SENSORS
a.k.a.
Interfacing to the Real World:
Review of Electrical Sensors and Actuators

Andrew Mason

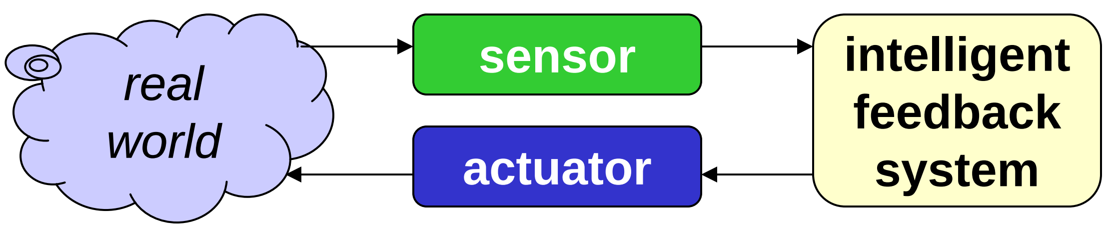
Associtate Professor, ECE

Teach: Microelectronics (analog & digital integrated Circ., VLSI)
Biomedical Engineering (instrumentation)

Research: Integrated Microsystems (on-chip sensors & circuits)

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

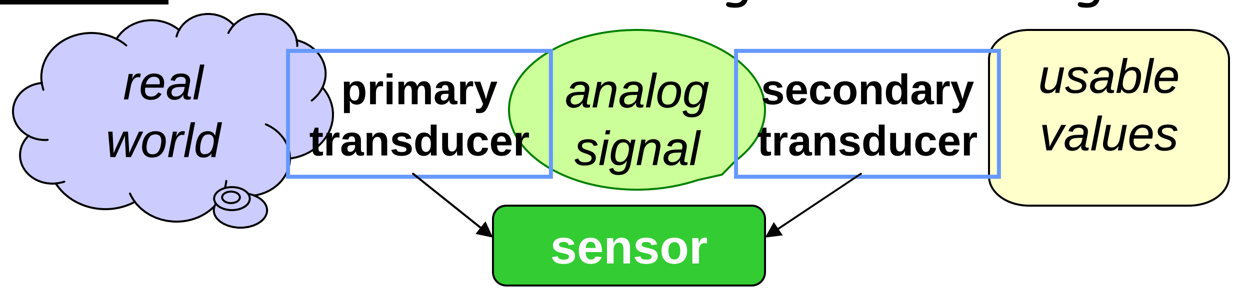


Sensor Systems

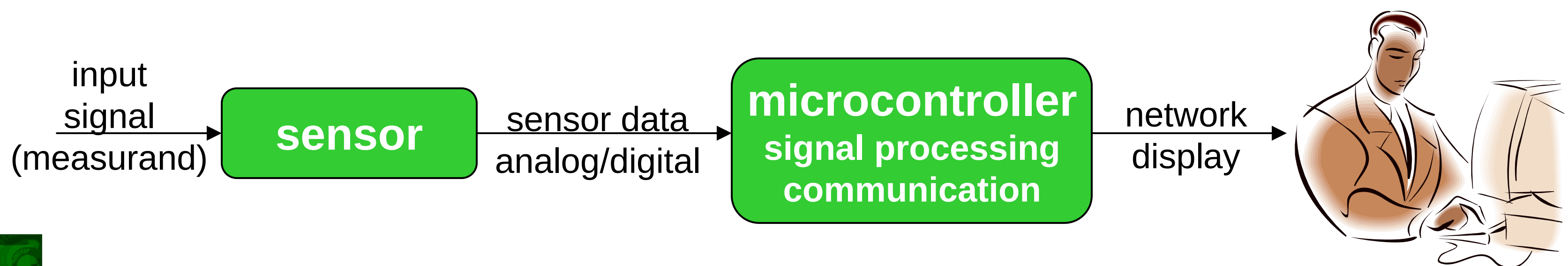
Typically interested in ***electronic sensor***

