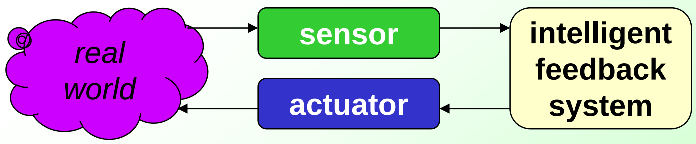
Chapter 2: Sensors

- Topics
  - Displacement Measurement
    - Resistive Sensors
      - Whetstone Bridge Circuits
    - Inductive Sensors
    - Capacitive Sensors
    - Piezoelectric Sensors
  - Temperature Measurement
    - Temperature Sensors
  - Optical Measurements
    - Light Sensors
  - Solid-State Sensors
  - MEMS Sensors
  - Sensor Calibration

Transducers

- Transducer
  - a device that converts a primary form of energy into a corresponding signal with a different energy form
    - Primary Energy Forms: mechanical, thermal, electromagnetic, optical, chemical, etc.
  - take form of a **sensor** or an **actuator**
- Sensor (e.g., thermometer)
  - a device that detects/measures a signal or stimulus
  - acquires information from the "real world"
- Actuator (e.g., heater)
  - a device that generates a signal or stimulus

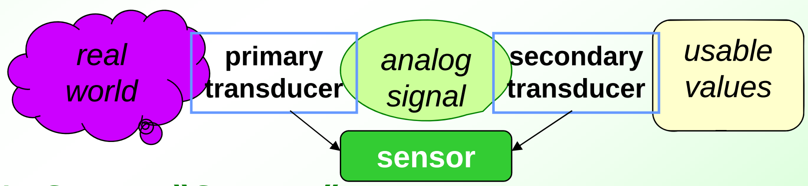


Sensor Systems

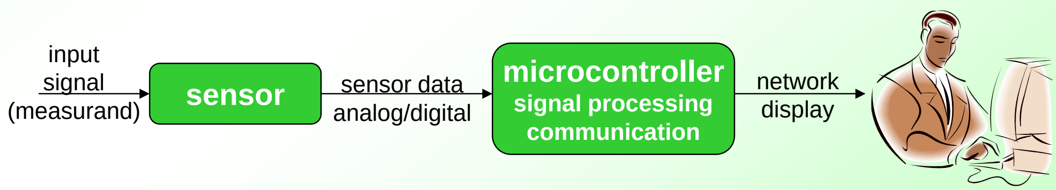
Typically interested in ***electronic sensor***

- convert desired parameter into electrically measurable signal

- General Electronic Sensor
  - primary transducer: changes "real world" parameter into electrical signal
  - secondary transducer: converts electrical signal into analog or digital values

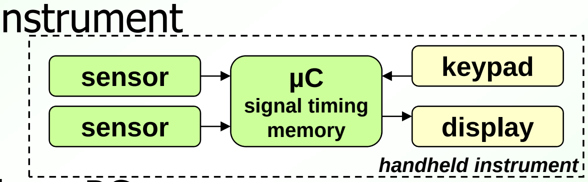


- Typical Electronic Sensor "System"

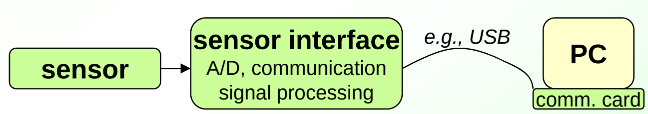


Example Electronic Sensor Systems

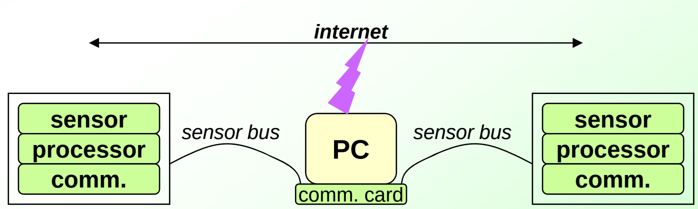
- Components vary with application
  - digital sensor within an instrument
    - microcontroller
      - signal timing
      - data storage



  - analog sensor analyzed by a PC



  - multiple sensors displayed over internet



Primary Transducers

- Conventional Transducers
  large, but generally reliable, based on older technology
  - thermocouple: temperature difference
  - compass (magnetic): direction
- Microelectronic Sensors
  millimeter sized, highly sensitive, less robust
  - photodiode/phototransistor: photon energy (light)
    - infrared detectors, proximity/intrusion alarms
  - piezoresisitve pressure sensor: air/fluid pressure
  - microaccelerometers: vibration, Δ-velocity (car crash)
  - chemical senors: O_2, CO_2, Cl, Nitrates (explosives)
  - DNA arrays: match DNA sequences

Direct vs. Indirect Measurement

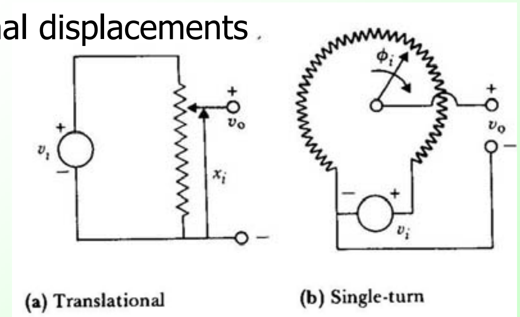
- Direct Measurement:
  - When sensor *directly* measures parameter of interest
  - Example, displacement sensor measuring diameter of blood vessel
  - Example, ??
- Indirect Measurement:
  - When sensor measures a parameter that can be translated into the parameter of interest
  - Example, displacement sensor measuring movement of a microphone diaphragm to quantify liquid movement through the heart
  - Example, ??

