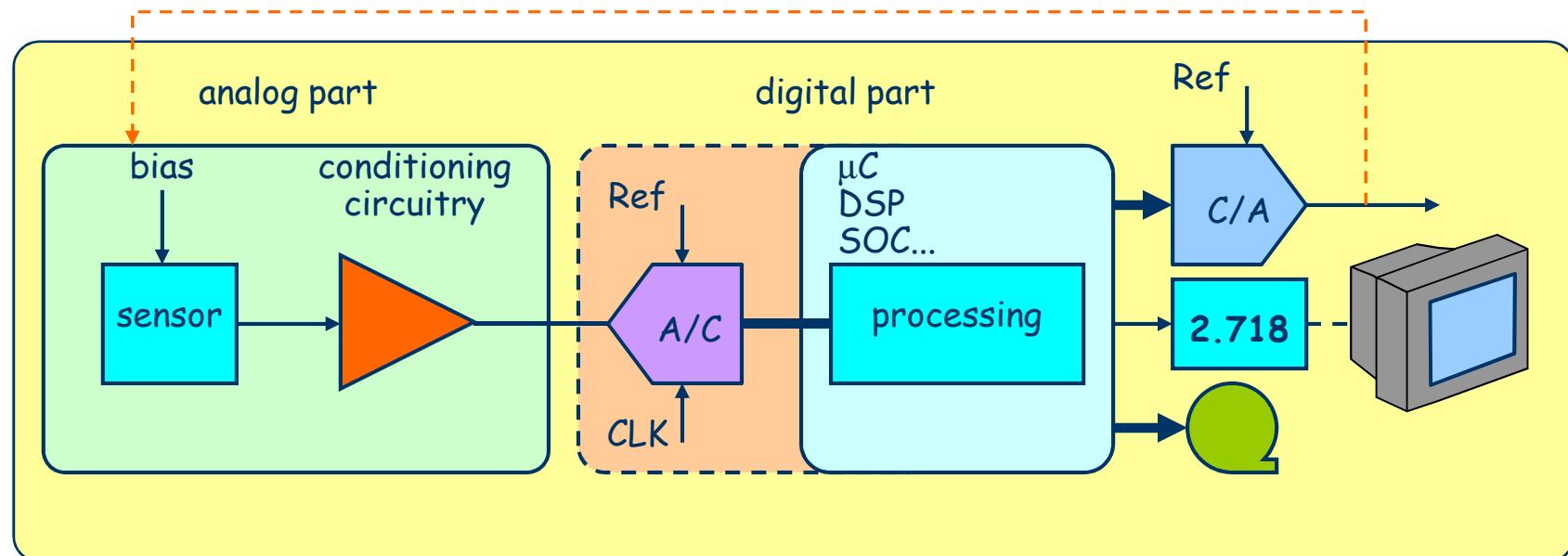


# Measurement of non-electrical quantities

# Measurement chain



## Sensor

a converter that measures a physical quantity, converting it into a signal convenient for an observer or some data acquisition system.

## Transducer

a device, converting one form of energy (eg. mechanical, thermal, electromagnetic etc.) into other form (often of electrical nature), convenient for transmission, presentation or processing.

# Which quantities can be measured...

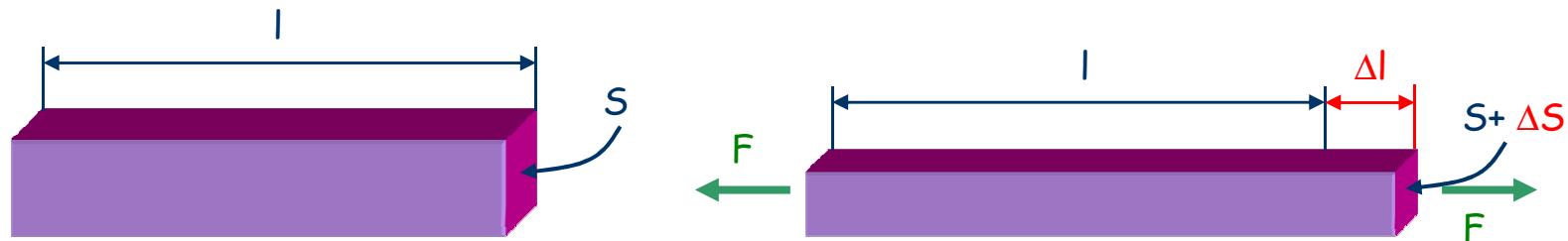
...almost all

- temperature (thermistor, termocouple)
- force, tension (tensometer)
- pressure (tensometer transducer)
- displacement (potentiometer, LVDT transformer)
- flow of substance (anemometer)
- speed, speed of rotation (gyroscope)
- acceleration
- distance
- vibrations (piezoelectric effect)
- humidity
- chemical composition
- time
- ....
- ECG signals
- HRM
- gesture, position
- smoke/particles detections ...

<https://www.analog.com/en/education/education-library/transducer-interfacing-handbook.html>

The screenshot shows a web browser displaying the 'Transducer Interfacing Handbook, 1980' from Analog Devices. The URL in the address bar is <https://www.analog.com/en/education/education-library/transducer-interfacing-handbook.html>. The page has a purple header with navigation links for MY HISTORY, PRODUCTS, APPLICATIONS, DESIGN CENTER, COMMUNITY, EDUCATION (which is highlighted), and SUPPORT. Below the header, the breadcrumb navigation shows 'Education > Education Library > Transducer Interfacing Handbook, 1980'. The main content area features a sidebar titled 'Modules and Courseware' with links to Education Library, FAQs, Technical Books, Training and Tutorials, Tutorials, Videos, Webcasts, White Papers, and Case Studies. The main content area is titled 'Education Library' and contains a summary of the handbook, its author (Dan Sheingold, Analog Devices, 1980), and its historical significance. It also mentions that the book is available for download. A list of chapters is provided, each with a PDF link. To the right of the content is a thumbnail image of the book cover.