- convert desired parameter into electrically measurable signal

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

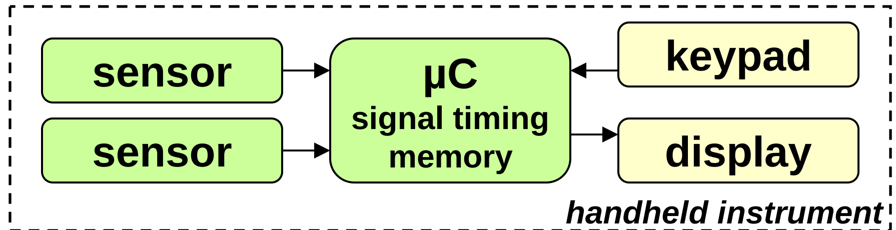


- Typical Electronic Sensor System

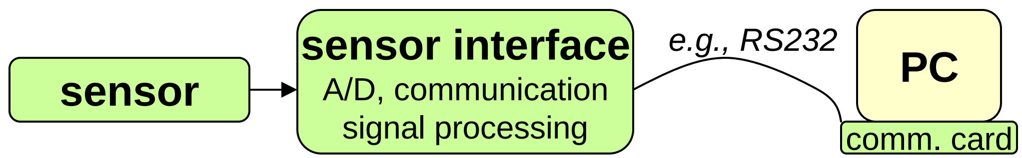


Example Electronic Sensor Systems

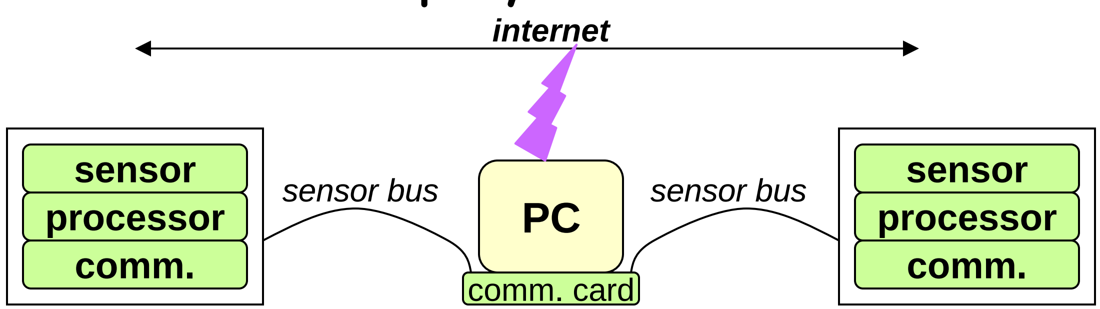
- Components vary with application
  - digital sensor within an instrument
    - microcontroller
      - signal timing
      - data storage



  - 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

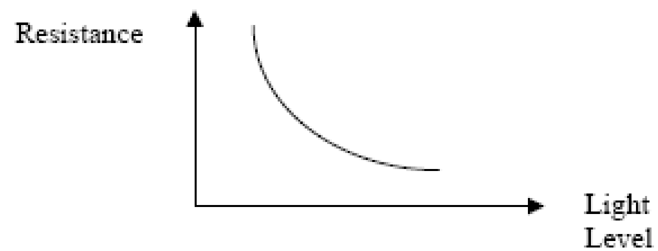
  millimeter sized, highly sensitive, less robust

  - 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

Example Primary Transducers

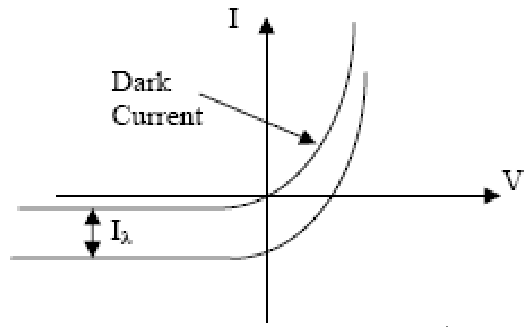
- Light Sensor
  - photoconductor
    - light → ΔR

Photoconductor: (Light sensitive semiconductor resistor)



  - photodiode
    - light → ΔI

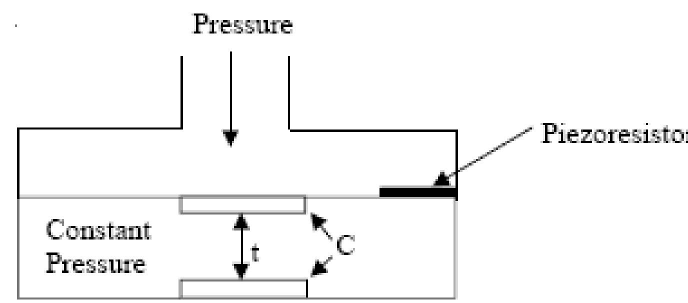
Photodiode:



$I=I_o[\exp(eV/kT)-1]-I_\lambda$

I_λ is proportion to the light level

  - membrane pressure sensor
    - resistive (pressure → Δ R)
    - capacitive (pressure → ΔC)



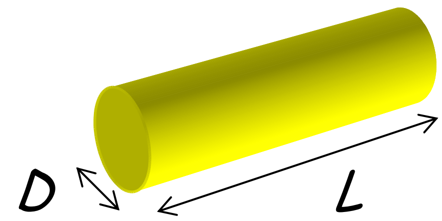
$C=\varepsilon A/t$

Displacement Measurements

- Measurements of size, shape, and position utilize displacement sensors
- Examples
  - diameter of part under stress (direct)
  - movement of a microphone diaphragm to quantify liquid movement through the heart (indirect)
- Primary Transducer Types
  - Resistive Sensors (Potentiometers & <u>Strain Gages</u>)
  - Inductive Sensors
  - Capacitive Sensors
  - Piezoelectric Sensors
- Secondary Transducers
  - Wheatstone Bridge
  - Amplifiers

