Aalto University
School of Engineering

MEC-E5003

FLUID POWER BASICS

Study Year 2020

Valves

Aalto University
School of Engineering

Lecture themes

How to control actuators'
- direction of movement
- velocity
- force/torque

How about the control forces or power?

Are valves just pure sources of joy?

Valves

Control of the hydraulic power (= $q_V \cdot p$)

Control of pressure:
- output forces and torques of actuators

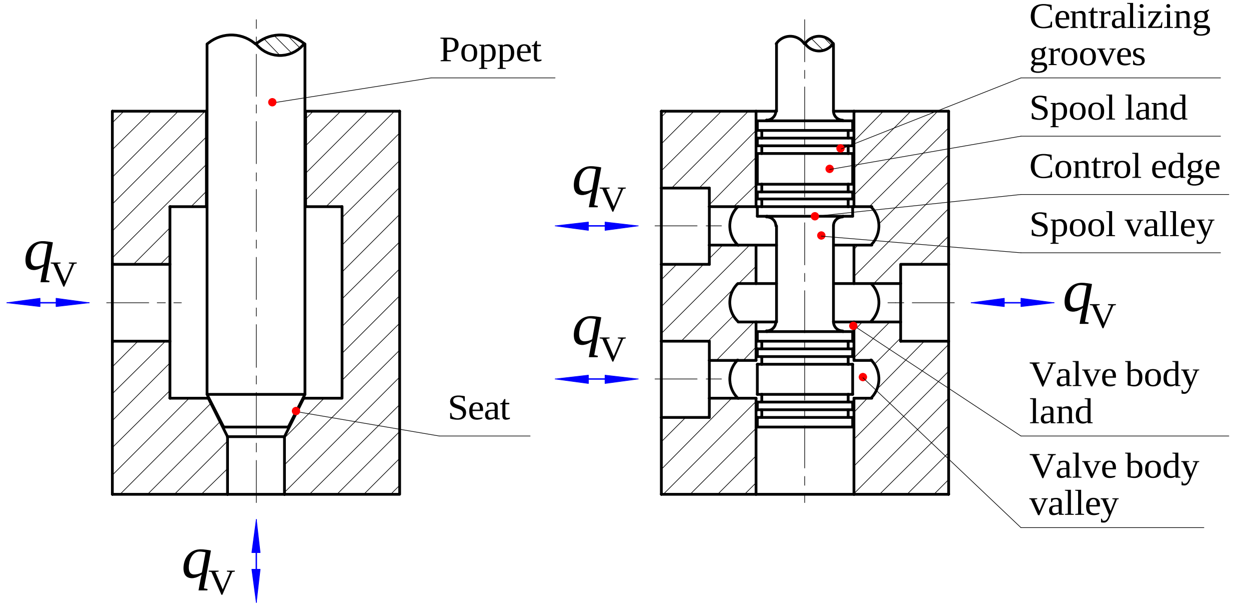
Control of flow magnitude:
- velocities of actuators

Control of flow direction:
- direction of movement of actuators

Pressure valves
Flow valves
Directional control valves

Construction

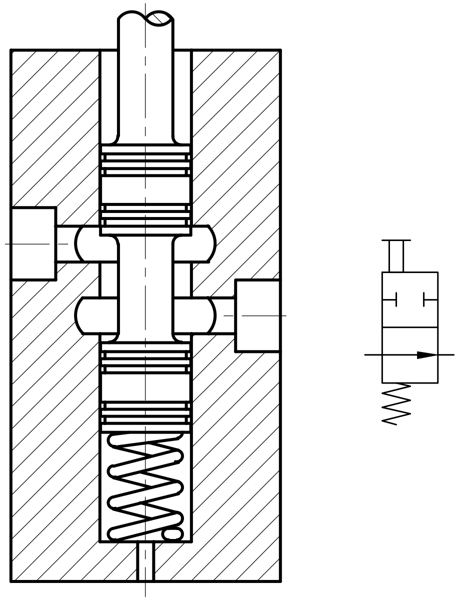
Slide types
- seat - poppet
- spool



Leakage?

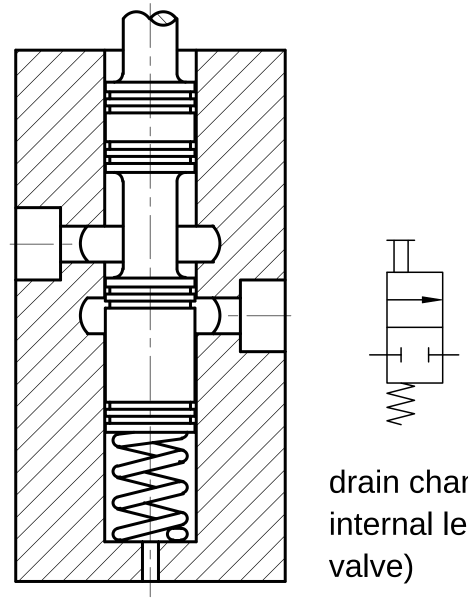
Construction types - Signal

- normally open
- normally closed



to tank

PUSH TO CLOSE



drain channel because of internal leakage (spool valve)

to tank

PUSH TO OPEN

Nominal sizes

NS = Nominal Size / NG (Nenngröbe)

Indicates the approximate inner diameter of a flow channel with circular cross-section (i.e. pipe or hose) to be connected to the valve in units [mm]

Most common sizes 6, 10, 16, 25 ja 32

Directional control valves

Control the direction of flow

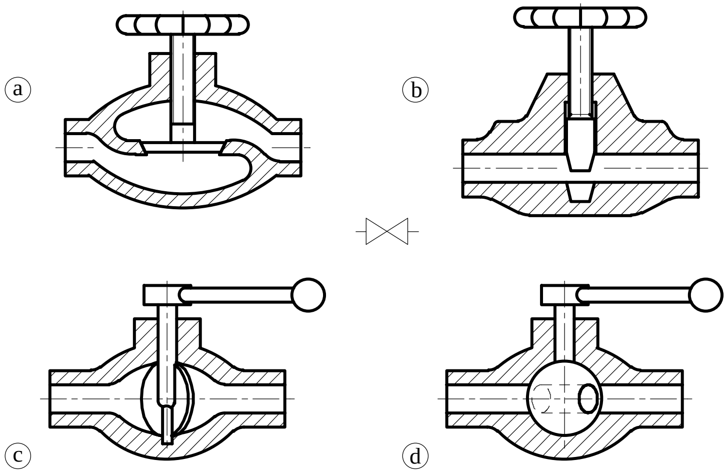
Shut-off valves
- either allow or restrain flow

Check valves
- allow flow to one direction and restrain to opposite direction

Actual directional control valves
- versatile control of flows

poppet valve
mushroom valve

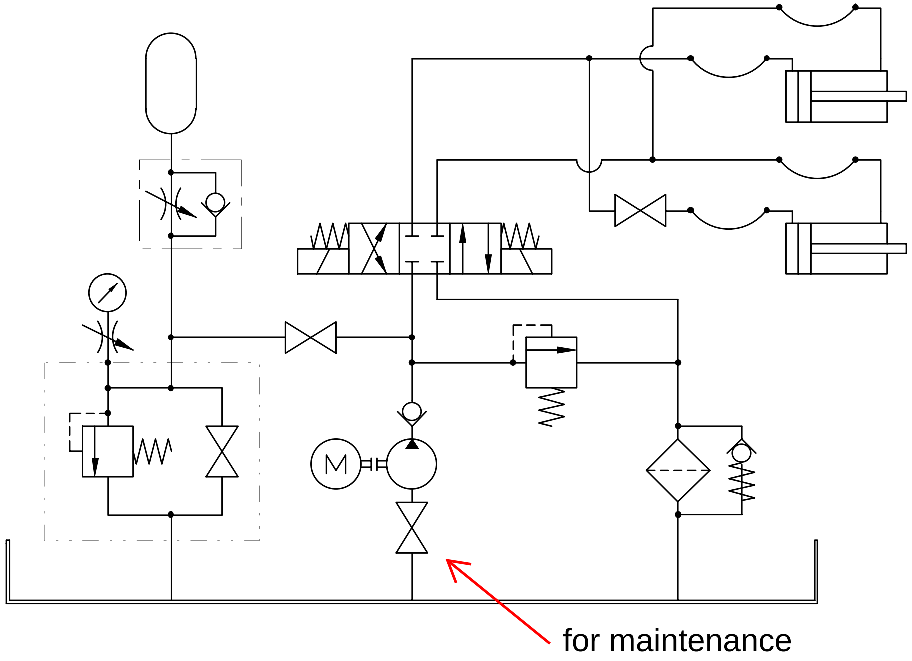
gate valve
sluice valve



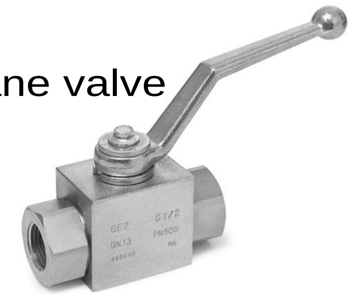
butterfly valve

ball valve

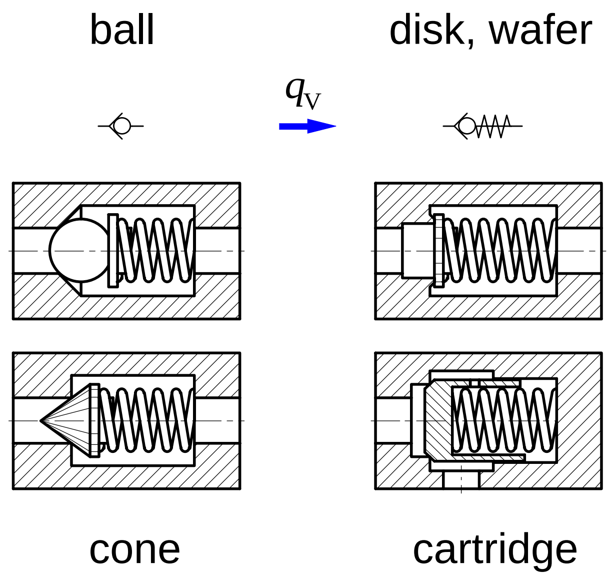
Shut-off valves
- allow or restrain flow

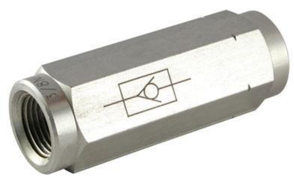


Also
- needle valve
- diaphragm/membrane valve



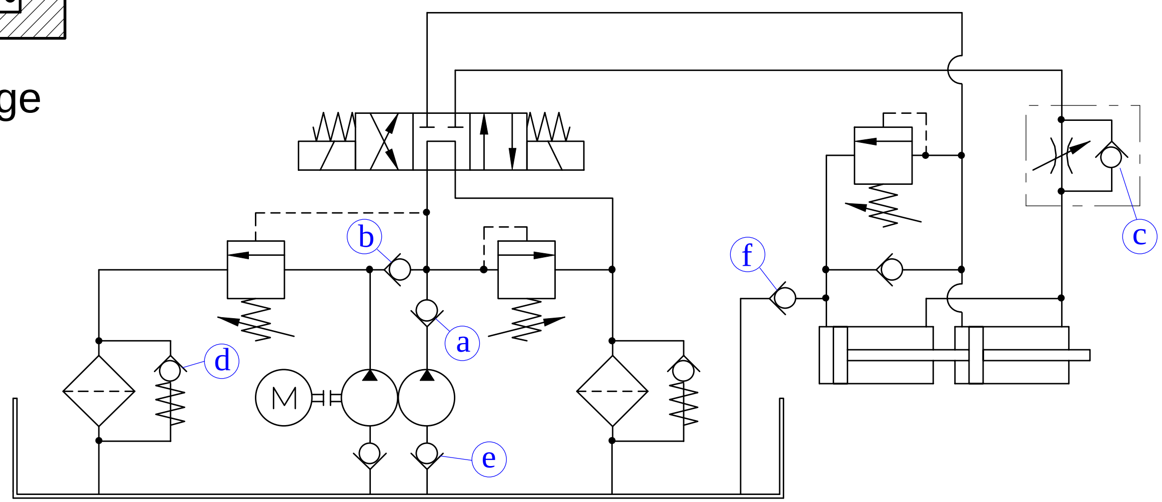
ball valve

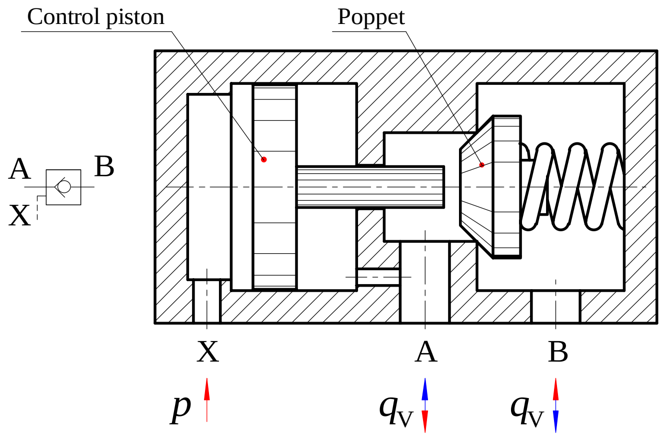


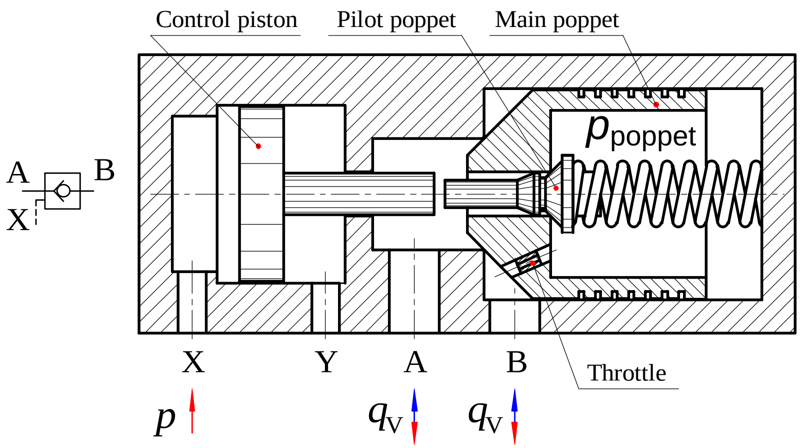


Check valves

- allow flow to one direction and restrain to opposite direction





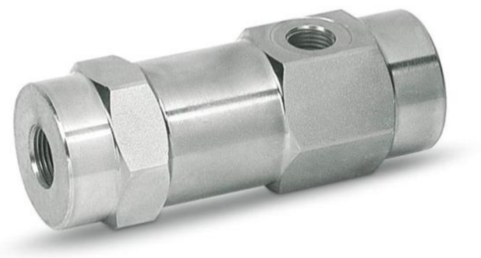


Pilot-operated check valves

- allow flow to one direction and restrain to opposite direction, but the flow can also be allowed to the normally restrained direction when the port X is pressurized

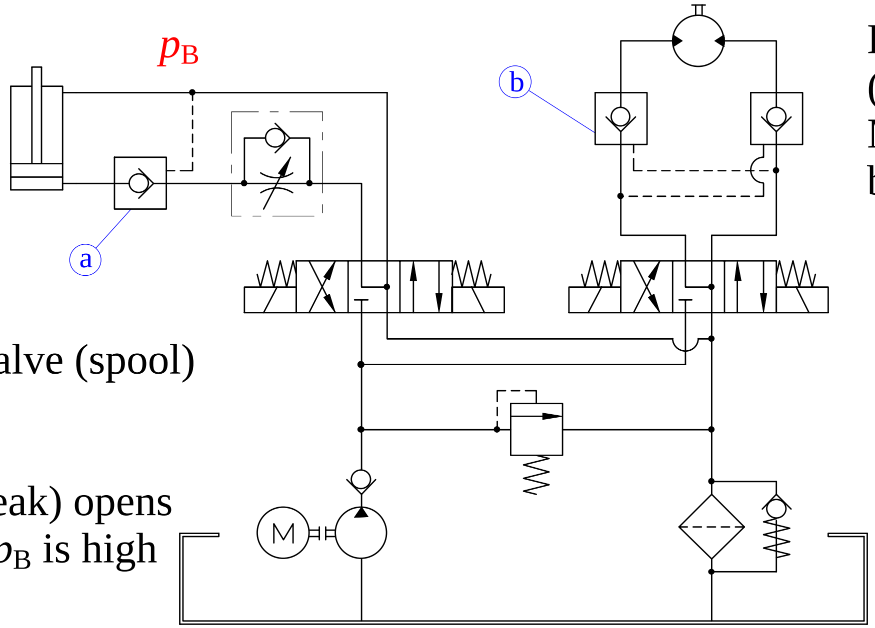
Pilot operated model (case: $p_B > p_A$), opening of B ⇒ A

- $p_{poppet} = p_B$ ("too high" for opening)
- pilot poppet opens by using moderate pressure p_X
- flow B ⇒ A through throttle



- p_{poppet} decreases ⇒ p_A
- hydraulic force (p_B), (ring area) finally wins hydraulic force in poppet-spring volume ⇒ main poppet opens letting flow from B ⇒ A

Pilot-operated check valves

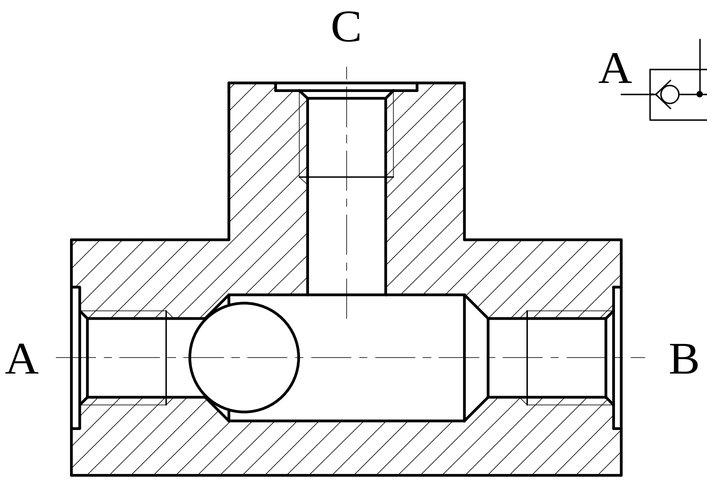


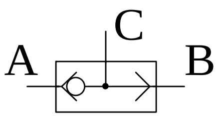
Load torque can't turn motor freely (only through leakage in motor)
Motor is operated only intentionally by using directional control valve

Problem
Cylinder load [G]
Leakage in directional control valve (spool)
Uncontrollable sinking of load
Solution
Pilot operated check valve (no leak) opens only intentionally if pressure at p_B is high enough
Running away of load is prevented

