University of Nottingham
UK | CHINA | MALAYSIA

Machine system design

Dr Hengan Ou

email: h.ou@nottingham.ac.uk

Learning objectives of this session

Part 1:

- To be able to use your knowledge of **machine elements/devices** and to effectively apply this knowledge in **Embodiment Design**

Part 2:

- To be able to bring individual parts or sub-systems together into a complete machine system: (**Design of a drive train)**
- To be able to understand the function and to calculate force/torque of **Hirth coupling/clutch to support Individual (Gearbox Actuator) design**

Part 3:

- To be able to select **suitable coil or disc springs** for engineering applications **to support Individual (Gearbox Actuator) design**

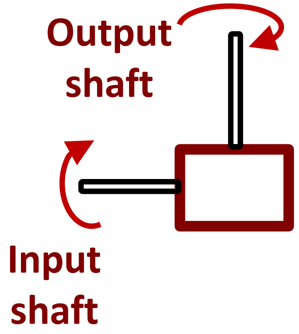
An overview of key stages of design

- A design process involves a number of key stages as Prof Geoff Kirk covered in 1st year MMME1024 (EDP) module:
  - Understanding of **Customer's Needs** and formulation of **Statement of Requirements**
  - **Conceptual design, Embodiment and Detailed design → from idea to solution**
- **Concept generation & evaluation**
  - **Creativity** delivered via methods incl. **Brainstorming**, **Morphology chart**, etc
  - **Best possible concept** selected using, e.g. **simple or weighted decision matrix method**
- **Embodiment** (to be discussed in this session)
- **Detail design**
  - **Detail design** refers to **a complete solution** presented by a set of documentations of **decisions**, **engineering calculations**, **GA and detail drawings** and **documents for production and integration** of individual components into the whole system.

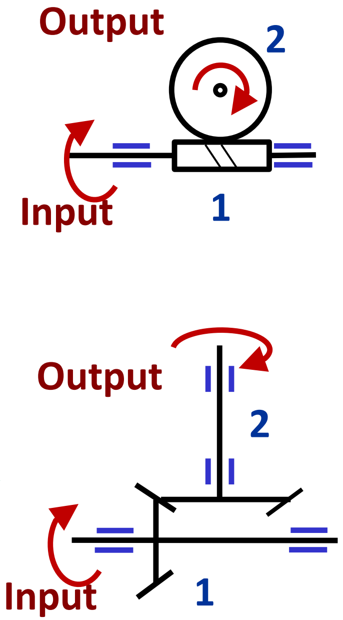
Embodiment Design: Definition & an example

Machine system
Part 1

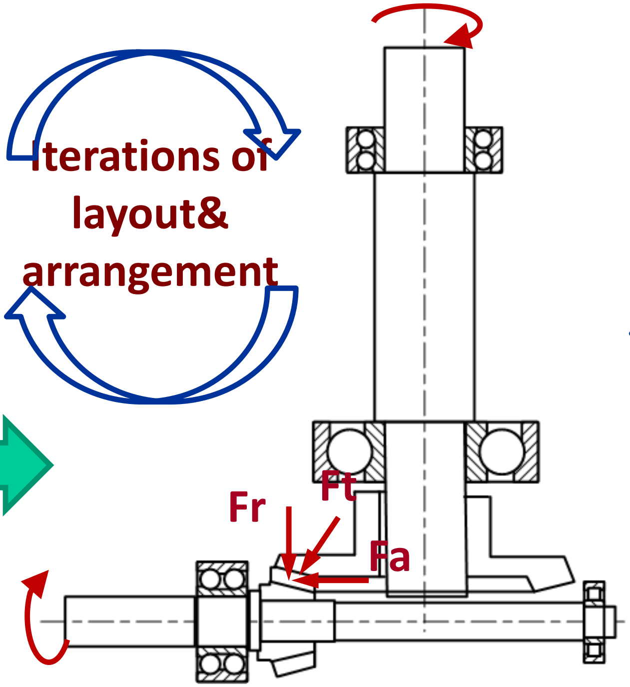
- **Embodiment Design** is to take the design concept to a clear definition of **overall layout (scaled sketches/drawings), preliminary form designs (component & material selection) and production processes**. It involves **corrective steps to allow evaluation & alternation** for an **optimised solution**.



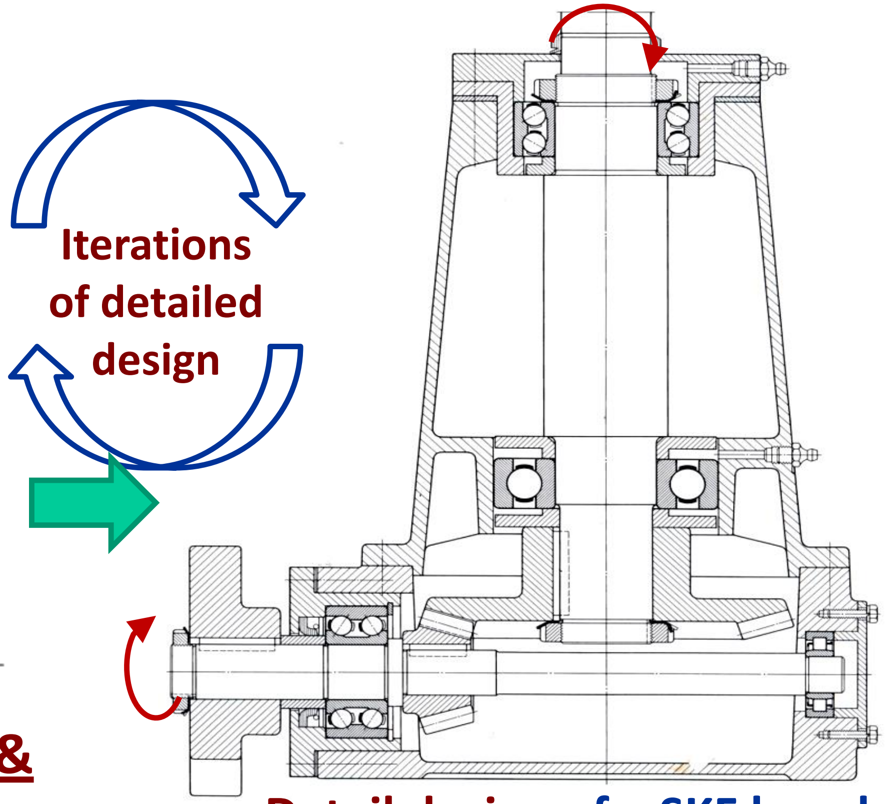
Requirement is to change power direction



Selection of concepts



Embodiment of layout& basic sizing



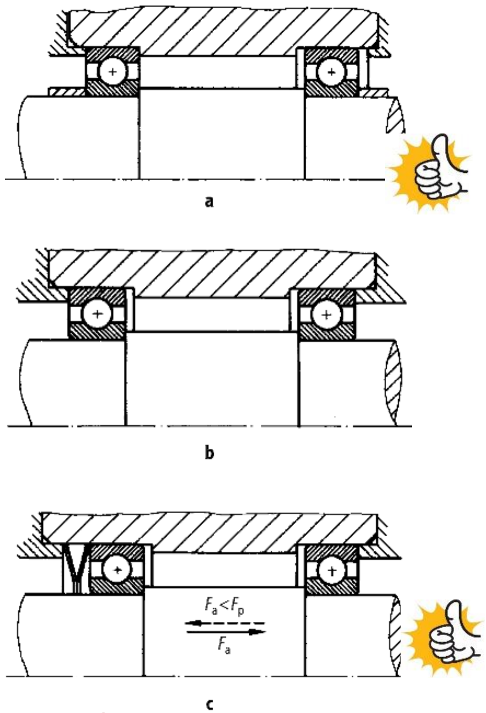
Detail design of a SKF bevel gearbox

"**Engineering Design A systematic approach**" by G. Pahl, W. Beitz, et al., 3rd ed, 2007

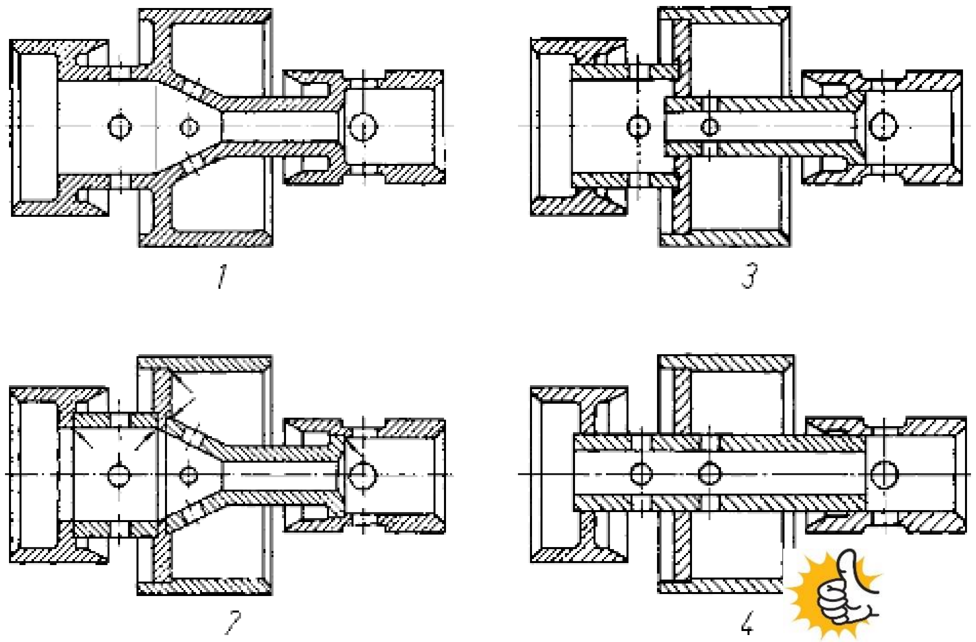
Embodiment Design: Basic rules

- **Clarity** for **unambiguous** relationship between sub-functions
- **Simplicity** for improved function, ease of manufacture, assembly, operation and maintenance
- **Safety and reliability** are important for functions, protection for engineers /workers and environment

