Electronics – 96032

POLITECNICO DI MILANO

Deformation and Temperature Sensors

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Disclaimer

Slides are supplementary material and are NOT a replacement for textbooks and/or lecture notes

Purpose of the lesson

- At this point, we know how to analyze and design simple amplifiers
- Effective amplifier design depend upon the input signal characteristics (impedance, bandwidth,…)
- In this part of the class we discuss a few sensor arrangement:
  - Wheatstone bridge (previous lesson)
  - Deformation and temperature sensors (this lesson)
  - Sensor technologies (optional overview)

Outline

- Deformation sensors
- Resistive temperature sensors
- Seebeck effect and thermocouples
- Appendix

Stress and strain

- For the uniform case under normal load we define the stress as

$$\sigma = \frac{F}{S}$$

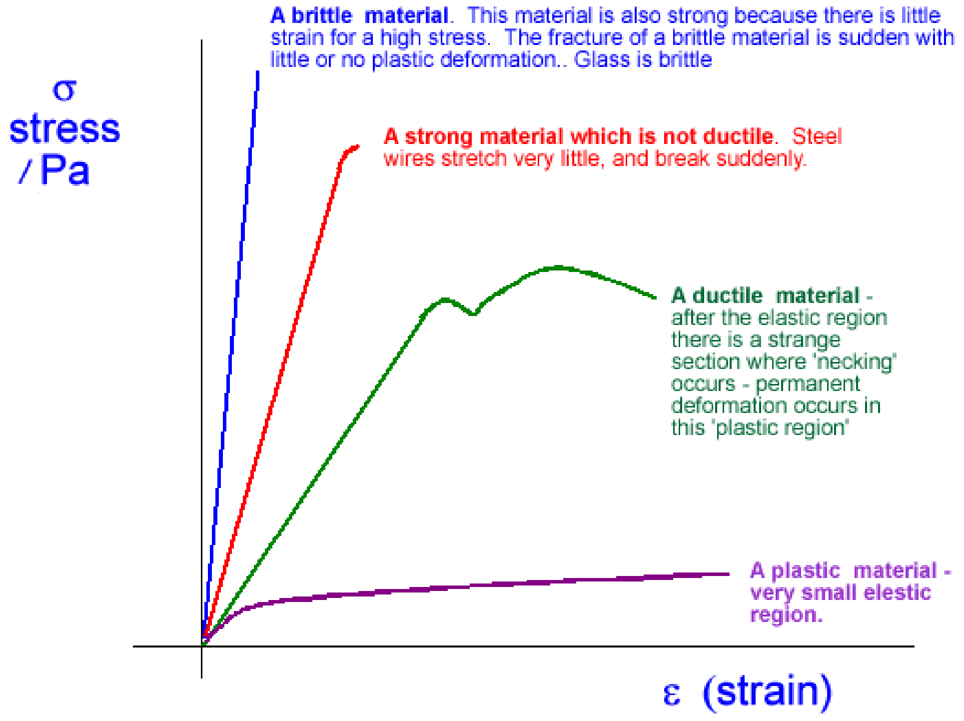
- Strain is the deformation per unit length

$$\varepsilon = \frac{\Delta L}{L}$$

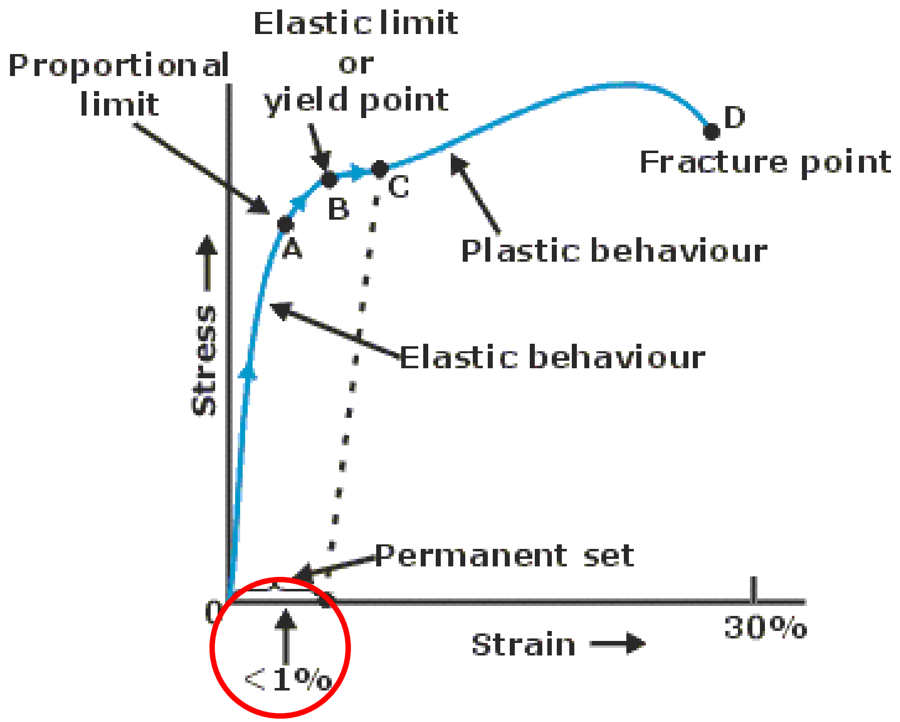
typical values are a few 10^{-3}; the value is usually expressed in *μstrain*

Materials behavior

From [1]



From [2]



In the elastic region, the material will return to its original shape when the stress is removed

Hookes’ law

- In the elastic region

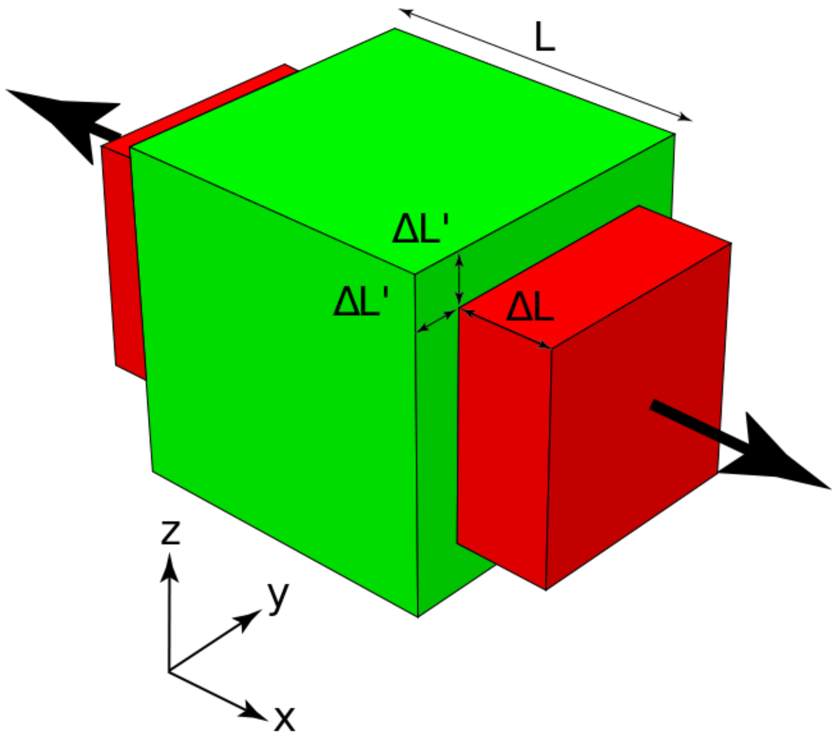
$$\sigma = E\varepsilon$$

where E = Young (or elasticity) modulus

- Axial strain is always accompanied by lateral strains of opposite sign in the two directions perpendicular to the axial strain
- Their ratio is called Poisson ratio

$$\nu = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}}$$

Poisson ratio and volume change



From [3]

$$V' = L^3(1+\varepsilon)(1-\nu\varepsilon)^2$$
$$\approx L^3(1+\varepsilon(1-2\nu))$$

$$\frac{\Delta V}{V} = \varepsilon(1-2\nu)$$

- If there is no volume change, $\nu = 0.5$
- Theoretical limits are $-1 < \nu \leq 0.5$

Typical values

- For compact, weakly compressible materials such as liquids and rubbers, where stress primarily results in shape change, $\nu \to 0.5$
- For most well-known solids such as metals, polymers and ceramics, $0.25 < \nu < 0.35$
- Glasses and minerals are more compressible, and for these $\nu \to 0$
- For gases, $\nu = 0$
- Materials with negative Poisson's ratio are called "auxetic" (e.g., *Gore-Tex*)

