POLITECNICO
MILANO 1863

Temperature sensors

SENSOR SYSTEMS

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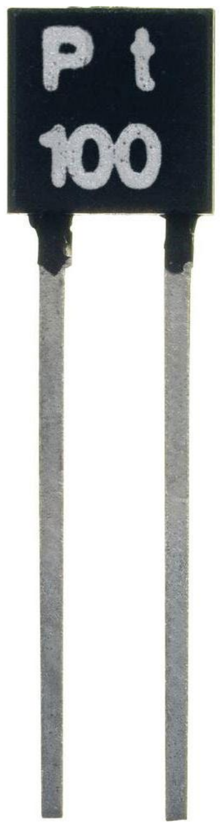
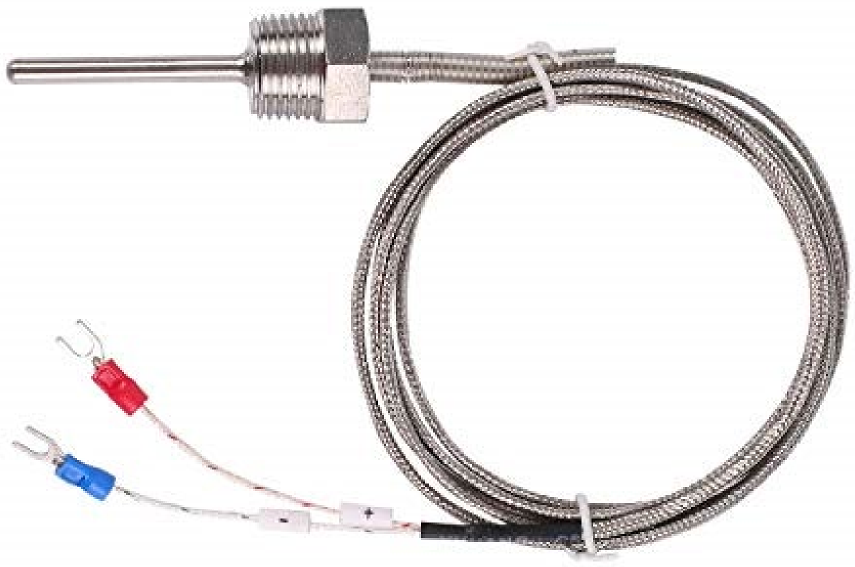
- Resistance Temperature Detectors
- Thermistors
- Thermocouple
- Diode and bandgap temperature sensors
- Infrared thermometer





WeBeep: 06 – Resistance Temperature Detectors

RTDs structures

resistance temperature detectors

An RTD is a device which contains a metallic electrical resistance (referred to as a “sensing element” or “bulb”) which changes resistance value depending on its temperature.

This change of resistance with temperature can be measured and used to determine the temperature of a material.

Resistance: 100Ω, 200Ω, 500Ω, 1000Ω (Tolerances ±0.05% - ±0.1%)
Materials: Platinum, Nickel, Copper, Iron, Silver, Gold
Most common RTD are **100Ω Platinum** sensors. → Pt 100

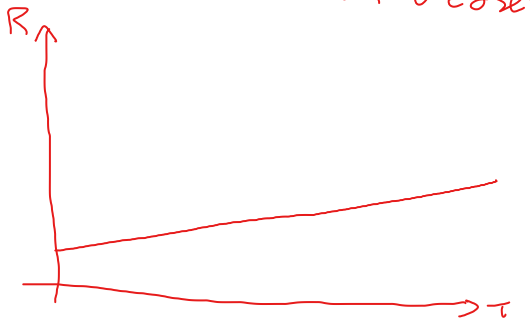
Temperature range: -200°C – 800°C

RTD sensing elements come in two basic structures

- Wire wound
  - Coiled design
  - Outer wound design

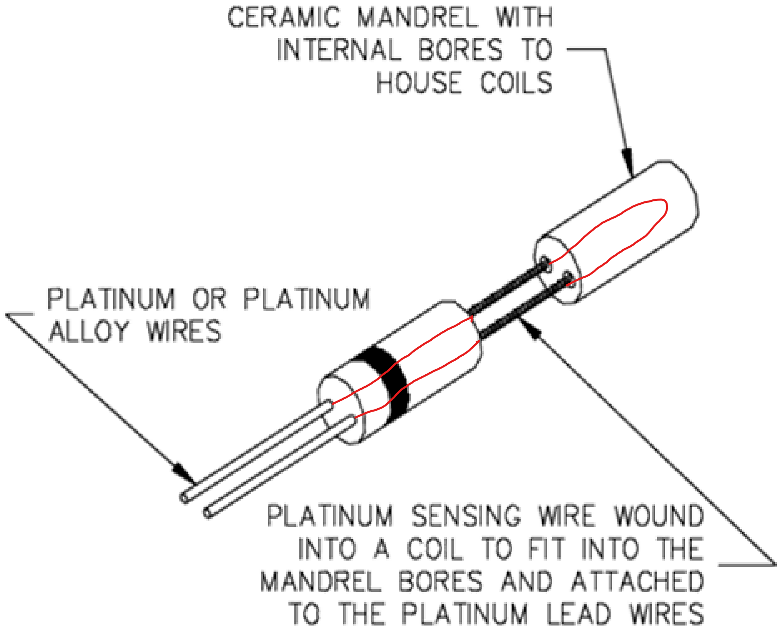
- Film pattern

usual in metals
PTC: Positive temperature coeff.
more or less linear: resistance increases when temperature increases

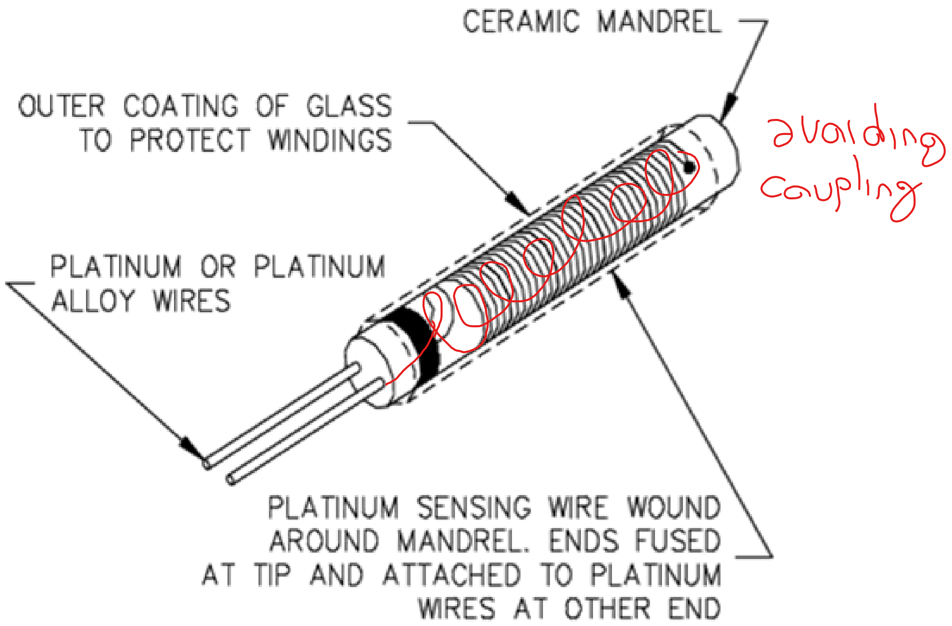


→ With increasing T, brownian motion increases and carrier electrons could be stopped

Wire wound elements contain a very small diameter metallic wire
(typically, 0.5 – 1.5 mil diameter, 1mil = 0.0254 mm).



WIRE WOUND ELEMENT – COILED DESIGN



WIRE WOUND ELEMENT – OUTER WOUND DESIGN

wound into a coil and
packaged inside a ceramic mandrel

wound around the outside of a ceramic housing
and coated with an insulating material

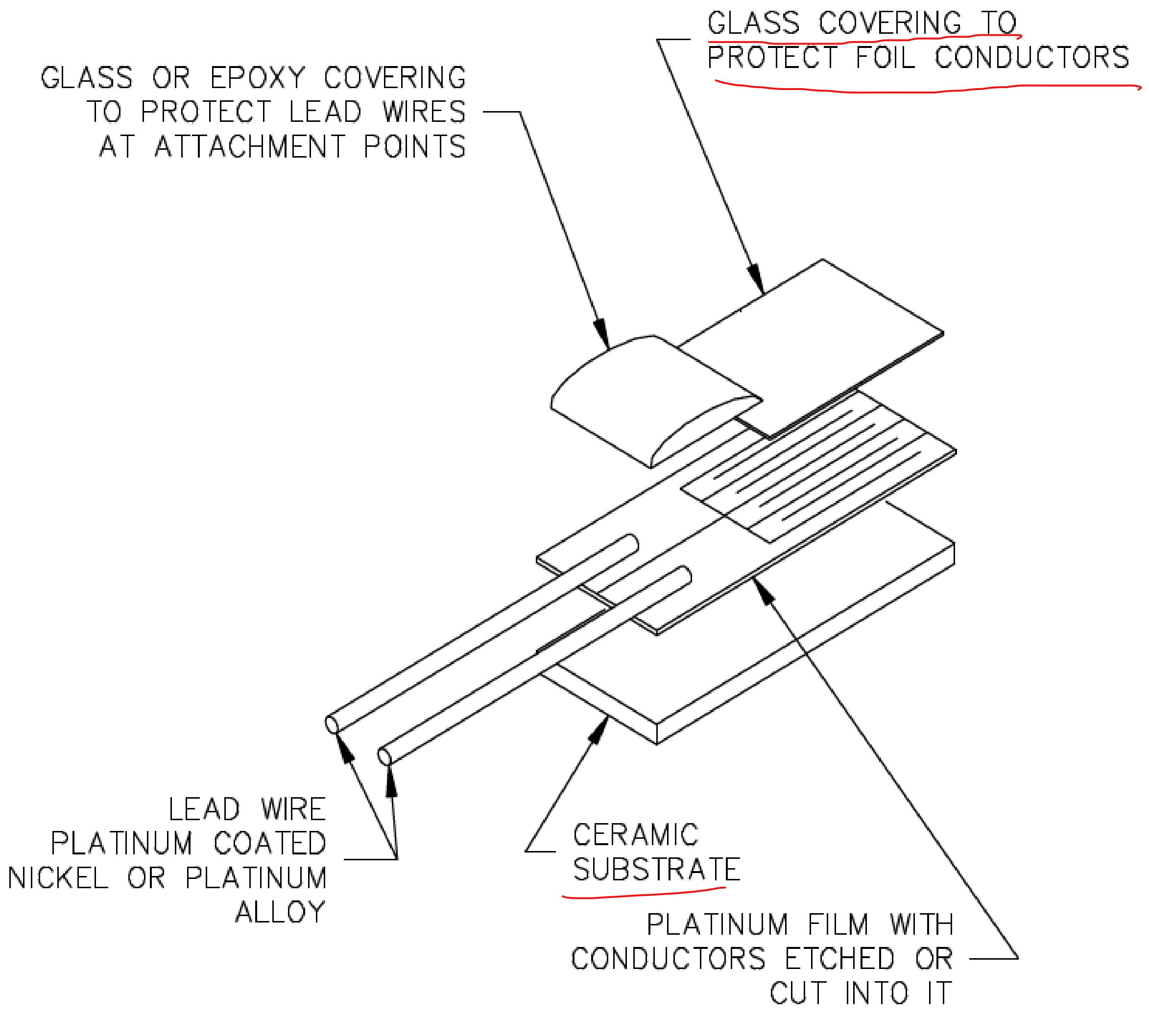
Film pattern (Preferred)

Film type sensing elements are made from a metal coated substrate which has a resistance pattern cut into it.

This pattern acts as a long, flat, skinny conductor, which provides the electrical resistance.

Lead wires are bonded to the metal coated substrate and are held in place using a bead of epoxy or glass.

Fabricated through photolithography



FILM STYLE ELEMENT

Sensitivity = quantity characteristic of a specific RTD

$$S = \frac{\Delta R}{\Delta T}\ \left({}^{\Omega}/_{\circ C}\right)$$

Temperature coefficient = quantity characteristic of a specific material:

$$\alpha = \frac{R_{100} - R_0}{100°C \cdot R_0} = \frac{S}{R_0} (\Omega/\Omega/°C)$$

RTDs typically have Positive Temperature Coefficient (**PTC**)

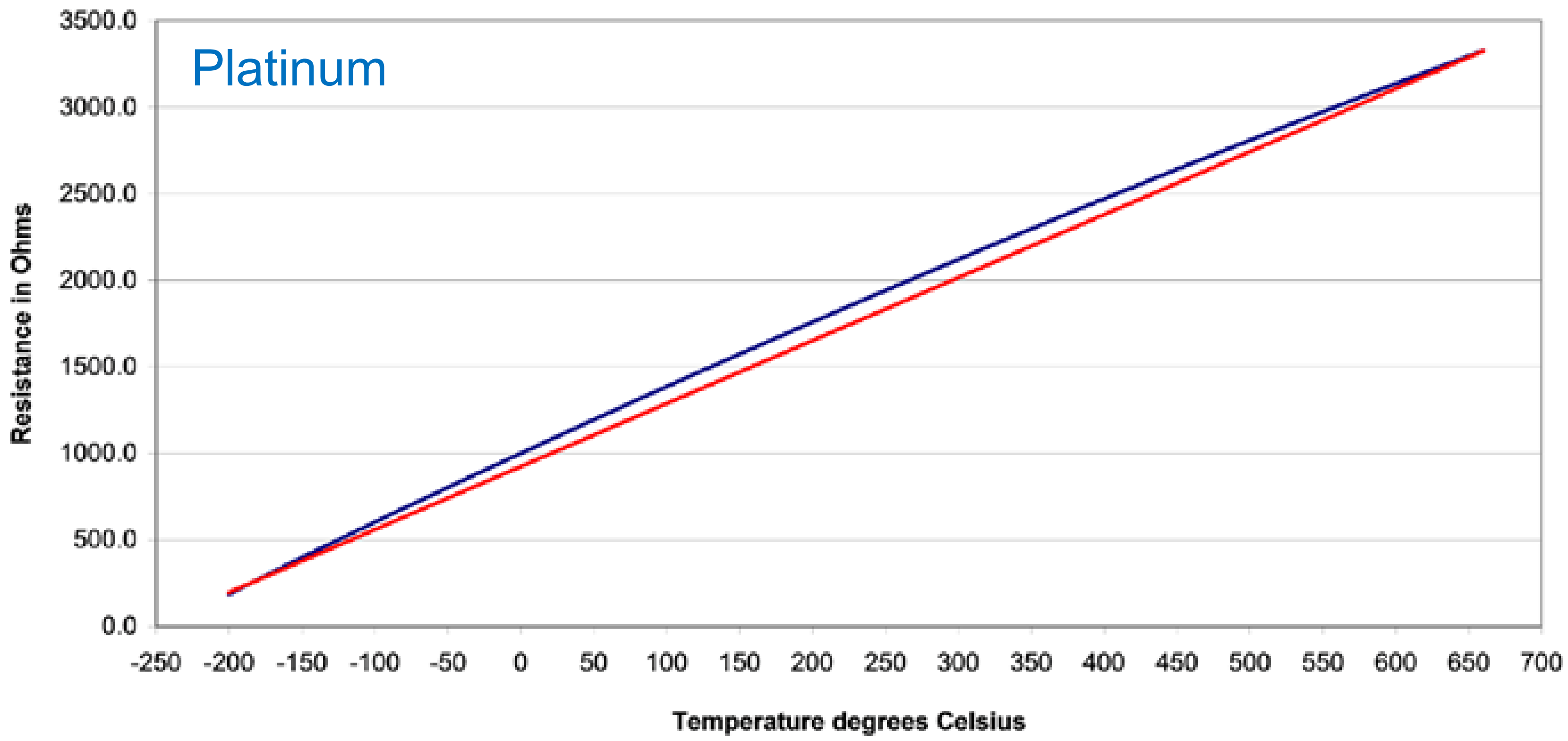
Characteristic equation:

$$R_{RTD} = R_0(1 + \alpha\Delta T) = R_0 + \Delta R$$

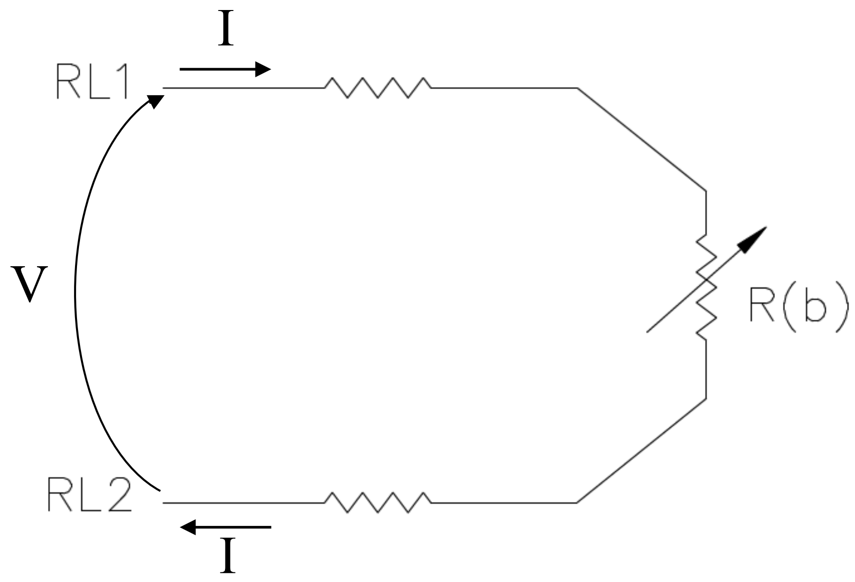
$$\Delta R = \alpha R_0 \Delta T$$

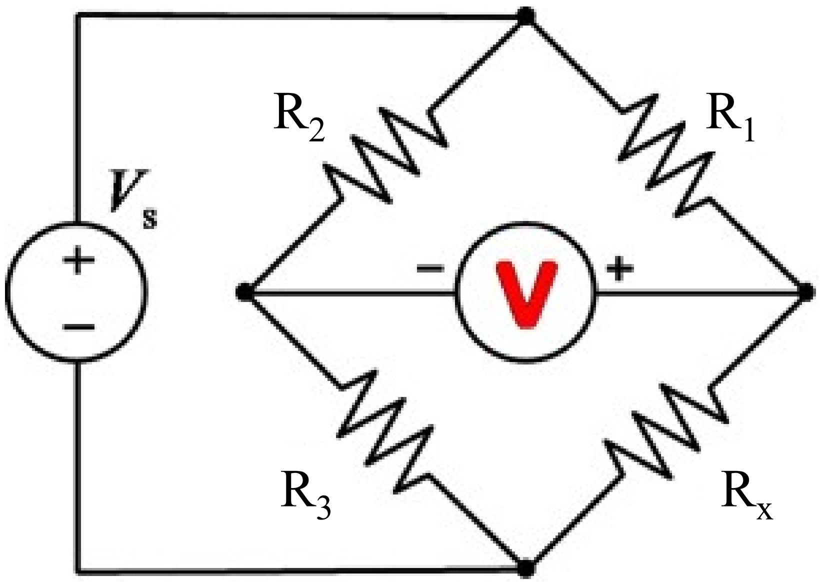
RTD temperature coefficient

Material	α
Platinum	0.0039 Ω/Ω/°C
Nickel	0.006 Ω/Ω/°C
Copper	0.0039 Ω/Ω/°C
Iron	0.005 Ω/Ω/°C
Silver	0.0038 Ω/Ω/°C
Gold	0.0034 Ω/Ω/°C



Measuring Circuits





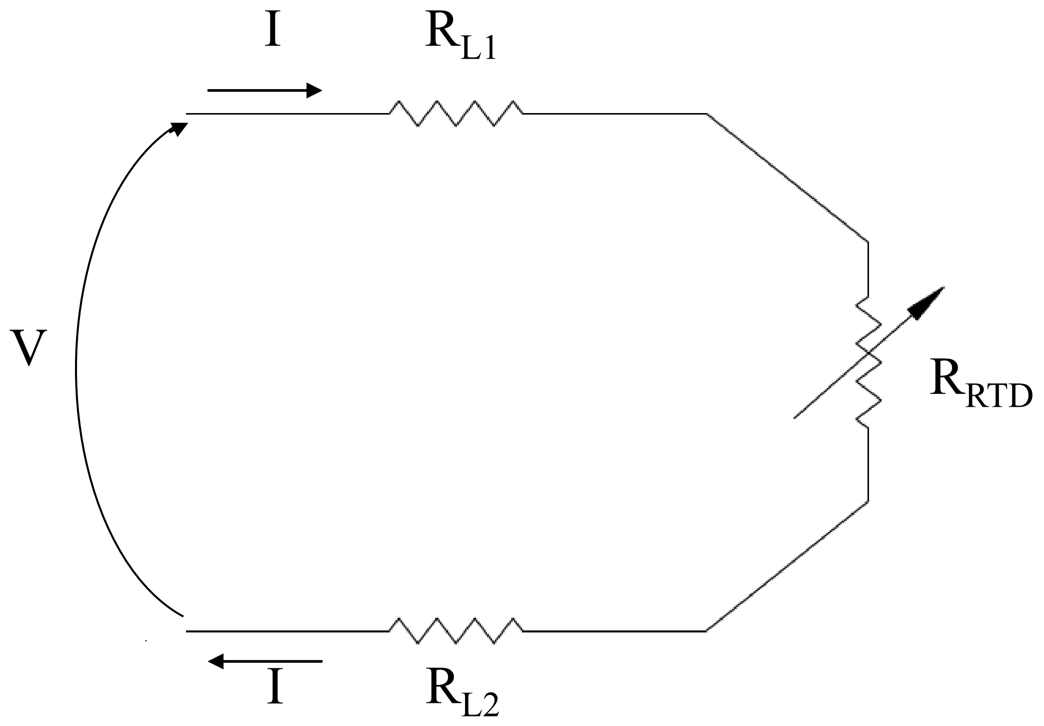
- 2 lead wires set-up
- 3 lead wires set-up
- 4 lead wires set-up

- Wheatstone bridge
- 3-wire bridge

It is the **least accurate**
since there is no way of eliminating the lead wire resistance from the sensor measurement.

2-wire RTD's are mostly used

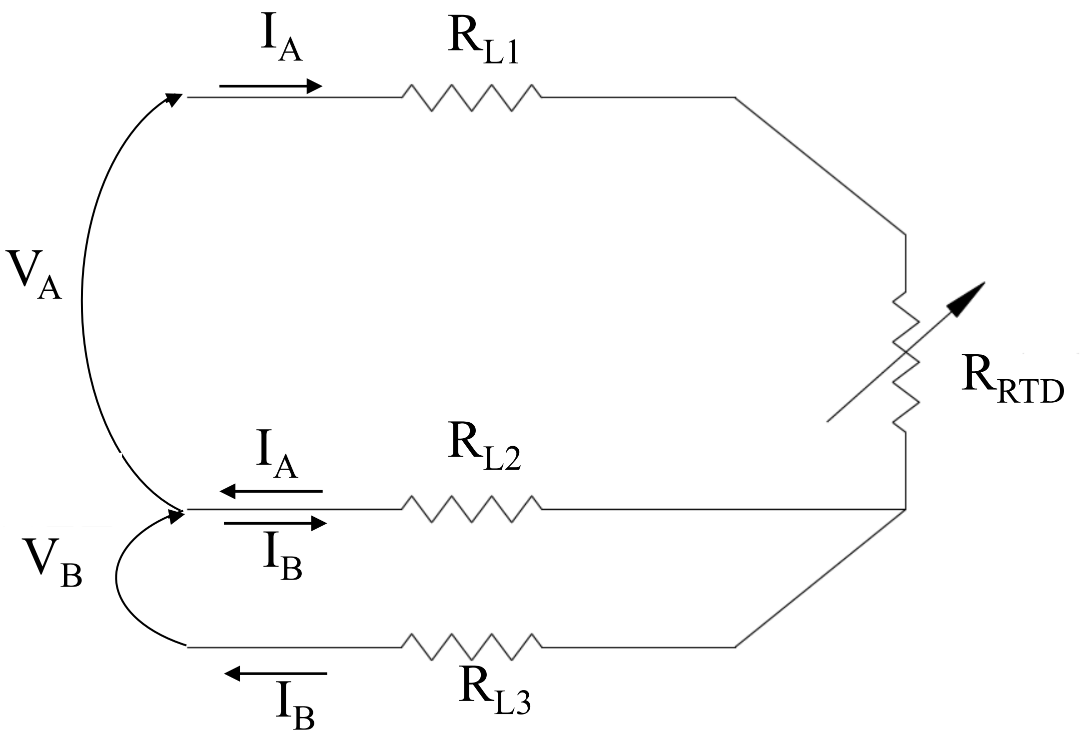
- with short lead wires
- where close accuracy is not required.



$$R_{meas} = R_{L1} + R_{L2} + R_{RTD}$$

It is the most used in **industrial applications**
where the third wire provides a method for removing the average lead wire resistance from the sensor measurement.

When long distances exist between the sensor and measurement/control instrument, significant savings can be made in using a three-wire cable instead of a four-wire cable.



$R_A = R_{L1} + R_{L2} + R_{RTD}$

$R_B = R_{L2} + R_{L3}$

$R_{meas} = R_A - R_B = R_{RTD}$

Assuming $R_{L1}=R_{L2}=R_{L3}$

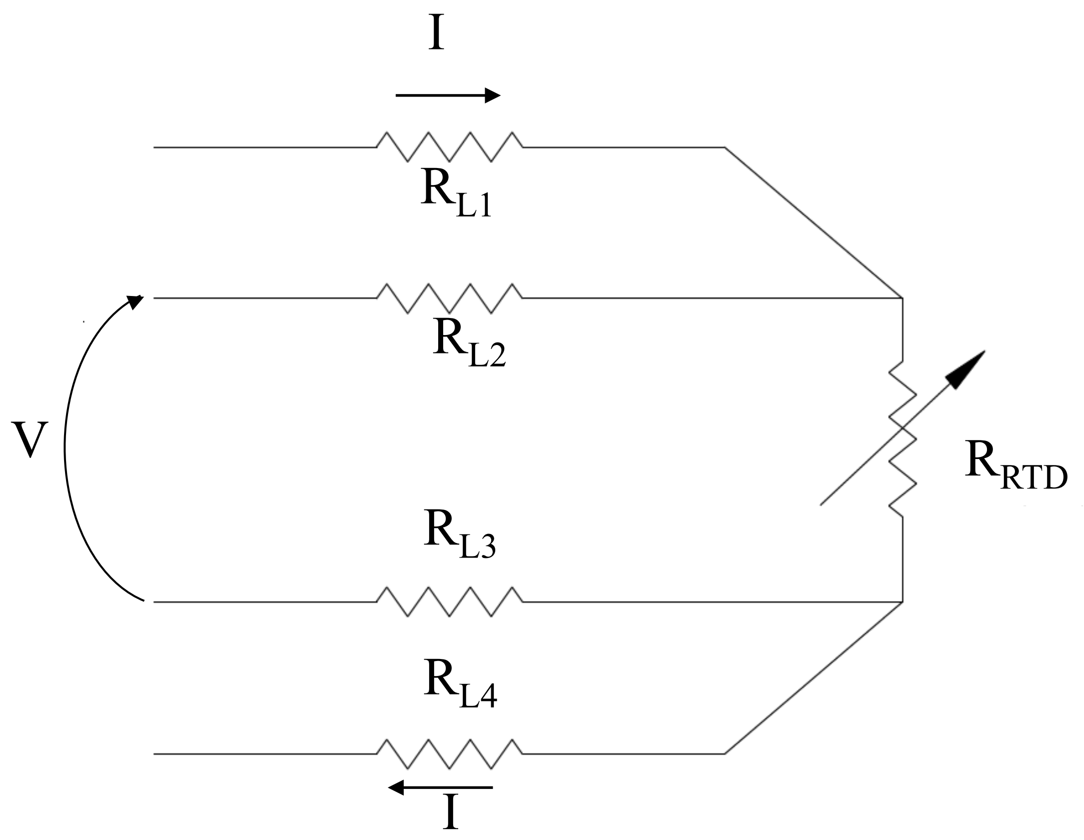
4 lead wire set-up

It is used primarily in **laboratory** where close accuracy is required.

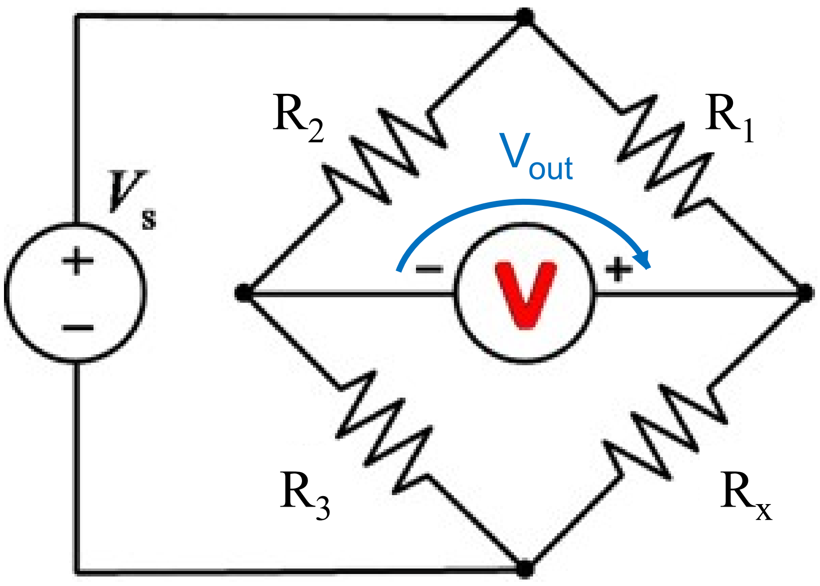
In a 4 wire RTD the actual resistance of the lead wires can be removed from the sensor measurement.

This method compensate for any differences in lead wire resistances.

The input impedance of the voltage measurement circuitry must be high enough to prevent any significant current flow in the voltage leads.



$$R_{meas} = R_{RTD}$$



R_{x0} nominal value of R_x → $R_x = R_{xo} + \Delta R$

In order to have V_{out}=0 when $R_x = R_{x0}$:

$$\frac{R_2}{R_3} = \frac{R_1}{R_{x0}}$$

Considering $R_1 = R_2$ and $R_3 = R_{x0}$:

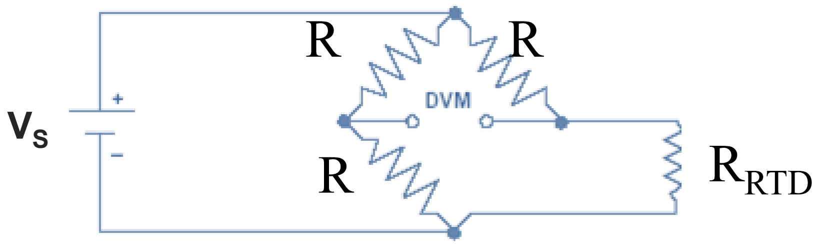
$$V_{out} = V_s \cdot \left[\frac{R_{xo} + \Delta R}{R_1 + R_{x0} + \Delta R} - \frac{R_{xo}}{R_1 + R_{x0}}\right] = V_s \cdot \frac{R_1}{(R_1 + R_{x0})^2} \cdot \frac{\Delta R}{1 + \frac{\Delta R}{R_1 + R_{x0}}}$$

$$V_{out} \approx V_s \cdot \frac{R_1}{(R_1 + R_{x0})^2} \cdot \Delta R = V_s \cdot \frac{R_1}{(R_1 + R_{x0})^2} \cdot \alpha R_{x0} \Delta T$$

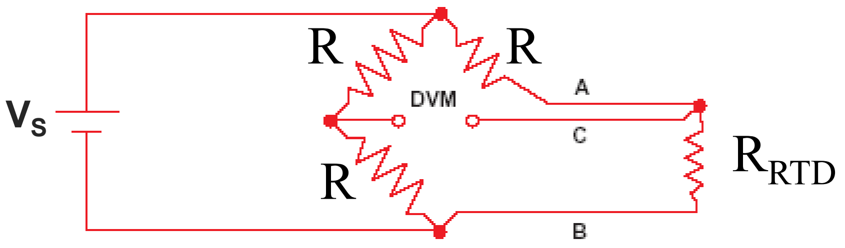
Choosing $R_1 = R_2 = R_3 = R_{x0}$ provides the maximum $\frac{V_{out}}{\Delta T}$ → $\frac{V_{out}}{V_s} = \frac{1}{4} \cdot \frac{\Delta R}{R_{x0}}$

2- and 3-wire bridge

2-wire



3-wire



Ideally (R_L = 0):

$$V_{out} = V_S\left(\frac{R+\Delta R}{2R+\Delta R} - \frac{1}{2}\right)$$

Considering $R_{L1}=R_{L2}=R_L$

In 2-wire bridge:

$$V_{out-2w} = V_S\left(\frac{R+\Delta R+2R_L}{2R+\Delta R+2R_L} - \frac{1}{2}\right)$$

$$\varepsilon = V_{out-2w} - V_{out} =$$

$$V_S\frac{2R_L \cdot R}{(2R+\Delta R)^2\left(1+\frac{2R_L}{2R+\Delta R}\right)} \approx V_S\frac{R_L}{2(R+R_L)}$$

In 3-wire bridge:

$$V_{out-3w} = V_S\left(\frac{R+\Delta R+R_L}{2R+\Delta R+2R_L} - \frac{1}{2}\right)$$

$$\varepsilon = V_{out-3w} - V_{out} =$$

$$V_S\frac{-R_L \cdot \Delta R}{(2R+\Delta R)^2\left(1+\frac{2R_L}{2R+\Delta R}\right)} \approx -V_S\frac{R_L}{2(R+R_L)} \cdot \frac{\Delta R}{2R}$$

Since RTDs are resistors, they will produce heat when a current is passed through them.

