many modern manual transmission cars, especially sports cars, now offer six speeds.

Reverse gear, however, is usually not synchromesh, as there is only one reverse gear in the normal automotive transmission and changing gears into reverse while moving is not required. Among the cars that have synchromesh in reverse are the 1995-2000 Ford Contour and Mercury Mystique, '00-'05 Chevrolet Cavalier, Mercedes 190 2.3-16, the V6 equipped Alfa Romeo GTV/Spider (916), certain Chrysler, Jeep, and GM products which use the New Venture NV3500 and NV3550 units, the European Ford Sierra and Granada/Scorpio equipped with the MT75 gearbox, the Volvo 850, and almost all Lamborghinis and BMWs.

Internals

Shafts

Like other transmissions, a manual transmission has several shafts with various gears and other components attached to them. Typically, a rear-wheel-drive transmission has three shafts: an input shaft, a *countershaft* and an output shaft. The countershaft is sometimes called a *layshaft*.

In a rear-wheel-drive transmission, the input and output shaft lie along the same line, and may in fact be combined into a single shaft within the transmission. This single shaft is called a *mainshaft*. The input and output ends of this combined shaft rotate independently, at different speeds, which is possible because one piece slides into a hollow bore in the other piece, where it is supported by a bearing. Sometimes the term *mainshaft* refers to just the input shaft or just the output shaft, rather than the entire assembly.

In some transmissions, it's possible for the input and output components of the mainshaft to be locked together to create a 1:1 gear ratio, causing the power flow to bypass the countershaft. The mainshaft then behaves like a single, solid shaft, a situation referred to as *direct drive*.

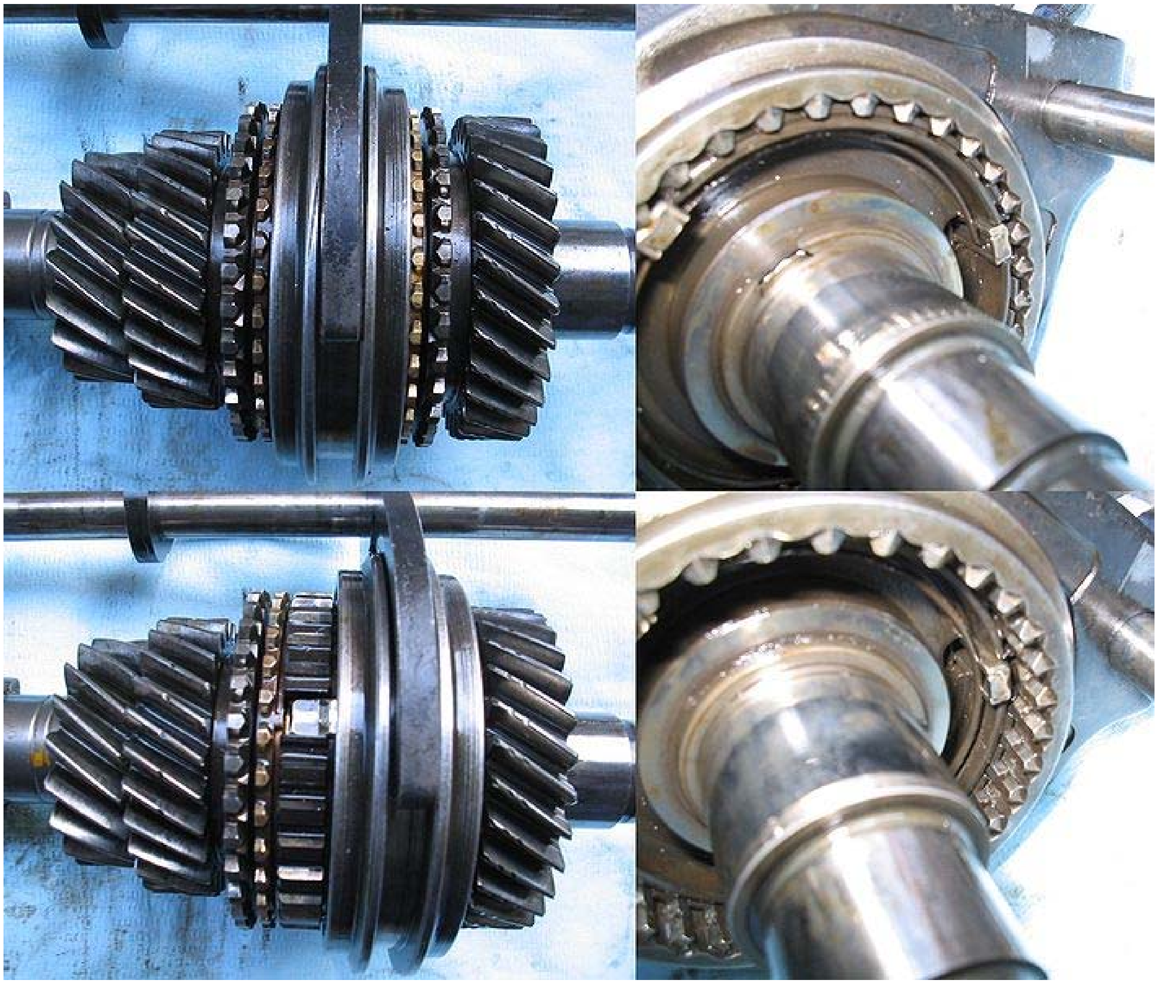
Even in transmissions that do not feature direct drive, it's an advantage for the input and output to lie along the same line, because this reduces the amount of torsion that the transmission case has to bear.

Under one possible design, the transmission's input shaft has just one pinion gear, which drives the countershaft. Along the countershaft are mounted gears of various sizes, which rotate when the input shaft rotates. These gears correspond to the forward speeds and reverse. Each of the forward gears on the countershaft is permanently meshed with a corresponding gear on the output shaft. However, these driven gears are not rigidly attached to the output shaft: although the shaft runs through them, they spin independently of it, which is made possible by bearings in their hubs.

Most front-wheel-drive transmissions for transverse engine mounting are designed differently. For one thing, they have an integral final drive and differential. For another, they usually have only two shafts; input and countershaft, sometimes called input and output. The input shaft runs the whole length of the gearbox, and there is no separate input pinion. At the end of the second (counter/output) shaft is a pinion gear that mates with the ring gear on the differential.

Front-wheel and rear-wheel-drive transmissions operate similarly. When the transmission is in neutral, and the clutch is disengaged, the input shaft, clutch disk and countershaft can continue to rotate under their own inertia. In this state, the engine, the input shaft and clutch, and the output shaft all rotate independently.

Dog clutch



Dog clutches. The gear-like teeth ("dogs", right-side images) engage and disengage with each other.

Among many different types of clutches, a dog clutch provides non-slip coupling of two rotating members. It is not at all suited to intentional slipping, in contrast with the foot-operated friction clutch of a manual-transmission car.

The gear selector does not engage or disengage the actual gear teeth which are permanently meshed. Rather, the action of the gear selector is to lock one of the freely spinning gears to the shaft that runs through its hub. The shaft then spins together with that gear. The output shaft's speed relative to the countershaft is determined by the ratio of the two gears: the one permanently attached to the countershaft, and that gear's mate which is now locked to the output shaft.

Locking the output shaft with a gear is achieved by means of a dog clutch selector. The dog clutch is a sliding selector mechanism which is splined to the output shaft, meaning that its hub has teeth that fit into slots (splines) on the shaft, forcing that shaft to rotate with it. However, the splines allow the selector to move back and forth on the shaft, which happens when it is pushed by a selector fork that is linked to the gear lever. The fork does not rotate, so it is attached to a collar bearing on the selector. The selector is typically symmetric: it slides between two gears and has a synchromesh and teeth on each side in order to lock either gear to the shaft.

Synchromesh

Synchronizer rings

If the teeth, the so-called dog teeth, make contact with the gear, but the two parts are spinning at different speeds, the teeth will fail to engage and a loud grinding sound will be heard as they clatter together. For this reason, a modern dog clutch in an automobile has a synchronizer mechanism or *synchromesh*, which consists of a cone clutch and blocking ring. Before the teeth can engage, the cone clutch engages first which brings the selector and gear to the same speed using friction. Moreover, until synchronization occurs, the teeth are prevented from making contact, because further motion of the selector is prevented by a *blocker* (or *baulk*) ring. When synchronization occurs, friction on the blocker ring is relieved and it twists slightly, bringing into alignment certain grooves and notches that allow further passage of the selector which brings the teeth together. Of course, the exact design of the synchronizer varies from manufacturer to manufacturer.

The synchronizer has to change the momentum of the entire input shaft and clutch disk. Additionally, it can be abused by exposure to the momentum and power of the engine itself, which is what happens when attempts are made to select a gear without fully disengaging the clutch. This causes extra wear on the rings and sleeves, reducing their service life. When an experimenting driver tries to "match the revs" on a synchronized transmission and force it into gear without using the clutch, the synchronizer will make up for any discrepancy in RPM. The success in engaging the gear without clutching can deceive the driver into thinking that the RPM of the layshaft and transmission were actually exactly matched. Nevertheless, approximate rev. matching *with clutching* can decrease the general delta between layshaft and transmission and decrease synchro wear.

Reverse

The previous discussion normally applies only to the forward gears. The implementation of the reverse gear is usually different, implemented in the following way to reduce the cost of the transmission. Reverse is also a pair of gears: one gear on the countershaft and one on the output shaft. However, whereas all the forward gears are always meshed together, there is a gap between the reverse gears. Moreover, they are both attached to their shafts: neither one rotates freely about the shaft. What happens when reverse is selected is that a small gear, called an *idler gear* or *reverse idler*, is slid between them. The idler has teeth which mesh with both gears, and thus it couples these gears together and reverses the direction of rotation without changing the gear ratio.

In other words, when reverse gear is selected, it is in fact *actual* gear teeth that are being meshed, with no aid from a synchronization mechanism. For this reason, the output shaft must not be rotating when reverse is selected: the car must be stopped. In order that reverse can be selected without grinding even if the input shaft is spinning inertially, there may be a mechanism to stop the input shaft from spinning. The driver brings the vehicle to a stop, and selects reverse. As that selection is made, some mechanism in the transmission stops the input shaft. Both gears are stopped and the idler can be inserted between them. There is a clear description of such a mechanism in the Honda Civic 1996-1998 Service Manual, which refers to it as a "noise reduction system":

Whenever the clutch pedal is depressed to shift into reverse, the mainshaft continues to rotate because of its inertia. The resulting speed difference between mainshaft and reverse idler gear produces gear noise [grinding]. The reverse gear noise reduction system employs a cam plate which was added to the reverse shift holder. When shifting into reverse, the 5th/reverse shift piece, connected to the shift lever, rotates the cam plate. This causes the 5th synchro set to stop the rotating mainshaft.

A reverse gear implemented this way makes a loud whining sound, which is not normally heard in the forward gears. The teeth on the forward gears of most consumer automobiles are helically cut. When helical gears rotate, there is constant contact between gears, which results in quiet operation. In spite of all forward gears being always meshed, they do not make a sound that can be easily heard above the engine noise. By contrast, most reverse gears are spur gears, meaning that they have straight teeth, in order to allow for the sliding engagement of the idler, which is difficult with helical gears. The teeth of spur gears clatter together when the gears spin, generating a characteristic whine.

It is clear that the spur gear design of reverse gear represents some compromises (less robust, unsynchronized engagement and loud noise) which are acceptable due to the relatively small amount of driving that takes place in reverse. The gearbox of the classic SAAB 900 is a notable example of a gearbox with a helical reverse gear engaged in the same unsynchronized manner as the spur gears described above. Its strange design allows reverse to share cogs with first gear, and is exceptionally quiet, but results in difficult engagement and unreliable operation. However, many modern transmissions now include a reverse gear synchronizer and helical gearing.

Design variations

Gear variety

Manual transmissions in passenger vehicles are often equipped with 4, 5, or more recently 6 forward gears in conventional manual transmissions with a gear stick, and up to 8 forward gears in semi-automatic transmissions. Nearly all have one reverse gear. In three or four speed transmissions, in most cases, the topmost gear is *direct* (i.e., a 1:1 ratio). For five speed or higher transmissions, the highest gear is usually an overdrive gear, with a ratio of less than 1:1. Older cars were generally equipped with 3-speed transmissions, or 4-speed transmissions for high performance models and 5-speeds for the most sophisticated of automobiles; in the 1970s, 5-speed transmissions began to appear in low priced mass market automobiles and even compact pickup trucks, pioneered by Toyota (who advertised the fact by giving each model the suffix *SR5* as it acquired the fifth speed). Today, mass market automotive manual transmissions are essentially all 5-speeds, with 6-speed transmissions beginning to emerge in high performance vehicles in the early 1990s, and recently beginning to be offered on some high-efficiency and conventional passenger cars. Some 7-speed manual-derived transmissions are offered on high-end performance cars, such as the Bugatti Veyron 16.4, or the BMW M5. Both of these cars feature a paddle shifter. Recently, even 8-speed transmissions were being offered, such as in the Lexus IS F, and in 2012 Mercedes-Benz plan to introduce a 9-speed gearbox.

External overdrive

On earlier models with three or four forward speeds, the lack of an overdrive ratio for relaxed and fuel-efficient highway cruising was often filled by incorporating a separate overdrive unit in the rear housing of the transmission. This unit was separately actuated by a knob or button, often incorporated into the gearshift knob.

Shaft and gear configuration

On a conventional rear-drive transmission, there are three basic shafts; the input, the output, and the countershaft. The input and output together are called the *mainshaft*, since they are joined inside the transmission so they appear to be a single shaft, although they rotate totally independently of each other. The input length of this shaft is much shorter than the output shaft. Parallel to the mainshaft is the countershaft. There are a number of gears fixed along the countershaft, and matching gears along the output shaft, although these are not fixed, and rotate independently of the output shaft. There are sliding *dog collars*, or *dog clutches*, between the gears on the output shaft, and to engage a gear to the shaft, the collar slides into the space between the shaft and the inside space of the gear, thus rotating the shaft as well. One collar is usually mounted between two gears, and slides both ways to engage one or the other gears, so on a four speed there would be two collars. A front-drive transmission is basically the same, but may be simplified. There often are two shafts, the input and the output, but depending on the direction of rotation of the engine, three may be required. Rather than the input shaft driving the countershaft with a pinion gear, the input shaft takes over the countershaft's job, and the output shaft runs parallel to it. The gears are positioned and engaged just as they are on the countershaft and output shaft of a rear-drive. This merely eliminates one major component, the pinion gear. Part of the reason that the input and output are in-line on a rear drive unit is to relieve torsional stress on the transmission and mountings, but this isn't an issue in a front-drive as the gearbox is integrated into the transaxle.

The basic process is not universal. The fixed and free gears can be mounted on either the input or output shaft, or both.

The distribution of the shifters is also a matter of design; it need not be the case that all of the free-rotating gears with selectors are on one shaft, and the permanently splined gears on the other. For instance a five speed transmission might have the first-to-second selectors on the countershaft, but the third-to-fourth selector and the fifth selector on the mainshaft, which is the configuration in the 1998 Honda Civic. This means that when the car is stopped and idling in neutral with the clutch engaged and the input shaft spinning, the third, fourth and fifth gear pairs do not rotate.

In some transmission designs (Volvo 850 and V/S70 series, for example) there are actually two countershafts, both driving an output pinion meshing with the front-wheel-drive transaxle's ring gear. This allows the transmission designer to make the transmission narrower, since each countershaft need only be half as long as a traditional countershaft with four gears and two shifters.

Clutch

In all vehicles using a transmission (virtually all modern vehicles), a coupling device is used to separate the engine and transmission when necessary. The clutch accomplishes this in manual transmissions. Without it, the engine and tires would at all times be inextricably linked, and any time the vehicle stopped the engine would stall. Without the clutch, changing gears would be very difficult, even with the vehicle moving already: deselecting a gear while the transmission is under load requires considerable force, and selecting a gear requires the revolution speed of the engine to be held at a very precise value which depends on the vehicle speed and desired gear. In a car the clutch is usually operated by a pedal; on a motorcycle, a lever on the left handlebar serves the purpose.

- When the clutch pedal is fully depressed, the clutch is fully disengaged, and no torque is transferred from the engine to the transmission (and by extension to the drive wheels). In this uncoupled state it is possible to select gears or to stop the car without stopping the engine.
- When the clutch pedal is fully released, the clutch is fully engaged, and practically all of the engine's torque is transferred. In this coupled state, the clutch does not slip, but rather acts as rigid coupling, and power is transmitted to the wheels with minimal practical waste heat.
- Between these extremes of engagement and disengagement the clutch slips to varying degrees. When the clutch slips it still transmits torque despite the difference in speeds between the engine crankshaft and the transmission input. Because this torque is transmitted by means of friction rather than direct mechanical contact, considerable power is wasted as heat (which is dissipated by the clutch). Properly applied, slip allows the vehicle to be started from a standstill, and when it is already moving, allows the engine rotation to gradually adjust to a newly selected gear ratio.
- Learning to use the clutch efficiently requires the development of muscle memory and a level of coordination analogous to that required to learn a musical instrument or to play a sport.
- A rider of a highly-tuned motocross or off-road motorcycle may "hit" or "fan" the clutch when exiting corners to assist the engine in revving to the point where it delivers the most power.

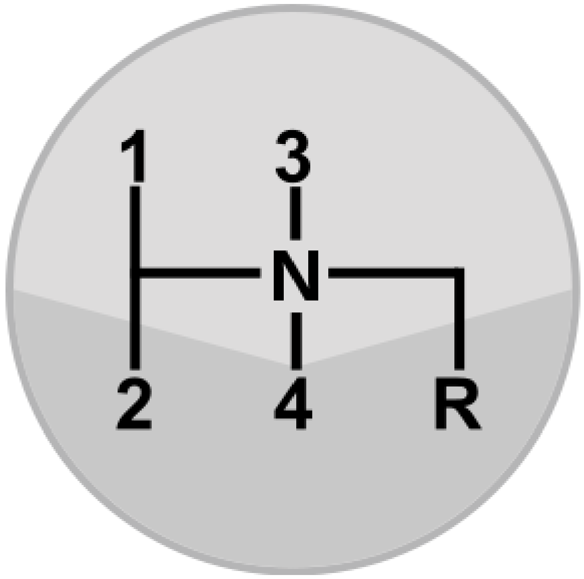
Gear shift types

Floor-mounted shifter

A 5 speed gear lever

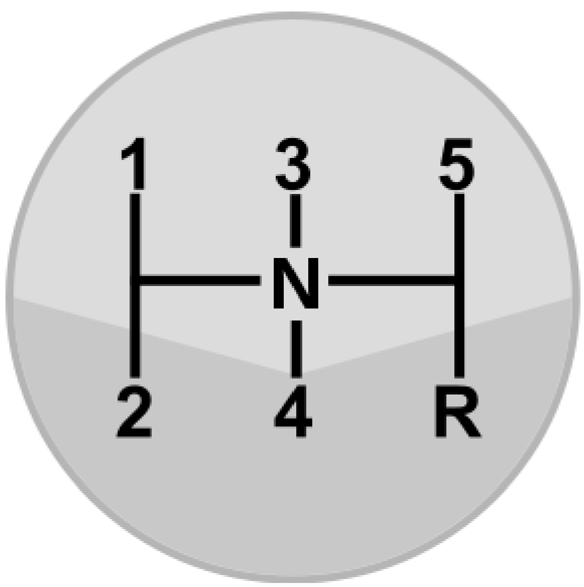
In many modern passenger cars, gears are selected by manipulating a lever connected to the transmission via linkage or cables and mounted on the floor of the automobile. This is called a **gear stick**, **shift stick**, **gearshift**, **gear lever**, **gear selector**, or **shifter**. Moving the lever forward, backward, left, and right into specific positions selects particular gears.

A sample layout of a *four-speed* transmission is shown below. **N** marks *neutral*, the position wherein no gears are engaged and the engine is decoupled from the vehicle's drive wheels. In reality, the entire horizontal line is a neutral position, although the shifter is usually equipped with springs so that it will return to the N position if not moved to another gear. The **R** marks reverse, the gear position used for moving the vehicle rearward.



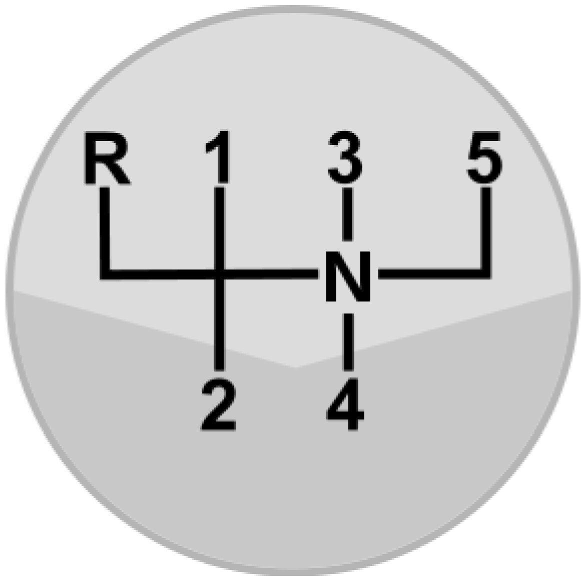
This layout is called the **shift pattern**. Because of the shift quadrants, the basic arrangement is often called an *H-pattern*. The shift pattern is usually molded or printed on or near the gear knob. While the layout for gears one through four is nearly universal, the location of reverse is not. Depending on the particular transmission design, reverse may be located at the upper left extent of the shift pattern, at the lower left, at the lower right, or at the upper right. There is usually a mechanism that only allows selection of reverse from the neutral position, or a reverse blockout that must be released by depressing the spring-loaded gear knob or lifting a spring-loaded collar on the shift stick, to reduce the likelihood that reverse will be inadvertently selected by the driver.

