MA2011
Mechatronics System Interfacing
(Part-II)

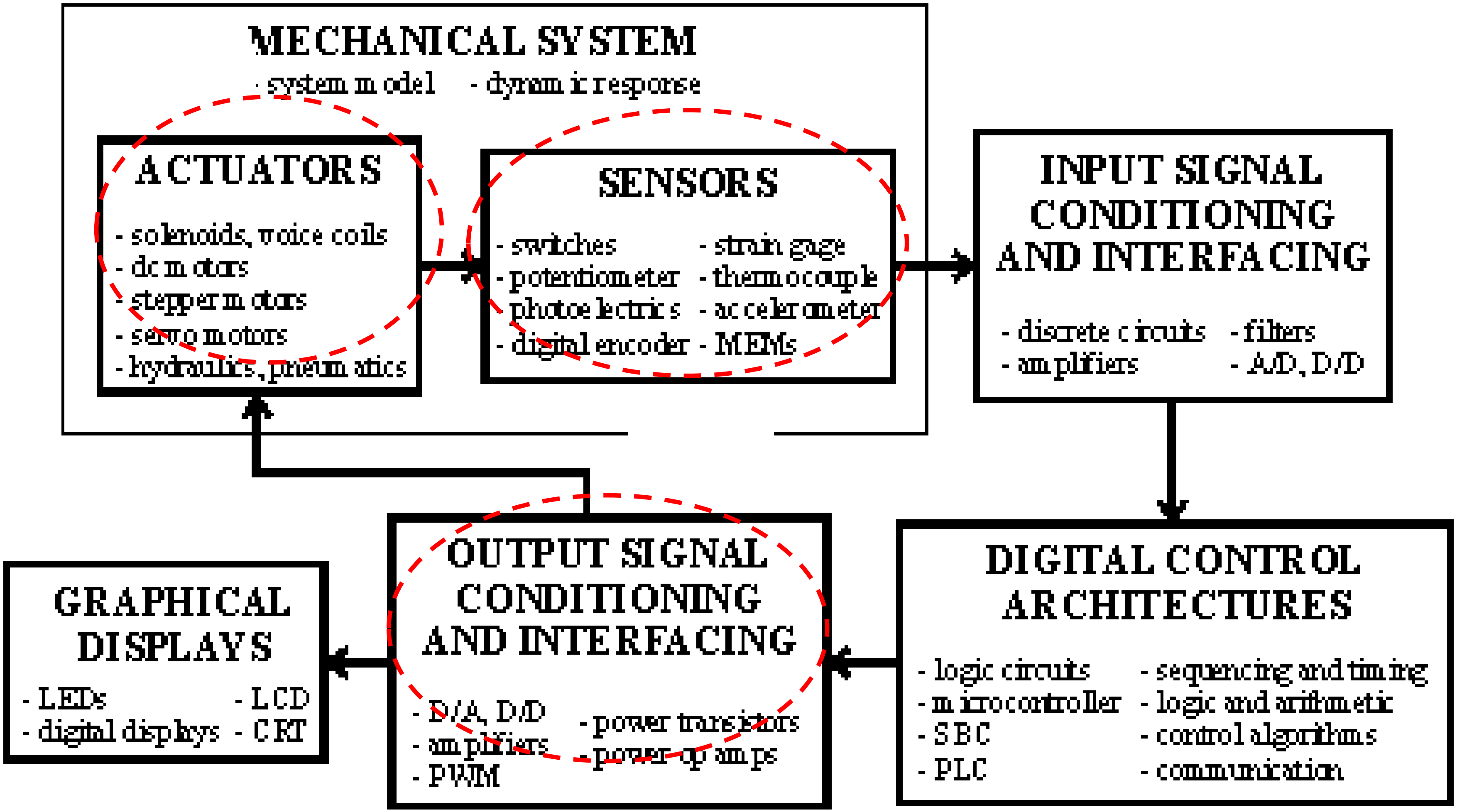
Domenico Campolo

d.campolo@ntu.edu.sg

Nanyang Technological University
School of Mechanical & Aerospace Engineering

Office: N3.2-02-74

topics in the text-book



Sensors

Basic Definitions

sensors: basic definitions

- transducers:
  - convert one form of energy into another
    - non necessarily to perform a measurement
- sensors:
  - produce an output signal (typically electrical) for the purpose of sensing a physical phenomenon

sensor classification

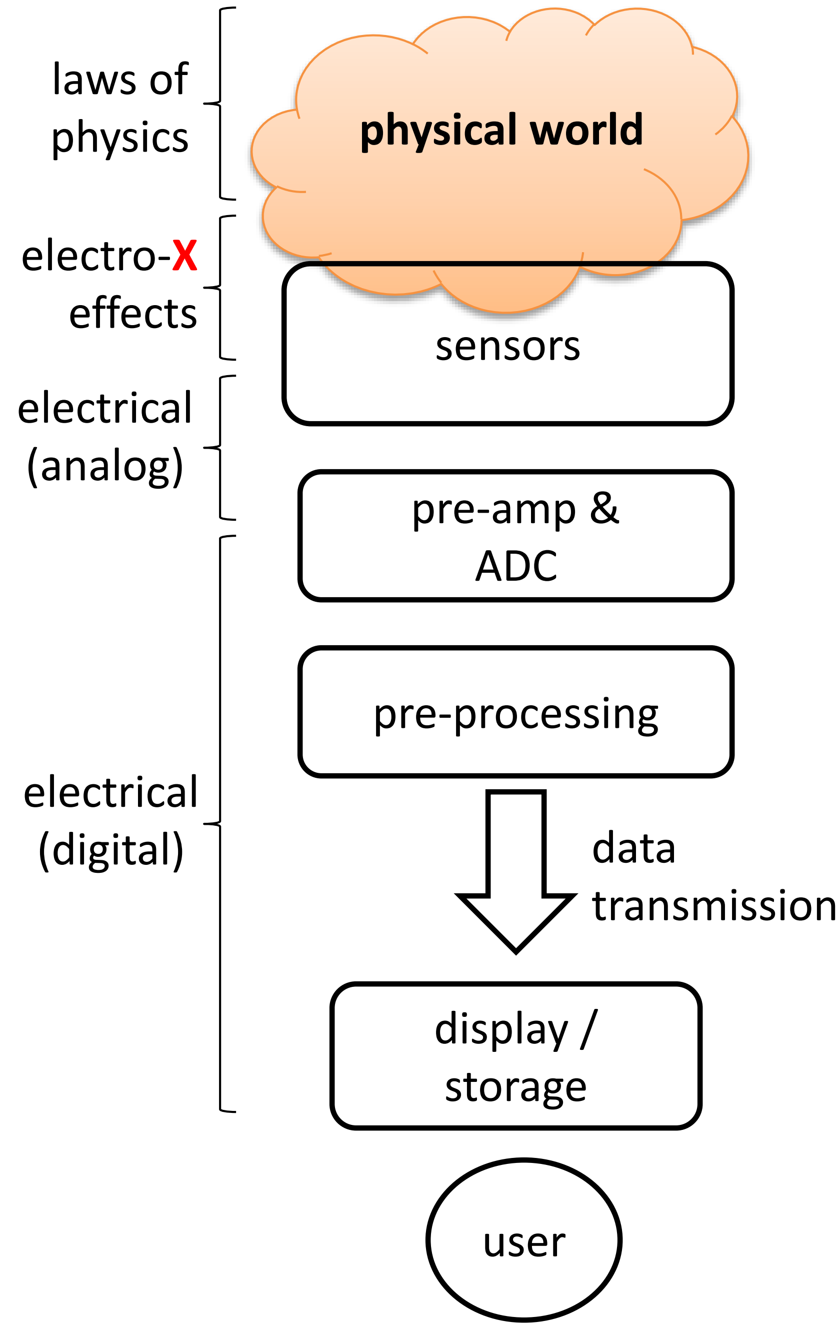
- analog vs digital
  - light on/off switch vs light dimmer
- passive vs active
  - passive sensors: do not require external power supplies, they draw the energy from the input signal itself
- null vs deflection type
  - null type: any deflection due to the measured quantity is balanced by an opposing calibrated force
- subject of measurement
  - mechanical, optical, thermal etc…

deflection-type

null-type

instrumentation systems

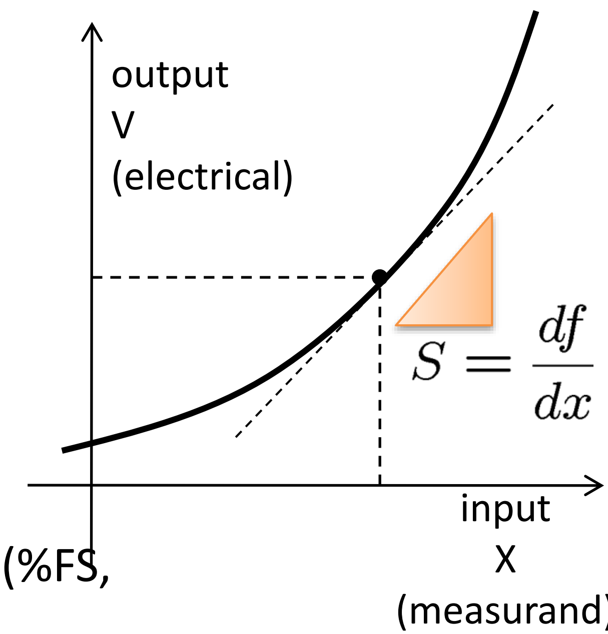
- sensing module
  - X=mechanical, thermal, optical, pyro, piezo,…
- conversion module
  - from analog to digital
- pre-processing
  - variable manipulation module
- data transmission
  - wired/wireless, over the web…
- presentation/storage
  - to the final user



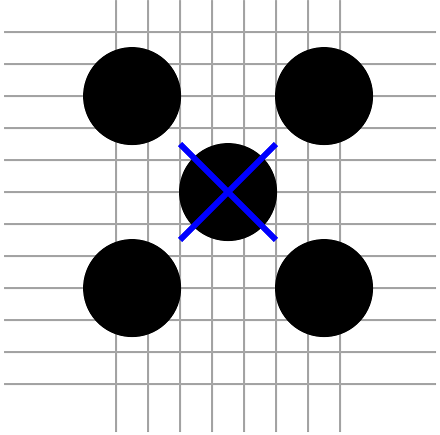
basic concepts

- I/O characteristic function or response:
  - **input**: stimulus or measurand
    - (temperature, pressure, strain…)
  - **output**: electrical signal
    - (voltage, current, frequency, phase…)
- sensitivity S
  - output variation / input variation
    - slope S = df/dx
- resolution
  - minimum change of the measurand that can be reliably detected
    - limited by noise, bit-conversion,…
- accuracy
  - difference of the measurement from the true value (%FS, Full Scale)

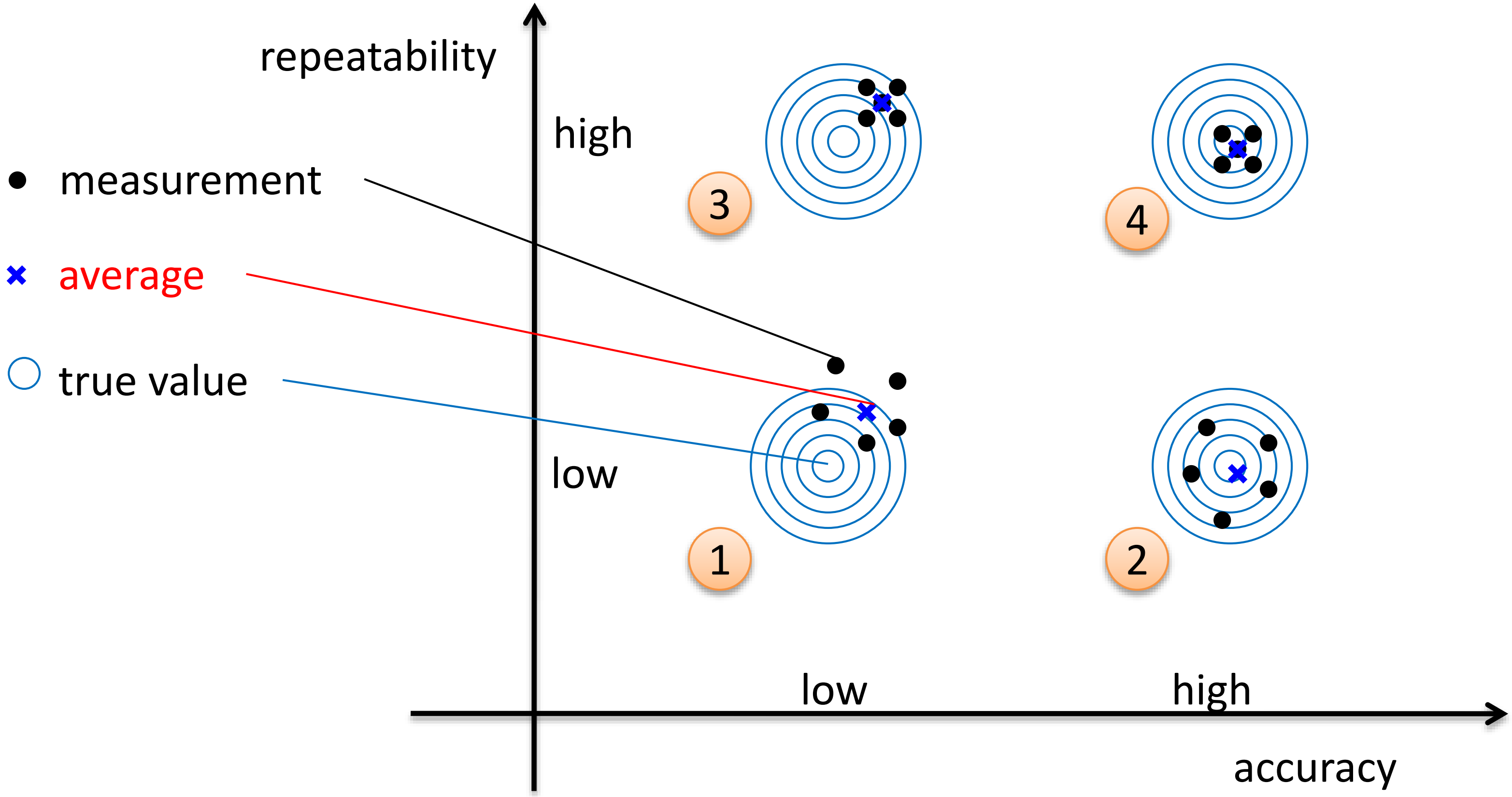
$$v_{out} = f(x)$$



instrument static parameters

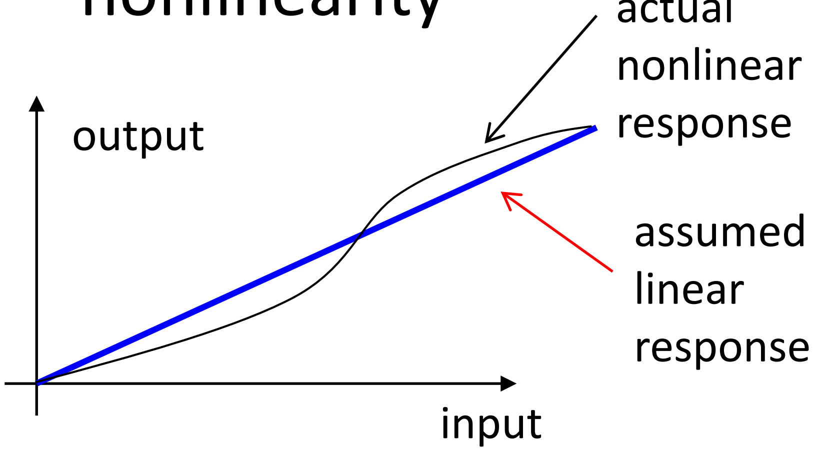


- repeatability
  - how well a system or device can reproduce an outcome in unchanged conditions