Shuttle valve

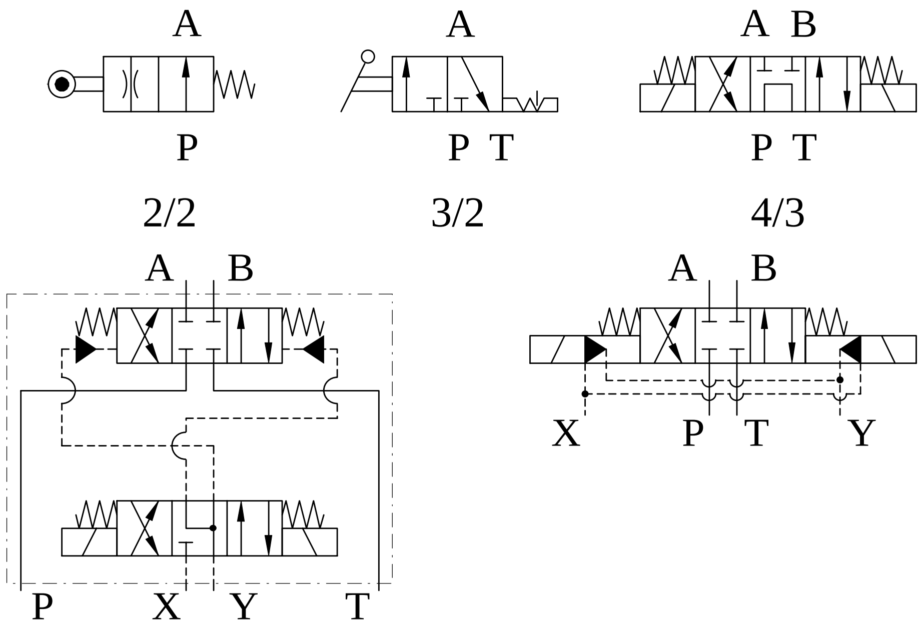
Flow direction (either A→C or B→C) is determined by the highest inlet pressure





Which inlet connection has the highest pressure?
A or B

Coding the directional control valves

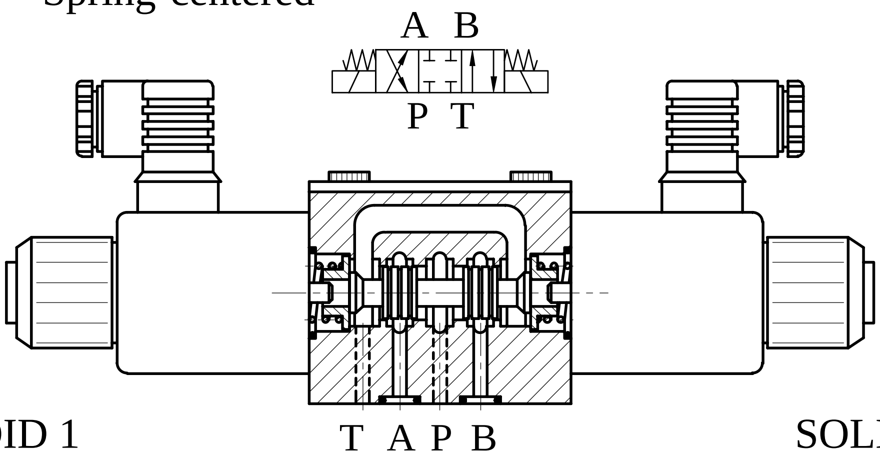


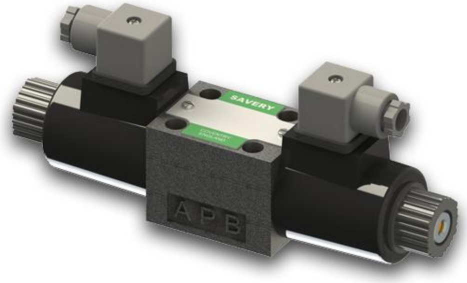
4-way, 3-position

Code: Number of connections / Number of switching positions

Slide types

Solenoid(s) operated (2)
Spring-centered

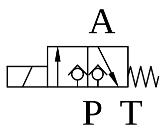


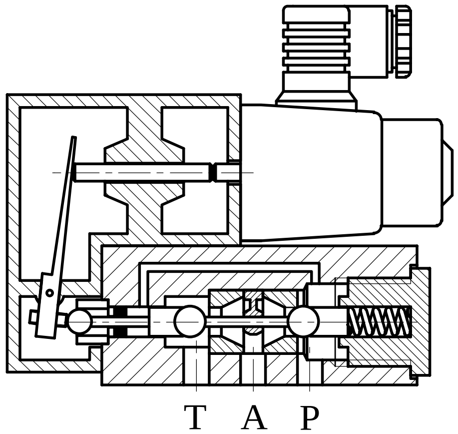


SOLENOID 1

SOLENOID 2

SPOOL

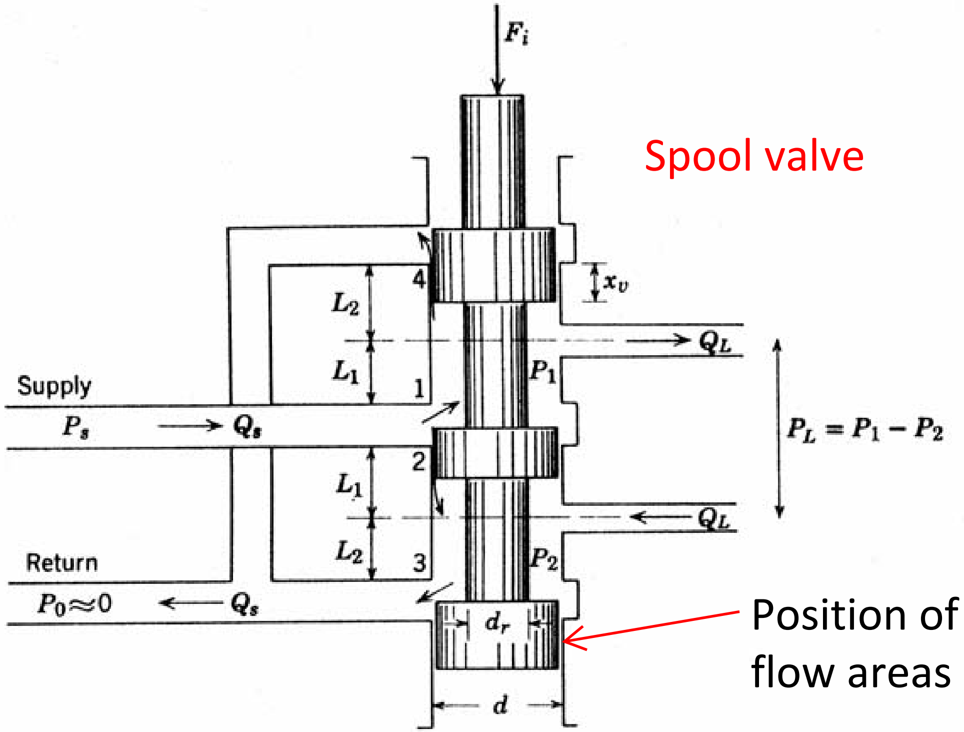




SOLENOID + SPRING

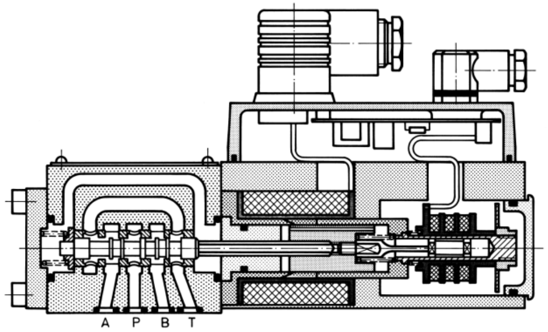
POPPET
- ball

Directional control valve

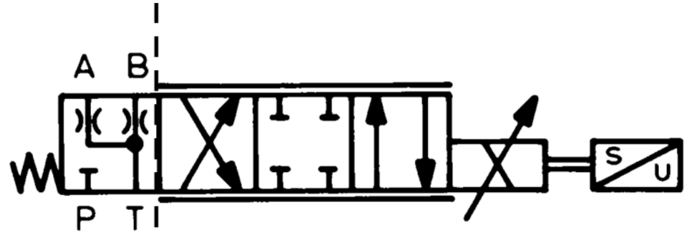


Spool valve

Position of spool defines flow areas of orifices.

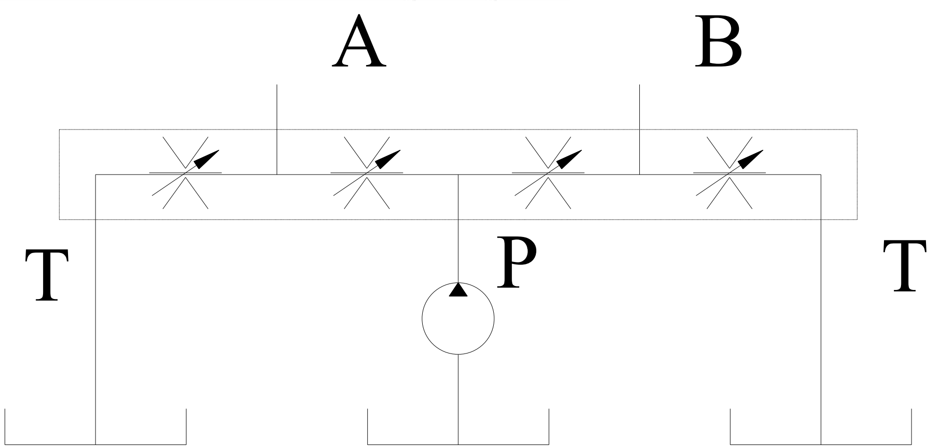


Proportional control valve



The model for proportional control valve can be constructed based on an assumption : the valve consists of four (4) orificices (control edges).

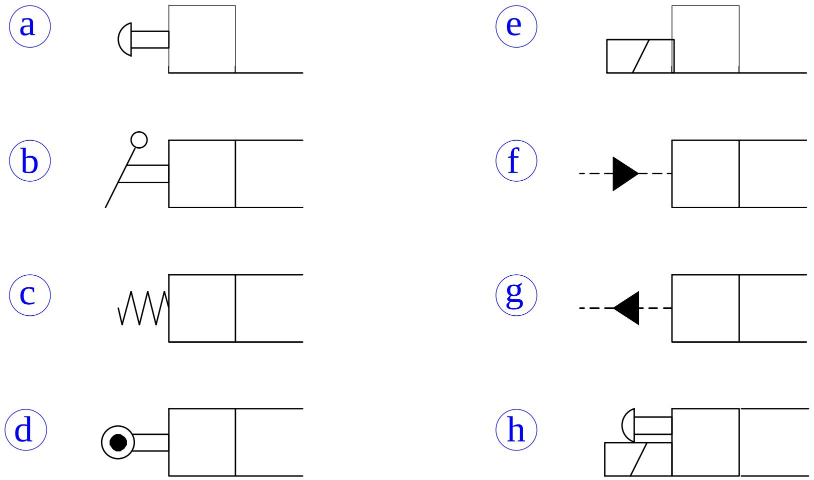
PA - PB - AT - BT



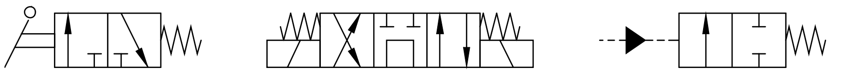
Proportional control valves are continuously adjustable valves. Proportional magnets (solenoids) are used in them as electric actuators.

https://www.hydraulicspneumatics.com/technologies/other-technologies/article/21884329/book-2-chapter-14-proportional-control-valves

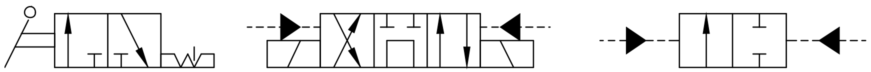
a) push-button
b) lever
c) spring
d) roller
e) electric ("solenoid")
f) pressure (increase)
g) pressure (decrease)
h) combined electric and manual (push-button)



Monostable



Bistable

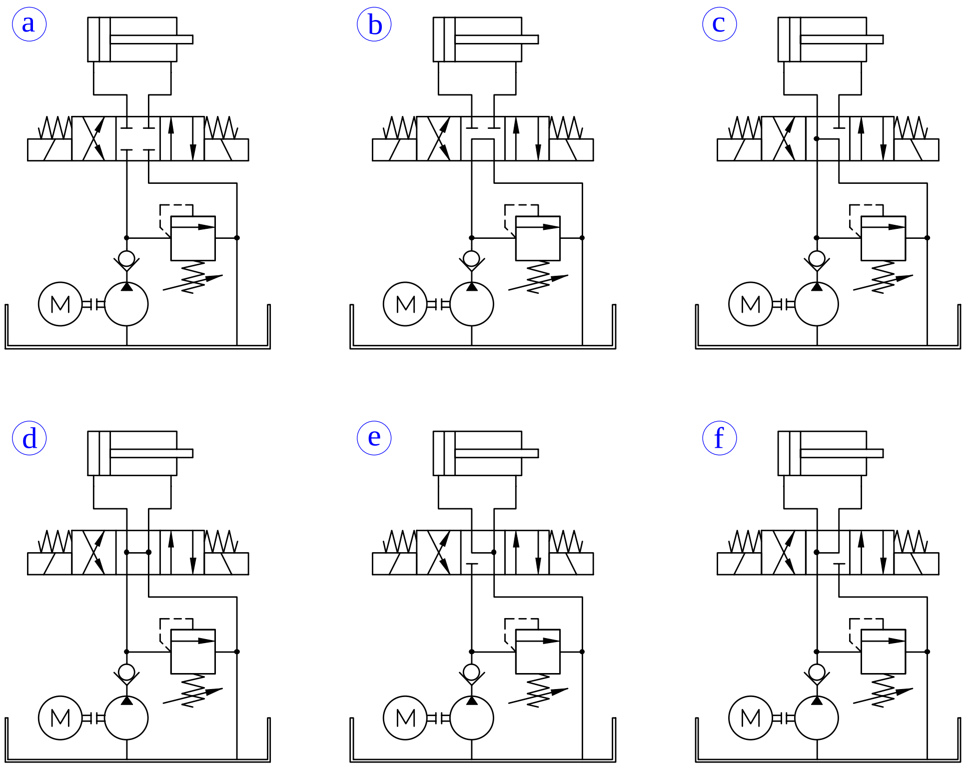


Examples of different connection variants

4/3 valve

Closed center position
Open center position

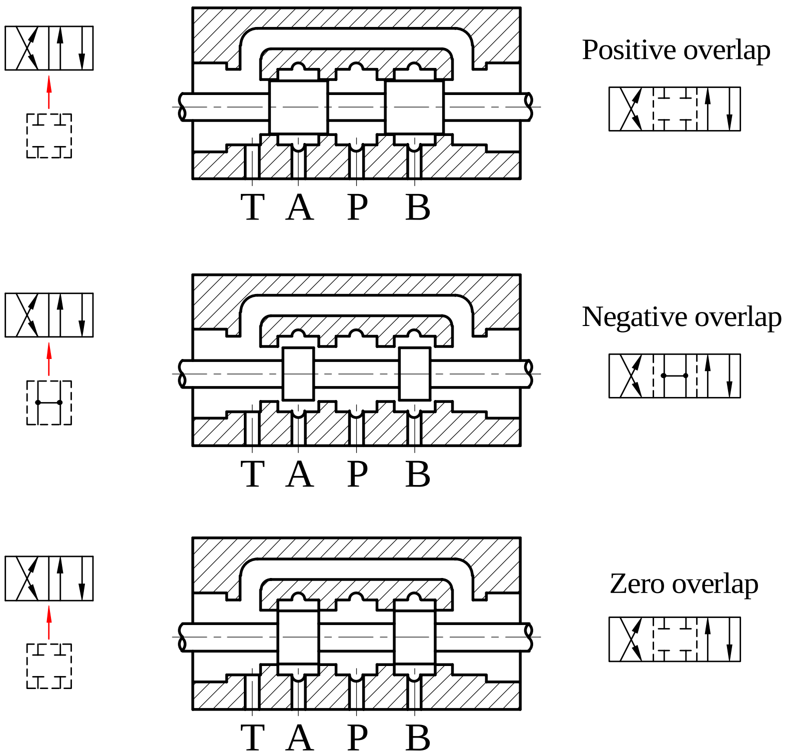
- Effect of external forces
- Possible movement
- Energy consumption
- Effect of valve leakages

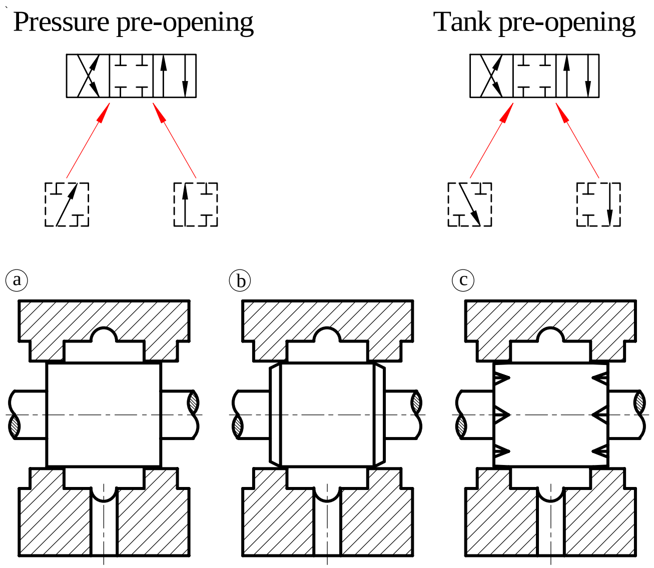


- Floating

Switching characteristics

Switching time
Spool lap
Spool shape





Directly operated / Pilot operated

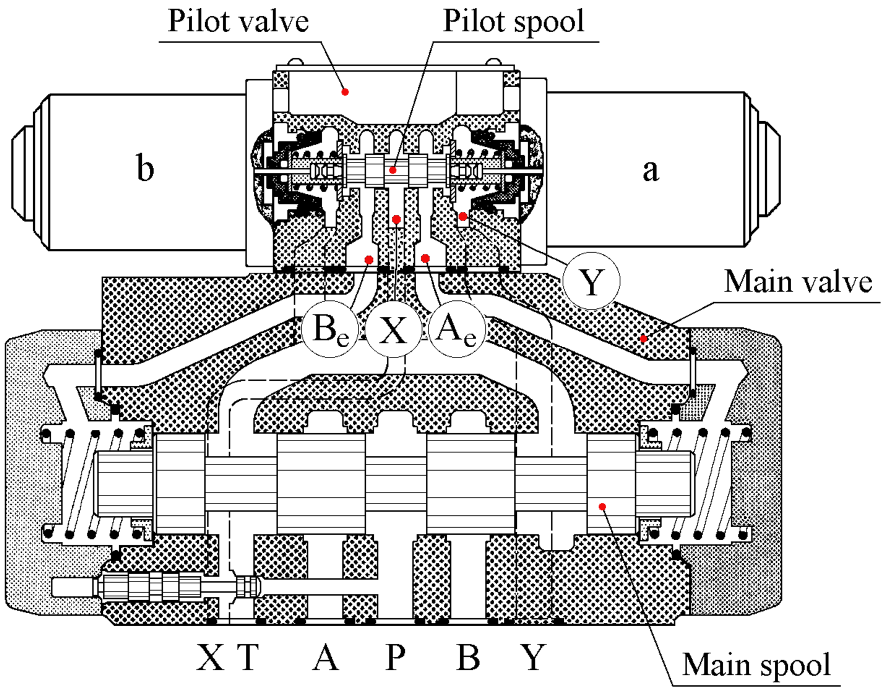
Directly operated = single stage
Pilot operated = multi stage (generally 2 or 3)