Strain gages/gauges

- Convert strain into a resistance change:

$$R = \rho \frac{L}{S}$$

Piezoresistivity

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta S}{S} = \frac{\Delta \rho}{\rho} + \varepsilon(1 + 2\nu)$$

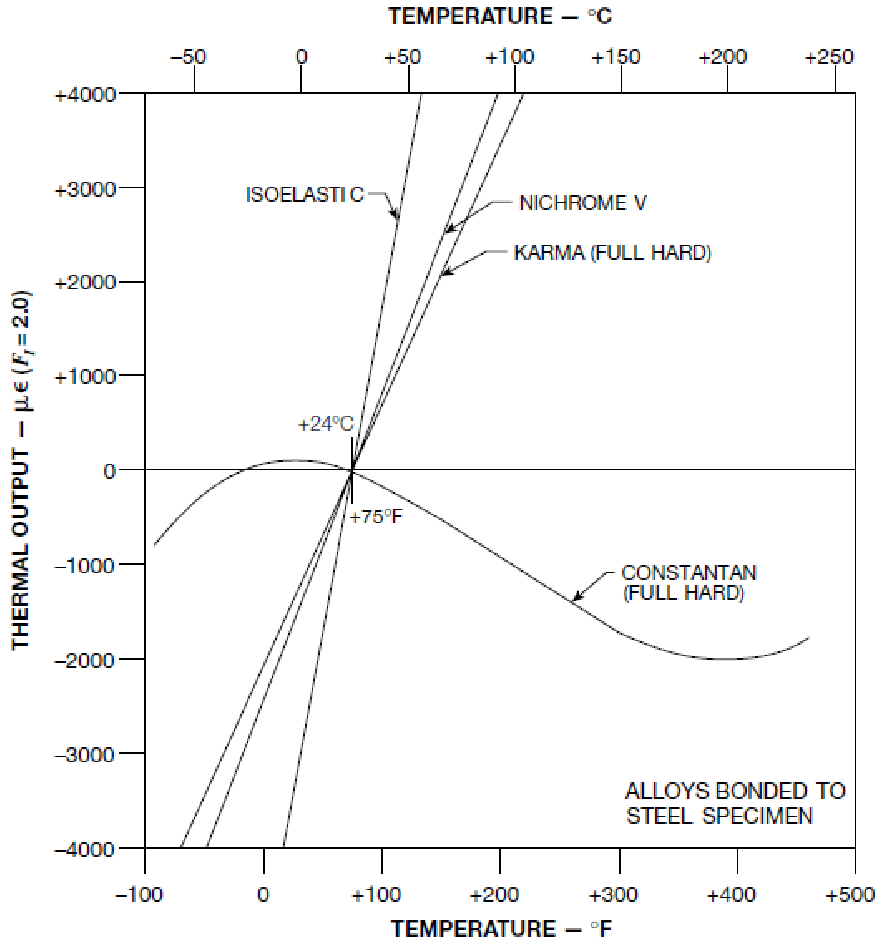
- The gauge factor (GF) is defined as

$$GF = \frac{\Delta R/R}{\varepsilon} = 1 + 2\nu + \frac{\Delta \rho/\rho}{\varepsilon}$$

Typical values

Material	GF
Constantans (Ni-Cu alloys)	$1.8 - 2.2$
Ni-Cr alloys	~ 1.9
Ni	-12
Pt-Ir	~ 5
Si (with various impurities)	$\pm 100 - \pm 200$
Poly-Si	± 30

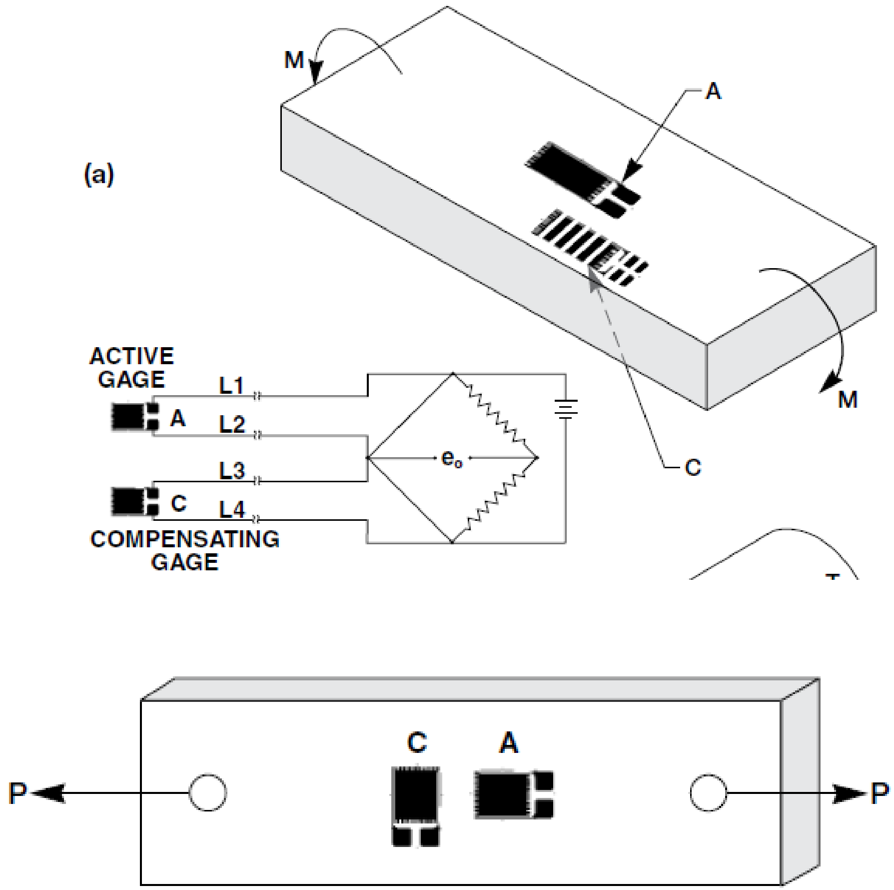
Temperature effects



From [9]

- SG resistance and GF depend on T
- T-compensated gages are available, depending on the substrate material
- Correction curves are also available

Dummy gage compensation



From [9]

- The compensation gage must be unstrained or suitably mounted to increase the output signal
- The temperature should be the same and the two SGs identical

References

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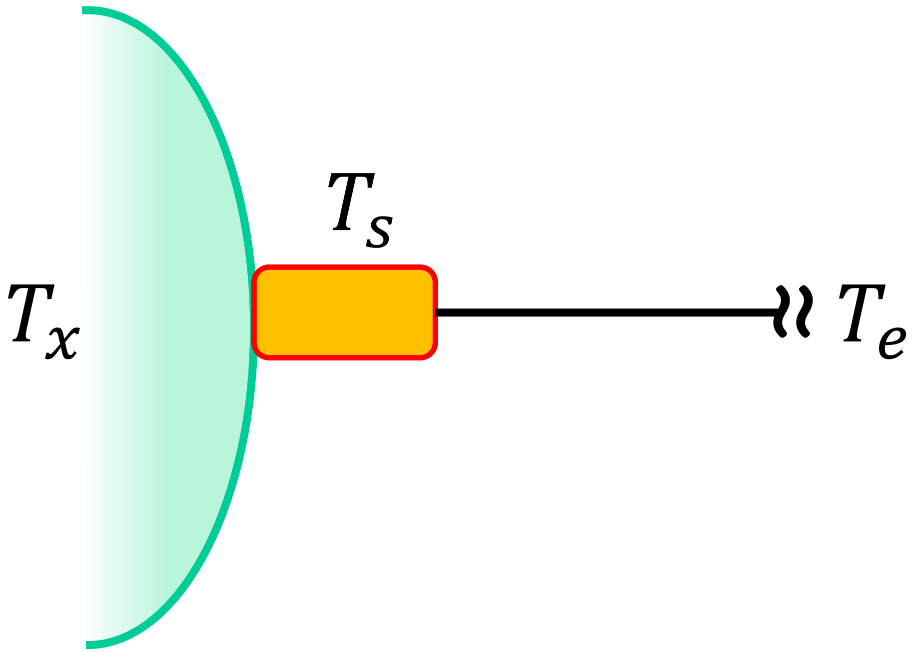
Outline