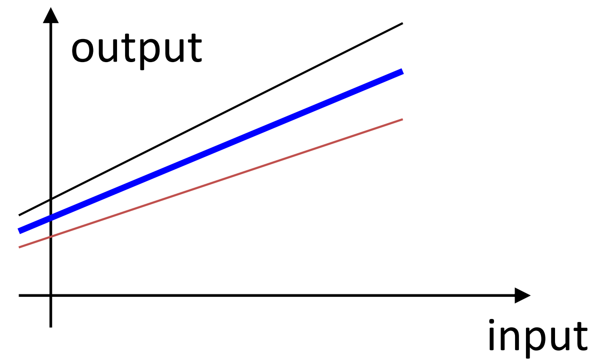


main instrument errors

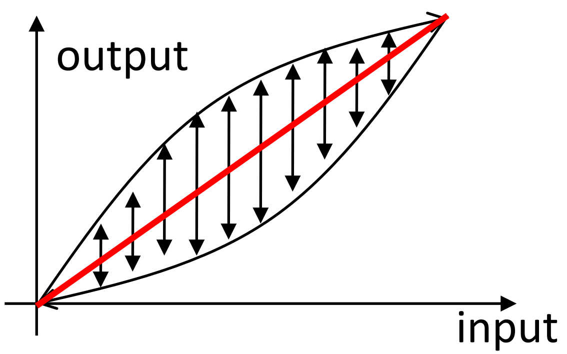
- nonlinearity



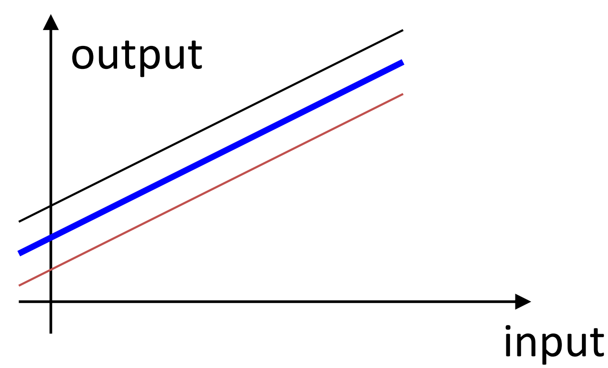
- sensitivity error



- hysteresis



- zero-shift error

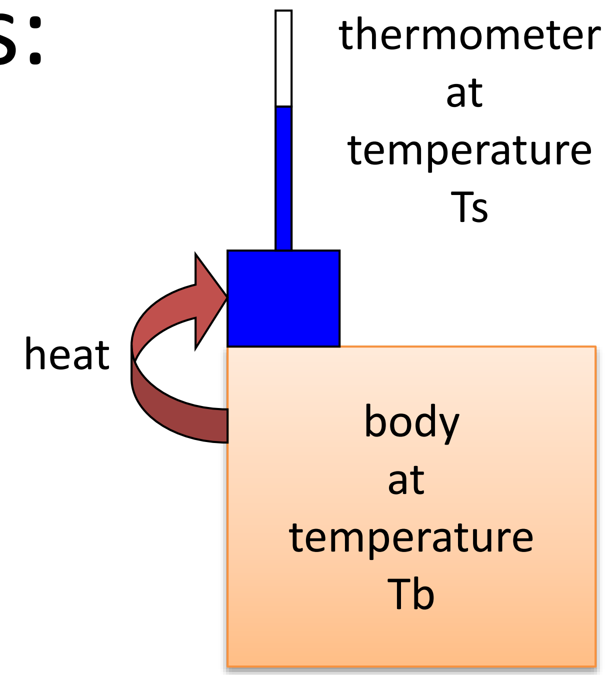


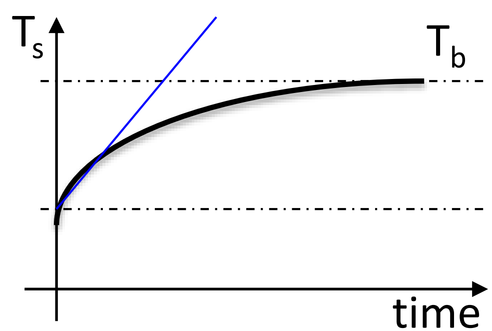
response dynamics

first and second order systems

1^{st} order systems: an example

- thermal measurements
  - heat $q = (T_b - T_s) / R$
    - R: thermal resistance
    - materials, geometries …
  - heat-up: $dT_s/dt = q / C$
    - C: thermal capacitance
  - if $dT_b/dt = 0$ …
  - $T_s(t) = T_{s0} + (T_b - T_{s0})\,(1 - e^{-t/RC})$





In general, the time response of a 1^{st} order system is

$x(t) = a + b\,e^{-t/\tau}$ where τ is the time constant.

1^{st} order systems: forced and natural response

- **general** (forced) equation
  - time constant τ
  - forcing input $f(t)$
  - initial condition x_0

$$\begin{cases} \dfrac{dx(t)}{dt} + \dfrac{x(t)}{\tau} = f(t) \\ x(0) = x_0 \end{cases}$$

uniqueness of solutions

- **natural** (unforced) equation
  - solution
    - satisfying the initial condition

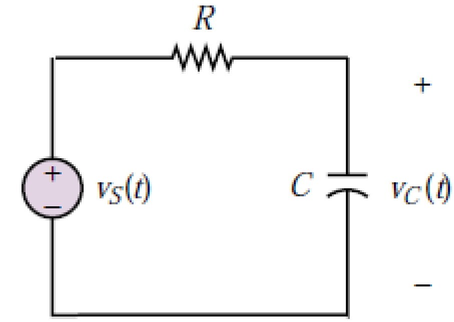
$$\begin{cases} \dfrac{dx_N(t)}{dt} + \dfrac{x_N(t)}{\tau} = 0 \\ x(0) = x_0 \end{cases}$$

$$x_N(t) = Ke^{-t/\tau}$$

$$x_N(0) = K = x_0$$

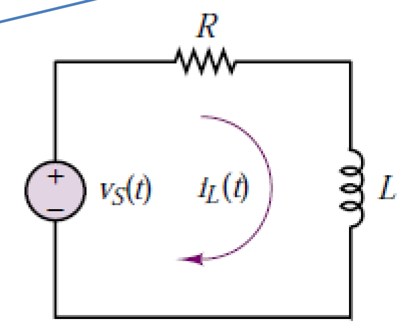
$$x_N(t) = x_0 e^{-t/\tau}$$

1^{st} order systems: time constant



RC circuit: $\frac{dv_C}{dt} - \frac{1}{RC}v_C - \frac{1}{RC}v_S = 0$

- electrical time constants
  - what are the units of RC or L/R?



RL circuit: $\frac{di_L}{dt} - \frac{R}{L}i_L - \frac{1}{L}v_S = 0$

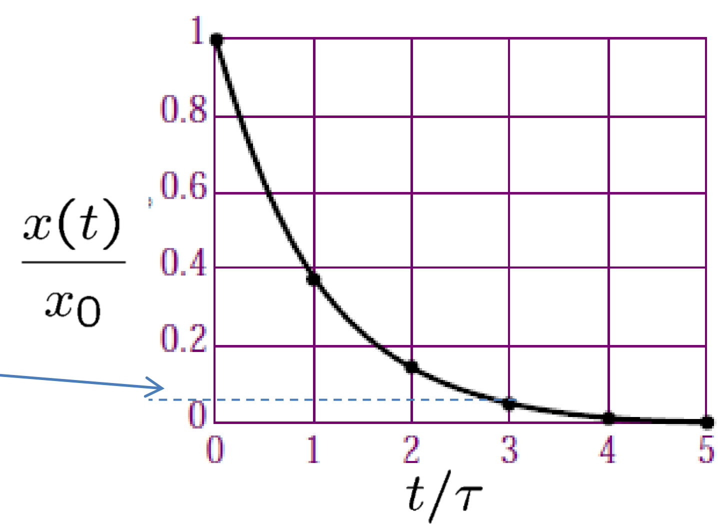
$$RC = \frac{voltage}{current} \cdot \frac{charge}{voltage} = \frac{charge}{charge/time} = time$$

$$\frac{L}{R} = \frac{voltage}{current/time} \cdot \frac{current}{voltage} = time$$

$$x(t) = x_0 e^{-t/\tau}$$

$\frac{x(t)}{X_0}$	n
1	0
0.3679	1
0.1353	2
0.0498	3
0.0183	4
0.0067	5

after 3 time-constants the signal decays to 5% of its initial value



1^{st} order systems response to **DC** forcing inputs

- we have the following problem
  - where $f(t)=F_0$ is a constant

$$\begin{cases} \frac{dx(t)}{dt} + \frac{x(t)}{\tau} = F_0 \\ x(0) = x_0 \end{cases}$$

- let's look for a particular (forced) solution $x_F(t)$
  - consider a **DC** steady-state solution $x_F(t) = x_{SS}$

$$\cancel{\frac{dx_{SS}}{dt}} + \frac{x_{SS}}{\tau} = F_0 \quad \Rightarrow \quad \frac{x_{SS}}{\tau} = F_0 \quad \Rightarrow \quad x_{SS} = F_0\tau = x_\infty$$

- now, let's determine a general solution
  - including the natural solution

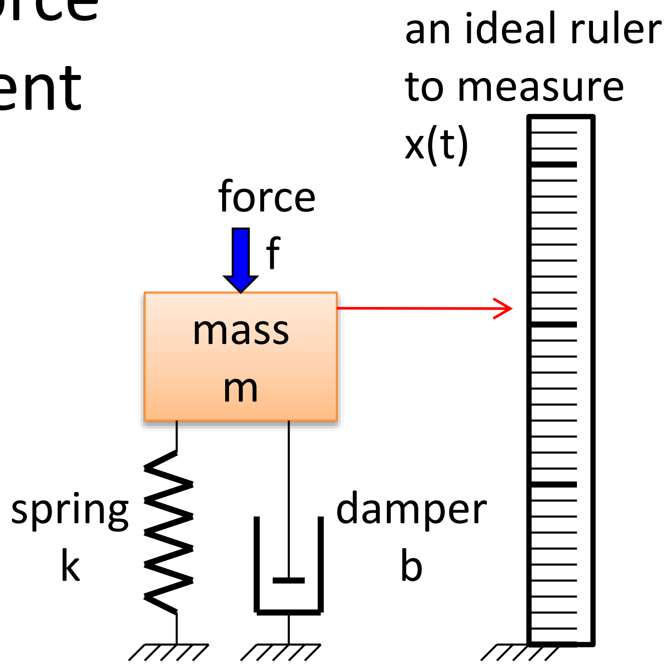
$$x(t) = x_N(t) + x_{SS}(t) = Ke^{-t/\tau} + x_\infty$$

  - satisfying the initial condition

$$x(0) = K + x_\infty = x_0 \quad \Rightarrow \quad \boxed{x(t) = \underbrace{(x_0 - x_\infty)e^{-t/\tau}}_{\textit{transient}} + \underbrace{x_\infty}_{\textit{steady state}}}$$

second order dynamics

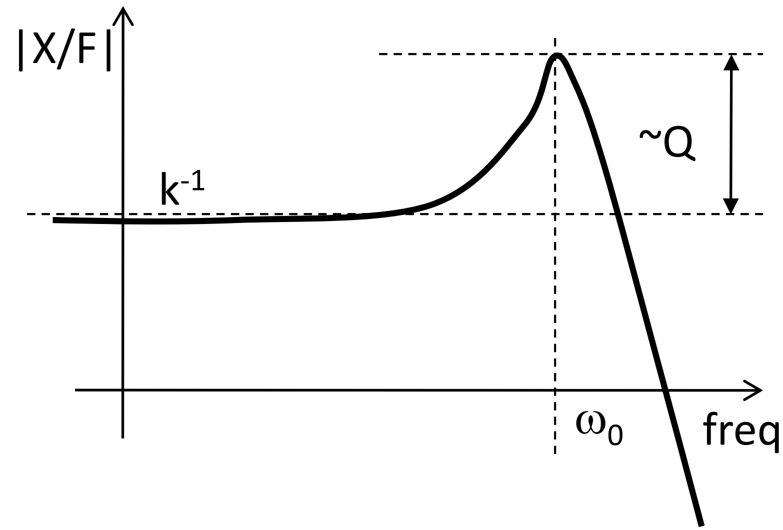
- we can indirectly estimate the force from a displacement measurement
  - dynamic equations
    - $f = m\ddot{x} + b\dot{x} + kx$
  - frequency response
    - $\dfrac{X}{F} = \dfrac{k^{-1}}{-\frac{\omega^2}{\omega_0^2} + \frac{j\omega}{Q\omega_0} + 1}$

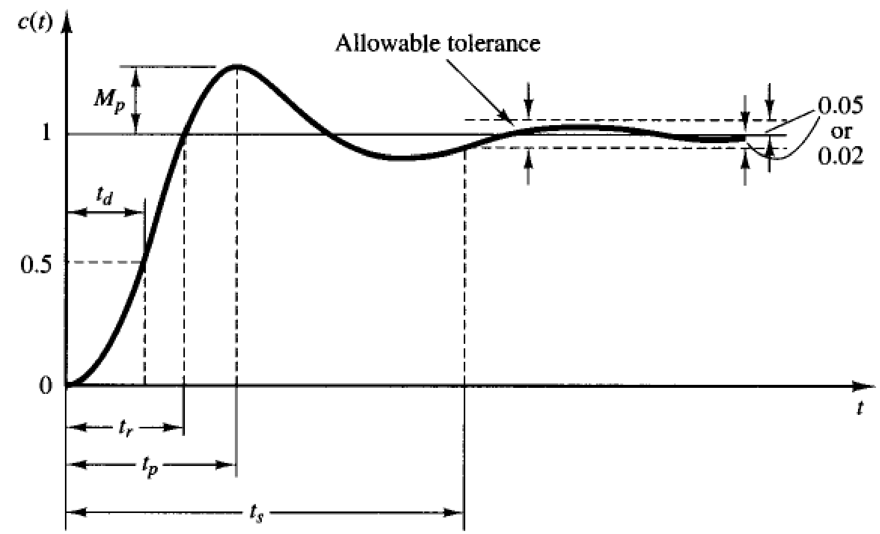


second order dynamics

$$\frac{X}{F} = \frac{k^{-1}}{-\frac{\omega^2}{\omega_0^2} + \frac{j\omega}{Q\omega_0} + 1}$$

- dynamic response characterized by
  - frequency response
    - resonance $\omega_0^2 = k/m$
      - bandwidth
    - mechanical Q: $Q^2 = km / b^2$
      - Q=0.5 → critical damping
  - time response
    - rise time
    - settling time
    - overshoot
    - …

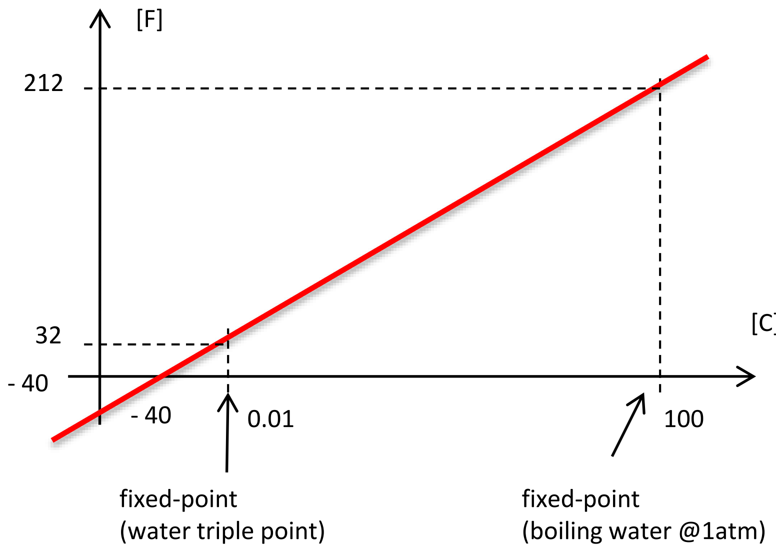




measuring temperature

RTD and Thermistors

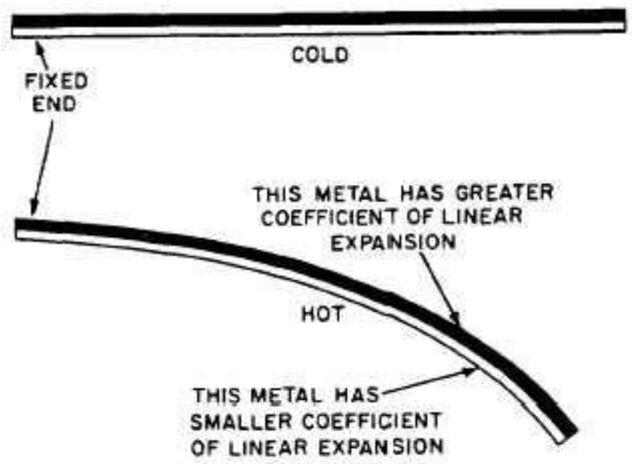
temperature scales

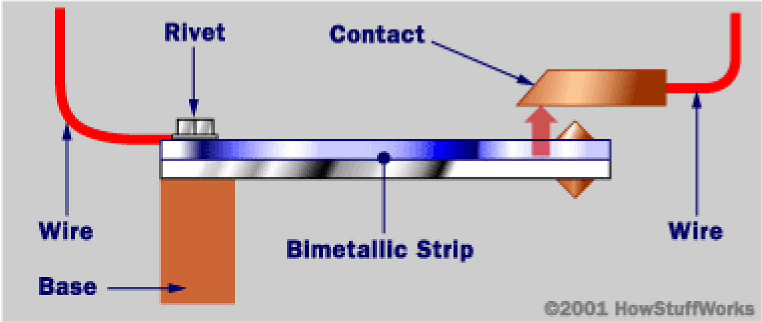


- Kelvin [K], Celsius [C], Fahrenheit [F]
  - [C] = [K] - 273.15
  - [F] = 1.8*[C] + 32
- based on
  - fixed-points
    - i.e. temperatures at phase transition, triple points…
  - size of the degree
    - e.g. 1/100 of the difference between icy and boiling water
  - interpolation method in-between fixed points
    - does 50[C] correspond to the level mercury which is half-way between the 0[C] and 100[C] levels?
- ITS-90 standard

