Signal Conditioning

W. Bolton, "Mechatronics --- Electronic control systems in mechanical and electrical engineering," 5th edition, Pearson Education Limited 2012, Chap 3

J. Edward Carryer, R. Matthew Ohline, Thomas W. Kenny, "Introduction to Mechatronic Design," Prentice Hall 2011, Chap 11 & 12

線上學習網站：https://www.electronics-tutorials.ws

PowerPoint 中部分圖片擷取和修改自教科書和網路圖片

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Signal Conditioning -1

- Goal
  - The output signal from the sensor of a measurement system has generally to be processed in some way to make it suitable for the next stage of the operation

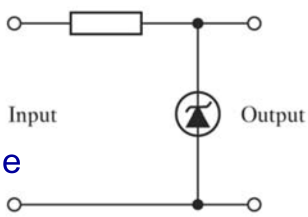
Signal Conditioning -2

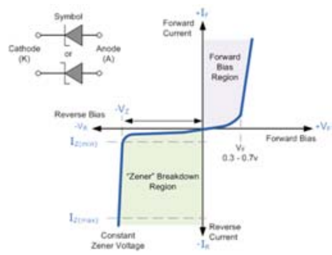
- Process
  - **Protection**: To prevent damage to the next element
    - Ex: Microprocessors - current & voltage limitations
  - Getting the signal into the **right type** of signal
    - Ex: AC-DC conversion, AD-DA conversion
  - **Amplification & Offset**
    - Ex: Wheatstone bridge (voltage amplification)
  - **Noise elimination** or reduction
    - Ex: Filters
  - **Signal manipulation**
    - Ex: Conditioner to linearize the signal

Protection -1

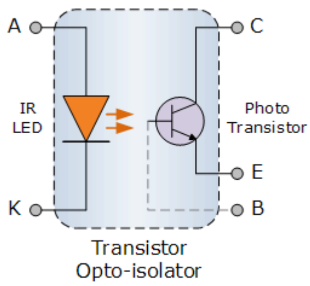
- High current
  - Incorporating a series resistor in the input line to limit the current
  - Incorporating a fuse to break if the current does exceed a safe level
- High voltage & wrong polarity
  - Zener diode circuit
    - Ex: for a 5V circuit

      Choose a 5.1V Zener diode



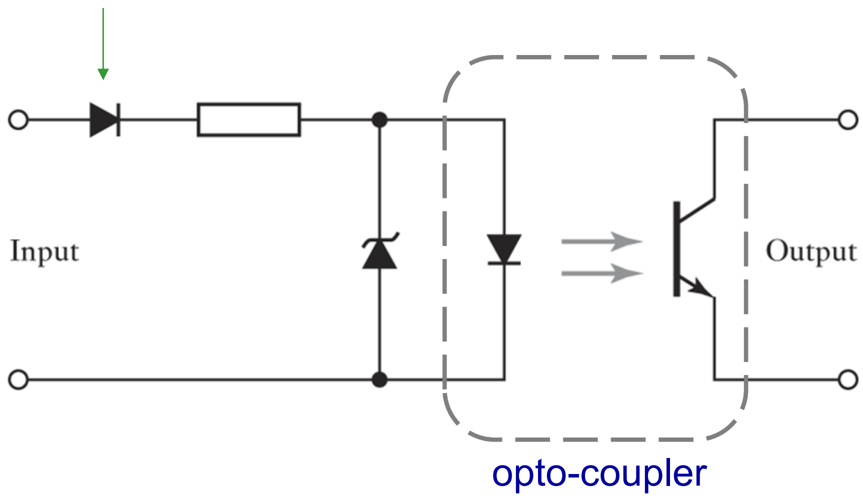


- Complete electrical isolation – opto-coupler



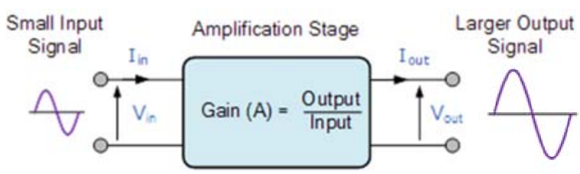
Protection -2

- Combined



Amplifier -1

- Definition
  - Describe a circuit which produces and increased version of its input signal
- Three kinds
  - Voltage gain (A_v)
  - Current gain (A_i)
  - Power gain ($A_p = A_v \times A_i$)
  - Can be represented in dB
    - $A_v = 20\log(A_v)$
    - $A_i = 20\log(A_i)$
    - $A_p = 10\log(A_p)$



Amplifier -2

- Ideal amplifier
  - Constant gain, independent of
    - Input signal conditions
    - Temperature
    - Time
- Components
  - BJT
  - MOSFET
  - Operational amplifier

Complex (Electrical) Impedance -1

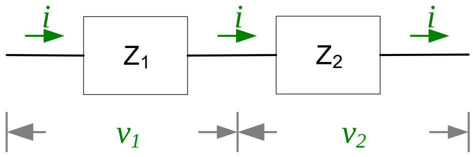
- Definition
  - The measure of the opposition that a circuit presents to a current when a voltage is applied
  - Quantitatively, the impedance of a two-terminal circuit element is the ratio of the complex representation of a sinusoidal voltage between its terminals to the complex representation of the current flowing through it

$$Z = R + jX = |Z|e^{j\arg(Z)}$$

$$Z \triangleq \frac{V}{I}$$

Complex (Electrical) Impedance -2

- Computation – circuit

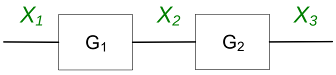


Current i : the same

$$V_1 = IZ_1 \qquad V_2 = IZ_2$$

$$V = V_1 + V_2 = IZ_1 + IZ_2 = I(Z_1 + Z_2) = IZ \qquad Z = Z_1 + Z_2$$

- Series and parallel laws applicable
- NOT transfer function



$$G_1 = \frac{X_2}{X_1} \qquad G_2 = \frac{X_3}{X_2}$$

$$G = \frac{X_3}{X_1} = \frac{X_2}{X_1}\frac{X_3}{X_2} = G_1G_2 \qquad G = G_1G_2$$

