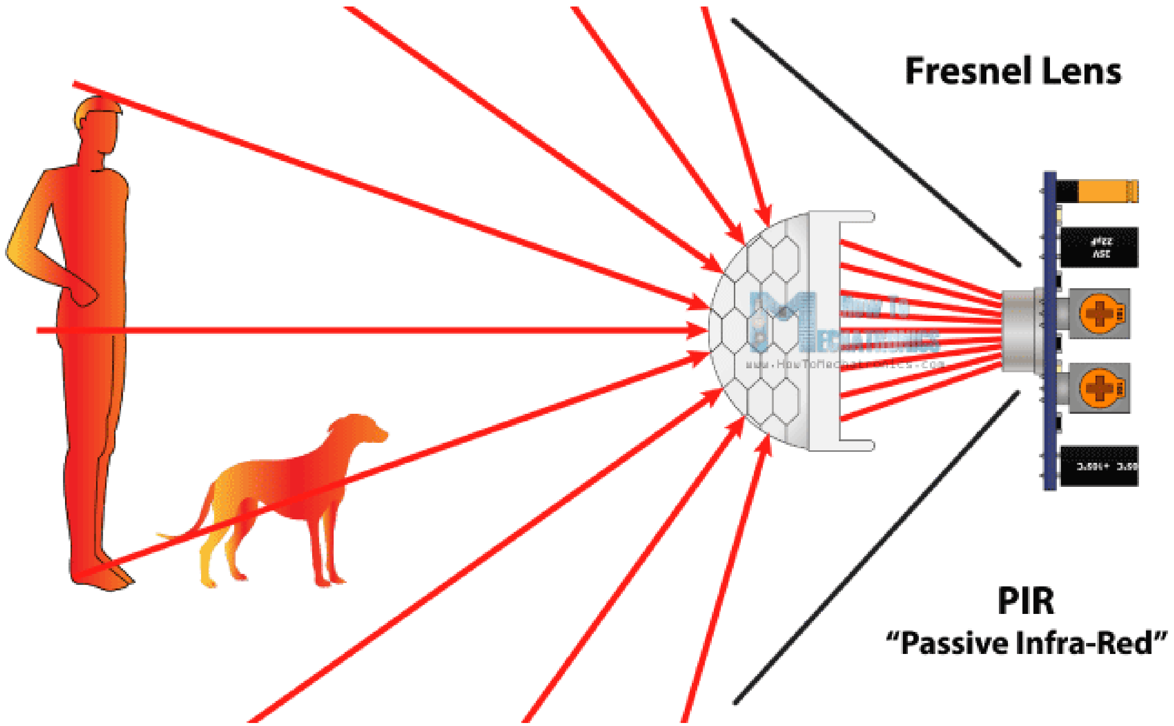
Signal Conditioning (Filters and Amplifiers)

Lecture Three

Amplifiers

- Signal conditioning elements exist to improve the quality of the output of a measurement system in some way.
- A very common type of signal processing element is the electronic amplifier, which amplifies the output of the primary sensor/transducer or conversion element, thus improving the sensitivity and resolution of measurement.
- For example, thermocouples have a typical output of only a few millivolts.
- Other types of signal conditioning element are those that filter out induced noise and remove mean levels, current to voltage conversion, etc.
- In some devices, signal processing is incorporated into a transducer, which is then known as a transmitter.

- Active circuits or modules (filters and amplifiers), on the other hand, incorporate operational amplifiers or transistors in addition to resistors and capacitors, and are more robust and effective as signal processing devices.



Signal Conditioning

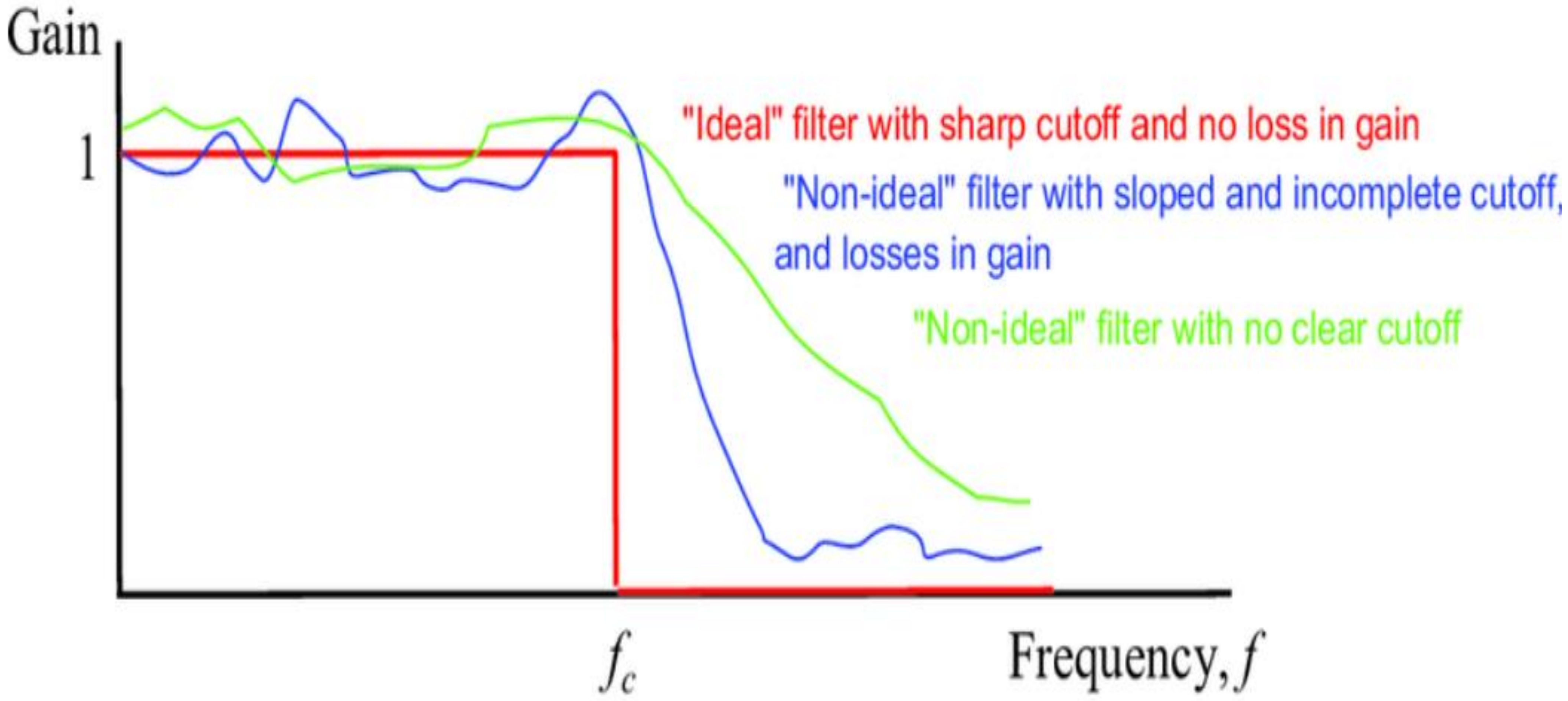
- Most sensors and transducers generate signals that must be conditioned before a measurement or DAQ device can reliably and accurately acquire the signal.
- This front-end processing is referred to as **signal conditioning**.
- The main tasks performed by signal conditioning are as follows:
    1) Filtering
    2) Amplification
    3) Linearization
    4) Isolation
    5) Excitation

Filtering

- In noisy environments, it is very difficult to acquire low magnitude signals received from sensors such as signals from thermocouples and strain gauges (in the order of mV).
- If the noise is of the same or greater order of magnitude than the required signal, the noise must first be filtered out.
- Signal conditioning equipment **often contain low-pass filters** designed to eliminate high-frequency noise that can lead to inaccurate data.
- Filtering is a process by which the unwanted noise frequencies are removed from the source signal.
- This is done before the signal is amplified to feed to the DAQ system.

- In general, analog filter hardware consists of two types of filters: Active filters and Passive filters.
- While active filters use components like OP-AMPs, passive filters consist of passive components like capacitors, inductors and resistors.
- Filters have certain attributes which define them as follows:
    1. **Cut-off Frequency:** It is the frequency beyond which the filter attenuates all the frequencies.

       In general, cut-off frequency is considered as frequency where the normalized gain of the signal drops below 0.707 times the maximum gain.
    2. **Roll Off:** This is the slope of the amplitude versus the frequency graph at the region of the cut-off frequency.
    3. **Quality Factor:** This factor determines the gain of the filter at the resonant frequency and the roll-off of the transfer characteristics on both sides of the resonant frequency.

