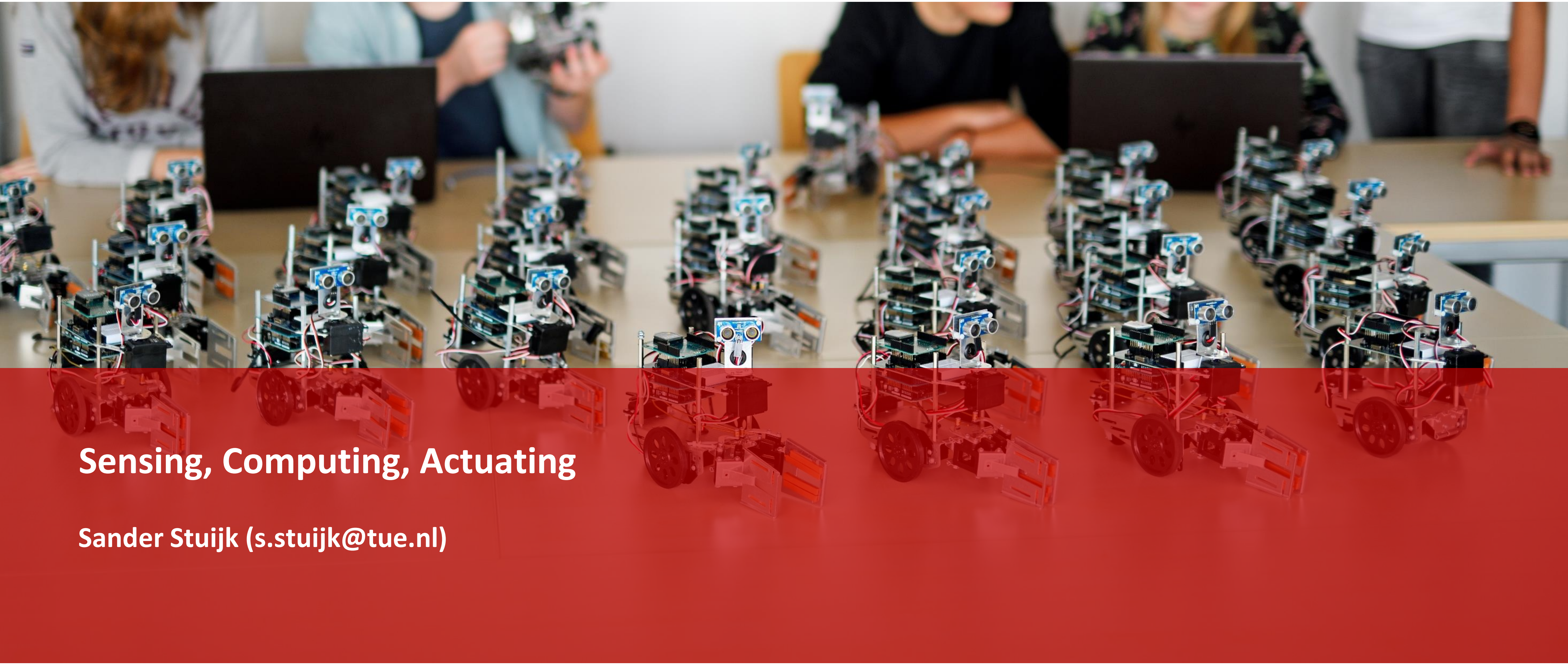
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY



Sensing, Computing, Actuating

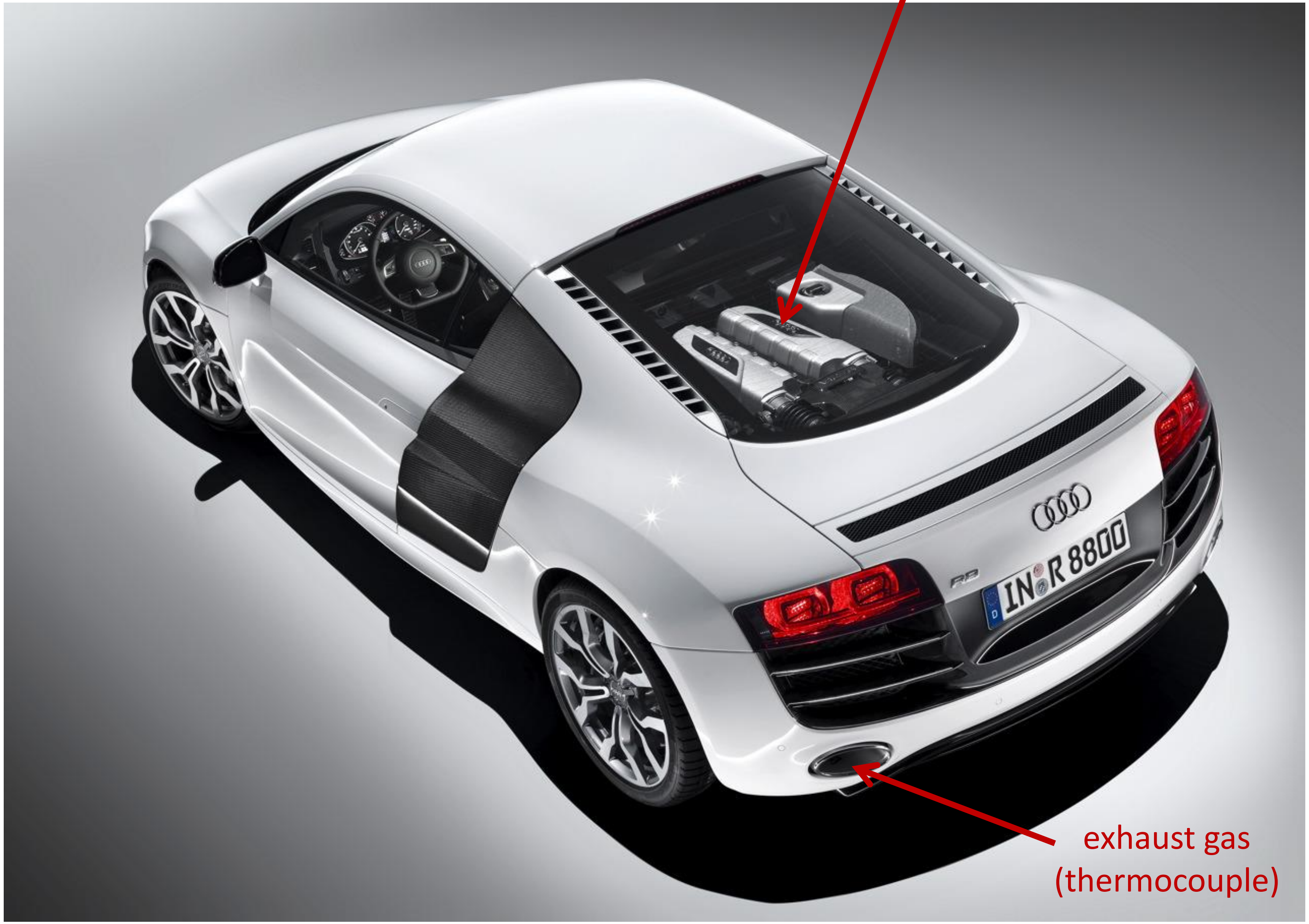
Sander Stuijk (s.stuijk@tue.nl)

THERMOELECTRIC EFFECT

(Chapter 5.11)

Thermocouple

cylinder head temperature (thermocouple)



exhaust gas (thermocouple)

Thermoelectric generator

- combustion engine in cars
  - 25% of potential energy turned into motion
  - 75% of potential energy wasted as heat

- Volkswagen
  - 600W power generation
  - 30% energy requirement of VW Golf
  - 5% fuel saving

Temperature sensors

placement	excitation	physical effect	material	thermal sensor
contact	passive	thermal expansion	metal	bimetal
contact	active	resistive effect	metal	RTD
contact	active	resistive effect	semiconductor	silicon resistive
contact	active	resistive effect	polymer or ceramic	thermistor
contact	**passive**	**thermoelectric effect**	**conductor**	**thermocouple**
contact	active	PN junction	semiconductor	
non-contact	passive	pyroelectric effect	pyroelectric	pyroelectric
non-contact	active	ultrasound	-	acoustic

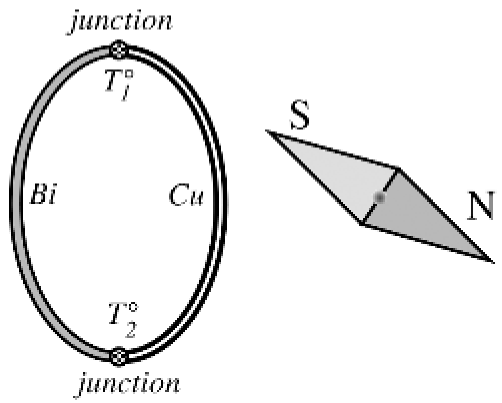
Thermocouple

TU/e

- two dissimilar metallic junctions at different temperatures
- thermoelectric effect causes current in metals

