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Applications of operational Amplifiers UNIT-II

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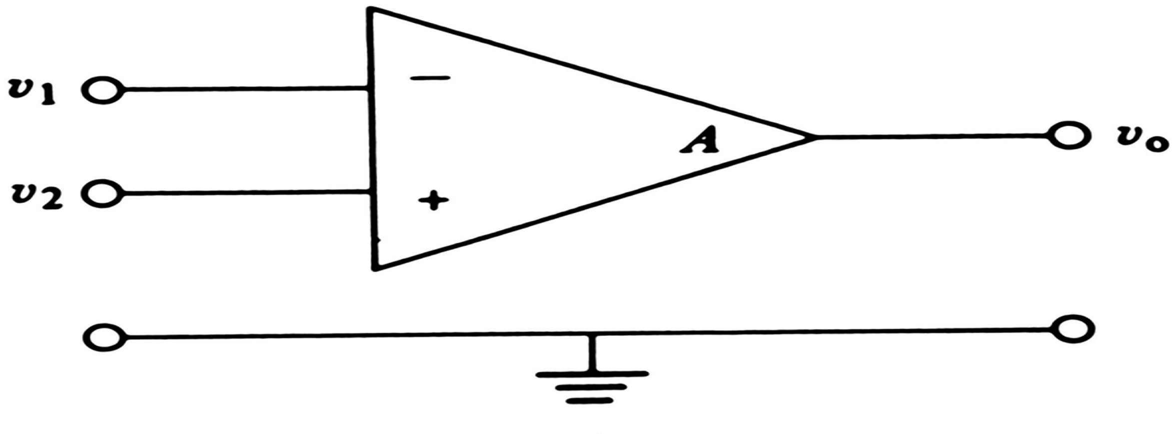
Two Basic Rules



- **Rule 1**
  - When the op-amp output is in its linear range, the two input terminals are at the same voltage.
- **Rule 2**
  - No current flows into or out of either input terminal of the op amp.

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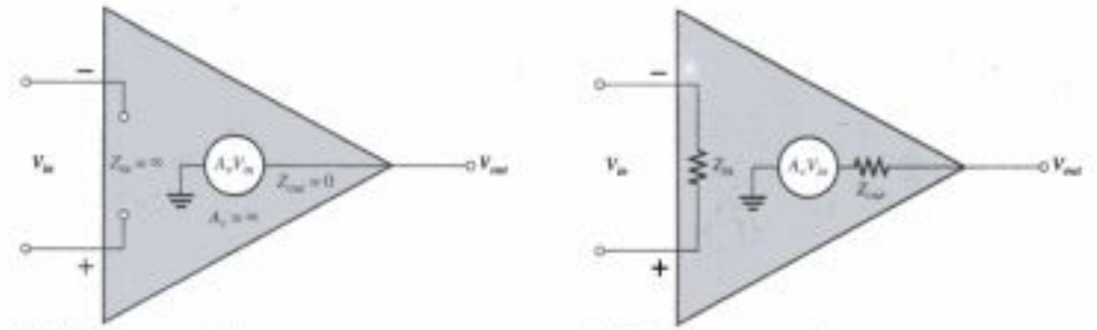
Characteristics of an Ideal Operational amplifier

Ideal op-amp has following characteristics -

- **Input Resistance Ri= ∞**
- **Output Resistance Ro= 0**
- **Voltage Gain A = ∞**
- **Bandwidth = ∞**
- **Perfect balance i.e vo= 0 when v1= v2**
- **Characteristics do not drift with temperature**



(a) Ideal op-amp representation (b) Practical op-amp representation

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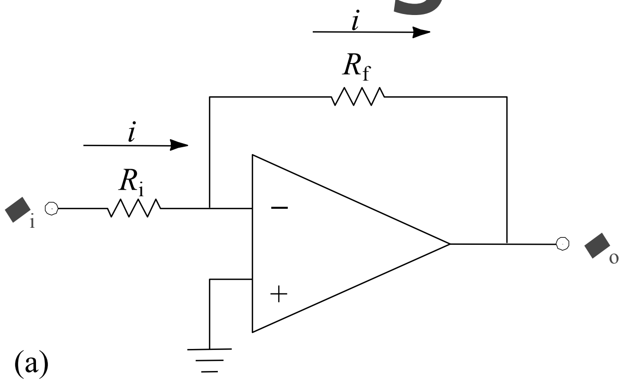
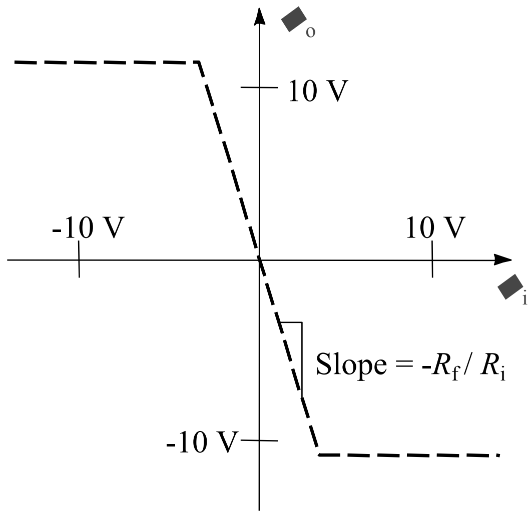
Inverting Amplifier





(b)

$$v_o = -\frac{R_f}{R_i} v_i \qquad G = \frac{v_o}{v_i} = -\frac{R_f}{R_i}$$

(a) An inverting amplified. Current flowing through the input resistor R_i also flows through the feedback resistor R_f .

(b) The input–output plot shows a slope of $-R_f / R_i$ in the central portion, but the output saturates at about ±13 V.

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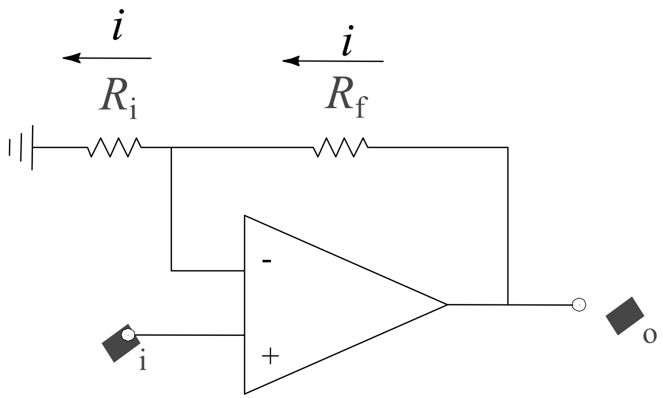
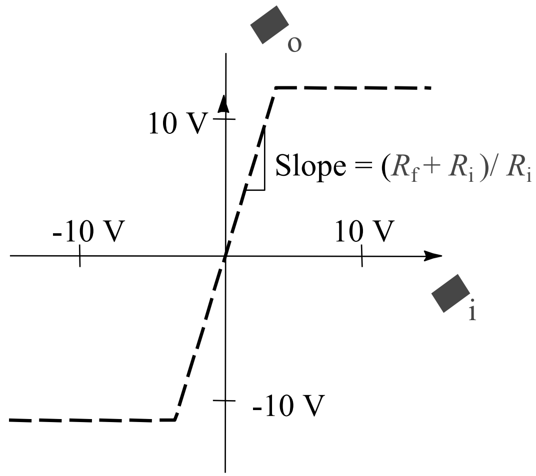
Noninverting Amplifier





$$v_o = \frac{R_f + R_i}{R_i} v_i$$

$$G = \frac{R_f + R_i}{R_i} = \left(1 + \frac{R_f}{R_i}\right)$$

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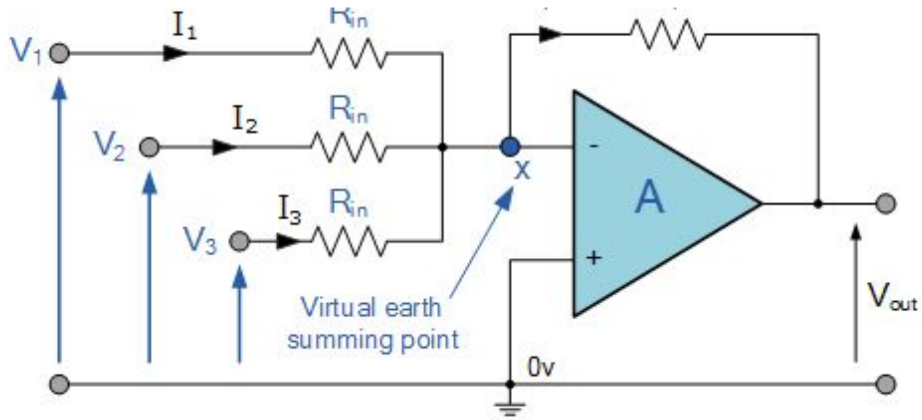
Summing Amplifier



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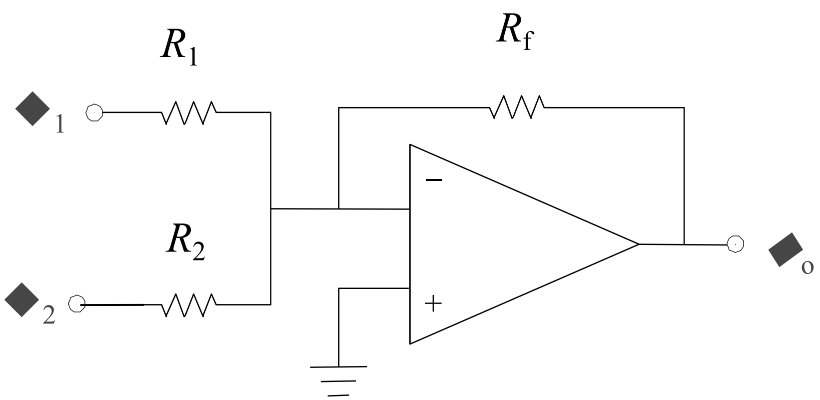
Summing Amplifier



$$v_o = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_2}\right)$$

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Summing Amplifier

$$I_F = I_1 + I_2 + I_3 = -\left[\frac{V1}{Rin} + \frac{V2}{Rin} + \frac{V3}{Rin}\right]$$