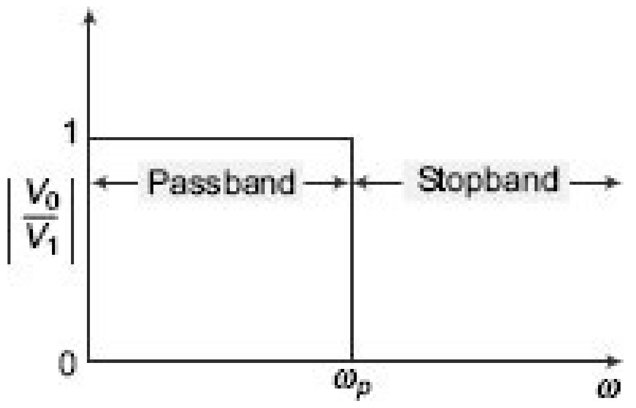

Gain
1
"Ideal" filter with sharp cutoff and no loss in gain
"Non-ideal" filter with sloped and incomplete cutoff,
and losses in gain
"Non-ideal" filter with no clear cutoff
f_c
Frequency, f

- Active filters are more frequently used as against the passive filters due to their sharper roll-of and better stability.

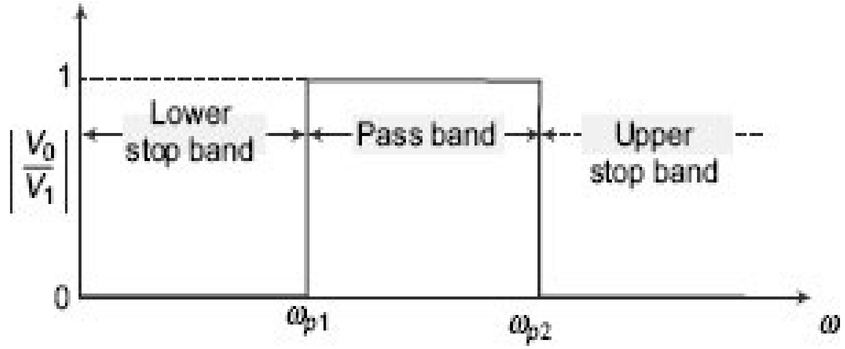
Types of Filters

- There are four kinds of filters, namely

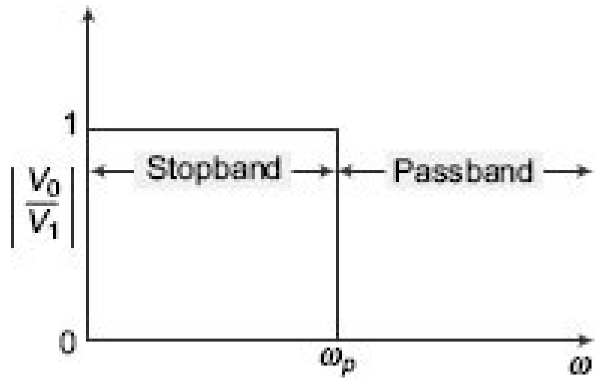
1) Low-pass filter
2) High-pass filter
3) Band-pass (selective) filter
4) Band-stop(notch) filter



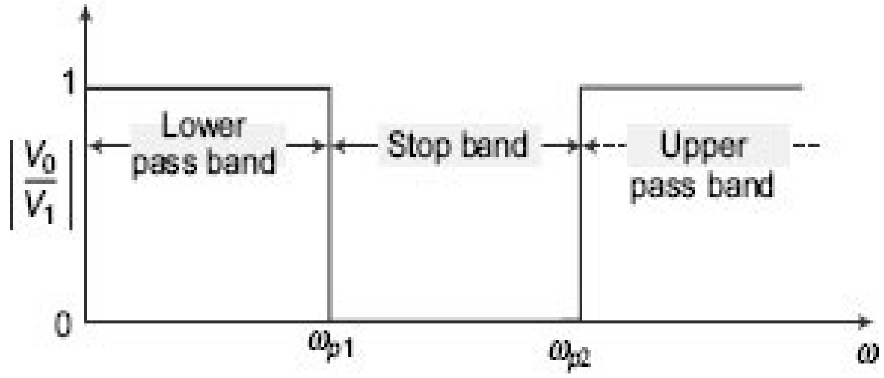
Ideal low-pass filter characteristics



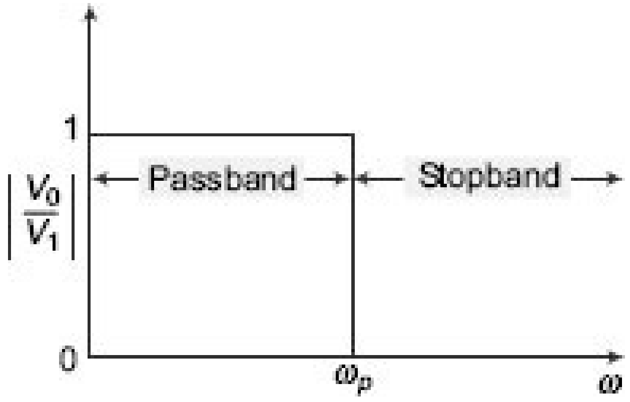
Ideal band-pass filter characteristics



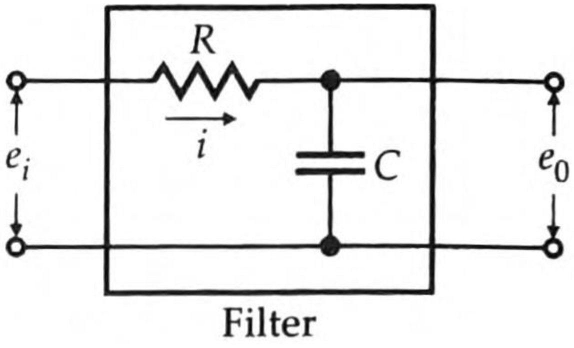
Ideal high-pass filter characteristics



Ideal band-stop filter characteristics



Ideal low-pass filter characteristics



Circuit diagram of an passive low-pass filter

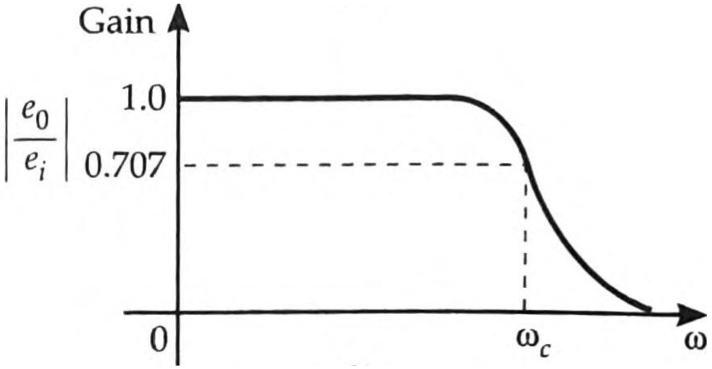


Fig. Low pass R-C filter and its characteristics.

The transfer function is

$$\frac{E_0}{E_i}(s) = \frac{1/sC}{R+1/sC} = \frac{1}{1+sRC}$$

$$= \frac{1}{1+s\tau}$$

where ω_p or ω_c are the filter cut-off frequency.

$$\frac{e_0}{e_i}(j\omega) = \frac{1}{1 + j\omega RC} = \frac{1}{1 + j\omega\tau}$$

$$\therefore \text{ Gain} \quad A = \left|\frac{e_0}{e_i}(j\omega)\right| = \frac{1}{\sqrt{1+(\omega RC)^2}}$$

$$= \frac{1}{\sqrt{1+(\omega\tau)^2}}$$

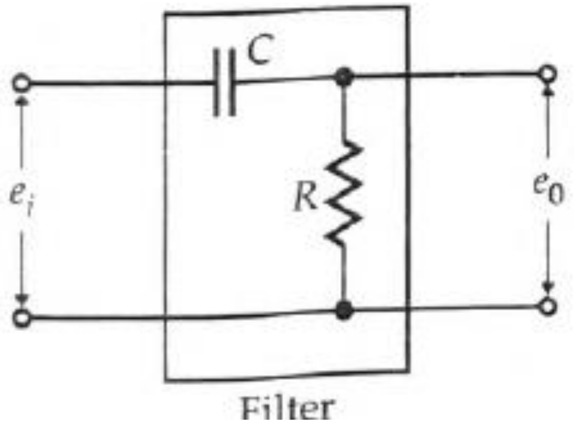
The gain drops to 0.707 at cut off frequency ω_c

$$0.707 = \frac{1}{\sqrt{1+(\omega_c RC)^2}}$$

$$\omega_c = \frac{1}{RC} = \frac{1}{\tau} \text{ rad/s}$$

The cut off frequency in Hz is : $f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi\tau}$

The transfer function of a high-pass filter is given by :



Circuit diagram of an passive high-pass filter

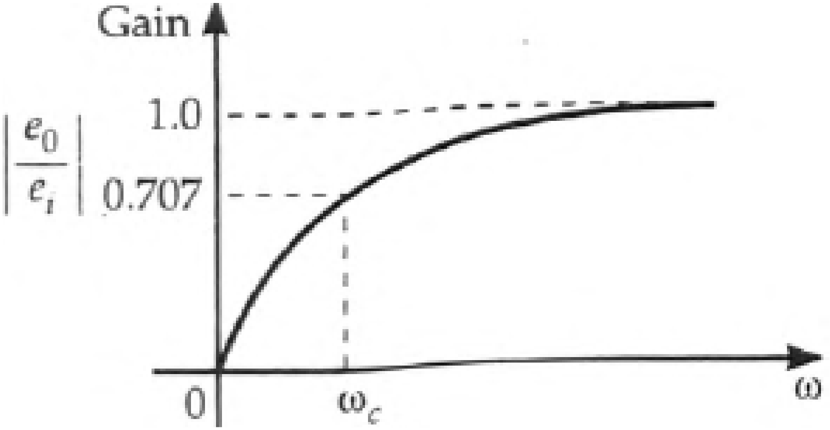


Fig. High pass R-C filter and its characteristics.

