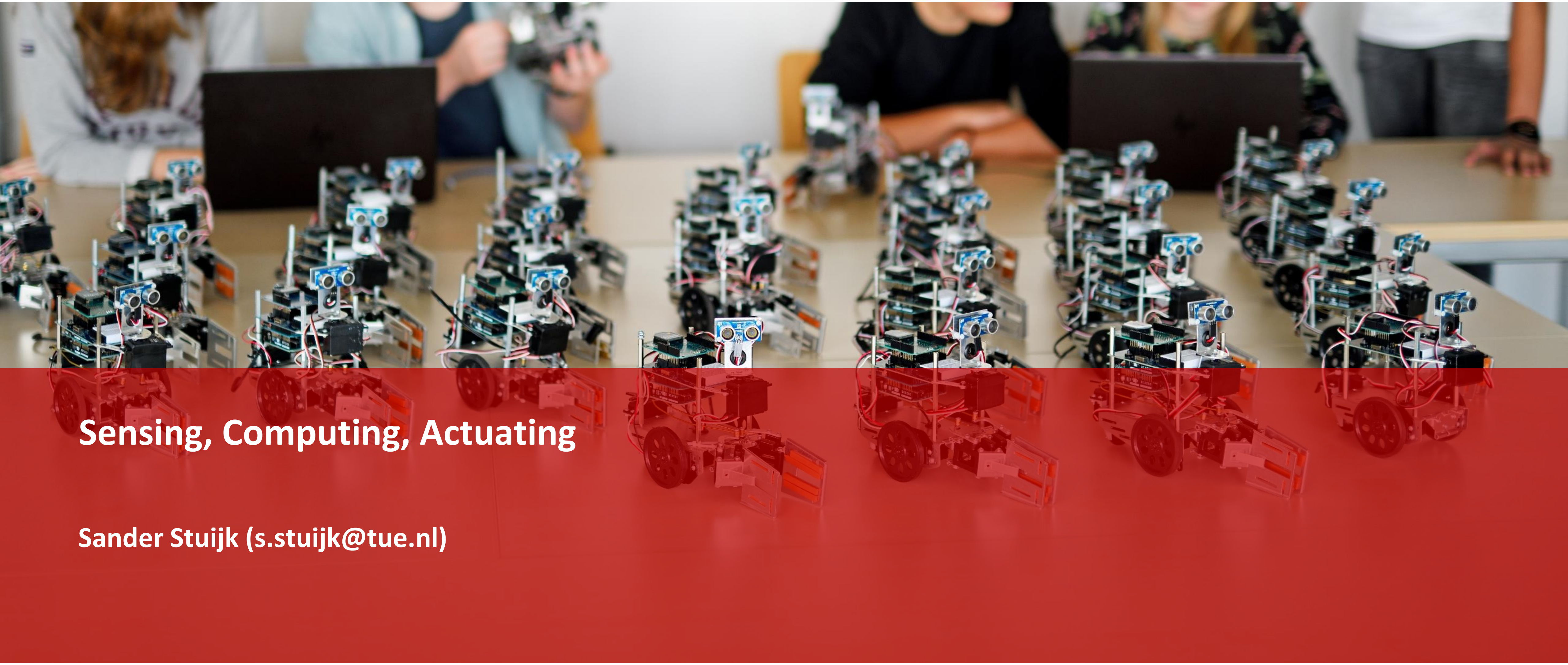


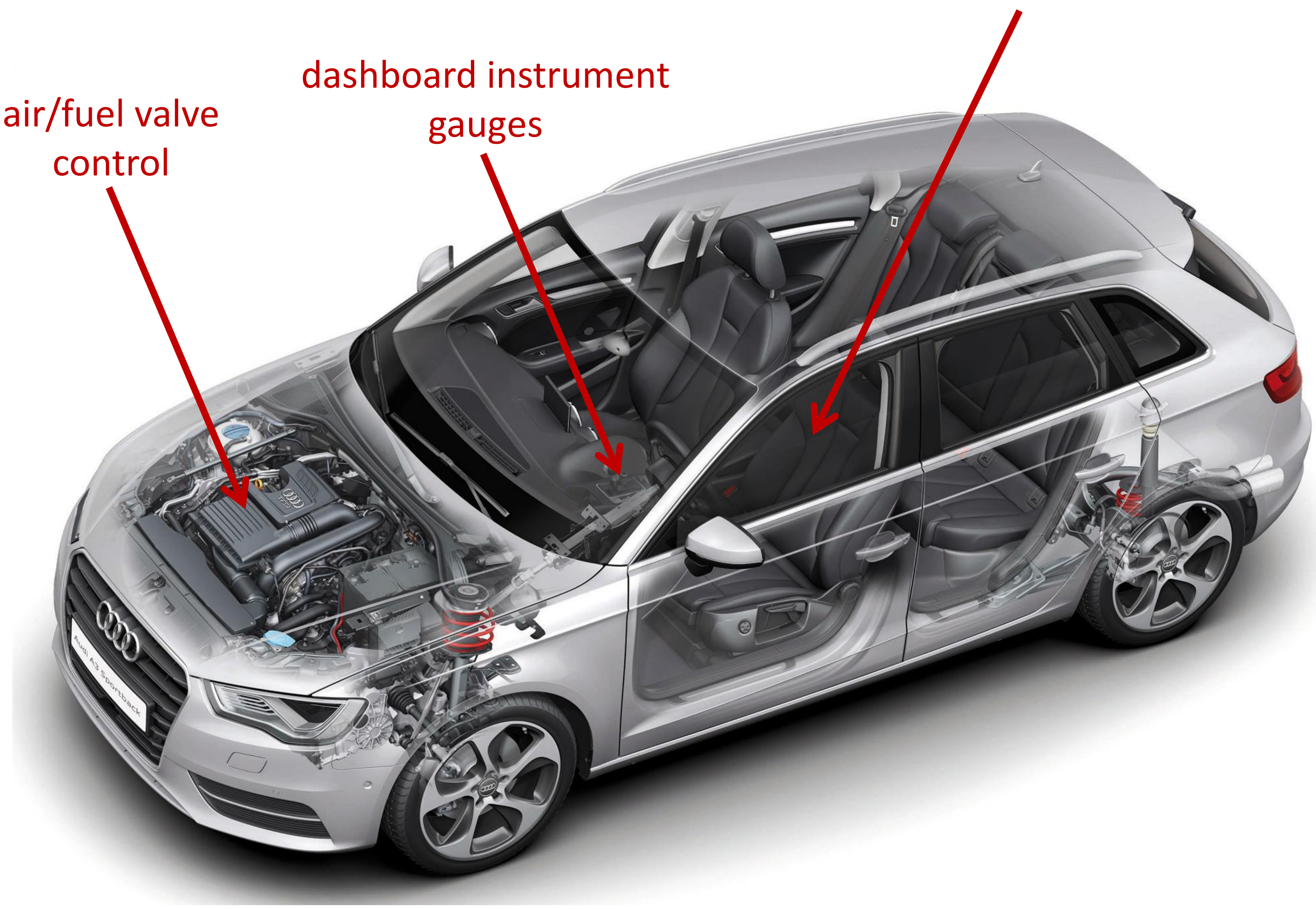
Sensing, Computing, Actuating

Sander Stuijk (s.stuijk@tue.nl)

STEPPER MOTOR

(Chapter 8.1, 8.2, 8.7, 8.8)

