ME-301 Measurement Techniques: **Temperature and Thermal Property Measurement**

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EPFL STI IGM ETA-LAB

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Intended Learning Objectives

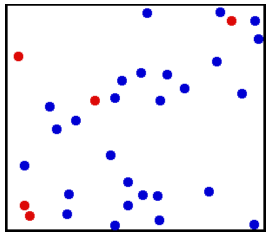
- Concept of temperature and temperature scale
- Different ways to measure temperature
  - Temperature measurement by mechanical effects
  - Temperature measurement by electrical effects
  - Temperature measurement by radiation
- Thermal conductivity measurement

Reading Materials: Chapter 8 and 9, *Experimental Methods for Engineers, 8th Edition, J.P. Holman*

What is Temperature?

Wikipedia

Temperature is a physical quantity that expresses quantitatively the perceptions of **hotness and coldness**.



Kinetic theory

Temperature is proportional to the **average kinetic energy of the molecules**

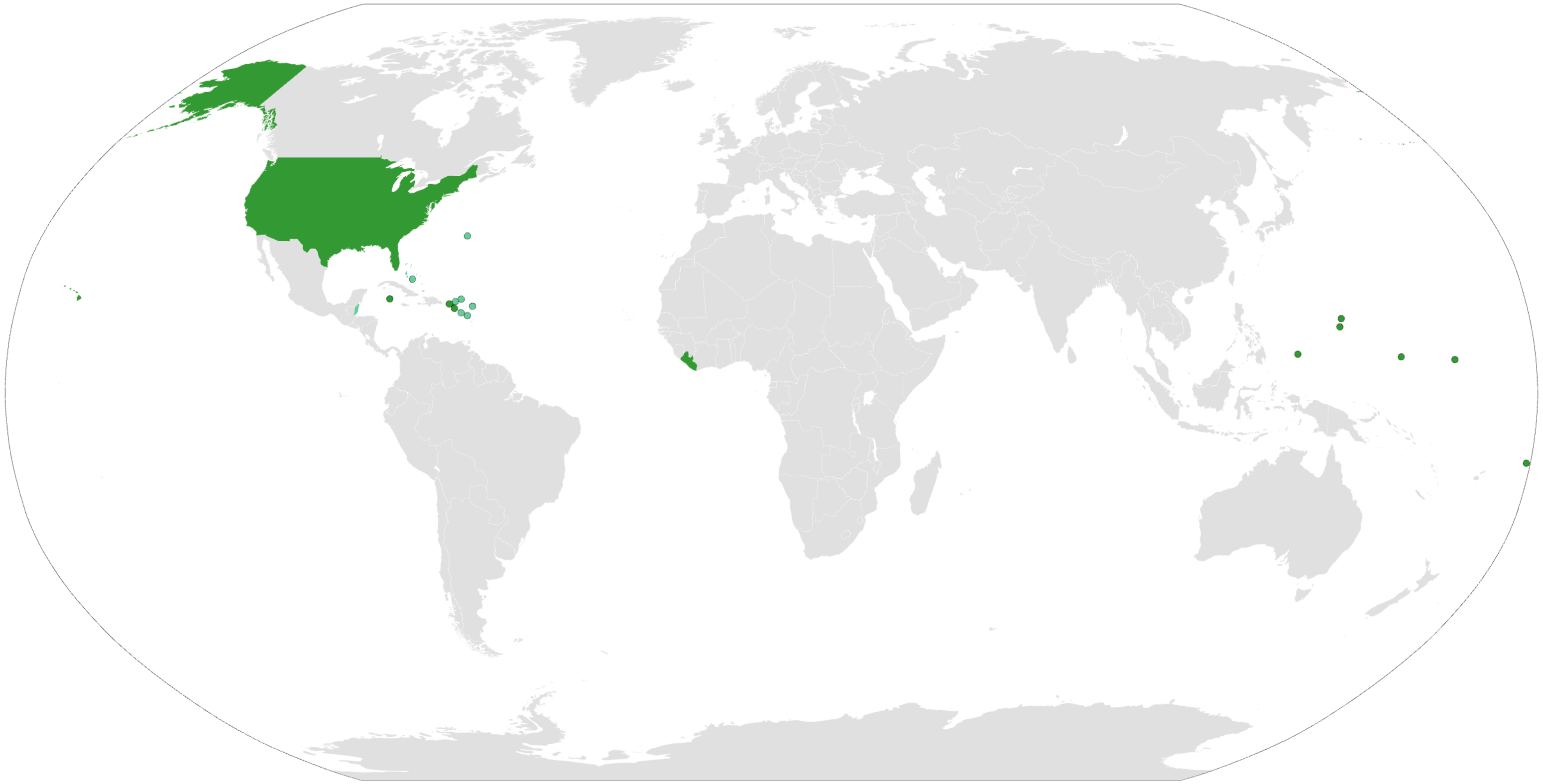
Temperature Scales

- Celsius Scale (°C)
  - 0 °C for the freezing point of water at 1 atm pressure
  - 100 °C for the boiling point of water at 1 atm pressure

- Fahrenheit (°F)
  - 32 °F for the freezing point of water at 1 atm pressure
  - 212 °F for the boiling point of water at 1 atm pressure

- Kelvin (K)
  - 0 K: lowest limit of thermodynamic temperature scale, -273.15 °C
  - 1 K interval is the same as 1 °C interval