## Strain gauge (gage), tensometer

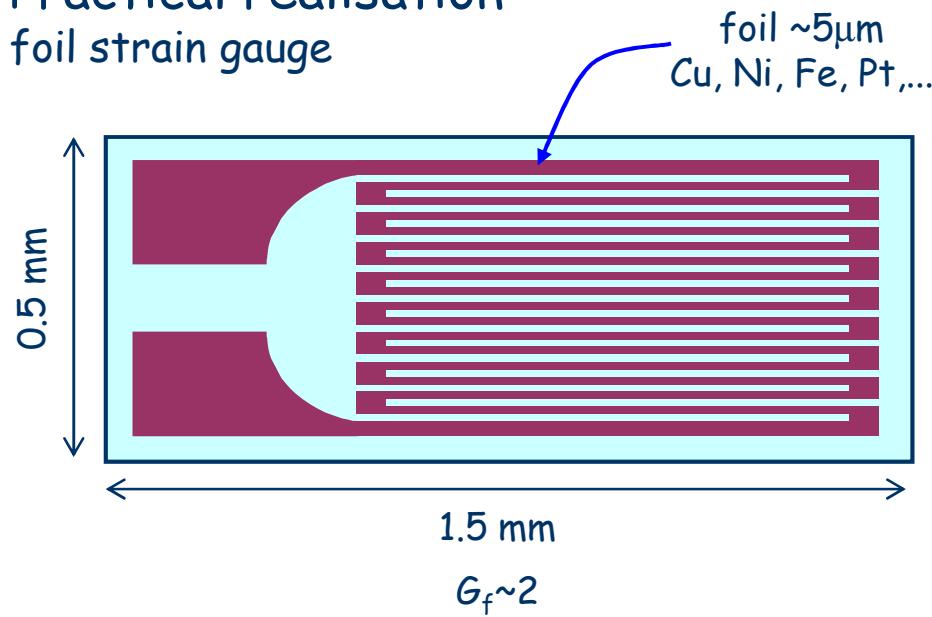


$$R = \frac{\rho \cdot l}{S}$$

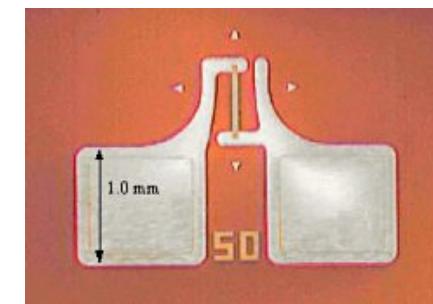
$$\Delta R = \frac{\partial R}{\partial l} \Delta l + \frac{\partial R}{\partial S} \Delta S + \frac{\partial R}{\partial \rho} \Delta \rho$$

$$\frac{\Delta R}{R} = G_f \frac{\Delta l}{l}$$

Practical realisation  
foil strain gauge

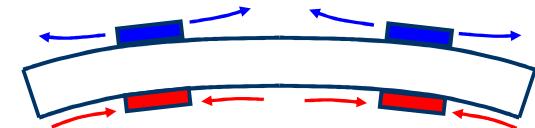
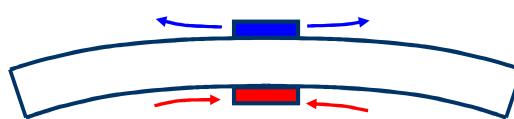
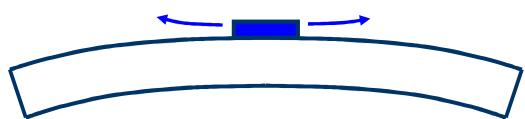
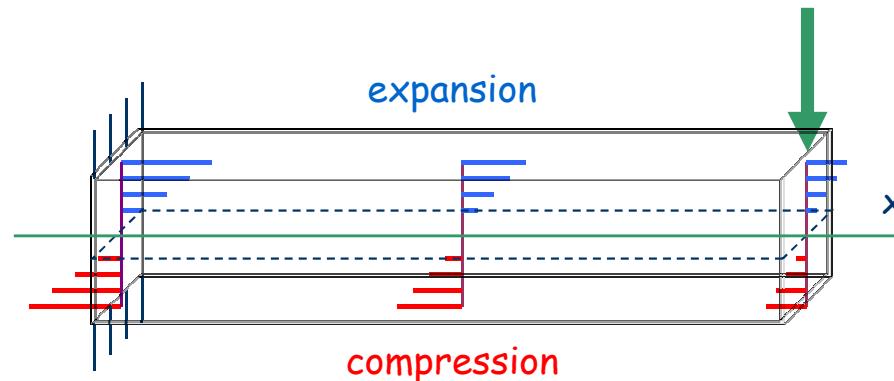
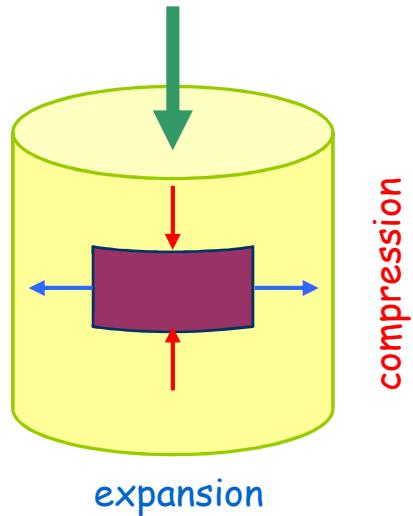


semiconductor strain gauge



$G_f \sim -100$  (Si)