The normal current limit for industrial RTDs is **1 mA**.

- Thin film RTDs are more susceptible to self-heating so 1 mA should not be exceeded.
- Wire wound RTDs can dissipate more heat so they can withstand more than 1 mA.

The larger the sheath or the more insulation there is the higher the error caused by self heating.

In some applications self-heating is exploited as an advantage.

RTDs pros and cons

Pros

- High stability
- High accuracy
- Great repeatability
- High sensitivity and linearity
- Robust signal
  less prone to EMI problems
- Moderate price

Cons

- Narrow measuring range
  particularly at the high end
- Require an external power source
- Slow response time
- Self-heating

RTD applications

RTD characteristics:

- High accuracy and stability
- Accuracy extended over a wide temperature range
- Area, rather than point sensing, improves control

Typical applications:

- Air conditioning and refrigeration servicing
- Food Processing
- Stoves and grills
- Plastics processing
- Microelectronics
- Air, gas and liquid temperature measurement

WeBeep: 07 – Thermistors

Types of thermistors

Thermistor = thermally sensitive resistor in which its primary function is to exhibit a change in electrical resistance with a change in body temperature.

Two basic types of thermistors:

- NTC thermistors = ceramic semiconductors (transition metal oxides), which decrease in resistance as the temperature increases.
- PTC thermistors = resistors generally made of polycrystalline ceramic materials, which increases in resistance as the temperature increases.

Typically, NTC or PTC thermistors do not increase or decrease in resistance linearly with temperature
Linear PTC thermistor that has a linear resistance temperature relationship has been recently developed by Vishay Dale.

Materials: metal oxides
(i.e., manganese, nickel, cobalt, iron, copper and aluminum)

Shape of the finished product: disc/chip, leaded/surface mounting device
(dictated by the specific applications)

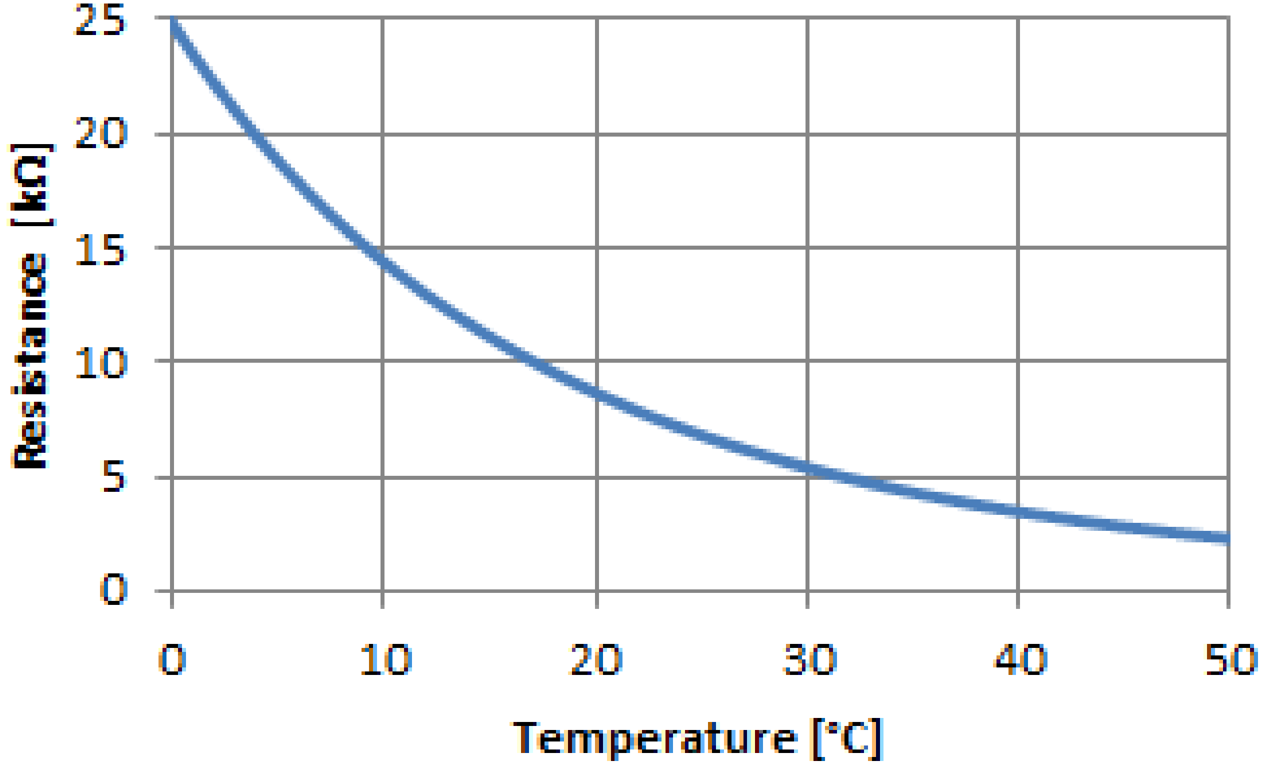
- Larger disc style NTC functions in the “self-heating” mode; that is, the change in resistance is a result of the wattage (heat developed by the passage of a relatively large current through the device).
- Smaller chip style NTC changes body temperature/resistance by absorbing the surrounding or ambient temperature.


disc


chip


smd

NTC characteristic



$$R(T) = R_{25} \cdot e^{\beta\left(\frac{1}{T}-\frac{1}{T_{25}}\right)}$$

R_{25} resistance at 25°

β thermistor constant (depends on material)

T temperature expressed in Kelvin

T_{25} = 298.15 K

Temperature Measurement

Low-cost temperature measurement applications.

Temperature Compensation

Precision circuits, which require temperature compensation
(i.e., Oscillators, LCD displays, battery under charge and some amplifiers).

Inrush Current Limiter

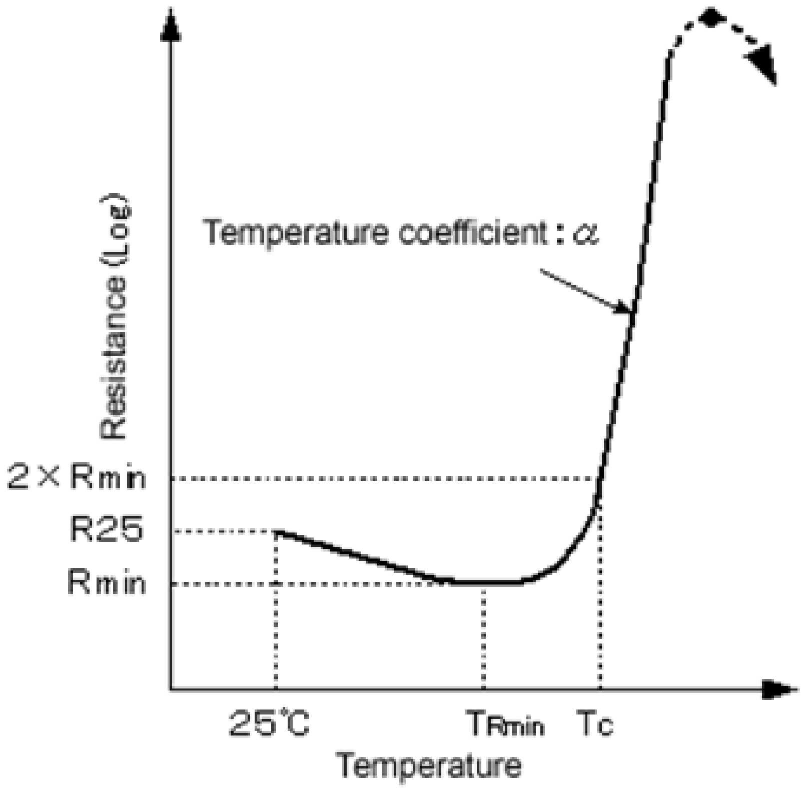
Disc NTC subjected to a change in power will experience a time lag before reaching a lower resistance. This time lag can be utilized to limit the inrush surge current (the larger the part, the greater the lag).

Fluid Level Applications

To sense the presence or absence of a liquid by using the difference in dissipation constants between a liquid and a gas.

Material: polycrystalline ceramic
(composed of oxalate or carbonate with added dopant materials)

The PTC thermistor exhibits only a slight change of resistance with temperature until the "switching point" is reached at which point an increase of several orders of magnitude in resistance occurs.



Tc = Curie temperature
the temperature at which resistance becomes twice the minimum resistance (Rmin)

→Correspond to the switch point

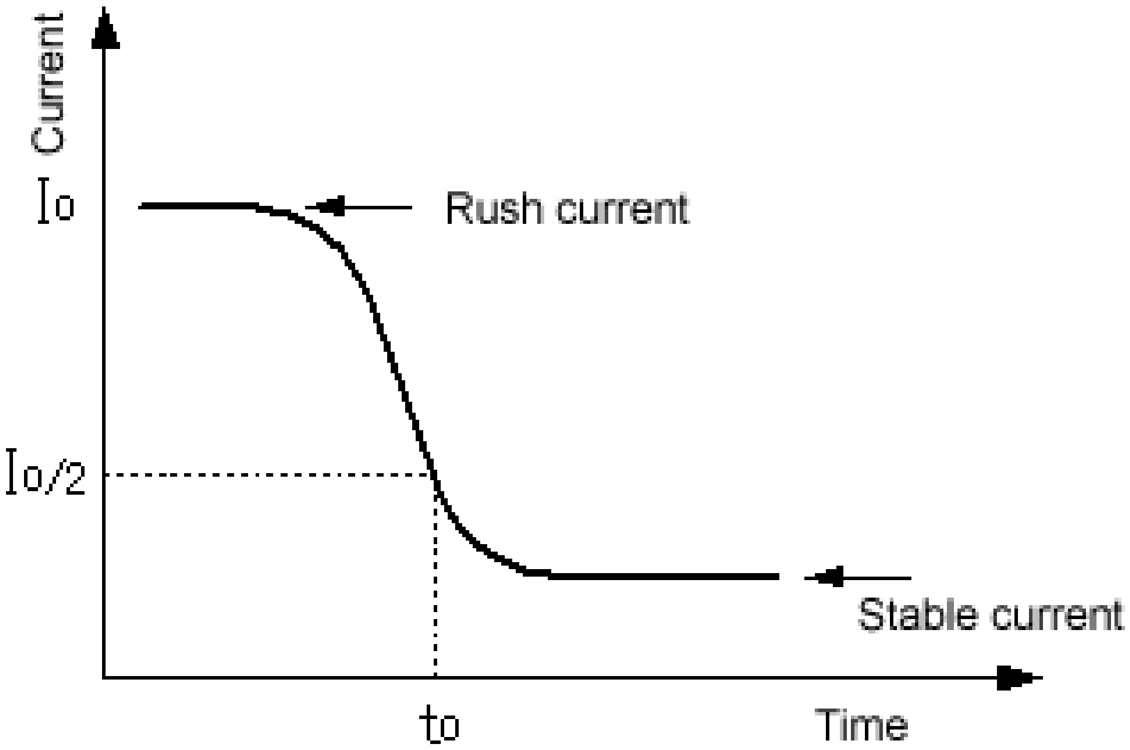
PTC applications

Overcurrent Protection

When a fault condition occurs, PTC will heat up causing it to switch from a low to a very high resistance.

Battery Management

As a rechargeable battery becomes fully charged, its temperature increases and the RTD increases rapidly reducing the charge to a very low level.



Thermistors pros and cons

Pros

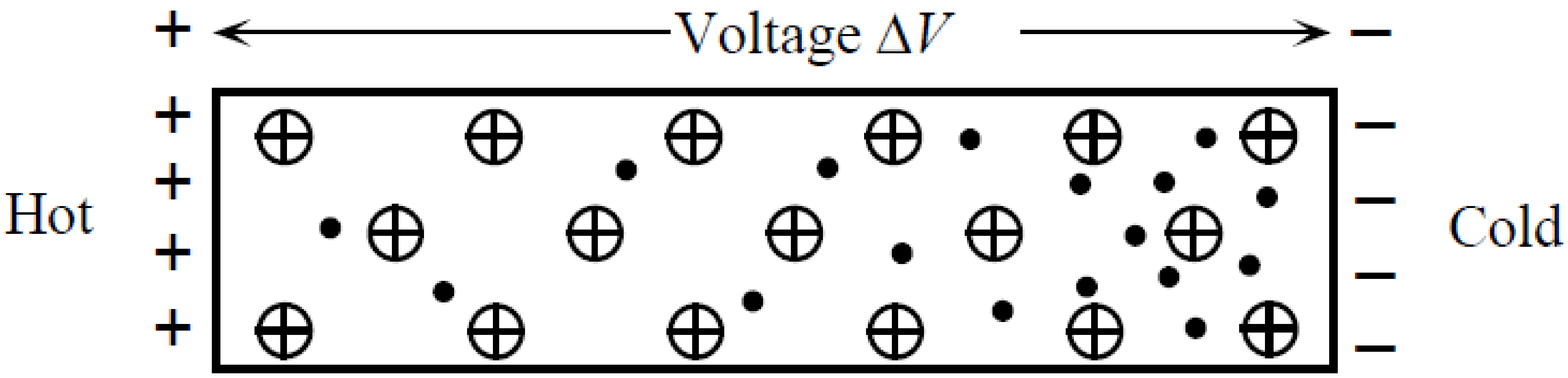
- High sensitivity (higher than RTD)
- Very moderate price
- Robust signal

Cons

- Very narrow measuring range (-100°C – 500°C)
- Low stability and linearity
- Medium accuracy
- Medium response time
- Self-heating

WeBeep: 08 – Thermocouples

A temperature difference between two points in a conductor or semiconductor results in a voltage difference between these two points.



The electrons in the hot region are more energetic (higher energy levels)

→ net diffusion of electrons from hot to cold

→ voltage

= sensitivity of the conductor/semiconductor: $S(T) = \frac{dV}{dT}$

The sign represents the potential of the cold side with respect to the hot side.

→ Typically metals and n-doped semiconductors have negative *S*, whereas p-doped semiconductors have positive *S*.

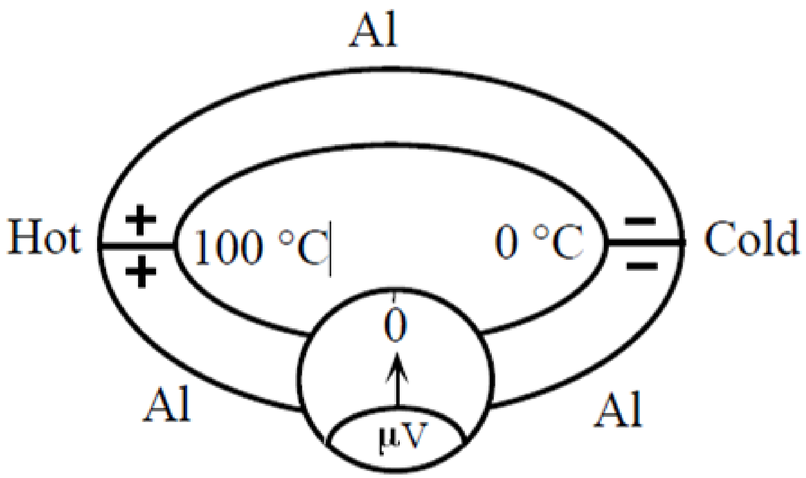
S depends on temperature, thus:

$$\Delta V = \int_{T_0}^{T} S(T) \cdot dT$$

Metal	*S* at 0°C ($\mu V\ K^{-1}$)	*S* at 27°C ($\mu V\ K^{-1}$)
Al	-1.60	-1.8
Pt	-4.45	-5.28
Cu	+1.70	+1.84
Chromel	-18.30	
Constantan	-39.90	

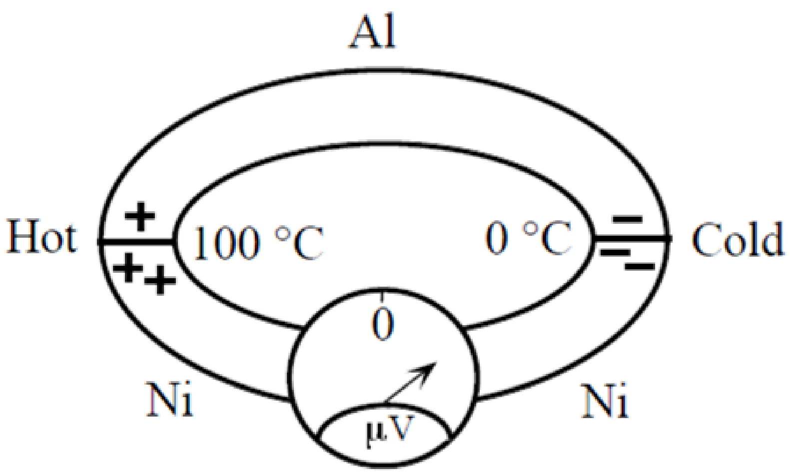
Only the net Seebeck voltage difference

between different metals can be measured.



If one metal is used

the net voltage is 0V.

