Aalto University
School of Electrical Engineering

# Temperature and humidity

*ELEC-E5710 Sensors and Measurement Methods*

# Why to measure temperature?

- One of the most important areas of measurement
- Most phenomena depend on the temperature
- Largest group of non-electric measurement devices in industrial sector and in research
- Temperature sensors are used to measure for example
  - Flow
  - Radiation
  - Pressure

# Effect of temperature

- Affects many phenomena → several ways to measure
- Mechanical
  - Thermal expansion: pillar of liquid, bimetal
  - Oscillating crystal
- Electrical
  - Resistor: RTD, thermistor
  - Voltage: thermocouple
- Semiconductor
  - Band-gap: threshold voltage of a pn-junction
- Radiation
  - Planck’s law: pyrometers

# Heat transfer mechanisms

- Conduction
  - Heat transfers inside the material through collisions between neighboring molecules (in all phases of matter)
  - Thermal conductivity [W/(K·m)]
- Convection
  - Heat transfers by collective movement of molecules in a fluid (in liquids, gases, plasmas)
  - Free convection (differences in density)
  - Forced convection
- Radiation
  - Depends on temperature and emissivity
  - Significant only with high temperatures

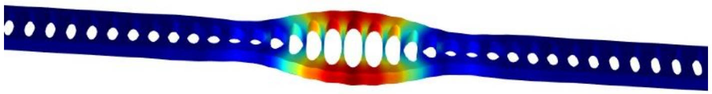
# Temperature scales

- Fahrenheit (in 1724)
  - Cool brine: sodium chloride + water (0 °F, −17.8 °C)
  - °C ≈ (°F-30)/2
- Celsius (in 1742)
  - Water freezing point (0 °C), boiling point (100 °C)
- Kelvin (in 1848)
  - Became SI quantity in 1954
  - ~~Absolute thermodynamic scale, the triple point of water (273.16 K = 0.01 °C, 611.73 Pa = 0.006 bar)~~
  - Boltzmann constant *k* equals 1.380649 $kg \cdot m^2 \cdot s^{-2} \cdot K^{-1}$

$$^\circ C = \frac{5}{9}(^\circ F - 32) \qquad ^\circ F = \frac{9}{5}{}^\circ C + 32 \qquad K = {}^\circ C + 273.15$$

# 2019 redefinition of SI base units

- Fixing the triple point of water contains uncertainties
  - VSMOW (Vienna Standard Mean Ocean Water)
- 20. May 2019, Kelvin will be redefined by setting exact numerical values for the Boltzmann constant 1.380649 $kg{\cdot}m^2{\cdot}s^{-2}{\cdot}K^{-1}$
- Realization based on e.g. Johnson noise thermometry, photonic thermometry, quantum thermometer
- Practical realization will remain using triple point of water [NIST]



# Requirements for a temperature sensor

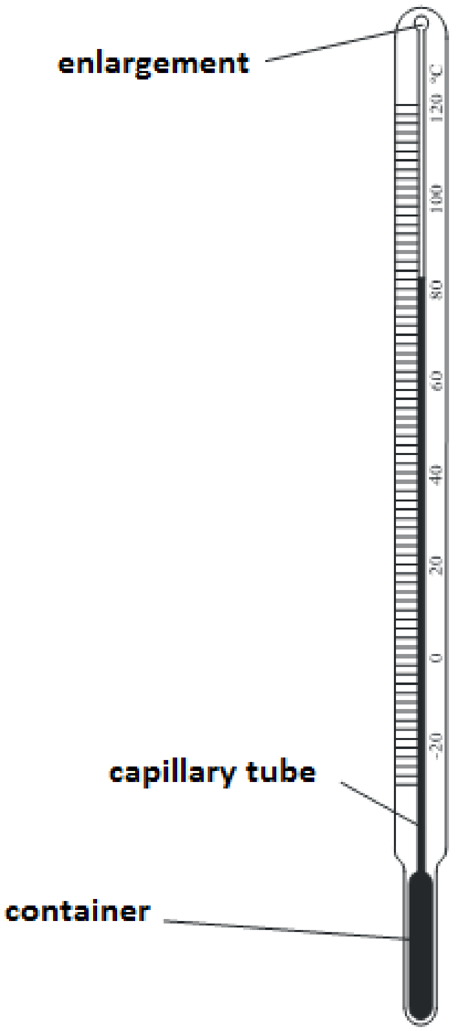
- Low specific heat, little mass and high thermal conductivity are required for a sensor element
- Low thermal conductivity and resistance for the contact between the sensor and measuring electronics
- Glue with good thermal conductivity or silicon paste and press can be used to attach the sensor to a surface
- Temperature gradient between the sensor and the surface can be reduced by placing the sensor to a hole or a channel filled with silicon paste

# Mechanical instrument

- Liquid filled thermometer
- Capillary thermometer
- Bimetal thermometer

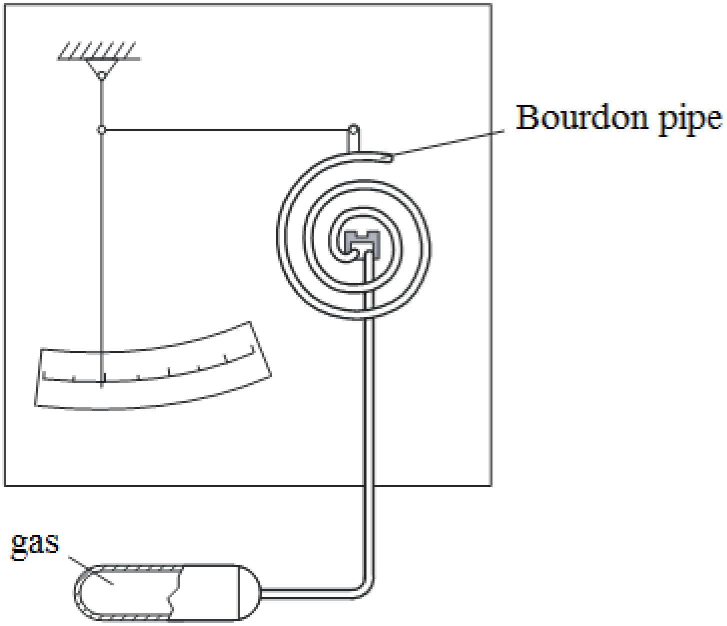
# Liquid-filled thermometer

- The oldest type
- Operating temperature
  - Mercury: -39 – +357 °C
  - Pressurized mercury: -39 – +750 °C
  - Alcohol: -114 – +78 °C
  - Pentane: -200 – 0 °C
    (C5H12, industrial solvent)
- Uncertainty of completely sinkable thermometer < 0.02°C
- Response time ~ 0.1 s – 1 min



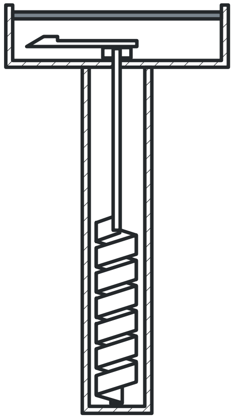
# Capillary thermometer

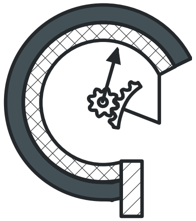
- A sensor container with a capillary connected to Bourdon tube
  - Container filled with liquid, gas, or vapor
- Changing pressure moves the pointer on the gauge
- Measurement range: ~ -200 – 750 °C
- Uncertainty > 1%
- Response time of ~ 0.1 s – 1 min



# Bimetal thermometer

- Two thin metal strips with different temperature coefficients rolled together
  - Bent to a helix or a spiral
- Used in rough measurements due to low-cost
- Temperature range: -70 – +500 °C
- Longer response time compared to liquid filled thermometers due to larger mass
- Used e.g. in sauna





# Electrical thermometers

- Resistance temperature detector (RTD)
- Thermistor – ceramic or polymer
- Thermocouple
- Semiconductor thermometer

# Resistance temperature detector (RTD)

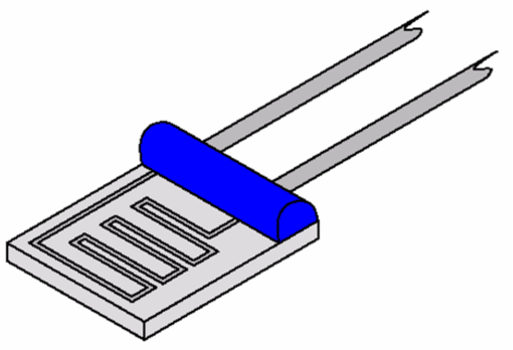
- Resistance of a metal is dependent on temperature

$$R(T) = R_0(1 + \alpha T + \beta T^2 + \ldots)$$

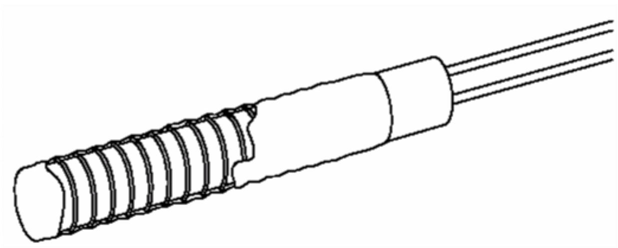
  - $\beta \ll \alpha$, can be approximated on the first degree
- Close to linear, $\beta$ may be 3-4 orders of magnitude smaller than $\alpha$