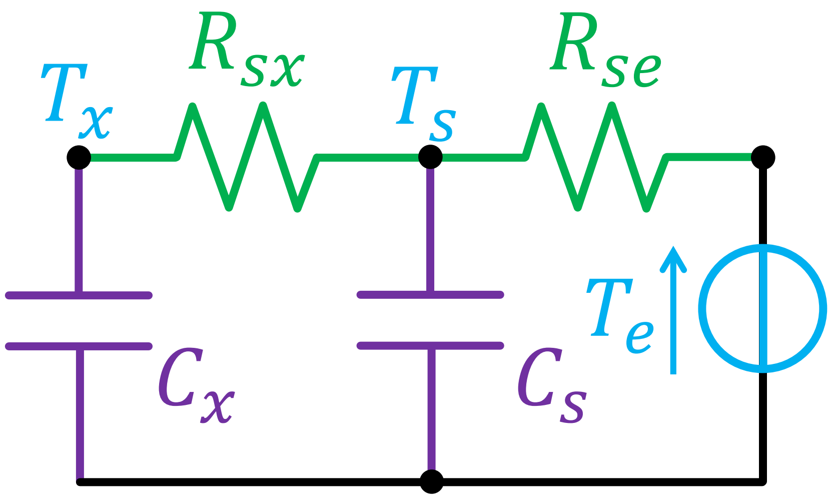
- Deformation sensors
- Resistive temperature sensors
- Seebeck effect and thermocouples
- Appendix

Contact sensors



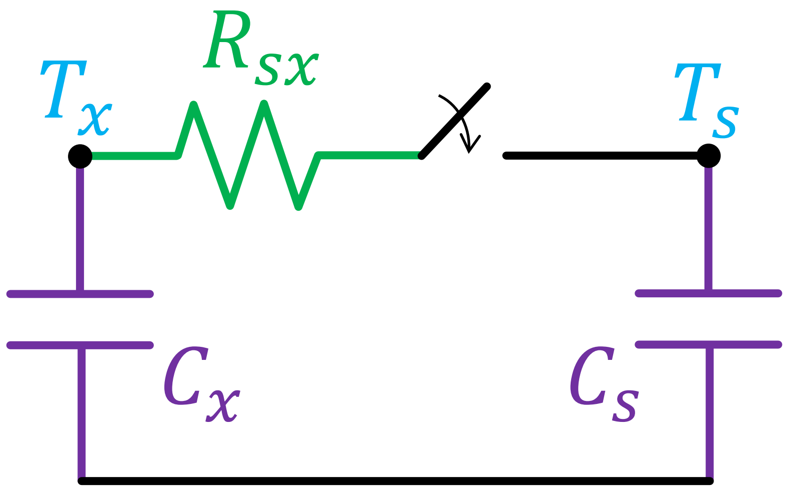
Goal is to make T_s as close to T_x as possible

Thermal circuit (Kelvin, 1841)



Thermal	Electrical
Temperature [K]	Voltage
Heat flow [W]	Current
Thermal resistance [K/W]	Resistance
Heat capacity [J/K]	Capacitance
$Q = \frac{\Delta T}{R_T}$	$I = \frac{\Delta V}{R}$
$Q = C_T \frac{dT}{dt}$	$I = C \frac{dV}{dt}$

Isolated system + sensor

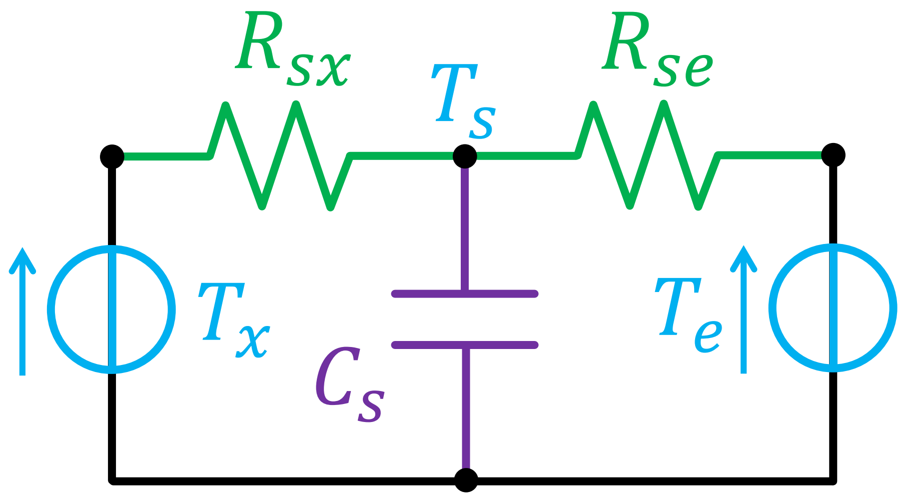


$$\tau = \frac{R_{sx}}{1/C_s + 1/C_x}$$

$$T_F = \frac{C_s T_s(0) + C_x T_x(0)}{C_s + C_x}$$

A small C_s minimizes both static and dynamic errors

Environment



$$\tau = C_s(R_{sx}||R_{se})$$

$$T_F = T_x + (T_e - T_x)\frac{R_{sx}}{R_{sx} + R_{se}}$$

A large R_{se}/R_{sx} is required to improve the sensor accuracy

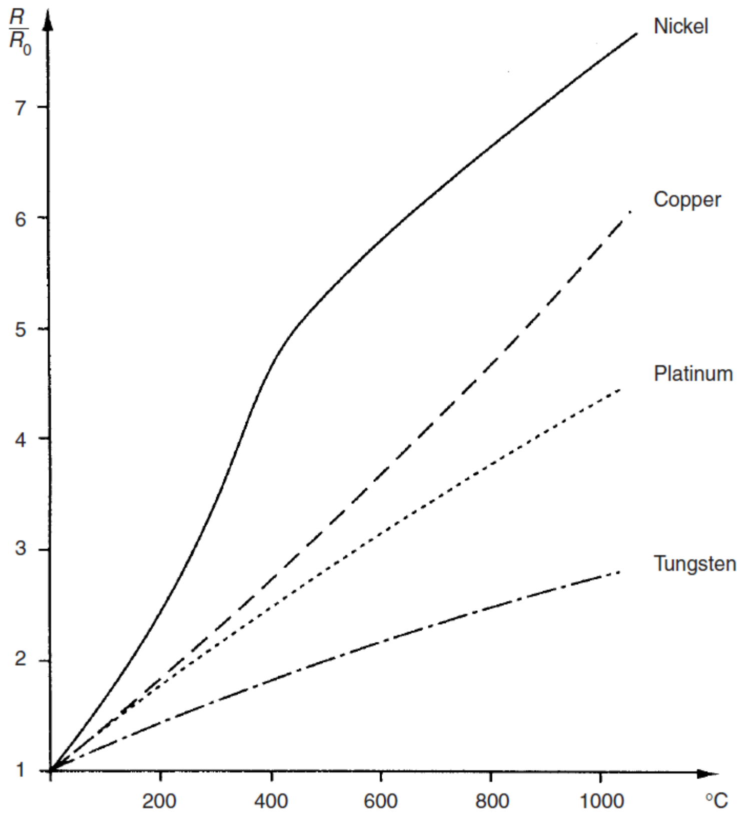
Requirements

- Small C_s
  - Small sensor
- Small R_{sx}
  - Good thermal contact $\Rightarrow$ maximize contact area and (for solids) use good thermal grease
- Large R_{se}
  - «Right» sensor connections $\Rightarrow$ use long, narrow connections with low thermal (and good electrical) conductivity (e.g., stainless steel, lead,…)

RTDs

- Resistance Temperature Detectors (RTDs) exploit the resistance change with temperature in certain metals
- They can provide highly accurate results (from 0.1 to 0.0001°C) and are used to assign the TP temperatures between about 14 and 1200 K
- Expensive!

