2

Physical Coupling

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References

[Edler2003]
Edler et al.
Noise temperature measurements for the determination of the thermo-dynamic temperature of the melting point of palladium.
Metrologia (2003) vol. 41 (1) pp. 47-55

[Peacock97]
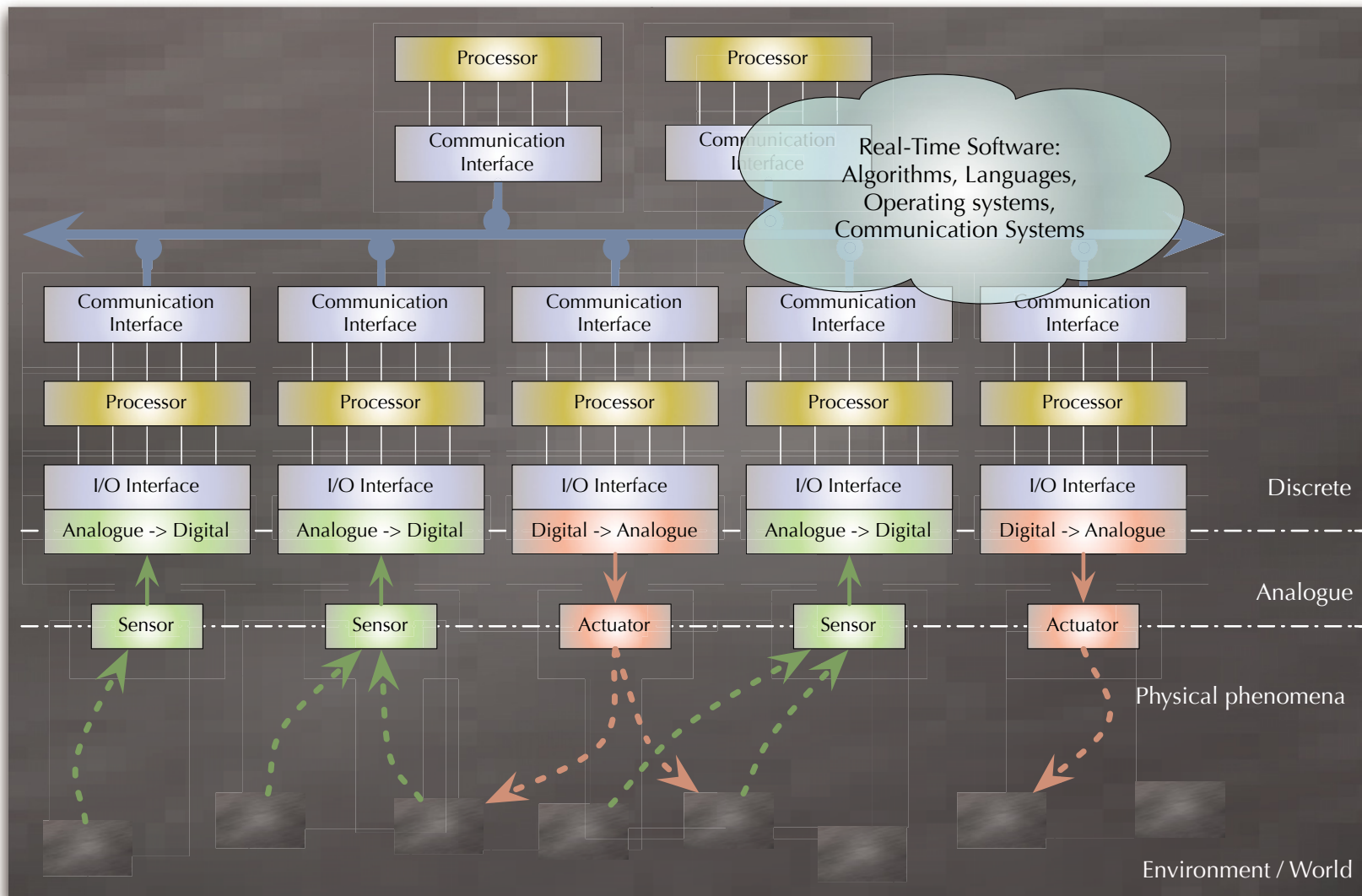G. R. Peacock
Standards for temperature sensors.
http://www.temperatures.com/resources/standards/ (1997)

(additional data-sheets)

Real-Time Systems Components: Physical coupling

Definition

First step to embed a system into the real world:

Transform physical phenomena into electrical signals

Usual intention:

*Transform **one** dominant phenomenon into **one** electrical signal*

☞ e.g. speed, pressure, brightness, loudness, colour, force, humidity, distance, salinity, density, radioactivity, spectrograms, reflectivity, acceleration, conduction, power, turbulence, deformation, …, …, …, or: temperature

Phenomena to voltage

Measuring temperature

Some observable effects of temperature changes:

- Mean square noise voltage changes
- Volume changes (gas, liquids, metals)
- Thermovoltage changes
- Changes in conductors and semiconductors
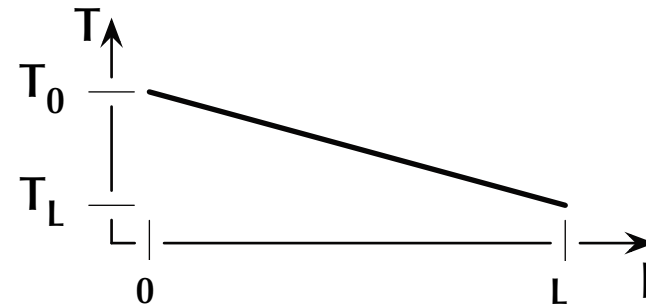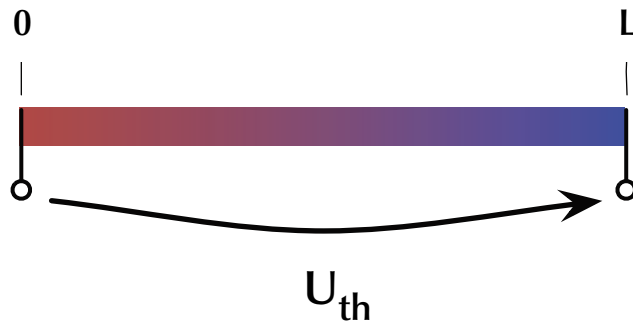- State changes: into solid, liquid, or gaseous

Measuring temperature (Thermoelements)

Seebeck Coefficient

$E_{th} = K \cdot \mathrm{grad}(T)$, with K being the **Seebeck coefficient** (material constant of conductors)

$$U_{th} = \int_0^L E_{th}\, dl = \int_0^L K \cdot \mathrm{grad}(T)\, dl = K(T_0 - T_L)$$

This phenomena stems from the characteristics of electrons to transfer electric potentials as well as to react to heat.
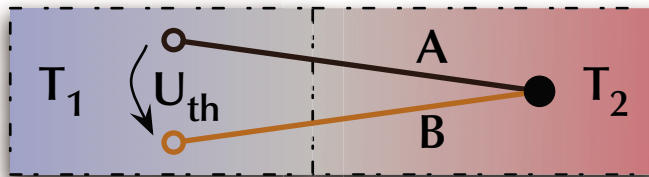
Measuring temperature (Thermoelements)

Thermocouple

- Connect two conductors *A* and *B* (of different Seebeck coefficients K_A and K_B) on one end.
- Place the connected end into the temperature zone T_2 which is to be measured.

- Measure the Voltage over the open ends in temperature zone T_1:

$$U_{th} = K_A(T_1 - T_2) + K_B(T_2 - T_1) = (K_A - K_B)(T_1 - T_2)$$

$$\text{☞} \; T_2 = T_1 - \frac{U_{th}}{(K_A - K_B)} \text{ with } T_1 \text{ known.}$$
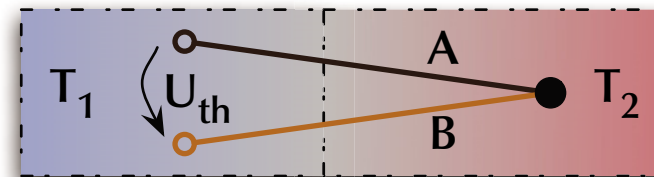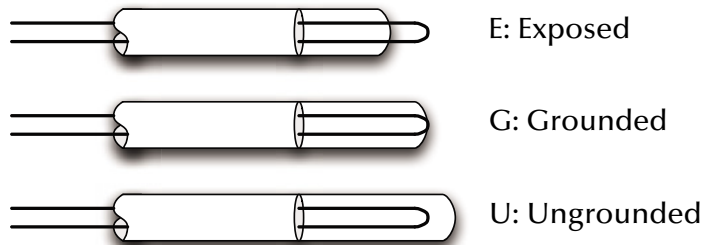
Measuring temperature (Thermoelements)

Thermocouple

Standard thermocouples come prefabricated for different applications:

E: Exposed

G: Grounded

U: Ungrounded

Short name	Material	$T_{\max}$	U_{th} with 0° to $T_{\max}$	$K_A - K_B$
(T)	Cu-Constantan	400°C	21.000 mV	42.5×10^{-6}
(J)	Fe-Constantan	700°C	39.720 mV	53.7×10^{-6}
(K)	NiCr-Ni	1000°C	41.310 mV	41.1×10^{-6}
(S)	PtRh-Pt	1300°C	13.138 mV	6.43×10^{-6}

Measuring temperature (Thermoelements)