This is the most common five-speed shift pattern:

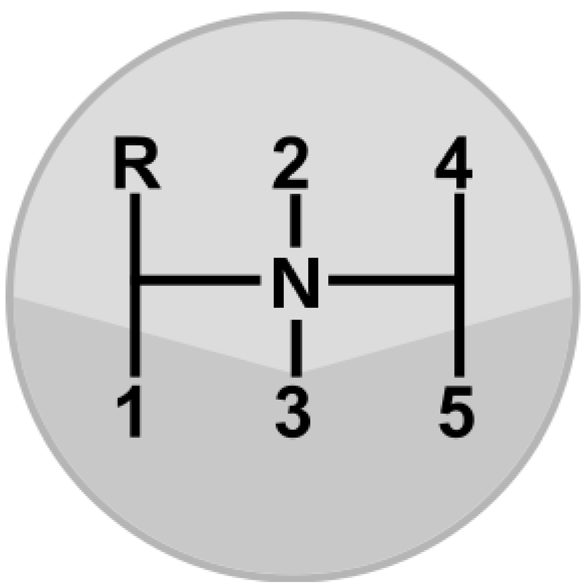


This layout is reasonably intuitive because it starts at the upper left and works left to right, top to bottom, with reverse at the end of the sequence and toward the rear of the car.

This is another five-speed shift pattern, which can be found in Saabs, BMWs, some Audis, Eagle, Volvos, Volkswagens, Škodas, Opels, Hyundais, most Renaults, some diesel Fords, and more:



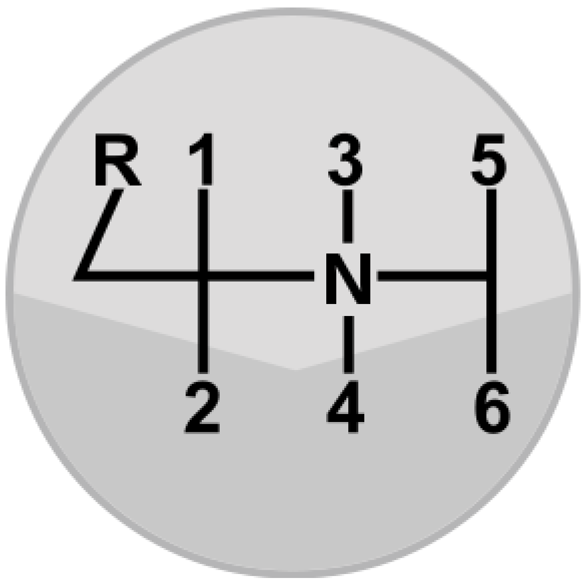
Dog-leg first shift patterns are used on many race cars and on older road vehicles with three-speed transmissions:



The name derives from the up-and-over path between first and second gears. Its use is common in race cars and sports cars, but is diminishing as six speed and sequential gearboxes are becoming more common. Having first gear across the dog leg is beneficial as first gear is traditionally only used for getting the car moving and hence it allows second and third gears to be aligned fore and aft of each other, which facilitates shifting between the two. As most racing gearboxes are non-synchromesh there is no appreciable delay when upshifting from first through the dog leg into second.

This gear pattern can also be found on some heavy vehicles in which first gear is an extra-low ratio for use in extreme standing-start conditions, and would see little use in normal driving.

This is a typical shift pattern for a six-speed transmission:



Six speeds is the maximum usually seen in single range transmissions, however many semi trucks and other large commercial vehicles have manual transmissions with 8, 16 or even 20 speeds, which is made possible due to multi-range gearboxes. In such a case, Reverse is placed outside of the "H," with a canted shift path, to prevent the shift lever from intruding too far into the driver's space (in left-hand drive cars) when reverse is selected. This is the most common layout for a six-speed manual transmission.

Most front-engined, rear-wheel drive cars have a transmission that sits between the driver and the front passenger seat. Floor-mounted shifters are often connected directly to the transmission. Front-wheel drive and rear-engined cars often require a mechanical linkage to connect the shifter to the transmission.

"Four-on-the-Floor"

Historically, four-speed floor shifters were sometimes referred to as "four on the floor," during the period when steering column mounted shifters were more common. The latter, often being the standard non-performance transmission, usually had only three forward speeds and were referred to as "three on the tree."

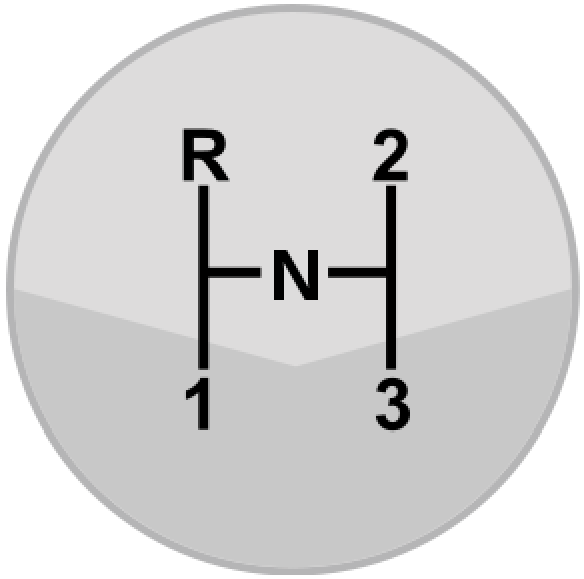
Column-mounted shifter

Column mounted gear shift lever in a Saab 96

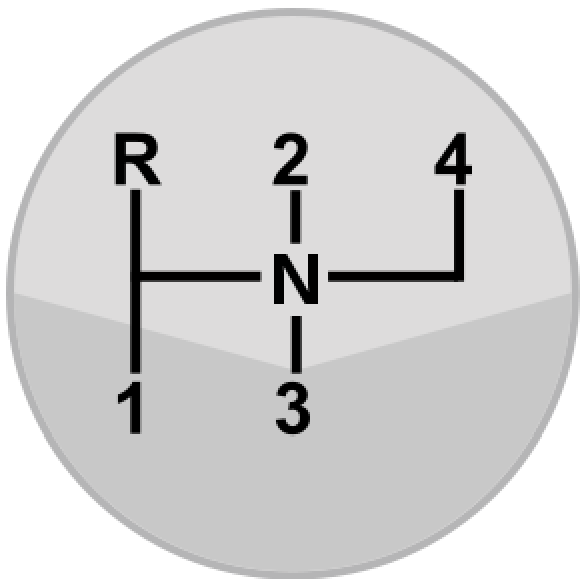
Some cars have a gear lever mounted on the steering column of the car. It was common in some countries in the past but is no longer common today. However, many automatic transmissions still use this placement.

Column shifters are mechanically similar to floor shifters, although shifting occurs in a vertical plane instead of a horizontal one. Column shifters also generally involve additional linkages to connect the shifter with the transmission. Also, the pattern is not "intuitive," as the shifter has to be moved backward and upward into R to make the car go backward. The major advantage of a column shifter is that the driver can switch between the two most commonly used gears without letting go of the steering wheel, by reaching the lever using the index and middle fingers.

A 3-speed column shifter, nicknamed "Three on the Tree" began appearing in America in the late 1930s and became common during the 1940s and '50s. Its layout is as shown below:



First gear in a 3-speed is often called "low," while third is usually called "high." There is, of course, no overdrive. Later, European and Japanese models began to have 4-speed column shifters and some of these made their way to the USA. Its layout is shown here:



However, the column manual shifter disappeared in North America by the mid 1980s, last appearing in the 1987 Chevrolet c10. But in the rest of the world, the column mounted shifter remained in production, and was in fact common in some places. For example, all Toyota Crown and Nissan Cedric taxis in Hong Kong had the 4-speed column shift until 1999 when automatic began to be offered. Since the late 1980s or early 1990s, a 5-speed column shifter has been made in some vans sold in Asia and Europe, such as Toyota Hiace and Mitsubishi L400.

Console-mounted shifter

Newer small cars and MPV's, like the Suzuki MR Wagon, the Fiat Multipla, the Toyota Matrix, the Pontiac Vibe, the Chrysler RT platform cars and the Honda Civic Si EP3 may feature a manual or automatic transmission gear shifter located on the vehicle's instrument panel. Console-mounted shifters are similar to floor-mounted gear shifters in that most of the ones used in modern cars operate on a horizontal plane and can be mounted to the vehicle's transmission in much the same way a floor-mounted shifter can. However, because of the location of the gear shifter in comparison to the locations of the column shifter and the floor shifter, as well as the positioning of the shifter to the rest of the controls on the panel often require that the gearshift be mounted in a space that does not feature a lot of controls integral to the vehicle's operation or frequently used controls, such as those for the car stereo or car air conditioning, to help prevent accidental activation or driver confusion, especially in right-hand drive cars.

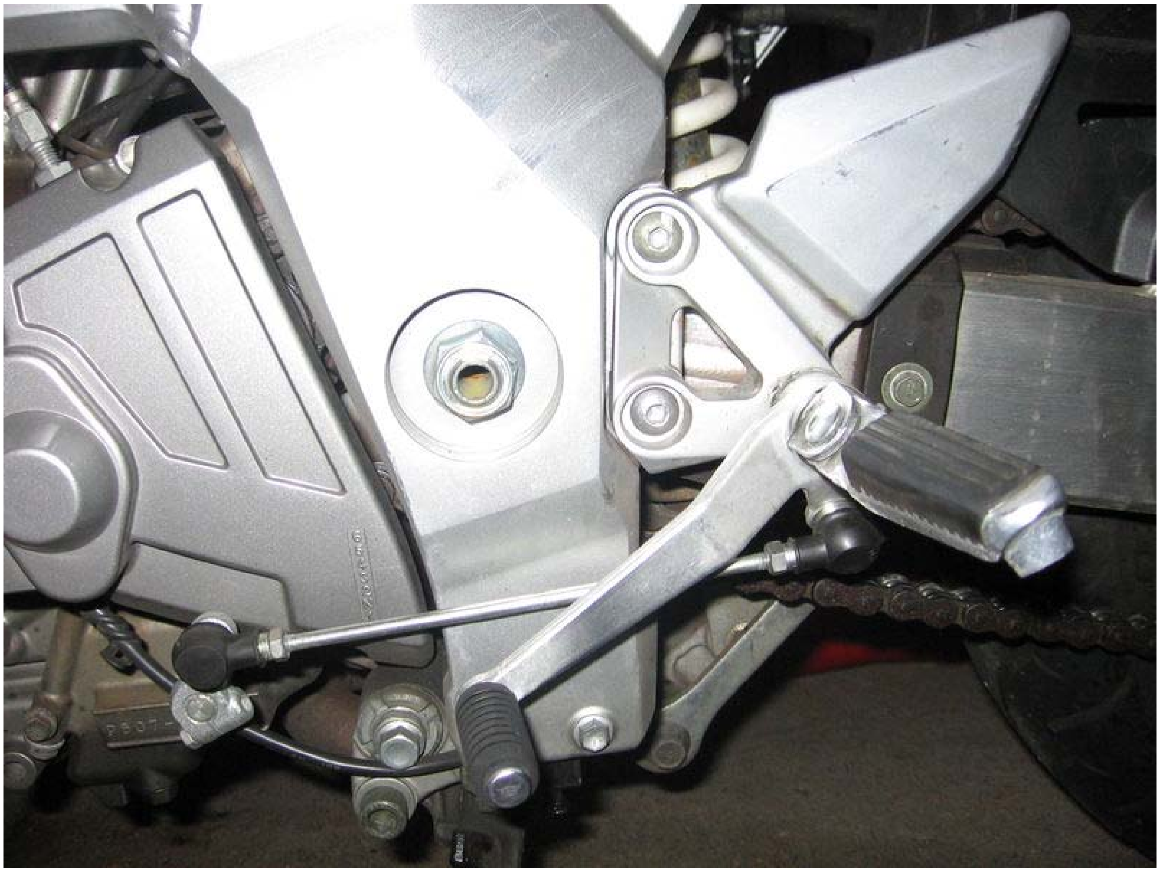
More and more small cars and vans from manufacturers such as Suzuki, Honda, and Volkswagen are featuring console shifters in that they free up space on the floor for other car features such as storage compartments without requiring that the gear shift be mounted on the steering column. Also, the basic location of the gear shift in comparison to the column shifter makes console shifters easier to operate than column shifters.

Sequential manual

Some transmissions do not allow the driver to arbitrarily select any gear. Instead, the driver may only ever select the next-lowest or next-highest gear ratio. Sequential transmissions often incorporate a synchro-less dog-clutch engagement mechanism (instead of the synchromesh dog clutch common on H-pattern automotive transmissions), in which case the clutch is only necessary when selecting first or reverse gear from neutral, and most gear changes can be performed without the clutch. However, sequential shifting and synchro-less engagement are not inherently linked, though they often occur together due to the environment(s) in which these transmissions are used, such as racing cars and motorcycles.

Sequential transmissions are generally controlled by a forward-backward lever, foot pedal, or set of paddles mounted behind the steering wheel. In some cases, these are connected mechanically to the transmission. In many modern examples, these controls are attached to sensors which instruct a transmission computer to perform a shift—many of these systems can be switched into an automatic mode, where the computer controls the timing of shifts, much like an automatic transmission.

Motorcycles typically employ sequential transmissions, although the shift pattern is modified slightly for safety reasons. In a motorcycle the gears are usually shifted with the left foot pedal, the layout being this:



The gear shift lever on a 2003 Suzuki SV650S motorcycle.

6 5 ┘ 4 ┘ 3 ┘ 2 ┘ N 1

The pedal goes one step–both up and down–from the center, before it reaches its limit and has to be allowed to move back to the center position. Thus, changing multiple gears in one direction is accomplished by repeatedly pumping the pedal, either up or down. Although neutral is listed as being between first and second gears for this type of transmission, it "feels" more like first and second gear are just "further away" from each other than any other two sequential gears. Because this can lead to difficulty in finding neutral for inexperienced riders most motorcycles have a neutral indicator light on the instrument panel to help find neutral. The reason neutral does not actually have its own spot in the sequence is to make it quicker to shift from first to second when moving. Depending on the age of your motorcycle, gearbox, or skill, you can accidentally shift into neutral, although most high end, newer model motorcycles have found ways around this. The reason for having neutral between the first and second gears instead of at the bottom is that when stopped, the rider can just click down repeatedly and know that they will end up in first and not neutral. This allows a rider to quickly move his bike from a standstill in an emergency situation. This may also help on a steep hill on which high torque is required. It could be disadvantageous or even dangerous to attempt to be in first without realizing it, then try for a lower gear, only to get neutral.

On motorcycles used on race tracks, the shifting pattern is often reversed, that is, the rider clicks down to upshift. This usage pattern increases the ground clearance by placing the riders foot above the shift lever when the rider is most likely to need it, namely when leaning over and exiting a tight turn.

The shift pattern for most underbone motorcycles with an automatic centrifugal clutch is also modified for two key reasons - to enable the less-experienced riders to shift the gears without problems of "finding" neutral, and also due to the greater force needed to "lift" the gearshift lever (because the gearshift pedal of an underbone motorcycle also operates the clutch). The gearshift lever of an underbone motorcycle has two ends. The rider clicks down the front end with the left toe all the way to the top gear and clicks down the rear end with the heel all the way down to neutral. Some underbone models such as the Honda Wave and Kawasaki Fury series have a "rotary" shift pattern, which means that the rider can shift directly to neutral from the top gear, but for safety reasons this is only possible when the motorcycle is stationary. Some models also have gear position indicators for all gear positions at the instrument panel.

Semi-manual

Some new transmissions (Alfa Romeo's Selespeed gearbox and BMW's *Sequential Manual Gearbox* (SMG) for example) are conventional manual transmissions with a computerized control mechanism. These transmissions feature independently selectable gears but do not have a clutch pedal. Instead, the transmission computer controls a servo which disengages the clutch when necessary.

These transmissions vary from sequential transmissions in that they still allow nonsequential shifts: BMWs SMG system, for example, can shift from 6th gear directly to 4th gear.

In the case of the early second generation Saab 900, a 'Seletronic' option was available where gears were shifted with a conventional shifter, but the clutch is controlled by a computer.

Benefits and drawbacks

Benefits

Manual transmissions generally offer better fuel economy than automatic torque converter transmissions; however the disparity has been somewhat offset with the introduction of locking torque converters on automatic transmissions. Increased fuel economy with a properly operated manual transmission vehicle versus an equivalent automatic transmission vehicle can range from 5% to about 15% depending on driving conditions and style of driving. Manual transmissions do not require active cooling and generally weigh less than comparable automatics. The manual transmission couples the engine to the transmission with a rigid clutch instead of a torque converter which slips by nature. Manual transmissions also lack the parasitic power consumption of the automatic transmission's hydraulic pump. Additionally, they require less maintenance and are easier to repair because they have fewer moving parts and are, mechanically, much simpler than automatic transmissions. When properly operated by an experienced driver, manual transmissions also tend to last longer than automatic transmissions.

Manual transmissions also generally offer a higher selection of gear ratios. Many vehicles offer a 5-speed or 6-speed manual, whereas the automatic option would typically be a 4-speed. The higher selection of gears allowed for more uses of the engine's power band, allowing for higher fuel economy and power output. This is generally due to the space available inside of a manual transmission versus an automatic since the latter requires extra components for self-shifting, such as torque converters and pumps. Automatic transmissions are now adding more speeds as the technology matures. ZF currently makes an 8-Speed automatic transmission, which is used on the Rolls Royce Ghost and the Bentley Mulsanne. The automatic transmission in the Nissan 370Z also has 7 speeds.

Manual transmissions are more efficient than conventional automatics and belt-driven continuously-variable transmissions. The driver has more direct control over the car with a manual than with an automatic, which can be employed by an experienced, knowledgeable driver who knows the correct procedure for executing a driving maneuver, and wants the vehicle to realize his or her intentions exactly and instantly. When starting forward, for example, the driver can control how much torque goes to the tires, which is useful on slippery surfaces such as ice, snow or mud. This can be done with clutch finesse, or by starting in second gear instead of first. An engine coupled with a manual transmission can often be started by the method of push starting. This is particularly useful if the starter is inoperable or defunct or the battery has drained below operable voltage. Likewise, a vehicle with a manual transmission and no clutch/starter interlock switch can be moved, if necessary, by cranking the starter while in gear. This is useful when the vehicle will not start, but must be immediately moved e.g. off the road in the event of a breakdown, if the vehicle has stalled on a railway crossing, or in extreme off-roading cases such as an engine that has stalled in deep water.

Currently only fully manual transmissions allow the driver to fully exploit the engine power at low to medium engine speeds. This is because even automatic transmissions which provide some manual mode (e.g. tiptronic), use a throttle kickdown switch, which forces a downshift on full throttle and causes the gearbox to ignore a user command to upshift on full throttle. This is especially notable on uphill roads, where cars with automatic transmission need to slow down to avoid downshifts, whereas cars with manual transmission and identical or lower engine power are still able to maintain their speed.

In contrast to most manual gearboxes, most automatic transmissions have a free-wheel-clutch. This means that the engine does not slow down the car when the driver steps off the throttle, also known as engine braking. This leads to more usage of the brakes in cars with automatic transmissions. However, the automatic gearboxes in commodity Nissans and Hondas disable the free wheel operation completely if the driver has selected a gear position other than "D" - either "1", "2", or "D with overdrive off". This works by blocking the free-wheel sprag using a multi-disk clutch called the "overrun clutch".

Drawbacks

The smoothness and correct timing of gear shifts are wholly dependent on the driver's experience and skill. If an inexperienced driver selects the wrong gear by mistake, she/he can do damage to the engine and/or transmission.

Attempting to select reverse while the vehicle is moving forward causes severe gear wear (except in transmissions with synchromesh on the reverse gear). Most manual transmissions have a gate that locks out reverse directly from 5th gear however, to help prevent this. In order to engage reverse from 5th, the shift lever has to be moved to the center position between 2nd and 3rd, then back over and into reverse. Many newer six-speed manual transmissions have a collar under the shift knob which must be lifted to engage reverse to also help prevent this.

Choosing too low a gear with the car moving at speed can over-rev and damage the engine. There is a learning curve with a manual transmission; the driver must develop a feel for properly engaging the clutch, especially when starting forward on a steep road or when parking on an incline.

Some automatic transmissions can shift ratios faster than a manual gear change can be accomplished, due to the time required for the average driver to push the clutch pedal to the floor and move the gearstick from one position to another. This is especially true in regards to dual clutch transmissions, which are specialized computer-controlled manual transmissions. Even though some automatic transmissions and semi-automatic transmissions can shift faster, many purists still prefer a regular manual transmission.

Manual transmissions place a slightly greater workload on the driver in heavy traffic situations, when the driver must often operate the clutch pedal. In comparison, automatic transmissions merely require moving the foot from the accelerator pedal to the brake pedal, and vice versa. Manual transmissions require the driver to remove one hand periodically from the steering wheel while the vehicle is in motion.

Applications and popularity

Many types of automobiles are equipped with manual transmissions. Small economy cars predominantly feature manual transmissions because they are cheap and efficient, although many are optionally equipped with automatics. Economy cars are also often powered by very small engines, and manual transmissions make more efficient use of the power produced.

Sports cars are also often equipped with manual transmissions because they offer more direct driver involvement and better performance. Off-road vehicles and trucks often feature manual transmissions because they allow direct gear selection and are often more rugged than their automatic counterparts.