Complex (Electrical) Impedance -3

- Passive components
  - Resistor

$$v = iR$$

$$Z_R = \frac{V}{I} = R$$

  - Capacitor

$$i = C\frac{dv}{dt}$$

$$Z_C = \frac{V}{I} = \frac{1}{Cs}$$

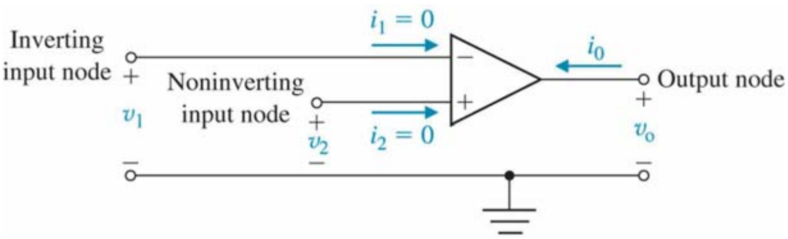
  - Inductor

$$v = L\frac{di}{dt}$$

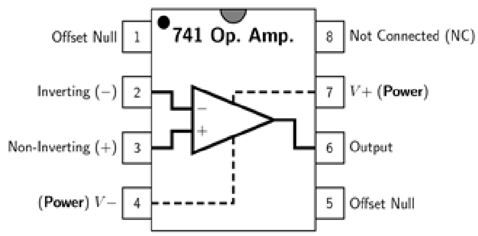
$$Z_L = \frac{V}{I} = Ls$$

The Operational Amplifier -1

- Definition
  - A DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output
  - Voltage gains ~100000
- Two Golden Rules
  - $i_1 = i_2 = 0$
  - $v_1 = v_2$



- Ex: OP741

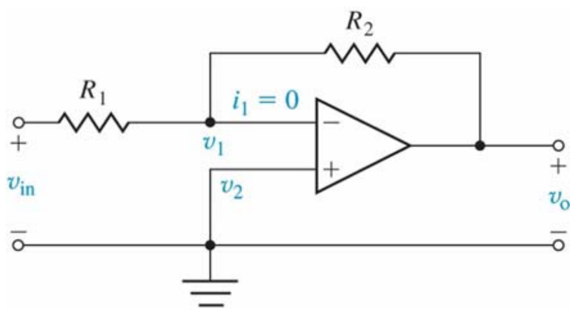


The Operational Amplifier -2

- Inverting amplifier
  - Resistors
    - $v_- = v_+ = 0$
    - $i = \frac{v_{in} - v_-}{R_1} = \frac{v_{in}}{R_1}$
    - $v_0 = v_- - R_2 i = -\frac{R_2}{R_1} v_{in}$

      ⇨ $G = \frac{v_0}{v_{in}} = -\frac{R_2}{R_1}$
    - Inverter, if $R_1 = R_2$

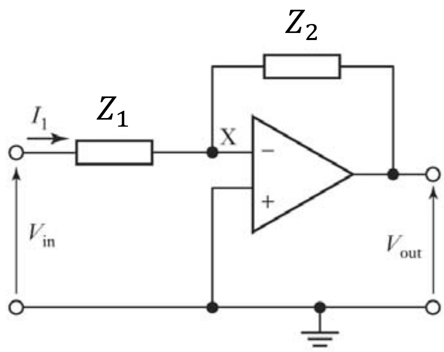
      ⇨ $G = \frac{v_0}{v_{in}} = -1$



The Operational Amplifier -3

- Inverting amplifier
  - Impedance – in Laplace domain

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = -\frac{Z_2}{Z_1}$$

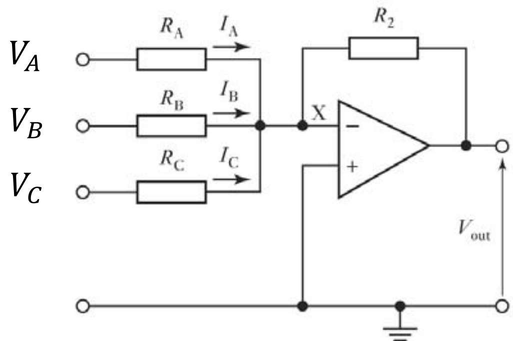


    - For general passive components
      - Ex: resistors, capacitors, inductors

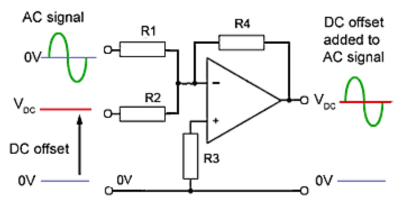
The Operational Amplifier -4

- Summing amplifier

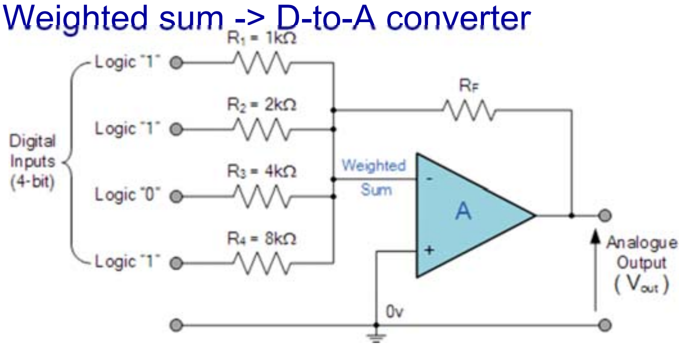
$$V_{out} = -(\frac{R_2}{R_A} V_A + \frac{R_2}{R_B} V_B + \frac{R_2}{R_C} V_C)$$



  - Ex: Offset the output

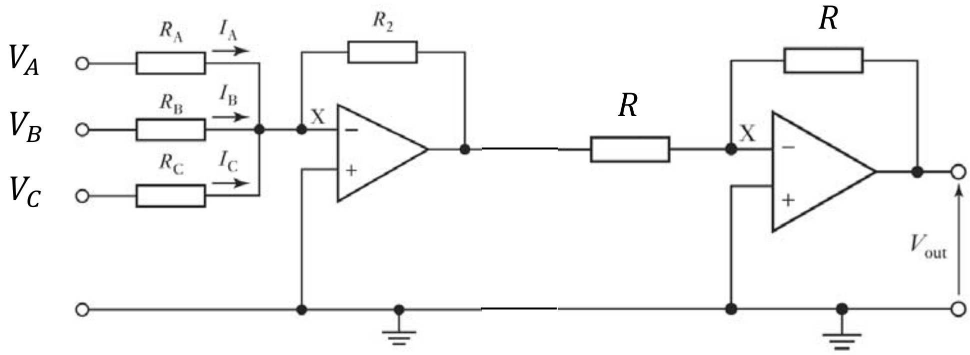


  - Ex: Weighted sum -> D-to-A converter



The Operational Amplifier -5

- (Non-inverted) summing amplifier
  - Adding an inverter



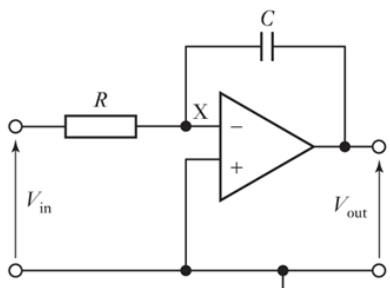
$$V_{out} = \frac{R_2}{R_A}V_A + \frac{R_2}{R_B}V_B + \frac{R_2}{R_C}V_C$$

  - How to build a subtractor?