Inverting Equation: $Vout = -\frac{Rf}{Rin} \times Vin$

then, $-Vout = \left[\frac{R_F}{Rin}V1 + \frac{R_F}{Rin}V2 + \frac{R_F}{Rin}V3\right]$

$$-Vout = \frac{R_F}{R_{IN}}\left(V1 + V2 + V3....etc\right)$$

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Non Inverting Summer

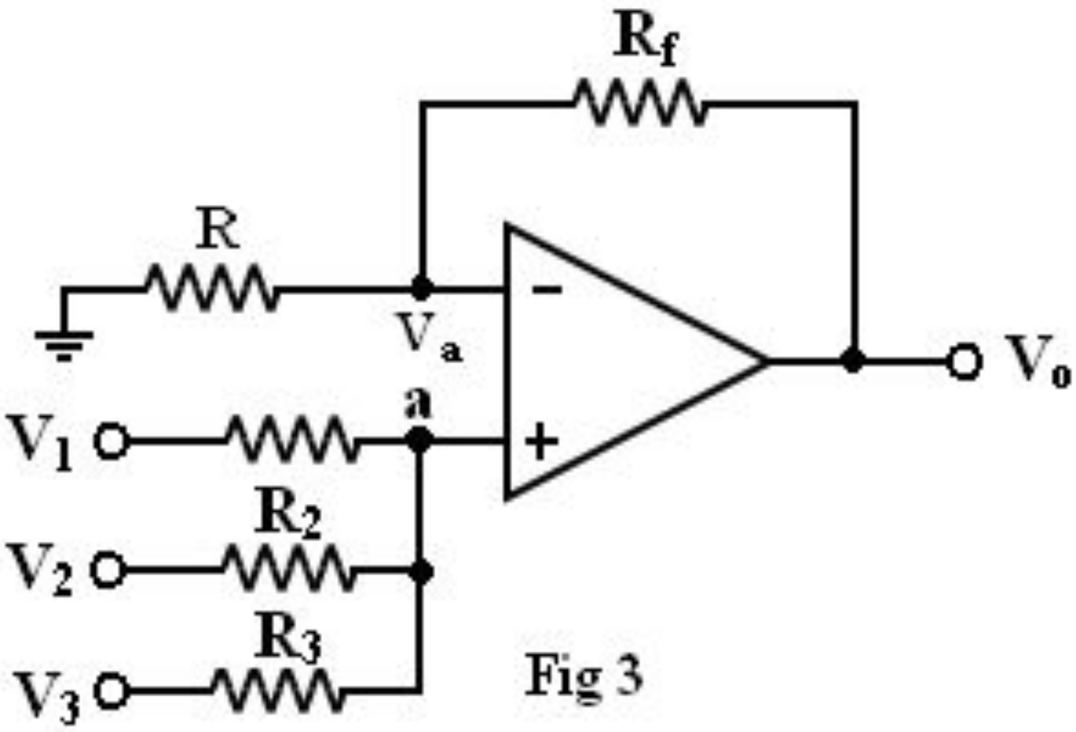

Fig 3

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Adder-Subtractor

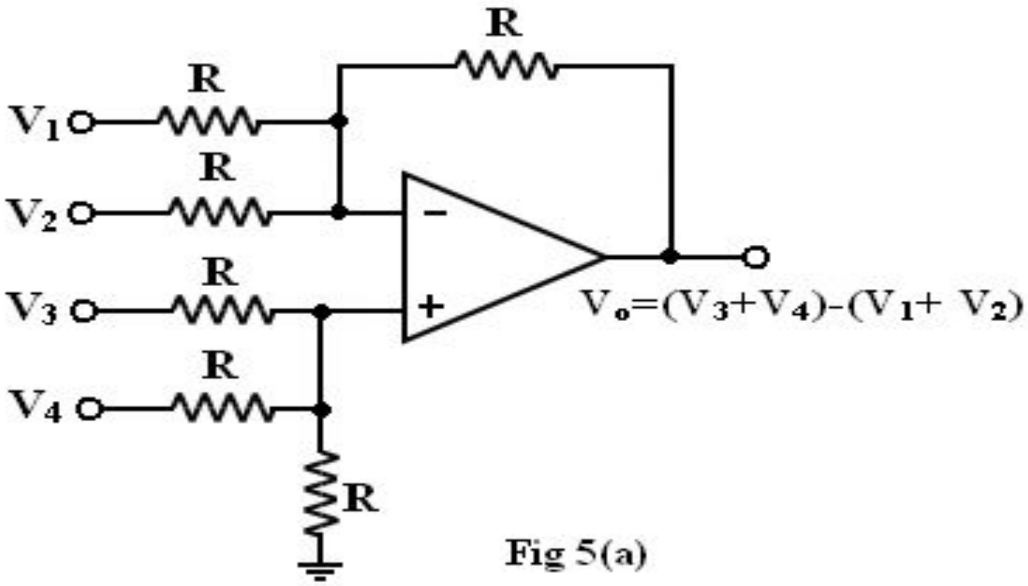

Fig 5(a)

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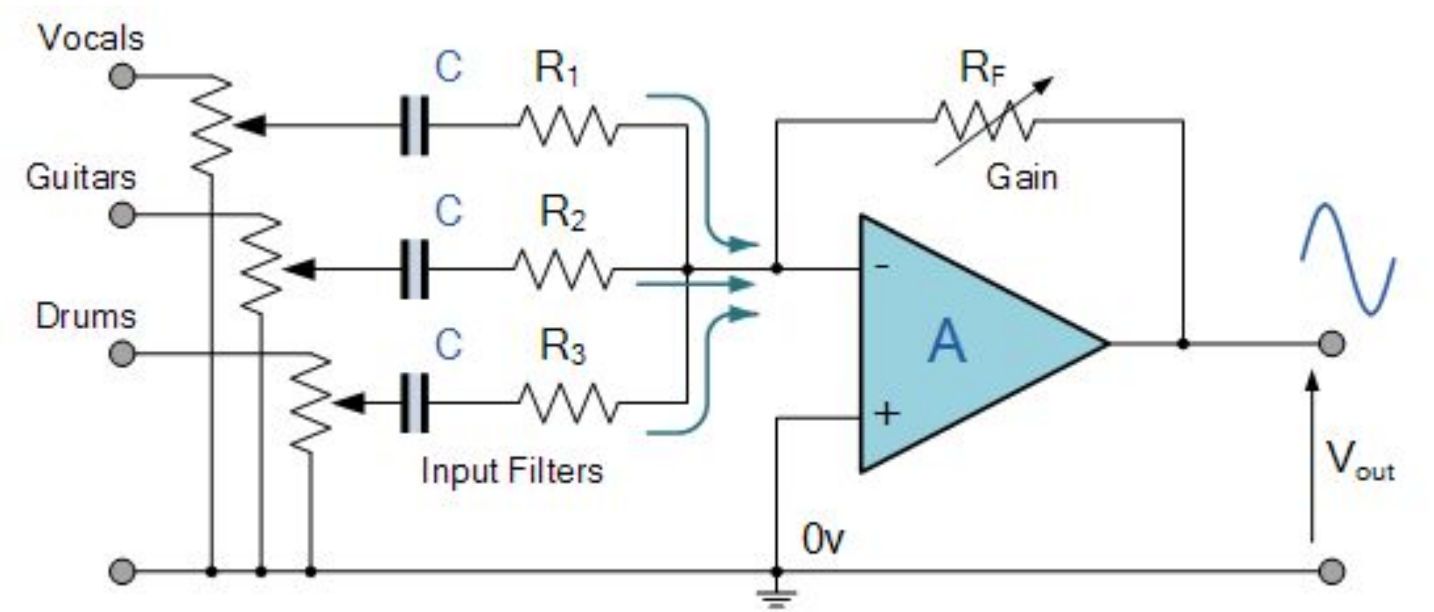
Audio Mixer



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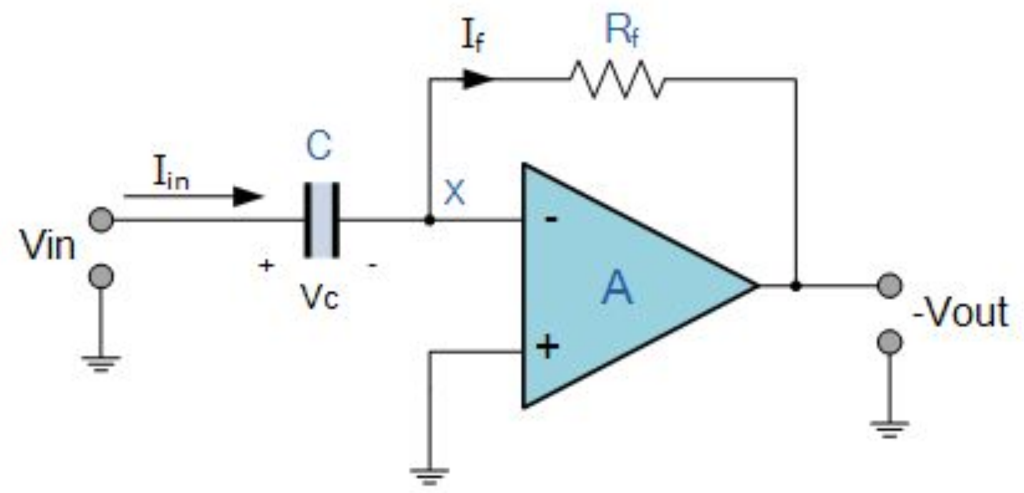
Op-amp Differentiator



Applying KCL at inverting node of opamp, we get

$$(0-V_{out})/R + I_c = 0$$

$$I_c = V_{out}/R$$

where $I_c = C*d(0-V_{in})/dt$. Hence we get $V_{out} = -R*C*dV_{in}/dt$.

$$V_{OUT} = -R_F C \frac{dV_{IN}}{dt}$$

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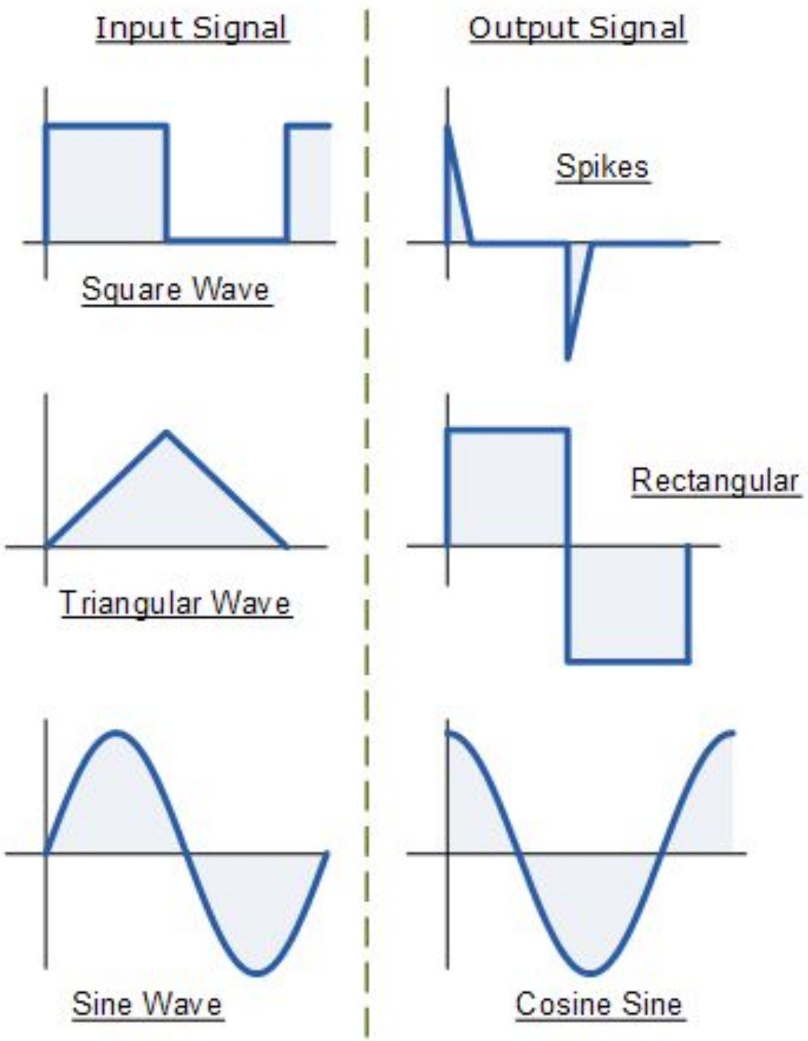
Op-amp Differentiator



