MECE 3320 – Measurements & Instrumentation

Temperature Measurement

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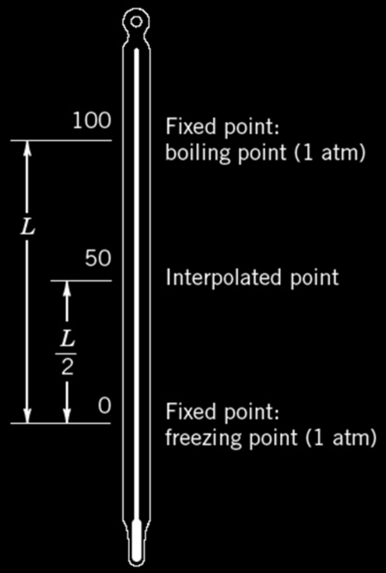
Introduction

Temperature is one of the most commonly used and measured engineering variables.

Temperature can be loosely described as the property of an object that describes its hotness or coldness, concepts that are clearly relative.

How do we quantify temperature? What are the essential aspects for a temperature scale?

1. Definition of the size of the degree
2. Fixed reference points for establishing known temperatures
3. A means for interpolating these fixed temperature points



Thermometry Based on Thermal Expansion

Liquid Glass Thermometers: Measures temperature by virtue of the thermal expansion of a liquid

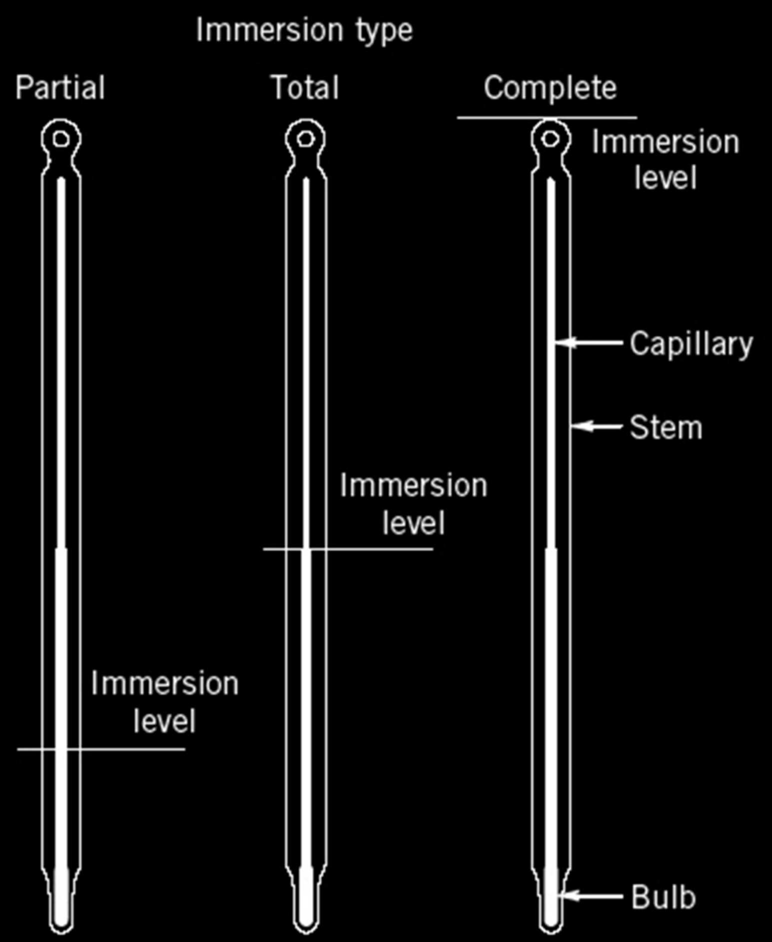


Figure 8.2 Liquid-in-glass thermometer.

Thermometry Based on Thermal Expansion

Bimetallic Thermometers: Measures temperature based on the principle of differential thermal expansion of two metals (e.g. Invar & Steel)

