Basic Sensors

ENGG 6150: Bio-Instrumentation

Basic Sensors

- Displacement Measurement
- Resistive Sensors
  - Whetstone Bridge Circuits
  - Inductive Sensors
  - Capacitive Sensors
- Temperature Measurement
  - Temperature Sensors
- Solid-State Sensors
- Sensor Calibration

Displacement Measurements

- Many biomedical parameters rely on measurements of size, shape, and position of organs, tissue, etc.
  - require displacement sensors

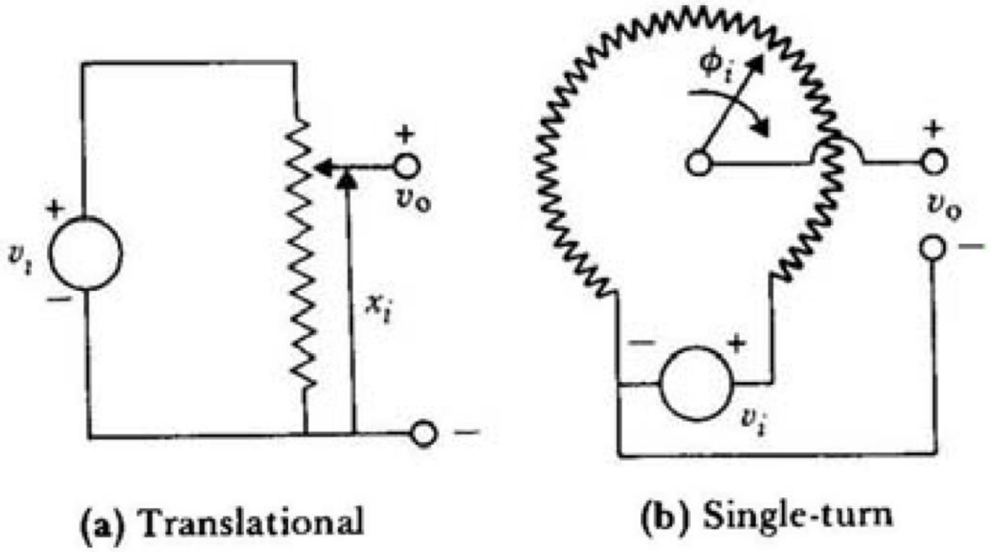
- Examples
  - (direct measurement) of the diameter of a blood vessel
  - (indirect measurement) of the movement of a microphone diaphragm in response to the blood flow to quantify liquid movement through the heart

Resistive Sensors

- The physical concept behind the resistive sensor is the change to the resistive value of the sensor through applying external force/pressure, or temperature
- Using the voltage division rule in circuits analysis we can relate this change into a change in voltage
- Some of those sensors are:
  - Potentiometer
  - Strain Gauge

1-Potentiometer

- Potentiometers produce output potential (voltage) change in response to input changes as displacement
  - typically formed with resistive elements e.g. carbon/metal film
    - $\Delta V = I \, \Delta R$
  - produce linear output in response to displacement
- Example potentiometric displacement sensors
  - Translational: small (~mm) linear displacements
    - V_o increases as X_i increases
- Single-Turn: small (10-50°) rotational displacements
  - V_o increases as $\Delta\phi i$ increases



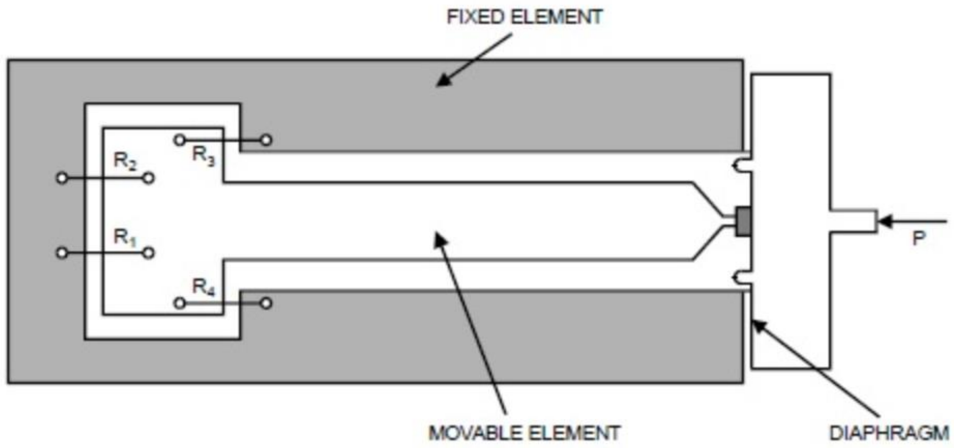
2- Strain Gauge

- A Strain gauge is a sensor whose resistance varies with applied force
  - It converts force, pressure, tension, weight, etc., into a change in electrical resistance which can then be measured.

- Those sensors can be classified under two different types as follow:

  - Unbonded Strain Gauge and Bonded Strain Gauge

Unbonded Strain Gauge



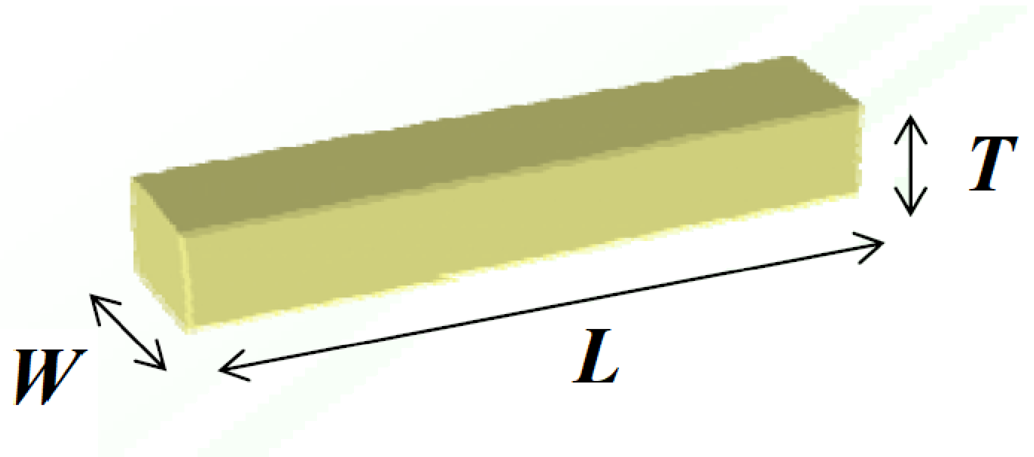
Unbonded strain-gage pressure transmitter with four wires.

- Force → Displacement→ Resistance change→ correlating the resistance change to applied force/pressure

- Has a frame of stationary and movable parts that are connected with wires .
- Wire tension increases and decreases with changes in pressure and as a result the resistance of the wire will change.
- The electronics convert this resistance measurement (through the Wheatstone bridge) into a pressure output.
- Pros and Cons
- High displacement, low mass and long-term stability. However, they are sensitive to shock.

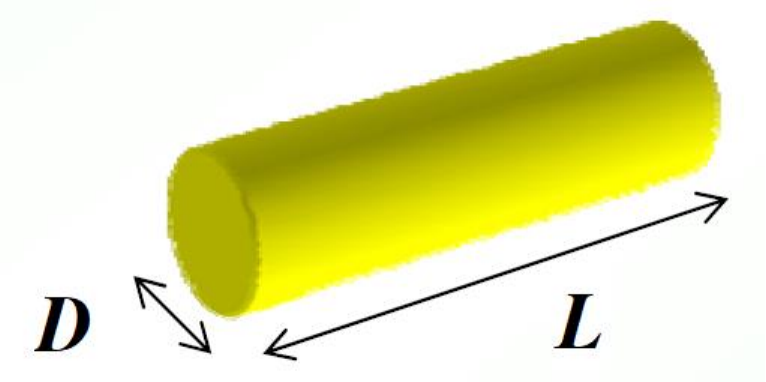
Strain Gauge Charactaristics

- Consider: a strain (stretch) of a thin wire (~25μm diamater)
  - its length increases and its diameter decreases
  - results in increasing resistance of the wire
- Can be used to measure extremely small displacements, on the order of nanometers
- For a rectangular wire
  - $R_{line} = \frac{L}{\sigma A} = \frac{L\rho}{A}$
  - A = WT
  - ρ is: resistivity, and σ is: conductivity
- Thus
  - ΔR/R = Δ L/L – ΔA/A + Δ ρ/ρ



Strain Gauge: Gage Factor

- For a cylindrical wire
    - A = π (D/2)^2 where A is the cross sectional area of the wire
    - Poisson's ratio, μ: relates change in diameter *D* to change in length *L*
  - $\frac{\Delta D}{D}$ = - μ $\frac{\Delta L}{L}$

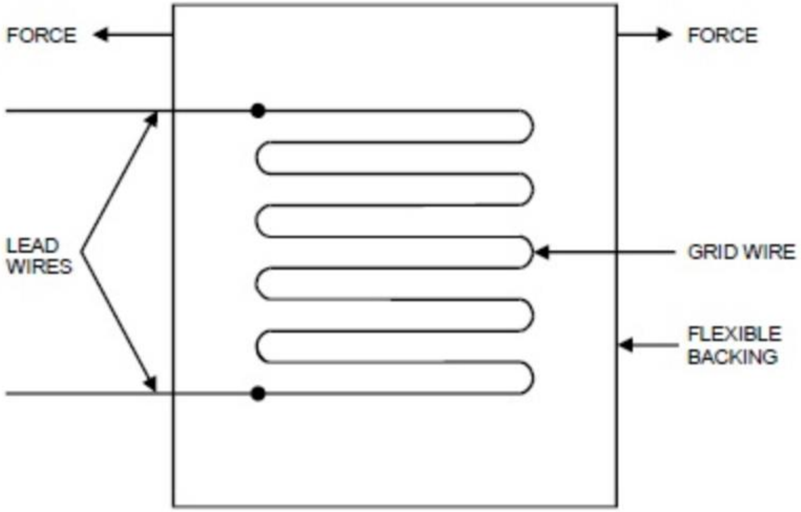


- Thus
  - Δ R/R = (1+2 μ) Δ L/L + Δ ρ/ρ

  dimensional effect piezoresistive effect

- Gauge Factor, G, used to compare strain-gate materials
  - $G = \frac{\Delta R/R}{\Delta L/L} = (1 + 2\mu) = \frac{\Delta\rho/\rho}{\Delta L/L}$

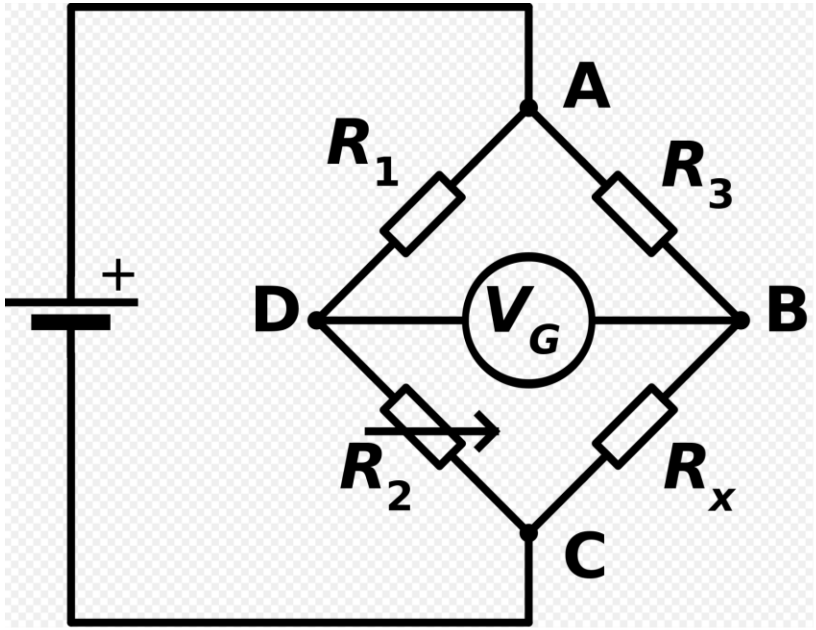
Bonded Strain Gauge



Bonded foil strain-gage pressure transmitter.