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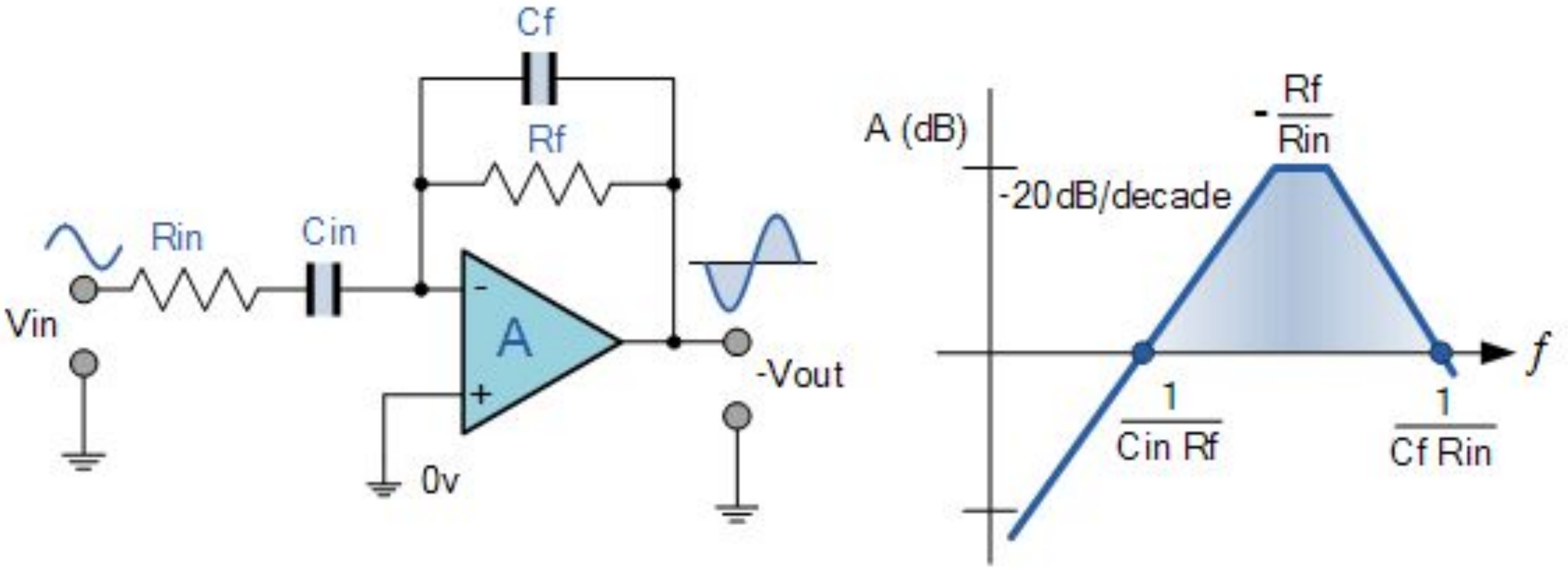
Improved Opamp Differentiator



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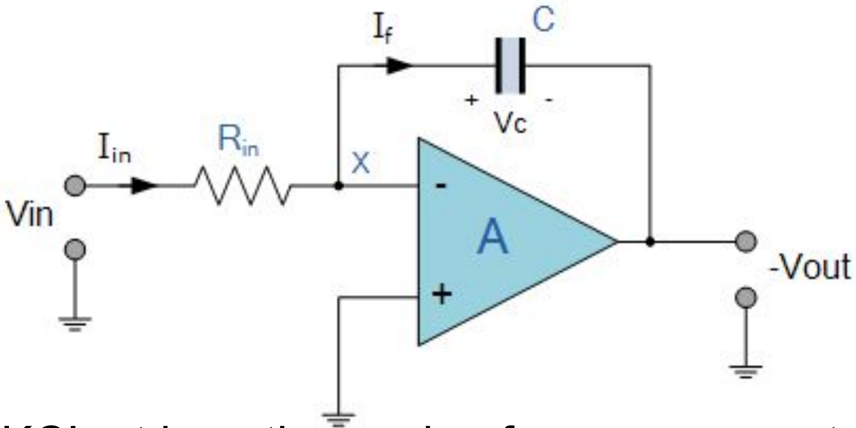
Opamp Integrator



Applying KCL at inverting node of opamp, we get

$$(0\text{-}V_{out})/R + I_c = 0$$

$$Ic = Vout/R= 1/\int V_{in} * dt$$

$$V_{out} = -\frac{1}{R_{in}C}\int_0^t V_{in}\,dt = -\int_0^t V_{in}\frac{dt}{R_{in}.C}$$

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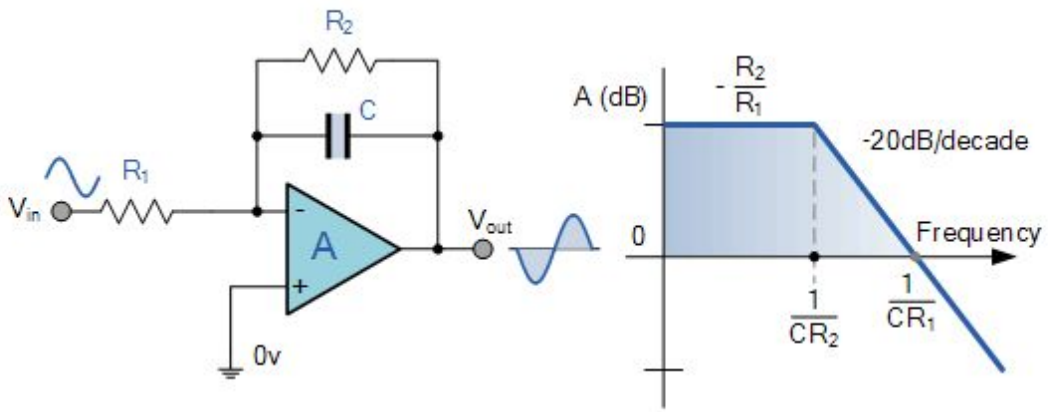
Practical Integrator



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$$\text{D.C. Voltage Gain, } (Av_0) = -\frac{R_2}{R_1}$$

$$\text{A.C. Voltage Gain, } (Av) = -\frac{R_2}{R_1} \times \frac{1}{(1 + 2\pi f C R_2)}$$

$$\text{Corner Frequency, } (f_0) = \frac{1}{2\pi C R_2}$$

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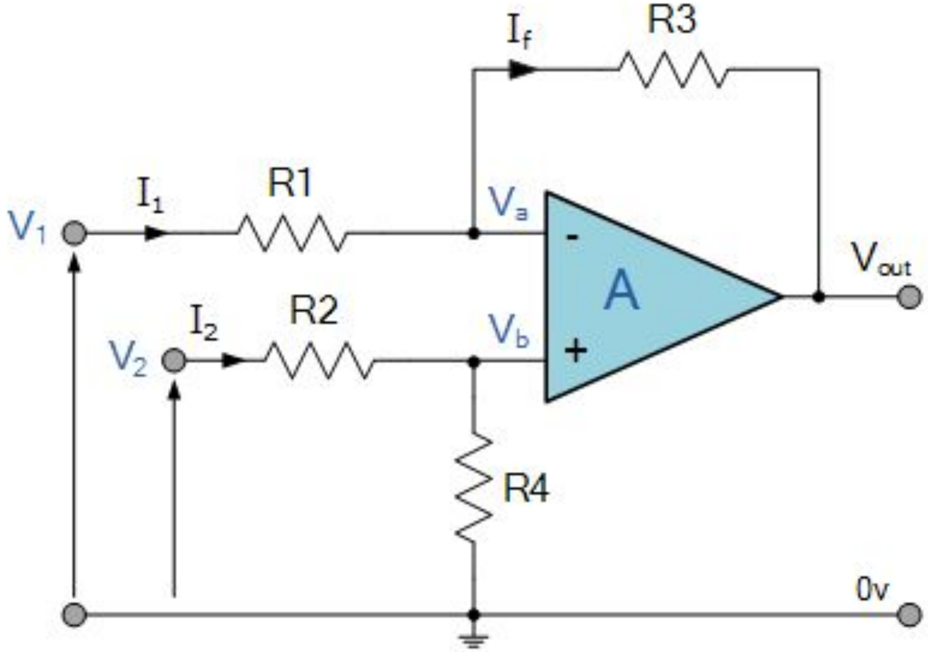
Differential Amplifier



$$V_{out} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right)$$

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- If V_1 = o then the op-amp became a non inverting amplifier. V_{out} for non inverting amplifier is given as :

$$V_{out(b)} = \frac{R_1 + R_3}{R_1}.V_b$$

$$and\ V_b = V_2\left(\frac{R_4}{R_4 + R_2}\right)$$

$$V_{out(b)} = V_2\left(\frac{R_4}{R_4 + R_2}\right).\frac{R_1 + R_3}{R_1}$$

- If V_2 = o then the op-amp function as inverting amplifier, V_{out} for inverting amplifier is given as :

$$V_{out(a)} = -V_a.\frac{R_3}{R_1} = -V_1.\frac{R_3}{R_1}$$

- The summing of $V_{out(a)}$ and $V_{out(b)}$ is given as :

$$V_{out} = V_{out(a)} + V_{out(b)}$$

$$V_{out} = -V_1.\frac{R_3}{R_1} + V_2\left(\frac{R_4}{R_4 + R_2}\right).\frac{R_1 + R_3}{R_1}$$

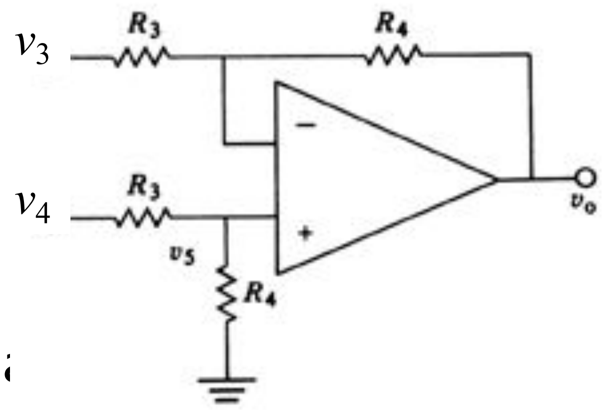
- If $R_1 = R_2$ and $R_3 = R_4$ we find :

$$V_{out} = \frac{R_3}{R_1}.(V_2 - V_1)$$

Differential Amplifiers

- **Differential Gain G_d**

$$G_d = \frac{v_o}{v_4 - v_3} = \frac{R_4}{R_3}$$



- **Common Mode Gain G_c**
  - For ideal op amp if the inputs are equa then the output = 0, and the G_c = 0.
  - No differential amplifier perfectly rejects the common-mode voltage.