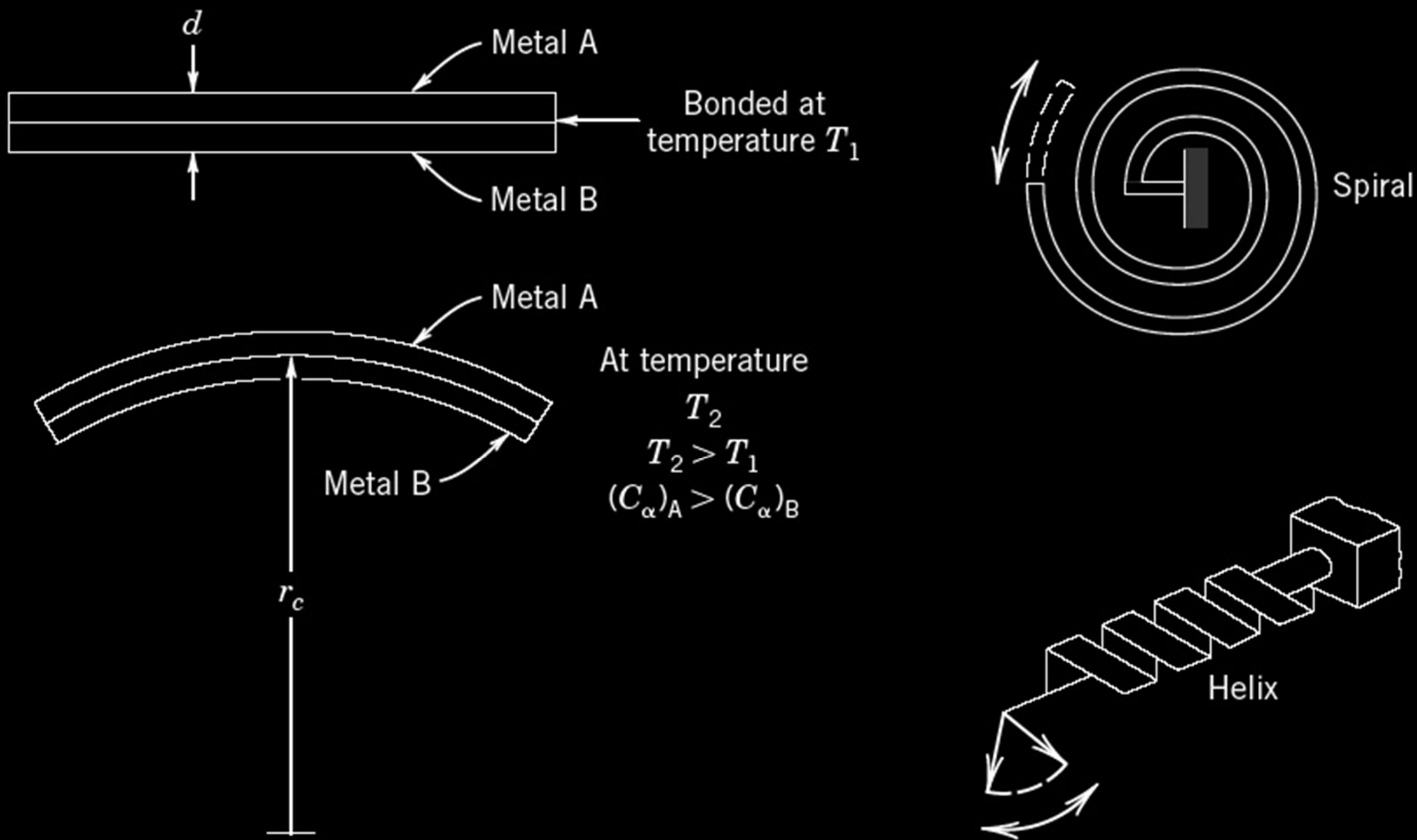


Figure 8.3 Expansion thermometry: bimetallic strip.

Electrical Resistance Thermometry

The electrical resistance of a conductor or a semiconductor varies with temperature.

There are two basic classes of resistance thermometers:
1. Resistance Temperature Detectors (RTD's) – conductor
2. Thermistors – semiconductor

Resistance Temperature Detectors:

$$R = R_0[1 + \alpha(T - T_0) + \beta(T - T_0)^2 + ...]$$

where R_0 is the reference resistance measured at temperature T_0, α, β are the material constants.