- Wires are bonded to a diaphragm.
- Changes in pressure cause the diaphragm to flex straining the wires
- The wires are distributed allover the diaphragm
- At the center, wires encounter maximum tangential strain
- At the circumference, wires encounter maximum radial strain.
- This is an improvement over the unbonded type since it eliminates the posts and frame.

Resistive Sensor Circuit



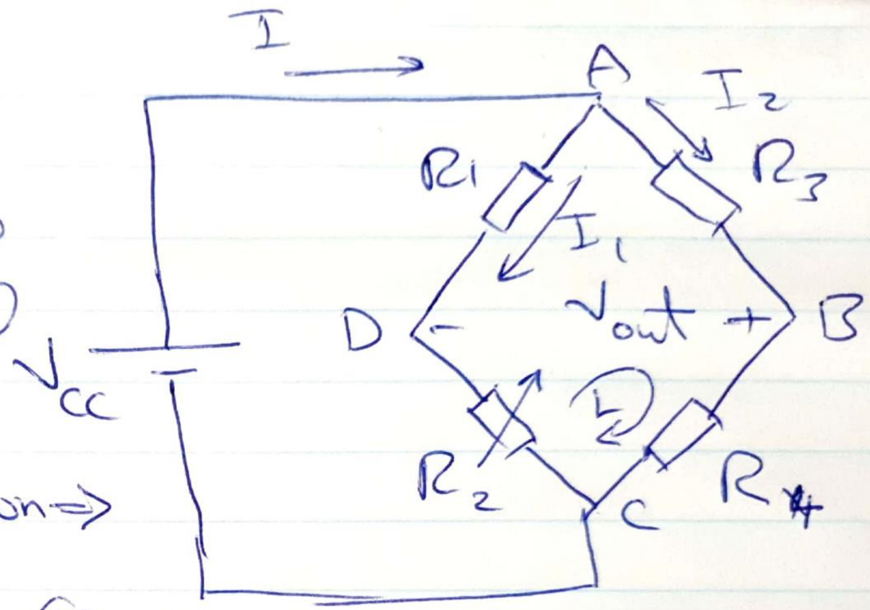
- Wheatstone bridge is a configuration variable and fixed elements used to monitor small variations in the elements
- The variable resistive element is the resistive sensor in our case which can be the strain gauge
- A change in the resistance in the sensor will result in a voltage drop shown between D and B.
- The change in the voltage will be related to the change in the resistance

Resistive Sensor Circuit

KVL @ L:

$$-V_{out} + V_{R_4} - V_{R_2} = 0$$

$$\Rightarrow \boxed{V_{out} = V_{R_4} - V_{R_2}} \quad (1)$$



from voltage division ⇒

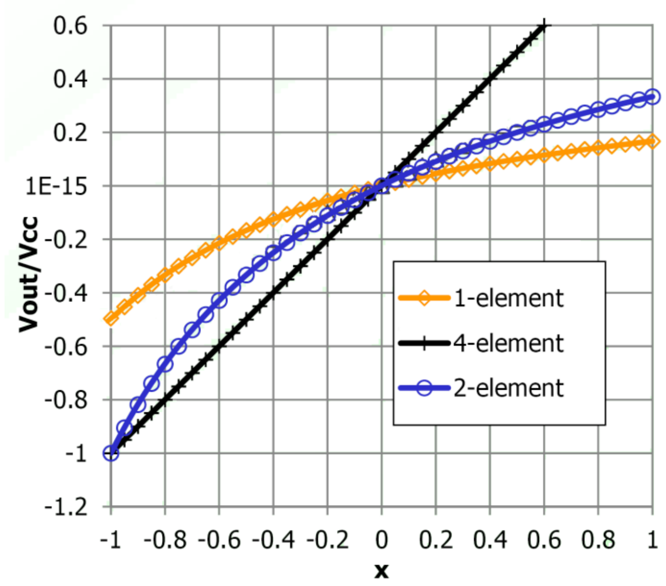
$$\boxed{V_{R_4} = V_{cc}\frac{R_4}{R_3+R_4}} \quad (2)$$

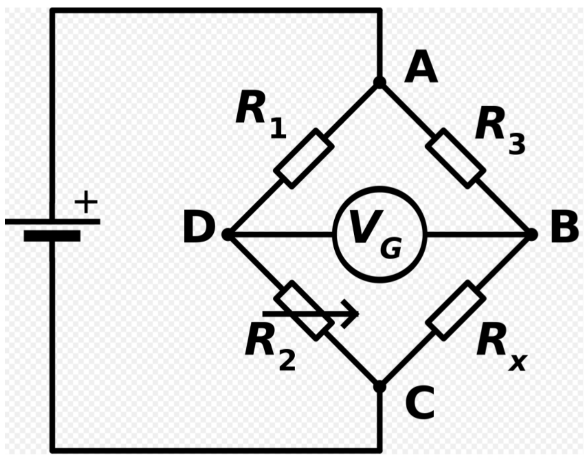
$$\boxed{V_{R_2} = V_{cc}\frac{R_2}{R_2+R_1}} \quad (3)$$

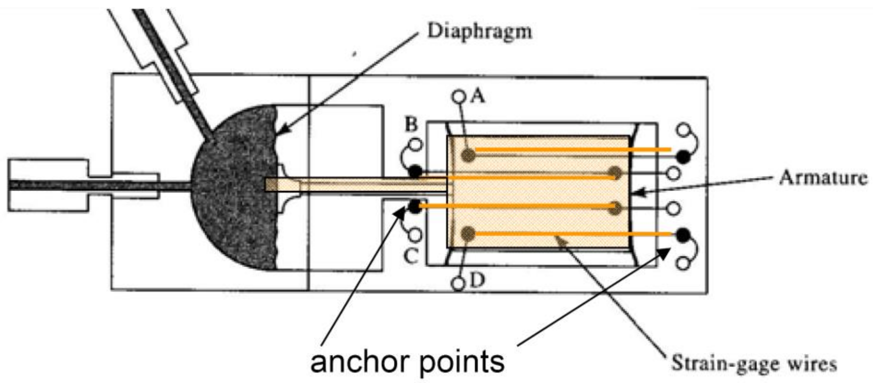
sub (2) & (3) in (1) ⇒

$$V_{out} = \left(\frac{R_4}{R_3+R_4} - \frac{R_2}{R_2+R_1}\right)V_{cc}$$ where R_2 is the resistive sensor

Wheatstone Bridge

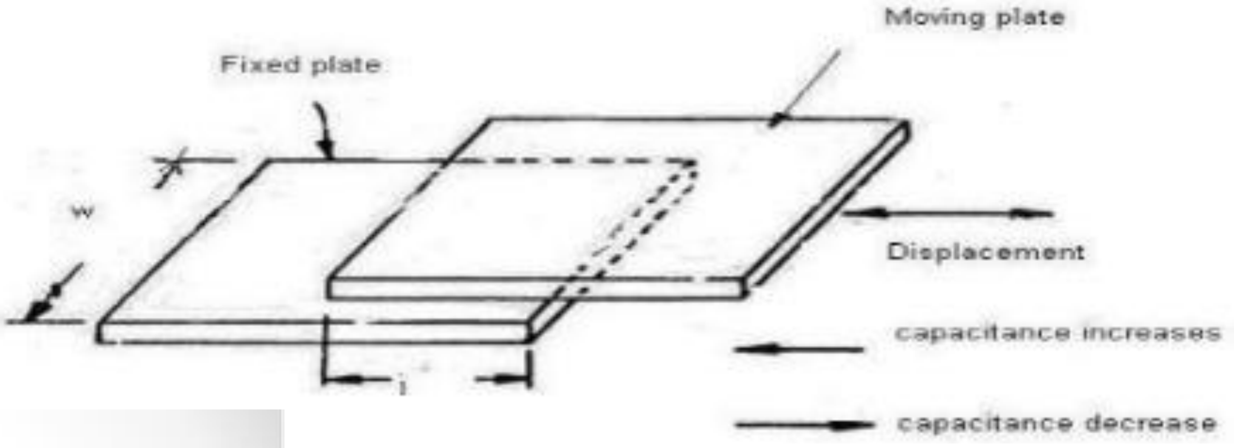


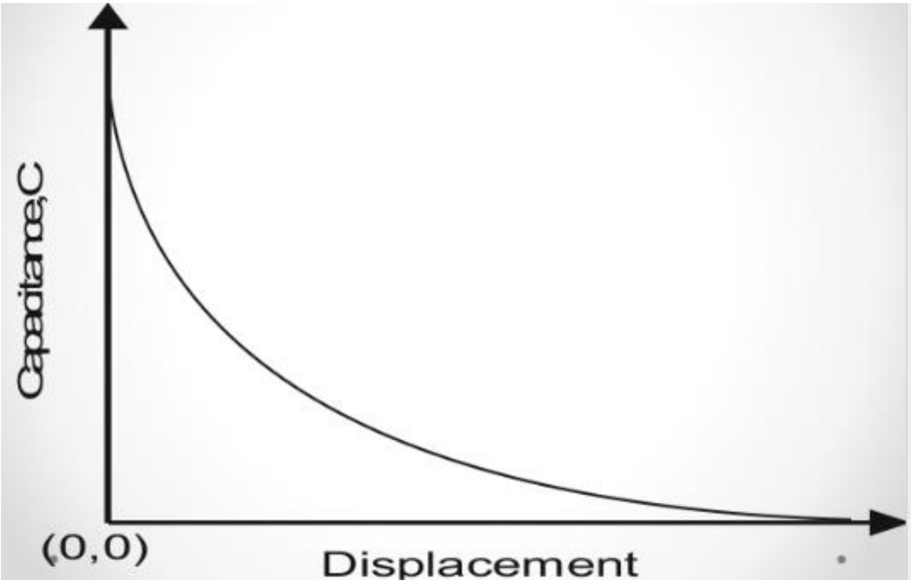




- In case one wire of the strain gauge is used “one element” as the component R2, then the response would be non-linear.
- Linearizing the response would be using more elements as:
- Two elements then R1 and R2 increasing and decreasing in length, respectively.
- Four elements then R2 and R3 are two wires increasing in length and R1 and Rx are decreasing in length.

Capacitive Transducer





$$C = \varepsilon \frac{A}{d} = \varepsilon \frac{x.w}{d}$$

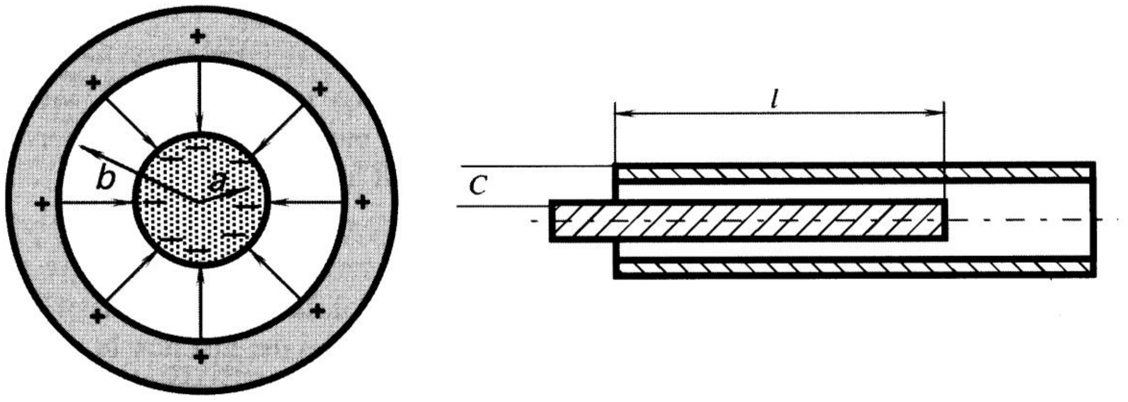
Where

x = Length of overlapping part of plates, m

w = width of plate, m

Capacitive Transducer

- If the inner conductor can be moved in and out, the measured capacitance will be a function of *L*.