- The most stable temperature sensor
- Temperature range: -250 °C – +950 °C
- Specific resistance: ~ 10 – 1000 Ω
- The most common type is platinum based Pt-100

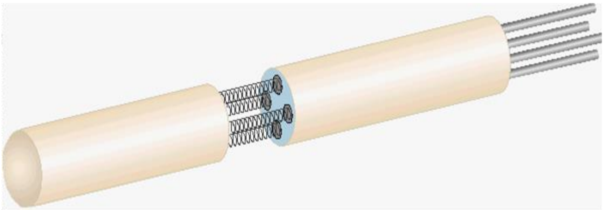
# RTD structures



- Film resistor
  - Thin → short response time
  - Inexpensive
  - Not very accurate (thermal expansion)



- Wire-wound resistor
  - Better accuracy
  - Wider temperature range
  - Compromise between accuracy and stability



- Resistor based on coil elements
  - The most accurate version
  - Expansion does not cause tension
- Platinum resistance thermometers as primary standard in ITS-90

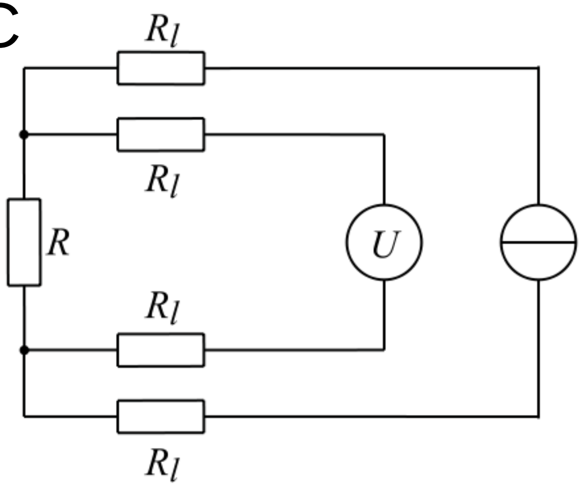
# Pt-100 sensor

- Specific resistance
  $R_0$ = 100 Ω (at 0 °C)
  – $\alpha = 3.9083 \cdot 10^{-3}$
  – $\beta = -5.775 \cdot 10^{-7}$
- 138.5 Ω at 100 °C
- Stable

- Measurement range: -259 – +962 °C
- Standard platinum sensor sensitivity:
  – 0.385 Ω/°C (European standard)
  – 0.392 Ω/°C (American standard uses more pure Pt)

# Measuring with Pt-100

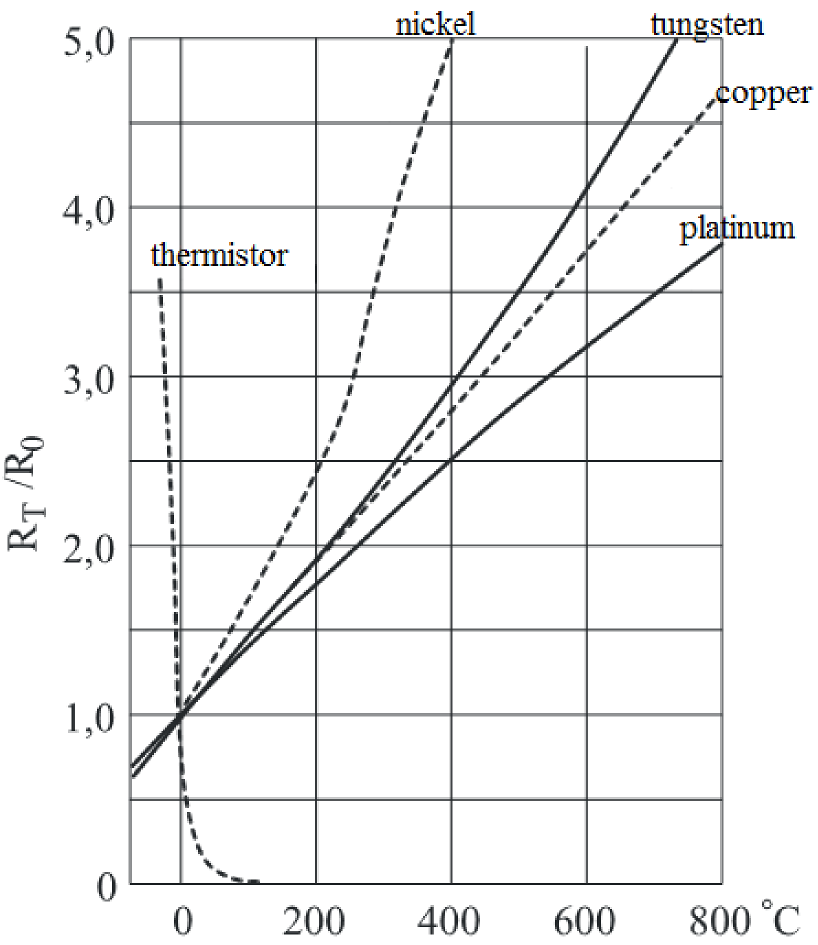
- Low resistance and sensitivity → four-point measurement often necessary
  - E.g. 1 ohm conductor wire/junction resistance is 1% of nominal value
  - E.g. 1 mA measuring current at 0 °C creates only 100 mV signal
- Error of 0.1 mV or 1 µA in signal to be measured would cause the temperature error of 0.4 °C
- Self heating
  - Measuring current of 1 mA produces 100 µW of heat
  - Low thermal resistance is important!



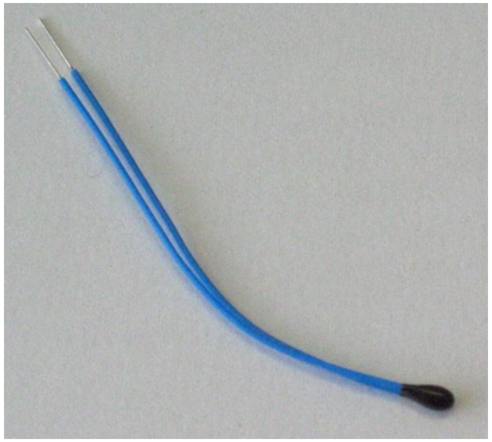
# RTD properties

- Temperature dependencies of resistance thermometers
- NTC thermistor plotted for comparison

- Copper is the most linear, but oxidizes intensively
- Platinum is the most stable



# Thermistor



- Usually ceramics (metal oxides) or polymers
- Based on temperature dependency of resistance
- NTC – negative factor, PTC – positive factor
- High sensitivity (2 – 8 %/°C)
- Non-linear:

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

- High specific resistance → error caused by the wires is small
- Faster and more sensitive than RTD and thermocouples

# NTC thermistor

- More accurate than PTC
- Size and material resistivity determines the resistance

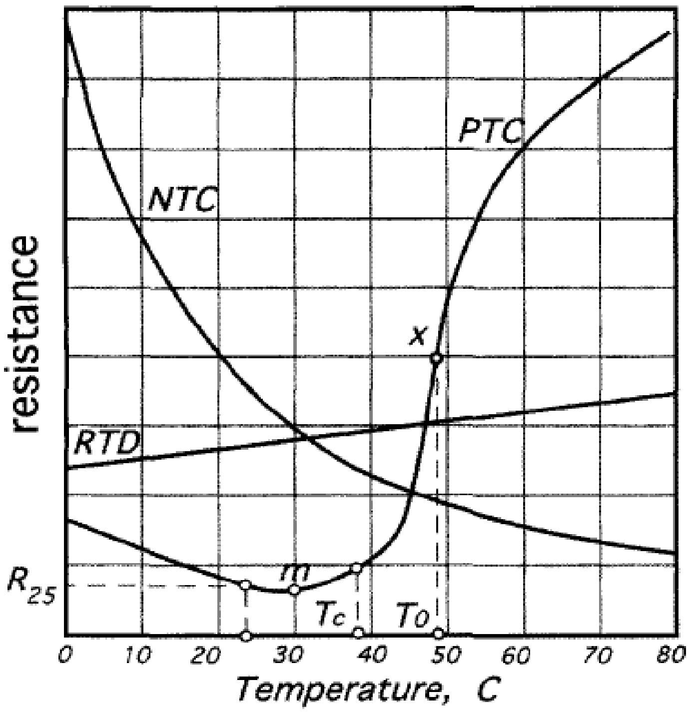
- Tolerance for mass produced thermistors is often ±20%