Displacement Measurements

- Many biomedical parameters rely on measurements of size, shape, and position of organs, tissue, etc.
  - require displacement sensors
- Examples
  - (direct) diameter of blood vessel
  - (indirect) movement of a microphone diaphragm to quantify liquid movement through the heart
- Primary Transducer Types
  - Resistive Sensors (Potentiometers & Strain Gages)
  - Inductive Sensors
  - Capacitive Sensors
  - Piezoelectric Sensors
- Secondary Transducers
  - Wheatstone Bridge
  - Amplifiers (next chapter)

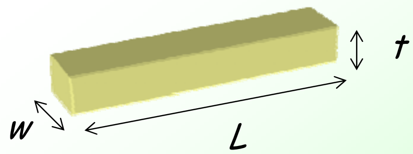
Potentiometer

- Potentiometers produce output potential (voltage) change in response to input (e.g., displacement) changes
  - 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 (10-50º) rotational displacements
    - v_o increases as ϕ_i increases



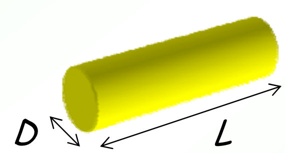
Strain Gage: Basics

- Consider: strain (stretch) a thin wire (~25μm)
  - 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
  - $R_{line} = \frac{L}{\sigma A} = \frac{\rho L}{A}$
    - $A = wt$
    - ρ = resistivity, σ = conductivity
- Thus
  - $\Delta R/R = \Delta L/L - \Delta A/A + \Delta\rho/\rho$



Strain Gage: Gage Factor

- Remember: for a strained thin wire
  - $\Delta R/R = \Delta L/L - \Delta A/A + \Delta\rho/\rho$
    - $A = \pi (D/2)^2$, for circular wire



- Poisson's ratio, μ: relates change in diameter D to change in length L
  - $\Delta D/D = -\mu\, \Delta L/L$
- Thus
  - $\Delta R/R = (1+2\mu)\, \Delta L/L + \Delta\rho/\rho$

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

Strain Gage: Materials

material	gage factor, G	TCR (10^{-5})
Ni_{80} Cr_{20}	2.1 - 2.6	10
Pt_{92} W_8	3.6 – 4.4	24
Silicon (*n* type)	-100 to -140	70 to 700
Germanium (*p* type)	102	

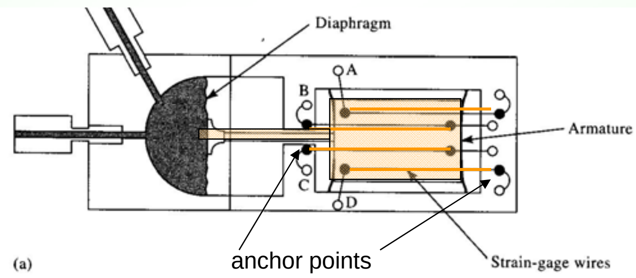
TCR = temperature coefficient of resistivity ($^oC^{-1}$)

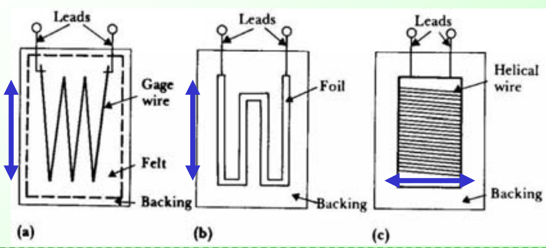
- Note:
  - G for semiconductor materials ~ 50-70 x that of metals
    - due to stronger piezoresistive effect
  - semiconductors have much higher TCR
    - requires temperature compensation in strain gage

Strain Gage

- Unbonded strain gage: end points are anchored but material between end points is unbonded
- Bonded strain gage: material is cemented to strained surface

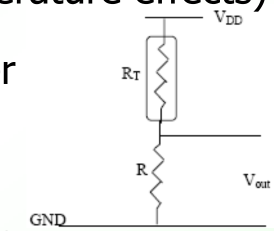
- Unbonded strain gage
  - diaphragm pressure ⇑
    - strain @ B & C ⇑
    - strain @ A & D ⇓
- Bonded strain gage
  - (a) resistive wire
  - (b) foil type
  - (c) helical wire
  - temperature compensation
    - unbonded 'dummy' strain gage
  - direction of max sensitivity ?

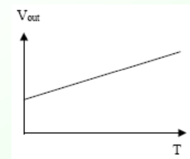




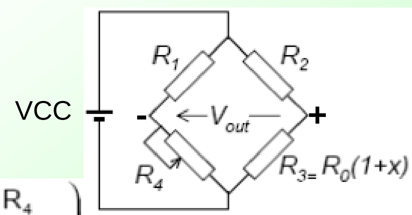
Wheatstone Bridge

- Wheatstone bridge is a configuration variable and fixed elements used to monitor small variations in the elements (and optionally compensate for temperature effects)
- Consider first: resistive voltage divider
  - V_{out} varies as R_T changes
  - readout method for 1 element sensor





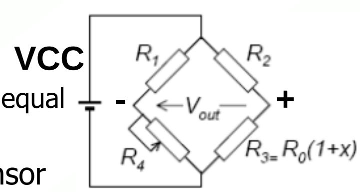
- 1 variable/sensor element bridge configuration
  - R_3 is sensor element
  - R_4 set to match nominal value of R_3
  - If $R_1 = R_2$, $V_{out\text{-}nominal} = 0$
  - V_{out} varies as R_3 changes



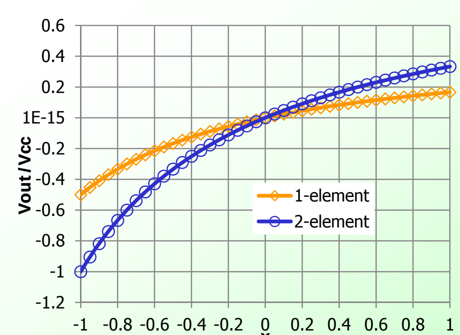
$$V_{out} = V_{CC}\left(\frac{R_3}{R_2 + R_3} - \frac{R_4}{R_1 + R_4}\right)$$

Wheatstone Bridge

- Balanced bridge → Vout = 0
  - occurs when R1/R2 = R4/R3
    - which is also R1/R4 = R2/R3 → mid-node voltages must be equal



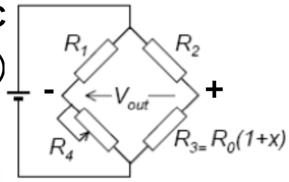
- Single element sensor
  - R3 = Ro (1+x), x = factional change in resistance of sensor
  - if R1 = R4 → V_{out}- = VCC/2
  - if R2 = Ro → V_{out}+ = VCC (Ro(1+x) / Ro(2+x))
    - Vout+ = VCC((1+x) / (2+x))
      - Vout+ increases as x increases
      - Vout+ = VCC/2 when x=0, =VCC when x=∝
    - Vout- is same, only Vout+ increases with x
    - Vout = VCC ((1+x)/(2+x) – 1/2)