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
  - $G = \dfrac{\Delta R/R}{\Delta L/L} = (1+2\mu) + \dfrac{\Delta\rho/\rho}{\Delta L/L}$

Temperature Sensor Options

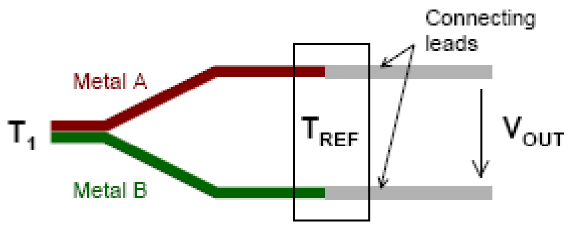
- Resistance Temperature Detectors (RTDs)
  - Platinum, Nickel, Copper metals are typically used
  - positive temperature coefficients

$$R_T = R_0[1 + \alpha_1 T + \alpha_2 T^2 + \cdots \alpha_n T^n +] \cong R_0[1 + \alpha_1 T]$$

- Thermistors ("thermally sensitive resistor")
  - formed from semiconductor materials, not metals
    - often composite of a ceramic and a metallic oxide (Mn, Co, Cu or Fe)
  - typically have negative temperature coefficients

$$R_T = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

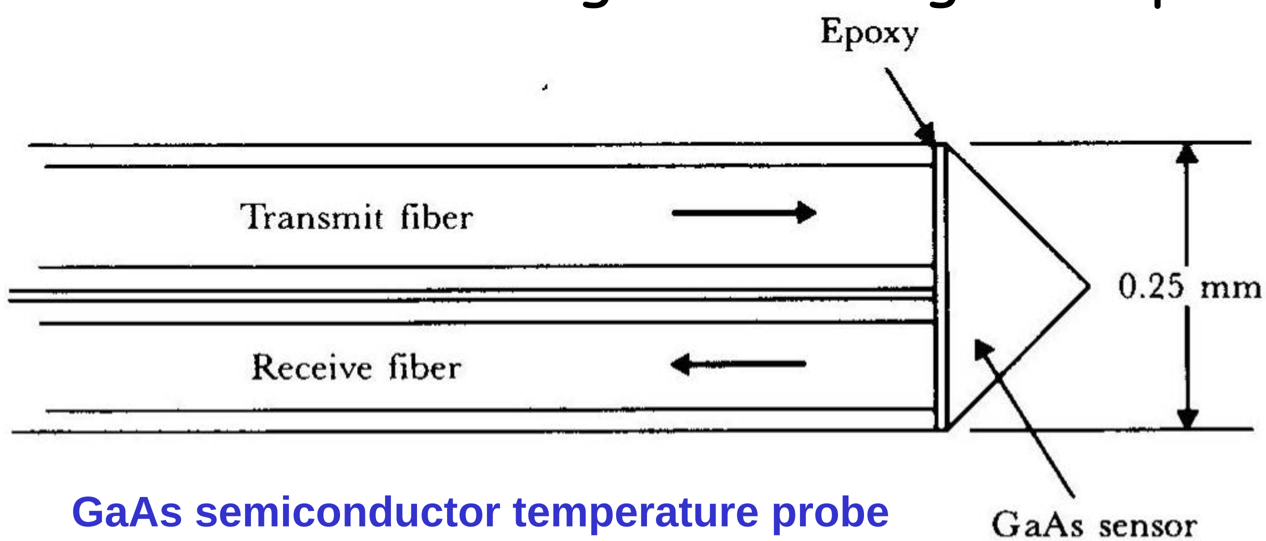
- **Thermocouples**
  - based on the Seebeck effect: dissimilar metals at diff. temps. → signal



	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

Fiber-optic Temperature Sensor

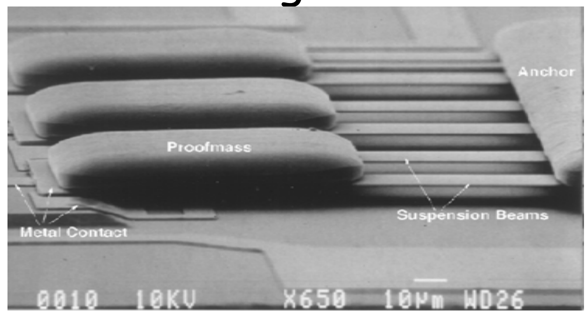
- Sensor operation
  - small prism-shaped sample of single-crystal undoped GaAs attached to ends of two optical fibers
  - light energy absorbed by the GaAs crystal depends on temperature
  - percentage of received vs. transmitted energy is a function of temperature
- Can be made small enough for biological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