Temperature Scales

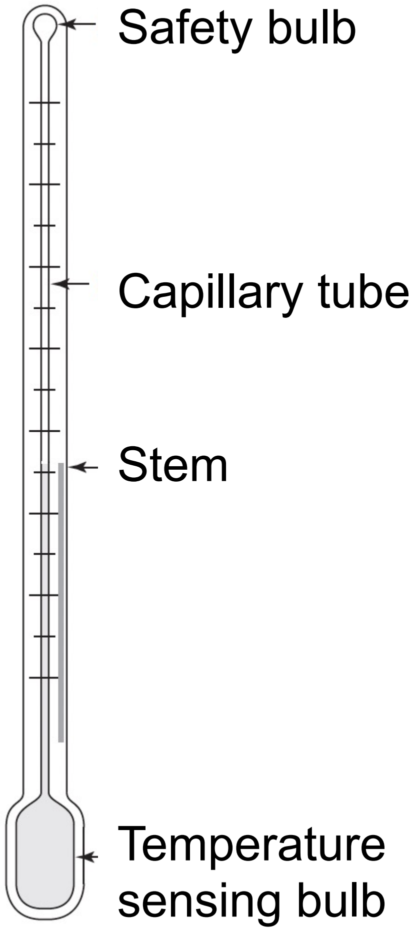


Countries which officially use Celsius

Countries which officially use Fahrenheit

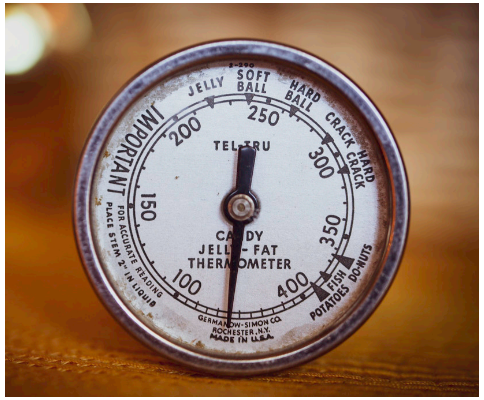
Countries which use both systems

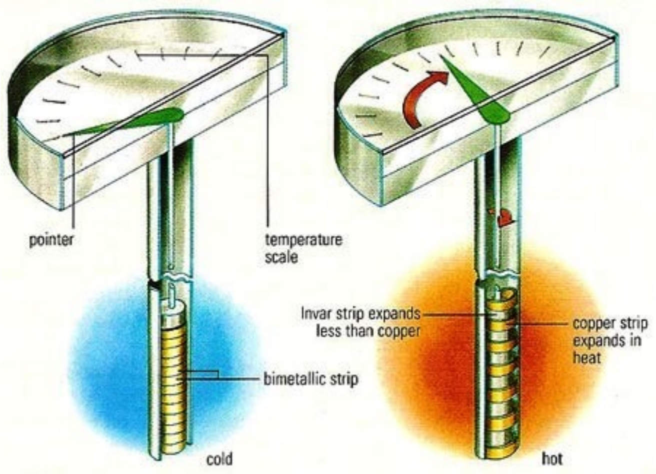
Temperature Measurement by Mechanical Effects

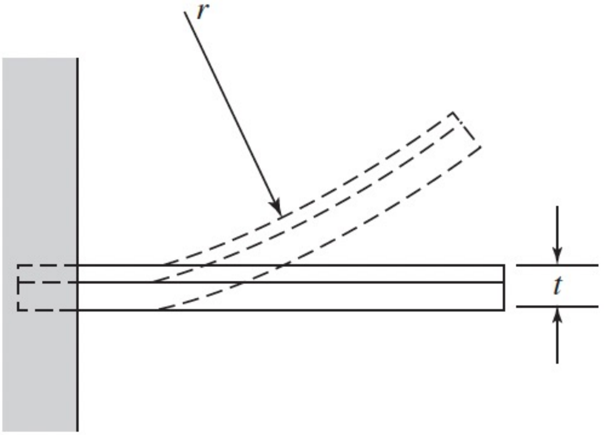


- Liquid-in-glass thermometer
  - Liquid expands when heated and rises in the capillary tube
  - Scale markings etched on the tube
  - Working fluids:
    - Mercury (not good for < -37.8 °C)
    - Alcohol (high thermal expansion coefficient, not good for high T)
  - Depth of immersion important for high accuracy measurement

Temperature Measurement by Mechanical Effects







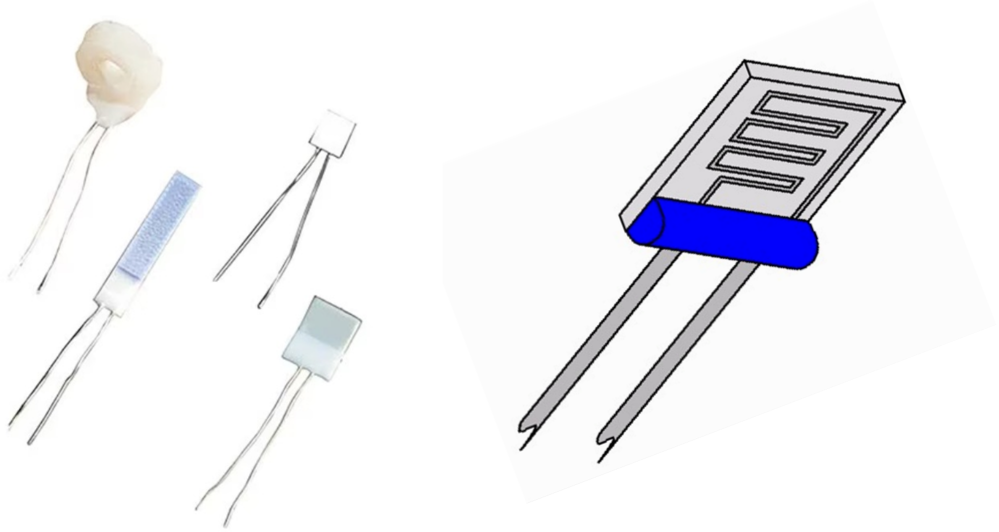
- Bimetallic Thermometer
  - Two pieces of metal with different coefficients of thermal expansion are bonded
  - Strip will bend in one direction when subjected to a temperature different from the bonding temperature
  - Low-cost, negligible maintenance expense, and stable operation

Temperature Measurement by Electrical Effects

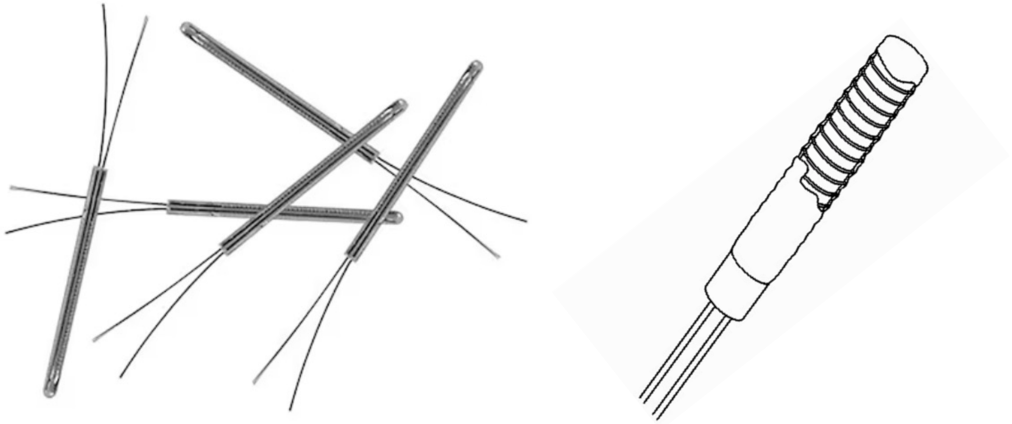
- Resistance Temperature Detector (RTD)

$$R = R_0[1 + \boldsymbol{\alpha}(T - T_0)]$$

$\boldsymbol{\alpha}$: linear temperature coefficient of resistance



Thin-film RTD



Wire-wound RTD

Resistance Temperature Detector (RTD)