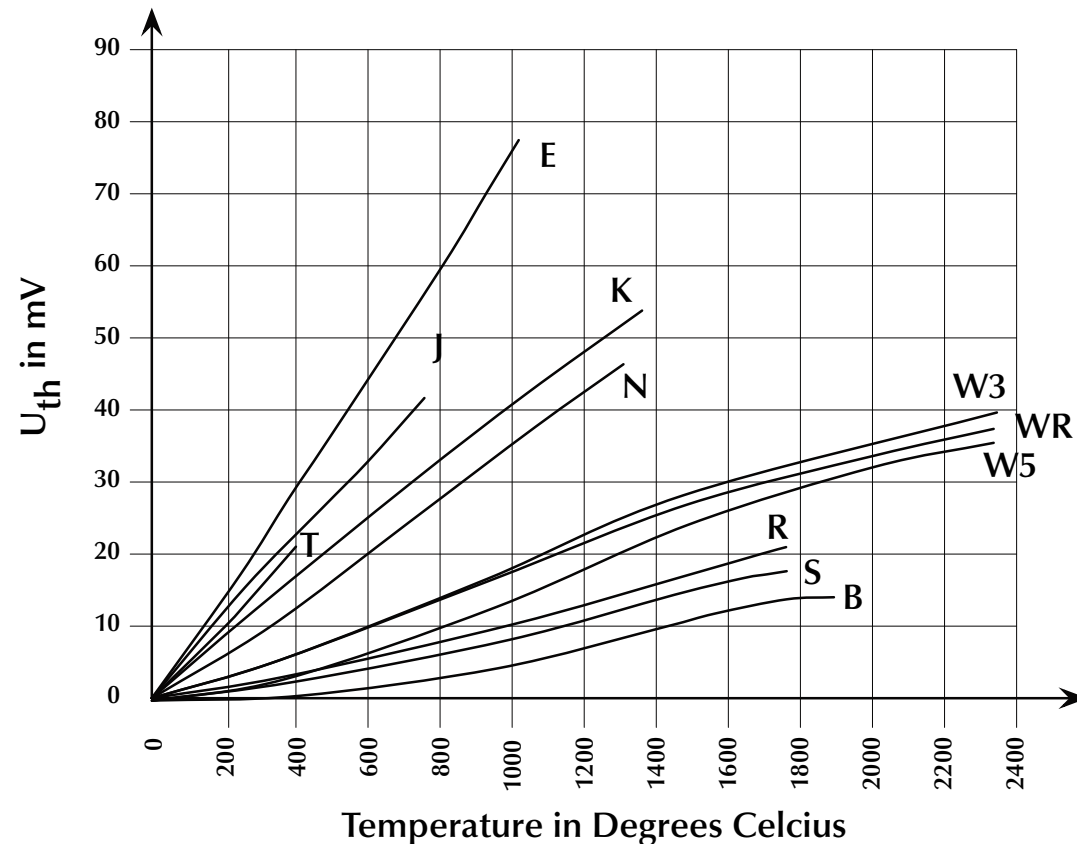# Thermocouple

Linearity of some standard thermocouples:

J-Type:

K-Type:

Measuring temperature (Thermoelements)

Applications of standard thermocouples

- **(TYPE N) Nicrosil-Nisil** thermocouples are suitable for use in oxidizing inert or dry reducing atmospheres. Must be protected from sulphurous atmospheres. Very accurate at high temperatures. Virtually the same emf (electromotive force) and range as Type K.

- **(TYPE J) Iron-Constantan** thermocouples are suitable for use in vacuum, oxidizing, reducing or inert atmospheres. Suitable for measuring temperatures up to 760°C for largest wire size.

- **(TYPE K) Chromel-Alumel** thermocouples are suitable for continuous use in oxidizing or inert atmospheres up to 1260°C for largest wire size. Because their oxidation resistance characteristics are better than those of other base metal thermocouples, they find widest use at temperatures above 538°C.

- **(TYPE E) Chromel-Constantan** thermocouples are suitable for use up to 781°C in oxidizing or inert atmospheres for largest gauge wires. Type E thermocouples develop the highest emf per degree of all commonly used thermocouples.

Measuring temperature (Thermoelements)

Applications of standard thermocouples

- **(TYPE T) Copper-Constantan** thermocouples are suitable for subzero temperatures with an upper temperature limit of 371 °C and can be used in vacuum, oxidizing, reducing or inert atmospheres.

- **(TYPE R) Platinum 13% Rhodium - Platinum** thermocouples are suitable for continuous use in oxidizing or inert atmospheres at temperatures up to 1482 °C.

- **(TYPE S) Platinum 10% Rhodium - Platinum** thermocouples are suitable for continuous use in oxidizing or inert atmospheres at temperatures up to 1482 °C.

- **(TYPE B) Platinum 30% Rhodium - Platinum 6% Rhodium** thermocouples are suitable for continuous use in oxidizing or inert atmospheres and short-term use in vacuum atmospheres at temperatures up to 1705 °C.

- **(TYPE W) Tungsten - Rhenium Alloy** thermocouples are used to measure temperatures up to 2760 °C. These thermocouples have inherently poor oxidation resistance and should be used in vacuum, hydrogen or inert atmospheres.

Measuring temperature (Thermoelements)

Thermocouple

Pro:

- Accepts high temperature.

- Small.

- Relatively cheap.

Contra:

- Requires stable amplifier.

- Temperature differences only.

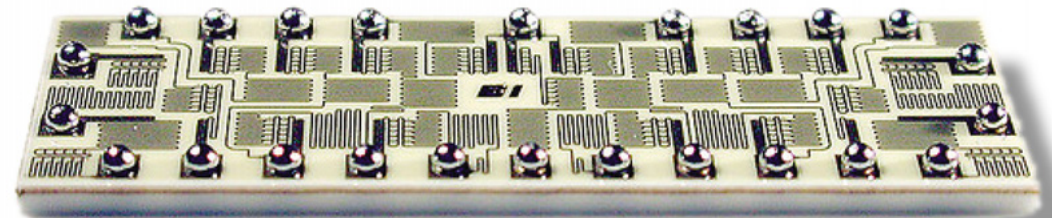- Cables between the amplifier and the sensor need to be of the same Seebeck coefficient.