$$v_o = \frac{R_4}{R_3}(v_4 - v_3)$$

- **Common-mode rejection ratio *CMMR***
  - Typical values range from 100 to 10,000

$$CMRR = \frac{G_d}{G_c}$$

- Disadvantage of one-op-amp differential amplifier is its low input resistance

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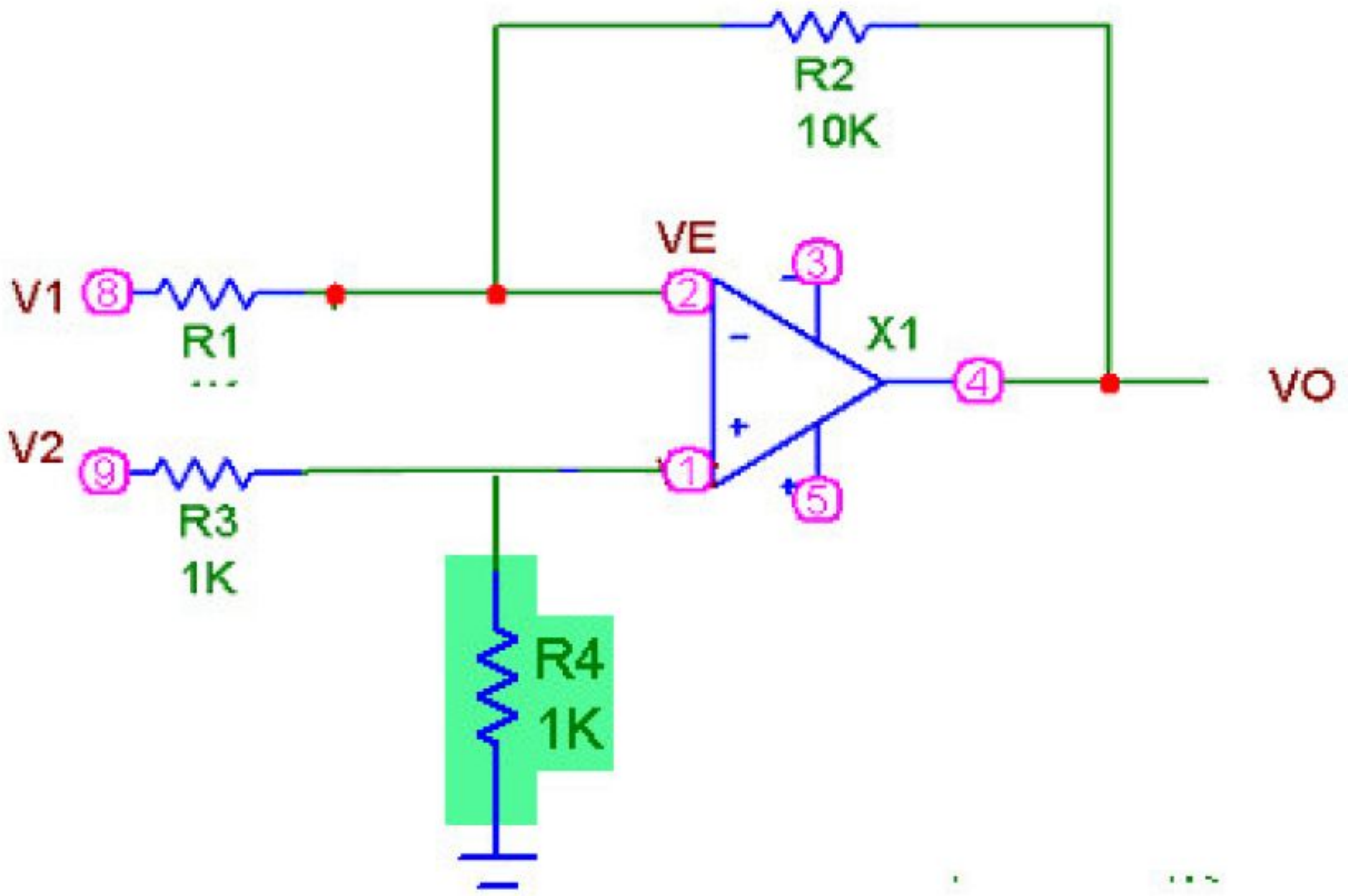
SUBTRACTOR



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Instrumentation Amplifier

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Introduction

- *Differential amplifier with high input resistance is used in instrumentation amplifier .*
- *The instrumentation amplifier is a closed loop device with carefully set gain. It is a dedicated differential amplifier with externally high input impedance*
- *It has a common mode rejection capability(i.e. it is able to reject a signal that is common to both terminal.)*
- *Instrumentation amplifiers are used to interface low level devices such as stain gauges, pressure transducers, analog to digital conversion.*

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An instrumentation amplifier is used to measure and control physical quantities such as temperature, humidity, light intensity, and waterflow.

Characteristics

- *High common mode rejection ratio(CMRR)*
- *High input impedance*
- *High slew rate*
- *Low output impedance*
- *Low power consumption*
- *Low thermal and time drift*

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- Instrumentation amplifier is the front end component of every measuring instrument which improves the signal to noise ratio of the input electrical signal from the transducer

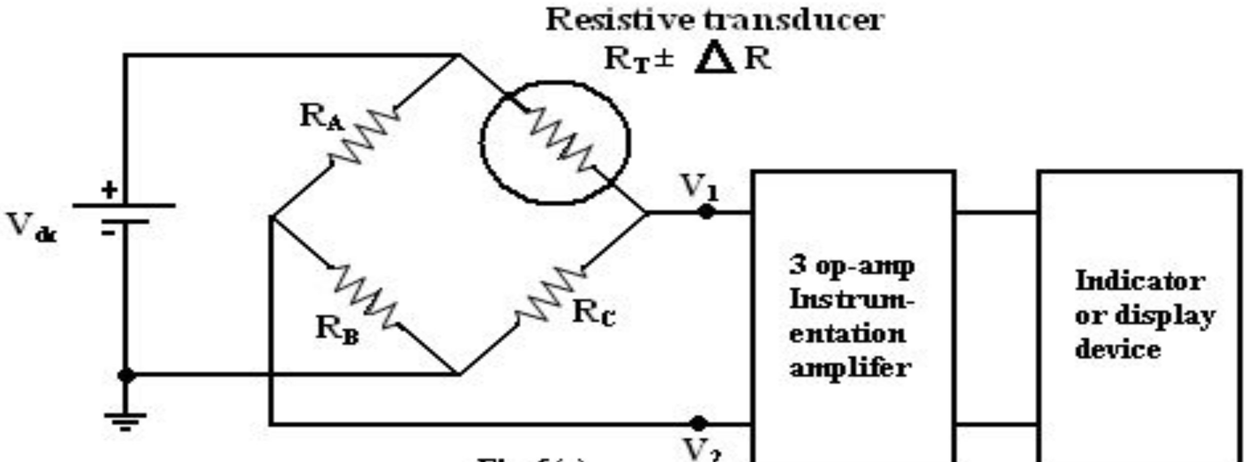
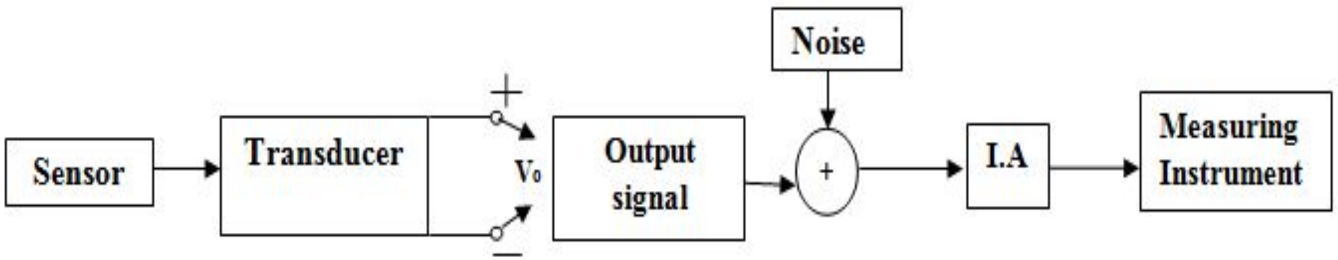


Fig 6(c)



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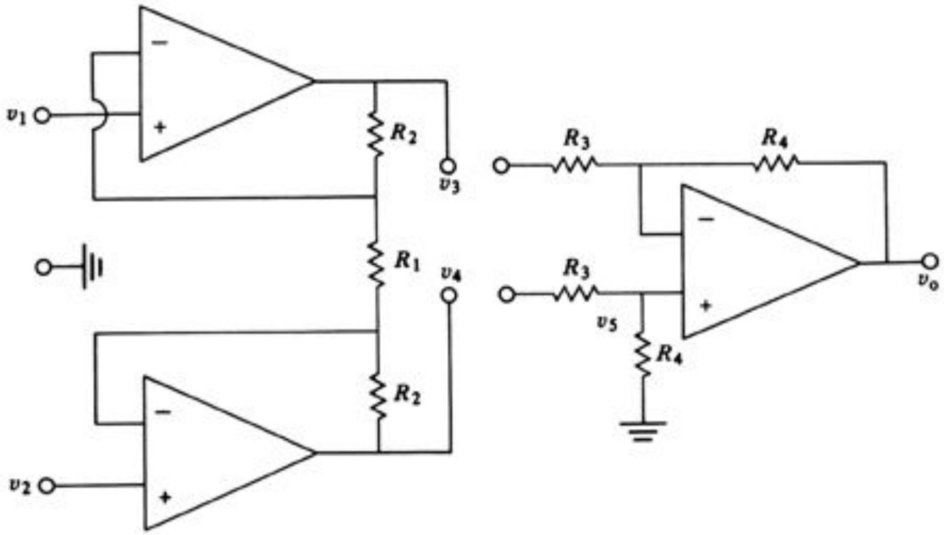
Instrumentation Amplifiers



Differential Mode Gain

$$v_3 - v_4 = i(R_2 + R_1 + R_2)$$

$$v_1 - v_2 = iR_1$$

$$G_d = \frac{v_3 - v_4}{v_1 - v_2} = \frac{2R_2 + R_1}{R_1}$$

Advantages: High input impedance, High CMRR, Variable gain

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Instumentation Amplifier

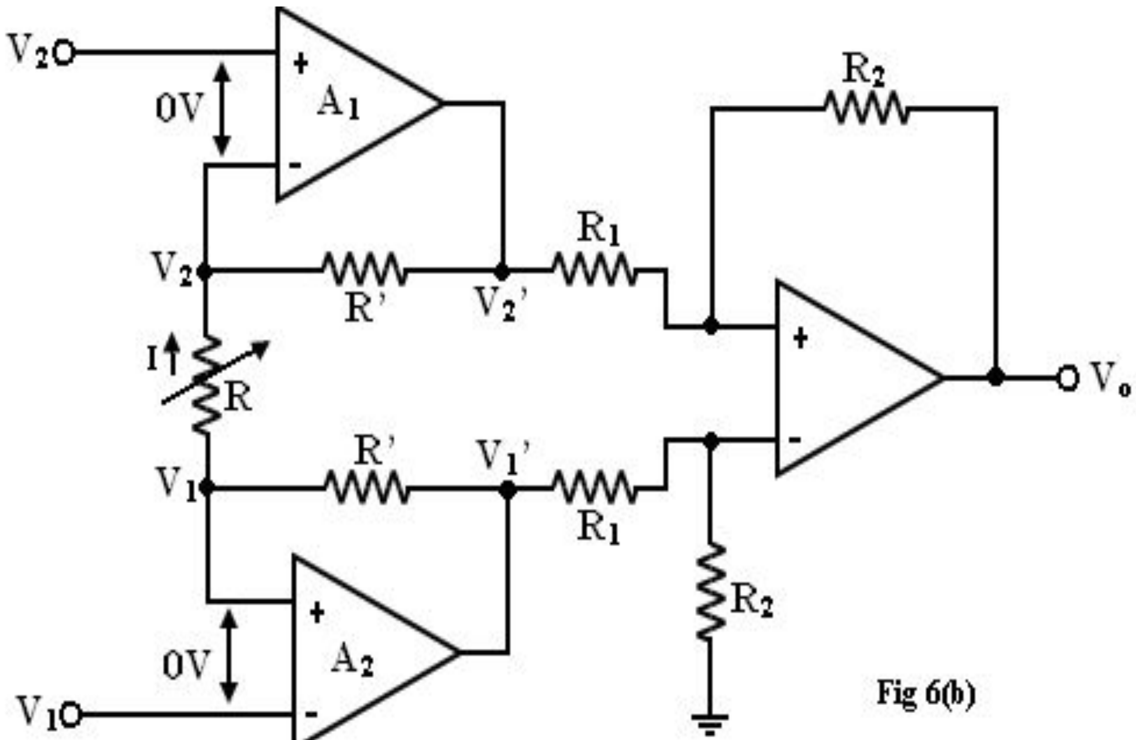

Fig 6(b)

$$V_{OUT} = (V_2 - V_1)\left[1 + \frac{2R_2}{R_1}\right]\left(\frac{R_4}{R_3}\right)$$

