Measurements

If you have a smart project, you can say "I'm an engineer"

Lecture 3

Staff boarder

Dr. Mostafa Elsayed Abdelmonem

Measurements

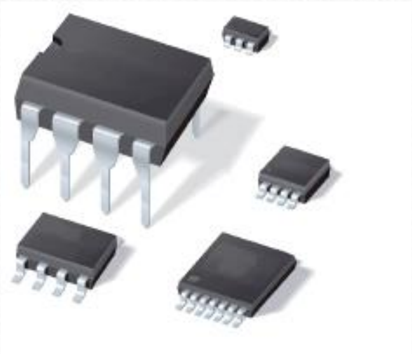
- **Lecture aims:**
  - Develop the Signal Conditioning for measurements
  - Formulate advanced problems for Filters

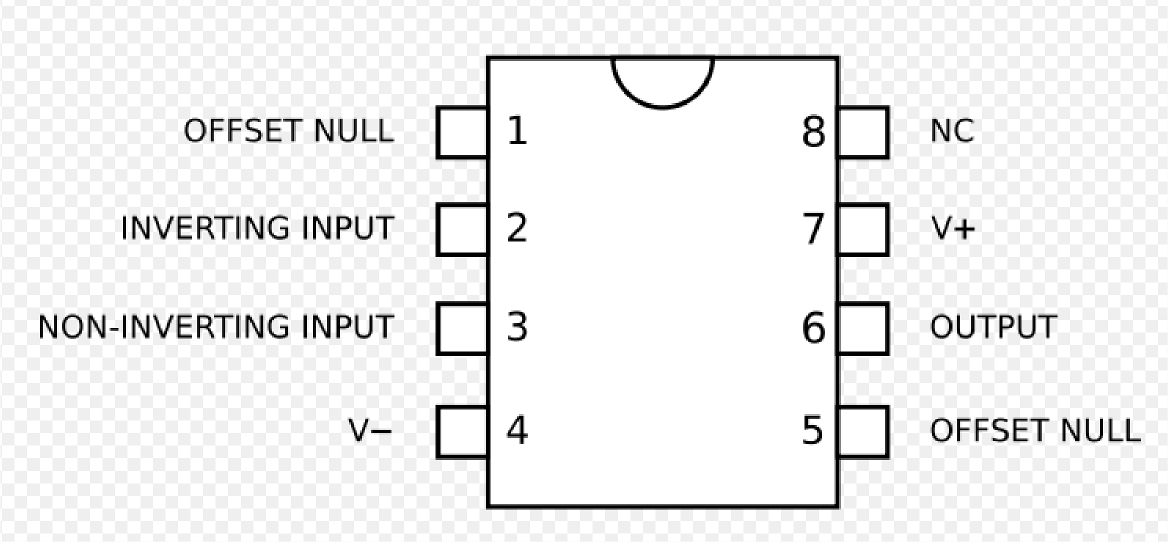
Signal Conditioning

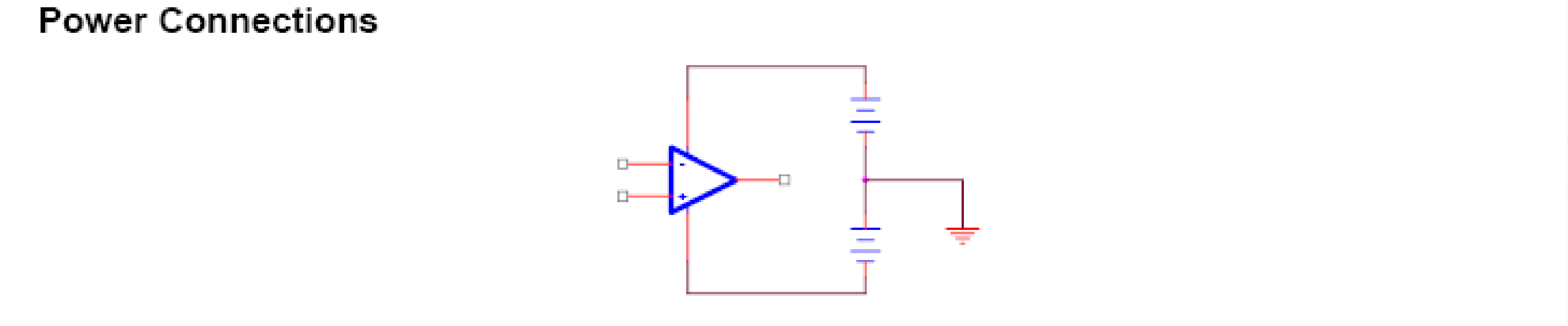
- The signal output from the sensor is usually small (in mV) and noisy
- Signal Conditioning is the process of filtering and amplifying this signal in order to process it to the computer
- Amplification was studied and therefore will not be covered here
- In this section, we will study analog filters