- effect discovered by Thomas Seebeck in 1821
  - observation: magnetic field around metals
  - idea: metals magnetically polarized due to temperature gradient
  - named the effect "thermomagnetism"

- magnetization is actually caused by charge current
- current is due to the thermoelectric effect



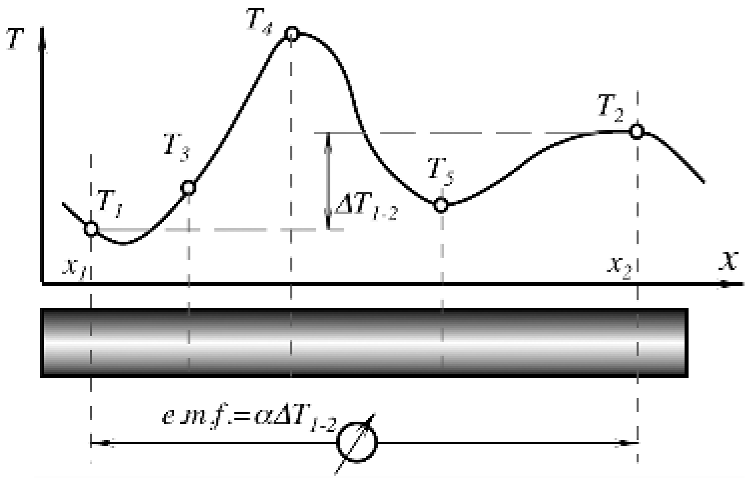
Thermoelectric effect

- thermoelectric effect is the direct conversion between a temperature difference and electric voltage

electric voltage (emf) $\xleftrightarrow{\text{thermoelectric effect}}$ temperature difference

- thermoelectric effect is reversible
- sensors based on this effect are passive sensors

- thermoelectric effect at atomic scale
  - temperature gradient causes charged carriers to move from hot to cold side
  - causes thermally induced current

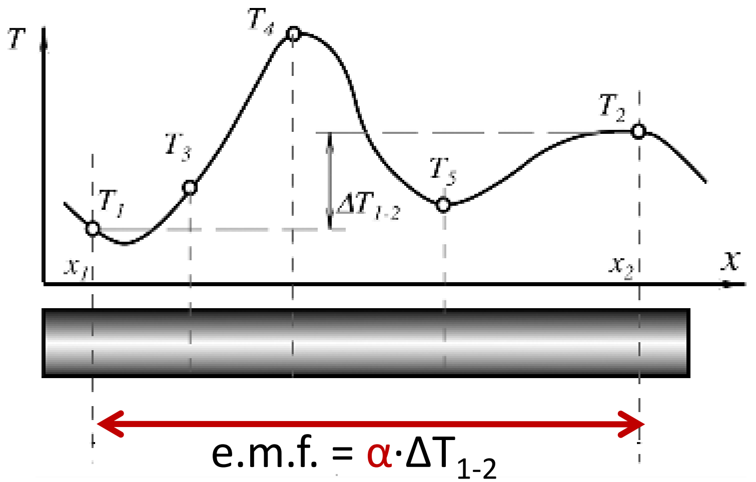


Thermoelectric effect

- thermoelectric effect applied to
  - measure temperature
  - generate electricity
  - cool objects
  - heat objects

Seebeck effect

- a metal bar with a non-uniform temperature
  - temperature difference leads to a current
  - current leads to an electric field
  - electric field results in voltage across the bar
- strength of electric field depends on material properties (α)
- temperature at intermediate points does not affect voltage

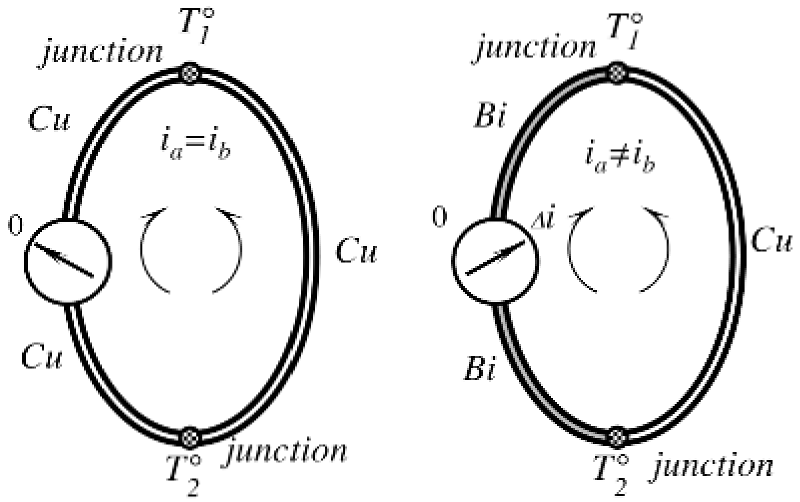


- voltage induced in metal bar can be measured
- measurement device becomes part of the circuit

Seebeck effect

- join two metal bars from the same material
  - electrical field in left and right arm produce equal currents
  - currents cancel each other

- join two metal bars from different material
  - currents in both arms do not cancel each other
  - difference between thermoelectric properties of materials can be measured
  - example: bismut (Bi), copper (Cu)



Seebeck effect

- current depends on many factors (e.g. resistance, shape, size)
- voltage depends only on materials and temperature difference
- thermally induced voltage of the junction (Seebeck potential)

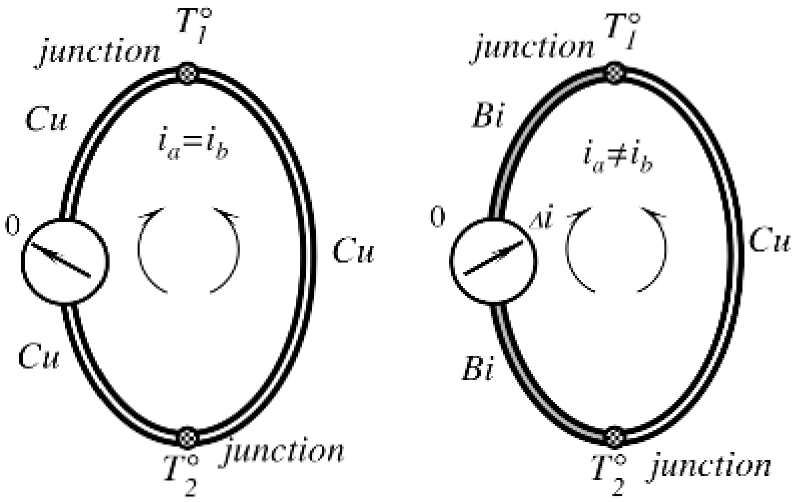
$$V_{AB} = \alpha_{AB} \cdot \Delta T$$

  - Seebeck coefficient

$$\alpha_{AB} = \alpha_A - \alpha_B$$

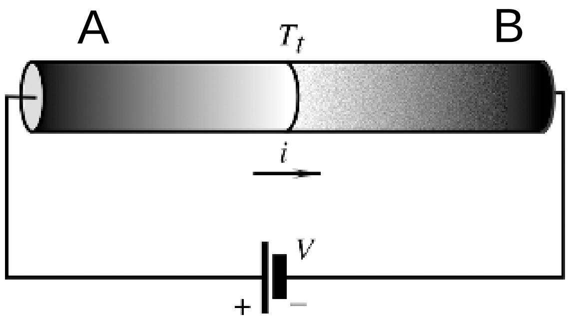
    - Seebeck coefficient is temperature dependent
    - Seebeck potential is very small
      - copper-constantan has Seebeck potential of 41µV/K

- Seebeck effect results from
  - Peltier effect
  - Thomson effect



Peltier effect in single junction

- current passed through a junction causes heat to be produced or released depending on the direction of the current (Peltier effect)



- heat absorbed or released at the junction
  - current must be continuous at junction
  - Fermi level of materials at junction differ
  - electrons use or liberate energy (heat) when crossing junction
  - heat is absorbed or produced at the junction

- heat produced per unit time

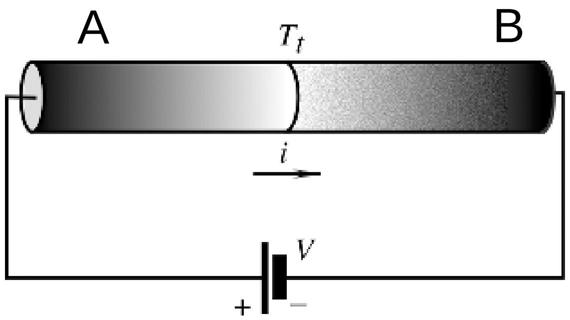
  $$Q_P = \pi_{AB} I$$

- Peltier coefficient

  $$\pi_{AB} = \pi_A - \pi_B = -\pi_{BA}$$

Peltier effect in single junction

- current passed through a junction causes heat to be produced or released depending on the direction of the current (Peltier effect)