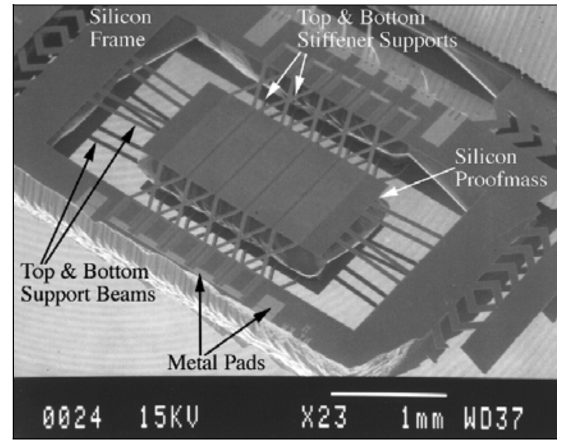


GaAs semiconductor temperature probe

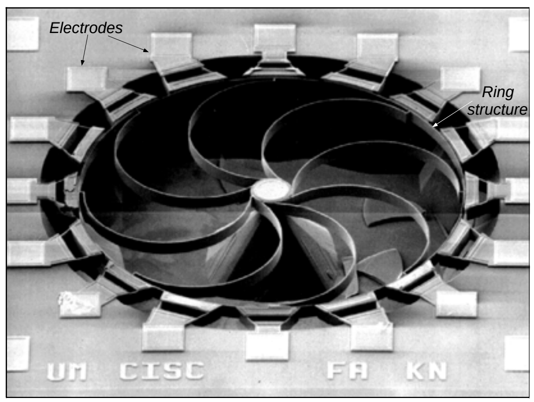
Example MEMS Transducers

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

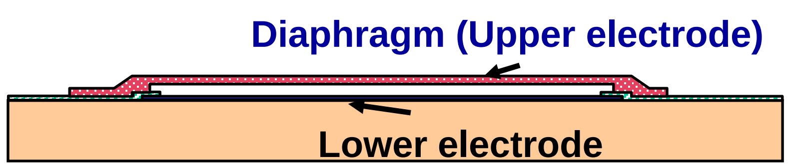


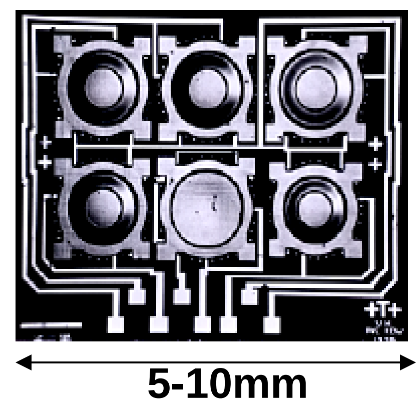


- Rotation
  - gyroscope



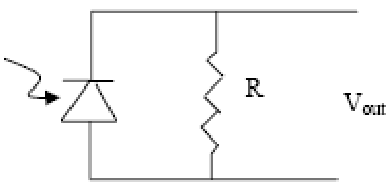
- Pressure

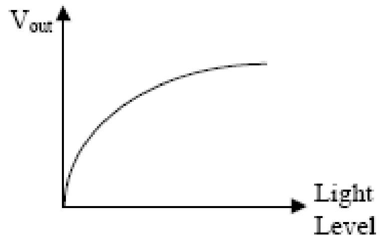


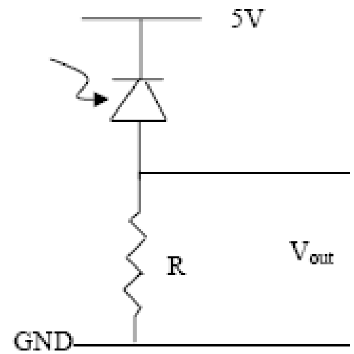


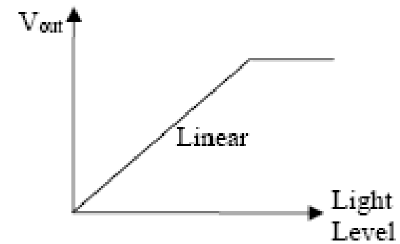
Passive Sensor Readout Circuit

- Photodiode Circuits

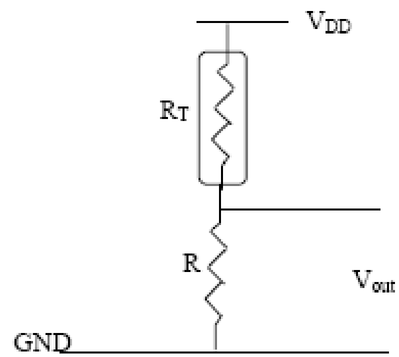


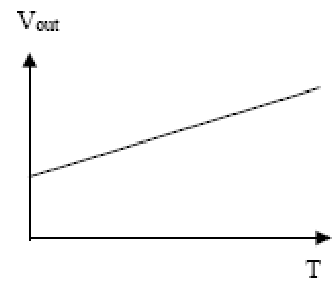






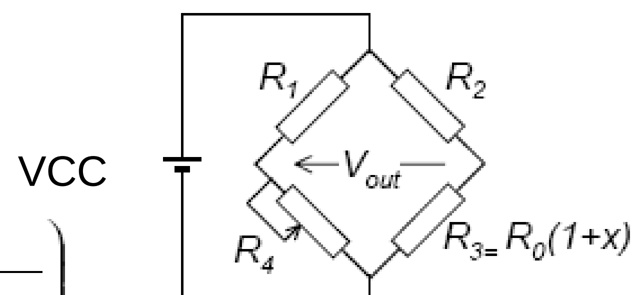
- Thermistor Half-Bridge
  - voltage divider
  - one element varies





- Wheatstone Bridge
  - R3 = resistive sensor
  - R4 is matched to nominal value of R3
  - If $R_1 = R_2$, $V_{out\text{-}nominal} = 0$