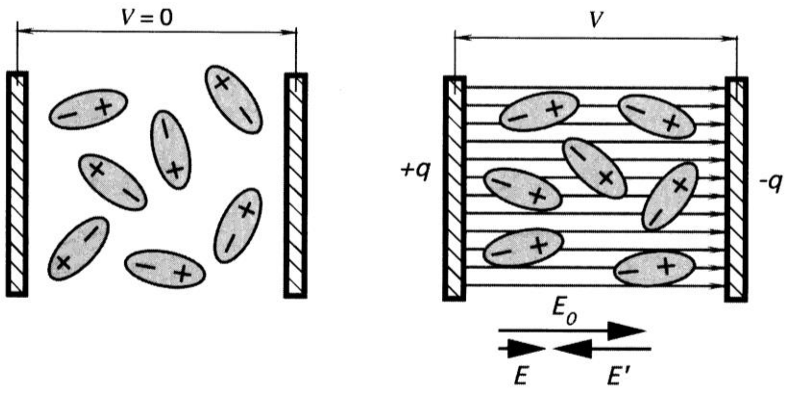


(A) (B)

$$C = \frac{2\pi\varepsilon_0 l}{\ln(b/a)}$$

Capacitive Transducer

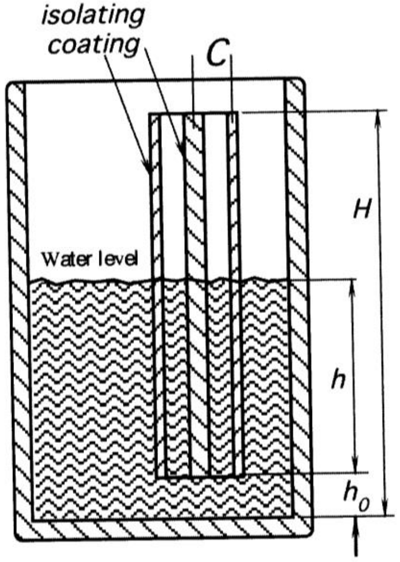
- The material between the plates of the capacitor can also be used to sense changes in the environment.
  - When vacuum (or air) is replaced by another material, the capacitance increases by a factor of ε, known as the dielectric constant of the material
  - The increase in C is due to the polarization of the molecules of the material used as an insulator.

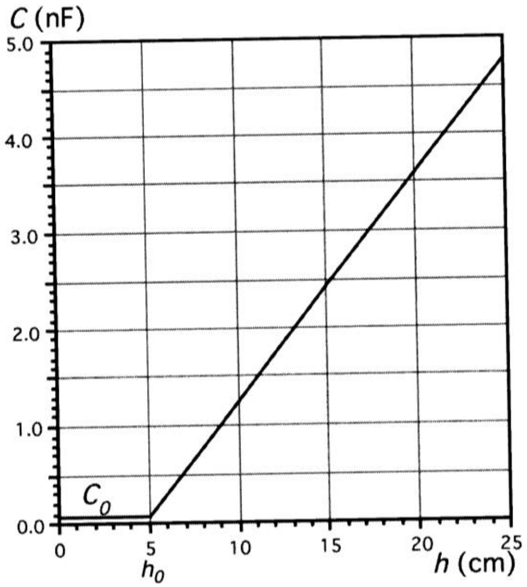


$$C = \varepsilon \frac{q}{V} = \frac{\varepsilon_o \varepsilon_r A}{d}$$

Capacitive Transducer

- The total capacitance of the coaxial sensor shown below is the capacitance of the water-free portion plus the capacitance of the water-filled portion. As the level of the water changes, the total capacitance changes.



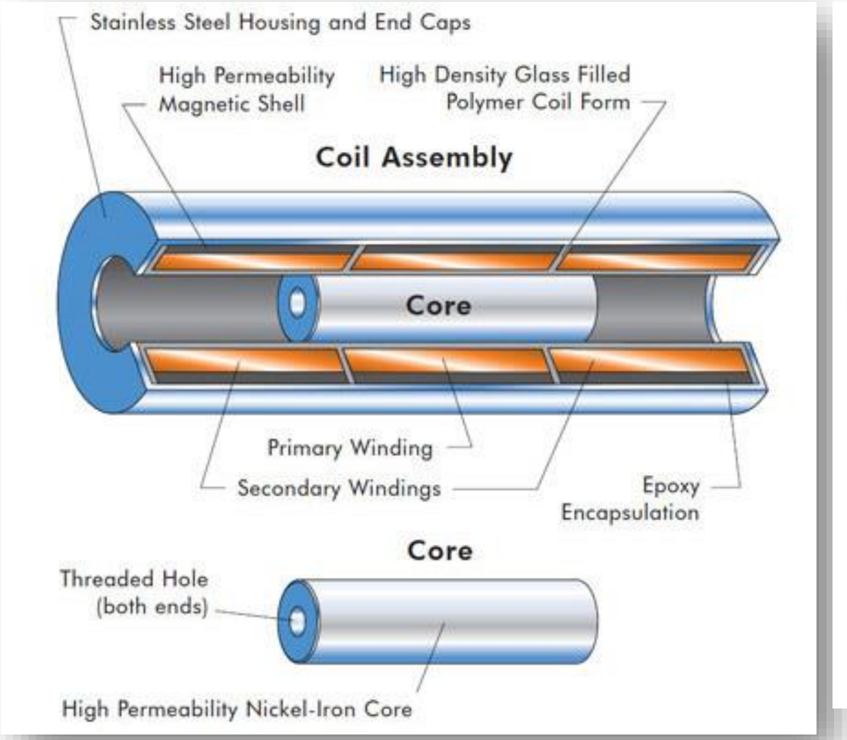


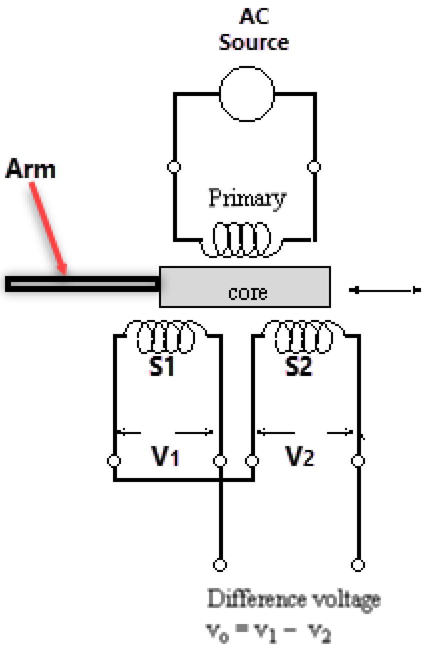
$$C_h = C_{free} + C_{filled}$$

$$C_h = \frac{2\pi\varepsilon_0}{\ln(b/a)}[H - h(1-\varepsilon_r)]$$

Linear variable differential transformer

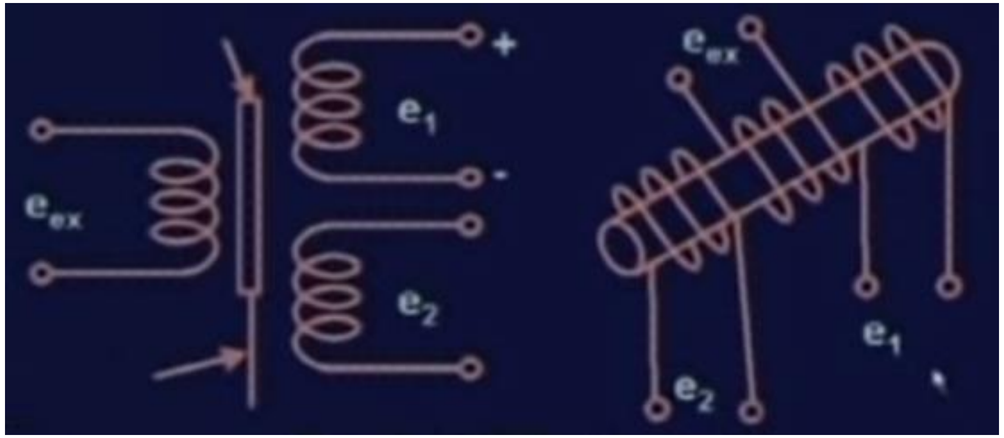
- LVDT: It is a sensor for displacement measurement.
- It converts linear motion into voltage.

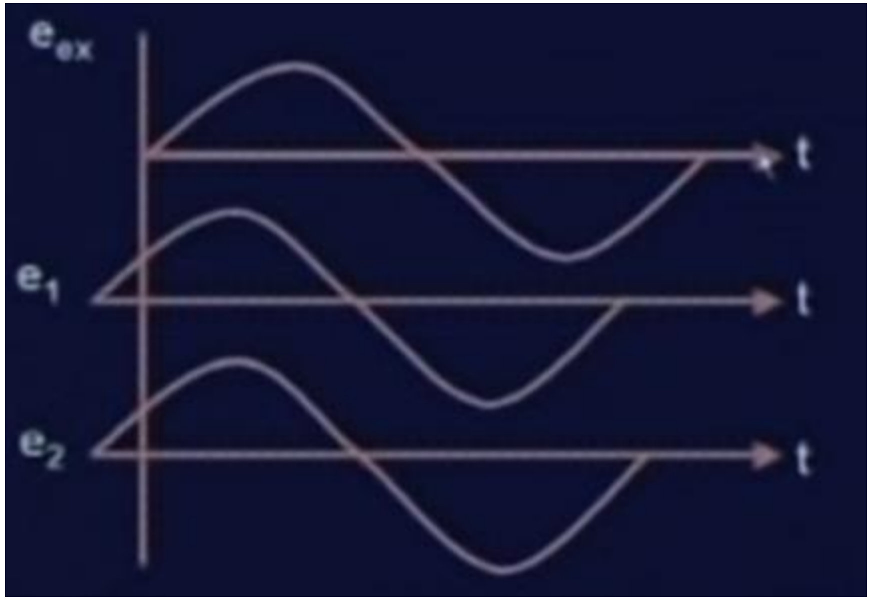




Linear variable differential transformer

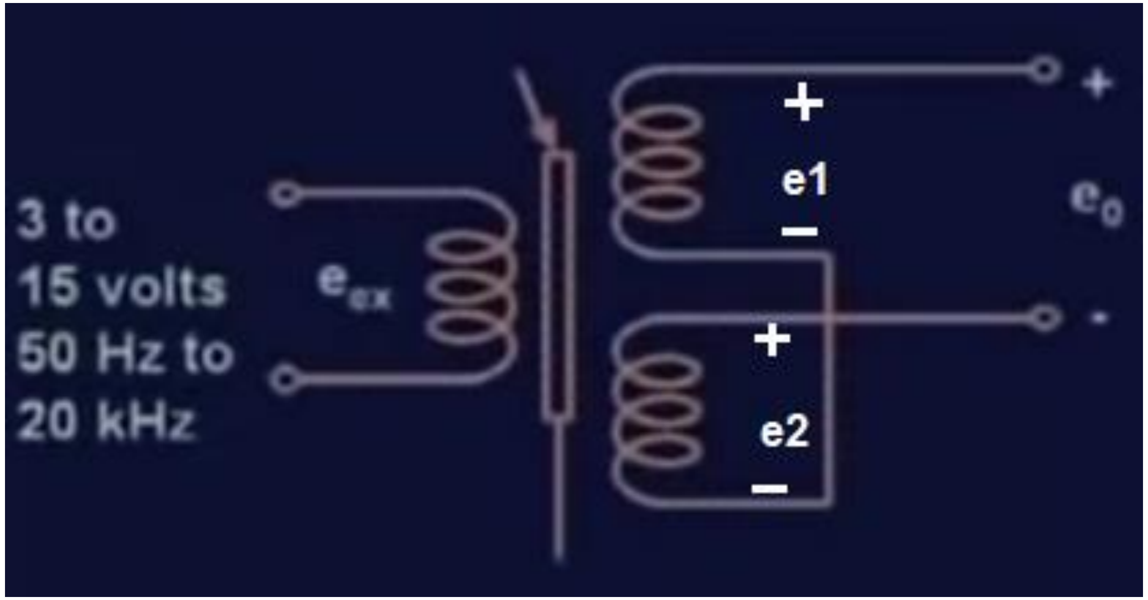
When the core is in the middle (null position), the output voltages will be as follows:





Linear variable differential transformer

- In practice we never use the two outputs separately. Instead the output of the two coils is connected as such:



e0 = e1 – e2

Linear variable differential transformer

- Coils connected so that the output voltage is the difference (hence "differential") between the top secondary voltage and the bottom secondary voltage.