- heat produced per unit time

  $Q_P = \pi_{AB} I$
- Peltier coefficient

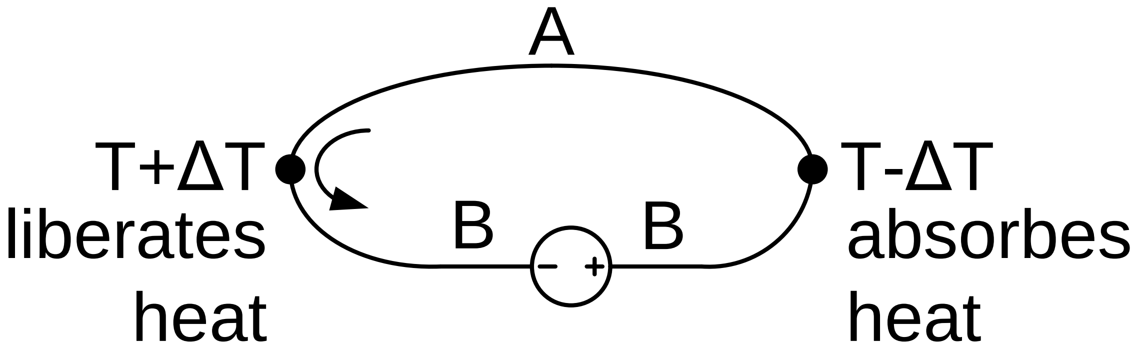
  $\pi_{AB} = \pi_A - \pi_B = -\pi_{BA}$

- **what happens when the current is reversed?**
  - Peltier coefficient changes sign
  - heat is no longer produced, but it is absorbed

- direction of current influences Peltier heating, but not Joule heating

Peltier effect in thermocouple

- current passed through a thermocouple circuit causes one junction to cool and the other junction to heat (Peltier effect)

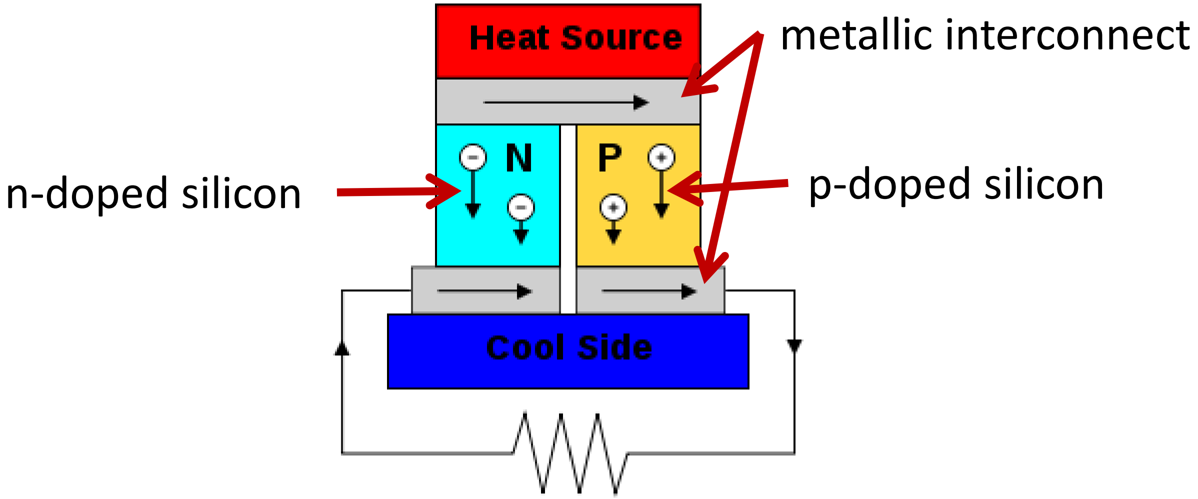


- Peltier effect is independent of the origin of the current
  - induced by thermoelectric effect at junction
  - external source
- Peltier effect can be used to
  - cool or heat
  - generate electricity

Peltier effect in silicon

- silicon has a large Seebeck coefficient
  - n-doped Si / p-doped Si junction has typically 0.3-0.6 mV/K
  - enables design of sensitive thermoelectric sensors in silicon

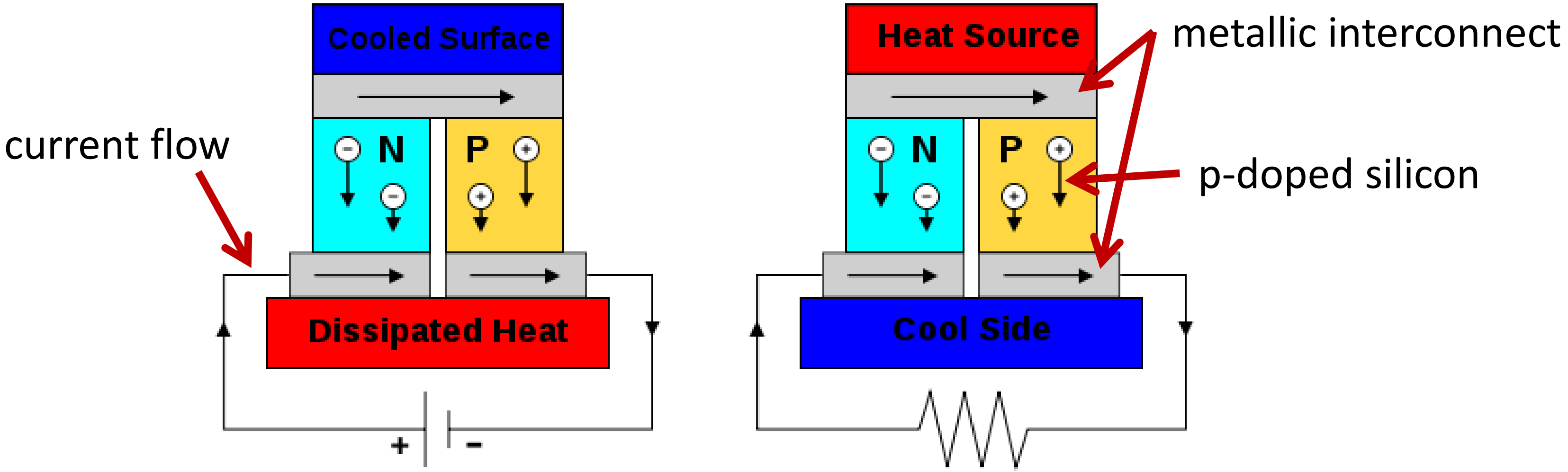
- Peltier generator converts thermal energy from heat source to electrical energy
  - heat source causes electrons and holes to move to cool side
  - electrons and holes create current through circuit



Peltier effect in silicon

- silicon has a large Seebeck coefficient
  - n-doped Si / p-doped Si junction has typically 0.3-0.6 mV/K
  - enables design of sensitive thermoelectric sensors in silicon

- Peltier heat pump replaces circuit with power source
  - electrons move opposite to flow, holes move along the flow
  - both effects remove heat from one side of the device
  - direction of the current determines heating/cooling of surface