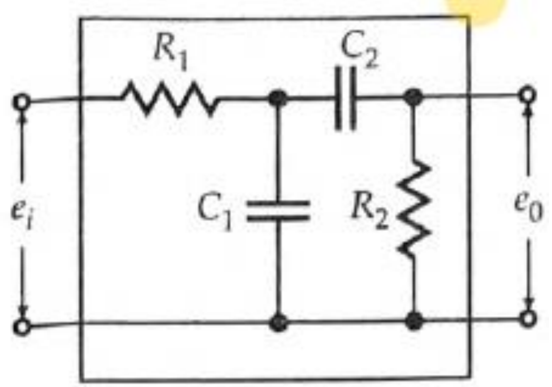
$$\frac{E_0(s)}{E_i(s)} = \frac{R}{R + 1/sC} = \frac{sRC}{1 + sRC} = \frac{\tau s}{1 + \tau s}$$

$$\frac{e_0}{e_i}(j\omega) = \frac{j\omega RC}{1 + j\omega RC}$$

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

Band Pass Filters

A simple band-pass filter can be constructed by cascading a low-pass and high-pass filter as shown



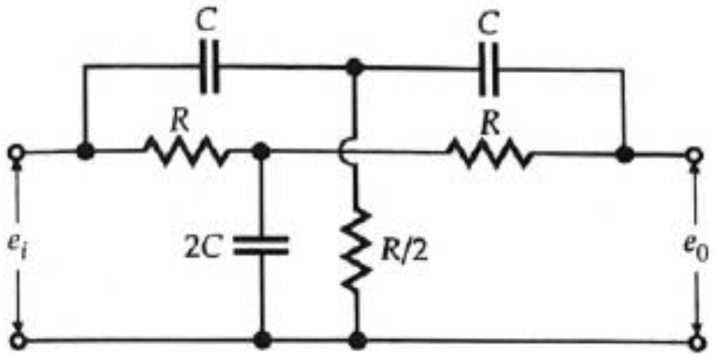
The lower cutoff frequency is

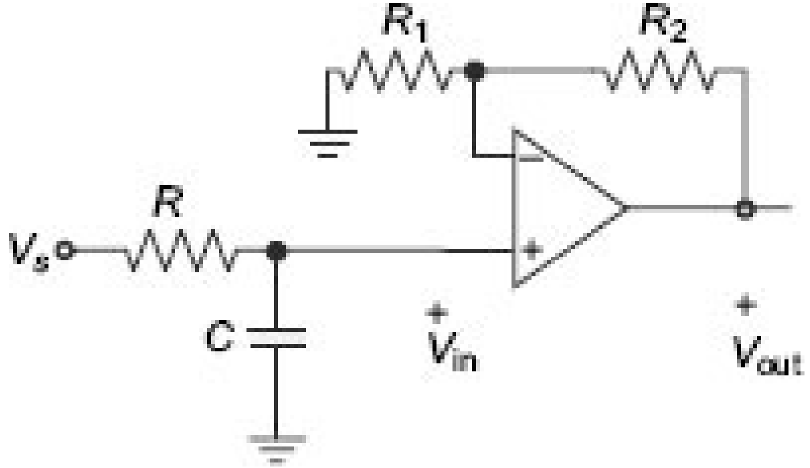
$$f_{C1} = 1/2\pi R_2 C_2$$

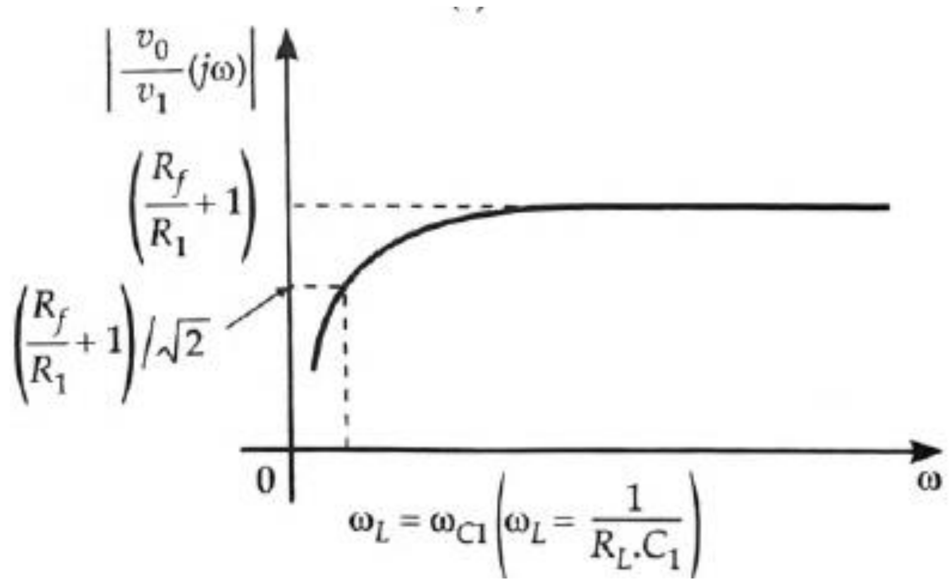
and the upper cutoff frequency is

$$f_{C2} = 1/2\pi R_1 C_1$$

Twin Notch Filter.





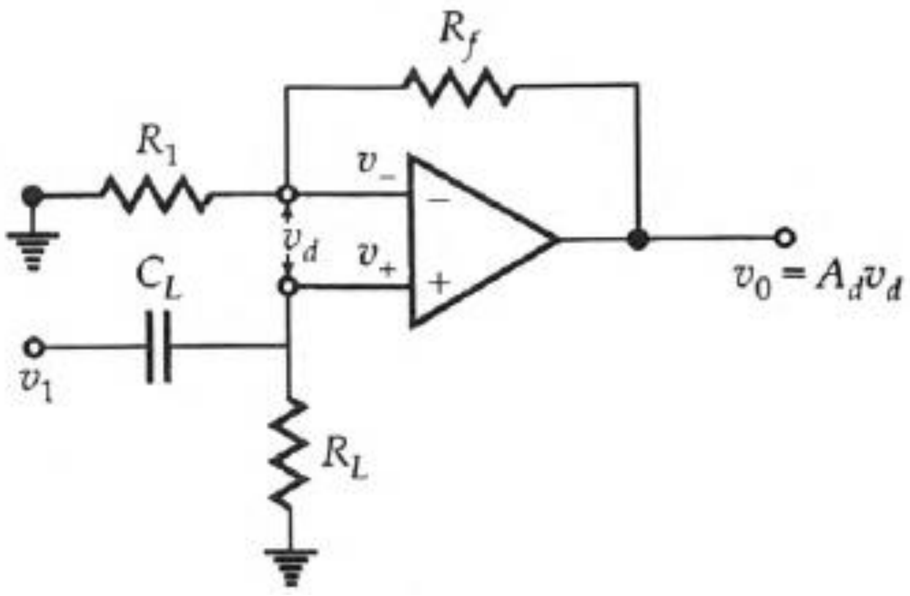


Circuit diagram of an active low-pass filter

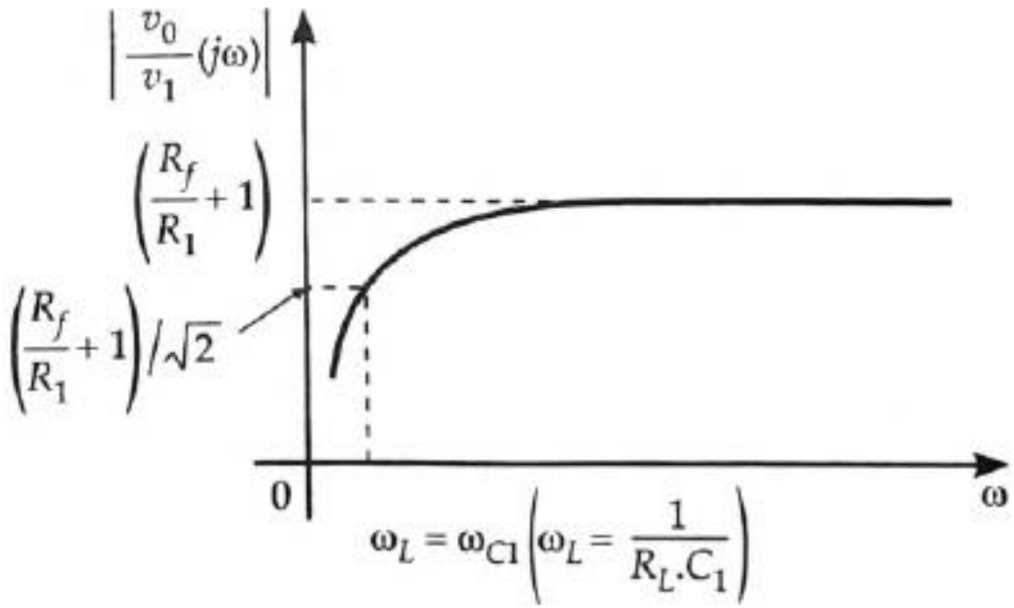
$R_f = R_2$, $R = R_L$, $C = C_L$

$$V_0 = \left(\frac{j\omega R_L C_L}{1 + j\omega R_L C_L}\right)\left(\frac{R_f}{R_1} + 1\right) V_1$$