- General specifications provided by manufacturer are often not accurate enough

- User can calibrate (several calibration points needed)

# PTC thermistor

- Response might be challenging to model
  - The temperature ranges can be modeled separately
- Often used as an overload protector (Polymeric Positive Temperature Coefficient, PPTC, polyfuse)
  - Self heating causes the resistance to increase



# Measurement equation of a thermistor

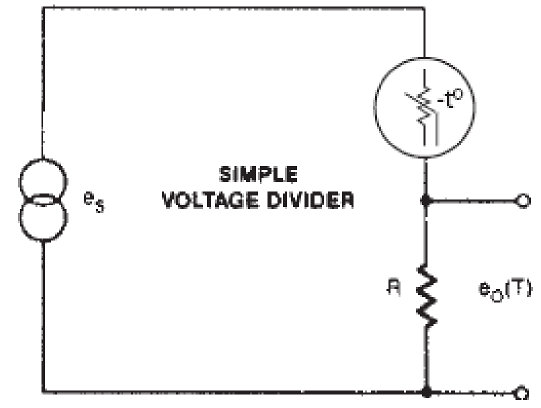
- The logarithm of thermistor's resistance depends on the following polynomial: $\ln(R) = A_0 + \frac{A_1}{T} + \frac{A_2}{T^2} + \frac{A_3}{T^3}$
- Approximation $\ln(R) \approx A + \frac{\beta}{T}$
  - $A$ is a constant and $\beta$ is a material dependent factor

$$\begin{cases} \ln(R_0) - \beta/T_0 = A \\ \ln(R) - \beta/T = A \end{cases} \Rightarrow \quad R = R_0 e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

- $\beta$ can be determined with two-point calibration

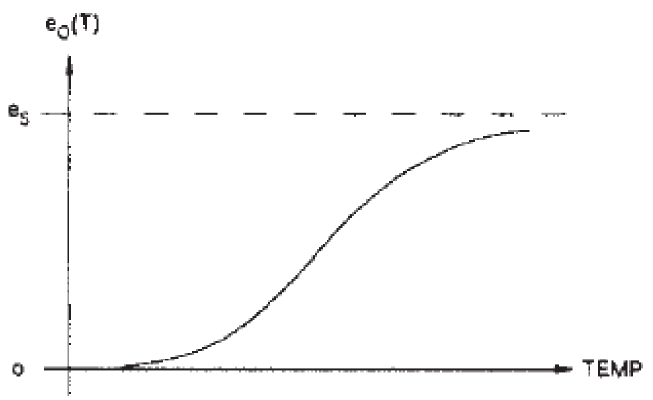
# Linearization of a thermistor

- Voltage dividing: Measuring voltage $e_o(T)$ increases as the temperature increases



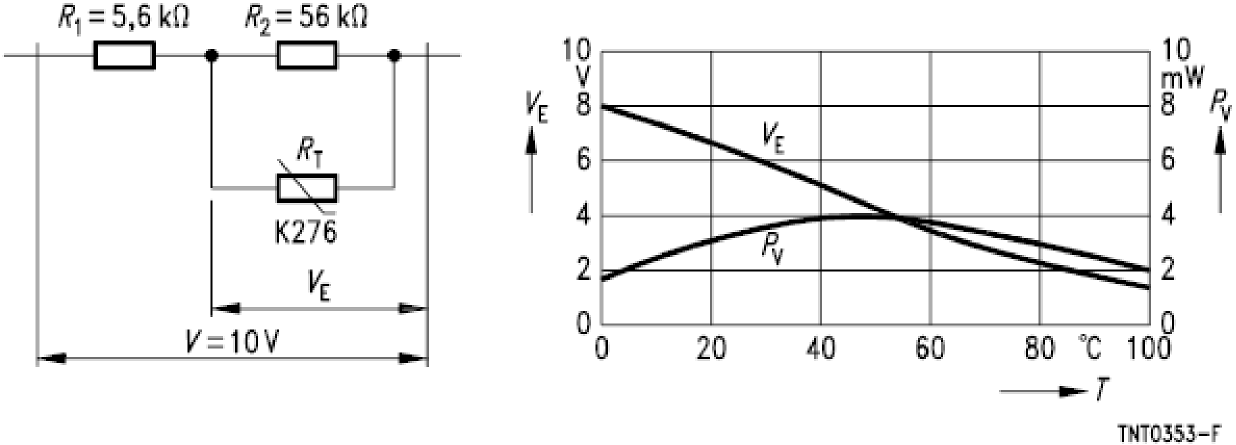

- Not completely linear

$$e_o(T) = \frac{R}{R + R_T} e_s$$



# Linearization of a thermistor

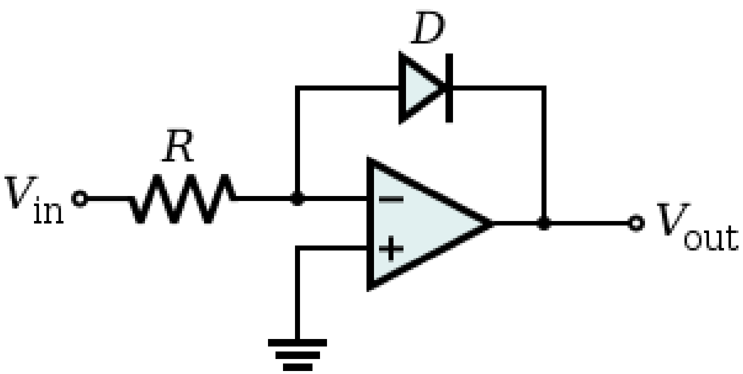
- Voltage divider with parallel resistance




- S-shaped transfer function has a bending point (a local maximum of a derivative)
  - By choosing suitable $R_1$ and $R_2$, this point is in the middle of the area
  - Better average linearity

# Linearization of a thermistor

- Logarithmic amplifier




$$V_{out} = -V_T ln\left(\frac{V_{in}}{I_S R}\right)$$

where $V_T$ is the thermal voltage and $I_S$ the saturation current

- Not perfect since the thermal voltage and saturation current of a diode are temperature dependent

# Self heating

- Resistance *R* of the sensor is measured with a small measurement current *I*
- Current heats the sensor with power $P = RI^2$
- Temperature of the sensor increases if it is not able to transfer the generated heat to surroundings efficiently

$$\Delta T = rP = rRI^2 ,$$

where *r* is the thermal resistance between the sensor and the surroundings

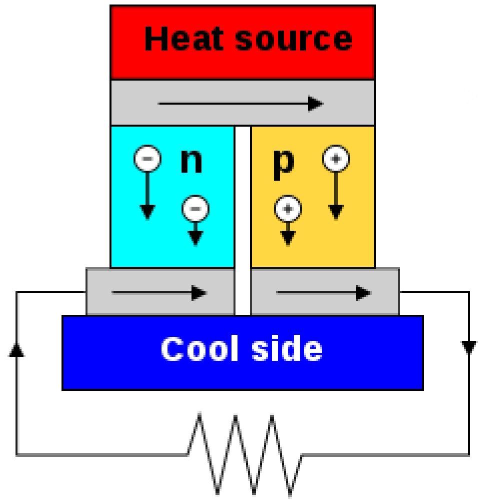
- $\Delta T$ is minimized by
  - Decreasing *r* (by better connection)
  - Choosing low resistance sensors (measurement current is constant)
  - Using pulsed current

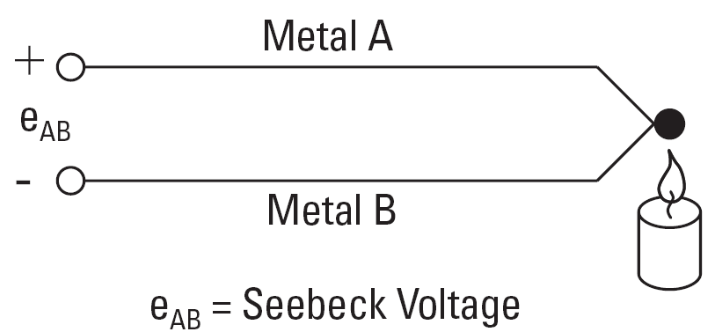
# The limitations of resistance thermometers

- Wire resistance and its temperature dependence
  - Junction resistance and its variation
- The thermal noise
- Resistance changes by time and by changing environment
- Self heating by the measurement current
  - Thermistors: nonlinearity
  - RTDs: large size, slow
- Highest temperature 660 °C

# Thermocouple

- Seebeck effect
  - Two different conducting material wires form a closed circuit. Current flows in the circuit as long as the junctions are in different temperature
  - The current is created by the thermo voltage
  - Sensitivity: 10–70 µV/°C