- When the core is in its central position, equidistant between the two secondaries, equal voltages are induced in the two secondary coils, but the two signals cancel, so the output voltage is theoretically zero.

Linear variable differential transformer

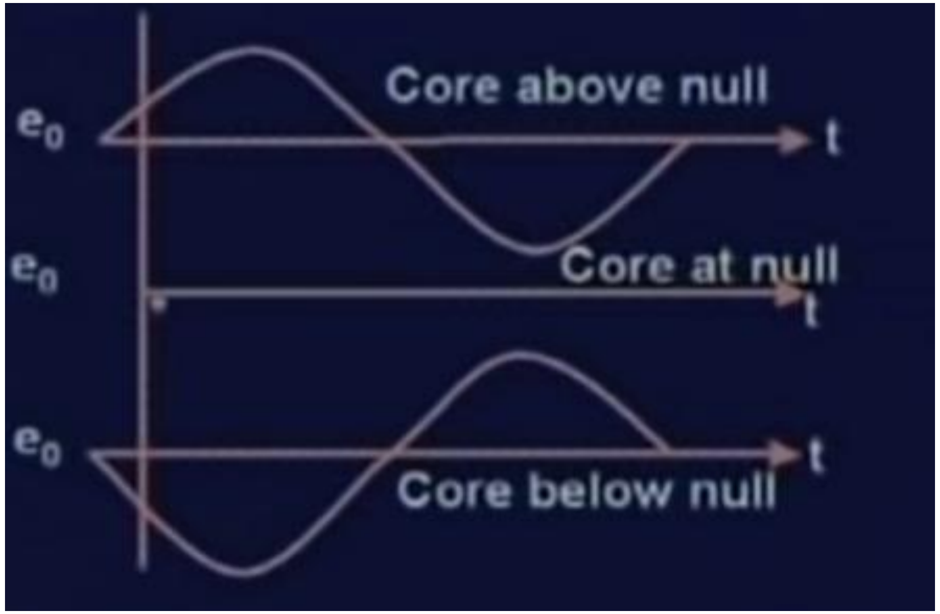
- When the core is displaced toward the top, the voltage in the top secondary coil increases as the voltage in the bottom decreases.

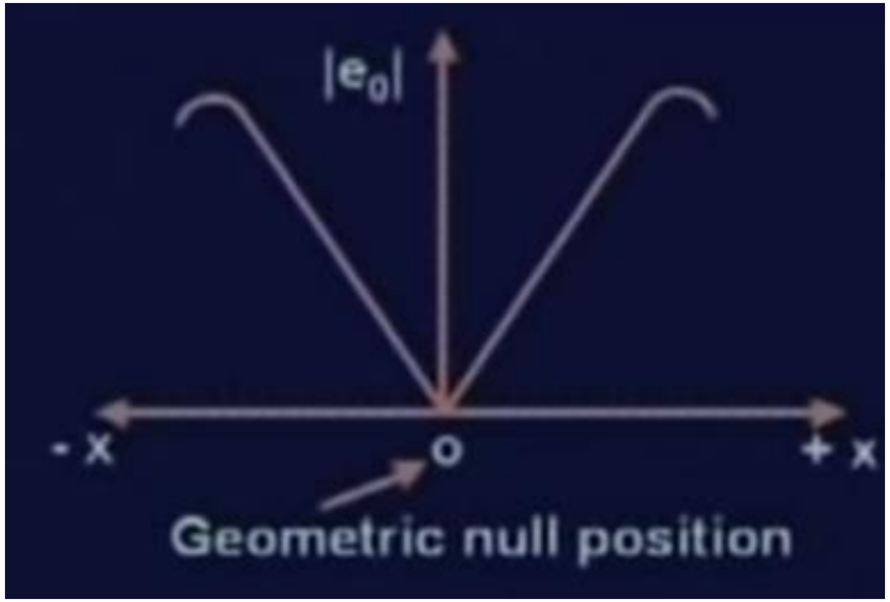
- The resulting output voltage increases from zero. This voltage is in phase with the primary voltage.

- When the core is displaced toward the bottom, the output voltage also increases from zero, but its phase is opposite to that of the primary.

Linear variable differential transformer

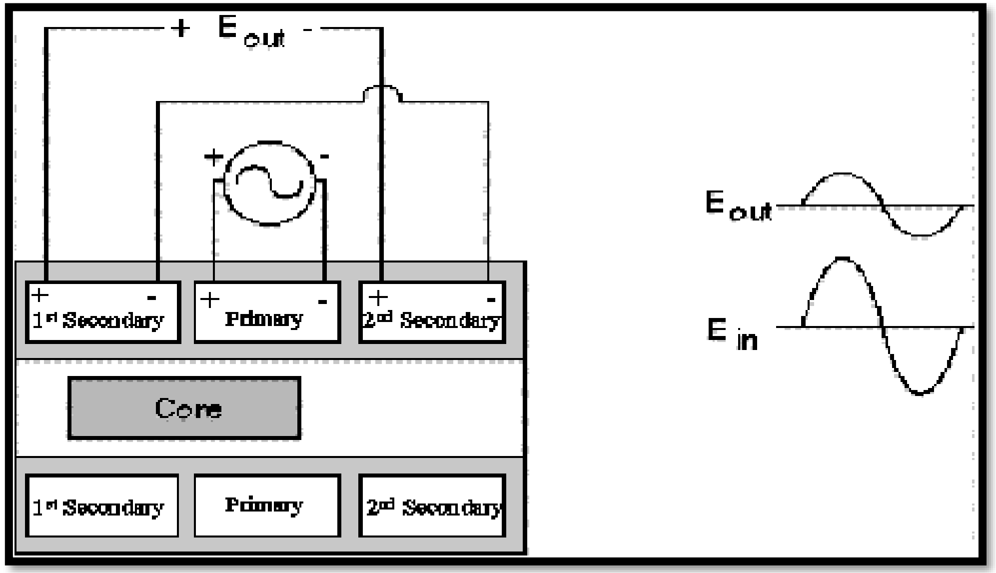
- So, the output voltage will look like the following:

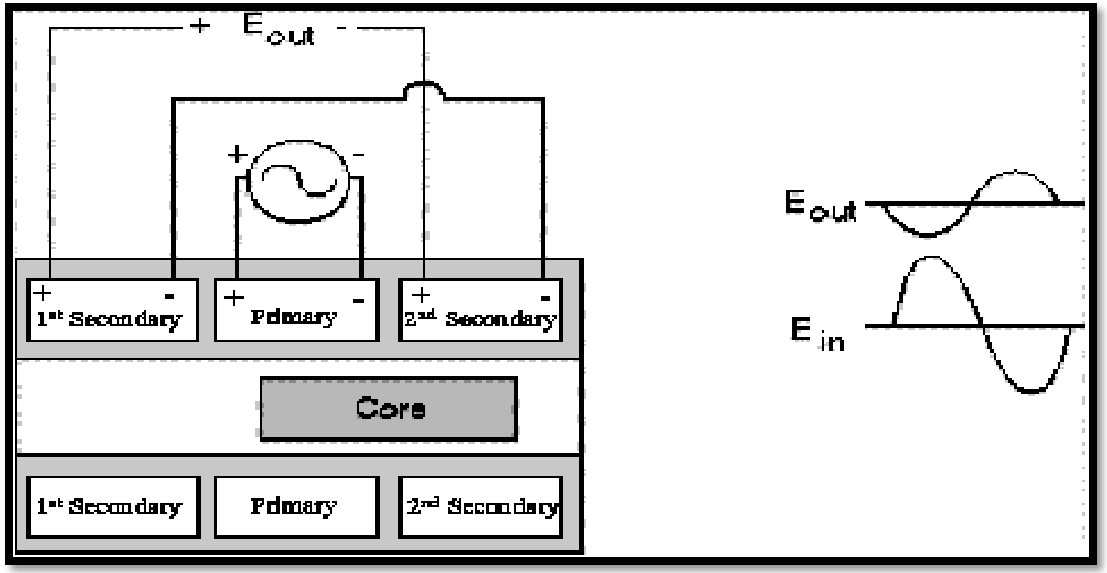




Output voltage of LVDT is a linear function of the core displacement within a limited range of the motion from the null position.

Linear variable differential transformer





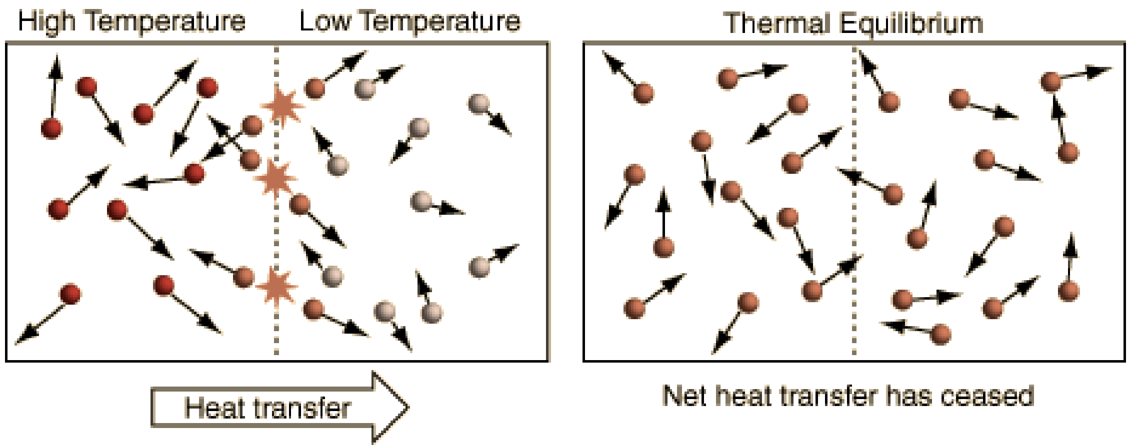
In phase

Out of phase

Reference: http://www.ni.com/white-paper/3638/en

What is Temperature?