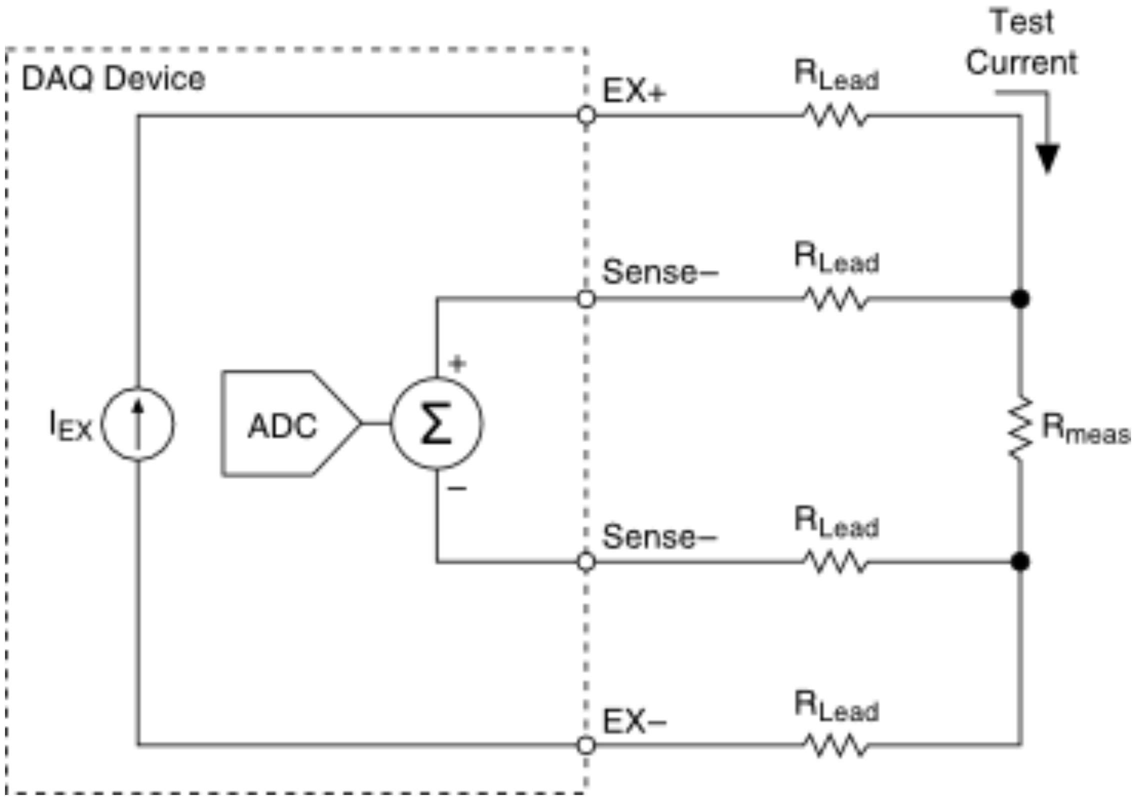
Substance	α (°C^{-1})	ρ ($\mu\Omega \cdot$ cm)
Nickel	0.0067	6.85
Iron (alloy)	0.002 to 0.006	10
Tungsten	0.0048	5.65
Aluminum	0.0045	2.65
Copper	0.0043	1.67
Lead	0.0042	20.6
Silver	0.0041	1.59
Gold	0.004	2.35
Platinum	0.00392	10.5
Mercury	0.00099	98.4
Manganin	±0.00002	44
Carbon	−0.0007	1400
Electrolytes	−0.02 to −0.09	Variable
Semiconductor (thermistors)	−0.068 to +0.14	10^9

$$R = R_0[1 + \alpha(T - T_0)]$$

Linearity usually holds within a certain temperature range

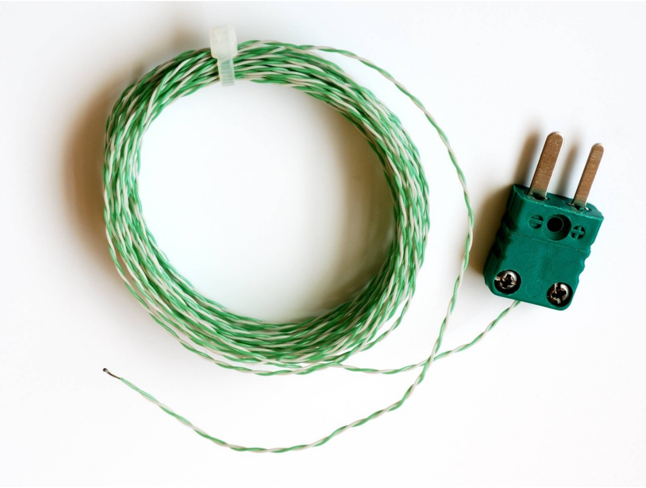
RTD Construction Requirement

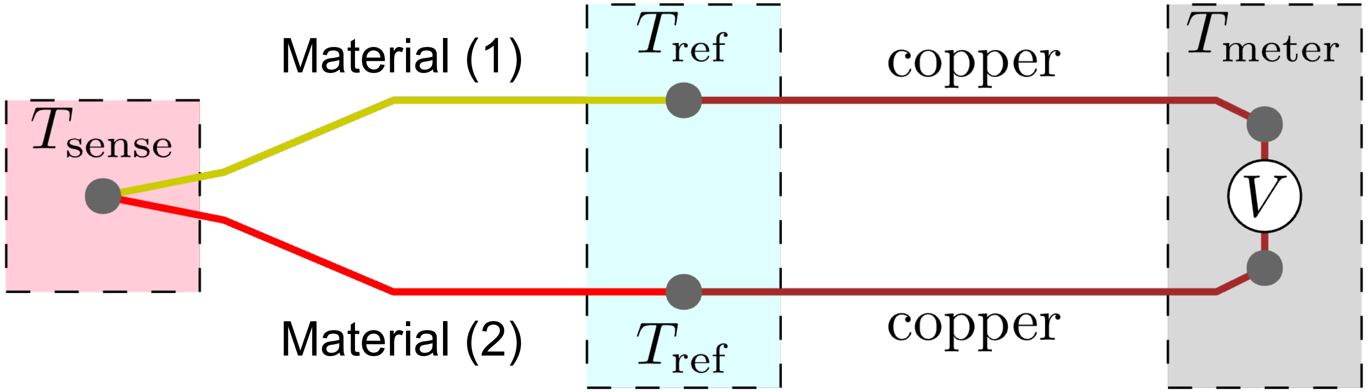
- Free of mechanical stress
- Insulated from moisture
- Account for self-heating
- **Account for lead resistance**



