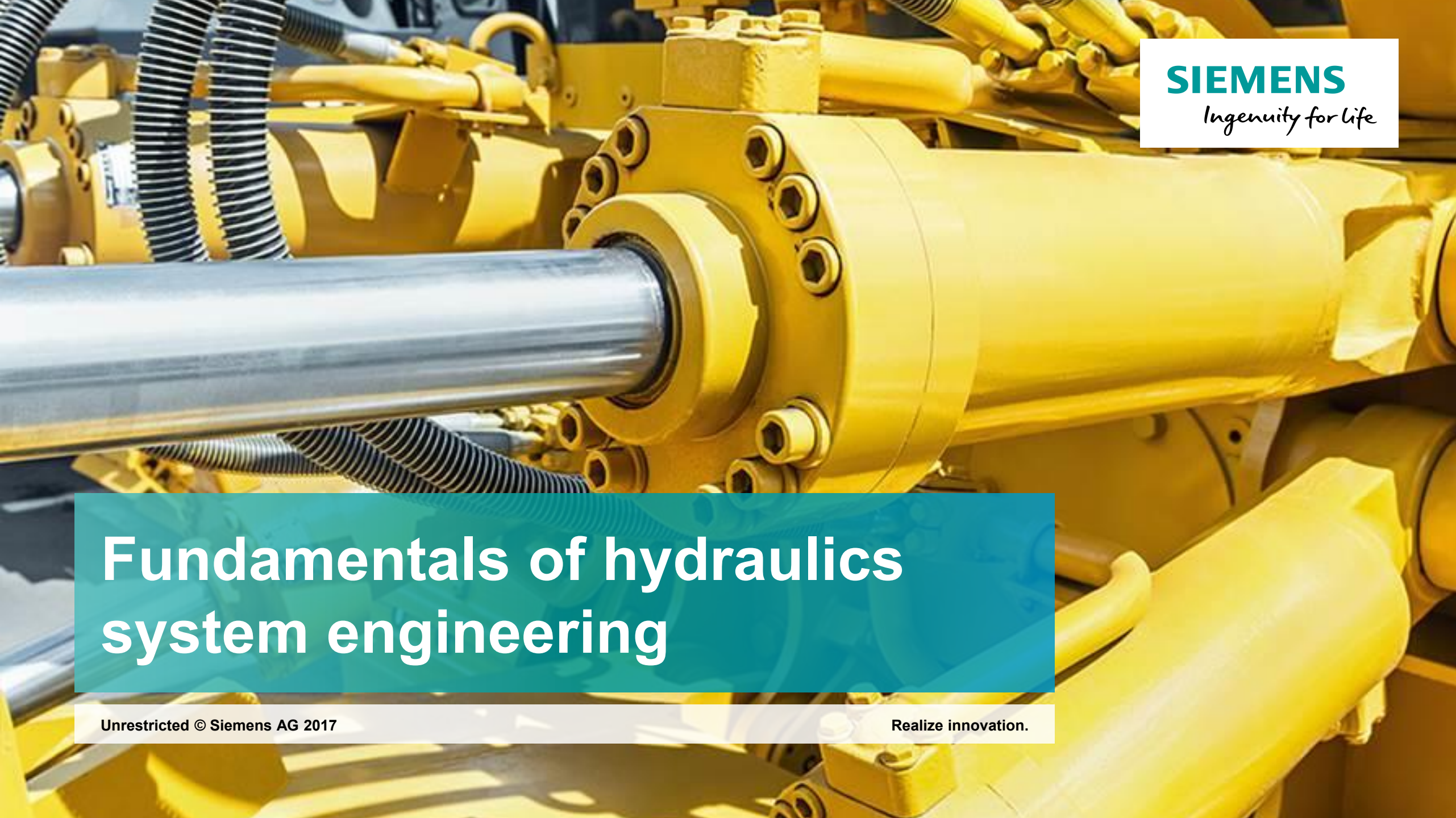

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Fundamentals of hydraulics system engineering

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Why hydraulics is so important in the industry?

What is an hydraulic fluid?

The **hydraulic fluid** represents one of the most important elements in the hydraulic system, with several tasks:

- Power/Energy transfer
- Generation and transmission of pilot signals for hydraulics
- Lubrication
- Heat transfer
- …others (corrosion protection, particles carrying …)

How to define a fluid?

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A lot of terms are usually associated with the description of a fluid:

Density **Compressibility** **Viscosity**

Thermal conductivity Specific heat Electrical properties

Stability Toxicity Lubricity… **Properties**

Saturation pressure Vapor pressure Flash and boiling points

Surface tension Thermal expansion… **Parameters**

Aeration Cavitation Foaming… **Phenomena**

However, **only a few of them are used** for dynamic hydraulic modelling.

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Fluid properties

Fluid density

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The **density ρ of a fluid** is defined as the mass per unit volume:

$$\rho = \frac{M}{V} \qquad [\,\mathrm{kg/m^3}]$$

where, using SI units:

M is the mass of the fluid [kg]

V is the volume of the fluid [m³]

The density is a function of:

- pressure
- temperature
- type of fluid

$$\rho = f(P, T, fluid)$$

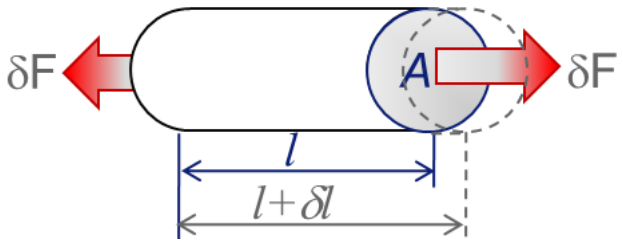
Density includes mass, hence it is responsible for inertia effects

Fluid compressibility

- **Every substance is**, to a certain extent, **compressible**!

- Similar to the the linear expansion caused by the pulling effort *dF* on a rod …

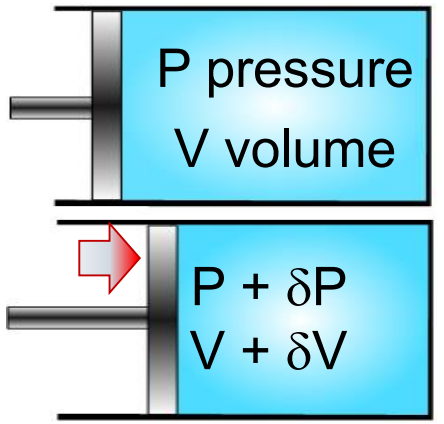
… the volume reduction $\frac{\delta V}{V}$ is linked to the pressure increase *dP*



$$\frac{\delta L}{L} = \frac{1}{E \cdot A} \cdot \delta F$$

with E: Young's Modulus of the material

Note: this is a deformation due to traction. With a compression force, a minus sign appears.