- Two element (half bridge)
  - R1 & R3 increases/decrease together
  - if R2=R4=Ro and R1=R3=Ro(1+x)
    - Vout- = VCC/(2+x), Vout+ = VCC((1+x) / (2+x)) → Vout = VCC (x/(2+x))
    - increasing positive values of x cause Vout to become more positive

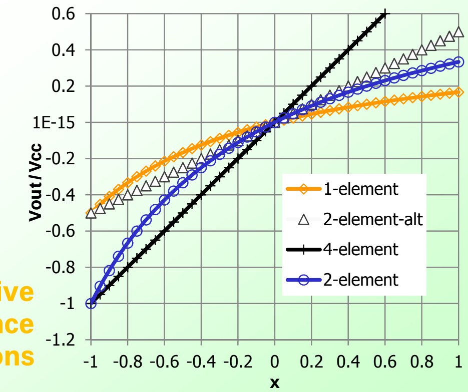
Wheatstone Bridge

- Two element (half bridge); alternative
  - R1=R4, R3 increases when R2 decreases (and visa versa)
  - if R1=R4=Ro, R3=Ro(1+x) and R2=Ro(1-x)
    - Vout- = VCC/2
    - Vout+ = VCC ((1+x)/2)
    - → Vout = VCC ((1+x)/2 – 1/2)
    - increasing positive values of x cause Vout to become more positive



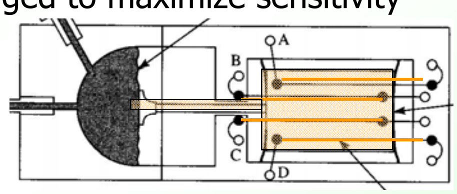
- Four element full bridge
  - R1 & R3 increases/decrease together
  - R2 & R4 decrease/increase together
    - change opposite of R1 & R3
  - if R1=R3=Ro(1+x) and R2=R4=Ro(1-x)
    - Vout+ = ??
    - Vout- = ??
    - Vout = ??

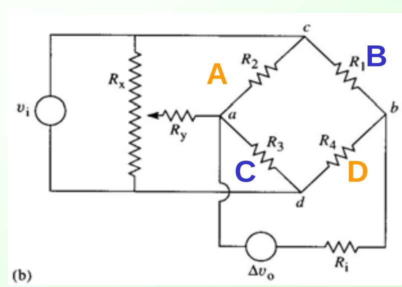
discuss relative performance of configurations



Wheatstone Bridge

- Full bridge configuration
  - all bridge elements are variable (sensors)
  - increasing & decreasing elements arranged to maximize sensitivity
  - Example: unbounded strain gage
    - B and C operate together
    - A and D operate together
    - Ry and Rx used to balance the bridge
    - output Δv_o
      - Ri voltmeter internal resistance

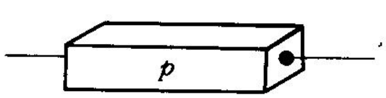




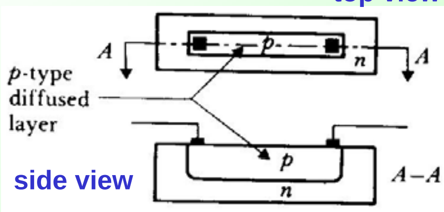
- Temperature Compensation
  - When all R's from same material
    - TCR of all elements cancel
    - change in temperature → no change in output voltage

Semiconductor Strain Gage

- Semiconductors
  - make highly sensitive strain gages
    - have higher gage factors than metals/alloys
  - more temperature sensitive than metals/alloys
  - less linear than metals/alloys
- Semiconductor strain gage options
  - bulk semiconductor material
    - p-type: positive gage factor
    - n-type: negative gage factor
    - lightly doped material gives high gage factor
  - diffused/doped semiconductor



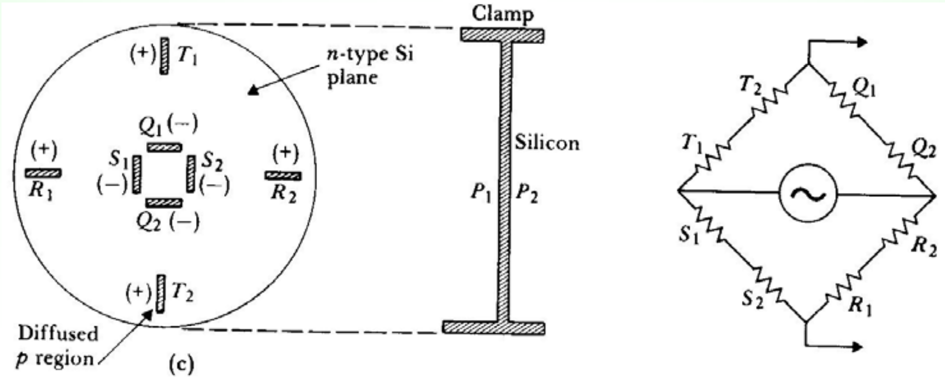
top view



side view

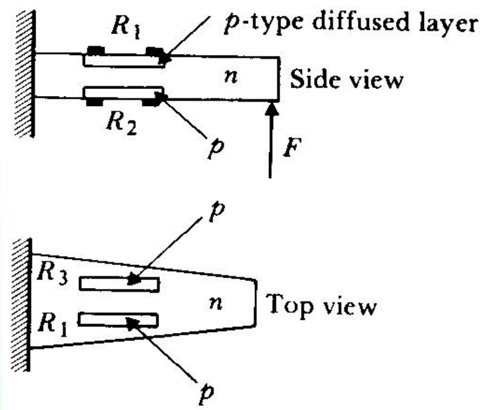
Semiconductor Strain Gage

- Integrated planer multi-element strain gage
  - Example: diaphragm pressure sensor
    - strain gage (resistors) integrated into the surface
  - when pressure is applied, diaphragm bends
    - outer strain gages stretch and inner gages compress
  - Wheatstone bridge configuration
    - high sensitivity & good temperature compensation



Semiconductor Strain Gage

- Cantilever-beam force sensor
  - 2 piezoresistors in top and two in bottom of a semiconductor beam
  - when force F is applied
    - R1 & R3 (on top) are compressed
    - R2 & R4 (on bottom) are stretched
  - can be read out with Wheatstone bridge