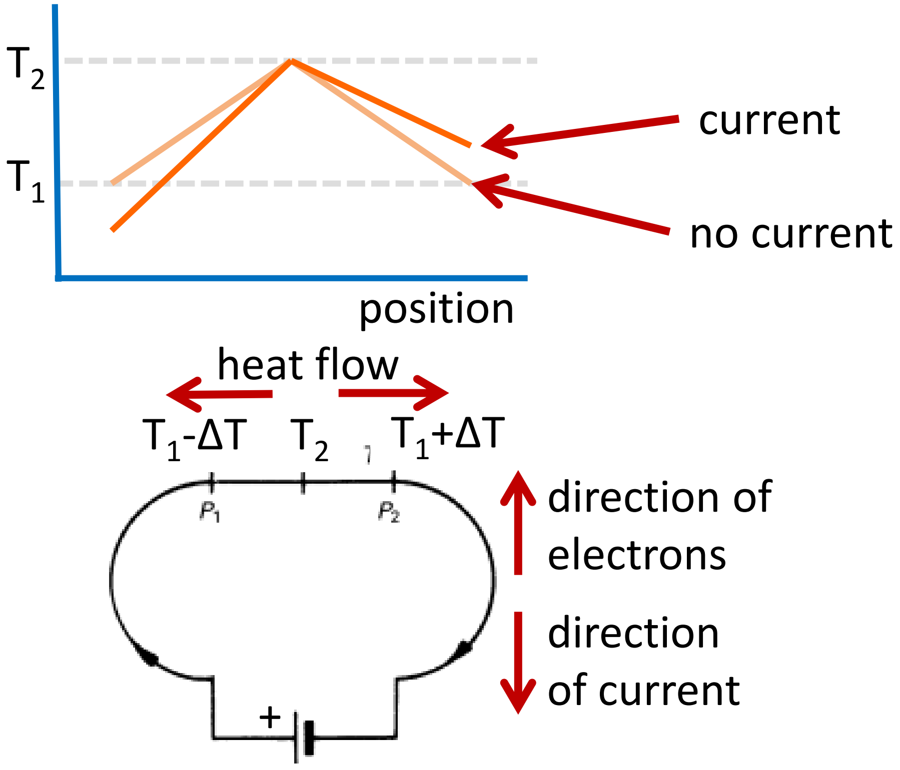


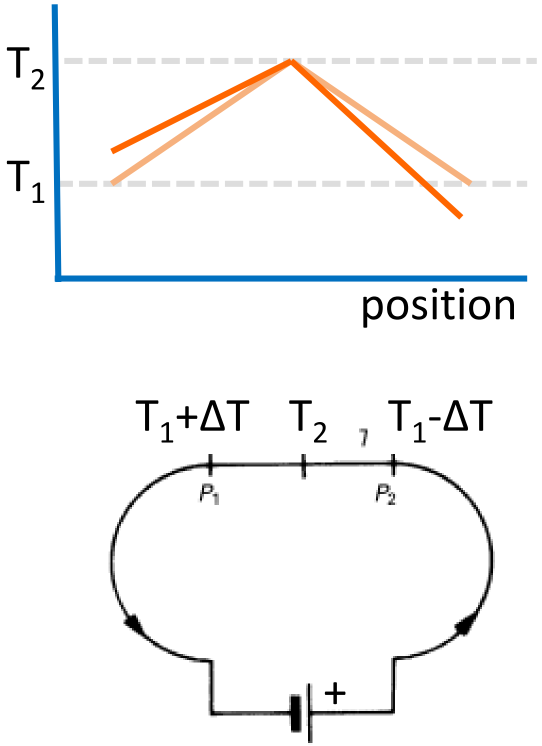
Thermoelectric effects

- thermoelectric effect is the direct conversion between temperature difference and electric voltage
- thermoelectric effect is explained by the Seebeck effect
  - temperature difference between two junctions of two dissimilar metals causes a current (Seebeck effect)
- Seebeck effect is explained by the Peltier and Thomson effect
  - amount of heat produced or consumed in a junction is proportional to the temperature at the junction and current through the junction (Peltier effect)

Thomson effect

- Thomson effect explains heat absorption or liberation in a homogeneous conductor with a non-homogeneous temperature





- heat absorbed when charges flow from cold to hot point
  - charge and heat flow in opposite directions
- heat liberated when charges flow from hot to cold point
  - charge and heat flow in same direction

Thomson effect

- heat produced along wire

$$Q_P = \underbrace{\boxed{I^2 \cdot R}}_{\text{irreversible Joule effect}} - \underbrace{\boxed{I \cdot \sigma \cdot \Delta T}}_{\text{reversible Thomson effect}}$$

  - ΔT – temperature gradient along the wire
  - σ – Thomson coefficient of material
    - can be positive or negative depending on the material
    - proper selection of materials will yield highest response

- amount of produced or consumed heat along a homogeneous conductor with a temperature gradient is proportional to the current (Thomson effect)

Thermoelectric effects

- thermoelectric effect is the direct conversion between temperature difference and electric voltage
- thermoelectric effect is explained by the Seebeck effect
  - temperature difference between two junctions of two dissimilar metals induces a current (Seebeck effect)
- Seebeck effect is explained by the Peltier and Thomson effects
  - amount of heat produced or consumed in a junction is proportional to the temperature at the junction and current through the junction (Peltier effect)
  - amount of heat produced or consumed along a homogeneous conductor with a temperature gradient is proportional to the current (Thomson effect)

Thermoelectric effects

- two metals A and B with junctions at T and T + ΔT
- current I small enough to ignore Joule heating
- thermally induced voltage (Seebeck potential)

$$V_{AB} = \alpha_{AB} \cdot \Delta T$$

- thermoelectric power

$$V_{AB} \cdot I = \alpha_{AB} \cdot \Delta T \cdot I$$

- converted thermal energy

$$Q_P = Q_{P,Peltier} + Q_{P,\mathrm{Thomson}}$$

$$Q_P = \pi_{AB}(T + \Delta T)I - \pi_{AB}(T)I + \sigma_{AB}(\Delta T)I$$

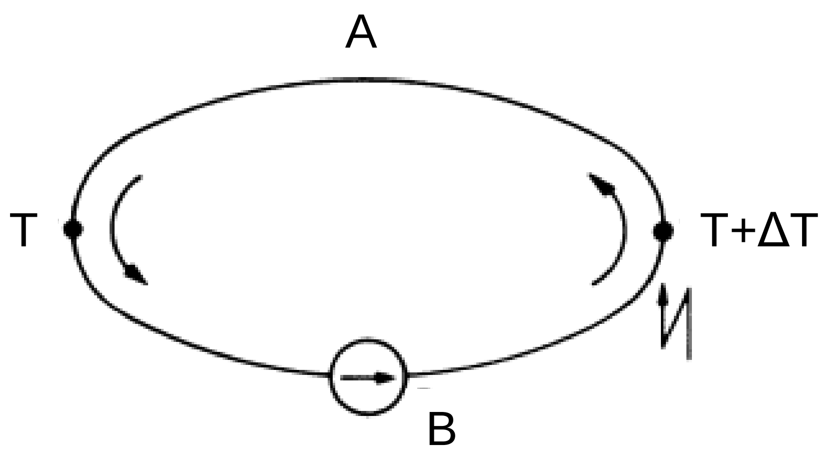
- power balance requires

$$\alpha_{AB} \cdot \Delta T \cdot I = \pi_{AB}(T + \Delta T)I - \pi_{AB}(T)I + \sigma_{AB}(\Delta T)I$$

$$\Rightarrow \alpha_{AB} \cdot \Delta T = \pi_{AB}(T + \Delta T) - \pi_{AB}(T) + \sigma_{AB}(\Delta T)$$

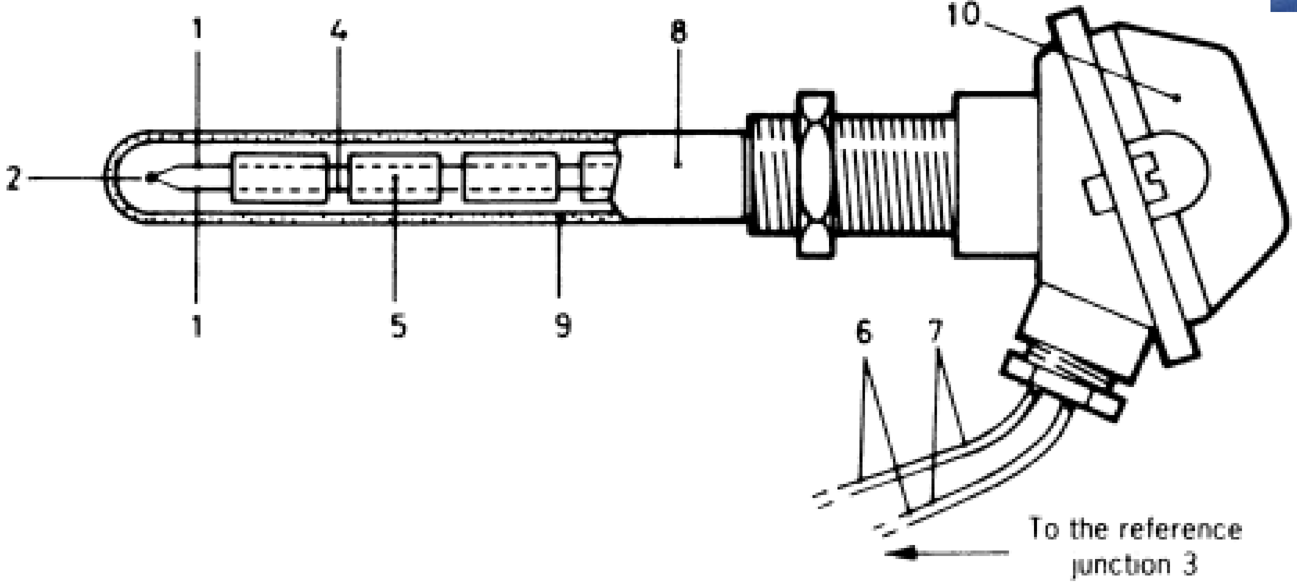
$$\Rightarrow \alpha_{AB} = \pi_{AB} + \sigma_{AB}$$

- Seebeck effect results from Peltier and Thomson effect



Thermocouple assemblies

- thermocouple assembly consists of
  - sensing element (junction)
  - protective tube (ceramic or metallic)
  - insulated thermocouple wires (isolate sensor)
  - terminations (connections)