Conversely, manual transmissions are no longer popular in many classes of cars sold in North America, Australia and Asia, although they remain dominant in Europe and developing countries. Nearly all cars are available with an automatic transmission option, and family cars and large trucks sold in the US are predominantly fitted with automatics, however in some cases if a buyer wishes he/she can have the car fitted with a manual transmission at the factory. In Europe most cars are sold with manual transmissions. Most luxury cars are only available with an automatic transmission. In most cases where both transmissions are available for a given car, automatics are an at cost option, but in some cases the reverse is true. Some cars, such as rental cars and taxis, are nearly universally equipped with automatic transmissions in countries such as the US, but the opposite is true in Europe. As of 2008, 75.2% of vehicles made in Western Europe were equipped with manual transmission, versus 16.1% with automatic and 8.7% with other.

In some places (for example Australia, New Zealand (for the second-phase Restricted licence, but not the final Full licence), Belgium, China, Estonia, Dominican Republic, Finland, France, Germany, Ireland, Israel, Netherlands, Norway, Poland, Singapore, Slovenia, South Africa, South Korea, Spain, Sri Lanka, Sweden, Turkey, U.A.E and the UK), when a driver takes the licensing road test using an automatic transmission, the resulting license is restricted to the use of automatic transmissions. This treatment of the manual transmission skill seems to maintain the widespread use of the manual transmission. As many new drivers worry that their restricted license will become an obstacle for them where most cars have manual transmissions, they make the effort to learn with manual transmissions and obtain full licenses. Some other countries (such as India, Pakistan, Malaysia, Serbia, Brazil, and Denmark) go even further, whereby the license is granted only when a test is passed on a manual transmission. In Denmark and Brazil you are allowed to take the test on an automatic if you are handicapped, with such license you will not be able to drive a manual transmission.

Truck transmissions

Some trucks have transmissions that look and behave like ordinary car transmissions - these transmissions are used on lighter trucks, typically have up to 6 gears, and usually have synchromesh.

For trucks needing more gears, the standard "H" pattern can get very complicated, so additional controls are used to select additional gears. The "H" pattern is retained, then an additional control selects among alternatives. In older trucks, the control is often a separate lever mounted on the floor or more recently a pneumatic switch mounted on the "H" lever; in newer trucks the control is often an electrical switch mounted on the "H" lever. Multi-control transmissions are built in much higher power ratings, but rarely use synchromesh.

There are several common alternatives for the shifting pattern. Usual types are:

- **Range transmissions** use an "H" pattern through a narrow range of gears, then a "range" control shifts the "H" pattern between high and low ranges. For example, an 8-speed range transmission has an H shift pattern with four gears. The first through fourth gears are accessed when low range is selected. To access the fifth through eighth gears, the range selector is moved to high range, and the gear lever again shifted through the first through fourth gear positions. In high range, the first gear position becomes fifth, the second gear position becomes sixth, and so on.
- **Splitter transmissions** use an "H" pattern with a wide range of gears, and the other selector splits each sequential gear position in two: First gear is in first position/low split, second gear is in first position/high split, third gear is in second position/low split, fourth gear is in second position/high split, and so on.
- **Range-Splitter transmissions** combine range-splitting and gear-splitting. This allows even more gear ratios. Both a range selector and a splitter selector are provided.

Although there are many gear positions, shifting through gears usually follows a regular pattern. For example, a series of upshifts might use "move to splitter direct; move to splitter overdrive; move shift lever to #2 and move splitter to underdrive; move splitter to direct; move splitter to overdrive; move shift lever to #3 and move splitter to underdrive"; and so on. In older trucks using floor-mounted levers, a bigger problem is common gear shifts require the drivers to move their hands between shift levers in a single shift, and without synchromesh, shifts must be carefully timed or the transmission will not engage. For this reason, some splitter transmissions have an additional "under under" range, so when the splitter is already in "under" it can be quickly downshifted again, without the delay of a double shift.

Today's truck transmissions are most commonly "range-splitter". The most common 13 speed has a standard H pattern, and the pattern from left upper corner is as follows: R, down to L, over and up to 1, down to 2, up and over to 3, down to 4. The "butterfly" range lever in the center front of the knob is flipped up to high range while in 4th, then shifted back to 1. The 1 through 4 positions of the knob are repeated. Also, each can be split using the thumb-actuated under-overdrive lever on the left side of the knob while in high range. The "thumb" lever is not available in low range, except in 18 speeds; 1 through 4 in low range can be split using the thumb lever and L can be split with the "Butterfly" lever. L cannot be split using the thumb lever in either the 13 or 18 speed. The 9 speed transmission is basically a 13 speed without the under-overdrive thumb lever.

Truck transmissions use many physical layouts. For example, the output of an N-speed transmission may drive an M-speed secondary transmission, giving a total of N*M gear combinations; for example a 4-speed main box and 3-speed splitter gives 12 ratios. Transmissions may be in separate cases with a shaft in between; in separate cases bolted together; or all in one case, using the same lubricating oil. The second transmission is often called a "Brownie" or "Brownie box" after a popular brand. With a third transmission, gears are multiplied yet again, giving greater range or closer spacing. Some trucks thus have dozens of gear positions, although most are duplicates. Sometimes a secondary transmission is integrated with the differential in the rear axle, called a "two-speed rear end." Two-speed differentials are always splitters. In newer transmissions, there may be two countershafts, so each main shaft gear can be driven from one or the other countershaft; this allows construction with short and robust countershafts, while still allowing many gear combinations inside a single gear case.

Heavy-duty transmissions are almost always non-synchromesh. One argument is synchromesh adds weight that could be payload, is one more thing to fail, and drivers spend thousands of hours driving so can take the time to learn to drive efficiently with a non-synchromesh transmission. Heavy-duty trucks driven frequently in city traffic, such as cement mixers, need to be shifted very often and in stop-and-go traffic. Since few heavy-duty transmissions have synchromesh, automatic transmissions are commonly used instead, despite their increased weight, cost, and loss of efficiency.

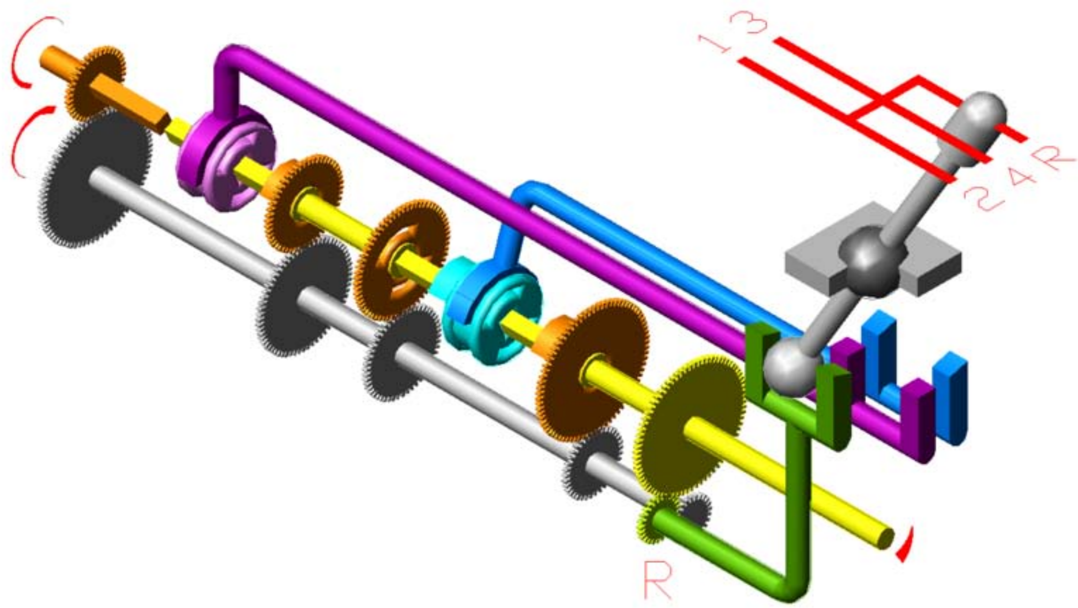
Heavy trucks are usually powered with diesel engines. Diesel truck engines from the 1970s and earlier tend to have a narrow power band, so need many close-spaced gears. Starting with the 1968 Maxidyne, diesel truck engines have increasingly used turbochargers and electronic controls that widen the power band, allowing fewer and fewer gear ratios. A transmission with fewer ratios is lighter and may be more efficient due to fewer transmissions in series. Fewer shifts also makes the truck more drivable. As of 2005, fleet operators often use 9,10,13 or 18-speed transmissions, but automated manual and semi-automatic transmissions are becoming more common on heavy vehicles, as they can improve efficiency and drivability, reduce the barrier to entry for new drivers, and may improve safety by allowing the driver to concentrate on road conditions.

Maintenance

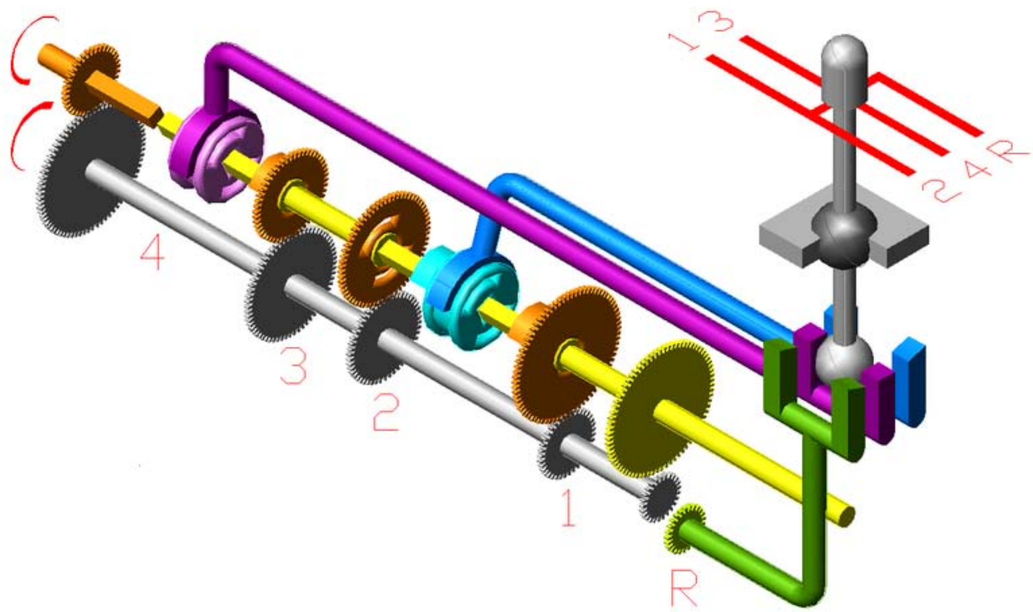
Because clutches use changes in friction to modulate the transfer of torque between engine and transmission, they are subject to wear in everyday use. A very good clutch, when used by an expert driver, can last hundreds of thousands of kilometres (or miles). Weak clutches, abrupt downshifting, inexperienced drivers, and aggressive driving can lead to more frequent repair or replacement.

Manual transmissions are lubricated with gear oil or engine oil in some cars, which must be changed periodically in some cars, although not as frequently as the automatic transmission fluid in a vehicle so equipped. (Some manufacturers specify that changing the gear oil is never necessary except after transmission work or to rectify a leak.)

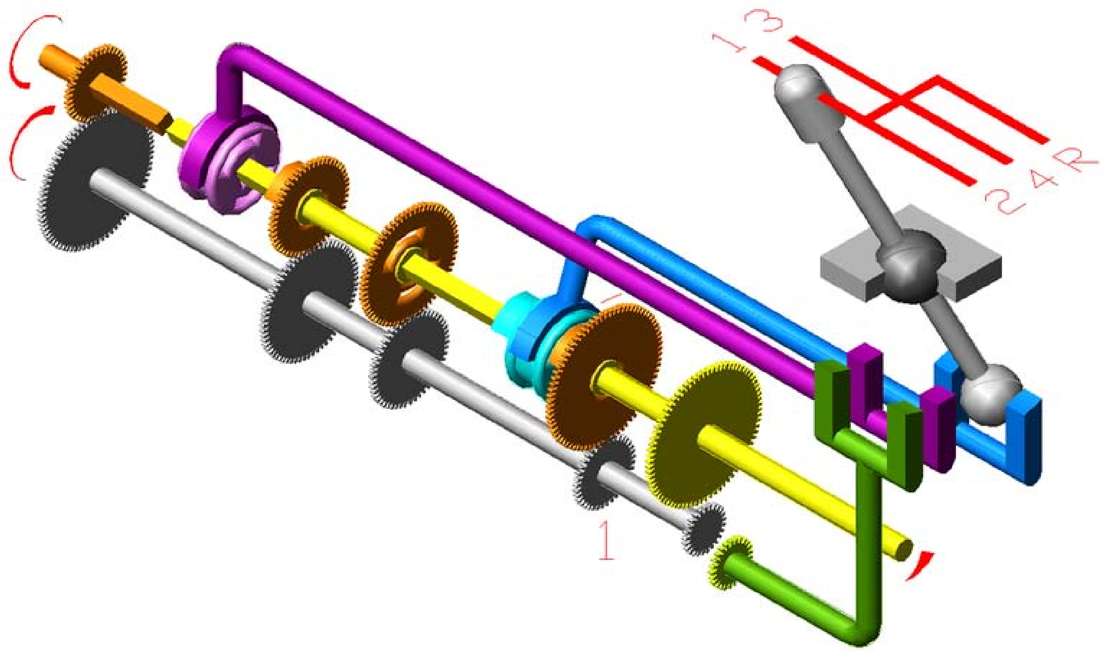
Gear oil has a characteristic aroma due to the addition of sulfur-bearing anti-wear compounds. These compounds are used to reduce the high sliding friction by the helical gear cut of the teeth (this cut eliminates the characteristic whine of straight cut spur gears). On motorcycles with "wet" clutches (clutch is bathed in engine oil), there is usually nothing separating the lower part of the engine from the transmission, so the same oil lubricates both the engine and transmission. The original Mini placed the gearbox in the oil sump below the engine, thus using the same oil for both.



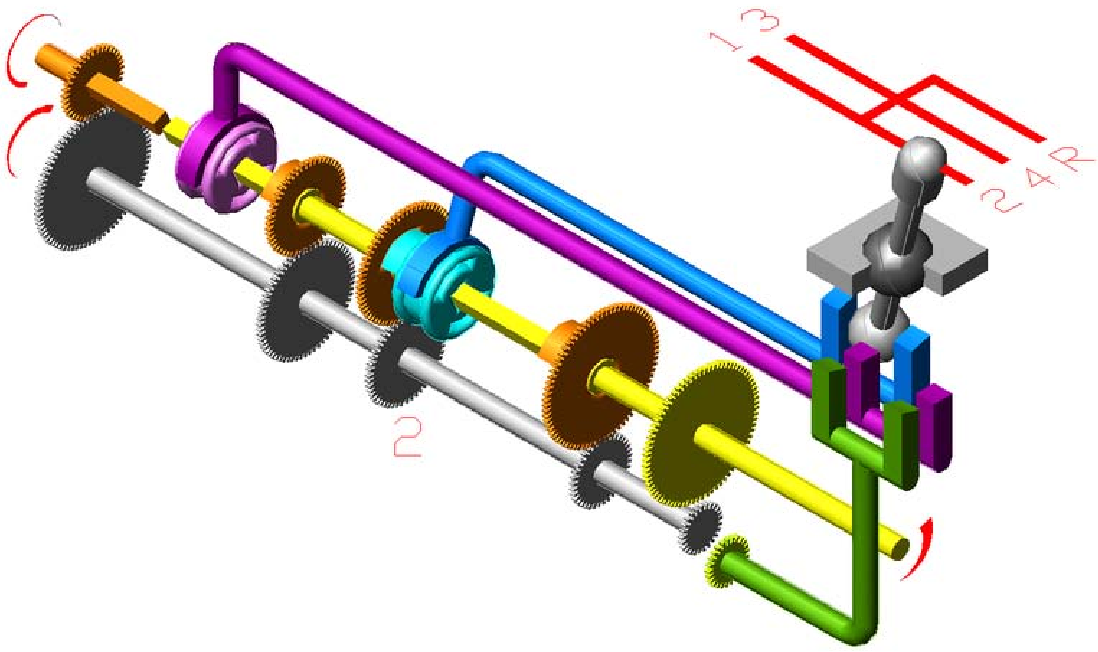
Reverse



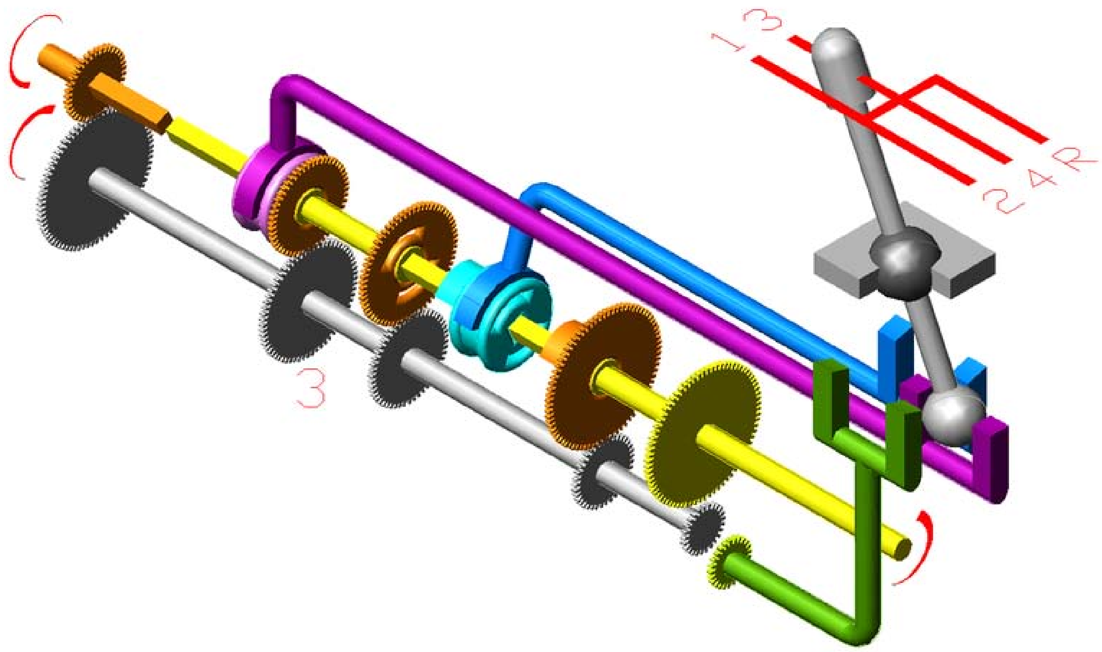
Neutral



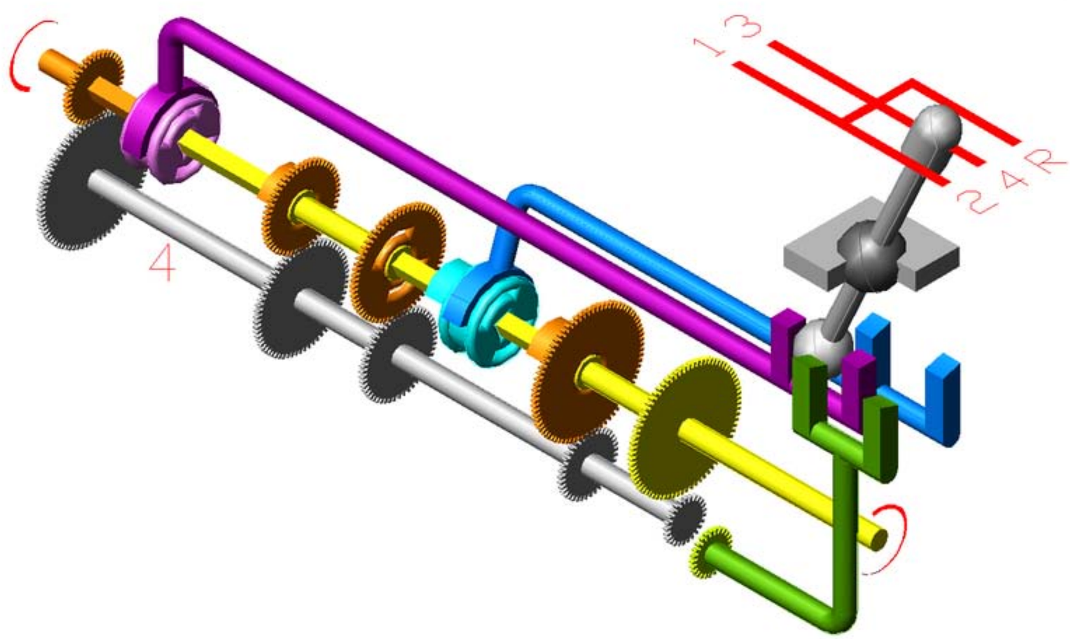
First gear



Second gear



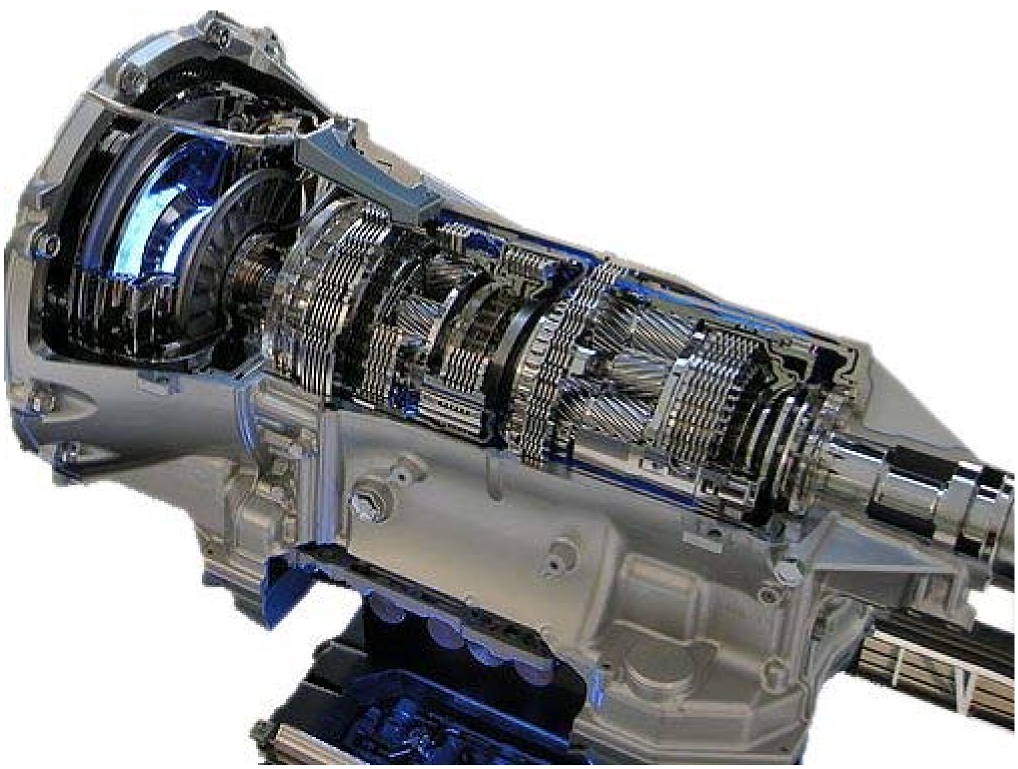
Third gear



Fourth gear

Chapter 11

Automatic Transmission



An 8-gear automatic transmission

An **automatic gearbox** is one type of motor vehicle transmission that can automatically change gear ratios as the vehicle moves, freeing the driver from having to shift gears manually. Most automatic transmissions have a defined set of gear ranges, often with a parking pawl feature that locks the output shaft of the transmission.