Resistance of metals



From [1]

- Metal resistance increases with T
  $$R = R_0(1 + a_1T + a_2T^2 + \cdots + a_nT^n)$$
- For small T range, a linear approximation is used, characterized by its relative slope
  $$\alpha = TCR = \frac{1}{R_0}\frac{\Delta R}{\Delta T}$$
- TCR = temperature coeff. of resistance (usually computed between 100 and 0°C)

TCR values

Metal	T range [°C]	TCR [°C^{-1}]
Pt	$-200, +850$	3.85×10^{-3}
Ni	$-100, +200$	6.72×10^{-3}
Cu	$-100, +250$	4.27×10^{-3}
W	$-100, +400$	4.8×10^{-3}

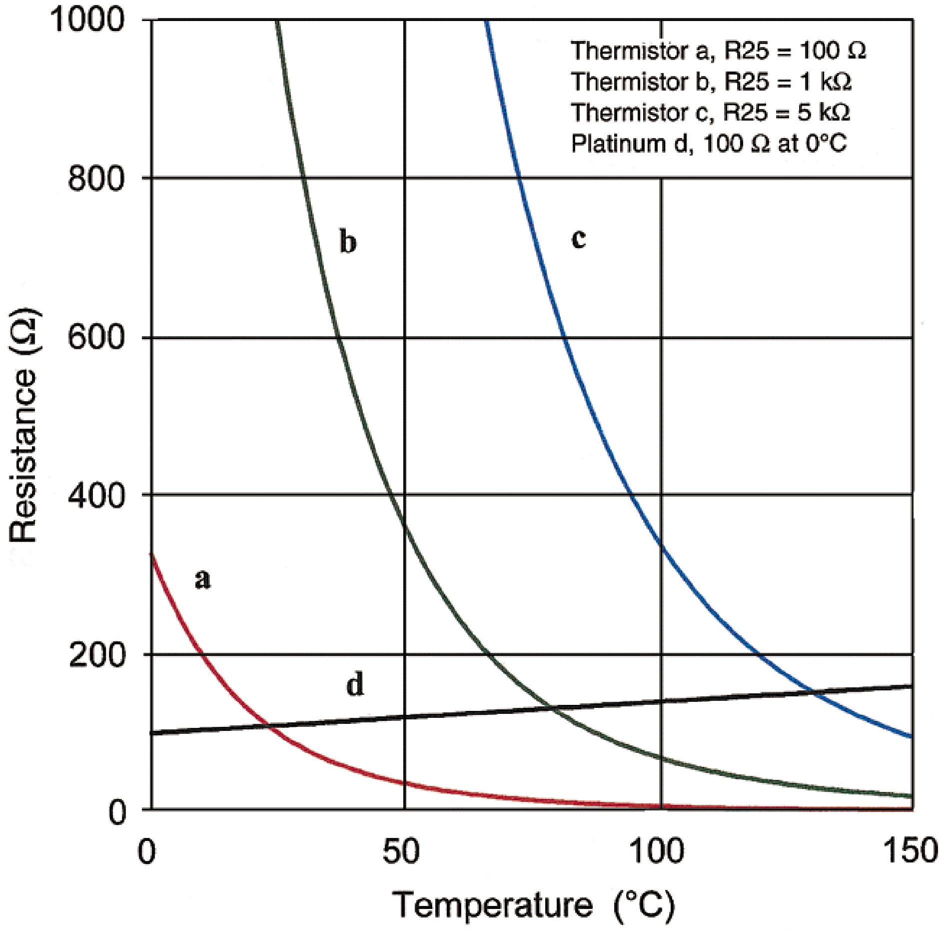
Pt RTD

- Platinum is mostly used for RTDs
  - Chemical inertness
  - Large enough TCR
  - Strain-free fabrication and weak dependence of R on strain
  - Almost linear $R - T$ relationship
- Resistance at 0°C is usually 100 or 1000 Ω (PT100 or PT1000 RTDs)
- Expensive!

Thermistors

- Made with transition metal (Cr, Co, Cu, Mn, Ni,…) oxides and showing a semiconductor-like behavior
- Strongly non-linear $R - T$ characteristic, but with high TCR, either positive (PTC) or negative (NTC)
- NTCs only are useful as sensors

R-T characteristics



From [7]

- The *R-T* characteristics of NTC thermistors follow the intrinsic semiconductor behavior

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

- Resistance value is usually referenced at 25°C and varies between 100 Ω and 100 kΩ

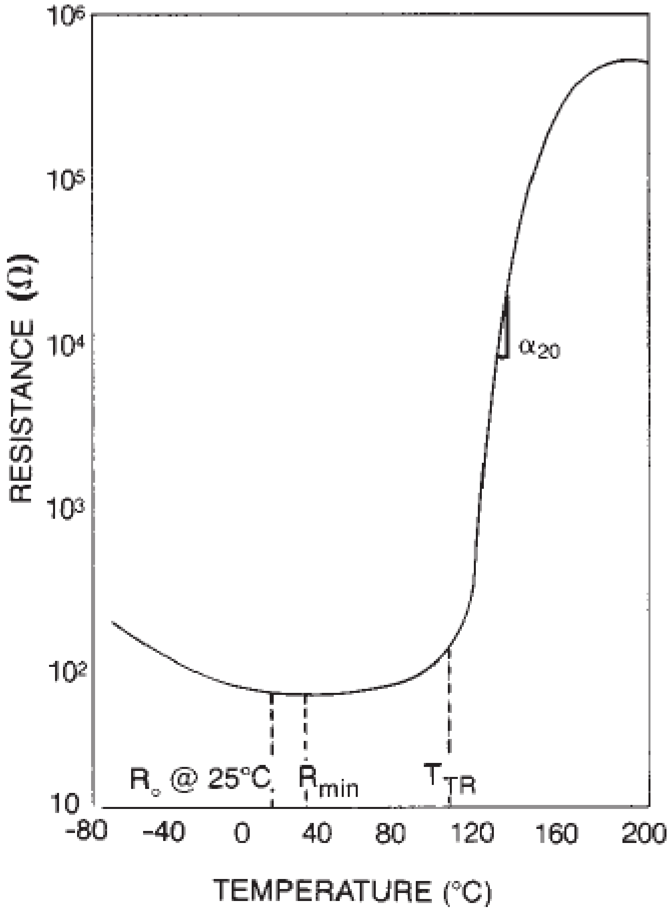
TCR of NTC thermistors

- The TCR can be expressed as

$$TCR = \alpha = -\frac{B}{T^2}$$

- Typical values are -3 to $-5\ \times 10^{-2}$/°C, i.e. about one order of magnitude larger than RTDs
- Owing to the large signal, 3- or 4-wire bridges are usually not necessary
- NTC thermistors are generally used between -50 and $+150$°C (up to 300°C for some glass-encapsulated units)

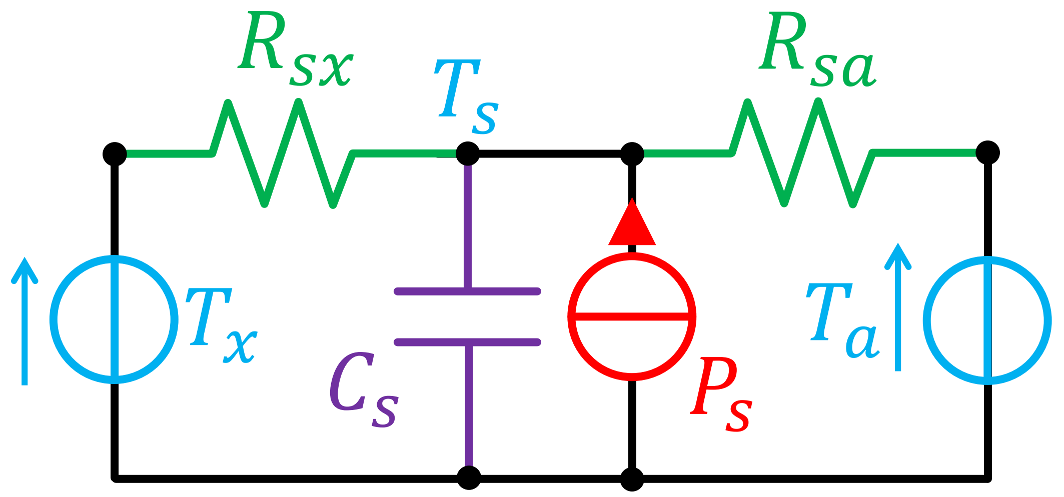
PTC thermistors



From [12]

- Polycrystalline ceramic materials made semiconductive by the addition of dopants
- Manufactured using compositions of Ba, Pb, and Sr titanates with additives (Y, Mn, Ta,…)
- Used as overcurrent protection, heaters,…

Sensor self-heating



$$T_F \approx T_x + P_s R_{sx}$$

- Ex. $I = 1$ mA, $R_{sx} = 1$°C/mW. For a PT100 RTD, $P_s = 100$ μW, i.e., $\Delta T = 0.1$°C
- If lower currents cannot be used, pulsed measurements (with synchronous detection) must be employed