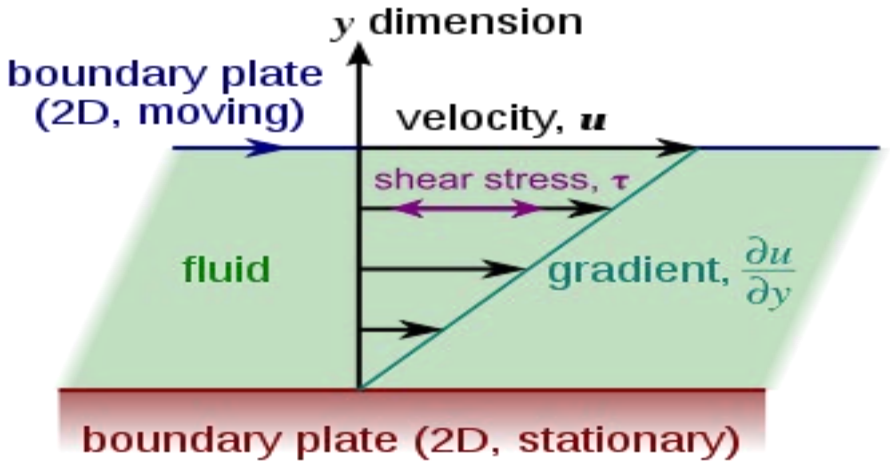


$$\beta(P,T) = -V \cdot \frac{\delta p}{\delta V}$$ **Fluid Bulk Modulus**

$$C_{fluid} = \frac{V}{\beta(p,T)}$$ **Fluid compressibility**

Fluid viscosity

In everyday terms, **viscosity is the inner molecular friction** between two adjacent fluid elements.



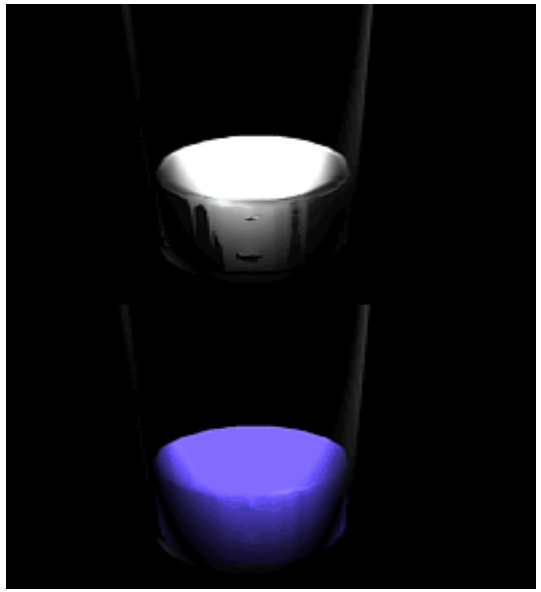
According to Newton's law:

$$F = \mu \cdot A \cdot \frac{dv}{dy}$$

A: contact area between the two layers

μ: absolute viscosity

v: fluid velocity

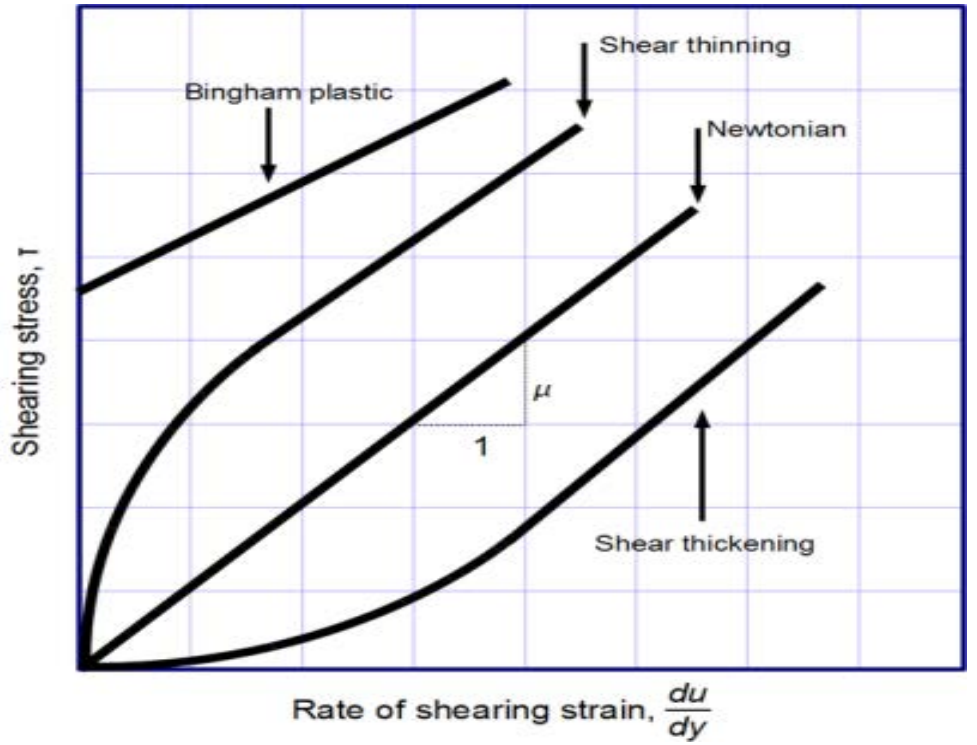


- Viscosity results from an exchange of quantity of movement by molecular diffusion between 2 layers of fluid with different velocities.
- In this sense, the viscosity is a fluid property and not a flow property.

Fluid viscosity

A **Newtonian fluid** has a stress-strain curve that is linear:

$$F = \mu \cdot A \cdot \frac{du}{dy}$$



A **non-Newtonian fluid** has a stress-strain relationship which is non-linear, and can even be time-dependent.

Fluid viscosity

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Newtonian or Non-Newtonian?