Similar but larger devices are also used for heavy-duty commercial and industrial vehicles and equipment. Some machines with limited speed ranges or fixed engine speeds, such as some forklifts and lawn mowers, only use a torque converter to provide a variable gearing of the engine to the wheels.

Besides automatics, there are also other types of automated transmissions such as continuous variable transmissions (CVTs) and semi-automatic transmissions, that free the driver from having to shift gears manually, by using the transmission's computer to change gear, if for example the driver were redlining the engine. Despite superficial similarity to other automated transmissions, automatic transmissions differ significantly in internal operation and driver's "feel" from semi-automatics and CVTs. An automatic uses a torque converter instead of clutch to manage the connection between the transmission gearing and the engine. In contrast, a CVT uses a belt or other torque transmission schema to allow an "infinite" number of gear ratios instead of a fixed number of gear ratios. A semi-automatic retains a clutch like a manual transmission, but controls the clutch through electrohydraulic means.

A conventional manual transmission is frequently the base equipment in a car, with the option being an automated transmission such as a conventional automatic, semi-automatic, or CVT. The ability to shift gears manually, often via paddle shifters, can also be found on certain automated transmissions (manumatics such as Tiptronic), semi-automatics (BMW SMG), and continuous variable transmissions (CVTs) (such as Lineartronic).

Comparison with manual transmission

Most cars sold in North America since the 1950s have been available with an automatic transmission. Conversely, automatic transmission is less popular in Europe, with 80% of drivers opting for manual transmission.. In most Asian markets and in Australia, automatic transmissions have become very popular since the 1990s.

Vehicles equipped with automatic transmissions are less complex to drive. Consequently, in some jurisdictions, drivers who have passed their driving test in a vehicle with an automatic transmission will not be licensed to drive a manual transmission vehicle. Examples of driving license restrictions are Croatia, Dominican Republic, Israel, United Kingdom, some states in Australia, France, Portugal, Latvia, Lebanon, Lithuania, Ireland, Belgium, Germany, Pakistan, the Netherlands, Sweden, Austria, Norway, Poland, Hungary, South Africa, Trinidad and Tobago, China, Hong Kong, Macau, Mauritius, South Korea, Romania, Singapore, Philippines, United Arab Emirates, India, Estonia, Finland, Switzerland, Slovenia, Republic of Ireland and New Zealand (Restricted licence only).

Automatic transmission modes

Conventionally, in order to select the transmission operating 'mode', the driver moves a selection lever located either on the steering column or on the floor (as with a manual). In order to select modes, or to manually select specific gear ratios, the driver must push a button in (called the shift lock button) or pull the handle (only on column mounted shifters) out. Some vehicles position selector buttons for each mode on the cockpit instead, freeing up space on the central console. Vehicles conforming to US Government standards must have the modes ordered P-R-N-D-L (left to right, top to bottom, or clockwise). Prior to this, quadrant-selected automatic transmissions often used a P-N-D-L-R layout, or similar. Such a pattern led to a number of deaths and injuries owing to unintentional gear selection, as well as the danger of having a selector (when worn) jump into Reverse from Low gear during engine braking maneuvers.

Automatic transmissions have various modes depending on the model and make of the transmission. Some of the common modes include

Park (P)

This selection mechanically locks the output shaft of transmission, restricting the vehicle from moving in any direction. A parking pawl prevents the transmission from rotating, and therefore the vehicle from moving, although the vehicle's non-driven roadwheels may still rotate freely. For this reason, it is recommended to use the hand brake (or parking brake) because this actually locks (in most cases) the rear wheels and prevents them from moving. This also increases the life of the transmission and the park pin mechanism, because parking on an incline with the transmission in park without the parking brake engaged will cause undue stress on the parking pin. An efficiently-adjusted hand brake should also prevent the car from moving if a worn selector accidentally drops into reverse gear during early morning fast-idle engine warm-ups. It should be noted that locking the transmission output shaft does not positively lock the driving wheels. If one driving wheel slips while the transmission is in "park," the other will roll freely as the slipping wheel rotates in the opposite direction. Only a (properly adjusted) parking brake can be relied upon to positively lock both of the parking-braked wheels. (This is not the case with certain 1950's Chrysler products that carried their parking brake on the transmission tailshaft, a defect compounded by the provision of a bumper jack). It is typical of front-wheel-drive vehicles for the parking brake to be on the rear (non-driving) wheels, so use of both the parking brake and the transmission park lock provides the greatest security against unintended movement on slopes. Unfortunately, the rear of most front-wheel-drive vehicles has only about half the weight on the rear wheel as is on the front wheels, greatly reducing the security provided by the parking brake as compared to either rear-wheel-drive vehicles with parking brake on the rear wheels (which generally have near half of the total vehicle weight on the rear wheels, except for empty pickup and open-bed trucks) or to front-wheel-drive vehicles with the parking brake on the front wheels, which generally have about two-thirds of the vehicle's weight (unloaded) on the front wheels.

A car should be allowed to come to a complete stop before setting the transmission into park to prevent damage. Usually, Park (P) is one of only two selections in which the car's engine can be started, the other being Neutral (N). In many modern cars and trucks, the driver must have the foot brake applied before the transmission can be taken out of park. The Park position is omitted on buses/coaches with automatic transmission (on which a parking pawl is not practical), which must be placed in neutral with the parking brakes set. Advice is given in some owner's manuals [example: 1997 Oldsmobile Cutlass Supreme owner's manual] that if the vehicle is parked on a steep slope using the park lock only, it may not be possible to release the park lock (move the selector lever out of "P"). Another vehicle may be required to push the stuck vehicle uphill slightly to remove the loading on the park lock pawl.

Most automobiles require **P** or **N** to be set on the selector lever before the internal combustion engine can be started. This is typically achieved via a normally open 'inhibitor' switch, which is wired in series with the starter motor engagement circuit, and is only closed when P or N is selected, thus completing the circuit (when the key is turned to the start position)

Reverse (R)

This engages reverse gear within the transmission, giving the ability for the vehicle to drive backwards. In order for the driver to select reverse in modern transmissions, they must come to a complete stop, push the shift lock button in (or pull the shift lever forward in the case of a column shifter) and select reverse. Not coming to a complete stop can cause severe damage to the transmission. Many modern automatic transmissions have a safety mechanism in place, which does to some extent prevent (but does not completely avoid) inadvertently putting the car in reverse when the vehicle is moving forwards. This mechanism usually consists of a solenoid-controlled physical barrier on either side of the Reverse position, which is electronically engaged by a switch on the brake pedal. Therefore, the brake pedal needs to be depressed in order to allow the selection of reverse. Some electronic transmissions prevent or delay engagement of reverse gear altogether while the car is moving.

Some shifters with a shift button allow the driver to freely move the shifter from R to N or D, or simply moving the shifter to N or D without actually depressing the button. However, the driver cannot put back the shifter to R without depressing the shift button to prevent accidental shifting, especially at high speeds, which could damage the transmission.

Neutral/No gear (N)

This disengages all gear trains within the transmission, effectively disconnecting the transmission from the driven roadwheels, so the vehicle is able to move freely under its own weight and gain momentum without the motive force from the engine (engine braking). This is the only other selection in which the vehicle's engine can be started.

Drive (D)

This position allows the transmission to engage the full range of available forward gear trains, and therefore allows the vehicle to move forward and accelerate through its range of gears. The number of gear 'ratios' a transmission has depends on the model, but they initially ranged from three (predominant before the 1990s), to four and five speeds (losing popularity to six-speed autos, though still favored by Chrysler and Honda/Acura). Six-speed automatic transmissions are now probably the most common offering Toyota Camry V6 models, the Chevrolet Malibu LTZ, Corvette, GM trucks, Pontiac G8, Ford Falcon BF 2005-2007 and Falcon FG 2008 - current in Australia with 6 speed ZF, and most newer model

Ford/Lincoln/Mercury vehicles). However, seven-speed autos are becoming available (found in Mercedes 7G gearbox), as are eight-speed autos in the newer models of Lexus and BMW cars.

OverDrive (D, OD, or a boxed [D])

This mode is used in some transmissions to allow early computer-controlled transmissions to engage the Automatic Overdrive. In these transmissions, Drive (D) locks the Automatic Overdrive off, but is identical otherwise. OD (Overdrive) in these cars is engaged under steady speeds or low acceleration at approximately 35–45 mph (56–72 km/h). Under hard acceleration or below 35–45 mph (56–72 km/h), the transmission will automatically downshift. Vehicles with this option should be driven in this mode unless circumstances require a lower gear.

Third (3)

This mode limits the transmission to the first three gear ratios, or sometimes locks the transmission in third gear. This can be used to climb or going down hill. Some vehicles will automatically shift up out of third gear in this mode if a certain RPM range is reached in order to prevent engine damage. This gear is also recommended while towing a caravan.

Second (2 or S)

This mode limits the transmission to the first two gear ratios, or locks the transmission in second gear on Ford, Kia, and Honda models. This can be used to drive in adverse conditions such as snow and ice, as well as climbing or going down hills in the winter time. Some vehicles will automatically shift up out of second gear in this mode if a certain RPM range is reached in order to prevent engine damage.

Although traditionally considered second gear, there are other names used. Chrysler models with a three-speed automatic since the late 1980s have called this gear **3** while using the traditional names for *Drive* and *Low*.

First (1 or L [Low])

This mode locks the transmission in first gear only. It will not change to any other gear range. This, like second, can be used during the winter season, or for towing.

As well as the above modes there are also other modes, dependent on the manufacturer and model. Some examples include

D5

In Hondas and Acuras equipped with five-speed automatic transmissions, this mode is used commonly for highway use (as stated in the manual), and uses all five forward gears.

D4

This mode is also found in Honda and Acura four- or five-speed automatics, and only uses the first four gear ratios. According to the manual, it is used for "stop and go traffic", such as city driving.

D3 or 3

This mode is found in Honda, Acura, Volkswagen and Pontiac four-speed automatics and only uses the first three gear ratios. According to the manual, it is used for "stop & go traffic", such as city driving.

S or Sport

This is commonly described as 'Sport mode'. It operates in an identical manner as 'D' mode, except that the upshifts change much higher up the engine's rev range. This has the effect on maximising all the available engine output, and therefore enhances the performance of the vehicle, particularly during acceleration. This mode will also downchange much higher up the rev range compared to 'D' mode, maximising the effects of engine braking. This mode will have a detrimental effect on fuel economy. Hyundai has a Norm/Power switch next to the gearshift for this purpose on the Tiburon.

Some early GM's equipped with Tourqueflite transmsissons used (S) to indicate Second gear, being the same as the 2 position on a Chrysler, shifting between only first and second gears. This would have been recommended for use on steep grades, or slippery roads like dirt, or ice, and limited to speeds under 40 mph. (L) was used in some early GM's to indicate (L)ow gear, being the same as the 2 position on a Chrysler, locking the transmission into first gear. This would have been recommended for use on steep grades, or slippery roads like dirt, or ice, and limited to speeds under 15 mph.

+ −, and M

This is for the 'manual mode' selection of gears in certain automatics, such as Porsche's Tiptronic. The M feature can also be found in Chrysler and General Motors products such as the Dodge Magnum and Pontiac G6, as well as Toyota's Camry, Corolla, Fortuner, Previa and Innova. Mitsubishi and some Audi models (TT), meanwhile do not have the M, and instead have the + and -, which is separated from the rest of the shift modes; the same is true for some Peugeot products like Peugeot 206. Meanwhile, the driver can shift up and down at will by toggling the (console mounted) shift lever like a semi-automatic transmission. This mode may be engaged either through a selector/position or by actually changing the gears (e.g., tipping the gear-down paddles mounted near the driver's fingers on the steering wheel).

Winter (W)

In some Mercedes-Benz, BMW and General Motors Europe models, a 'Winter mode' can be engaged so that second gear is selected instead of first when pulling away from stationary, to reduce the likelihood of loss of traction due to wheelspin on snow or ice. On GM cars, this was D2 in the 1950s, and is Second Gear Start after 1990. On Ford, Kia, and Honda automatics, this feature can be accessed by moving the gear selector to 2 to start, then taking your foot off the accelerator while selecting D once the car is moving.

Brake (B)

A mode selectable on some Toyota models. In non-hybrid cars, this mode lets the engine do compression braking, also known as engine braking, typically when encountering a steep downhill. Instead of engaging the brakes, the engine in a non-hybrid car switches to a lower gear and slows down the spinning tires. The engine holds the car back, instead of the brakes slowing it down. For hybrid cars, this mode converts the electric motor into a generator for the battery. It is not the same as downshifting in a non-hybrid car, but it has the same effect in slowing the car without using the brakes. GM called this HR (hill retarder) and GR (grade retarder) in the 1950s.

Hydraulic automatic transmissions

The predominant form of automatic transmission is hydraulically operated; using a fluid coupling or torque converter, and a set of planetary gearsets to provide a range of gear ratios.

Parts and operation

A cut-away model of a torque converter

A hydraulic automatic transmission consists of the following parts:

- *Torque converter*: A type of fluid coupling, hydraulically connecting the engine to the transmission. It takes the place of a mechanical clutch, allowing the transmission to stay 'in gear' and the engine to remain running while the vehicle is stationary, without stalling. A torque converter differs from a fluid coupling, in that it provides a variable amount of torque multiplication at low engine speeds, increasing "breakaway" acceleration. This is accomplished with a third member in the "coupling assembly" known as the stator, and by altering the shapes of the vanes inside the coupling in such a way as to curve the fluid's path into the stator.

The stator captures the kinetic energy of the transmission fluid, in effect using the leftover force of it to enhance torque multiplication.

- *Pump*, not to be confused with the impeller inside the torque converter, is typically a gear pump mounted between the torque converter and the planetary gearset. It draws transmission fluid from a sump and pressurizes it, which is needed for transmission components to operate. The input for the pump is connected to the torque converter housing, which in turn is bolted to the engine's flywheel, so the pump provides pressure whenever the engine is running and there is enough transmission fluid.
- *Planetary gearset*: A compound epicyclic planetary gearset, whose bands and clutches are actuated by hydraulic servos controlled by the valve body, providing two or more gear ratios.
- *Clutches and bands:* to effect gear changes, one of two types of clutches or bands are used to hold a particular member of the planetary gearset motionless, while allowing another member to rotate, thereby transmitting torque and producing gear reductions or overdrive ratios. These clutches are actuated by the valve body (see below), their sequence controlled by the transmission's internal programming. Principally, a type of device known as a sprag or roller clutch is used for routine upshifts/downshifts. Operating much as a ratchet, it transmits torque only in one direction, free-wheeling or "overrunning" in the other. The advantage of this type of clutch is that it eliminates the sensitivity of timing a simultaneous clutch release/apply on two planetaries, simply "taking up" the drivetrain load when actuated, and releasing automatically when the next gear's sprag clutch assumes the torque transfer. The bands come into play for manually selected gears, such as low range or reverse, and operate on the planetary drum's circumference. Bands are not applied when drive/overdrive range is selected, the torque being transmitted by the sprag clutches instead. Bands are used for braking; the GM Turbo-Hydramatics incorporated this..
- *Valve body*: hydraulic control center that receives pressurized fluid from the *main pump* operated by the fluid coupling/torque converter. The pressure coming from this pump is regulated and used to run a network of spring-loaded valves, check balls and servo pistons. The valves use the pump pressure and the pressure from a centrifugal governor on the output side (as well as hydraulic signals from the range selector valves and the *throttle valve* or *modulator*) to control which ratio is selected on the gearset; as the vehicle and engine change speed, the difference between the pressures changes, causing different sets of valves to open and close. The hydraulic pressure controlled by these valves drives the various clutch and brake band actuators, thereby controlling the operation of the planetary gearset to select the optimum gear ratio for the current operating conditions. However, in many modern automatic transmissions, the valves are controlled by electro-mechanical servos which are controlled by the electronic engine control unit (ECU) or a separate transmission control unit (TCU).
- *Hydraulic & lubricating oil*: called automatic transmission fluid (ATF), this component of the transmission provides lubrication, corrosion prevention, and a hydraulic medium to convey mechanical power (for the operation of the transmission). Primarily made from refined petroleum, and processed to provide

properties that promote smooth power transmission and increase service life, the ATF is one of the few parts of the automatic transmission that needs routine service as the vehicle ages.

The multitude of parts, along with the complex design of the valve body, originally made hydraulic automatic transmissions much more complicated (and expensive) to build and repair than manual transmissions. In most cars (except US family, luxury, sport-utility vehicle, and minivan models) they have usually been extra-cost options for this reason. Mass manufacturing and decades of improvement have reduced this cost gap.

Energy efficiency

Hydraulic automatic transmissions are almost always less energy efficient than manual transmissions due mainly to viscous and pumping losses; both in the torque converter and the hydraulic actuators. A relatively small amount of energy is required to pressurize the hydraulic control system, which uses fluid pressure to determine the correct shifting patterns and operate the various automatic clutch mechanisms.

Manual transmissions use a mechanical clutch to transmit torque, rather than a torque converter, thus avoiding the primary source of loss in an automatic transmission. Manual transmissions also avoid the power requirement of the hydraulic control system, by relying on the human muscle power of the vehicle operator to disengage the clutch and actuate the gear levers, and the mental power of the operator to make appropriate gear ratio selections. Thus the manual transmission requires very little engine power to function, with the main power consumption due to drag from the gear train being immersed in the lubricating oil of the gearbox.

The energy efficiency of automatic transmission has increased with the introduction of the torque converter lock-up clutch, which practically eliminates fluid losses when engaged. Modern automatic transmission also minimize energy usage and complexity, by minimizing the amount of shifting logic that is done hydraulically. Typically, control of the transmission has been transferred to computerized control systems which do not use fluid pressure for shift logic or actuation of clutching mechanisms.

The on road acceleration of an automatic transmission can occasionally exceed that of an otherwise identical vehicle equipped with a manual transmission in turbocharged diesel applications. Turbo-boost is normally lost between gear changes in a manual whereas in an automatic the accelerator pedal can remain fully depressed. This however is still largely dependent upon the number and optimal spacing of gear ratios for each unit, and whether or not the elimination of spooldown/accelerator lift off represent a significant enough gain to counter the slightly higher power consumption of the automatic transmission itself.

History and improvements

Modern automatic transmissions can trace their origins to an early "horseless carriage" gearbox that was developed in 1904 by the Sturtevant brothers of Boston, Massachusetts. This unit had two forward speeds, the ratio change being brought about by flyweights that were driven by the engine. At higher engine speeds, high gear was engaged. As the vehicle slowed down and engine RPM decreased, the gearbox would shift back to low. Unfortunately, the metallurgy of the time wasn't up to the task, and owing to the abruptness of the gear change, the transmission would often fail without warning.

The next significant phase in the automatic transmission's development occurred in 1908 with the introduction of Henry Ford's remarkable Model T. The Model T, in addition to being cheap and reliable by the standards of the day, featured a simple, two speed plus reverse planetary transmission whose operation was manually controlled by the driver using pedals. The pedals actuated the transmission's friction elements (bands and clutches) to select the desired gear. In some respects, this type of transmission was less demanding of the driver's skills than the contemporary, unsynchronized manual transmission, but still required that the driver know when to make a shift, as well as how to get the car off to a smooth start.

