COMP0205 Mechatronics and Making

Transmissions

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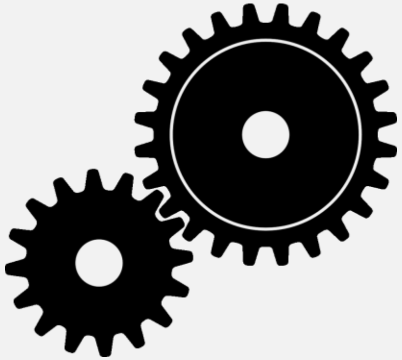
Today’s Objectives

- Learn what **motion transmission mechanisms** are
- Discuss their **main characteristics**
- Become familiar the **most common types** of motion transmission mechanisms

Motion Transmission

Many mechatronic systems require the **motion** generated by the **actuators** to be **transmitted to the tool**.

- This calls for the use of **motion transmission mechanisms**.



Motion transmission mechanisms perform two different roles:

1. **Transmit motion** from actuator to tool when the actuator cannot be designed into the same location.
2. **Increase or reduce torque and speed** between input and output shafts while maintaining the power conservation (output power is input power minus the power losses).

Transmission Mechanism Types

The most common motion transmission mechanisms fit into one of three major categories:

1. **Rotary-to-rotary** mechanisms (*gears, belts and pulleys*)
2. **Rotary-to-translational** mechanisms (*lead-screw, ball screw, rack-pinion*)
3. **Cyclic motion transmission** mechanisms (*linkages and cams*)

Common for all of these mechanisms is that an input shaft displacement is related to the output shaft displacement with a **fixed mechanical relationship**.

Efficiency

The efficiency of a motion transmission mechanism is defined as the ratio between the output power and input power,

$$\eta = \frac{P_{out}}{P_{in}}$$

The efficiency can vary (often from 50-60% to 95%) depending on transmission type. However, when determining the input-output relationships, we will assume **perfect efficiency** ($P_{out} = P_{in}$).

Recall that **mechanical power** can be found as

$$P = T\dot{\theta} \quad \text{or} \quad P = F\dot{x}$$

Gear (Transmission) Ratio

The construction of the mechanism determines the **ratio of input displacement to output displacement**, which is called the **effective gear ratio**.

- The effective gear ratio is **not influenced by efficiency**. If a mechanism is not 100% efficient, the **loss is a percentage of the torque** or force transmitted.

Let us consider a simple rotary gear mechanism with a **gear ratio**

$$N = \frac{\Delta\theta_{in}}{\Delta\theta_{out}} = \frac{\dot{\theta}_{in}}{\dot{\theta}_{out}}$$

Main Characteristics of Transmissions

A motion transmission mechanism is characterised by the following main specs:

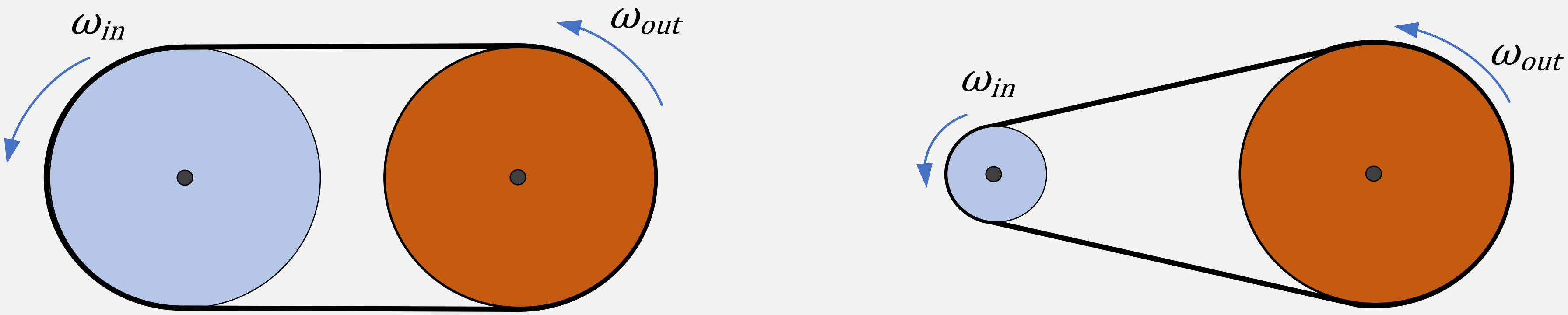
1. **Gear ratio**: the main characteristic of any transmission mechanism.
2. **Efficiency**. For any real transmission efficiency is always less than 100%.
3. **Backlash**: A clearance or **lost motion** in a mechanism caused by gaps between the parts.
4. **Stiffness**. Transmission components are **not perfectly rigid** (especially true for cables and flexible elements like the spline in harmonic drives).
5. **Back drivability**: The ability of a system of gears to operate in the reverse direction (output to input).

Rotary-to-Rotary Transmissions (Gears)

Pulleys and Belts: Recap (1)

Pulleys and belts transfer rotating motion from one shaft to another. The motion depends on the **frictional forces** of connecting belts, chains, ropes, or cables to transfer torque.

- If both pulleys have the **same diameter**, they will rotate at the **same speed**.
- However, if one pulley is **larger than the other**, **mechanical advantage** and **velocity ratio** are gained.

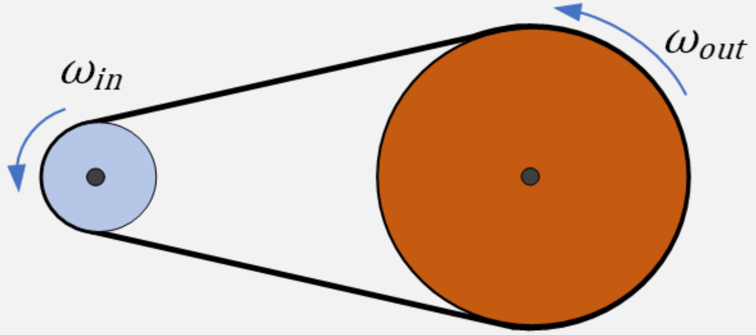


Pulleys and Belts: Recap (2)

Assuming there is **no slip** between the belt and pulleys on both shafts, the linear displacement along the belt and both pulleys should be equal:

$$x = \Delta\theta_{in} r_{in} = \Delta\theta_{out} r_{out}$$

where the terms $\Delta\theta_{[\cdot]}$ and $r_{[\cdot]}$ denote the increment in respective pulley's angle and its radius.



Manipulating the relationship above, we see that

$$\frac{\omega_{in}}{\omega_{out}} = \frac{r_{out}}{r_{in}}$$

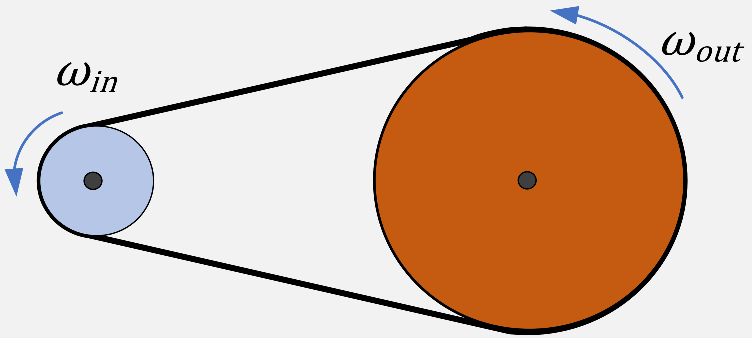
Pulleys and Belts: Recap (3)

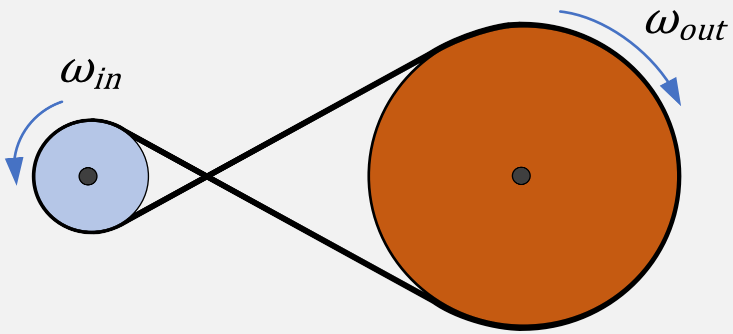
$$\frac{\omega_{in}}{\omega_{out}} = \frac{r_{out}}{r_{in}}$$

Thus, the **velocities of pulleys are inversely proportional to their diameters**.