Ketchup

Honey

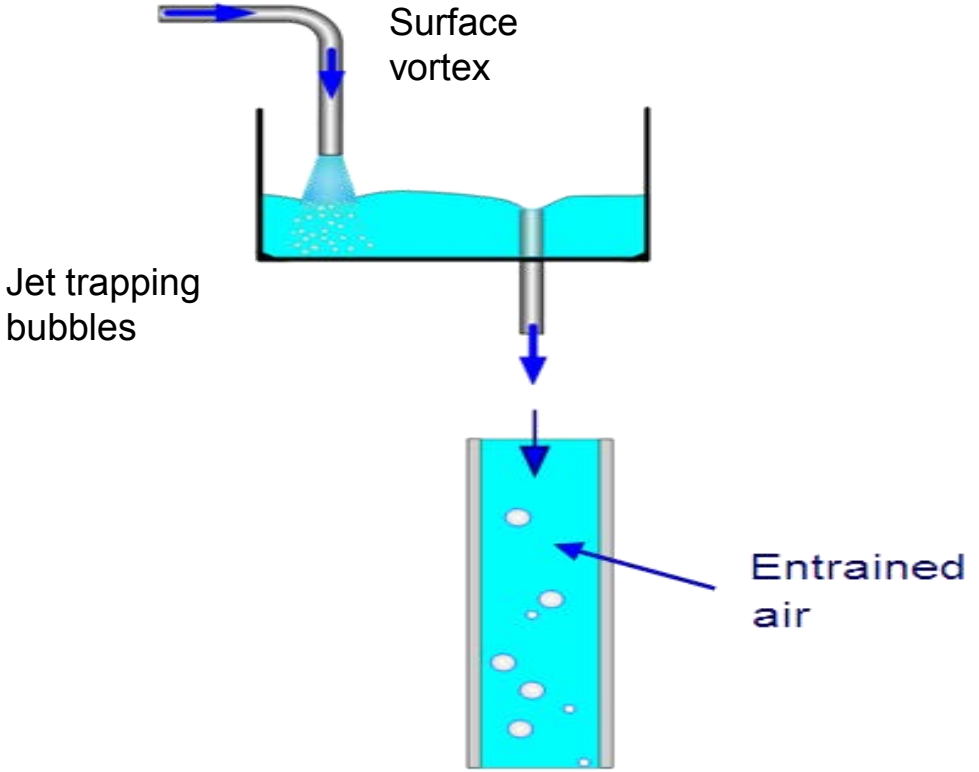
Water

Fluid phenomena

Aerated liquids

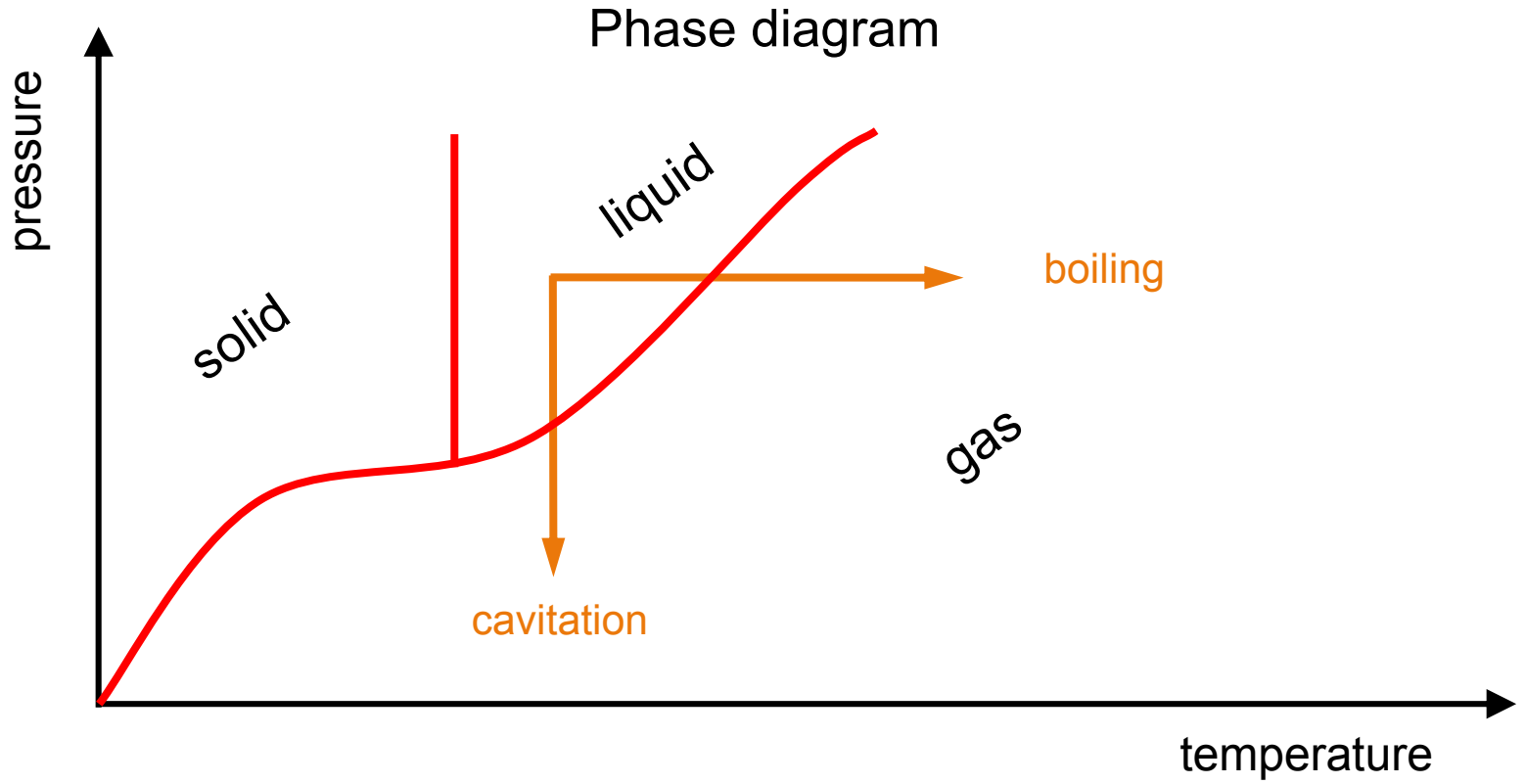
Very often, the fluid used in the hydraulic system is **aerated**.

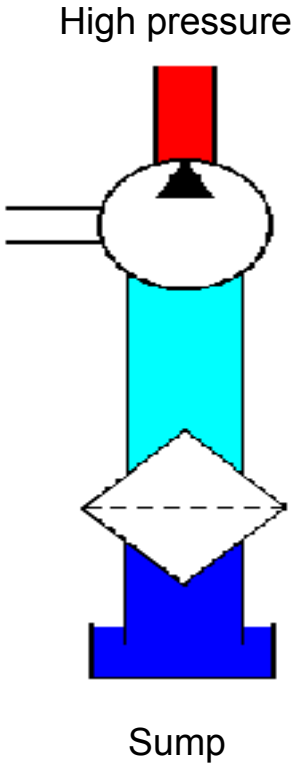
Lubricant aeration in running engine



Fluid cavitation

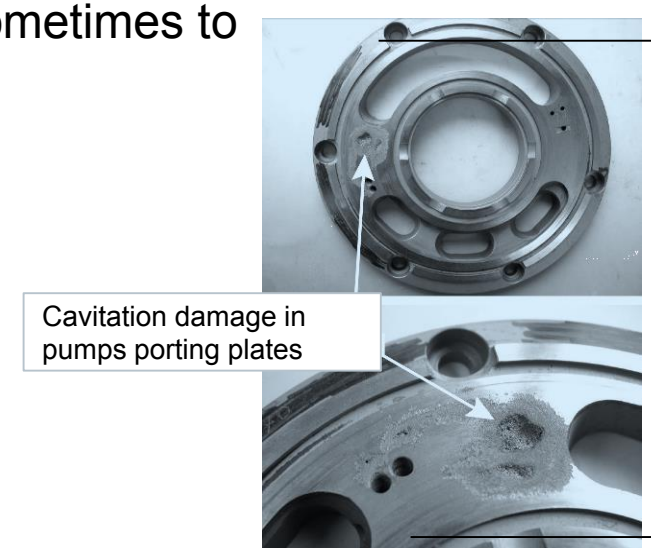
Cavitation is the formation of vapour bubbles inside the fluid due to the **pressure decrease below the vapour pressure** (phase change)

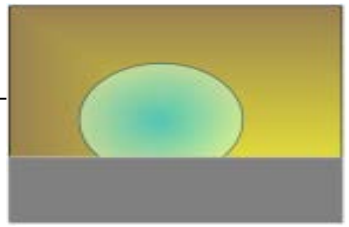


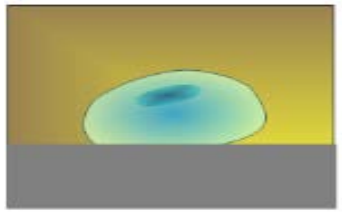


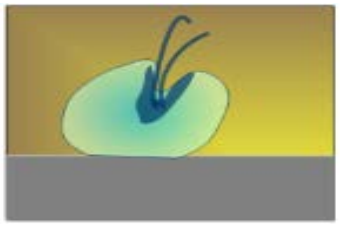
Fluid cavitation

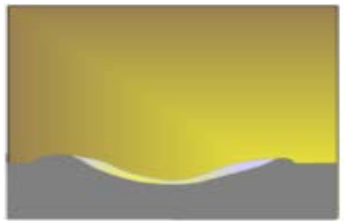
- In fluid systems the term "**cavitation** " usually refers to the formation and collapse of cavities in the liquid.
- The cavities may contain air or gas. If the pressure is low enough, the liquid starts to vaporize and vapor cavities will form.
- **Cavitation damage**:
  Some aspects of the bubble growing and its implosion that leads sometimes to destruction of material.