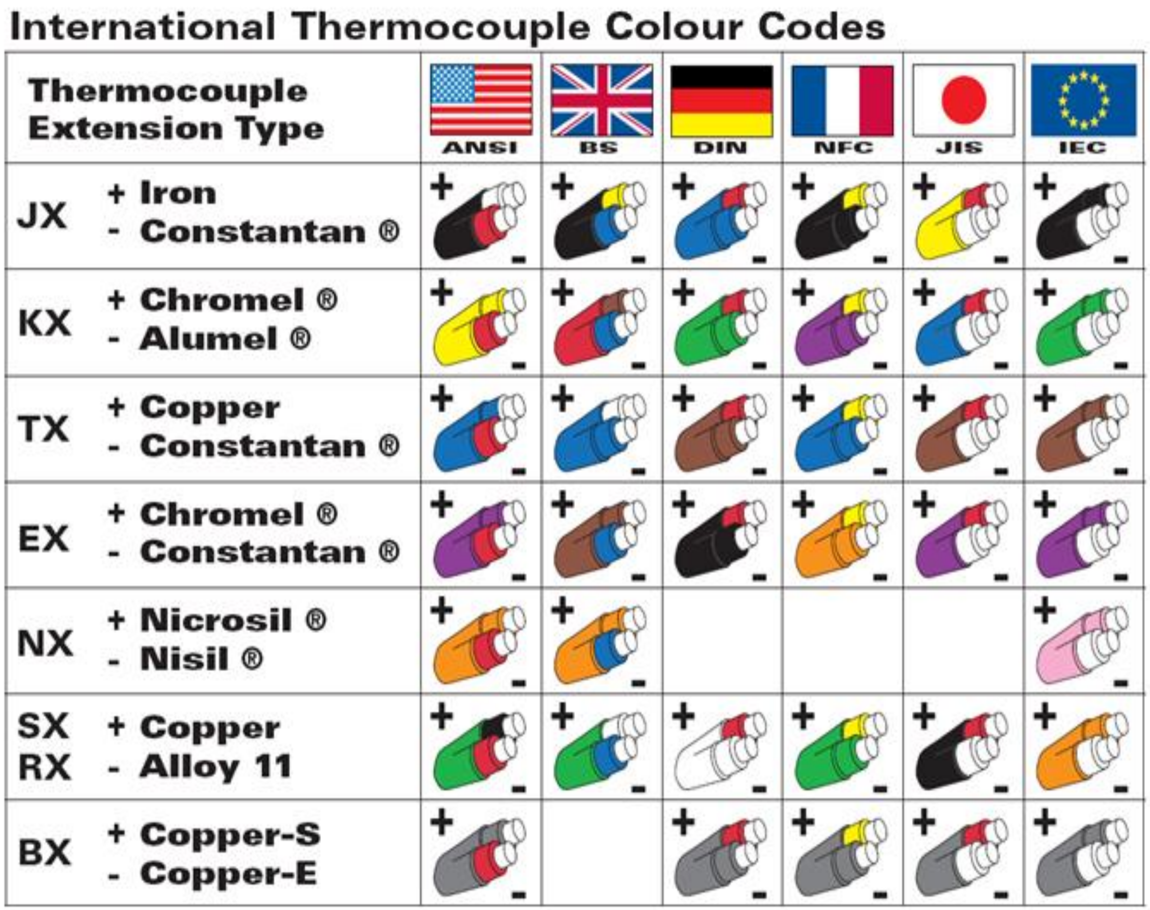


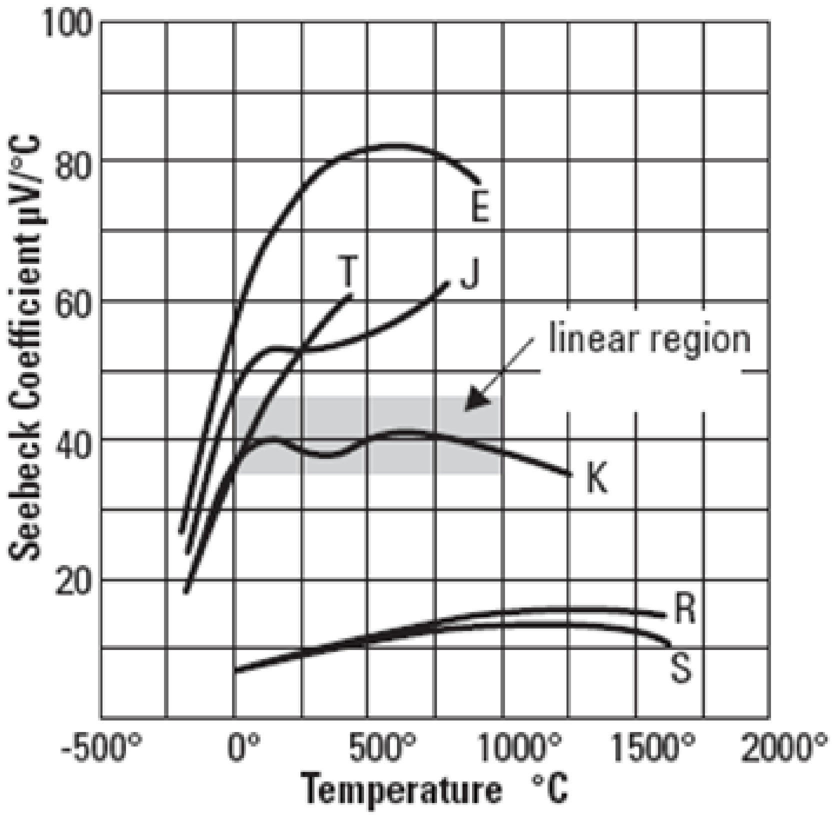
# Thermocouples

| Type | Positive element | Negative element | Temperature range / °C | Notes |
|---|---|---|---|---|
| E | Chromel | Constantan | -240 – +800 | For low temperatures, high sensitivity |
| J | Fe | Constantan | 0 – +800 | Used commonly in old devices (inexpensive, high sensitivity) |
| K | Chromel (90% Ni, 10% Cr) | Alumel (95% Ni, 2% Mg, 2% Al, 1% Si) | -200 – +1200 | The most common, inexpensive |
| N | Nicrosil (84.1 % Ni, 14.4% Cr, 1.4% Si, 0.1% Mg) | Nisil (95.5% Ni, 4.4% Si, 0.1% Mg) | -250 – +1300 | New enhanced K-type, to high temperatures, good resistance to oxidizing |
| B | Pt | $Pt_{80}Rh_{20}$ | 870 – 1700 | Expensive, stable, corrosion resistant (noble metal), for high temperatures |
| R | Pt | $Pt_{87}Rh_{13}$ | 0 – 1480 | |
| S | Pt | $Pt_{90}Rh_{10}$ | 0 – 1480 | |
| T | Cu | Constantan | -200 – +400 | |

# Color codes for thermocouples



# Sensitivities of thermocouples



# Measuring with a thermocouple

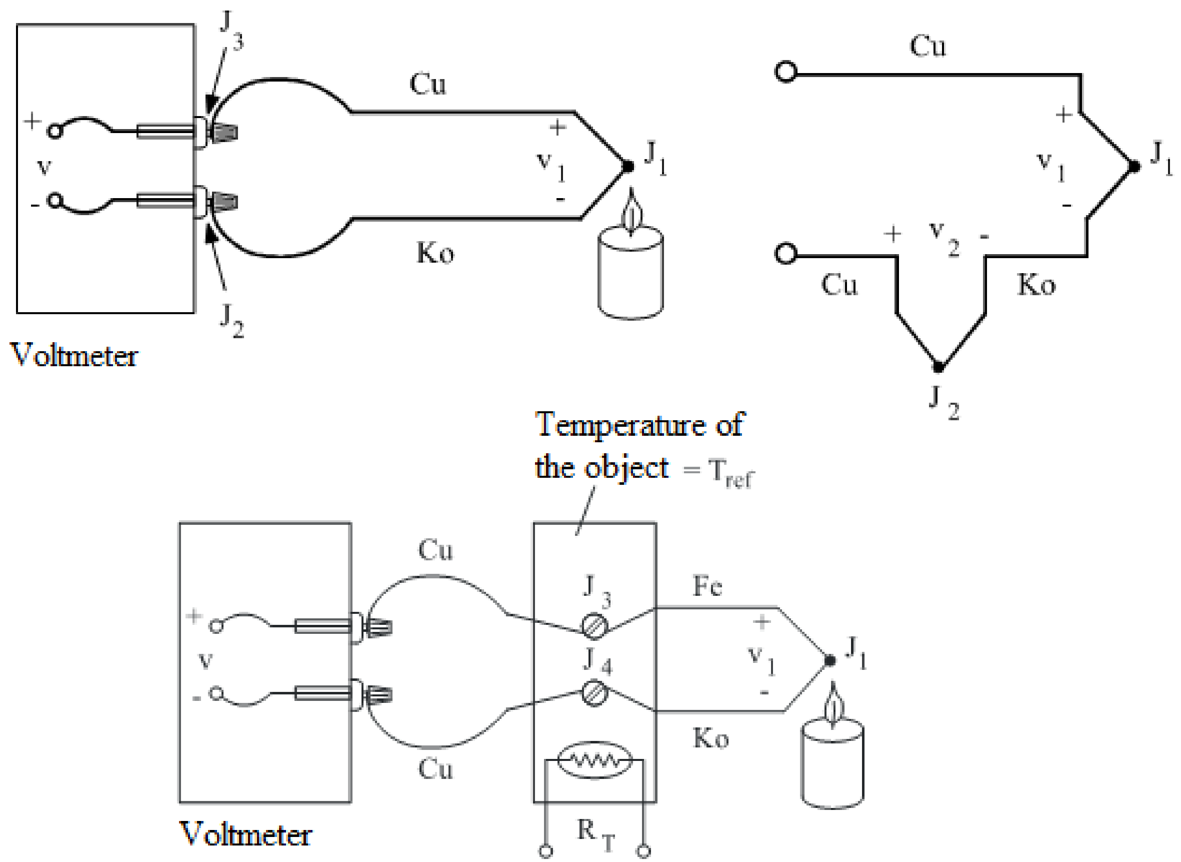
- The connection between the measuring instrument and the thermocouple wire makes another junction
  - If the temperature of 500 °C of an oven is measured, the thermo voltage depends on the oven temperature and the room temperature where the measuring instrument is placed

