Sensors

- Learning Outcomes
  - Sensors
  - Resolution, Sensitivity, Operating Range
  - Displacement Sensors
    - Potentiometers
    - Strain Gauges
    - Capacitive Sensors
    - Inductive Sensors
  - Temperature Sensors
    - Thermistors
    - Thermocouples

Sensors

Sensor: device which detects changes in quantities of interest and provides a readable output

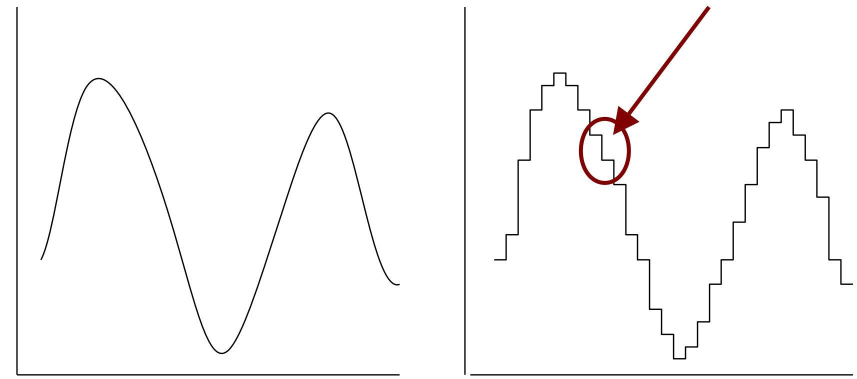
Examples

- Thermocouple converts temperature to voltage.
- Mercury thermometer converts temperature to a reading on a calibrated glass tube.

Instrument Characteristics: Resolution and Sensitivity

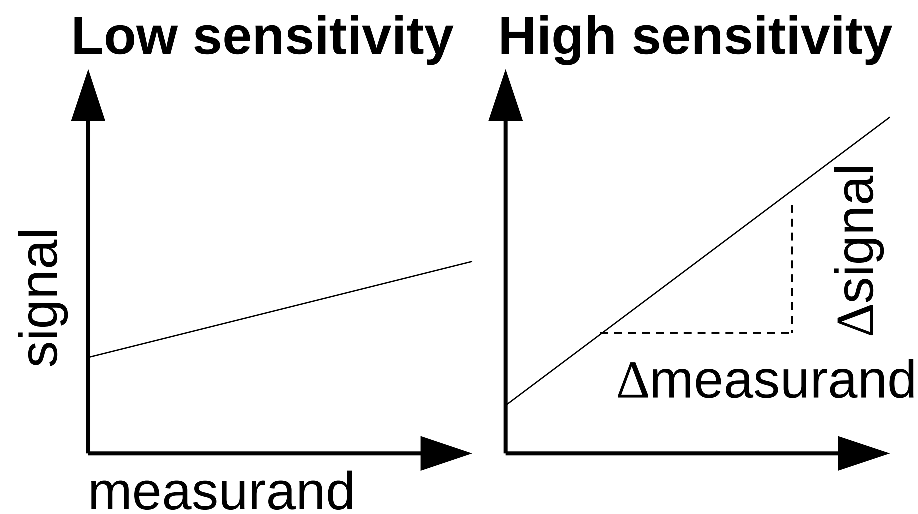
Resolution

- Smallest change measurable



Sensitivity

= (Δsignal)/(Δmeasurand)

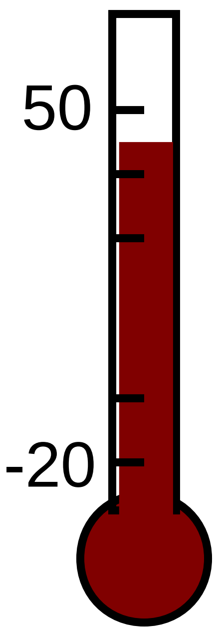


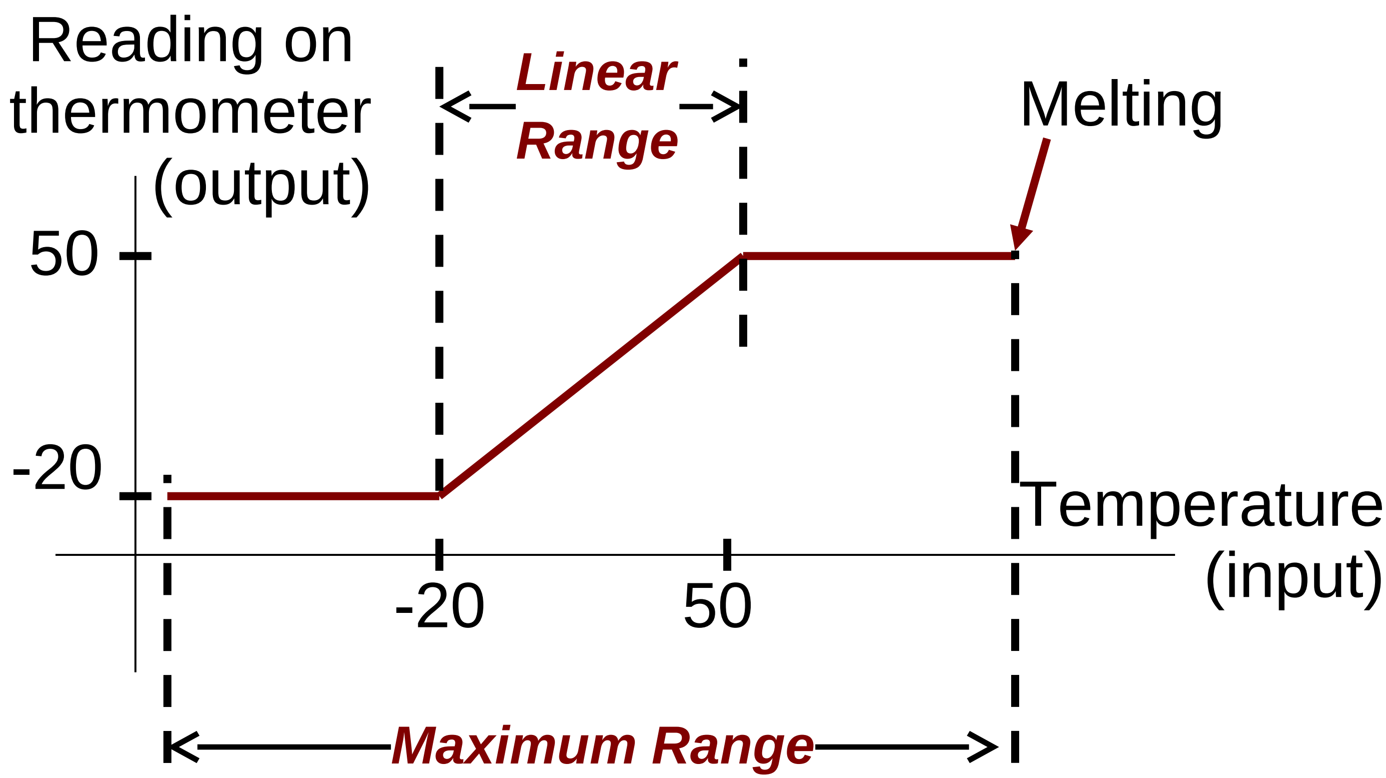
Sensitivity and operating range

Many sensors have a linear operating range.