  - V_{out} varies as R_3 changes

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

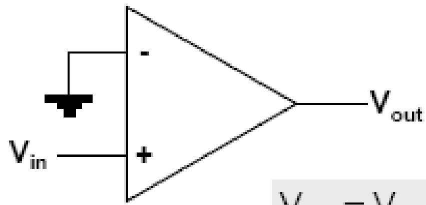


Operational Amplifiers

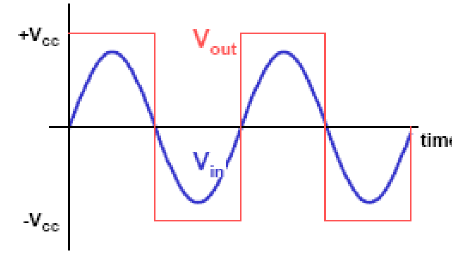
- Properties
  - open-loop gain: ideally infinite: practical values 20k-200k
    - high open-loop gain → virtual short between + and - inputs
  - input impedance: ideally infinite: CMOS opamps are close to ideal
  - output impedance: ideally zero: practical values 20-100Ω
  - zero output offset: ideally zero: practical value <1mV
  - gain-bandwidth product (GB): practical values ~MHz
    - frequency where open-loop gain drops to 1 V/V
- Commercial opamps provide many different properties
  - low noise
  - low input current
  - low power
  - high bandwidth
  - low/high supply voltage
  - special purpose: comparator, instrumentation amplifier