Initial Bubble

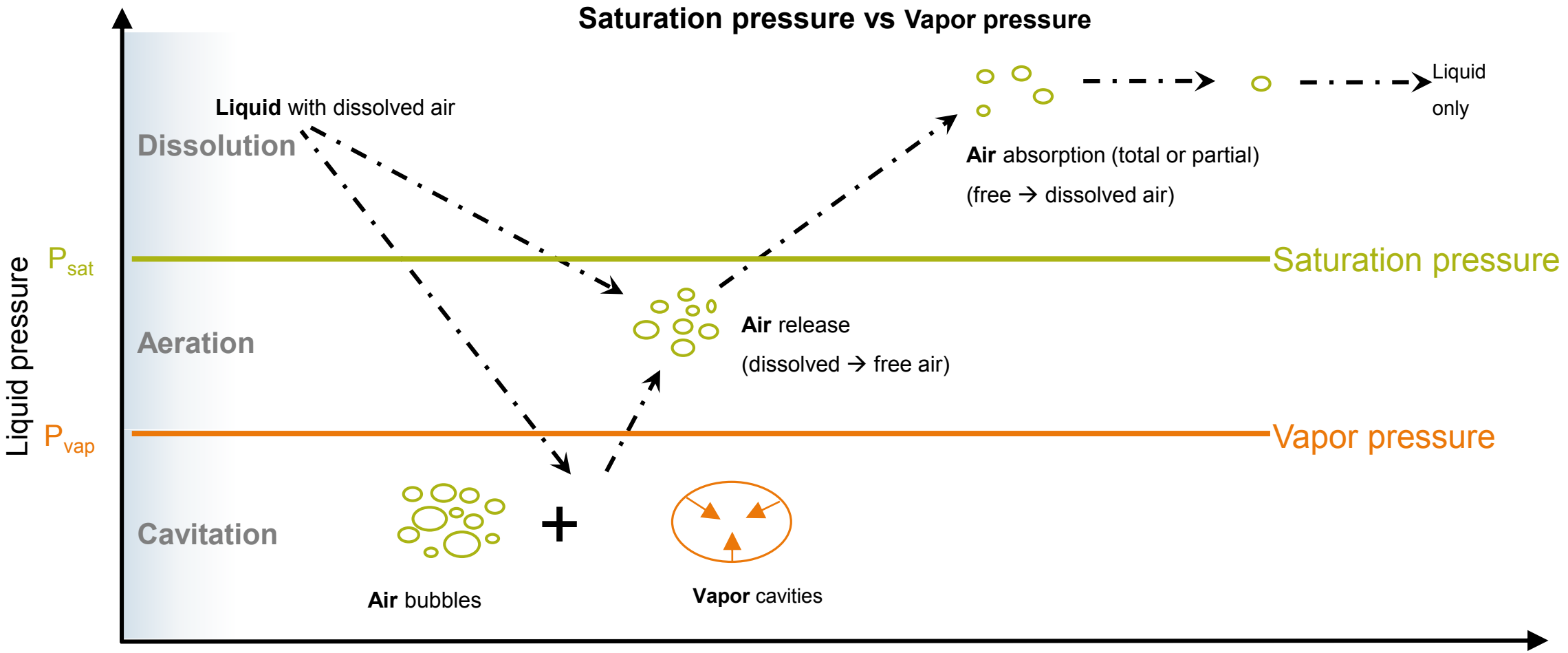

Initiation of Bubble Collapse


Forming of liquid jet


Impact and metal extrusion

Fluid parameters

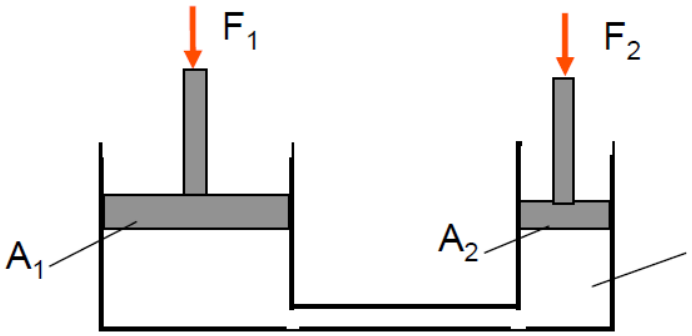
Saturation pressure and vapor pressure



What is an hydraulic system?

Hydraulic systems

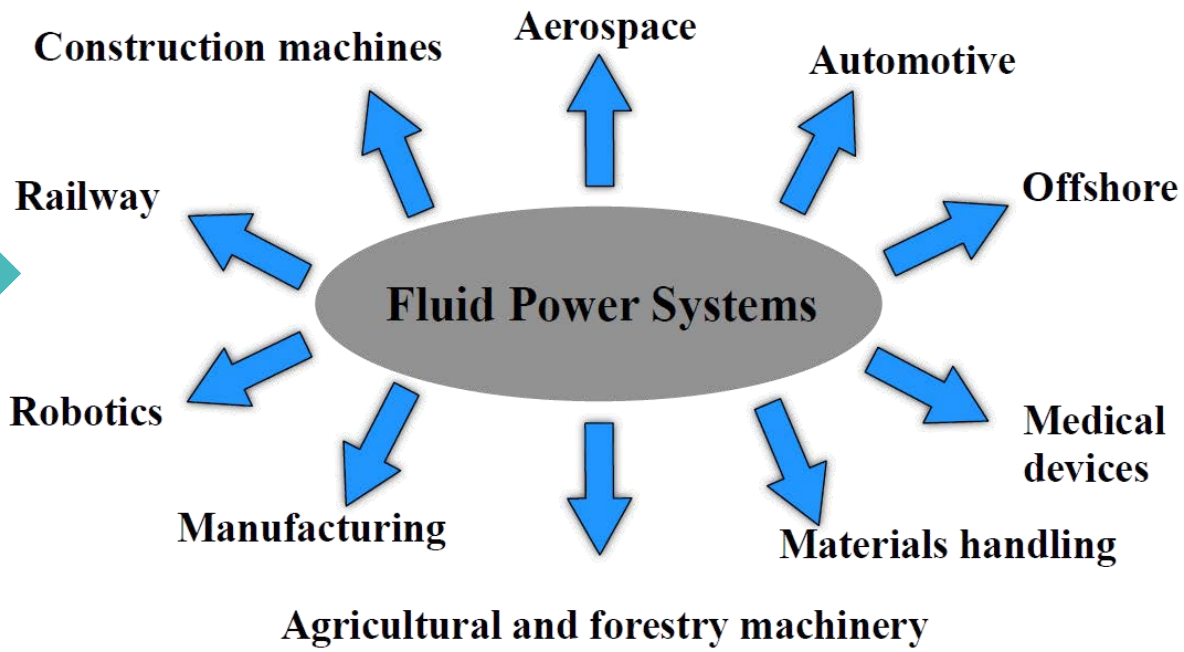
Hydraulic systems rely on **capability of the liquid to transmit forces with the help of the static pressure**. Thus we can build **components to multiply forces**!



$$p = \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

"*Any change of pressure at any point of an incompressible fluid at rest, is transmitted equally in all directions.*"