Consider a small (drive) pulley driving a larger driven pulley by means of a belt.

- The larger pulley **rotates slower** than the smaller pulley **in the same direction** as shown (figure on the left).
- If the **belt is crossed**, the larger pulley also rotates slower than the smaller pulley, but its **rotation is in the opposite direction**.

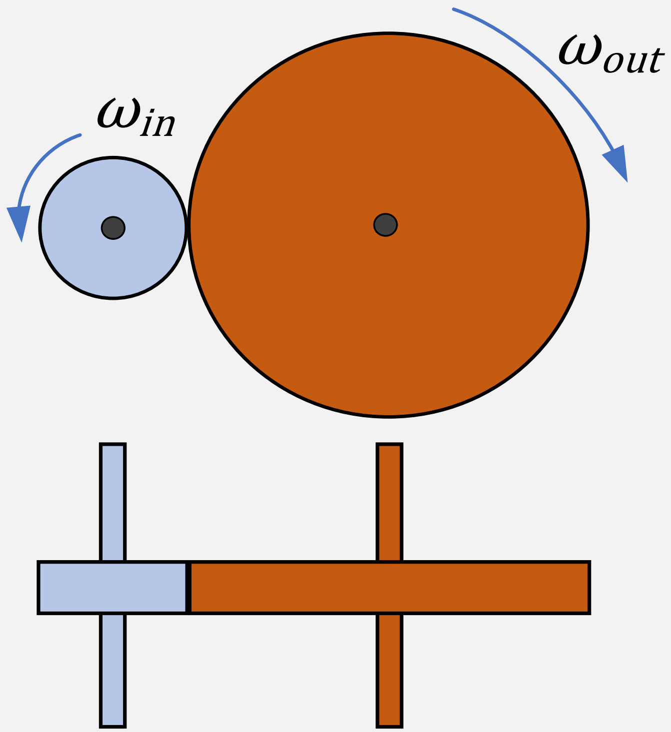




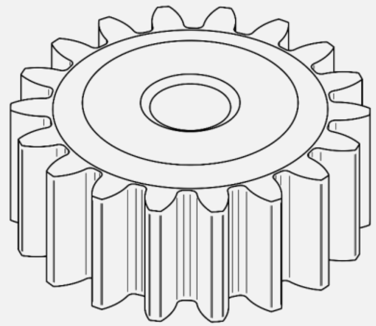
Rolling Cylinders

A pair of **rolling cylinders** can transfer rotary motion from one shaft to another, however there is a possibility of **slip**.

- The transfer of the motion between the two cylinders depends on the **frictional** forces between the two surfaces in contact.
- Slip can be prevented by the addition of **meshing teeth** to the two cylinders.



Gears and Gear Trains (1)



A **gear** is a wheel with evenly sized and spaced teeth machined or formed around its perimeter. Two or more meshing gears, working in a sequence, are called a **gear train or a transmission**.

- Gears are used in rotating machinery not only to **transmit motion** from one point to another, but also for the **mechanical advantage** they offer.

Gears are used for many purposes: **changing rotational speed** or **direction**, changing the **angular orientation** of rotational motion, **multiplication** or division **of torque** or magnitude of rotation, converting rotational to linear motion, and others.

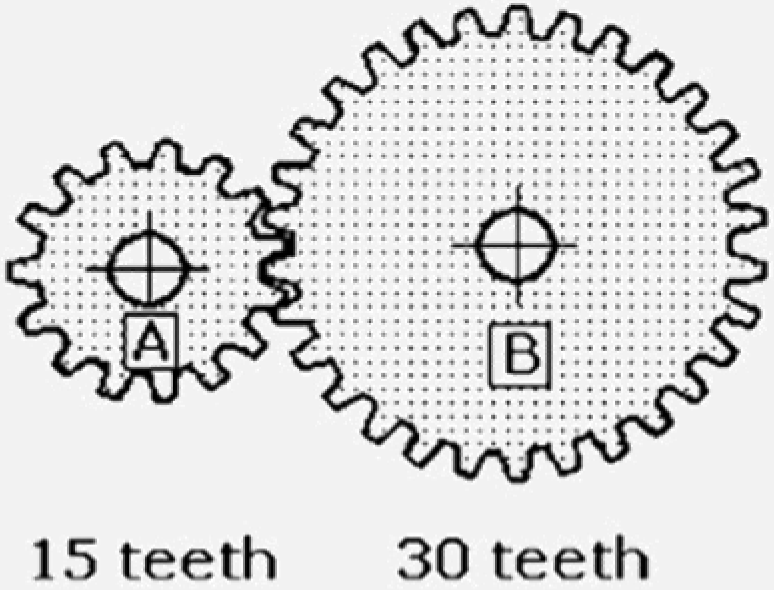
Gears and Gear Trains (2)

The teeth of a gear can be considered as **levers** when they mesh with the teeth of an adjoining gear.

However,

- **gears can be rotated continuously** instead of rocking back and forth through short distances as is typical of levers.

A gear is defined by the number of its teeth and its diameter. The gear that is connected to the source of power is called the **driver**, and the one that receives power from the driver is the **driven gear**.

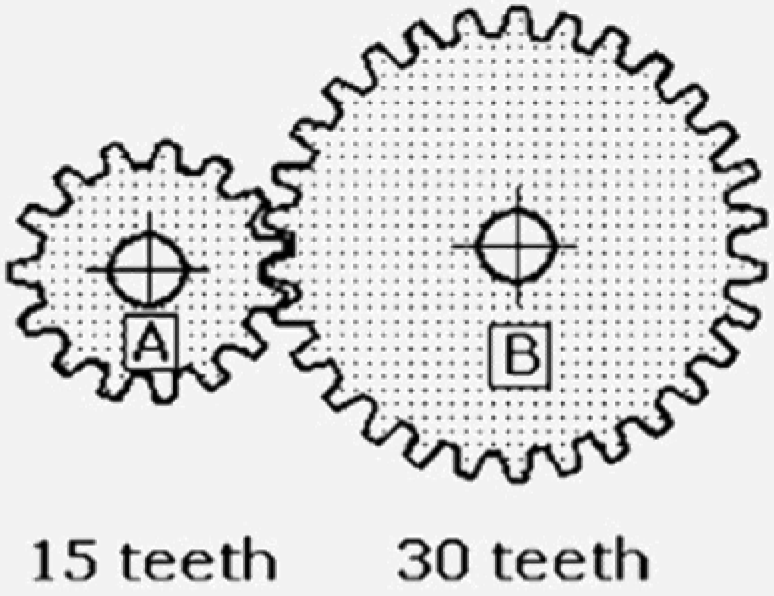


Gears and Gear Trains (3)

The driven gear always **rotates in a direction opposing** that of the driver; if both gears have the same number of teeth, they will rotate at the same speed.