Outside this range we have the maximum operating range (that doesn't damage the instrument)

Thermometer





Sensors

Sensor Types:

- Displacement Sensors:
  - Resistive
  - Inductive
  - Capacitive
- Temperature Measurement
  - Thermistors
  - Thermocouples
- Also: time, light, chemical, electromagnetic ...

Potentiometers

Construction
- Wire wound
- Carbon film
- Ceramic
- Conducting plastic

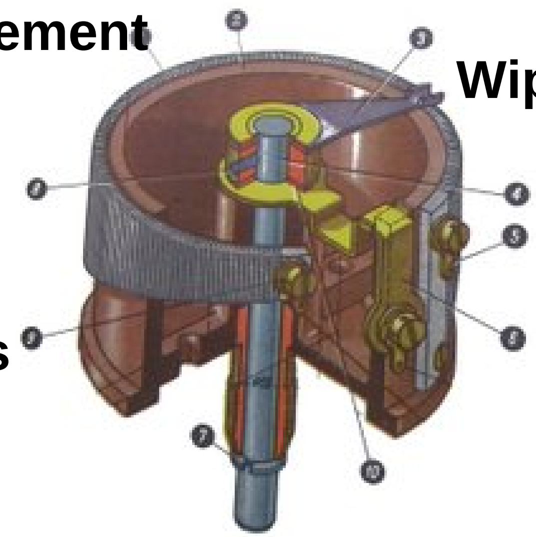
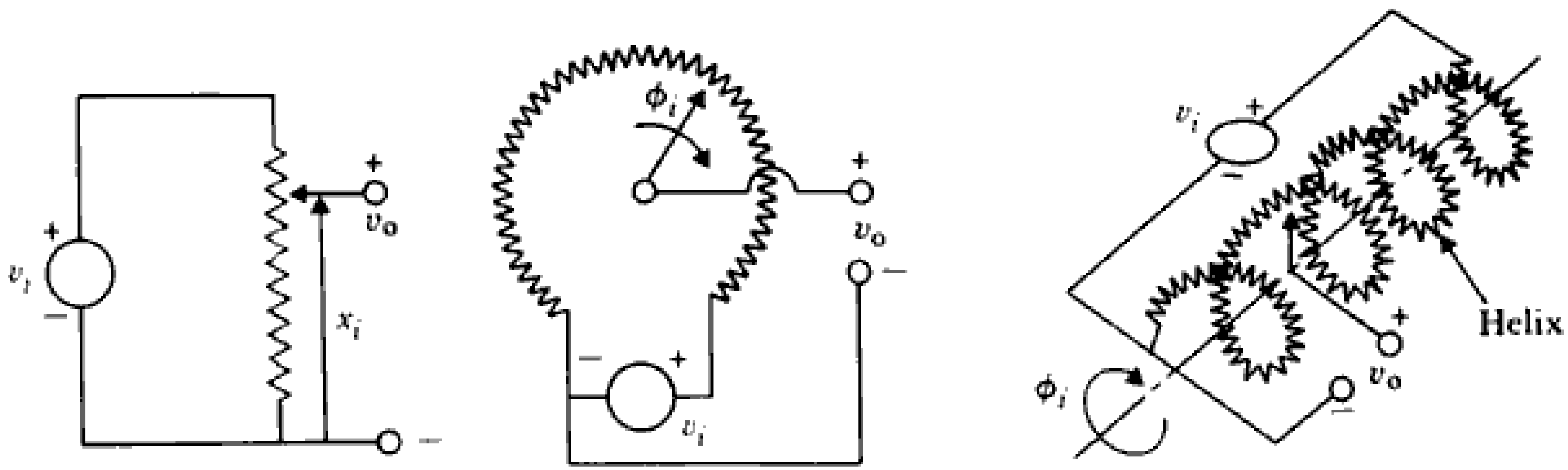


Image source: Wikipedia



(a) Translational (b) Single-turn (c) Multi-turn

Sensors

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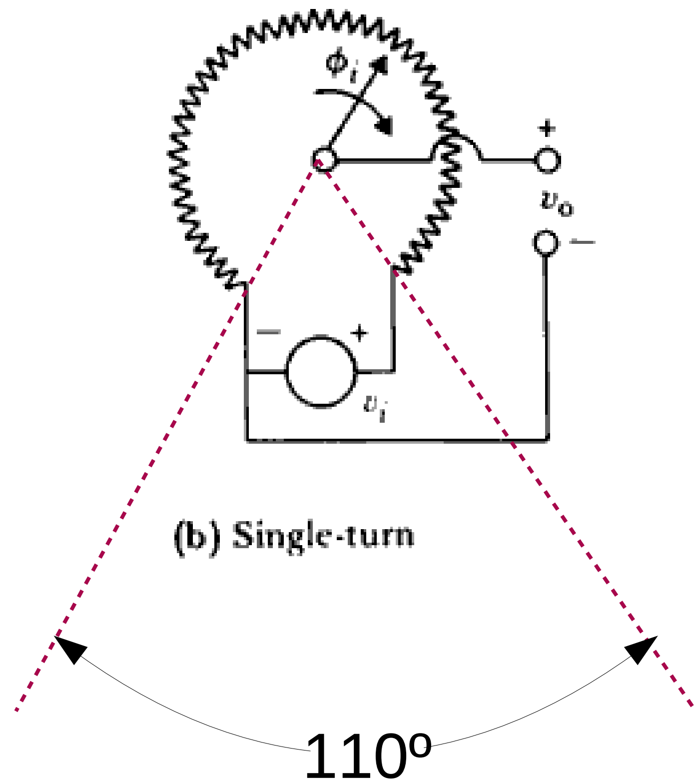
Question:

If we apply 10V across a single turn potentiometer with 50 wire turns covering 250º.

- What is sensitivity (in volts/degree)?
- What is resolution?

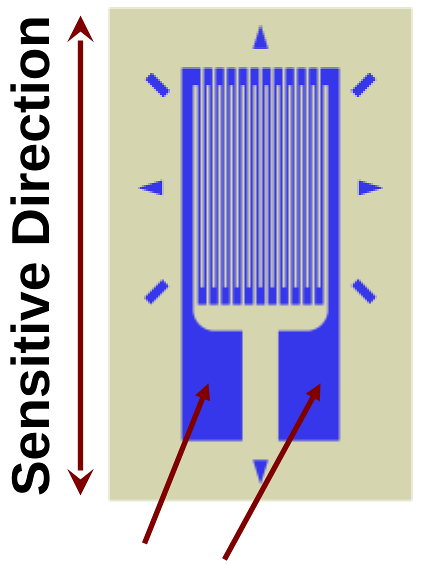


(b) Single-turn

Strain Gauges

Strain gauge measures strain (deformation) by a change in resistance.