References

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Outline

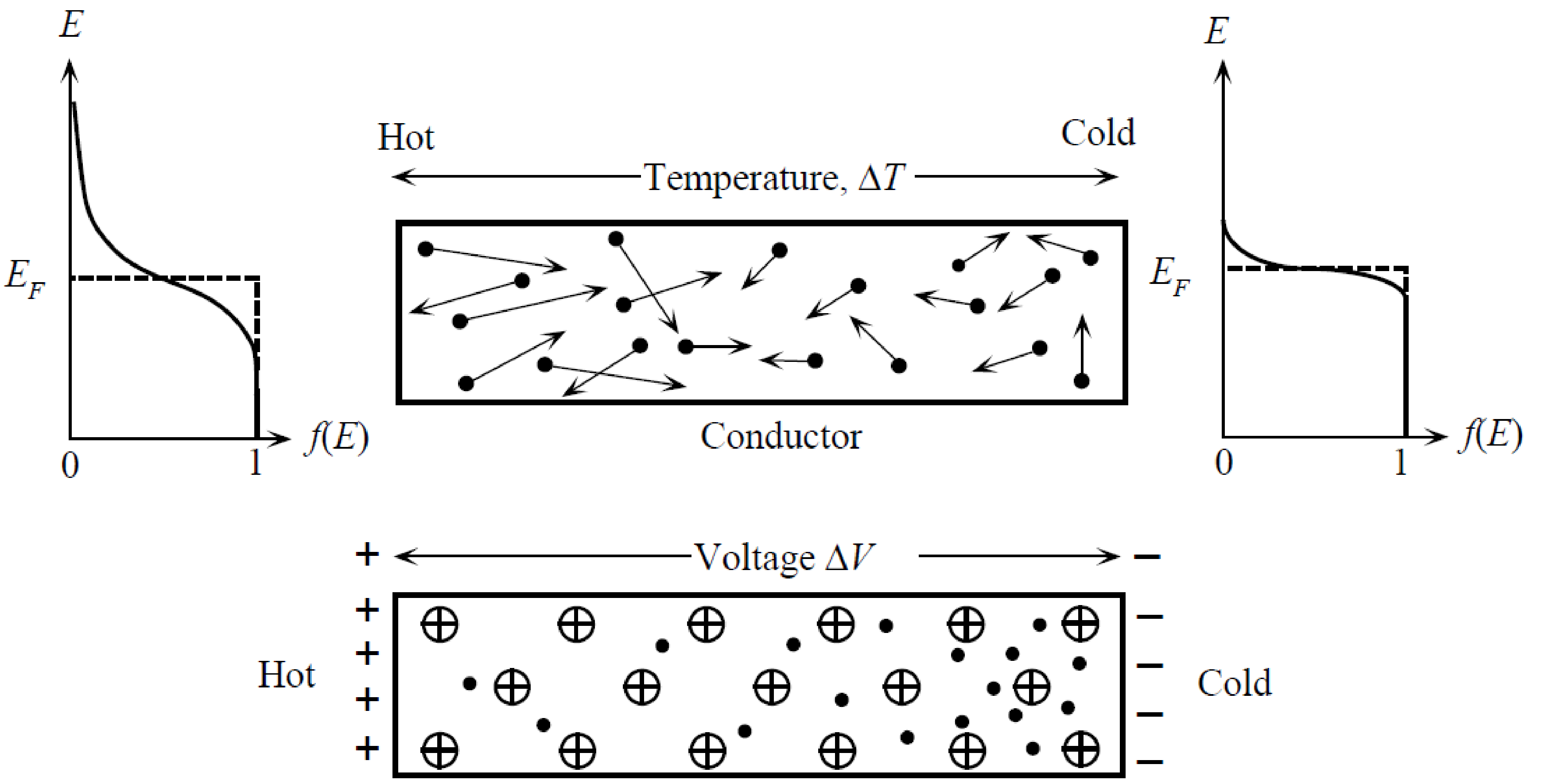
- Deformation sensors
- Resistive temperature sensors
- Seebeck effect and thermocouples
- Appendix

Seebeck effect

From [1]

- A temperature difference between two conductors or semiconductors generates a voltage difference or a current flow
- Discovered accidentally by Thomas Seebeck in 1826

Physical picture



From [2]

Seebeck coefficient

- Is the ratio between voltage drop and thermal gradient

$$S = \frac{dV}{dT}$$

- Aka *thermoelectric power*
- By convention, the sign of S indicates the potential of the cold side with respect to the hot side

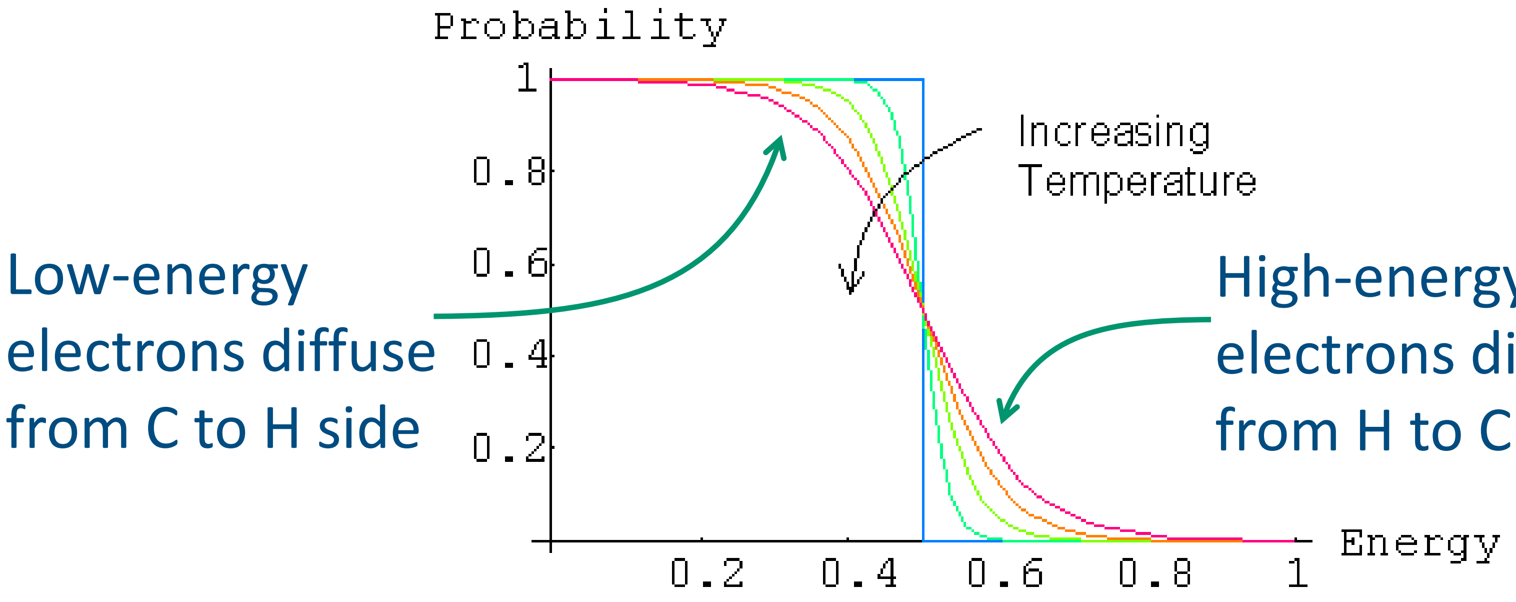
Typical values at 0°C

From [3]

Metal	S [µV/K]
Sb	42
Li	14
Mo	4.7
Cd	2.6
W	2.5
Cu	1.6
Ag	1.5
Ta	0.05

Metal	S [µV/K]
Bi	-68
K	-13
Pd	-9
Na	-6.5
Pt	-4.5
C	-2
Al	-1.6
Pb	-1.1

The sign of S



The sign of S is related to the energy dependence of the diffusion coefficient, i.e., of the scattering mechanisms

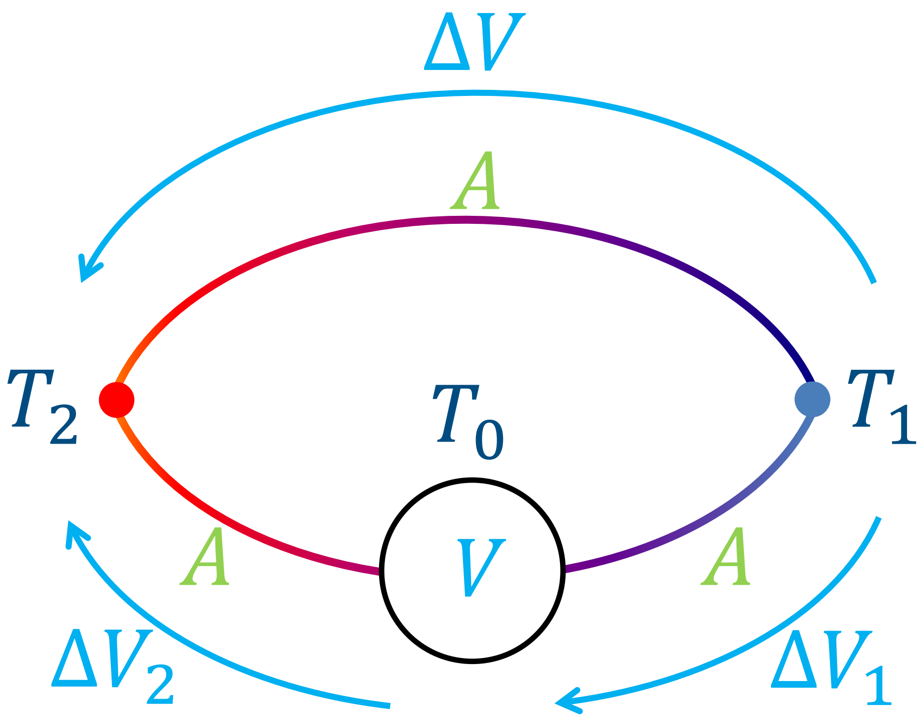
Seebeck effect in semiconductors

From [3]