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Advantages

An instrumentation amplifier is beneficial for several reasons-

- *High input impedance, unlike the lower input impedance of a differential amplifier by itself.*
- *High CMRR.*
- *Good for smaller, insignificant input signals*
- *Gain of the non-inverting amplifier can be varied by the rheostat.*
- *Even a small value of input voltage can be amplified using instrumentation amplifier.*

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Applications

- Audio applications involving weak audio signal or noisy environment
- Medical instruments
- High frequency signal amplification in cable RF
- Current/voltage monitoring
- Data acquisition

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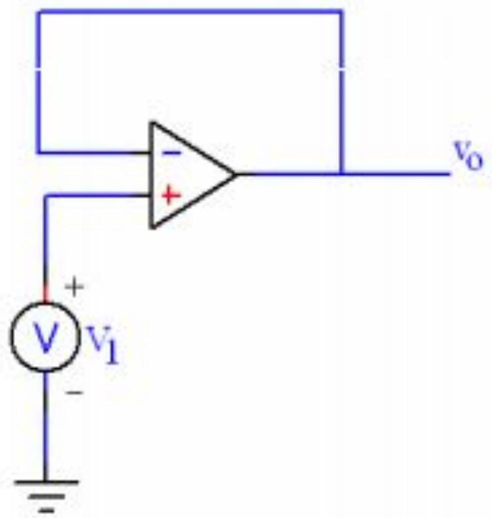
Voltage Follower

- The lowest gain that can be obtained from a non-inverting amplifier with feedback is 1.

- When the non-inverting amplifier gives unity gain, it is called voltage follower because the output voltage is equal to the input voltage and in phase with the input voltage. In other words the output voltage follows the input voltage.

$$V_o = V_{in}$$



- Voltage follower has very high input impedance and very low output impedance hence used as a buffer amplifier for interfacing high impedance source and low impedance load.

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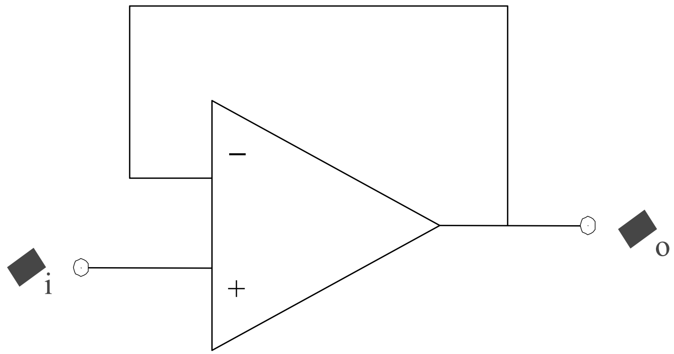
Follower (buffer)

- Used as a buffer, to prevent a high source resistance from being loaded down by a low-resistance load. In another word it prevents drawing current from the source.



$$v_o = v_i \qquad G = 1$$

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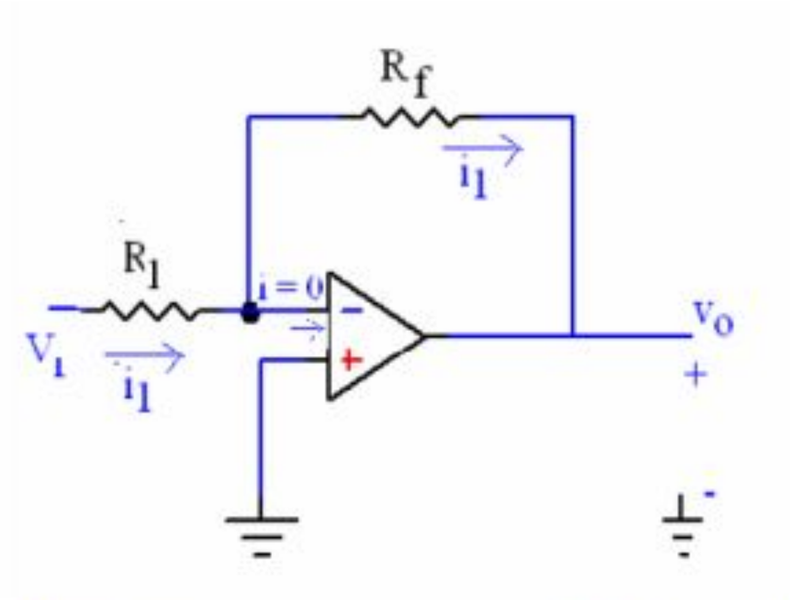
Inverting Amplifier or Scale Changer



Using KVL,

$v_1 - i_1R_1 = 0$

$\Rightarrow \; i_1 = v_1/R_1$

&

$0 - i_1R_f - v_o = 0$

or, $v_o = -i_1R_f = -v_1R_f/R_1$

$v_0/v_1 = -R_f/R_1$

If $R_1 = R_f$ then $v_O = -v_1$, the circuit behaves like an inverter.

If $R_f / R_1 = K$ (a constant) then the circuit is called inverting amplifier or scale changer voltages.

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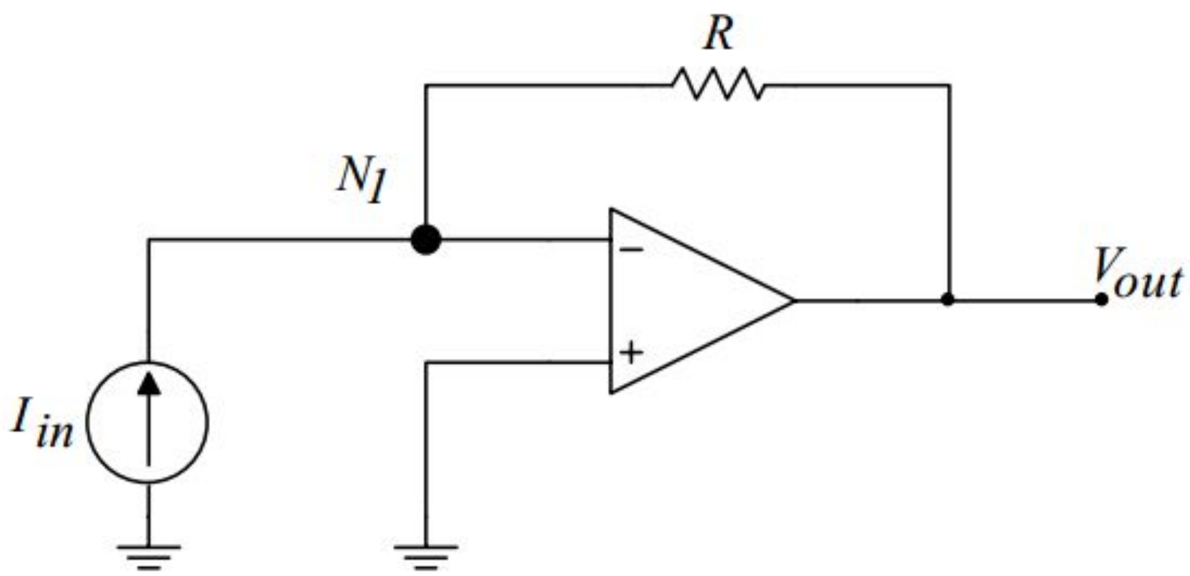
Current to Voltage Converter (Transresistance Amplifier)



$$I_1 + \left(\frac{V_{out} - 0}{R} \right) = 0 \Rightarrow \boxed{V_{out} = -RI_1}$$

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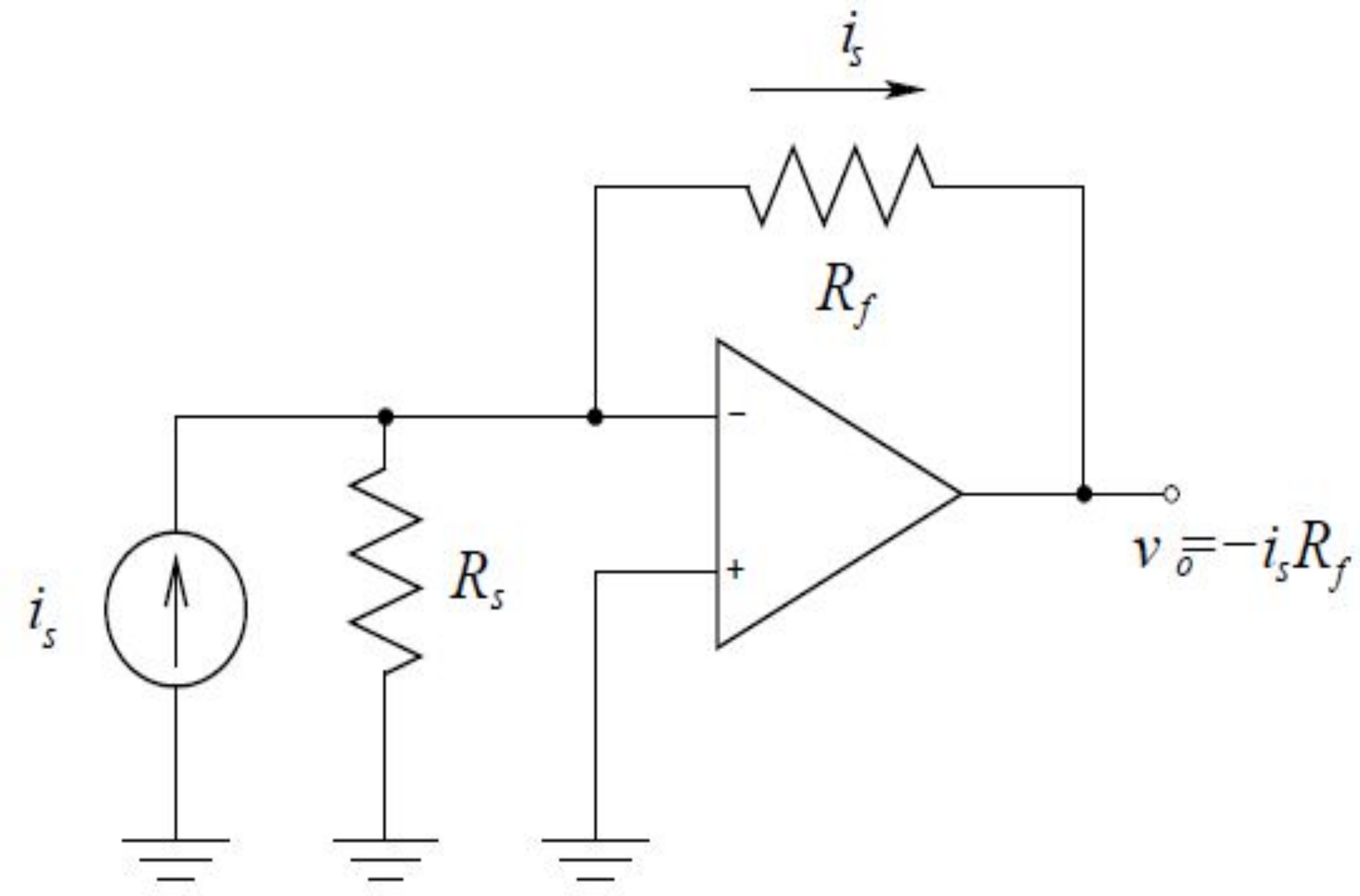
i_s
R_f
R_s
i_s
$v_o = -i_s R_f$