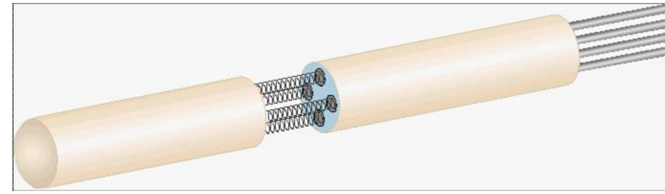
bimetallic thermometers

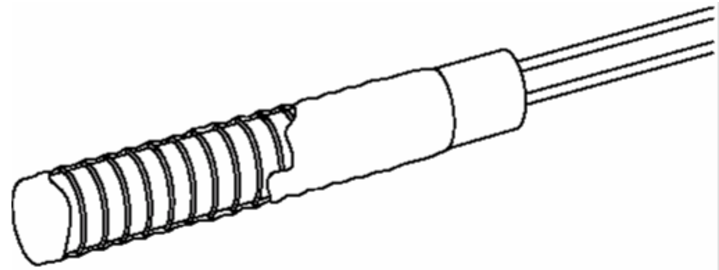
- differential thermal expansion of different metals
  - metal A and B bonded at temperature T1
  - bending occurs at different temperatures
- furnace thermostat
  - switch-control

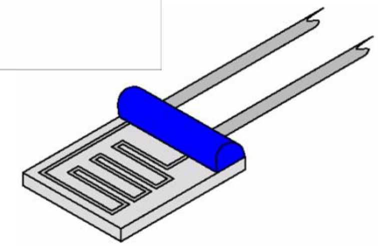




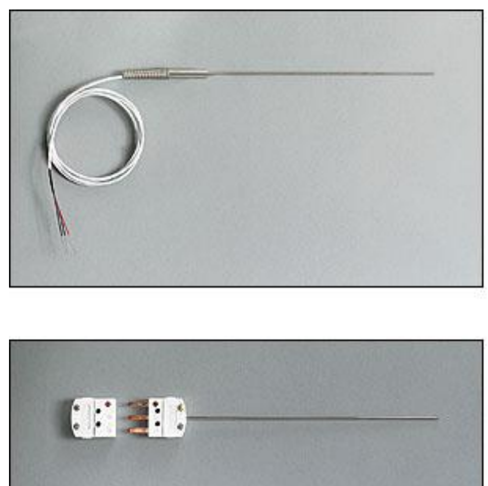
resistance temperature detectors (RTD)







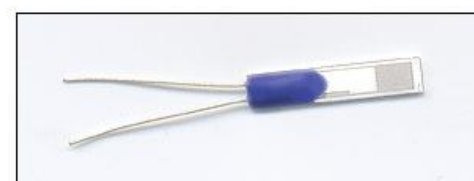
- based on changes of resistance with temperature
  - **metal wire** on insulating support
    - eliminate mechanical strain
  - encasing
    - minimize environment influence (e.g. corrosion)



Typical RTD Probes

Thick Film Omega Film Element

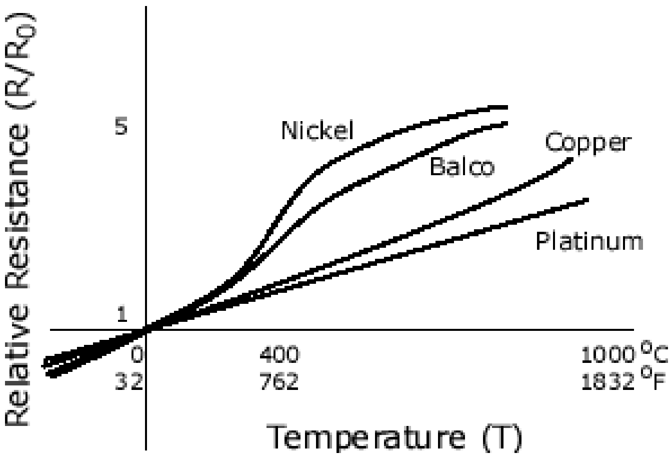
Glass sealed Biflar Winding



Thin Film Omega TFD Element

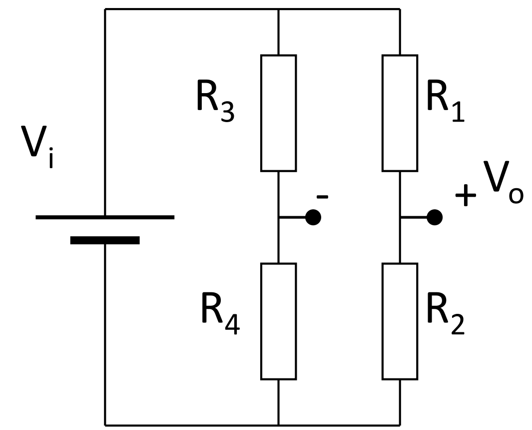
RTD: linearity range

- for a given material, a linear relationship can be assumed for a **limited range**
  - $$R/R_0 = 1 + \alpha(T - T_0)$$
    - R resistance at temp. T ([C] or [K])
    - R0: resistance at temp. T0
    - α: temp. coefficient



- platinum
    - ±0.3% over the range 0-200 [C]
    - ±1.2% over the range 200-800 [C]

Wheatstone bridge



- bridge equations

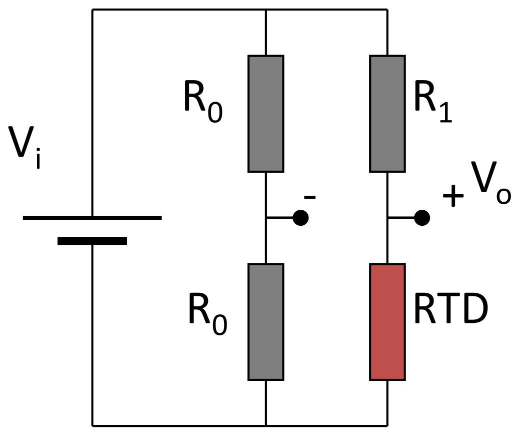
$$\begin{cases} \dfrac{V^+}{V_i} = \dfrac{R_2}{R_1 + R_2} \\ \dfrac{V^-}{V_i} = \dfrac{R_4}{R_3 + R_4} \end{cases} \Rightarrow \boxed{\dfrac{V_o}{V_i} = \dfrac{R_2}{R_1 + R_2} - \dfrac{R_4}{R_3 + R_4}}$$

- bridge balance condition:

$$\boxed{V_o = 0 \quad \Leftrightarrow \quad R_1 R_4 = R_2 R_3}$$

(product of opposite sides)

RTD: numerical example



- An RTD forms one arm of an equal-arm Wheatstone bridge

  $R_0 = R_0 = 25\Omega$

  At 0^oC, RTD = 25Ω

  and $\alpha = 0.003925\ ^oC^{-1}$

- If R_3 required to balance the bridge is 37.36Ω, find the temperature of the RTD

RTD: numerical example (solution)

- Bridge-balance condition

  $\cancel{R_0} * RTD = R_1 * \cancel{R_0}$

  i.e. $RTD = R_1 = 37.36\Omega$

From $R_{RTD}/R_0 = 1 + \alpha(T - T_0)$, numerically

$$\frac{37.36\Omega}{25\Omega} = 1 + 0.003925(T - 0)$$

i.e.

$$T = 126^oC$$

RTD: measurements

- Wheatstone bridge
  - **low resistance** (conductors)
  - subject to **self-heating**
- lead-wire effects
  - 2-wires
    - long wires are also subject to temp-resistance changes
    - RTD +2*r0 = R1
  - 3-wires
    - RTD+r0 = R1+r0 → RTD=R1
  - 4-wires

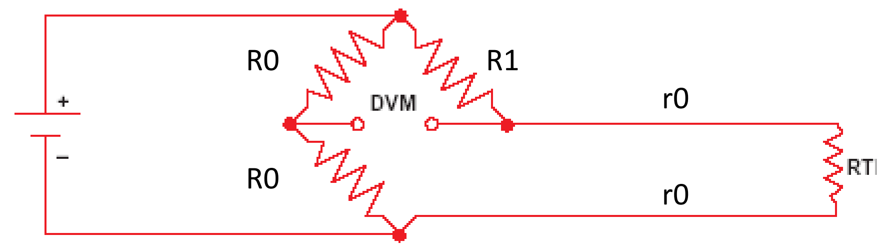
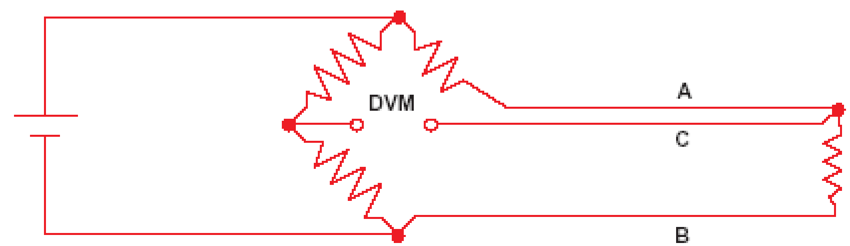
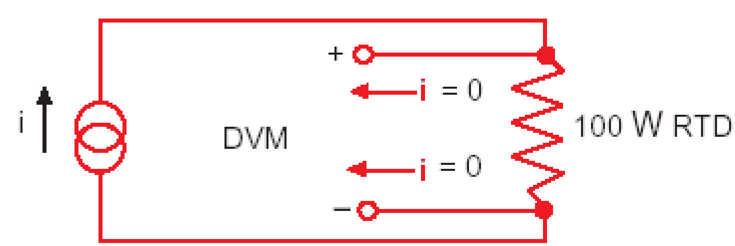


Figure 40



3-WIRE BRIDGE

Figure 41

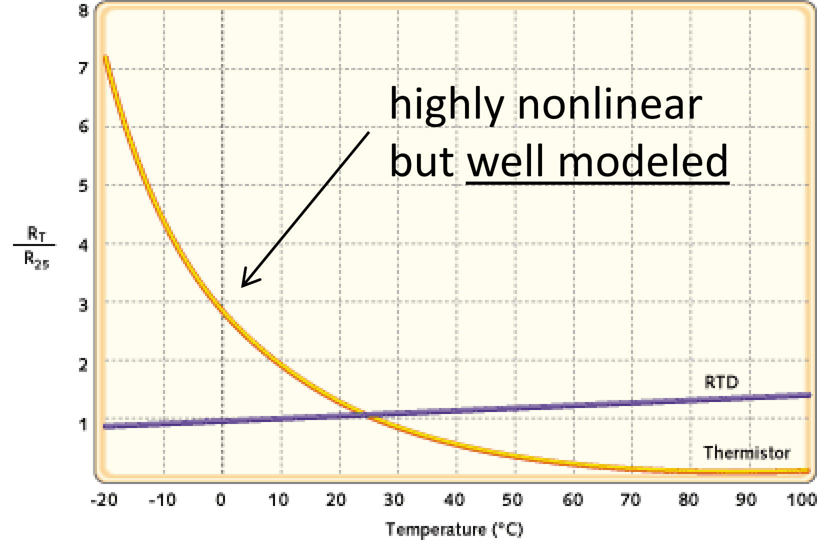


4-WIRE OHMS MEASUREMENT

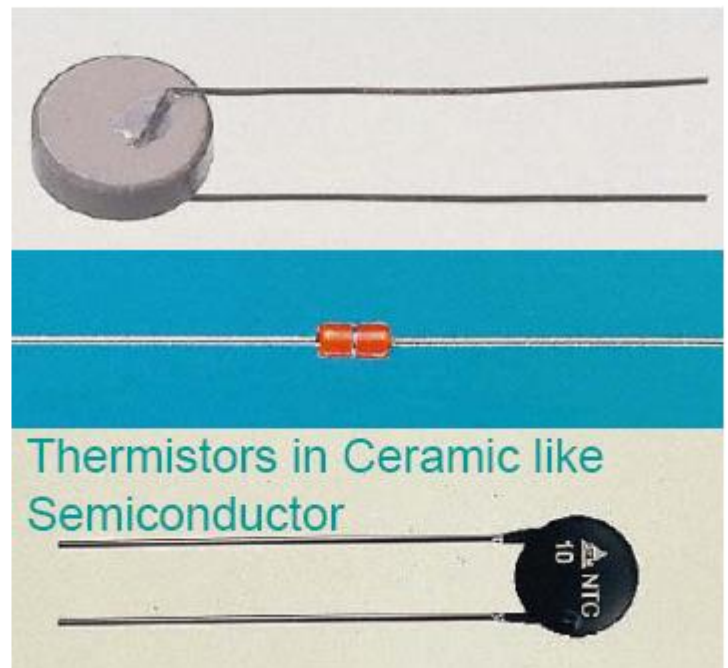
Figure 42

thermistors

- <u>therm</u>ally sensitive res<u>istors</u>
  - ceramic-like **semiconductors**
    - R0 much larger than RTD
  - resistance decreases rapidly with temperature
    - high-sensitivity
    - ruggedness
    - fast time-response



$$R = R_0 e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$



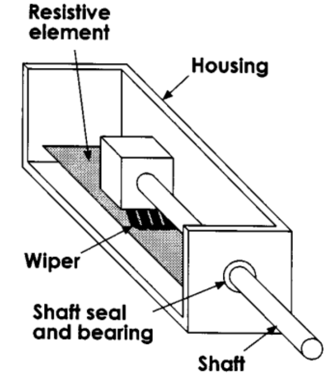
measuring displacement (linear/angular)

resistive sensors

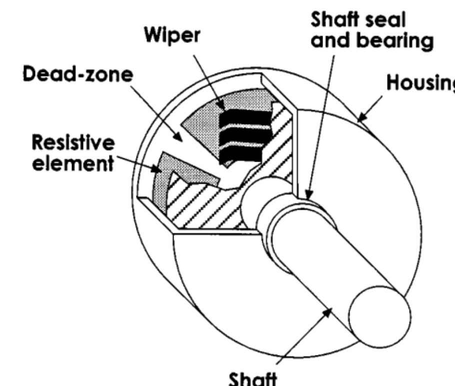
resistive sensors

- potentiometer (aka ‘pot’)
  - **3-terminal** electromechanical device based on a conductive **wiper** sliding against a fixed, resistive element
  - many varieties (quality/function)
    - rheostats, trimmers, volume control,

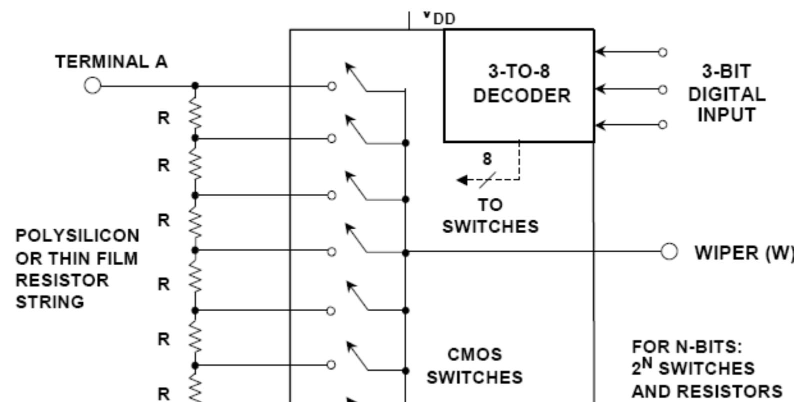
  - precision potentiometers
    - manually or **digitally** tunable