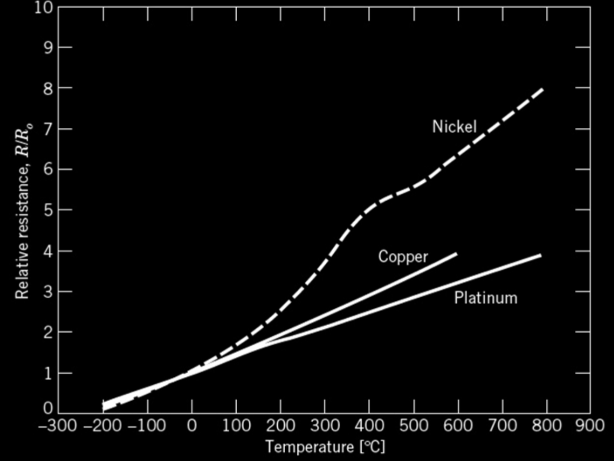
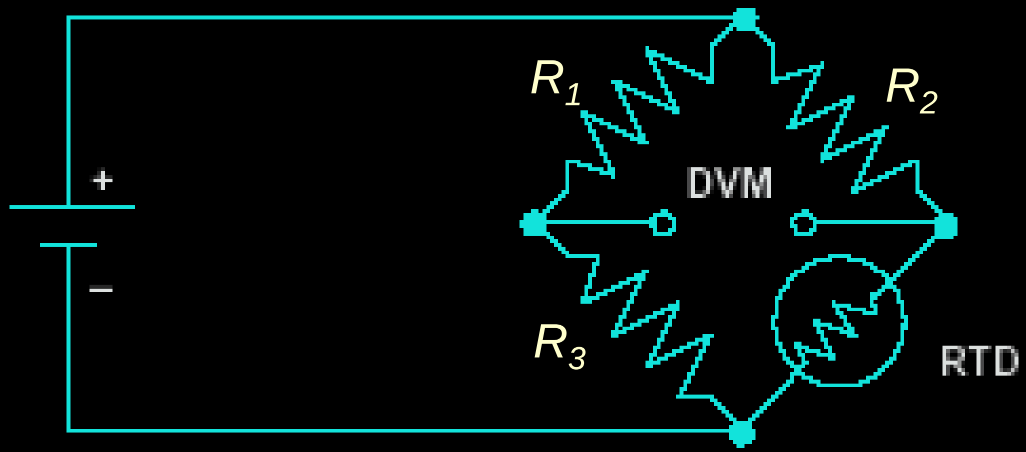


Figure 8.5 Relative resistance of several pure metals (R_o at 0°C).

RTD Resistance Measurement

The choice of a resistance measuring device must be made based on the required level of uncertainty in the final temperature measurement. Conventional ohmmeters can cause a small current to flow during resistance measurements creating self-heating in the RTD.

A *Wheatstone bridge circuit* is commonly used to measure resistance of an RTD.



WHEATSTONE BRIDGE

At balanced condition:

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

RTD Resistance Measurement

The major source of error in RTD measurements is the non-compensation for the resistance of the lead cables.

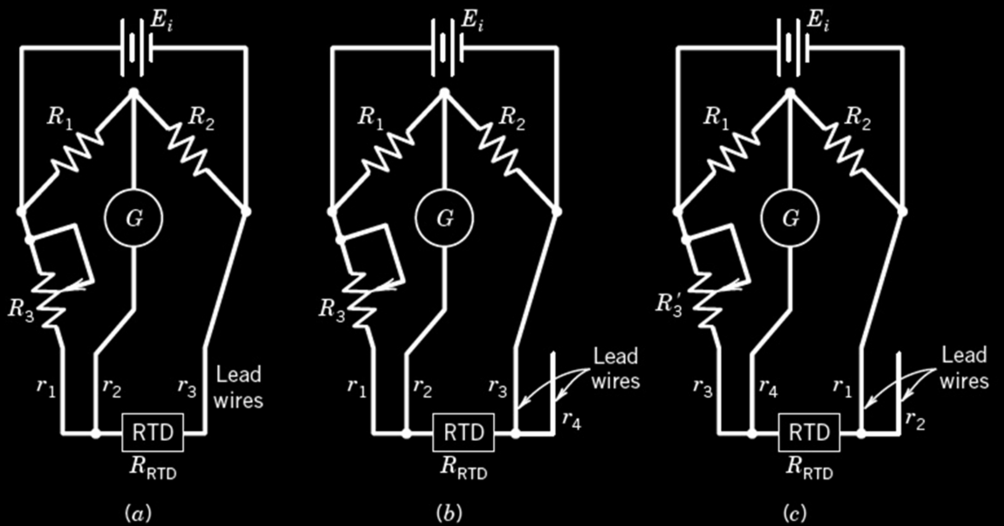


Figure 8.6 Bridge circuits. Average of the two readings (in b and c) eliminates the effect of lead wire resistances.

$$\frac{R_1}{R_2} = \frac{R_3 + r_1}{R_{RTD} + r_3}$$

$$\text{If } R_1 = R_2, R_{RTD} = R_3 + r_1 - r_3$$

The thermal response of RTD's is generally quite slow compared to other temperature sensors.

RTD's are generally not used for transient temperature measurements.

Thermistors

➢ Thermistors (*therm*ally sensitive res*istors*) are ceramic-like semiconductors whose resistance decreases rapidly with temperature.