Pressure Sensor: Biomedical Application

- Disposable blood-pressure sensor

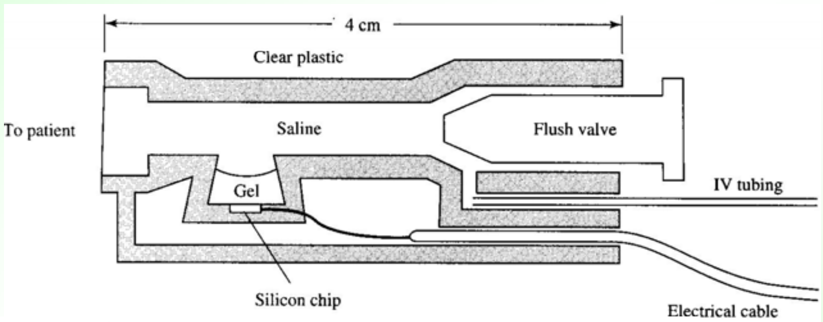
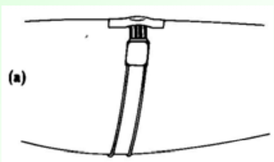


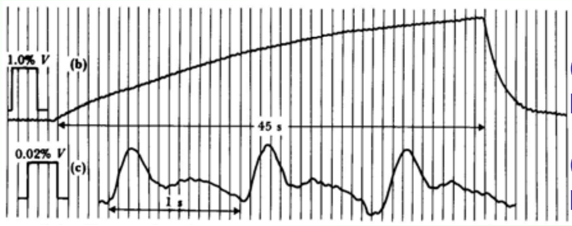
Figure 14.15 Isolation in a disposable blood-pressure sensor Disposable blood pressure sensors are made of clear plastic so air bubbles are easily seen. Saline flows from an intravenous (IV) bag through the clear IV tubing and the sensor to the patient. This flushes blood out of the tip of the indwelling catheter to prevent clotting. A lever can open or close the flush valve. The silicon chip has a silicon diaphragm with a four-resistor Wheatstone bridge diffused into it. Its electrical connections are protected from the saline by a compliant silicone elastomer gel, which also provides electrical isolation. This prevents electric shock from the sensor to the patient and prevents destructive currents during defibrillation from the patient to the silicon chip.

Biomedical Applications of Strain Gages

- Extensively used in cardiovascular and respiratory measurments
  - dimensional determinations
  - plethysmographic (volume-measuring) determinations



strain gage on human calf



bridge output

(b) venous-occlusion plethysmography

(c) arterial-pulse plethysmography

- Other stuff to know
  - elastic strain gage is typically linear with 1% for 10% of maximal extension
  - thus, strain gages are only good measuring small displacements

Inductive Displacement Sensors

- Inductance, $L = n^2 G \mu$
  - n = number of turns in coil
  - G = geometric form factor
  - μ = effective permeability of the medium
- Varying any of these 3 parameters can be used to measure displacement of a magnetic core

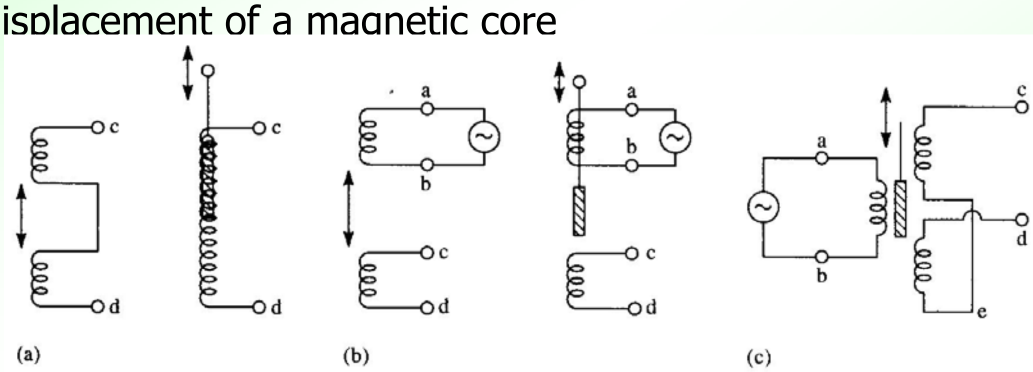
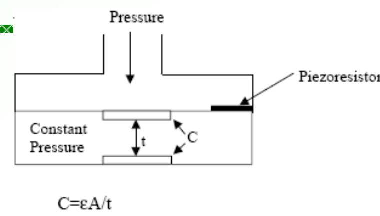
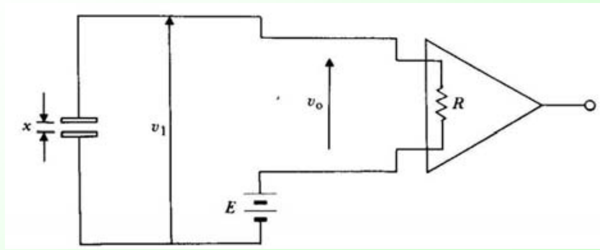


Figure 2.6 Inductive displacement sensors (a) Self-inductance. (b) Mutual inductance. (c) Differential transformer.

Capacitive Sensors

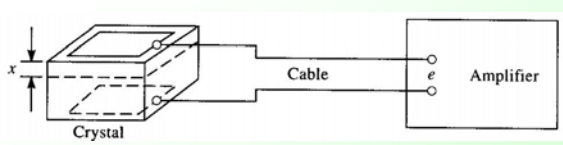


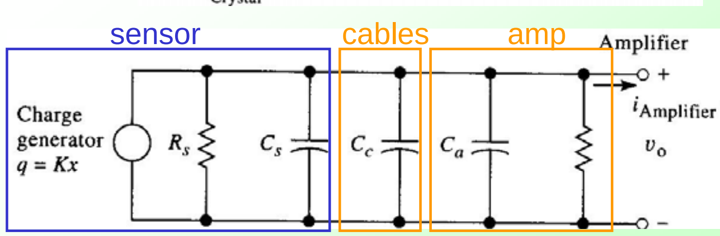
- Capacitance, $C = \varepsilon A/x$
  - ε = dielectric constant
  - A = area of capacitor plate
  - x = plate separation distance
- Generally, displacement sensors rely on changes in x
- Sensitivity, K, to Δx is $K = \varepsilon A/x^2$
  - higher sensitivity for devices with smaller separation
    - motivation of microsensors
- Many methods for capacitance readout
  - switched capacitor amplifier
    - may cover later
  - example: dc-excited circuit
    - when capacitor stationary
      - no current through C → V1 = E
    - when Δx → ΔC, Vo = V1 - E