Amplifiers

Operational amplifier

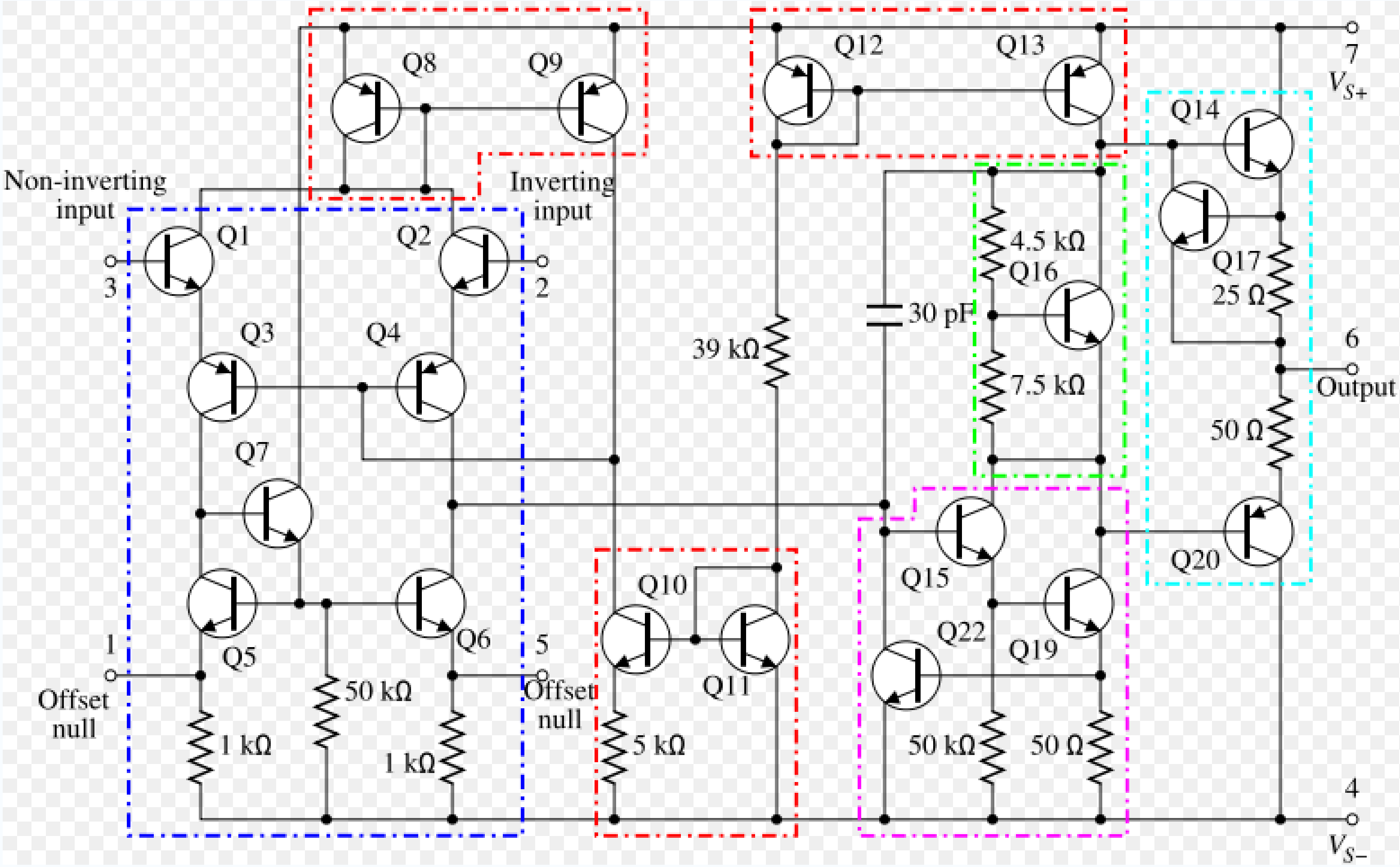






Amplifiers

Image: OpAmp Transistor Level



Amplifiers

Operational amplifier

$$\frac{(E-)+E_I}{R_I} = \frac{E_O-((E-)+E_I)}{R_O}$$

but:

$$E_O = -A\cdot(E-)$$

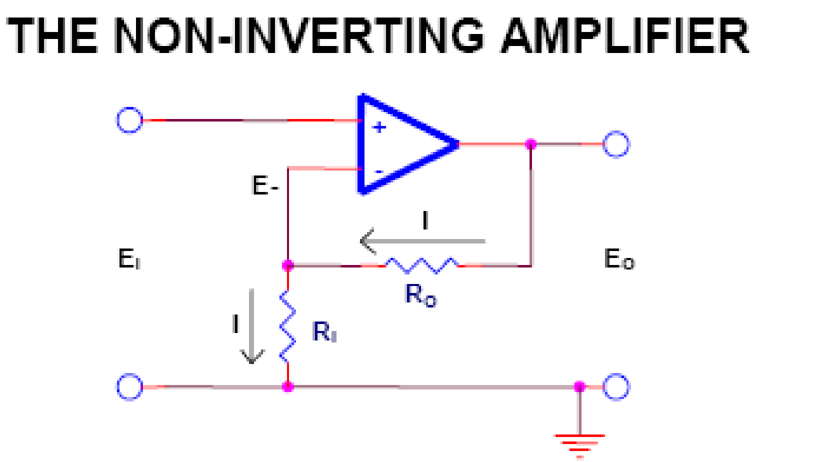
$$(E-) = \frac{-E_O}{A}$$

$$\frac{E_I}{R_I} = \frac{E_O - E_I}{R_O}$$

Solving:

$$E_I(R_O + R_I) = E_O R_I$$

$$\frac{E_O}{E_I} = \frac{R_O+R_I}{R_I} = 1 + \frac{R_O}{R_I}$$



Amplifiers

Let the voltage at the inverting input be E- and the open loop operational amplifier gain be A (ideally, $A = \infty$).

Since equal currents flow in R_O and R_I:

$$\frac{E_I - (E-)}{R_I} + \frac{E_O - (E-)}{R_O} = 0$$

But by definition:

$$E_O = A \cdot (E-)$$

$$(E-) = -\frac{E_O}{A}$$

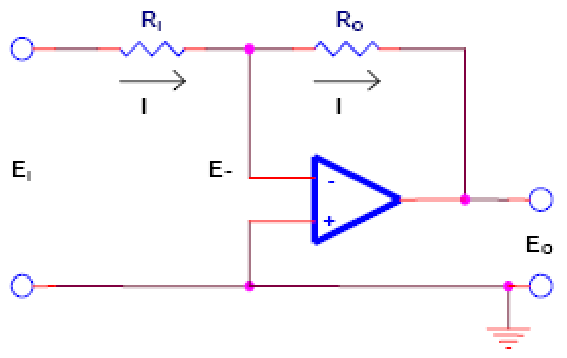
Letting A go to infinity, E- approaches zero and:

$$\frac{E_I}{R_I} + \frac{E_O}{R_O} = 0$$

or:

$$\frac{E_O}{E_I} = -\frac{R_O}{R_I}$$

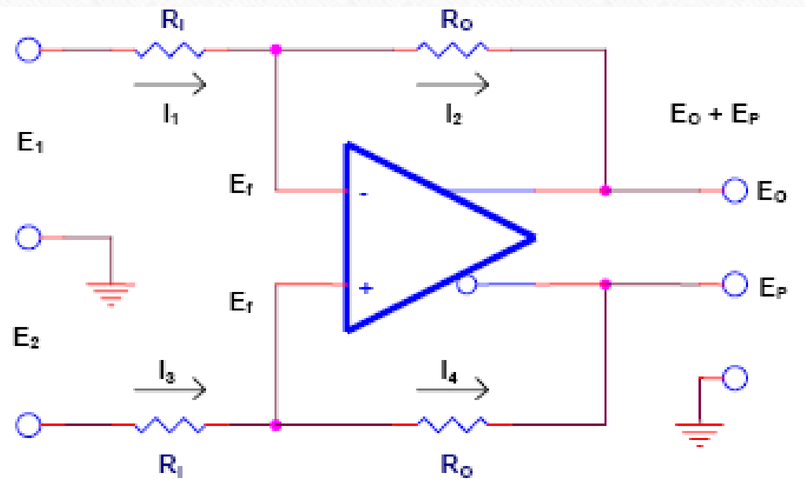
THE INVERTING AMPLIFIER



Amplifiers

THE DIFFERENTIAL (BALANCED) OUTPUT AMPLIFIER

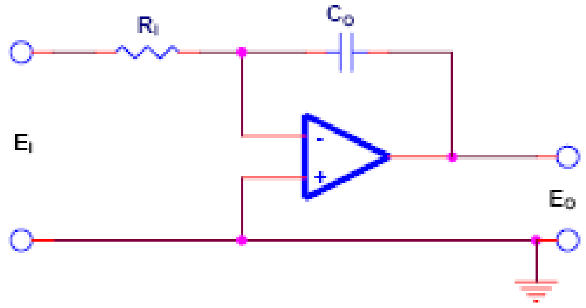
$$E_O = \frac{R_O}{R_I}(E_2 - E_1)$$



Amplifiers

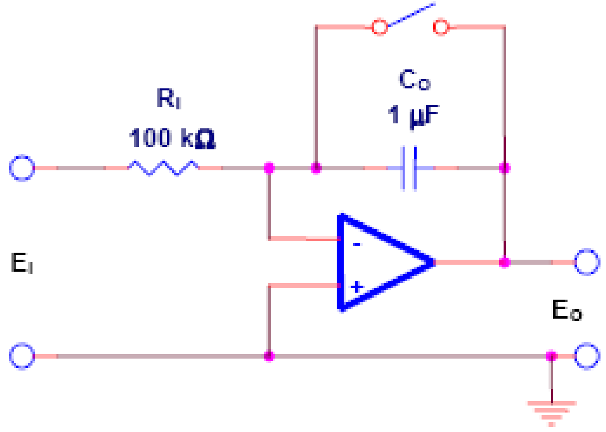
INTEGRATORS

$$E_O = \frac{-Z_O}{Z_I} E_I = \frac{-E_I}{R_I C_{Op}} = -\frac{1}{R_I C_O} E_I dt$$



PRACTICAL INTEGRATORS

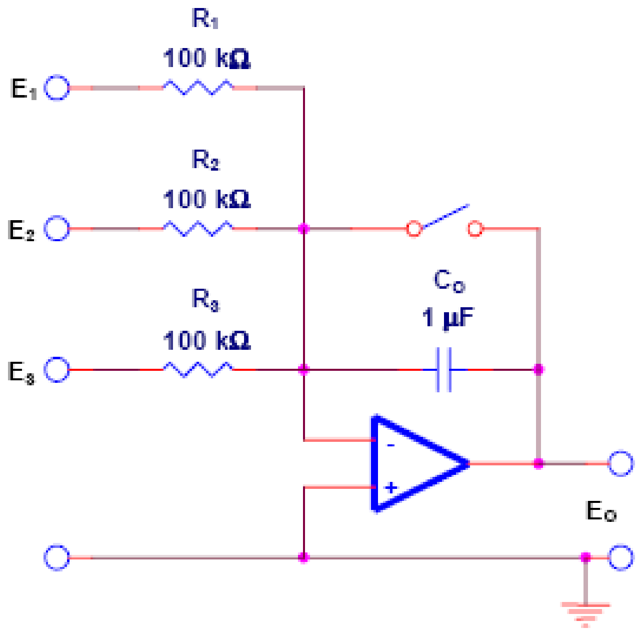
Simple integrator circuits operate successfully but current offset is stored in the feedback capacitor causing output voltage error. This is corrected with low drift chopper stabilized amplifier and/or current biasing networks.



Amplifiers

Summing Integrator

$$E_O = \frac{-1}{RC}\int(E_1 + E_2 + E_3)dt$$
$$= -10\int(E_1 + E_2 + E_3)dt$$

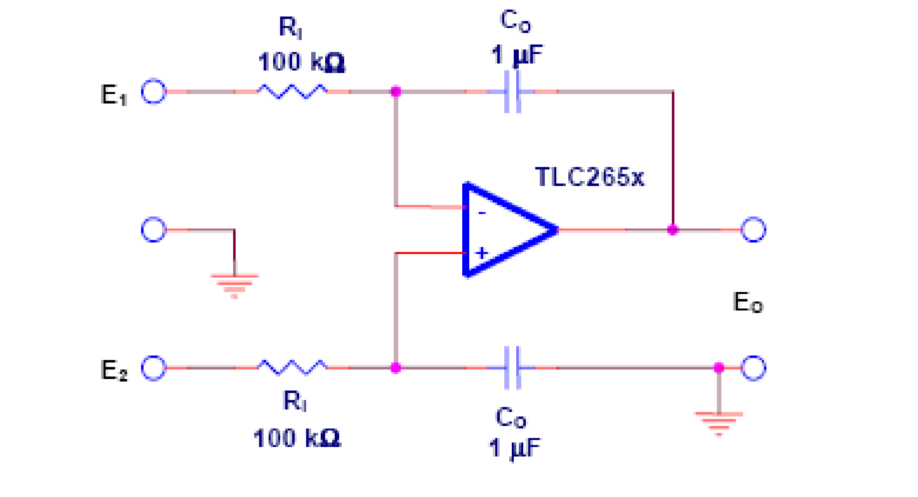


Amplifiers

Differential Integrator

$$E_O = \frac{-1}{R_I C_O} (E_I - E_2)dt$$

$$= 10 (E_2 - E_1)dt$$



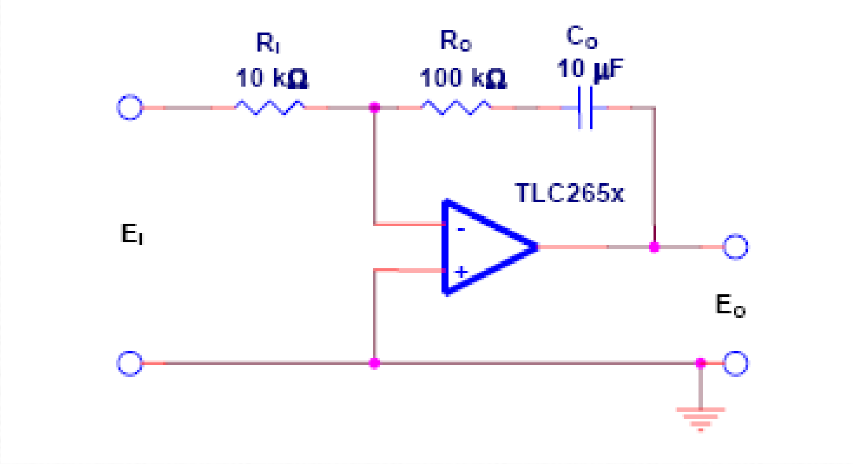
Amplifiers

Augmenting Integrator

Sums the input signal and its time integral.