➢ Semi-conductor materials – typically oxides of

- Manganese
- Cobalt
- Iron
- Nickle
- Copper
- Uranium

➢ Resistance function is non-linear

➢ Static sensitivity is much larger than RTD

Thermistor Transfer Equation

- The resistance of a thermistor is a function of the *absolute* temperature.

$$R_T = R_0 e^{\beta(1/T - 1/T_0)}$$

- R_T: resistance at temperature T (in K)
- R_0: resistance at T_0 (in K)
- β: constant that depends on the thermistor

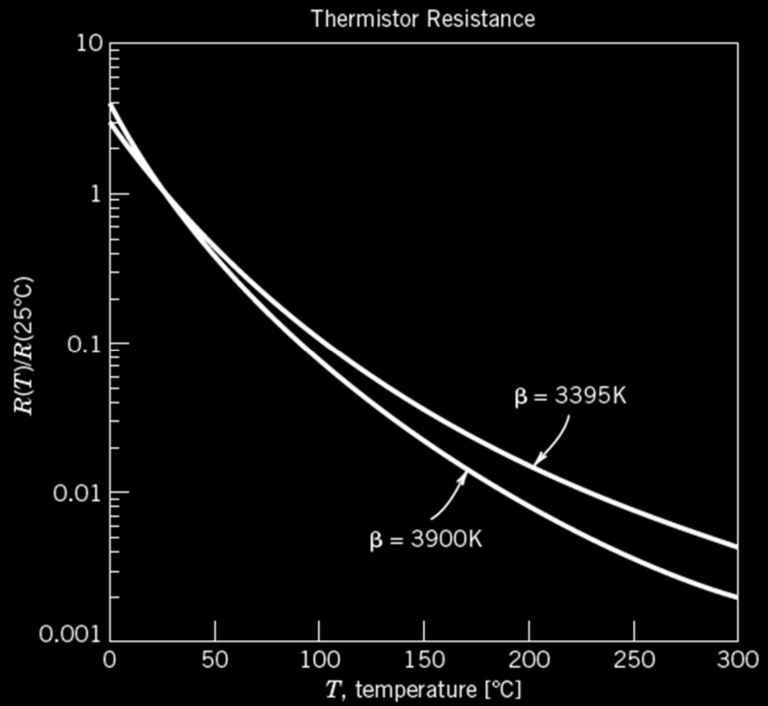


Figure 8.8 Representative thermistor resistance variations with temperature.

Steinhart-Hart Equation

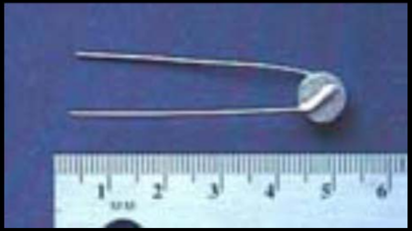
- Research has shown that a better relationship of temperature T and thermistor resistance R_T is given by

$$R_T = \exp(a_0 + \frac{a_1}{T} + \frac{a_3}{T^3})$$

- This is one version of the Steinhart-Hart equation.
- Very non-linear
- Non-linearity is corrected using bridge circuits or by using microprocessors.
- The use of this equation requires many calibration coefficients.

Thermistor Advantages

- High resistance (1kΩ - 100k Ω)
  - Eliminates the need for lead cable resistance compensation
- Non-linear R_T vs T
  - Mostly negative temperature coefficients with metal oxides
  - Can be linearized
- Small physical size
  - Fast response time
  - Not as small as thermocouples



- Lower cost than RTD’s
  - Can be mass manufactured
- Wide temperature range and high sensitivity & resolution
  - Up to 1000 times more sensitive than RTD’s
- Can withstand shock & vibration and are accurate

Thermistor Disadvantages

- Non-linear response requires extra circuitry
- With the additional circuitry, range of linear response is limited
- very delicate, can break if mishandled
- requires excitation current
- high resistance can lead to self heating errors
- less stable than RTD’s

Resistance Thermometers: Summary

- Electrical resistance of several materials change in a reproducible way when subjected to temperature variations

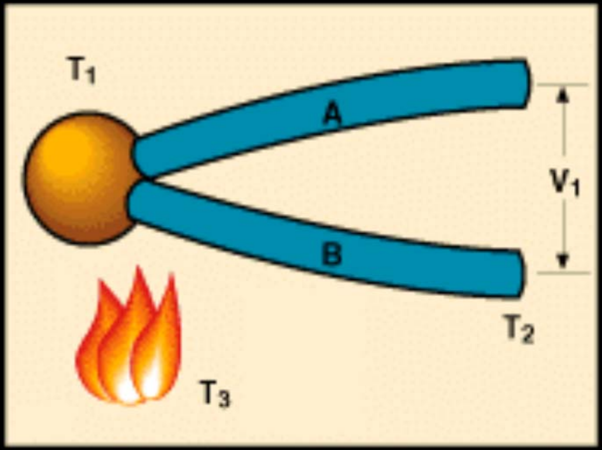
- An RTD is a temperature sensing device whose resistance increases as temperature increases (positive temperature coefficient). Thy are typically composed of a conductor, e.g. Platinum wire, wound on an insulator substrate.

- A thermistor is also a temperature sensing device whose resistance decreases with increasing temperature (negative temperature coefficient). They are typically constructed from semiconductor devices. Their resistance responds non-linearly to temperature.