In 1934, both REO and General Motors developed semi-automatic transmissions that were less difficult to operate than a fully manual unit. These designs, however, continued to use a clutch to engage the engine with the transmission. The General Motors unit, dubbed the "Automatic Safety Transmission," was notable in that it employed a power-shifting planetary gearbox that was hydraulically controlled and was sensitive to road speed, anticipating future development.

Parallel to the development in the 1930s of an automatically-shifting gearbox was Chrysler's work on adapting the fluid coupling to automotive use. Invented early in the 20th century, the fluid coupling was the answer to the question of how to avoid stalling the engine when the vehicle was stopped with the transmission in gear. Chrysler itself never used the fluid coupling with any of its automatic transmissions, but did use it in conjunction with a hybrid manual transmission called "Fluid Drive" (the similar Hy-Drive used a torque converter). These developments in automatic gearbox and fluid coupling technology eventually culminated in the introduction in 1939 of the General Motors Hydra-Matic, the world's first mass-produced automatic transmission.

Available as an option on 1940 Oldsmobiles and later Cadillacs, the Hydra-Matic combined a fluid coupling with three hydraulically-controlled planetary gearsets to produce four forward speeds plus reverse. The transmission was sensitive to engine throttle position and road speed, producing fully automatic up- and down-shifting that varied according to operating conditions.

The Hydra-Matic was subsequently adopted by Cadillac and Pontiac, and was sold to various other automakers, including Bentley, Hudson, Kaiser, Nash, and Rolls-Royce. It also found use during World War II in some military vehicles. From 1950-1954, Lincoln cars were also available with the Hydra-Matic. Mercedes-Benz subsequently devised a four-speed fluid coupling transmission that was similar in principle to the Hydra-Matic, but of a different design.

Interestingly, the original Hydra-Matic incorporated two features which are widely emulated in today's transmissions. The Hydra-Matic's ratio spread through the four gears produced excellent "step off" and acceleration in first, good spacing of intermediate gears, and the effect of an overdrive in fourth, by virtue of the low numerical rear axle ratio used in the vehicles of the time. In addition, in third and fourth gear, the fluid coupling only handled a portion of the engine's torque, resulting in a high degree of efficiency. In this respect, the transmission's behavior was similar to modern units incorporating a lock-up torque converter.

In 1956, GM introduced the "Jetaway" Hydra-Matic, which was different in design than the older model. Addressing the issue of shift quality, which was an ongoing problem with the original Hydra-Matic, the new transmission utilized two fluid couplings, the primary one that linked the transmission to the engine, and a secondary one that replaced the clutch assembly that controlled the forward gearset in the original. The result was much smoother shifting, especially from first to second gear, but with a loss in efficiency and an increase in complexity. Another "innovation" for this new style Hydra-Matic was the appearance of a "Park" position on the selector. The original Hydra-Matic, which continued in production until the mid-1960s, still used the "Reverse" position for parking pawl engagement.

The first torque converter automatic, Buick's Dynaflow, was introduced for the 1948 model year. It was followed by Packard's Ultramatic in mid-1949 and Chevrolet's Powerglide for the 1950 model year. Each of these transmissions had only two forward speeds, relying on the converter for additional torque multiplication. In the early 1950s, BorgWarner developed a series of three-speed torque converter automatics for American Motors, Ford Motor Company, Studebaker, and several other manufacturers in the US and other countries. Chrysler was late in developing its own true automatic, introducing the two-speed torque converter PowerFlite in 1953, and the three-speed TorqueFlite in 1956. The latter was the first to utilize the Simpson compound planetary gearset.

General Motors produced multiple-turbine torque converters from 1954 to 1961. These included the Twin-Turbine Dynaflow and the triple-turbine Turboglide transmissions. The shifting took place in the torque converter, rather than through pressure valves and changes in planetary gear connections. Each turbine was connected to the drive shaft through a different gear train. These phased from one ratio to another according to demand, rather than shifting. The Turboglide actually had two speed ratios in reverse, with one of the turbines rotating backwards.

By the late 1960s, most of the fluid-coupling four-speed and two-speed transmissions had disappeared in favor of three-speed units with torque converters. Also around this time, whale oil was removed from automatic transmission fluid. By the early 1980s, these were being supplemented and eventually replaced by overdrive-equipped transmissions providing four or more forward speeds. Many transmissions also adopted the lock-up torque converter (a mechanical clutch locking the torque converter pump and turbine together to eliminate slip at cruising speed) to improve fuel economy.

As computerised engine control units (ECUs) became more capable, much of the logic built into the transmission's valve body was offloaded to the ECU. (Some manufacturers use a separate computer dedicated to the transmission, but sharing information with the engine management computer.) In this case, solenoids turned on and off by the computer control shift patterns and gear ratios, rather than the spring-loaded valves in the valve body. This allows for more precise control of shift points, shift quality, lower shift times, and (on some newer cars) semi-automatic control, where the driver tells the computer when to shift. The result is an impressive combination of efficiency and smoothness. Some computers even identify the driver's style and adapt to best suit it.

ZF Friedrichshafen and BMW were responsible for introducing the first six-speed (the ZF 6HP26 in the 2002 BMW E65 7-Series). Mercedes-Benz's 7G-Tronic was the first seven-speed in 2003, with Toyota introducing an eight-speed in 2007 on the Lexus LS 460. Derived from the 7G-Tronic, Mercedes-Benz unveiled a semi-automatic transmission with the torque converter replaced with a wet multi clutch called the AMG SPEEDSHIFT MCT.

Automatic transmission models

Some of the best known automatic transmission families include:

- General Motors — Powerglide, "Turbo-Hydramatic" TH350, TH400 and 700R4, 4L60-E, 4L80-E, Holden Trimatic
- Ford: Cruise-O-Matic, C4, C6, AOD/AODE, E4OD, ATX, AXOD/AX4S/AX4N
- Chrysler: TorqueFlite 727 and 904, A500, A518, 45RFE, 545RFE
- BorgWarner (later Aisin AW)
- ZF Friedrichshafen automatic transmissions
- Allison Transmission
- Voith Turbo
- Aisin AW; Aisin AW is a Japanese automotive parts supplier, known for its automatic transmissions and navigation systems
- Honda
- Nissan/Jatco
- Volkswagen Group - 01M
- Drivetrain Systems International (DSI) - M93, M97 and M74 4-speeds, M78 and M79 6-speeds

Automatic transmission families are usually based on Ravigneaux, Lepelletier, or Simpson planetary gearsets. Each uses some arrangement of one or two central sun gears, and a ring gear, with differing arrangements of planet gears that surround the sun and mesh with the ring. An exception to this is the Hondamatic line from Honda, which uses sliding gears on parallel axes like a manual transmission without any planetary gearsets.

Although the Honda is quite different from all other automatics, it is also quite different from an automated manual transmission (AMT).

Many of the above AMTs exist in modified states, which were created by racing enthusiasts and their mechanics by systematically re-engineering the transmission to achieve higher levels of performance. These are known as "performance transmissions". An example of a manufacturer of high performance transmissions of General Motors and Ford transmissions is PerformaBuilt.

Continuously variable transmissions

A fundamentally different type of automatic transmission is the *continuously variable transmission* or *CVT*, which can smoothly and steplessly alter its gear ratio by varying the diameter of a pair of belt or chain-linked pulleys, wheels or cones. Some continuously variable transmissions use a hydrostatic drive — consisting of a variable displacement pump and a hydraulic motor — to transmit power without gears. CVT designs are usually as fuel efficient as manual transmissions in city driving, but early designs lose efficiency as engine speed increases.

A slightly different approach to CVT is the concept of *toroidal CVT* or *infinitely variable transmission* (IVT). These concepts provide zero and reverse gear ratios.

Some current hybrid vehicles, notably those of Toyota, Lexus and Ford Motor Company, have an "electronically-controlled CVT" (E-CVT). In this system, the transmission has fixed gears, but the ratio of wheel-speed to engine-speed can be continuously varied by controlling the speed of the third input to a differential using an electric motor-generator.

Manually controlled automatic transmissions

Most automatic transmissions offer the driver a certain amount of manual control over the transmission's shifts (beyond the obvious selection of forward, reverse, or neutral). Those controls take several forms:

Throttle kickdown

: Most automatic transmissions include some means of forcing a downshift into the lowest possible gear ratio if the throttle pedal is fully depressed. In many older designs, kickdown is accomplished by mechanically actuating a valve inside the transmission. Most modern designs use a solenoid-operated valve that is triggered by a switch on the throttle linkage or by the engine control unit (ECM) in response to an abrupt increase in engine power.

Mode selection

: Allows the driver to choose between preset shifting programs. For example, 'Economy mode' saves fuel by upshifting at lower engine speeds, while 'Sport mode' (aka Power or Performance) delays shifting for maximum acceleration. The modes also change how the computer responds to throttle input.

Low gear ranges

Conventionally, automatic transmissions have selector positions that allow the driver to limit the maximum ratio that the transmission may engage. On older transmissions, this was accomplished by a mechanical lockout in the transmission valve body preventing an upshift until the lockout was disengaged; on computer-controlled transmissions, the same effect is accomplished by firmware. The transmission can still upshift and downshift automatically between the remaining ratios: for example, in the *3* range, a transmission could shift from first to second to third, but not into fourth or higher ratios. Some transmissions will still upshift automatically into the higher ratio if the engine reaches its maximum permissible speed in the selected range.

Manual controls

Some transmissions have a mode in which the driver has full control of ratio changes (either by moving the selector, or through the use of buttons or paddles), completely overriding the automated function of the hydraulic controller. Such control is particularly useful in cornering, to avoid unwanted upshifts or downshifts that could compromise the vehicle's balance or traction. "Manumatic" shifters, first popularized by Porsche in the 1990s under the trade name Tiptronic, have become a popular option on sports cars and other performance vehicles. With the near-universal prevalence of electronically controlled transmissions, they are comparatively simple and inexpensive, requiring only software changes, and the provision of the actual manual controls for the driver. The amount of true manual control provided is highly variable: some systems will override the driver's selections under certain conditions, generally in the interest of preventing engine damage. Since these gearboxes also have a throttle kickdown switch, it is impossible to fully exploit the engine power at low to medium engine speeds.

Second gear takeoff

Some automatics, particularly those fitted to larger capacity or high torque engines, either when '2' is manually selected, or by engaging a "winter mode", will start off in second gear instead of first, and then not shift into a higher gear until returned to D. Also note that as with most American automatic transmissions, selecting "2" using the selection lever will not tell the transmission to be in only 2nd gear, rather, it will simply limit the transmission to 2nd gear after prolonging the duration of 1st gear through higher speeds than normal operation. The 2000-2002 Lincoln LS V8 (the five-speed automatic *without* manumatic capabilities (as opposed to the optional sport package w/ manu-matic 5sp) started in 2nd gear during most starts both in winter and summer by selecting the "D5" transmission selection notch in the shiftgate (For fuel savings), whereas "D4" would always start in 1st gear. This is done to reduce torque multiplication when proceeding forward from a standstill in conditions where traction was limited — on snow- or ice-covered roads, for example.

Some automatic transmissions modified or designed specifically for drag racing may also incorporate a transmission brake, or "trans-brake," as part of a manual valve body. Activated by electrical solenoid control, a trans-brake simultaneously engages the first and reverse gears, locking the transmission and preventing the input shaft from turning.

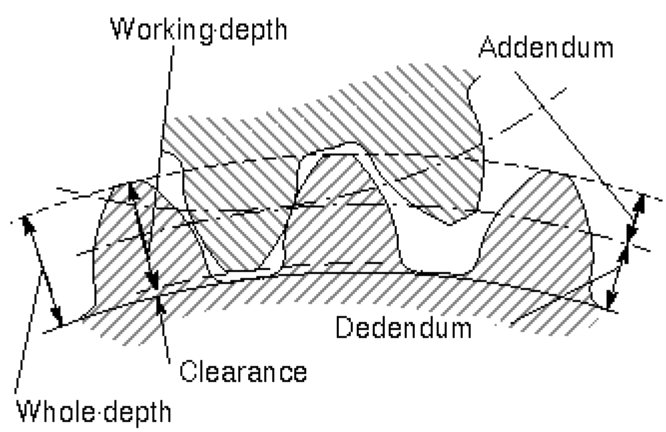
This allows the driver of the car to raise the engine RPM against the resistance of the torque converter, then launch the car by simply releasing the trans-brake switch.

Chapter 12

List of Gear Nomenclature

Gears have a wide range of unique terminology known as **gear nomenclature**. Many of the terms defined cite the same reference work.

Addendum



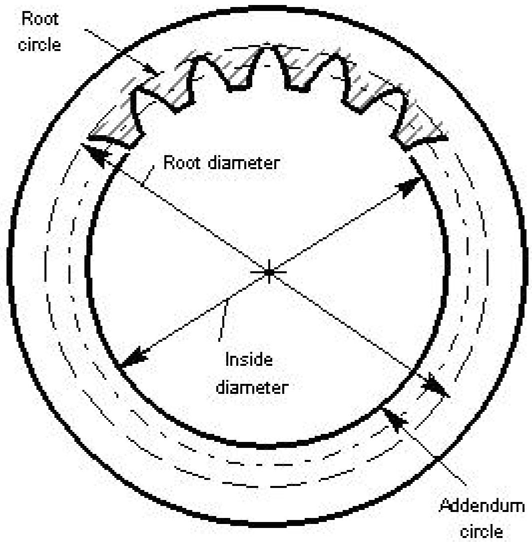
Principal dimensions

The **addendum** is the height by which a tooth of a gear projects beyond (outside for external, or inside for internal) the standard pitch circle or pitch line; also, the radial distance between the pitch circle and the addendum circle.

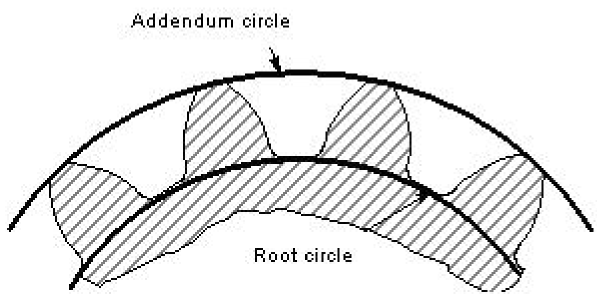
Addendum angle

Addendum angle in a bevel gear, is the angle between elements of the face cone and pitch cone.

Addendum circle



Internal gear diameters

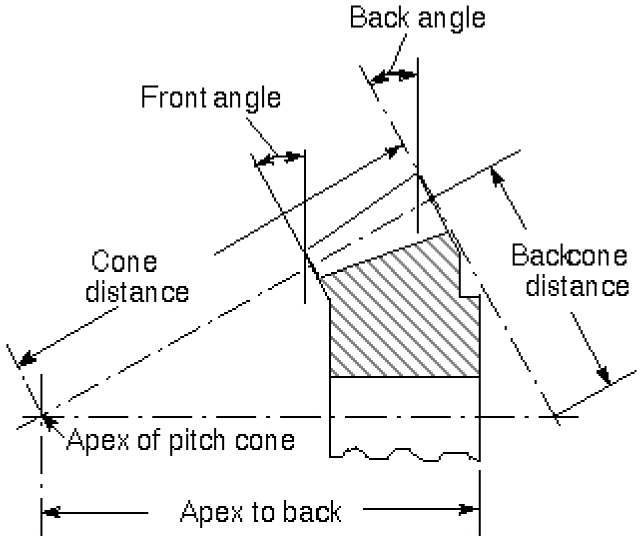


Root circle

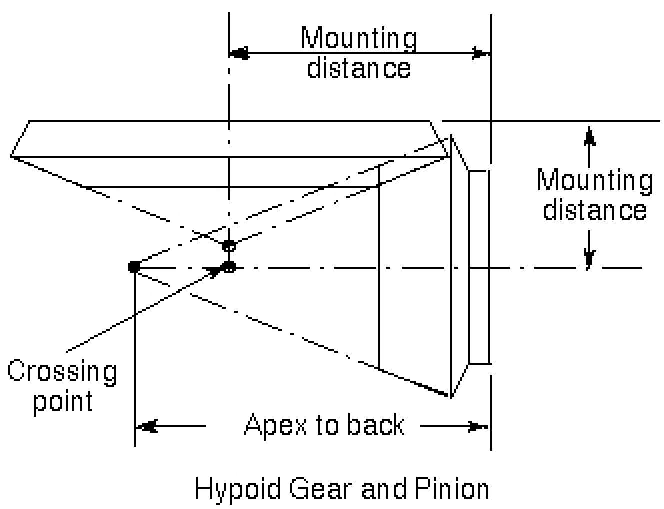
The **addendum circle** coincides with the tops of the teeth of a gear and is concentric with the standard (reference) pitch circle and radially distant from it by the amount of the addendum. For external gears, the addendum circle lies on the outside cylinder while on internal gears the addendum circle lies on the internal cylinder.

Angle of pressure

Apex to back



Apex to back



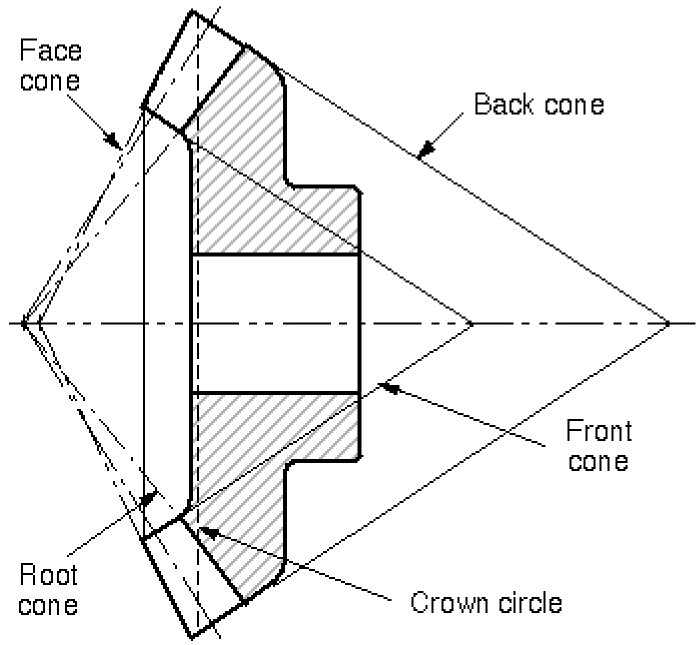
Mounting distance

Apex to back, in a bevel gear or hypoid gear, is the distance in the direction of the axis from the apex of the pitch cone to a locating surface at the back of the blank.

Back angle

The **back angle** of a bevel gear is the angle between an element of the back cone and a plane of rotation, and usually is equal to the pitch angle.

Back cone



Principal dimensions

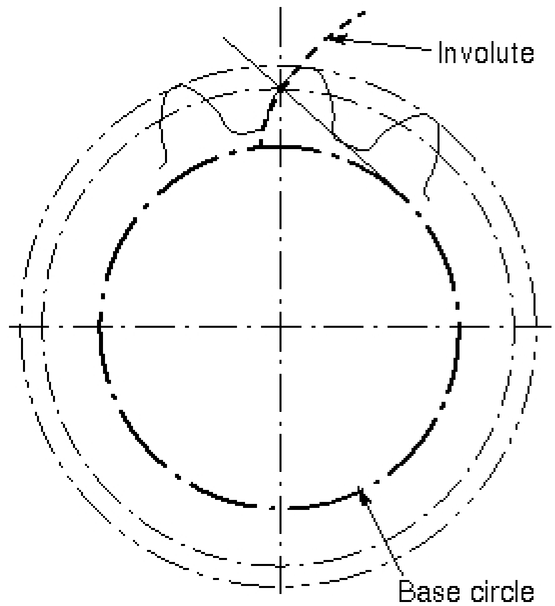
The **back cone** of a bevel or hypoid gear is an imaginary cone tangent to the outer ends of the teeth, with its elements perpendicular to those of the pitch cone. The surface of the gear blank at the outer ends of the teeth is customarily formed to such a back cone.

Back cone distance

Back cone distance in a bevel gear is the distance along an element of the back cone from its apex to the pitch cone.

Backlash

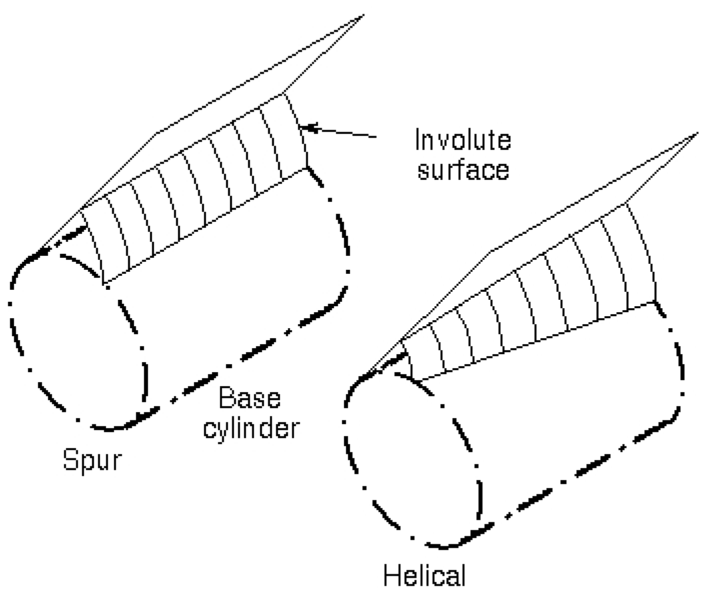
Base circle



Involute teeth

The **base circle** of an involute gear is the circle from which involute tooth profiles are derived.