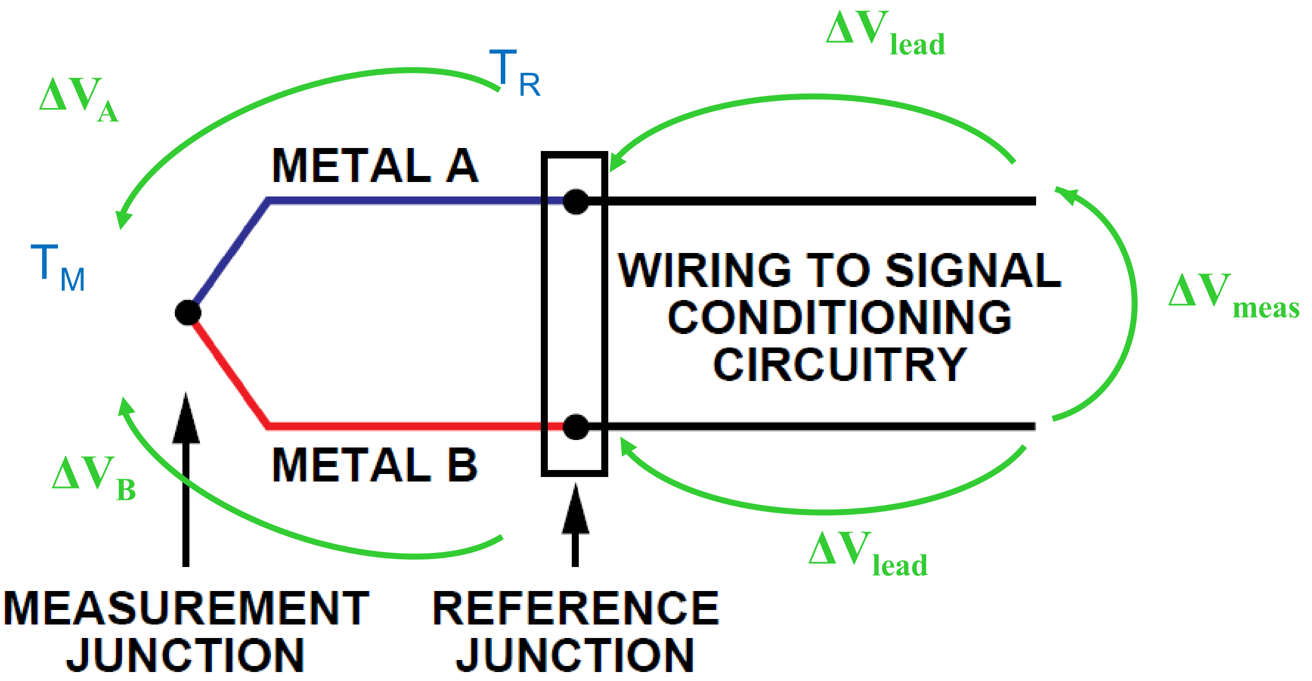


If two metals with different

Seebeck coefficient are used

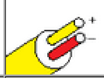
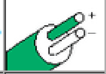
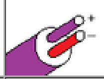
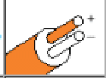
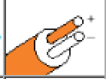
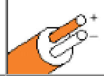
there is a net voltage.

Thermocouple structure

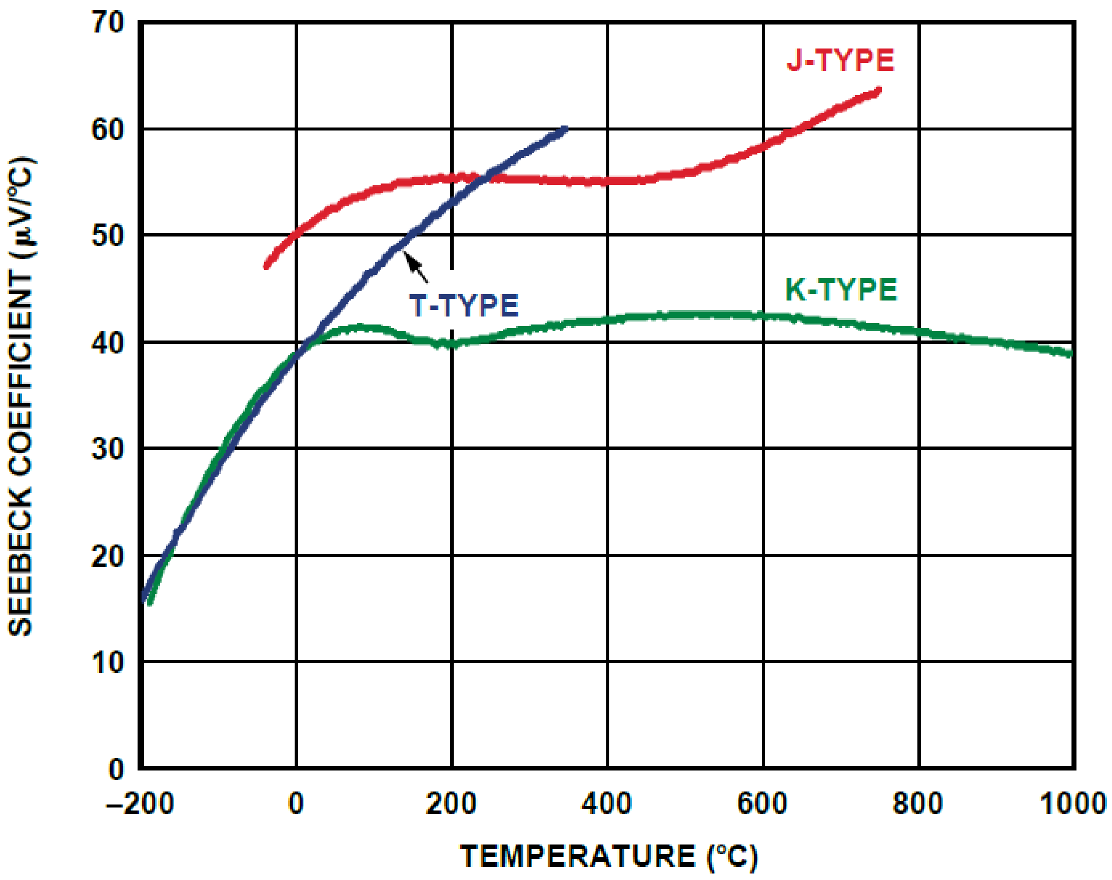


$$\Delta V_{meas} = \Delta V_{lead} + \Delta V_B - \Delta V_A - \Delta V_{lead} = \Delta V_B - \Delta V_A \quad \rightarrow \quad \Delta V_{meas} = \int_{T_R}^{T_M} (S_B(T) - S_A(T)) \cdot dT = \int_{T_R}^{T_M} S_{AB}(T) \cdot dT$$

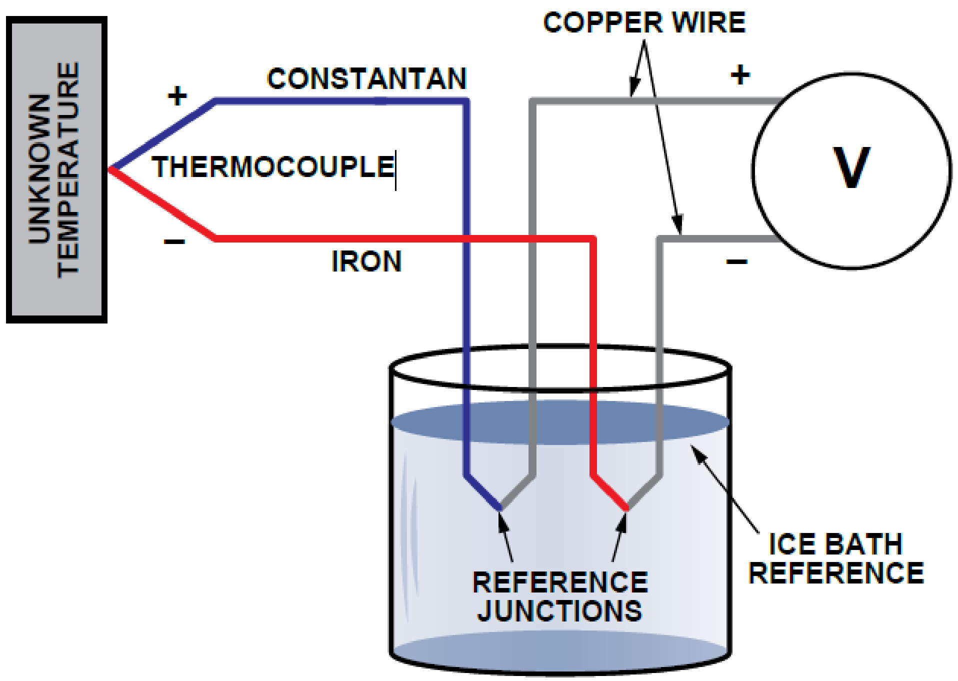
$$S_{AB}(T) = S_B(T) - S_A(T)$$

ANSI Code	Alloy Combination		Color Coding		Maximum Useful Temperature Range ++	Maximum Thermocouple Grade Temperature Range	EMF (mV) Over Max. Temperature Range	Standard Limits of Error** (above 0°C)	Special Limits of Error** (above 0°C)	International IEC 584-3	Comments Environment — Bare Wire	IEC Code
	+ Lead	- Lead	Thermocouple Grade	Extension Grade								
J	IRON Fe (magnetic)	CONSTANTAN COPPER-NICKEL Cu-Ni			Thermocouple Grade: 32 to 1382°F 0 to 750°C Extension Grade: 32 to 392°F 0 to 200°C	–346 to 2193°F –210 to 1200°C	–8.095 to 69.553	greater of 2.2°C or 0.75%	greater of 1.1°C or 0.4%		Reducing, Vacuum, Inert. Limited Use in Oxidizing at High Temperatures. Not Recommended for Low Temperatures.	J
K	CHROMEGA® NICKELCHROMIUM Ni-Cr	ALOMEGA® NICKEL-ALUMINUM Ni-Al (magnetic)			Thermocouple Grade: –328 to 2282°F –200 to 1250°C Extension Grade: 32 to 392°F 0 to 200°C	–454 to 2501°F –270 to 1372°C	–6.458 to 54.886	greater of 2.2°C or 0.75%	greater of 1.1°C or 0.4%		Clean Oxidizing and Inert. Limited Use in Vacuum or Reducing. Wide Temperature Range, Most Popular Calibration	K
T	COPPER Cu	CONSTANTAN COPPER-NICKEL Cu–Ni			Thermocouple Grade: –328 to 662°F –250 to 350°C Extension Grade: –76 to 212°F –60 to 100°C	–454 to 752°F –270 to 400°C	–6.258 to 20.872	greater of 1.0°C or 0.75%	greater of 0.5°C or 0.4%		Mild Oxidizing, Reducing Vacuum or Inert. Good Where Moisture Is Present. Low Temperature and Cryogenic Applications	T
E	CHROMEGA® NICKELCHROMIUM Ni-Cr	CONSTANTAN COPPER-NICKEL Cu-Ni			Thermocouple Grade: –328 to 1652°F –200 to 900°C Extension Grade: 32 to 392°F 0 to 200°C	–454 to 1832°F –270 to 1000°C	–9.835 to 76.373	greater of 1.7°C or 0.5%	greater of 1.0°C or 0.4%		Oxidizing or Inert. Limited Use in Vacuum or Reducing. Highest EMF Change Per Degree	E
N	OMEGA-P® NICROSIL Ni-Cr-Si	OMEGA-N® NISIL Ni-Si-Mg			Thermocouple Grade: –450 to 2372°F –270 to 1300°C Extension Grade: 32 to 392°F 0 to 200°C	–450 to 2372°F –270 to 1300°C	–4.345 to 47.513	greater of 2.2°C or 0.75%	greater of 1.1°C or 0.4%		Alternative to Type K. More Stable at High Temps	N
R	PLATINUM-13% RHODIUM Pt-13% Rh	PLATINUM Pt	NONE ESTABLISHED		Thermocouple Grade: 32 to 2642°F 0 to 1450°C Extension Grade: 32 to 300°F 0 to 150°C	–58 to 3214°F –50 to 1768°C	–0.226 to 21.101	greater of 1.5°C or 0.25%	greater of 0.6°C or 0.1%		Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temperature	R
S	PLATINUM-10% RHODIUM Pt-10% Rh	PLATINUM Pt	NONE ESTABLISHED		Thermocouple Grade: 32 to 2642°F 0 to 1400°C Extension Grade: 32 to 300°F 0 to 150°C	–58 to 3214°F –50 to 1768°C	–0.236 to 18.693	greater of 1.5°C or 0.25%	greater of 0.6°C or 0.1%		Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temperature	S
U	COPPER Cu	COPPER-LOW NICKEL Cu-Ni	NONE ESTABLISHED		Extension Grade: 32 to 122°F 0 to 50°C						Extension Grade Connecting Wire for R and S Thermocouples, Also Known as RX and SX Extension Wire.	U
B	PLATINUM-30% RHODIUM Pt-30% Rh	PLATINUM-6% RHODIUM Pt-6% Rh	NONE ESTABLISHED		Thermocouple Grade: 32 to 3092°F 0 to 1700°C Extension Grade: 32 to 212°F 0 to 100°C	32 to 3308°F 0 to 1820°C	0 to 13.820	0.5% over 800°C	NOT ESTABLISHED		Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temperature. Common Use in Glass Industry	B
G* (W)	TUNGSTEN W	TUNGSTEN-26% RHENIUM W-26% Re	NONE ESTABLISHED		Thermocouple Grade: 32 to 4208°F 0 to 2320°C Extension Grade: 32 to 500°F 0 to 260°C	32 to 4208°F 0 to 2320°C	0 to 38.564	greater of 4.5°C or 1.0%	NOT ESTABLISHED		Vacuum, Inert, Hydrogen. Beware of Embrittlement. Not Practical Below 399°C (750°F). Not for Oxidizing Atmosphere	G (W)
C* (W5)	TUNGSTEN-5% RHENIUM W-5% Re	TUNGSTEN-26% RHENIUM W-26% Re	NONE ESTABLISHED		Thermocouple Grade: 32 to 4208°F 0 to 2320°C Extension Grade: 32 to 1600°F 0 to 870°C	32 to 4208°F 0 to 2320°C	0 to 37.066	greater of 4.5°C or 1.0%	NOT ESTABLISHED		Vacuum, Inert, Hydrogen. Beware of Embrittlement. Not Practical Below 399°C (750°F) Not for Oxidizing Atmosphere	C (W5)
D* (W3)	TUNGSTEN-3% RHENIUM W-3% Re	TUNGSTEN-25% RHENIUM W-25% Re	NONE ESTABLISHED		Thermocouple Grade: 32 to 4208°F 0 to 2320°C Extension Grade: 32 to 500°F 0 to 260°C	32 to 4208°F 0 to 2320°C	0 to 39.506	greater of 4.5°C or 1.0%	NOT ESTABLISHED		Vacuum, Inert, Hydrogen. Beware of Embrittlement. Not Practical Below 399°C (750°F)–Not for Oxidizing Atmosphere	D (W3)

Thermocouple linearity



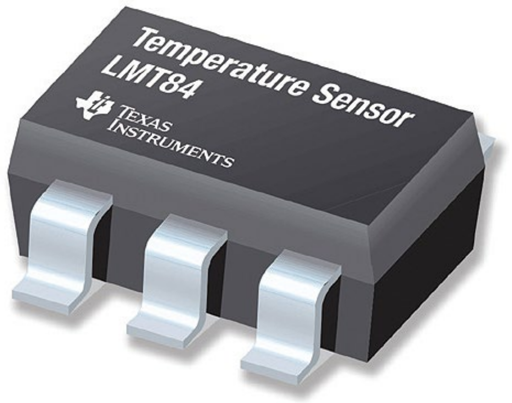
→ The voltage signal is not linear; a calibration is required.

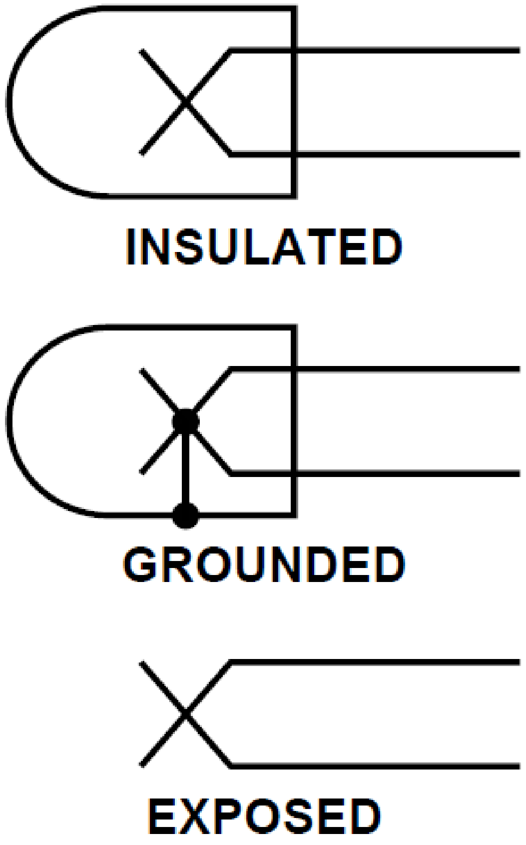


NOT PRACTICAL !!