Measuring temperature (Resistors)

Thermoresistors

Thin film resistor arrays

PT_{100} casings

PT_{100} resistors are commonly manufactured as (thin film) Platinum wire on / around glass / ceramic tubes / plates.
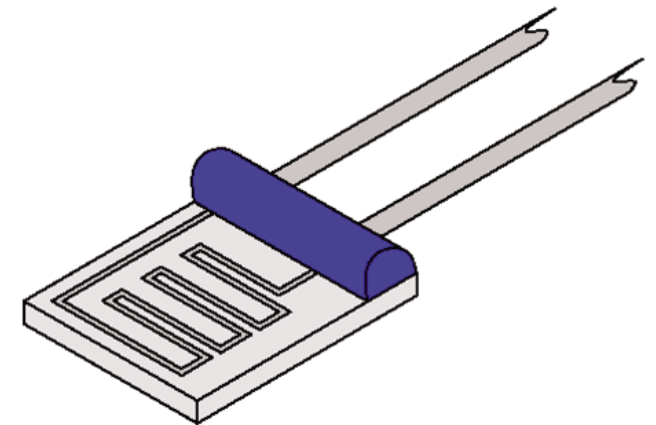
Measuring temperature (Resistors)

Thermoresistors

General case: $R_T = R_0[1 + A(T - T_0) + B(T - T_0)^2 + C(T - T_0)^3 + ...]$

Platinum: $A \approx 3.27 \times 10^{-3} \, \frac{1}{K}$ (at $550°C$) ... $4.2 \times 10^{-3} \, \frac{1}{K}$ (at $-150°C$)

PT_{100}

- *Calibrated value*: $0° \Rightarrow R_T = 100\Omega \pm 0.1\Omega; 0.1\Omega \Rightarrow \pm 0.26 \, K$

- *Range*: $-200°C... + 650°C$

- *Response time*: $\approx 0.1s$ in flowing water
  ... multiple seconds in still air.

Measuring temperature (Resistors)

Thermoresistors: Heating & Measuring

Assume the PT_{100} to be potted in a TO18 enclosure:

Thermal resistance: $R_{th} = \dfrac{T_{PT_{100}} - T_E}{P_V} = 480°C \Big/ W$

Assume we want to limit the sensing error to $\pm 0.5°C$ around $0°C$ ($R_T = 100\Omega$):

$R_{th} = \dfrac{T_{PT_{100}} - T_E}{P_V} \Rightarrow P_V = \dfrac{\triangle T}{R_{th}} = \dfrac{U^2}{R} \Rightarrow U = \sqrt{\dfrac{\triangle T \cdot R}{R_{th}}}$

$\Rightarrow U_{\max} = \sqrt{\dfrac{\triangle T \cdot R_T}{R_{th}}} \approx 0.323 V$

Thus in order to prevent heating the sensor element by more than 0.5°C we need to keep the operating voltage under 0.323V.
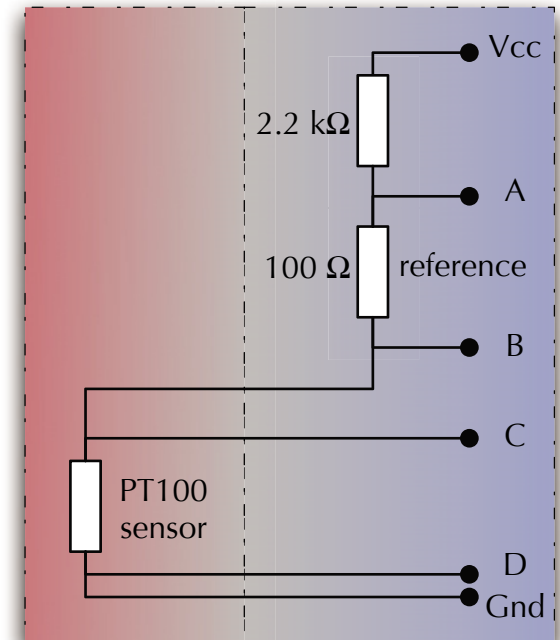
Measuring temperature (Resistors)

Thermoresistors: Connections

Separating currents from signals ☞ Four wire setup:

Further measures:

- Adding a reference resistor.

- Limit the cable length.

- Keeping all cables on the same temperatures.

- Limit the current.

- Model the non-linearity on the sensor itself.

Measuring temperature (Thermoelements)

Thermoresistors

Pro:

- Potentially higher accuracy.
- Less non-linearities.
- Long term stability.
- Absolute temperature.

Contra:

- Limited temperature range $(-200°C ... +650°C)$.
- Slower reaction time.
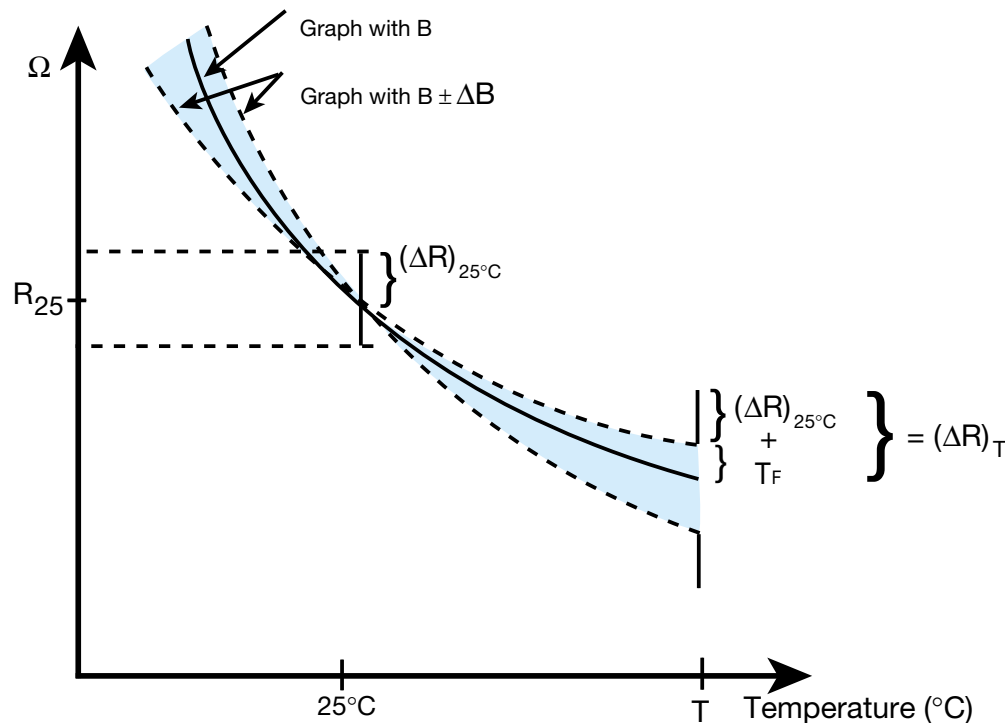- More expensive.
- Less robust.
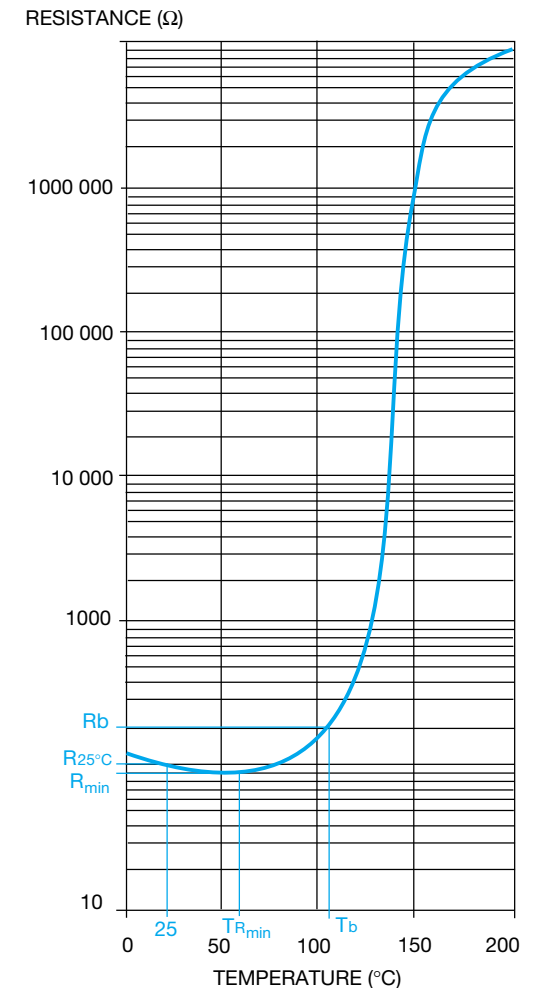- Usually bigger.

Measuring temperature (Thermistors)

Temperature Sensitive Semi-conductors

NTC:

$$R_{NTC} \approx A \cdot e^{\frac{B}{T}}$$

PTC:

Source: AVX

Measuring temperature (Thermistors)

Temperature Sensitive Semi-conductors

Pro:

- Cheap.
- Can be accurate if combine with compensation for non-linearities.
- Large effects with temperatures (easy instrumentation).
- Long term stability (some models).

Contra:

- Further limited temperature range (-40°C… $+350^\circ$C).
- "Strongly" non-linear.
- Comparatively large.
- Generally instable and inaccurate.