- However, if the number of teeth differs, the gear with the **smaller number of teeth will rotate faster**.
- The **size and shape of all gear teeth** that are to mesh properly for working contact **must be equal**.

$$N = \frac{30}{15} = \frac{2}{1} \text{ (also written as } 2:1)$$

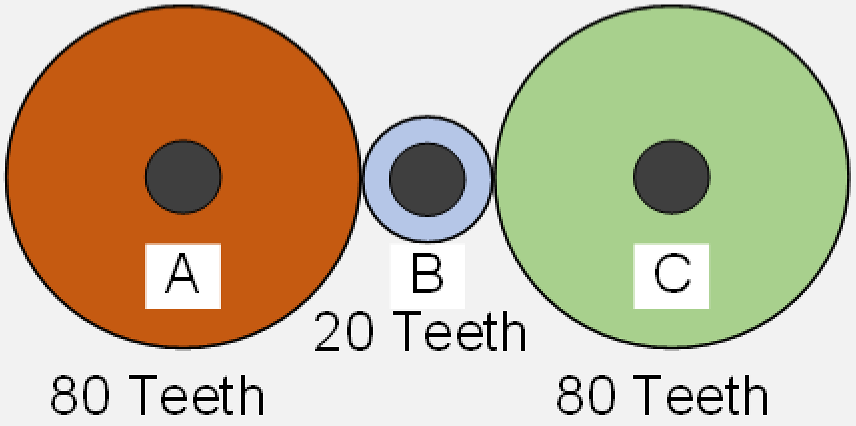


Gear B has twice as many teeth as gear A, and it turns at half the speed of gear A

Simple Gear Trains

A gear train made up of multiple gears can have **several drivers and several driven gears**.

- If the train contains an **odd number of gears**, the output gear will rotate in the **same direction** as the input gear, and vice versa.
- The number of teeth on the **intermediate gears does not affect** the overall velocity ratio, which is governed purely by the number of teeth on the first and last gear.
- The gear in the middle is called an **idler**.



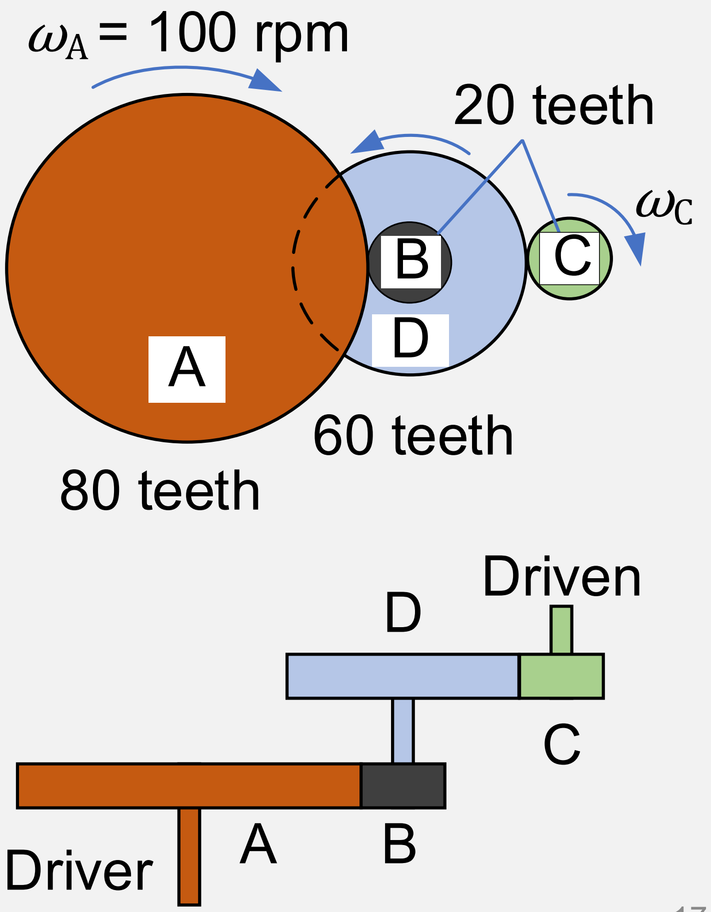
Compound Gear Trains

More complex **compound gear trains** can achieve **high and low gear ratios** in a restricted space by coupling large and small gears on the same axle.

This way gear ratios of adjacent gears can be multiplied through the gear train.

- The two gears B and D mounted **rotate at the same speed** because they are fastened together.

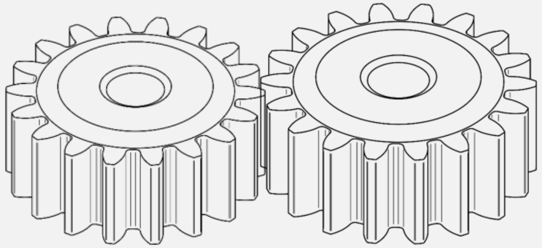
Q: If gear A (80 teeth) rotates at 100 rpm clockwise, what is the speed of gear C?

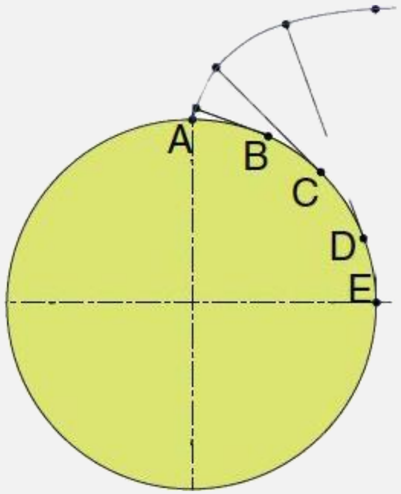


Spur Gears

Spur gears (shown on the right) are the simplest type of gear. They consist of a cylinder or disk with **teeth** projecting radially.

Usually, industrial gears' teeth are not straight-sided (mainly **involute**), however, the edge of each tooth is straight and aligned parallel to the axis of rotation.



