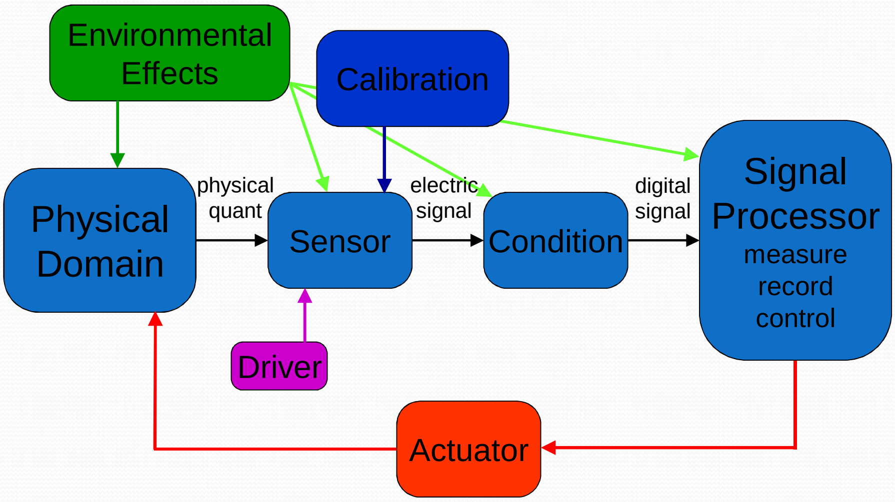
Sensors & Actuators

Section 10

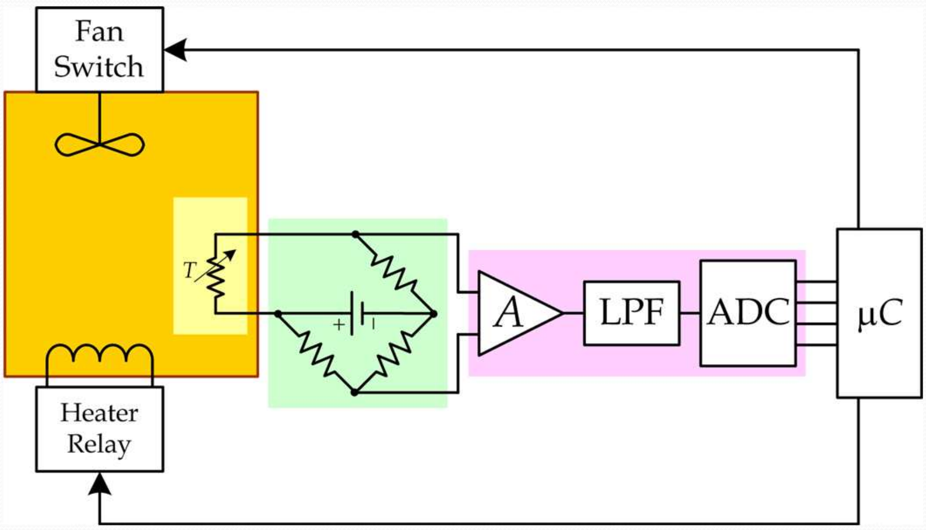
Definitions

- Sensor
  - a device that converts a physical parameter to an electrical output (e.g. temperature sensor)
- Actuator
  - a device that converts an electrical signal to a physical output (e.g. a speaker)
- Transducer
  - a device that converts one form of energy into another

Overview



Example



Physical Quantities

- Temperature
- Forces
  - Pressure
  - Torque
  - Weight
- Location and Motion
  - position, flow, rate, acceleration
- Sound
- Light
- Magnetic Field
- Concentration
- Radiation

Think of any other?
Think of Classification?

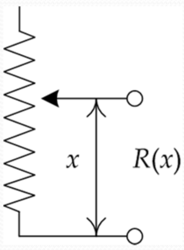
A Good Sensor

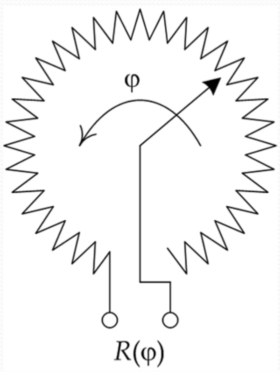
- is insensitive to noise
- is linear
  - $p = k \times v$
- does not change measured media
- does not drift with time
- does not have hysteresis measurement
  - same readout when value is increasing or decreasing