Semiconductor	S [µV/K]
Se	900
Te	500
Si	435
Ge	300
PbTe	-180
PbGeSe	-2000 +1700
BiTe	-230

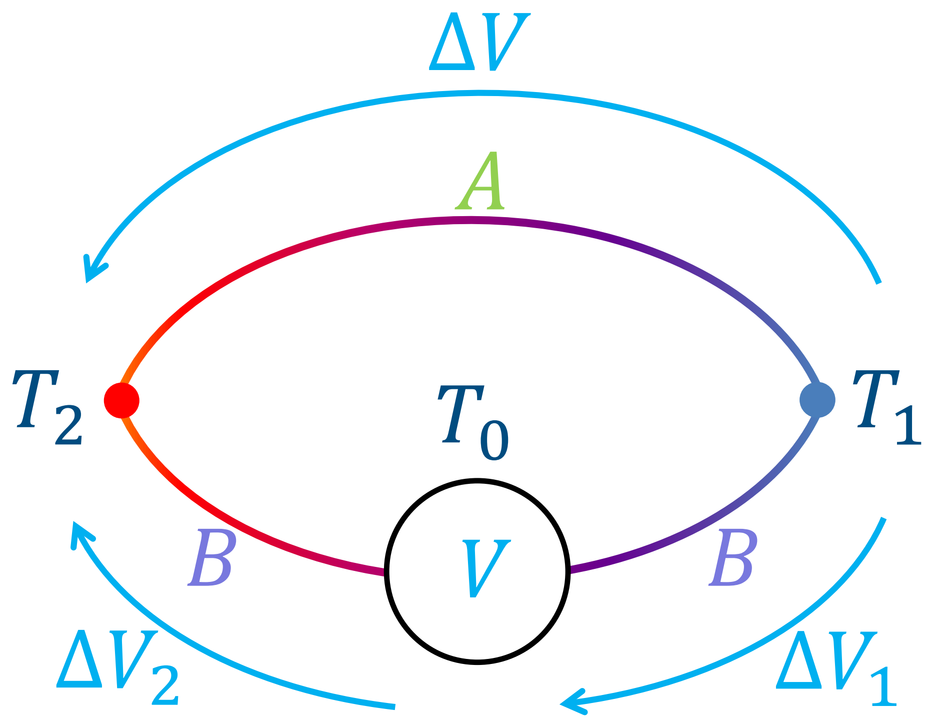
Much larger than in metals because of the exponential dependence of carrier concentration on temperature (see Appendix)

Measurement of S



$$\Delta V = S\Delta T = 0$$

Measurement of S



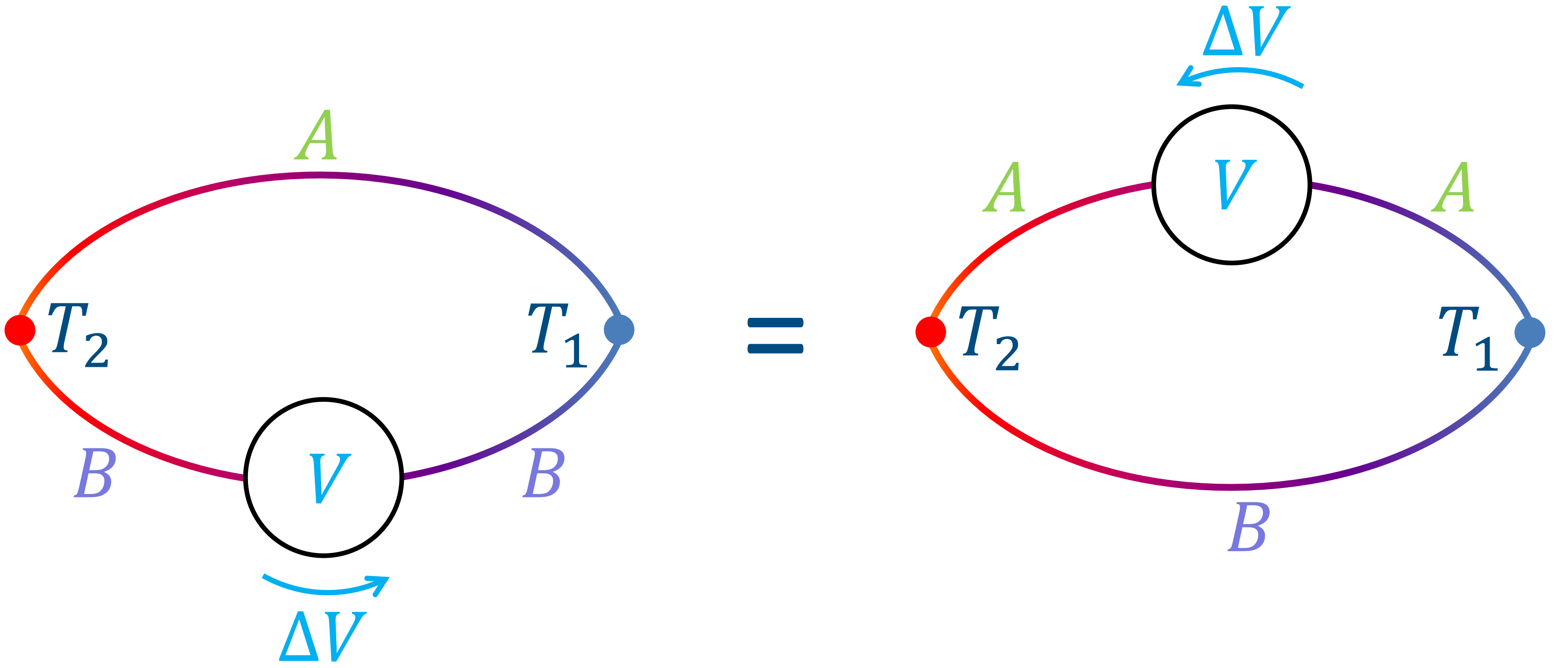
$$\Delta V = S_A \Delta T - S_B \Delta T = S_{AB} \Delta T$$

In brief…

- A circuit made with one conductor will not generate any emf irrespective of the thermal gradient
- A circuit made with two conductors will not generate any emf when isothermal

- Different materials and different temperatures are needed!
- ΔV is only dependent on the junction temperatures, not on the temperature profiles along the wires

Thermocouples are emf sources!