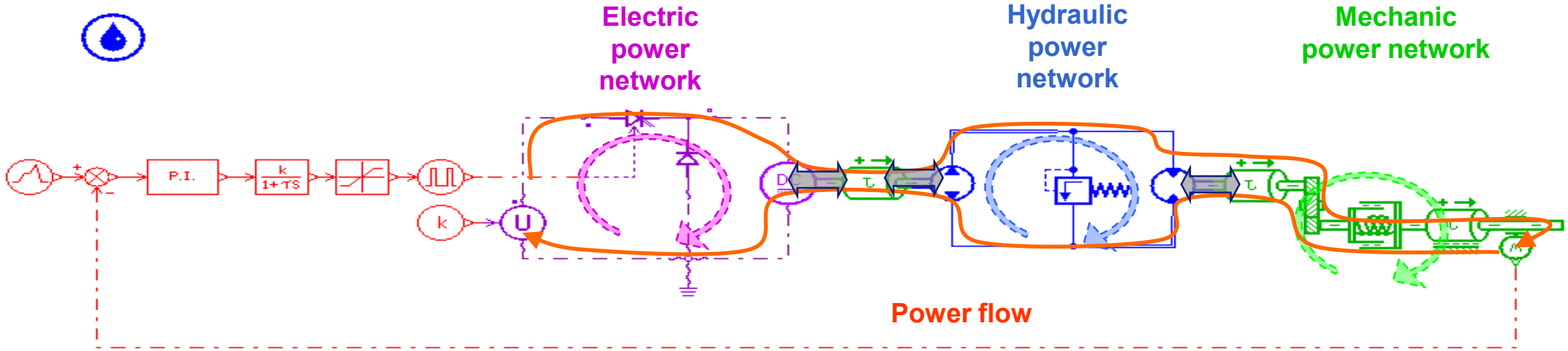
Pascal, 1651



Hydraulic systems

Hydraulic systems include hydraulic components:

- Hydraulic **pumps**: transforming the input mechanical or electrical energy into output hydraulic energy
- Hydraulic **valves** to control either flow or pressure
- **Auxiliaries**: filters, heat exchangers, reservoirs …
- Hydraulic **lines**: rigid pipes or hoses, conducting the liquid along a distance (that can be very long) also in an open space → transmission lines
- Hydraulic **actuators**: transforming the input hydraulic energy into output mechanical energy (**rotary** actuator: hydraulic motor, **linear** actuator: cylinder)



Hydraulic pumps and motors

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The function of the **pump** is to **generate a flow rate to hydraulic circuit**.
The pump flow rate is usually a function of pump speed, pressure head, …

Different types of pump technologies:

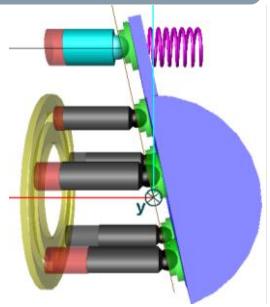
- **Hydrostatic pumps** (pistons, membranes, gears, vanes…) based on the volume-displacement principle
  - with inlet and outlet check valves (opening/closing controlled by pressure), or
  - with inlet and outlet ports (e.g. bean shape, opening and closing function of the rotation angle)
- **Centrifugal pumps**

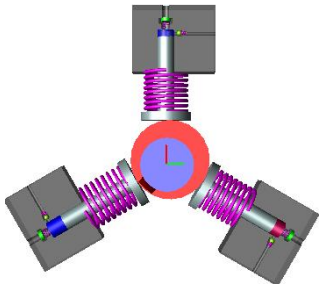
The function of the motor is to drive a rotary shaft (with a certain load applied) using the hydraulic power.
Hydraulic motors are mostly used in the fluid power industry.

Many hydrostatic pumps based on displacement principle

Piston pumps

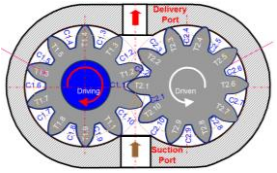
- Axial piston pumps
  - Swash plate
  - Bent axis
- Radial piston pumps
- In line piston pumps

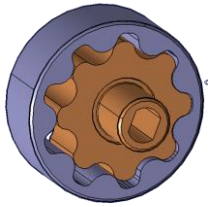




Gear pumps

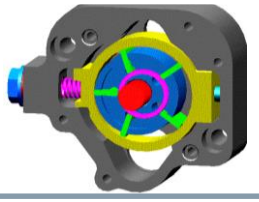
- External gears
- Internal gears

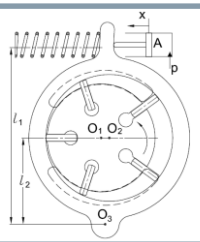




Vane pumps

- Translating stator ring
- Rotating stator ring

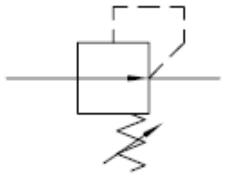




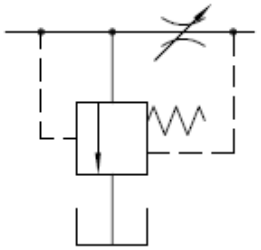
Others...

Hydraulic valves

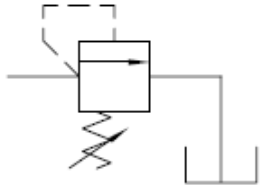
The function of hydraulic valves is either to **control a certain variable** or to **provide the flow rate to the right final consumers**.



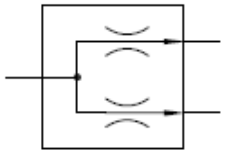
Pressure reducing



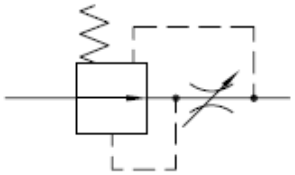
Flow control



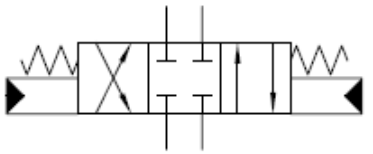
Limiting pressure



Flow divider



Flow control



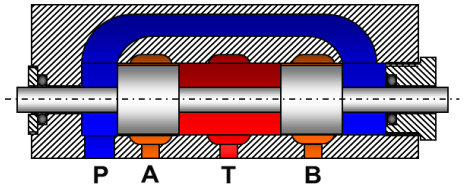
Directional control

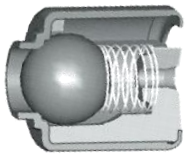
… and many others!

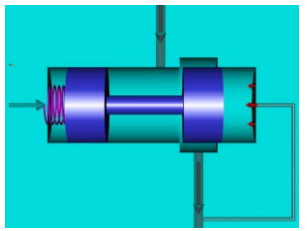
Different classifications of hydraulic valves, depending on...

Regulated / controlled variable

- Directional control valves
- Pressure control valves
- Flow control valves

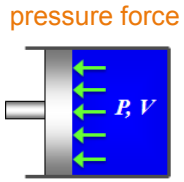


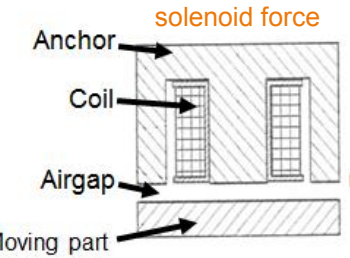


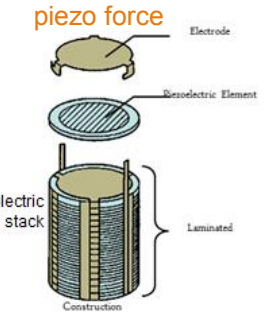


Type of valve operation

- Mechanic
- Hydraulic / pneumatic
- Electric:
  - Solenoid actuation: continuously variable force or PWM
  - Piezoelectric actuation (fast dynamics)

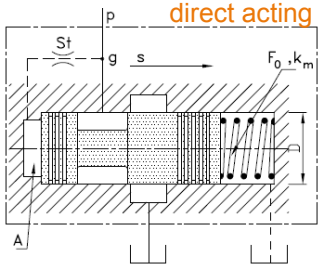


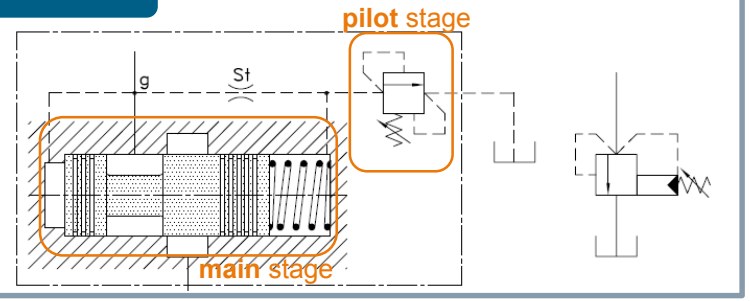




Number of stages

- One main stage: direct acting valves
- Pilot and main stages (high power):
  - Piloted valves





Auxiliaries: accumulators

- An accumulator is a liquid reservoir in which a fluid is held under pressure by an external source like a spring or a gas volume.