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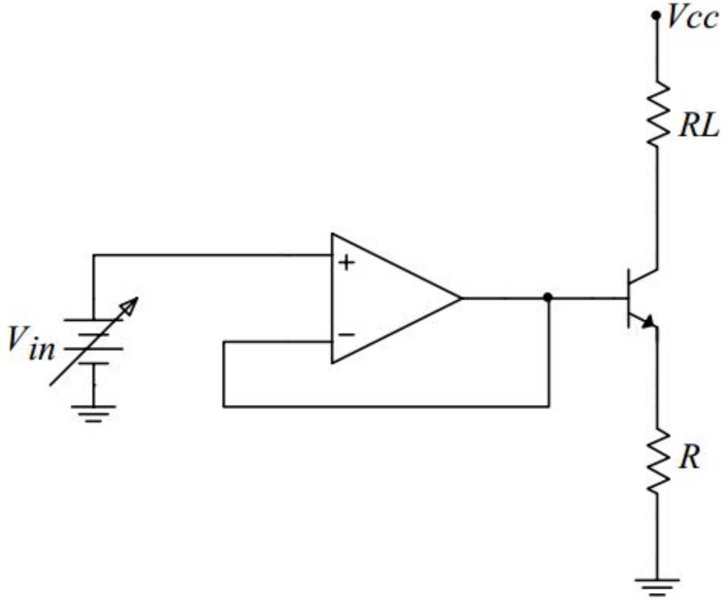
Voltage to Current Converter (Transconductance Amplifier)



$$I_{out} = SV_{in}$$

Where S is the sensitivity or gain of the V-I converter.

$$I_L = Vin/R_L$$

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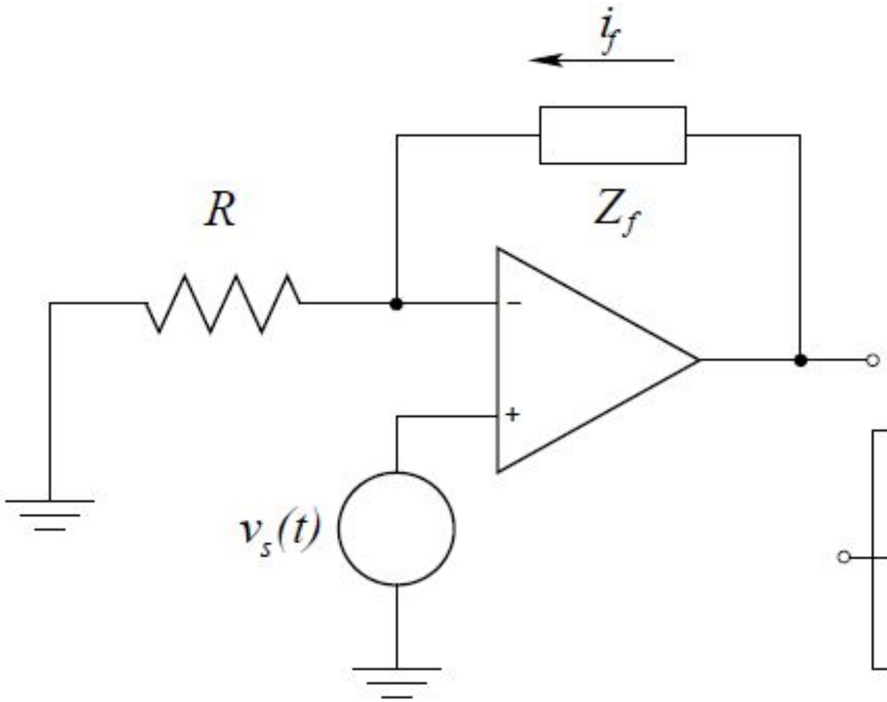
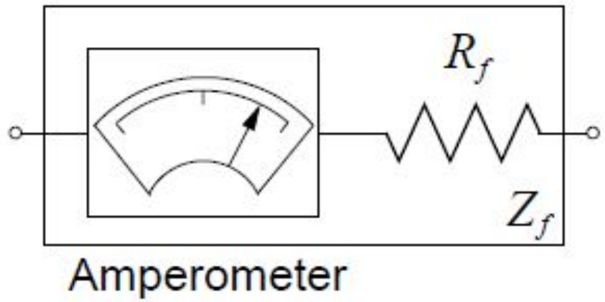
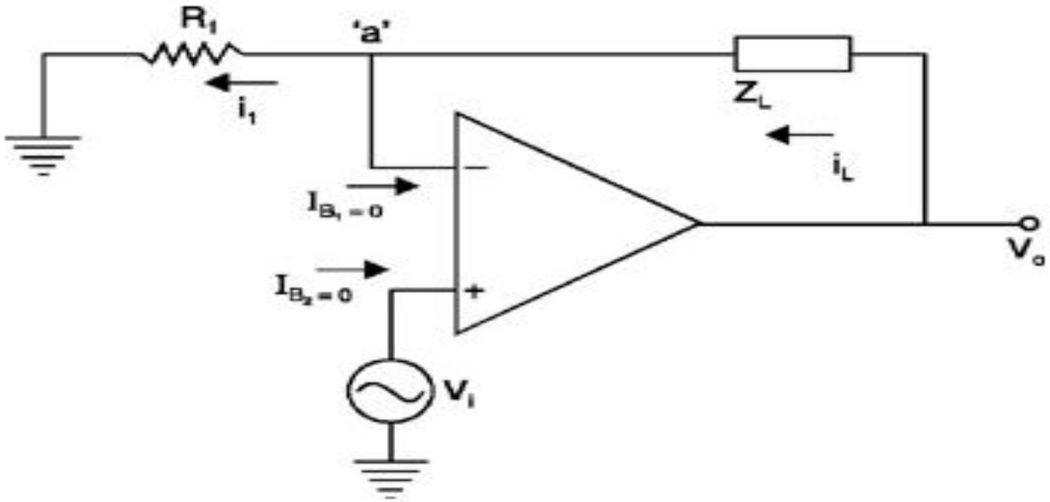
Voltage to Current Converter (Transconductance Amplifier)



$$i_f(t) = \frac{v_s(t)}{R}.$$



Transconductance amplifier with floating Load



$$V_a = V_i$$

$$I_{B1} = I_{B2} = 0$$

$$i_L + I_{B1} = i_1$$

$$i_L = i_1$$

$$i_1 = \frac{V_a - 0}{R_1}$$

$$i_1 = \frac{V_a}{R_1}$$

$$i_L = \frac{V_i}{R_1}$$

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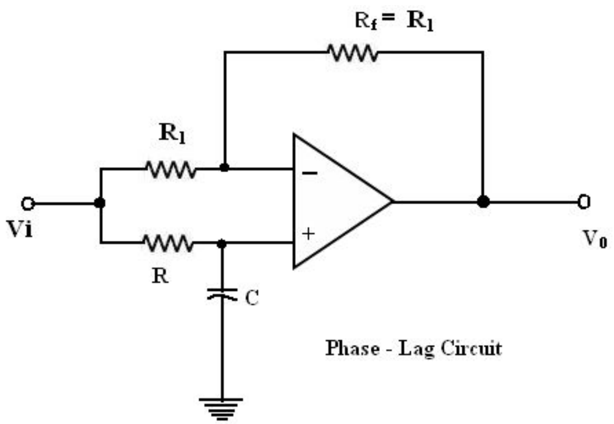
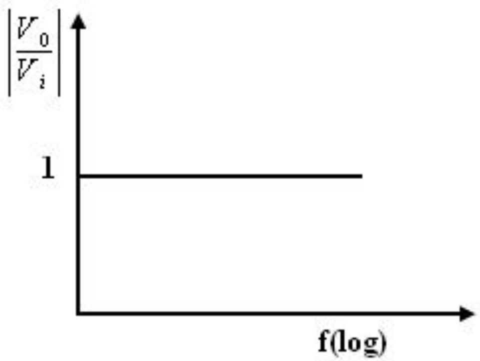
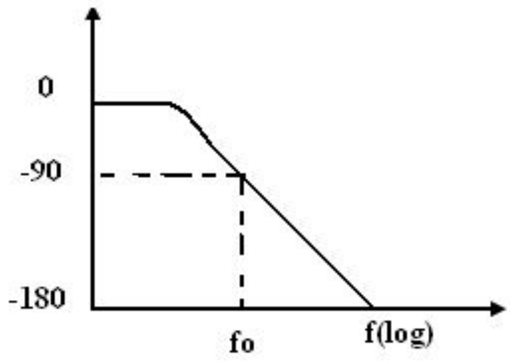
PHASE SHIFT CIRCUITS

- The phase shift circuits produce phase shifts that depend on the frequency and maintain a constant gain. These circuits are also called constant-delay filters or all-pass filters.
- **Phase-lag circuit:**