Thermoelectric Temperature Measurement

The most common method of measuring and controlling temperature uses an electrical circuit called a *thermocouple*.

What are thermocouples?



➢ A thermocouple consists of two electrical conductors that are made of dissimilar metals and have at least one electrical connection referred to as a junction. The junction can produce a measurable EMF when a temperature gradient is imposed.

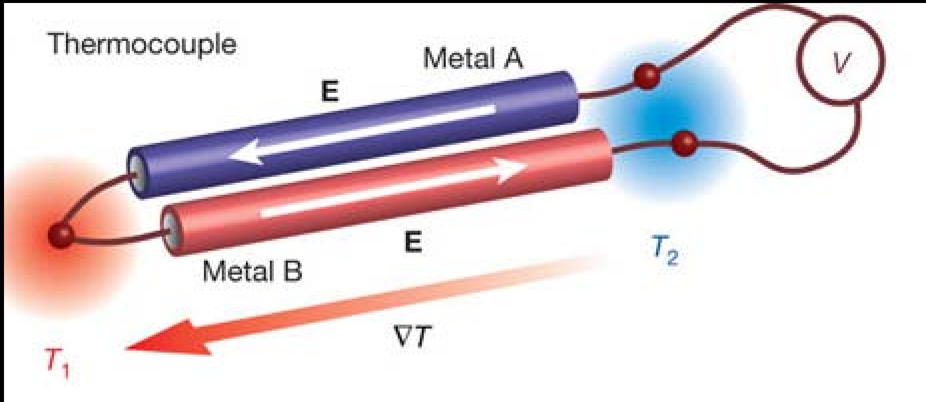
Thermocouple Principle of Operation

There are three basic phenomena that occur in a thermocouple circuit:

- *Seeback Effect*
- *Peltier Effect*
- *Thomson Effect*

Seeback Effect

- A voltage potential is generated in an open thermocouple circuit due to a difference in temperature between junction in the circuit.

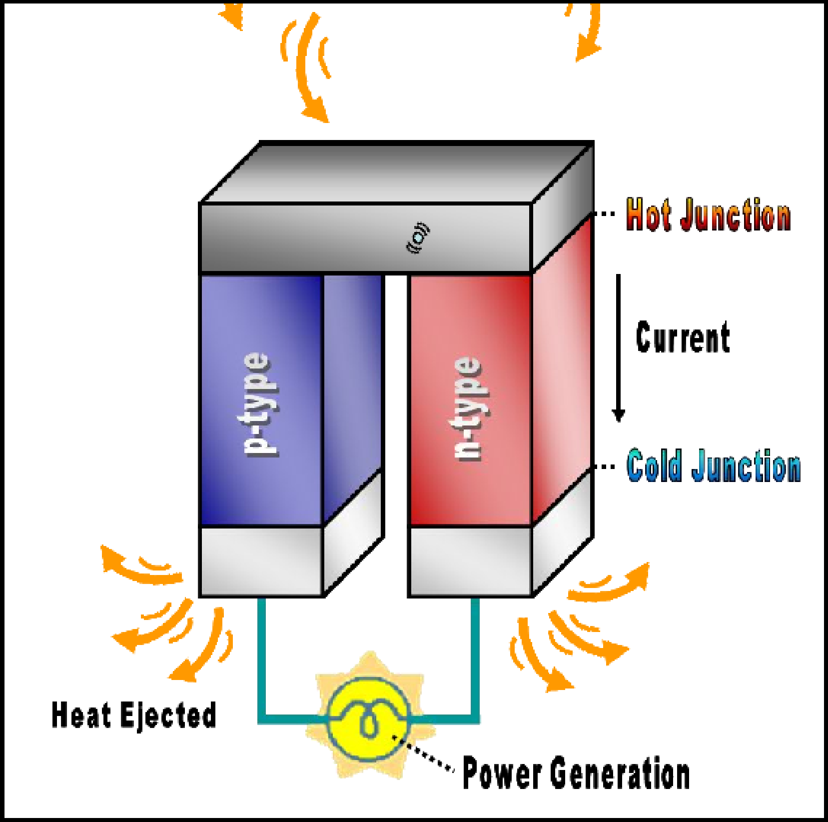


$$\text{Seeback Coefficient } \alpha_{AB} = \left[\frac{\partial(emf)}{\partial T}\right]_{open\ circuit}$$