$$E_O = \frac{-R_O E_I}{R_I} - \frac{1}{C_O R_I} \quad E_I dt$$

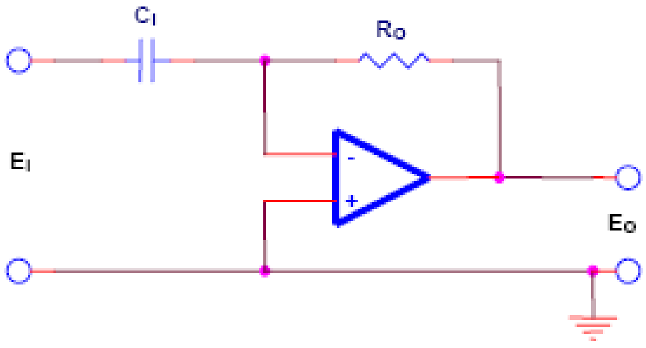
$$= -10E_I - \quad E_I dt$$



Amplifiers

DIFFERENTIATORS

For the differentiator; $Z_O = R_O, \quad Z_I = \frac{1}{C_p}$



$$E_O = \frac{-Z_O}{Z_I} E_I = -R_O C_I p E_I = -R_O C_I \frac{dE_I}{dt}$$

Amplifiers

THE VOLTAGE SUMMER

Assume the ideal summing paint restraints:

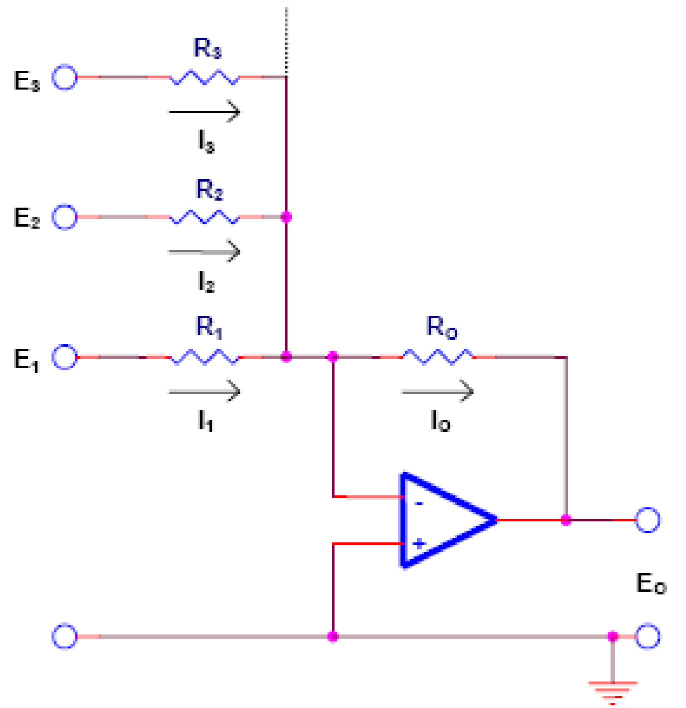
1. Pin (1) is at ground potential
2. $-I_O + I_1 + I_2 + I_3 + \ldots = 0$

The current, I_O, is given by:

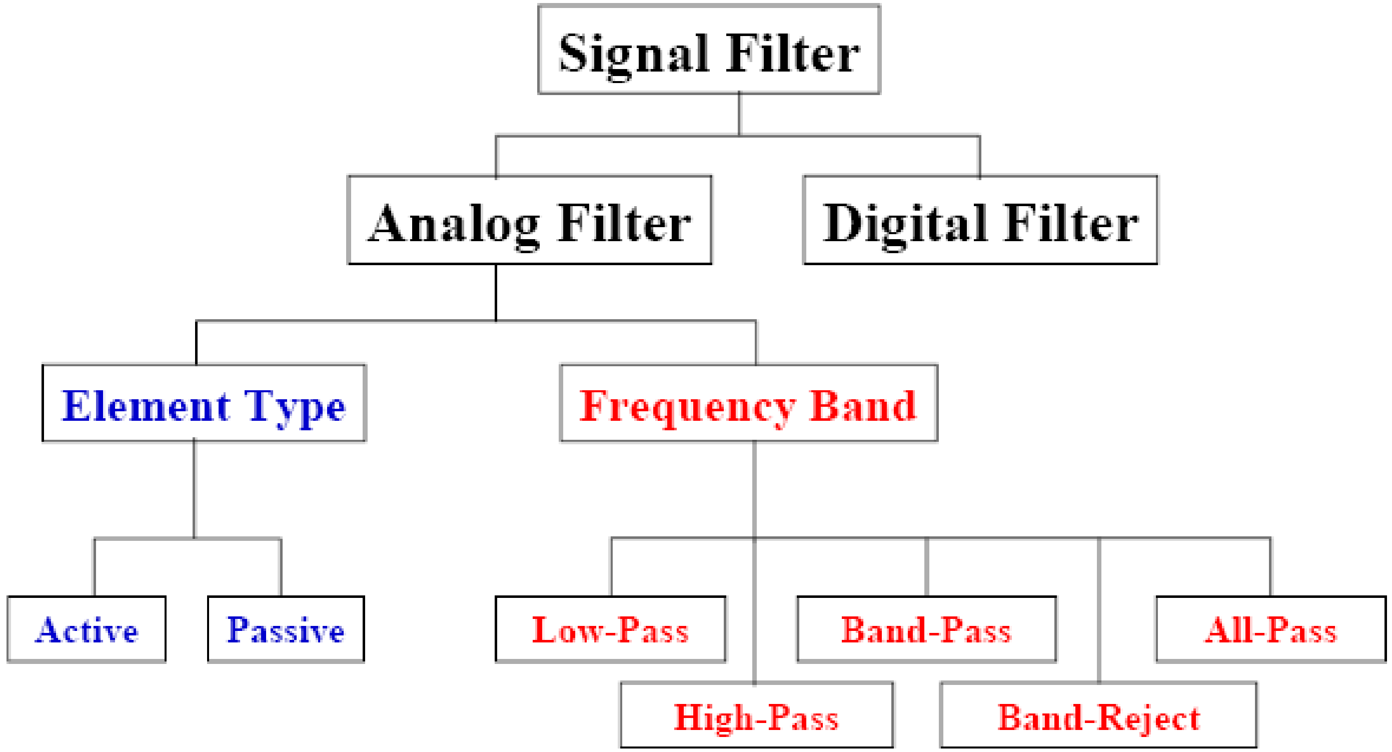
$$I_O = \frac{-E_O}{R_O} = \frac{E_1}{R_1} + \frac{E_2}{R_2} + \frac{E_3}{R_3} + \ldots$$

So that:

$$E_O = -R_O\left(\frac{E_1}{R_1} + \frac{E_2}{R_2} + \frac{E_3}{R_3} + \ldots\right)$$