- Measurement circuits typically use Wheatstone bridge



Gauge Factor: measure of gauge sensitivity

$$GF = (\Delta R/R) / \text{strain}$$

R: undeformed resistance

ΔR: change in R due to strain

strain: fractional change in length (ΔL/L)

Strain Gauge: analysis

Gauge Factor

$$G = \frac{\partial R/R}{\partial L/L} = \underbrace{1 + 2\mu}_{\text{Dimensional Effect}} + \underbrace{\frac{\partial \rho/\rho}{\partial L/L}}_{\text{Piezoresistive Effect}}$$

Dimensional Effect

Piezoresistive Effect
- Metals ≈ 0
- Ceramics / Semiconductors have large effect

Examples:
- Metals G = 1+2(0.3) = 1.6
- n-Si G ≈ 100
- p-Si G ≈ -100

(large temperature drift in semis)

Sensors

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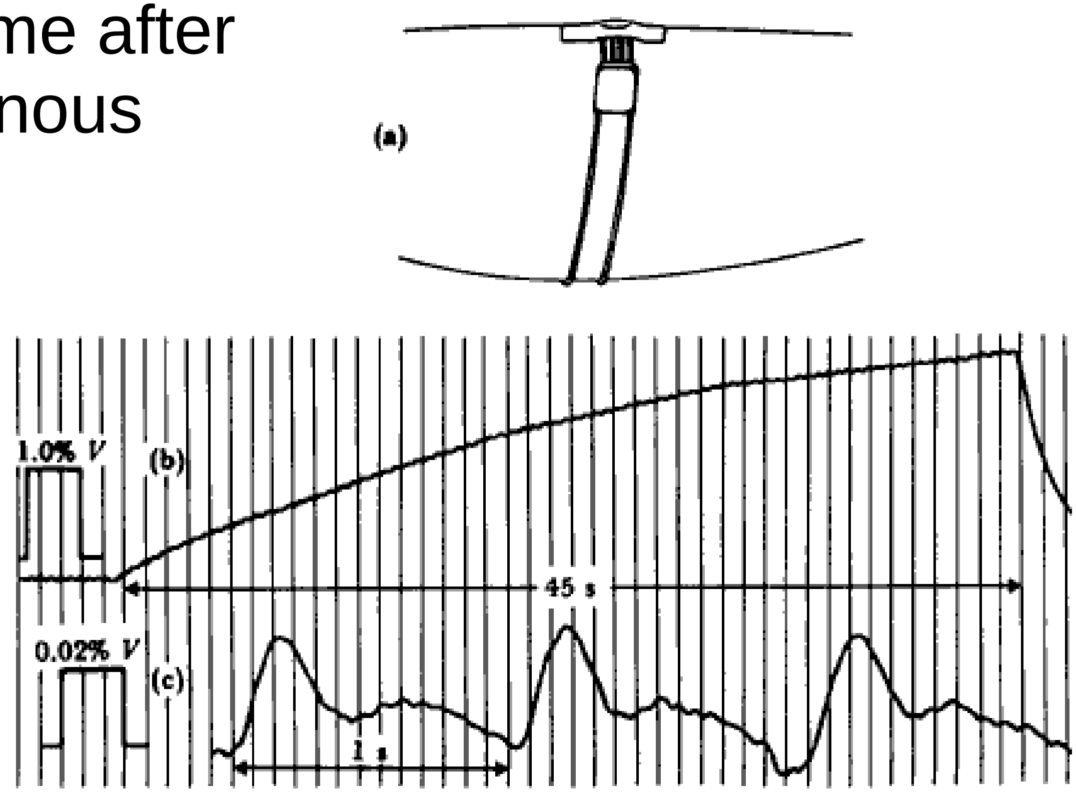
Question

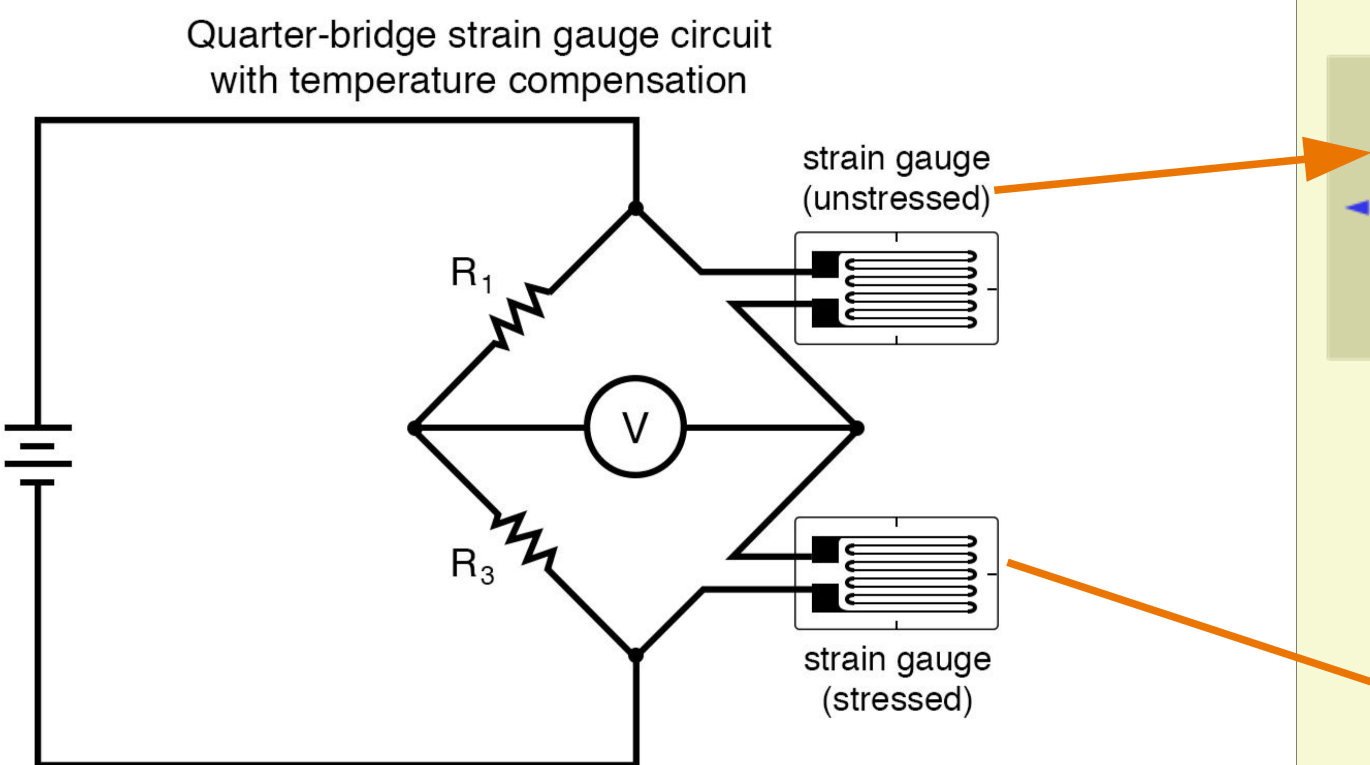
Mercury plethysmograph measures change in leg blood volume after pressure cuff applied (venous occlusion)