$$\omega_{C1} = \omega_L = 1 / R_L C_L$$



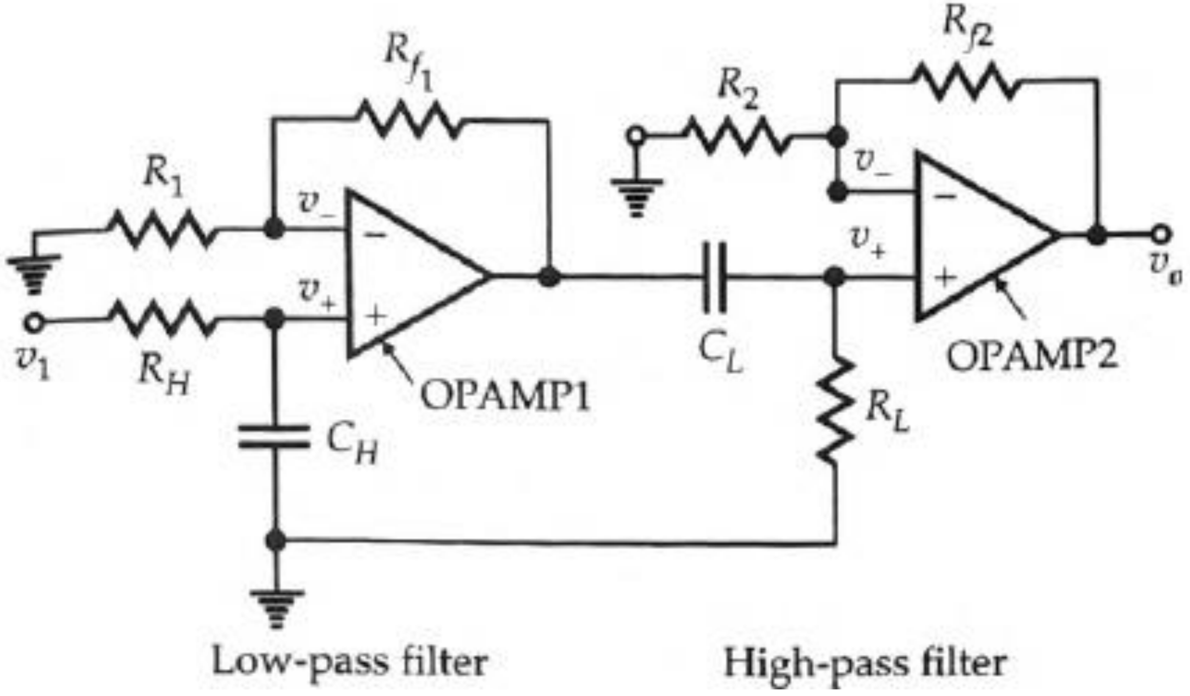
High-pass filter

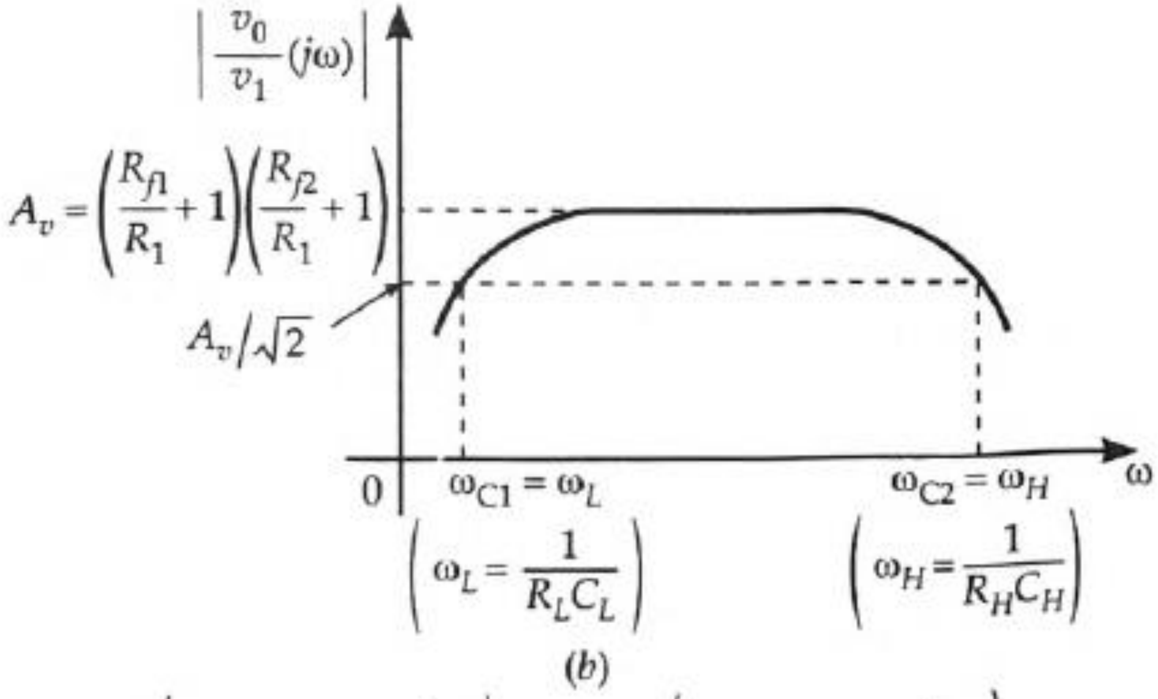


High-pass filter response.

$$V_0 = \left(\frac{j\omega R_L C_L}{1 + j\omega R_L C_L}\right)\left(\frac{R_f}{R_1} + 1\right) V_1$$

Active Band Pass Filters





$$\left(\omega_{C2} = \omega_H = \frac{1}{R_H C_H}\right) \qquad \left(\omega_{C1} = \omega_L = \frac{1}{R_L C_L}\right)$$

$$\left(\omega_{C1} = \omega_L = \frac{1}{R_L C_L}\right) \qquad \left(\omega_{C1} = \omega_H = \frac{1}{R_H C_H}\right)$$

Butterworth Filter

- This is a kind of active filter which provides a better level of low-pass filtering.
- This is achieved by cascading two or more stages of low-pass filters.
- The number of stages of filtering determines how sharp the roll-off is at the cut-off frequency.
- Figure shows a two-stage Butterworth filter.

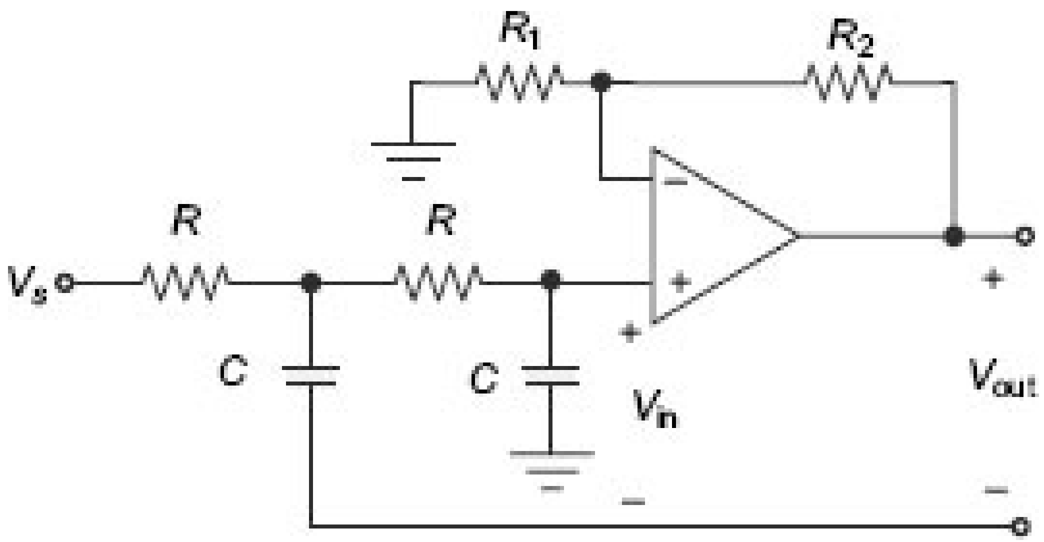


Figure: A two-stage Butterworth filter

Anti-Aliasing Filter

- Aliasing is an effect that causes different signals to become indistinguishable (or aliases of one another) when sampled.
- An anti-aliasing filter is a filter used before a signal sampler to restrict the bandwidth of a signal to satisfy the Nyquist sampling theorem over the band of interest.
- If the sampling rate is sufficiently high, the loss of fidelity is not significant.
- The Nyquist rate of a band-limited signal is twice the maximum frequency of that signal.