AN OVERLY SIMPLIFIED DESCRIPTION OF TEMPERATURE



SOURCE: http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/temper2.html#c1

- "Temperature is a measure of the tendency of an object to spontaneously give up energy to its surroundings. When two objects are in thermal contact, the one that tends to spontaneously lose energy is at the higher temperature.“

Temperature Measurement

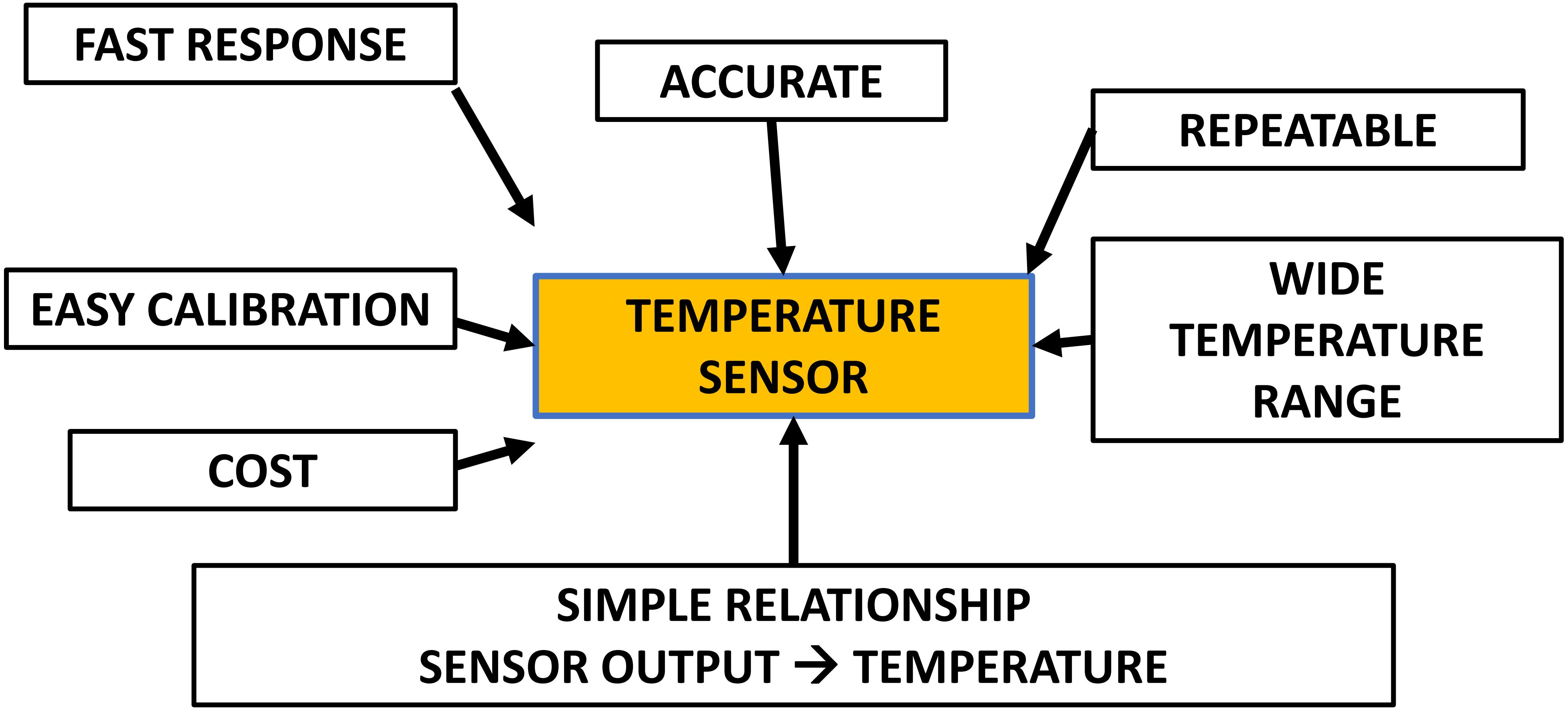
Monitoring temperature is becoming more important as:

- Electronic systems become increasingly dense and power hungry.
- Systems are affected by temperature extremes
- Components may be damaged if the temperature falls outside the operating range.

Types of Temperature Sensors

- Thermocouples
- Thermistors
- Resistance Temperature Detectors (RTDs)
- Semiconductors
- Infrared Sensors

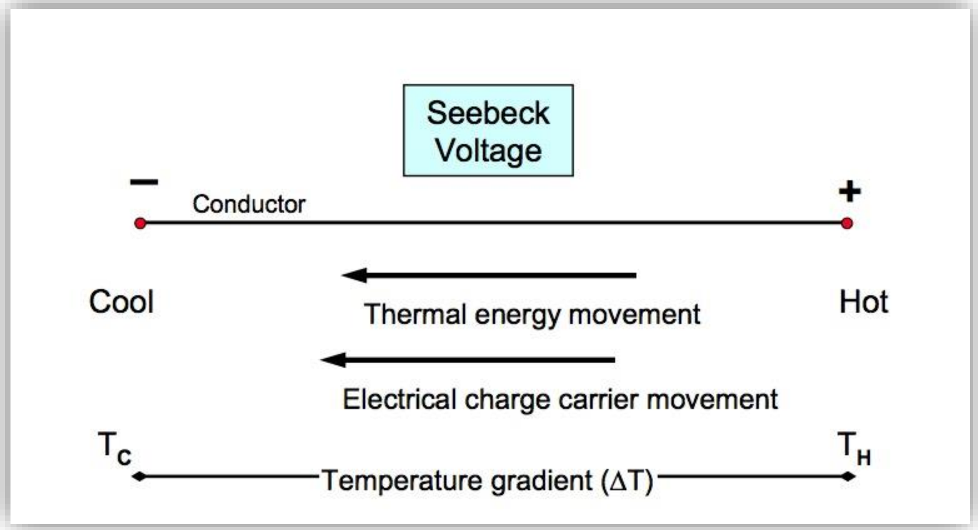
Desirable Temperature Sensor Characteristics



Thermocouples

Thermocouples: basics

- When one end of a conductive material is heated to a temperature larger than the opposite end:
  - Electrons at the hot end are more thermally energized than the electrons at the cooler end
  - Diffusion starts towards the cooler end
  - This creates (-) charge at the cool end and (+) charge at the hot end
  - It is impossible to measure this voltage (Seebeck voltage)



Thermocouples: basics

- Different metals, metal alloys and semiconductor materials are employed in the construction of thermocouples.
- Each metal has its own "thermoelectric sensitivity", or "Seebeck coefficient",
- Seebeck coefficient may be positive or negative

Thermocouples: basics

The Seebeck coefficients (thermoelectric sensitivities) of some common materials at 0 °C (32 °F) are listed in the following table.

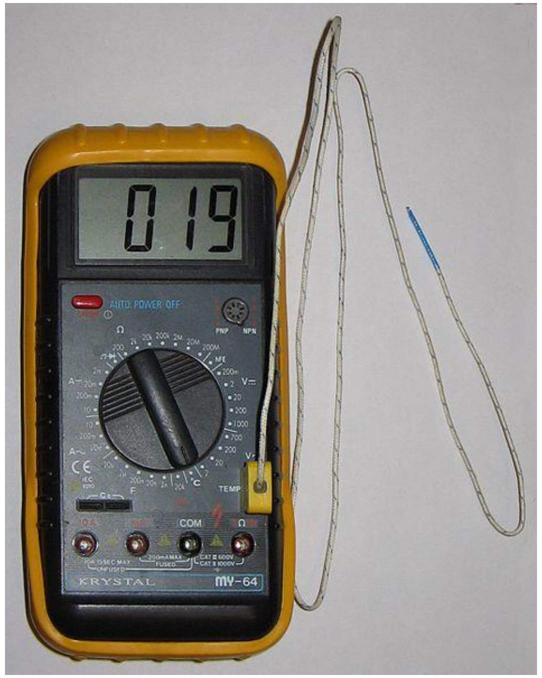
Material	Seebeck Coeff. *	Material	Seebeck Coeff. *	Material	Seebeck Coeff. *
Aluminum	3.5	Gold	6.5	Rhodium	6.0
Antimony	47	Iron	19	Selenium	900
Bismuth	-72	Lead	4.0	Silicon	440
Cadmium	7.5	Mercury	0.60	Silver	6.5
Carbon	3.0	Nichrome	25	Sodium	-2.0
Constantan	-35	Nickel	-15	Tantalum	4.5
Copper	6.5	Platinum	0	Tellurium	500
Germanium	300	Potassium	-9.0	Tungsten	7.5

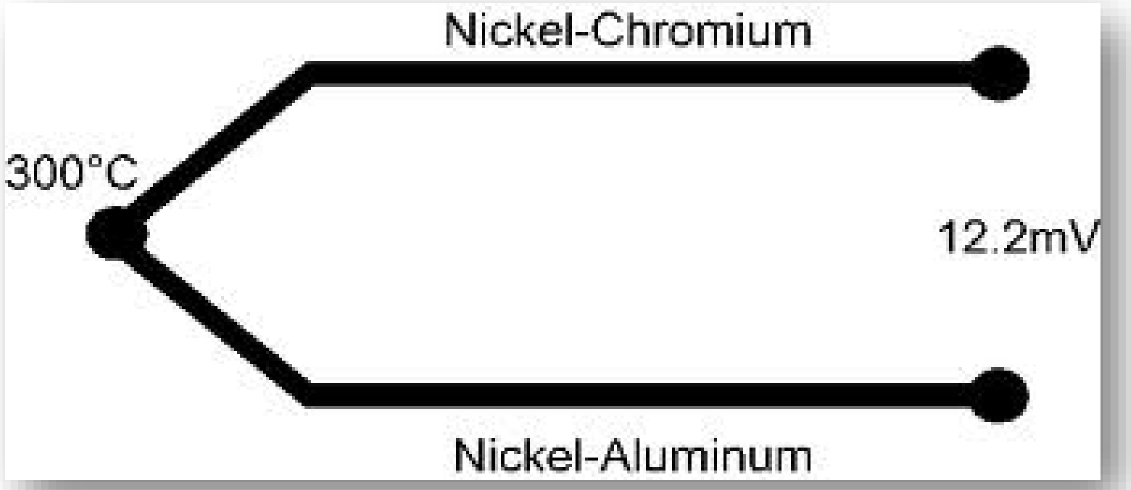
*: Units are μV/°C; all data provided at a temperature of 0 °C (32 °F)

www.efunda.com

Thermocouples: basics

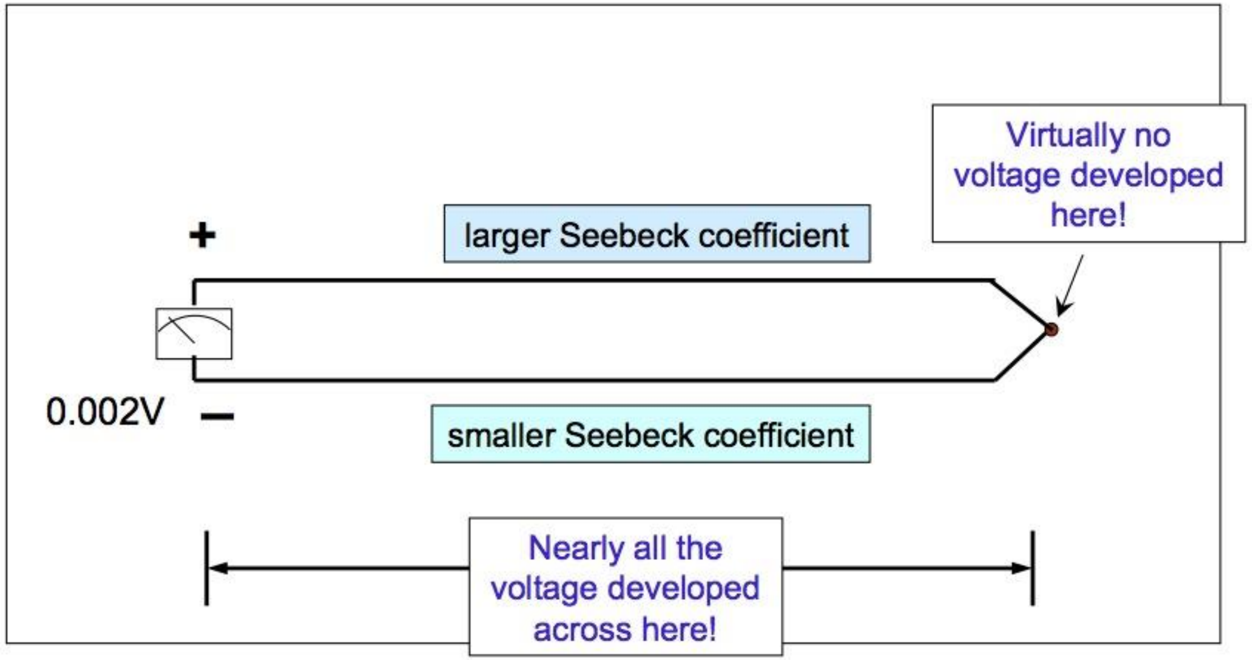
- Electric current is maintained in a circuit of two dissimilar metals when their junctions are held at different temperatures.