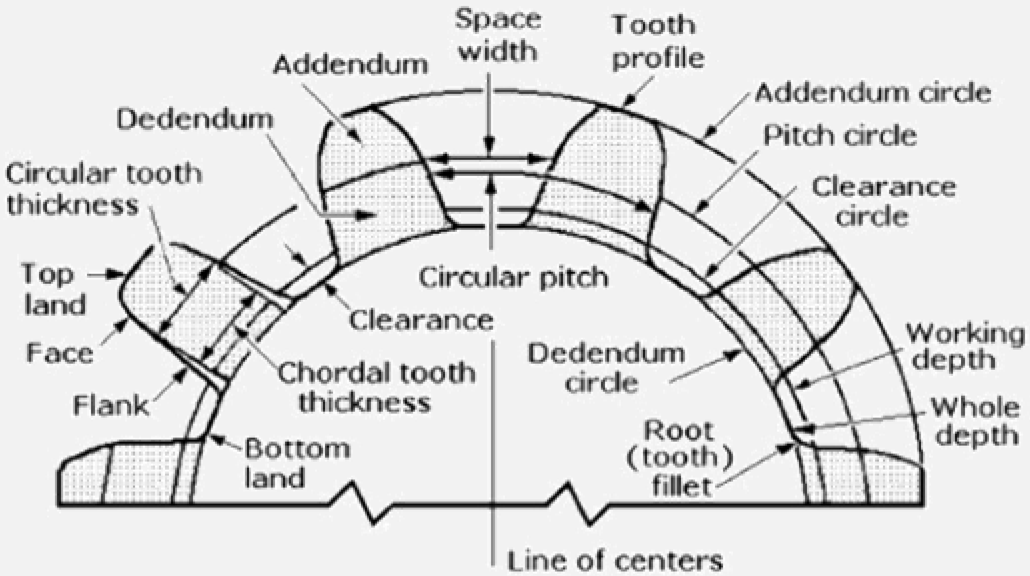


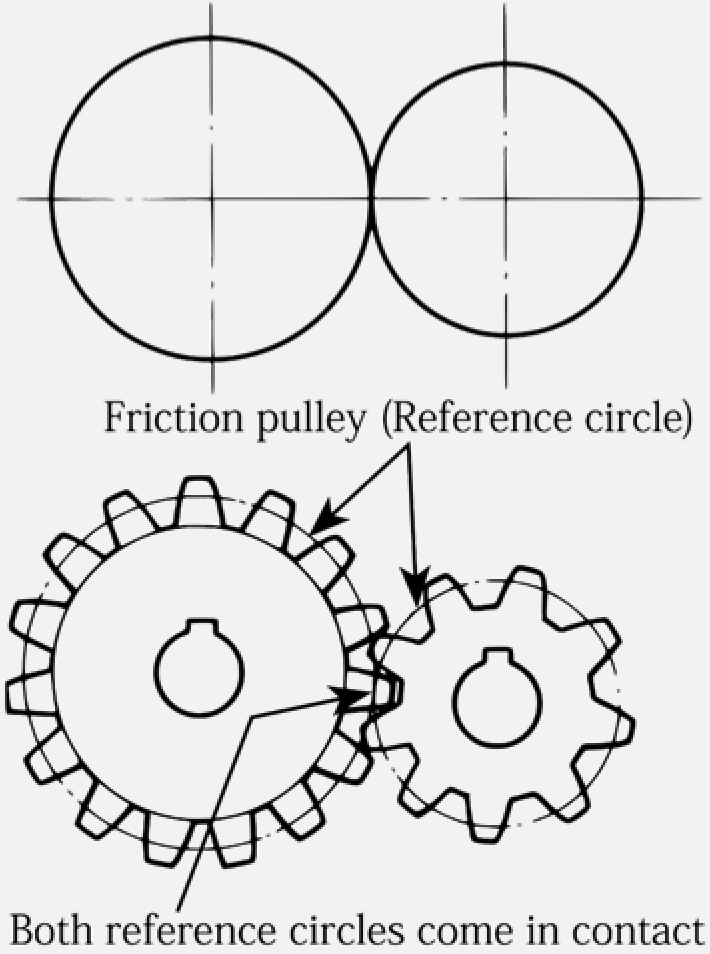
Their main features are as follows:

- Generally used for **moderate speeds**
- One can also create **multi-stage** gear reducers.
- The gears **mesh** correctly only if their **axes of rotation are parallel**

Gear Terminology

Assume that there are two friction pulleys in contact, as the surfaces are smooth, the rotation will not go properly when great force is applied. This problem will be solved if there are teeth on the periphery of the friction pulley. And this is the concept of gearing.





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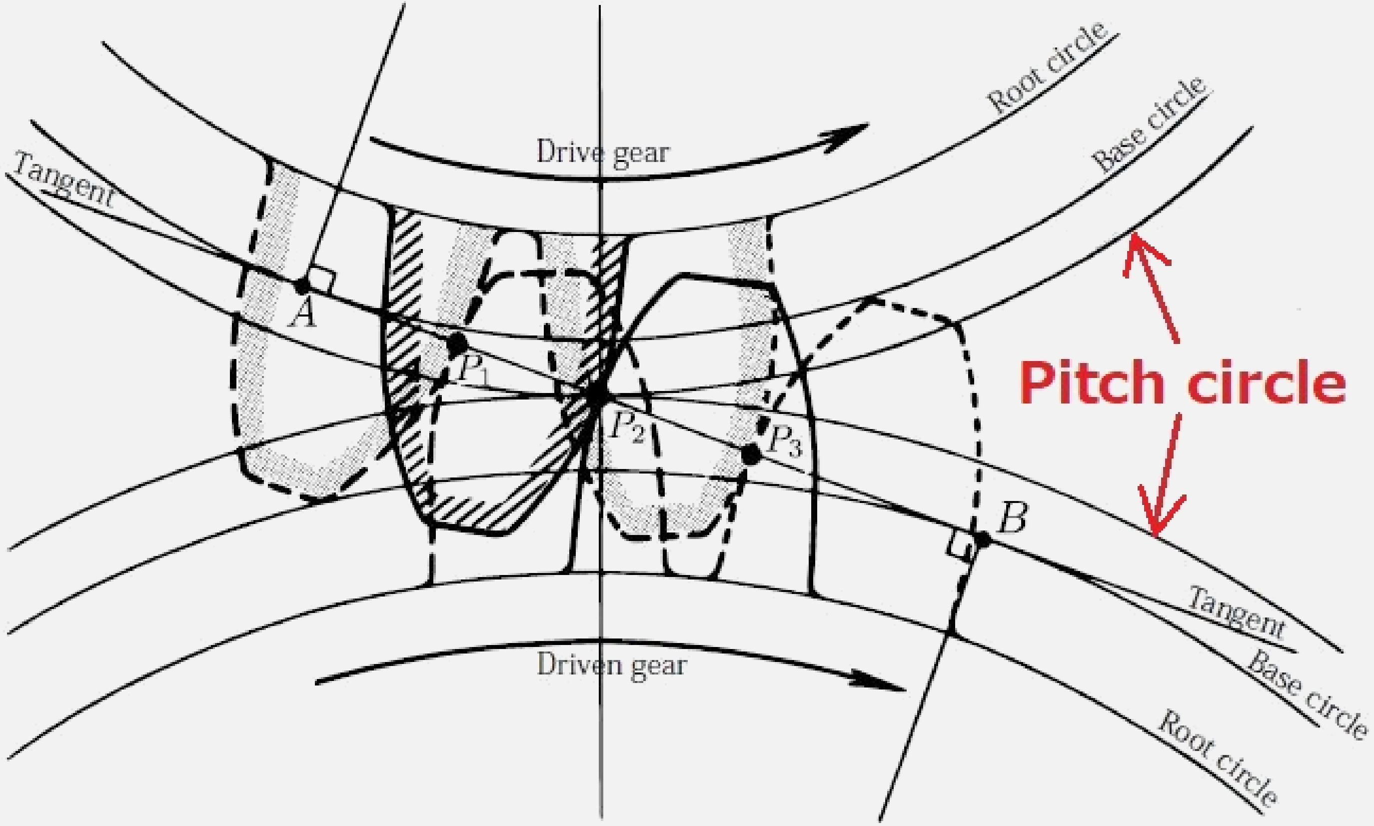
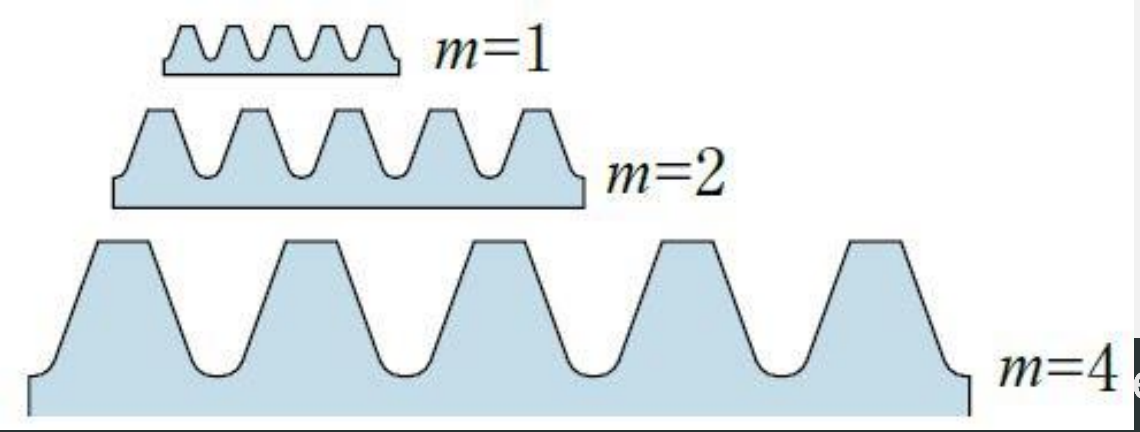
Pitch circle

- The **pitch circle** of a gear corresponds to the outer circumference of the friction wheel (gears can be thought of as friction wheels with teeth attached) and is the reference circle for determining the pitch of the gear teeth.