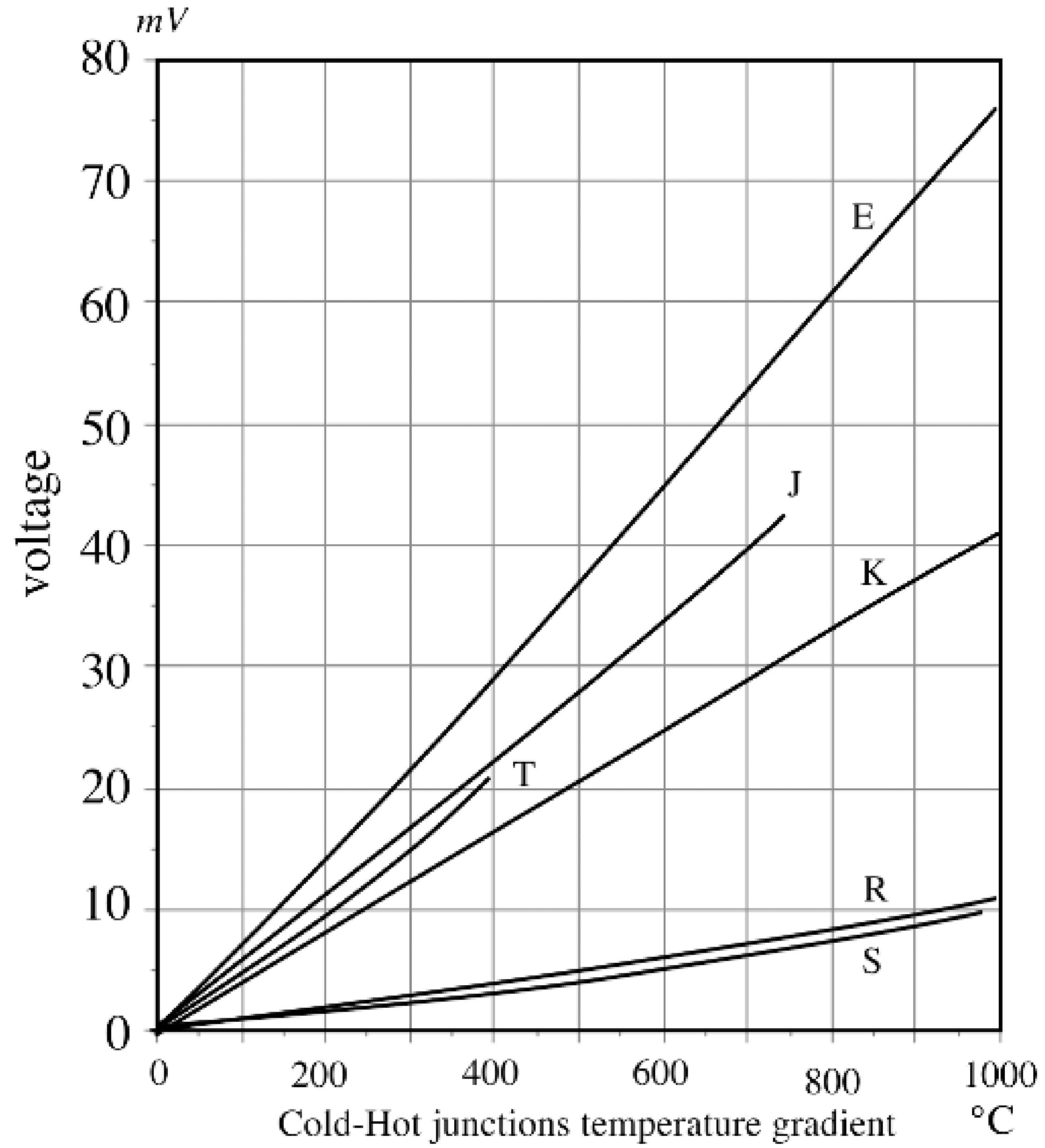


Thermocouple types

Junction materials (+/-)	Sensitivity (at 25°C) (μV/°C)	Full-range output (mV)	Error (°C)	Temperature range (°C)	Type
Copper / constantan	40.9	26.0	±1.0	-184 to 400	T
Iron / constantan	51.7	43.0	±2.2	-184 to 760	J
Chromel / alumel	40.6	56.0	±2.2	-184 to 1260	K
Chromel / constantan	60.9	75.0	±1.0	0 to 982	E
Silicon / aluminium	446	51.8	±2.2	-40 to 150	

- many types have a very low sensitivity
- silicon is special
    - small temperature range
    - larger sensitivity
- error due to temperature dependence of Seebeck coefficient

Transfer function of a thermocouple



Transfer function of a thermocouple

- Seebeck potential can be approximated by

  $$V_{AB} \approx C_1(T_1 - T_2) + C_2(T_1^2 - T_2^2) \approx (T_1 - T_2)[C_1 + C_2(T_1 + T_2)]$$

  - C_1, C_2 – constants depending on material

- Seebeck potential depends on
  - temperature difference
  - absolute temperature

- error reduced by selecting a thermocouple with small C_2
  - $C_2 \approx 0.036 \mu V/K^2$ for a T-type thermocouple

- Seebeck coefficient
  - not dependent on nature of thermocouple (e.g. welded, pressed)
  - depends only on the temperature and materials at the junction

Thermocouple

example – J-type thermocouple

- one junction at 0°C and other at 45°C
- sensitivity 51.7μV/K
- **what is the open circuit voltage?**
  - V = 51.7μV/°C · (45°C - 0°C) = 2.3 mV

example – J-type thermocouple

- circuit with one junction at 10°C generates 5mV output voltage
- sensitivity 51.7μV/K
- **what is the temperature at the measuring junction?**
  - using specified sensitivity we find T = 107°C or T = -87°C
  - correct answer depends on polarity of junctions

Thermocouple

- Thermocouple versus RTD

  (+) broader measurement range (-270°C to 3000°C)

  (+) robust, simple to use

  (+) no self-heating problem (usable in gas measurement)

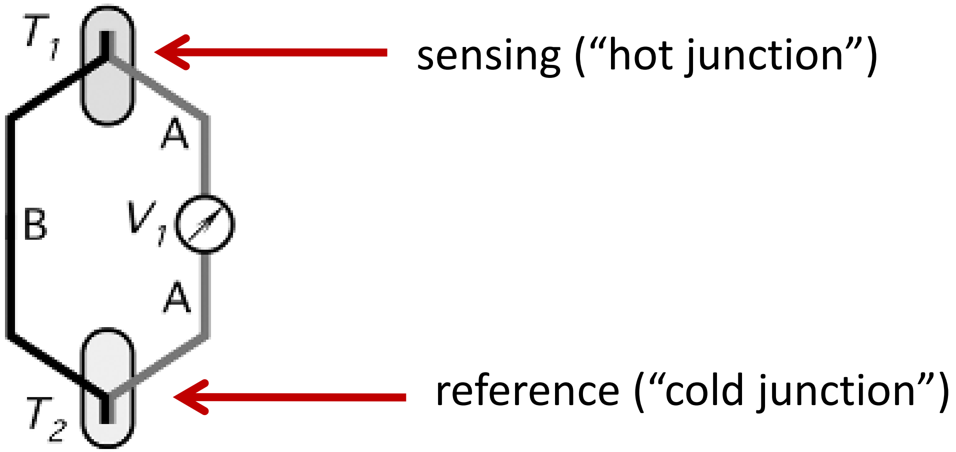
  (+) accepts long connection wires

  (-) lower sensitivity (µV/°C)

  (-) known reference temperature needed

Thermoelectric laws

- temperature difference between two thermocouple junctions leads to a voltage between the open ends of the circuit
  - junctions of different materials lead to different sensitivity
  - voltage is proportional to the temperature difference
  - reference junction must be at known, constant temperature