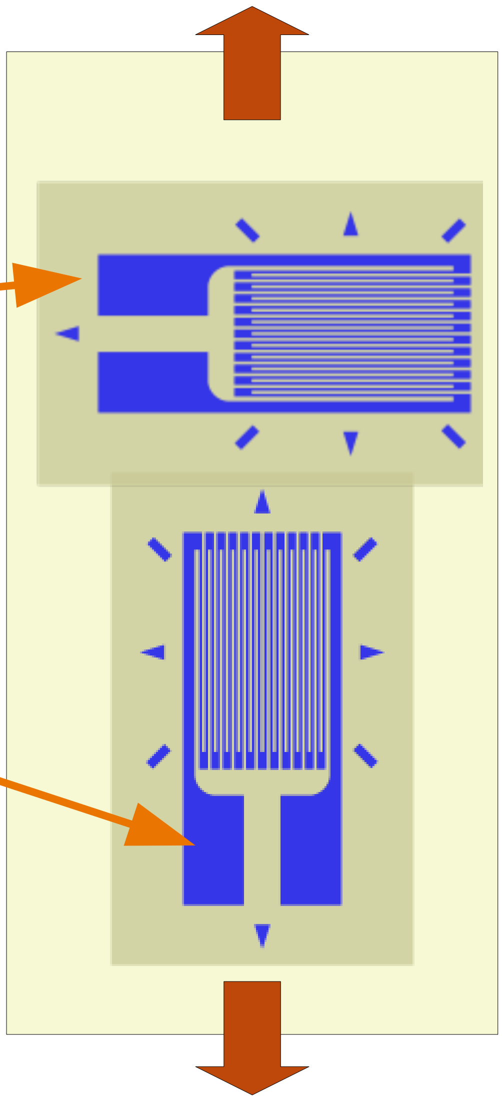
- µ for Hg is 0.5
- Calculate ΔR/R if blood makes 10% increase in diameter
- G = 1 + 2×0.5 = 2
- ΔR/R = G × (ΔR/R) = 0.2



Note: Hg no longer used.

Strain Gauges + Bridge Circuits





Source: https://www.allaboutcircuits.com/textbook/direct-current/chpt-9/strain-gauges/

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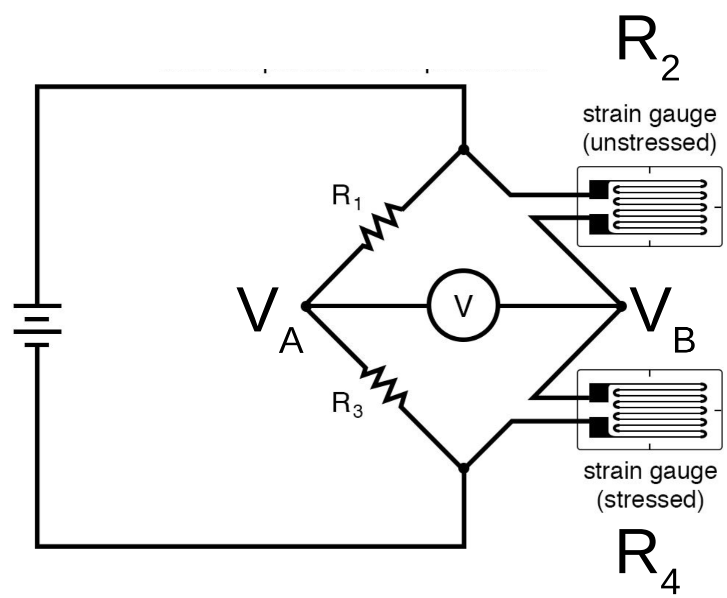
Question

- Initially R_1=R_2=R_3=R_4 = 1k
- Source V = 10V
- Strain makes R_4 increase to 1.1k
- Strain makes R_2 increase to 1.01k
- What is V?
  - V_A = 5V
  - $V_B = 10V \times R_4/(R_2+R_4) = 5.21V$
  - $V = V_A - V_B = -0.21V$
- Temperature increase makes both R_4 and R_2 decrease by 5%. What is V?



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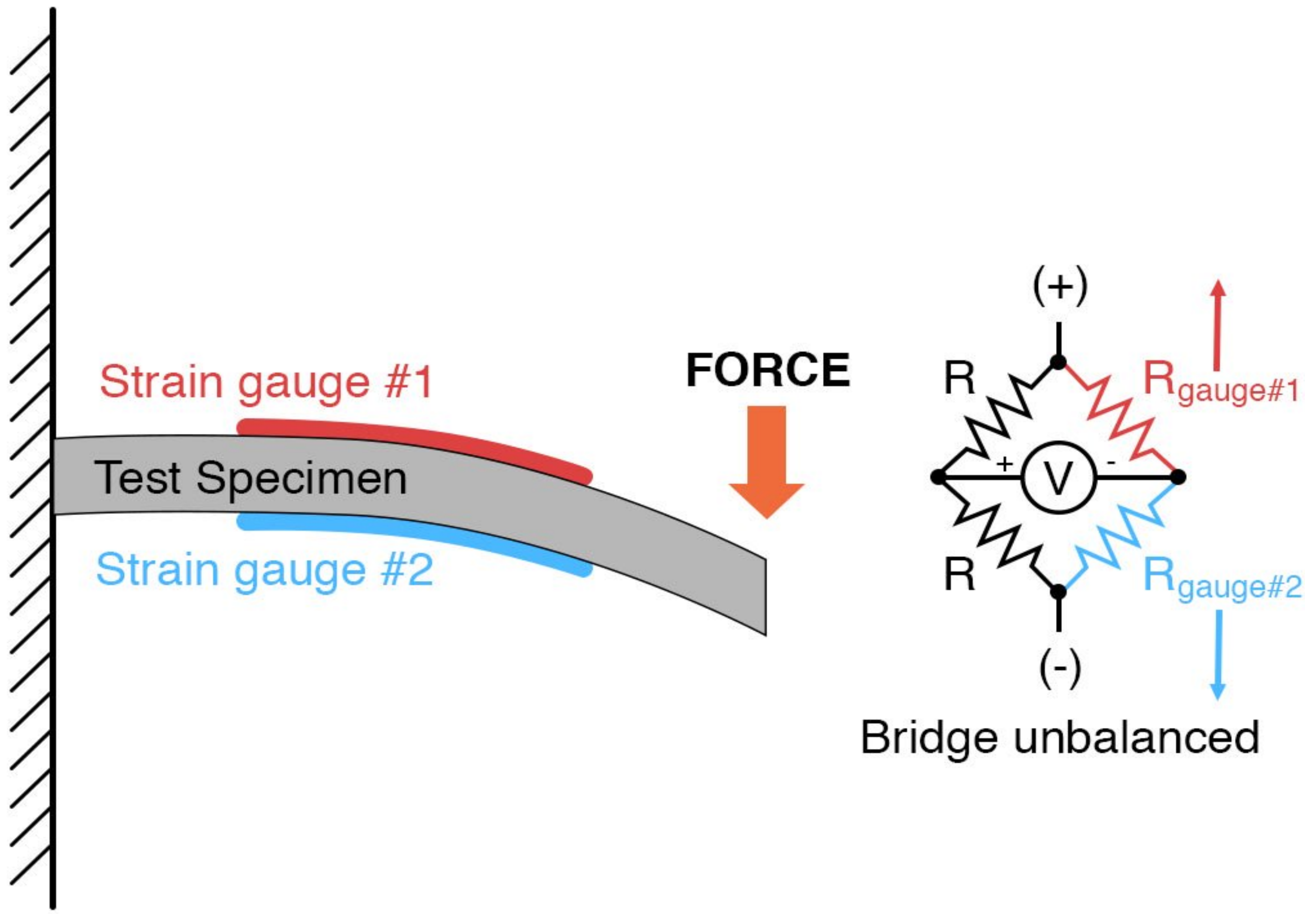
Strain Gauges + Bridge Circuits