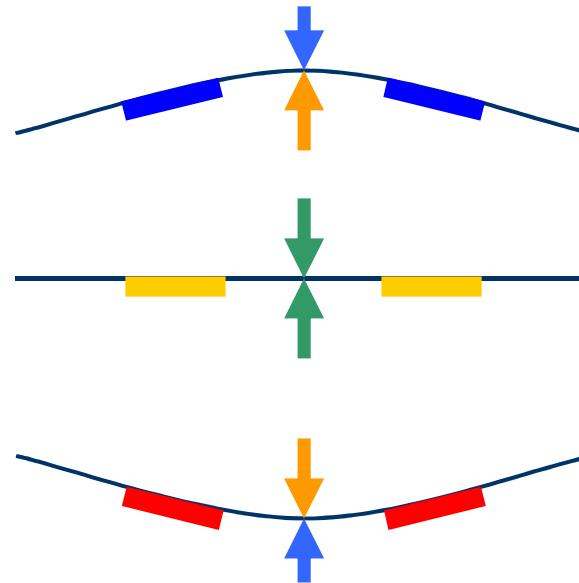
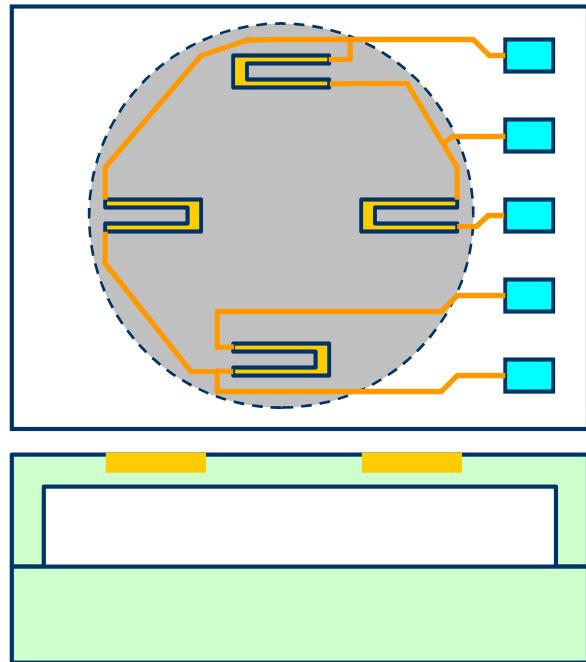
# Strain measurement (force, mass, pressure, tension...)



$$\frac{\Delta R}{R} = G_f \frac{\Delta l}{l} \Rightarrow \Delta R = R \cdot G_f \frac{\Delta l}{l}$$

$$\begin{aligned}\Delta l/l &\sim 0.4 \div 1\% \\ R &= 1 \text{ k}\Omega \\ \Delta R &\sim 8 \div 20 \Omega \text{ (assuming } G_f = 2)\end{aligned}$$

# Pressure transducer

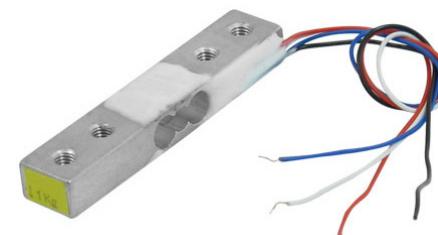
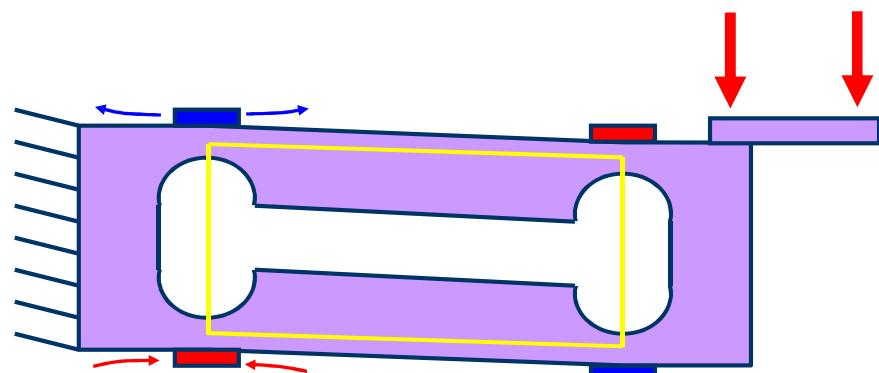
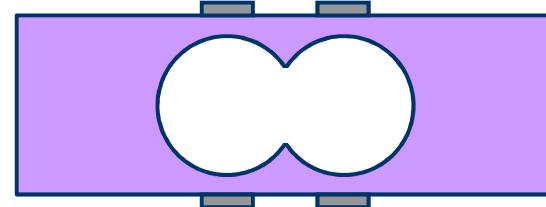
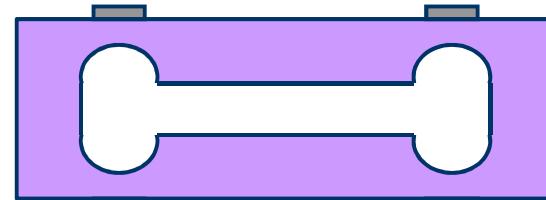
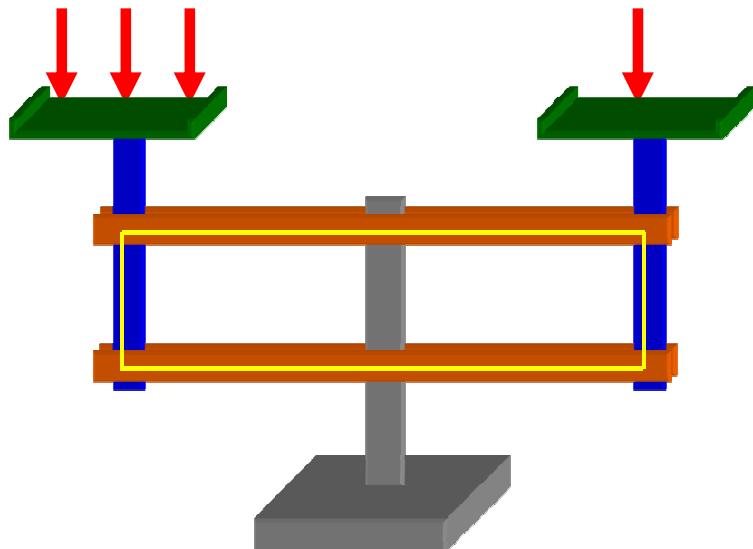