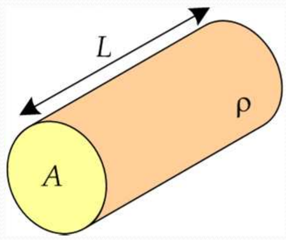
Passive Sensors

- Resistive
  - R is changed due to measured quantity
- Capacitive
  - C is changed due to measured quantity
- Inductive
  - L is changed due to measured quantity

Resistive Sensors



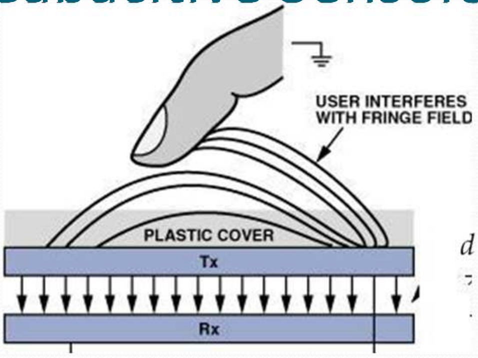


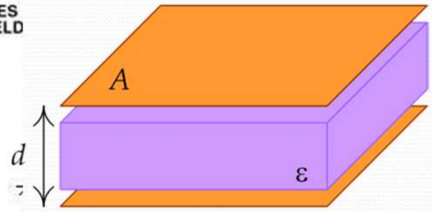


$$R = \rho \frac{L}{A}$$

- $R = f(x)$
- Applications:
  - tuning, position sensing, sound volume

Capacitive Sensors

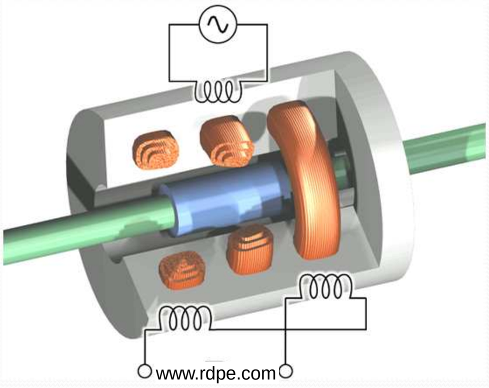


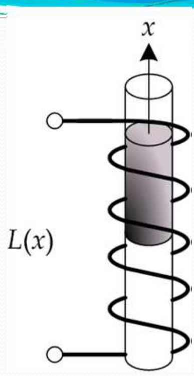


$$C = \varepsilon \frac{A}{d}$$

- $C = f(d)$
- Applications:
  - button switches, calculator key pads, position sensing, small dynamic motion

Inductive Sensors

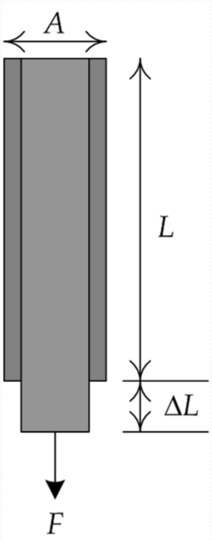




$$L = \mu \cdot N^2 \frac{A}{l}$$

- $L = f(\mu)$
- Applications:
  - precise displacement

Strain Gage



- Stress
  - Resistance to external force
  - Force per unit area

$$\sigma_a = \frac{F}{A}\left(N/m^2\right)$$

- Strain
  - Displacement due to external force
  - Fractional change in length

$$\varepsilon_a = \frac{\Delta L}{L}\left(\mu m/m\right)$$

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Elastic Region

- Elastic Region in Materials:
  - Displacement is linear with Force applied
  - Doubling the force will double the deformation

  - Stress and Strain are Linearly related

$$\sigma_a = E_y \times \varepsilon_a$$

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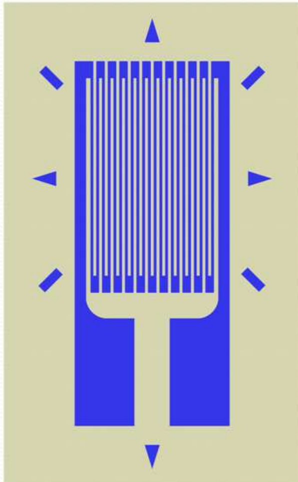
Strain Gage