Classification of Filters

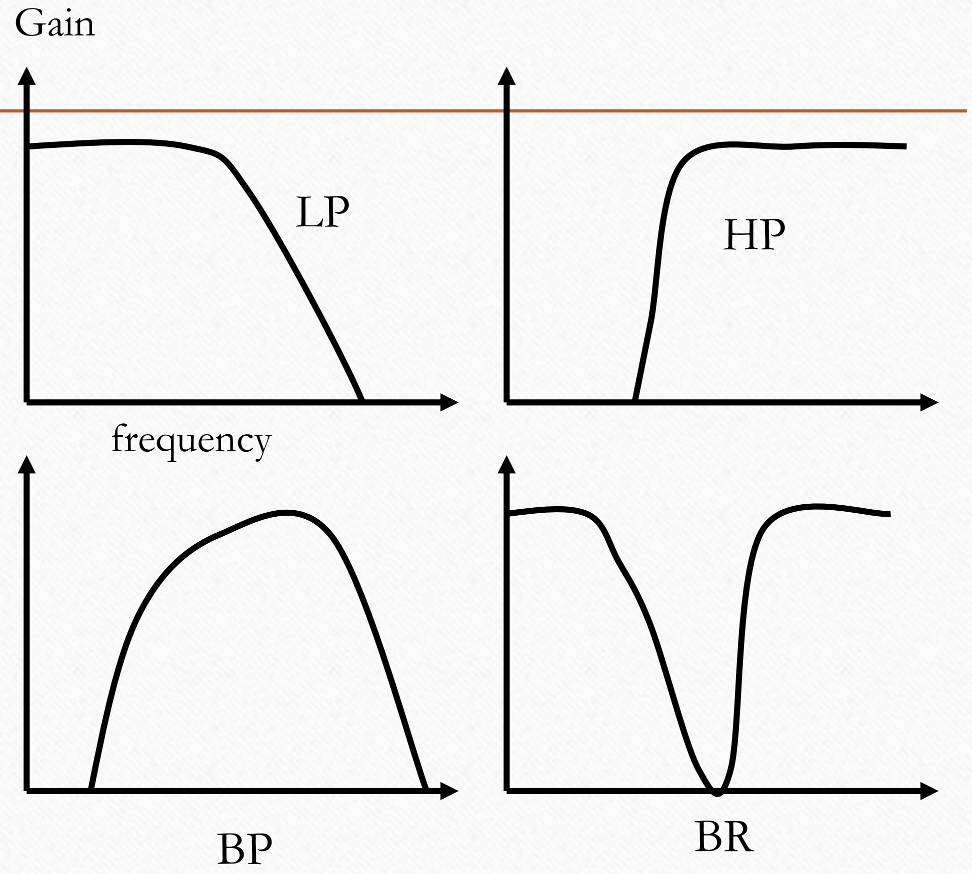


Analog Filters

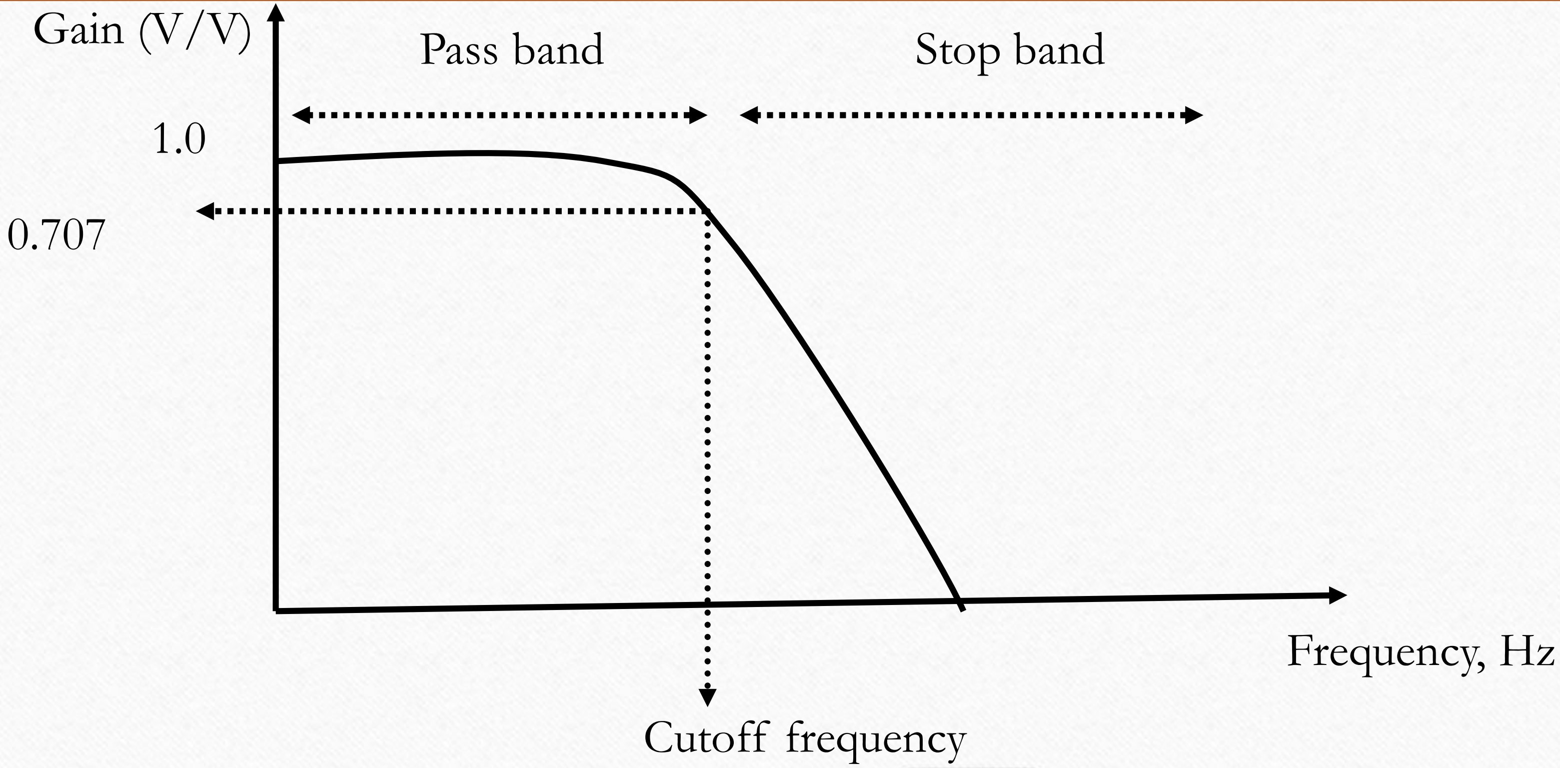
- Electrical filters are designed to eliminate unwanted frequencies (i.e. noise)
- Filters are divided into Passive and Active filters.
- Passive filters use only resistors, capacitors, and inductors
- Active filters contain op-amps and therefore can amplify the signal