Basic Opamp Configuration

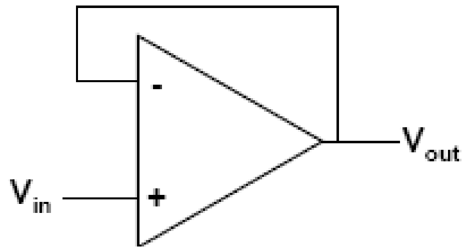
- Voltage Comparator
  - digitize input



$$V_{out} = V_{CC}\,\mathrm{sign}(V_{in})$$

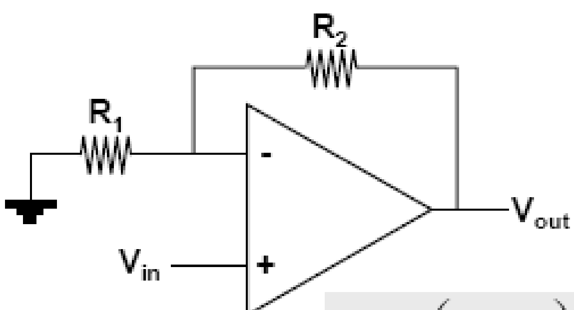


- Voltage Follower
  - buffer



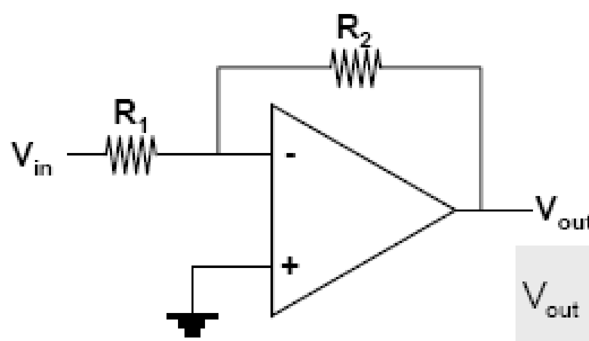
$$V_{out} = V_{in}$$

- Non-Inverting Amp



$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

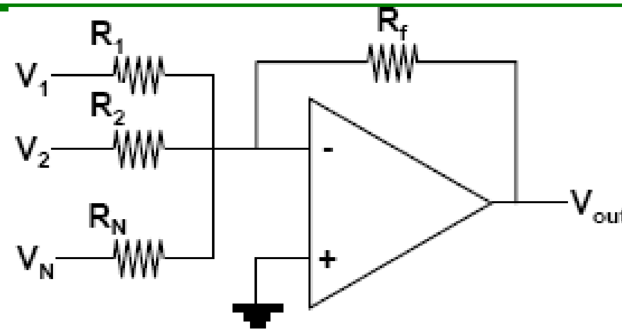
- Inverting Amp



$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

More Opamp Configurations

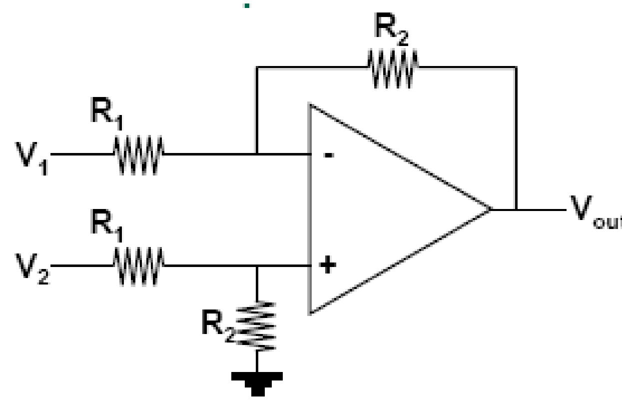
- Summing Amp



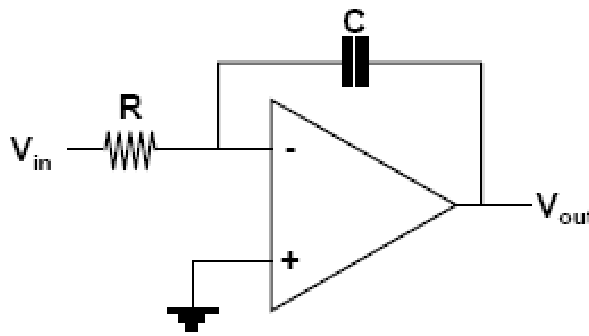
$$V_{out} = -\left(V_1\frac{R_f}{R_1} + V_2\frac{R_f}{R_2} + \cdots + V_N\frac{R_f}{R_N}\right)$$