- R changes with L
  - Linearly

$$\frac{\Delta R}{R} = K \times \varepsilon_a$$

- R and k are given in datasheet

- Typically ΔR is very small



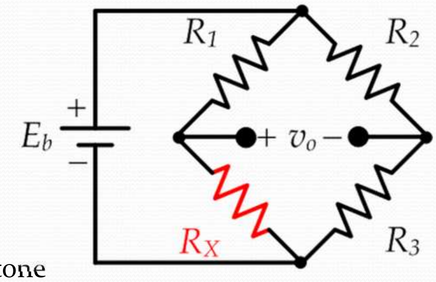
Example

- A strain gage having
  - $K = 2 \quad R = 350\Omega$
- It exposed to an axial strain of
  - $\varepsilon_a = 300\ \mu m/m$

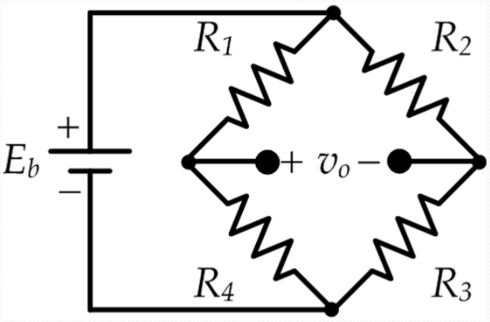
$$\begin{aligned} \frac{\Delta R}{R} &= K \times \varepsilon_a \\ \Delta R &= 2 \times 300 \times 10^{-6} \times 350 \\ &= 210\, m\Omega \end{aligned}$$

Wheatstone Bridge

- to measure small resistance changes
- History:
  - 1833
    - invented by Samuel Christie
  - 1834
    - improved by Charles Wheatstone
  - 1865
    - extended to AC by James Maxwell