Stepper motor

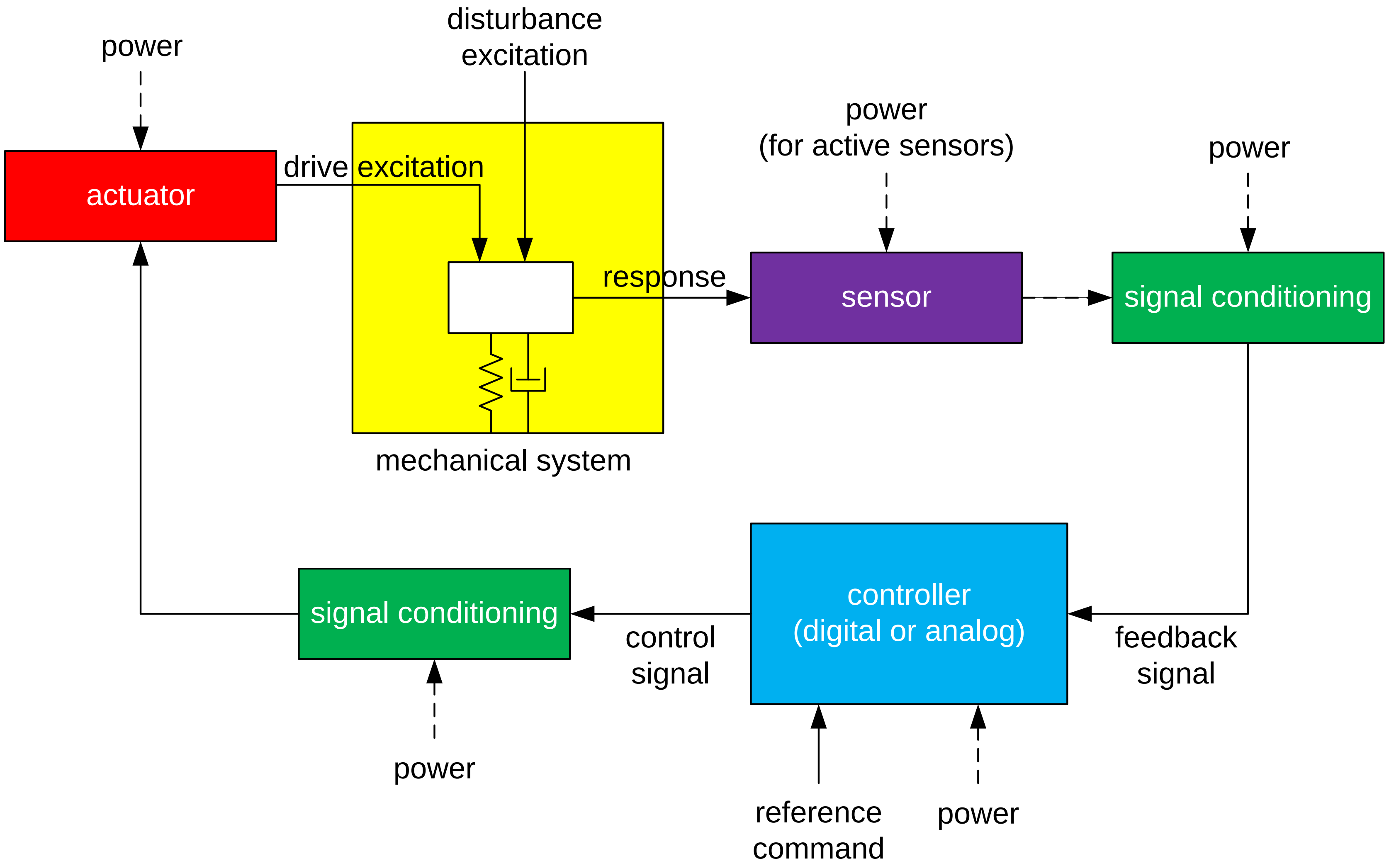


air/fuel valve control

dashboard instrument gauges

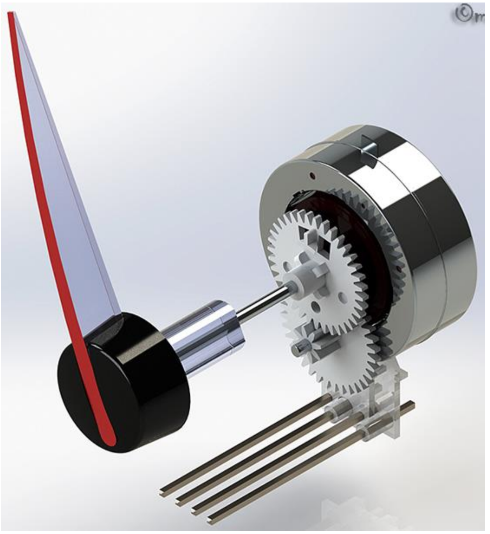
electric window

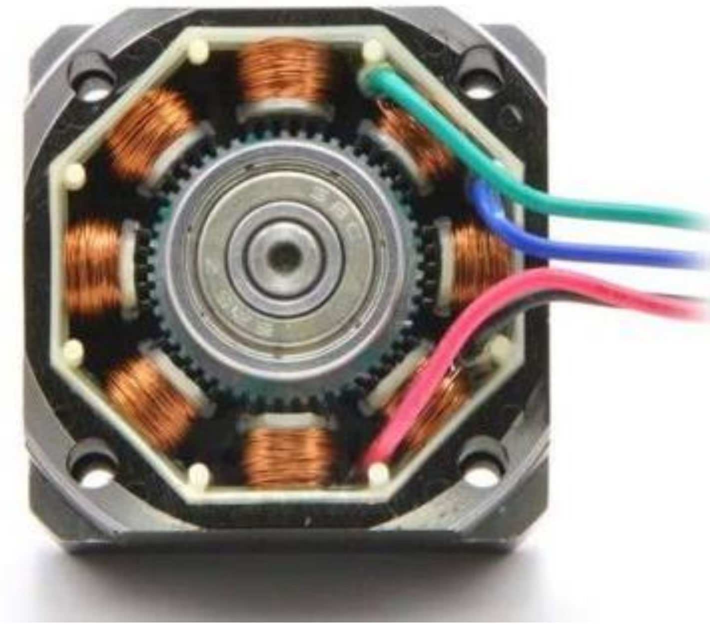
Control system



Stepper motor

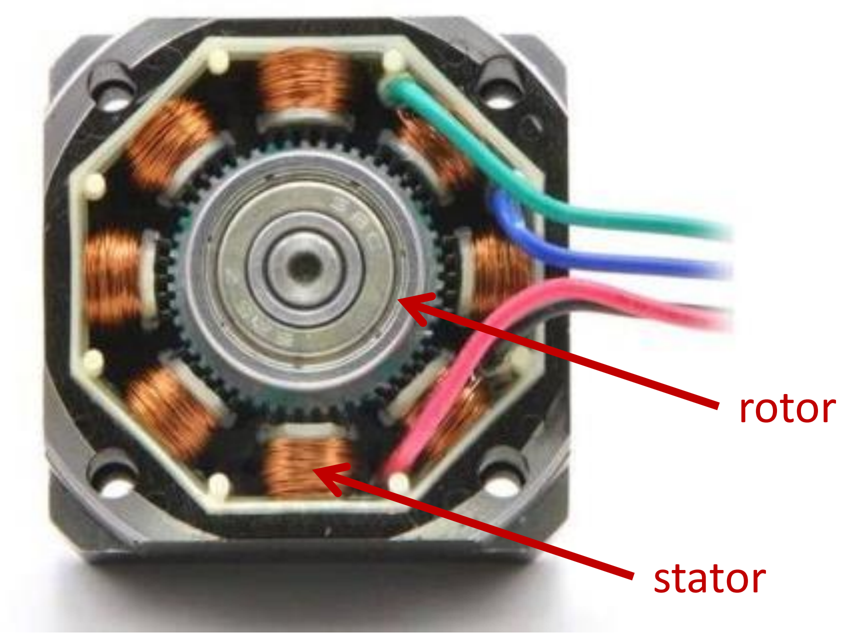
- converts digital electrical signal to mechanical signal
  - fixed angular step per pulse
  - typical values: 2°, 2.5°, 5°, 7.5°, 15°
  - available in several horse power ratings
  - can track input signal up-to 1200 pulses/sec.

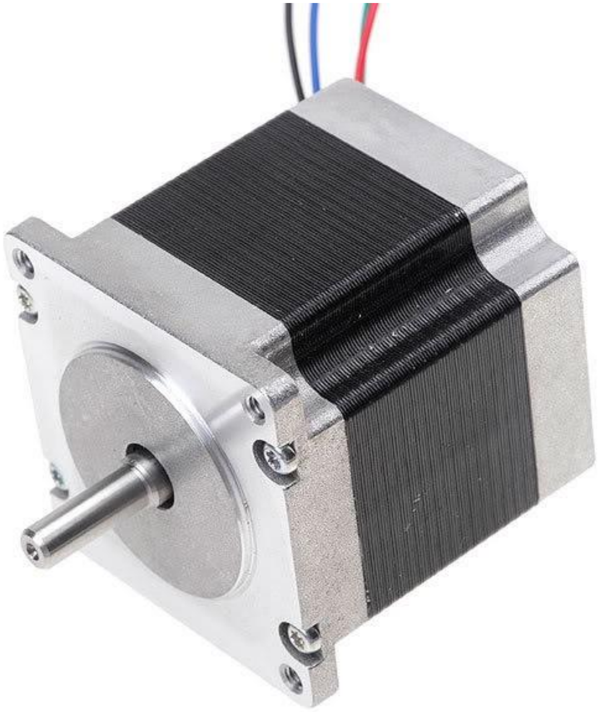




Principle of operation

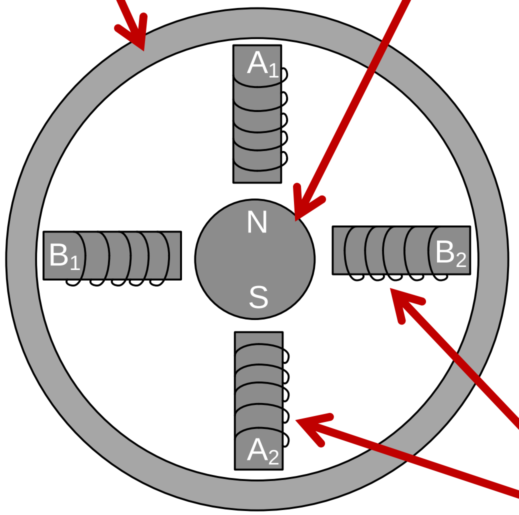
- 3 types of stepper motors
  - variable-reluctance (VR) with soft-iron core (teeth on rotor)
  - permanent-magnet (PM) with magnetized rotors
  - hybrid (HB) combination of VR and PM





Permanent magnet step motor

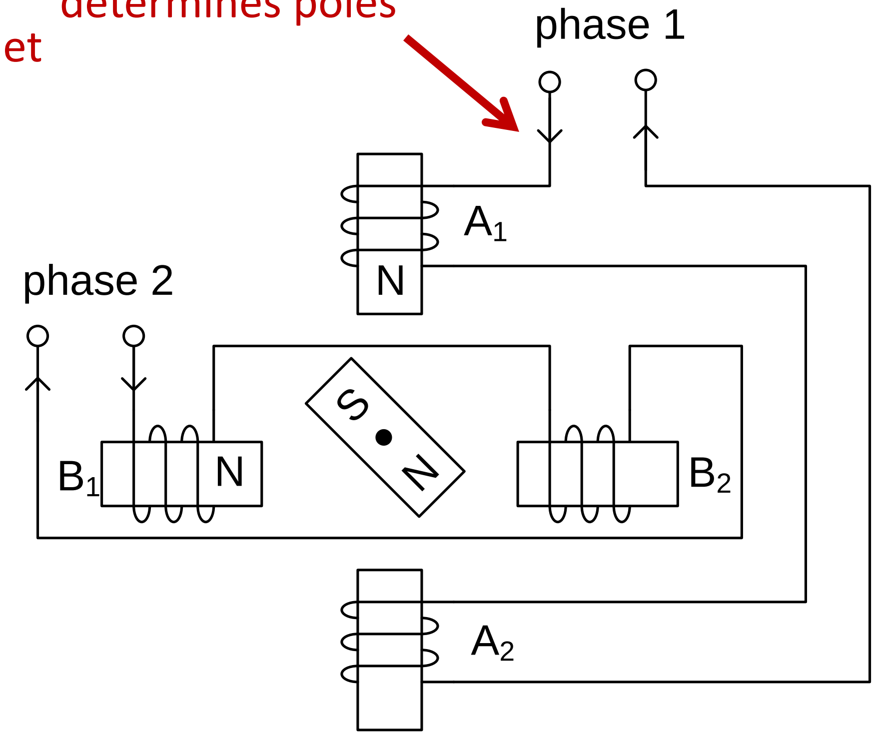
- two-phase two-pole permanent magnet step motor
  - two phases → two windings
  - two-poles → rotor has one permanent magnet