MPX2300 (Freescale)

sensitivity  $5 \mu\text{V/V/mmHg}$   
 $U_{FS} = 3 \text{ mV}$

# A weighting scale

Roberval mechanism (Gilles Personne de Roberval, 1602-1675)



sensitivity 0.5 - 1 mV/V/FL (full load)  
FL: ranges from grams to tons

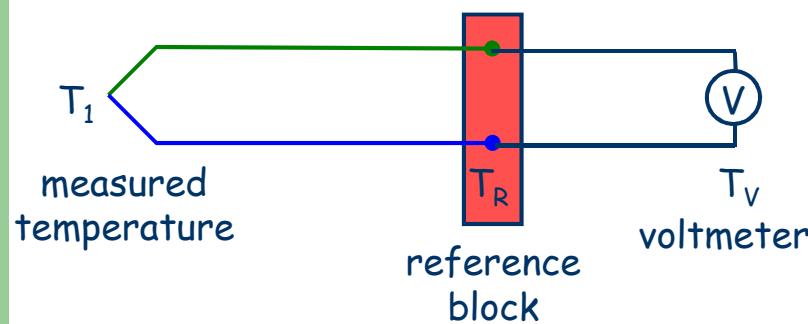
# Temperature measurement

Thermocouple - thermoelectric effect

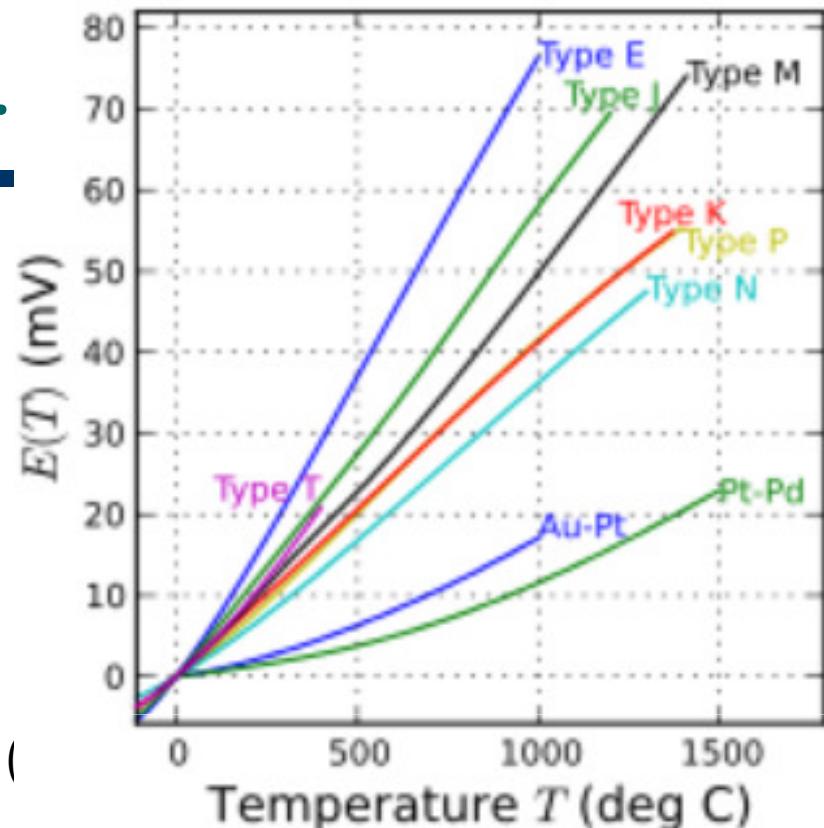
Seebeck effect (Thomas J. Seebeck, 1821)

$$T_1 \quad \Delta V = -S(T) \cdot \Delta T \quad T_2$$

Standard measurement setup



$$\begin{aligned}V_T &= \int_{T_R}^{T_1} (S_A(\\&= E(T_1) - E(T_R)\end{aligned}$$



Possible solutions

- cold junction, aka „ice bath”
- compensated cold junction
- hot junction (rare)

Standard thermocouple junctions

type	junction	range [°C]	sensitivity [ $\mu\text{V}/\text{°C}$ ]
K	chromel/alumel	-200 ÷ 1200	39
E	chromel/constantan	0 ÷ 900	76
J	iron/constantan	-200 ÷ 760	55
T	copper/constantan	-200 ÷ 400	45