The Operational Amplifier -6

- Integrating amplifier

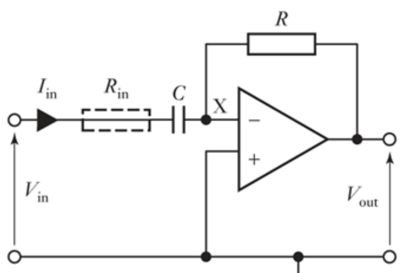
$$V_{out}(s) = -\frac{1}{RCs}V_{in}(s)$$



(a)

- Differentiating amplifier

$$V_{out}(s) = -RCsV_{in}(s)$$



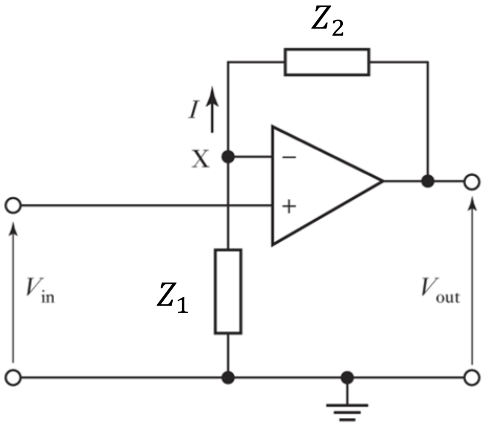
(b)

The Operational Amplifier -7

- Non-inverting amplifier
  - $V_{out} = V_- + Z_2 I = V_+ + Z_2 \frac{V_+}{Z_1}$

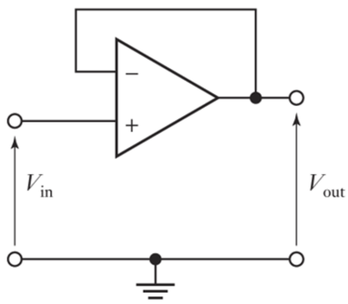
    $= \left(1 + \frac{Z_2}{Z_1}\right) V_{in} = G V_{in}$

    ➡ $G = \frac{V_{out}(s)}{V_{in}(s)} = 1 + \frac{Z_2}{Z_1}$



- Voltage follower
  - If $Z_2 \to 0$ and $Z_1 \to \infty$

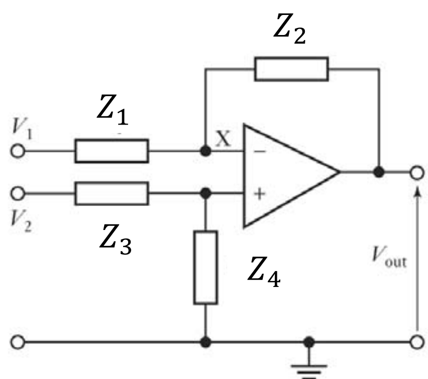
    ➡ $G \to 1$



The Operational Amplifier -8

- Differential amplifier
  - Impedance
    - $V_+ = \frac{Z_4}{Z_3+Z_4} V_2 = V_-$
    - $V_{out} = V_- - \frac{V_1 - V_-}{Z_1} Z_2$

  ➡ $V_{out} = \frac{Z_1 + Z_2}{Z_1} \frac{Z_4}{Z_3 + Z_4} V_2 - \frac{Z_2}{Z_1} V_1$



small input signal

gain

- If $Z_3 = Z_1$ and $Z_4 = Z_2$ ➡ $V_{out} = \frac{Z_2}{Z_1}(V_2 - V_1) = G_{diff} \Delta V$

- Set $V_{ref} = \frac{Z_4}{Z_3+Z_4} V_2$

offset

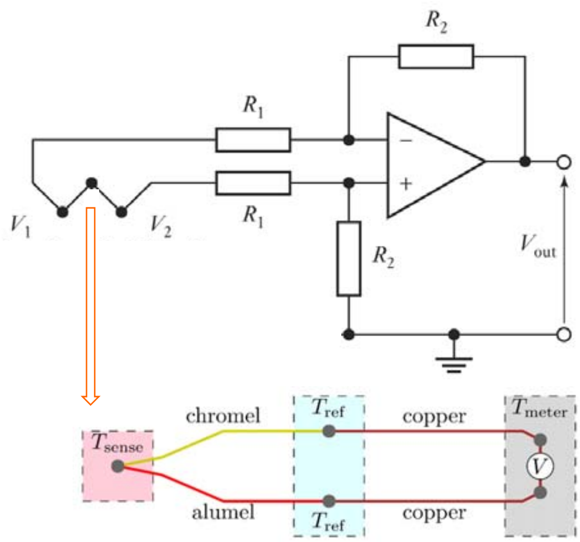
  ➡ $V_{out} = \frac{Z_1 + Z_2}{Z_1} V_{ref} - \frac{Z_2}{Z_1} V_1 = \frac{Z_2}{Z_1}(V_{ref} - V_1) + V_{ref}$

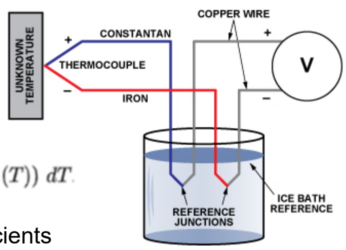
The Operational Amplifier -9

- Empirically, common mode voltage may affect the output
  - $V_{out} = G_{diff}\Delta V + G_{CM}V_{CM}$
  - Common mode rejection ratio (CMRR) = $\frac{G_{diff}}{G_{CM}}\ (dB)$
    - Ex: 10000 -> $20\log 10000 = 80\ (dB)$

The Operational Amplifier -10

- Ex: Thermalcouple (measurir
  - Advantages
    - Low cost
    - Accurate and repeatable
    - Wide temperature range
    - Reliable
    - Easy to setup
  - Disadvantages
    - Time constant: a function of wire mass
    - Small output voltage
    - Need electrical insulation