motor case

permanent magnet core

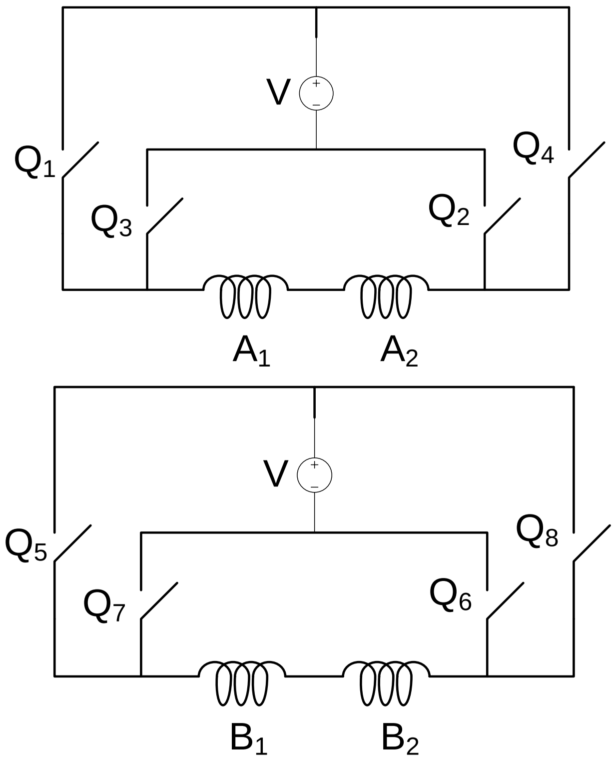
coils



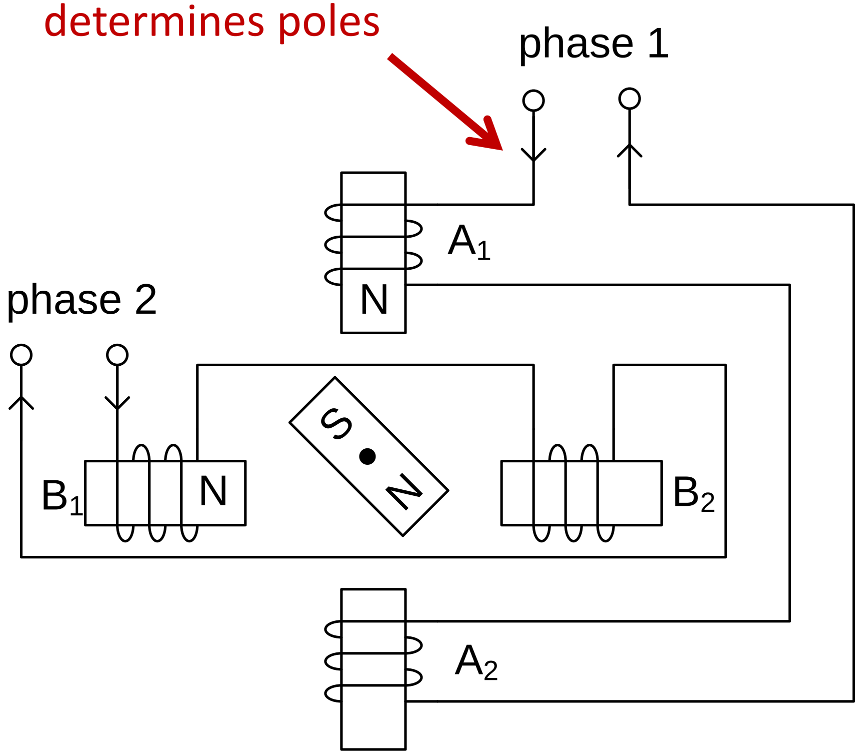
direction of current determines poles

Permanent magnet step motor

- dc voltage applied to both phases
  - direction of current through windings A1 and A2 controlled with switches Q1, Q2, Q3, Q4
  - direction of current through windings B1 and B2 controlled with switches Q5, Q6, Q7, Q8

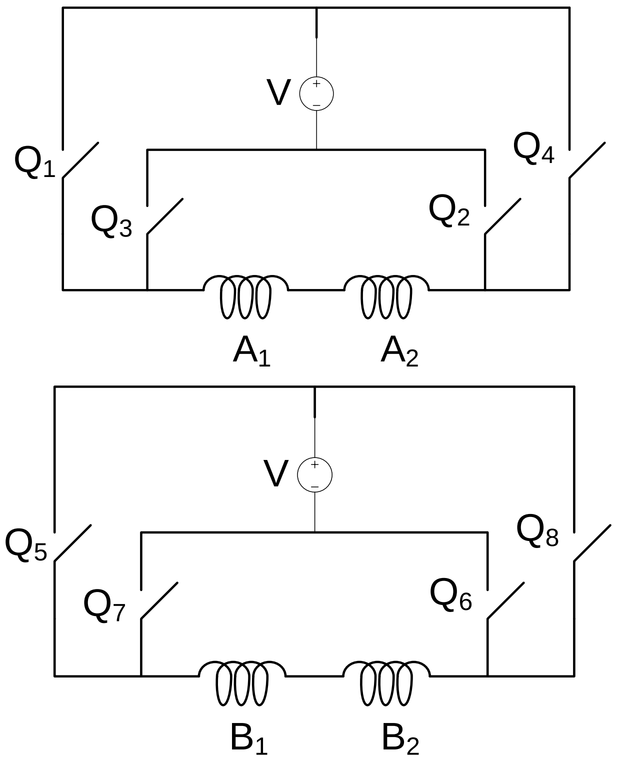


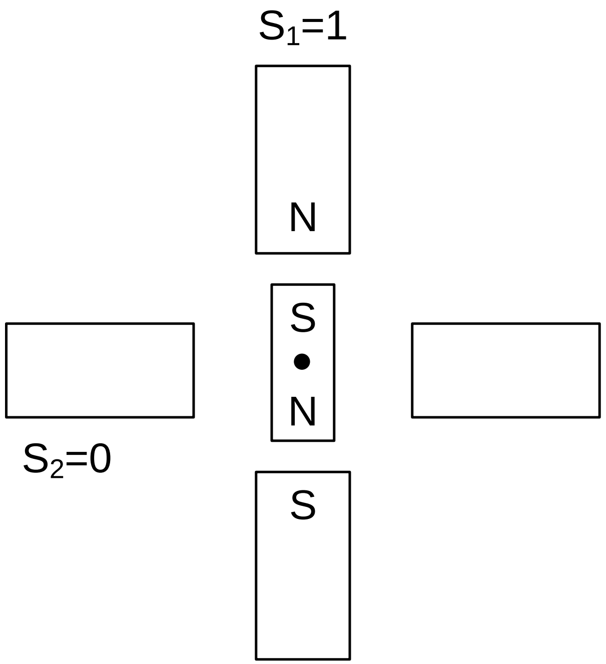
direction of current determines poles



Permanent magnet step motor

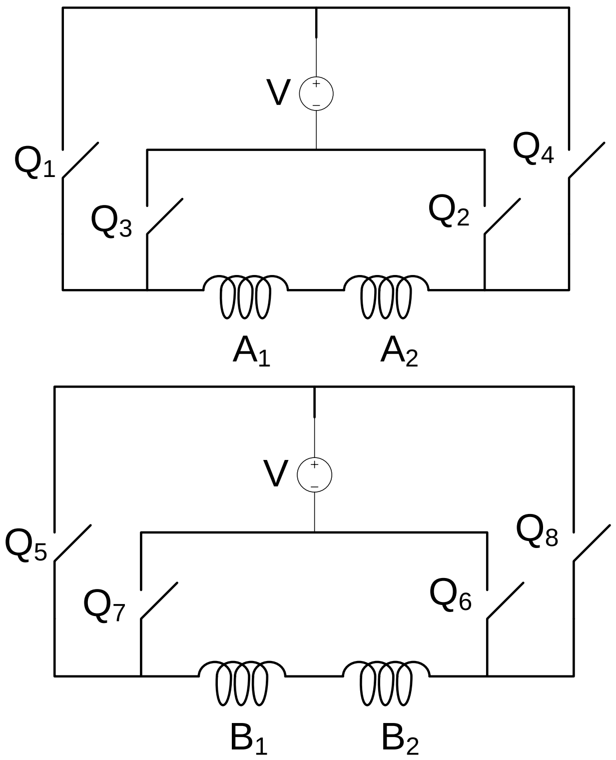
	step 1	step 2	step 3	step 4
Q_1-Q_2	ON (S_1=1)			
Q_3-Q_4				
Q_5-Q_6				
Q_7-Q_8				

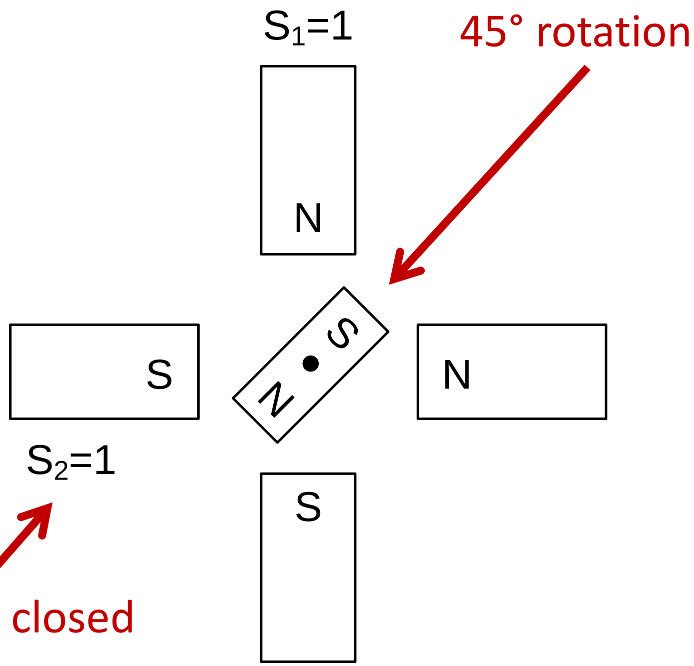




Permanent magnet step motor

	step 1	step 2	step 3	step 4
Q_1-Q_2	ON (S_1=1)	ON (S_1=1)		
Q_3-Q_4				
Q_5-Q_6				
Q_7-Q_8		ON (S_2=1)		