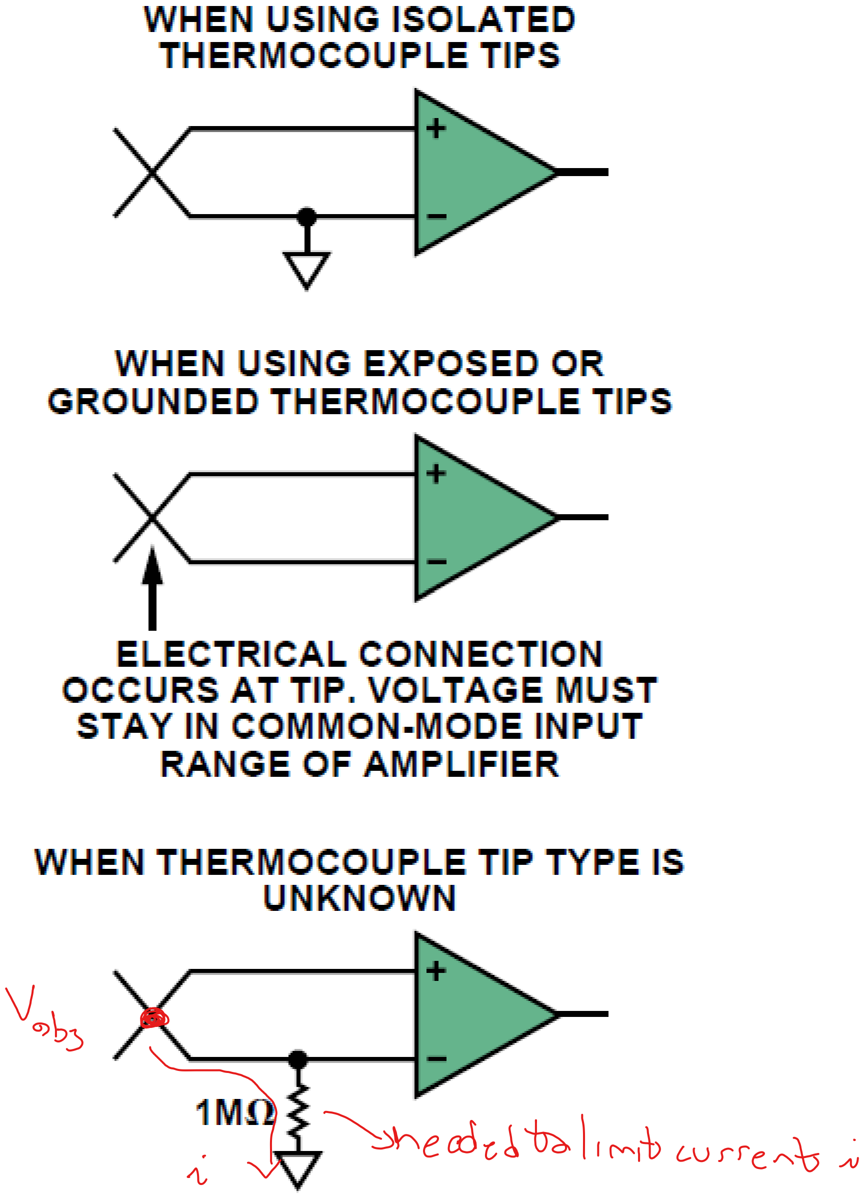
Reference-junction compensation
= the reference junction temperature is measured with another temperature sensitive device:

- RDT
- thermistor
- thermal diode
- integrated temperature sensor



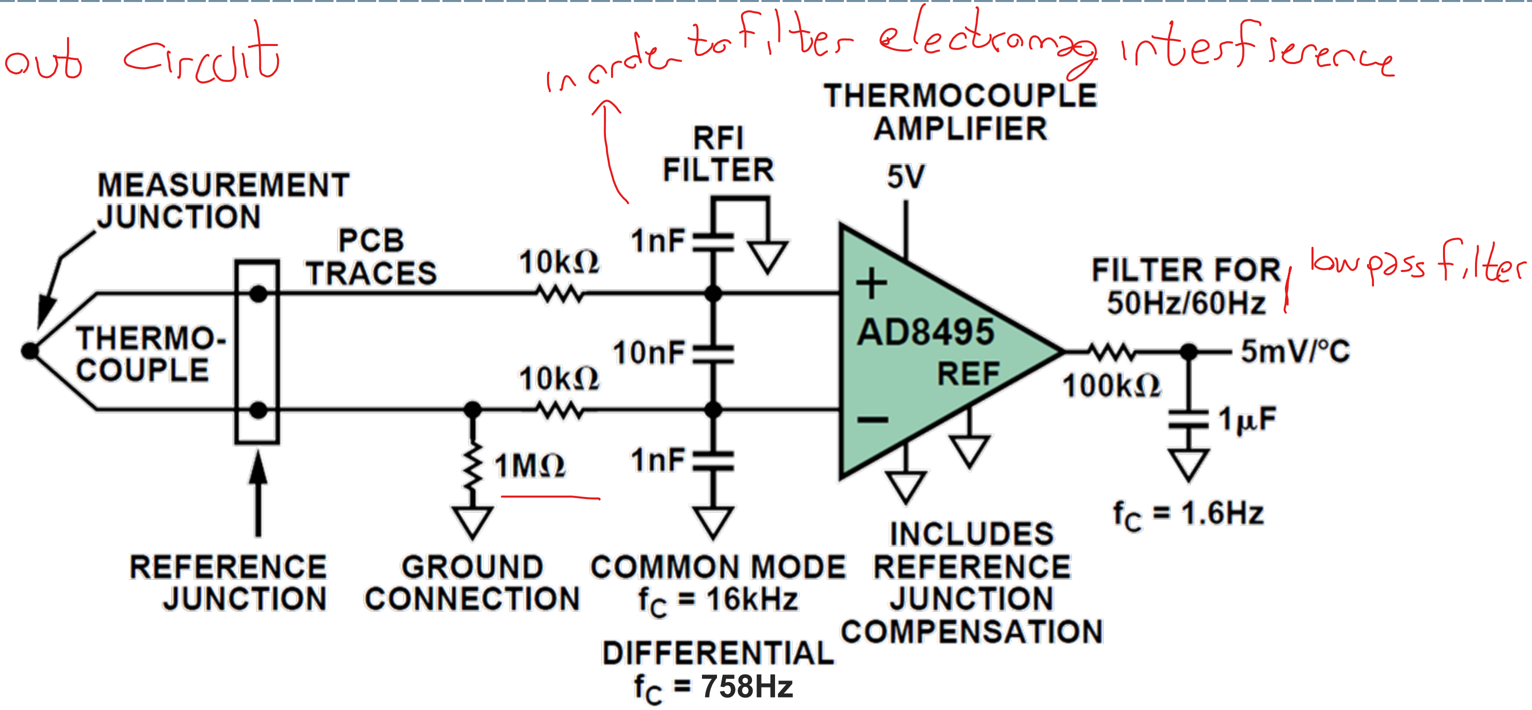


INSULATED
GROUNDED
EXPOSED



WHEN USING ISOLATED THERMOCOUPLE TIPS
WHEN USING EXPOSED OR GROUNDED THERMOCOUPLE TIPS
ELECTRICAL CONNECTION OCCURS AT TIP. VOLTAGE MUST STAY IN COMMON-MODE INPUT RANGE OF AMPLIFIER
WHEN THERMOCOUPLE TIP TYPE IS UNKNOWN
1MΩ
needed to limit current i
i

readout circuit



INA

Gain = 122

Ref Temperature compensation

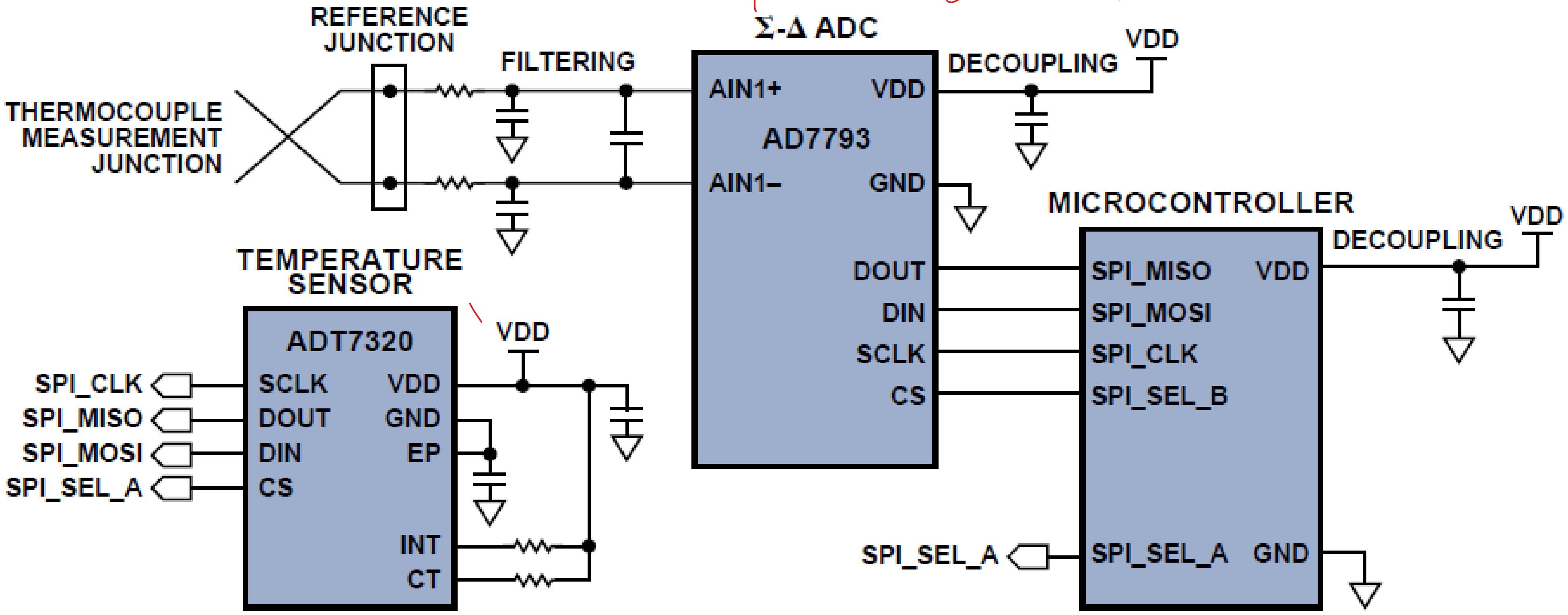
Non-linearity correction for k-thermocouples

Noise/disturbances reduction:

- Differential input (eliminates common mode disturbances)
- Radio Frequency Interference filter (low pass filter)
- Filter for 50/60Hz

Measuring circuits examples (2/2)

fast and single wire output



in order to measure temperature of junction

We have integrated ADC with MCU

- Flexible (J-, K-, T-type thermocouples)
- Optimized for accuracy
- INA included in the ADC

Thermocouple pros and cons

Pros

- Wide measuring ranges including very high limits
- Fast response times
- Tiny measuring point
- Moderate price
- No self heating
- Robust to mechanical stress

Cons (its only differential)

- Medium accuracy
- Low sensitivity
- Linearity is only fair
- Only relative temperature (not absolute)
- Signal strength is very low and prone to EMI problems

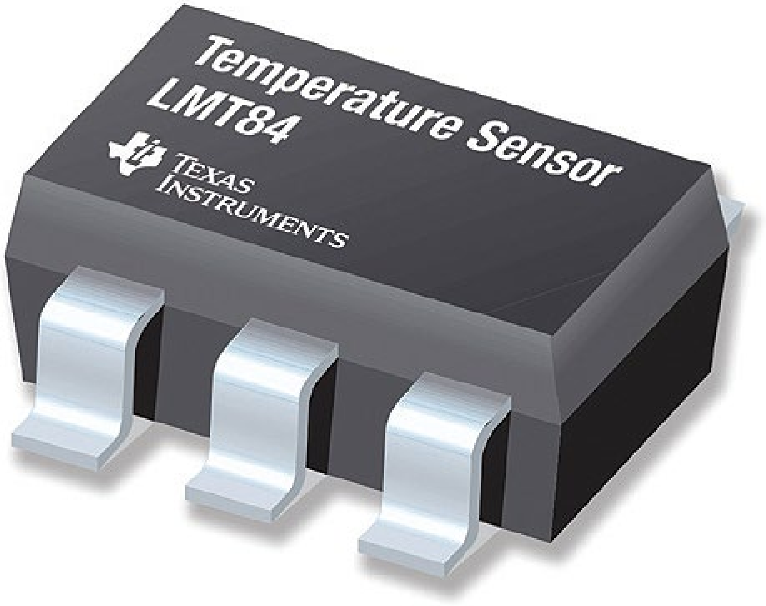
need another sensor to measure temp of junction

RTD, thermistor, termocouple comparison

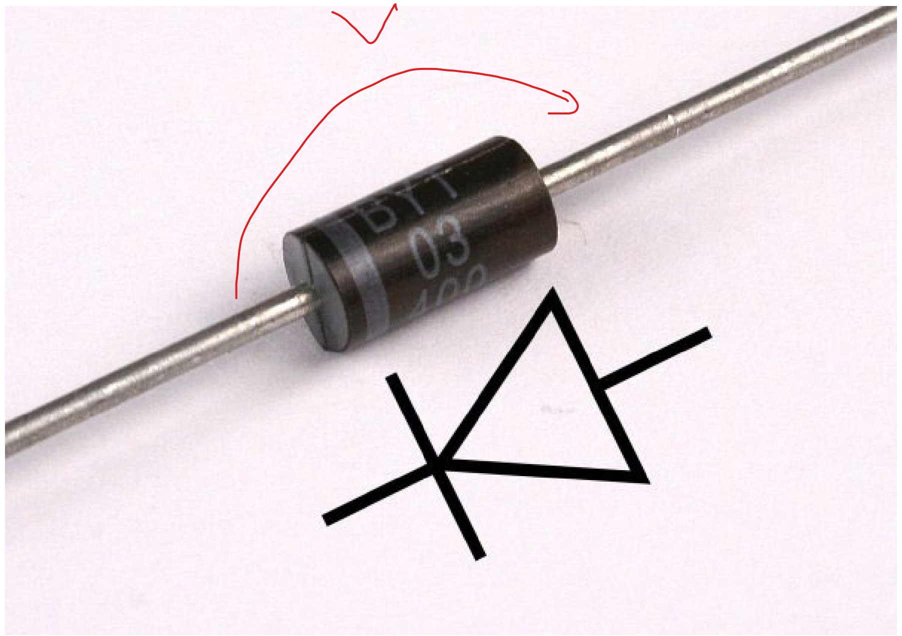
	RTD	Thermistor	Thermocouple
sensitivity	0.4 Ω/°C	**200 Ω/°C**	40-50 μV/°C
range	-200°C to 800°C	-100°C to 500°C	**-240°C to 2400°C**
accuracy	**0.5%**	1%	0.75%
linearity	**Best**	Not linear	Good
cost	≈ 5-10€	**≈ 0.5€**	≈ 5-10€

Diode and bandgap temperature sensors

Solid state (can be integrated in CMOS technologies)



Thermal diode



satur current → depends on temperature

$$I = I_s \cdot (e^{\frac{qV}{mkT}} - 1)$$

I_s reverse saturation current

m technology parameter

$$V = m\frac{kT}{q} \cdot ln\left(\frac{I}{I_S} + 1\right)$$

$$\downarrow$$

Sensitivity

$$\frac{\Delta V}{\Delta T} = m\frac{k}{q} \cdot ln\left(\frac{I}{I_S} + 1\right)$$