Source: https://www.allaboutcircuits.com/textbook/direct-current/chpt-9/strain-gauges/

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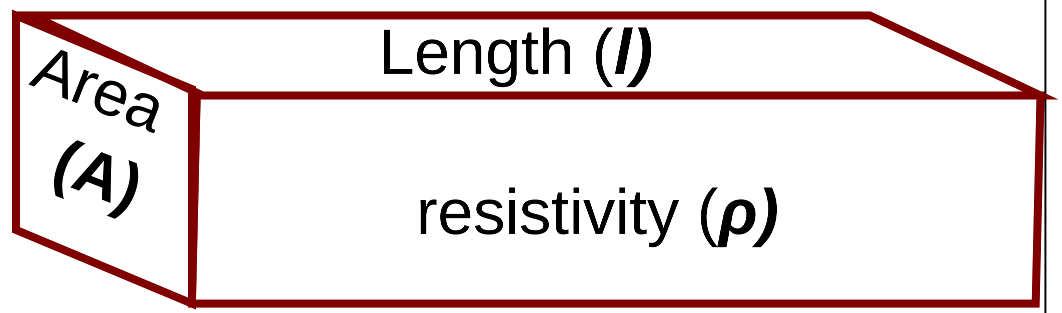
Gauge Factor: analysis

Analysis of SG



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

$$\partial R = \frac{L}{A}\partial\rho + \frac{\rho}{A}\partial L - \frac{L}{A^2}\partial A$$

$$\frac{\partial R}{R} = \frac{\partial\rho}{\rho} + \frac{\partial L}{L} - \frac{\partial A}{A}$$

$$\frac{\partial R}{R} = \frac{\partial\rho}{\rho} + (1+2\mu)\frac{\partial L}{L}$$

$$G = \frac{\partial R/R}{\partial L/L} = 1 + 2\mu + \frac{\partial\rho/\rho}{\partial L/L}$$

Poisson's Ratio (***μ***)

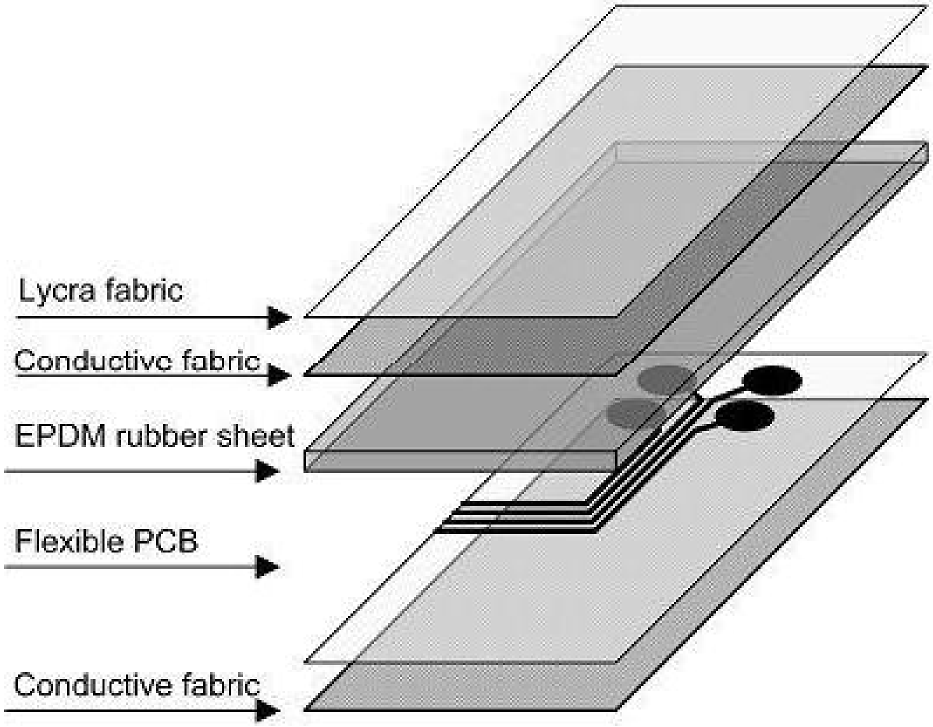
$$\frac{\partial A}{2A} = -\mu\frac{\partial L}{L}$$

For incompressible media μ=0.5. Calculate from Vol = D^2L is const

Capacitive sensors

Capacitive sensors

- Low cost, small, mechanically strong
- Quite non-linear, better to indicate contact



Source: Salpavaara, et al,, 2008.