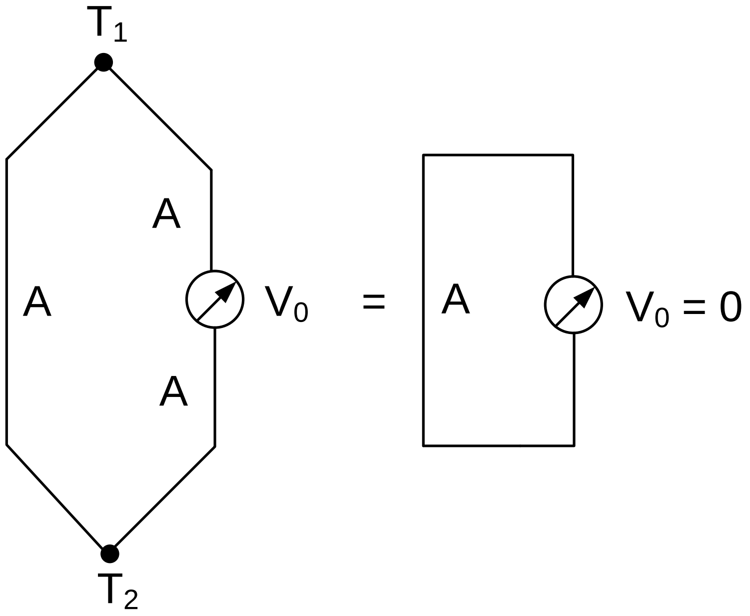


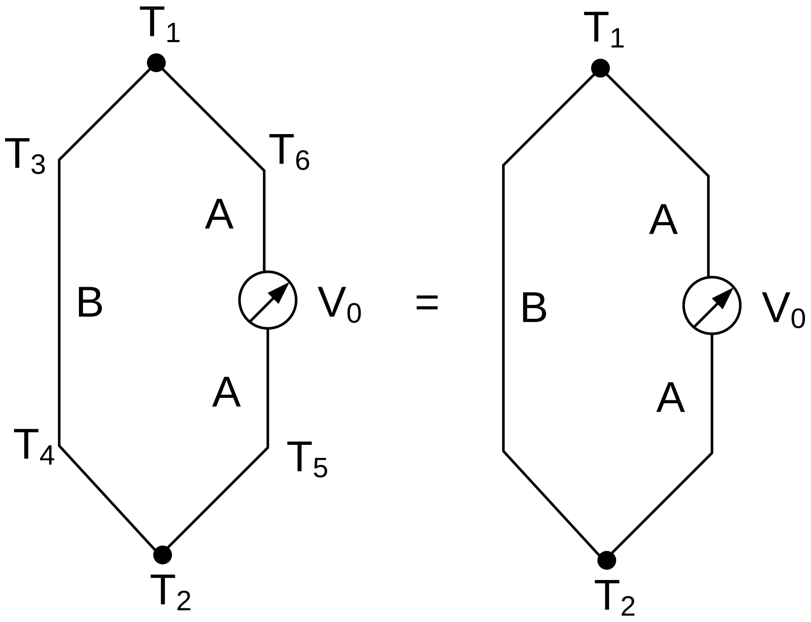
- operation of thermocouples governed by three thermoelectric laws
- thermoelectric laws simplify the analysis of thermocouple circuits
- useful as practical systems may contain more than just two junctions

Thermoelectric laws

- law of homogeneous circuits: thermoelectric current cannot be maintained in a homogeneous circuit by heat alone

- implications
  - junctions of different materials must be used
  - single conductor will never cause a Seebeck potential
  - intermediate temperatures do not influence Seebeck potential

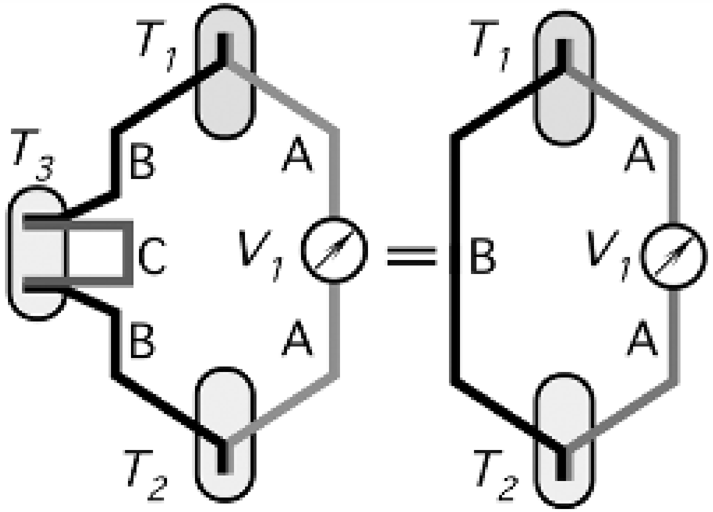




Thermoelectric laws

- law of intermediate metals: algebraic sum of all Seebeck potentials in a circuit composed by several different materials remains zero when the whole circuit is at a uniform temperature

- implication
  - materials may be connected in the circuit without affecting the output of the circuit as long as the new junctions are kept at the same temperature

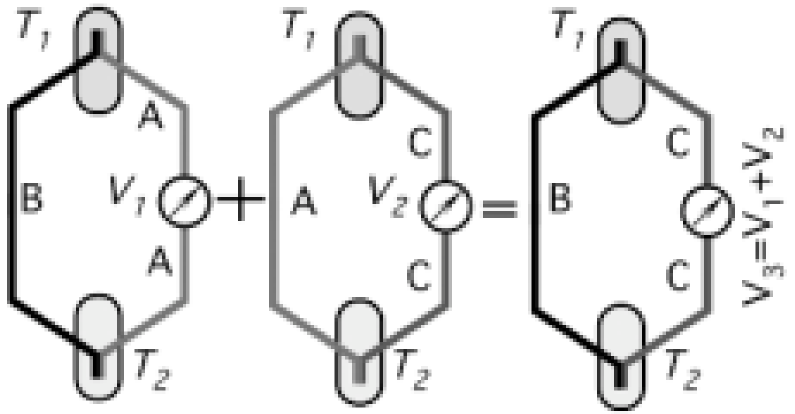


Thermoelectric laws

- law of intermediate metals: algebraic sum of all Seebeck potentials in a circuit composed by several different materials remains zero when the whole circuit is at a uniform temperature

- corollary
  - thermal relation between metals B and C follows from the relation between A and B and the relation between A and C

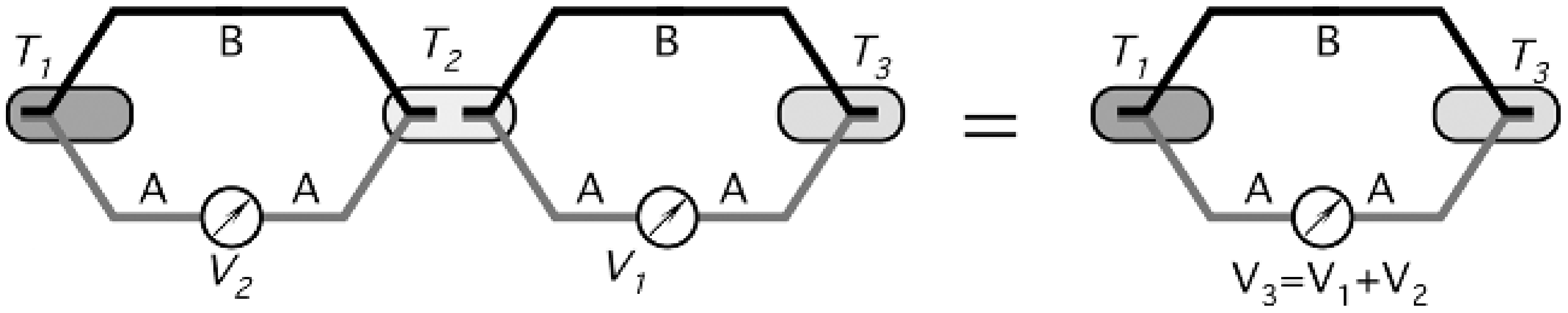
- implication
  - not all material combinations need to be known
  - use single material as reference



Thermoelectric laws

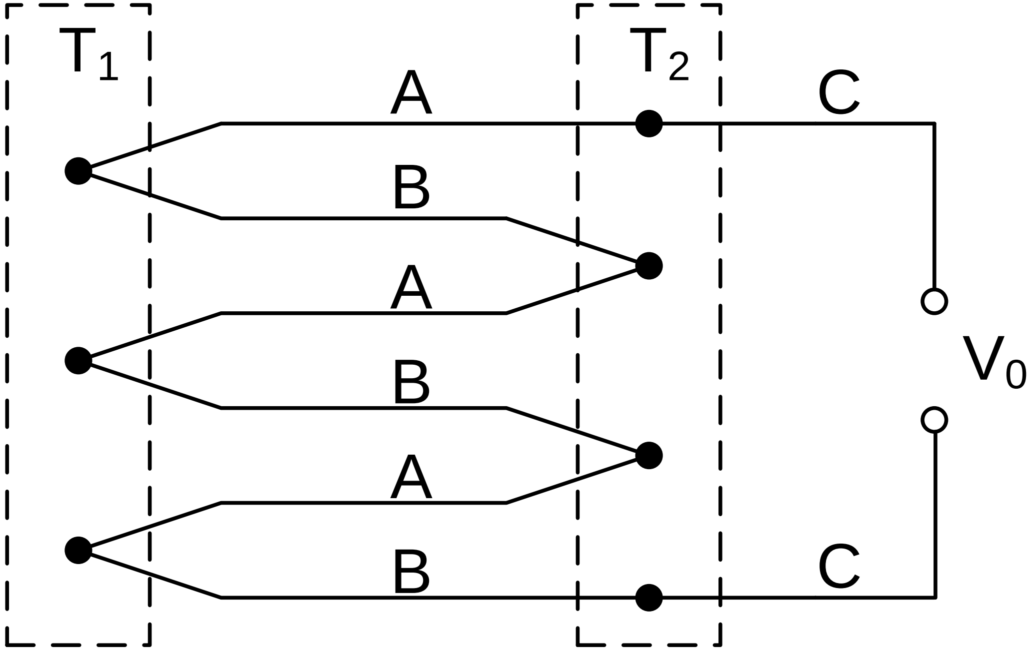
- law of intermediate temperatures:
  - two junctions at T_1 and T_2 produce Seebeck voltage V_2
  - two junction at T_2 and T_3 produce Seebeck voltage V_1
  - then temperatures T_1 and T_3 will produce $V_3 = V_1 + V_2$

- implications
  - calibration can be done at reference temperature T_2 and device can used with different reference temperature T_3