# Temperature measurement

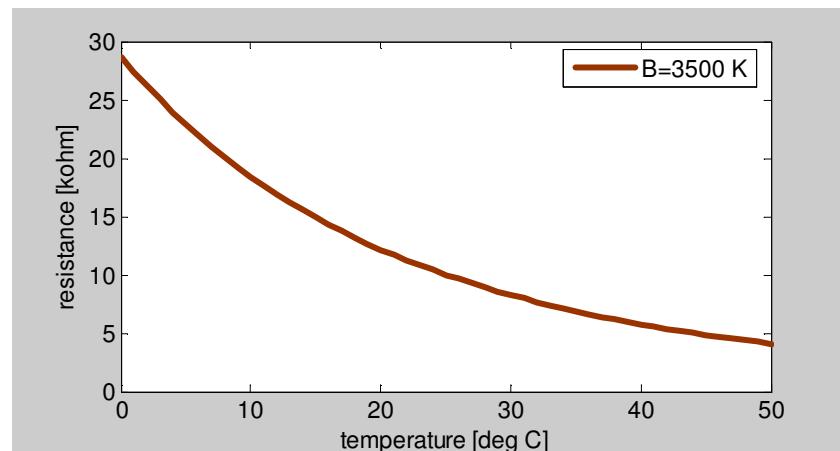
## Thermistor

Steinhart-Hart equation

$$a + b \ln R_T + c(\ln R_T)^3 = T^{-1}$$

For NTC thermistors

$$R_T = R_0 \exp \left[ B \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]$$



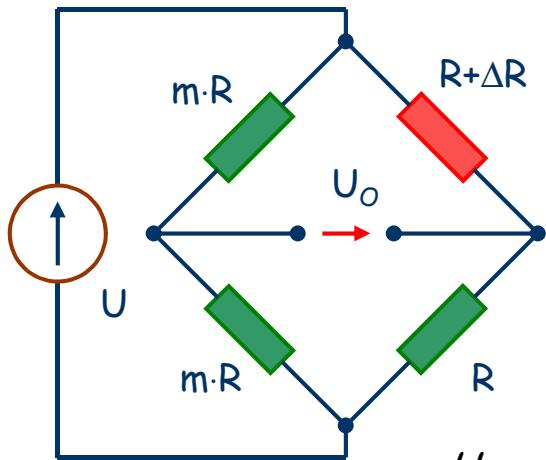
Resistive thermometer detector RTD (William Siemens, 1871)

$$R_T = R_0 (1 + C_1 T + C_2 T^2 + C_3 T^3 + \dots)$$

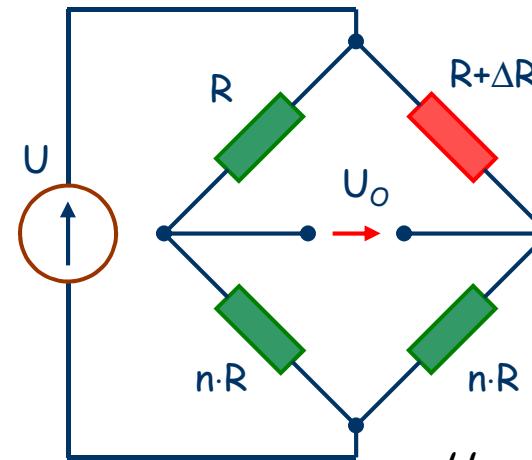
Pt-100 sensor - 100 Ω @ 0°C;  $C_1 \sim 0.75 \Omega/\text{°C}$



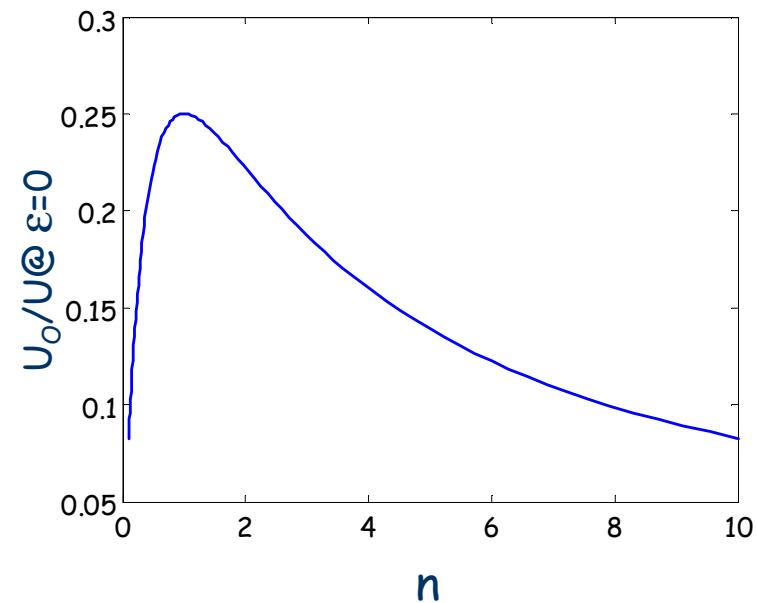
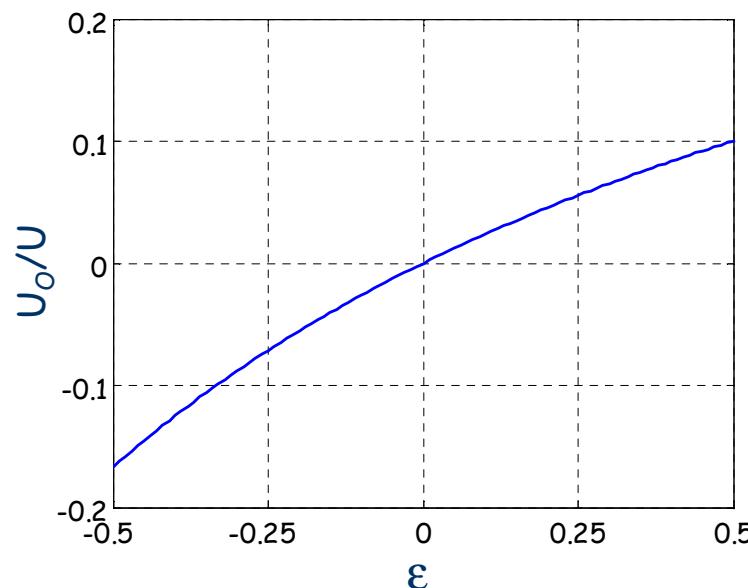
# Unbalanced bridge - linearity problem