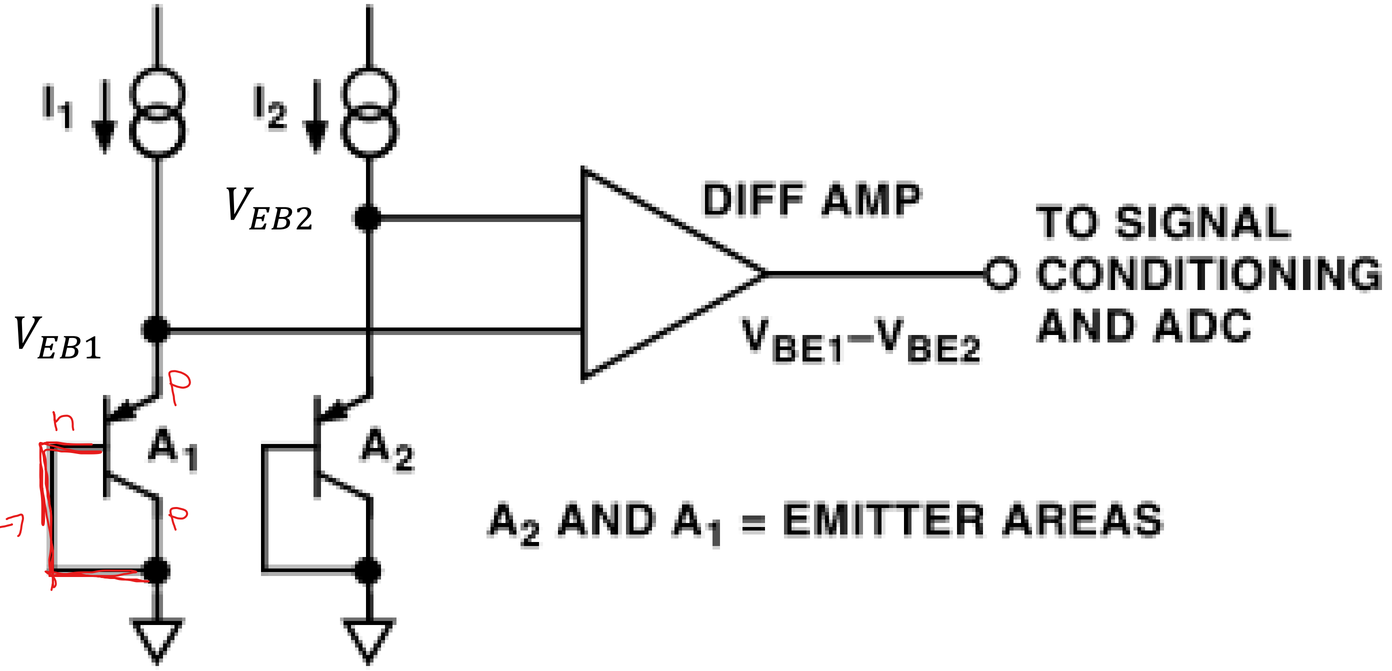
Not linear since I_s depends on temperature

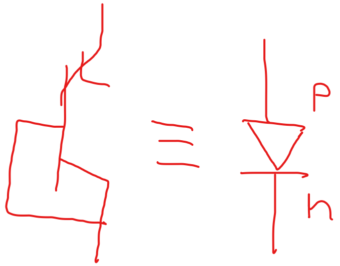
Bandgap temperature sensor

differential approach

BJT transistors

shorting together two junctions equivalent to diodes





$$V_{EB1} \approx \frac{kT}{q} \cdot ln\left(\frac{I_1}{A_1 J_s}\right) \quad V_{EB2} \approx \frac{kT}{q} \cdot ln\left(\frac{I_2}{A_2 J_s}\right) \rightarrow V_{EB1} - V_{EB2} = \boxed{\frac{kT}{q} \cdot ln\left(\frac{I_1 A_2}{I_2 A_1}\right)}$$

$J_s = \frac{I_s}{Area}$ constant cause same technologies and integrated.

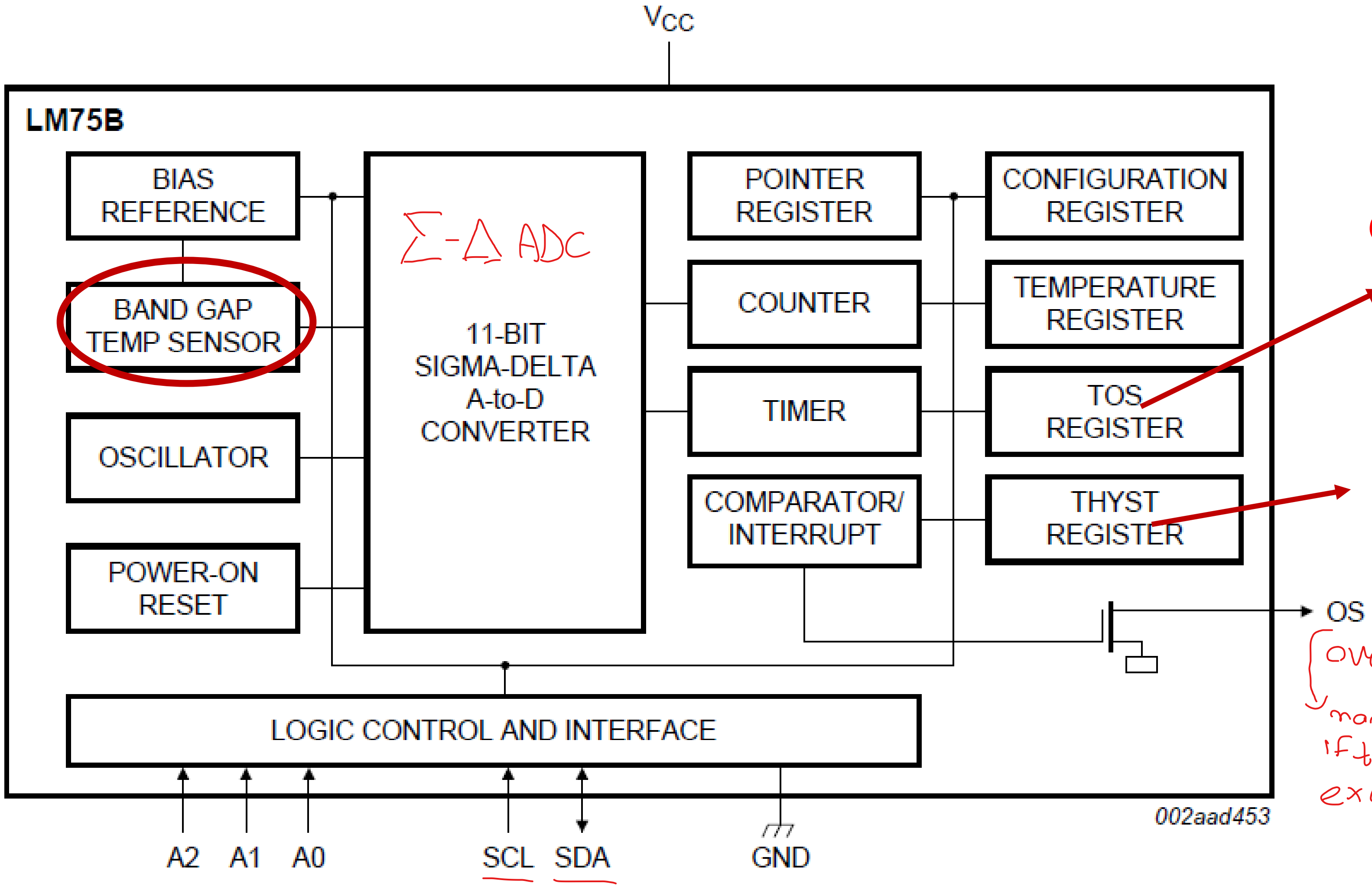
If $I_1 = I_2$ and $\frac{A_2}{A_1} = r$ $\rightarrow$ $V_{EB1} - V_{EB2} = \frac{kT}{q} \cdot \ln(r)$

Could also do opposite same area and diff I_1 and I_2

$T_{measured} = const \cdot (V_{EB1} - V_{EB2})$ with $const = \frac{q}{k \cdot \ln(r)}$

Digital temperature sensor

Smart sensor



Over-temperature shutdown

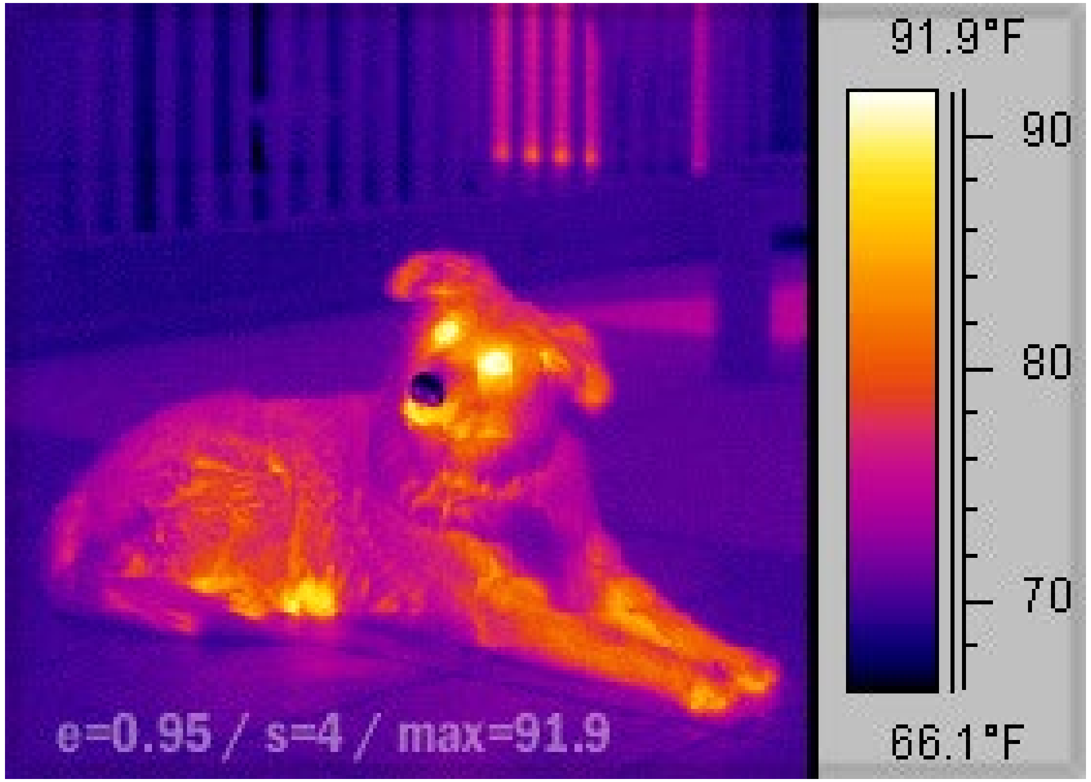
Hysteresis temperature

overtemperature shutdown

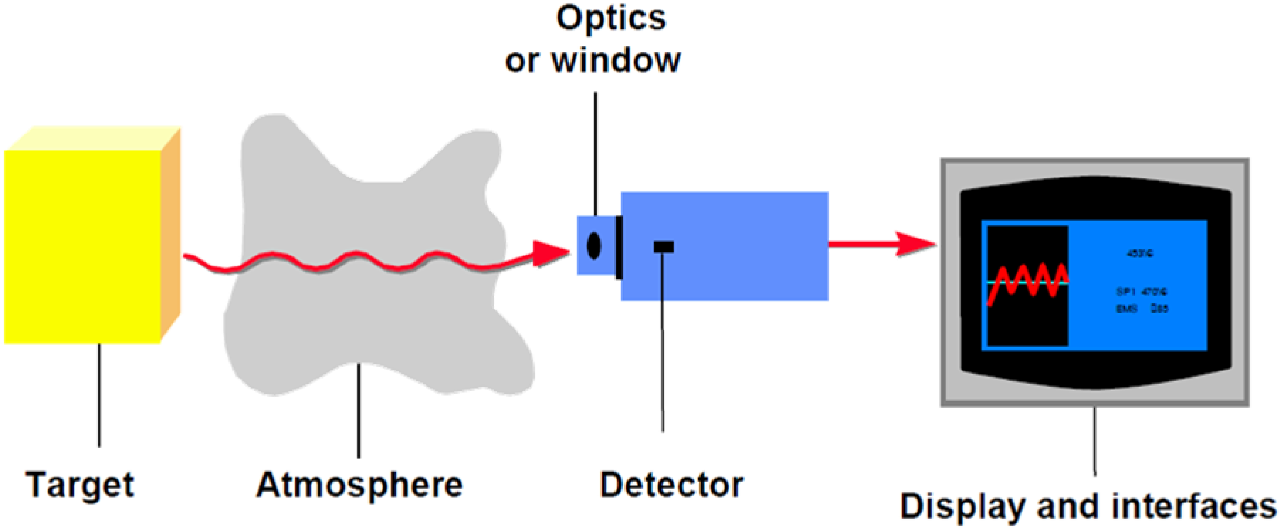
monitor pin in order to check if temperature threshold is exceeded

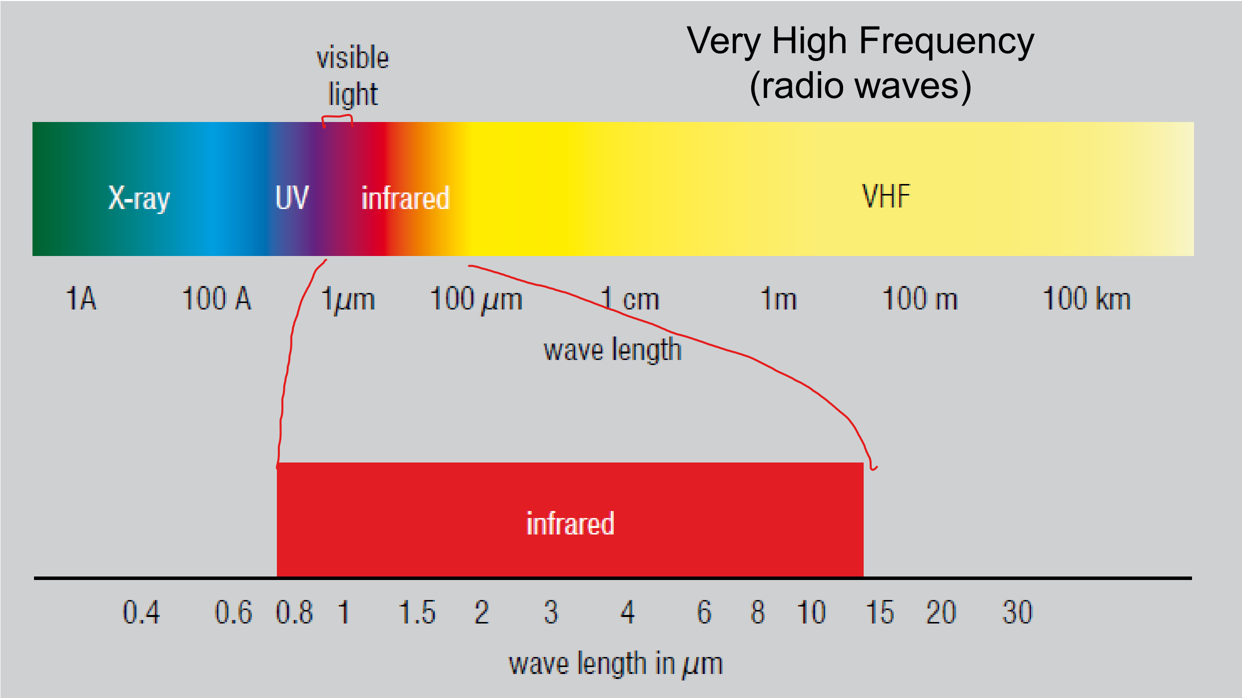
I^2C interface

measure IR emissions

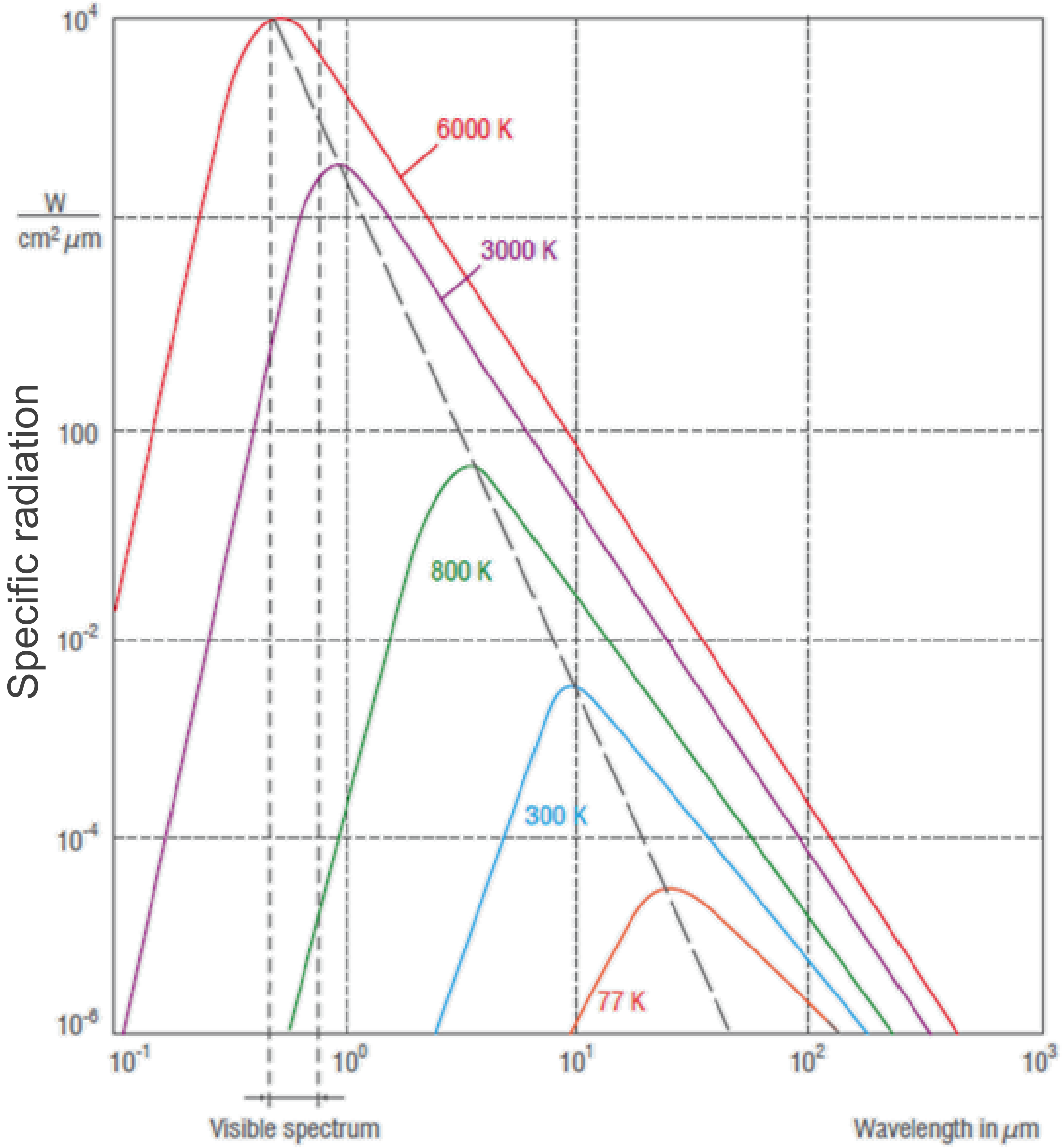


WeBeep: 09 – Infrared thermometer

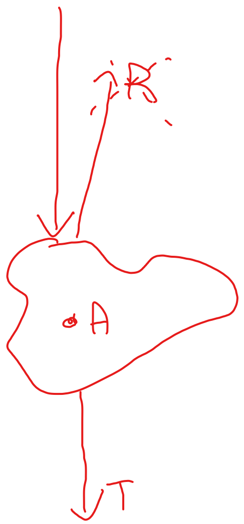

Optics
or window
Target
Atmosphere
Detector
Display and interfaces


visible
light
Very High Frequency
(radio waves)
X-ray
UV
infrared
VHF
1A
100 A
1µm
100 µm
1 cm
1m
100 m
100 km
wave length
infrared
0.4
0.6
0.8
1
1.5
2
3
4
6
8
10
15
20
30
wave length in µm