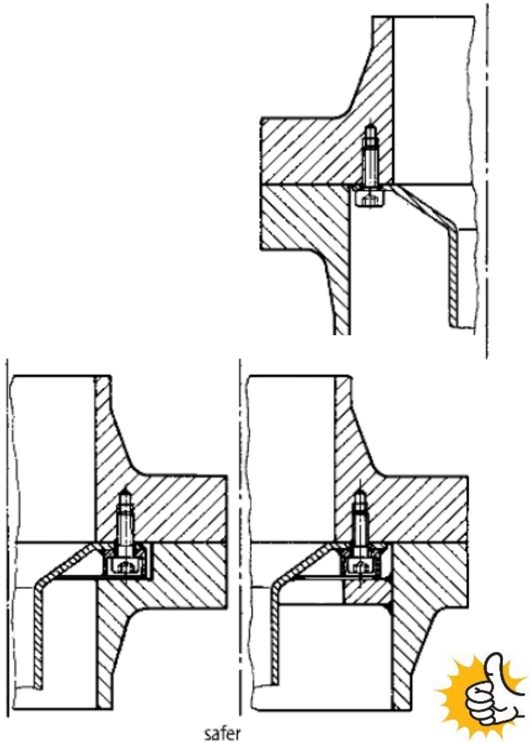
The same rules apply to your Gearbox Actuator design in terms of Clarity, Simplicity & reliability



Basic bearing arrangement



Simplification options of a sliding valve

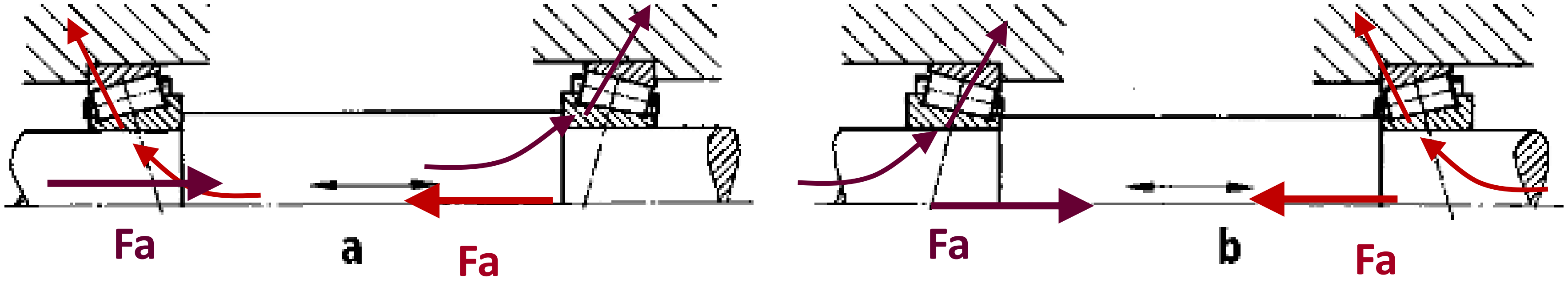


Funnel design to prevent broken screw falling

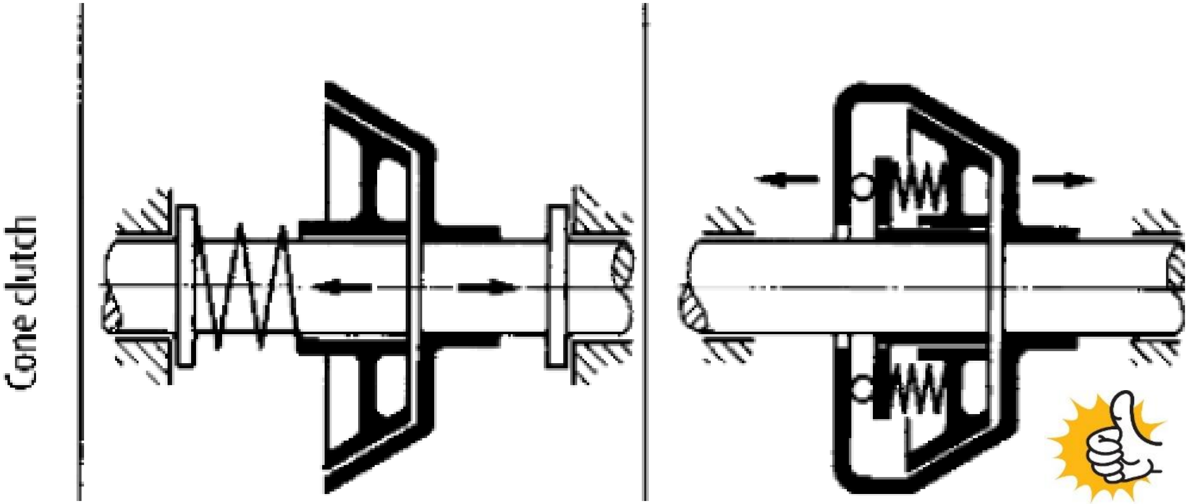
"**Engineering Design A systematic approach**" by G. Pahl, W. Beitz, J. Feldhusen & K.H. Grote, 3rd ed, 2007 **(TA174 ENG)**

Embodiment Design: Principles

- **Principle of force transmission: load path analysis**
- **Principle of uniform strength & balanced forces**



Load paths with different bearing arrangement



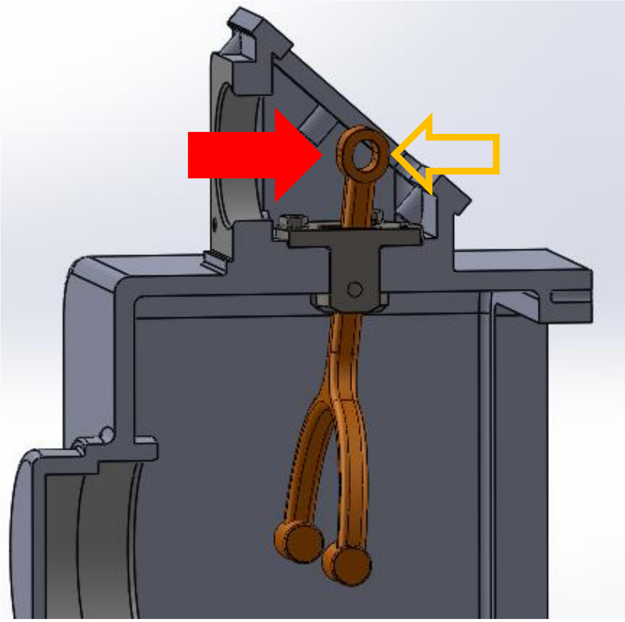
A good example of Force balance in a cone clutch

"**Engineering Design A systematic approach**" by G. Pahl, W. Beitz, J. Feldhusen & K.H. Grote, 3rd ed, 2007 (**TA174 ENG)**

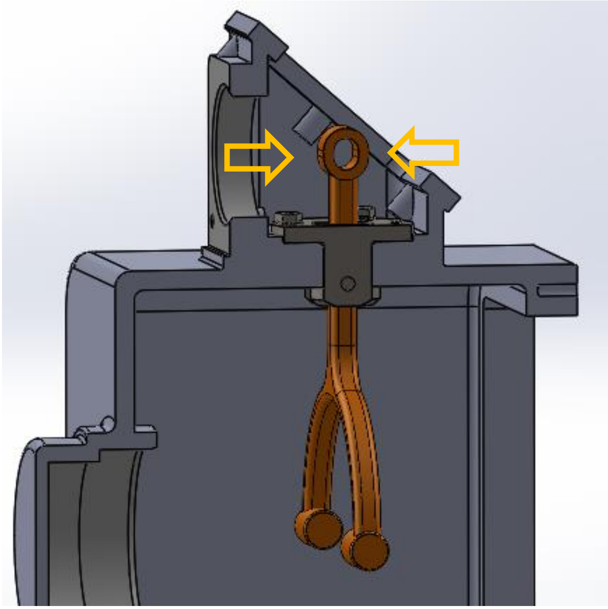
Embodiment Design: Principles

- **Principle of force transmission: An example of the Gearbox Actuator**

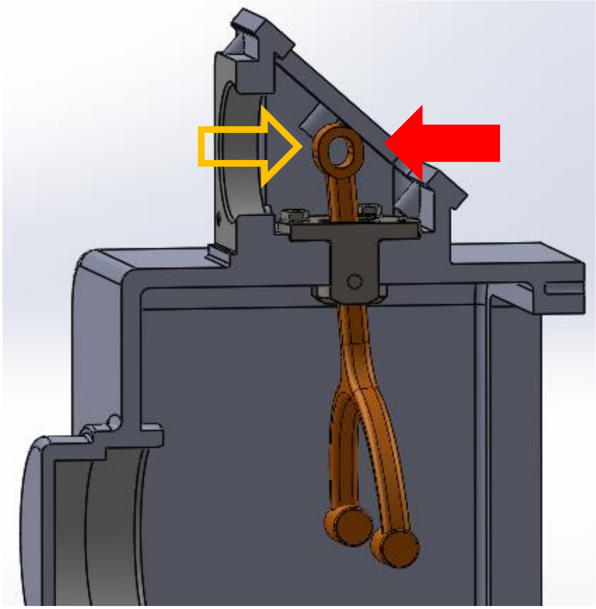
What is the load path/condition of the Gearbox Actuator?