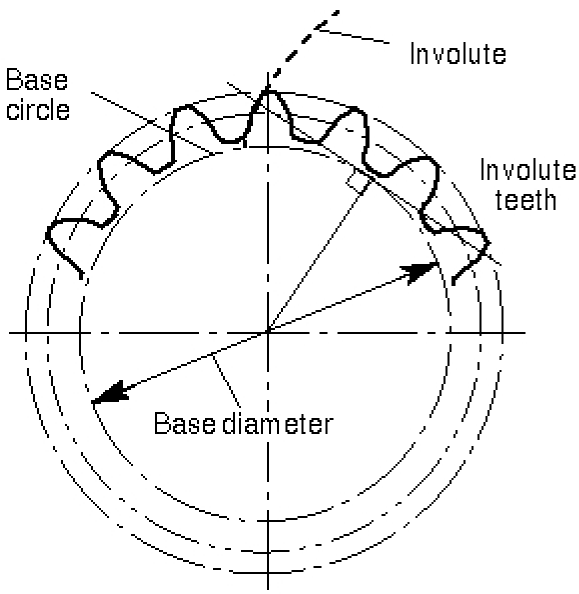
Base cylinder



Base cylinder

The **base cylinder** corresponds to the base circle, and is the cylinder from which involute tooth surfaces are developed.

Base diameter



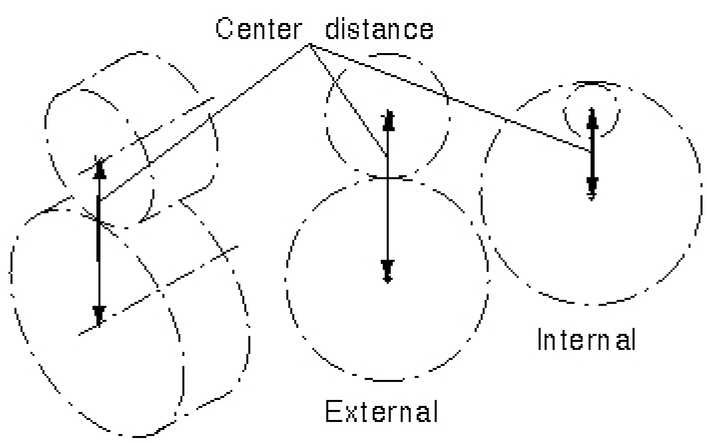
Base diameter

The **base diameter** of an involute gear is the diameter of the base circle.

Bull gear

The term **bull gear** is used to refer to the larger of two spur gears that are in engagement in any machine. The smaller gear is usually referred to as a pinion.

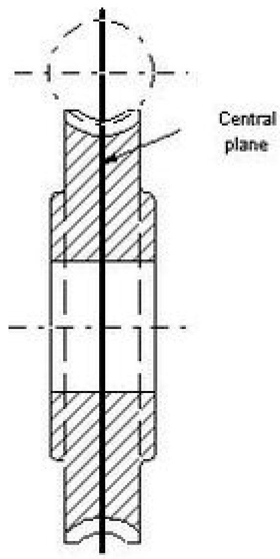
Center distance



Center distance

Center distance (operating) is the shortest distance between non-intersecting axes. It is measured along the mutual perpendicular to the axes, called the line of centers. It applies to spur gears, parallel axis or crossed axis helical gears, and worm gearing.

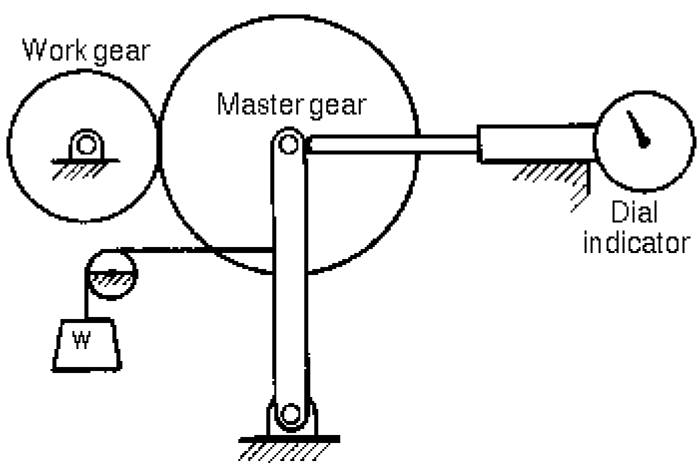
Central plane



Central plane

The **central plane** of a worm gear is perpendicular to the gear axis and contains the common perpendicular of the gear and worm axes. In the usual case with axes at right angles, it contains the worm axis.

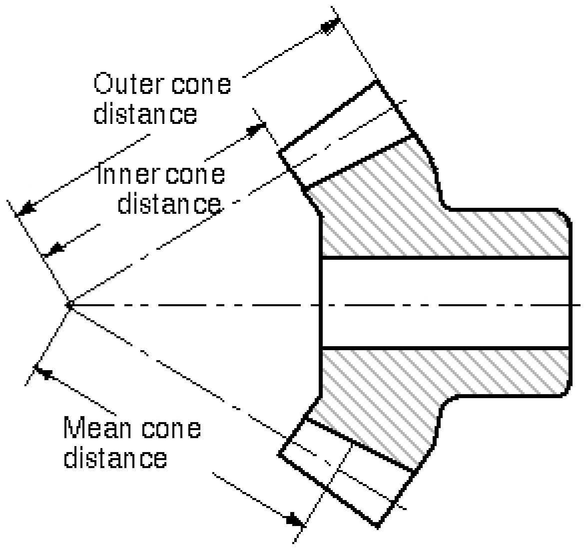
Composite action test



Schematic of the composite action test

The **composite action test** (double flank) is a method of inspection in which the work gear is rolled in tight double flank contact with a master gear or a specified gear, in order to determine (radial) composite variations (deviations). The composite action test must be made on a variable center distance composite action test device.

Cone distance



Cone distance

Cone distance in a bevel gear is the general term for the distance along an element of the pitch cone from the apex to any given position in the teeth.

Outer cone distance in bevel gears is the distance from the apex of the pitch cone to the outer ends of the teeth. When not otherwise specified, the short term cone distance is understood to be outer cone distance.

Mean cone distance in bevel gears is the distance from the apex of the pitch cone to the middle of the face width.

Inner cone distance in bevel gears is the distance from the apex of the pitch cone to the inner ends of the teeth.

Conjugate gears

Conjugate gears transmit uniform rotary motion from one shaft to another by means of gear teeth. The normals to the profiles of these teeth, at all points of contact, must pass through a fixed point in the common centerline of the two shafts.

Crossed helical gear

A **crossed helical gear** is a gear that operate on non-intersecting, non-parallel axes.

The term crossed helical gears has superseded the term *spiral gears*. There is theoretically point contact between the teeth at any instant. They have teeth of the same or different helix angles, of the same or opposite hand. A combination of spur and helical or other types can operate on crossed axes.

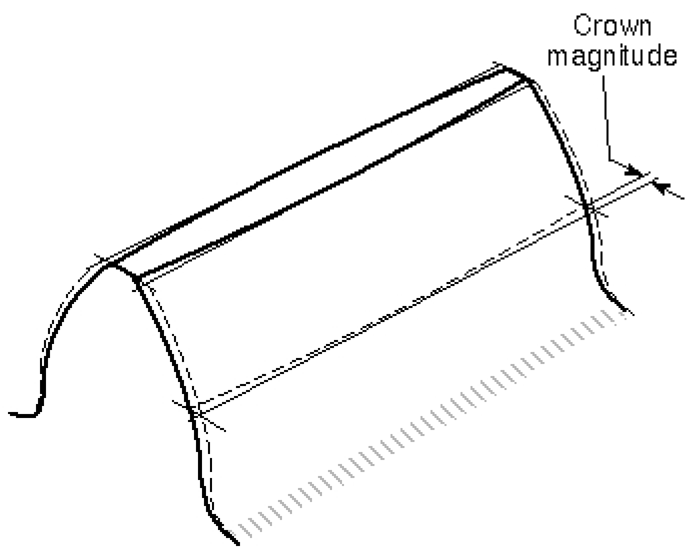
Crossing point

The **crossing point** is the point of intersection of bevel gear axes; also the apparent point of intersection of the axes in hypoid gears, crossed helical gears, worm gears, and offset face gears, when projected to a plane parallel to both axes.

Crown circle

The **crown circle** in a bevel or hypoid gear is the circle of intersection of the back cone and face cone.

Crowned teeth



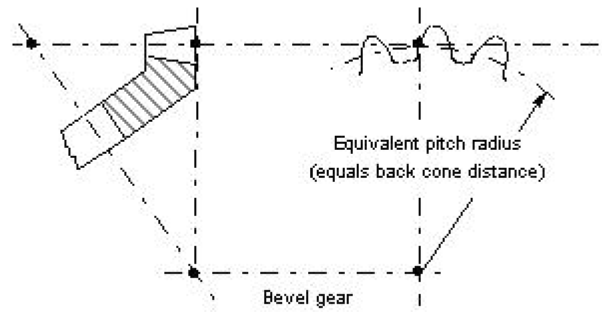
Crowned gear

Crowned teeth have surfaces modified in the lengthwise direction to produce localized contact or to prevent contact at their ends.

Dedendum angle

Dedendum angle in a bevel gear, is the angle between elements of the root cone and pitch cone.

Equivalent pitch radius



Back cone equivalent

Equivalent pitch radius is the radius of the pitch circle in a cross section of gear teeth in any plane other than a plane of rotation. It is properly the radius of curvature of the pitch surface in the given cross section. Examples of such sections are the transverse section of bevel gear teeth and the normal section of helical teeth.

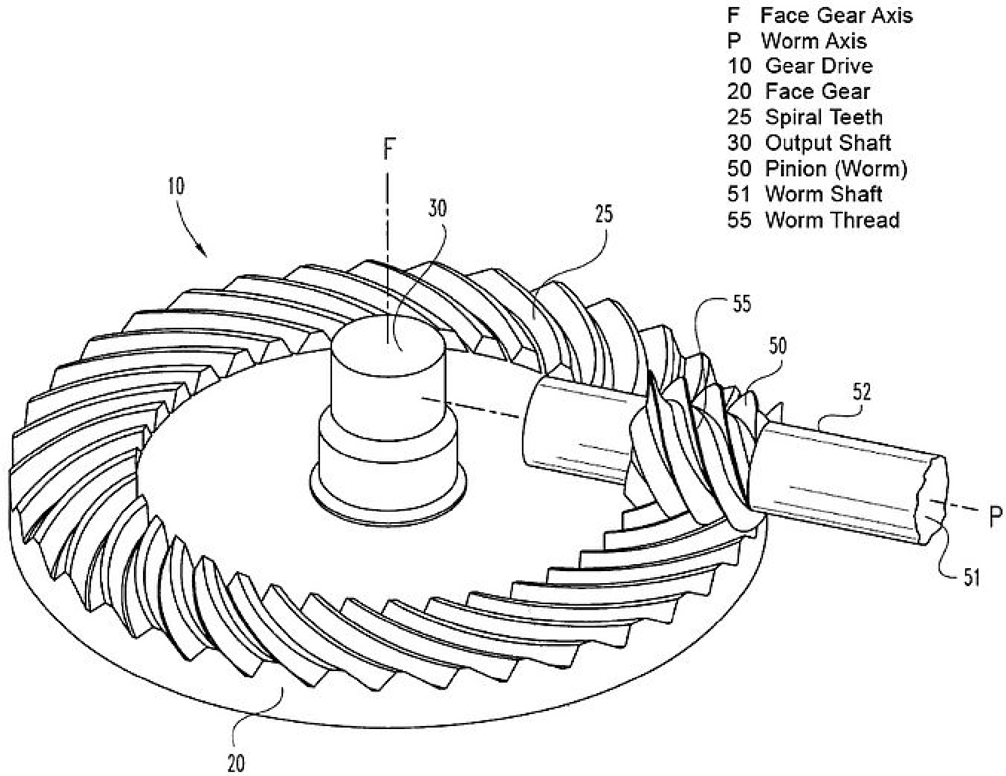
Face (tip) angle

Face (tip) angle in a bevel or hypoid gear, is the angle between an element of the face cone and its axis.

Face cone

The **face cone**, also known as the **tip cone** is the imaginary surface that coincides with the tops of the teeth of a bevel or hypoid gear.

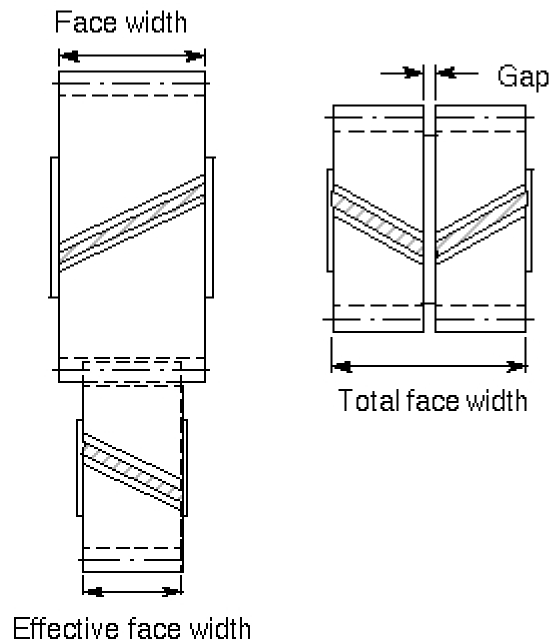
Face gear



Face worm gear

A **face gear** set typically consists of a disk-shaped gear, grooved on at least one face, in combination with a spur, helical, or conical pinion. A face gear has a planar pitch surface and a planar root surface, both of which are perpendicular to the axis of rotation. It can also be referred to as a **face wheel**, **crown gear**, **crown wheel**, **contrate gear** or **contrate wheel**.

Face width



Face width

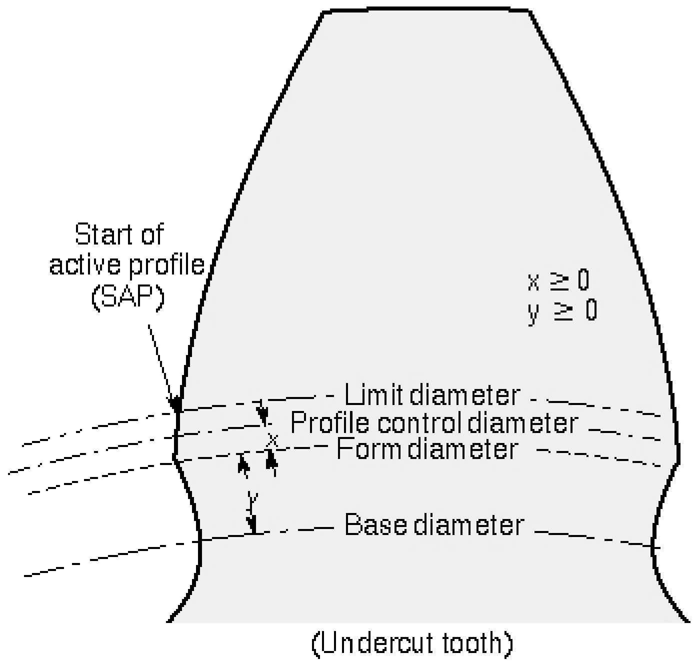
The **face width** of a gear is the length of teeth in an axial plane. For double helical, it does not include the gap.

Total face width is the actual dimension of a gear blank including the portion that exceeds the effective face width, or as in double helical gears where the total face width includes any distance or gap separating right hand and left hand helices.

For a cylindrical gear, effective face width is the portion that contacts the mating teeth. One member of a pair of gears may engage only a portion of its mate.

For a bevel gear, different definitions for effective face width are applicable.

Form diameter



Form diameter

Form diameter is the diameter of a circle at which the trochoid (fillet curve) produced by the tooling intersects, or joins, the involute or specified profile. Although these terms are not preferred, it is also known as the true involute form diameter (TIF), start of involute diameter (SOI), or when undercut exists, as the undercut diameter. This diameter cannot be less than the base circle diameter.

Front angle

The **front angle**, in a bevel gear, denotes the angle between an element of the front cone and a plane of rotation, and usually equals the pitch angle.

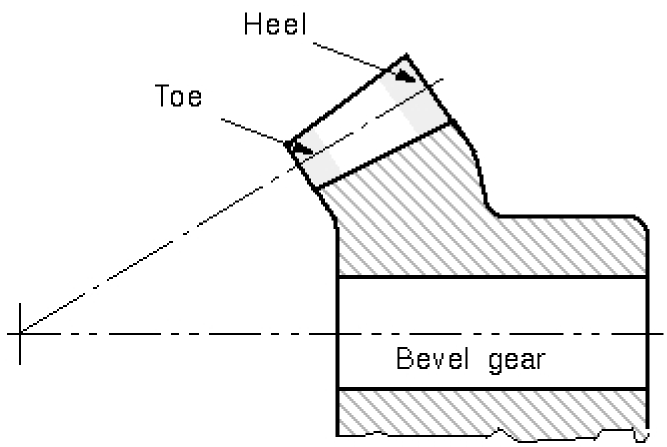
Front cone

The **front cone** of a hypoid or bevel gear is an imaginary cone tangent to the inner ends of the teeth, with its elements perpendicular to those of the pitch cone. The surface of the gear blank at the inner ends of the teeth is customarily formed to such a front cone, but sometimes may be a plane on a pinion or a cylinder in a nearly flat gear.

Gear center

A **gear center** is the center of the pitch circle.

Heel



Heel and toe

The **heel** of a tooth on a bevel gear or pinion is the portion of the tooth surface near its outer end.

The **toe** of a tooth on a bevel gear or pinion is the portion of the tooth surface near its inner end.

Helical rack

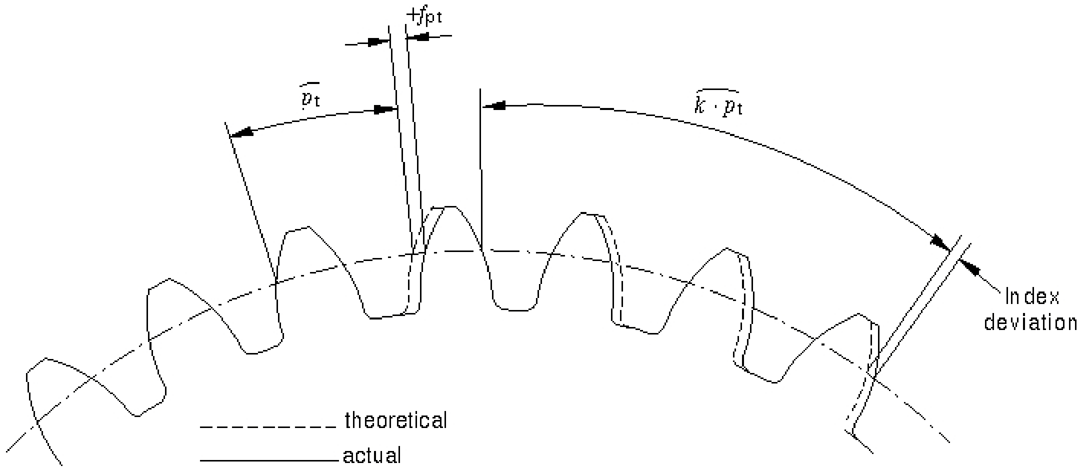
A **helical rack** has a planar pitch surface and teeth that are oblique to the direction of motion.

Index deviation

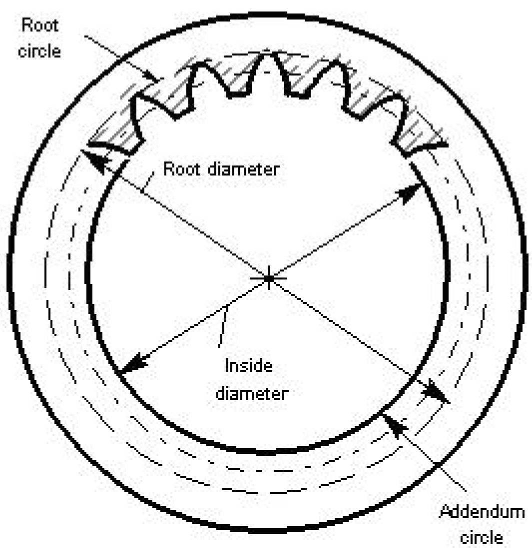
The displacement of any tooth flank from its theoretical position, relative to a datum tooth flank.

Distinction is made as to the direction and algebraic sign of this reading. A condition wherein the actual tooth flank position was nearer to the datum tooth flank, in the specified measuring path direction (clockwise or counterclockwise), than the theoretical position would be considered a minus (-) deviation. A condition wherein the actual tooth flank position was farther from the datum tooth flank, in the specified measuring path direction, than the theoretical position would be considered a plus (+) deviation.

The direction of tolerancing for index deviation along the arc of the tolerance diameter circle within the transverse plane.



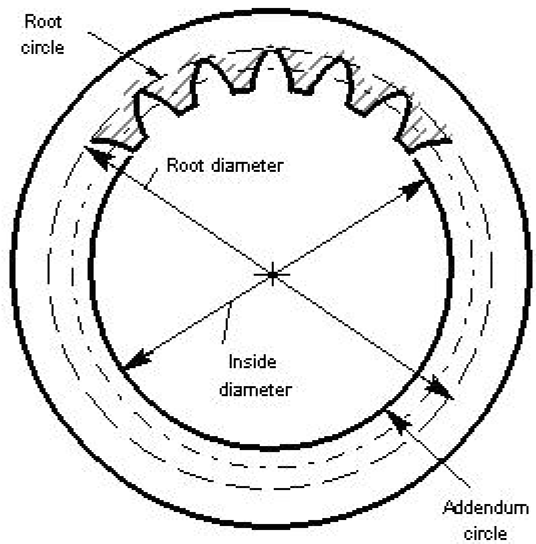
Inside cylinder



Diameters, Internal Gear

The **inside cylinder** is the surface that coincides with the tops of the teeth of an internal cylindrical gear.