- If room temperature is 20 °C, voltage reading is the difference of thermo voltages at 500 °C and 20 °C!
  - Voltage caused by 20 °C is negative because of the inverted polarity of the junction

# Measuring with a thermocouple

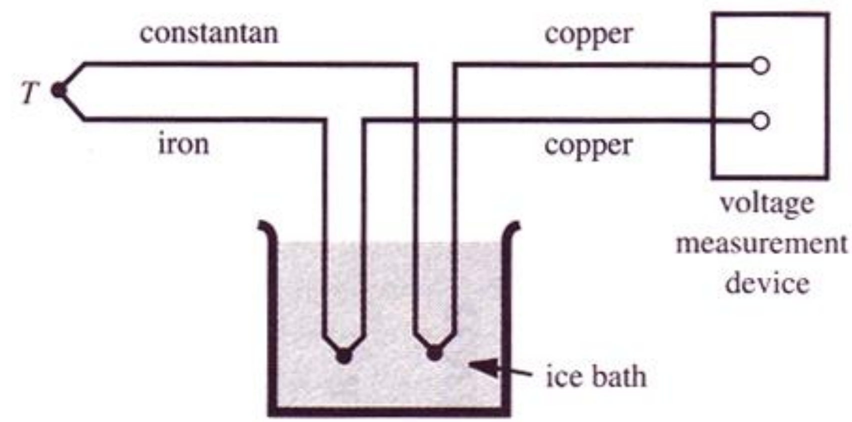
- Digital voltmeters often used
  - contain a reference temperature from which a built-in processor calculates the thermo voltage
  - sums the thermo voltage produced by the thermocouple and calculates the temperature according to standard
- If accurate measurements are required, reference junctions are used in a controlled temperature

# Reference junction in a thermocouple measurement

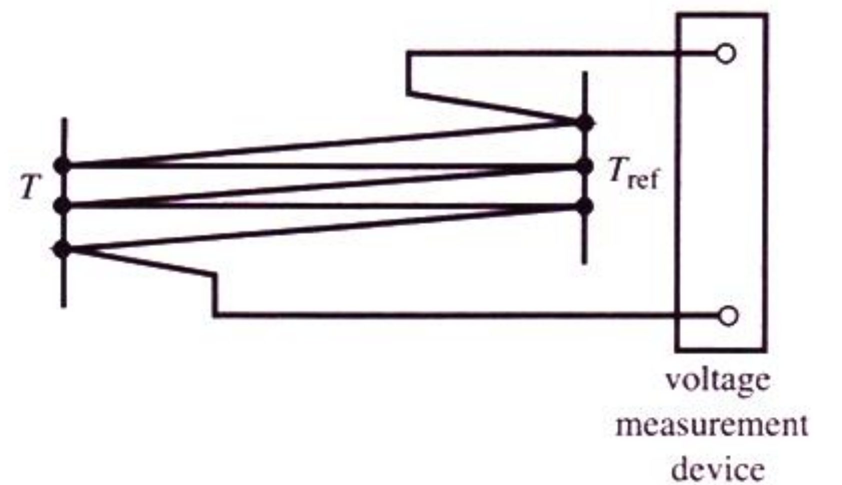


# Practical connections for a thermocouple

- Reference junction can be implemented with extension wires




- Parallel connection produces higher voltage (Thermopile)



# Limitations in a thermocouple measurement

- Requires the reference temperature
- Extension wires must be the same type as the wires in the thermocouple
  - The polarity of the extension wires
- Nonlinear dependency of thermo voltage on temperature

# Semiconductor thermometers

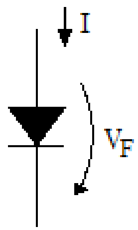
- Temperature affects significantly to the number of charge carriers
  - This affects both conductivity (thermistors) and band gap

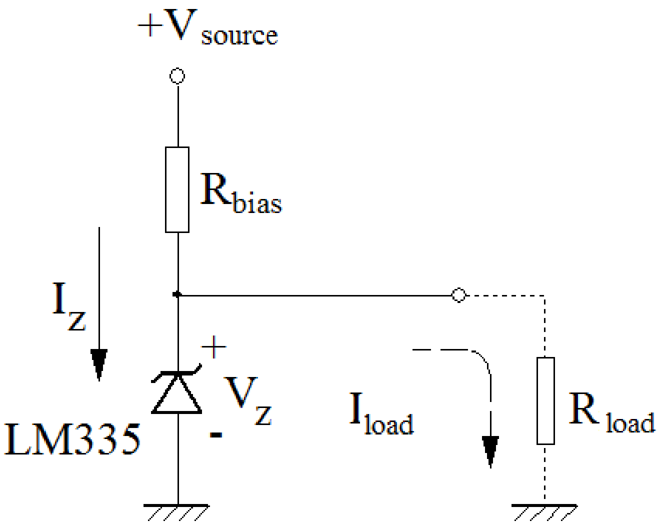
- Voltage drop over the pn-junction of a diode and a transistor

- Very common in integrated circuits
- Highest temperature about 250 °C

# Diode sensor

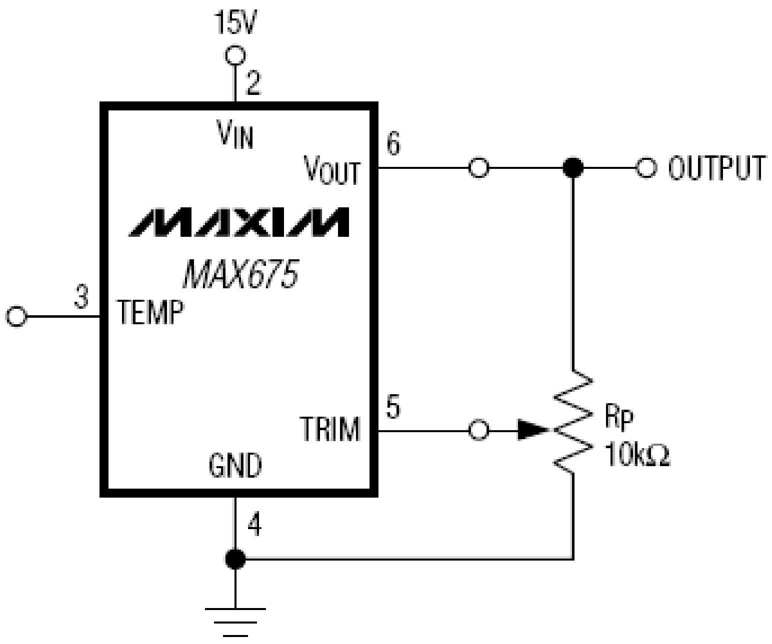
- Diode forward voltage $V_F$ is proportional to the temperature.
- Zener voltage is temperature dependent.
- Properties
  - Temperature range: -40 – +125°C
  - Sensitivity: +10 mV/K
  - Nonlinearity: 0.5 °C at range -10 – +100°C