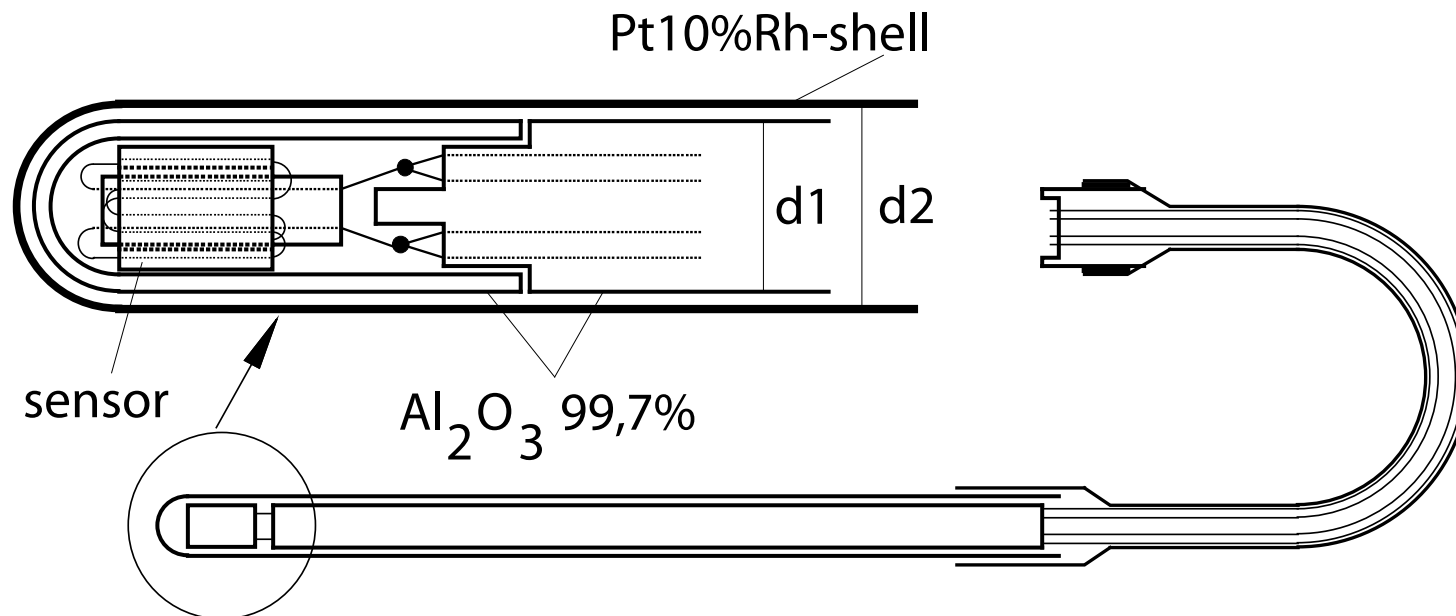**Measuring temperature (Noise Voltage)**

Noise temperature measurement

Based in Nyquist formula: $\overline{U^2} = 4kTR\triangle f$

Pt10%Rh-shell

d1 d2

sensor

Al_2O_3 99,7%

(source: Physikalisch-Technische Bundesanstalt, Berlin)

with k: Boltzmann constant, T: thermodynamic temperature,
R: electric resistance, and $\triangle f$: the measurement bandwidth.

Measuring temperature (Noise Voltage)

Noise temperature measurement

Pro:

- Linear.

- Highly accurate.

- Long term stability.

- Wide temperature range:
  1...2500°K,
  at $\pm 0.1\%$ accuracy
  over the full range.

Contra:

- Expensive.

- Large.

- Sophisticated amplification
  required (small effect).

Phenomena to voltage

Further methods of measuring temperature ...

- Spreading resistors.

- Piezos and other temperature sensitive crystals.

- Temperature controlled current sources (e.g. AD590).

- Watch Mercury filled thermometers with cameras.

- Sense blackbody radiation
  (e.g. infrared-, or more generally: thermal radiation-thermometers)

- ...

Phenomena to voltage

First conclusions

… we only scratched the surface of conversion methods for *one* physical value (temperature).

☞ Converting physical phenomena into analogue voltages seems to be a complex matter.

… in fact a whole industry is dedicated to this field exclusively.

☞ Always ask for the full sensor specifications (and read them).

☞ Never assume that the voltage output is a linear translation of a single physical value.

Physical coupling is not the only loss afflicted stage of conversion,
yet it is often the most complex one.

Phenomena to voltage

Range and relative speed measurements
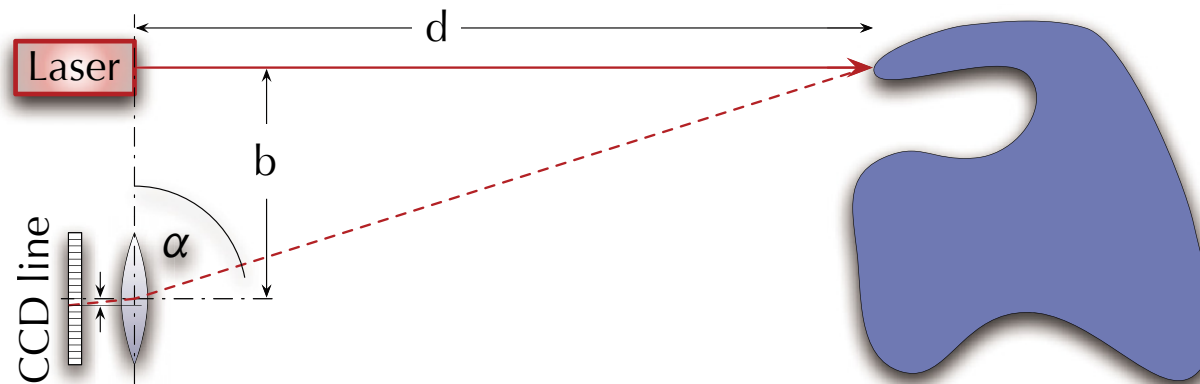
Some commonly employed principles:

- Triangulation (optical)

- Time of flight (optical, acoustical, electro-magnetic)

- Phase correlation (optical, acoustical, electro-magnetic)

- Intensity (optical, acoustical)

- Doppler methods (acoustical, electro-magnetic)

- Interferometry (optical, electro-magnetic)