- Accumulators can have different functions either for fast or slow operating conditions of the hydraulic system:
  - Solve the problem of liquid expansion with temperature
  - Reduction of the pressure pulsations (waves)
  - Compensation of rapid changes in flow delivery or consumption
  - Maintain the pressurization of a liquid (when the pump is stopped, leakages compensation…)

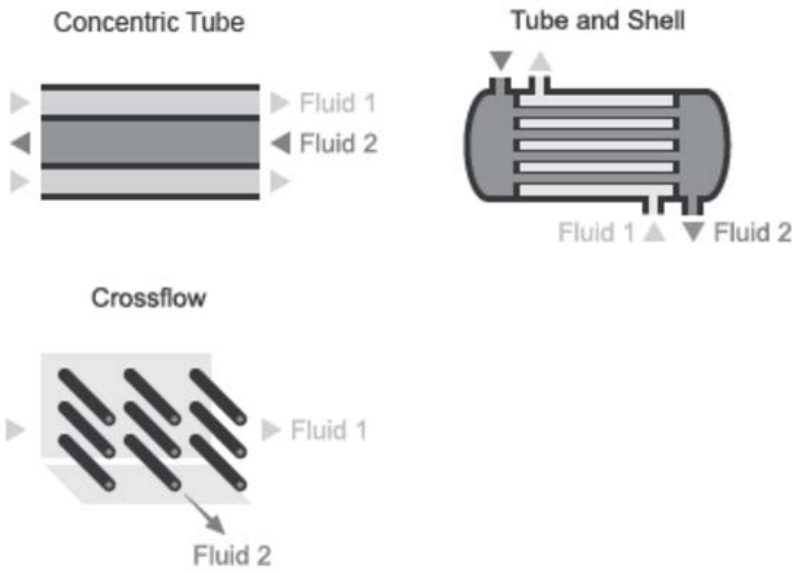
Auxiliaries: heat exchangers

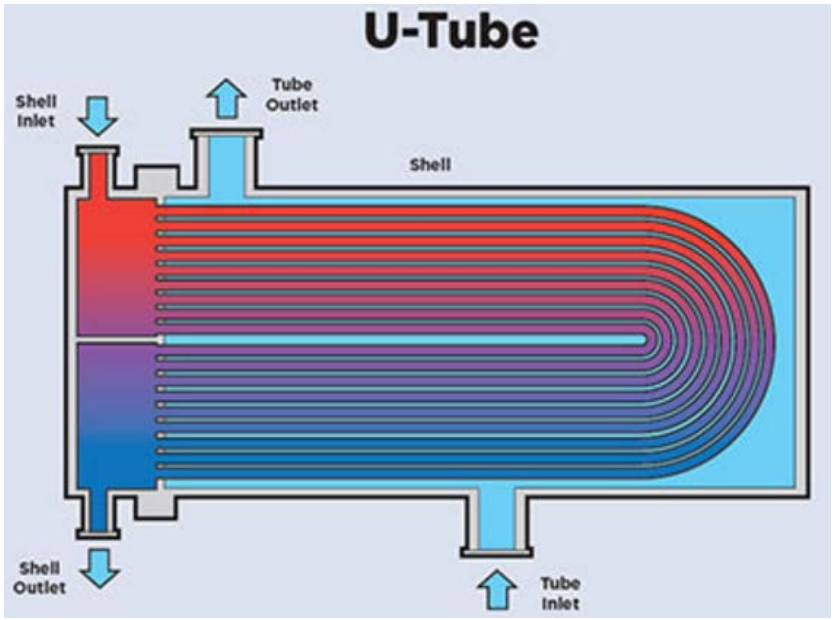
Heat exchangers are **components for heat transfer between a solid material and fluids (gas or liquids)**

Several types of heat exchangers exist:

- Liquid / Liquid
- Liquid / Gas
- Gas / Gas
- 2-phase / Gas

with **different configurations for flow directions**.



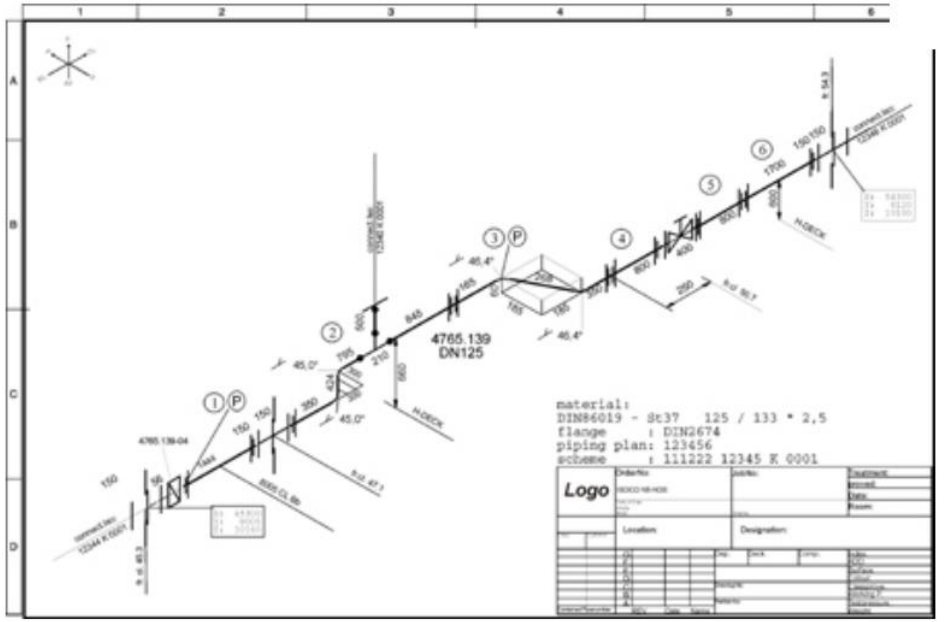


Hydraulic lines

An hydraulic line **transfer the liquid** from the inlet to the outlet.

Three fluid effects might determine the line behavior:

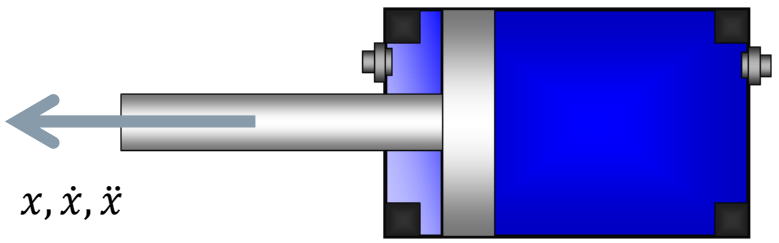
- **Compressibility** (C): pressure increase or decrease due to inlet or outlet flows
- **Friction** (R): regular pressure losses along the length
- **Inertia** (I): waves propagations



Hydraulic actuators

They **transform the inlet hydraulic power into outlet mechanical power**, either as linear or rotary motion.