Piezoelectric Sensors

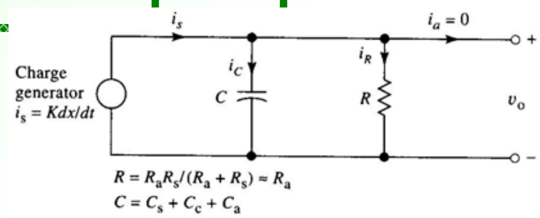
- Piezoelectric materials generate electric potential when mechanically strained or visa versa
- Used to measure physiological displacements and record heart sounds
- Modes of operation
  - thickness (longitudinal) compression
  - transversal compression
  - thickness-shear action
  - face-shear action
- Equivalent circuit model
  - deflection x → charge q
    - K = constant



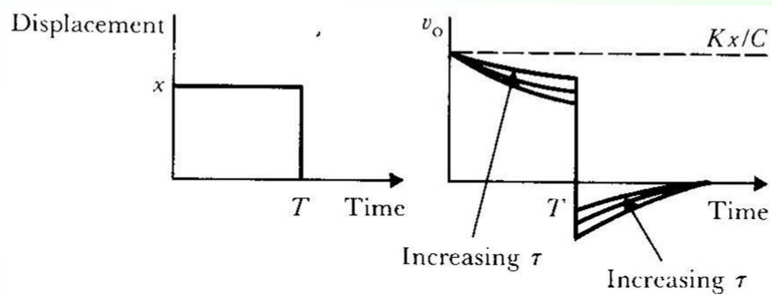


Piezoelectric Sensors: step response

- Simplified circuit model
  - combined C's and R's
  - replace charge gen. with current



- Step response for displace x at time T
  - exponential decay due to leakage through internal resistance
    - note: piezoelectric devices have ~1G-ohm internal resistances
  - decay and undershoot can be reduced by increasing RC time constant



Temperature Measurement

- Temperature is extremely important to human physiology
  - example: low temperature can indicate onset of problems, e.g., stroke
  - example: high temperature can indicate infection
- Temperature sensitive enzymes and proteins can be destroyed by adverse temperatures
- Temperature measurement and regulation is critical in many treatment plans

Temperature Sensor Options

- **Thermoelectric Devices**
  - most common type is called ***Thermocouple***
  - can be made small enough to place inside catheters or hypodermic needles
- **Resistance Temperature Detectors** (RTDs)
  - metal resistance changes with temperature $R_T = R_0[1+\alpha_1 T + \alpha_2 T^2 + \cdots \alpha_n T^n +] \cong R_0[1+\alpha_1 T]$
  - Platinum, Nickel, Copper metals are typically used
  - positive temperature coefficients
- **Thermistors** ("thermally sensitive resistor")
  - formed from semiconductor materials, not metals $R_T = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$
    - often composite of a ceramic and a metallic oxide (Mn, Co, Cu or Fe)
  - typically have negative temperature coefficients
- **Radiant Temperature Sensors**
  - photon energy changes with temperature
  - measured optically (by photo detector)
- **Integrated Circuit** (IC) **Temperature Sensors**
  - various temperature effects in silicon manipulated by circuits
  - proportional to absolute temperature (PTAT) circuit: Si bandgap = *f*(Temp)

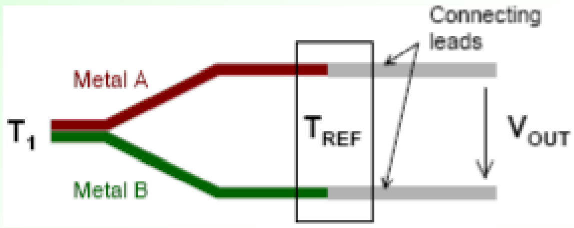
Temperature Sensor Options

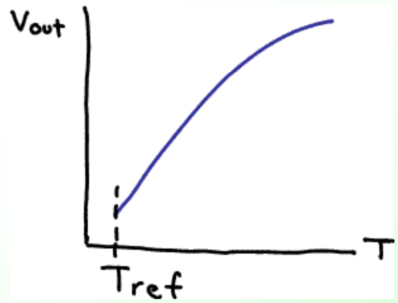
- Comparison of common temperature sensors

	THERMOCOUPLES	RTD	IC
ACCURACY	Limits of error wider than RTD or IC Sensor	Better accuracy than thermocouple	Best accuracy
RUGGEDNESS	Excellent	Sensitive to strain and shock	Sensitive to shock
TEMPERATURE	-400 to 4200° F	-200 to 1475° F	-70 to 300° F
DRIFT	Higher than RTD	Lower than TC	
LINEARITY	Very non-linear	Slightly non-linear	Very linear
RESPONSE	Fast dependent on size	Slow due to thermal mass	Faster than RTD
COST	Rather inexpensive except for noble metals TCs, which are very expensive	More expensive	Low cost

Thermocouples

- Seebeck-Peltier Effect
  - dissimilar metals at diff. temps. → signal
  - electromotive force (emf) is established by the contact of two dissimilar metals at different temperatures

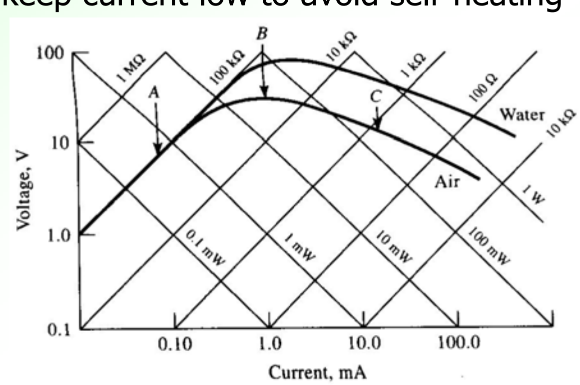


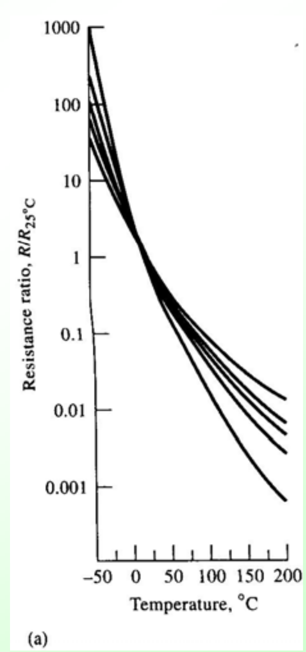


- Thermocouple features:
  - rugged and good for very high temperatures
  - not as accurate as other Temp sensors (also non-linear and drift)