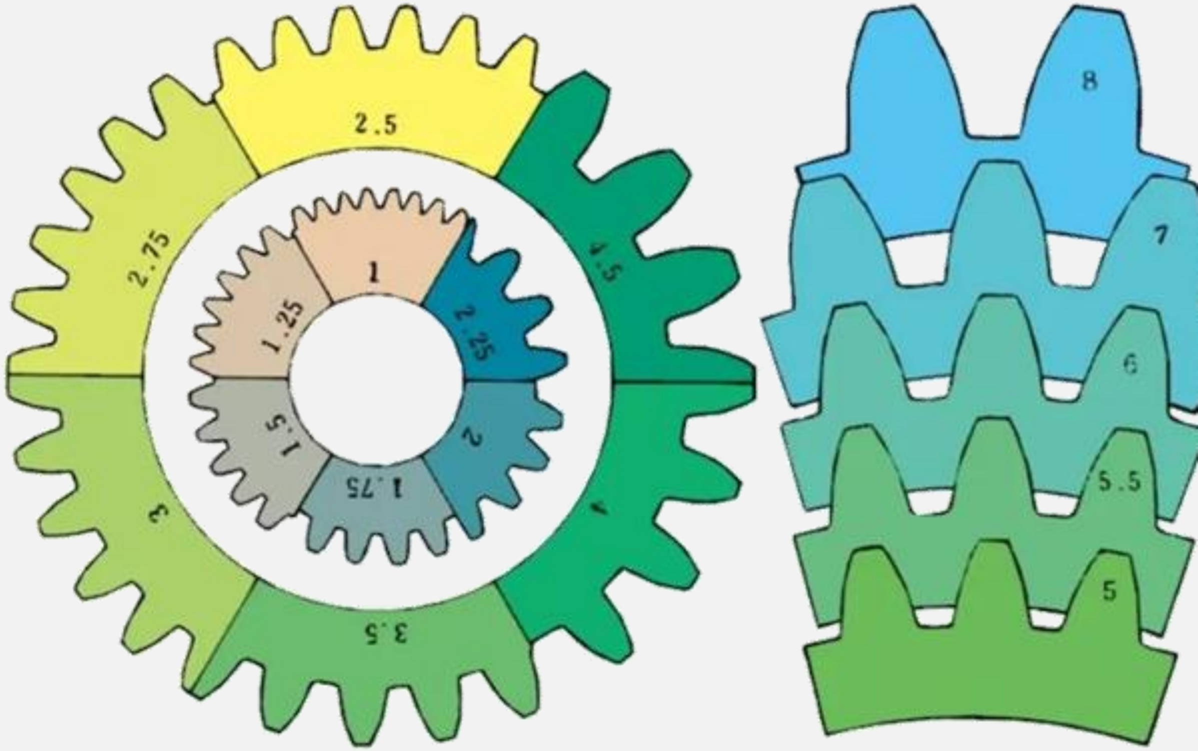
Module as tooth size

- ISO specifies the use of the **module** as the unit of measurement for gear **tooth size**, and metric gears that use the module as the unit of tooth size are actually used in many countries around the world.
- Gears will only mesh with each other if they have the same module.
- module (m) is **m = d / z**, where d is the pitch circle diameter and z is the number of teeth. The larger the module number, the larger the tooth size.
- Unit of module?
- Pitch from module?



Standard modules

- As with pitch, the larger the module value, the larger the tooth size.
- The modules have been standardized in the following numbers (mm)：
  - First series (recommended): 0.1, 0.12, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, 20, 25, 32, 40, 50
  - Second series (less used): 0.35, 0.7, 0.9, 1.75, 2.25, 2.75, 3.25, 3.5, 3.75, 4.5, 5.5, 6.5, 7, 9, 11, 14, 18, 22, 28, 30, 36, 45



Helical Gears

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 makes the tooth shape a **segment of a helix**.

Image source: [EMERSON POWER TRANSMISSION.]

Helical gears can be meshed in **parallel** or **crossed orientations**.

The main pros and cons of helical gears are:

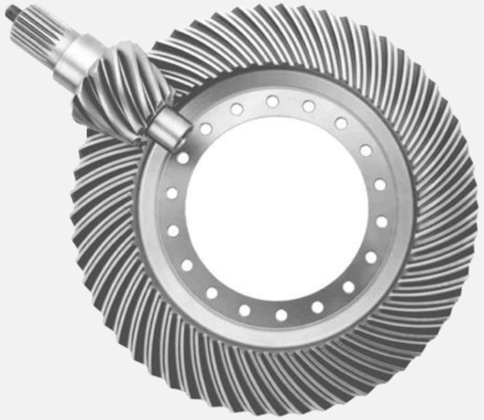
\+ The angled teeth **engage more gradually** than do spur gear teeth, causing them to run more smoothly and quietly. For this helical gears are used in high-speed applications, large power transmission, or where low noise is important

\- There is a **thrust along the axis** of the gear.

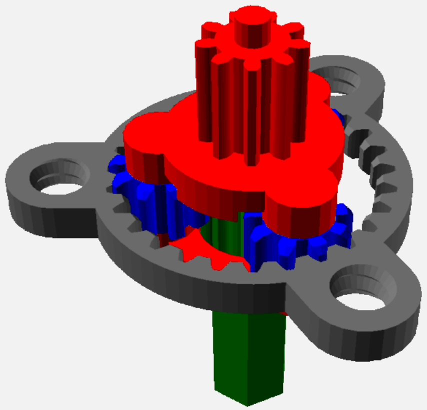
Bevel Gears

Bevel gears have straight or helical teeth (the latter are called **spiral bevel gears**) cut into conical circumferences which mate on **axes that intersect**.

- Straight bevel gears provide **moderate torque transmission**, but they are not as smooth running or quiet as spiral bevel gears because and permit **medium load capacity**.
- Spiral bevel gears permit substantial tooth overlap so that the teeth engage gradually and at **least two teeth** are in contact at the same time. These gears can turn up to 8 times faster and permit **high load capacity**.



Planetary Gears (1)

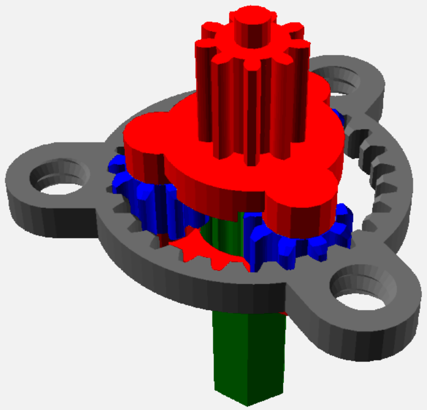


Planetary gear consists of two gears mounted so that **the centre of one gear revolves around the centre of the other**.

- A **carrier** (**red** piece on the right) is coaxial with the gear underneath it called the **sun gear** (**green**).
- The carrier also connects the centres of several **planet gears** (**blue**) and carries them around the sun gear.
- The planet gears are supported by the **ring gear** (**grey**).

The planet gears ('satellites') rotate around their axes and move around the sun gear in circular orbits, much like celestial planets, which is why this gear train is called 'planetary gear'.

Planetary Gears (2)



The main pros and cons of planetary gears are:

+ **Compact** form factors,
+ **High gear ratios**,
+ Low axial loadings,
+ **High efficiency**.

- Mechanical **complexity**,
- Increased manufacturing **tolerance** requirements,
- Decreased **efficiency** at high gear ratios.

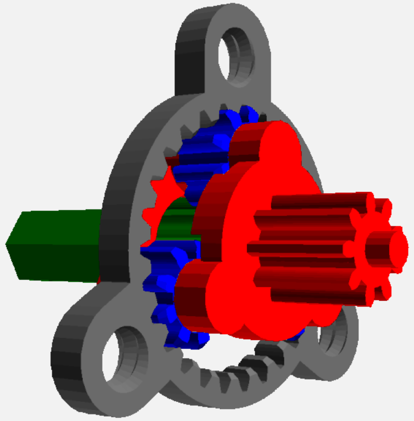
Planetary Gears (3)

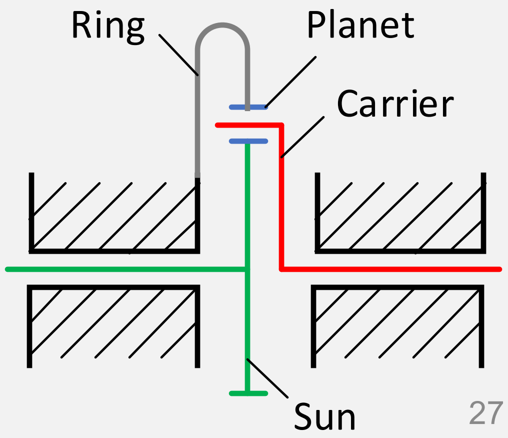
- If the **ring gear <u>is fixed</u>**, rotation of the sun gear with speed ω_s causes rotation of **planet gears** ω_p around their axes, which makes them roll along the ring gear and drive the carrier.
- Assume we have a single-stage planetary gear shown schematically on the right. If the number of teeth of the ring and sun gear are denoted as N_r and N_s, we have

$$N_s \omega_s = (N_s + N_r)\omega_c$$

Thus, the gear ratio is

$$N = \frac{\omega_{in}}{\omega_{out}} = \frac{\omega_s}{\omega_c} = \frac{N_s + N_r}{N_s} = 1 + \frac{N_r}{N_s}$$