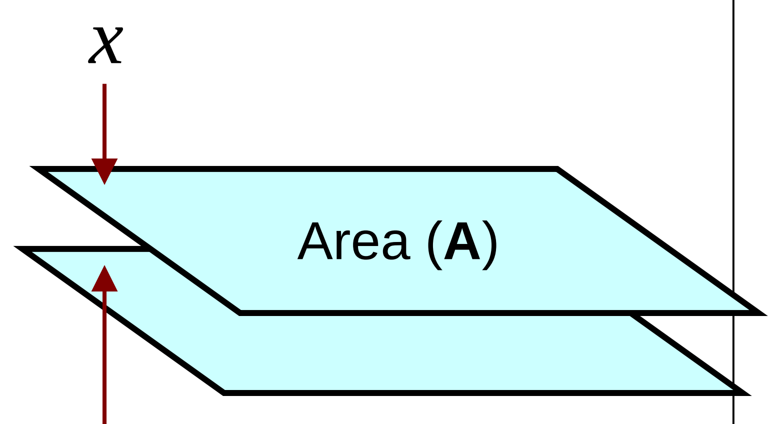
Capacitive sensors

Electromagnetic analysis

$$C = \epsilon_0 \epsilon_r \frac{A}{x}, \qquad \epsilon_0 = 8.86 \times 10^{-12} \frac{F}{m}$$

Permittivity of free space

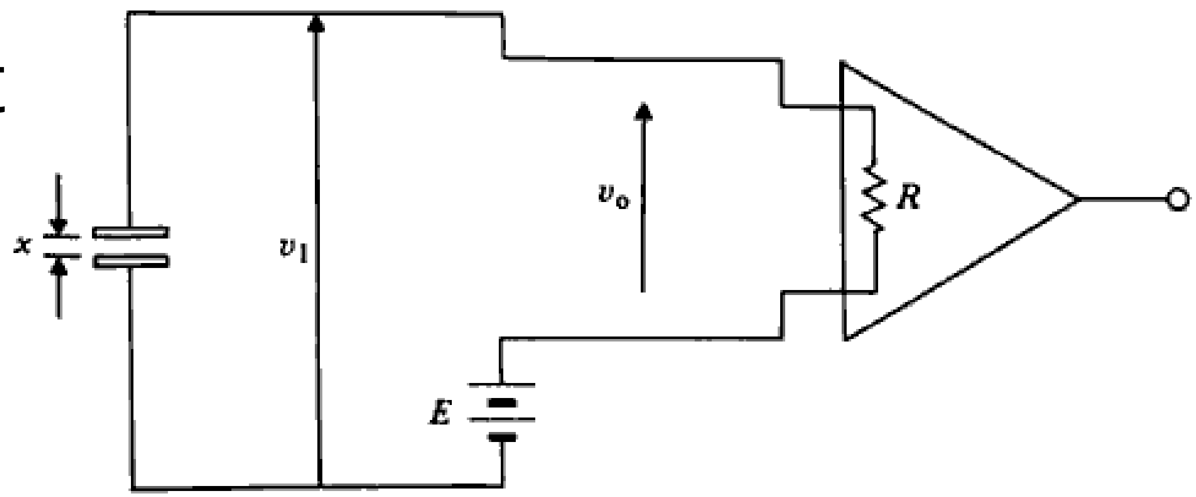
Relative Permittivity



$$K = \frac{dC}{dx} = -\epsilon_0 \epsilon_r \frac{A}{x^2}$$

Non-linear Sensitivity

Electronic Circuit



Sensors

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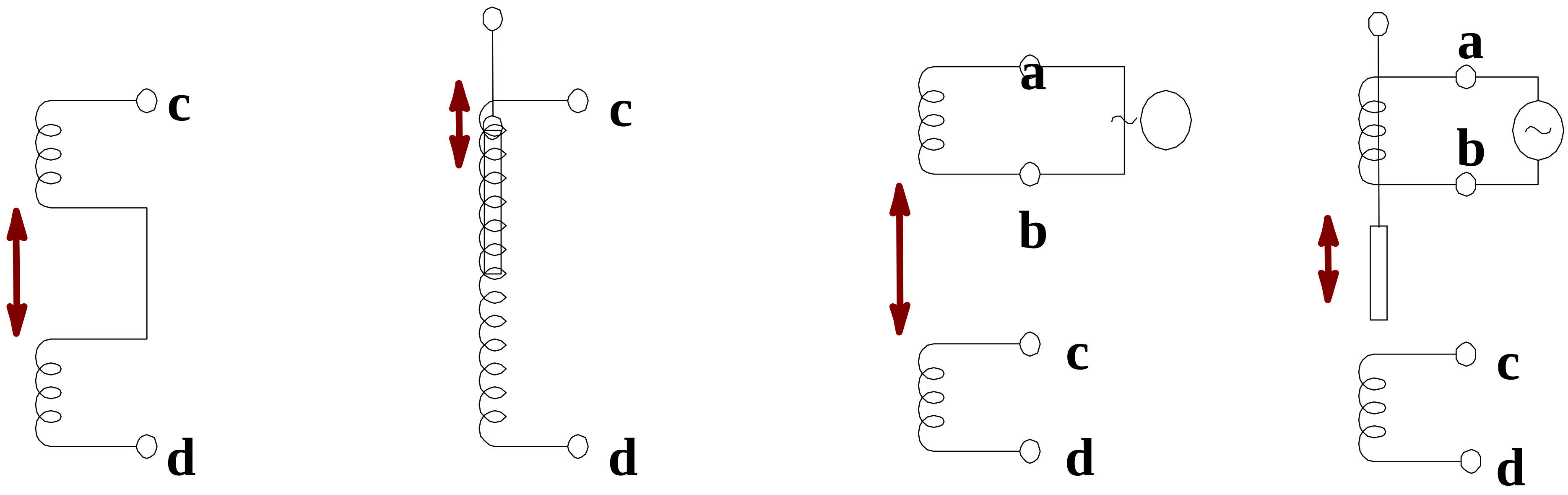
Inductive Sensors



Self-inductance Mutual inductance

- Inductance sensor measures displacement by changes in geometry.
- Tend to be non-linear, since geometry to inductance relationship is non-linear
- Many applications: metal detectors, proximity detector, traffic light car presence detector

Questions

- What is the Gauge factor? What kinds of materials have large G? When is this useful?
- Why is temperature variation in R of a strain gauge a problem? What strategies can be used to help deal with it?
- Name some applications for inductive sensors?
- Since capacitive sensors are highly non-linear, what kinds of applications are they useful for?

Temperature Measurement

Why measure temperature

- Body is a heat engine. We burn food + oxygen to get energy for life. Temperature monitors the functioning of the engine
- Temperature increase – hyperthermia
  - typical cause: infection
- Temperature decrease – hypothermia
  - typical cause: shock

Instruments

- Thermistors
- Thermocouples
- Radiation (hot objects emit IR radiation – not included)

Sensors

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Thermistors

thermistor is a type of resistor with resistance varying according to its temperature.

thermal and *resistor* = thermistor

- Many applications for thermistors: current-sensing, thermal protectors, self-regulating heaters.
- Biomedical applications: thermometers, flow sensing, breathing (nasal thermistor)
- All resistors have some temperature variation. Thermisors have large tempco (%change/ºC)
- material is generally a ceramic or polymer