(a)

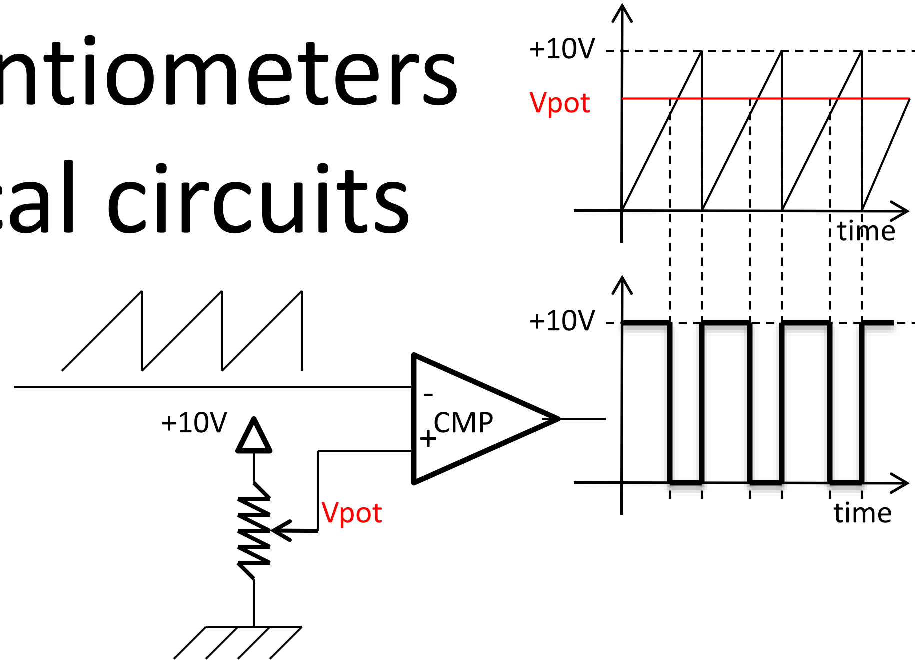


(b)

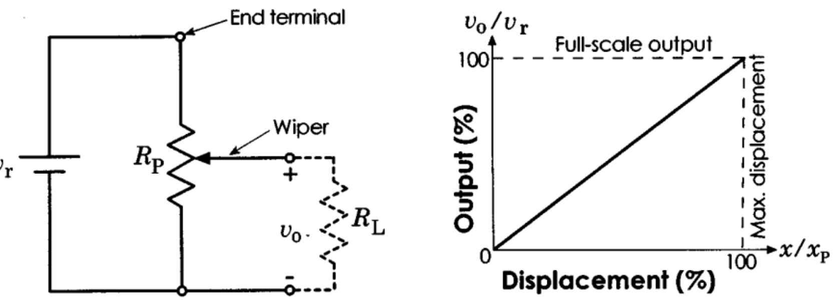


from ANALOG DEVICES

using potentiometers in electrical circuits

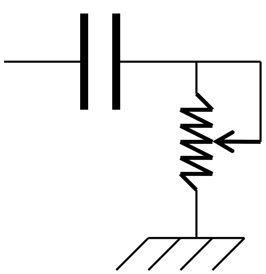


- voltage divider

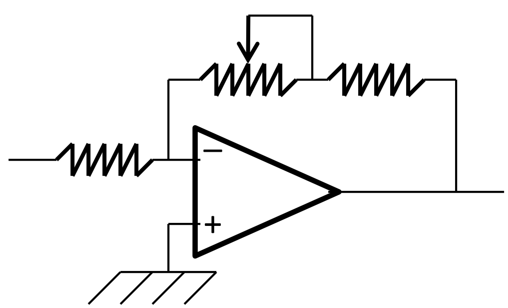


(a) (b)

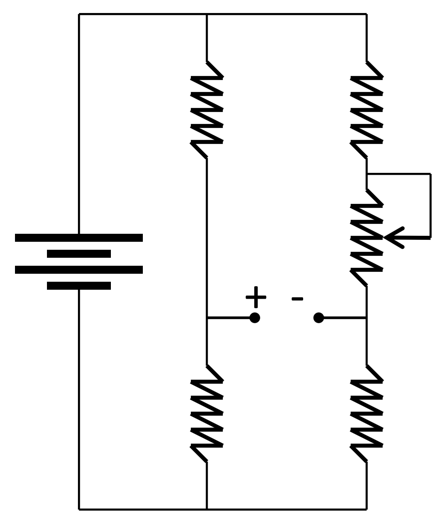
- variable resistance



tunable filters



variable gain amplifier



Wheatstone bridge
with adjustable offset

measuring forces through displacement

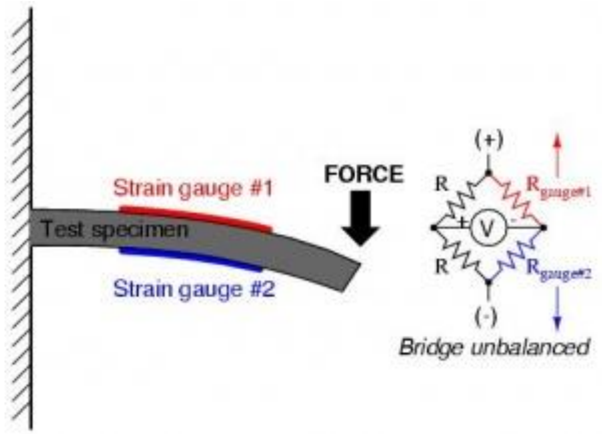
force sensors

strain gauges

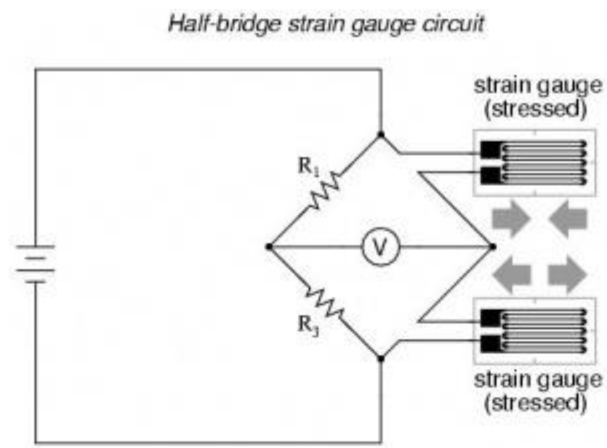
Force measurements

always indirectly via

deformations



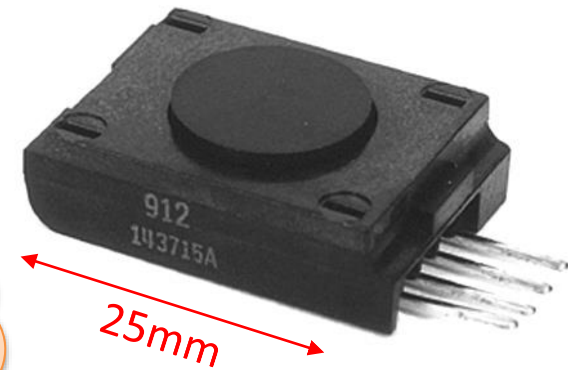
Phidgets Micro Load Cell (0-780g)

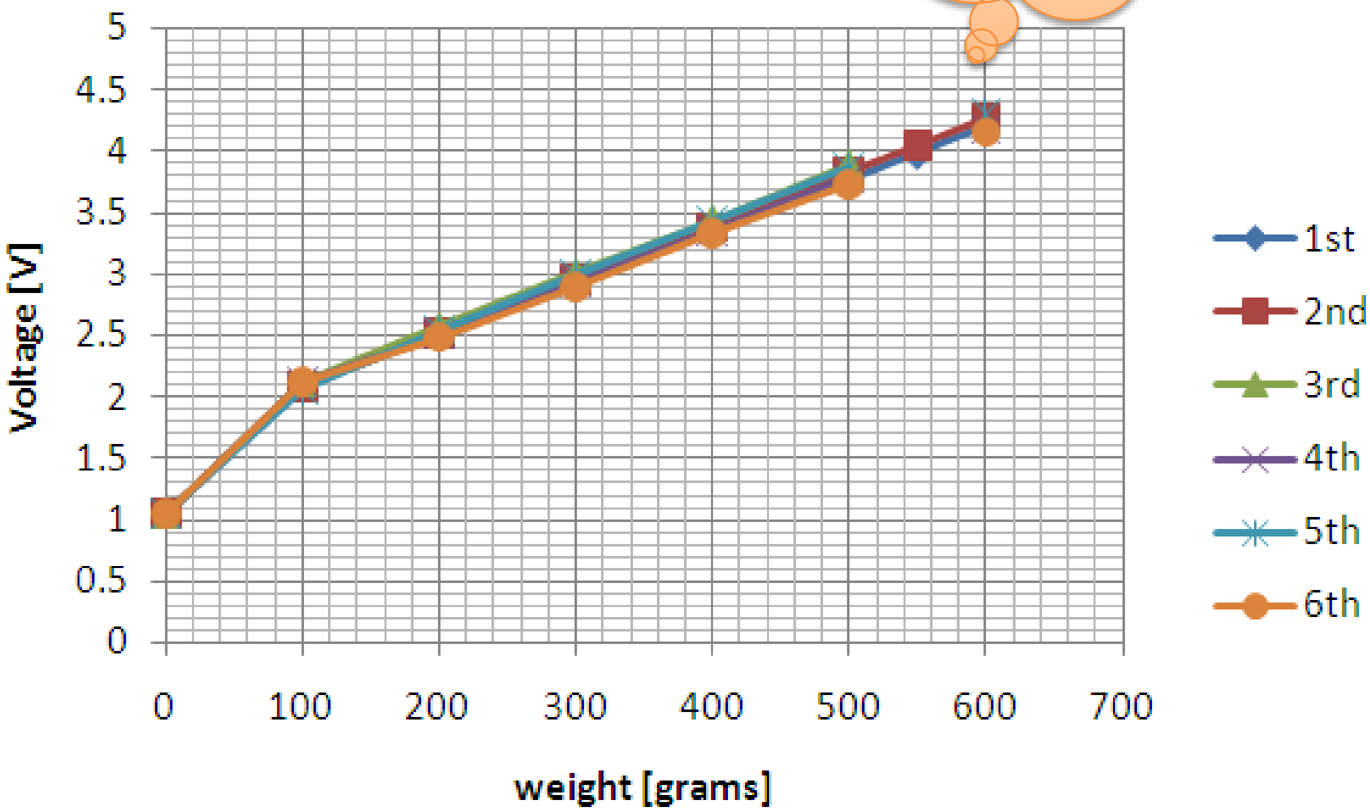


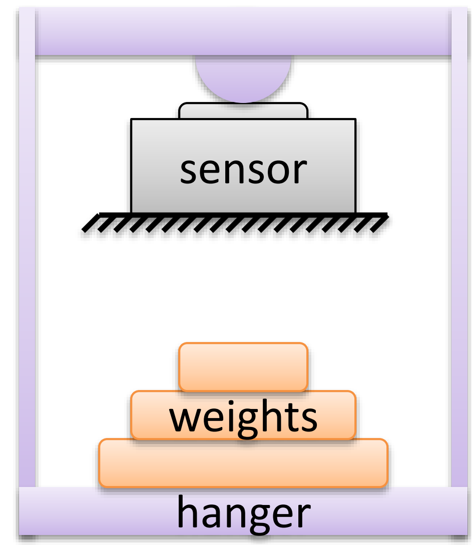
Honeywell FS01 piezoresistive force sensor

- calibration curve

What is wrong with this graph?

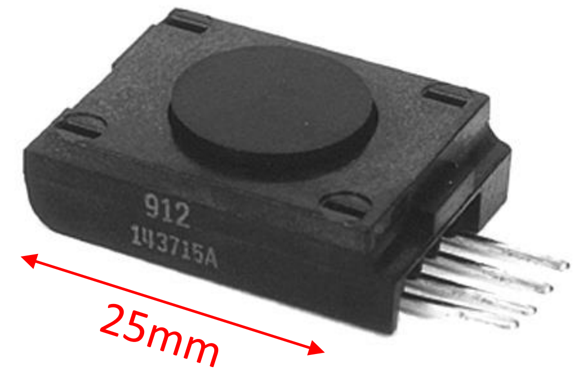


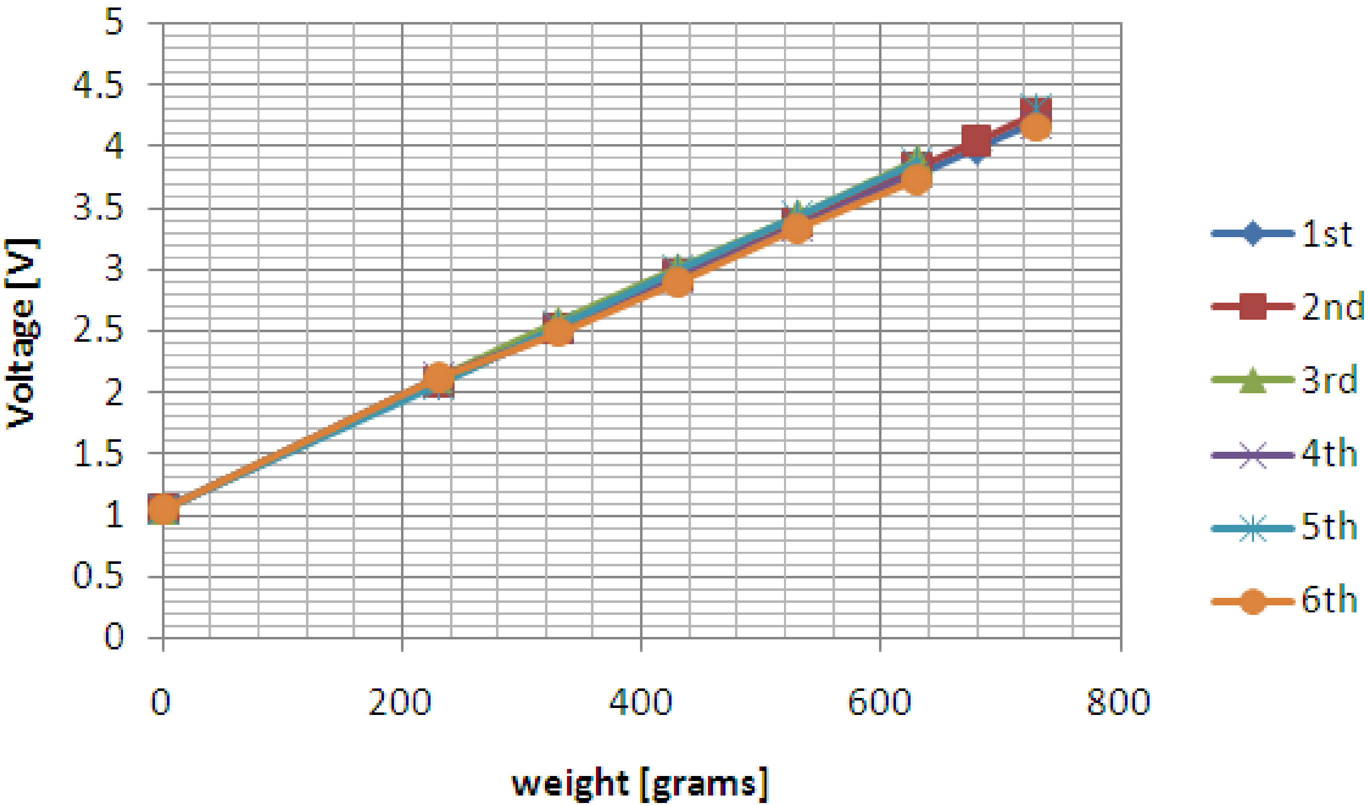


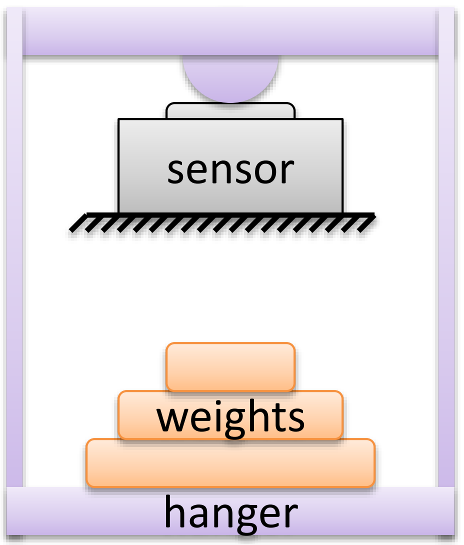


Honeywell FS01 piezoresistive force sensor

- calibration curve







measuring displacement (linear/angular)