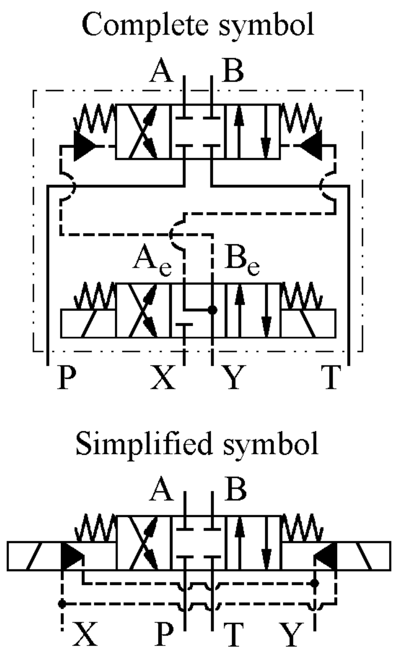
Control force demand increases with flow

Pilot operated = hydraulic amplification of control force

Nominal size	Normal flow range [l/min]	Maximum flow [l/min]	Control type	Structure type
NS 6	0- 20	25	directly operated	poppet
NS 10	10- 30	36	directly operated	poppet
NS 6	0- 30	60	directly operated	spool
NS 10	20- 60	100	directly operated	spool
NS 10	20- 80	160	pilot operated	spool
NS 16	50- 200	400	pilot operated	spool
NS 25	100- 500	700	pilot operated	spool
NS 32	250- 800	1100	pilot operated	spool

Pilot operated, spring centered



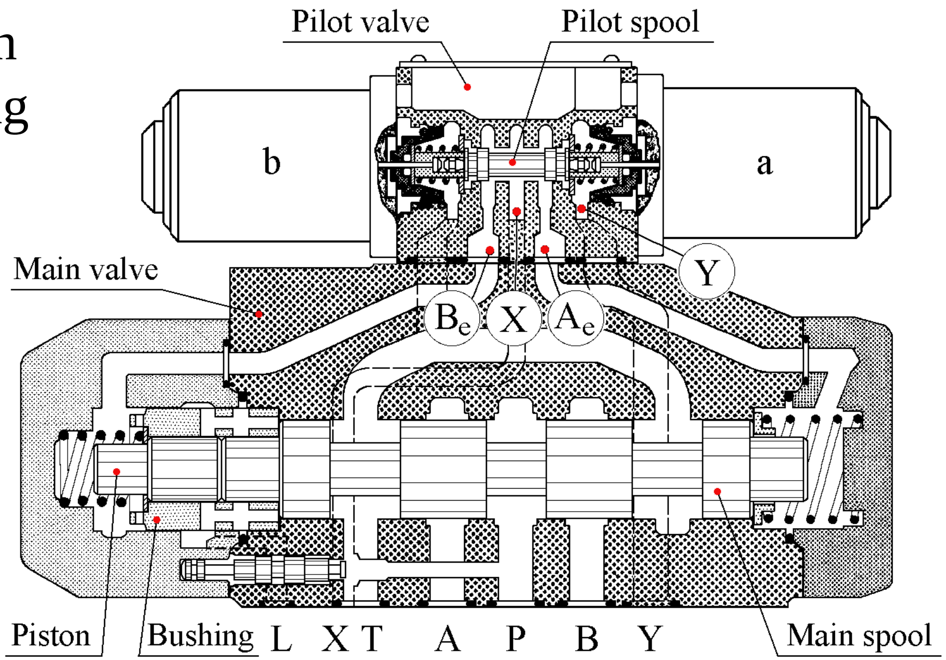


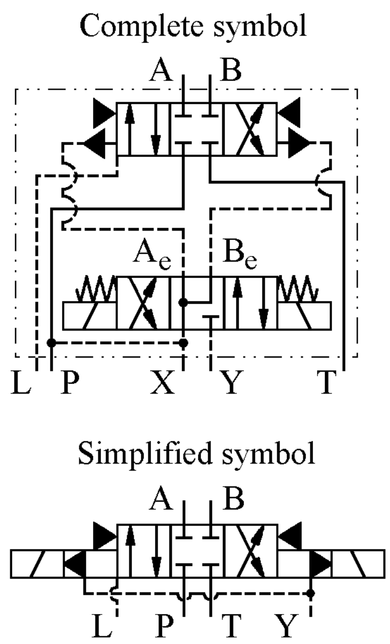
Pilot operated, pressure centered

Amplification of centralizing signal

High flow forces

More force required





Left end and right end spool areas are different, also bushing area on the left, limited bushing movement!

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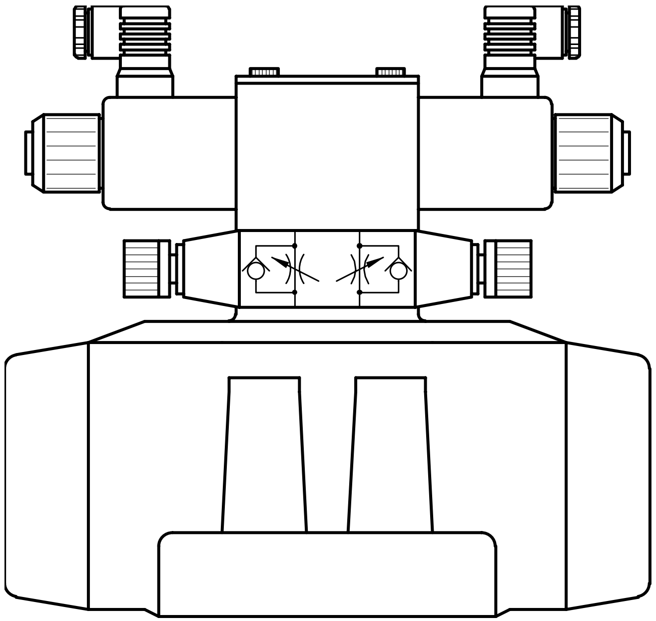
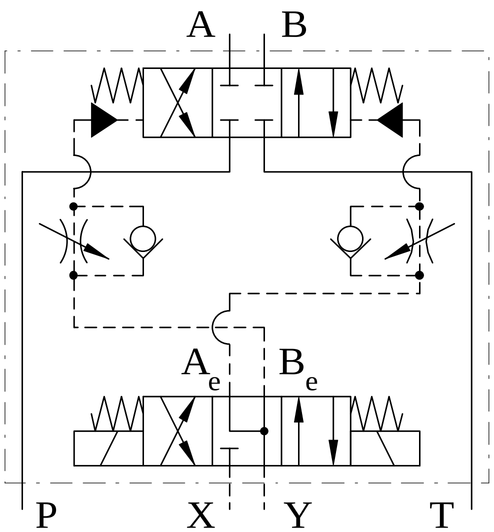
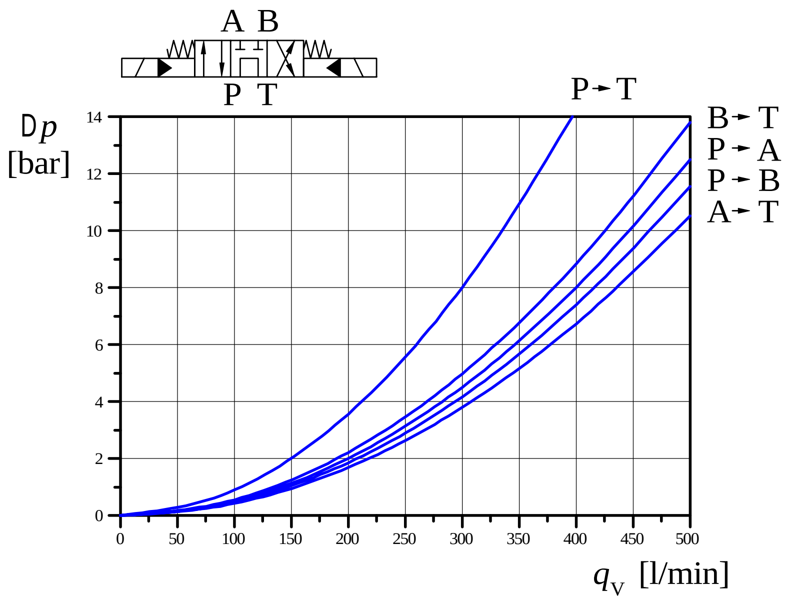
Switching time of pilot operated directional control valve



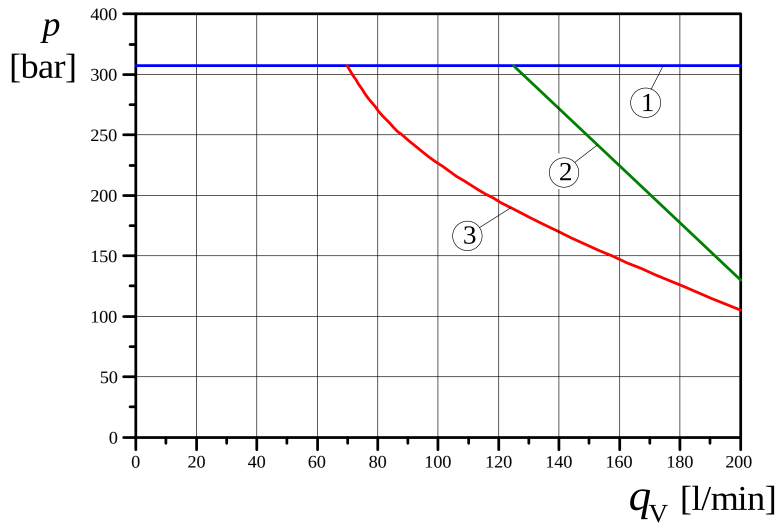


Slowing (restraining) spool main movements by using throttles in control channels



Operating range of directional control valve

High flow forces may restrict the controllable power of the valve (1 - 2 - 3).



Flow rate
Pressure loss
Control force

Pressure valves

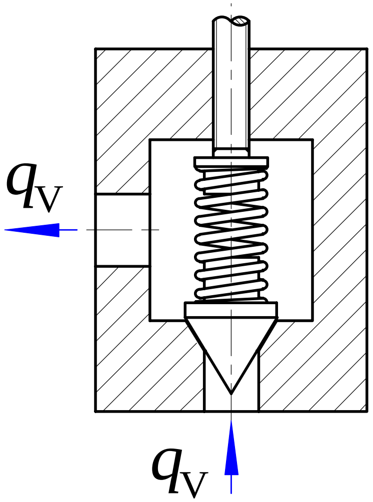
Govern/control the pressure
Govern the system on the grounds of pressure signal

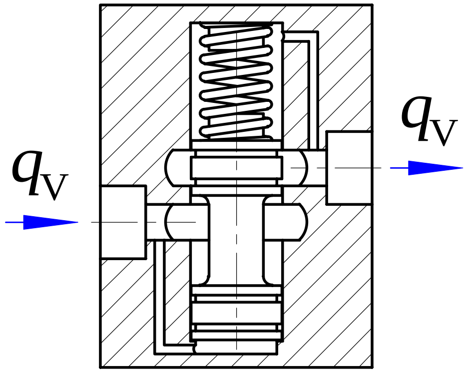
Governing/controlling the pressure
- restraining the system main pressure
- restraining the pressure of a subsystem

Governing the system on the grounds of pressure
- sequencing the operation of system
- unloading the pump
- governing external load

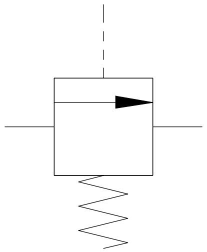
Construction

Pressure forces
Spring forces





Too small inlet pressure will move the spool downwards which restricts the flow more and increases pressure
Too high pressure ... vice versa



Slide types
- poppet/seat
- spool

Construction types - Signal

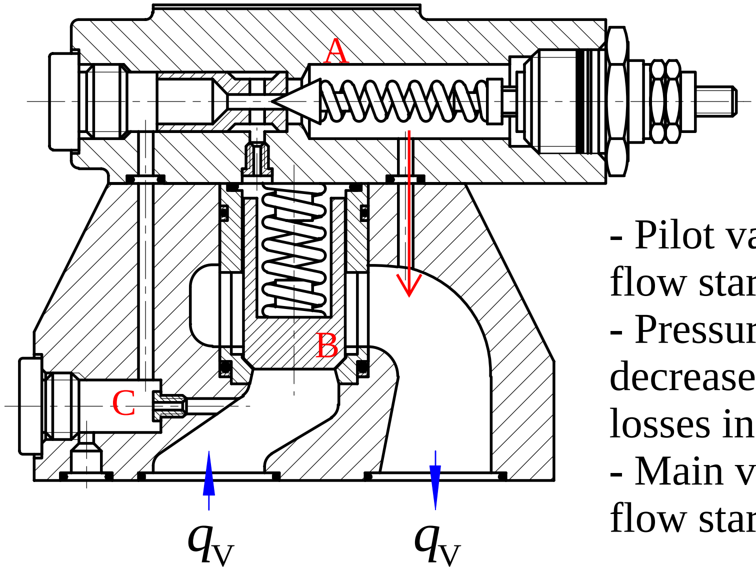
- normally closed
- normally open

Direct operated / Pilot operated

Direct operated = single stage
Pilot operated = multi stage (generally 2, possibly 3)

Control force demand increases with flow

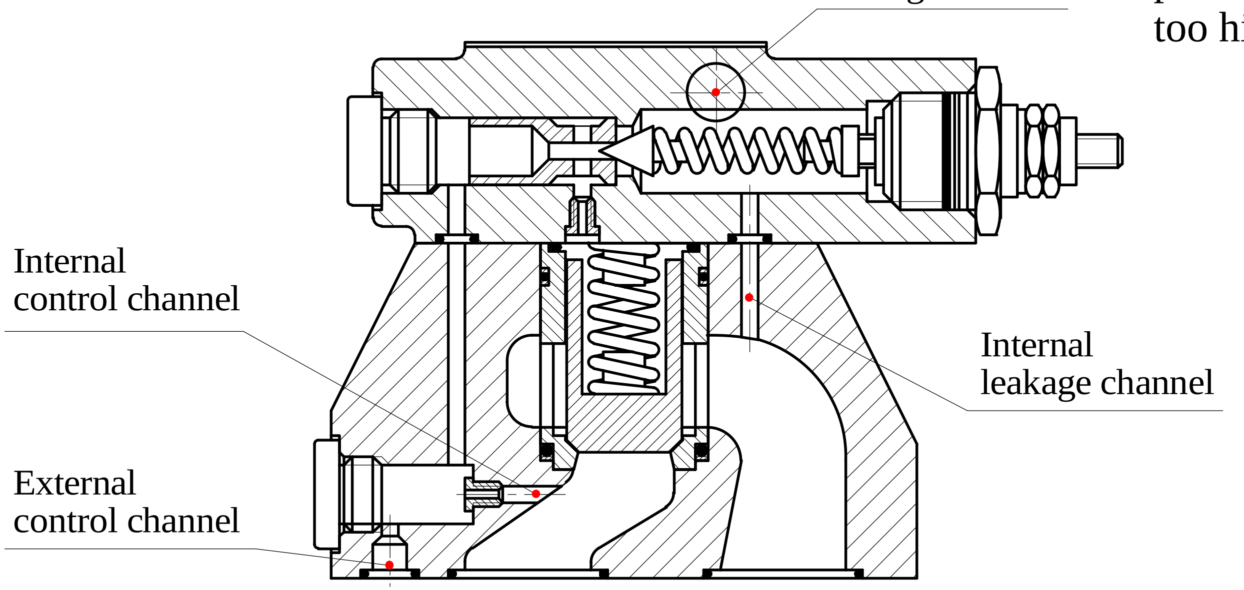
Pilot operated = hydraulic amplification of control force



- Pilot valve (A) opens and pilot flow starts
- Pressure above main valve (B) decreases because of pressure losses in throttle (C)
- Main valve (B) opens and flow starts through it also

Controls and depressurization of control spring volume

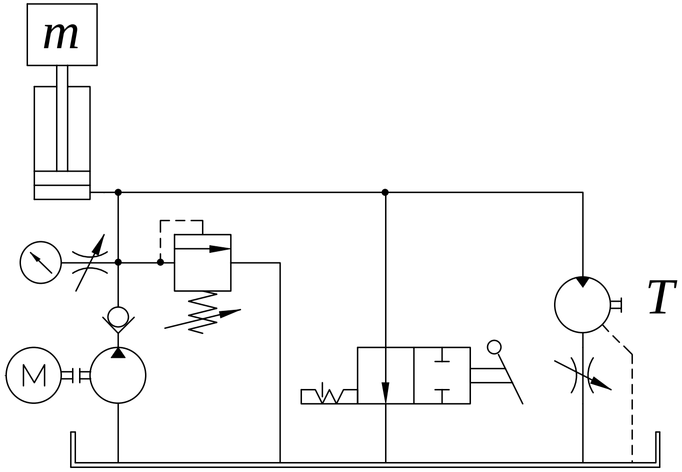
If tank line pressure is too high

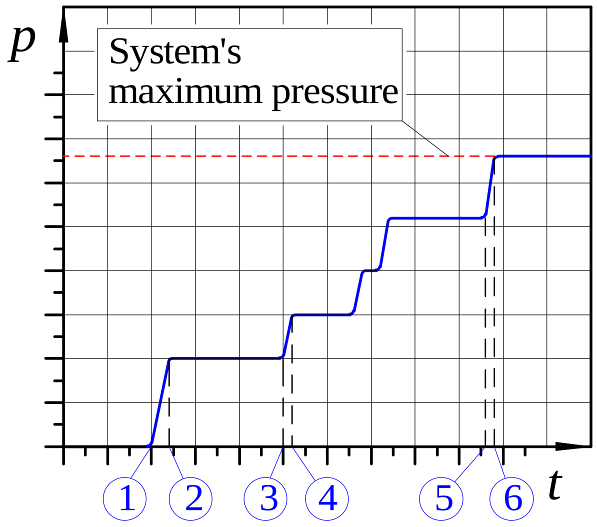


Pressure relief valve

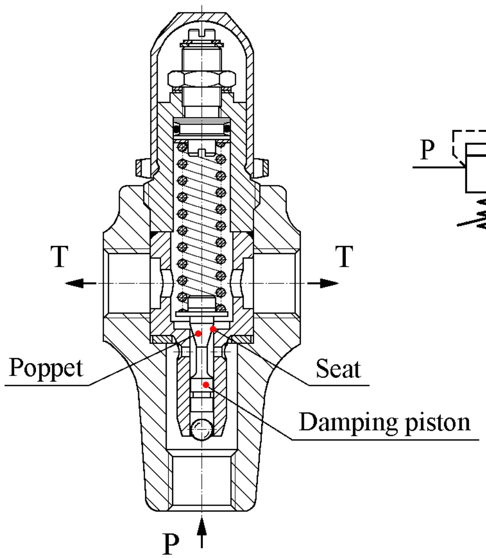
Restrains the system main max pressure level

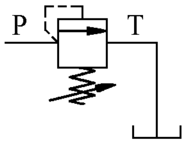
Protects the hydraulic system and the structures attached to it from overloading

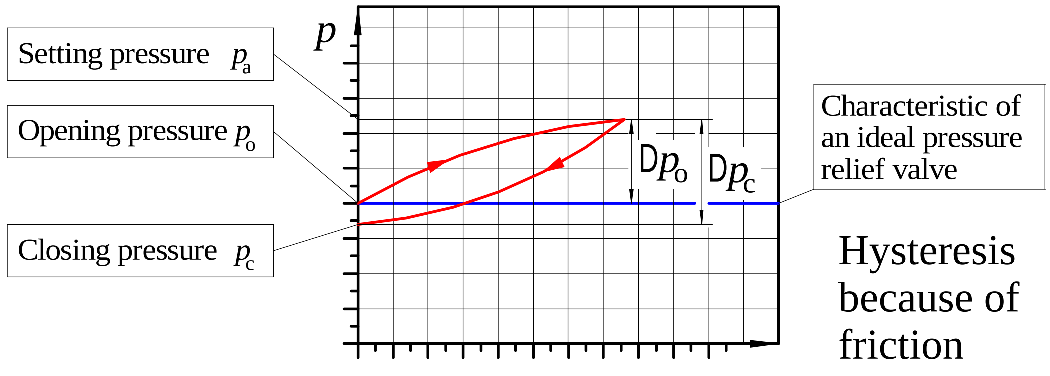




1	2/2 valve OFF
2	lifting of mass (cylinder)
3	mass lifted (end position)
4	motor starts to rotate
5	throttle adjusted (more pressure loss)
6	pressure relief valve opens