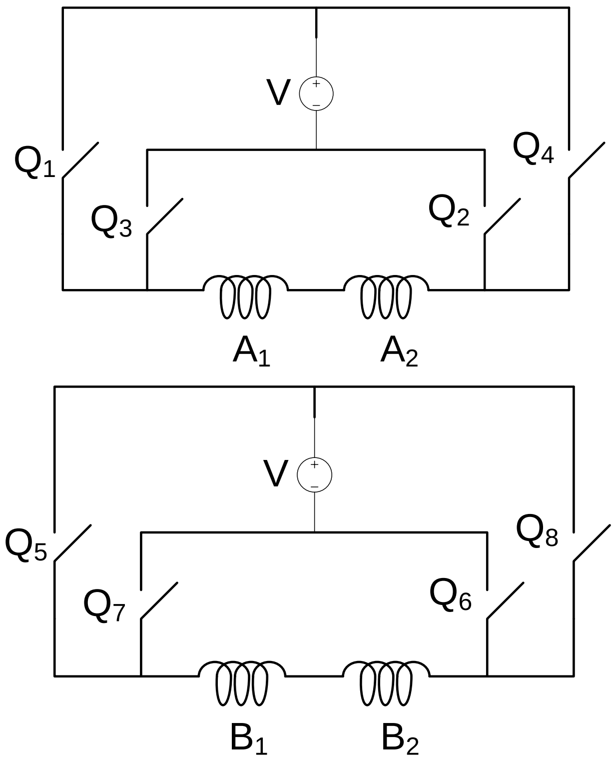


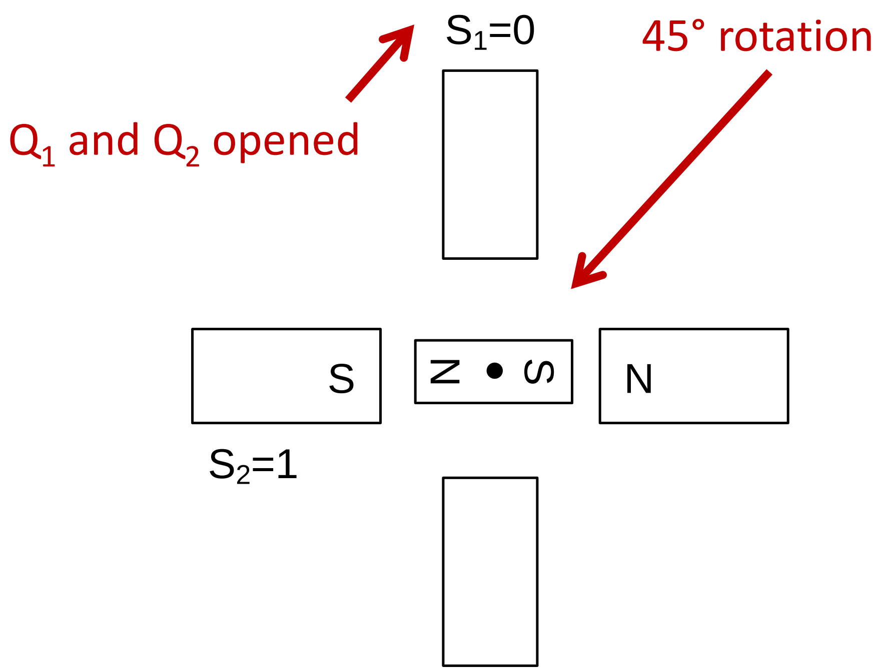
45° rotation

Q_7 and Q_8 closed

Permanent magnet step motor

	step 1	step 2	step 3	step 4
Q_1-Q_2	ON (S_1=1)	ON (S_1=1)		
Q_3-Q_4				
Q_5-Q_6				
Q_7-Q_8		ON (S_2=1)	ON (S_2=1)	



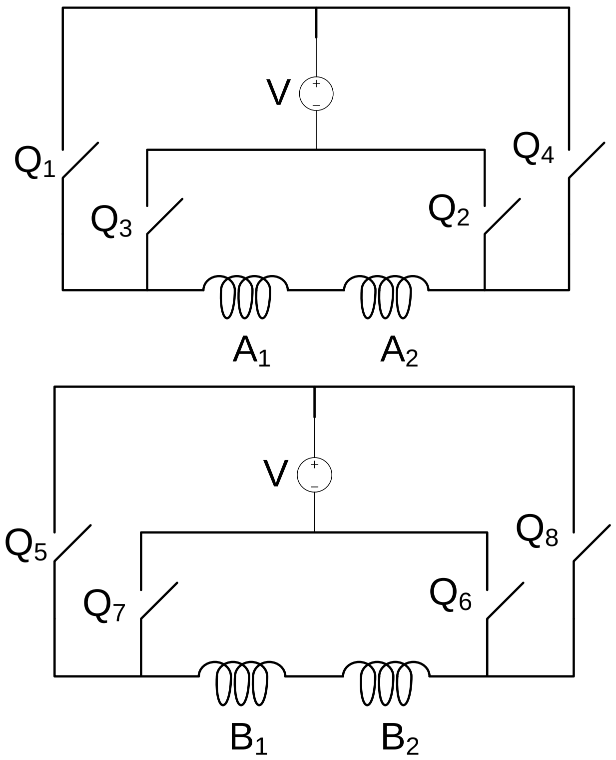


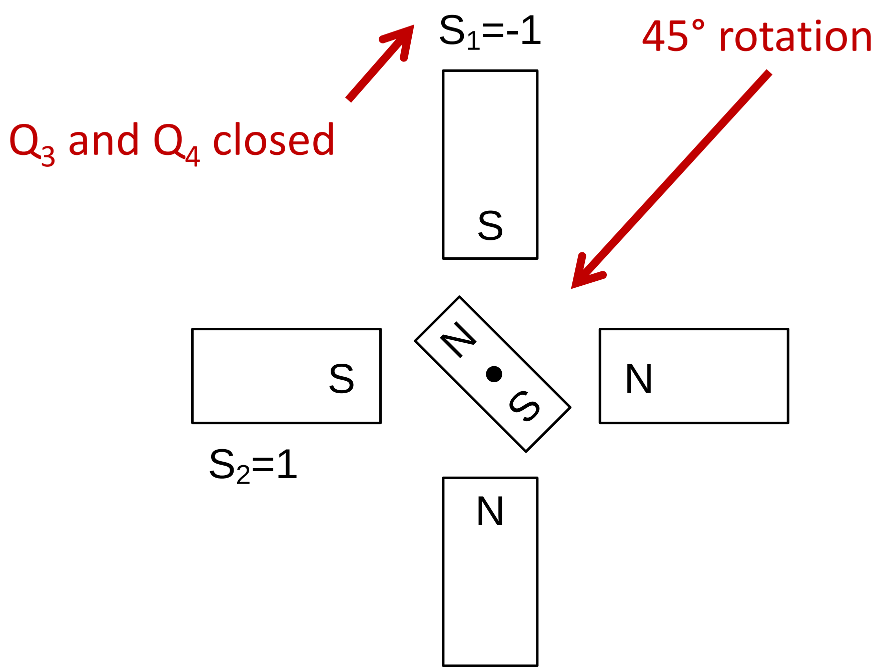
Q_1 and Q_2 opened

45° rotation

Permanent magnet step motor

	step 1	step 2	step 3	step 4
Q_1-Q_2	ON (S_1=1)	ON (S_1=1)		
Q_3-Q_4				ON (S_1=-1)
Q_5-Q_6				
Q_7-Q_8		ON (S_2=1)	ON (S_2=1)	ON (S_2=1)





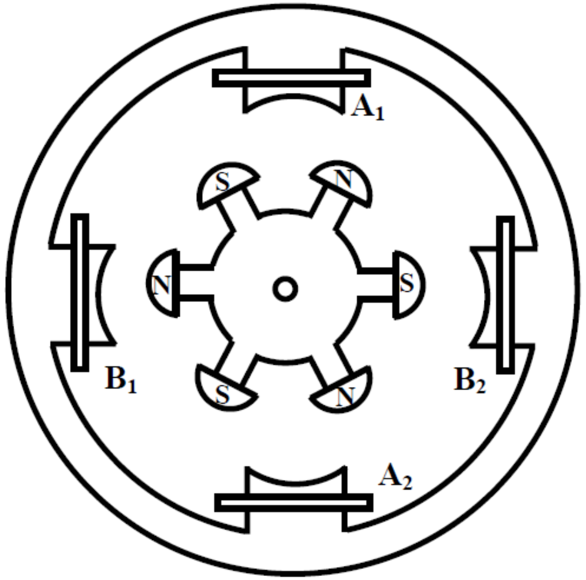
Permanent magnet step motor

	step 1	step 2	step 3	step 4
Q_1-Q_2	ON (S_1=1)	ON (S_1=1)		
Q_3-Q_4				ON (S_1=-1)
Q_5-Q_6				
Q_7-Q_8		ON (S_2=1)	ON (S_2=1)	ON (S_2=1)

- switching step angle 45°
- 8 steps needed for complete revolution
- each alternating step two windings are energized (half stepping)
- direction of rotation reversed by reversing step switching sequence

Permanent magnet step motor

- example: two-phase six-pole permanent magnet motor
  - stator pitch $\Theta_s = 360° / 4 = 90°$
  - rotor pitch $\Theta_r = 360° / 6 = 60°$
  - full step angle $\Theta_{fs} = \Theta_s - \Theta_r = 30°$
  - half step angle $\Theta_{hs} = (\Theta_s - \Theta_r) / 2 = 15°$