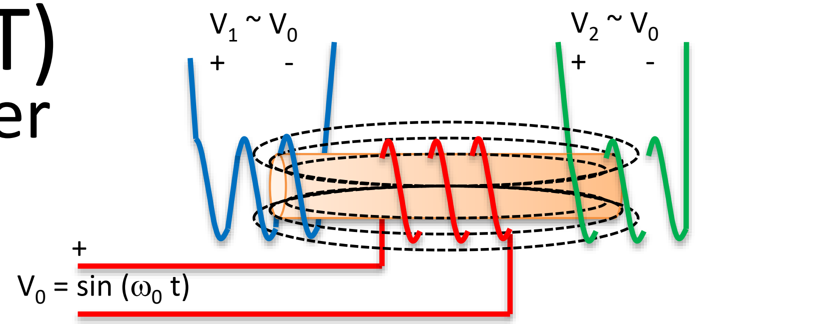
inductive sensors and

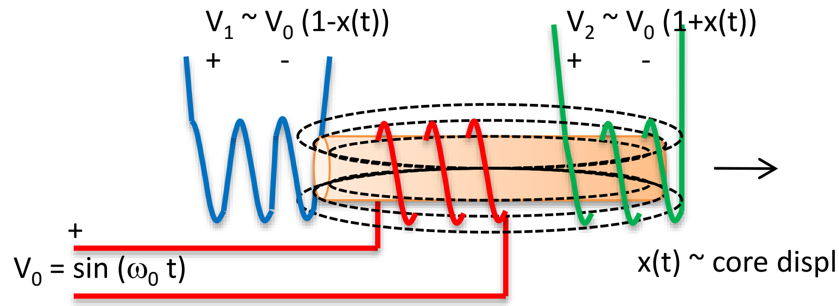
amplitude modulation

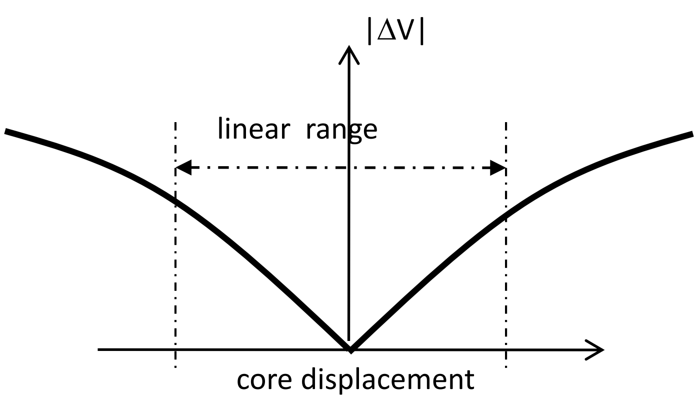
Linear Variable Differential Transformer (LVDT)

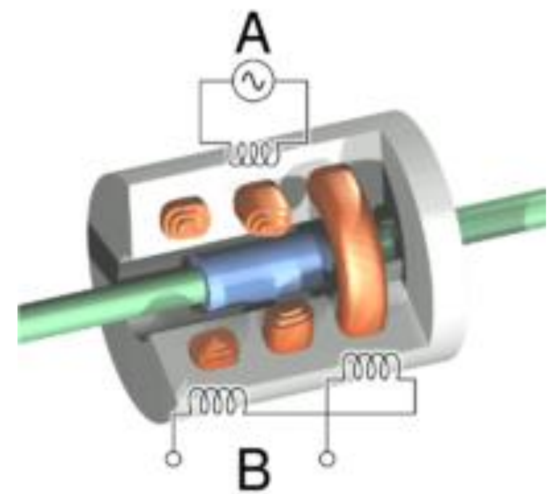
- a type of electrical transformer
  - measuring **linear** displacement
  - **variable** coupling via sliding ferromagnetic core
    - primary coil (AC driven, kHz)
    - two secondary coils
  - **differential** voltage

$$V_{OUT} = \Delta V = V_2 - V_1 \simeq x(t)\, V_0$$

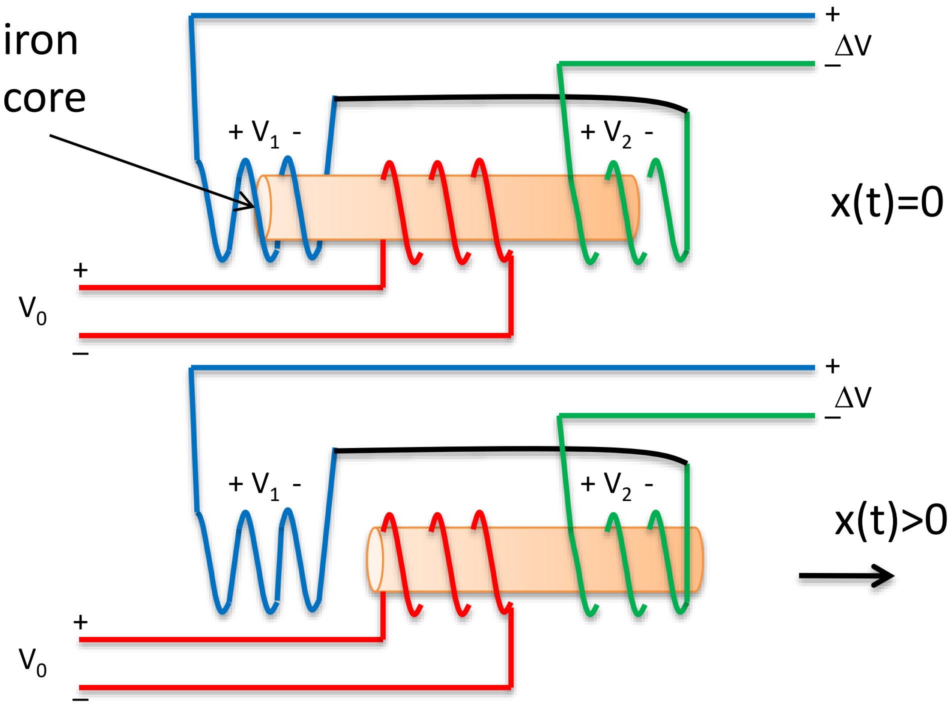


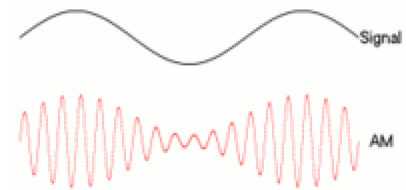




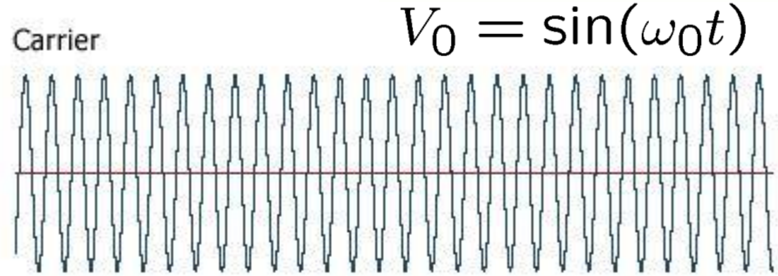


LVDT: amplitude modulation (AM)

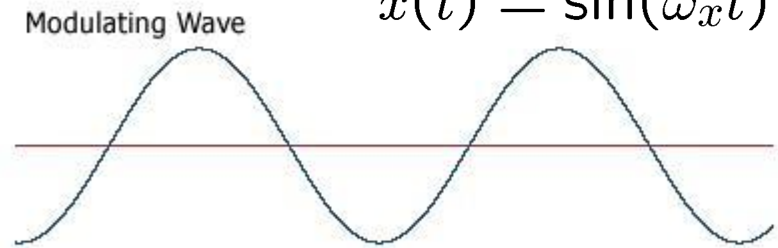




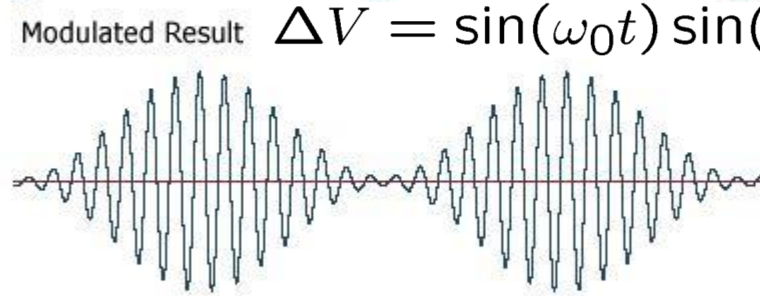
$$V_0 = \sin(\omega_0 t)$$



$$x(t) = \sin(\omega_x t)$$



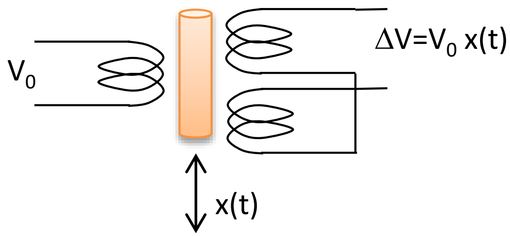
$$\Delta V = \sin(\omega_0 t)\sin(\omega_x t)$$

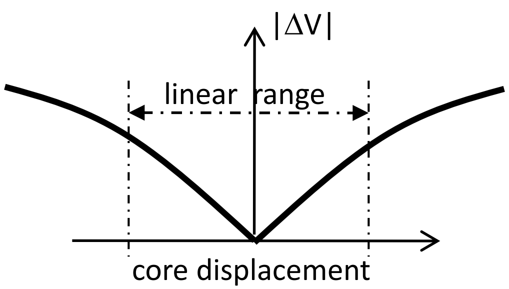


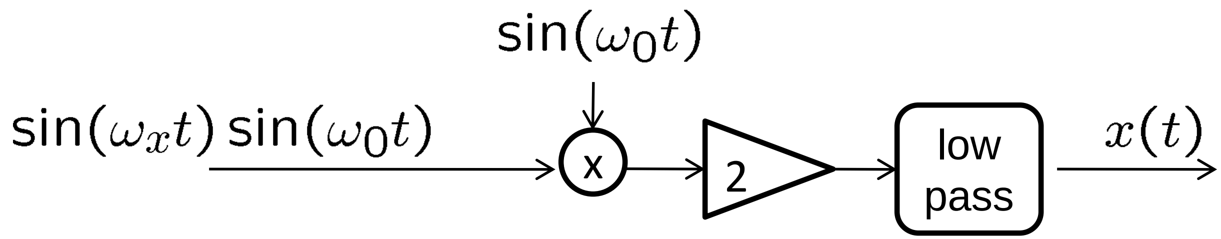
the **amplitude** of the output voltage is **modulated** by the physical displacement:

$$\Delta V \approx V_0\, x(t) = \sin(\omega_0 t)\sin(\omega_x t)$$

LVDT: amplitude demodulation







$$\sin(\omega_x t)\sin^2(\omega_0 t)$$

$$\sin(\omega_x t)\frac{1-\cos(2\omega_0 t)}{2}$$

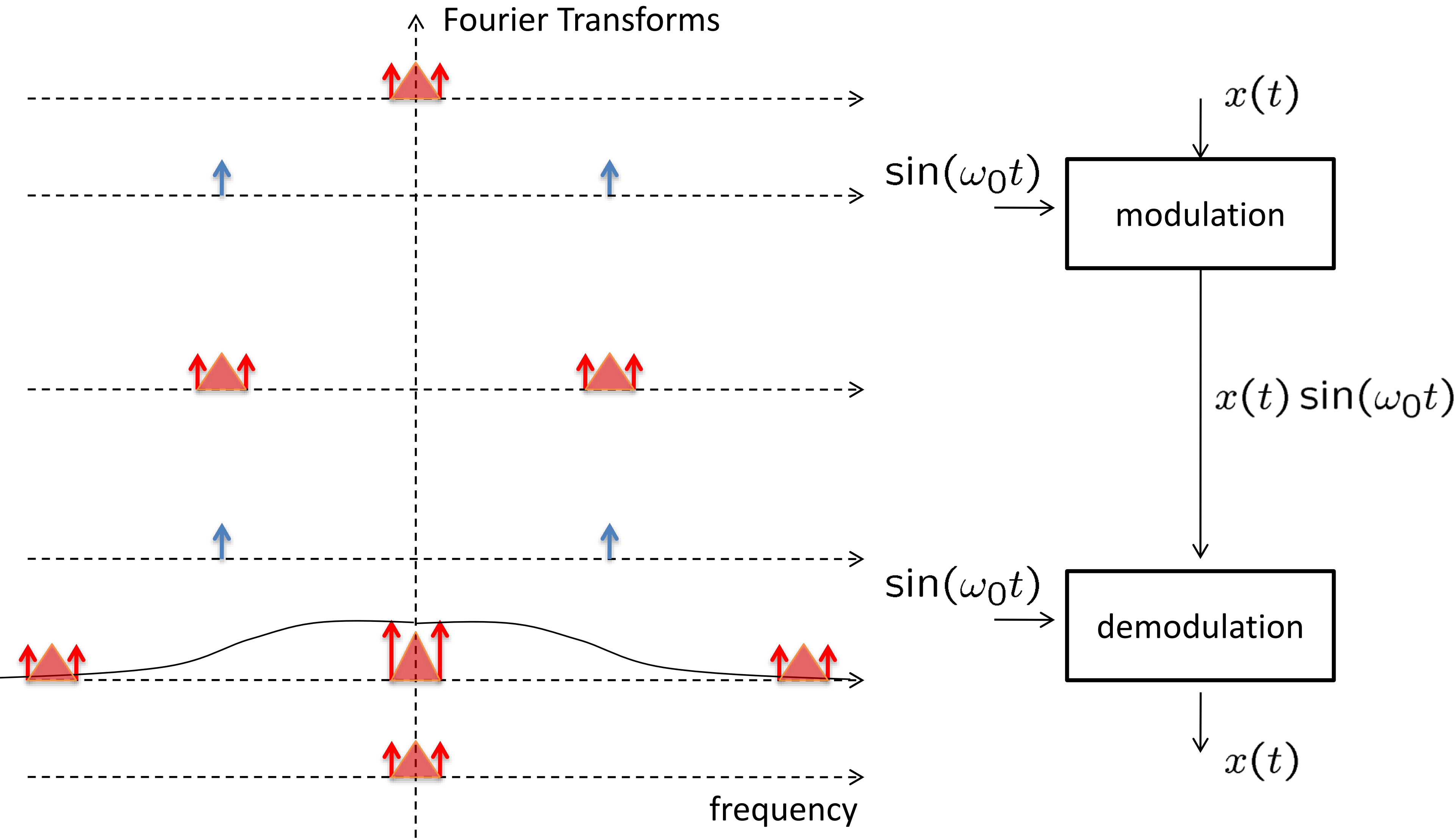
$$\underbrace{\frac{1}{2}\sin(\omega_x t)}_{\text{low frequency}}+\underbrace{\frac{\sin((2\omega_0+\omega_x)t)-\sin((2\omega_0-\omega_x)t)}{4}}_{\text{high frequency}}$$

high frequency
unwanted - to be filtered-out

$$V_0=\sin(\omega_0 t)$$
$$x(t)=\sin(\omega_x t)$$

$$\boxed{\omega_x \ll \omega_0}$$

Amplitude Modulation/Demodulation



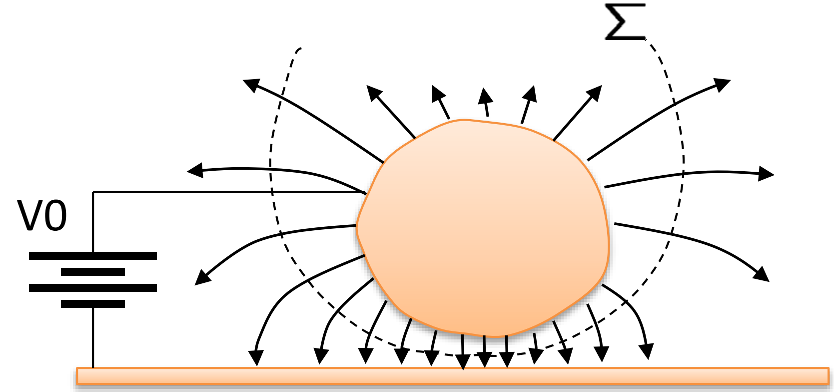
measuring displacement (linear/angular)

capacitive sensors

(proximity sensor)