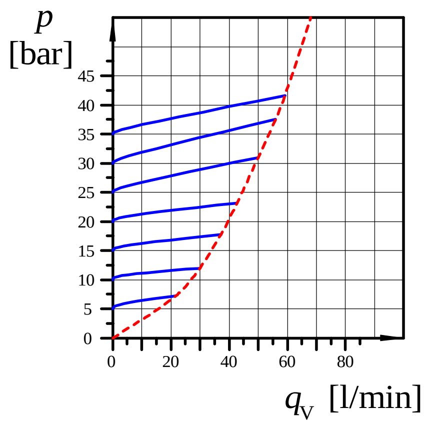


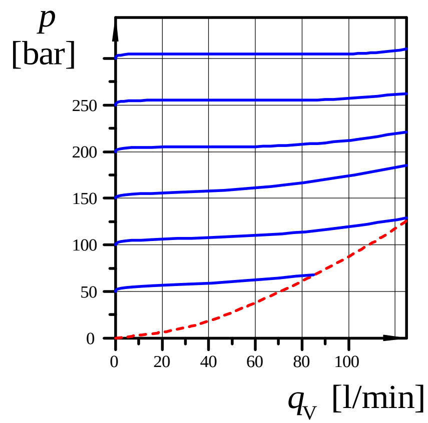


Hysteresis because of friction

Opening pressure adjustment by spring pretension

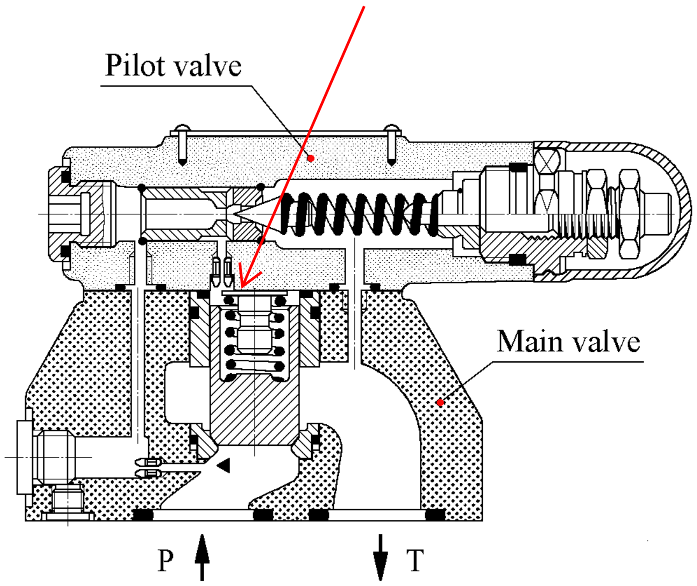
Direct operated pressure relief valve



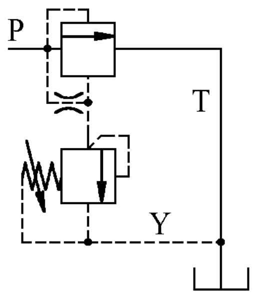


Saturation limit

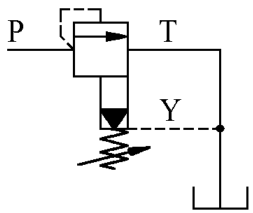
Drop pressure here to open the main valve
Use pilot flow and throttle for pressure loss



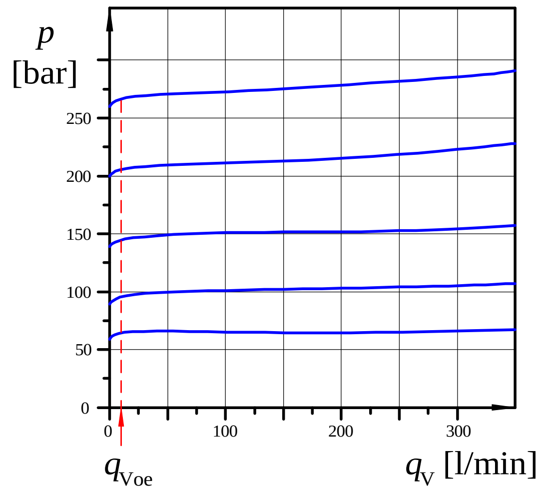
Complete symbol



Simplified symbol

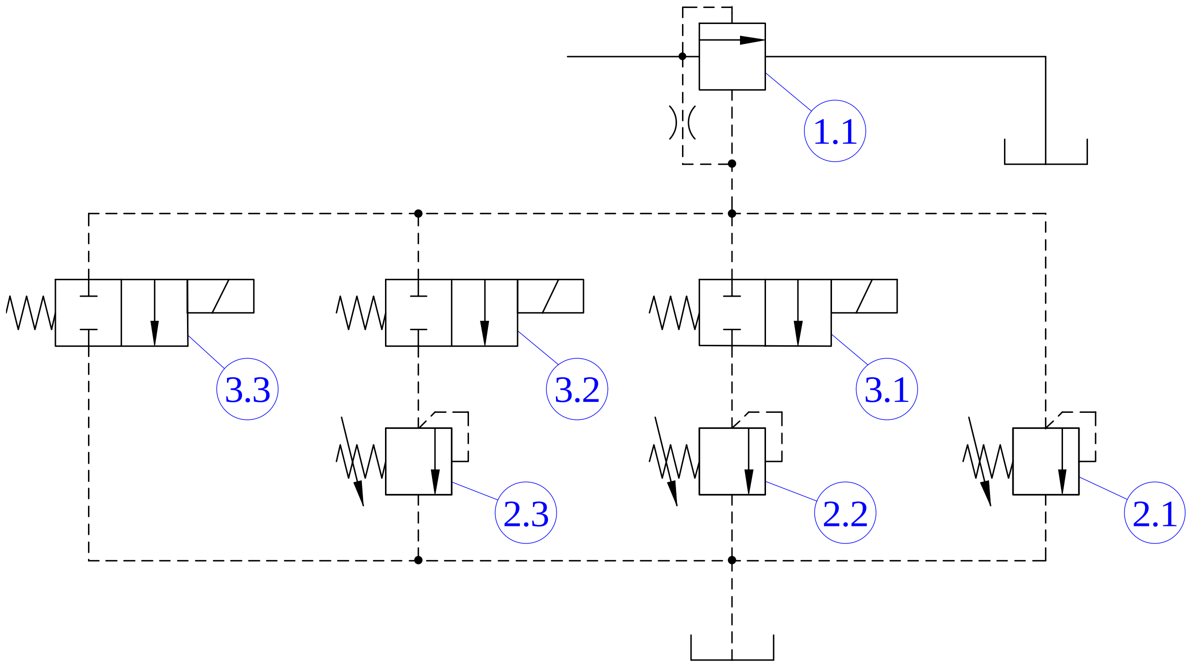


Flow through
pilot valve - pilot and main valve



Pilot operated pressure relief valve for better static properties.
High flow capacity direct operated PRV requires a large spring.

Realizing several pressure levels with one main valve and several pilot valves



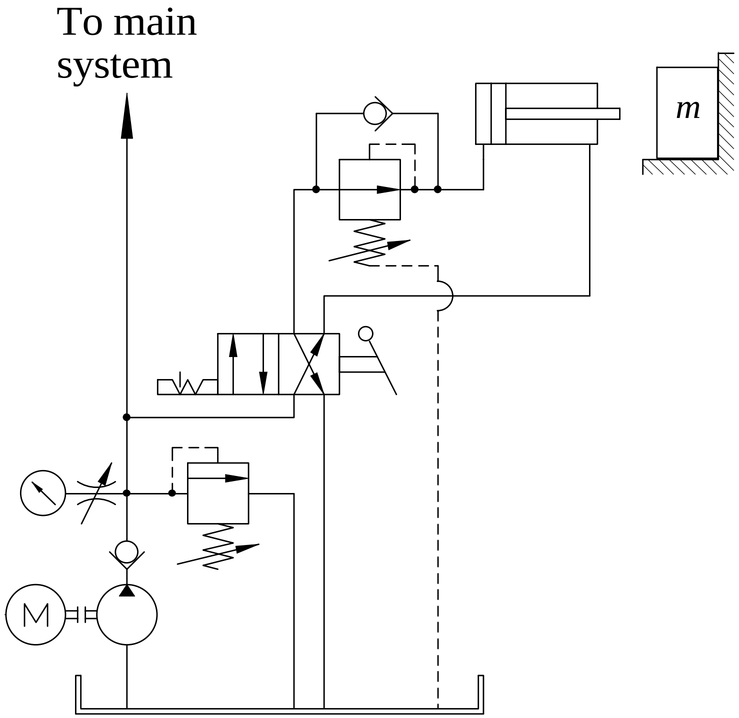
Pressure reducing valve

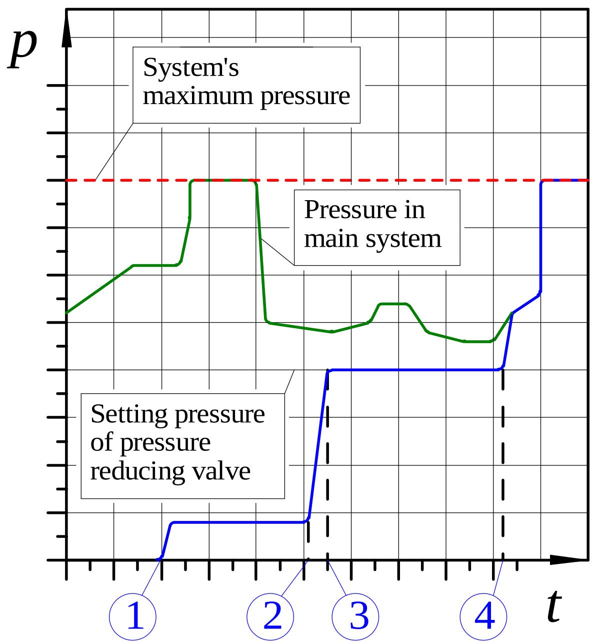
Restrains the max pressure level of subsystem, i.e., reduces the pressure of a subsystem to a lower level compared with the main system pressure

® enables different pressure levels at different subsystems

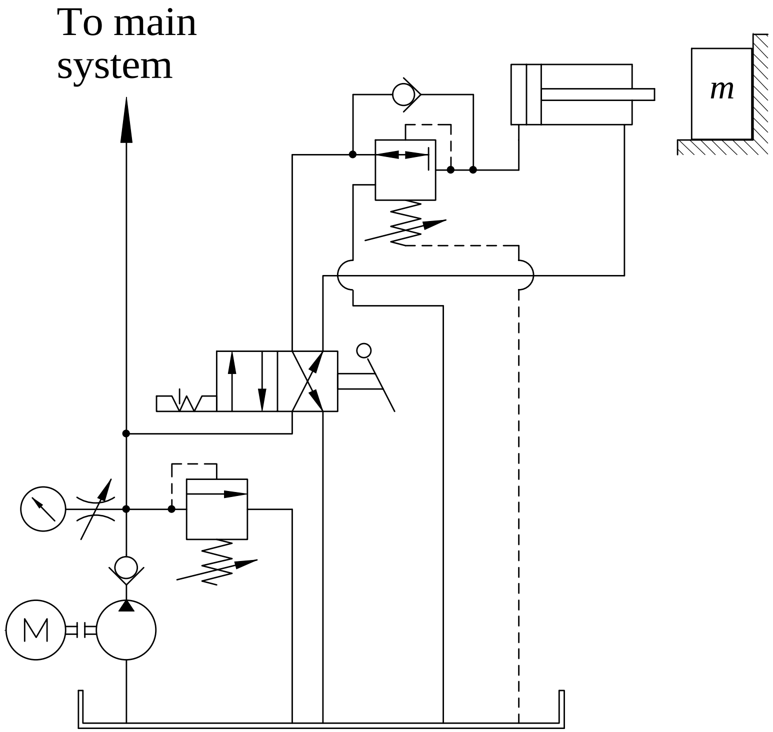
2-way valve
3-way valve
- contains pressure relief function

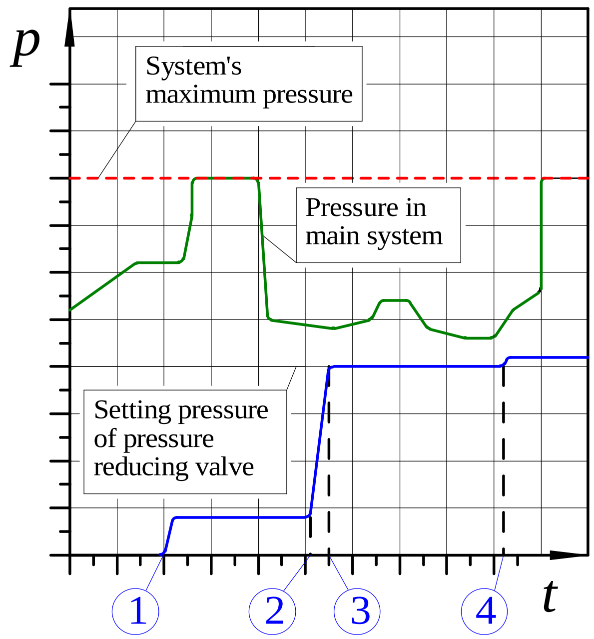
2-way valve


To main
system
m
M

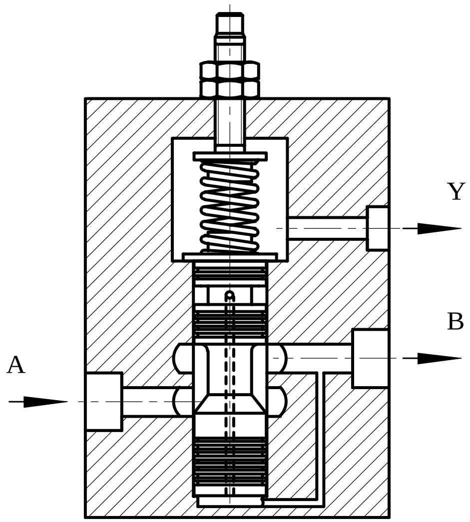

p
System's
maximum pressure
Pressure in
main system
Setting pressure
of pressure
reducing valve
1
2
3
4
t

3-way valve

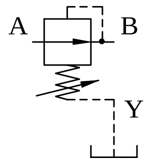

To main
system
M
m


p
System's
maximum pressure
Pressure in
main system
Setting pressure
of pressure
reducing valve
t
1
2
3
4

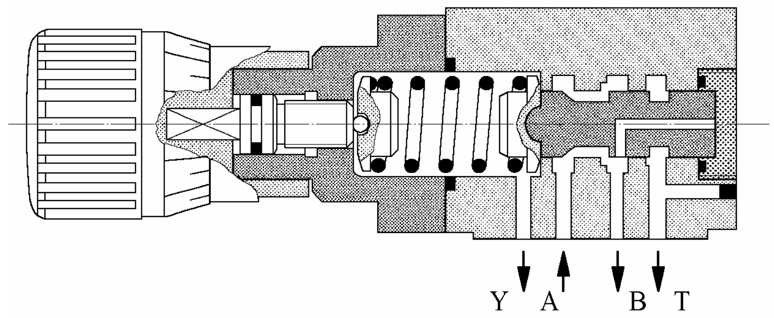
Direct controlled pressure reducing valves

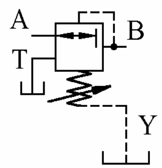


2-way

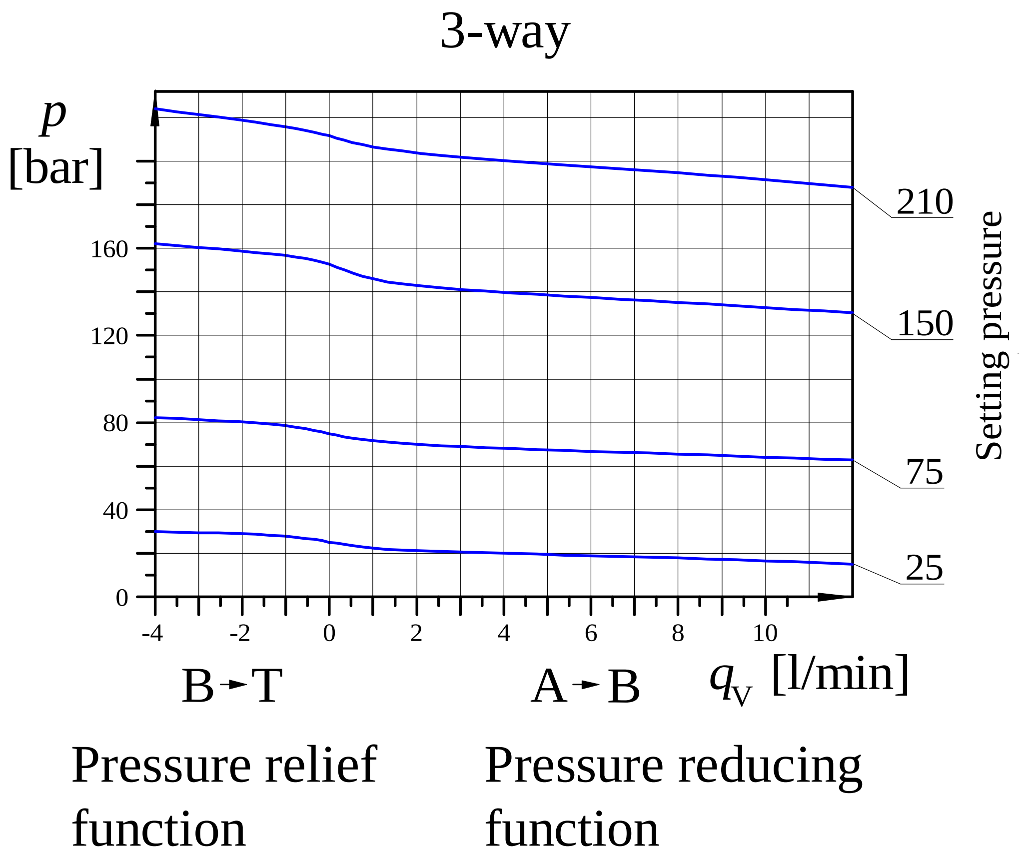


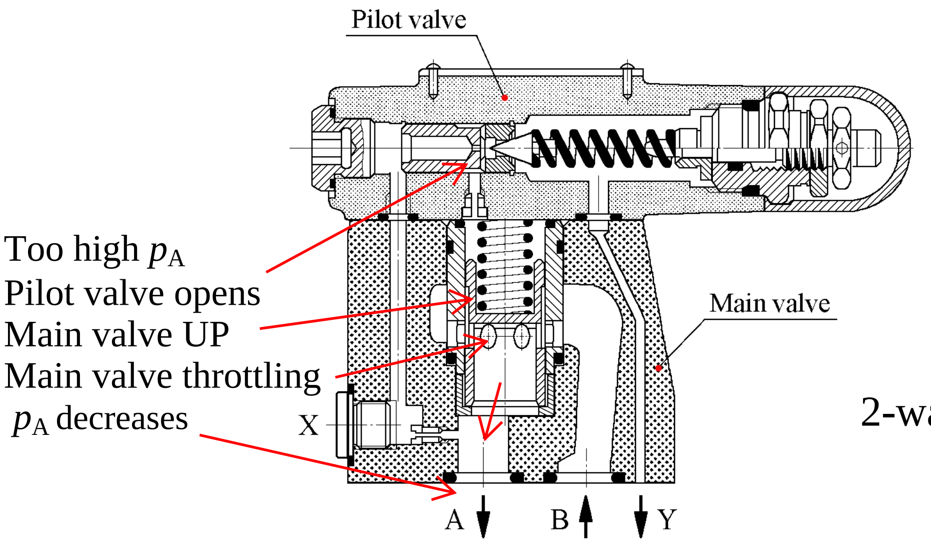
3-way

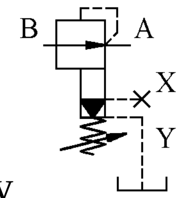




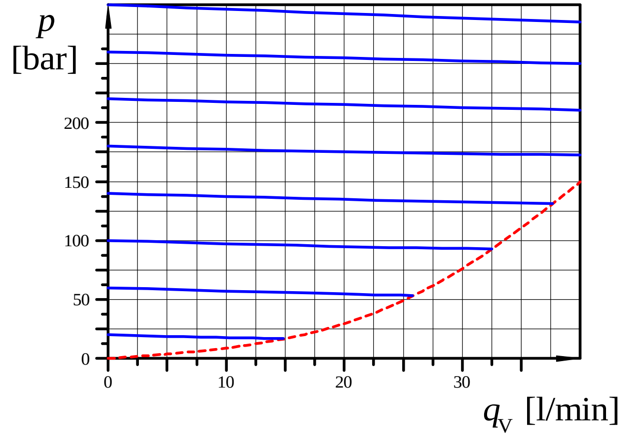
Direct controlled pressure reducing valve