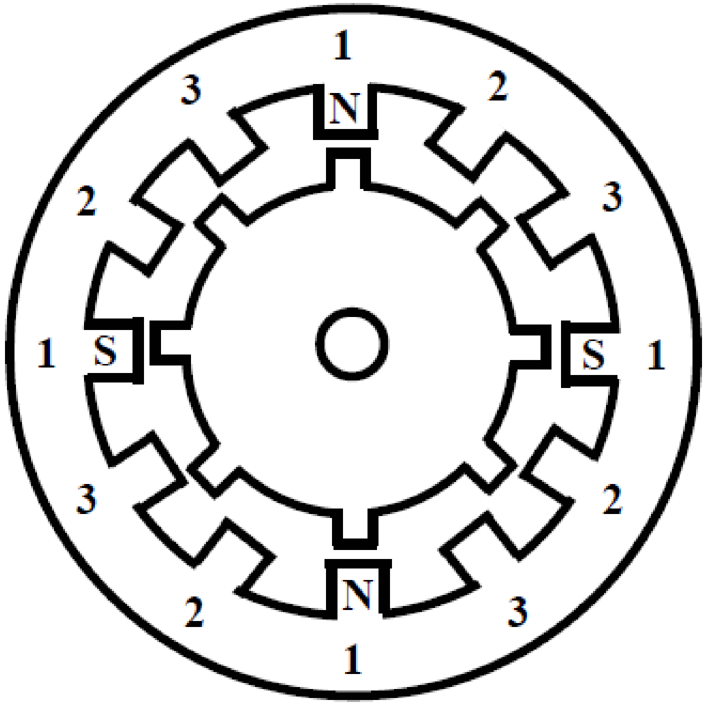


- permanent magnet provides holding torque
  - rotor locks itself when coils are not energized
- direction of current needs to be reversed for each winding
  - requires transistor circuit
  - two solutions to this problem
    - use two windings per pole (one for each direction)
    - use variable magnet step motor

Variable reluctance step motor

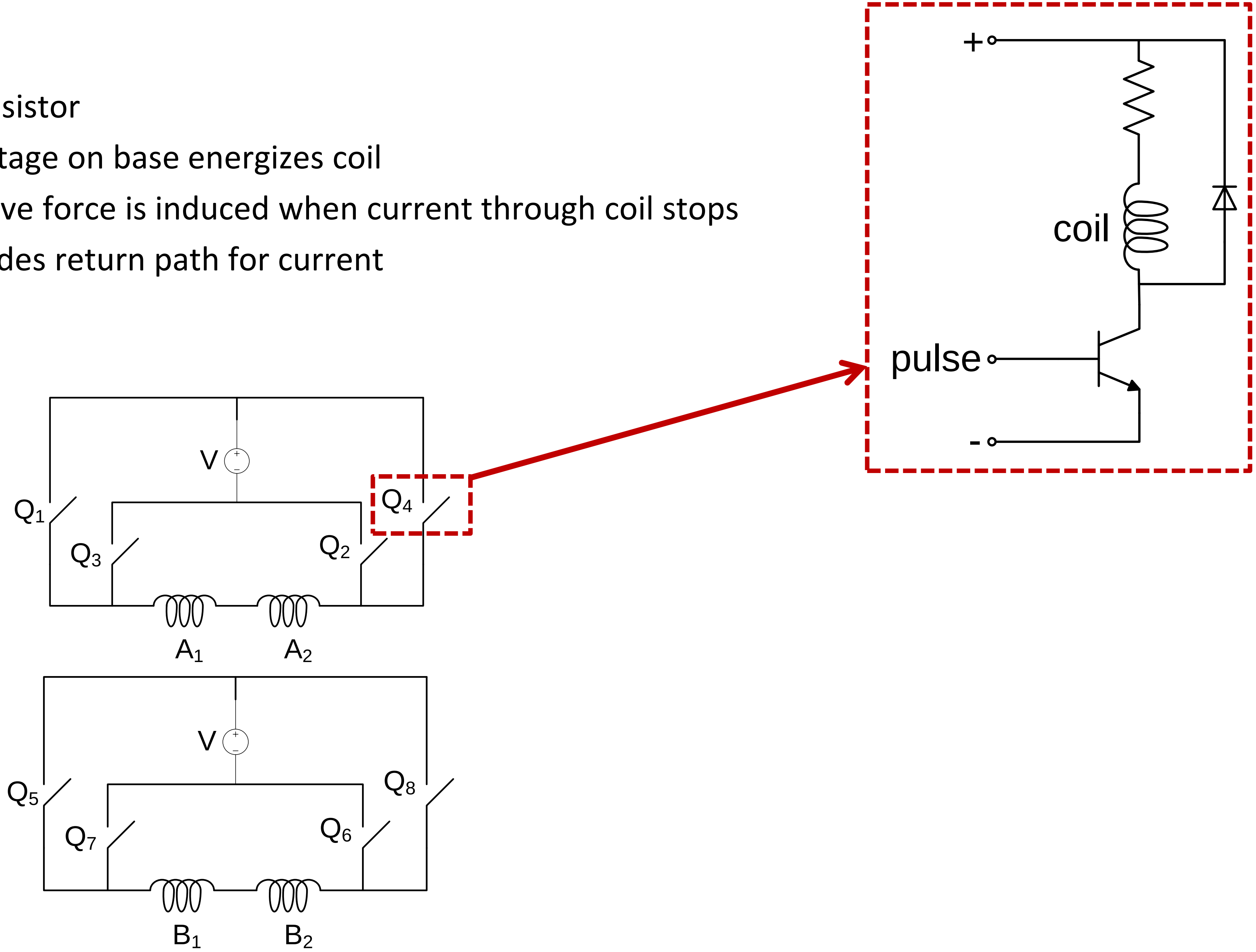
- cylindrical soft-iron core with projected teeth
- operation
  - energy specific stator coil (phase)
  - rotor aligns to minimum reluctance path
- example: three-phase, 12 stator teeth, 8 rotor teeth VR step motor
  - stator pitch $\Theta_s = 360° / 12 = 30°$
  - rotor pitch $\Theta_r = 360° / 8 = 45°$
  - full step angle $\Theta_{fs} = 15°$
  - half step angle $\Theta_{hs} = 7.5°$

  - half-step counter clock-wise
    step sequence
    1-(1,2)-2-(2,3)-3-(3,1)-1



Driving circuit

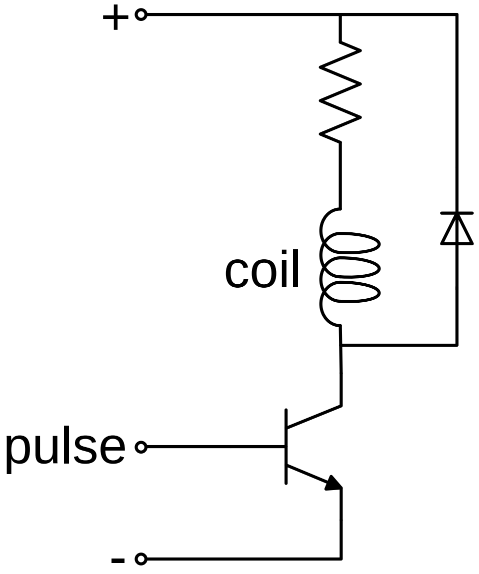
- switching transistor
  - positive voltage on base energizes coil
  - electromotive force is induced when current through coil stops
  - diode provides return path for current

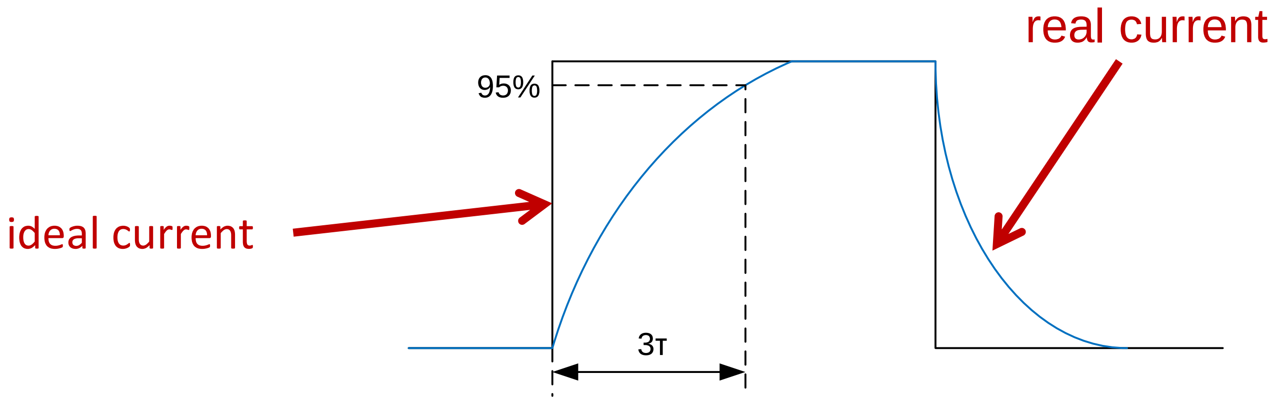


Driving circuit

- switching transistor
  - positive voltage on base energizes coil
  - emf is induced when current through coil stops
  - diode provides return path for current

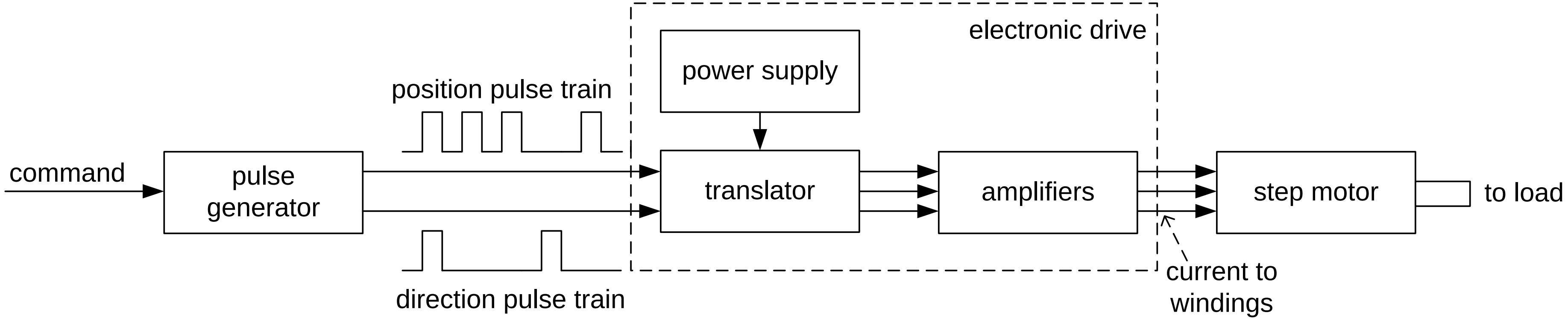
- current pulse
  - presence of inductor causes delay in actual response
  - sufficient torque provided after 3τ (time constant)
  - pulse width should be 6-8τ