Thermistors

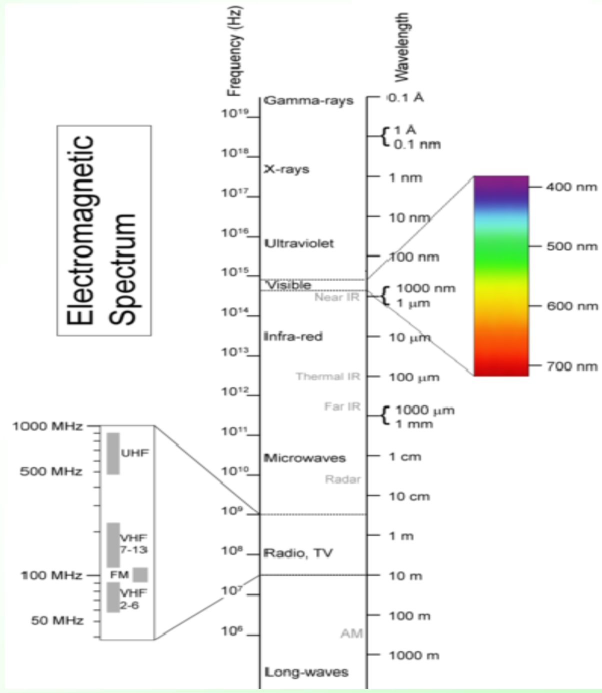
- Heavily used in biomedical applications
  - base resistivity: 0.1 to 100 ohm-meters
  - can be made very small, ~500um diameter
  - large sensitivity to temperature (3-4% / ºC)
  - excellent long-term stability
- Resistance vs. temperature
  - keep current low to avoid self-heating





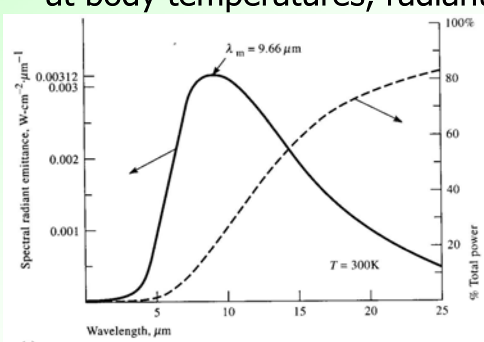
Electromagnetic Radiation Spectrum

- Visible light wavelength
  - ~400-700nm
- Shorter wavelengths
  - ultraviolet, ~100nm
  - x-ray, ~1nm
  - gamma rays, ~0.1nm (=1Å)
- Longer wavelengths
  - infrared IR: broad spectrum
    - near IR, ~1000nm = 1μm
    - thermal IR, ~100μm
    - far IR, ~1mm
  - microwave, ~1cm
  - radar, ~1-10cm
  - TV & FM radio, ~1m
  - AM radio, ~100m

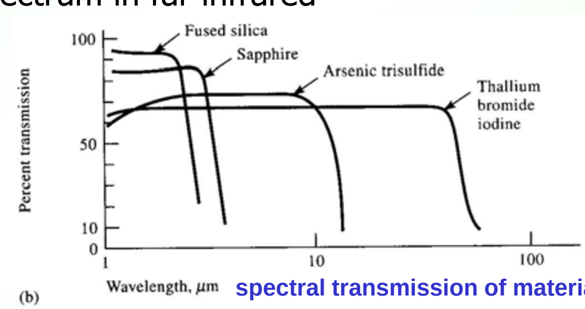


Radiation Thermometry

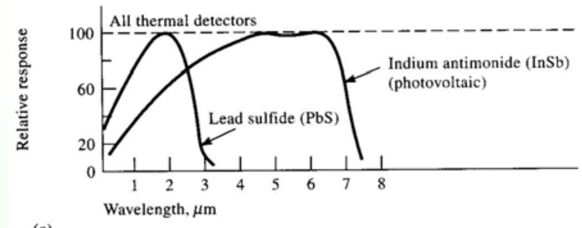
- Radiant power of an object is related to its temperature
  - makes it possible to measure temperature without physical contact
  - at body temperatures, radiant spectrum in far infrared



spectral radiant emittance & % of total energy



spectral transmission of materials



spectral sensitivity of photon and thermal detectors

infrared spectrum: ~0.7 to 300 μm

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Human Temperature Measurement

- Radiation thermometry is good for determining internal (core body) temperature
  - measures magnitude of infrared radiation from tympanic membrane & surrounding ear canal
    - tympanic membrane is perfused by the same vasculature as the hypothalamus, the body's main thermostat
  - advantages over thermometers, thermocouples or thermistors
    - does not need to make contact to set temperature of the sensor
    - fast response time, ~0.1sec
    - accuracy ~ 0.1ºC
    - independent of user technique or patient activity
  - requires calibration target to maintain accuracy

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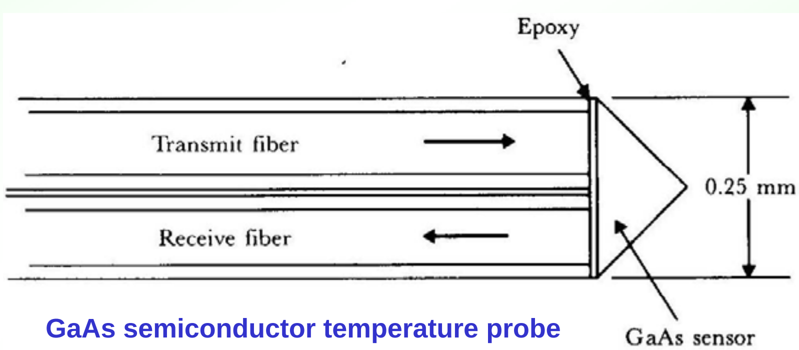
Fiber-optic Temperature Sensor