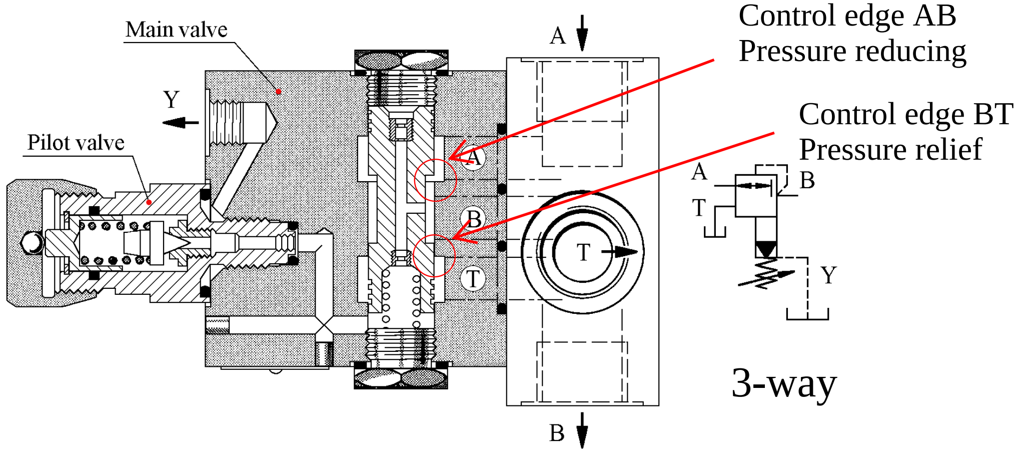




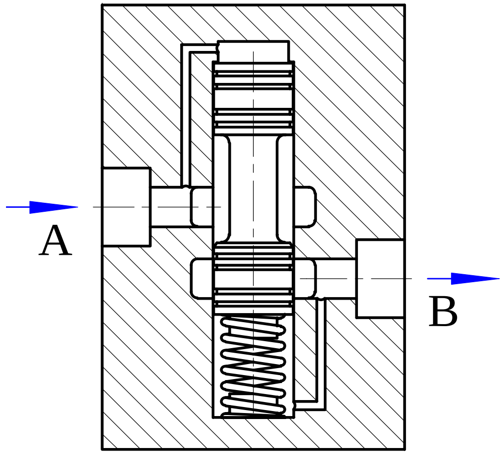
2-way

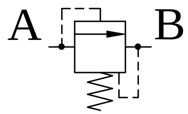


Pilot controlled pressure reducing valves



$F_{spring} = p_A A_A - p_B A_B$ -> $F_{spring} = (p_A - p_B) A$

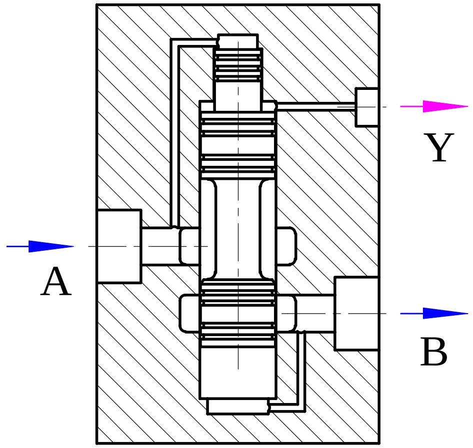


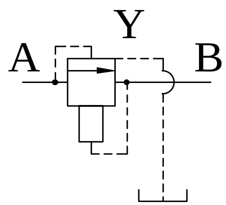


$p_A - p_B$

¬ Constant pressure difference between connections

Constant pressure ratio between connections ®





$p_A A_A = p_B A_B$ (in force balance)

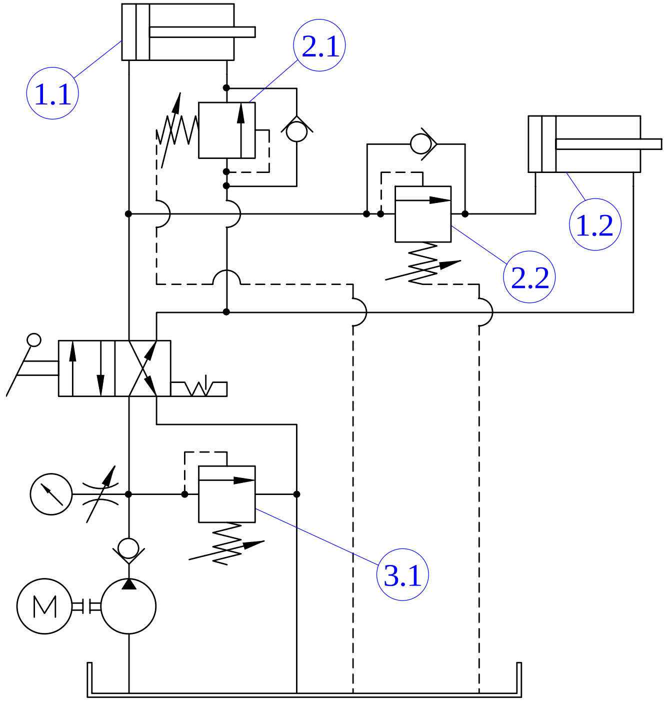
Sequence valve

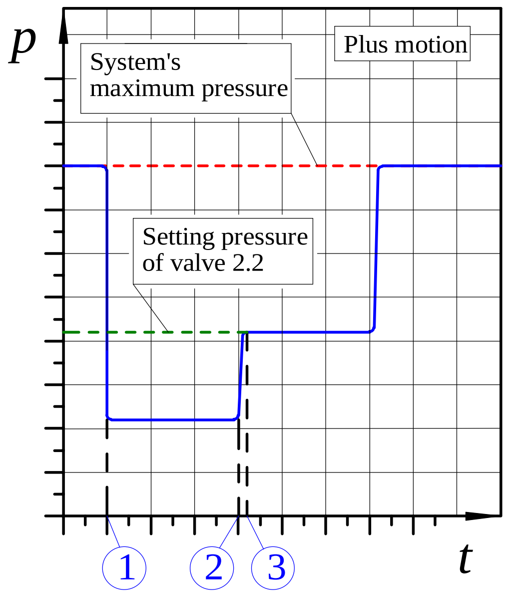
Governs the operation of system
on grounds of the pressure signal

Internally controlled valve
Externally controlled valve

Internally controlled valve

1 valve position change -> flow to 1.1
2 end position for cylinder 1
3 sequence valve 2.2 opens
3.1 piston in cylinder 2 moves
3.2 end position for piston
3.3 pressure relief valve pressure

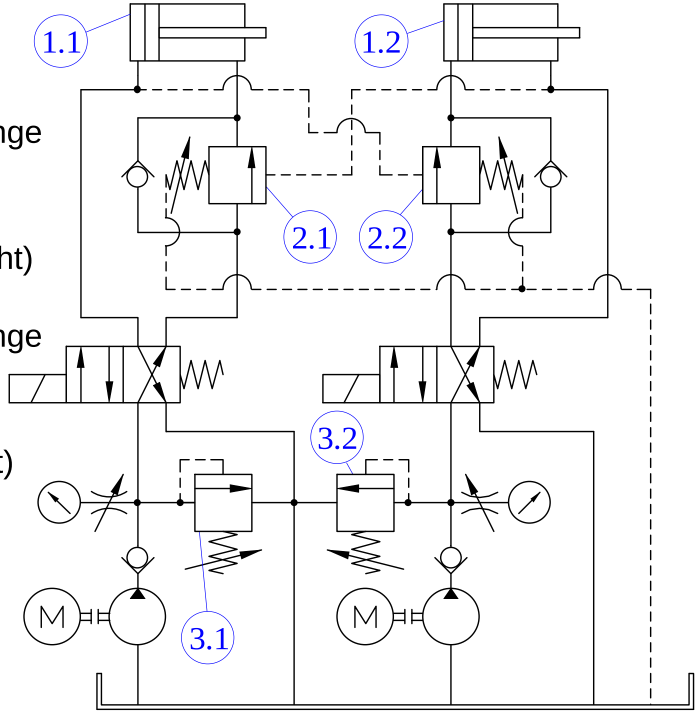


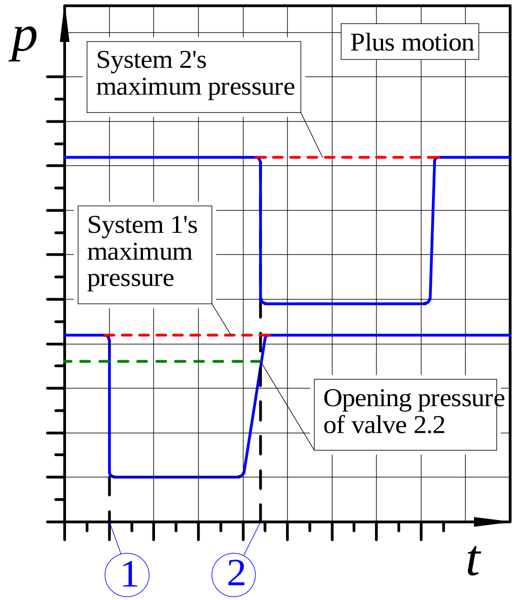


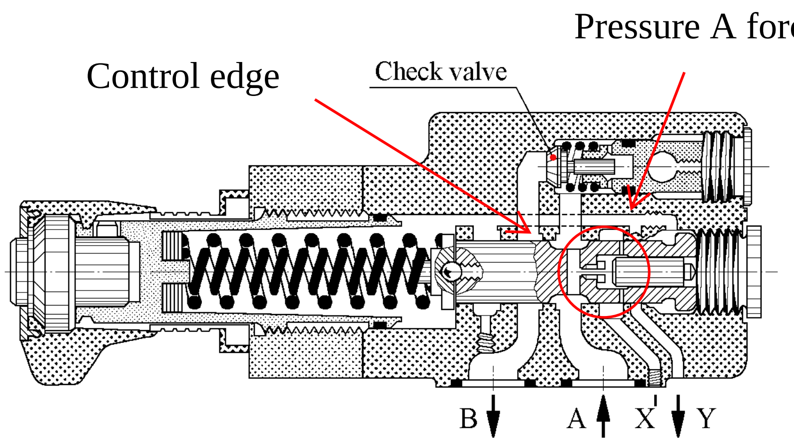
Externally controlled valve

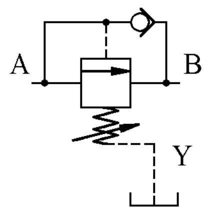
+ movement
1 control valve(s) position change
1.1 moves (1.2 is stationary)
2.2 opens as 1.1 piston at end
1.2 piston starts to move (to right)

- movement
1 control valve(s) position change
1.2 moves (1.1 is stationary)
2.1 opens as 1.2 piston at end
1.1 piston starts to move (to left)





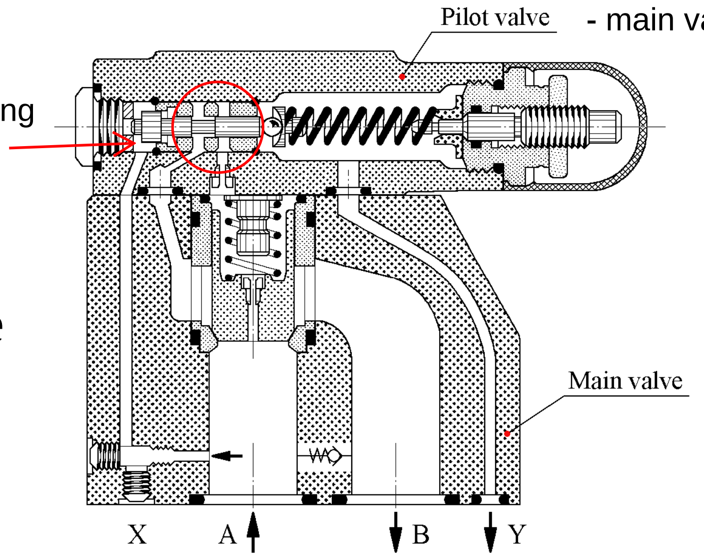


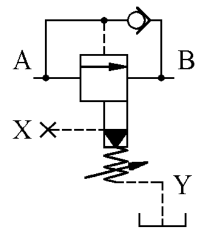


Direct operated sequence valve

- pilot valve (spool) is opened
- flow through main valve throttle
- pressure decreases above main valve
- main valve opens

Pilot operated sequence valve

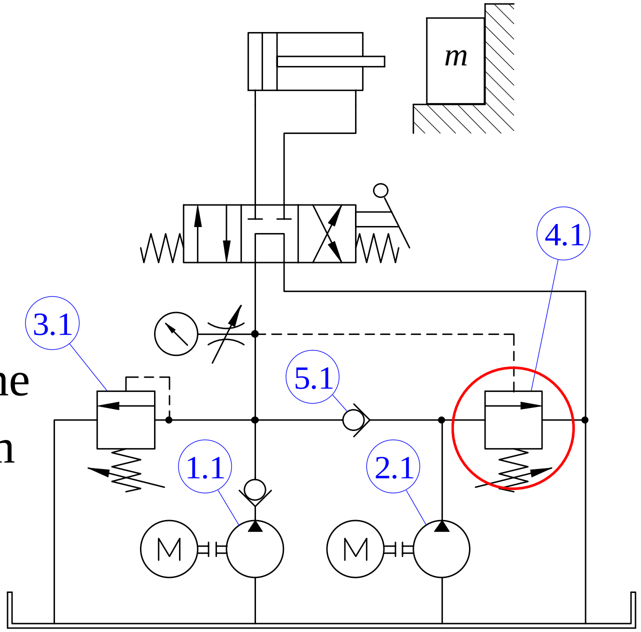


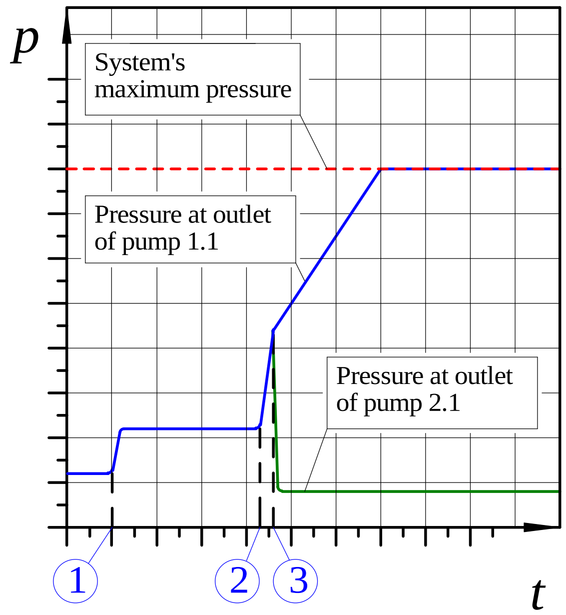


Rapid motion by using two (2) pumps
Pump 2.1 flow is connected to tank as cylinder starts to compress the workpiece (m)
High (compression) pressure and power is needed only for pump 1.1

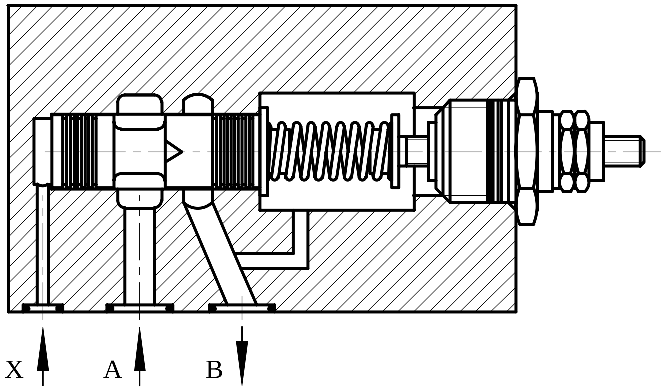
Unloading valve

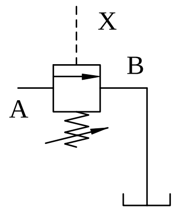
Governs the direction of pump flow on grounds of pressure signal, i.e. “eases” the operating power of the system





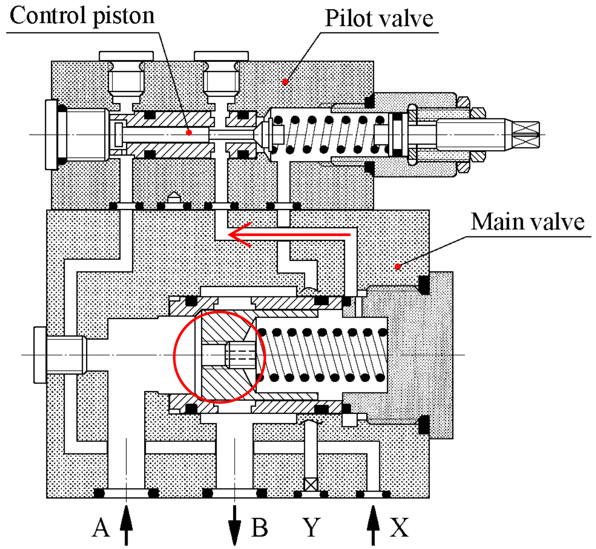
Direct operated unloading valve

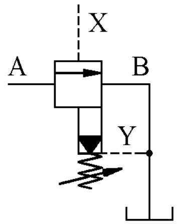




Control piston opens pilot valve
Flow starts from A through main valve throttle
Pressure drops in spring volume
Main valve opens