Control of step motor

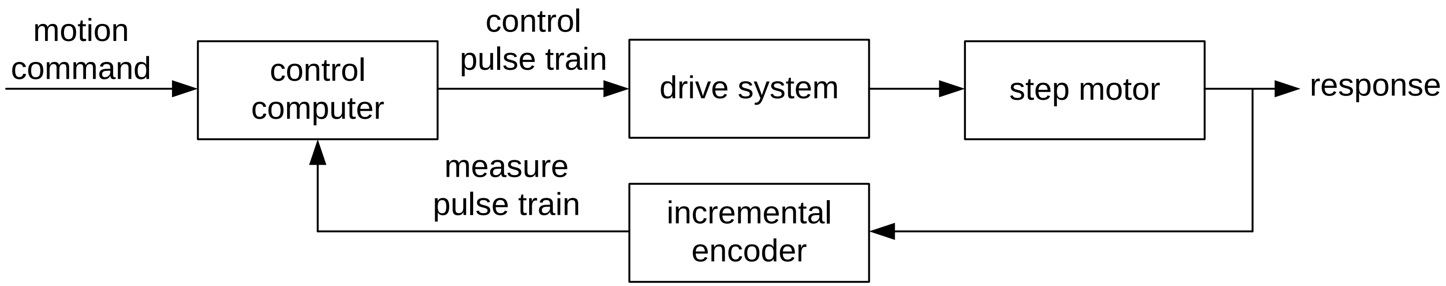
- open-loop control of step motor



- translator distributes position pulse train to phases
- direction of rotation reversed with direction pulses
- missed pulse may cause erratic behavior of rotor

Control of a step motor

- closed-loop feedback control of step motor



- sensor needed to measure rotation
- incremental optical encoder often used for this purpose

DIGITAL TRANSDUCERS

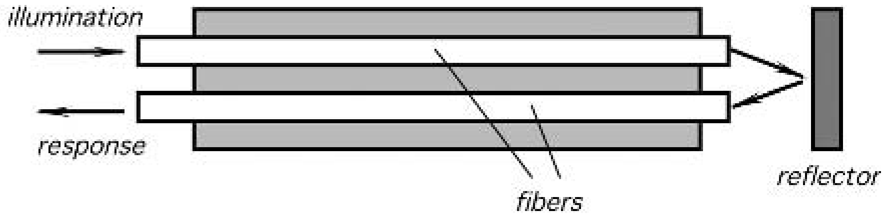
(Chapter 5)

Optical sensors

- optical sensors are widely used for position and displacement sensing

- advantages
  - no loading effects
  - relative long operating distances
  - insensitive to magnetic fields and electrostatic interference

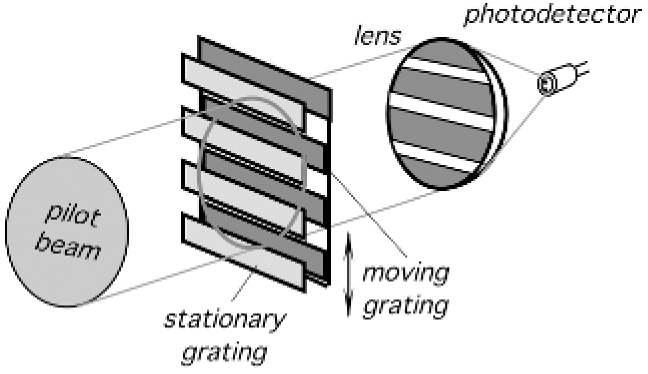
- optical sensor consists of
  - light source
  - photo detector
  - light guidance device

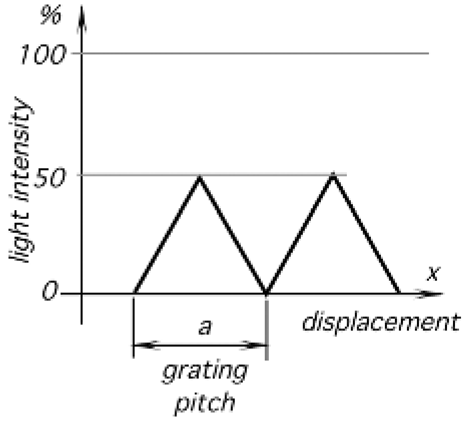


Optical sensors

- grating sensor is an optical displacement transducer
- two overlapping gratings serve as a light-intensity modulator

- operation
  - incoming light beam strikes first grating
  - grating passes 50% of light towards second, moving grating
  - depending on the alignment between the grating a fraction of the light can pass through this second grating
  - intensity of passed light is sensed with photo-detector

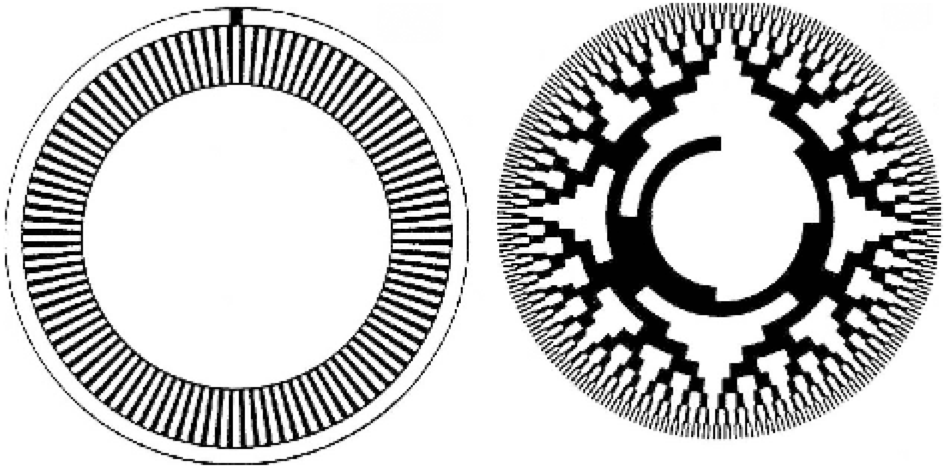




Optical sensors

- full-scale displacement is equal to size of an clear (opaque) sector
- gives trade-off between sensitivity and dynamic range
  - large sensitivity requires small opaque sector (pitch)
  - large dynamic range (displacement) requires large pitch

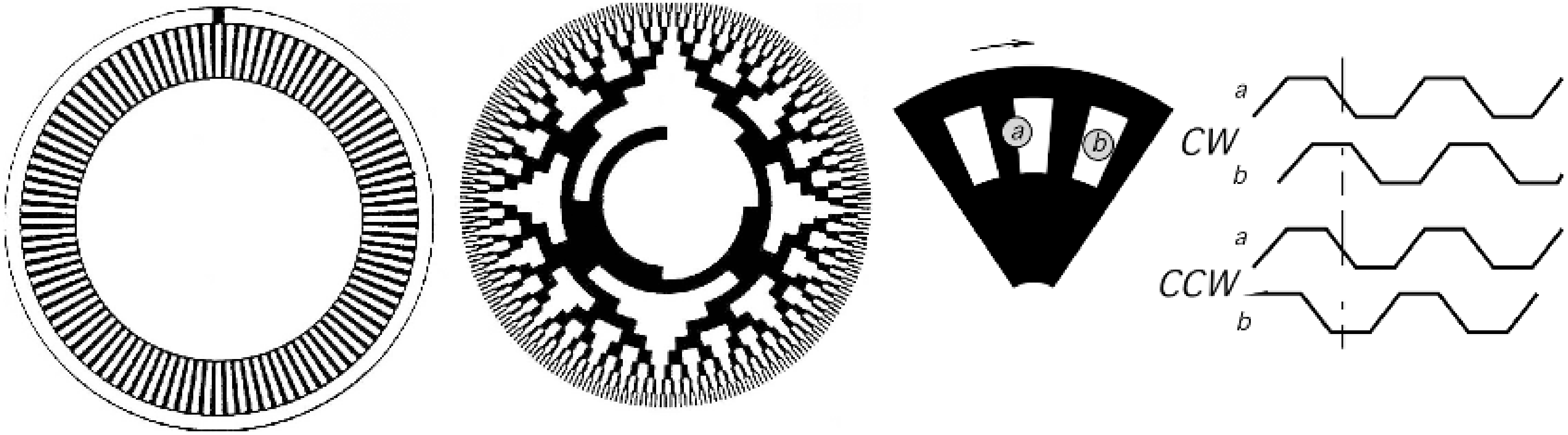
- grating principle is used in rotating and linear encoders
- two types of encoders are distinguished
  - incremental position encoders (left)
  - absolute position encoders (right)