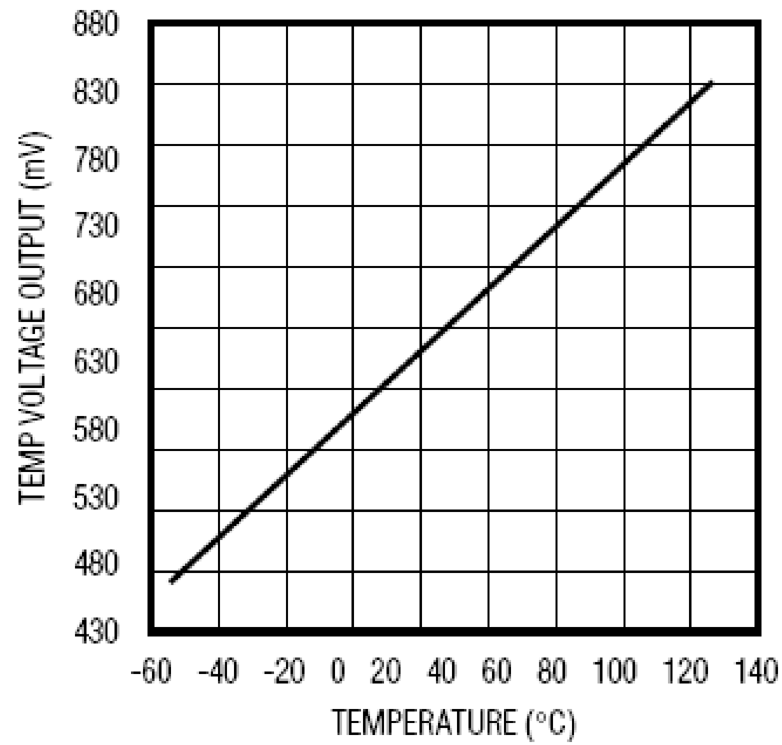



# IC sensor

- Linear, high output voltage, and inexpensive
- Temperatures <250 °C, slow, self heating

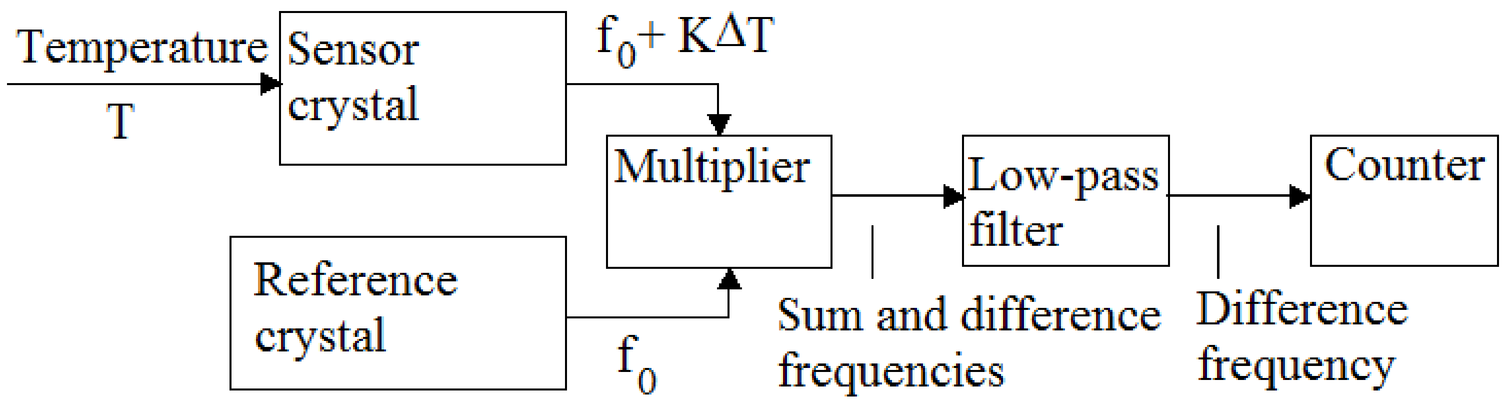


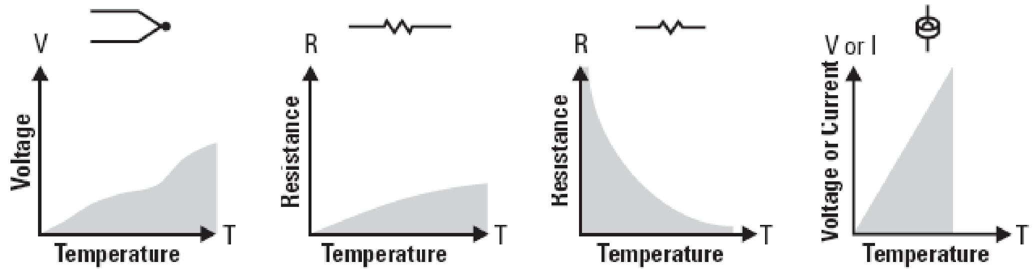

REFERENCE WITH TRIMMED OUTPUT



# Crystal thermometer

- Frequency of the oscillating crystal depends on temperature
- Signal is multiplied with a signal from a reference oscillator
- The temperature is calculated from sum and difference frequencies
- Mechanically very stable → even ~0.001 °C accuracy






| | Thermocouple | RTD | Thermistor | I. C. Sensor |
|---|---|---|---|---|
| Advantages | • Self-powered<br>• Simple<br>• Rugged<br>• Inexpensive<br>• Wide variety of physical forms<br>• Wide temperature range | • Most stable<br>• Most accurate<br>• More linear than thermocouple | • High output<br>• Fast<br>• Two-wire ohms measurement | • Most linear<br>• Highest output<br>• Inexpensive |
| Disadvantages | • Non-linear<br>• Low voltage<br>• Reference required<br>• Least stable<br>• Least sensitive | • Expensive<br>• Slow<br>• Current source required<br>• Small resistance change<br>• Four-wire measurement | • Non-linear<br>• Limited temperature range<br>• Fragile<br>• Current source required<br>• Self-heating | • T < 250° C<br>• Power supply required<br>• Slow<br>• Self-heating<br>• Limited configurations |

# Calibrating thermometers

- Conditions may change etc. → calibrating regularly
- Comparison meters
  - Mercury thermometers
  - Platinum resistance thermometers in more accurate measurements
  - Pyrometers at high temperatures
- Comparison meters are calibrated to reference points
  - Inaccuracy of a reference point $10^{-3}$ – $10^{-4}$ K

# Optical thermometers

- Measure photons emitted by objects
- Enable non-contact temperature measurements
- Based on Planck’s law

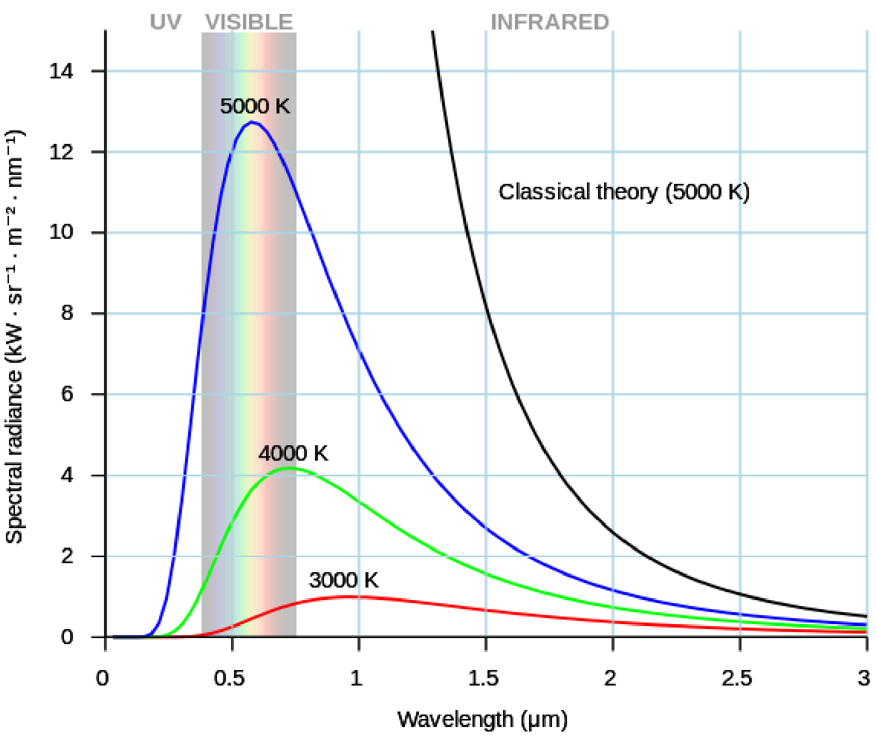

- Pyrometers
  - Total radiation pyrometer
  - Selective radiation pyrometer
- Infrared camera

# Planck's law

- Spectral radiance of an object

$$B_\lambda(\lambda, T) = \varepsilon \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

- Emissivity *ε* is
  - 1 for a black body
  - <1 for a grey body
  - 0 – 1 for real objects having the wavelength dependence



# Black body

- A black body absorbs all incoming radiation (0% is reflected)
- Spectrum of a black-body radiation depends only on its temperature
- Total radiation power is the integral of Planck's law