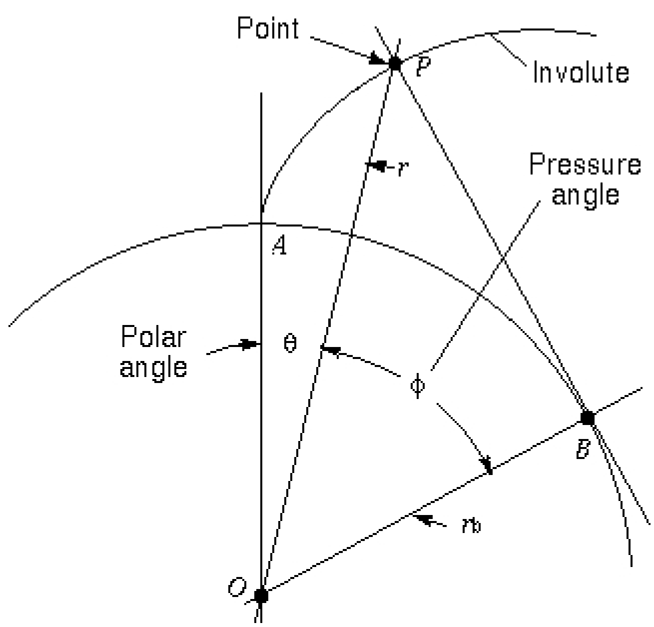
Inside diameter



Internal gear diameters

Inside diameter is the diameter of the addendum circle of an internal gear.

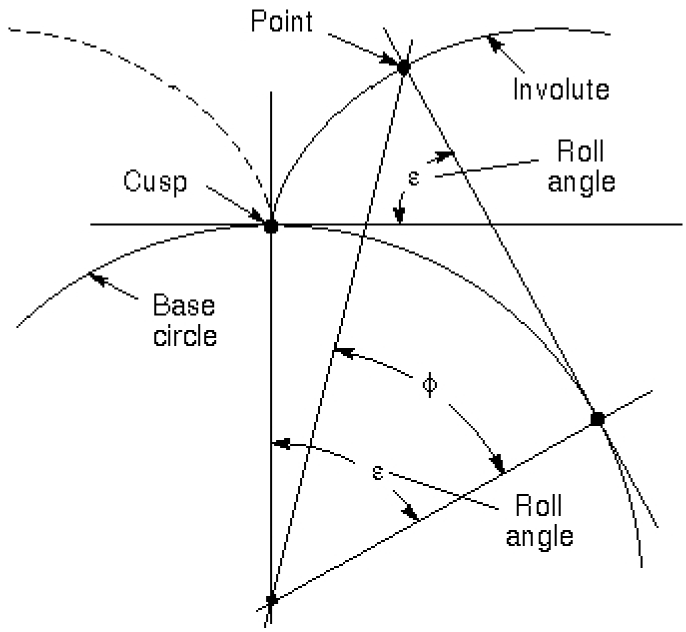
Involute polar angle



Involute polar angle

Expressed as θ, the **involute polar angle** is the angle between a radius vector to a point, *P*, on an involute curve and a radial line to the intersection, *A*, of the curve with the base circle.

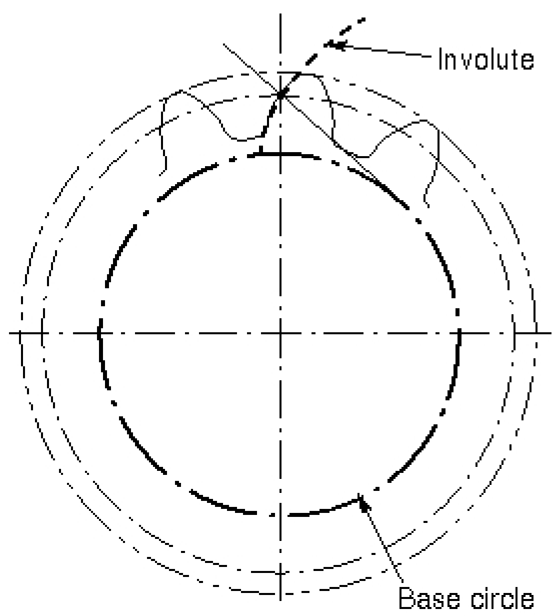
Involute roll angle



Involute roll angle

Expressed as ε, the **involute roll angle** is the angle whose arc on the base circle of radius unity equals the tangent of the pressure angle at a selected point on the involute.

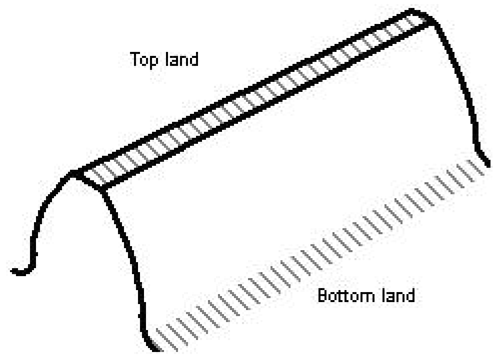
Involute teeth



Involute teeth

Involute teeth of spur gears, helical gears, and worms are those in which the profile in a transverse plane (exclusive of the fillet curve) is the involute of a circle.

Lands



Top and bottom lands

Bottom land

The **bottom land** is the surface at the bottom of a gear tooth space adjoining the fillet.

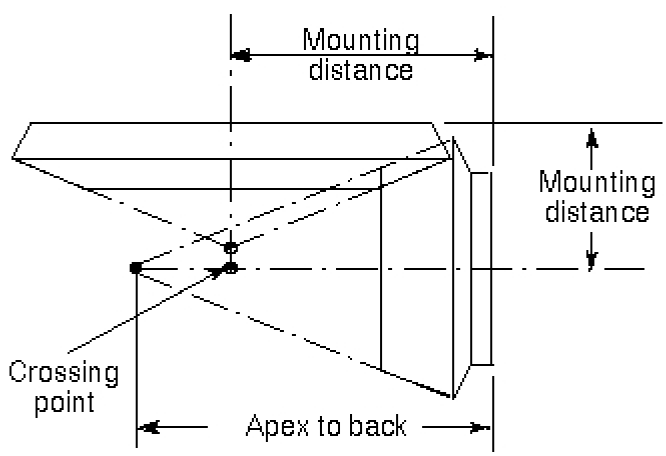
Top land

Top land is the (sometimes flat) surface of the top of a gear tooth.

Line of centers

The **line of centers** connects the centers of the pitch circles of two engaging gears; it is also the common perpendicular of the axes in crossed helical gears and wormgears. When one of the gears is a rack, the line of centers is perpendicular to its pitch line.

Mounting distance



Hypoid Gear and Pinion

Mounting distance

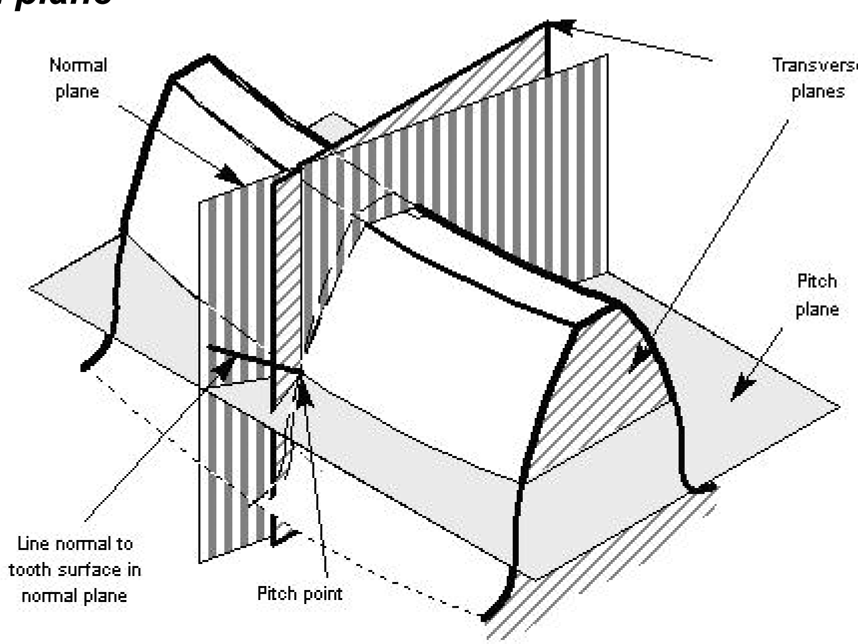
Mounting distance, for assembling bevel gears or hypoid gears, is the distance from the crossing point of the axes to a locating surface of a gear, which may be at either back or front.

Normal module

Normal module is the value of the module in a normal plane of a helical gear or worm.

$$m_n = m_t \cos\beta$$

Normal plane



Planes at a pitch point on a helical tooth

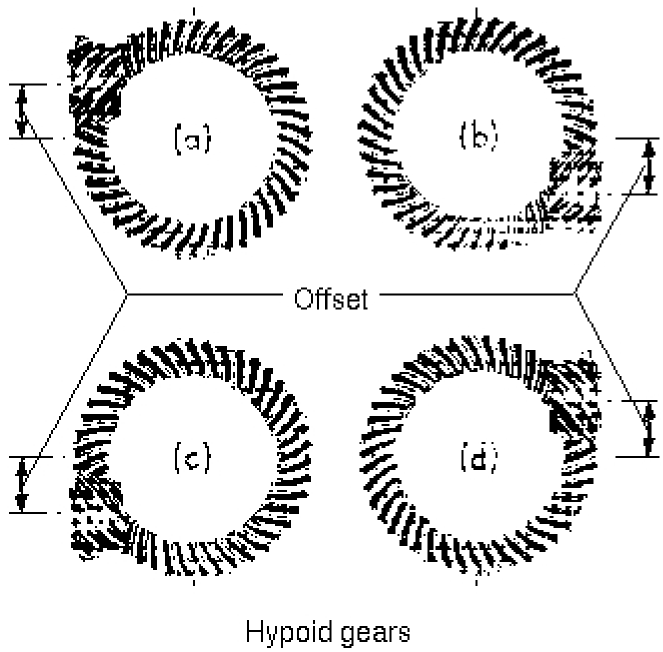
A **normal plane** is normal to a tooth surface at a pitch point, and perpendicular to the pitch plane. In a helical rack, a normal plane is normal to all the teeth it intersects. In a helical gear, however, a plane can be normal to only one tooth at a point lying in the plane surface. At such a point, the normal plane contains the line normal to the tooth surface.

Important positions of a normal plane in tooth measurement and tool design of helical teeth and worm threads are:

1. the plane normal to the pitch helix at side of tooth;
2. the plane normal to the pitch helix at center of tooth;
3. the plane normal to the pitch helix at center of space between two teeth

In a spiral bevel gear, one of the positions of a normal plane is at a mean point and the plane is normal to the tooth trace.

Offset

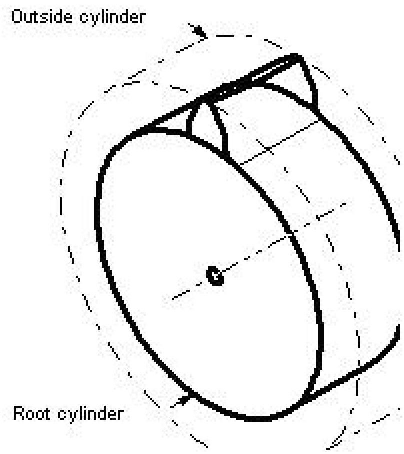


Offset

Offset is the perpendicular distance between the axes of hypoid gears or offset face gears.

In the diagram to the right, (a) and (b) are referred to as having an offset *below center*, while those in (c) and (d) have an offset *above center*. In determining the direction of offset, it is customary to look at the gear with the pinion at the right. For below center offset the pinion has a left hand spiral, and for above center offset the pinion has a right hand spiral.

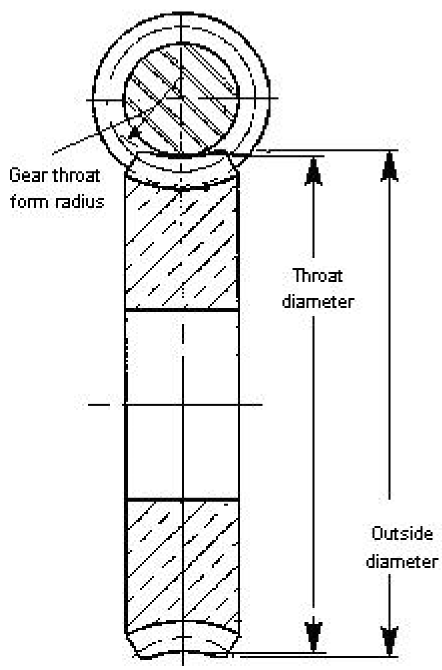
Outside cylinder



Cylindrical surfaces

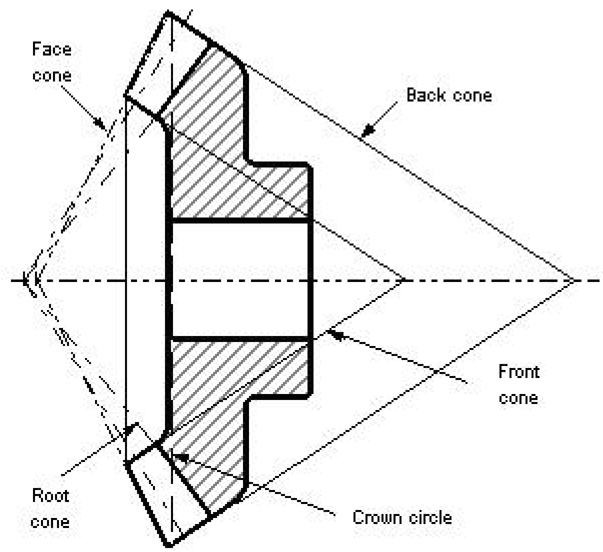
The **outside** (tip or addendum) **cylinder** is the surface that coincides with the tops of the teeth of an external cylindrical gear.

Outside diameter



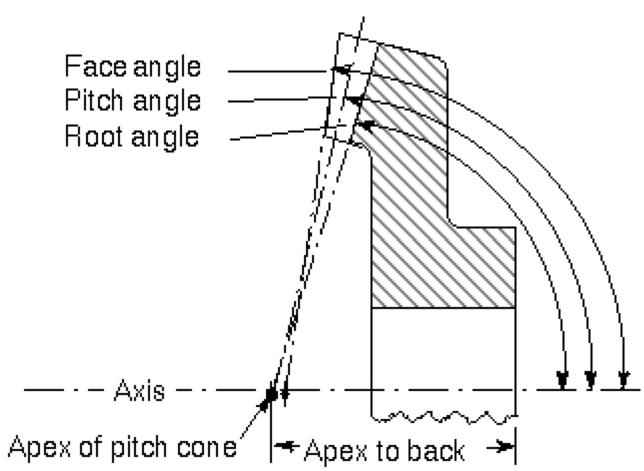
Wormgear diameters

The **outside diameter** of a gear is the diameter of the addendum (tip) circle. In a bevel gear it is the diameter of the crown circle. In a throated wormgear it is the maximum diameter of the blank. The term applies to external gears.

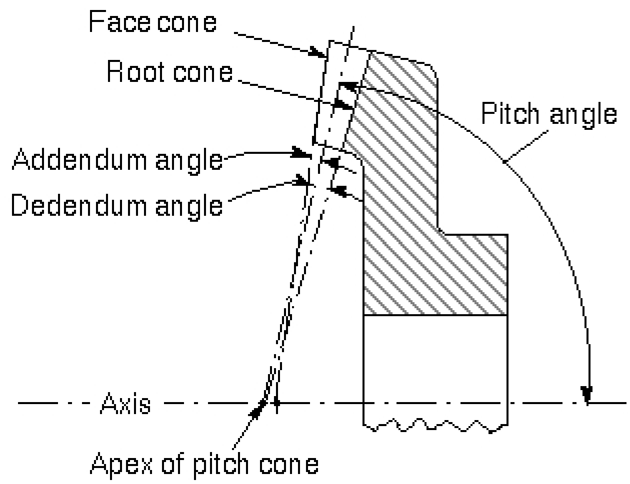


Conical surfaces

Pitch angle



Angle relationships



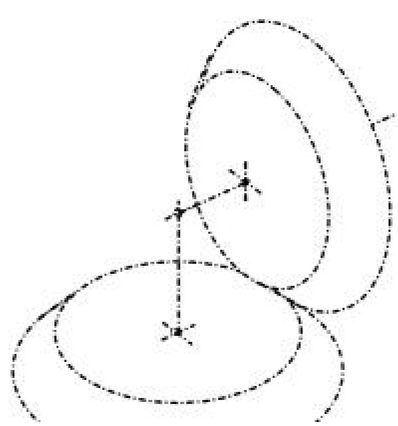
Angles

Pitch angle in bevel gears, is the angle between an element of a pitch cone and its axis. In external and internal bevel gears, the pitch angles are respectively less than and greater than 90 degrees.

Pitch circle

A **pitch circle** (operating) is the curve of intersection of a pitch surface of revolution and a plane of rotation. It is the imaginary circle that rolls without slipping with a pitch circle of a mating gear.

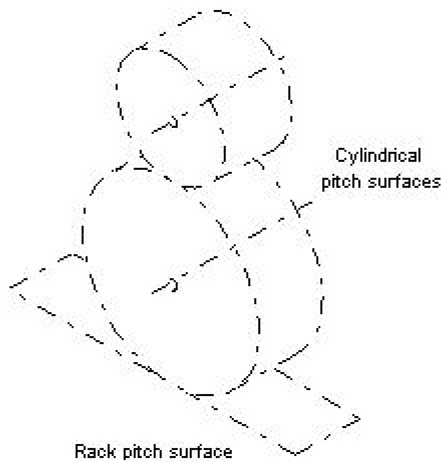
Pitch cone



Pitch cones

A **pitch cone** is the imaginary cone in a bevel gear that rolls without slipping on a pitch surface of another gear.

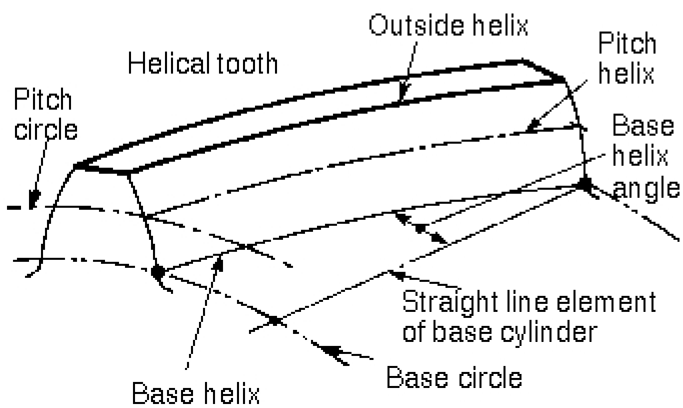
Pitch cylinder



Pitch cylinder

A **pitch cylinder** is the imaginary cylinder in a spur or helical gear that rolls without slipping on a pitch plane or pitch cylinder of another gear.

Pitch helix



Tooth helix

The **pitch helix** is the intersection of the tooth surface and the pitch cylinder of a helical gear or cylindrical worm.

Base helix

The **base helix** of a helical, involute gear or involute worm lies on its base cylinder.

Base helix angle

Base helix angle is the helix angle on the base cylinder of involute helical teeth or threads.

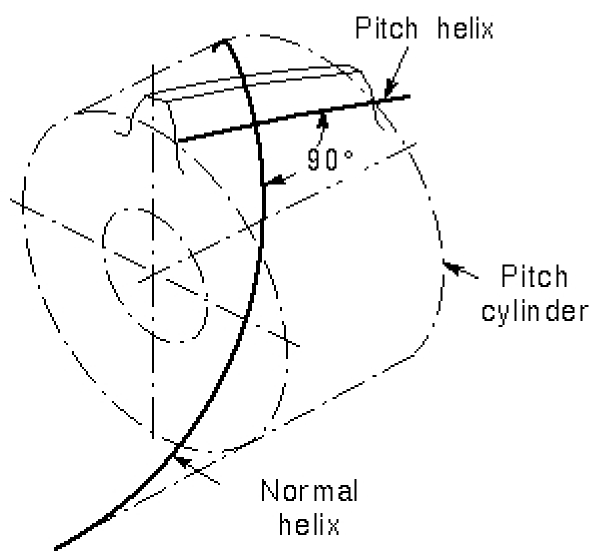
Base lead angle

Base lead angle is the lead angle on the base cylinder. It is the complement of the base helix angle.

Outside helix

The **outside** (tip or addendum) **helix** is the intersection of the tooth surface and the outside cylinder of a helical gear or cylindrical worm.

Outside helix angle



Normal helix

Outside helix angle is the helix angle on the outside cylinder.

Outside lead angle

Outside lead angle is the lead angle on the outside cylinder. It is the complement of the outside helix angle.

Normal helix

A **normal helix** is a helix on the pitch cylinder, normal to the pitch helix.