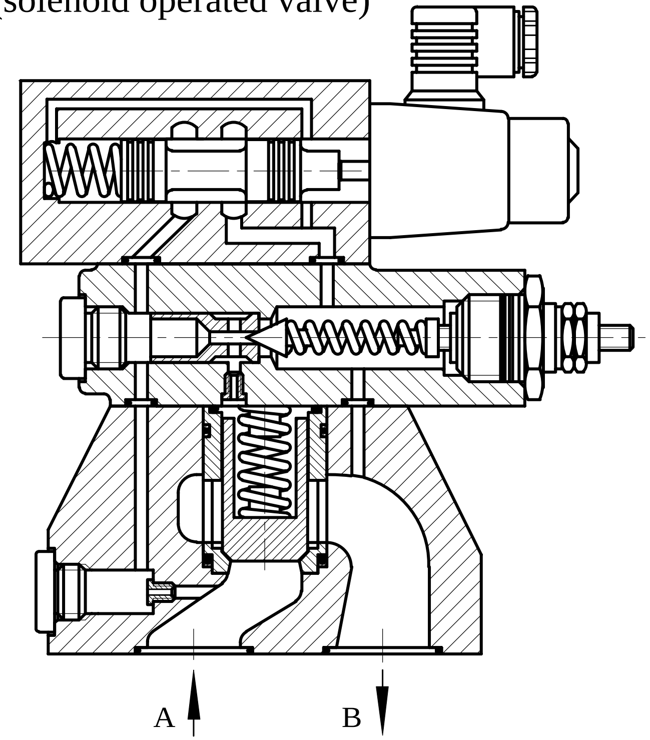
Pilot operated unloading valve

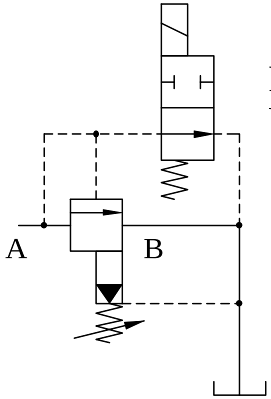




Pilot operated relief valve - Unloading valve

Relief operation with electric control
(solenoid operated valve)

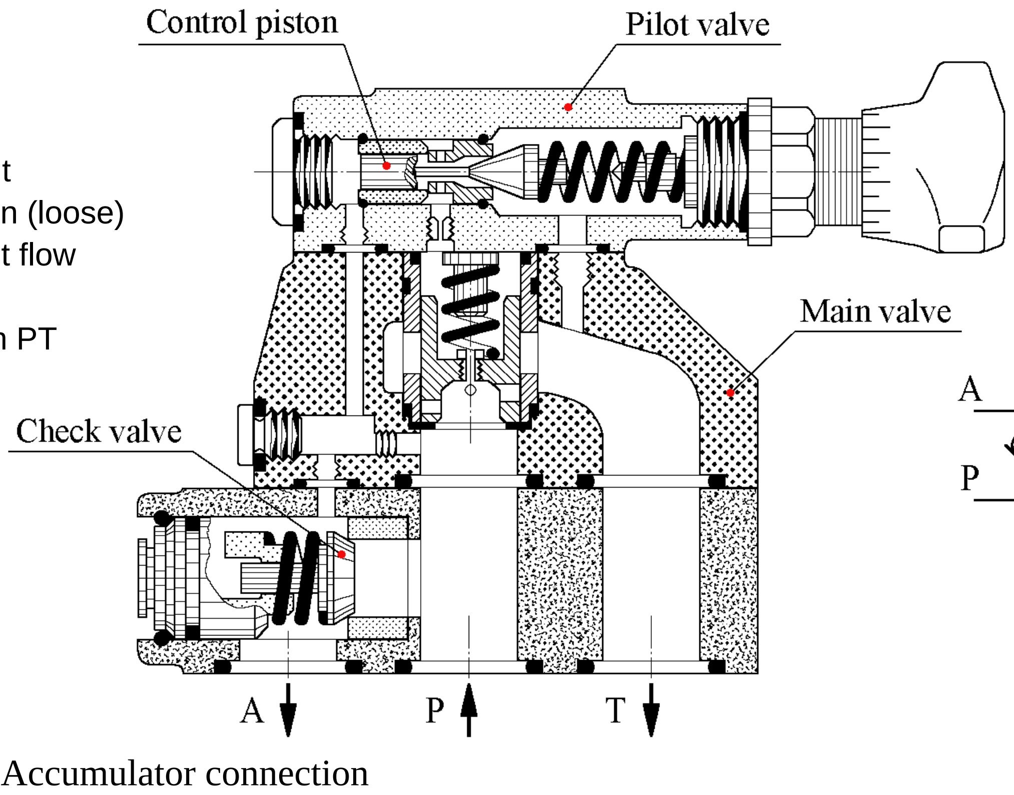


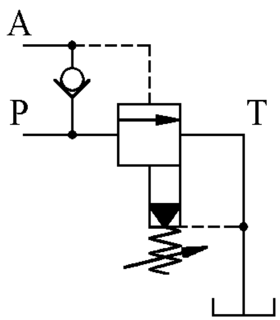


Pressure relief valve operation (CLOSED)
Unloading valve operation (OPEN)

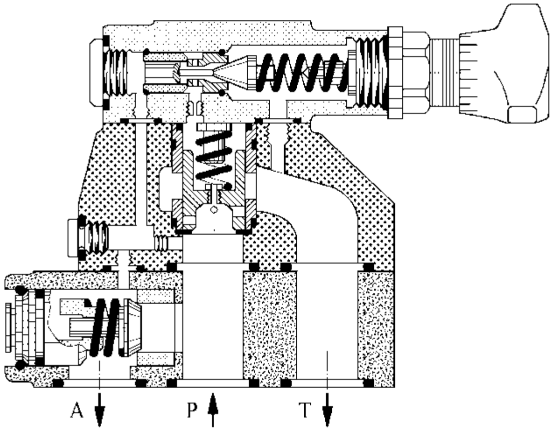
Pilot operated pressure accumulator charging valve

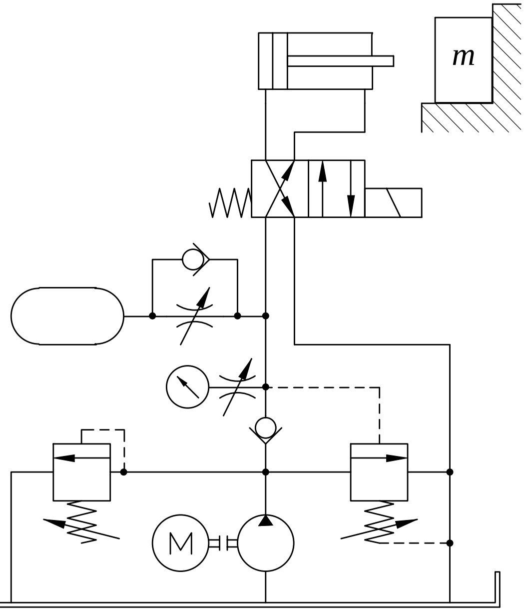
Accumulator pressure reaches setpoint
Accumulator pressure on Control piston (loose)
Control piston opens Pilot valve -> pilot flow
Pressure loss in main valve throttle
Main valve moves and opens flow path PT
Pump pressure may decrease

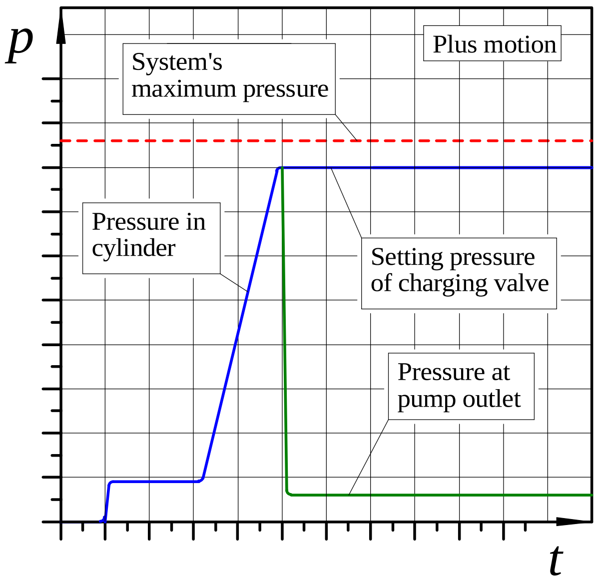




Pilot operated pressure accumulator charging valve





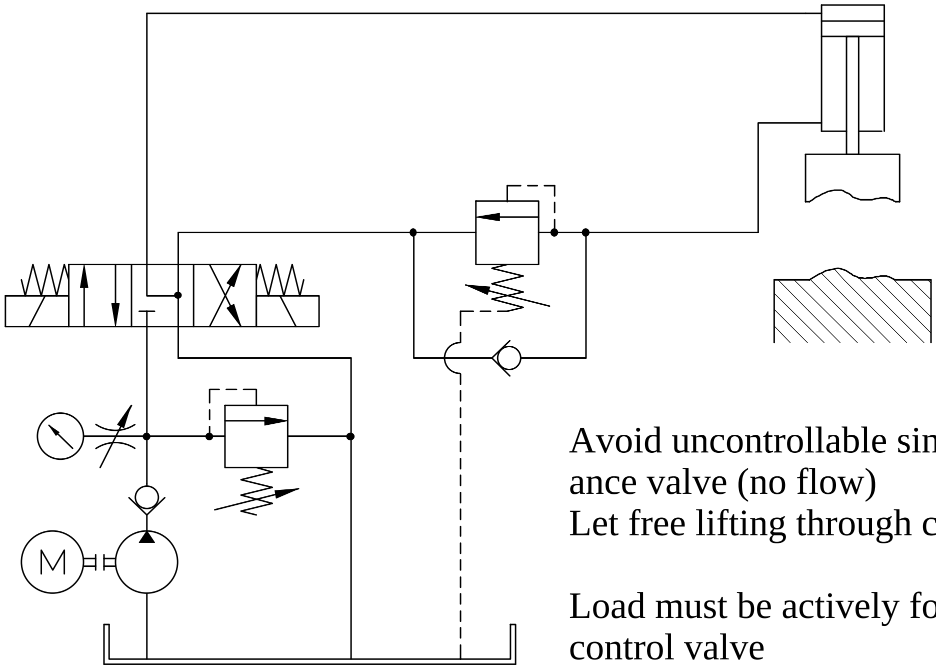


Counterbalance valve

Induces a hydraulic counter load to negative external load thus enabling the governing of the load

Internally controlled valve
Externally controlled valve
Internally and externally controlled valve

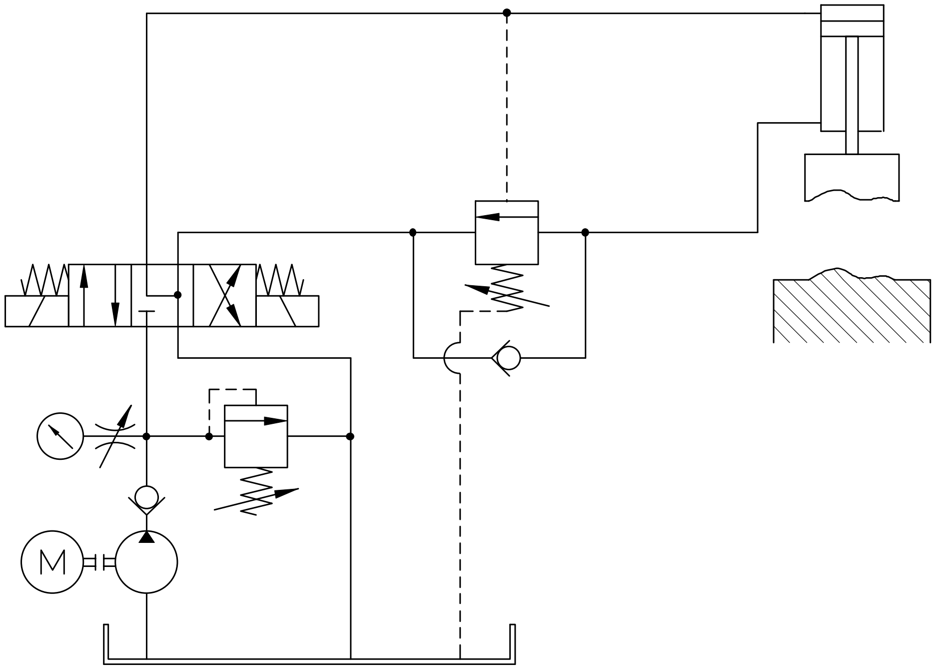
Internally controlled valve



Avoid uncontrollable sinking of mass/tool with counterbalance valve (no flow)
Let free lifting through check valve

Load must be actively forced down by using directional control valve
However, increasing load force might bring load down

Externally controlled valve

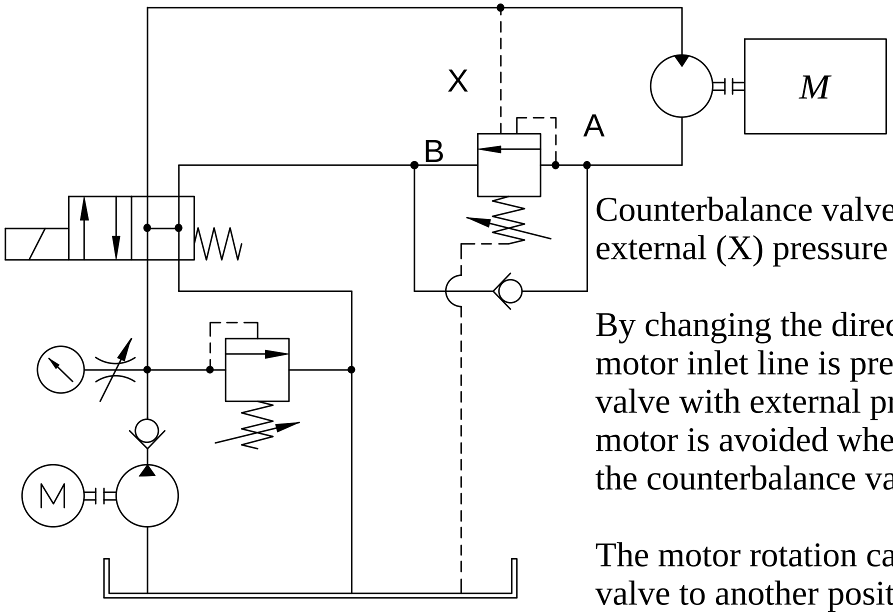


Load down only if + chamber is pressurized

Rod side chamber (- chamber) pressure does not need to be highly pressurized

If load starts to fall too fast + chamber pressure drops and shuts counterbalance valve -> falling stops

Internally and externally controlled valve

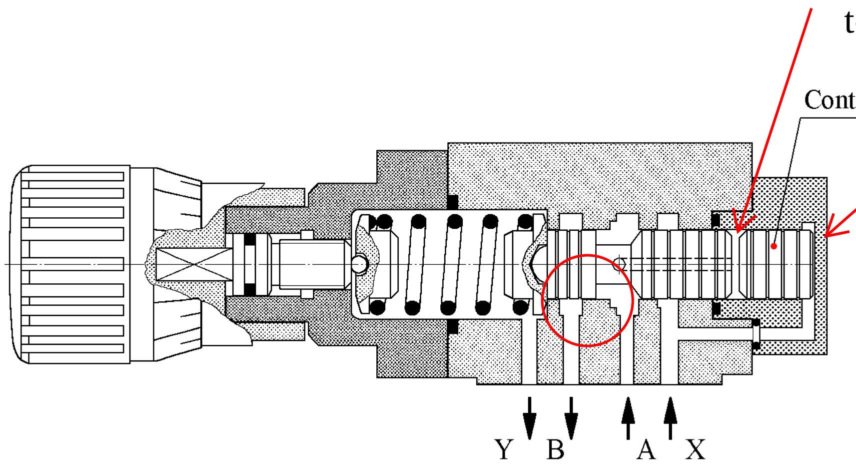


Counterbalance valve can be operated with both internal (A) and external (X) pressure signals

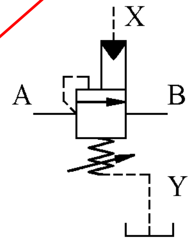
By changing the directional control valve position (H -> II) the motor inlet line is pressurized which opens the counterbalance valve with external pressure signal (X), uncontrollable rotation of motor is avoided when control pressure X drops and starts to close the counterbalance valve

The motor rotation can be decelerated and stopped by switching the valve to another position (H), the internal control signal (A) keeps the valve open and valve creates flow resistance and acts as a brake

Spool can be operated and valve opened with both internal (A) and external (X) pressure signals



Control edge AB



Direct operated counterbalance valve

Flow valves

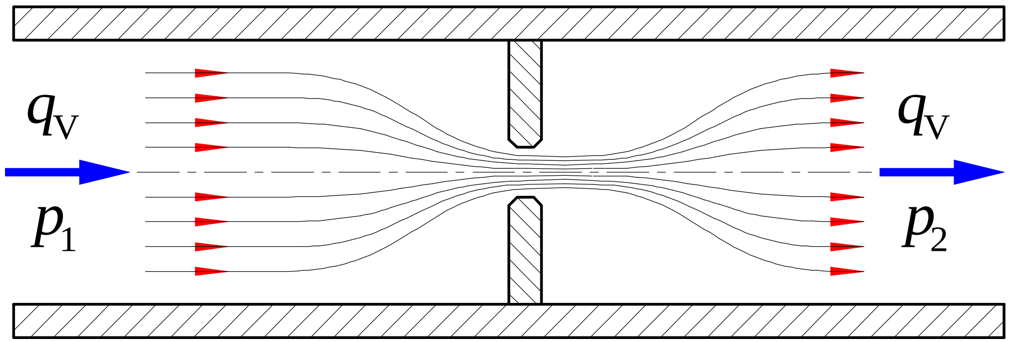
Govern/control the flow rate

Governing/controlling the flow rate
- affecting the speeds of actuators
- affecting the internal functions of components