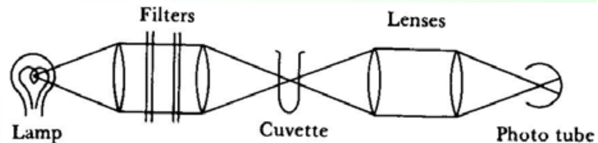
- Sensor operation
  - small prism-shaped sample of single-crystal undoped GaAs attached to ends of two optical fibers
  - light energy absorbed by the GaAs crystal depends on temperature
  - percentage of received vs. transmitted energy is a function of temperature
- Can be made small enough for biological implantation



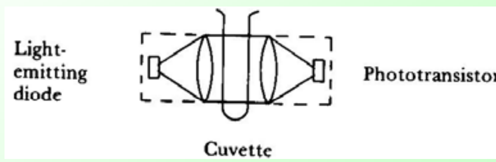
GaAs semiconductor temperature probe

Optical Measurement

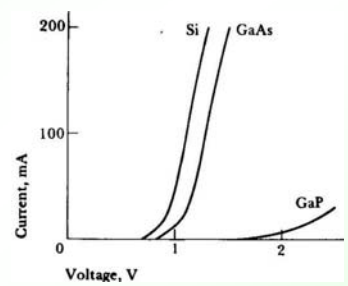
- Widely used in medical diagnosis
  - clinical-chemistry lab: blood and tissue analysis
  - cardiac catheterization: measure oxygen saturation of hemoglobin
- Optical system components
  - source
  - filter
  - detector
- Conventional optical system



- Solid-state (semiconductor) optical system
  - miniaturize and simplify



Optical/Radiation Sources



forward biased diodes

- Tungsten lamp
  - very common radiation source
  - emissivity is function of wavelength, λ
    - ~40% for $\lambda < 1\mu m$ (1000nm)
  - output varies significantly with temperature
    - note 2000K and 3000K spectra on next slide
    - higher temperature shortens life of lamp filament
- Arc discharge lamps
  - fluorescent lamps filled with, e.g., carbon, mercury, sodium, xenon
  - more compact w/ high output per unit area
- Light emitting diodes (LED)
  - silicon band gap ~1.1eV not very efficient for detection
  - GaAs, higher energy (lower wavelength), fast (~10ns) switching
  - GaP & GaAsP have even higher energy
- LASER
  - common lasers: He-Ne, Argon (high power, visual spectrum), CO_2
  - semiconductor laser not preferred; energy too low (infrared)
  - lasers also used to mend tears, e.g., in retina

Example Spectrum

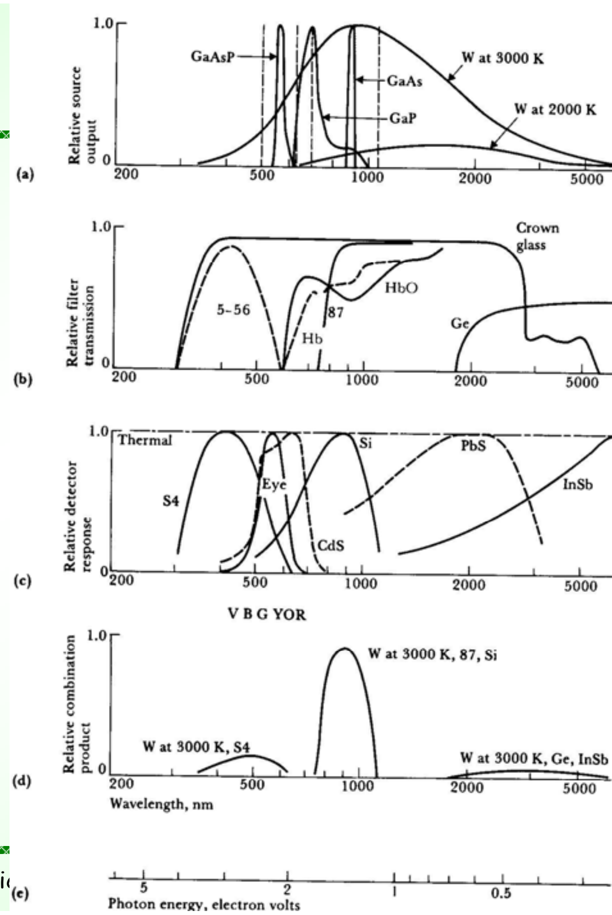
(a) source spectrum

(b) filter spectrum

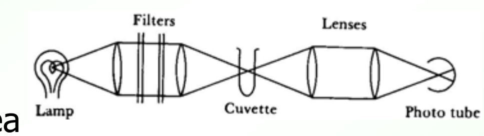
(c) detector response
- eye
- S4 phototube
- Si p-n junction

(d) combined response

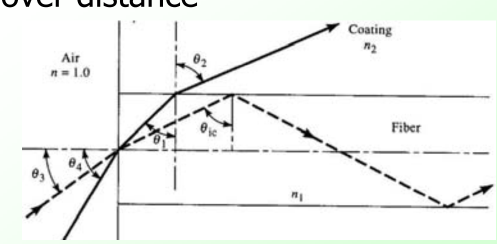
(e) energy
- less than 1eV too weak to measure



Optical Transmitter & Filters



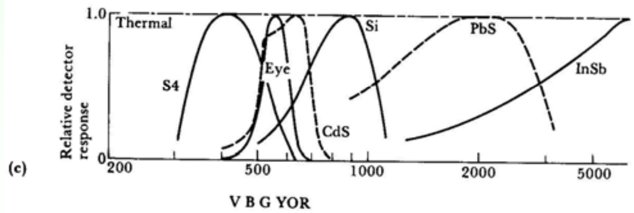
- Geometrical Optics: Lenses
  - focus energy from source into smaller area
  - placed to collimate radiation (rays are parallel)
  - focus energy from target into detector
- Fiber Optics
  - efficient transmission of optical signals over distance
  - example medical application:
    - endoscope



- Filters
  - control transmitted power
  - determine wavelengths (colors) transmitted
  - produce wavelength spectrum (diffraction grating)