Sensors

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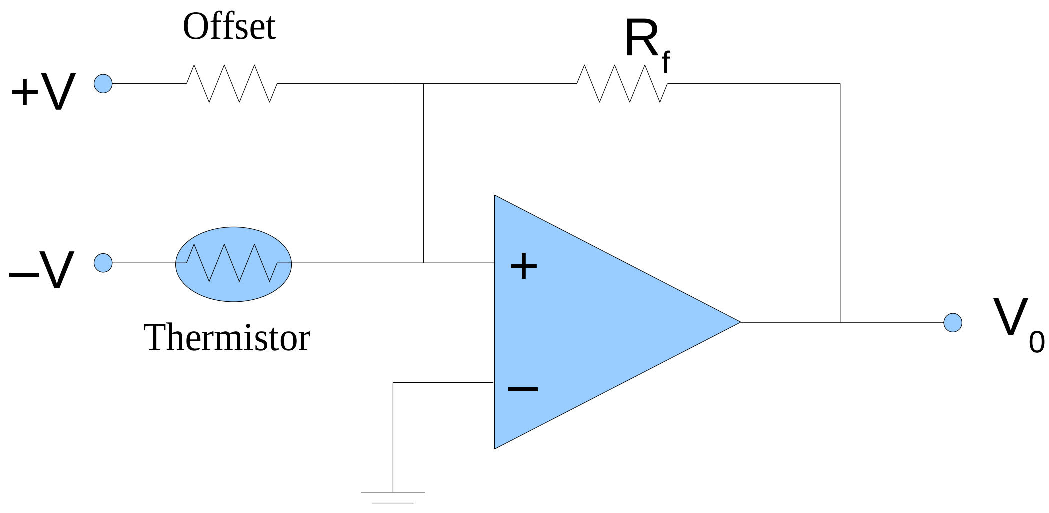
Thermistor: circuit



As temperature increases, the thermistor resistance decreases, yielding more current that flows through R_f, thus V_o increases.

Many different sizes:

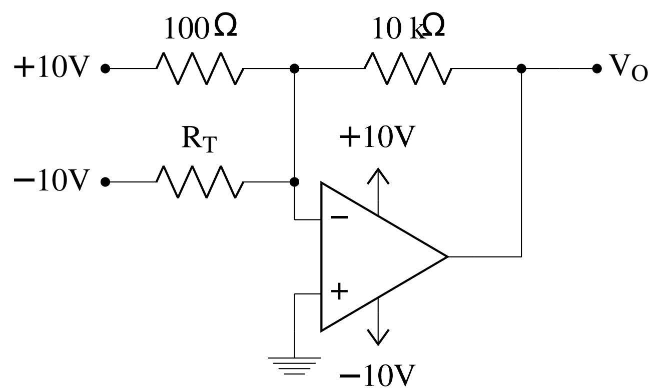
- Small Thermistors are more fragile,faster (2s)
- Larger Thermistors respond slowly (10s)

Thermistors

Midterm#2 2016

1B. (5 points) A thermistor, R_T is used in the circuit below. At 35 °C, $R_T = 100\Omega$ and at 36 °C, $R_T = 101\Omega$. **What is** V_O **for** at 35°C and 36°C?

1C. (5 points) **What is the sensitivity** of at the output of the sensor, V_O, in V/ °C over the range from 35°C to 36°C?



The circuit is a summing inverting amplifier, whose output we can therefore write as

$$V_O = -10\ k\Omega \quad \frac{10V}{100\Omega} - \frac{10V}{R_T}$$

At 35°C, $R_T = 100\Omega$ and so $V_O = 0V$, while at 36°C, $R_T = 101\Omega$ and so

$$V_O = -\frac{10\ k\Omega}{100\ \Omega} \quad 1 - \frac{1}{1.01} \quad (10V) = -9.90V$$

from which the sensitivity is seen to be −9.90 V/°C.

Sensors

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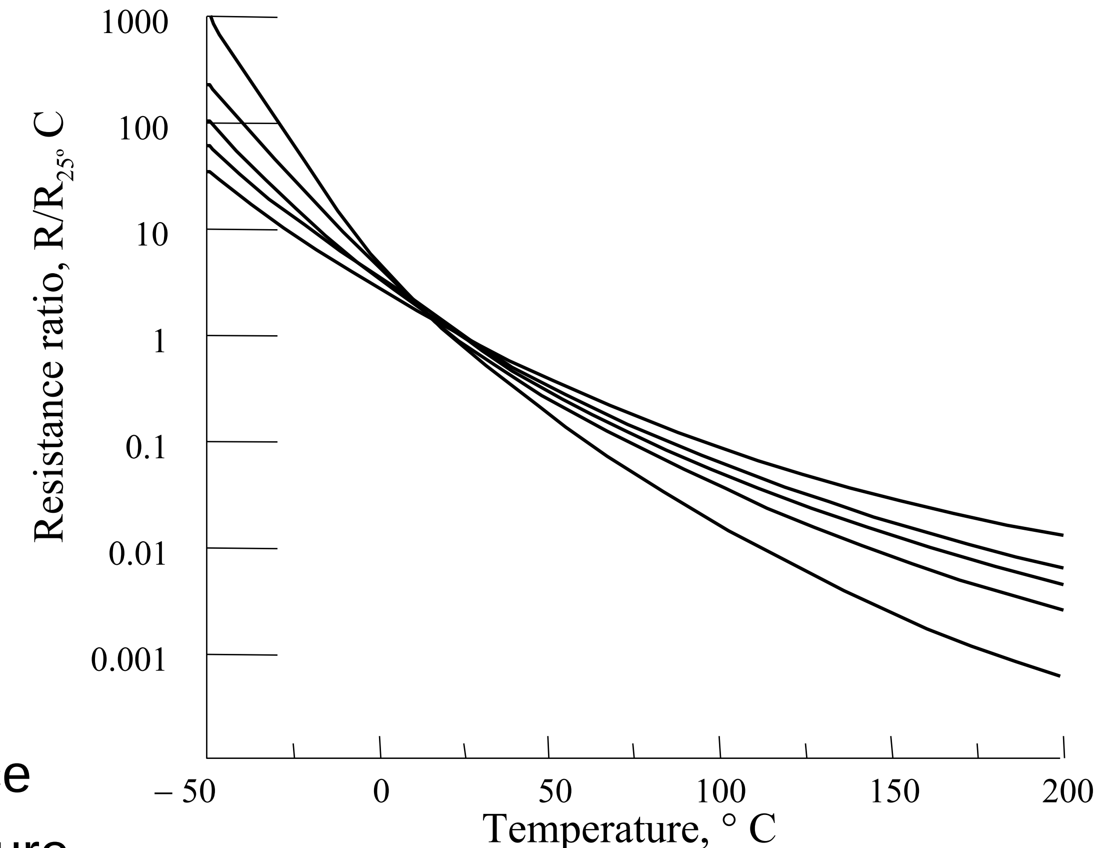
Thermistor: sensitivity model

Typical thermistor temperature characteristics for various materials.