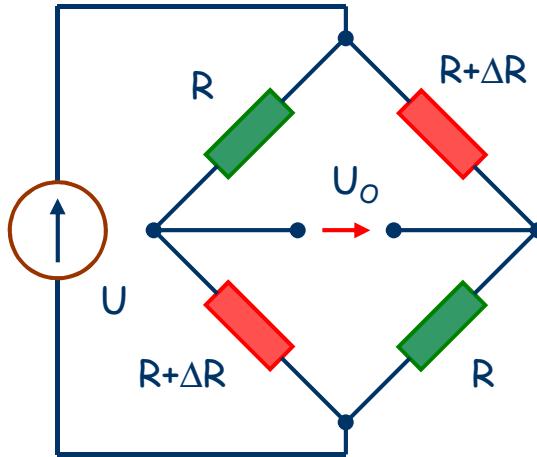
$$\frac{U_o}{U} = \frac{\varepsilon}{2(2 + \varepsilon)}$$



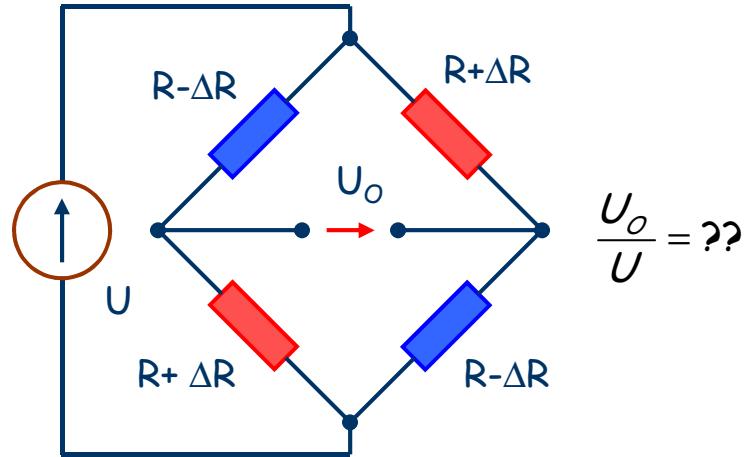
$$\frac{U_o}{U} = \frac{n \cdot \varepsilon}{(n+1)^2 + (n+1)\varepsilon}$$