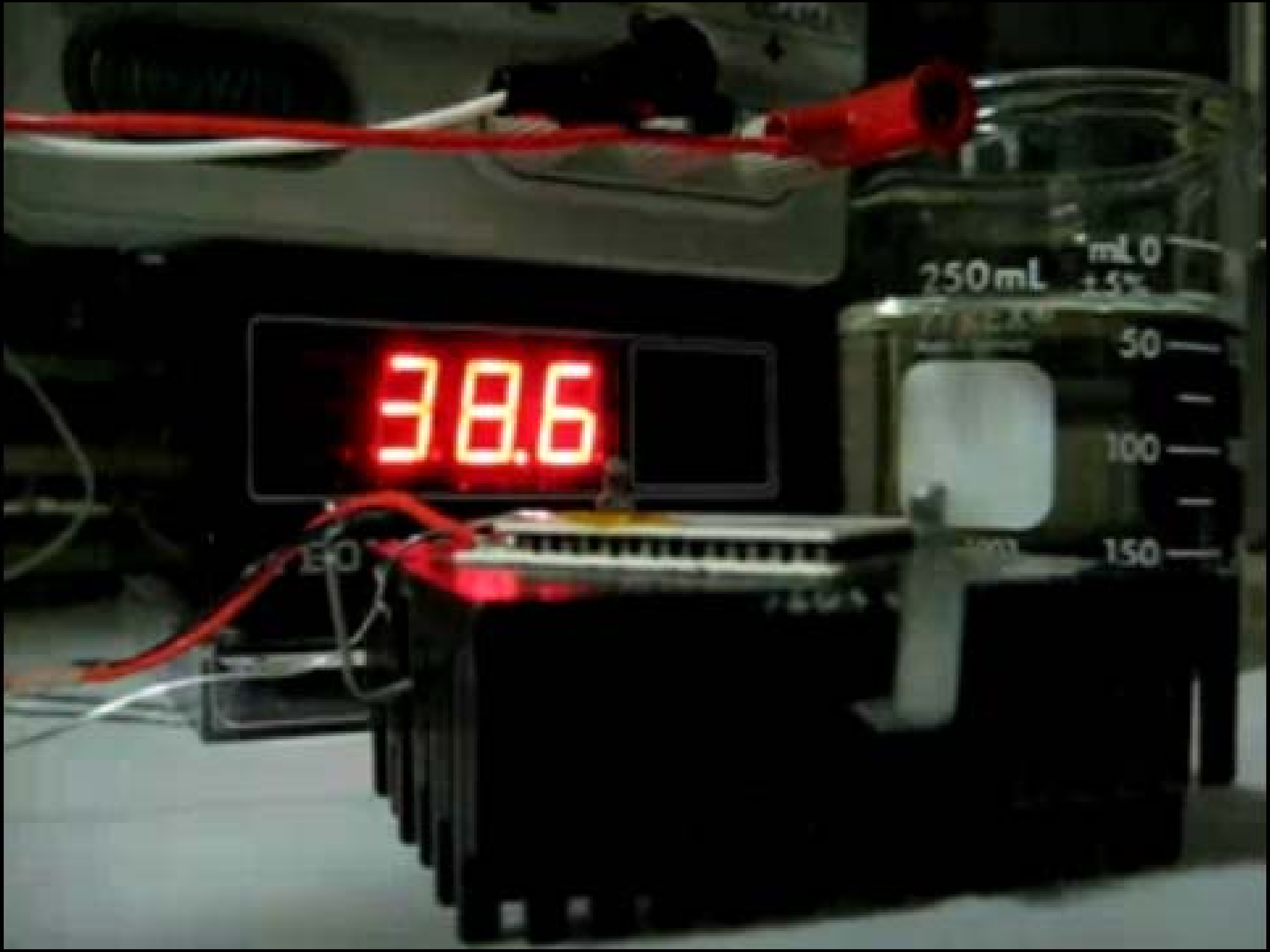
Thermocouple Principle of Operation

Peltier Effect

➢ The junction of two dissimilar metals is heated or cooled (*joule heating: I^2R*) depending on the direction of the flow of electrical current (*opposite of Seeback effect*).