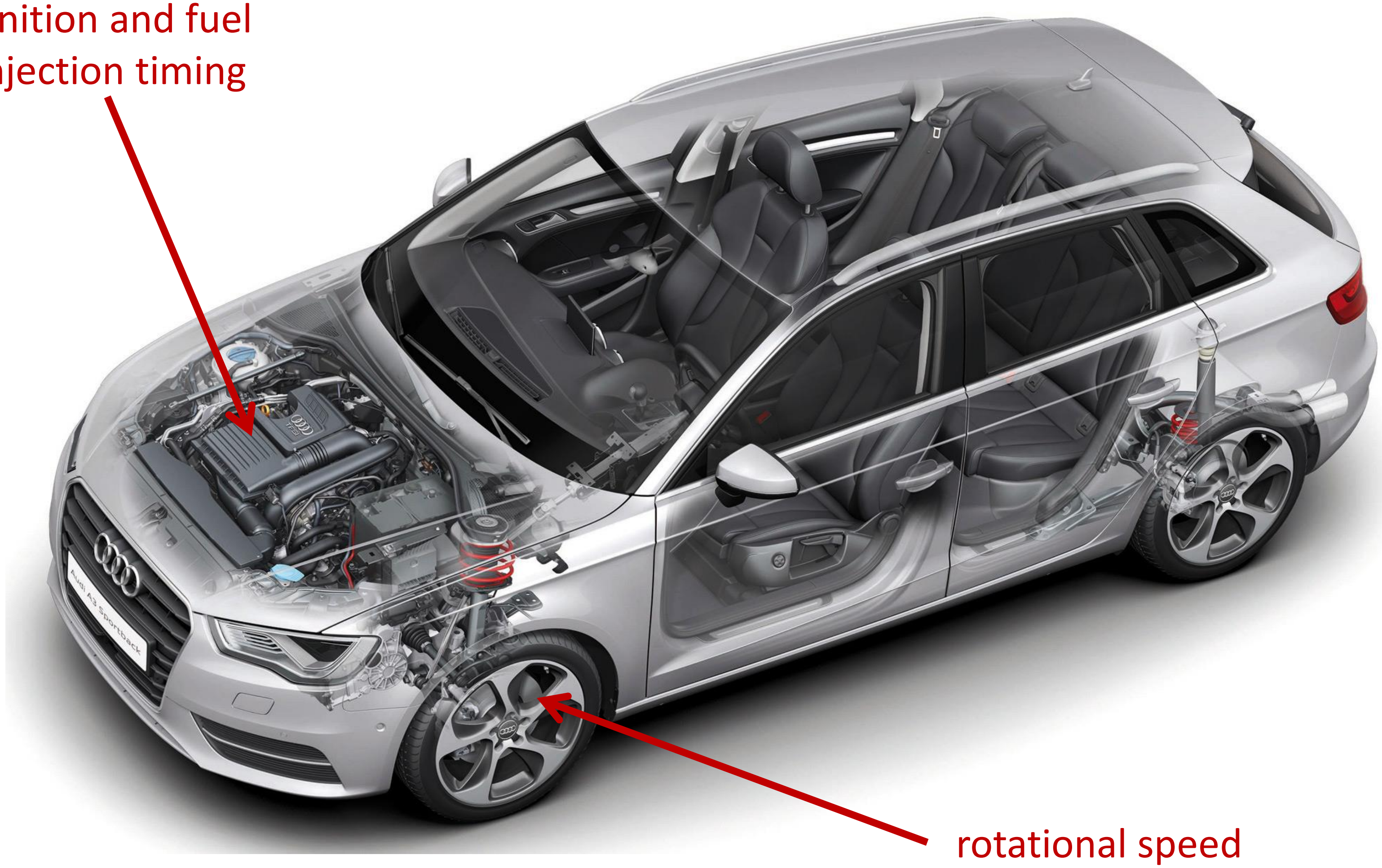
Optical sensors

- incremental encoders produce a pitch when rotated for one pitch
- absolute encoders produce a binary value encoding position

- incremental encoders can use one or two optical channels
  - one channel allows sensing of movement
  - two channels allows sensing of movement and direction
    - use time difference between detectors a and b to determine direction (CW – clock-wise or CCW – counter-clock-wise)



Hall effect sensor



ignition and fuel injection timing

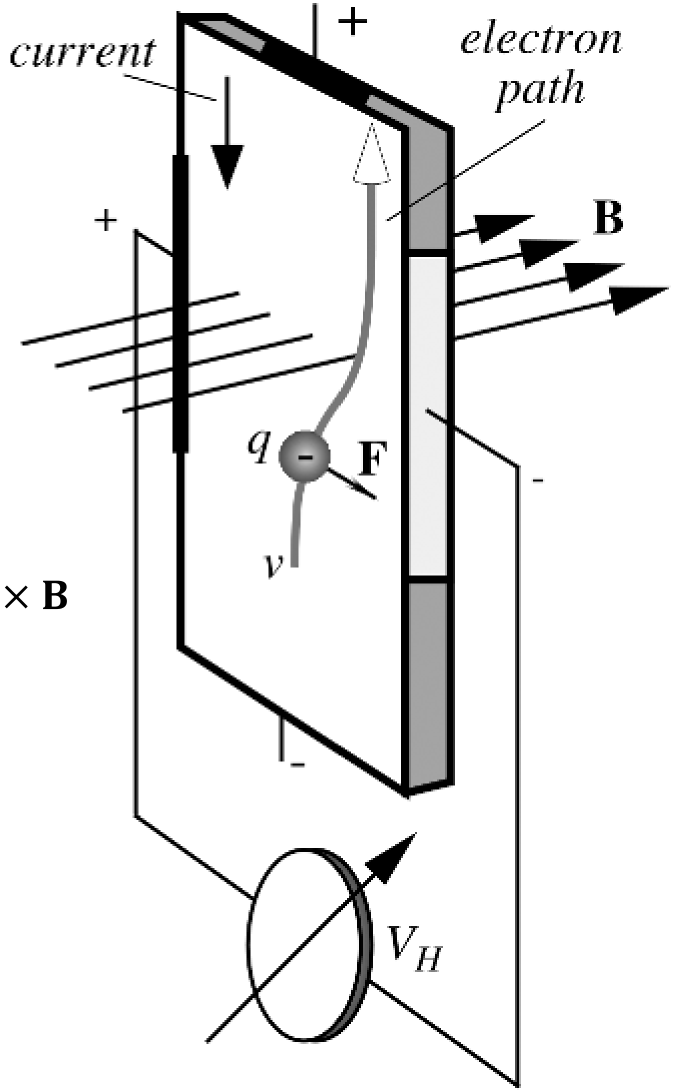
rotational speed

Hall effect sensor

- effect discovered in 1879 by Edward Hall
- effect exists in all conducting materials
- used extensively in sensing position, displacement, and magnetic fields

- effect based on interaction between
  - moving electric carriers (i.e., electrons in metals or holes in semiconductors)
  - external magnetic field

- electron moving through magnetic field is subject to sideways Lorentz force $\mathbf{F} = q\mathrm{v} \times \mathbf{B}$
  - q – electronic charge (1.6x10-19C)
  - B – magnetic field
  - v – speed of an electron (v = μEL)
  - μ – carrier mobility
  - EL – longitudinal electrical field



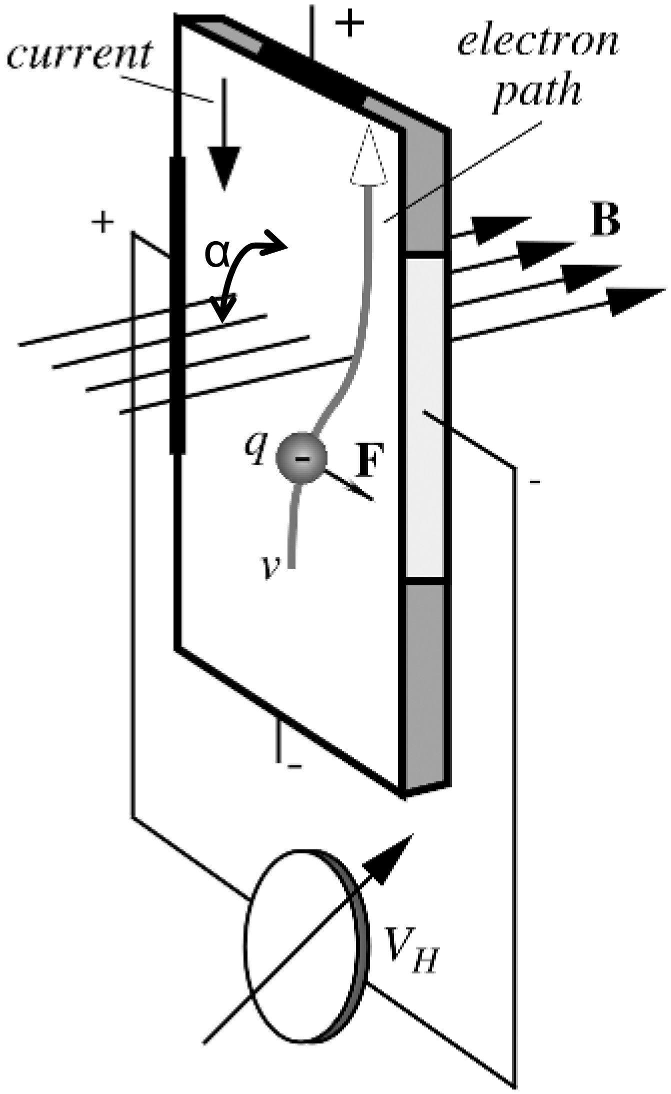
Hall effect sensor

- Lorentz force causes charge carriers to accumulate on one side
  - electrons in conductors to right
  - holes in semiconductor to left
- force results in a transversal electrical field
- electrical field balances force exerted by magnetic field

- transverse Hall potential

$$V_H = \frac{1}{Ncq}\frac{iB}{d}\sin\alpha$$

  - i – primary current
  - N – free electrons per unit volume
  - c – speed of light
  - d – thickness of the conductive strip
  - α – angle between magnetic field and strip



Hall effect sensor

- transverse Hall potential

$$V_H = \frac{1}{Ncq}\frac{iB}{d}\sin\alpha$$

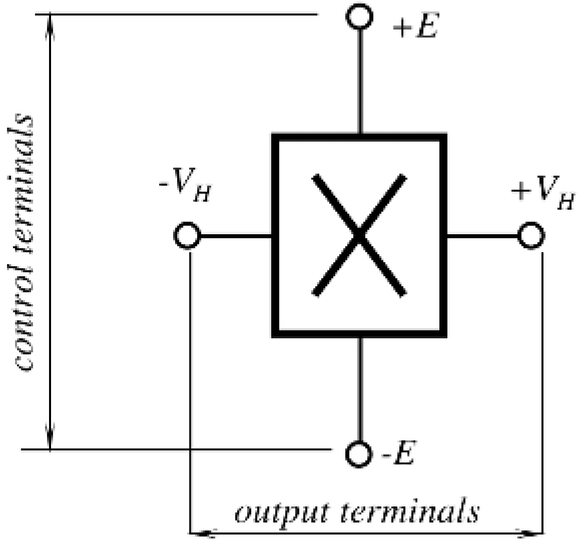
- factor 1/Ncq is material dependent and is called Hall coefficient
- polarity of V_H depends on direction of current and magnetic field
- magnitude of V_H depends on magnetic field strength (linear) and angle (non-linear)