Amplification

- It is a process by which an input signal of weak signal strength (low amplitude) is converted into a signal of higher signal strength (high amplitude), so as to be readable by the processing devices.
- In signal conditioning, amplification serves two main purposes:
  1) Increases resolution of the input signal
  2) Increases Signal-to-Noise ratio (SNR)

Refers to OP-AMP from analogue electronics

Amplifiers

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- For example, thermocouples have a typical output of only a few millivolts.
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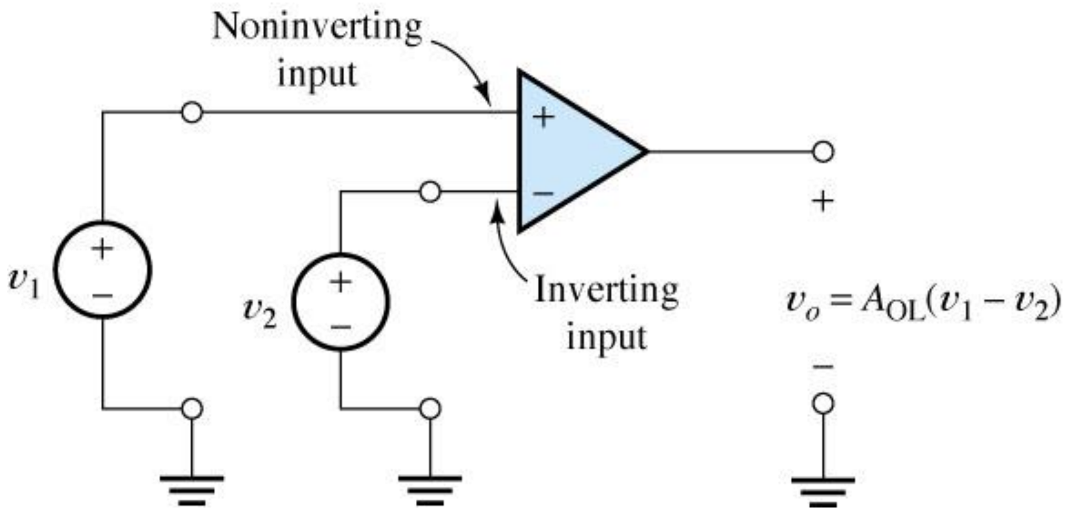
Operational Amplifier

- Operational Amplifiers take small voltages and make them MUCH larger.



Golden Rules (Op amp with negative feedback):

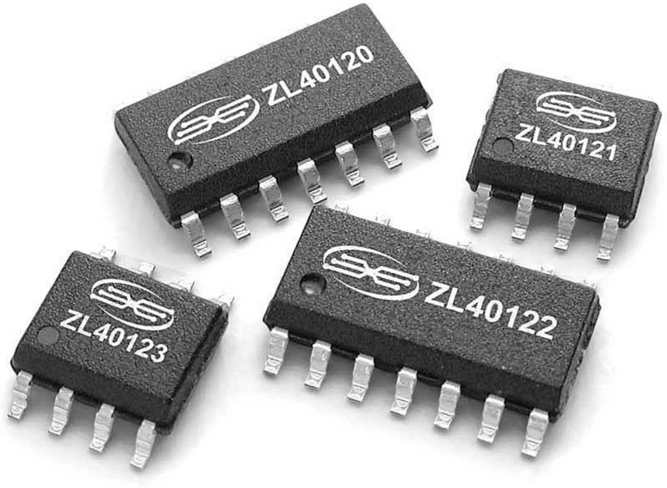
(1) No-current flows into either (+) or (-) inputs.

(2) The (+) and (-) inputs are at the same voltage.

https://www.google.com/search?q=Golden+Rules+(Op+amp+with+negative+feedback)&rlz=1C1BNSD_enTZ991TZ992&oq=Golden+Rules+(Op+amp+with+negative+feedback)&aqs=chrome..69i57j0i546l2.5576j0j15&sourceid=chrome&ie=UTF-8#fpstate=ive&vld=cid:c916f9db,vid:PT1J0dpe8j4,st:20

Operational Amplifier

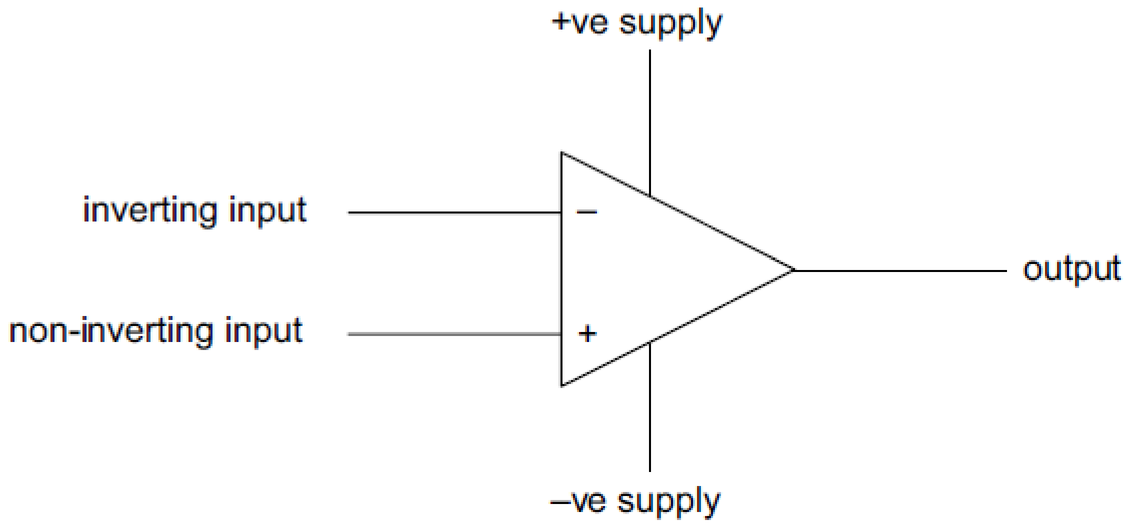
- In some applications, the change in output voltage from the potential divider may be small.
- Any small change can be amplified using an electrical circuit incorporating an operational amplifier (op-amp).
- **Operational Amplifiers**, or **Op-amps** are one of the basic building blocks of Analogue Electronic Circuits.



- It is a device that has all the properties required for nearly ideal DC amplification.
- It is an integrated circuit (IC) of about twenty transistors together with resistors and capacitors, all formed on a small slice of silicon.

The Output Voltage

- The op-amp symbol are shown:



- When connected to appropriate power supplies, an op-amp produces an output voltage V_{out} that is proportional to the difference between the voltage V^+ at the non-inverting input and the voltage V^- at the inverting input.

$$V_{out} = A_0\,(V^+ - V^-),$$

- where A_0 is the open-loop gain of the op-amp.

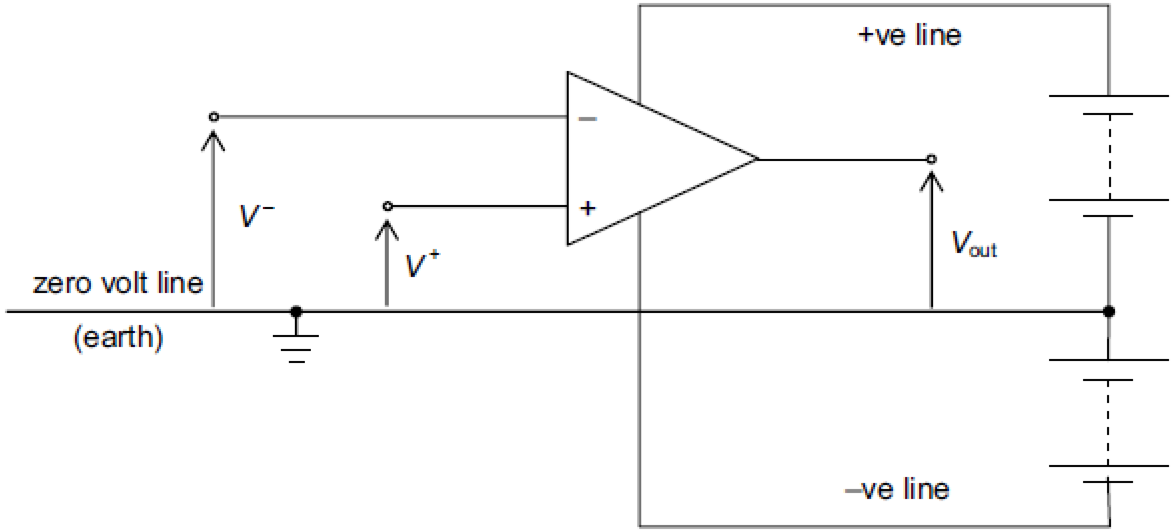
Properties of an Ideal Op-Amp

- Infinite Input impedance, (Z_{in})
  - Input impedance is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry.
- Infinite Open loop Voltage Gain, (A)
  - The main function of an operational amplifier is to amplify the input signal and the more open loop gain it has the better, so for an ideal amplifier the gain will be infinite.
- Zero Output impedance, (Z_{out})
  - The output impedance of the ideal operational amplifier is assumed to be zero so that the whole of the output voltage is provided across the output load.
- Infinite Bandwidth, (BW)
  - An ideal operational amplifier has an infinite Frequency Response and can amplify any frequency signal so it is assumed to have an infinite bandwidth.
- Infinite Slew Rate
  - Slew rate is a measure of the time delay between the changes to the input and output.
  - With an infinite slew rate there is no delay.