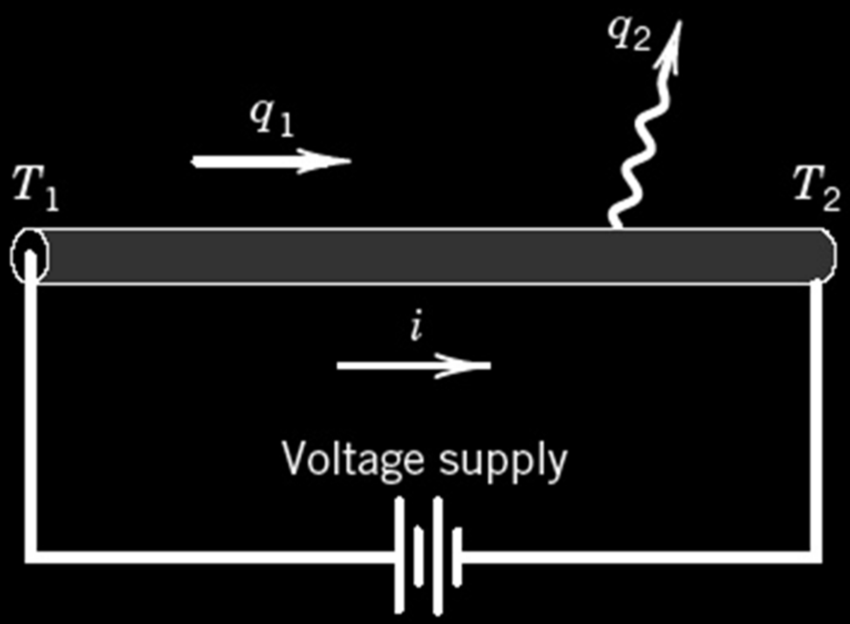
The Peltier Effect



Thermocouple Principle of Operation

Thomson Effect

➢ A conductor that is subjected both temperature gradient and a potential difference can emit or absorb heat depending on the direction of current flow.



q_1 Energy flow as a result of a temperature gradient
q_2 Heat transfer to maintain constant temperature

Law of Homogeneous Materials

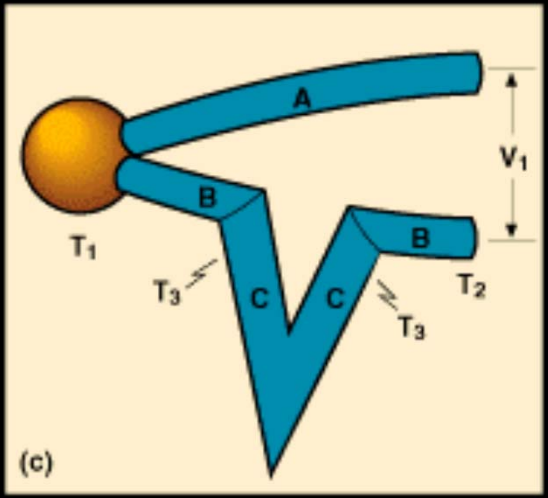
- *A thermoelectric current cannot be sustained in a circuit of a single homogeneous material by the application of heat alone, regardless of how it might vary in cross section.*

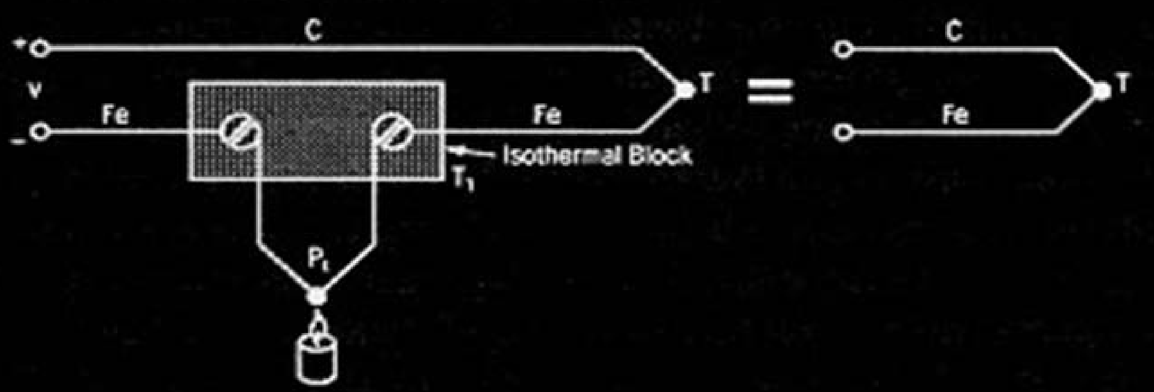
- It requires at least two materials to be used to construct a thermocouple circuit.

- Current may occur in an inhomogeneous wire that is nonuniformly heated. However, this is neither useful nor desirable in a thermocouple.

Law of Intermediate Materials

- Insertion of an intermediate metal into a thermocouple circuit will not affect the emf voltage output so long as the two junctions are at the same temperature and the material is homogeneous.
    - Permits soldered and welded joints.

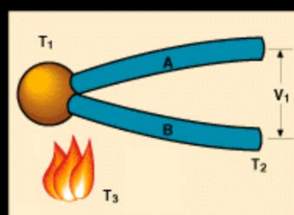




Law of Intermediate Temperatures

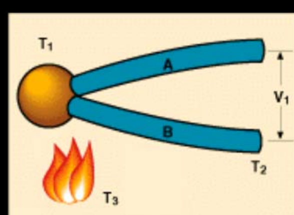
- If a thermocouple circuit develops a net $emf_{1\text{-}2}$ for measuring junction temperatures T_1 and T_2, and a net $emf_{2\text{-}3}$ for temperatures T_2 and T_3, then it will develop a net voltage of $emf_{1\text{-}3} = emf_{1\text{-}2} + emf_{2\text{-}3}$ when the junctions are at temperatures T_1 and T_3. are at the same temperature and the material is homogeneous.