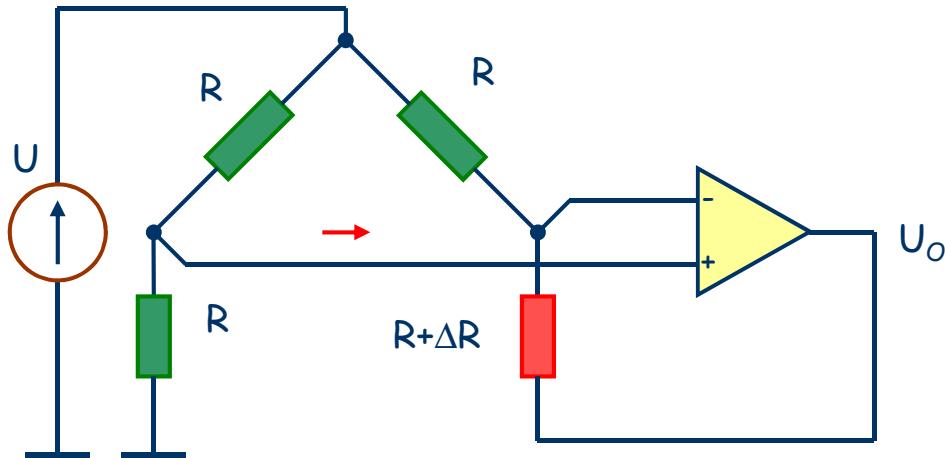
# Methods of bridge linearisation



$$\frac{U_o}{U} = ??$$



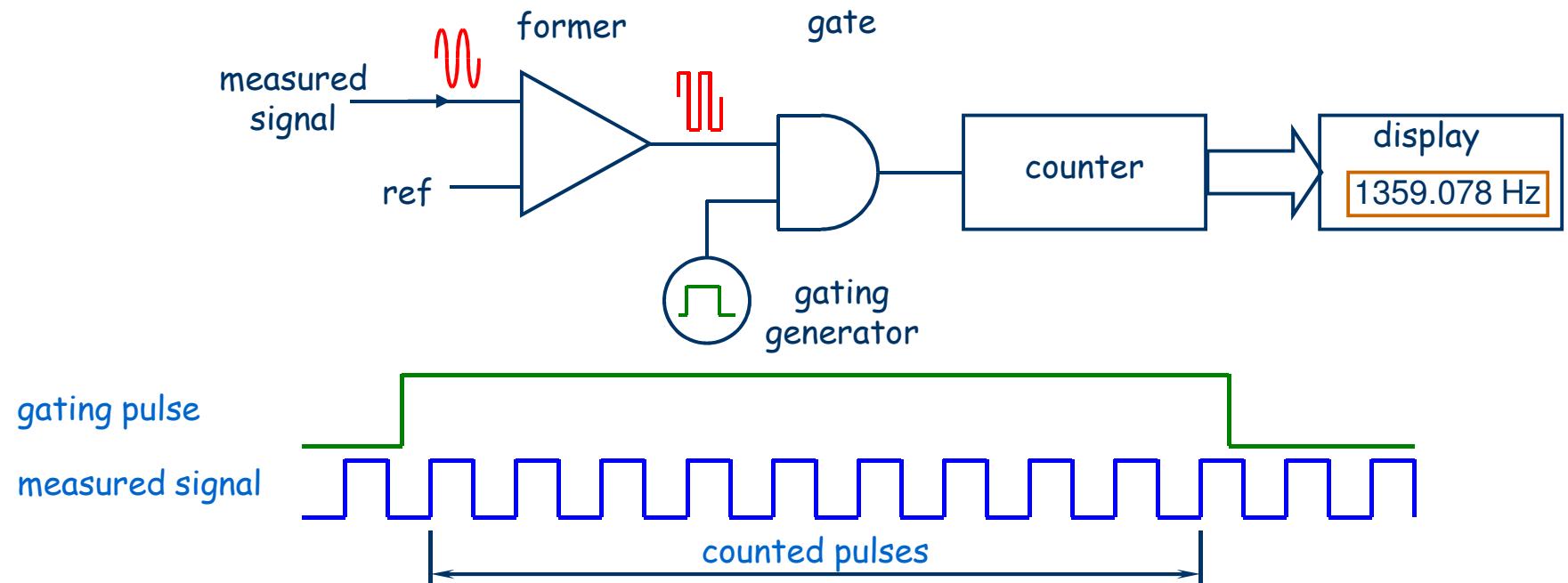
$$\frac{U_o}{U} = ??$$



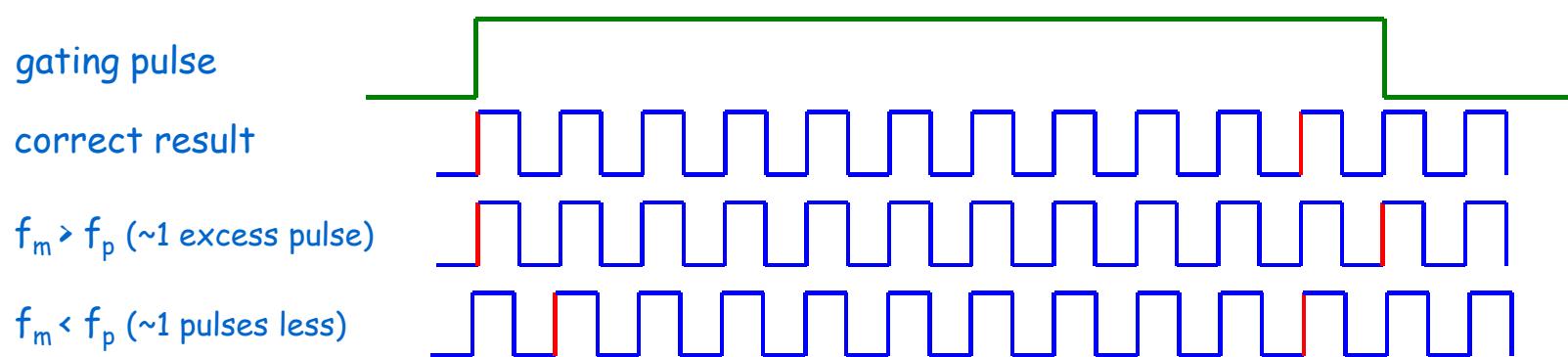
$$\frac{U_o}{U} = -\frac{\varepsilon}{2}$$

# Frequency

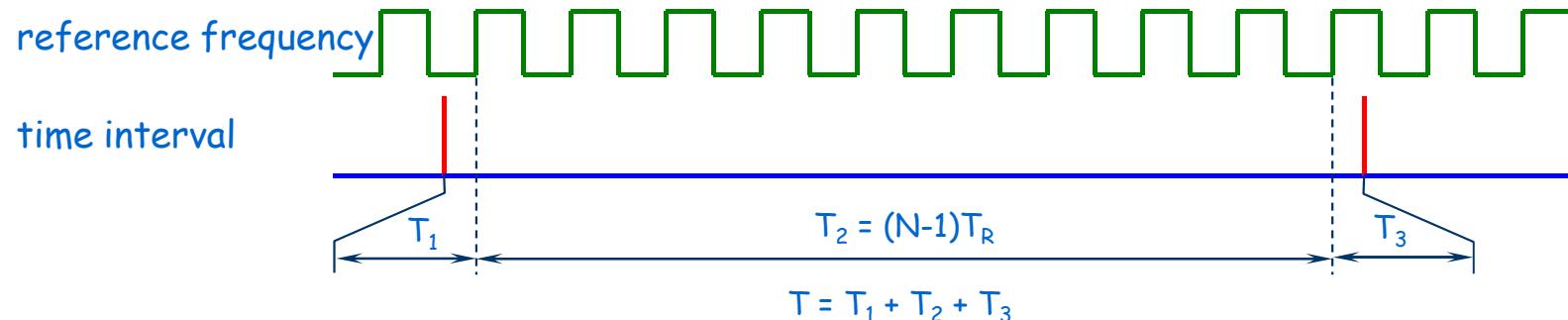
## Frequency measurement



What is a „true” frequency value?