Actuation force to
Z=2:1 gear ratio



Initial load in
Neutral position

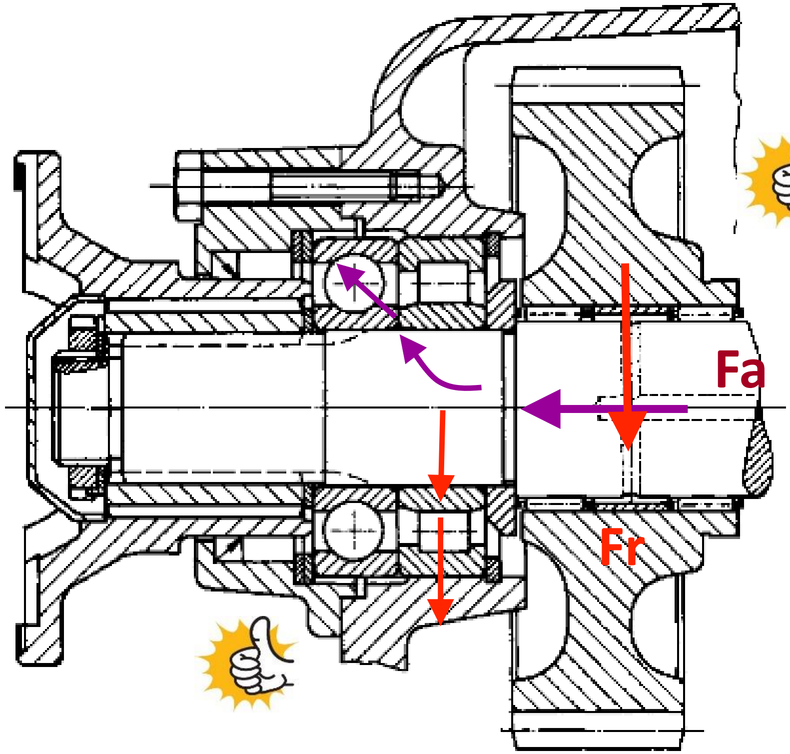


Actuation force to
Z=1:1 gear ratio

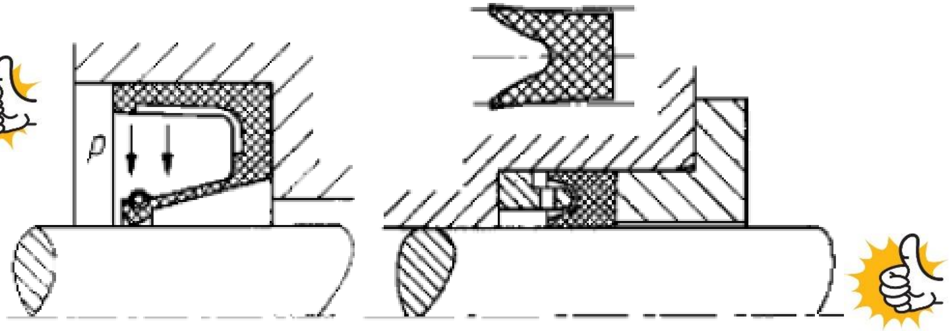
How to calculate these actuation forces and what's actuation displacement?

Embodiment Design: Principles

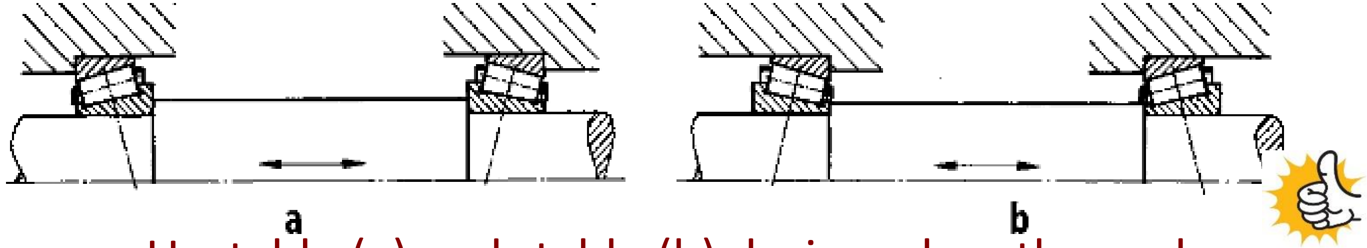
- **Principle of division of tasks:** assignment of sub-functions
- **Principle of self-help:** useful features for improved functions
- **Principle of stability:** minimised effect due to small amount of disturbance



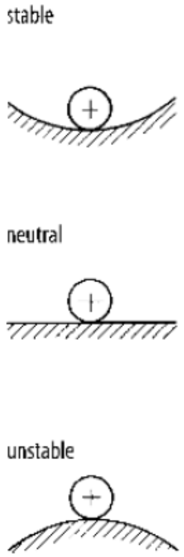
Separate load paths for radial & axial forces in a gearbox



Self-energising in radial lip and U shape seals



Unstable (a) and stable (b) design when thermal expansion of the shaft is significant

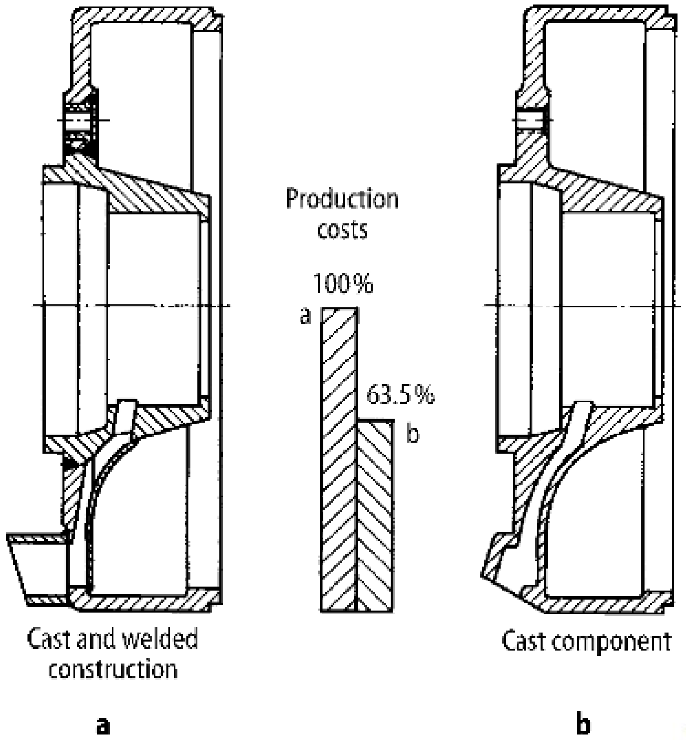


"**Engineering Design A systematic approach**" by G. Pahl, W. Beitz, J. Feldhusen & K.H. Grote, 3rd ed, 2007, (**TA174 ENG)**