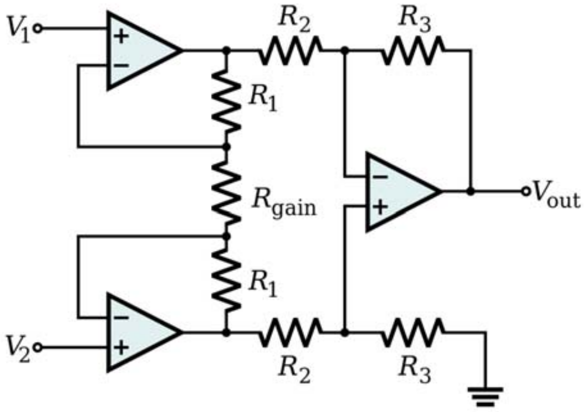
$$V = \int_{T_{ref}}^{T_{sense}} (S_+(T) - S_-(T))\, dT$$

S_+ S_-: Seebeck coefficients

Also need to know T_{ref} (cold junction compensation)

The Operational Amplifier -11

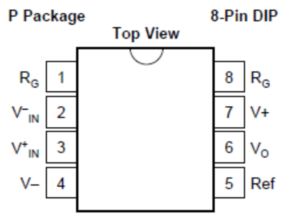
- Instrumentation amplifier
  - High input impedance
  - High gain
  - Excellent CMRR
    - >100 dB

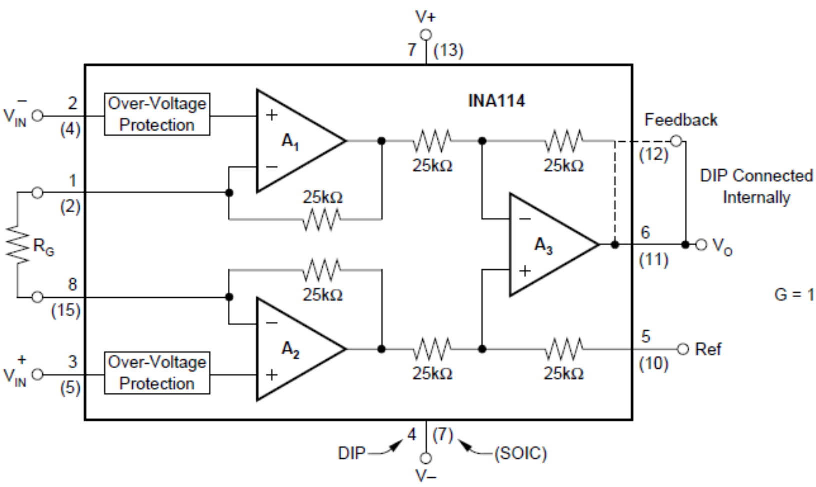


$$\frac{V_{out}}{V_2 - V_1} = G = \frac{R_3}{R_2}\left(1 + \frac{2R_1}{R_{gain}}\right)$$

The Operational Amplifier -12

- Instrumentation amplifier
  - Ex: INA114





$$G = 1 + \frac{50k\Omega}{R_G}$$

Input impedance, differential common mode: 10^{10} Ω in parallel with 6 pF

Input common mode range: ±13.5 V

Common mode rejection, G = 1:90 dB, G = 1000:110 dB

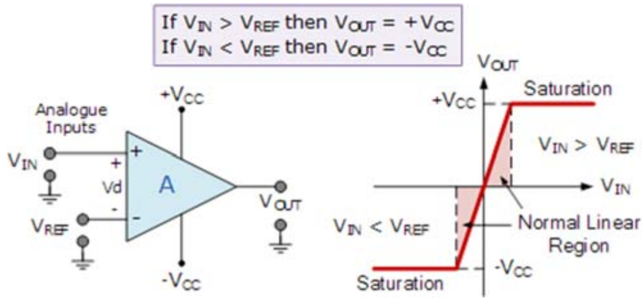
Gain range 1 to 10,000

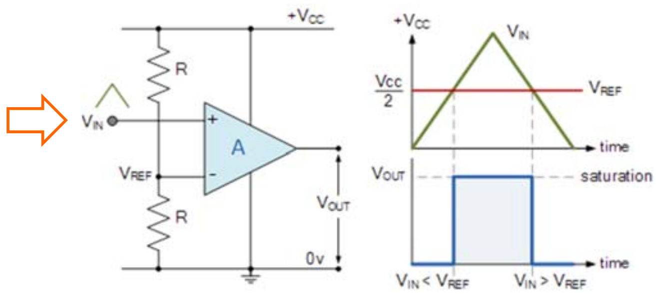
Gain error: 2% max.

Output voltage: ±13.7 V (V_s = ±15 V)