Operating principle

Throttle

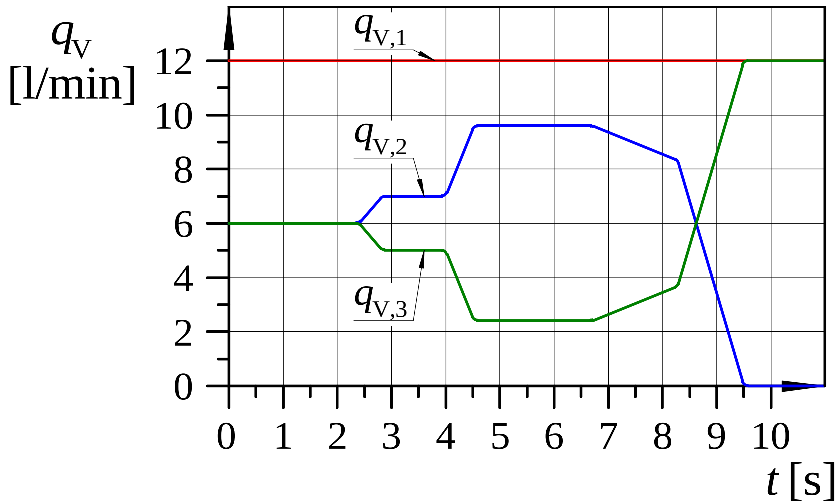
$$p_1 - p_2 = \Delta p$$

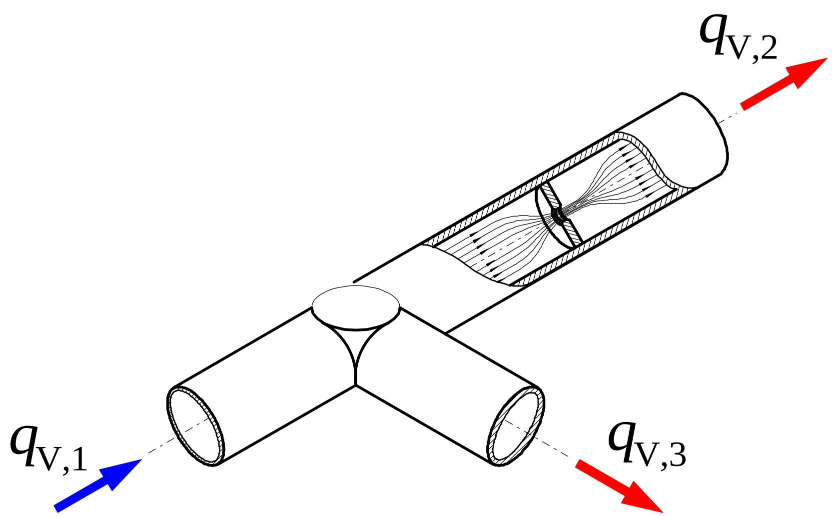


$$q_V \longrightarrow \Delta p$$

$$q_V \longleftarrow \Delta p$$

Operational precondition

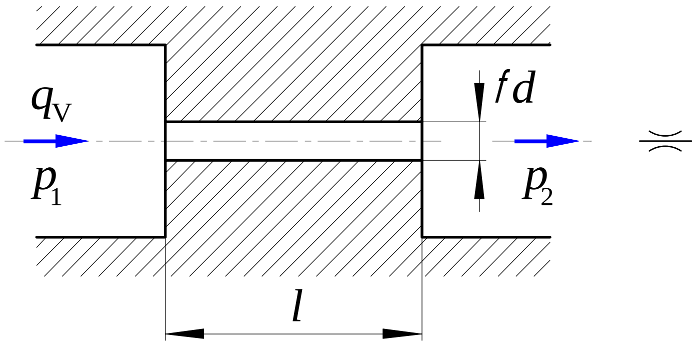




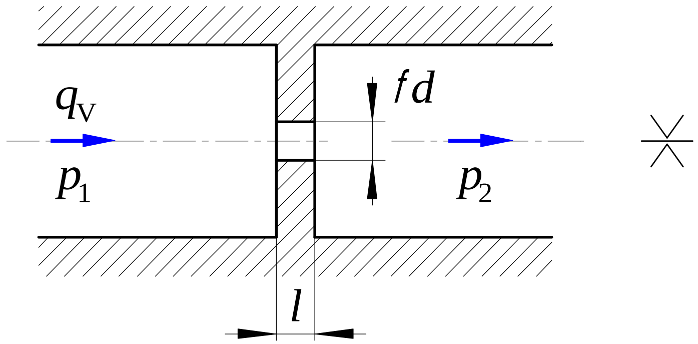
Governing or controlling flow rate with a throttle requires existence of an alternative flow path

Throttle types

Laminar



Turbulent



$$q_V = \frac{\pi \cdot D_H^4}{128 \cdot \eta \cdot l} \cdot (p_1 - p_2)$$

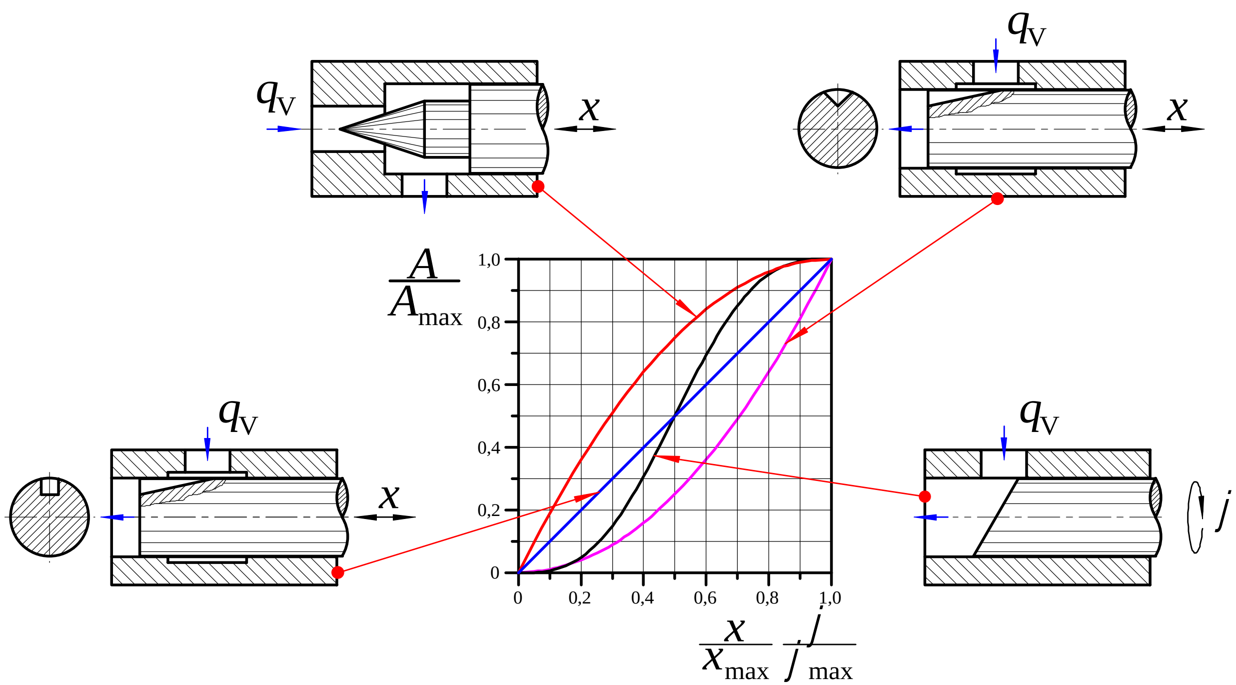
viscosity

$$q_V = C_q \cdot \frac{\pi \cdot D_H^2}{4} \cdot \sqrt{\frac{2}{\rho} \cdot (p_1 - p_2)}$$

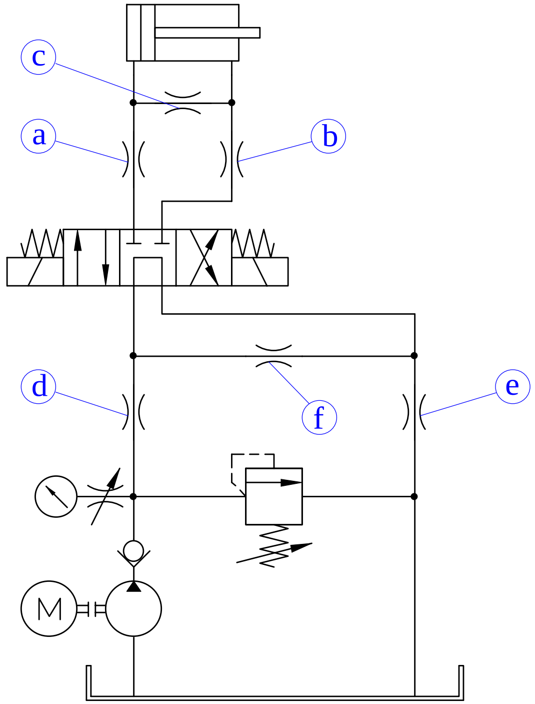
density (no viscosity)

Throttle shapes

Depending on the geometry the flow areas increase differently



Governing/Controlling speed of actuator



Alternative sites of a throttle

Eg., named after movement to positive direction

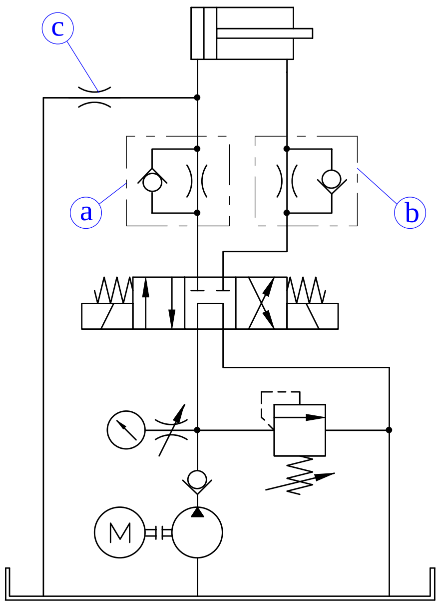
a, d = input channel

b, e = output channel

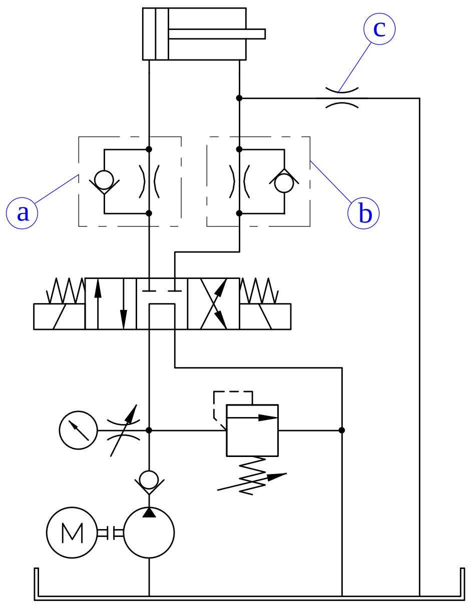
c, f = parallel channel of cylinder

Governing/Controlling the speeds of actuator independently to each direction

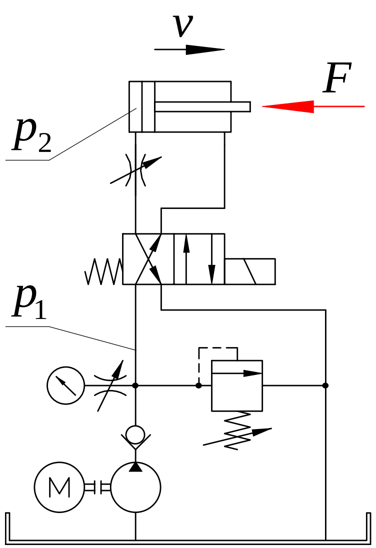
Positive direction

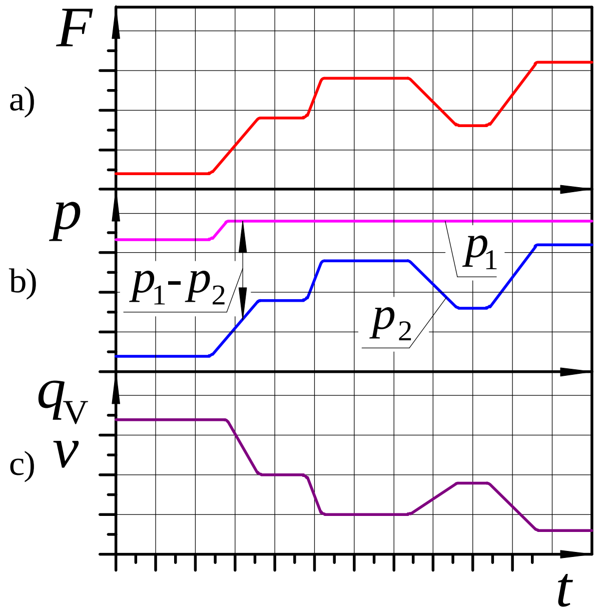


Negative direction



Throttle valves



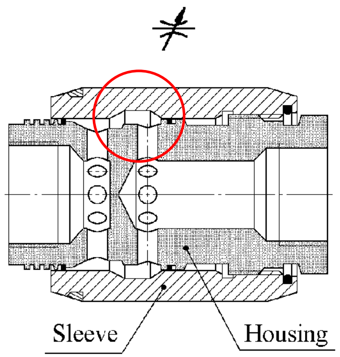


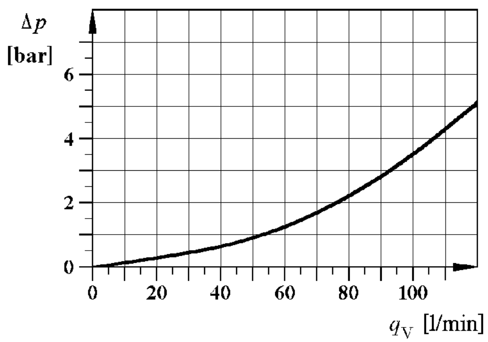
At first velocity is limited by maximum pump flow rate -> all flow to cylinder

After increasing force load pump pressure increases -> flow is limited by maximum pressure, certain amount of low directly to tank

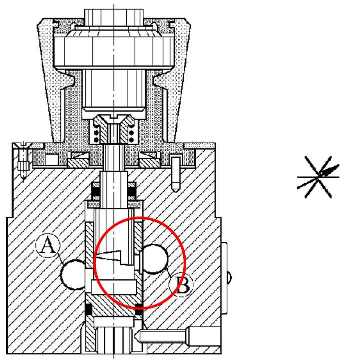
Loading of the actuator affects the actuator speed

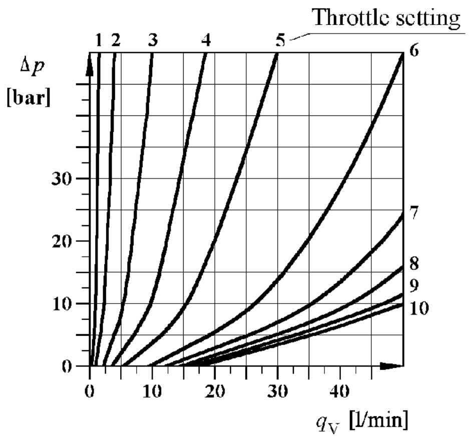
Long flow path - also viscosity has an effect on flow rate



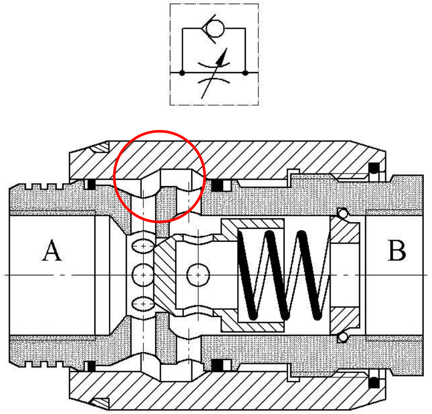


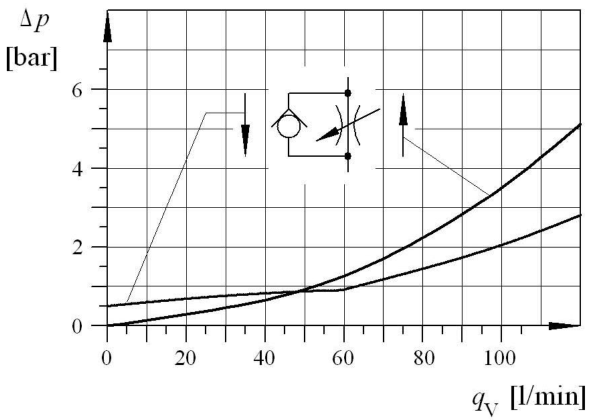
Short flow path - viscosity has minor effect on flow rate





One-way restrictor valve



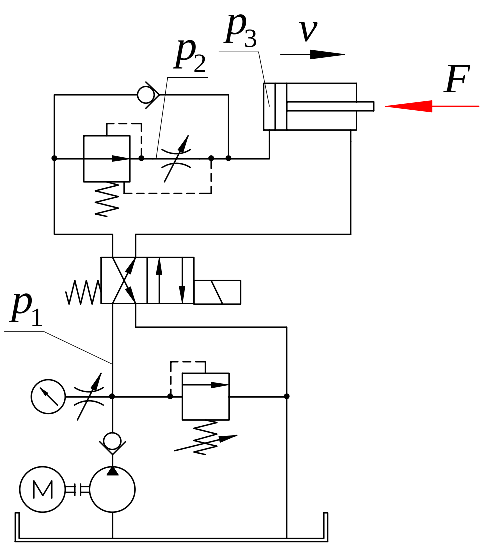


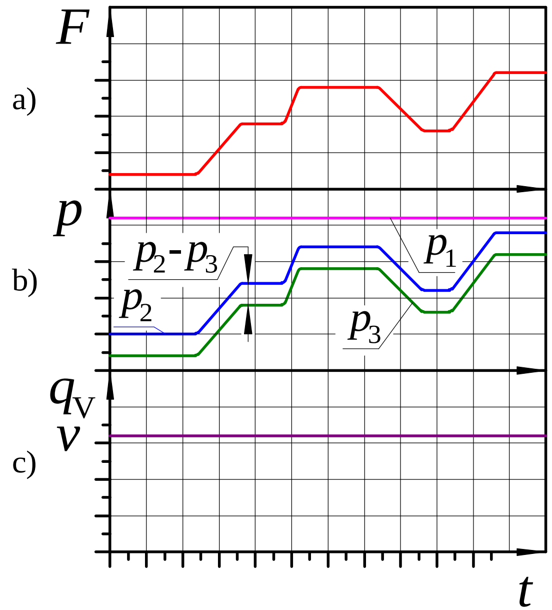
Flow control valves

2-way valve
3-way valve
- incorporates pressure relief function

2-way valve

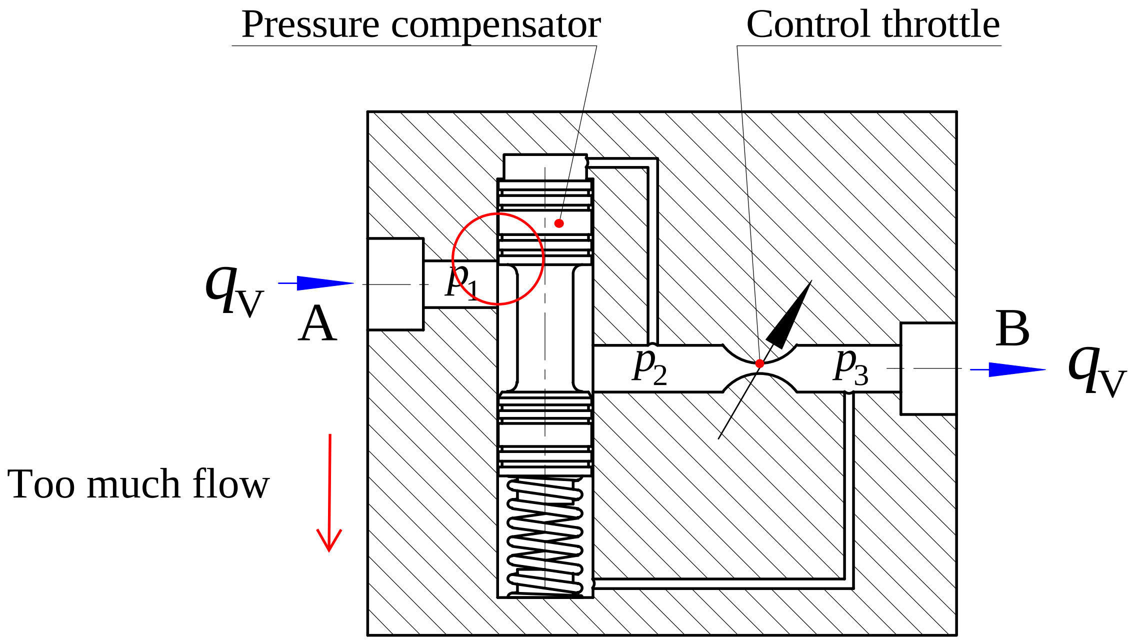
Flow through orifice the same - pressure loss over orifice the same