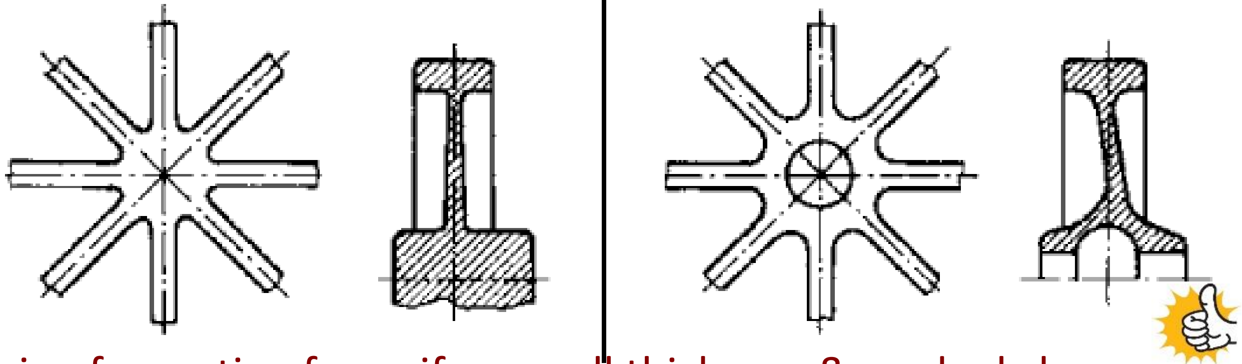
Machine system Part 1

Embodiment Design: Guidelines

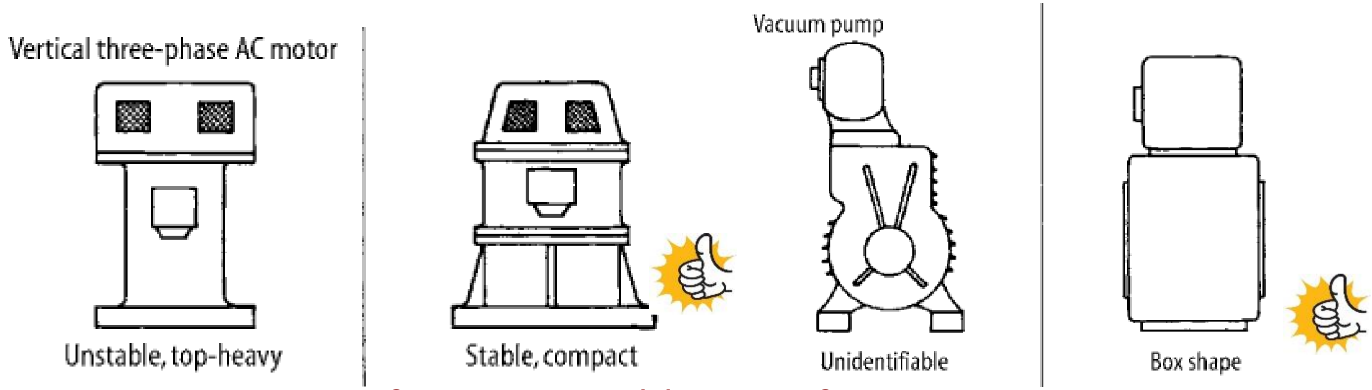
- **Design for production (DfMA):** directly affect the function, performance, cost and manufacturing capabilities
- **Design against** corrosion/wear, design for ergonomics/aesthetics, design for maintenance/disposal



Welded and a single cast piece of an electric motor cover



Design for casting for uniform wall thickness & gradual changes of cross section (a better option at RHS)



Design for recognisable & uniform expression

"**Engineering Design A systematic approach**" by G. Pahl, W. Beitz, J. Feldhusen & K.H. Grote, 3rd ed, 2007 (**TA174 ENG)**

Machine system design

End of Part 1

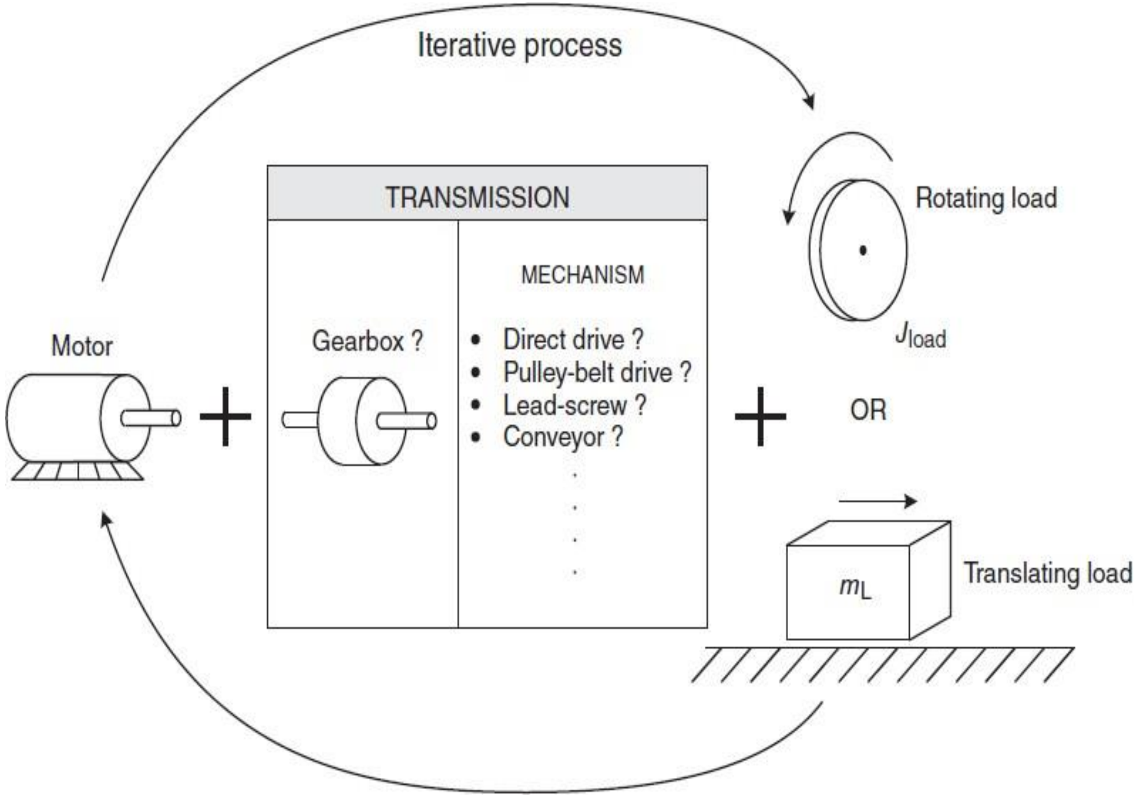
Machine system design

Part 2

Design of a drivetrain or power train

- **A drivetrain** is a whole system of a power unit which includes an engine or **electric motor** through power/motion transmission unit(s) to the load or tool (mechanical device/unit).

- With specified load and motion, the aim is **to select suitable motor (power source) and transmission** that ensures
  - **Sufficient torque** from the motor
  - **Proper inertia relationship** between the motor and the load
  - **Additional criteria**, e.g. cost, precision, stiffness, cycle time met



An iterative process in drive-train design & selection

"**Industrial Motion Control: Motor Selection, Drives, Controller Tuning, Applications.**" by H. Gurocak, 2016, **(Available online at NUSearch)**

Considerations for selecting a power source

Machine system
Part 2

- **Electric motors** (→continuous rotation)
  - **Pros: high performance, low cost**, a wide range of sizes & capability, accuracy, repeatability & compactness
  - **Cons: limited choice of gearbox**, power may not be as high as hydraulics
- **Hydraulic systems** (→ reciprocation)
  - **Pros: high load-carrying capacity, low inertia**, high flexibility & good strength
  - **Cons: high cost of servo system**, need for precision feedback, leakage, lack of small actuator, difficulties in maintenance
- **Pneumatic systems** (→ reciprocation)
  - **Pros: wide availability of compressed air, simple, easy & clean operation, fast & possibility of high load-carrying capacity**
  - **Cons:** low precision, high energy cost & noise in operation

What would be suitable power source for the Gearbox Actuator?

Considerations for system integration

[Machine system Part 2]

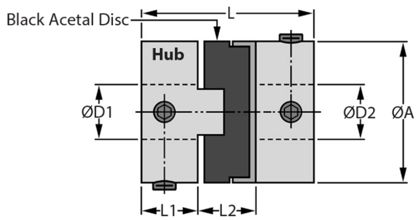
- **Considerations for system integration and design**
  - **Suitable power source**, e.g. electric motor, hydraulic/ pneumatic systems, IC engine or other forms of power/actuation
  - Need of **mechanical transmission**, e.g. gearbox, chain/belt or lead/ball screw drive for the required power, forms of motion (speed/distance), force or torque
  - **Design or purchase** of a functional device, e.g. power transmission unit/device

- **Sound solutions/decisions require**
  - **Detailed assessment** of **pros/cons** of different power drives
  - **Working knowledge** of functional requirements /operational conditions
  - **Access** and assessment of technical data and specs from a supplier /manufacturer

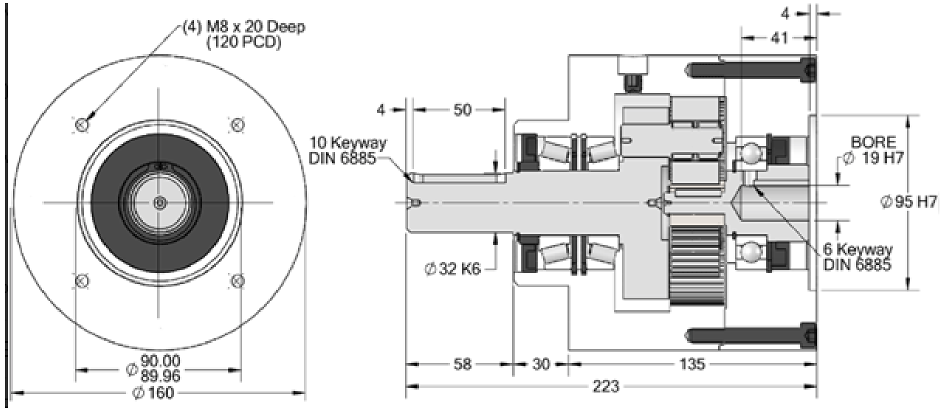
Selection of standard & supplied components