Law of intermediate temperatures

$$V = S_{AB}(T_2 - T_1) = S_{AB}(T_2 - T_0 + T_0 - T_1)$$
$$= S_{AB}(T_2 - T_0) - S_{AB}(T_1 - T_0)$$

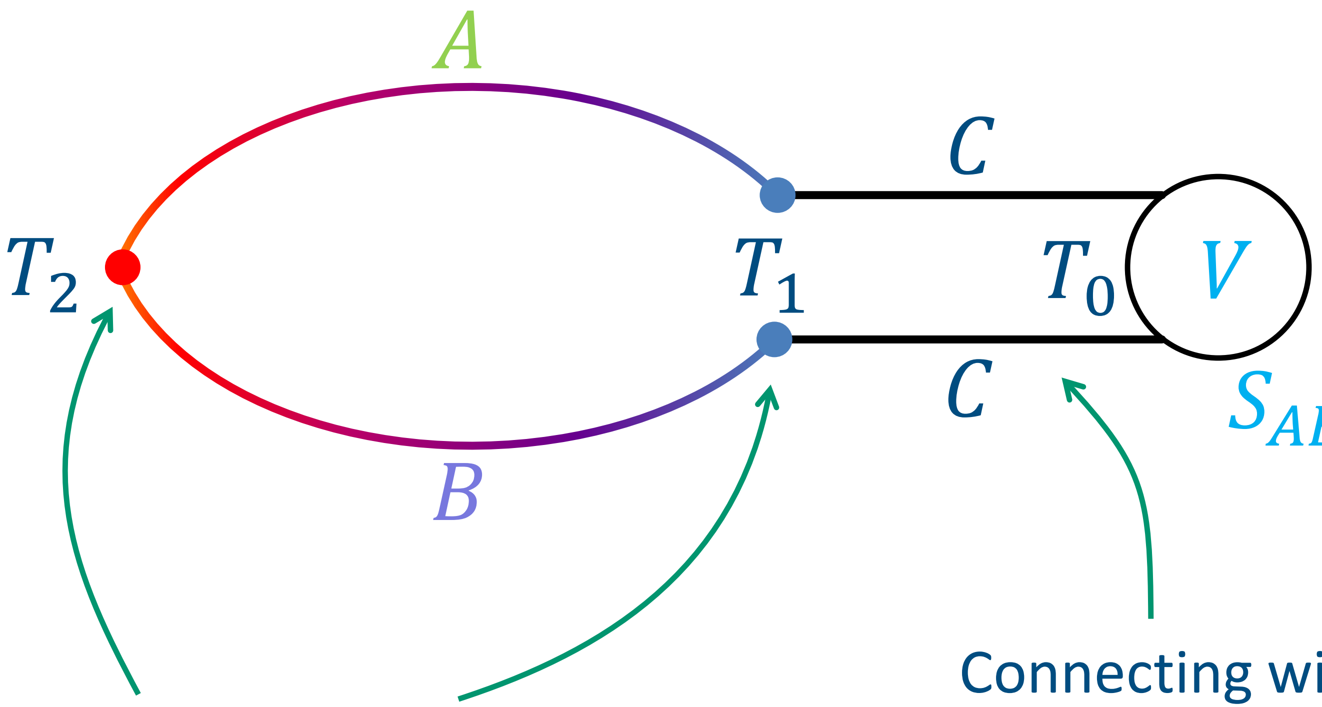
- If the emfs with respect to a reference temperature T_0 are known, they can be used to compute the emf for any ΔT
- For example, is a TC is calibrated for a given temperature T_0, it can be used with any other T_1 with a simple offset
- Also valid if $S = S(T)$

Law of intermediate metals

$$V = (S_A - S_B)\Delta T = (S_A - S_M + S_M - S_B)\Delta T$$
$$= (S_A - S_M)\Delta T - (S_B - S_M)\Delta T$$

- Is the emfs with respect to a reference electrode M are known, they can be used to compute the emf for any couple of metals
- Also valid if $S = S(T)$

Thermocouple measurements

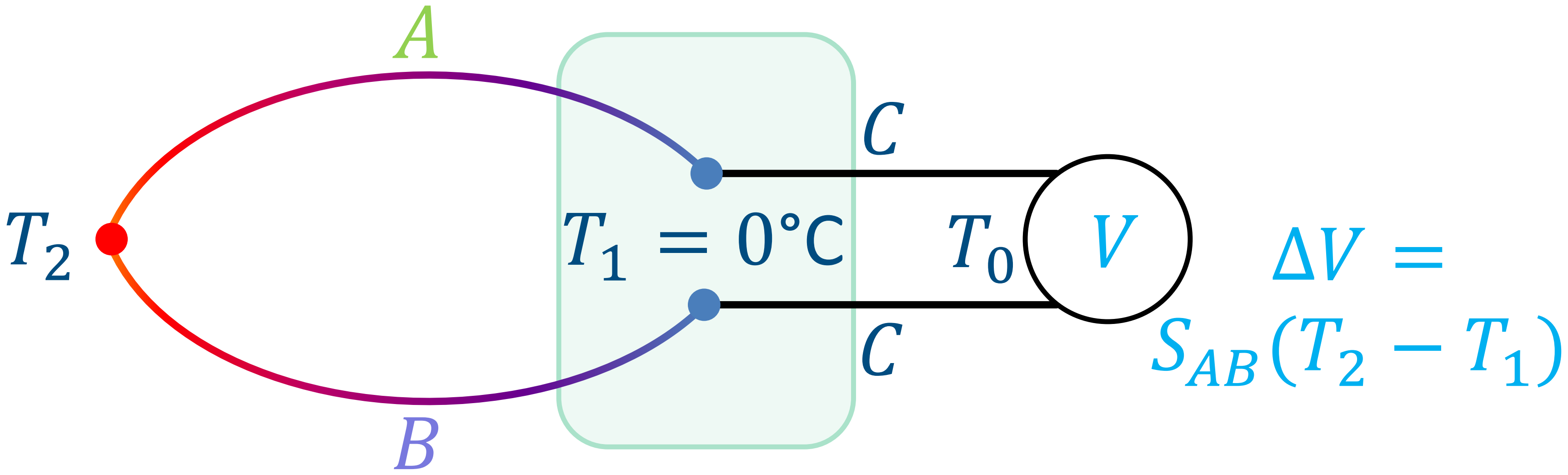


$\Delta V = S_{AB}(T_2 - T_1)$

Soldering metals will not generate any emf if isothermal

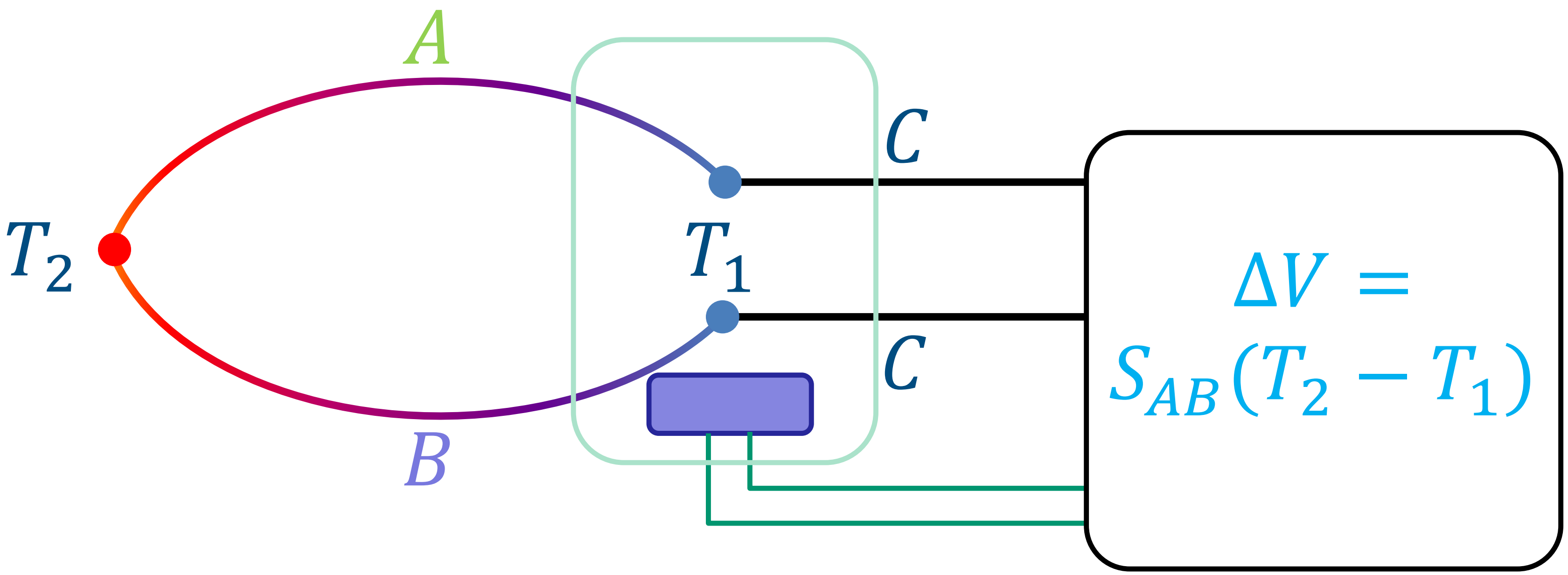
Connecting wires of the same material will not generate any emf

The ice bath



- T_1 is kept stable by using an ice bath and the constant offset is then subtracted
- Impractical in modern systems

Cold junction compensation



- T_1 is measured by a thermistor or RTD and its contribution is subtracted (e.g., via SW)
- Single reference can be used for multi-point

A few notes

- Open-circuit voltage must be measured
- Thin thermocouple wires are used to reduce $C_s \Rightarrow$ high resistance and noise $\Rightarrow$ keep the TC short and use thicker connection wires
- TCs decalibrate over time due to chemical contamination (recalibration may not be easy)
- Grounded, ungrounded or exposed TC junctions are available