Temperature Measurement by Electrical Effects

- Thermocouples



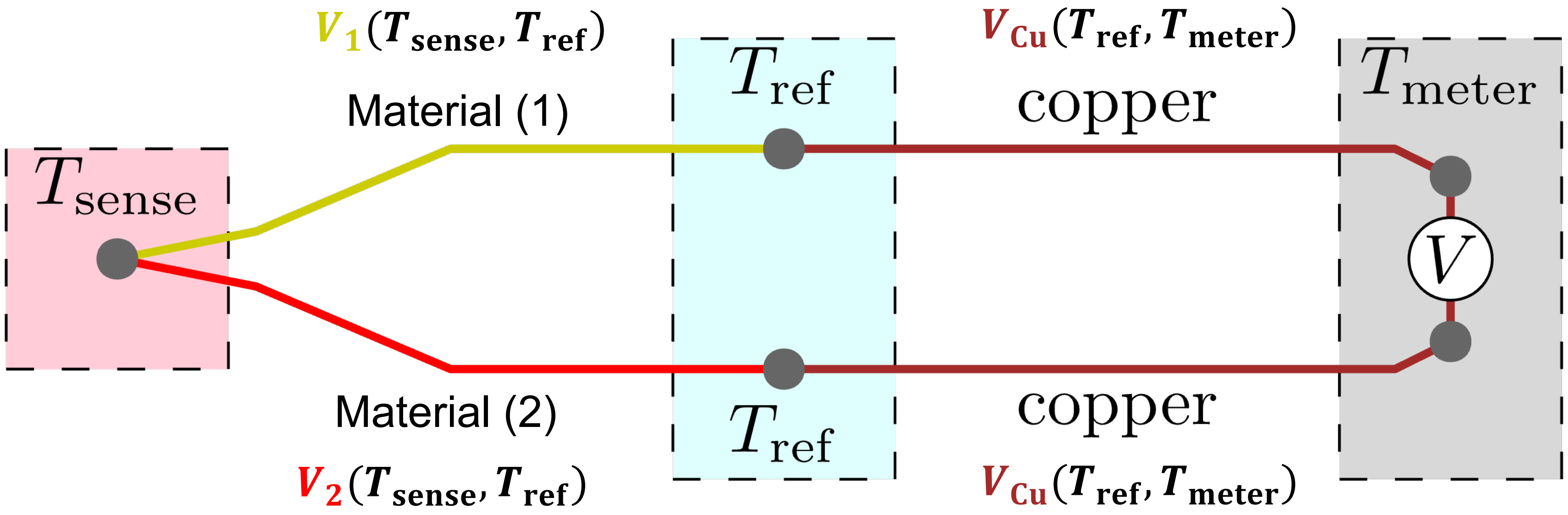


Seebeck effect: an electromotive force can be developed across two points of an electrically conducting material due to the temperature difference

$$\nabla V = -\boldsymbol{S}\nabla T$$

$\boldsymbol{S}$: Seebeck coefficient, temperature and material dependent

Thermocouple Working Principle

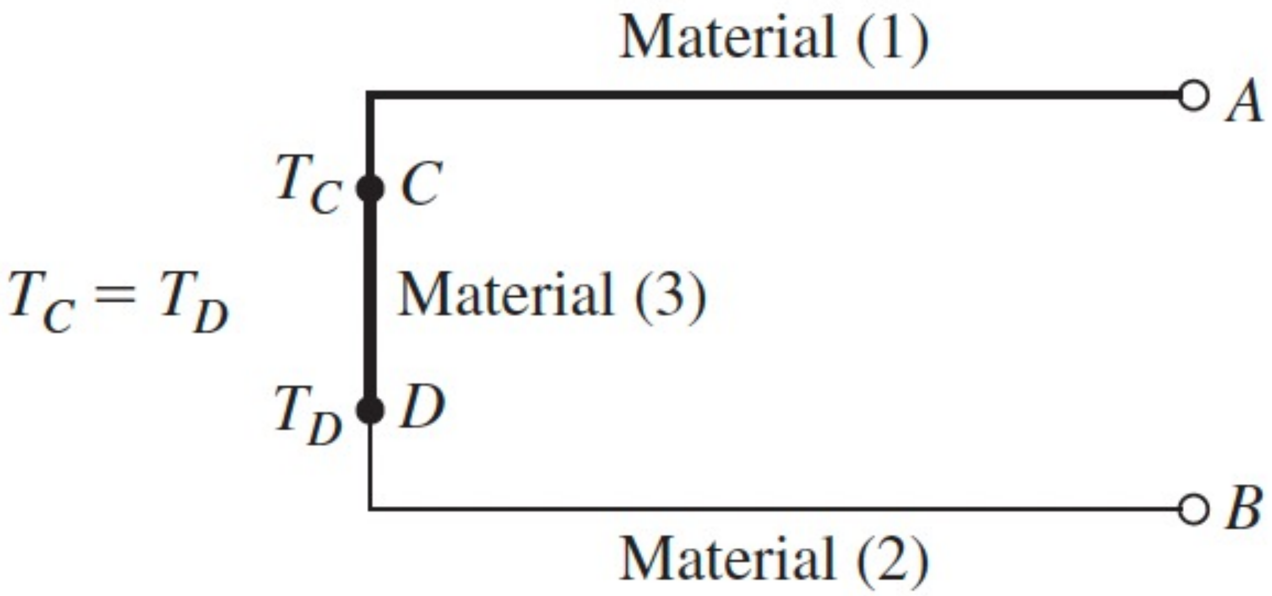


$$\nabla V = -\boldsymbol{S}\nabla T$$

$$V_{\text{measure}} = V_1(T_{\text{sense}}, T_{\text{ref}}) + V_{\text{Cu}}(T_{\text{ref}}, T_{\text{meter}}) - V_2(T_{\text{sense}}, T_{\text{ref}}) - V_{\text{Cu}}(T_{\text{ref}}, T_{\text{meter}})$$

$$= V_1(T_{\text{sense}}, T_{\text{ref}}) - V_2(T_{\text{sense}}, T_{\text{ref}})$$

Effect of Intermediate Metals



- The voltage measured between A and B is not affected by the presence of Material (3) if it's at the junction temperature