Linear model:

$$\Delta R = k \Delta T$$

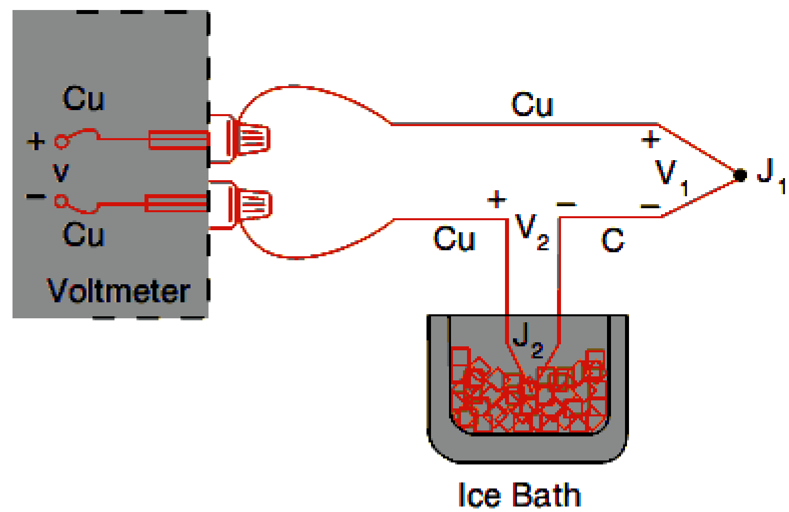
where

- ΔR = change in resistance
- ΔT = change in temperature
- k = first-order temperature coefficient of resistance

Linear model only works over small range

Thermocouples

- Based on Seebeck effect: when a conductor (such as a metal) is subjected to a thermal gradient, it will generate a voltage.
- Thermocouples measure the temperature difference, not absolute temperature.
- Traditionally, one of the junctions—the cold junction—was maintained at a known (reference) temperature, while the other end was attached to a probe.
- Thermocouples are faster, smaller, more robust, more linear than thermistors



EXTERNAL REFERENCE JUNCTION
Figure 5

One way to determine the temperature of J_2 is to physically put the junction into an ice bath, forcing its temperature to be 0˚C and establishing J_2 as the *Reference Junction*. Since both voltmeter terminal junctions are now copper-copper, they create no thermal emf and the reading *V* on the voltmeter is proportional to the temperature difference between J_1 and J_2.

Now the voltmeter reading is (see Figure 5):

$$V = (V_1 - V_2) \cong \alpha(t_{J_1} - t_{J_2})$$

Source: Omega.com

Sensors

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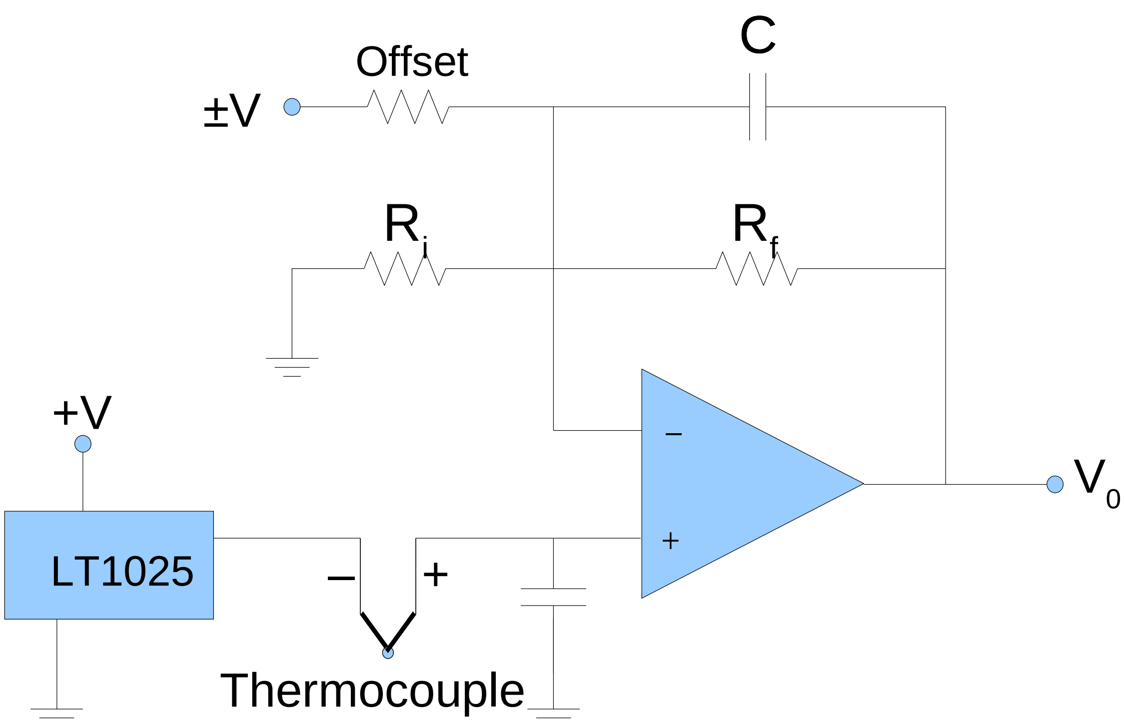
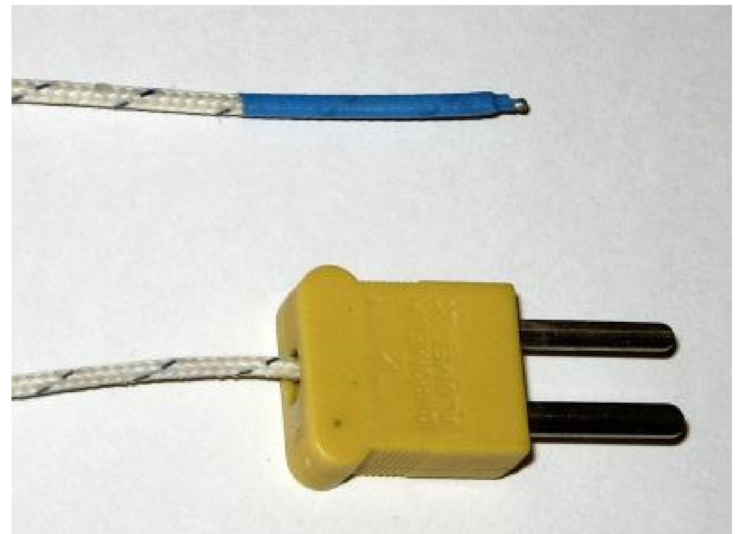
Thermocouples: Usage





The hot junction is at the thermocouple. The LT1025 electronic cold junction compensates for ambient temperature changes. The noninverting amplifier provides a high input impedance and high gain.

Type K (chromel–alumel) commonly used general purpose thermocouple. Inexpensive. Available in the −200°C to +1350°C range.

Sensitivity ≈ 41 µV/°C.

Questions

Thermocouple or thermistor?

- Cheap
- Mechanically strong
- Simplest electrical circuit
- Capable of high temperatures
- Fastest response

Questions

- How does a thermistor differ from a thermocouple? Which is more linear? Which is less brittle? Which can have the fastest response?
- What would you build the temperature cut-off switch in a computer from?
- Why does a thermocouple need a reference circuit?
- What strategies are used to help reduce drift in radiation thermal detectors?