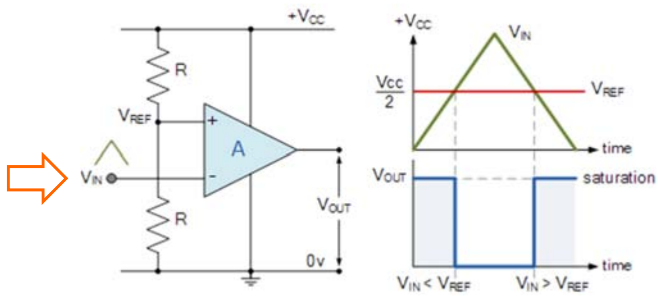
The Operational Amplifier -13

- Comparator





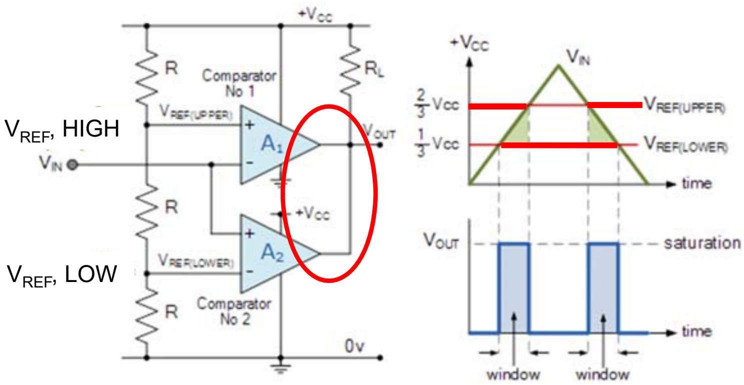
Non-inverting comparator circuit



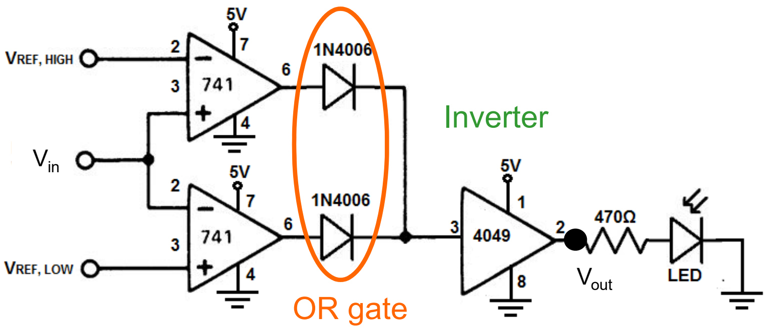
Inverting comparator circuit

The Operational Amplifier -14

- Window comparator
  - Method 1



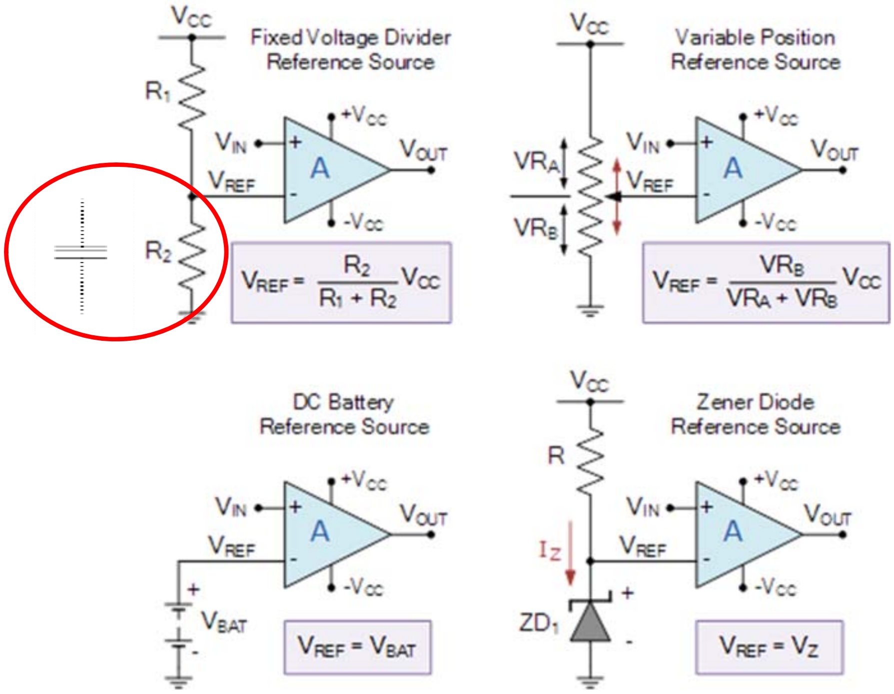
  - Method 2



From http://www.learningaboutelectronics.com

The Operational Amplifier -15

- Comparator – reference voltage

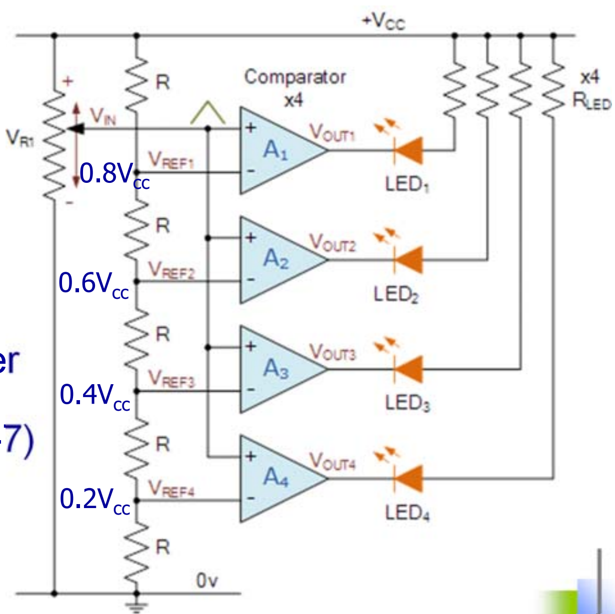


The Operational Amplifier -16

- Comparator – voltage level detector
  - Five levels: $0.2V_{CC}$ $0.4V_{CC}$ $0.6V_{CC}$ $0.8V_{CC}$ V_{CC}

LED$_4$ LED$_1$

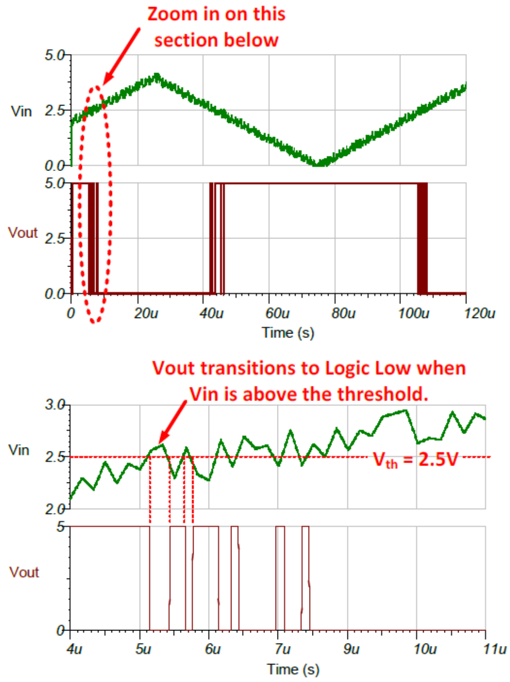
  - Five resistors
  - Four reference voltages



- 3-bit ADC
  - 7 Ops + 8-to-3 line digital decoder
  - Analog → 3-bit binary code (0-to-7)