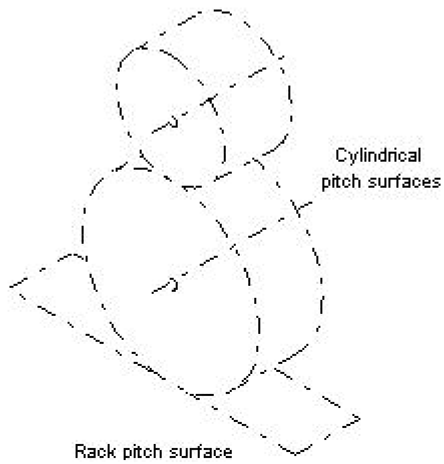
Pitch line

The **pitch line** corresponds, in the cross section of a rack, to the pitch circle (operating) in the cross section of a gear.

Pitch point

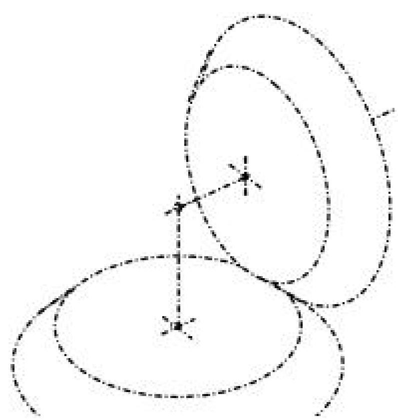
The **pitch point** is the point of tangency of two pitch circles (or of a pitch circle and pitch line) and is on the line of centers.

Pitch surfaces



Pitch surfaces

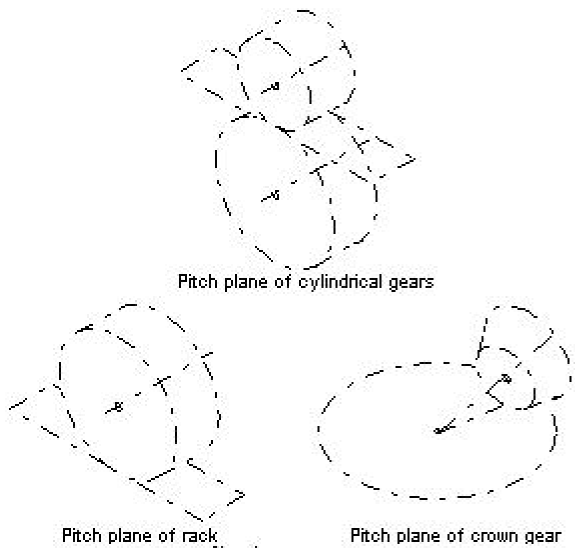
Pitch surfaces are the imaginary planes, cylinders, or cones that roll together without slipping. For a constant velocity ratio, the pitch cylinders and pitch cones are circular.



Pitch cones

Planes

Pitch plane



Pitch planes

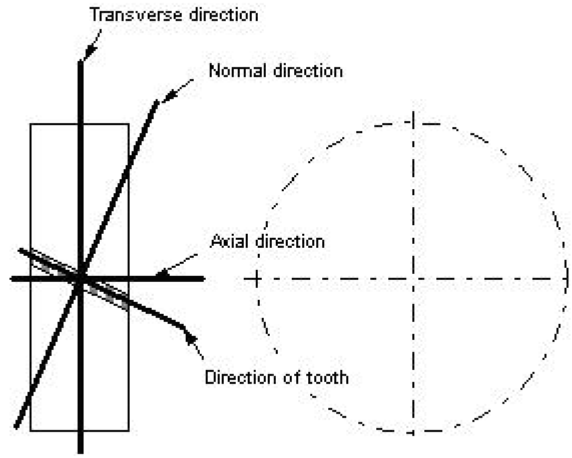
The **pitch plane** of a pair of gears is the plane perpendicular to the axial plane and tangent to the pitch surfaces. A pitch plane in an individual gear may be any plane tangent to its pitch surface.

The pitch plane of a rack or in a crown gear is the imaginary planar surface that rolls without slipping with a pitch cylinder or pitch cone of another gear. The pitch plane of a rack or crown gear is also the pitch surface.

Transverse plane

The **transverse plane** is perpendicular to the axial plane and to the pitch plane. In gears with parallel axes, the transverse and the plane of rotation coincide.

Principal directions



Principal directions

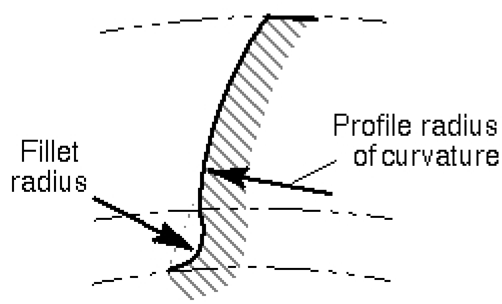
Principal directions are directions in the pitch plane, and correspond to the principal cross sections of a tooth.

The axial direction is a direction parallel to an axis.

The transverse direction is a direction within a transverse plane.

The normal direction is a direction within a normal plane.

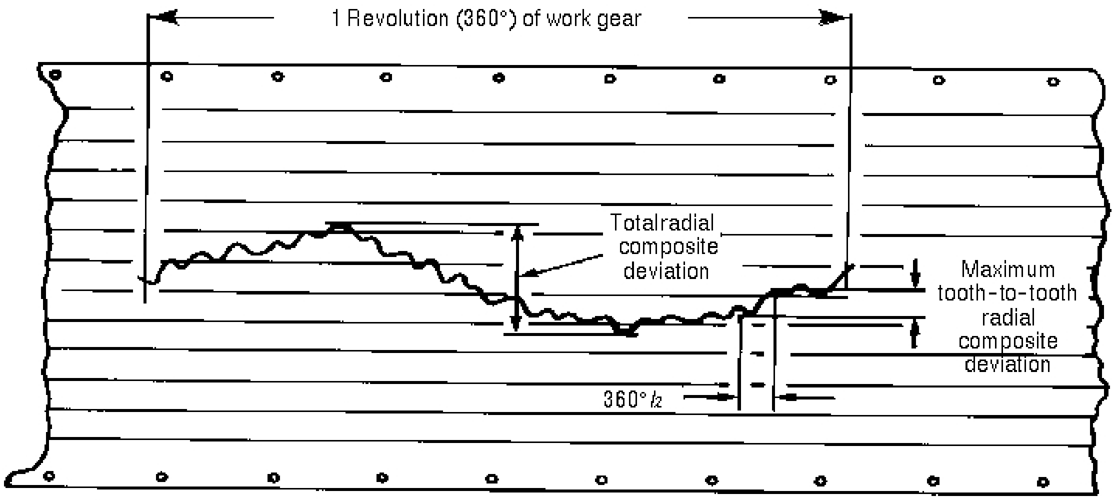
Profile radius of curvature



Fillet radius

Profile radius of curvature is the radius of curvature of a tooth profile, usually at the pitch point or a point of contact. It varies continuously along the involute profile.

Radial composite deviation



Total composite variation trace

Tooth-to-tooth **radial composite deviation** (double flank) is the greatest change in center distance while the gear being tested is rotated through any angle of 360 degree/z during double flank composite action test.

Tooth-to-tooth radial composite tolerance (double flank) is the permissible amount of tooth-to-tooth radial composite deviation.

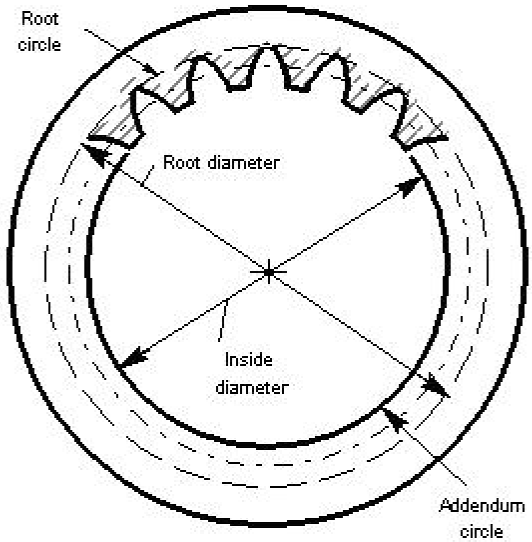
Total radial composite deviation (double flank) is the total change in center distance while the gear being tested is rotated one complete revolution during a double flank composite action test.

Total radial composite tolerance (double flank) is the permissible amount of total radial composite deviation.

Root angle

Root angle in a bevel or hypoid gear, is the angle between an element of the root cone and its axis.

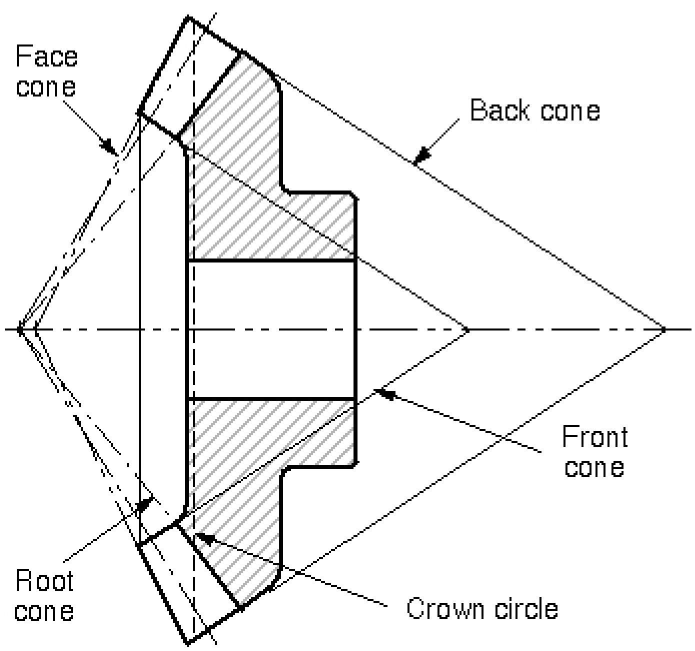
Root circle



Internal gear diameters

The **root circle** coincides with the bottoms of the tooth spaces.

Root cone



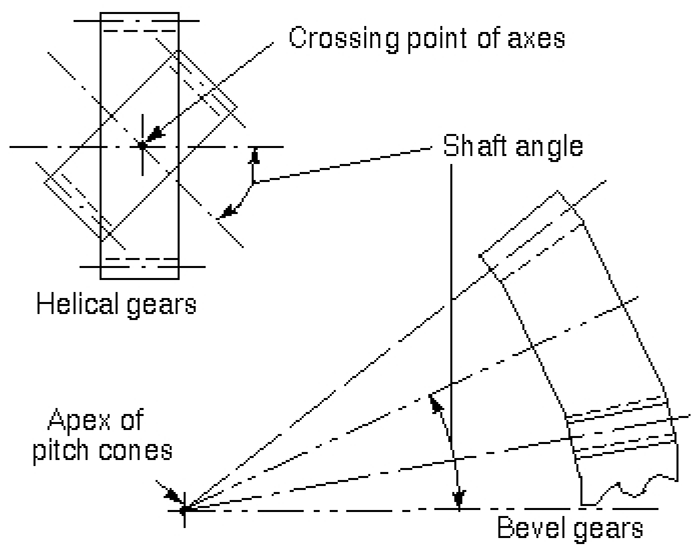
Principal dimensions

The **root cone** is the imaginary surface that coincides with the bottoms of the tooth spaces in a bevel or hypoid gear.

Root cylinder

The **root cylinder** is the imaginary surface that coincides with the bottoms of the tooth spaces in a cylindrical gear.

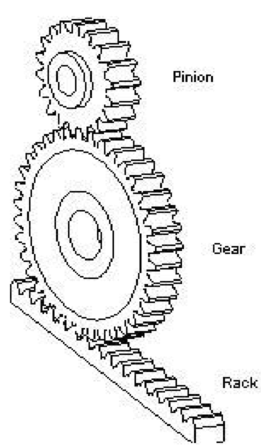
Shaft angle



Shaft angle

A **shaft angle** is the angle between the axes of two non-parallel gear shafts. In a pair of crossed helical gears, the shaft angle lies between the oppositely rotating portions of two shafts. This applies also in the case of worm gearing. In bevel gears, the shaft angle is the sum of the two pitch angles. In hypoid gears, the shaft angle is given when starting a design, and it does not have a fixed relation to the pitch angles and spiral angles.

Spur gear



Spur gear

A **spur gear** has a cylindrical pitch surface and teeth that are parallel to the axis.

Spur rack

A **spur rack** has a planar pitch surface and straight teeth that are at right angles to the direction of motion.

Standard pitch circle

The **standard pitch circle** is the circle which intersects the involute at the point where the pressure angle is equal to the profile angle of the basic rack.

Standard pitch diameter

The **standard reference pitch diameter** is the diameter of the standard pitch circle. In spur and helical gears, unless otherwise specified, the standard pitch diameter is related to the number of teeth and the standard transverse pitch. The diameter can be roughly estimated by taking the average of the diameter measuring the tips of the gear teeth and the base of the gear teeth.

The pitch diameter is useful in determining the spacing between gear centers because proper spacing of gears implies tangent pitch circles. The pitch diameters of two gears may be used to calculate the gear ratio in the same way the number of teeth is used.

$$d = \frac{N}{P_d} = \frac{pN}{\pi} \quad \text{Spur gears}$$
$$d = \frac{N}{P_{nd}\cos\psi} \quad \text{Helical gears}$$

Where N is the total number of teeth, p is the circular pitch, P_d is the diametrical pitch, and ψ is the helix angle for helical gears.

Standard reference pitch diameter

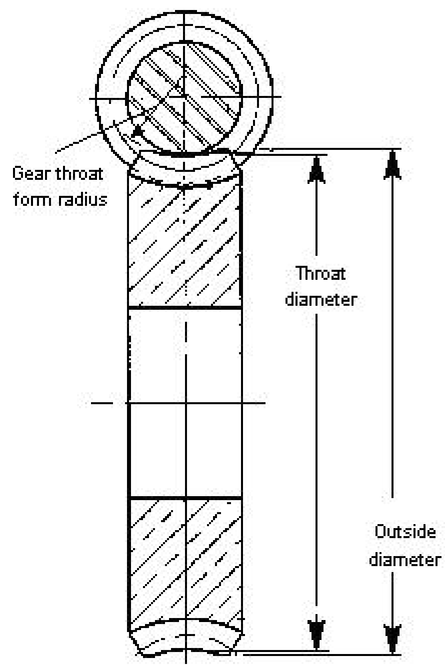
The **standard reference pitch diameter** is the diameter of the standard pitch circle. In spur and helical gears, unless otherwise specified, the standard pitch diameter is related to the number of teeth and the standard transverse pitch. It is obtained as:

$$d = zm = \frac{zp}{\pi} = z\frac{m_n}{\cos\beta}$$
$$D = \frac{N}{P_d} = \frac{Np}{\pi} = \frac{N}{P_{nd}\cos\psi}$$

Test radius

The **test radius** (**R_r**) is a number used as an arithmetic convention established to simplify the determination of the proper test distance between a master and a work gear for a composite action test. It is used as a measure of the effective size of a gear. The test radius of the master, plus the test radius of the work gear is the set up center distance on a composite action test device. Test radius is not the same as the operating pitch radii of two tightly meshing gears unless both are perfect and to basic or standard tooth thickness.

Throat diameter



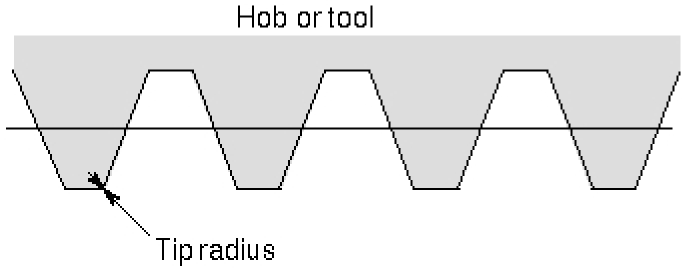
Wormgear diameters

The **throat diameter** is the diameter of the addendum circle at the central plane of a wormgear or of a double-enveloping wormgear.

Throat form radius

Throat form radius is the radius of the throat of an enveloping wormgear or of a double-enveloping worm, in an axial plane.

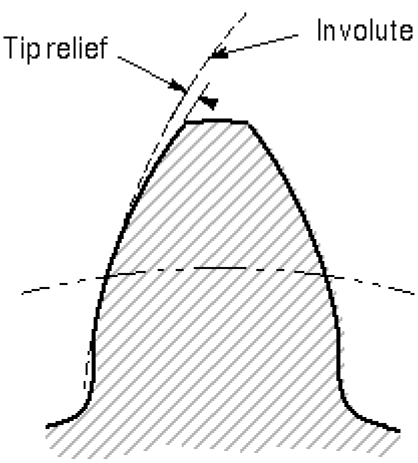
Tip radius



Tip radius

Tip radius is the radius of the circular arc used to join a side-cutting edge and an end-cutting edge in gear cutting tools. Edge radius is an alternate term.

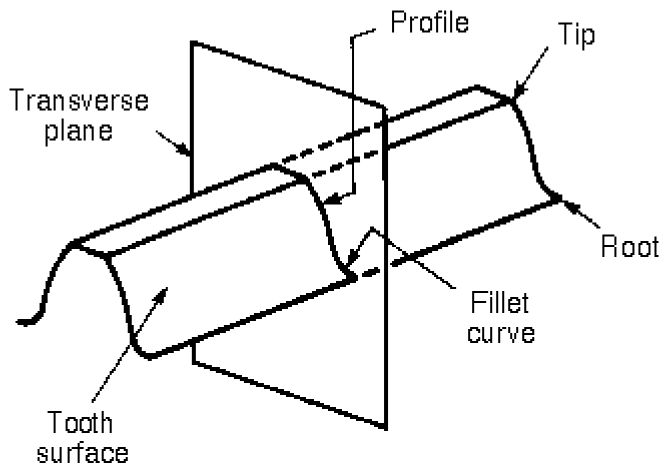
Tip relief



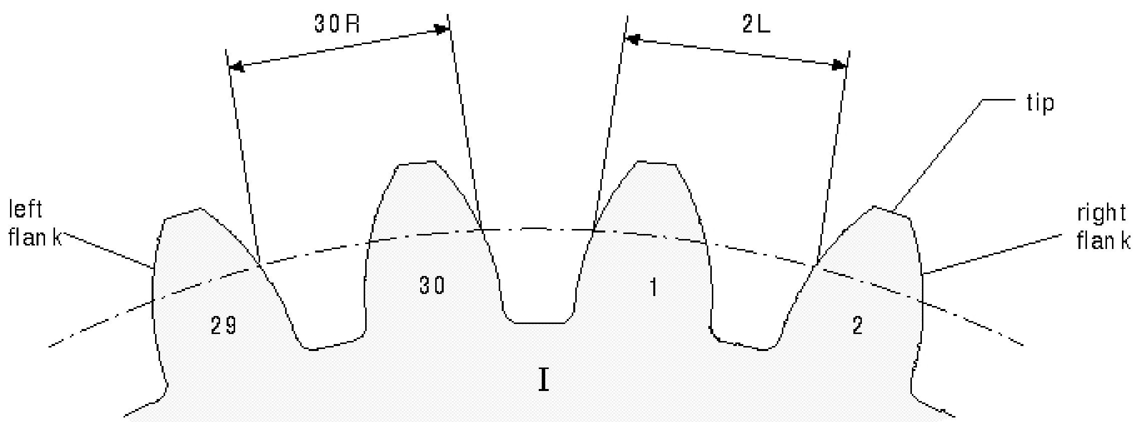
Tip relief

Tip relief is a modification of a tooth profile whereby a small amount of material is removed near the tip of the gear tooth.

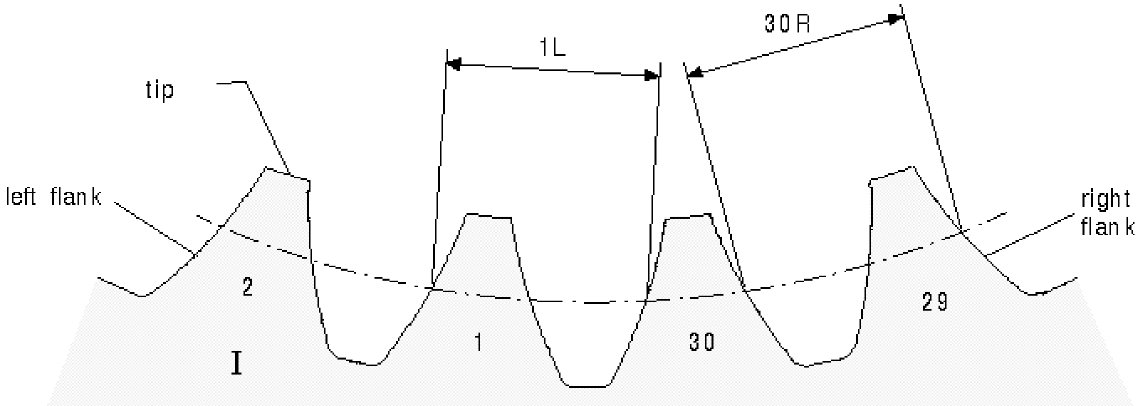
Tooth surface



Profile of a spur gear



Notation and numbering for an external gear



Notation and numbering for an internal gear

The **tooth surface** (flank) forms the side of a gear tooth.

It is convenient to choose one face of the gear as the reference face and to mark it with the letter “I”. The other non-reference face might be termed face “II”.

For an observer looking at the reference face, so that the tooth is seen with its tip uppermost, the right flank is on the right and the left flank is on the left. Right and left flanks are denoted by the letters “R” and “L” respectively.