The Real Op-Amp

- Input impedance, (Z_{in})
  - The input impedance is not infinite but usually between 10^6 Ω and 10^{12} Ω .
- Open loop Voltage Gain, (A)
  - The open loop gain is not infinite but 10^5 for constant voltages.
- Output impedance, (Z_{out})
  - The output impedance is not zero but 10^2 Ω.
- Bandwidth, (BW)
  - Bandwidth is not unlimited.
- Slew Rate
  - Slew rate is not infinite but 10 V μs^{-1}.

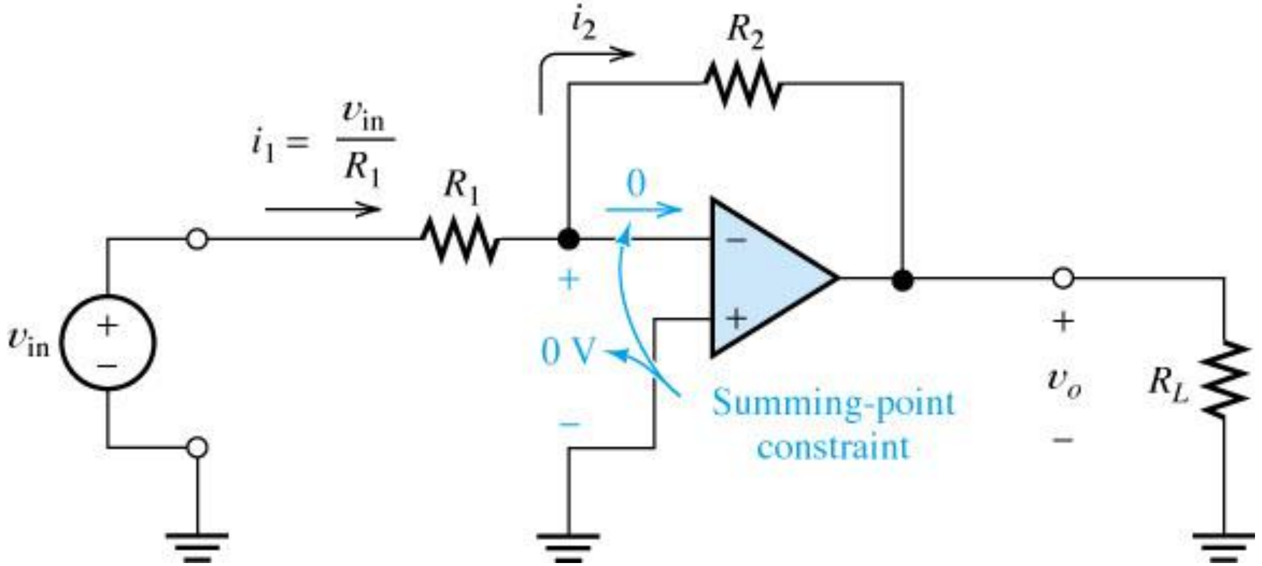
The Power Supply



- The common link between the two sets of batteries is termed the zero-volt, or earth, line.
- This forms the reference line from which all input and output voltages are measured.
- Connecting the supplies in this way enables the output voltage to be either positive or negative.

Signal amplification

- A sample configuration is given in

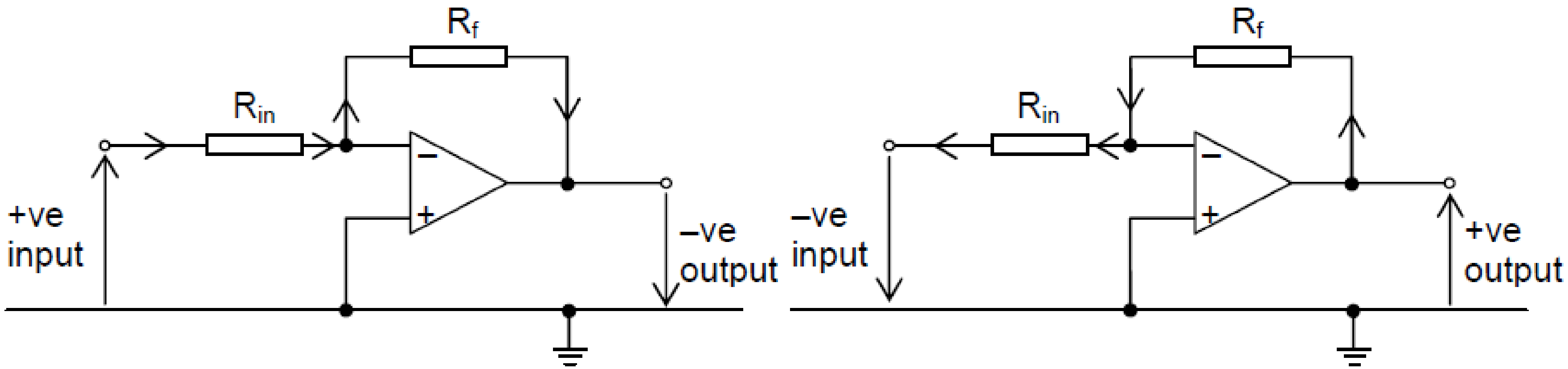


Active inverting amplifier.

$$\frac{v_i - v}{R_1} = \frac{v \quad - v_o}{R_2}$$

$$v_o = -\frac{R_2}{R_1} v_i$$

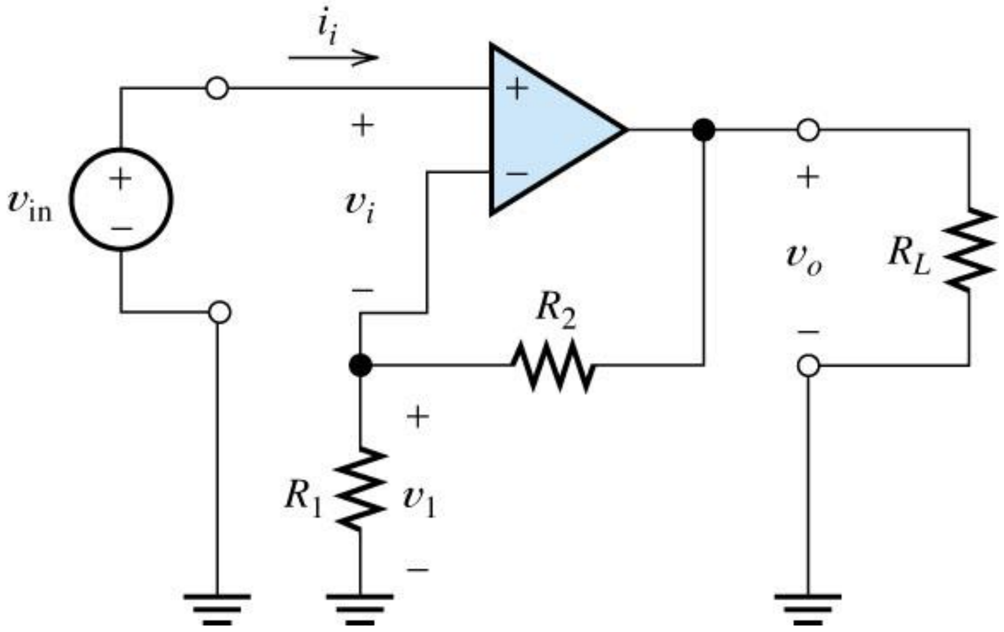
The Inverting Amplifier



- If the input is negative, current flows in the opposite direction but it is still the same current flowing through both R_{in} and R_f.