Thermocouples in series

- thermocouple laws allow analysis of circuits like



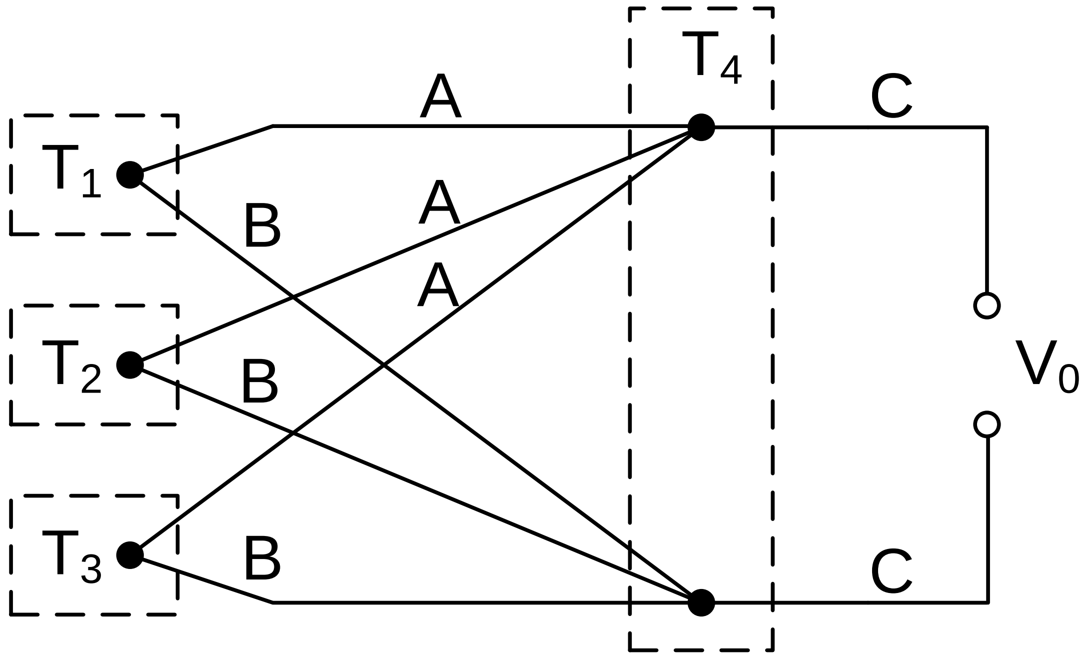
- output voltage multiple of single thermocouple

$$V_o = \alpha_{AB}(T_2 - T_1) + \alpha_{AB}(T_2 - T_1) + \alpha_{AB}(T_2 - T_1) = 3 \cdot \alpha_{AB}(T_2 - T_1)$$

- circuit know as thermopile
- amplifies output voltage without use of operational amplifier

Thermocouples in parallel

- thermocouple laws allow analysis of circuits like



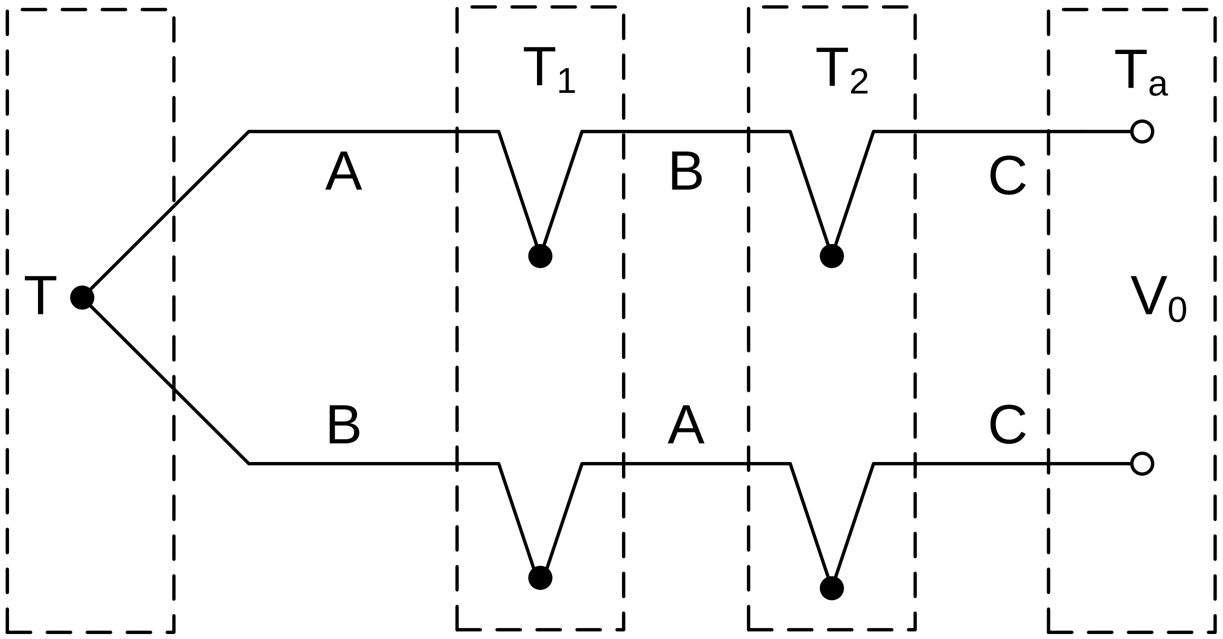
- output voltage proportional to the average temperature

$$V_o = \alpha_{AB} \frac{(T_4 - T_1) + (T_4 - T_2) + (T_4 - T_3)}{3}$$

Thermoelectric laws

example – simulate reference temperature of 0°C

- three types of wires (A, B, C) combined into thermocouples with two intermediate temperatures T_1 and T_2 and temperature T at measurement junction

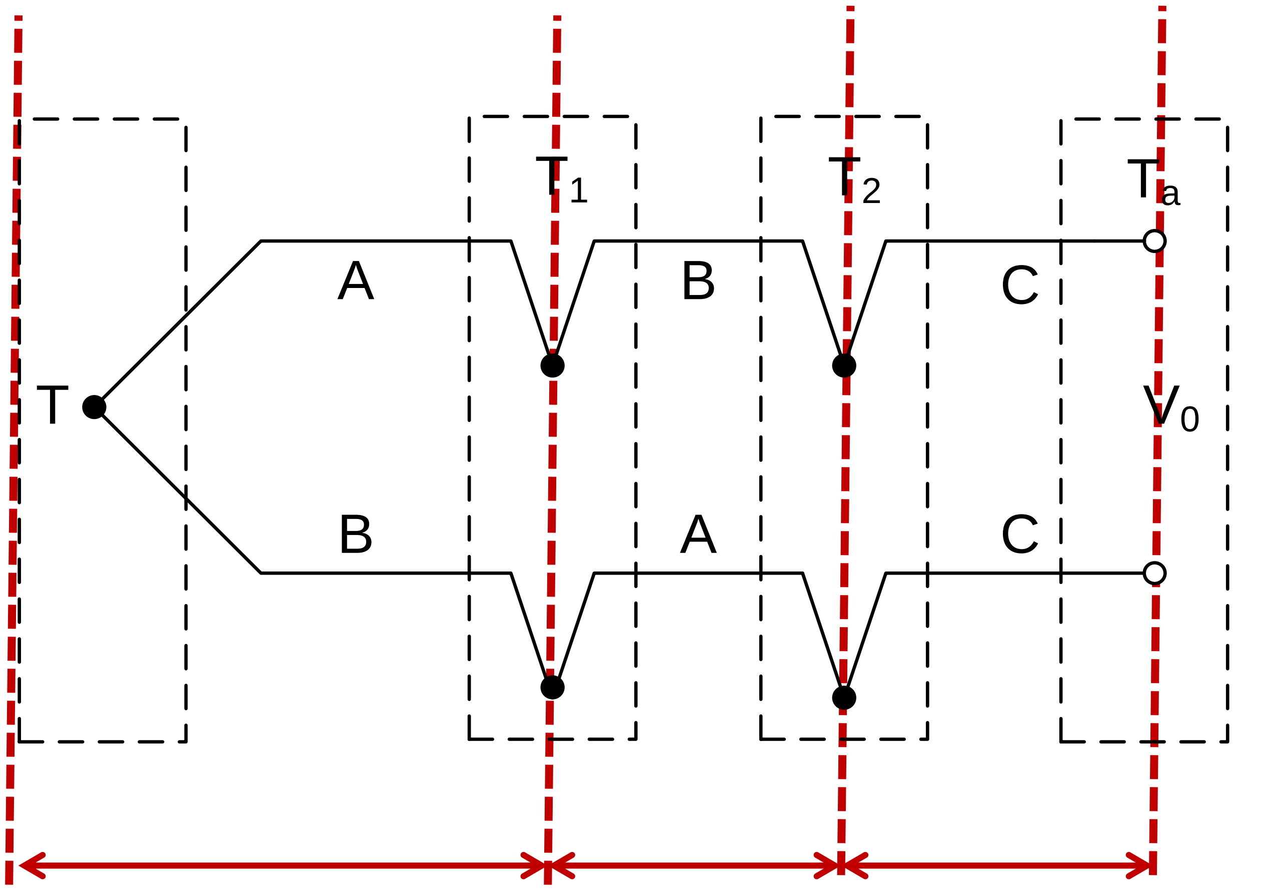


- **what relation must T_1 and T_2 have such that the output voltage only depends on T?**