Thermocouple standards

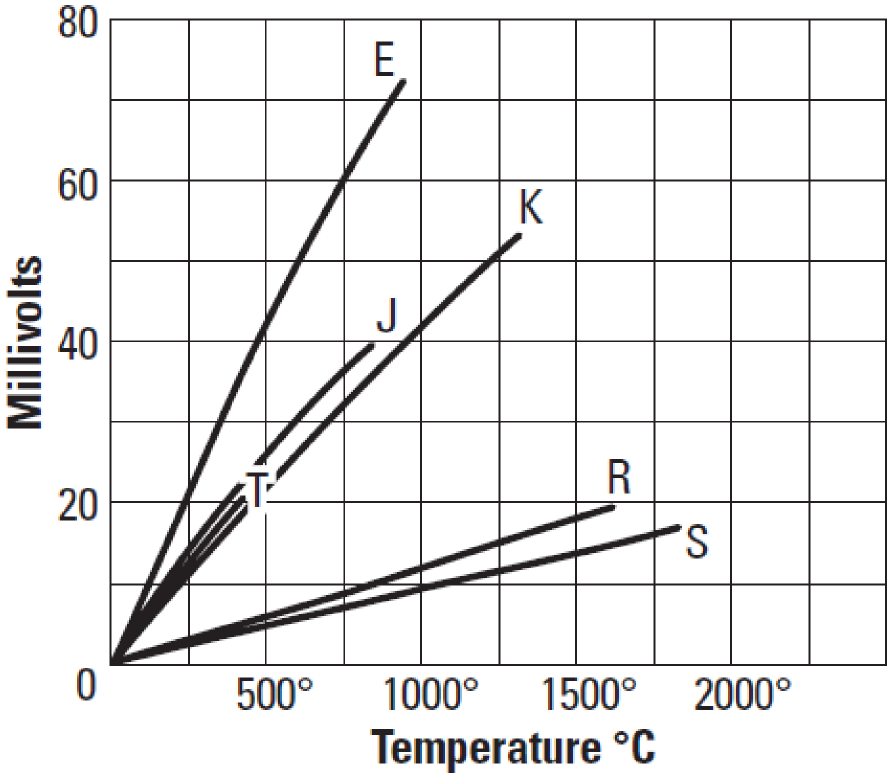
From [6]

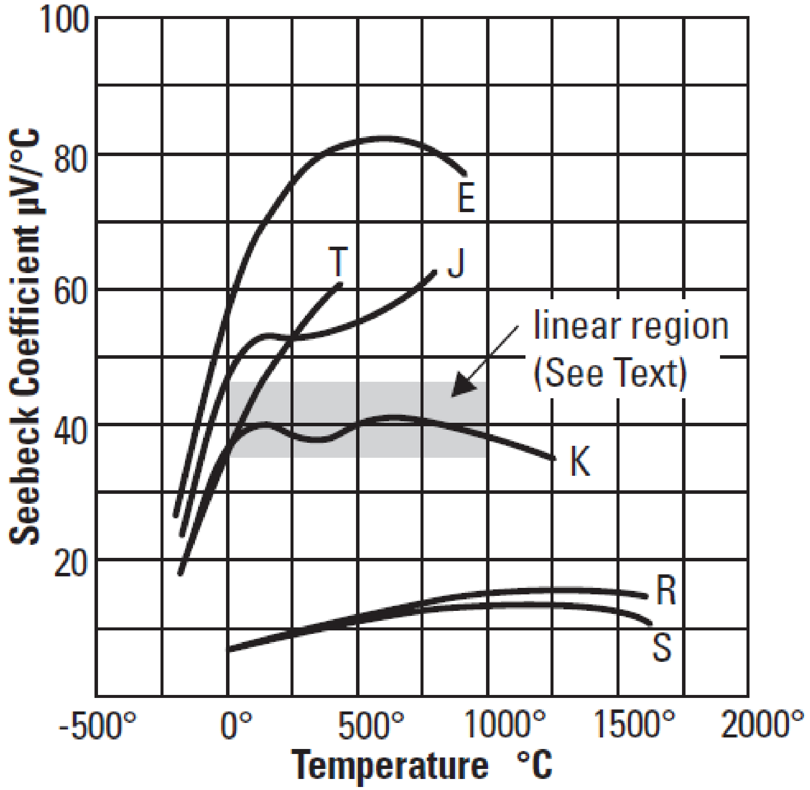
	Thermocouple Standard Type	Metal Content in Positive Leg	Metal Content in Negative Leg	Temperature Range	Av. S [µV/K]
Noble metals	B	70.4% Platinum (Pt), 29.6% Rhodium (Rh)	93.9% Pt, 6.1% Rh	1600 - 3100°F (870 - 1700°C)	10
High sensitivity	E	90% Nickel, (Ni), 10% Chromium (Cr)	55% Copper (Cu), 45% Ni	32 - 1650°F (0 - 900°C)	68
Inexpensive, accurate, most common	J	99.5% Iron (Fe)	55% Cu, 45% Ni	32 - 1380°F (0 - 750°C)	55
	K	90% Ni. 10% Cr	95% Ni, 5% Various Elements	32 - 1380°F (0 - 1250°C)	41
	N	84.4% Ni, 14.2% Cr 1.4% Silicon	95.5% Ni, 4.4% Si	32 - 2280°F (0 -1250°C)	37
Noble metals (high T, high accuracy, low S)	R	87% Pt, 13% Rh	100% Pt	32 - 2640°F (0 - 1450°C)	14
	S	90% Pt, 10% Rh	100% Pt	32 - 2640°F (0 - 1450°C)	12
Low T	T	100% Copper (Cu)	55% Cu, 45% Ni	-330 - 660°F (-200 - 350°C)	51
	C*	95% Tungsten (W), 5% Rhenium (Re)	74% Tungsten (W), 26% Rhenium (Re)	32 - 4200°F (0 - 2315°C)	15
	D*	97% W, 3% Re	75% W, 25% Re	32 - 4200°F (0 - 2315°C)	19
	G*	100% W	74% W, 26% Re	32 - 4200°F (0 - 2315°C)	

* Not Official ANSI (American National Standards Institute) designations.

Typical data

From [7]





Sensor comparison

From [6]

Sensor	Advantages	Disadvantages
Thermocouple	• Simple, Rugged • High temperature operation • Low cost • No resistance lead wire problems • Point temperature sensing • Fastest response to temperature changes	• Least stable, least repeatable • Low sensitivity to small temperature changes • Extension wire must be of the same thermocouple type • Wire may pick up radiated electrical noise if not shielded • Lowest accuracy
RTD	• Most stable over time • Most accurate • Most repeatable temperature measurement • Very resistant to contamination/ corrosion of the RTD element	• High cost • Slowest response time • Low sensitivity to small temperature changes • Sensitive to vibration (strains the platinum element wire) • Decalibration if used beyond sensor's temperature ratings • Somewhat fragile
Thermistor	• High sensitivity to small temperature changes • Temperature measurements become more stable with use • Copper or nickel extension wires can be used	• Limited temperature range • Fragile • Some initial accuracy "drift" • Decalibration if used beyond the sensor's temperature ratings • Lack of standards for replacement
Infrared	• No contact with the product required • Response times as fast or faster than thermocouples • No corrosion or oxidation to affect sensor accuracy • Good stability over time • High repeatability	• High initial cost • More complex - support electronics required • Emissivity variations affect temperature measurement accuracy • Field of view and spot size may restrict sensor application • Measuring accuracy affected by dust, smoke, background radiation, etc.

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Seebeck effect in metal: model

- Average energy of electrons in metals

$$E = \frac{3}{5} E_F \left[1 + \frac{5\pi^2}{12} \left(\frac{k_B T}{E_F} \right)^2 \right]$$

- The increase in energy after ΔT is

$$\Delta E = \frac{\partial E}{\partial T} \Delta T = \frac{\pi^2 k_B^2 T}{2 E_F} \Delta T,$$

balanced by the electrostatic energy $-q\Delta V$. Then

$$S = \frac{\Delta V}{\Delta T} = -\frac{\pi^2 k_B^2 T}{2 q E_F}$$

Seebeck effect in semiconductors: model

Drift-diffusion current density:

$$J_n = qn\mu_n F + qD_n \frac{dn}{dx}$$

where $\frac{dn}{dx} = \frac{\partial n}{\partial x} + \frac{\partial n}{\partial T}\frac{dT}{dx} = \frac{\partial n}{\partial x} + n\frac{E_C - E_F}{k_B T^2}\frac{dT}{dx}$

$$J_n = qn\mu_n \left(F + \frac{E_C - E_F}{qT}\frac{dT}{dx} \right)$$

$$J_n = 0 \Rightarrow S = -\frac{dV}{dT} = -\frac{E_C - E_F}{qT}$$