T_2



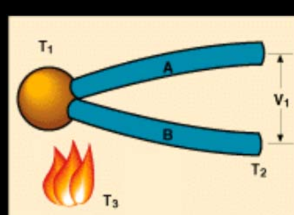
T_1

T_3



T_2

T_3



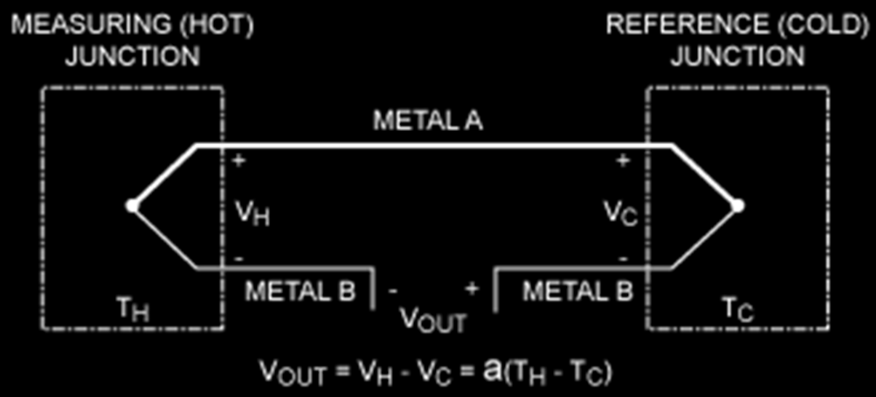
T_1

$$emf_{1\text{-}2} + emf_{2\text{-}3} = emf_{1\text{-}3}$$

Basic Measurement with Thermocouples

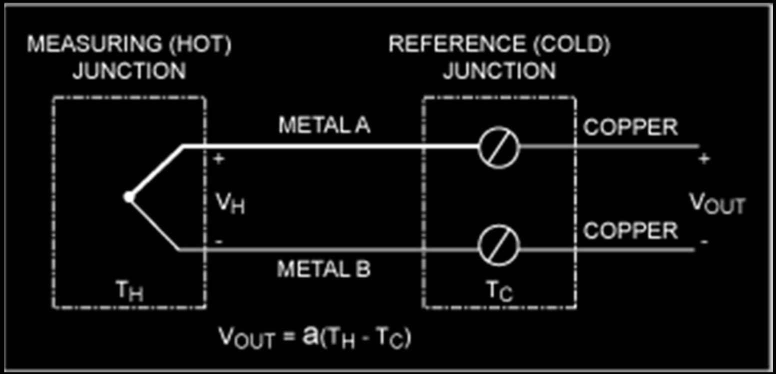
➢ *Measured output voltage, V_{OUT}, is the difference between the measuring (hot) junction voltage and the reference (cold) junction voltage*

➢ *Since V_H and V_C are generated by a temperature difference between the two junctions, V_{OUT} is also a function of this temperature difference*



Basic Measurement with Thermocouples

- Configuration most commonly used in thermocouple applications introduces a third metal (also known as an intermediate metal) into the loop and hence two additional junctions
- The open ends of each wire are electrically connected to wires or traces made of copper. These connections introduce two additional junctions into the system. As long as these two junctions are at the same temperature, the intermediate metal (copper) has no effect on the output voltage.
- V_{OUT} is still a function of the difference between hot and cold-junction temperatures, related by the Seebeck coefficient. However, since the thermocouple measures temperature differentially, the cold-junction temperature must be known in order to determine the actual temperature measured at the hot junction.
- The simplest case occurs when the cold junction is at 0°C, also known as an *ice-bath reference (Cold Junction Compensation)*. If T_C = 0°C, then $V_{OUT} = V_H$



Thermocouple Types

Common Thermocouple Temperature Ranges

Calibration	Temp Range	Std. Limits of Error	Spec. Limits of Error
J	0°C to 750°C (32°F to 1382°F)	Greater of 2.2°C or 0.75%	Greater of 1.1°C or 0.4%
K	–200°C to 1250°C (–328°F to 2282°F)	Greater of 2.2°C or 0.75%	Greater of 1.1°C or 0.4%
E	–200°C to 900°C (–328°F to 1652°F)	Greater of 1.7°C or 0.5%	Greater of 1.0°C or 0.4%
T	–250°C to 350°C (–328°F to 662°F)	Greater of 1.0°C or 0.75%	Greater of 0.5°C or 0.4%

Thermocouple Measurement Errors

- Conduction
- Convection
- Radiation
- Response Time
- Noise
- Grounding issues and shorts, especially on metal surfaces