- Differential Amp

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$



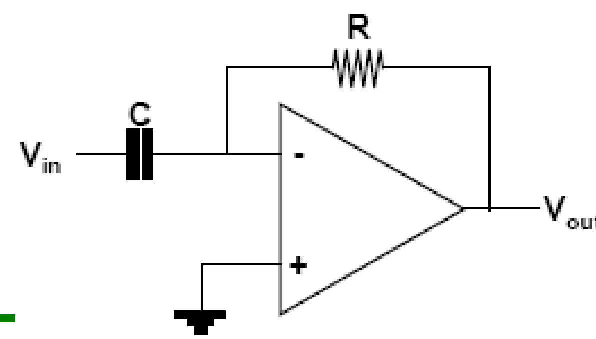
- Integrating Amp



$$V_{out} = -\frac{1}{j\omega CR}V_{in} = -\frac{1}{RC}\int V_{in}dt$$

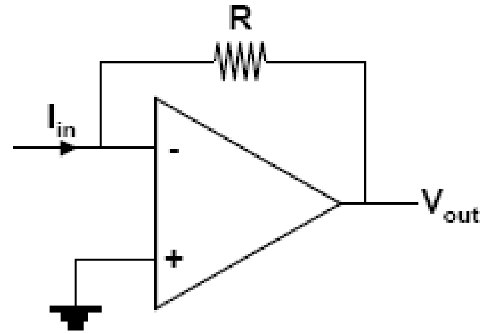
- Differentiating Amp

$$V_{out} = -\frac{R}{\frac{1}{j\omega C}}V_{in} = -RC\frac{dV_{in}}{dt}$$



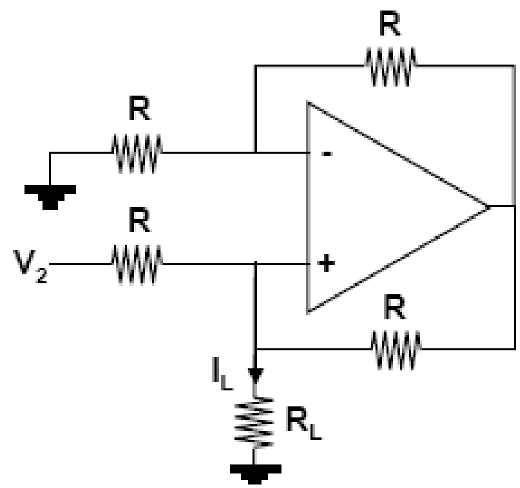
Converting Configuration

- Current-to-Voltage



$$V_{out} = -I_{in}R$$

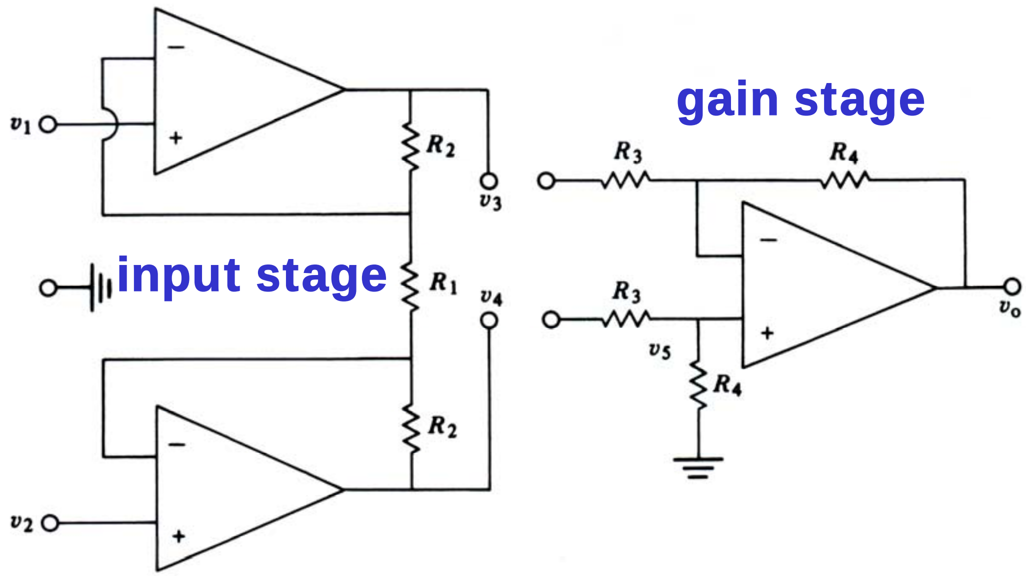
- Voltage-to-Current



$$I_L = \frac{V_{in}}{R}$$

Instrumentation Amplifier

- Robust **differential gain** amplifier

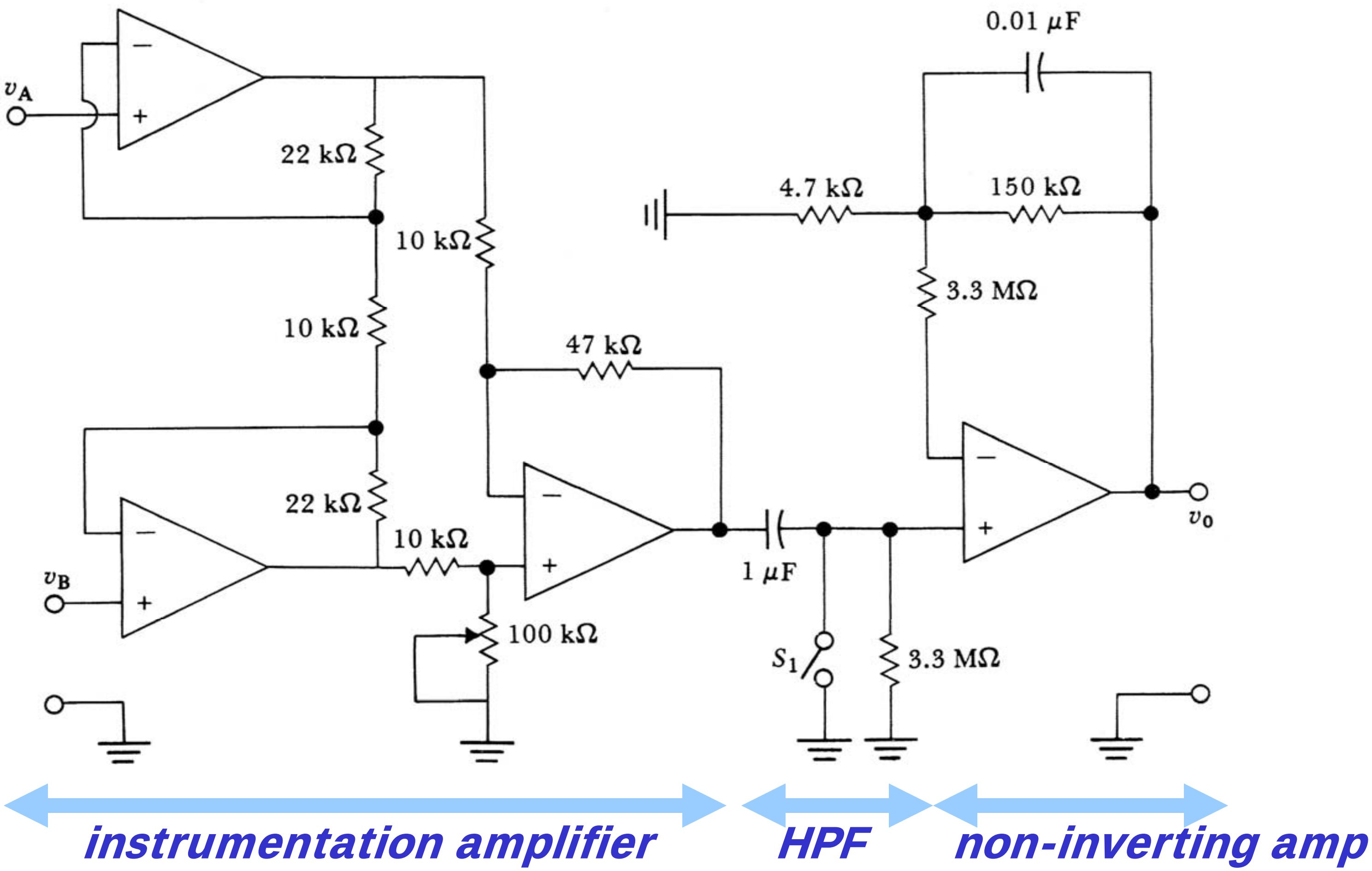


- Input stage
  - high input impedance
    - buffers gain stage
  - no common mode gain
  - can have differential gain
- Gain stage
  - differential gain, low input impedance
- Overall amplifier
  - amplifies only the differential component
    - high common mode rejection ratio
  - high input impedance suitable for biopotential electrodes with high output impedance

total differential gain

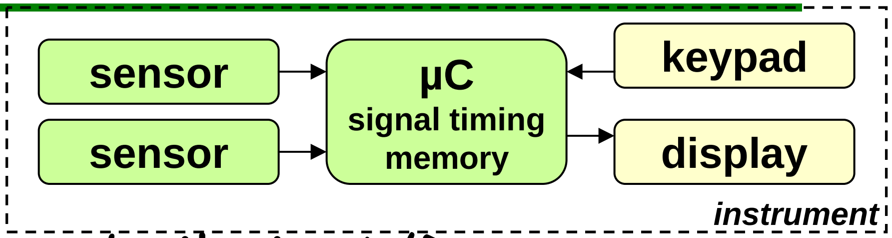
$$G_d = \frac{2R_2 + R_1}{R_1}\left(\frac{R_4}{R_3}\right)$$

Instrumentation Amplifier w/ BP Filter



With 776 op amps, the circuit was found to have a CMRR of 86 dB at 100 Hz and a noise level of 40 mV peak to peak at the output. The frequency response was 0.04 to 150 Hz for ±3 dB and was flat over 4 to 40 Hz. The total gain is 25 (instrument amp) x 32 (non-inverting amp) = 800.

Connecting Sensors to Microcontrollers



- Analog