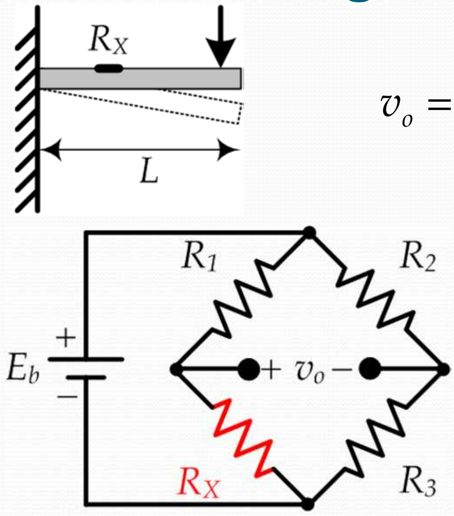


Balanced Bridge



$$R_1 \cdot R_3 = R_2 \cdot R_4 \quad \rightarrow \quad v_o = 0$$

Quarter Bridge

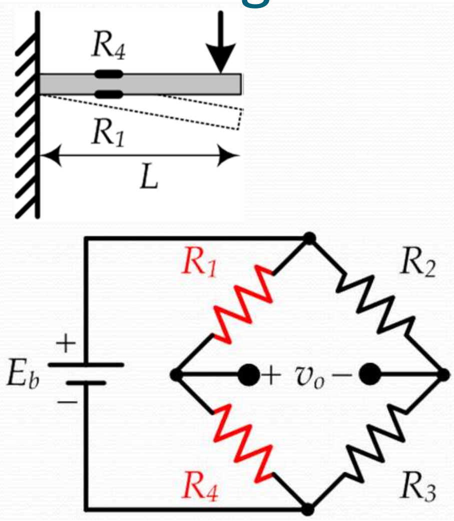


$$v_o = E_b \cdot \left(\frac{R_4}{R_1 + R_4} - \frac{R_3}{R_2 + R_3} \right)$$

$$R = R_1 = R_2 = R_3$$
$$R_X = R + \Delta R$$

$$v_o = \frac{E_b \cdot \Delta R}{2(\Delta R + 2R)}$$

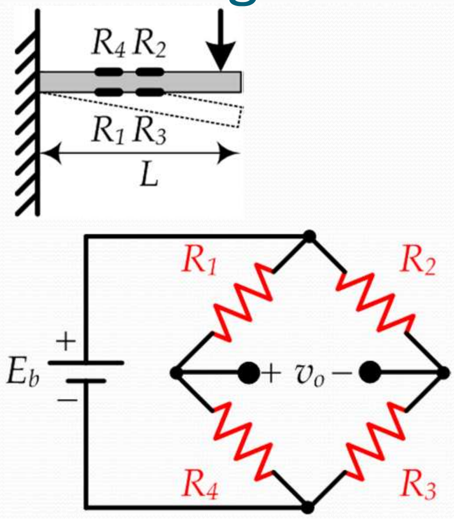
Half Bridge



$$R = R_2 = R_3$$
$$R_1 = R - \Delta R$$
$$R_4 = R + \Delta R$$

$$v_o = \frac{E_b \cdot \Delta R}{2R}$$

Full Bridge



$$R_1 = R_3 = R - \Delta R$$
$$R_2 = R_4 = R + \Delta R$$

⇓

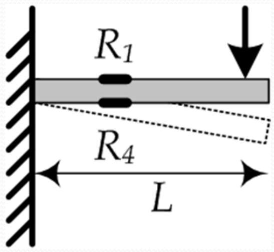
$$v_o = \frac{E_b \cdot \Delta R}{R}$$

Strain from the Bridge

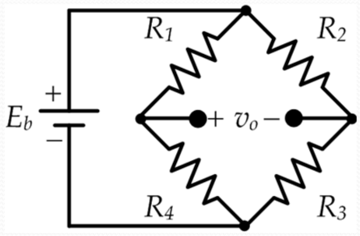
Quarter Bridge	$v_o = \frac{E_b}{2} \cdot \frac{K \cdot \varepsilon_a}{K \cdot \varepsilon_a + 2}$	$\varepsilon_a = \frac{4 v_o}{K \cdot (E_b - 2 v_o)}$
Half Bridge	$v_o = \frac{E_b \cdot K}{2} \cdot \varepsilon_a$	$\varepsilon_a = \frac{2 v_o}{K \cdot E_b}$
Full Bridge	$v_o = E_b \cdot K \cdot \varepsilon_a$	$\varepsilon_a = \frac{v_o}{K \cdot E_b}$

Examples

- A bridge has two active strain gages (R_1,R_4) installed as shown.
- Express the bridge output voltage, v_o, as a function of E_b, R, and ΔR



- Calculate the beam displacement ΔL when
  - E_b=10V
  - bridge resistors R=10kΩ
  - v_o=–50mV
  - L=0.5m
  - K=3



Temperature Sensors

1. Thermocouple
2. Thermistor
3. Infrared

Temperature

- An expression for the kinetic energy of vibrating atoms and molecules of matter
  - Freezing point & Boiling Point of Water

Kelvin	Celsius	Fahrenheit
0K no vibration	divide into 100°	divide into 180°

$$°F = 1.8 \times ℃ + 32$$
$$K = ℃ + 273.15$$

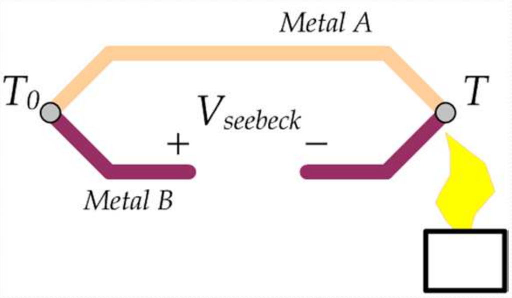
Measuring Temperature

- Temperature Sensors
  - thermocouples
  - resistive devices
  - infrared devices
- By Secondary Phenomena:
  - change of volume (mercury)
  - change or pressure
  - change of resistance
  - change of electromagnetic force
  - change of electron surface charge
  - change of emission of electromagnetic radiation

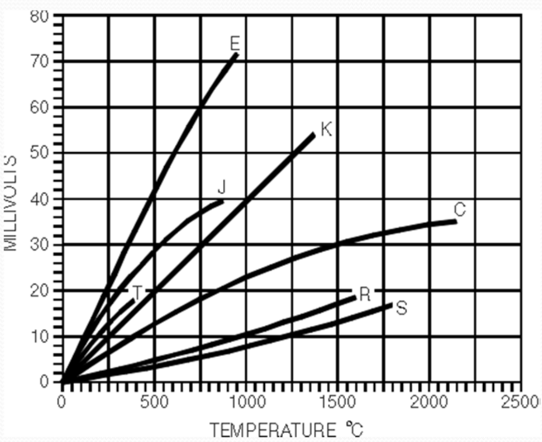
Thermocouple

- heating a joint of two different metals induces an EMF voltage (Seebeck voltage)
- applying a voltage to a joint of two different metals causes a temperature change (Peltier effect)

$$\Delta T = f\left(V_{seebeck}\right) = \sum_{i=1}^{n} \alpha_i \times v^i$$



Thermocouple



ANSI Type	Materials	Temp (°C)	EMF (mV)
T	Copper	-200	-5.60
	Constantan	350	17.82
J	Iron	0	0
	Constantan	750	42.28
E	Chromel	-200	-8.82
	Constantan	900	68.78
K	Chromel	-200	-5.97
	Alumel	1250	50.63
R	Platinum 13% Rhodium	0	0
	Platinum	1450	16.74
S	Platinum 10% Rhodium	0	0
	Platinum	1450	14.97
C	Tungsten 5% Rhenium	0	0
	Tungsten 26% Rhenium	2320	37.07