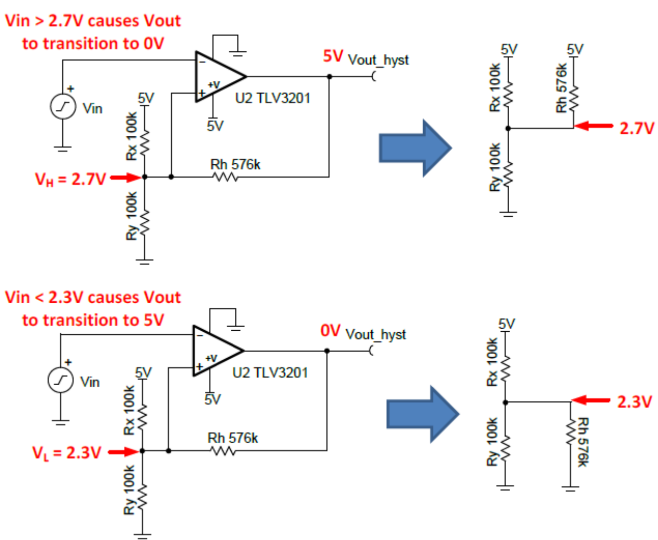
The Operational Amplifier -17

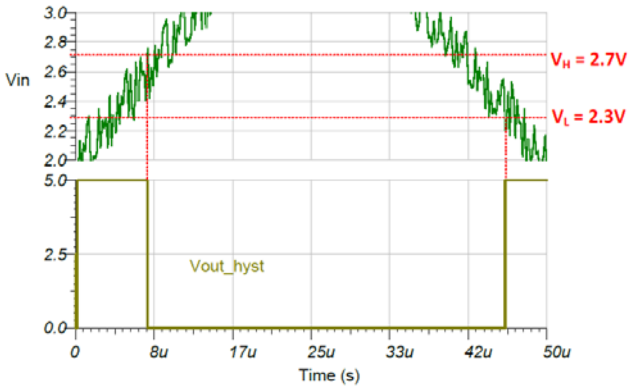
- Comparator with hysteresis
  - Original open-loop design
    - If the input signal varies rapidly: fine
    - If the input signal varies slowly or the noise exists: Oscillating switching back and forth between the two saturation states



The Operational Amplifier -18

- Comparator with hysteresis
  - Closed-loop design





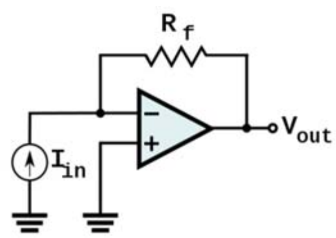
The Operational Amplifier -19

- Notes
  - Ops are optimized for linear operation, not in saturation mode
  - Dedicated voltage comparator: Allows for heavy saturation, due to its very high gain, when the input signals differs by a relatively small amount
  - Ex: LM311, LM339, LM393…

The Operational Amplifier -20

- Transimpedance amplifier
  - A current to voltage converter

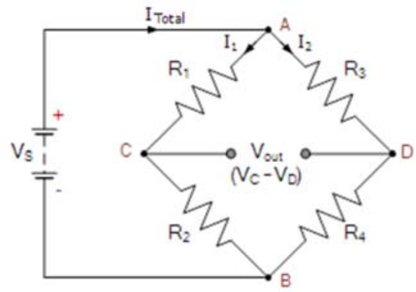
➡ $V_{out} = -R_f I_{in}$

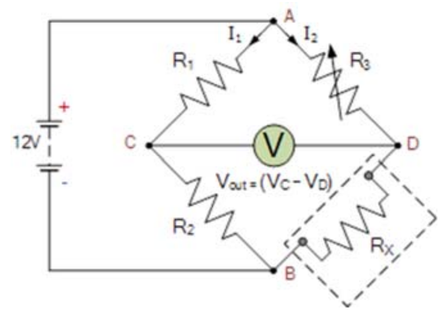


Wheatstone Bridge -1

- Definition
  - A combination of four resistances connected to give a null center value
  - Interfacing various transducers and sensors to the amplifier circuits
  - Input vs. output =?
- Wheatstone bridge circuit
  - R_x: sensing
  - R_3: "balance" the bridge

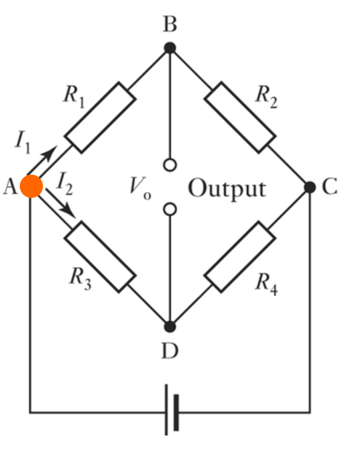
$$\frac{R_1}{R_2} = \frac{R_3}{R_x} = 1$$



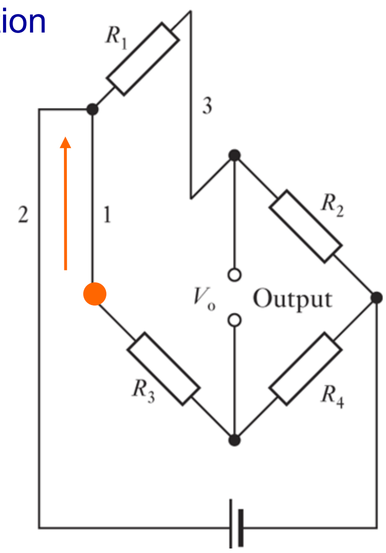


Wheatstone Bridge -2

- Lead compensation
  - If the sensing element is at the end of a long lead
    - Original form: temperature change matters
    - Three-lead form: "temperature compensation
      - Line 1: $R_1 \rightarrow R_3$



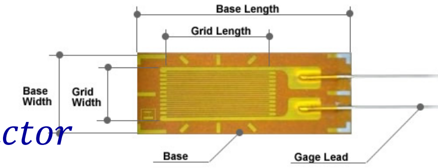
Original form

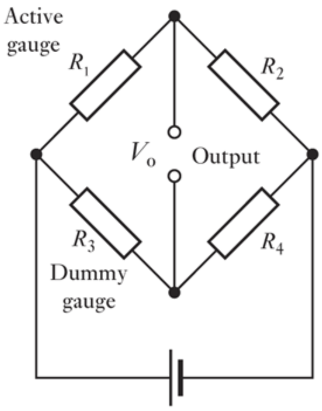


Three-lead form

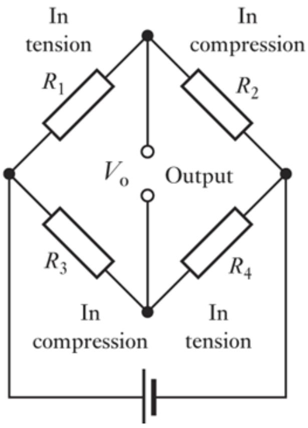
Wheatstone Bridge -3

- Ex: Strain gauges
  - $\frac{\Delta R}{R} = G\varepsilon$, G = gauge factor
  - $G = \sim 2, metal\ wire$; $G = \sim 100, semiconductor$