Planetary Gears (4)

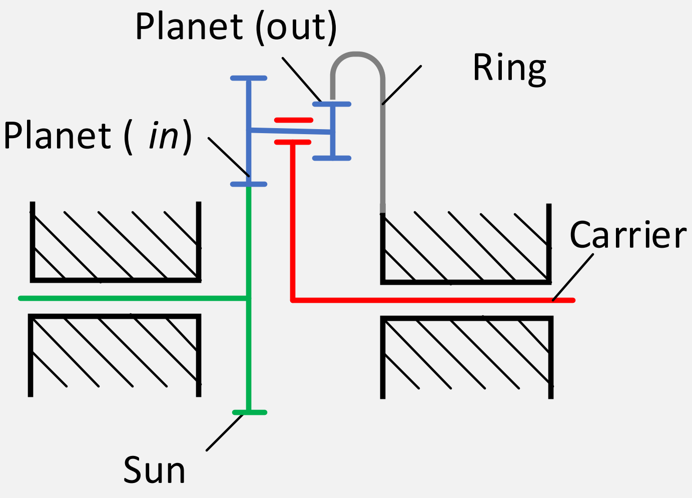
Since the **gear ratio** of such mechanism **is relatively low**, we need an alternative.

- It involves one external (sun – planet in) and 1 internal (planet out – ring) meshing ('**Type 2**'). The gear ratio of this transmission can be found as

$$N = 1 + \frac{N_r N_{p-in}}{N_s N_{p-out}}$$

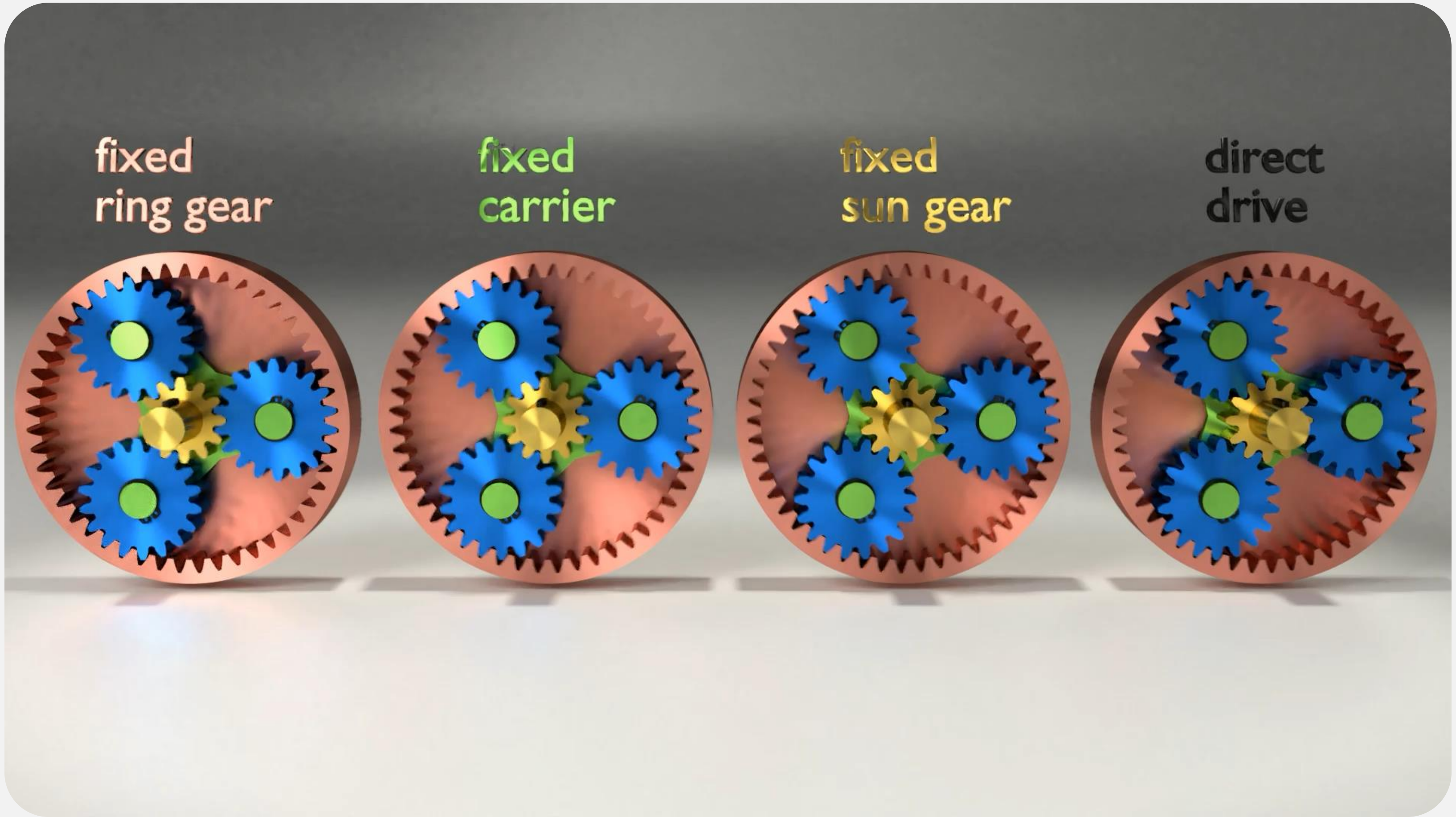
Its main features are:

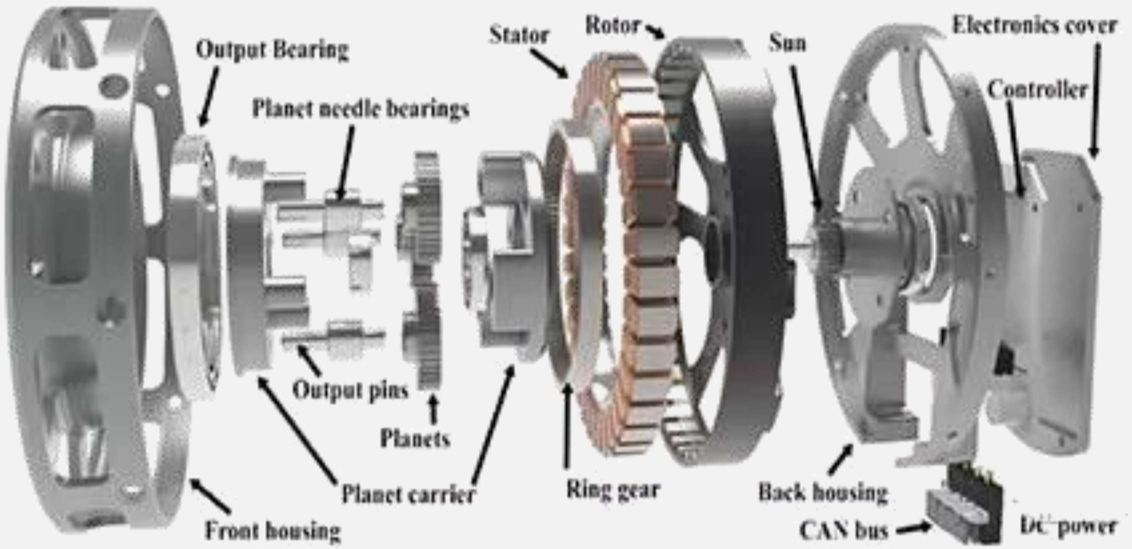
- **Higher efficiency** (comparable with 'Type 1')
- More **complicated mechanically** (two sets of teeth on planet gear)



'Type 2' planetary gear

Operating modes of planetary gears




Output Bearing
Planet needle bearings
Stator
Rotor
Sun
Electronics cover
Controller
Output pins
Planets
Planet carrier
Ring gear
Back housing
Front housing
CAN bus
DC power

Harmonic Drive (1)

Harmonic drives work on a principle of motion transmission via **wave-like deformation** of one of the elements of mechanism.