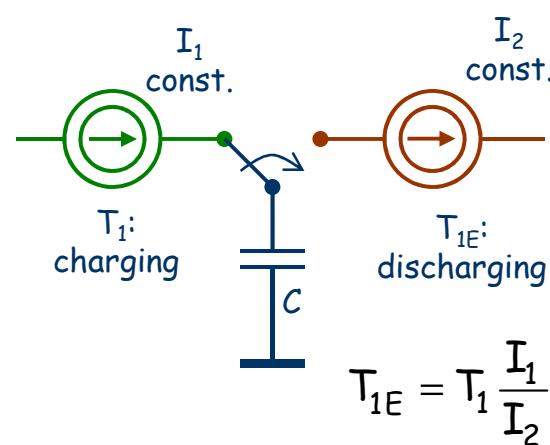


# Time interval/frequency measurement

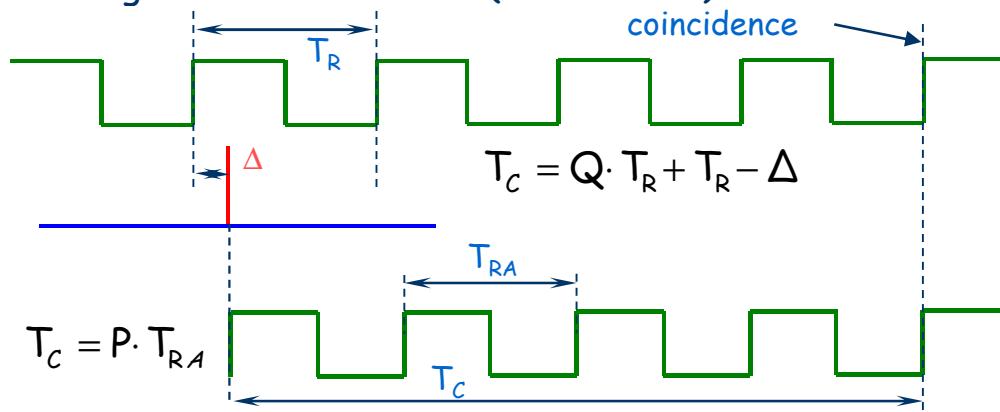


How to determine the „tails”?

„analog” method



digital vernier method (coincidence)



$$\Delta = (Q+1) \cdot T_R - P \cdot T_{RA}$$

$$T_{RA} < T_R \rightarrow P = Q + 1$$

$$\Delta = (Q+1) \cdot (T_R - T_{RA})$$

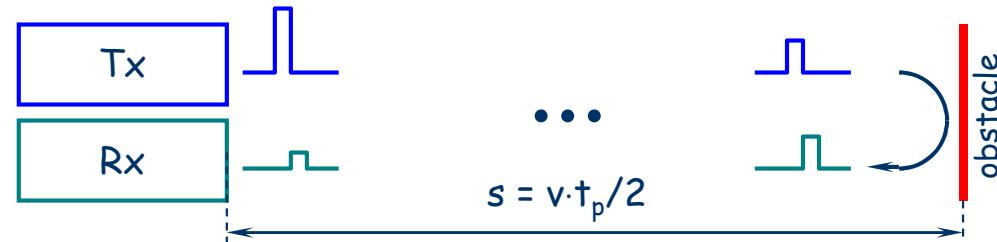
$$\Delta = T_R \cdot (Q+1) \cdot \left(1 - \frac{A}{B}\right)$$

$$\text{eg.: } A/B = 9/10$$

$$\Delta = \frac{1}{10} T_R \cdot (Q+1)$$

# Distance measurement (ranging)

## 1. Pulse „reflectometric” method



acoustic waves:

$$v \approx 300 \text{ m/s}$$

$$@ 100 \text{ kHz} \rightarrow \lambda \approx 3 \text{ mm}$$

$$T = 10 \mu\text{s}$$

resolution limit - wavelength  
...but there are other problems...

optical waves:

$$v \approx 3 \cdot 10^8 \text{ m/s}$$

$$@ \lambda \approx 700 \text{ nm} \rightarrow 430 \text{ THz}$$

$$T \approx 2.3 \text{ fs}$$

resolution limit - technical capabilities  
of time interval measurement

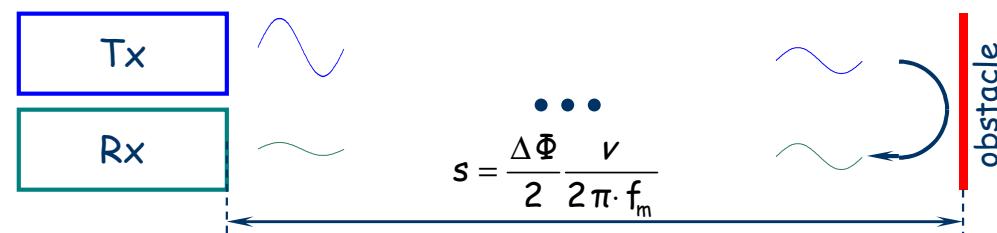
measurement resolution:

- wavelength  $\lambda$ ,

- time interval measurement:

$$\Delta s = 0.5v\Delta t_p$$

## 2. „Coherent” method → phase shift measurement of CW signal

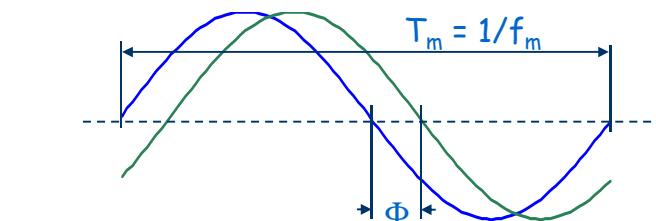


$$\Delta\Phi = 2s \cdot \beta = 2s \frac{2\pi}{\lambda_m} = 2s \cdot 2\pi \frac{f_m}{v}$$

measurement resolution - phase shift

$$v \approx 3 \cdot 10^8 \text{ m/s}$$

$$f_m = 100 \text{ MHz}$$



$$\Delta\Phi = 1^\circ \rightarrow \Delta s \approx 4 \text{ mm...}$$