Linear — **cylinders**



Rotary — **motors**

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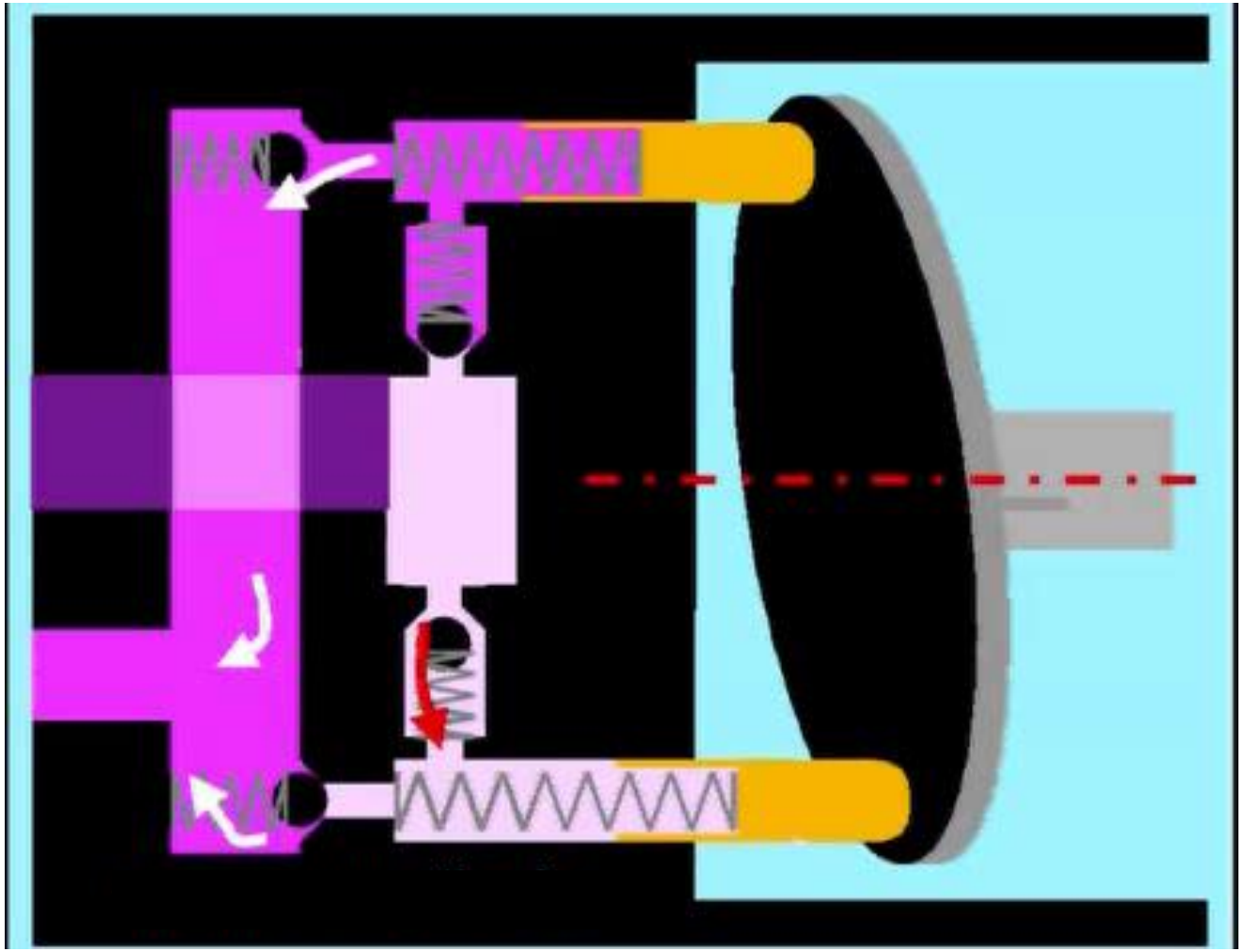
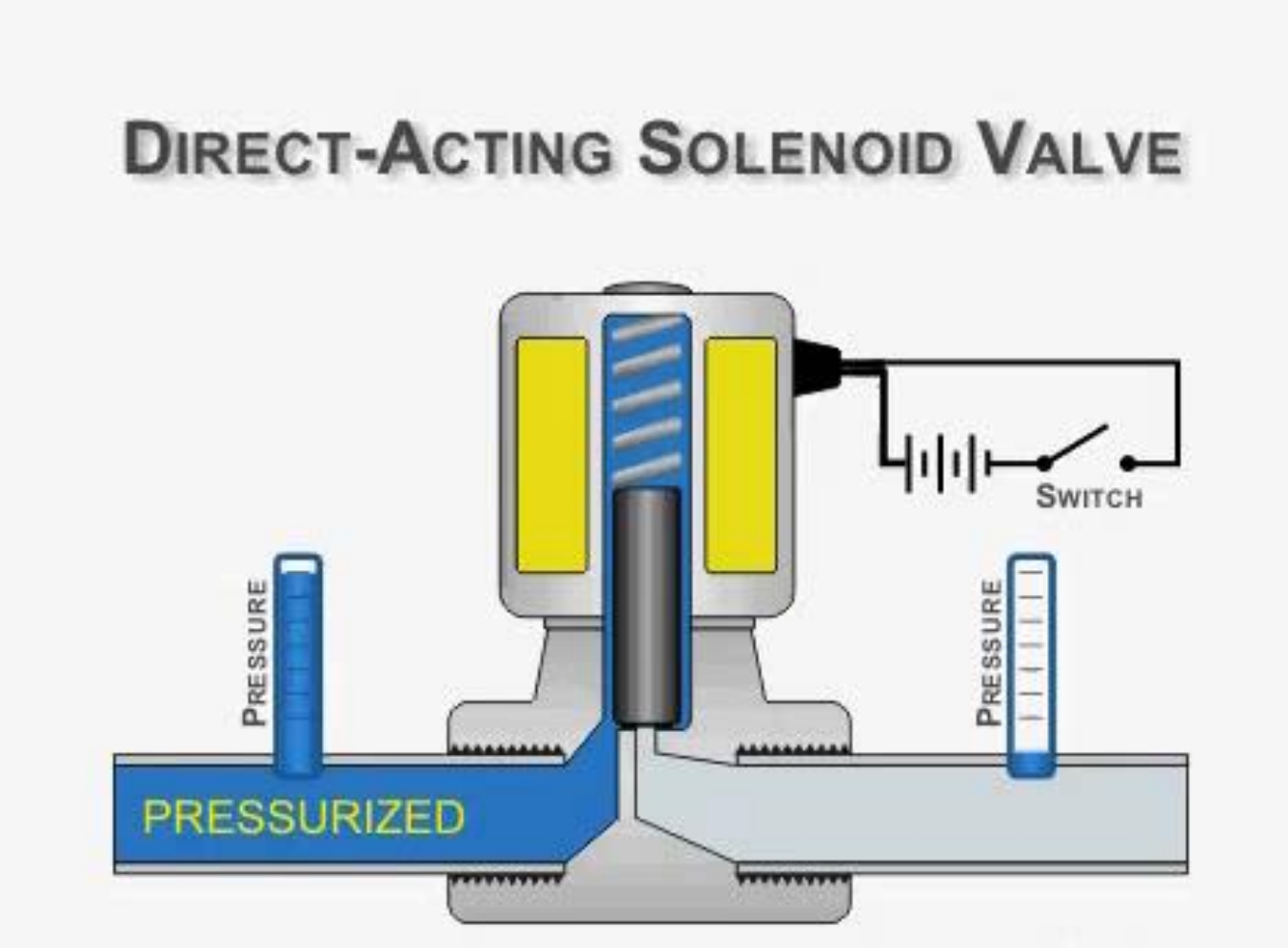
Hydraulic systems examples