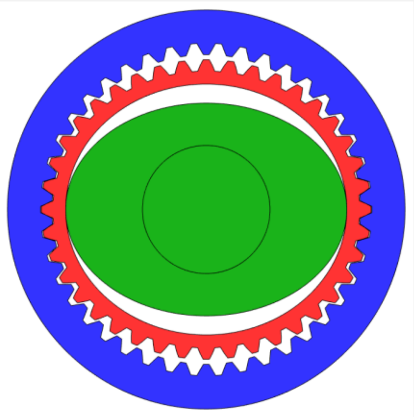
A harmonic drive has 3 main components:

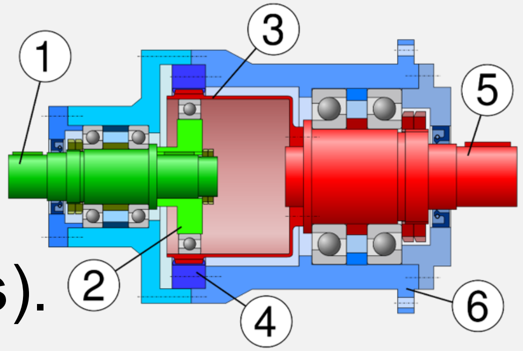
1. A **wave generator** (filled with **green** or number “2” on the right),
2. A flex spline (**red**/“3”), and
3. A circular spline (**blue**/“4”).

The number of teeth on the flex spline N_{flex} is **always less** than that of the circular spline N_{circ} (they **move in opposite directions**).

The gear ratio of harmonic drives can be found as

$$N = \frac{N_{circ} - N_{flex}}{N_{flex}}$$





Cross-section of a harmonic gear: 1) Input shaft, 2) wave generator, 3) flexible spline, 4) circular spline, 5) output shaft, 6) housing

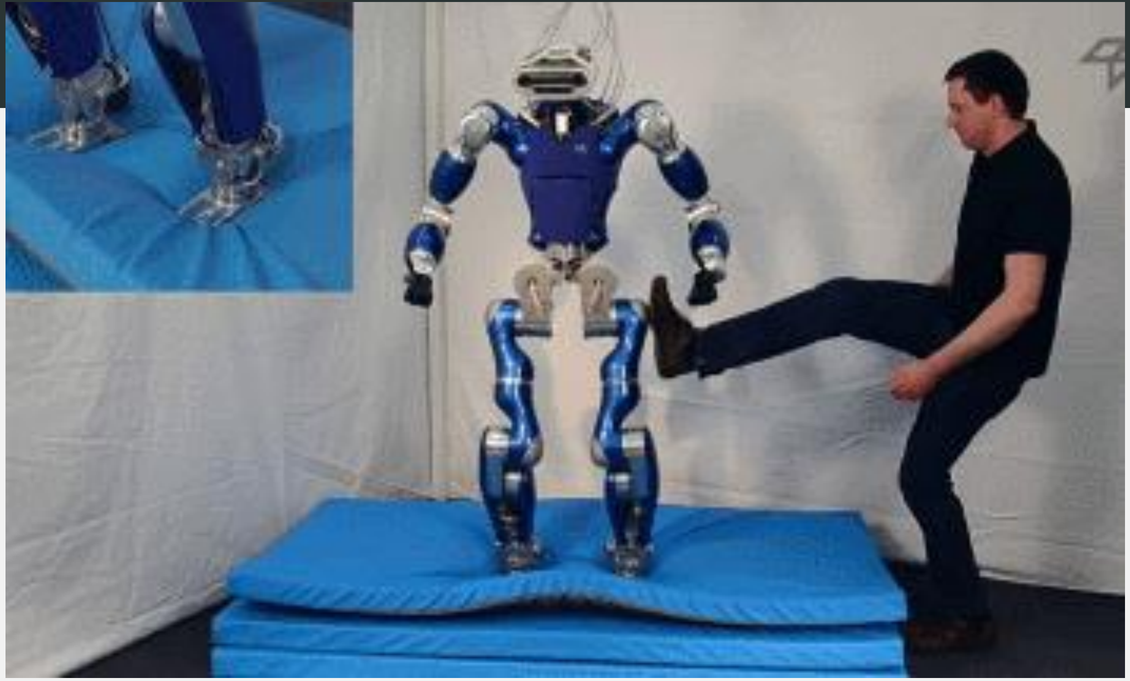
Harmonic Drive (2)

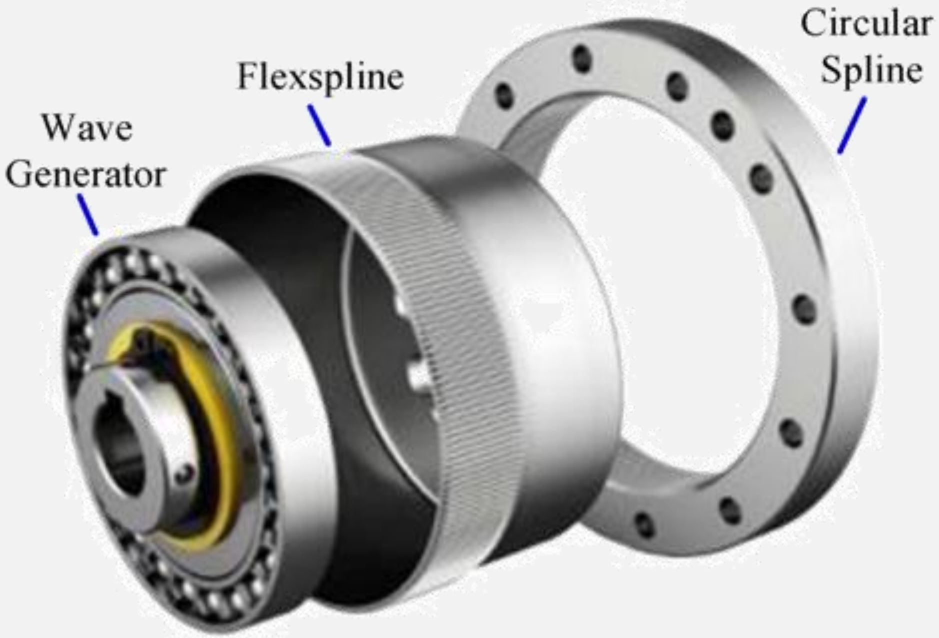
The main pros and cons of harmonic drives are:

+ **No backlash**
+ **Compactness** (3-30 times greater reduction ratios for identical volume when compared to planetary gears)
+ Light weight
+ High **gear ratios**
+ **High torque** capabilities (at any point in time, 30-50% of teeth are meshing)
+ High **efficiency** (80-90%)