Machine system Part 2

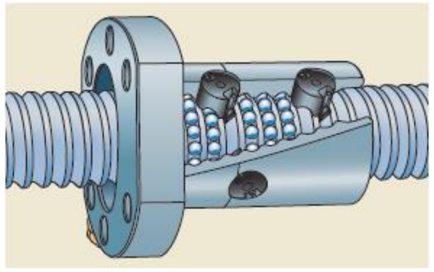
- Use of BSI/ISO standard & manufacturer's catalogues for **standard components**, e.g.
  - SKF or Schaeffler INA-FAG's website for suitable **rolling element or plain bearings**
  - Trelleborg or James Walker's website for **sealing devices**
- Use of manufacturer's catalogues for more mechanical transmission units/devices, e.g. **gearboxes, couplings, lead & ball screws, pneumatic & hydraulic actuators**



Oldham Couplings: 3000rpm/peak torque 30Nm (https://www.ondrives.com/bg50-t)



6:1 ratio epicyclic gearbox with a max 250 Nm at 1000rpm (https://www.ondrives.com/ehd16-6)



SKF precision screws with nominal dia 16~63 mm (https://www.skfmotiontechnologies.com/en/gb/products/ball-roller-screws)

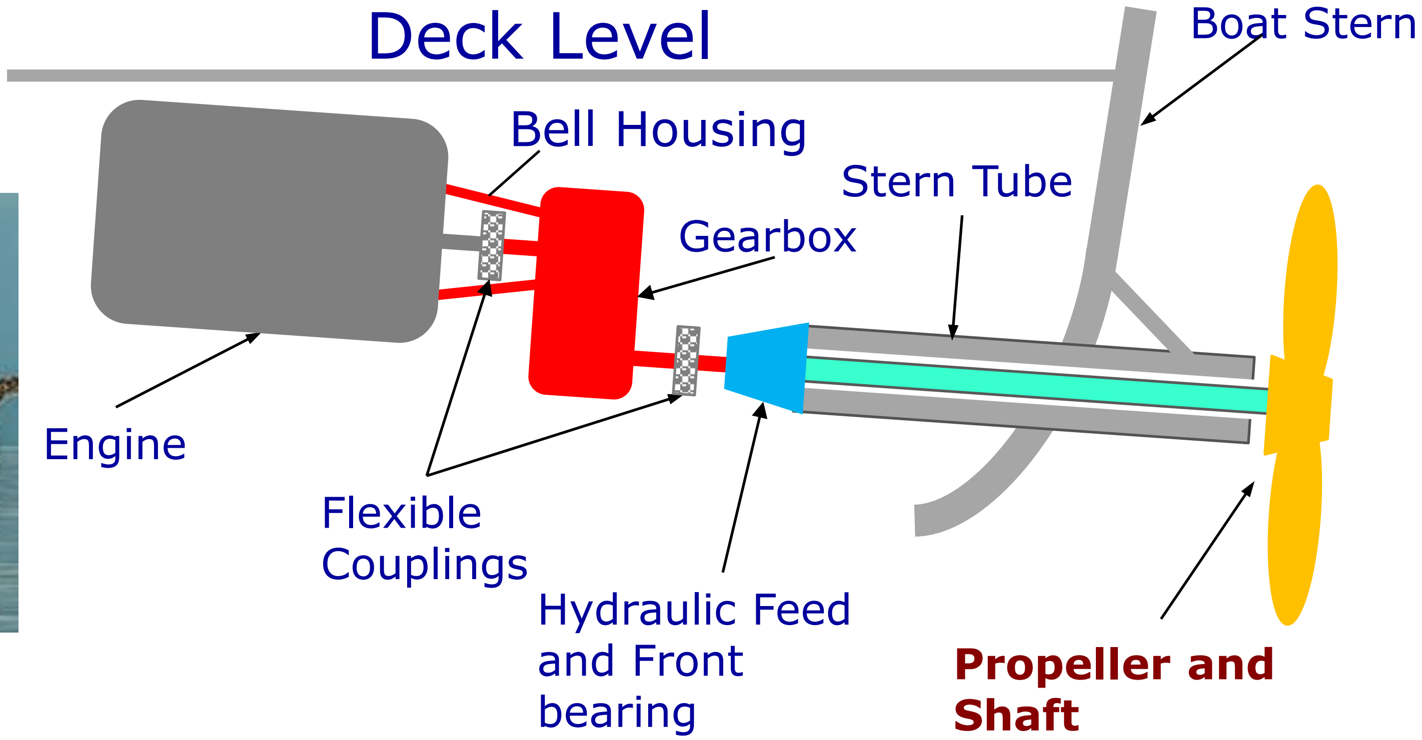
James Walker: https://www.jameswalker.biz/en

Trelleborg: https://www.tss.trelleborg.com/en/products-and-solutions

An example: Power train for a fishing boat

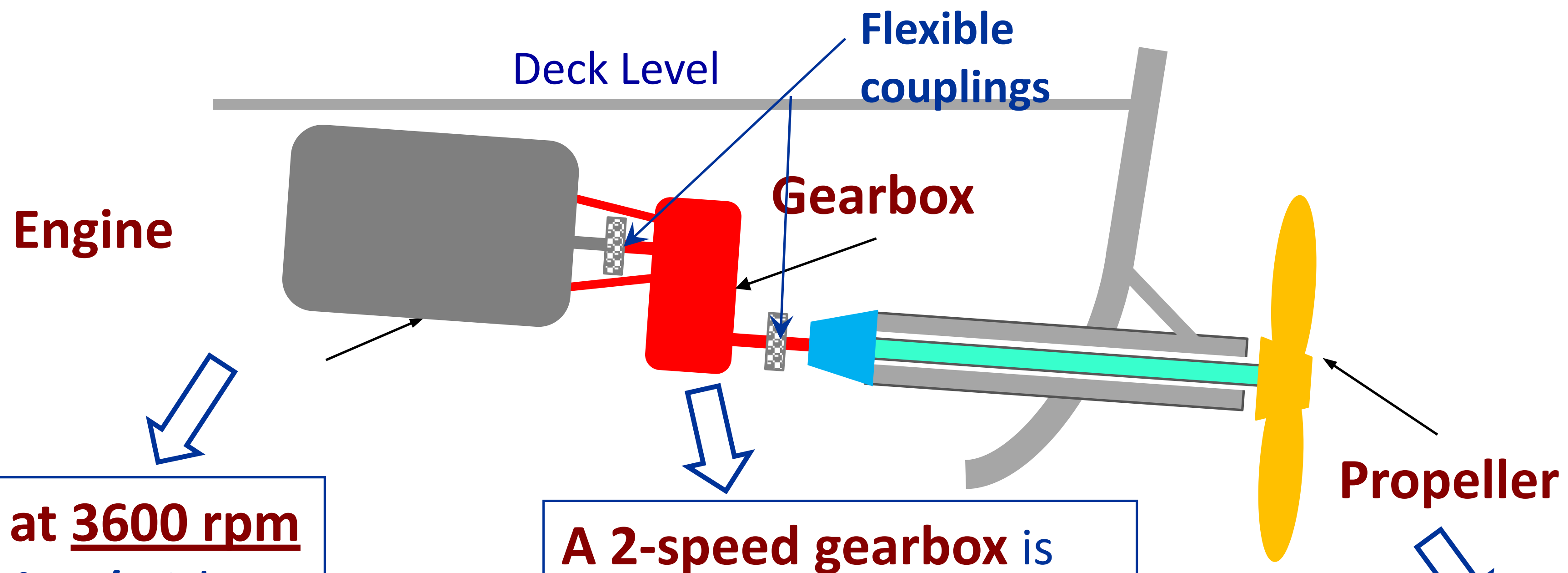
- **Design of a whole system** requires an **understanding of the power source, transmission and work units** so as to define an **optimal solution** for **expected function and performance** of the system in consideration of **other factors.**

A small fishing boat



- The main task is to design a **gearbox**, which enables **power transmission with 2-speed options** for different fishing or sailing conditions.

An example: Power train for a fishing boat



20.8 kW at 3600 rpm from engine (with max torque reached at 1700 to 3600 rpm)

A 2-speed gearbox is designed to transmit **15 kW at 1300 or 2600 rpm** from output shaft

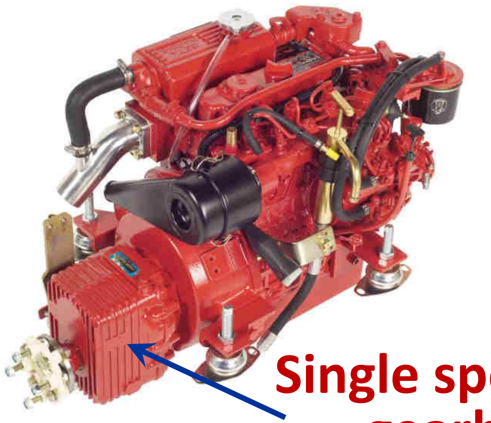
15 kW power required to achieve **10 knots speed at 1300 rpm** and **20 knots at 2600 rpm**

- Selection of **suitable power source,** design or selection of **transmission unit** and **joints/connections** is an integral part of design