Phenomena to voltage

Range measurements by triangulation

$d = b \cdot \tan \alpha$ ☞ non-linear and poor accuracy for $d \gg b$
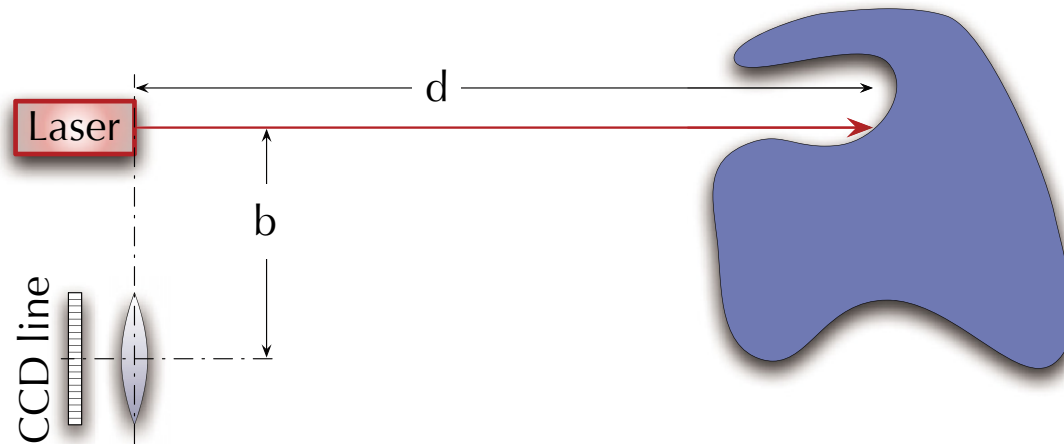
- Laser required.
- otherwise simple setup with slow components, often used for liquid level measurements.
- Measures along the optical axis only ☞ problematic for safety applications.

Phenomena to voltage

Range measurements by triangulation

$d = b \cdot \tan\alpha$ ☞ non-linear and poor accuracy for $d \gg b$

☞ Occlusion omits readings ☞ not suited for randomly curved surfaces

Phenomena to voltage

Range measurements by time of flight / phase

Method: measure the time of flight between the outgoing signal and the received, reflected signal.

☞ In case of light, this method requires high resolution timers (> 1 GHz).

- Method is linear.
- The achieved resolution depends on the precision of the signal's rising edge and the resolution of employed timers.
- Signals can be formed and volume measurements are possible.

☞ In order to increase the resolution, the outgoing signals are often modulated and the phase shifts between outgoing and reflected signals are detected.

Phenomena to voltage

Range and relative speed measurements

2-d Scanning Laser Range Finders

Hokuyo UTM-30:

- 905 nm semiconductor laser.

- Nominal range:
  0.1 … 30 m outdoors.

- Maximum range: 60 m

- Accuracy: 10…50 mm depending range and background light.
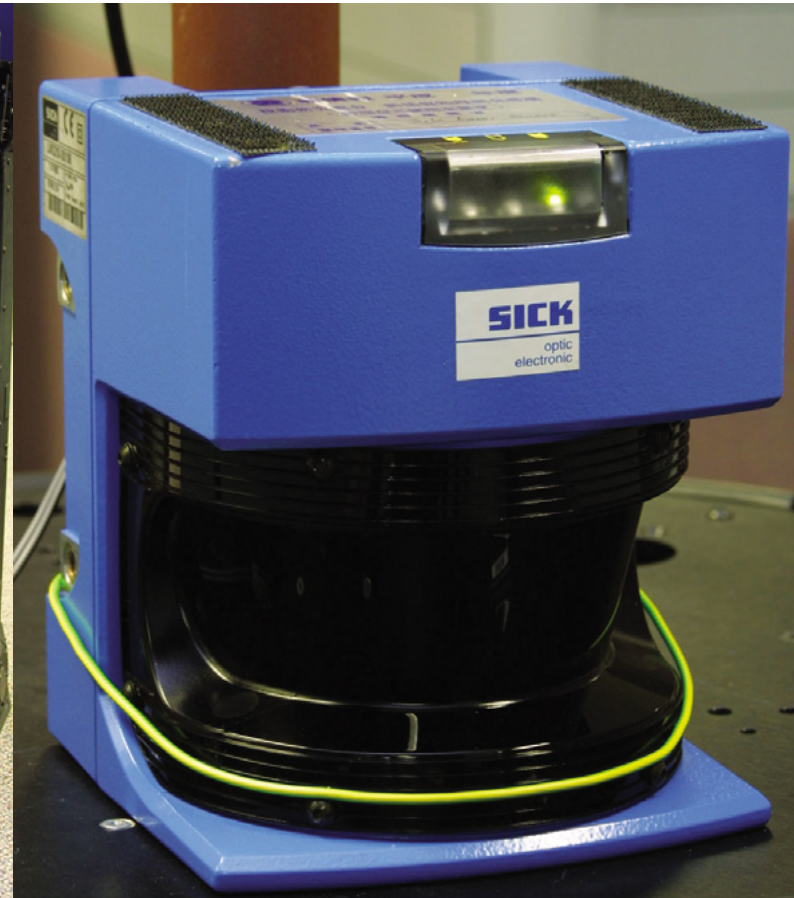
- Coverage: 270°.

- Weight: 210 g.

Phenomena to voltage

Range and relative speed measurements

2-d Scanning Laser Range Finders

SICK (indoor):

- 905 nm semiconductor laser.

- Maximum range: 80 m.

- Accuracy: 5-10 mm (typical).