Types of filters

- Filters can be divided into 4 types:
  - Low Pass (LP) filters
  - High Pass (HP) filters
  - Band Pass (BP) filters
  - Notch or Band Reject (BR) filters



Low Pass Filter



Filter Characteristics

- Ideally, Low Pass Filter passes frequencies < cutoff frequency (*fc*) and blocks frequencies > *fc*
- ***Cutoff Frequency*** is the frequency at which the voltage gain of the filter drops to 0.707 of its maximum value
- The range of frequencies that pass the filter are called ***Passband***
- The range of frequencies that do Not pass through the filter are called ***Stopband***
- For passive filters, the gain in the passband is equal to 1

Passive LP filter example: RC Circuit

The transfer function can be found using voltage divider rule

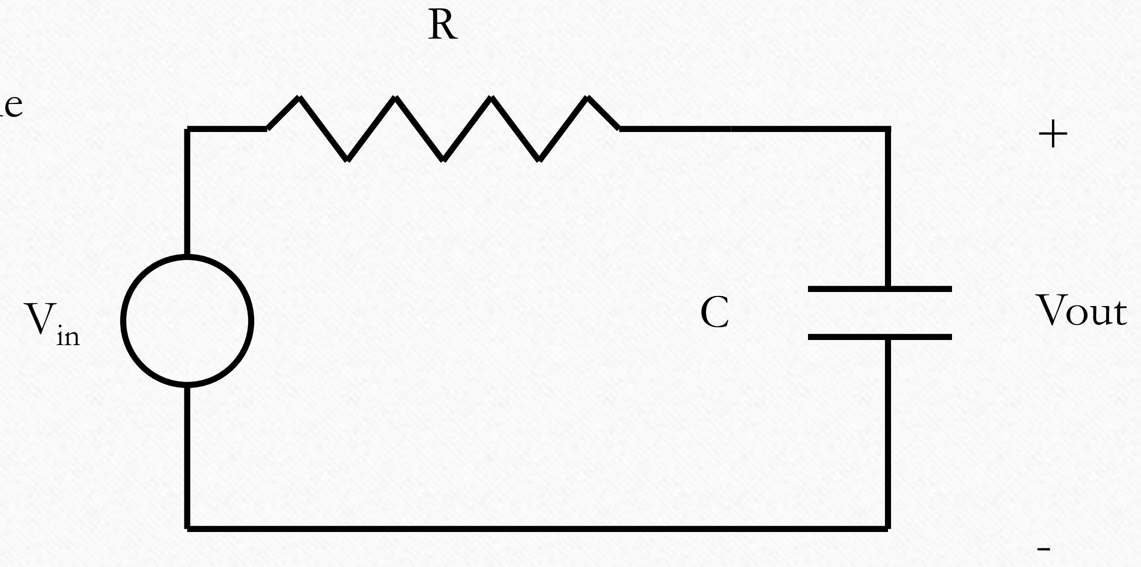
$$H(j\omega) = \frac{1/j\omega C}{1/j\omega C + R}$$

The magnitude is found using

$$|H(j\omega)| = \sqrt{\mathrm{Re}\{H(j\omega)\}^2 + \mathrm{Im}\{H(j\omega)\}^2}$$

The phase is found using

$$\Phi(j\omega) = \tan^{-1}\frac{\mathrm{Im}\{H(j\omega)\}}{\mathrm{Re}\{H(j\omega)\}}$$



RC circuit example

This in turn gives the magnitude to be equal to

$$|H(j\omega)| = \frac{1/RC}{\sqrt{\omega^2 + (1/RC)^2}}$$

$$|H(j\omega_c)| = \frac{1}{\sqrt{2}} H_{\max} = \frac{1}{\sqrt{2}} (1)$$

In order to get, f_c, we solve the following equation

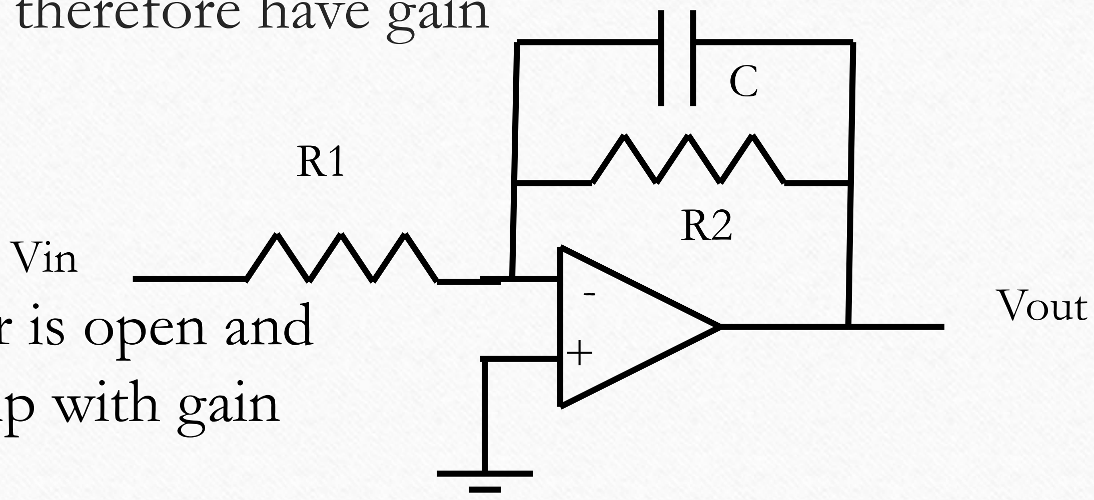
$$\Rightarrow \frac{1}{\sqrt{2}} = \frac{1/RC}{\sqrt{\omega_c^2 + (1/RC)^2}}$$

$$\Rightarrow \omega_c = 1/RC$$

$$\Rightarrow f_c = 1/2\pi RC$$

Active Filters: LP

- Active filters use op-amps in their design and therefore have gain
- An active low pass filter is shown below



When input frequency is 0, then the capacitor is open and the circuit becomes a regular inverting op-amp with gain R2/R1

When input frequency is infinite, the capacitor is short and the Output voltage becomes zero

Active Filters: LP

The transfer function, magnitude, and the cutoff frequency of the circuit shown is derived to be