  $P = A\sigma T^4$ (Stefan-Boltzmann law),

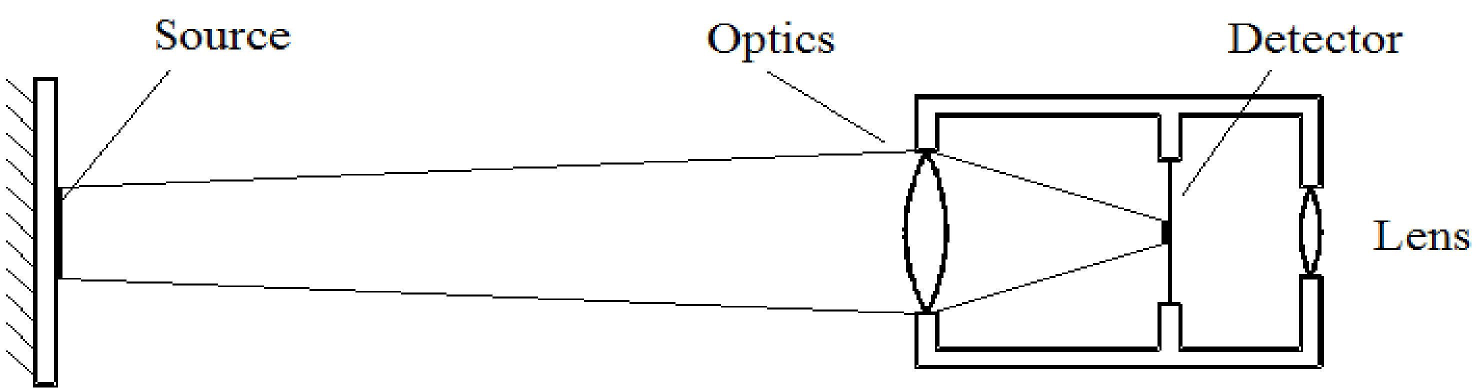
  where $A$ is the area of the object and $\sigma$ is Stefan-Boltzmann constant
- The peak wavelength of the spectrum

  $\lambda = b/T$ (Wien's displacement law),

  where *b* is Wien's displacement constant

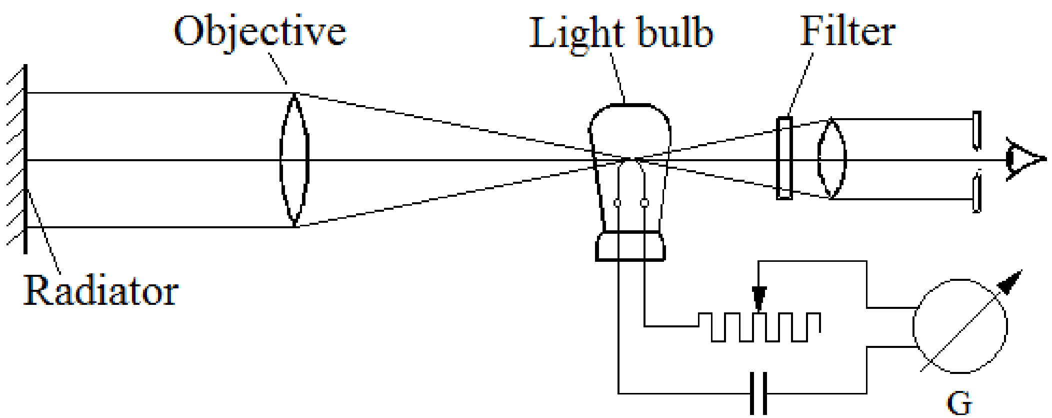
# Total radiation pyrometer

- Temperature is calculated according to Stefan-Boltzmann law
- The problem are absorptions by the air and optics and emissivity
- Detector can be e.g. thermocouple, bolometer, thermopile etc.

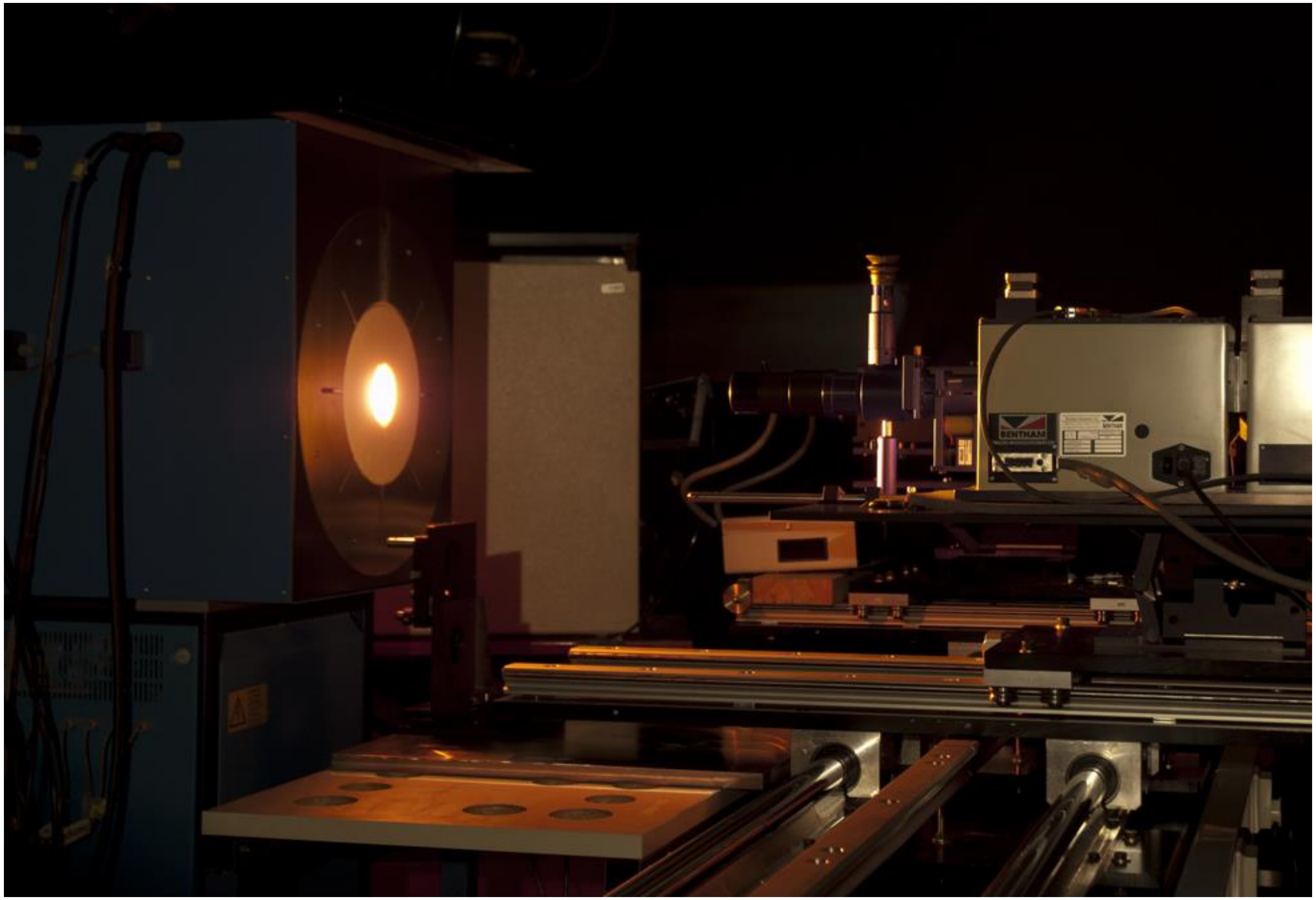


# Optical pyrometer

- Was the first pyrometer (in 1901)
  - Selective radiation pyrometer (red filter), only for high temperatures
- Current of the glowing filament is adjusted so that it ”disappears” from the picture. Therefore, its temperature corresponds to the temperature of the radiator
  - Emissivity is approximated to be the same



# Black body



# What is humidity?

Water vapor in gas or in other substances

- In gas: Humidity
- In other substances: Water content

Described with differend quantities:

- Absolute humidity
- Mass mixing ratio
- Specific humidity
- Relative humidity

# Absolute and relative humidity

- The mass of water vapour in a certain volume of gas:

$$AH = \rho_V = m_v / V$$

- Know also as volumetric humidity
- Absolute humidity (AH) changes as a function of temperature and pressure
  - The quantity does not fit well to situation where temperature changes a lot
- Relative humidity (RH), expressed as a percent, measures the current absolute humidity relative to the maximum (highest point) for that temperature.