- $$A_0 = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

Noninverting Amplifier



Noninverting amplifier

$$\frac{v_i}{R_1}+\frac{v_i-v_o}{R_2}=0$$

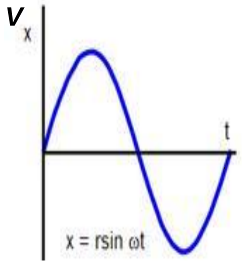
$$\frac{v_o}{R_2}=v_i\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$$

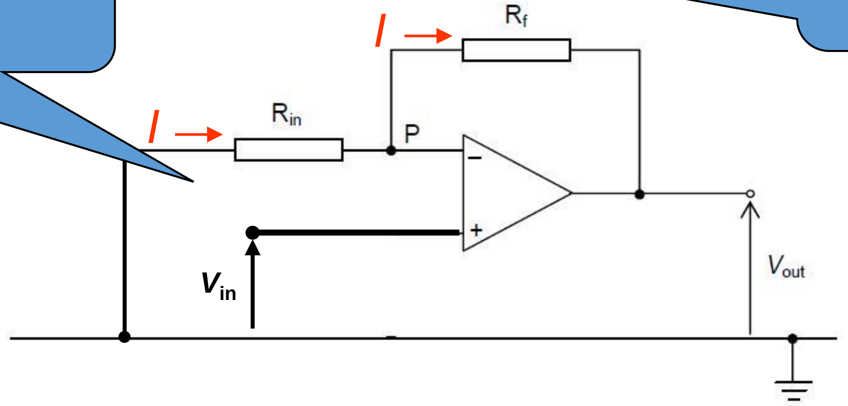
$$\frac{v_o}{v_i}=\left(1+\frac{R_2}{R_1}\right)$$

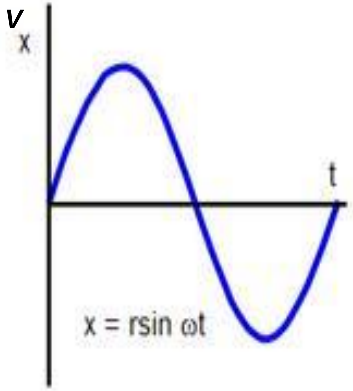
The Non-inverting Amplifier

For non-inverting amplifier, V_{in} is fed into V^+.

The non-inverting amplifier is a negative feedback connection.







At V^+, $V = V_{in}$

To ensure amplifier is not saturated, $V^- \approx V^+ \approx V_{in}$

As $V_P = V^-$, therefore $V_P = V_{in}$

Current through R_{in} = Current through $R_f = I$

p.d. across R_{in} and R_f: $V_{out} - 0 = I\,(R_{in} + R_f)$

p.d. across R_{in}: $V_p - 0 = I\,R_{in} \rightarrow V_{in} = I\,R_{in}$

Therefore, $V_{out} / V_{in} = (R_{in} + R_f) / R_{in}$

A_0

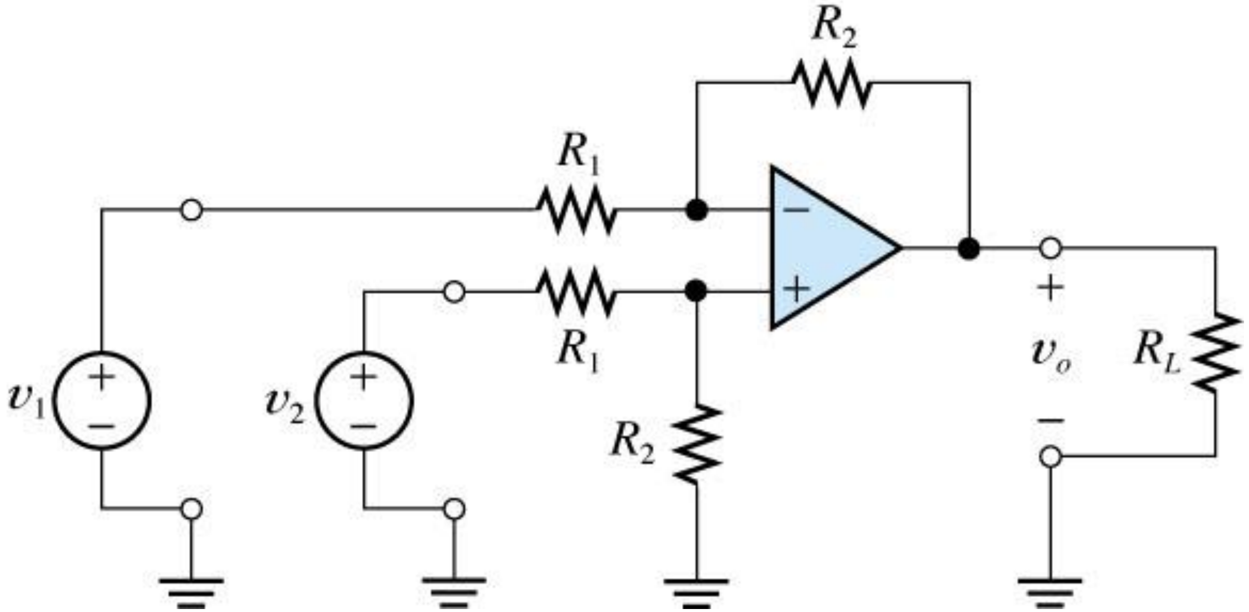
$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_{in}}$$

The non-inverting amplifier:

- increases the output
- produces an output voltage that is in phase with the input voltage.

Differential amplification

- common amplifier configuration used to amplify the small difference that may exist between two voltage signals, VA and VB.
- These may represent the pressures on either side of an obstruction device placed in a pipe to measure the flow rate of fluid flowing.
- The output voltage Vo is determined as follows



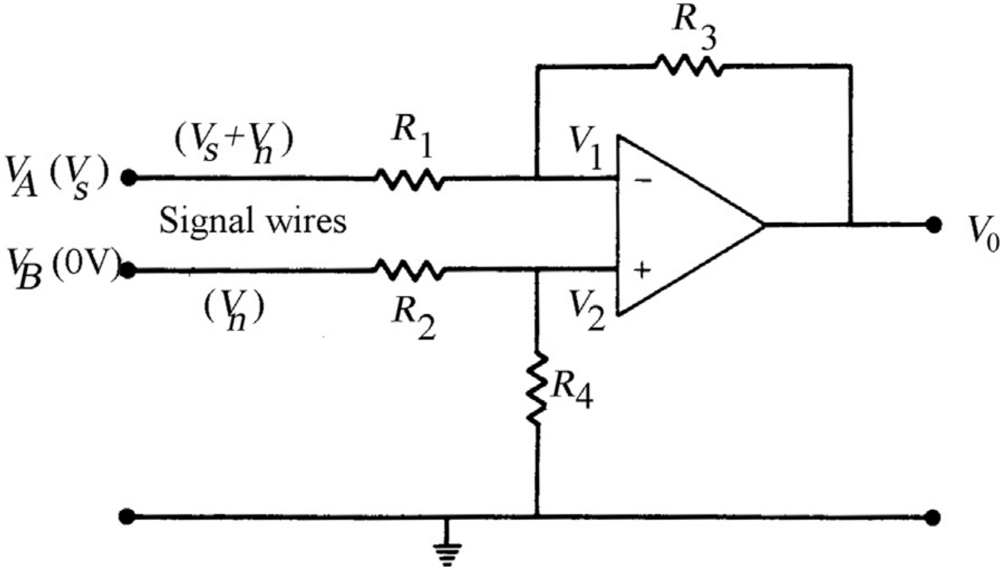


Fig. Active differential amplifier

$$\frac{V_A - V_1}{R_1} = \frac{V_1 - V_o}{R_3}$$

$$V_2 = \frac{R_4}{R_2 + R_4} V_B$$

$$V_2 \approx V_1$$

$$\frac{V_0}{R_3} = V_1 \left(\frac{1}{R_1} + \frac{1}{R_3} \right) - \frac{V_A}{R_1}$$

$$V_0 = V_1 \left(\frac{R_1 + R_3}{R_1} \right) - V_A \frac{R_3}{R_1}$$

$$V_0 = \frac{R_4}{R_2 + R_4} \left(\frac{R_1 + R_3}{R_1} \right) V_B - \frac{R_3}{R_1} V_A$$