Thermocouples: basics

- No voltage is produced at the junction.
- The junction completes the circuit so that current flow can take place.



Thermocouples: basics

- A voltage is developed along each wire as the temperature changes.
- The voltage difference is observed at the receiving end
- The voltage is produced because the two differing metals have different Seebeck coefficients and produce a voltage difference at the meter point.

Thermocouples: basics

- In use, the junction is exposed to the hot or cold temperature point. The leads connect between the junction and a *measurement device* located at a different temperature such as room.

- It is along these lead lengths where the temperature gradient is present resulting in the generation of the two individual Seebeck electromotive force (EMF).

Thermocouples: basics

- The emf, that is a function of the temperature, is given by the following relation:

$$V = a_1 t + a_2 t^2 + a_3 t^3 + \cdots$$

- Therefore, the temperature – emf relationship is clearly non-linear.
- Several of the thermocouples relationship is represented by 7^{th} – 9^{th} order polynomial.
- The values of a1, a2, depend on the metals A and B.

Thermocouples: types

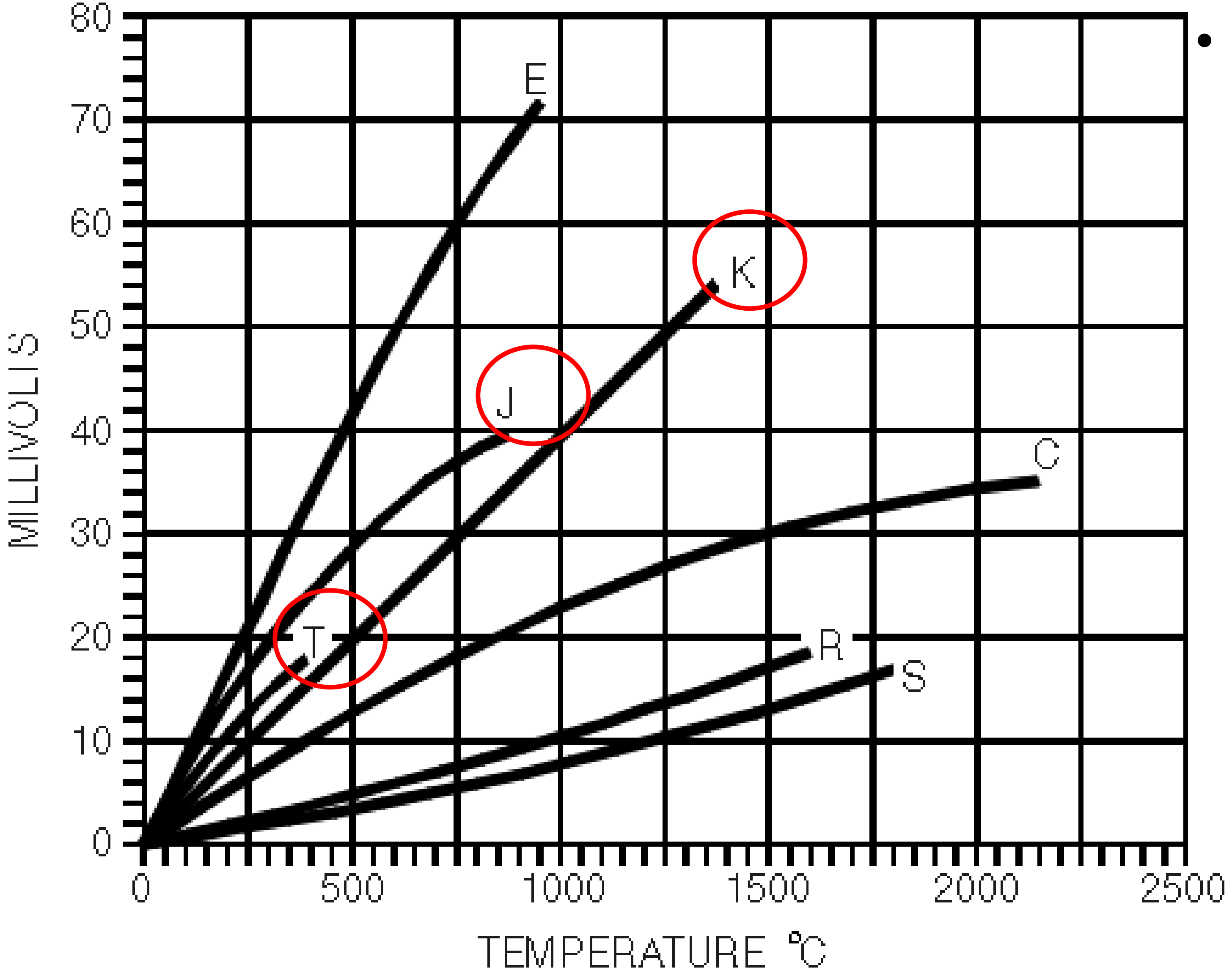
- Thermocouples are classified by type based on their useable temperature range, sensitivity and accuracy.

- The commonly used metals include: chromium, copper, nickel, iron, platinum, rhodium, and rhenium.

- In the next slide, illustrated charts provide the thermal response of thermocouples.

Thermocouples: types

Types T, J, and K are most commonly used thermocouples

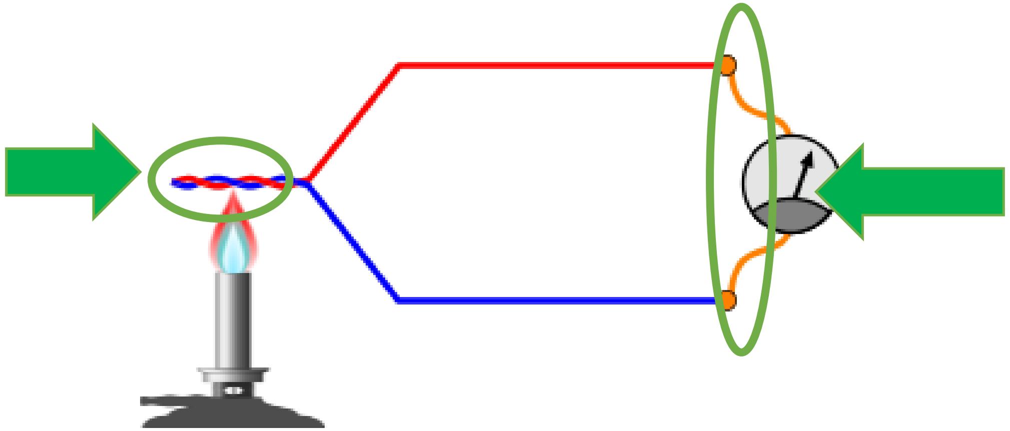


- **Notes on the chart:**
  - Type "T" thermocouple has a limited use temperature range compared to the others.
  - Differences in the thermocouple sensitivities and their linearity ΔV/ΔT.
  - Thermocouples with limited temperature range have better linearity characteristics.
  - Because of poor linearity some higher temperature thermocouples aren't used in measuring temperatures below 0°F (-18°C).

Measuring Temperature

- To measure temperature using a thermocouple, you can’t just connect the thermocouple to a measurement system (e.g. voltmeter)
- The voltage measured by your system is proportional to the temperature difference between the primary junction (hot junction) and the junction where the voltage is being measured (Ref junction)

To determine the absolute temperature at the hot junction…

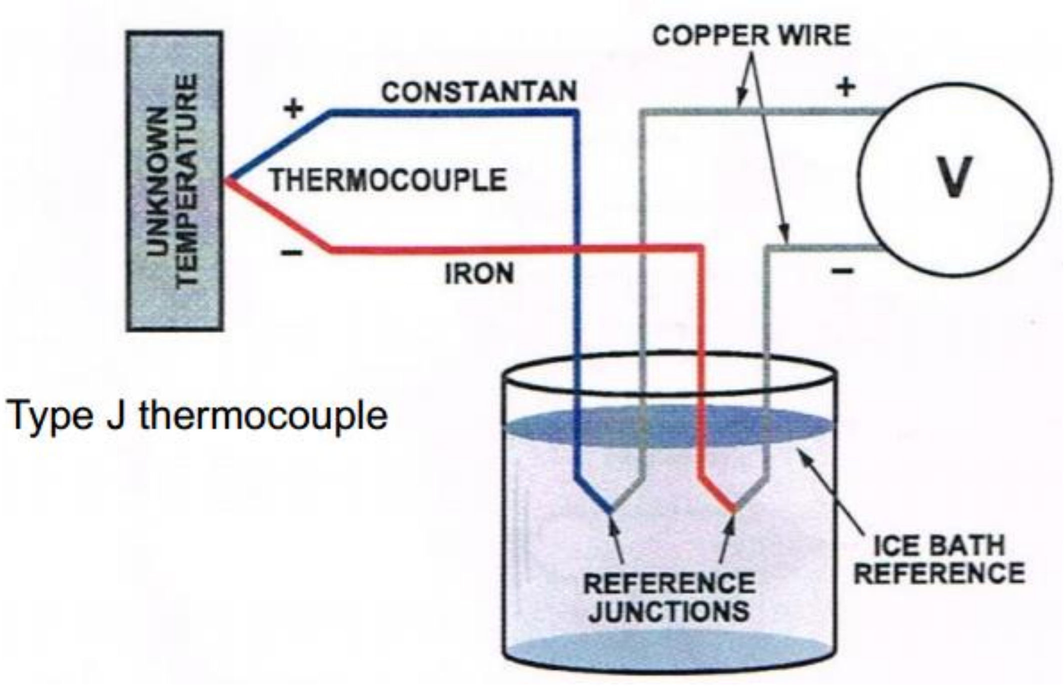


You need to know the temperature at the Ref junction!

How can we determine the temperature at the reference junction?