Black-body emission



for black body R=0 and T=0
only absorbed



Black-body:

A = ε = 1 R =T = 0

A absorption
ε emissivity
T transmissivity
R reflection

Stefan-Boltzmann law:

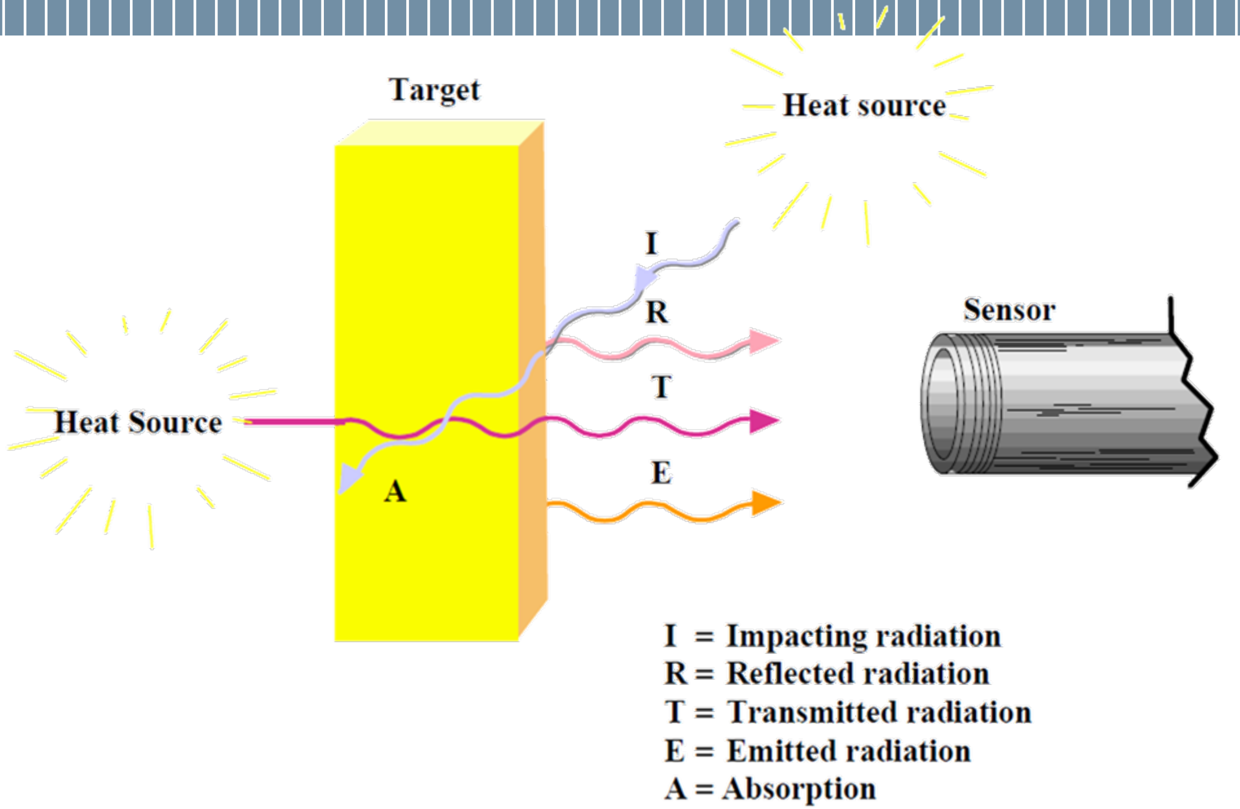
$$\frac{P}{A} = \varepsilon \cdot \sigma \cdot T^4$$

$\sigma = 5.67 \cdot 10^{-8}$ W/(m^2K^4)
Stefan-Boltzmann constant

Wien displacement law:

$$\lambda_{max} \cdot T = 2898\ \mu m \cdot K$$

Gray-body



Generic grey-body:

$A = \varepsilon < 1$
$R + T + \varepsilon = 1$

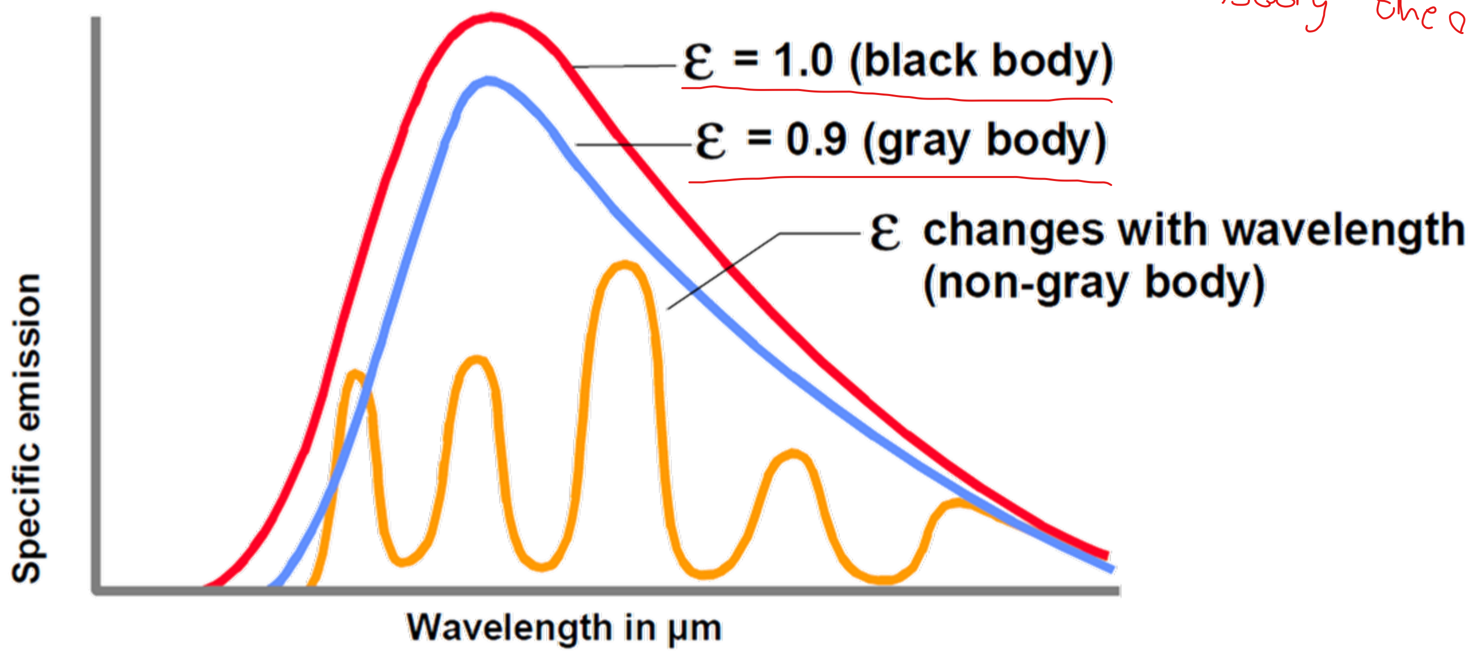
Solid grey-body:

$A = \varepsilon < 1$
$R + \varepsilon = 1 \quad T = 0$

Non-metallic materials (wood, plastic, rubber, organic materials, rock)
→ low reflectivity, high emissivity (0.8 - 0.95)
Metals (especially those with polished or shiny surfaces)
→ low emissivity (around 0.1)

→ Need of a calibration to estimate ε

ε is "how much of black body" the object is



Non gray-body: non-oxidized metals, glass, plastic films

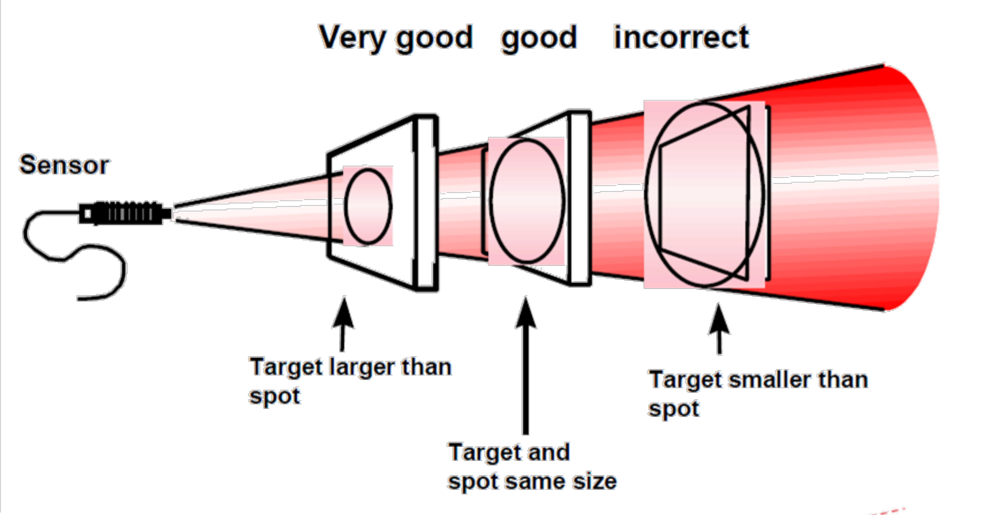
→ Better to consider one single wavelength

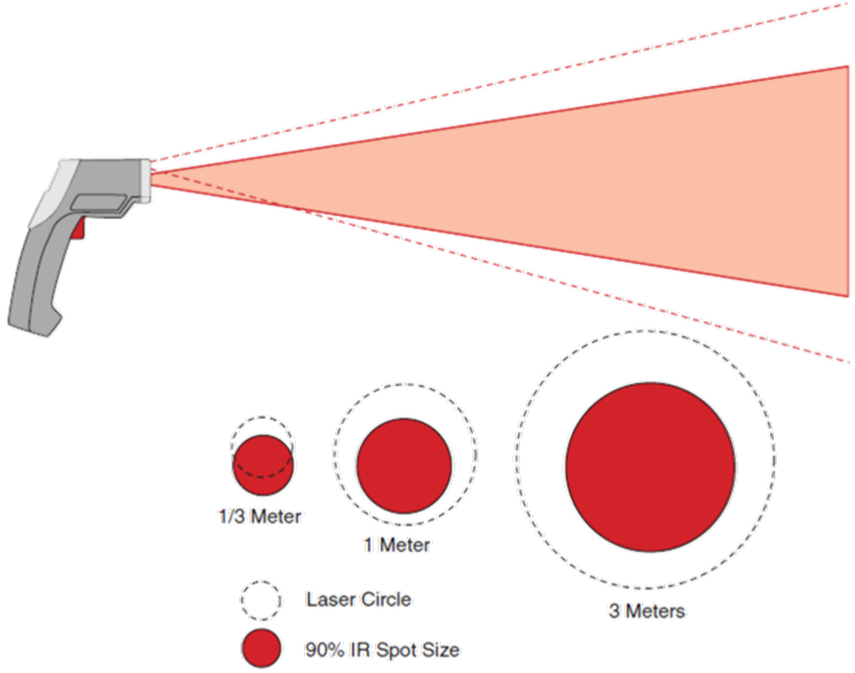
Determining emissivity

1) Determine temperature very accurately using a contact thermometer.
Then measure the target temperature with the IR thermometer and adjust ε.
Keep ε for all future measurements of that target.

2) Attach to the target a plastic sticker with known ε and use the infrared sensor to determine the temperature with the known ε.
Then measure the target temperature with the IR thermometer and adjust ε.
Keep ε for all future measurements of that target.

laser is only pointer





Single spot sensor

or

cameras

Laser pointer

for exact spot size making

(even very precise
coaxial pointers)

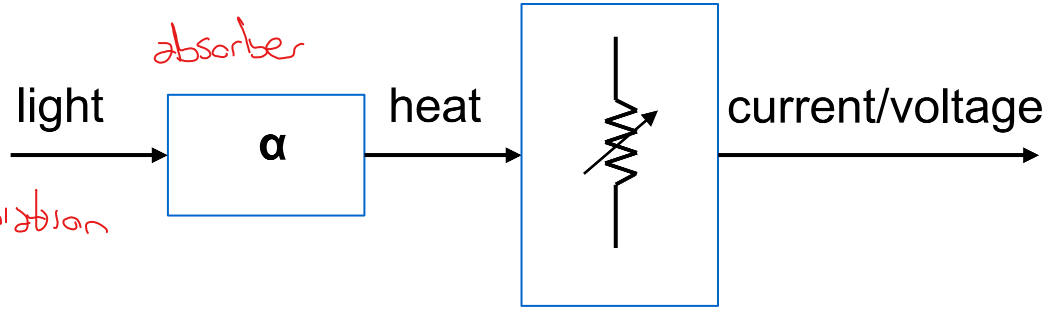
Infrared detectors

Thermal detectors:
- Thermopile detector
- Bolometer FPA (for IR cameras)
  (Focal Plane Array)
- Pyroelectric detector

Quantum detectors like normal photodiodes
can't do with silicon (high energy gaps)