- Coverage: 180°, 0.25° resolution.

- Response time: 53 ms.

- Weight: 4.5 kg.

- MTBF: 80,000 h

Phenomena to voltage

Range and relative speed measurements

2-d Scanning Laser Range Finders

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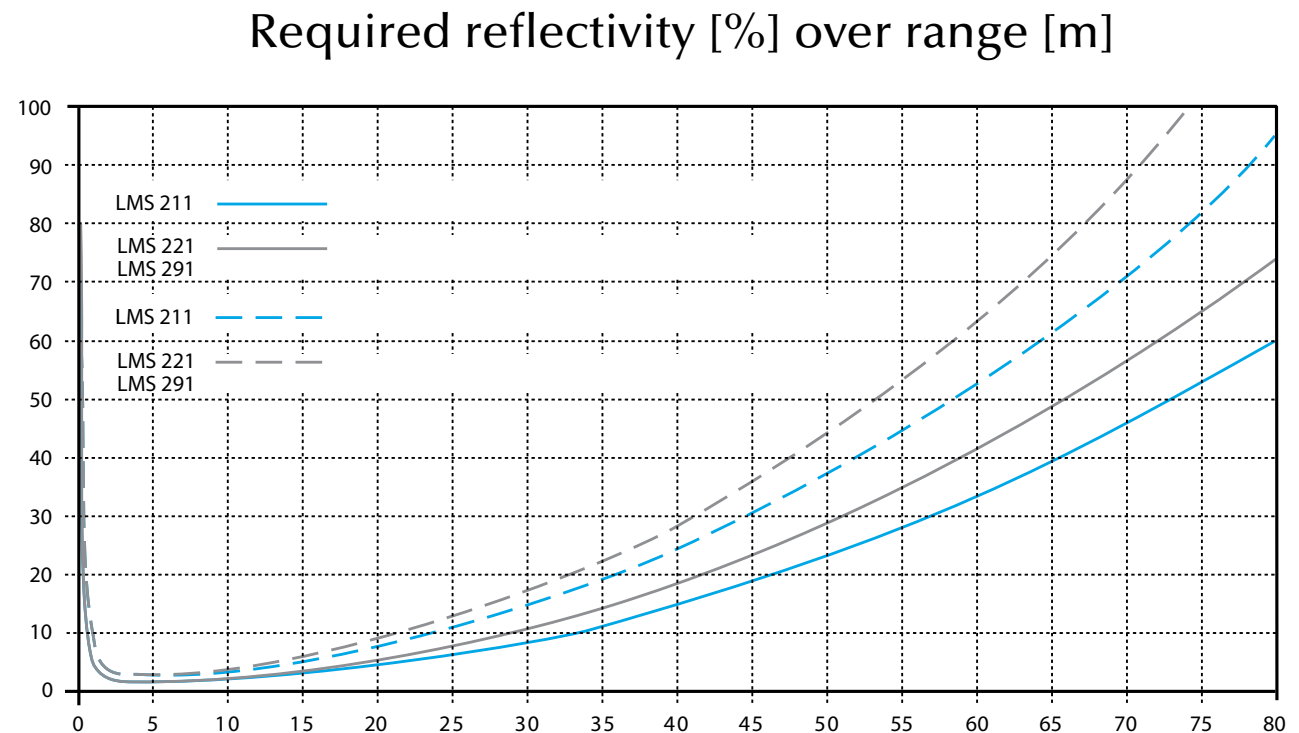- Response time: 53 ms.

- Weight: 4.5 kg.

- MTBF: 80,000 h

Required reflectivity [%] over range [m]

LMS 211
LMS 221
LMS 291
LMS 211
LMS 221
LMS 291

(source: SICK AG, Germany)

Black leather: ≈ 2% reflectivity

Phenomena to voltage

Range and relative speed measurements

Ultrasound time-of-flight & Infrared reflected-intensity

Classical "low end" sensors:

- US signal is transmitted and received on the same membrane.

- ☞ Minimal range limitations.

- ☞ Specular reflections lead to potential overestimation.

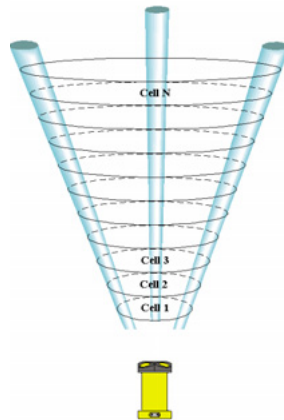- IR intensity readings depend on object material.

Phenomena to voltage

Speed measurements: Doppler current profilers

Doppler shift frequency: $f_d = -2 f_s \dfrac{v}{c}$

with source frequency f_s, relative velocity v and signal speed c.

- Signal: 250 kHz - 3 MHz

- Range: 160 m,
  Accuracy: $\pm 1\%$

- Velocity range: $\pm 10 \,{}^{m}\!/_{s}$

- Blanking zone: 0.2-2.0 m

Summary

Physical coupling

- **Physical phenomena**

- **Measuring temperature**
  - Thermoelements, thermocouples, Thermoresistors, Thermistors, Noise temperature measurement) and many others …

- **Measuring range and relative speed**
  - Triangulation, Time of flight, Intensity, Doppler methods, Interferometry

- Examples: **Common acoustical and optical sensors**