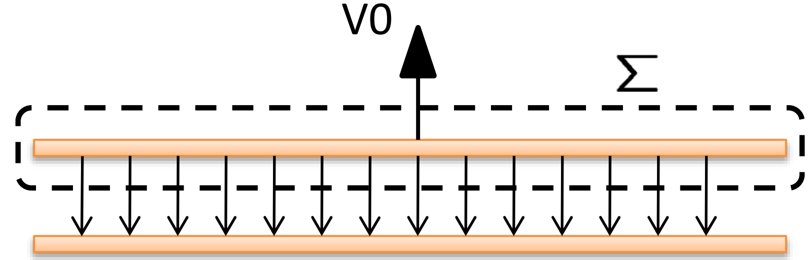
capacitive sensing: principle

- capacitance definition
  - C := Q / V
- ideal case
  - infinite parallel plates
- applications
  - proximity sensing

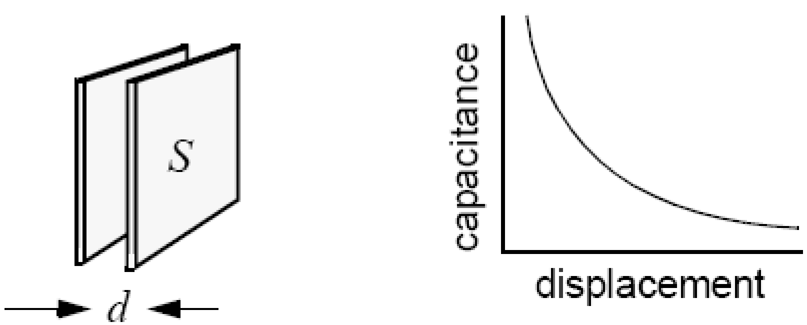


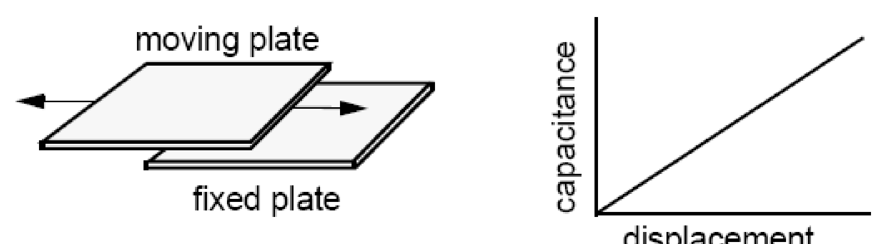
$$Q = \int\int_{\Sigma} \epsilon_0 \epsilon_r \mathbf{E} \, dS$$

Gauss's law



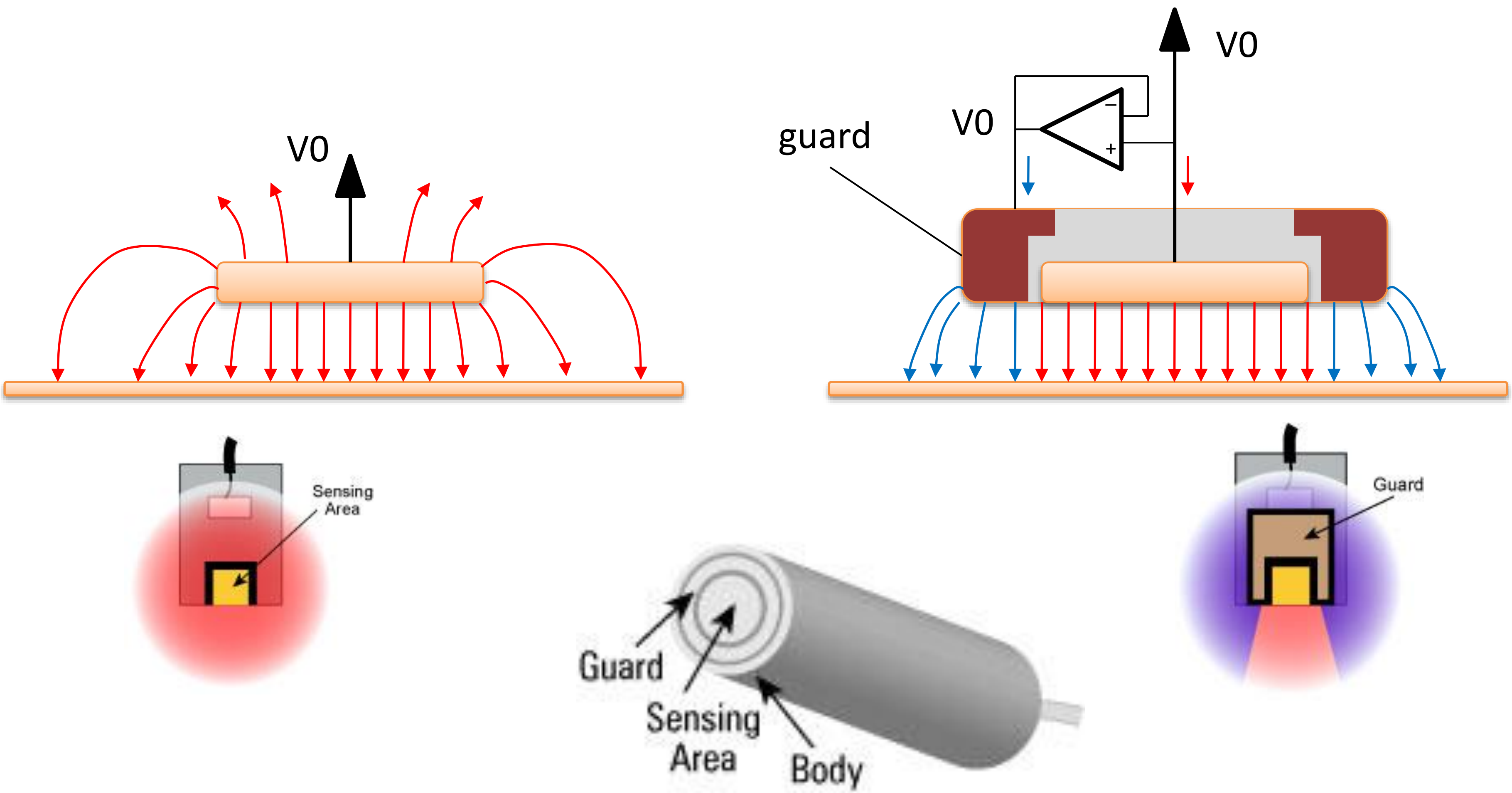
$$C = \frac{Q}{V} = \frac{\epsilon_0 \epsilon_r E S}{E d} = \frac{\epsilon_0 \epsilon_r S}{d}$$





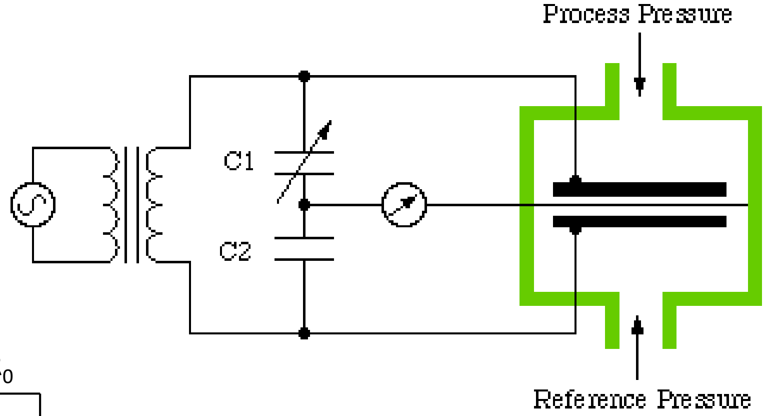
capacitive sensing: guard electrode

- the guard electrode limits field-fringing effects

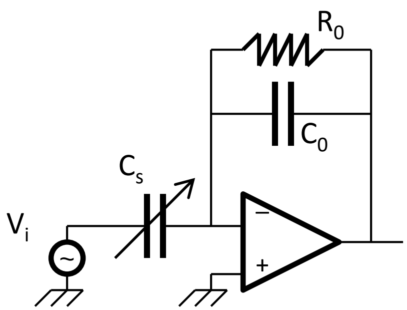


interfacing with capacitive sensors: AC

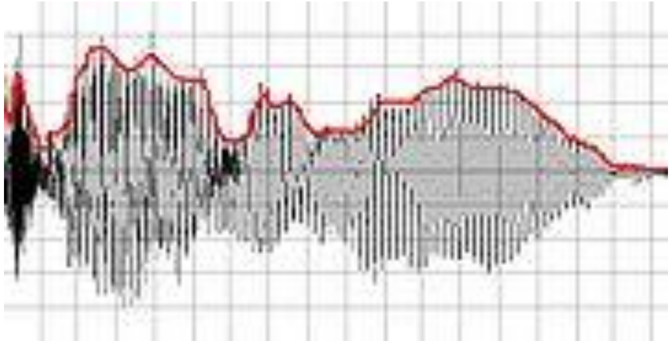
- AC bridge

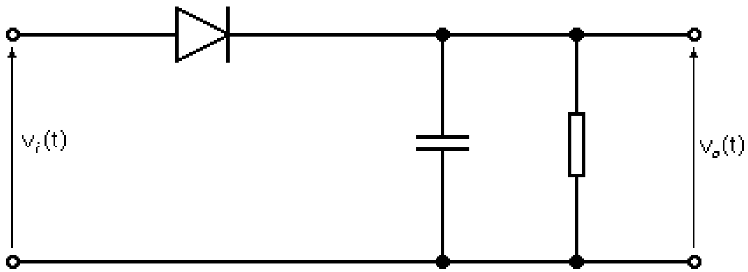


- AC driving



- Modulation
  - envelope demodulator
    - simplest demodulation
    - for non-negative signals