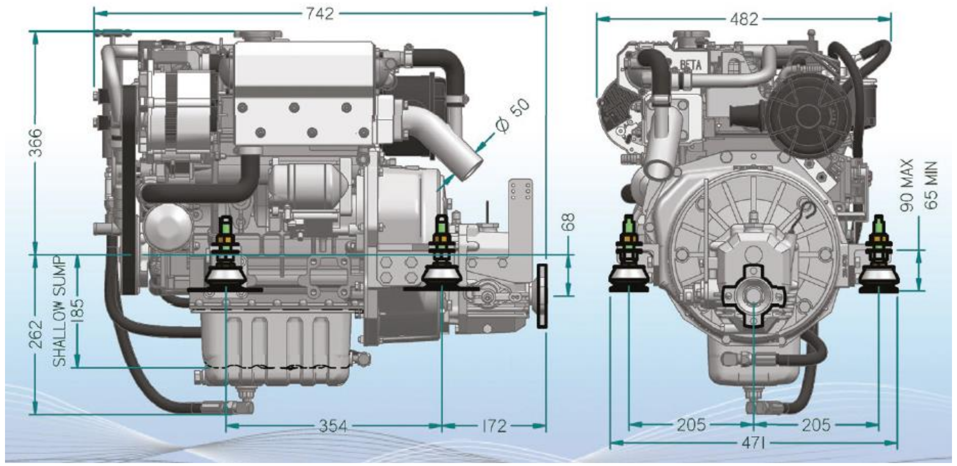
Selection of a suitable engine

(often power units can be sourced from a manufacturer)

- **Beta Marine B30 3 cylinder diesel engine**
  http://www.betamarine.co.uk/
  - Max power **21.7 kW** is delivered at 3600rpm;
  - Max torque **58 Nm** is delivered at 2600rpm;
  - Weight 139 kg
  - **Options for 2:1 ratio signle speed gearbox**

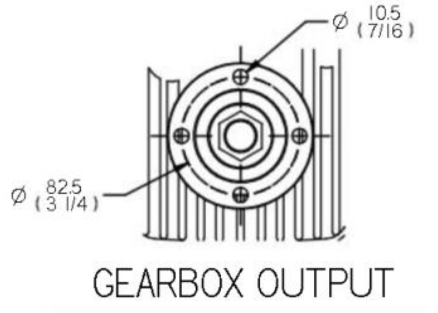


Single speed gearbox

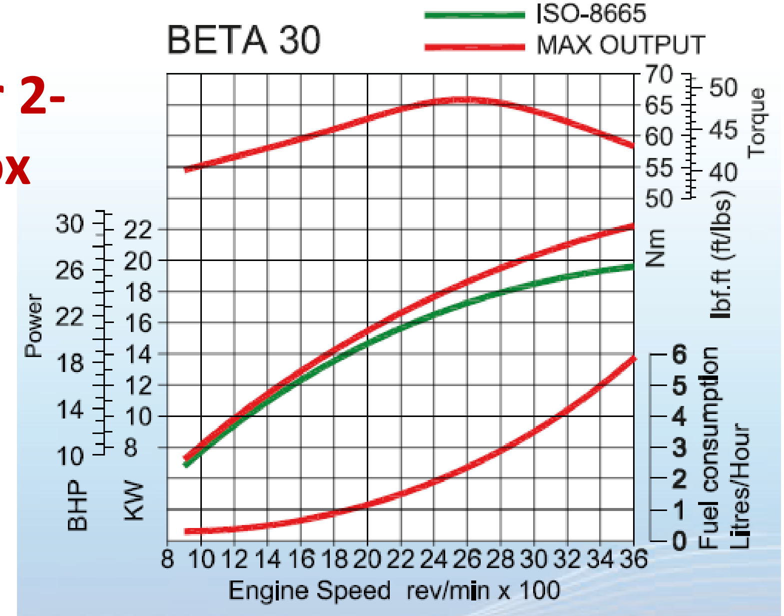


Beta Marine B30 engine key dimensions

No option for 2-speed gearbox



Gearbox output interface

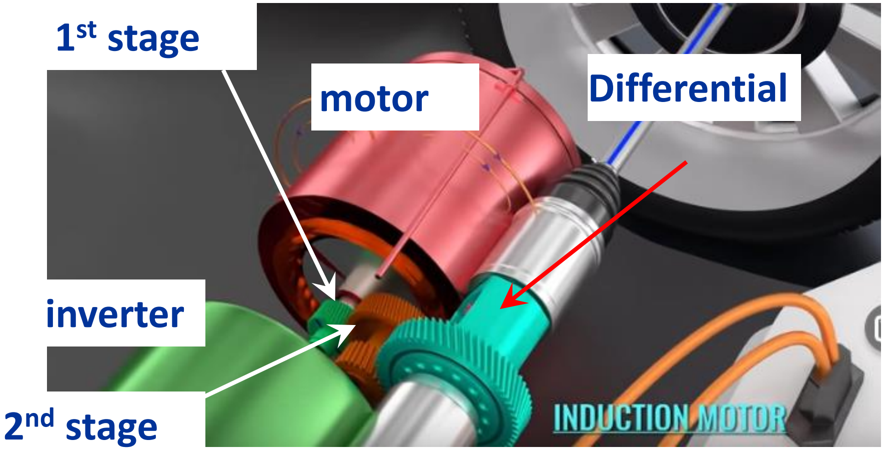


Beta Marine 3 cyl engine (21.7kW)

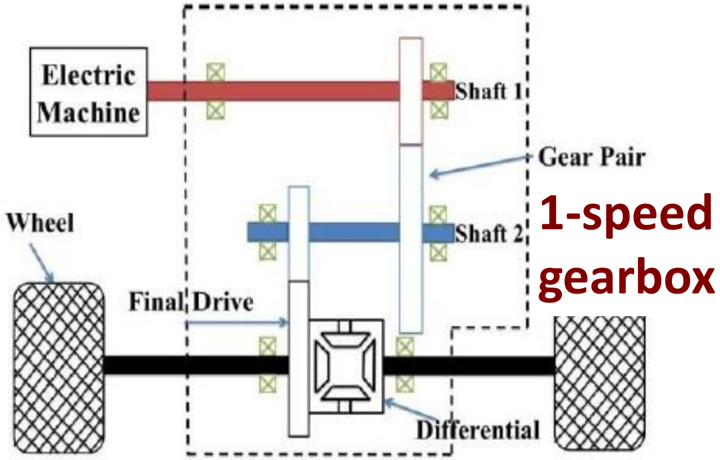
Another example: Power train for battery electric vehicles

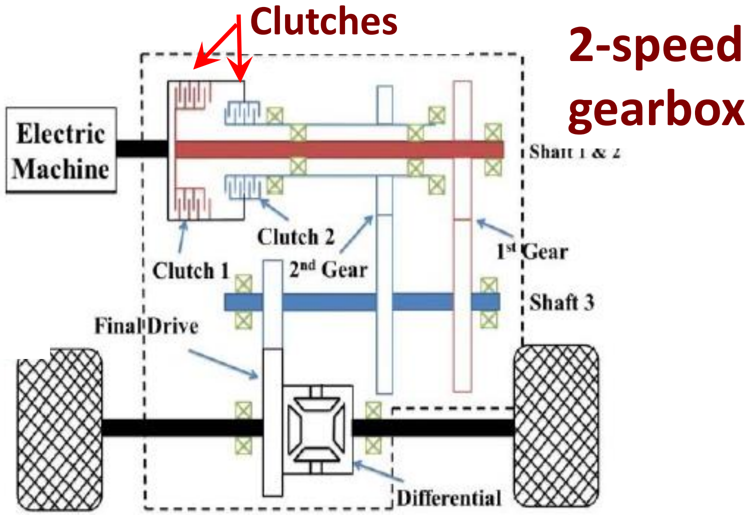
[Machine system Part 2]

- **Most of current BEVs adopt a 1-speed gearbox with a differential unit**

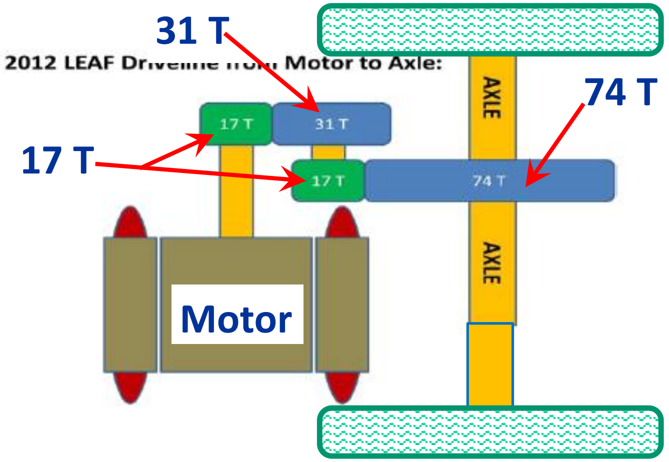


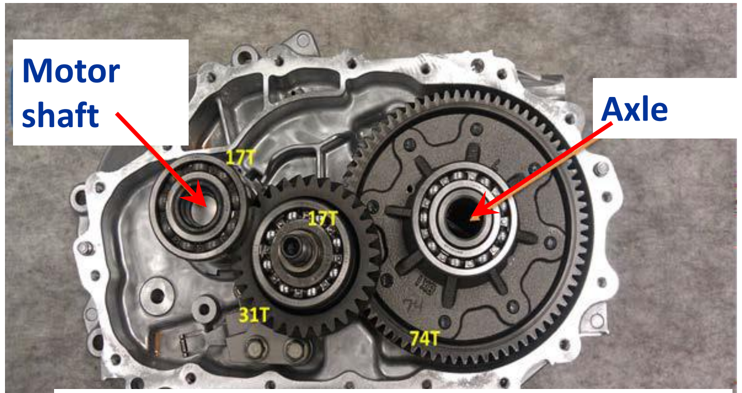
Tesla models use a single speed gearbox together with a differential unit
https://www.youtube.com/watch?v=3SAxXUIre28





Single and 2-speed gearbox for BEVs in the future?