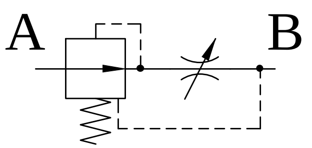


Loading of the actuator does not affect the actuator speed

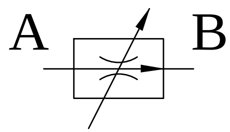
2-way valve



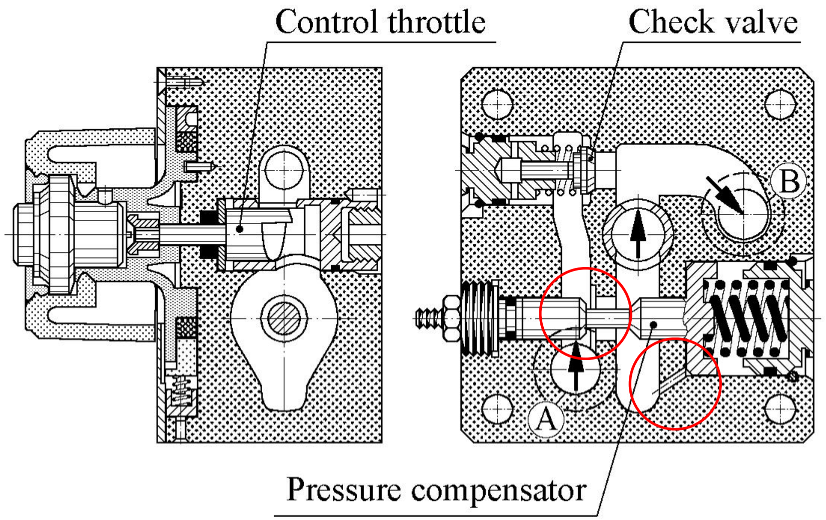
Complete symbol



Simplified symbol

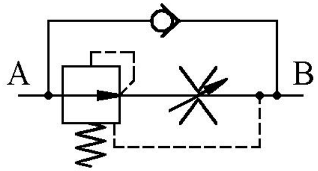


2-way valve

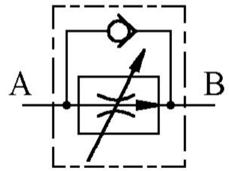


With integrated check valve

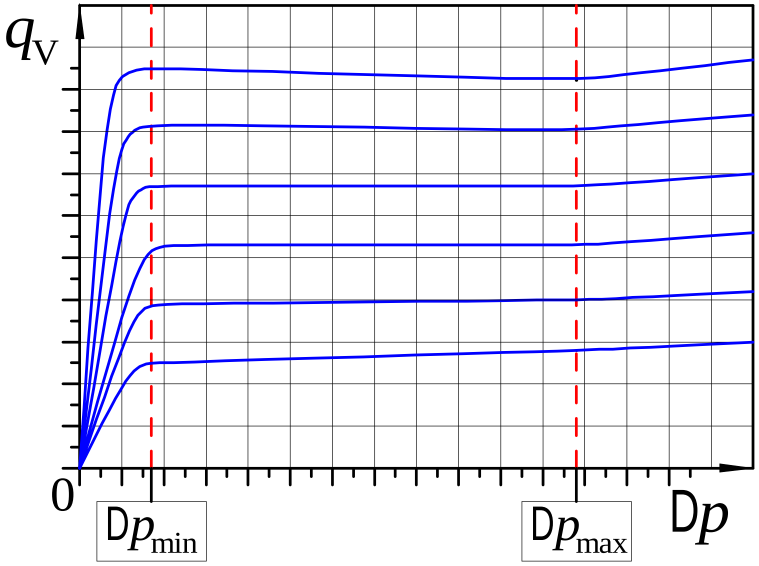
Complete symbol



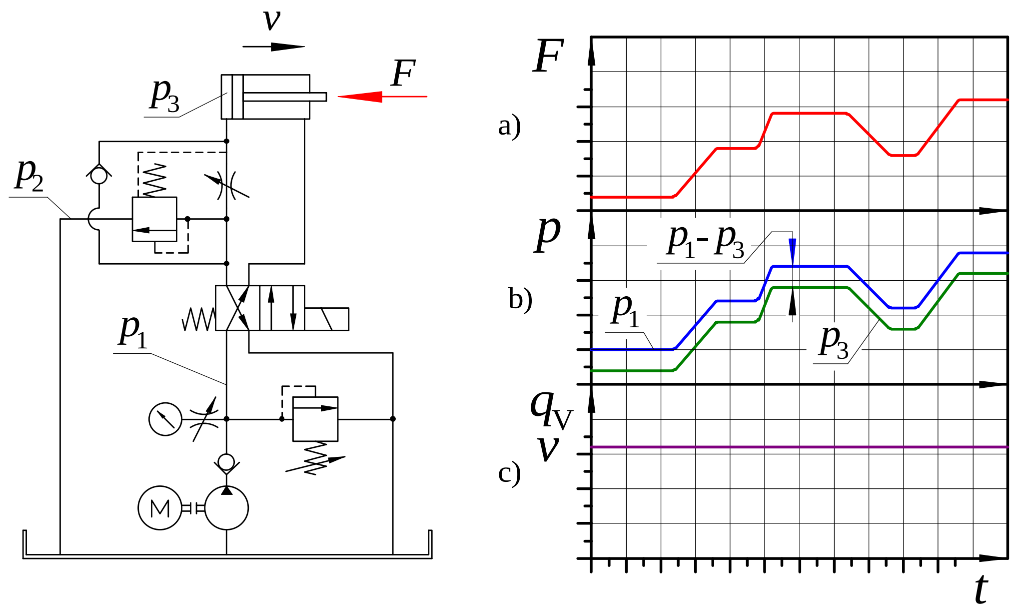
Simplified symbol



Boundary conditions of control function

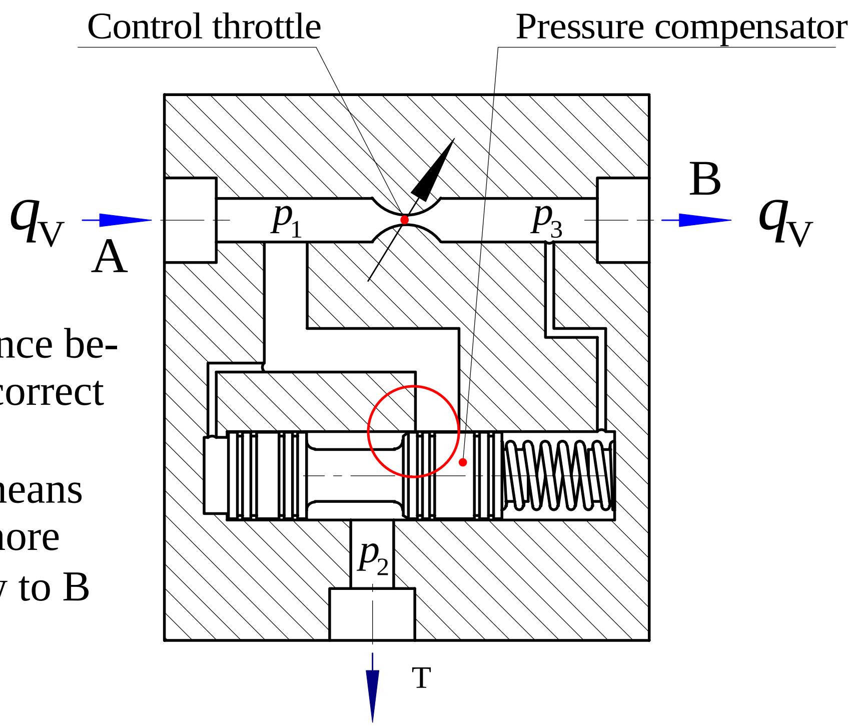


3-way valve

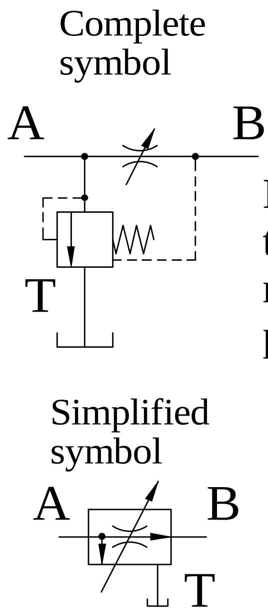


Loading of the actuator does not affect the actuator speed

3-way valve



Correct pressure difference between p_1 and p_3 means correct flow rate.
Too much flow (to B) means that p_3 is "too low" -> more flow to tank -> less flow to B

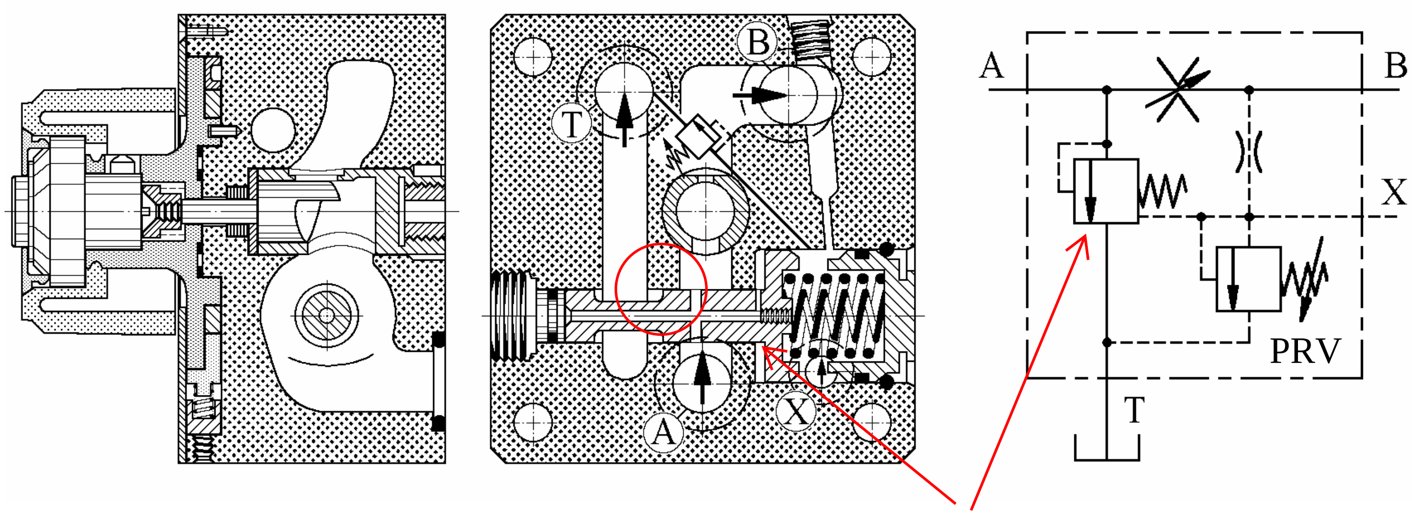


Excess flow directly to tank, not through pressure relief valve (at high pressure)

3-way valve

Also external command signal (X) and pressure relief valve (PRV)

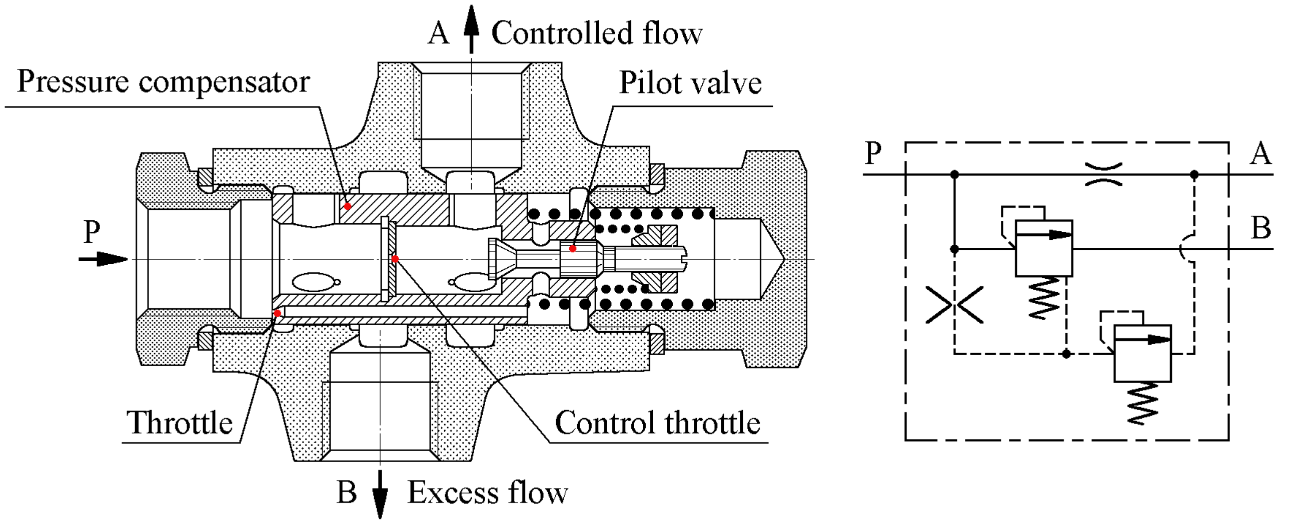
Too much flow AB, "too high pressure" at A, pressure compensator opens (more)



Pressure compensator

3-way valve

Pilot operated

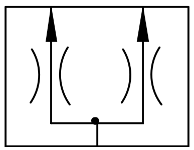


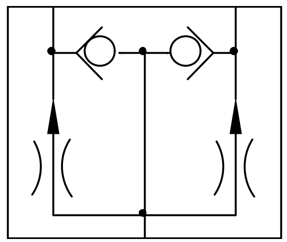
Flow divider valves

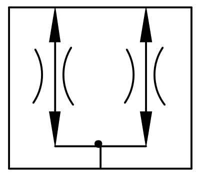
Single-acting
- flow to only one direction

Single-acting
- controlled flow to one direction,
  free flow to the opposite direction

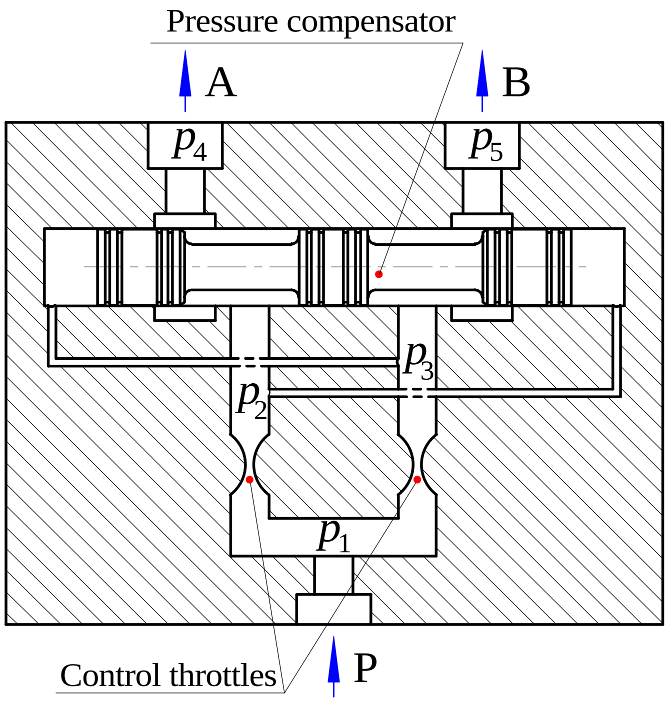
Double-acting
- controlled flow to both directions

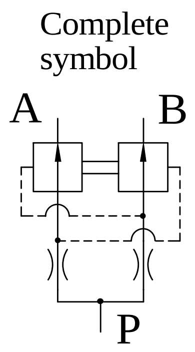


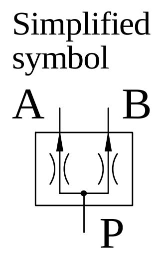


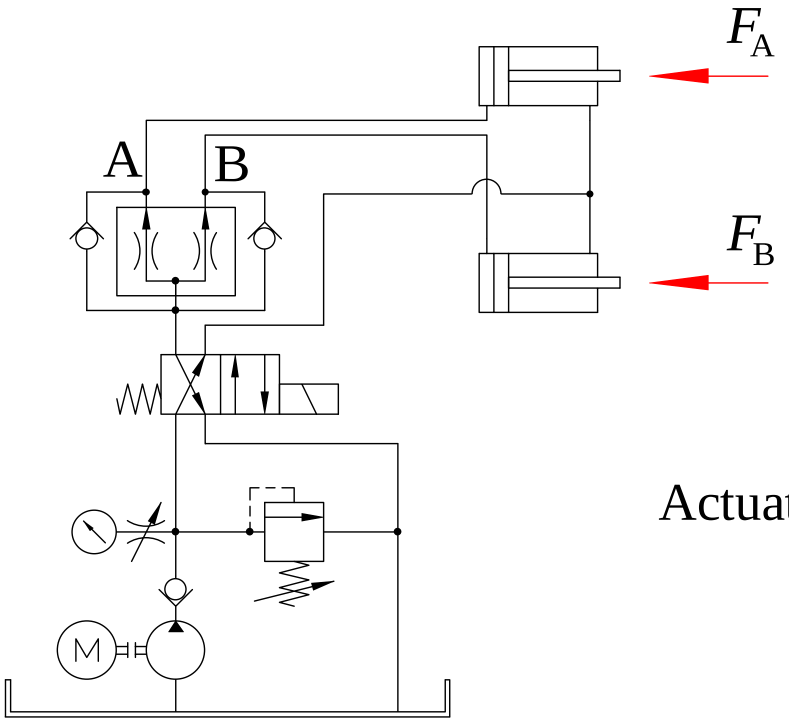


Single-acting flow divider valve



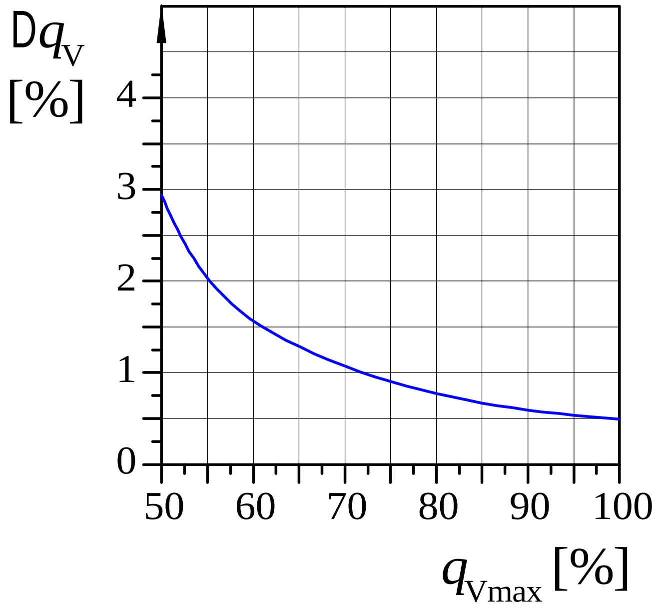






Actuator speeds ~ equal

Effect of flow rate to the control accuracy



Lecture themes - Recap

Actuators
- control of direction of movement?
- control of speed?
- control of force or torque?

Can valves be used for other control purposes?

How to produce the force needed to control valve slides?

Any disadvantages in flow valves?

Valve slide types?