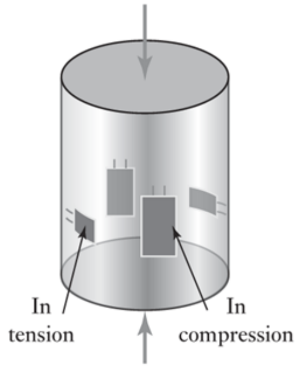




One gauge



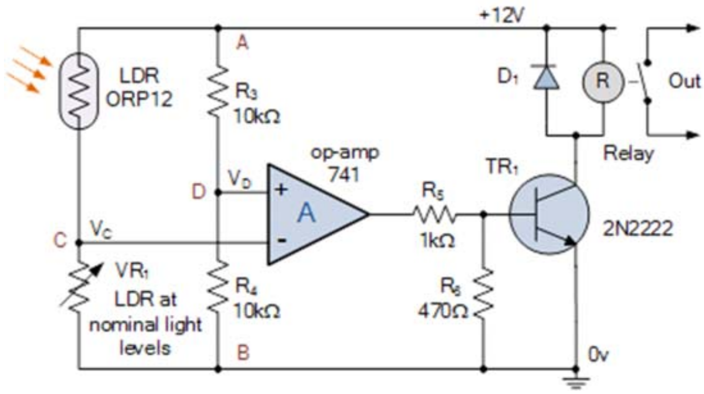
Four gauge



Dummy gauge:
for temperature compensation

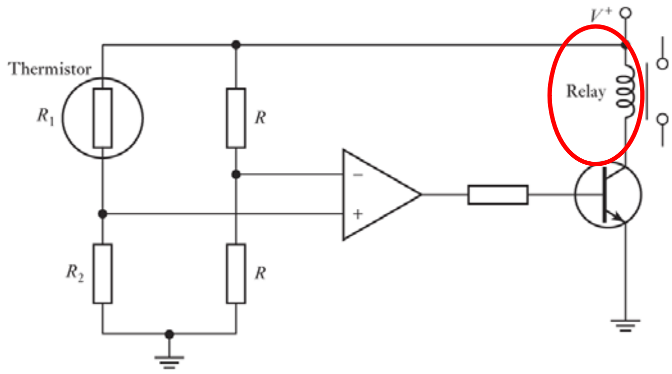
Wheatstone Bridge -4

- Ex: Wheatstone bridge light detector
  - Bridge + OP comparator
  - LDR: Light dependent resistor
  - VR_1: Balance the bridge circuit at the required light intensity
  - Ex: ORP12, $R = 10M\Omega$ (dark) → 100Ω (light)



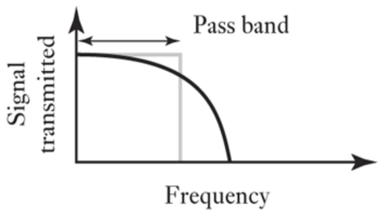
Wheatstone Bridge -5

- Ex: Wheatstone bridge air conditioner
  - Bridge + OP comparator
  - Thermistor
    - Ex: 10KΩ at 25˚C and 100Ω at 100˚C
  - Temperature ↑ ; R_1 ↓ ; V_+ ↑ ; OP ON; NPN saturated

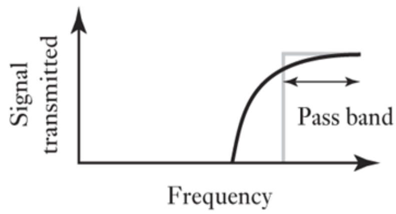


Filtering -1

- Definition
  - The process of removing a certain band of frequencies from a signal and permitting others to be transmitted
- Pass band

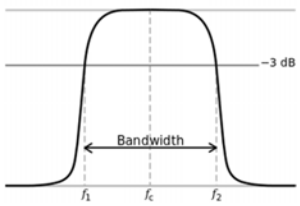


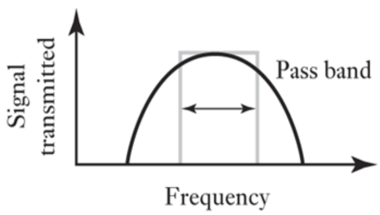
Low-pass



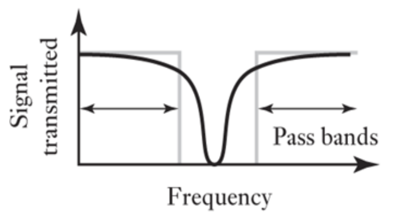
High-pass

Quality factor: $Q = \frac{f_c}{f_2 - f_1}$





Band-pass



Band-stop (notch filter)

Filtering -2

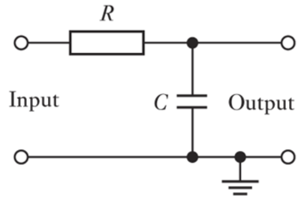
- Composition
  - Passive: using resistors, capacitors, and inductors
    - Disadvantage: The current drawn by the output may change the frequency characteristics of the filter

$$G(s) = -\frac{R_2}{R_1}\frac{1}{1+R_2Cs}$$

  - Active: Using OP

$$G(s) = \frac{1}{1+RCs}$$

  - Ex: a low-pass filter



- Goal: High signal to noise ratio (SNR) (in dB)

Filtering -3

- Frequency Response: The steady-state response of the system to a sinusoidal input

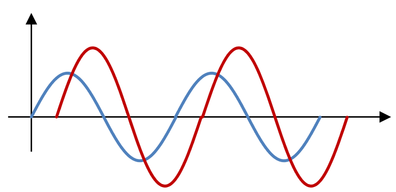
A well-studied periodic signal readily available in many instruments

input → (Stable) linear system, $T(s)$ → output

$r(t) = A\sin(\omega t)$

$y(t) = A|T(j\omega)|\sin(\omega t + \phi)$

$\phi = \angle T(j\omega)$



Input vs. output

Same frequency

Different amplitude & phase angle

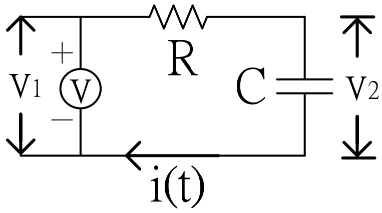
- How to obtain $T(j\omega)$? $\Rightarrow T(j\omega) = T(s)|_{s=j\omega}$

Filtering -4

- Ex: A RC circuit (low-pass filter)

$V_R = RI$

$V_C = \frac{I}{Cs}$



$G(s) = \frac{V_C}{V_R+V_C} = \frac{\frac{I}{Cs}}{RI+\frac{I}{Cs}} = \frac{1}{RCs+1}$