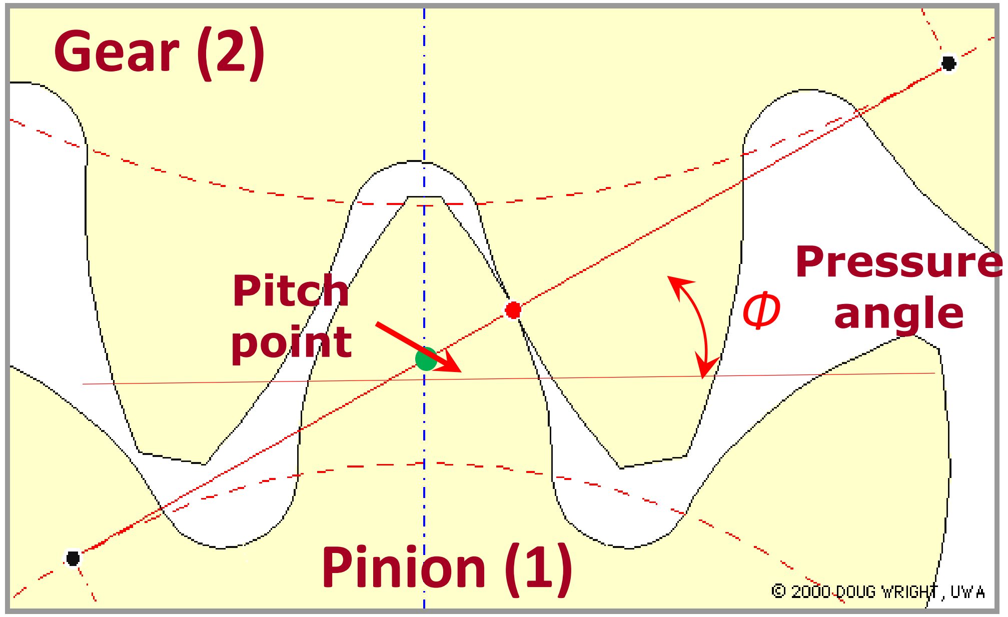




Nissan Leaf single speed gearbox

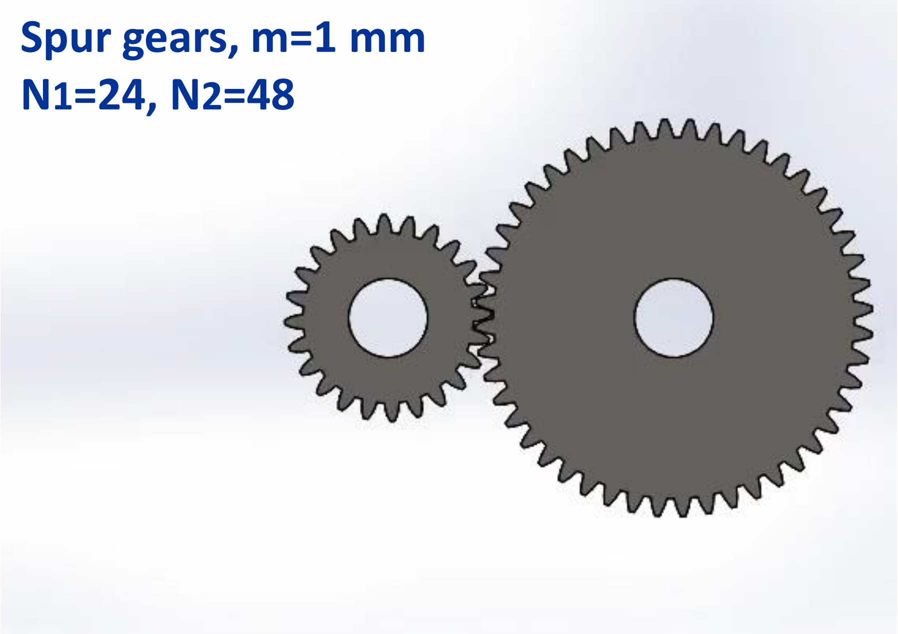
Recap of Gears 1

Gears are the most rugged, durable and efficient means of power transmission between two shafts.



http://www.mech.uwa.edu.au/DANotes/gears/meshing/meshing.html

Spur gears, m=1 mm
N1=24, N2=48



Details to refer **Gears 1 Lecture slides and Handouts** available on Moodle

Gear ratio equation: $Z = \dfrac{\omega_1}{\omega_2} = \dfrac{d_2}{d_1} = \dfrac{N_2}{N_1}$

Necessary & sufficient conditions :

$$m_1 = m_2, \quad \phi_1 = \phi_2$$

Note: The most commonly used pressure angle is ϕ or $\alpha = 20^0$

Pitch diameter: d=mN,

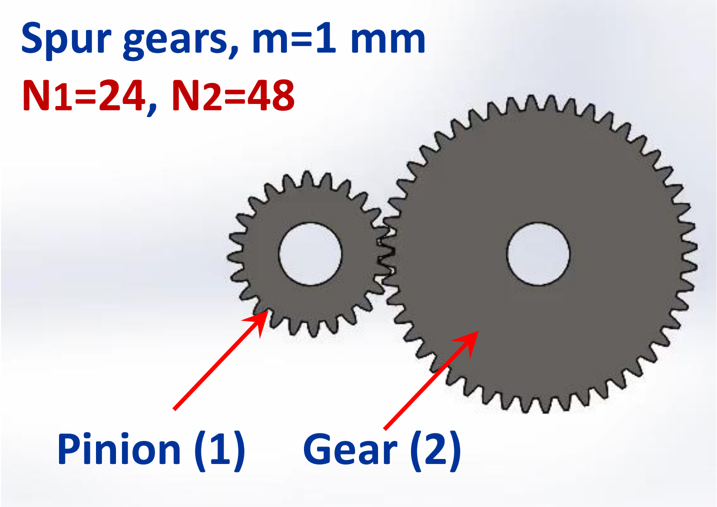
m is Module, *in mm (SI unit)*

N is number of teeth

An example: Power & torque calculation of a gear train

- **Power equation of a rotating system** (as of the air motor)

$$P = T \times \omega \qquad \& \qquad \omega = \frac{2\pi}{60} n$$



where,

P is power (W),
T is torque (Nm),
ω is rotating speed (rad/s),
n is rotating speed (rpm).

For the simple gear train shown, the power input is ***P = 50 W*** from **pinion (1)** at ***n1 = 200 rpm***. Calculate the rotating speed and torque output from **gear (2)**.

Note: Spur gears are highly efficient so **power loss can be neglected in calculation**.

1) Use gear ratio equation: $Z = \frac{\omega_1}{\omega_2} = \left(\frac{n_1}{n_2}\right) = \frac{N_2}{N_1}$ $\qquad n_2 = \frac{N_1}{N_2} \times n_1 = \frac{24}{48} \times 200 = 100\ (rpm)$

2) Use power equation:

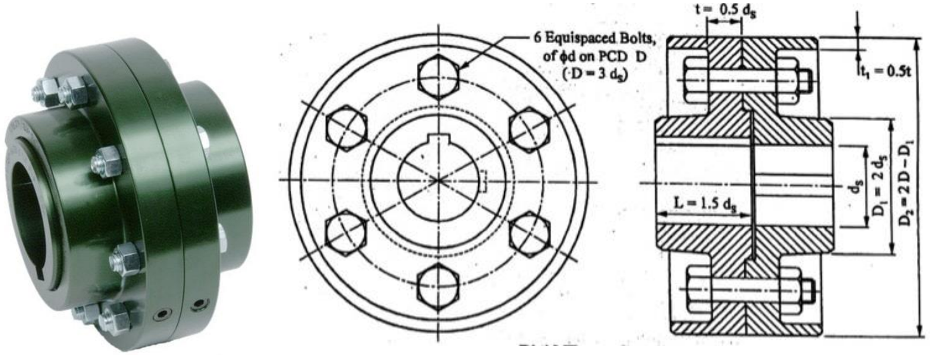
$$T_2 = \frac{P}{\omega_2} = \frac{P}{n_2} \times \frac{60}{2\pi} = \frac{50}{100} \times \frac{60}{2\pi} = 4.8\ (Nm)$$

Can you calculate torque & speed of the 2-speed gearbox at given operation condition?