Thermocouple

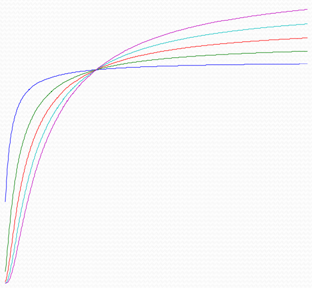
Thermocouple Curves – Types E, K, and T

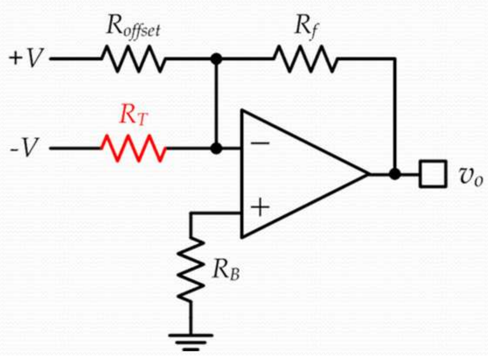
Type E Chromel vs. Constantan		Type K Chromel vs. Alumel		Type T Copper vs. Constantan	
Temp (K)	V_{TC}(mV)	Temp (K)	V_{TC}(mV)	Temp (K)	V_{TC}(mV)
3.0	–9.8355	3.0	–6.4582	3.0	–6.2584
5.6	–9.8298	6.0	–6.4551	6.5	–6.2523
9.0	–9.8182	10.0	–6.4486	11.0	–6.2401
13.5	–9.7956	14.5	–6.4376	16.5	–6.2184
19.0	–9.7570	19.5	–6.4205	22.0	–6.1888
25.0	–9.7013	25.0	–6.3951	29.0	–6.1404
32.0	–9.6204	32.0	–6.3529	38.0	–6.0615
40.0	–9.5071	40.0	–6.2913	48.0	–5.9535

Thermistor

- very sensitive resistor to a change in T

$$R = R_0 \cdot e^{\beta \frac{T_0 - T}{T \cdot T_0}}$$





Infrared Temperature Sensor

- measures blackbody radiation (generally infrared) emitted from objects
- operation:
  - lens to focus the infrared energy
  - converts energy to electrical signal
  - compensate for ambient temperature variation
- special care needed when object is:
  - moving
  - in electromagnetic field (induction heating)
  - in vacuum or other controlled atmosphere
  - or in applications where a fast response is required

Infrared Temperature Sensor

- some applications:
  - clouds detection for remote telescope operation
  - material monitoring in processes
  - hot spots measurements:
  - mechanical equipment
  - circuit breakers
  - heaters and ovens
  - fire fighting situations

Industry Considerations

- repeatability often is more important then absolute accuracy
- good linearity and low hysteresis
- temperature compensators must be used
- power supply variations reduce performance

Motion Sensors

- Measure:
  - location
  - altitude
  - speed
  - flow
  - acceleration
  - angular rate
- Major Sensors
  - gyroscopes
  - accelerometers
  - tilt sensors
- Accessories
  - signal processors
  - pressure sensors
  - temperature sensors

Other Sensors

- Biosensors
  - tissue, microorganisms, organelles, cell receptors, enzymes, antibodies, nucleic acids, etc.
  - biomimic: biological derived material
- Nano-Sensors
  - point sensors: identify nano-particles
  - future: nano-robots, nano-computers
  - what exists now: biological sensors:
  - example: particle mass detection (Georgia Tech)
    - attach a single particle onto the end of a carbon nanotube
    - measure the vibrational frequency with and without it

Sensors Specifications

- Dynamic Range
  - min and max range of the measured physical quantity
  - min and max range for electric output
- Linearity
- Sensitivity, Resolution, or Accuracy
- Power Requirements
  - Passive vs. Active
  - Power Consumption
- Bandwidth (response time)
- Calibration Procedure
- Physical Dimensions and Weight
- Reliability, Environmental Effects