Ice Bath Method (Forcing a Temperature)

- Thermocouples measure the voltage difference between two points
- To know the absolute temperature at the hot junction, one must know the temperature at the Ref junction



Type J thermocouple

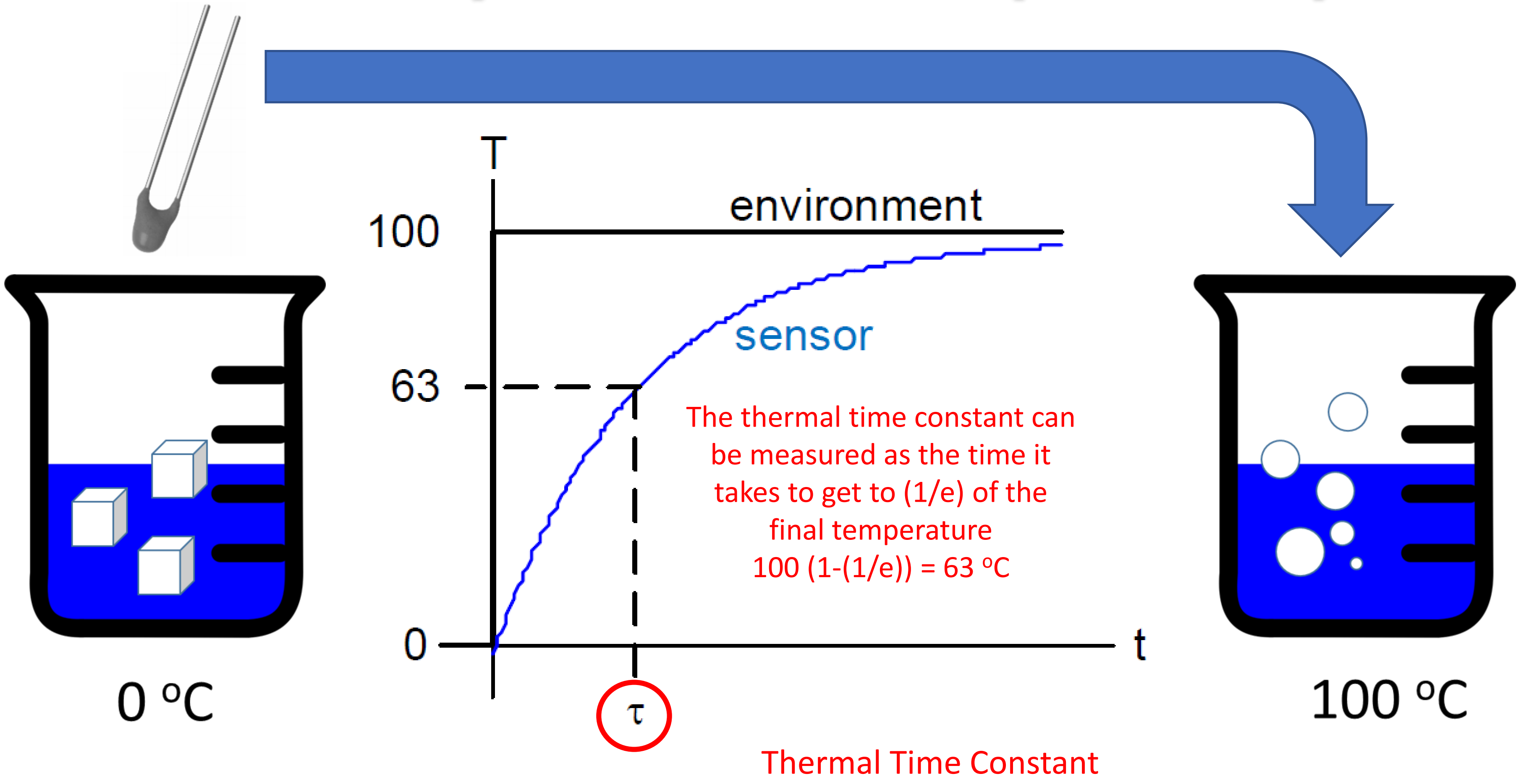
- NIST thermocouple reference tables are generated with T_{ref} = 0 °C

$$V_{meas} = V(T_{hot}) - V(T_{ref})$$

$$V(V_{hot}) = V_{meas} + V(T_{ref})$$

If we know the voltage-temperature relationship of our thermocouple, we could determine the temperature at the hot junction

Thermal System Step Response



Thermistors

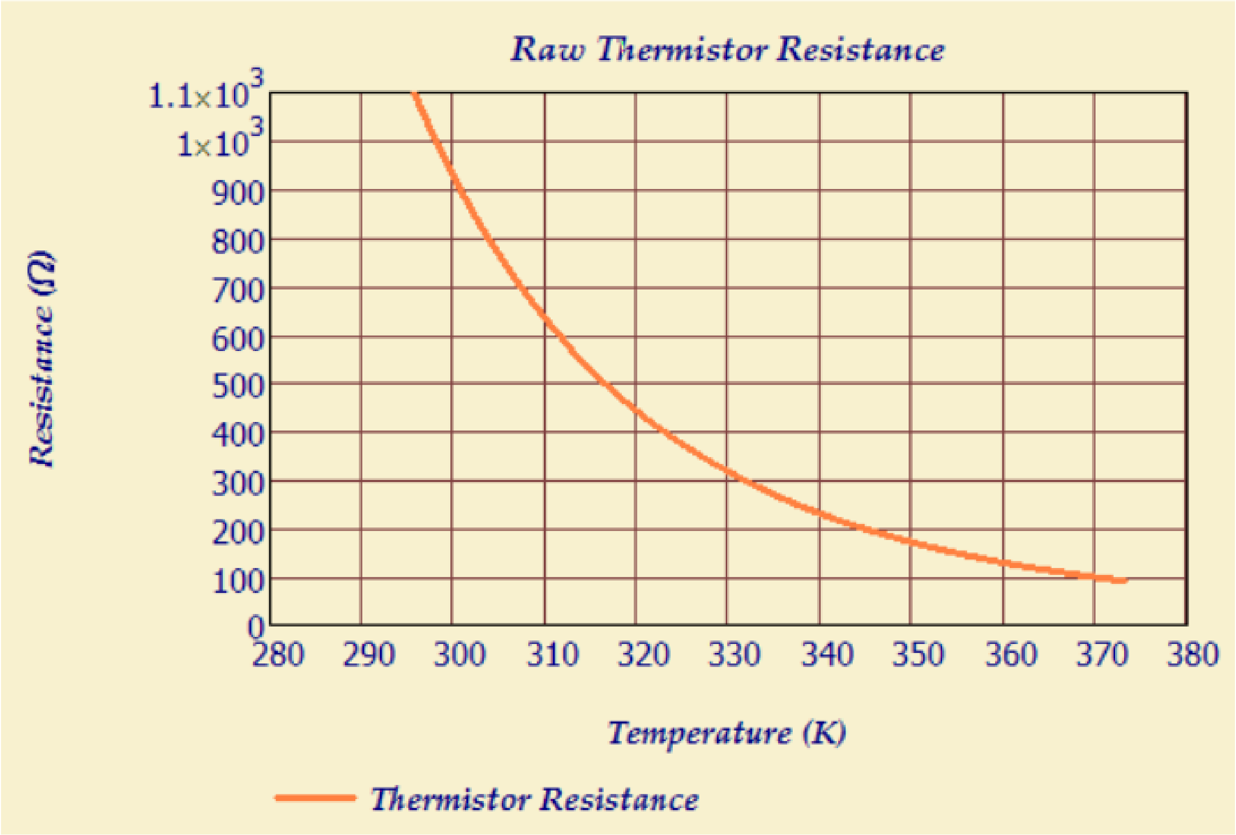
Thermistor

Thermistor – a resistor whose resistance changes with temperature

- Resistive element is generally a metal-oxide ceramic containing Mn, Co, Cu, or Ni
- Packaged in a thermally conductive glass bead or disk with two metal leads
- Suppose we have a “1 kΩ thermistor”
  - What does this mean?
  - At room temperature, the resistance of the thermistor is 1 kΩ
  - What happens to resistance as we increase temperature?

Negative Temperature Coefficient

- Unlike metals, thermistors resistance decreases as the temperature increases.



Negative Temperature Coefficient

Alternatively:

- **The Steinhart-Hart Equation** relates temperature to resistance
- $$\boxed{T_{(R)} = \left(A_1 + B_1 \ln \frac{R}{R_{ref}} + C_1 \ln^2 \frac{R}{R_{ref}} + D_1 \ln^3 \frac{R}{R_{ref}}\right)^{-1}}$$ or
- T is the temperature (in Kelvin)
- R is the resistance at T and R_{ref} is resistance at T_{ref}
- A_1, B_1, C_1, and D_1 are the Steinhart-Hart Coefficients
- The Steinhart-Hart equation is an empirical expression that has been determined to be the best mathematical expression for the resistance - temperature relationship of a negative temperature coefficient thermistor. It is usually found explicit in T where T is expressed in degrees Kelvin.

Negative Temperature Coefficient

$$\frac{1}{T} = A + B * ln(R) + C * ln(R)^3$$

- Where ln(R) is the natural logarithm of the resistance at temperature T in Kelvin, and A, B and C are coefficients derived from experimental measurements. These coefficients are usually published by thermistor vendors as part of the datasheet. The Steinhart-Hart formula is typically accurate to around ±0.15°C over the range of -50°C to +150°C, which is plenty for most applications. If superior accuracy is required, the temperature range must be reduced and accuracy of better than ±0.01°C over the range of 0°C to +100°C is achievable.

- https://www.thinksrs.com/downloads/programs/Therm%20Calc/NTCCalibrator/NTCcalculator.htm
- Read more http://www.resistorguide.com/ntc-thermistor/

Negative Temperature Coefficient

- The resistance – temperature relationship can be expressed as:

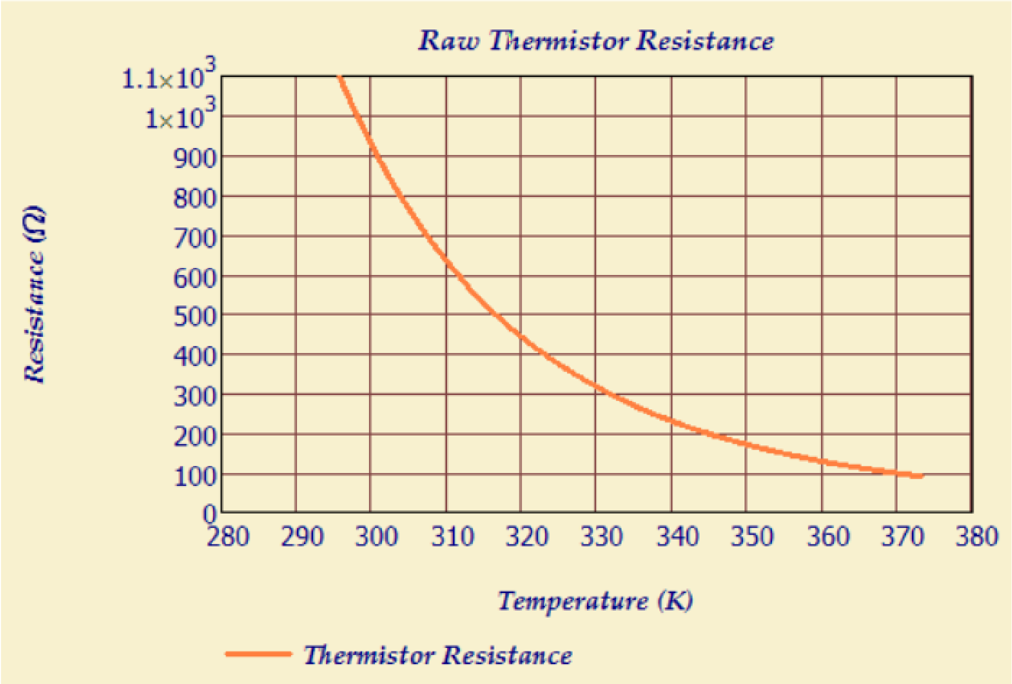
$$R = R_0 e^{\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

Where:

R = resistance of thermistor at T K

R_0 = resistance of thermistor at T_0 K

β = material constant that ranges from 3000 – 5000 K

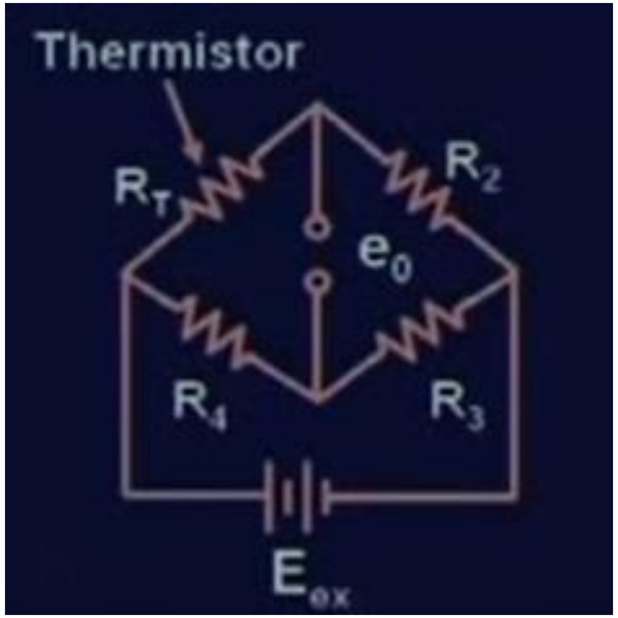


Manufacturing process

- Two or more semiconductor powder are mixed to form a slurry.
- Small drops of the slurry are formed over the lead wires, dried and put in a sintering furnace.
- During sintering, the metallic oxides shrunk onto the lead wires and form the electrical connection.
- The beads are then sealed by coating it by glass.
- The glass coating improves the stability by eliminating water absorption.