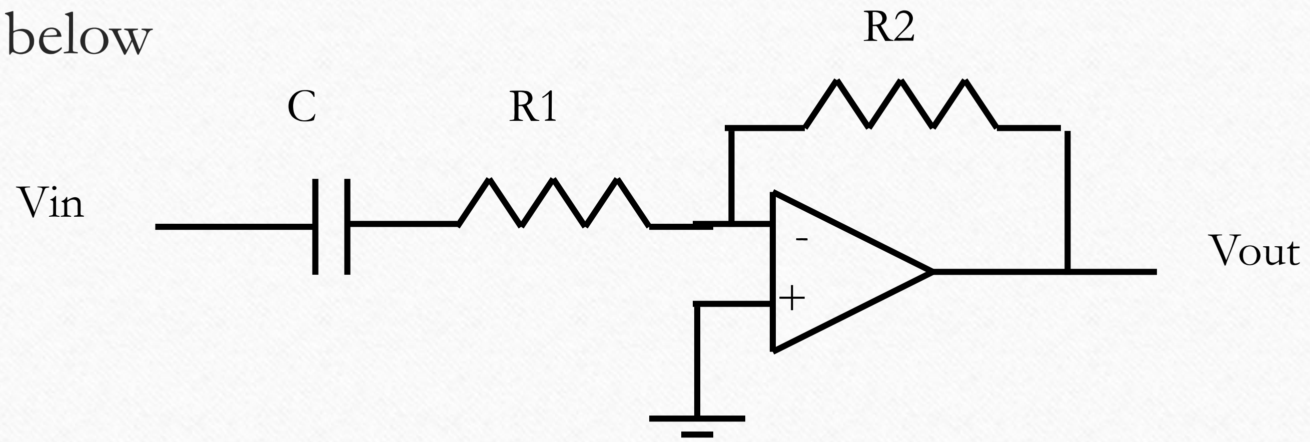
$$H(j\omega) = \frac{-Z_{out}}{Z_{in}} = \frac{-R_2 \,||\, (1/j\omega C)}{R_1}$$

$$|H(j\omega)| = \frac{R_2}{R_1} \frac{1}{\sqrt{(R_2 C\omega)^2 + 1}}$$

$$\omega_c = 1/R_2 C$$

Active Filters: HP

An active high pass filter is shown below



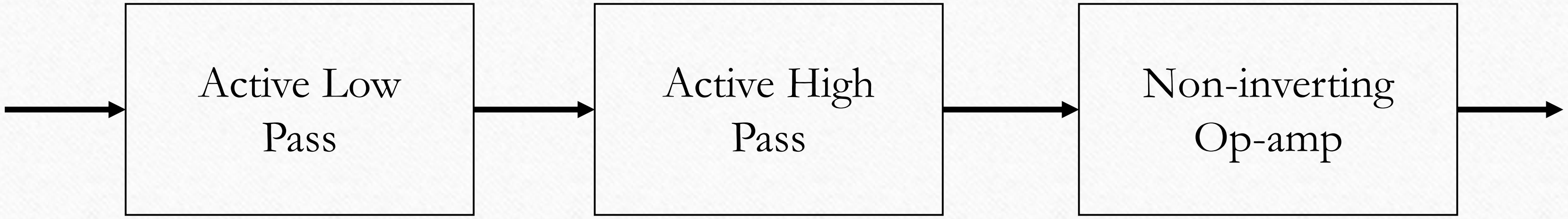
The transfer function and the cutoff frequency of the circuit shown is derived to be

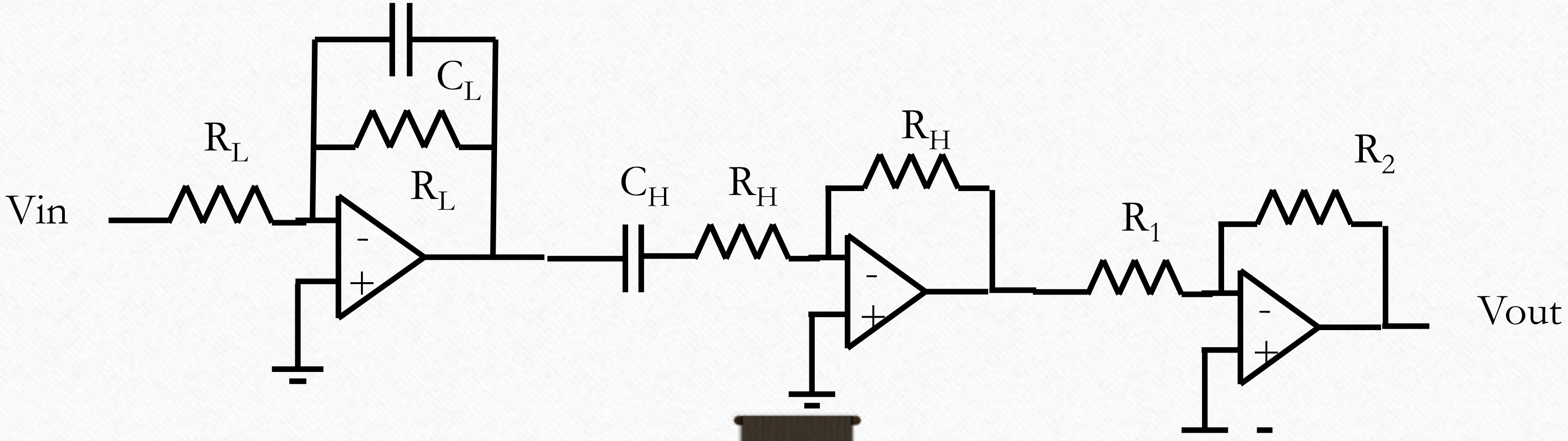
$$H(j\omega) = \frac{-R_2}{R_1} \frac{j\omega}{j\omega + 1/R_1C}$$