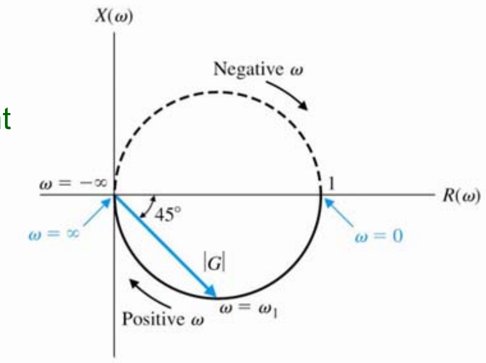
$G(j\omega) = \frac{1}{j\omega(RC)+1} = \frac{1}{j(\omega/\omega_1)+1} = \frac{1-j(\omega/\omega_1)}{(\omega/\omega_1)^2+1}$ $\tau = \mathrm{RC},\ \omega_1 = \frac{1}{RC}$

$= \frac{1}{(\omega/\omega_1)^2+1} + j\frac{-(\omega/\omega_1)}{(\omega/\omega_1)^2+1}$ a circle centered at $(\frac{1}{2}, 0)$

$|G(\omega)| = \frac{1}{\sqrt{1+(\frac{\omega}{\omega_1})^2}}$ $\phi(\omega) = \underline{tan2}^{-1}(-\frac{\omega}{\omega_1}, 1)$

Trajectory in the 4th quadrant

	$R(\omega)$	$X(\omega)$	$\lvert G(\omega)\rvert$	$\phi(\omega) =$
$\omega = 0$	1	0	1	0
$\omega = \omega_1$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{\sqrt{2}}$	$-45°$
$\omega \to \infty$	0	0	0	$-90°$



Filtering -5

$G(j\omega) = G(s)\Big|_{s=j\omega} = \frac{1}{RCs+1}\Big|_{s=j\omega} = \frac{1}{j\omega\tau+1}$ $\tau = RC$

$G_{dB}(\omega) = 20log|G(\omega)| = 20log(\frac{1}{1+(\omega\tau)^2})^{\frac{1}{2}}$

$= -10log(1+(\omega\tau)^2)$

$\omega \ll \frac{1}{\tau}$ $G_{dB}(\omega) = -10log(1) = 0\ dB$

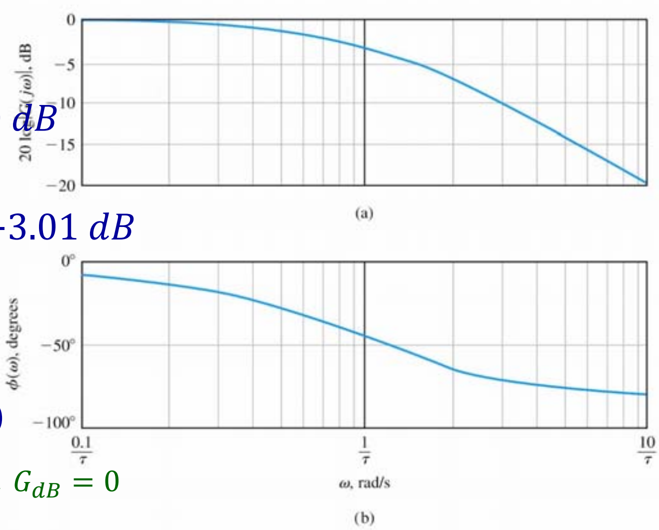
$\omega = \frac{1}{\tau}$ $G_{dB}(\omega) = -10log(2) = -3.01\ dB$

$\omega \gg \frac{1}{\tau}$ $G_{dB}(\omega) = -20log(\omega\tau)$

$= \underline{-20log(\tau) - 20log(\omega)}$

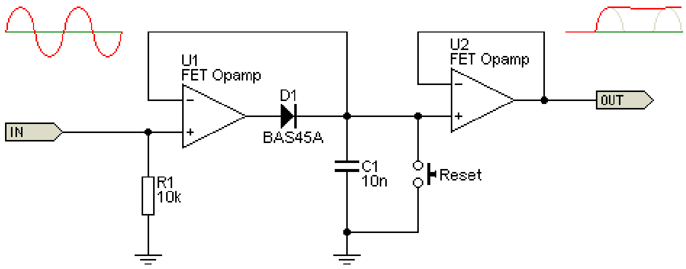
When $\omega = \frac{1}{\tau}$, $G_{dB} = 0$

$\phi(\omega) = -tan^{-1}\omega\tau$



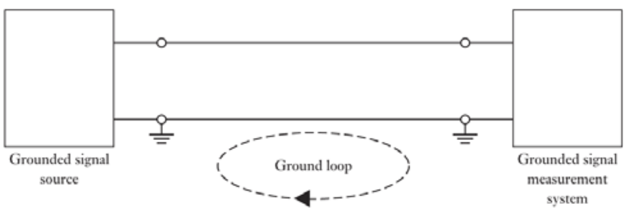
Peak Detection

- Two methods
  - In microprocessor (software), suitable for low-frequency signals
  - In circuit, good for high-frequency signals

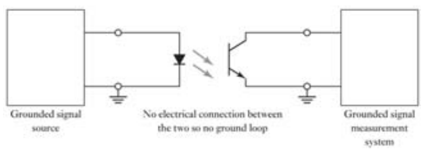


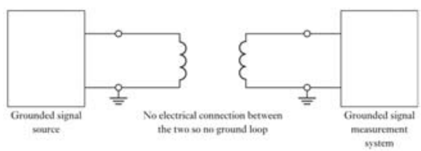
Problems with Signals -1

- Ground loop
  - Occurring when two points of a circuit both intended to be at ground reference potential have a potential between them
  - A major cause of noise, hum, and interference in audio, video, and computer systems



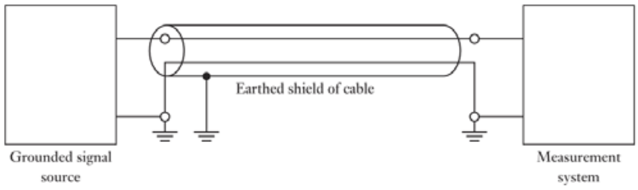
  - Solution: Electrical isolation
    - Ex: opto-coupler, transformer



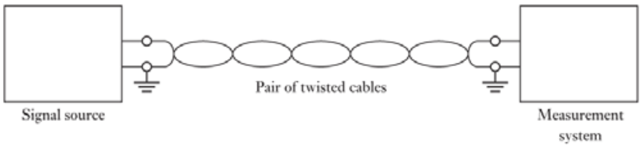


Problems with Signals -2

- Electromagnetic interference
  - Resulting from time-varying electric and magnetic fields
  - Ex: motors, relay coils, fluorescent lamps…
  - Occurring as a result of mutual capacitance between neighboring conductors



  - Solution: Electric shielding, Use of twisted pairs of wires for interconnections



End

- Questions?