Different Types of Thermocouples

Different material combinations		Temperature range	Standard limit of error	Special limit of error
J	Iron/Copper-Nickel	0° to 750°C (32° to 1382°F)	Greater of 2.2°C or 0.75%	Greater of 1.1°C or 0.4%
K	Chromel/Alumel	-200° to 1250°C (-328° to 2282°F)	Greater of 2.2°C or 0.75%	Greater of 1.1°C or 0.4%
E	Nickel-Chromium/ Copper-Nickel	-200° to 900°C (-328° to 1652°F)	Greater of 1.7°C or 0.5%	Greater of 1.0°C or 0.4%
T	Copper/ Copper-Nickel	-250° to 350°C (-418° to 662°F)	Greater of 1.0°C or 0.75%	Greater of 0.5°C or 0.4%

Reference Temperature

- After measuring the voltage, T_{ref} must be known to obtain T_{sense}
    - Ice bath method to set $T_{\mathrm{ref}} = 0\ °\mathrm{C}$
    - Cold-junction temperature compensation (measure the reference temperature in a different way, e.g., using a RTD)
    - Compact solution available commercially

RTDs vs Thermocouples

- Temperature range
  - Thermocouple can be used to measure higher temperatures (>800 °C)
- Response time
  - Thermocouple response time is usually faster
- Size
  - Commercial thermocouple is much smaller than commercial RTD
- Accuracy
  - RTD can offer higher accuracy (typically ~0.1 °C) and a higher accuracy stability (thermocouple drift)
- Cost
  - Thermocouple is considerably cheaper

Ask Yourself These Questions For Your Exp.

- What is the range of temperature I'm measuring?
- How quick is the phenomena I'm trying to observe?
- How much space do I have for the temperature sensor?
- How accurate does this measurement need to be?
- What is my budget?
- Do I need a **data acquisition system** to convert electrical signal to temperature data?

Temperature Measurement by Radiation

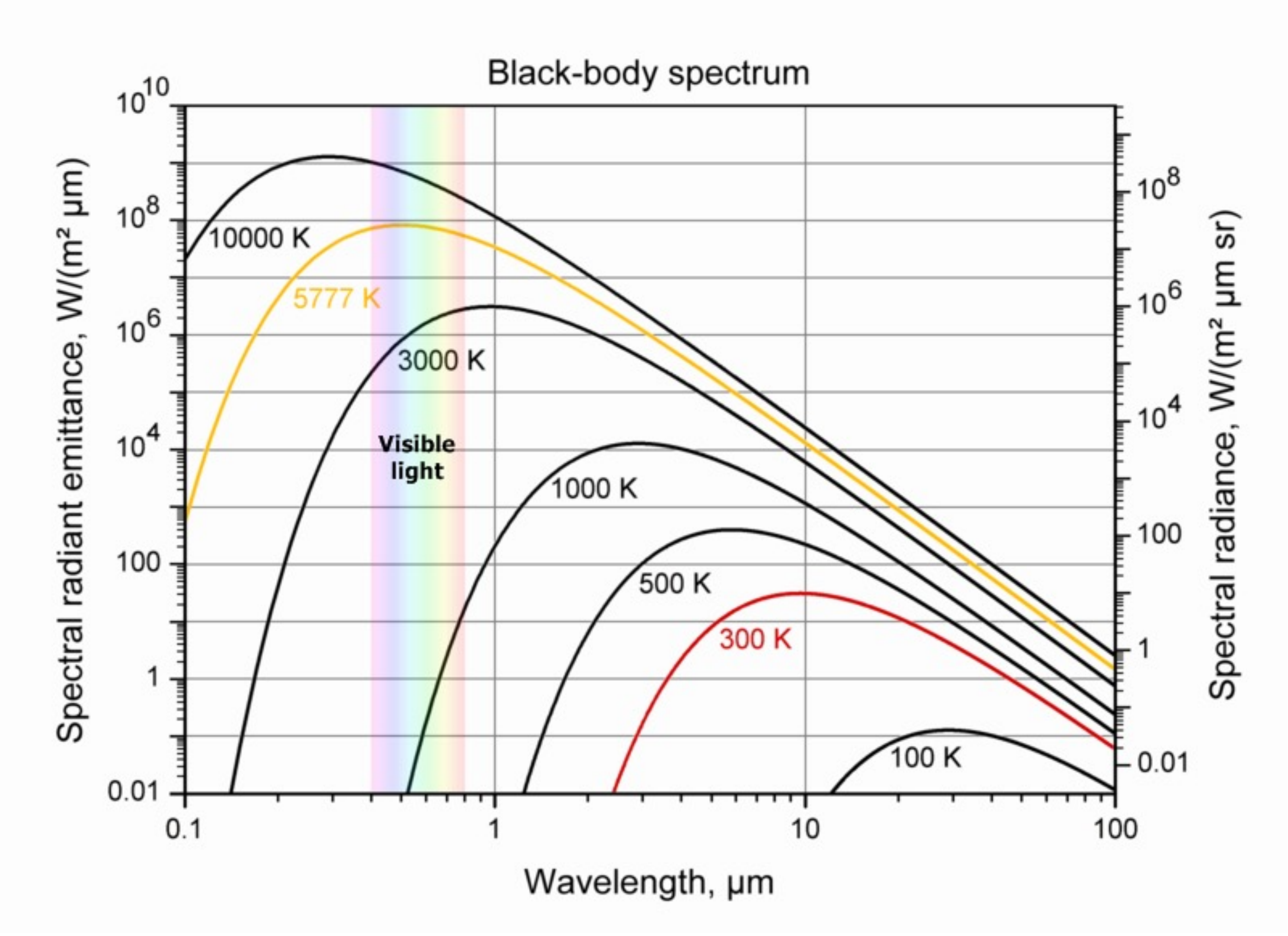
- Review of thermal radiation
  - Electromagnetic radiation emitted by a surface as a result of its temperature