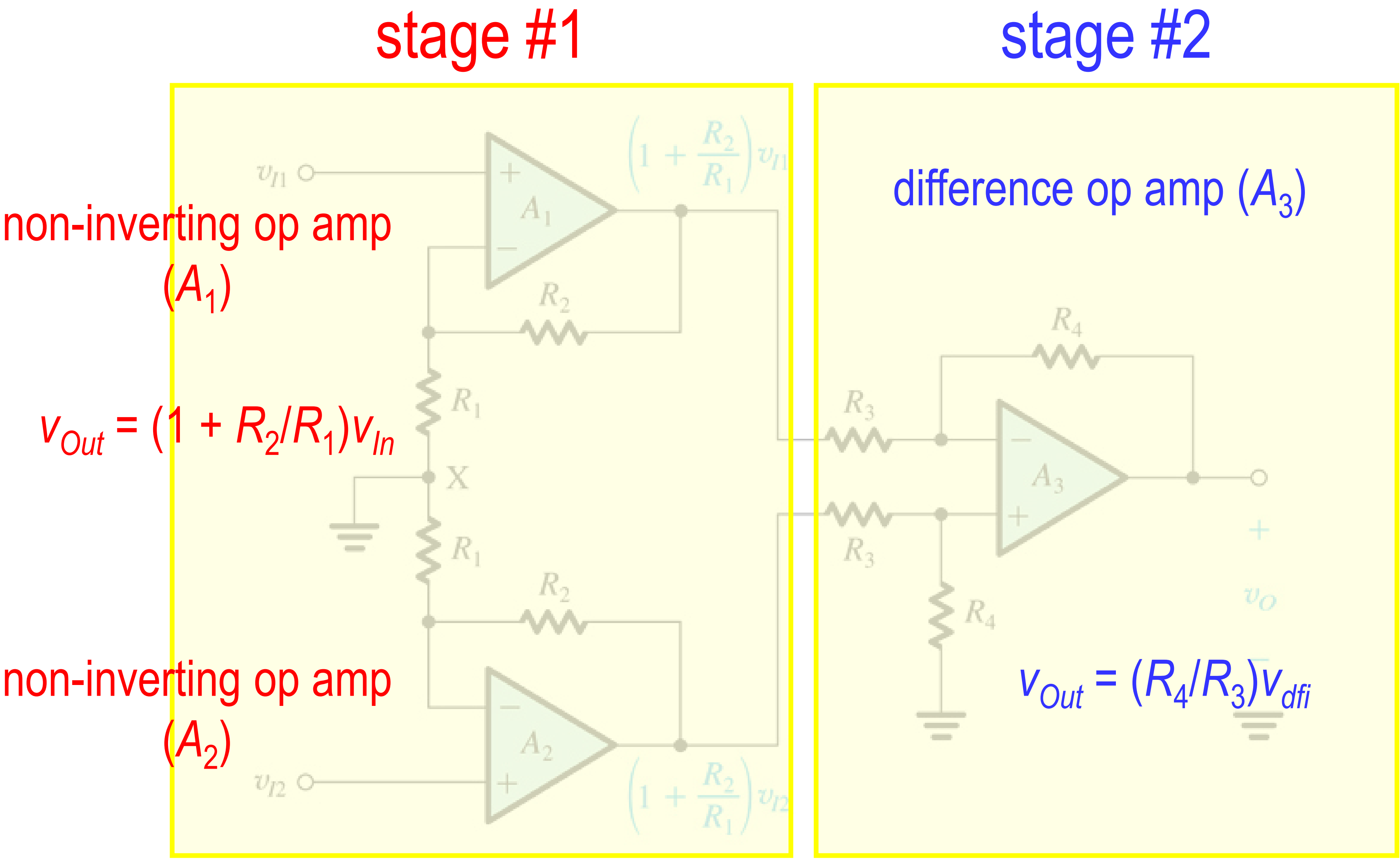
Now, for $R_3 = R_1$ and $R_4 = R_2$, these equations resolve into:

$$V_0 = V_B - V_A$$

INSTRUMENTATION AMPLIFIER

- For applications requiring the amplification of very low-level signals, a special type of amplifier known as an instrumentation amplifier is used.
- The advantage of the instrumentation amplifier compared with a standard operational amplifier is that its differential input impedance is much higher.
- In consequence, its common mode rejection capability is much better.
- This means that, if a twisted wire pair is used to connect a transducer to the differential inputs of the amplifier, any induced noise will contaminate each wire equally and will be rejected by the common mode rejection capacity of the amplifier.

Figure: A popular circuit for an instrumentation amplifier.



$$\overbrace{v_{Out} = \underbrace{\frac{R_4}{R_3}\left(1+\frac{R_2}{R_1}\right)}_{\mathbf{A}_{Inst}(\underline{R})} v_{dfi}}^{\text{transfer function for instrumentation amplifier of figure}}$$

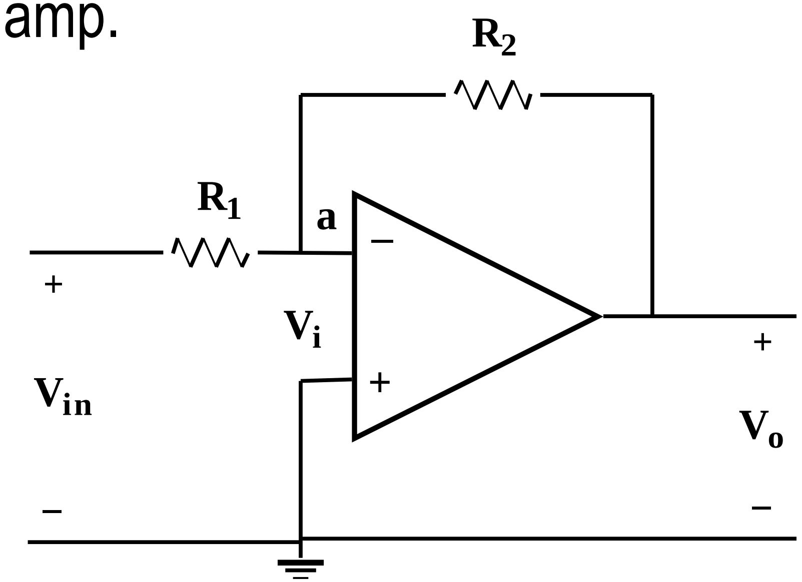
additional voltage gain

- **advantages** of instrumentation amp
  - very high input resistance
  - high differential gain
  - symmetric gain (assuming that A_1 and A_2 are matched)
- **disadvantages** of instrumentation amp
  - A_{Di} and A_{Cm} are equal in first stage – meaning that the common-mode and differential inputs are amplified with equal gain…

Recall:

- **advantages** of instrumentation amp
  - very high input resistance
  - high differential gain
  - symmetric gain (assuming that A_1 and A_2 are matched)
- **disadvantages** of instrumentation amp
  - A_{Di} and A_{Cm} are equal in first stage – meaning that the common-mode and differential inputs are amplified with equal gain…
  - need for matching – if two op amps which comprise stage #1 are not perfectly matched, one will see unintended effects

The inverting op amp.

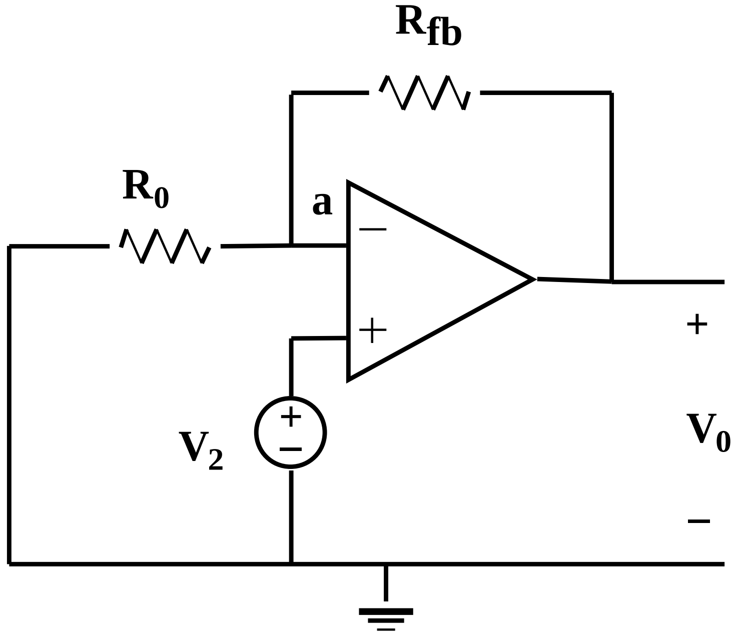


$$\frac{(V_{in}+V_i)}{R_1} = -\frac{(V_i+V_o)}{R_2}$$

With V_i = 0 we have;

$$V_0 = \frac{-R_2}{R_1} V_{in}$$

The noninverting op amp.



$$\frac{\boldsymbol{V_2}}{\boldsymbol{R_0}} + \frac{(\boldsymbol{V_2}-\boldsymbol{V_0})}{\boldsymbol{R_{fb}}} = \mathbf{0}$$

so

$$\frac{\boldsymbol{V_0}}{\boldsymbol{R_{fb}}} = \boldsymbol{V_2}\left[\frac{\mathbf{1}}{\boldsymbol{R_0}} + \frac{\mathbf{1}}{\boldsymbol{R_{fb}}}\right]$$

which gives,

$$\boldsymbol{V_0} = \left(\mathbf{1} + \frac{\boldsymbol{R_{fb}}}{\boldsymbol{R_0}}\right)\boldsymbol{V_2}$$

- Amplification mainly serves for increasing resolution of the input signal.
- If, for example, a low-level signal of the order of a few mV is fed to a 12-bit ADC, there will be a loss of precision as the resolution of the ADC is of the order of 2 mV.
- However, if the signal is amplified to the order of 10 V (full scale voltage for ADC), we get the maximum precision.
- Amplifying a signal before sending it through a cable to the receiving end enables high SNR to the noises introduced in the path having noise interference.
- This ensures the improved precision of the measurement.
- If, however, the signal is amplified after the noise interference causes low SNR which implies the noise causes a considerable error in the input signal.