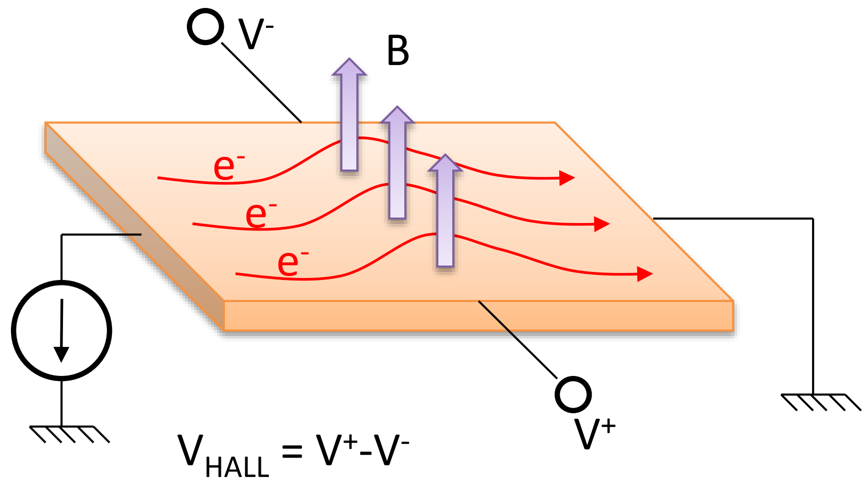
proximity sensors

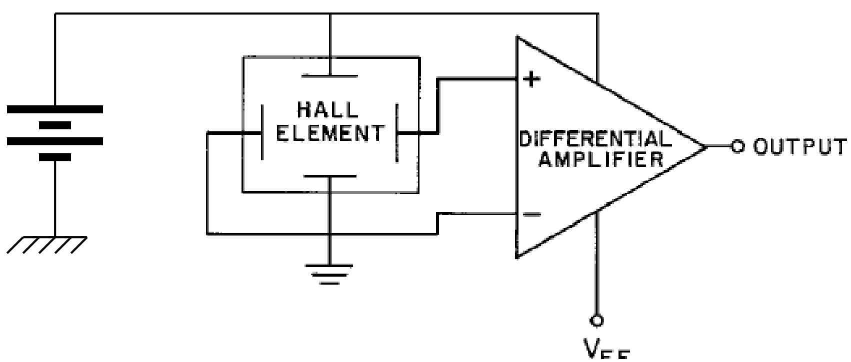
magnetic and optical

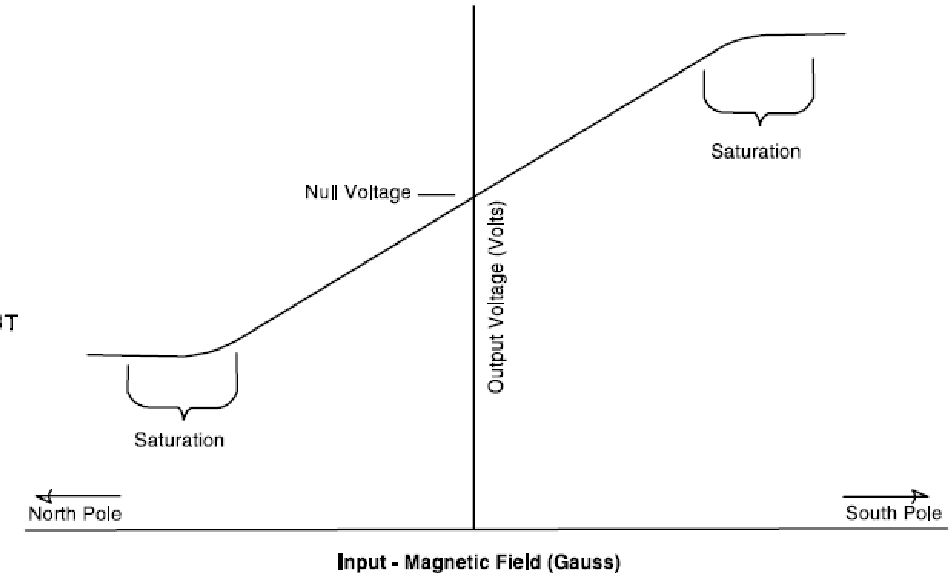
Hall effect

- Lorentz force

$$\vec{F} = q\vec{v} \times \vec{B}$$

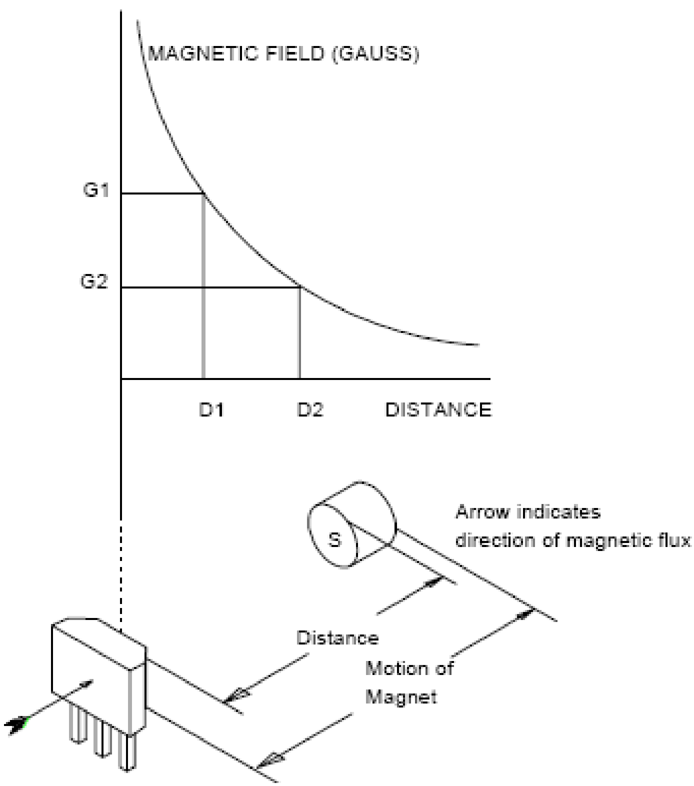




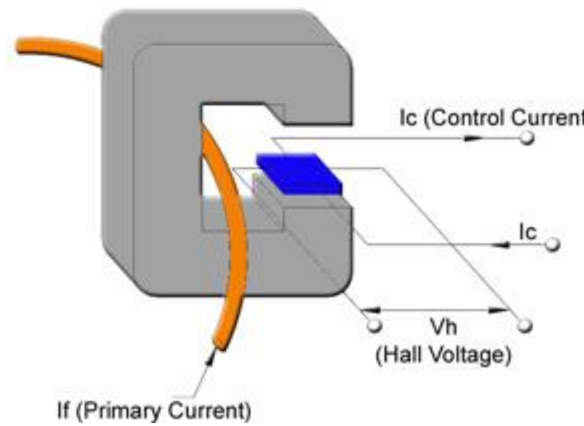


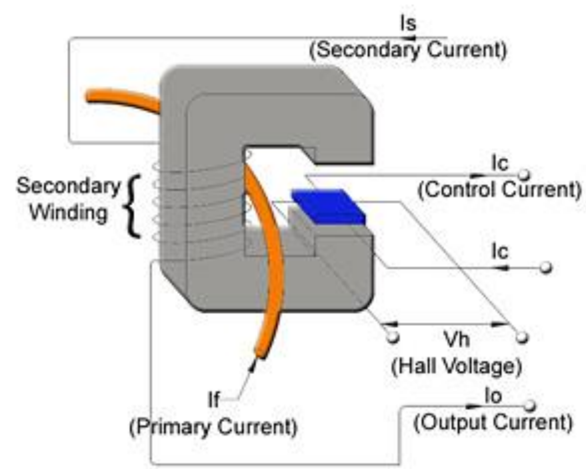
Hall effect sensors applications

- proximity sensor
  - contactless switch



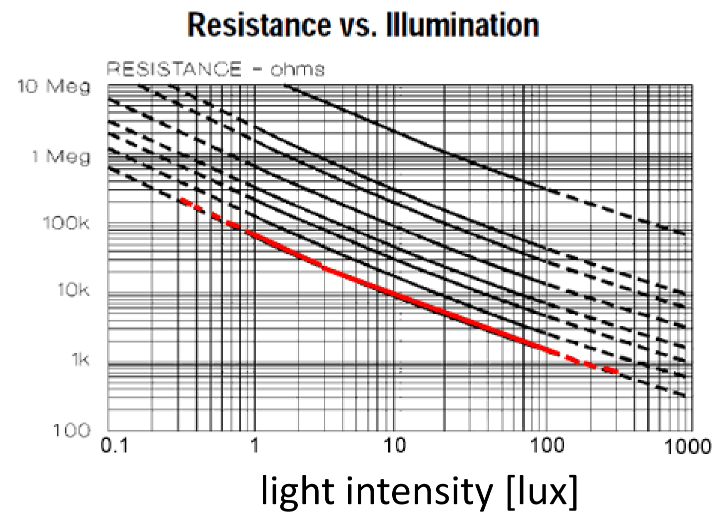
- current sensor

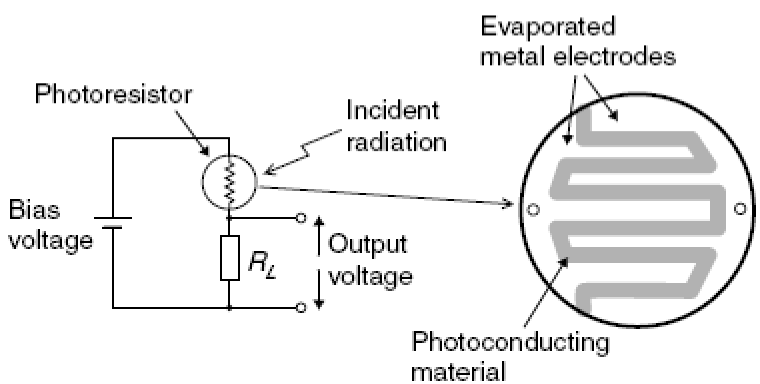


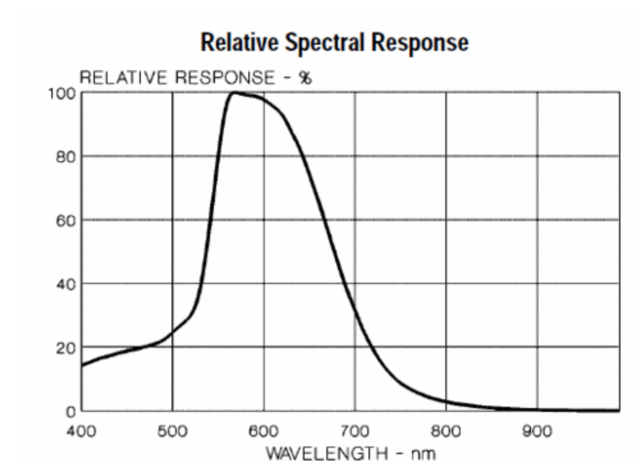


light detectors

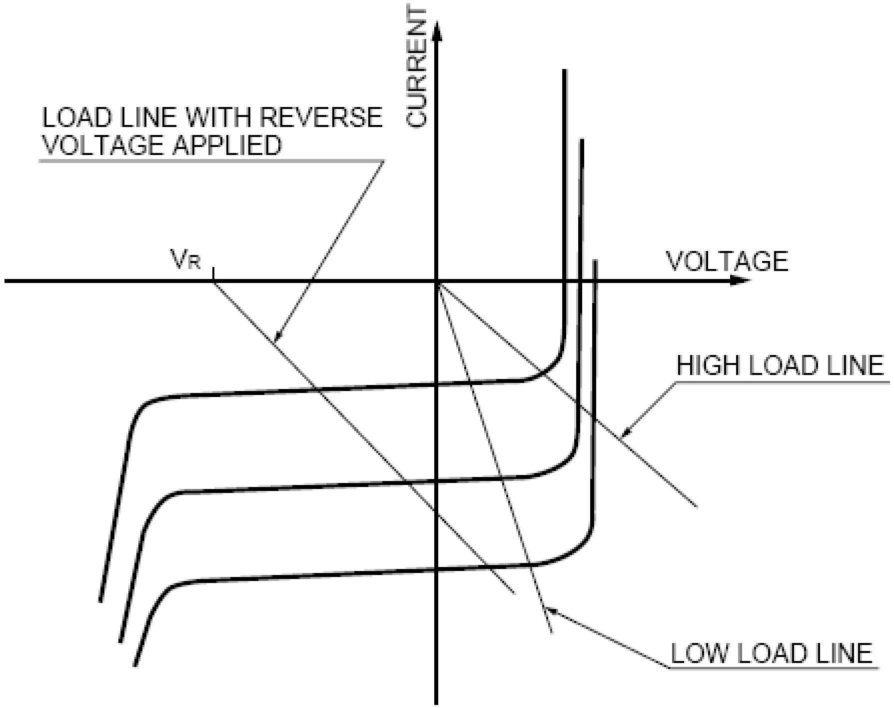
- photo-resistors



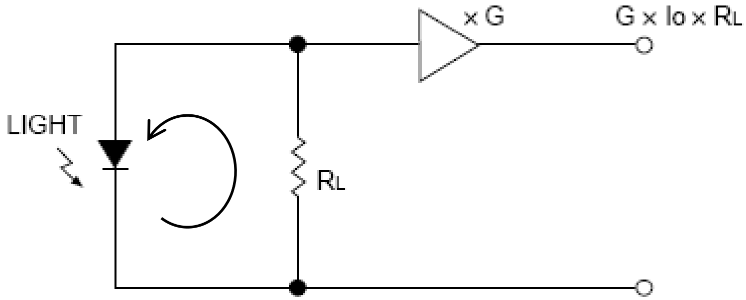




light detectors



- photo-diodes
  - load resistance



  - op-amp circuit

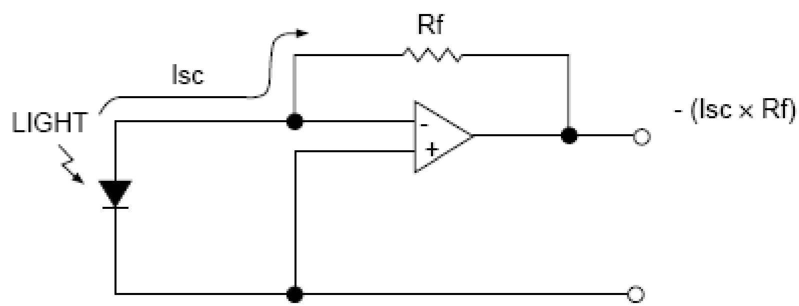
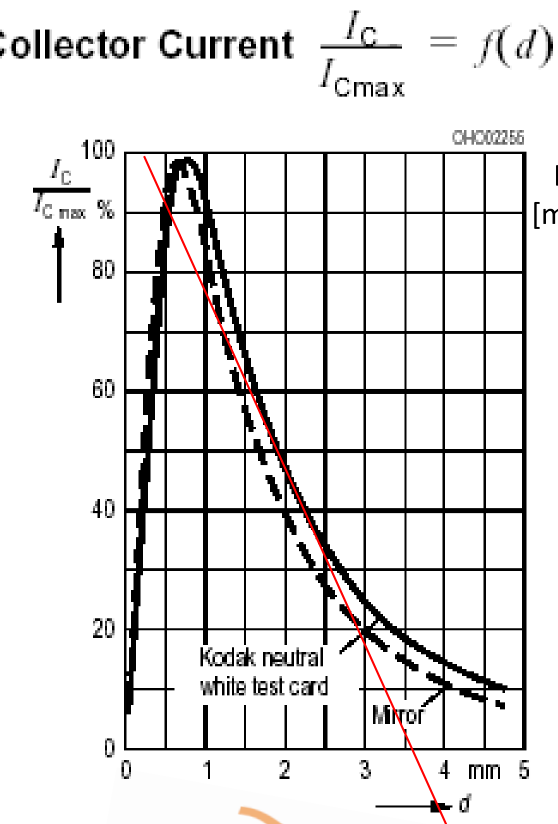
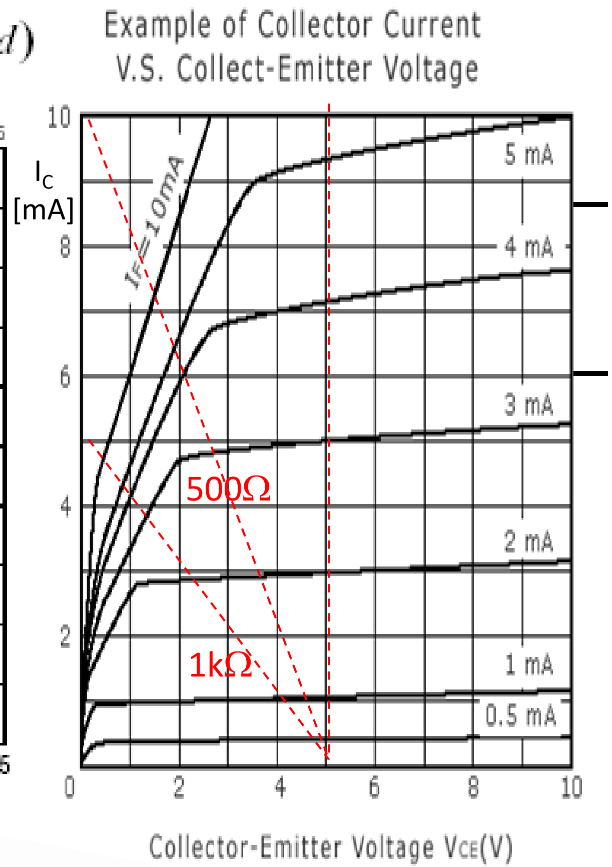
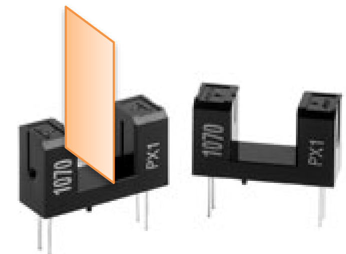
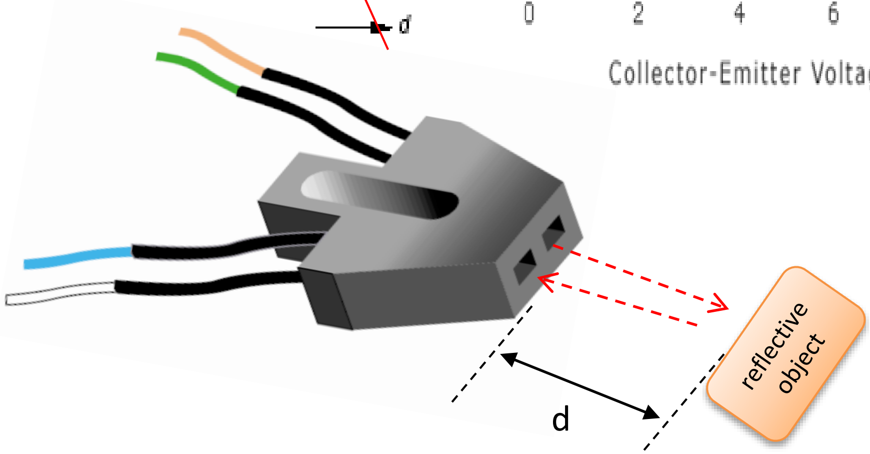


photo-transistors

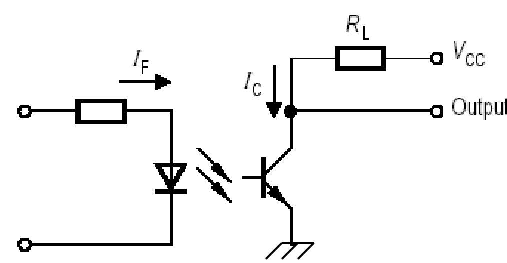






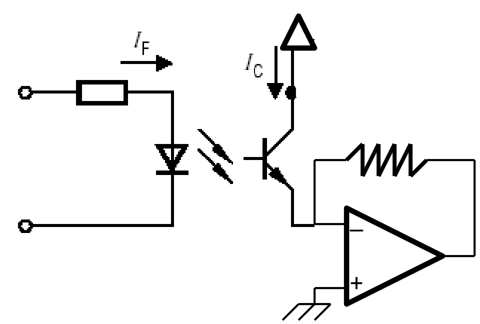


- transmissive
  - photo-interrupter
- reflective
  - resistive load



V_{CC} = 5 V
R_L = 1kΩ

  - current-voltage op-amp



digital encoders

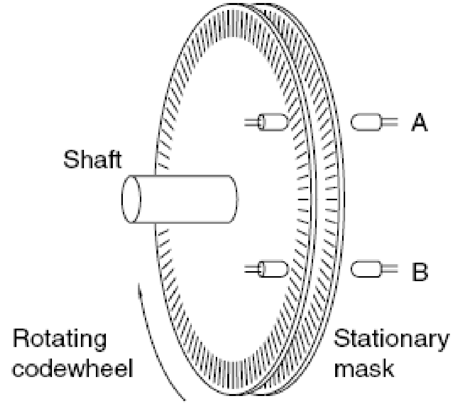
linear / angular

absolute / incremental

digital encoders

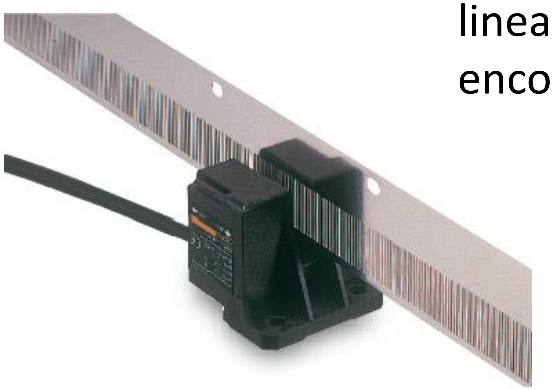
- convert motion
  - either linear or **rotary**

  into a sequence of digital pulses
  - optical transmitter/receiver pairs
    - glass/plastic material photographically patterned
  - Hall effect sensors
    - coupled with magnetic rings / bars