Thermoelectric laws

example – simulate reference temperature of 0°C

- three thermocouples formed



$V_1 = \alpha_{AB} \cdot (T_1 - T)$ $V_2 = \alpha_{BA} \cdot (T_2 - T_1)$ $V_3 = \alpha_{CC} \cdot (T_a - T_2)$

Thermoelectric laws

example – simulate reference temperature of 0°C

- three thermocouples formed

  $V_1 = \alpha_{AB} \cdot (T_1\text{-}T)$

  $V_2 = \alpha_{BA} \cdot (T_2\text{-}T_1)$

  $V_3 = \alpha_{CC} \cdot (T_a\text{-}T_2)$

- output voltage V_o is equal to

  $V_o = V_1 + V_2 + V_3$ (law of intermediate metals)

- it holds

  $\alpha_{AB} = -\alpha_{BA}$

  $\alpha_{cc} = 0$ (law of homogeneous circuits)

- output voltage V_o is thus equal to

  $V_o = \alpha_{AB} \cdot (T_1\text{-}T) - \alpha_{AB} \cdot (T_2\text{-}T_1) = \alpha_{AB} \cdot (2T_1 - T_2 - T)$

Thermoelectric laws

example – simulate reference temperature of 0°C

- output voltage V_o is thus equal to

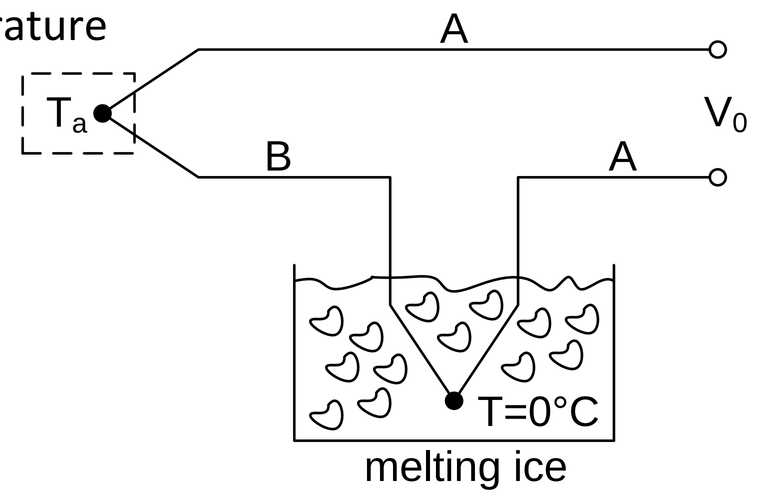
  $V_o = \alpha_{AB} \cdot (T_1\text{-}T) - \alpha_{AB} \cdot (T_2\text{-}T_1) = \alpha_{AB} \cdot (2T_1 - T_2 - T)$

- requirement: V_o only depends on T
- requirement fulfilled when $2T_1 = T_2$

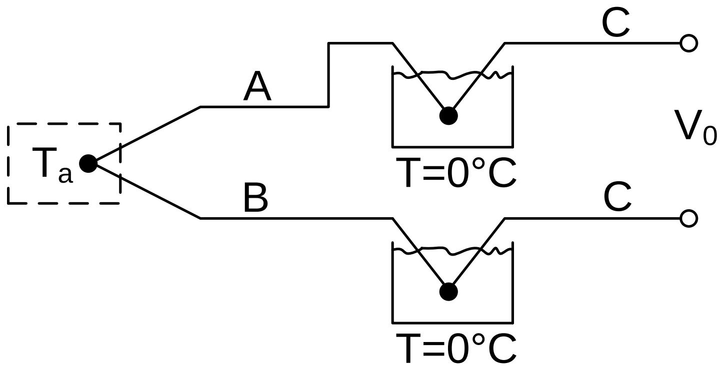
- circuit simulates references temperature of 0°C through controlled temperatures T_1 and T_2

Thermocouple circuit

- reference junction must be kept at constant, known temperature
  - water-ice bath or boiling water
  - requires frequent maintenance
  - one of the wires must be very long

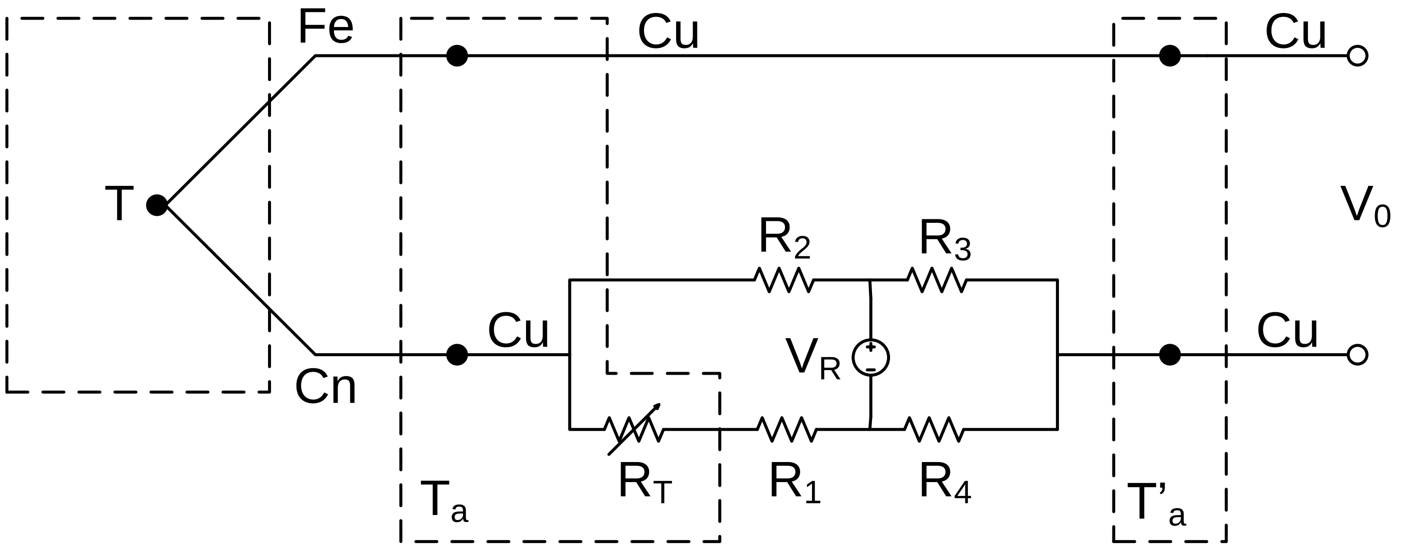


- law of intermediate metals solves wiring problem
  - fixed reference still needed

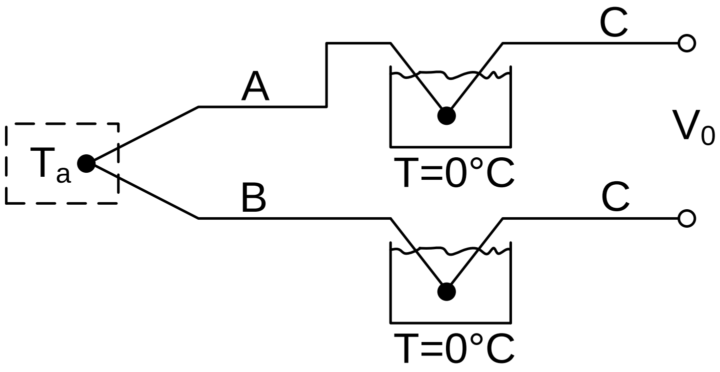


Thermocouple circuit

- reference junction at ambient temperature
- circuit directly compensates for temperature fluctuations

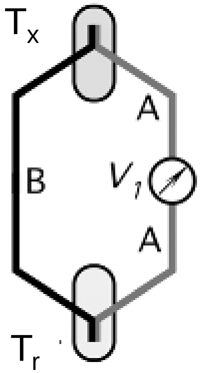


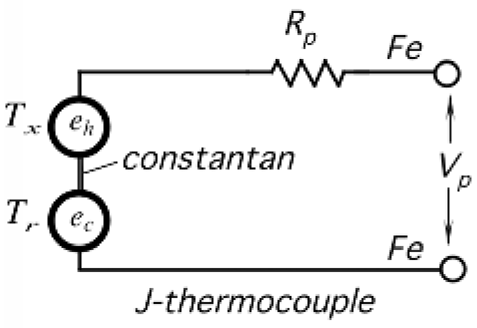
- law of intermediate metals solves wiring problem
  - fixed reference still needed



Thermocouple output

- equivalent electrical circuit for a thermocouple





  - R_p – internal resistance of the thermocouple
  - e_h, e_c – model Seebeck potential of hot and cold junction
  - V_p – Seebeck potential at terminals of the thermocouple

- thermocouple requires cold junction at reference temperature