# Mass ratios

- Specific humidity is the mass of water vapour in relation to the total mass

$$SH = m_v / m_t$$

$$m_v + m_g = m_t$$

- Mass mixing ratio is the mass of water vapour in relation to the mass of dry gas

$$MR = r = m_v / m_g$$

- Temperature does not affect mass ratios (unless condensation happens)

# Relative humidity (RH)

- Ratio of the vapour pressure to the saturated vapour pressure at the same temperature

$$RH = \phi = \frac{p_{(H_2O)}}{p^*_{(H_2O)}} \times 100\% = \frac{MR}{MR^*} \times 100\% = \frac{SH}{SH^*} \times 100\%$$

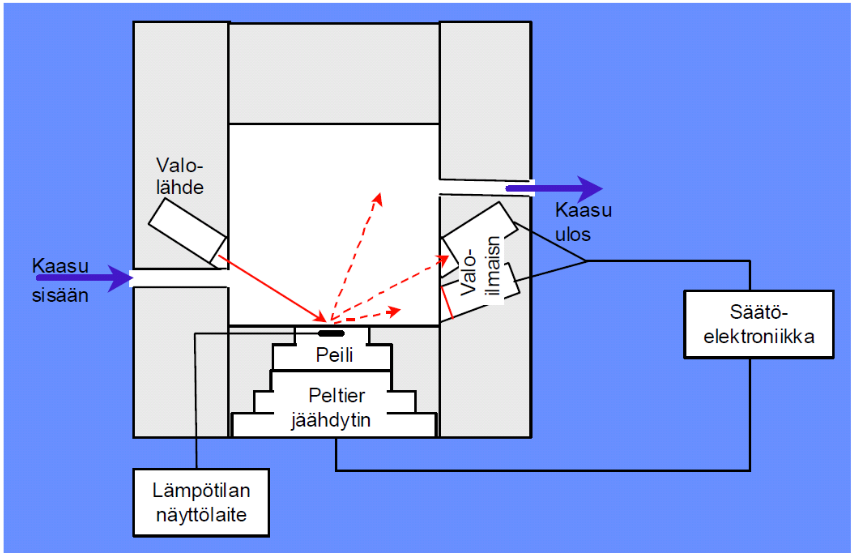
- Reveals how close the dew point is
- Important at weather forecasts
- Affects to human's comfort
  - Thermal regulation of a body, high dew point less comfortable

# Hygrometer (atmospheric humidity meter)

- Most accurate result by measuring the dew point
  - Detecting the phase change of water
- The effect of water vapour to electrical, mechanical, and optical properties of a material

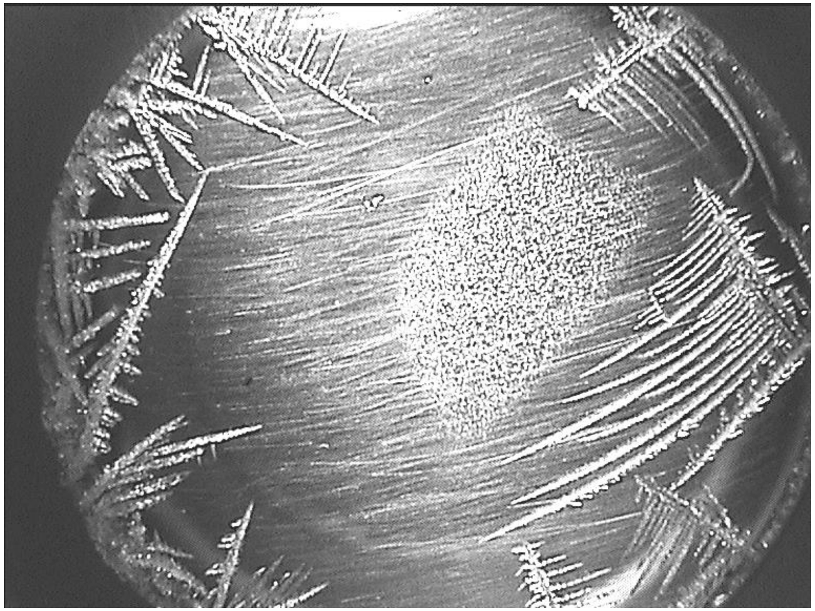
# Detecting the phase change of water:
## Optical dew point sensor

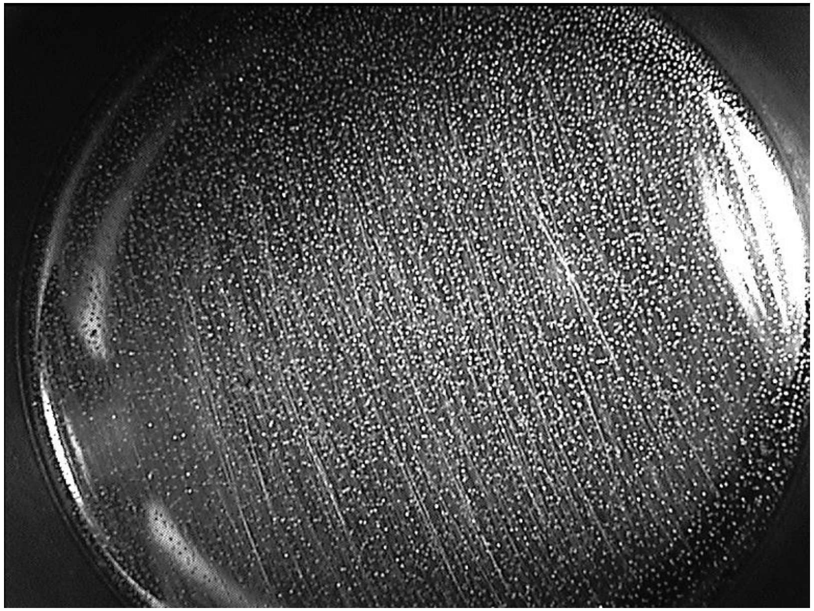
- A mirror is cooled to the dew point
- The deposit of moisture on the mirror surface is kept constant by controlling the Peltier element
- The deposit of moisture is measured optically and the signal then controls the Peltier element




- The uncertainty of the device is 0.1-0.3 °C

# Detecting the phase change of water:
## Optical dew point sensor





# Detecting the phase change of water:
## Optical dew point sensor

+ Accurate
+ Wide range (-80 °C … +100 °C)
+ Stable

– Expensive
– The mirror needs regular cleaning
– Slow

# Detecting the phase change of water:
## Other dew point sensors

Instead of optical detection:

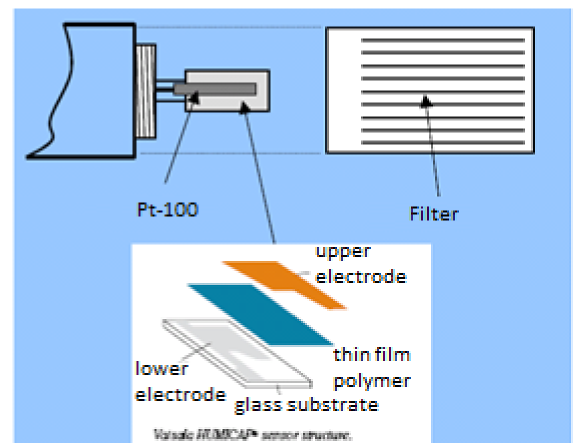
- Quartz crystal microbalance, QCM (change of frequency)
  - Especially below 0 °C
  - Relatively new method, not widely in use
- Impedance
  - Normal humidity zone
  - Fast

# Capasitive polymer sensors

- The most common RH sensor type
- Measurement range even 0-100 %RH
- Uncertainty at best 2 %RH
- Wide temperature range: -40 … +80 °C

[VaisalaNews 163/2003]

[www.epluse.com]




[B210781EN-B ©Vaisala 2009]

# Capasitive polymer sensors

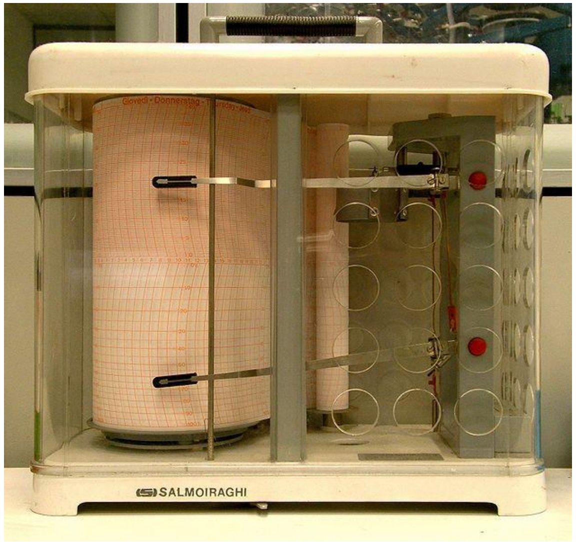
+ Easy to use, small scale
+ Withstands exposure to water (after that requires a calibration)
+ Fast, sensitive, wide temperature range

– Relatively poor stability
– Hysteresis
– Temperature dependency (temperature sensor in the same device)
– Individuality (necessity to calibrate)

# Other sensor types

- Resistive sensors
  - Conducting polymers
  - Usually less sensitive and accurate than capasitive

- Mechanical
  - Thermohygrographs, hair tension hygrometers
  - No longer in use



# Other sensor types

- Optical
  - Spectroscopic:
    air absorption
  - Fiber optical:
    moisture detector


- Mechanical properties
  - Quartz crystal microbalance (QCM)