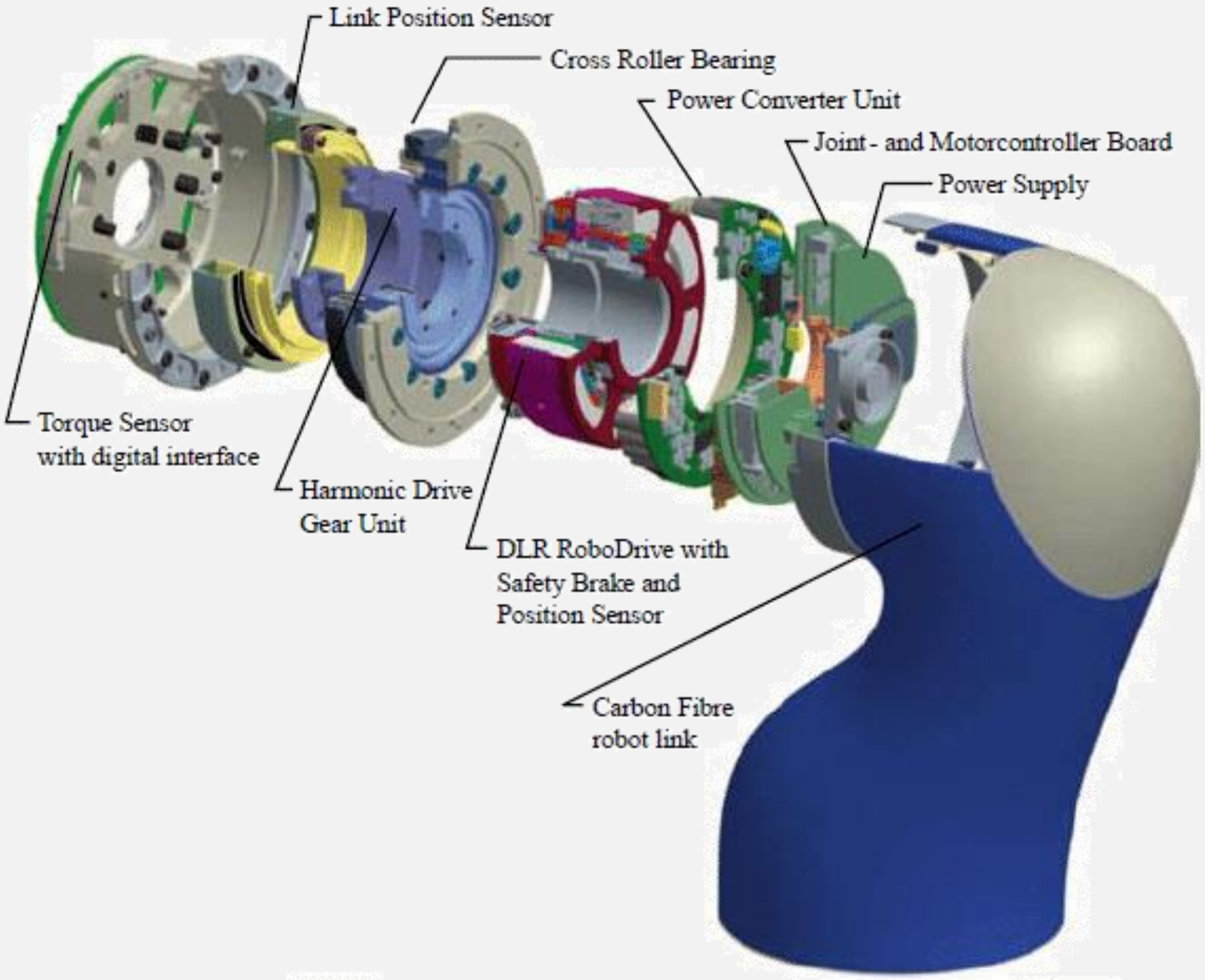
The main cons are:

- **Lower stiffness**
- Limited angular speeds for larger spline sizes





Wave
Generator
Flexspline
Circular
Spline



Link Position Sensor
Cross Roller Bearing
Power Converter Unit
Joint - and Motorcontroller Board
Power Supply
Torque Sensor
with digital interface
Harmonic Drive
Gear Unit
DLR RoboDrive with
Safety Brake and
Position Sensor
Carbon Fibre
robot link

Worm Drive

A **worm drive** (“endless screw”) is a gear arrangement in which a **worm** (which is a gear in the form of a screw) meshes with a **worm wheel** (which is similar in appearance to a spur gear). The two elements are also called the worm screw and worm gear.

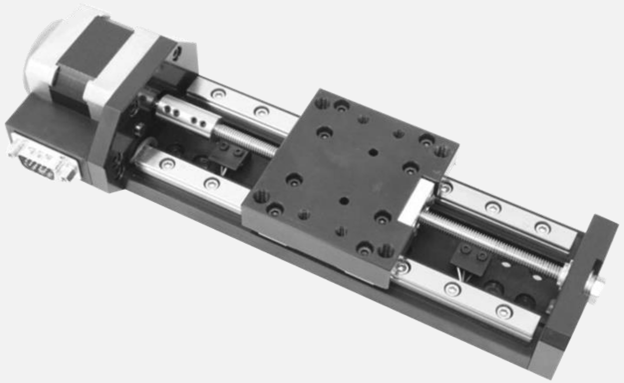
- A gearbox designed using a worm and worm wheel is **considerably smaller** than one made from plain spur gears, and has its drive axes at 90 deg to each other.
- They are **non-backdrivable**.
- **Low efficiency** due to sliding contact.

A worm drive

Rotary-to-Translational Transmissions

Lead Screw (1)

Lead screw is one of the most widely used precision mechanisms for rotary-to-linear motion conversion.

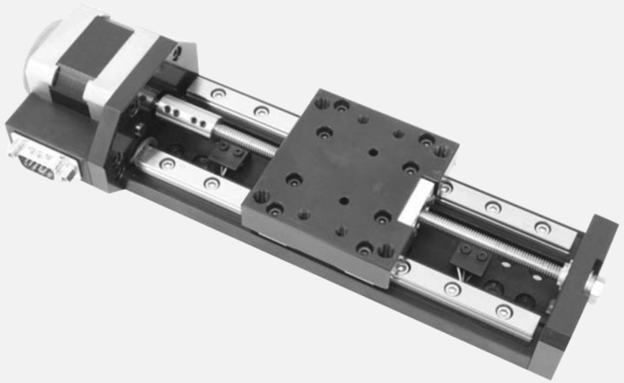


The lead screw is basically a **precision threaded screw** and nut. In a screw and nut pair, typically we turn the nut and it advances linearly on the stationary screw.

In lead screw, however, things are exactly the opposite:

- the **nut**, supported by linear bearings, is **not allowed to rotate** around the screw,
- the **screw is rotated** which causes **the nut to travel along it**.

Lead Screw (2)



The main pros of lead screws are:

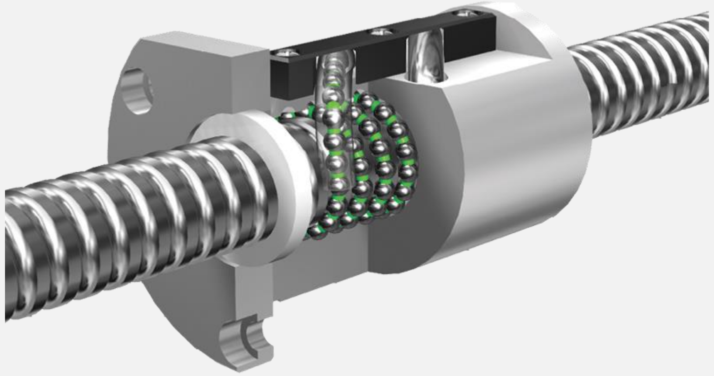
+ Mechanical and manufacturing **simplicity**
+ Compactness, even when designed for high payloads
+ Smooth and quiet operation
+ **High gear ratios** support precise output motion

The main cons include

- **Increased wear** of threads due to **high friction**
- **Low efficiency**
- **Backlash**

Ball Screw

Ball screw design uses precision ground **spherical balls in the groove** between the screw and nut threads to reduce backlash and friction in the motion transmission mechanism.



The main pros of ball screws are:

+ **High efficiency** (0.9-0.95)
+ **Reduced wear** and long lifetime
+ **High accuracy**
+ **Zero backlash**
+ High sensitivity to microscopic motion
+ Limited lubrication requirements

The cons are:

– Often **back-drivable**
– **Mechanical complexity**
– **High cost**
– Low damping
– **Lower payloads** than lead screws
– Need in dust protection

Rack-and-Pinion Mechanism

In a **rack-and-pinion mechanism**, a rotating small gear (pinion) engages a linear gear (the rack), thus converting rotational motion into the linear one, or vice versa.

- **Rollers** can be also used in place of gears (shown on the left figure), in which case it is called roller pinion mechanism.