Radiation Sensors

- Spectral response
  - Si, no response above 1100nm
  - special materials (InSb)
    - monitor skin radiation (300K)
- Thermal sensors
  - transforms radiation into heat
  - flat spectral response but slow
  - subject to error from changes in ambient temperature
  - example thermal sensors: thermistors, thermocouples
- Quantum sensors
  - transform photon energy into electron release
  - sensitive over a limited spectrum of wavelengths
  - example quantum sensors: eye, photographic emulsion, sensors below
    - Photoemissive sensors, e.g. phototube
    - Photoconductive cells
    - Photojunction sensors
    - Photovoltaic sensors



Photoemissive Sensors

- Construction & Operation
  - photocathode coated with alkali metal
  - incoming photons (with enough energy, >1eV or 1200nm) release electrons from photocathode
  - released electrons attracted to anode and form a current proportional to incoming photon energy
- Example: phototube, like the S4 in the spectrum plots
- Photomultiplier: phototube combined with electron amplifier
  - very (the most?) sensitive photodetector
    - cooled to prevent thermal excitation of electrons
    - can count individual photons
  - fast response, ~10ns
  - compare to the eye, which can detect ~6photons within 100ms

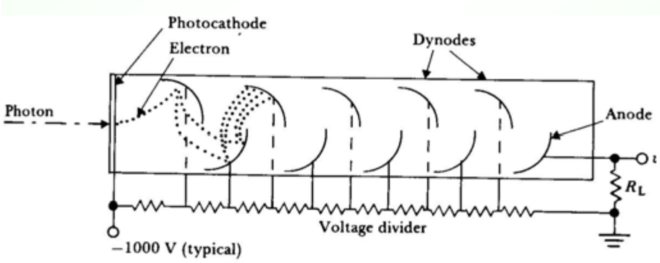
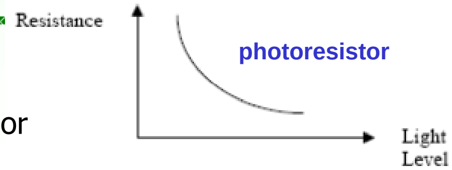
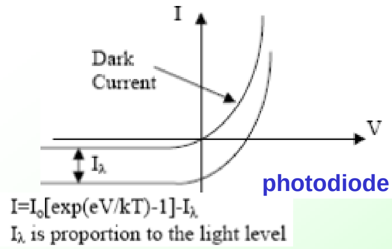


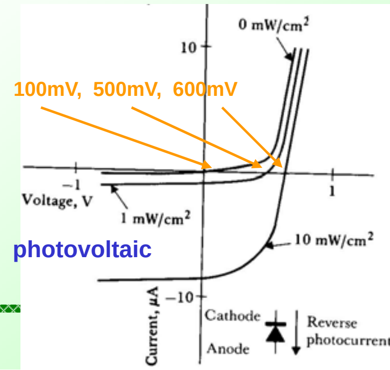
Figure 2.21 Photomultiplier An incoming photon strikes the photocathode and liberates an electron. This electron is accelerated toward the first dynode, which is 100 V more positive than the cathode. The impact liberates several electrons by secondary emission. They are accelerated toward the second dynode, which is 100 V more positive than the first dynode. This electron multiplication continues until it reaches the anode, where currents of about 1 μA flow through R_L.

Solid-State Photoelectric Sensors

- Photoconductive cells
  - photoresistor
    - photosensitive crystalline material such as CdS or PbS
    - incoming radiation causes electrons to jump band gap and produce electron-hole pairs → lower resistance
- Photojunction sensors
  - incoming radiation generates electron-hole pairs in diode depletion region
  - minimum detectable energy based on band gap of the diode substrate (e.g., Si)
  - can be used in photovoltaic mode
    - change in open-circuit voltage is monitored
- Photon coupler
  - LED-photodiode combination
    - used to isolate electrical circuits
    - prevent current from leaking out of equipment and into the heart of a patient

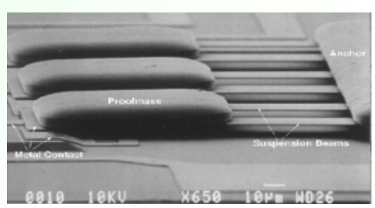


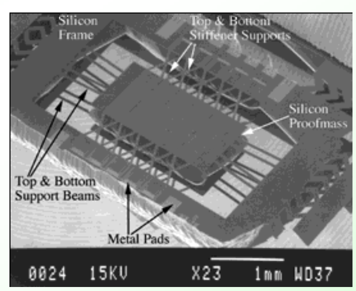




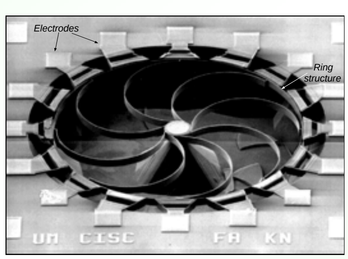
Example MEMS Transducers

- MEMS = micro-electro-mechanical system
  - miniature transducers created using IC fabrication processes
- Microaccelerometer
  - cantilever beam
  - suspended mass

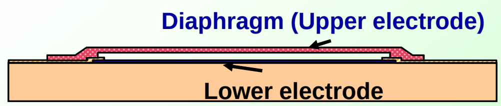


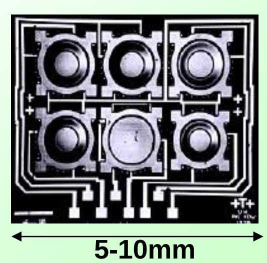


- Rotation
  - gyroscope



- Pressure





Sensor Calibration

- Sensors can exhibit non-ideal effects
  - offset: nominal output ≠ nominal parameter value
  - nonlinearity: output not linear with parameter changes
  - cross parameter sensitivity: secondary output variation with, e.g., temperature

- Calibration = adjusting output to match parameter
  - analog signal conditioning
  - look-up table
  - digital calibration
    - $T = a + bV + cV^2$,
      - T= temperature; V=sensor voltage;
      - a,b,c = calibration coefficients
- Compensation
  - remove secondary sensitivities
  - must have sensitivities characterized
  - can remove with polynomial evaluation
    - $P = a + bV + cT + dVT + e V^2$, where P=pressure, T=temperature