$$q_{\mathrm{emit}} = \varepsilon\sigma T^4$$

Stefan-Boltzmann Law

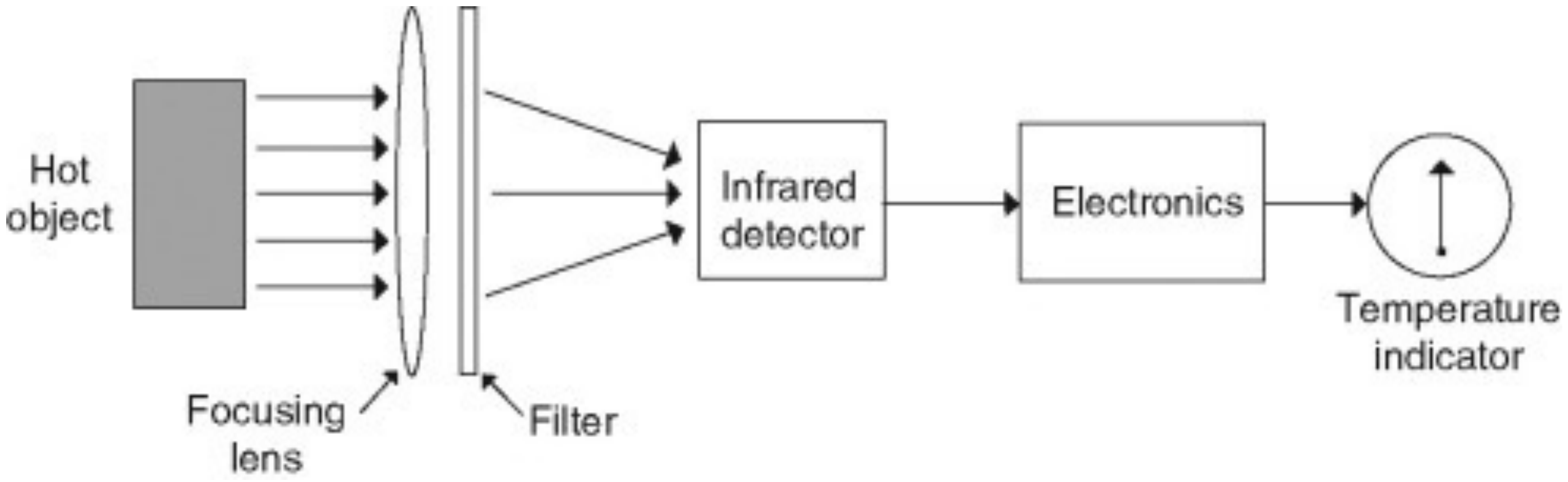
q_{emit} : energy flux emitted by thermal radiation **[W/m^2]**
T : surface temperature **[K]**
ε : emittance (unitless; $0 \le \varepsilon \le 1$; **ε = 1 for a black body**)
σ : Stefan-Boltzmann constant 5.67×10^{-8} **[W/(m^2·K^4)]**

Black-Body Radiation



- Sunlight can be approximated as black-body radiation at 5800 K
- Room temperature black-bodies emit in the infrared (IR) range

IR Thermometer



- Focusing emitted IR onto a special detectors: thermopile or IR photon detector
  - Thermopiles convert the absorbed thermal energy into electrical signal (cheaper)
  - IR photon detector directly convert the IR photon to electrical signal (more sensitive)

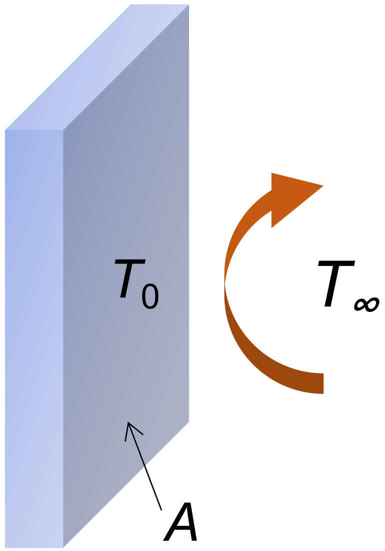
Importance of Knowing Emissivity

- What is really measured with an IR thermometer:
  IR radiation received at the detector

- What is desired: $T = \left(\frac{q_{\mathrm{emit}}}{\boldsymbol{\varepsilon}\sigma}\right)^{1/4}$

- Things affecting $\boldsymbol{\varepsilon}$: surface finish, oxidation, contamination,…
  (calibration usually needed)

Review of Newton's Law of Cooling



- **Mechanism:** thermal energy transferred due to **bulk movement** of fluids (gas and liquid)

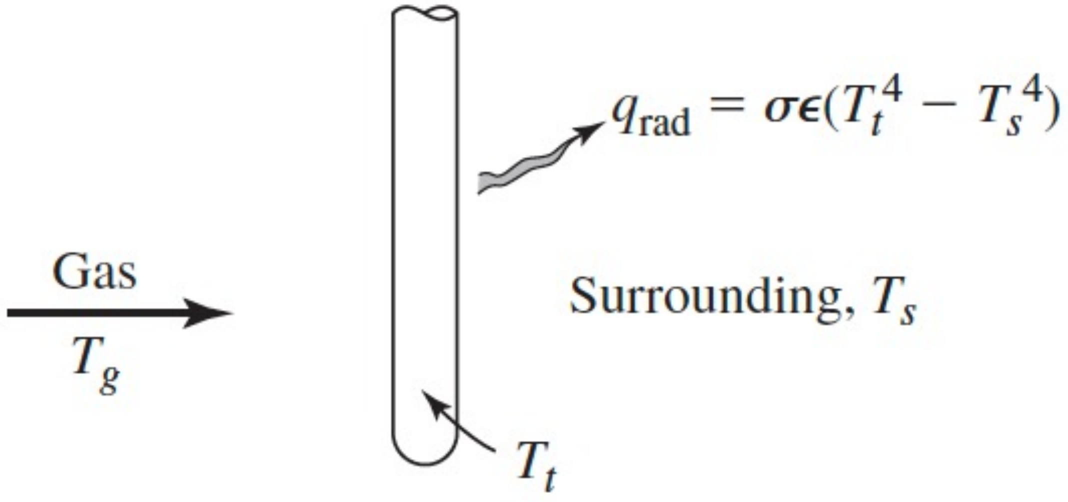
- **Rate Equation:**

$$Q = hA(T_0 - T_\infty)$$

Units: Q **[W]**, A **[m²]**, (T_0 - T_∞) **[K]**
Unit of heat transfer coefficient h: **[W/(m²·K)]**