$$\omega_c = 1/R_1C$$

Active Filters: Band Pass

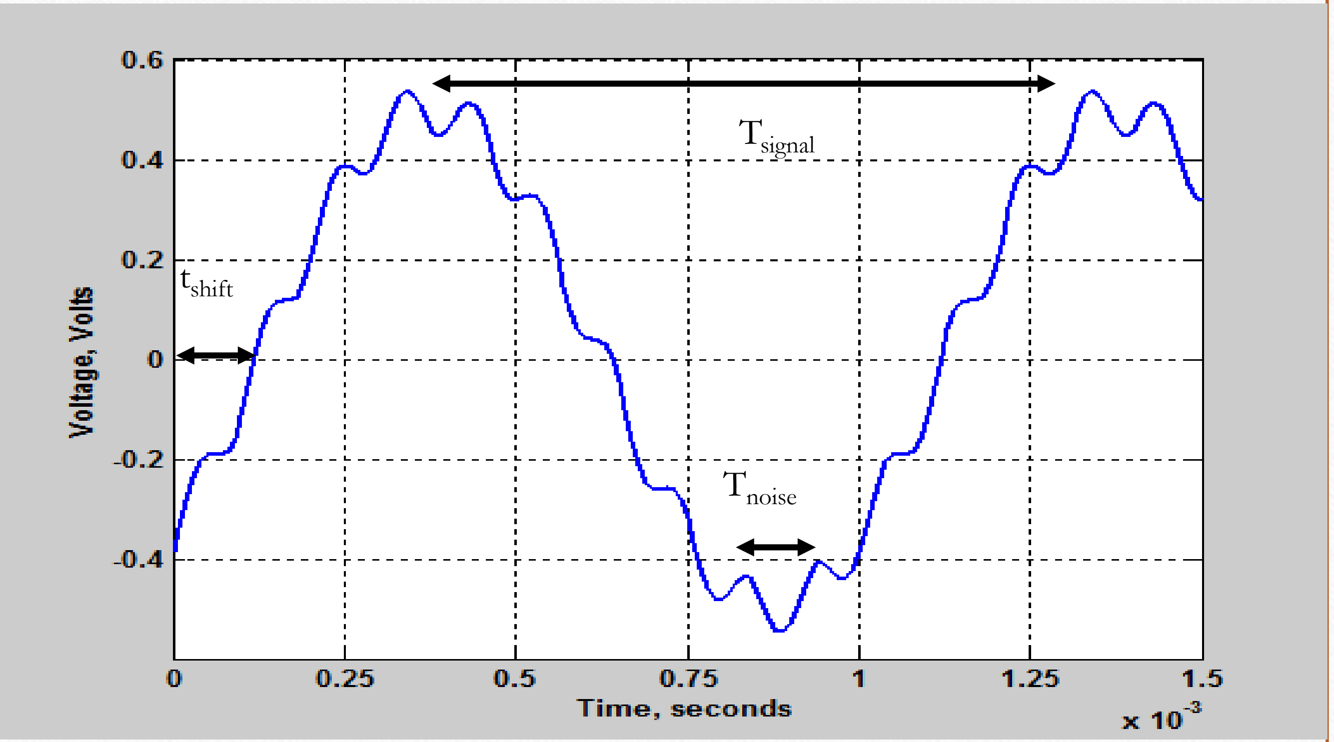
We can construct an active band pass filter using 3 cascade stages





Active Filter Design Example

Problem Statement: A transducer is used as an input to a PC. The measured signal is sinusoidal with high frequency noise added. The signal is shown in figure below. Design an analog signal conditioning circuit to filter out the noise and give a gain of 10 for the sinusoidal signal



Example continued

The original signal had a period, T_{signal}, of 1 ms => F_{signal} = 1,000 Hz

The time shift, t_{shift}, is equal to 0.125 ms => phase shift is 0.125ms x360^0/1ms = 45 degrees

Then, the signal can be represented as

$$x(t) = 0.5\,sin\left(2\pi(1{,}000)t - 45\right) + noise$$

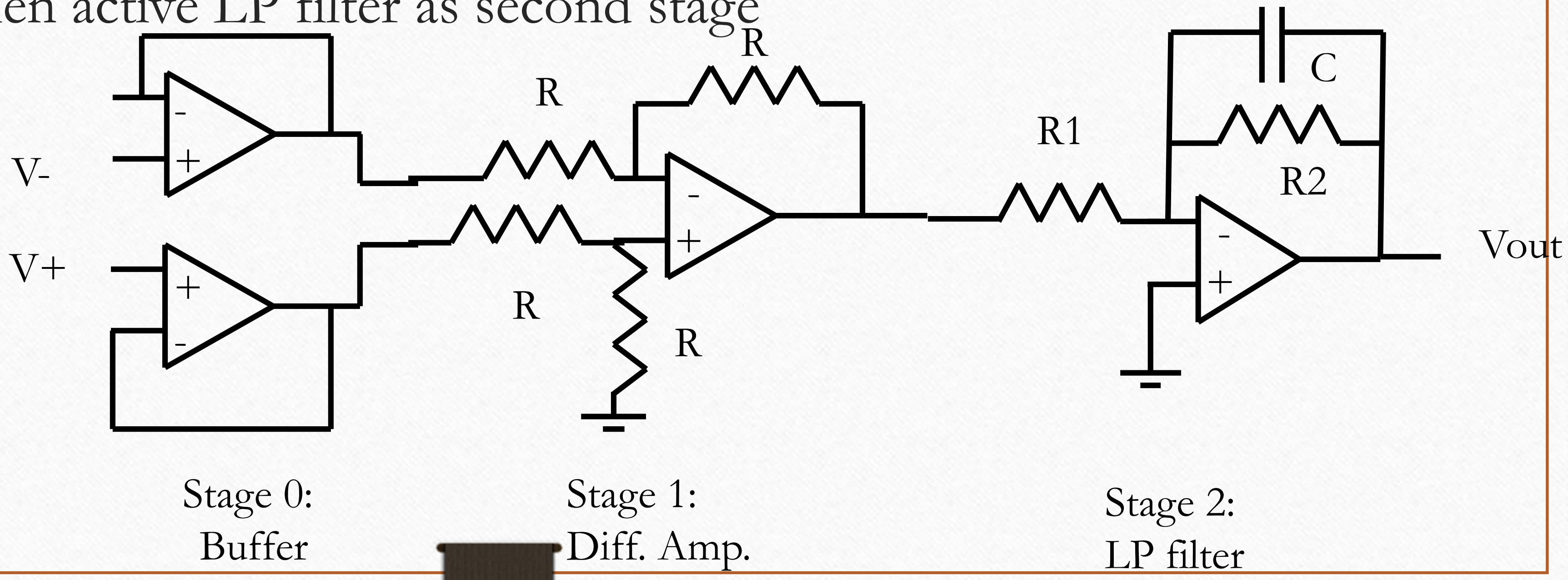
Amplitude   frequency   Phase shift

The noise frequency is calculated to be around 8 KHz
And since the signal frequency is 1 KHz
=> need LP filter with cutoff frequency around 4 KHz

Example continued

There are many ways to design this filter. Here is one way:

Since the transducer signal is differential => use a difference amplifier at first stage and then active LP filter as second stage



Example continued

Use R = 1KΩ at the buffers (no gain)

The cutoff frequency is $\omega_c = 1/CR_2$

Let C = 0.1μF and since $\omega_c = 2{,}000\ \pi$ => $R_2 = 398\ \Omega$

Gain is equal $R_2/R_1 = 10$ => R1 = 39.8 Ω

Summary

- Signal Conditioning is the process of filtering and amplification of signals
- Filters are divided into 4 types: low pass, high pass, band pass, and band reject
- Cutoff frequency, pass band and stop band are important filter characteristics
- Active filters use op-amps in their design and therefore create impedance isolation between stages. They have better accuracy than passive filters