Thermistor in Wheatstone bridge

- So, if the bridge is balanced, the output voltage is zero.
- If there is temperature change, then the bridge will not be balanced and the voltage will not be zero.



$$e_o = E_{ex}\left(\frac{R_T R_3 - R_4 R_2}{(R_T + R_2)(R_4 + R_3)}\right)$$

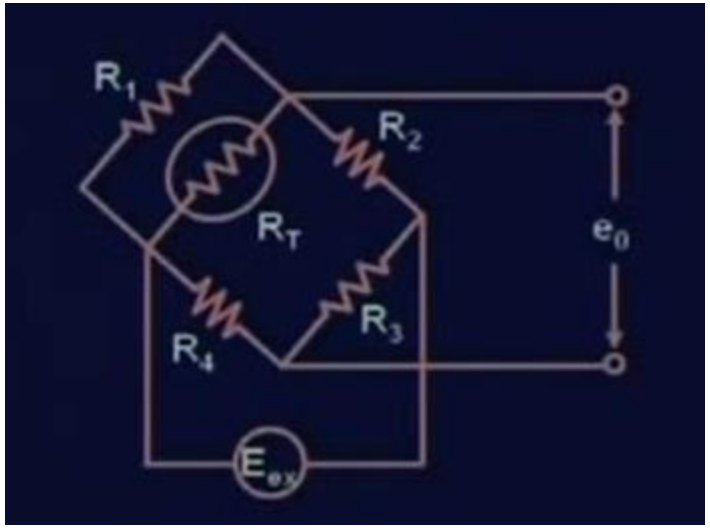
- If R_T increased by ΔR_T, then:

$$e_o = E_{ex}\left(\frac{\Delta R_T R_3}{(R_T + \Delta R_T + R_2)(R_4 + R_3)}\right)$$

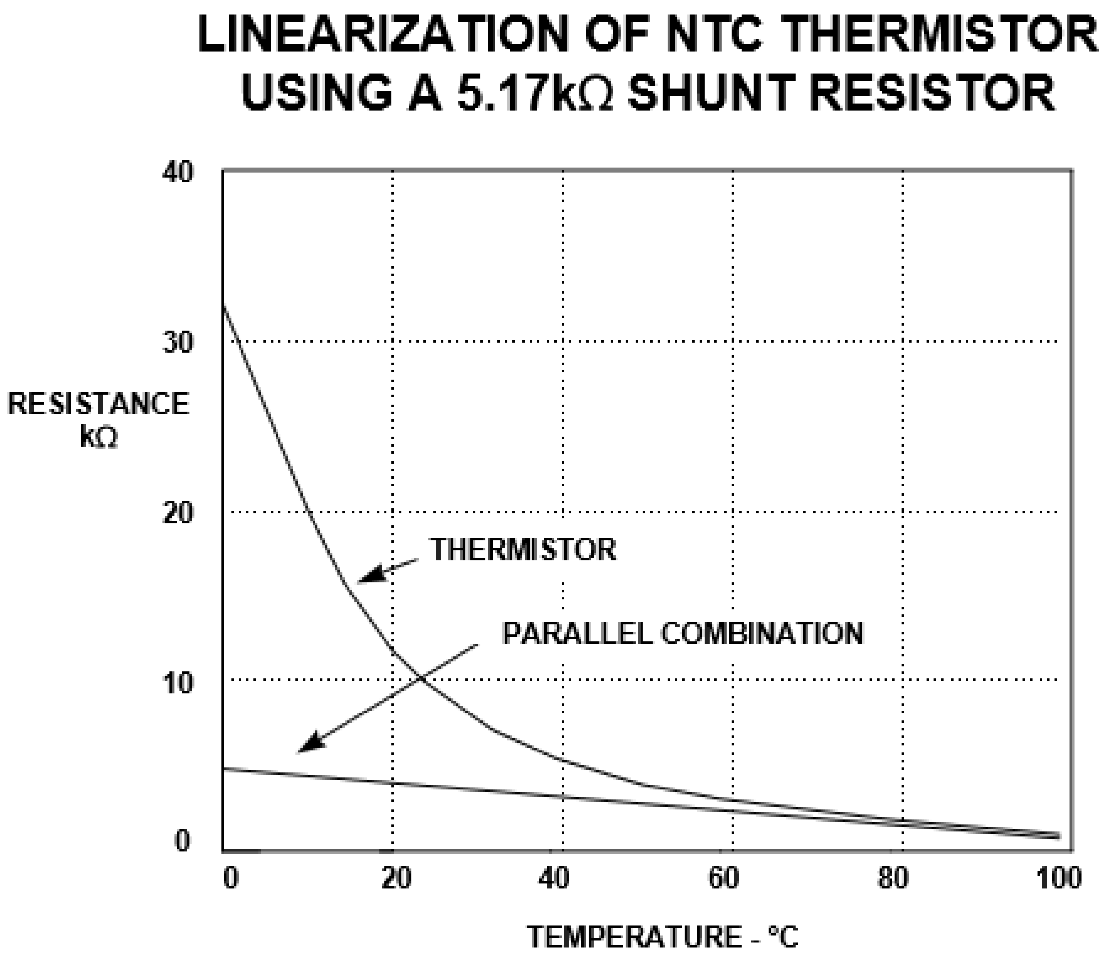
Note that ΔR_T can't be ignored because it is large

Thermistor in Wheatstone bridge

- Sometime we connect the bridge as follows, i.e. R_T in parallel with R_1.
- This will change the characteristics of the non-linear resistor to be less non-linear and hence for small range can be used as a linear resistance.
- However, this will reduce the sensitivity.



Thermistor in Wheatstone bridge



Infrared Sensors

What is Infrared?

- All matter (gases, planets, etc) emits some amount of electromagnetic radiation across a range of energies (or wavelengths). “Infrared” refers to the portion of the electromagnetic spectrum where biological life-forms emit the most light, at wavelengths slightly longer than what we perceive as the color red.

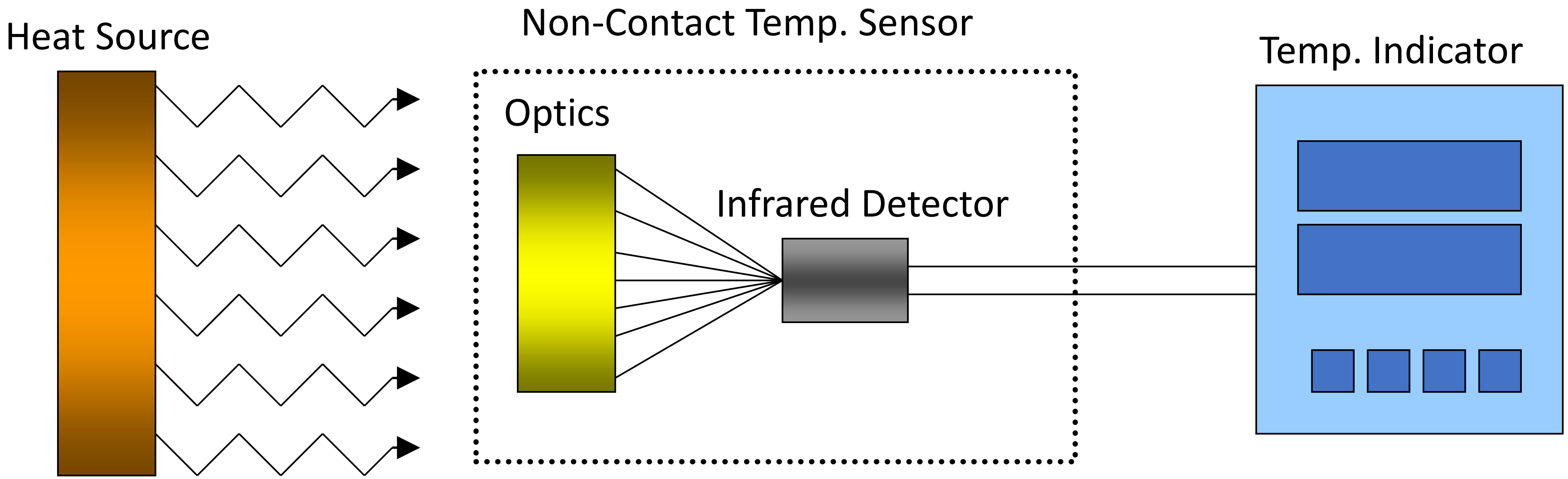
Why Don’t We See It?

- Put simply, our eyes do not have the elements necessary for detecting infrared. While there are practical evolutionary reasons for this, infrared is a reality that exists behind the scenes.

  However, We may not be able to see infrared, but we can still *sense* it through what is commonly called heat.

Infrared Sensors

- Intercepts portion of infrared energy radiated by object (λ = 8 - 14 microns).
- Waves focused through lens on infrared detector, converting to an electric output signal

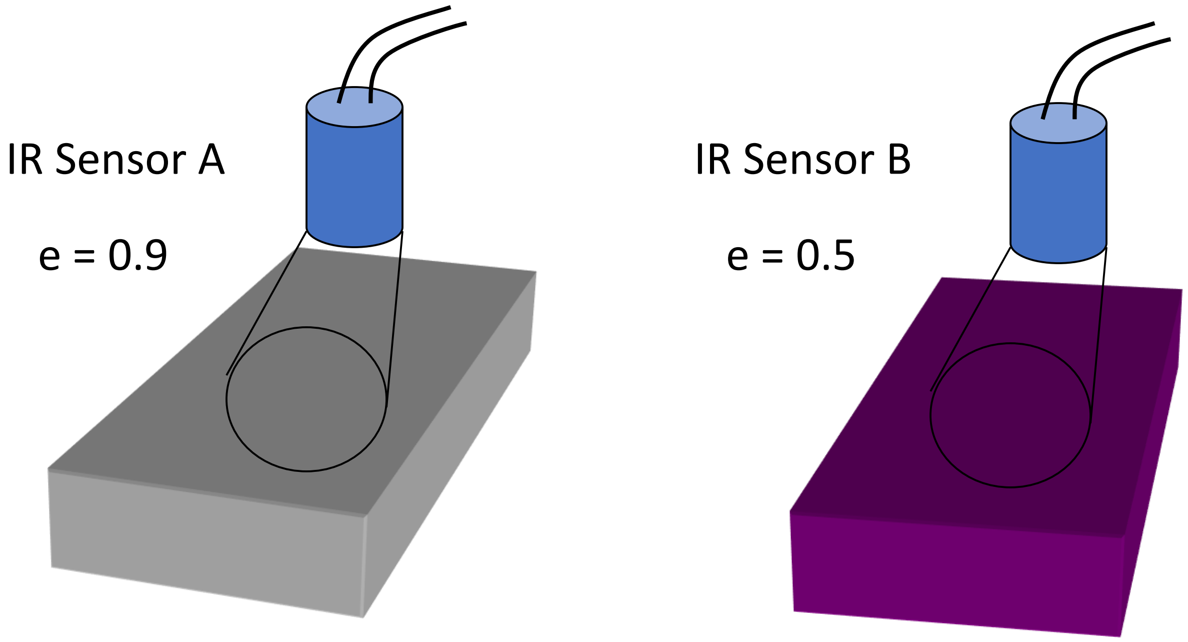


Emissivity

- Def: The ability of a material to radiate or absorb electromagnetic waves. Higher = Better!
  - Ex: Given values below & emissivity varies by 0.05, what is measuring error?

  Ans: IR Sensor A 5.5% (0.05/0.9)

  IR Sensor B 10% (0.05/0.5)



Field of View

- All infrared radiation in this field of view will be detected by the sensor