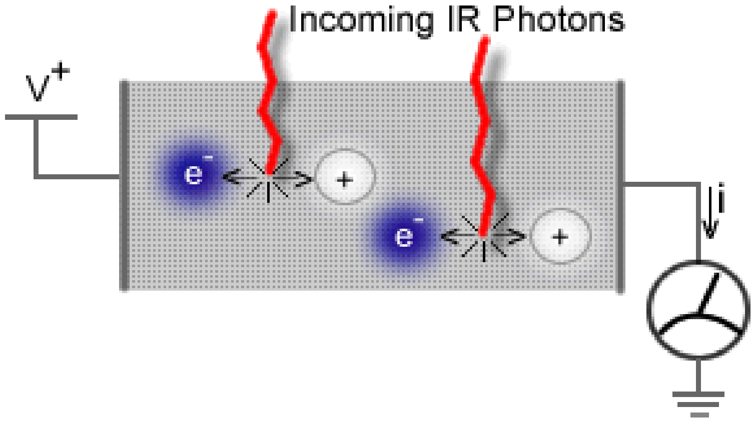
temperature sensor

absorber



radiation

Thermal detector

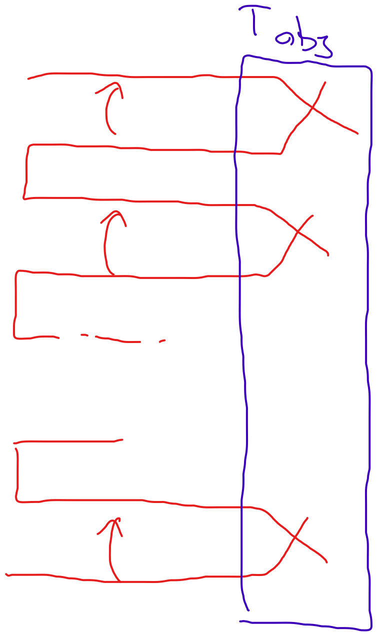


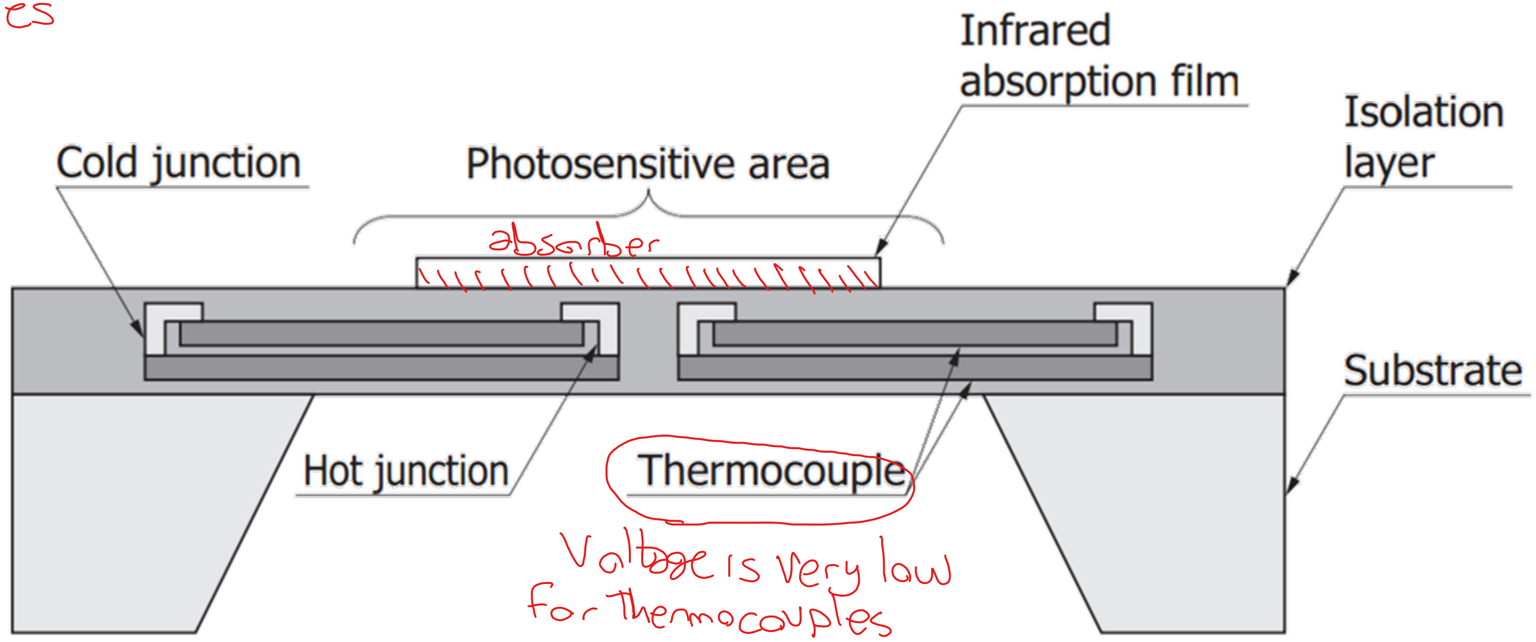
Quantum detector

Thermopile detectors

Single point detector

series of thermocouples





A large number of thermocouples in series
measure the temperature of the IR absorption film.

Larger photosensitive area → large number of thermocouples → better sensitivity

↓

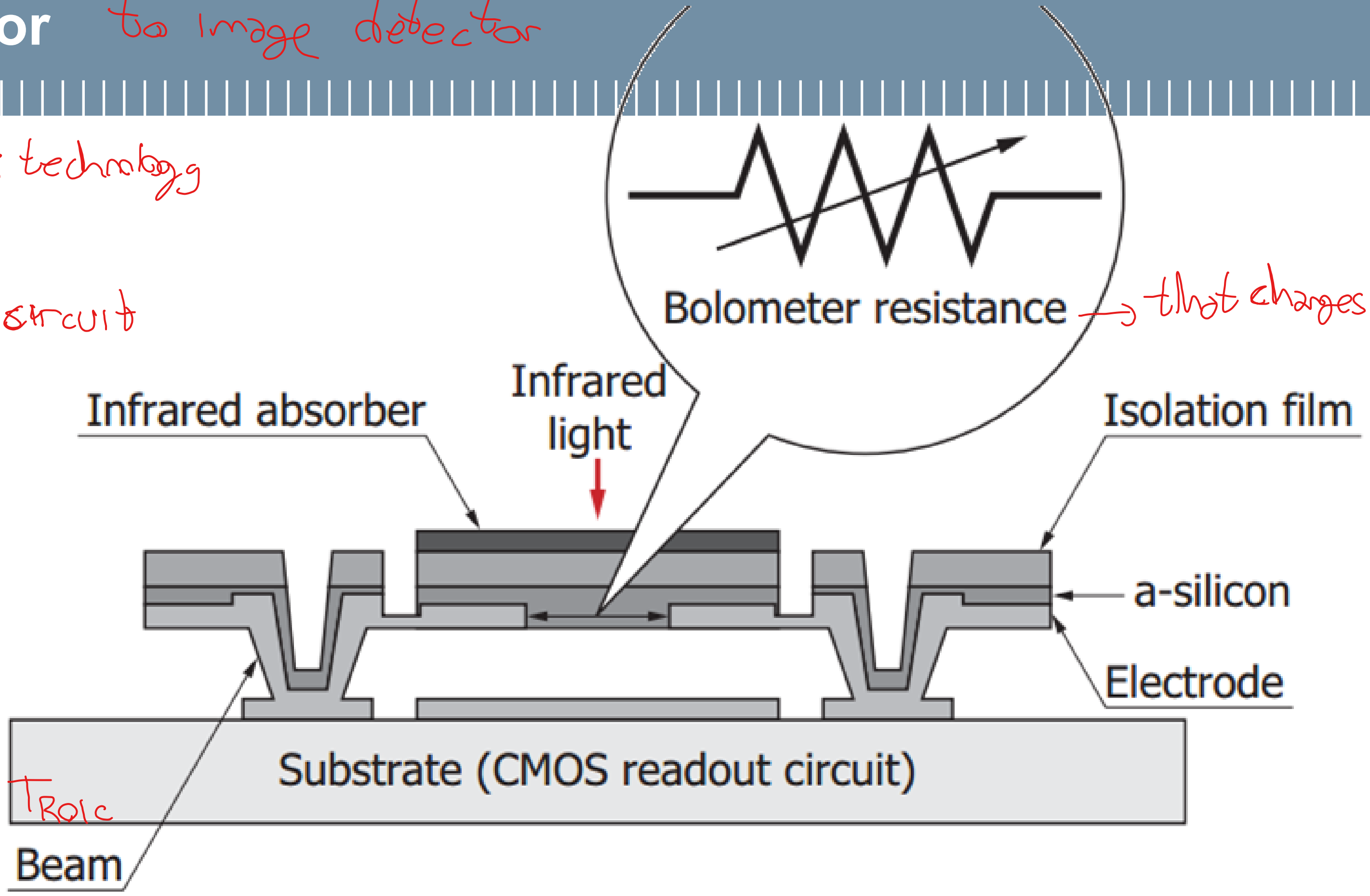
Typically single-element detector or array with limited number of elements

Bolometer detector

to image detector

can be integrated to CMOS technology

ROIC read out integrated circuit



→ that changes with temperature

Boolometer resistance = metallic or semiconductor PTC resistor.

+

Read Out Integrated Circuit to sense the resistance variations.

Thermal isolation between boolometer resistance and CMOS ROIC

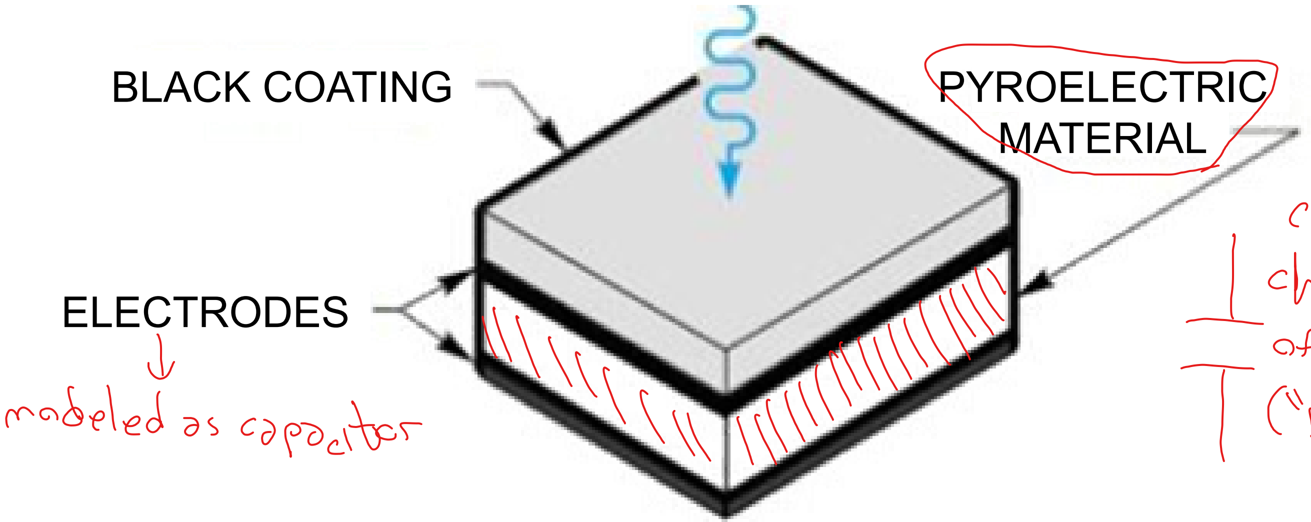
Commonly used for multi-pixel cameras.

Pyroelectric detector

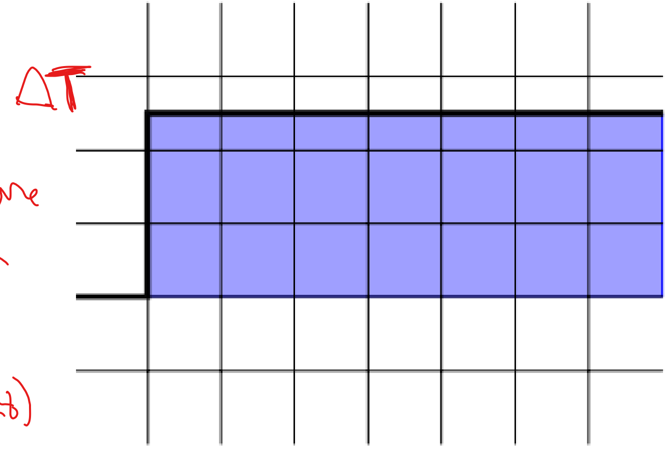
→ similar to piezoelectric effect

Variation of temperature

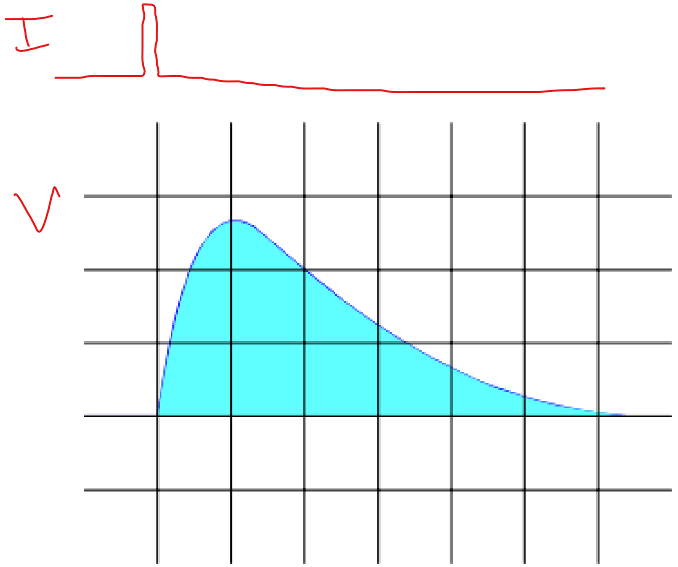
if we want to measure constant temperature: optical shutter



change in temperature changes polarization of dipole ("like" injecting current)



Infrared input to detector (step)

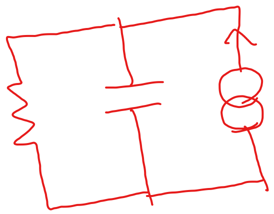


Response of pyroelectric detector

Pyroelectric material: heat variation polarizes dipoles

→ charge is collected on the electrodes (like in a capacitor)

leakage currents discharge the capacitor



↓

The incoming light is modulated with optical shutter.

Working principle similar to photodiode (electron-hole pair generation).

- II-VI materials: HgCdTe (Mercury Cadmium Telluride)

  → very low energy gap (0.1-0.4 eV)

- III-V materials: InAs/GaSb (Indium Arsenide-Gallium Antimonide)

  → very low energy gap (0.15 eV) of the heterojunction

Spectral responsivity: $S = \frac{\Delta_{out}}{\Delta_{in}}$ $\Delta V, \Delta R, \Delta Q \ldots$

For **thermal detectors** it is independent from λ.
Depends on the efficiency of the absorber and the sensitivity of the temperature sensor.

For **quantum detectors** ($S = \frac{I_{out}}{P_{in}}$) it depends on λ, in fact:

Detector efficiency: $\boxed{\eta = \frac{n_e}{n_p}}$ (n_e electrons generation rate, n_p incoming photons rate)

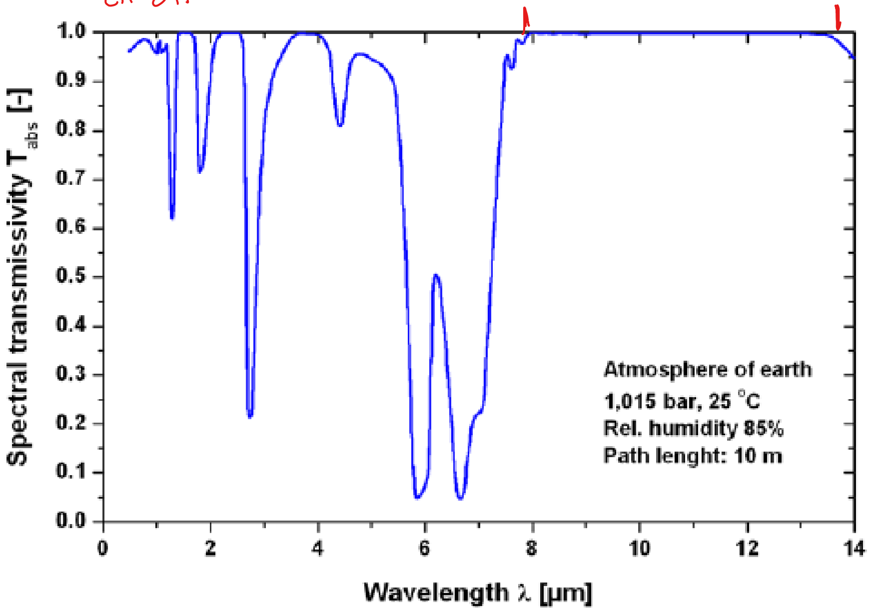
$$S = \frac{I}{P} = \frac{n_e \cdot q}{n_p \cdot h\nu} = \frac{n_e \cdot q}{n_p \cdot \frac{hc}{\lambda}} = \frac{n_e}{n_p} \cdot \frac{\lambda}{\frac{hc}{q}} = \eta \cdot \frac{\lambda}{1.24}$$

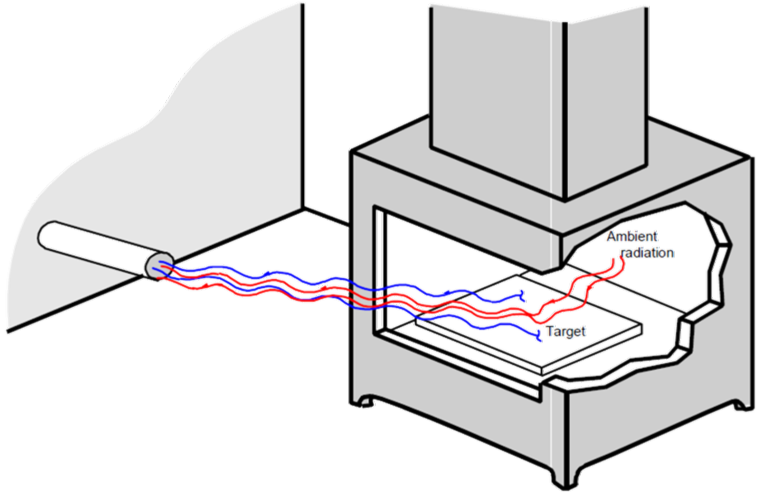
non-idealities

- Spectral transmissivity of air → wavelength selection
- Ambient radiations → Compensation or shielding
- Dust and particles in the ambient → Auto polishing of lenses

absorpsion of air

flat on long wavelength infrared





Applications

- Maintenance and service in industrial applications

  (moving machines, medium and high voltage facilities…)

- Measuring temperature of electronic circuits

- Over-heating of electric bus contacts

- Checking of transformers

- Localization of defective cables