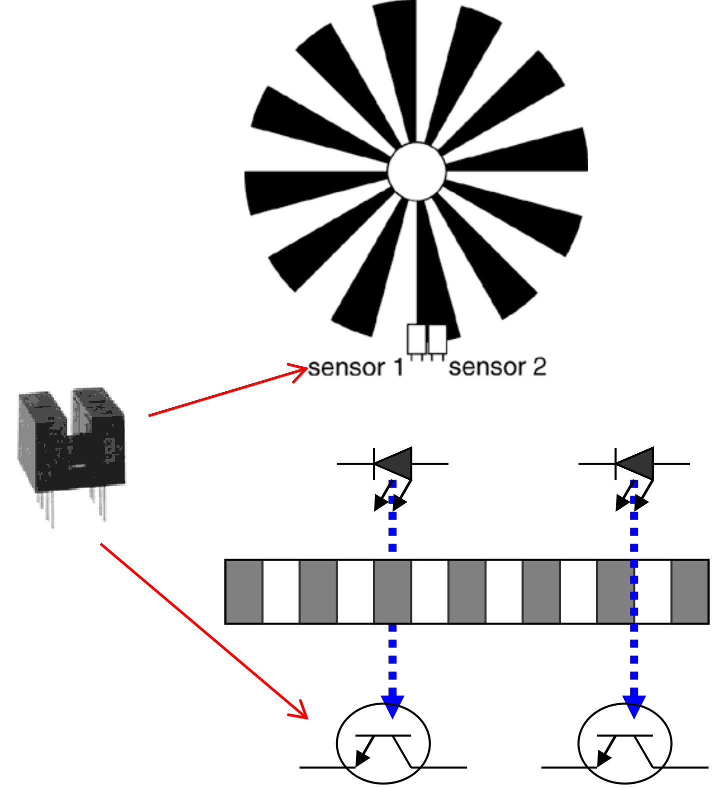
rotary encoders

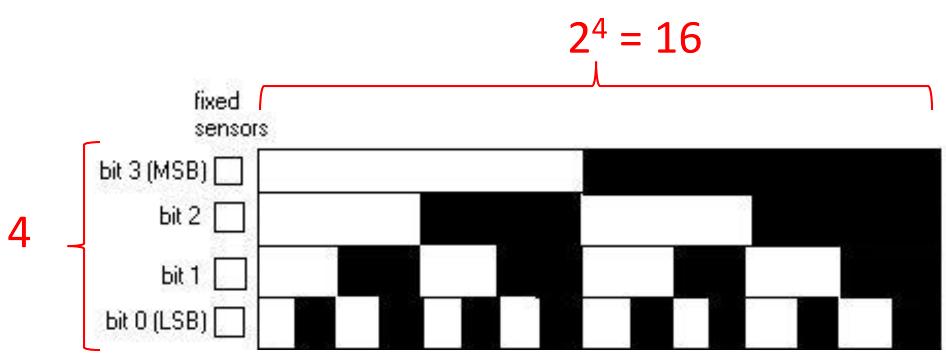
linear encoders

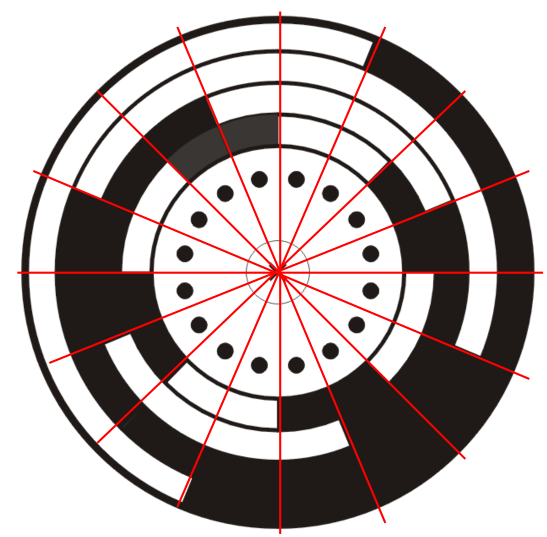


digital encoders

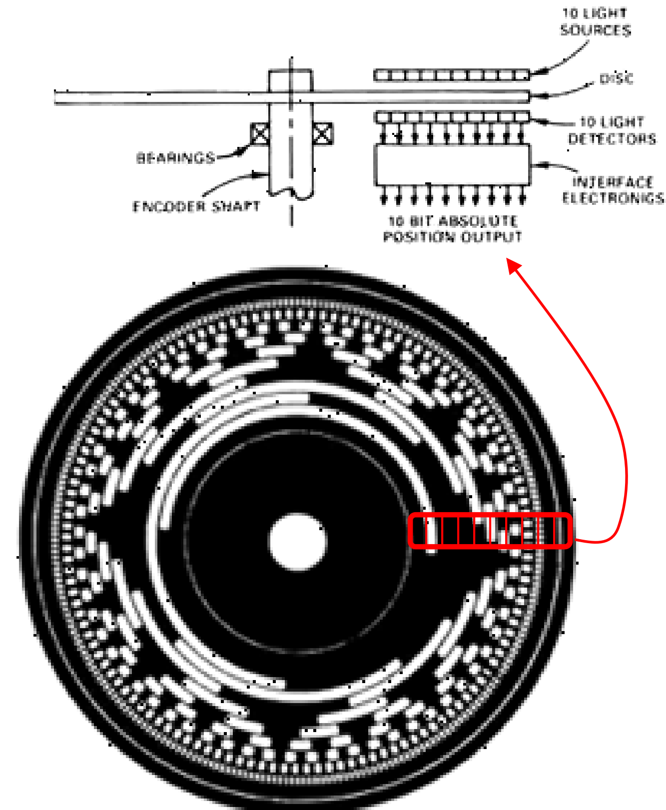
- incremental encoders
  - minimum 2 Tx/Rx pairs
    - encoding steps and direction
- absolute encoders
  - n Tx/Rx pairs for coding 2^n sectors



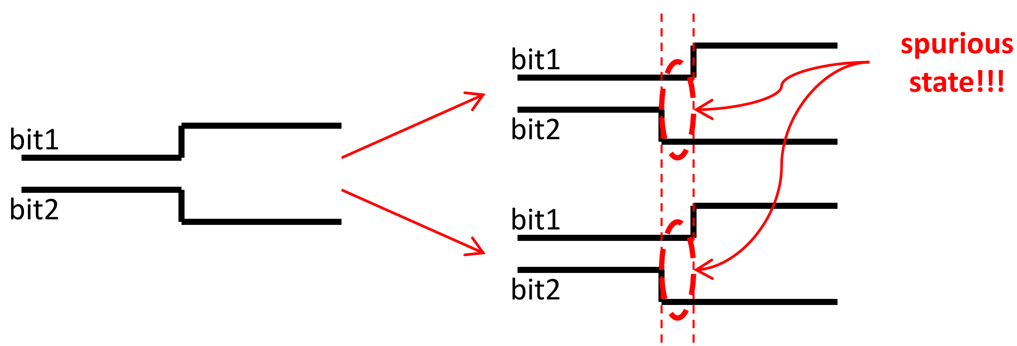


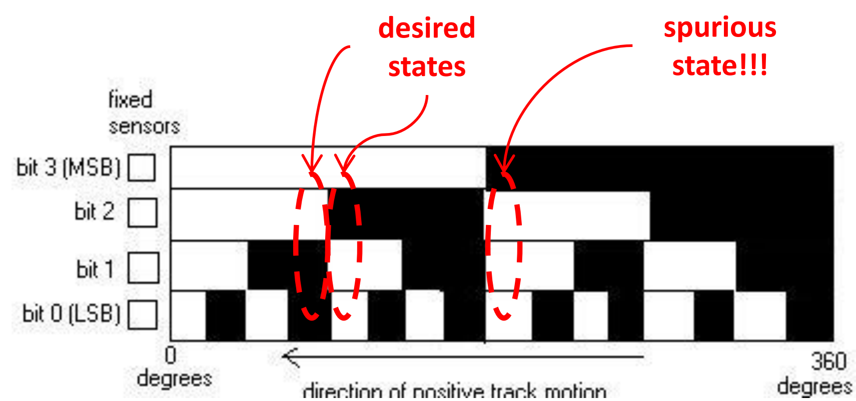


absolute encoders



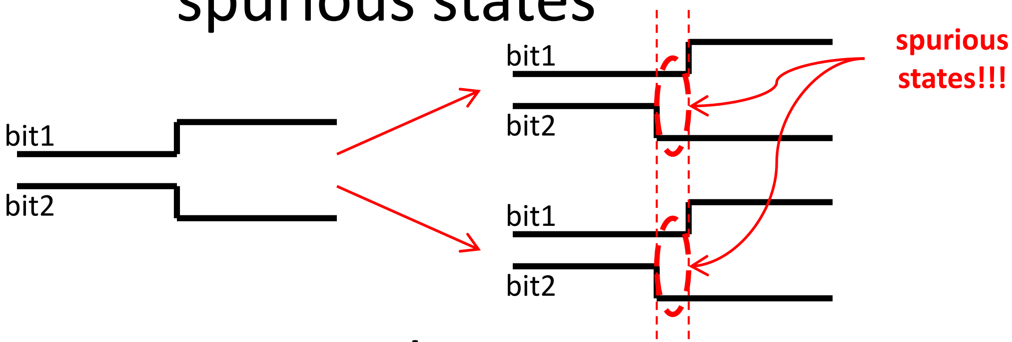
- angular n-bits encoders
  - $360°/ 2^n$ resolution
    - n=10 → 360°/1024=0.35°
  - more expensive
    - require n Tx/Rx pairs
  - **CAVEAT**: spurious states may arise from contemporary transitions



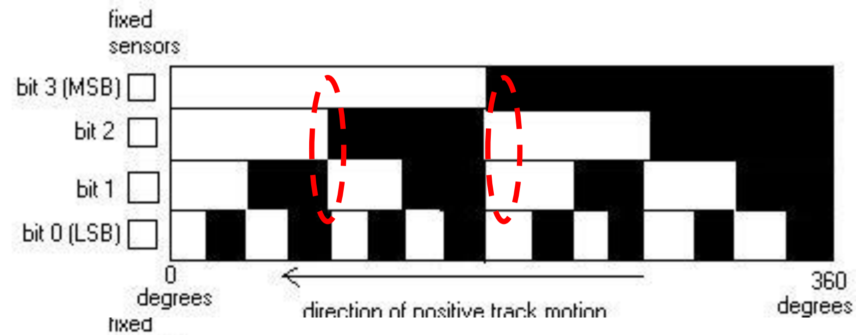


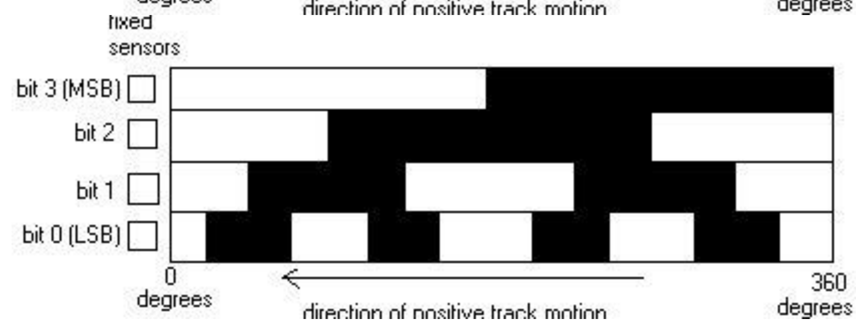
absolute encoders

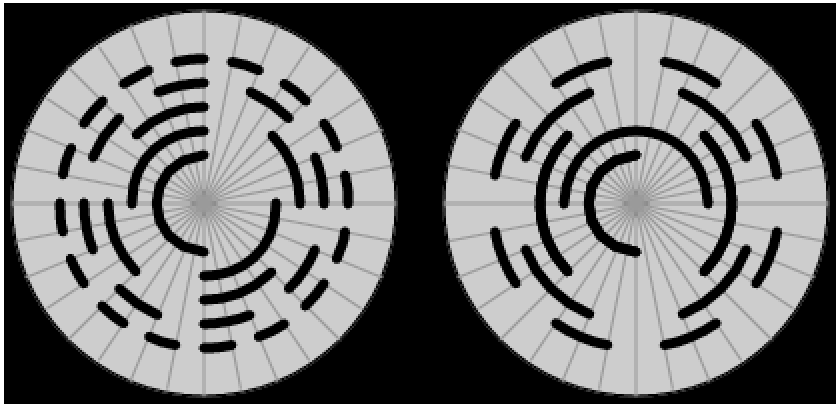
- natural binary code vs. **Gray code**
  - contemporary transitions might lead to temporary spurious states



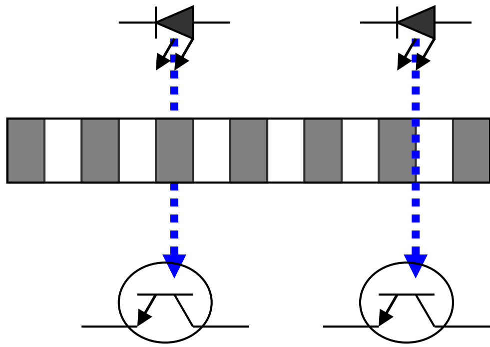
  - Gray code ensures no contemporary transitions



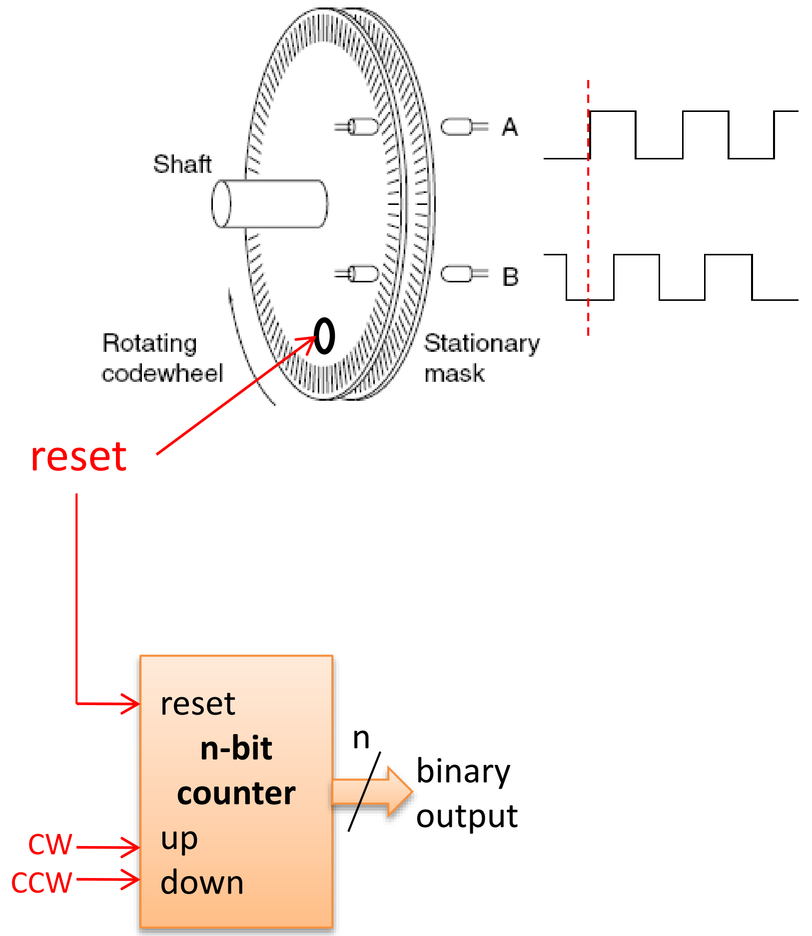


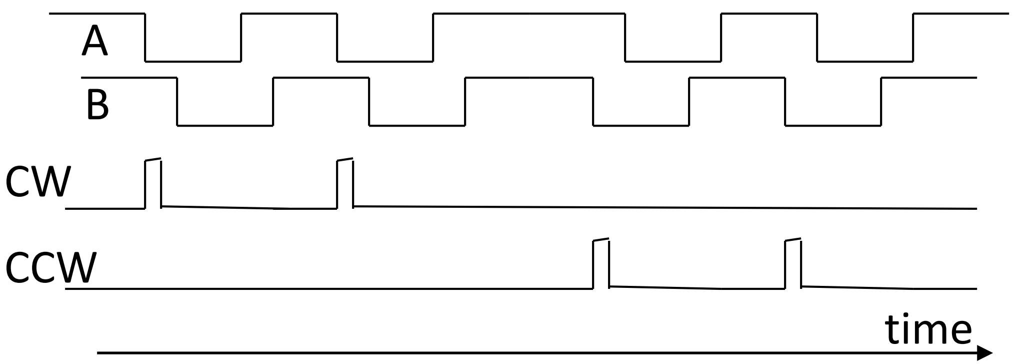


incremental encoders



- simpler design
    - a single pair not sufficient to encode the direction
    - 2 Tx/Rx pairs plus a 'reset' position are required
  - quadrature signals
    - ¼ cycle out-of-phase





measuring higher kinematics

please, refer to this case study

D. Campolo, S. E. Maini, F. Patanè, C. Laschi, P. Dario, F. Keller, E. Guglielmelli, Design of a Sensorized Ball for Ecological Behavioral Analysis of Infants, IEEE Intl. Conf. on Robotics and Automation (ICRA), Rome, Italy, pp. 1529 - 1534, April 10-14, 2007

http://www3.ntu.edu.sg/home/d.campolo/pdf/2007_ICRA_BALL.pdf