  - many microcontrollers have a built-in A/D
    - 8-bit to 12-bit common
    - many have multi-channel A/D inputs
- Digital
  - serial I/O
    - use serial I/O port, store in memory to analyze
    - synchronous (with clock)
      - must match byte format, stop/start bits, parity check, etc.
    - asynchronous (no clock): more common for comm. than data
      - must match baud rate and bit width, transmission protocol, etc.
  - frequency encoded
    - use timing port, measure pulse width or pulse frequency

Connecting Smart Sensors to PC/Network

- "Smart sensor" = sensor with built-in signal processing & communication
  - e.g., combining a "dumb sensor" and a microcontroller
- Data Acquisition Cards (DAQ)
  - PC card with analog and digital I/O
  - interface through LabVIEW or user-generated code
- Communication Links Common for Sensors
  - asynchronous serial comm.
    - universal asynchronous receive and transmit (UART)
      - 1 receive line + 1 transmit line. nodes must match baud rate & protocol
    - RS232 Serial Port on PCs uses UART format (but at +/- 12V)
      - can buy a chip to convert from UART to RS232
  - synchronous serial comm.
    - serial peripheral interface (SPI)
      - 1 clock + 1 bidirectional data + 1 chip select/enable
  - I^2C = Inter Integrated Circuit bus
    - designed by Philips for comm. inside TVs, used in several commercial sensor systems
  - IEEE P1451: Sensor Comm. Standard
    - several different sensor comm. protocols for different applications

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