Example Problem

Temperature measurement in gas flow with a contact thermometer



At steady-state

$$hA\left(T_g - T_t\right) = \sigma\varepsilon A(T_t^4 - T_s^4)$$

h : convection heat transfer coefficient between gas and thermometer

A : thermometer surface area

ε: thermometer surface emittance

T_t: thermometer temperature

T_g: gas temperature

T_s: effective radiation temperature of the surrounding

Error Estimation

$$hA\left(T_g - T_t\right) = \sigma\varepsilon A(T_t^4 - T_s^4)$$

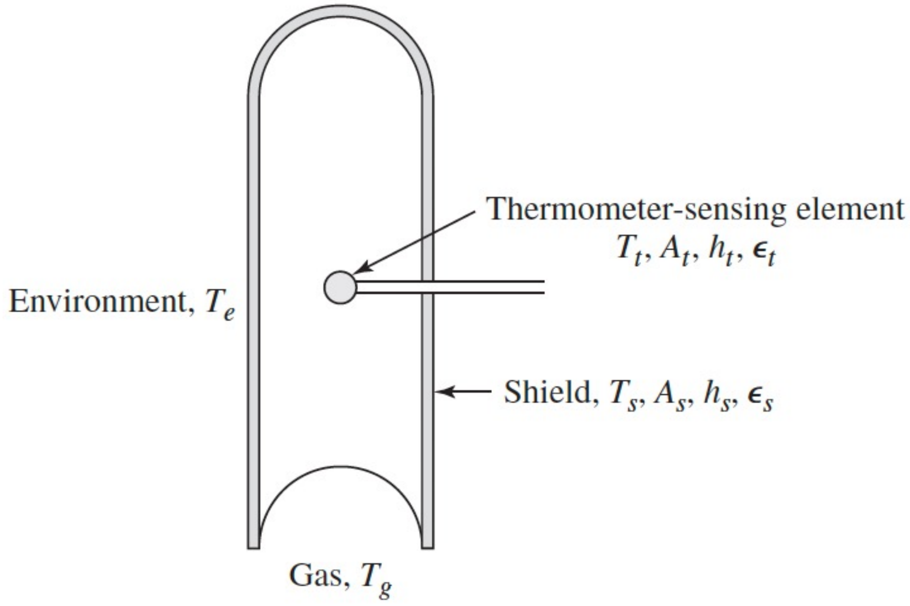
Assuming $T_s \ll T_t$ $\quad h\left(T_g - T_t\right) \approx \sigma\varepsilon T_t^4$

Plugging in some realistic numbers, $h = 10$ W/m^{2}K, $\varepsilon = 0.2$

Now your thermometer reads $T_t = 200$ °C

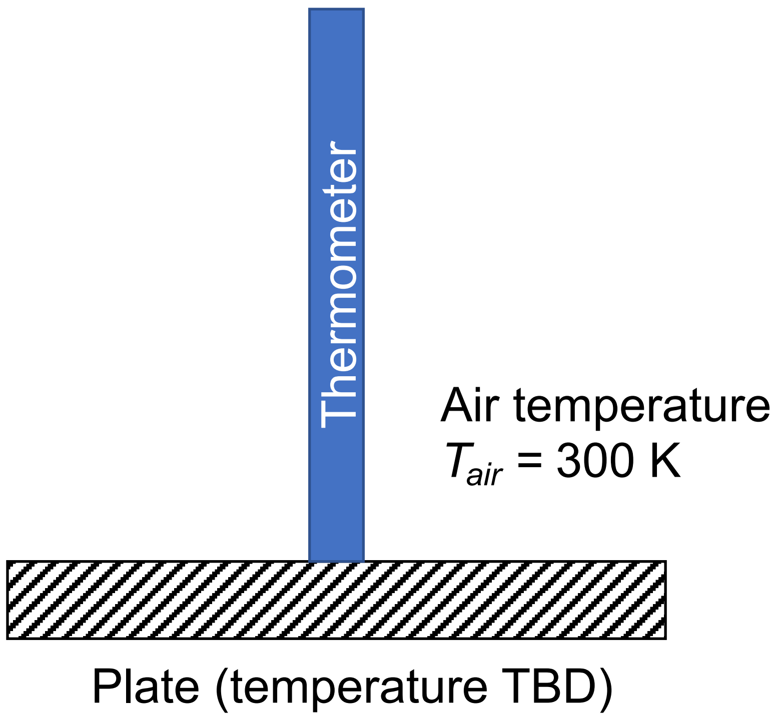
In fact, $T_g - T_t \approx \frac{\sigma\varepsilon T_t^4}{h} = \frac{5.67\times10^{-8}\cdot0.2\cdot(273.15+200)^4}{10} = \mathbf{56.8\ K}$

Radiation Shield



$$hA(T_g - T_t) = \sigma \varepsilon A(T_t^4 - T_s^4)$$

Another Example



Thermometer reads
T_t = 350 K

Contact area between air and thermometer $\boldsymbol{A_{at}} = 5$ mm^2

Convective heat transfer coefficient between air and thermometer $\boldsymbol{h_{at}}$ = 10 W/m^{2}K

Contact area between plate and thermometer $\boldsymbol{A_{pt}} = 1$ mm^2

Contact heat transfer coefficient between plate and thermometer $\boldsymbol{h_{pt}}$ = 100 W/m^{2}K

$$h_{at}A_{at}(T_t - T_{air}) = h_{pt}A_{pt}\left(T_p - T_t\right)$$

In fact, $T_p - T_t = \frac{h_{at}A_{at}(T_t - T_{air})}{h_{pt}A_{pt}} = \mathbf{25\ K}$

Improve Thermal Contact

- Increasing h_{pt} = 100 W/m^{2}K to 10000 W/m^{2}K

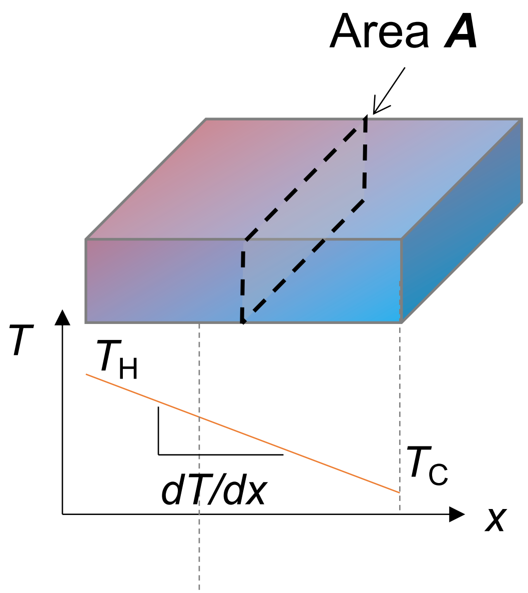
$$T_p - T_t = \frac{h_{at}A_{at}(T_t - T_{air})}{h_{pt}A_{pt}} = \mathbf{0.25\ K}$$

- Thermal contact can be improved by cleaning the surface, applying higher contact pressure, increasing actual contact area, using thermal grease…