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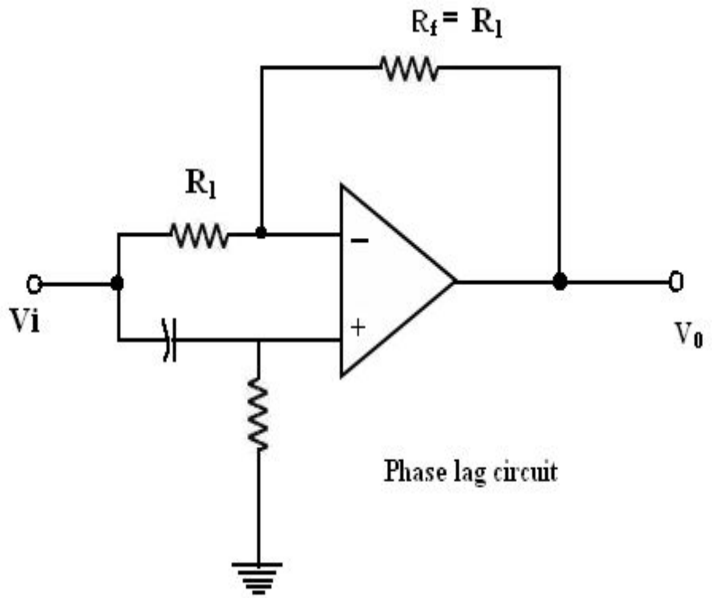
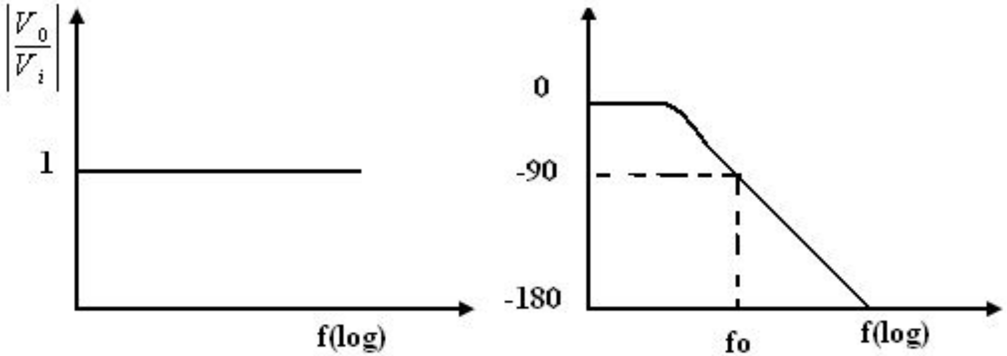
Phase lag circuit





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Non-Linear Op-Amp Applications

- Applications using saturation
  - Comparators
  - Comparator with hysteresis (Schmitt trigger)
  - Oscillators
- Applications using active feedback components
  - Log, antilog, squaring etc. amplifiers
  - Precision rectifier

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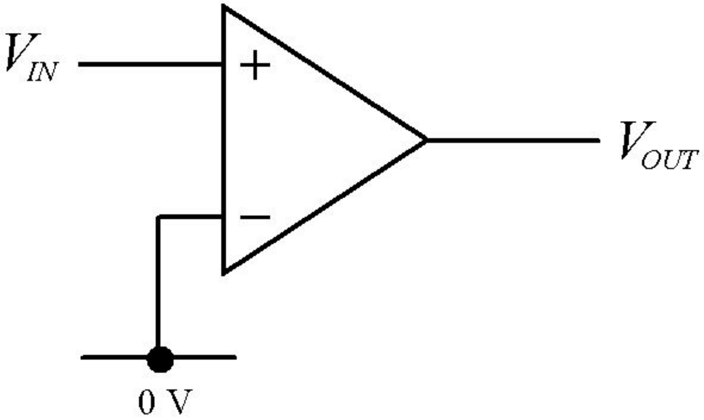
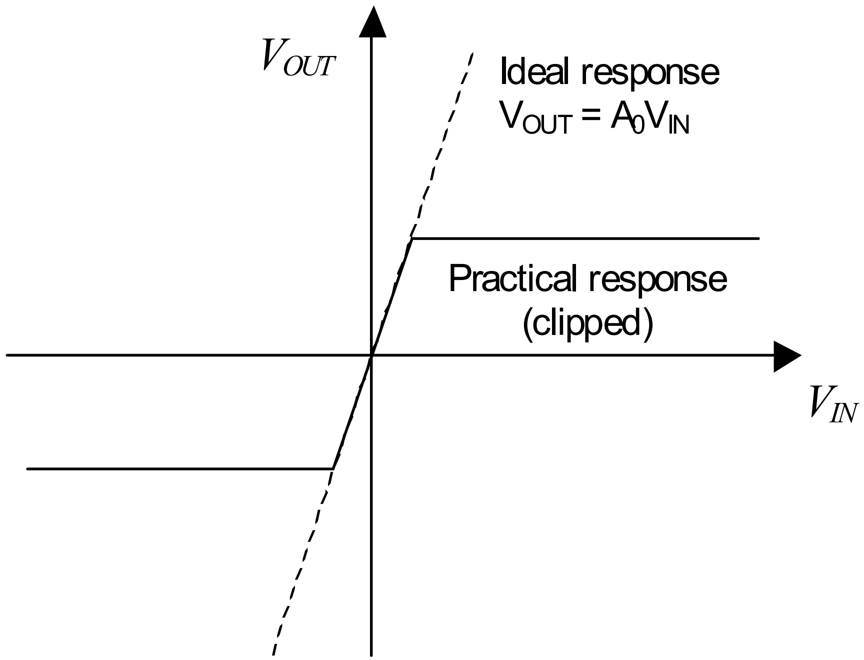
Comparators





If A_0 is large, practical response can be approximated as :

$$V_{IN} > 0 \Rightarrow V_+ > V_- \Rightarrow V_{OUT} = +V_{SAT}$$
$$V_{IN} < 0 \Rightarrow V_+ < V_- \Rightarrow V_{OUT} = -V_{SAT}$$

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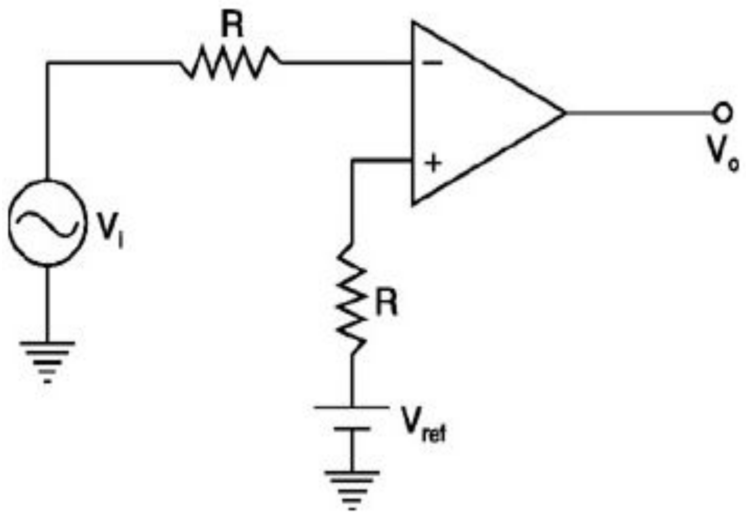
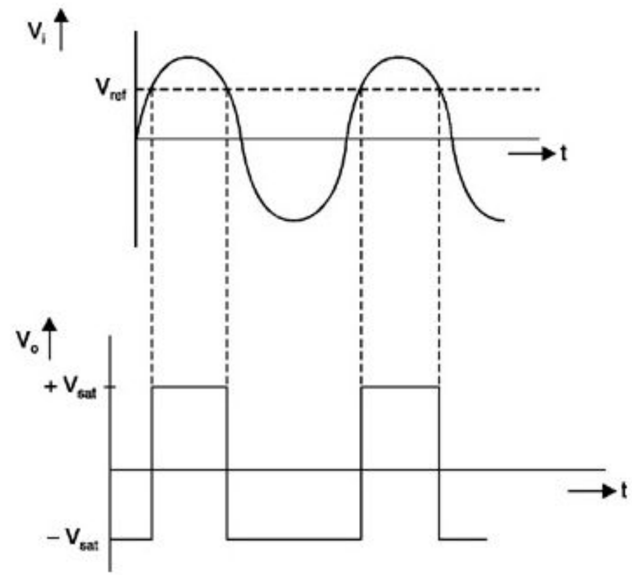
Non-Inverting Comparator

❖A comparator compares a signal voltage applied at the input of an op-amp with a known reference voltage V_{ref} given at the other input.
❖It is an open-loop operation, *i.e.*, there is no feedback path in the case of a comparator.





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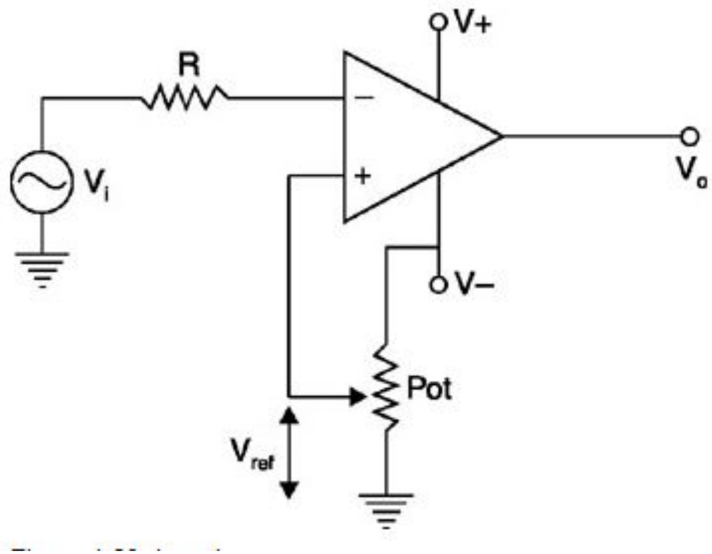
INVERTING COMPARATOR



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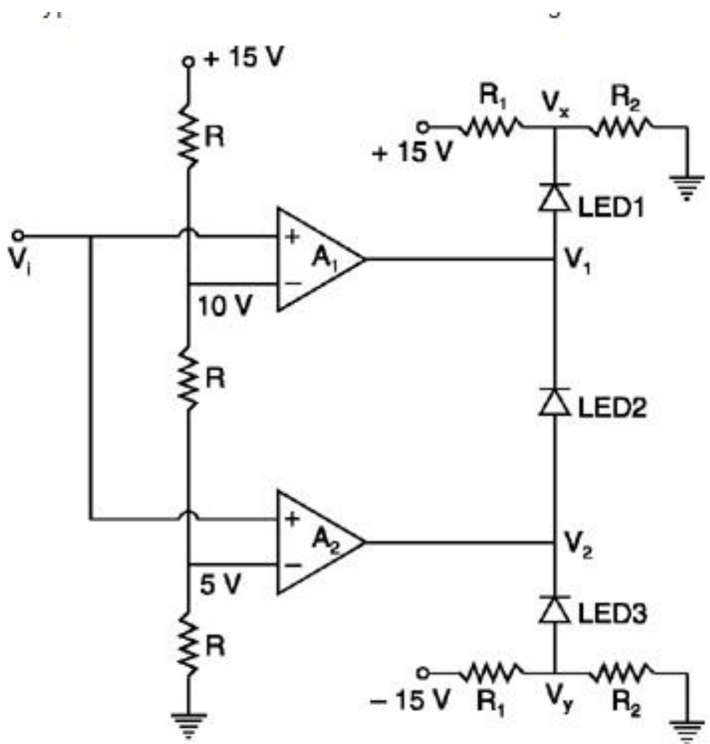
Window Detector