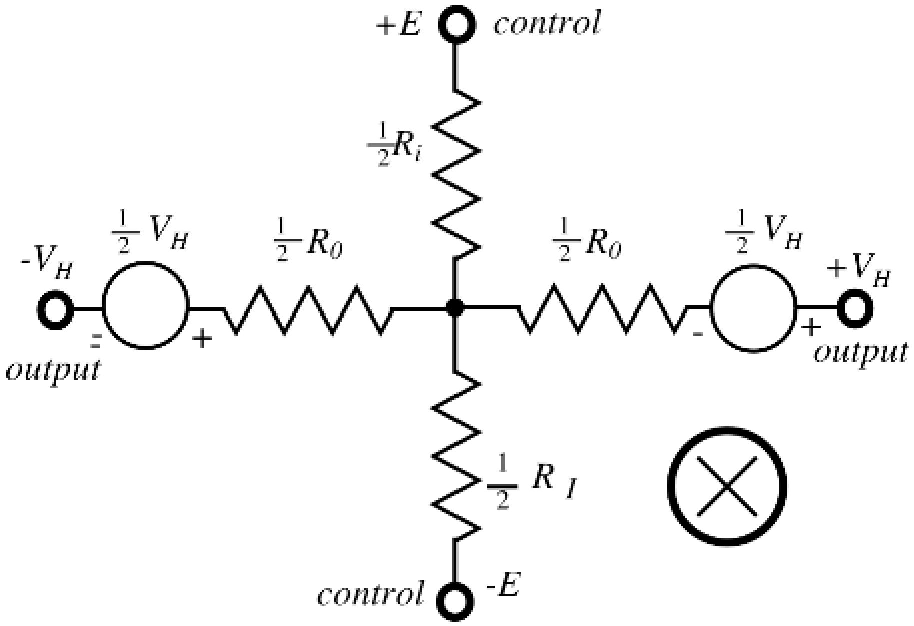
- **how to use device as sensor?**
  - move magnetic object to/from sensor device (change B)
  - rotate magnetic object at fixed distance (change α)

Hall effect sensor

- sensor packaged in four terminal housing
  - two control terminals
  - two output terminals
  - cross indicates direction of magnetic field
    - field moves away from viewer

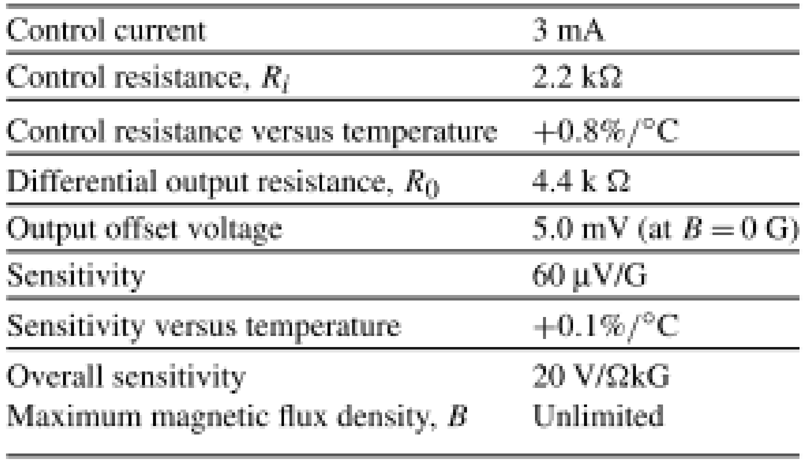
- equivalent model for sensor
  - two control resistances R_i
  - two output resistances R_o
  - Hall effect voltage V_H





Hall effect sensor

- characteristics of a semiconductor Hall effect sensor

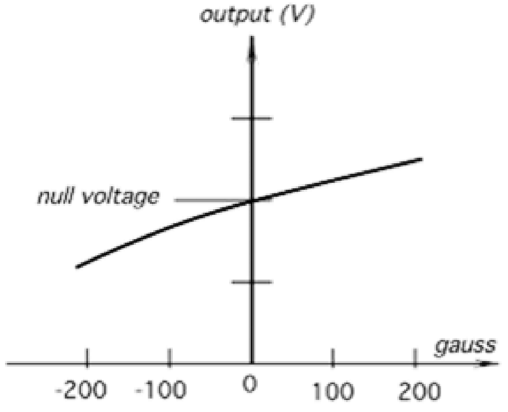


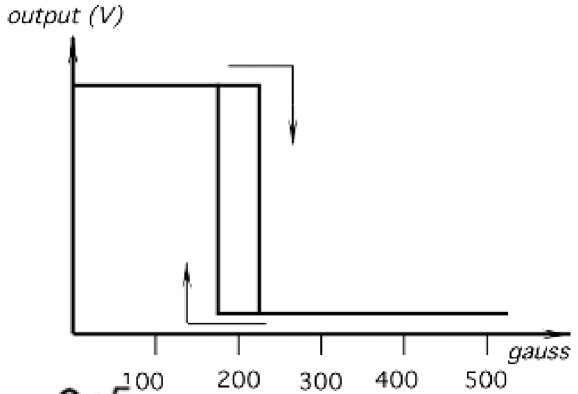
Control current	3 mA
Control resistance, R_i	2.2 kΩ
Control resistance versus temperature	+0.8%/°C
Differential output resistance, R_0	4.4 k Ω
Output offset voltage	5.0 mV (at $B = 0$ G)
Sensitivity	60 μV/G
Sensitivity versus temperature	+0.1%/°C
Overall sensitivity	20 V/ΩkG
Maximum magnetic flux density, B	Unlimited

- Hall coefficient (sensitivity) is small (60μV/Gauss)
  - most sensed fields are smaller then 1x10^4G
  - Hall voltage can be as small as a few μV
  - Hall voltage must often be amplified before processing
- sensitivity and resistance are temperature dependent
  - same polarity for both effects in semiconductor
  - different polarities in metals (allows compensation)

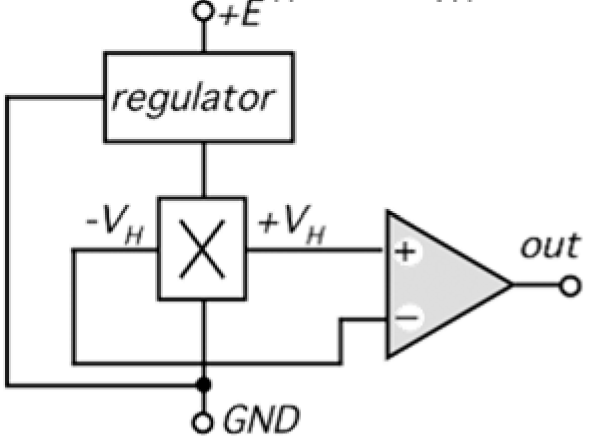
Hall effect sensor

- two types of sensors
  - linear sensor
  - threshold sensor

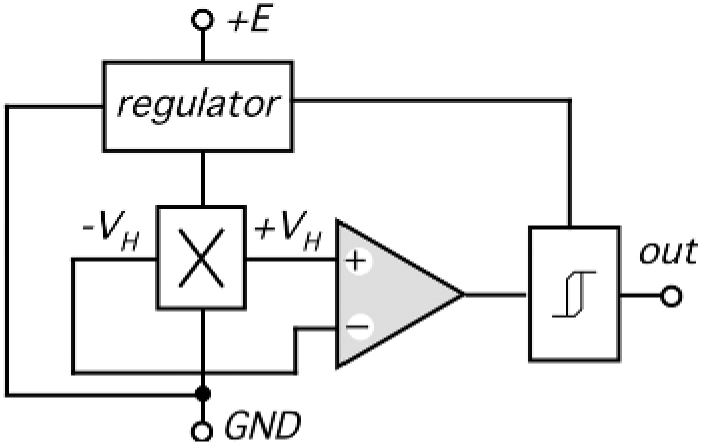




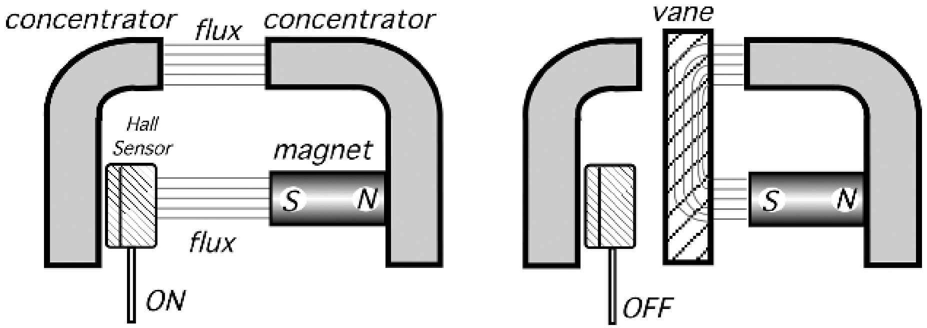
- linear sensor
  - basic hall effect sensor
  - voltage regulator to create constant control current
  - amplifier to enlarge Hall voltage (why an offset voltage?)



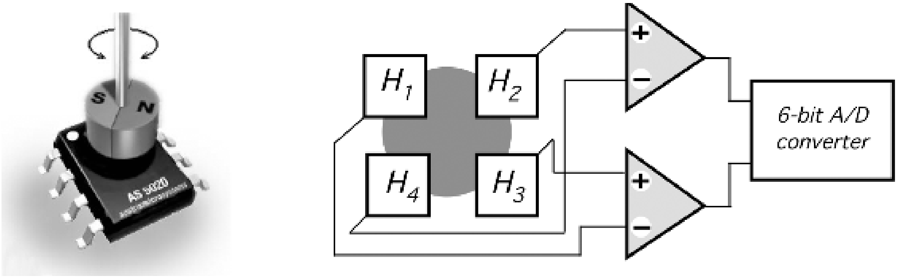
- threshold sensor
  - linear sensor
  - Schmitt trigger with build-in hysteresis



Hall effect sensor



threshold sensor



linear (rotation) sensor