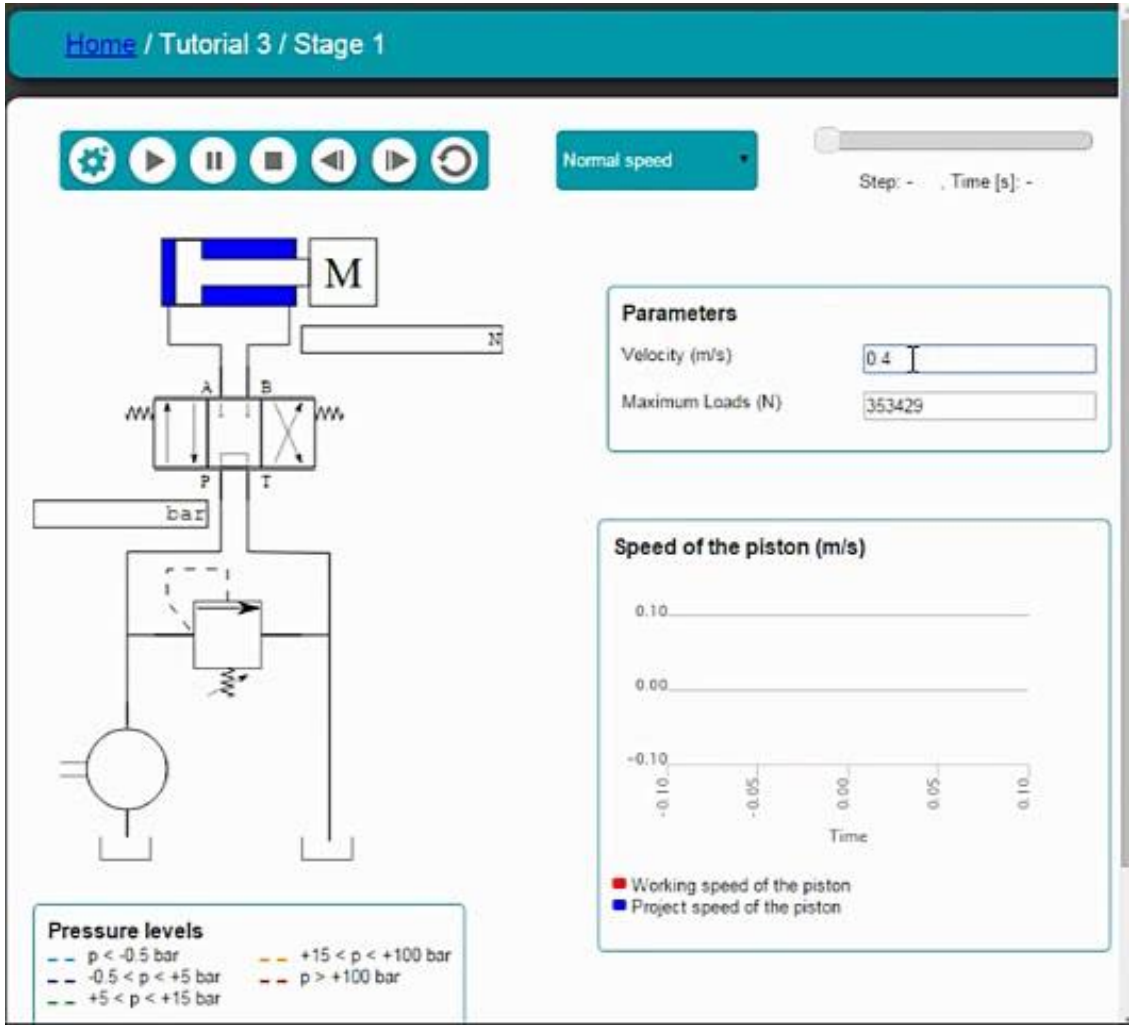
Axial piston pump – swash plate
Working principle



Direct acting 2-2 way solenoid valve
Working principle



Open-loop hydraulic actuation system for a double acting cylinder
Working principle



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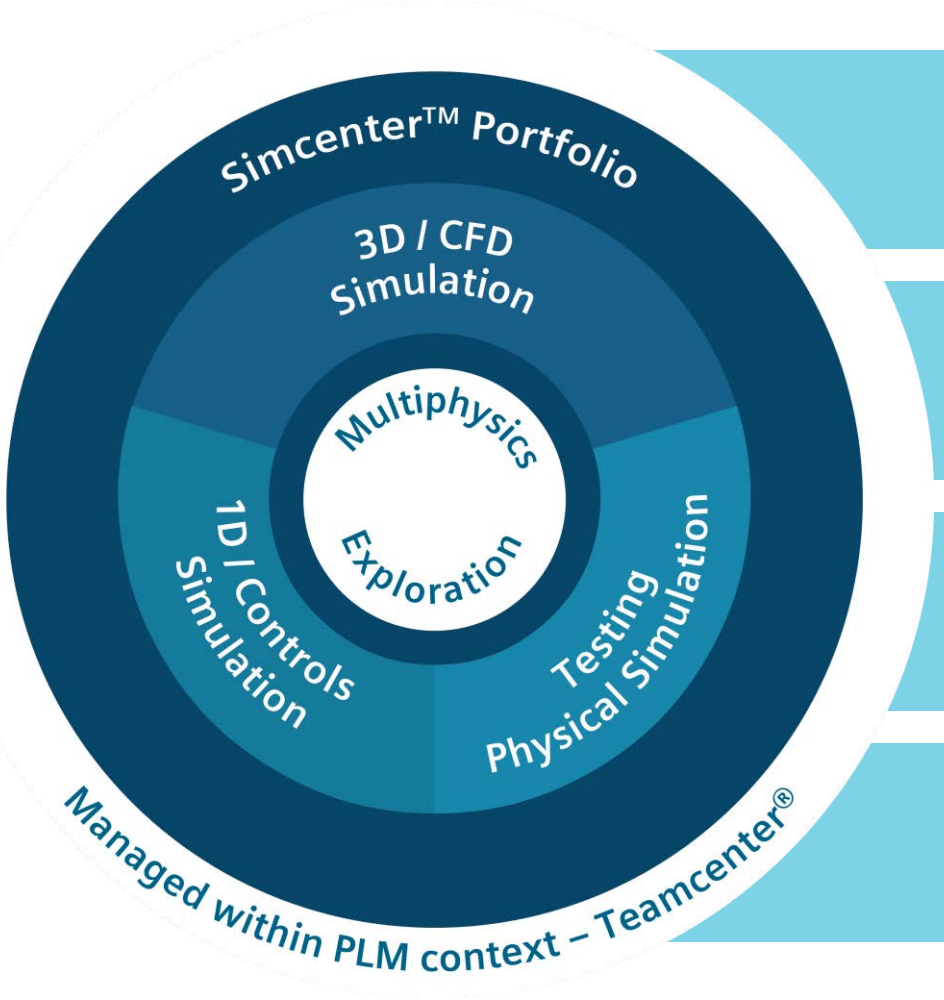

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