Review of Fourier’s Law

Joseph Fourier
(1768 – 1830)

$$q = -k\frac{dT}{dx}$$



Heat flow rate *Q* **[W]**

x

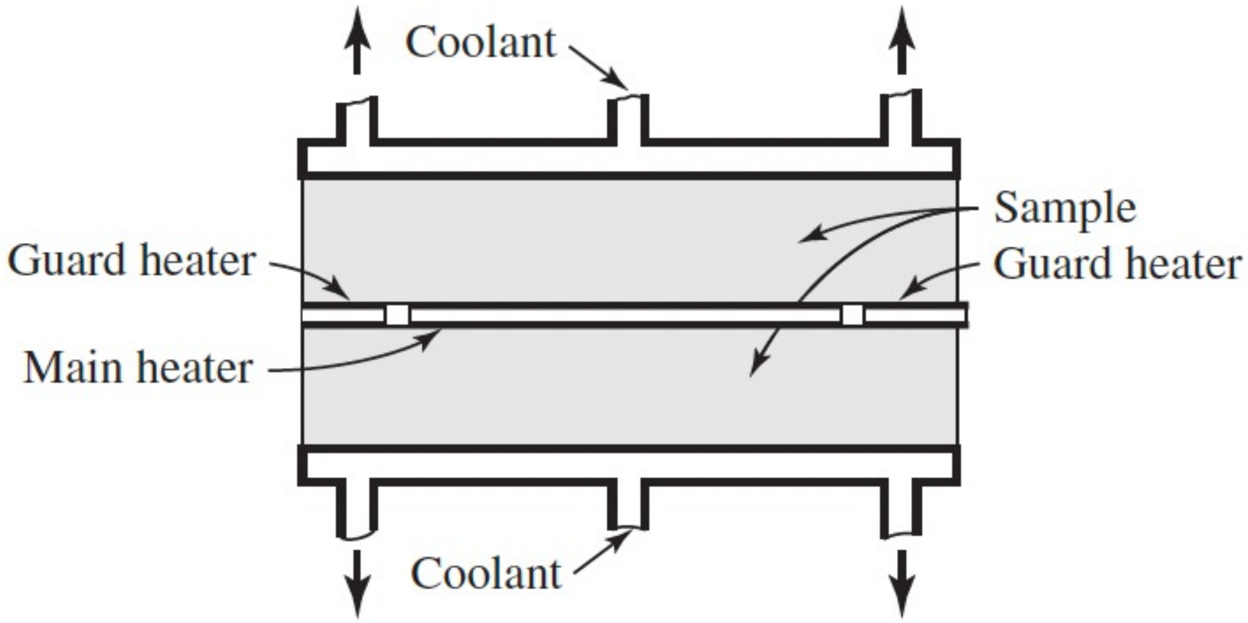
Heat flux $q = \frac{Q}{A}\ \left[\frac{\mathbf{W}}{\mathbf{m^2}}\right]$

$$q \propto -\frac{dT}{dx}\ \left[\frac{\mathbf{K}}{\mathbf{m}}\right]$$

Proportionality *k*: thermal conductivity $\left[\frac{\mathbf{W}}{\mathbf{m \cdot K}}\right]$

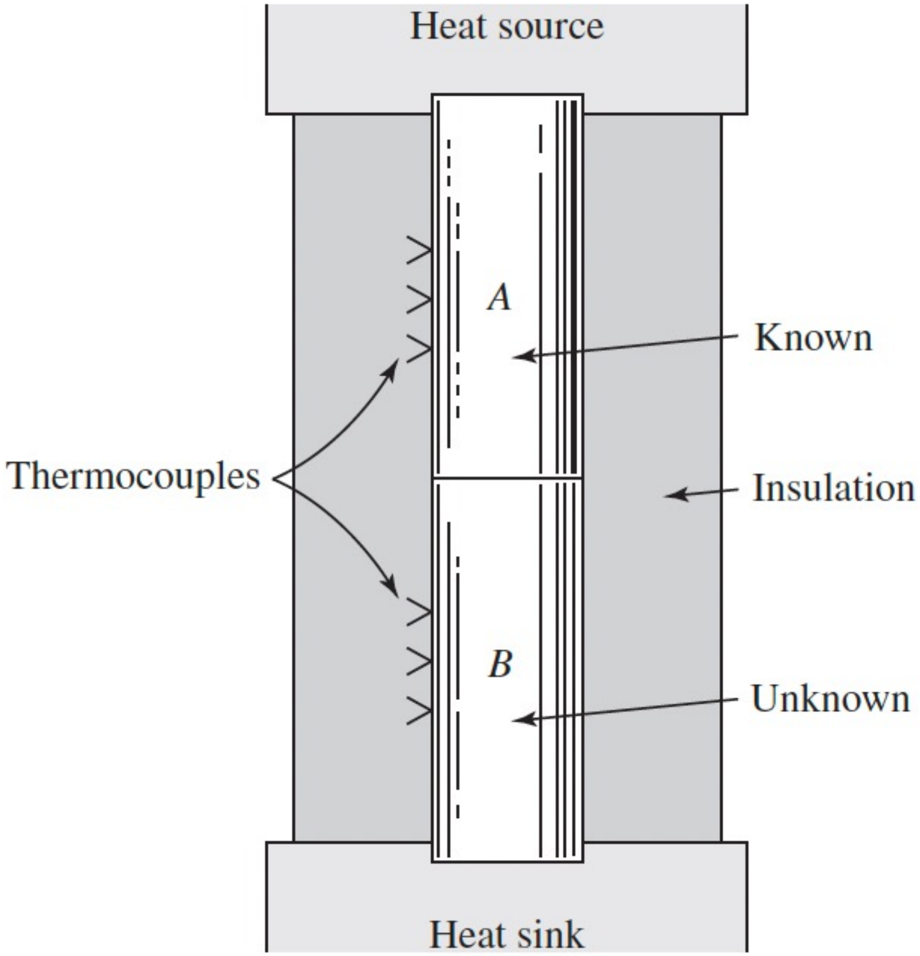
Measurement of Thermal Conductivity

- Guarded hot plate method



- Designed to keep heat transfer 1D
- Guarded heater surrounding the main heater controlled at the same temperature
- Coolant sets the cold side temperature
- Useful for moderate or low thermal conductivity material

For High Thermal Conductivity Materials



- k_A known, k_B unknown
- Heat source and heat sink set the temperature of two ends
- Insulation to minimize side loss
- Energy balance allows for calculation of k_B

$$q = -k_A A \left(\frac{dT}{dx}\right)_A = -k_B A \left(\frac{dT}{dx}\right)_B$$

Summary

- Temperature scale: Celsius, Fahrenheit, and Kelvin
- Contact thermometers
  - Liquid-in-glass, bimetallic strip
  - **RTD, thermocouple**
- Non-contact thermometers
  - IR thermometer
- Things to note during thermal experiments
  - Radiation shield
  - Thermal contact between sensor and object
- Thermal conductivity measurement