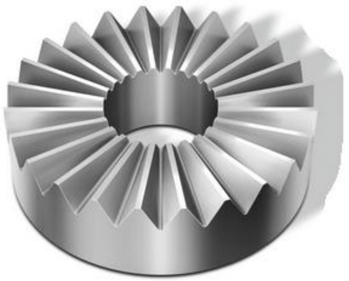
Couplings and Clutches

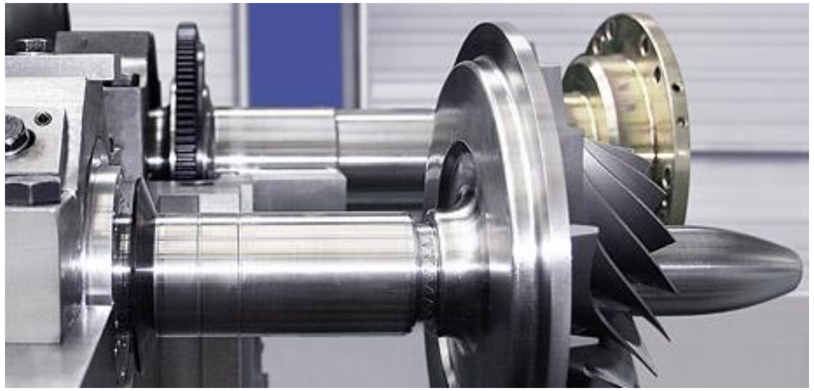
Machine system
Part 2

- **Couplings** are commonly used to connect two rotating shafts in line
- **Clutches** are used to engage and disengage two rotating shafts



Rigid flange coupling

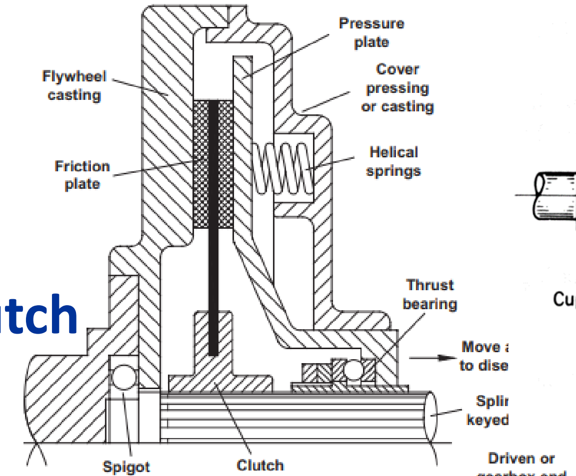




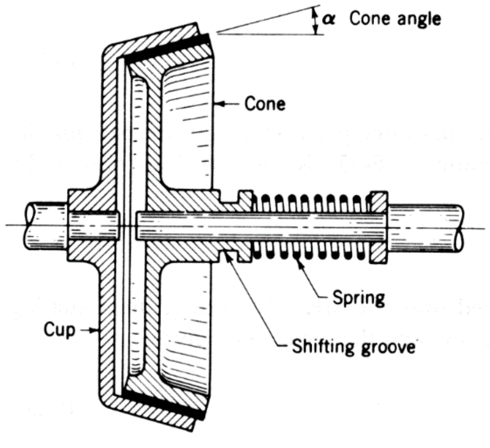
Hirth coupling used in high speed rotating shaft

Oldham coupling

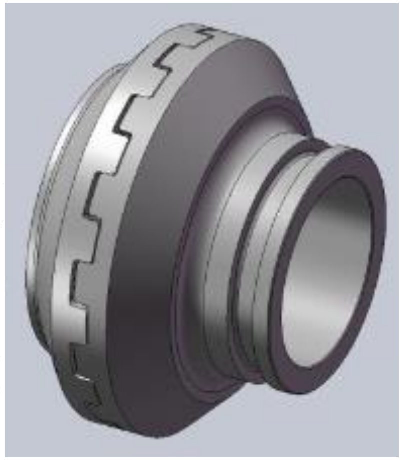
Bushed pin coupling



Disc clutch



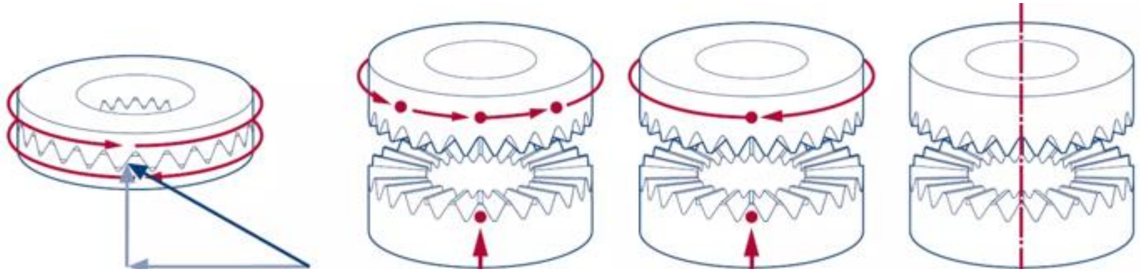
Cone clutch



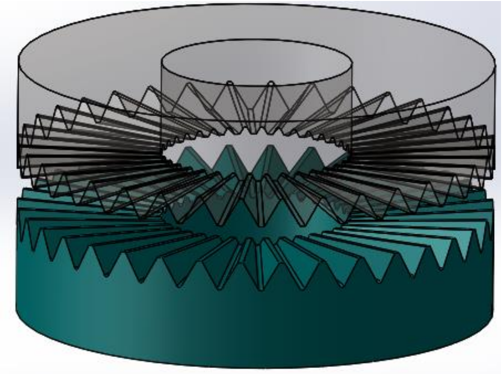
Dog teeth clutch

Hirth Coupling and Clutch

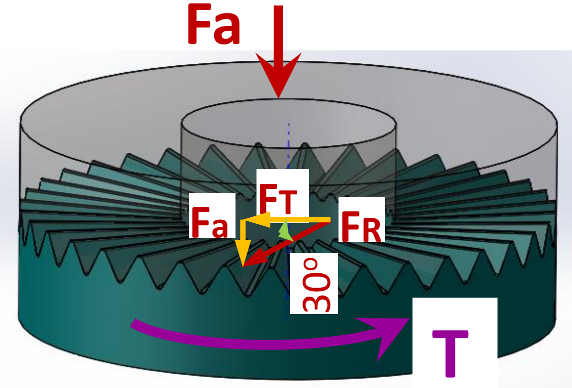
- Hirth couplings have advantages of positive locking, high indexing and repeat accuracy, self-centring and torque capability
- Hirth coupling can be used as Clutches as in the Gearbox Actuator to engage and disengage by applying axial force (see Fig 2 Project brief)



https://voith.com/corp-en/products-services/connection-components-couplings/hirth-serrations.html



Disengaged



Engaged

$$F_a = kF_T \tan\left(\frac{\pi}{6}\right)$$

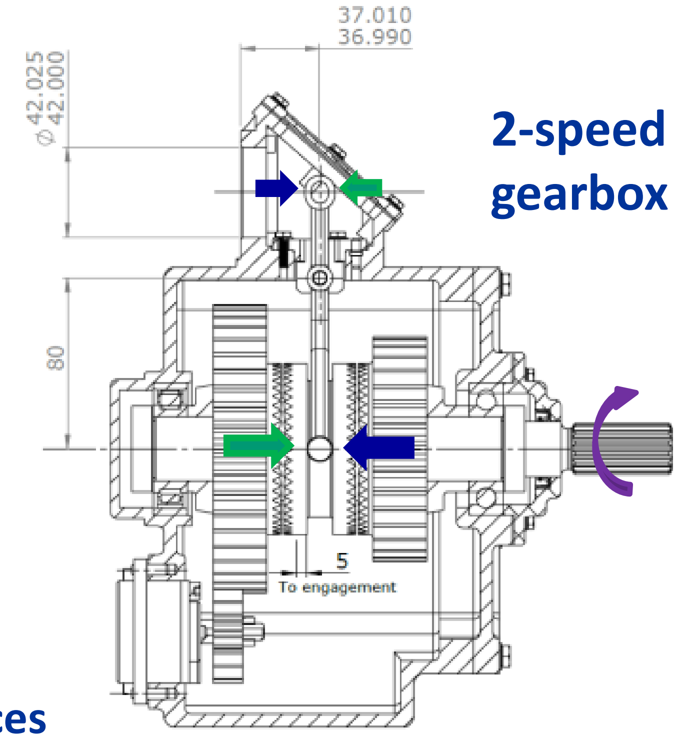
$$F_T = \frac{T}{R_m}$$

where, *k=1.5*

Fa, FT – axial, tangential forces

T – torque

Rm – medium radius of Hirth coupling



2-speed gearbox

Can you work out the axial force & torque relations of the Gearbox Actuator design?

Summary

- **Embodiment** is an important design stage, which requires iterations to ensure
  - Proper functions with **clarity, simplicity and safety**
  - Detailed evaluation of **load path** and specification of **sub-functions & working mechanisms**
  - Sufficient consideration to design for production, assembly, operation & maintenance

- Embodiment design involves **iteration and sound decision making**, which requires
  - **Clear understanding** of requirements for **function and power, forms of motion, speed, load, reliability,** etc
  - **Detailed evaluation** of **suitable power drives**, e.g. different types of motor or hydraulic/pneumatic actuator
  - **Correct calculation** of **torque capability, power range, inertia and other measures**
  - **Effective use** of **BSI/ISO standards and manufacturer's catalogues** to **select power drives, transmission units and standard components**
  - **You can** use these methods/principles in the **Individual (Gearbox actuator) design**

Machine system design

End of Session