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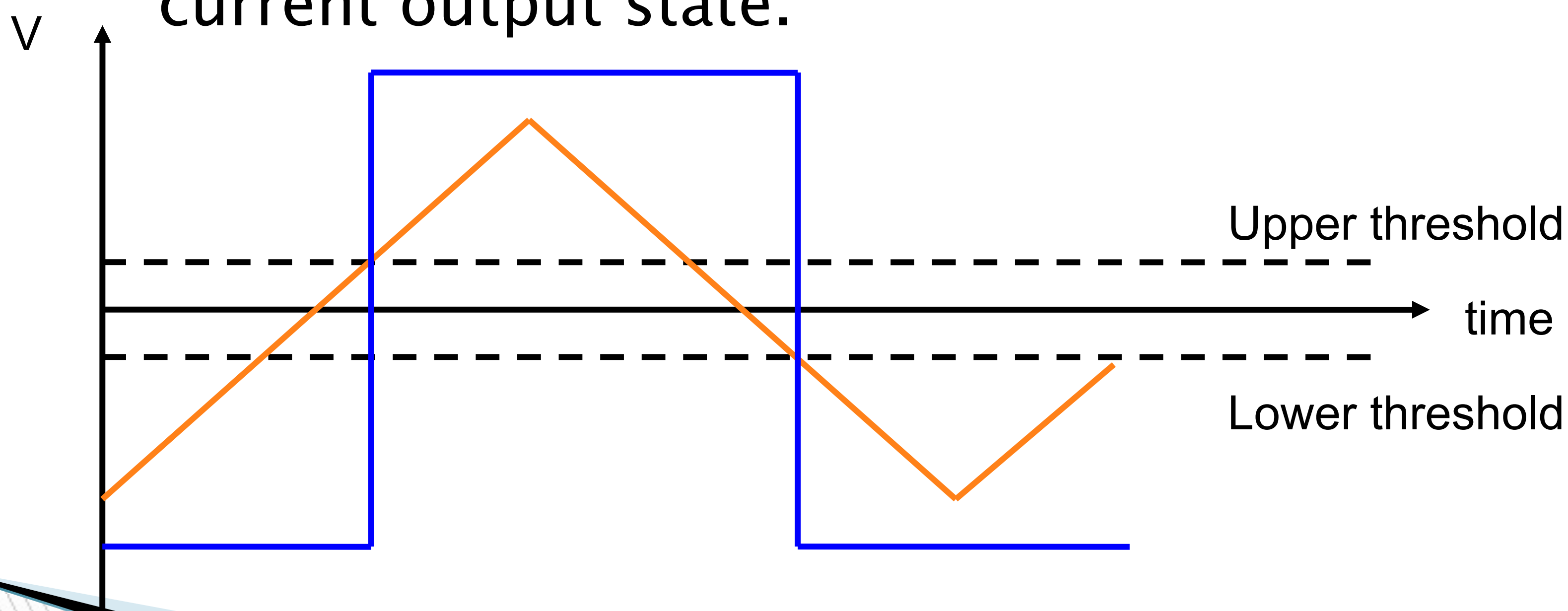
Hysteresis

- A comparator with hysteresis has a ‘safety margin’.
- One of two thresholds is used depending on the current output state.



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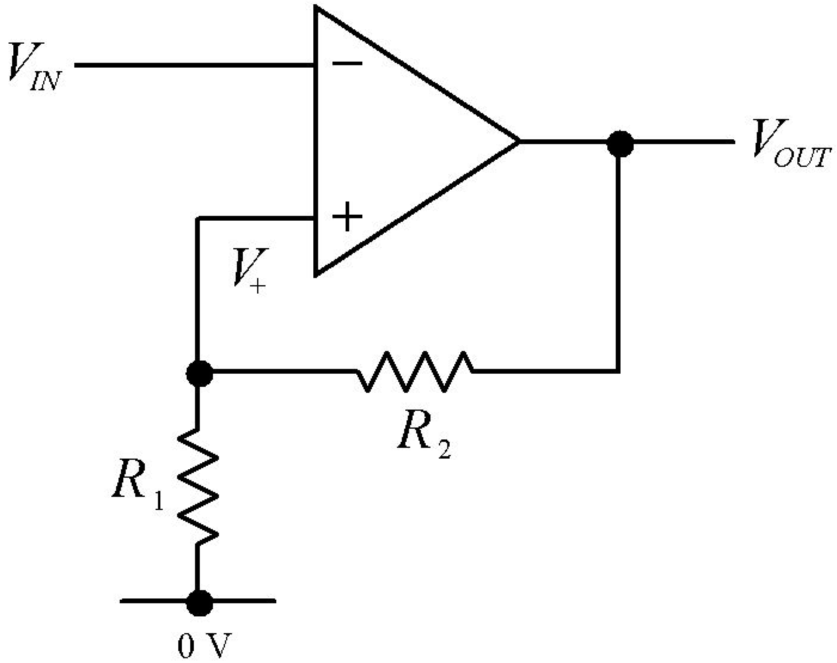
Schmitt Trigger

- The Schmitt trigger is an op-amp comparator circuit featuring hysteresis.
- The inverting variety is the most commonly used.



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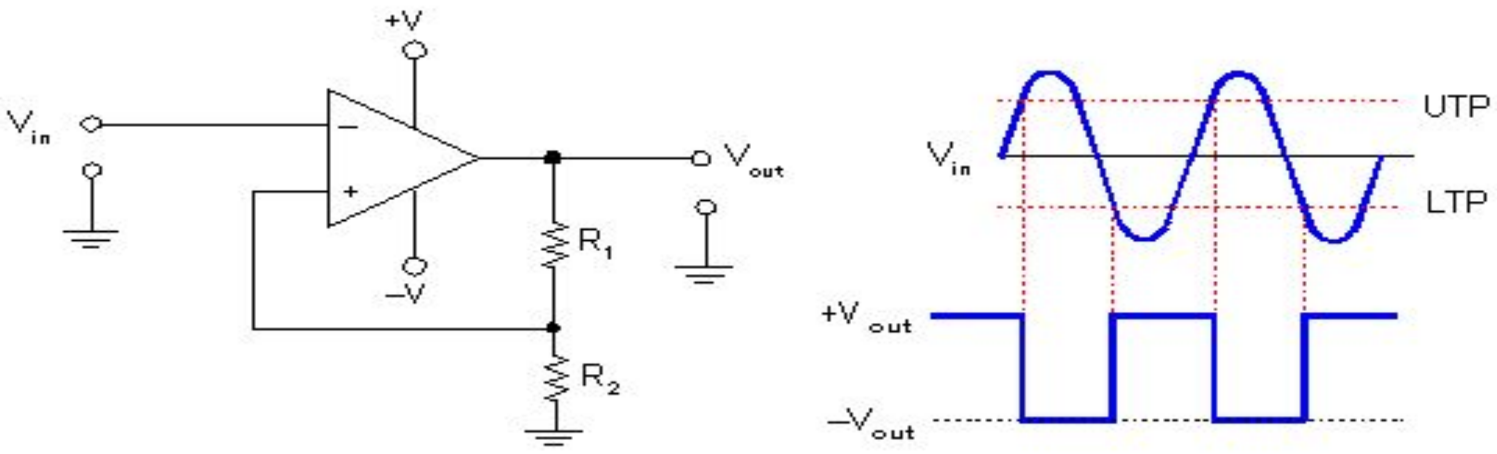
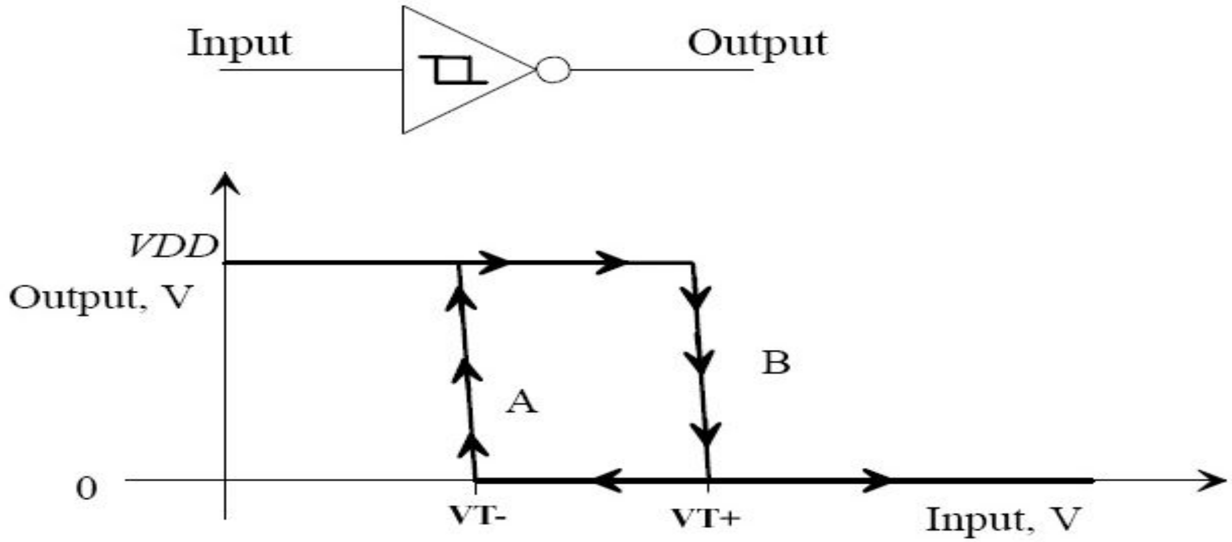


It is obvious from the circuit that positive feedback is employed in the circuit.
The feedback factor

$$\beta = V_f \ / \ V_o = R_2/(R_2+R_1).$$

Hysterisis



Transfer characteristics of a Schmitt trigger

Hysteresis = $V_{upper\ threshold} - V_{lower\ threshold}$

$= \beta * V_{cc} - (-\beta * V_{cc}) = 2 * \beta * V_{cc} = 2 * V_{cc} * R_2/(R_2+R_1)$

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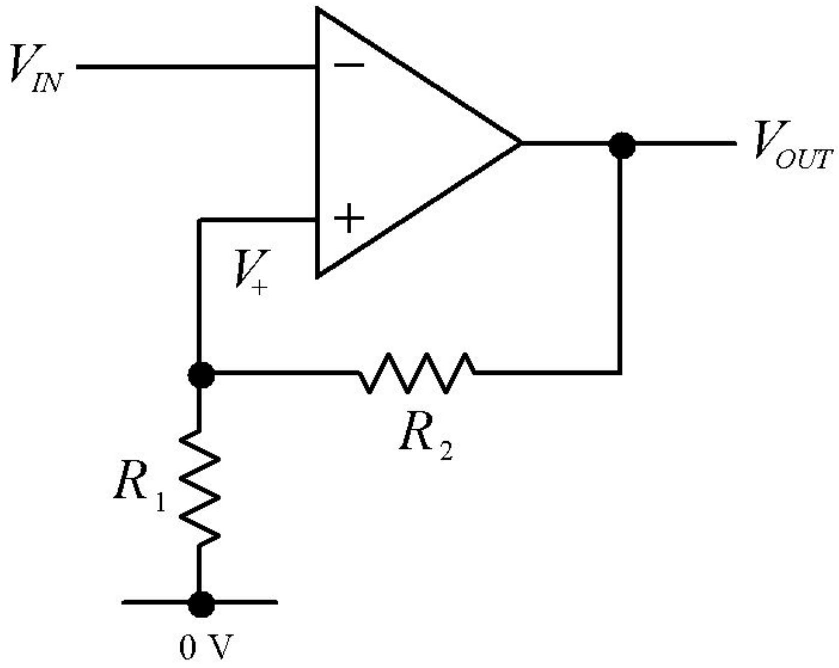
Schmitt Trigger Analysis



Switching occurs when:

$$V_{IN} = V_- = V_+ = V_{OUT} \frac{R_1}{R_1 + R_2}$$

But,

$$V_{OUT} = \pm V_{SAT}$$

$$\therefore V_{THRESH} = \pm V_{SAT} \frac{R_1}{R_1 + R_2}$$

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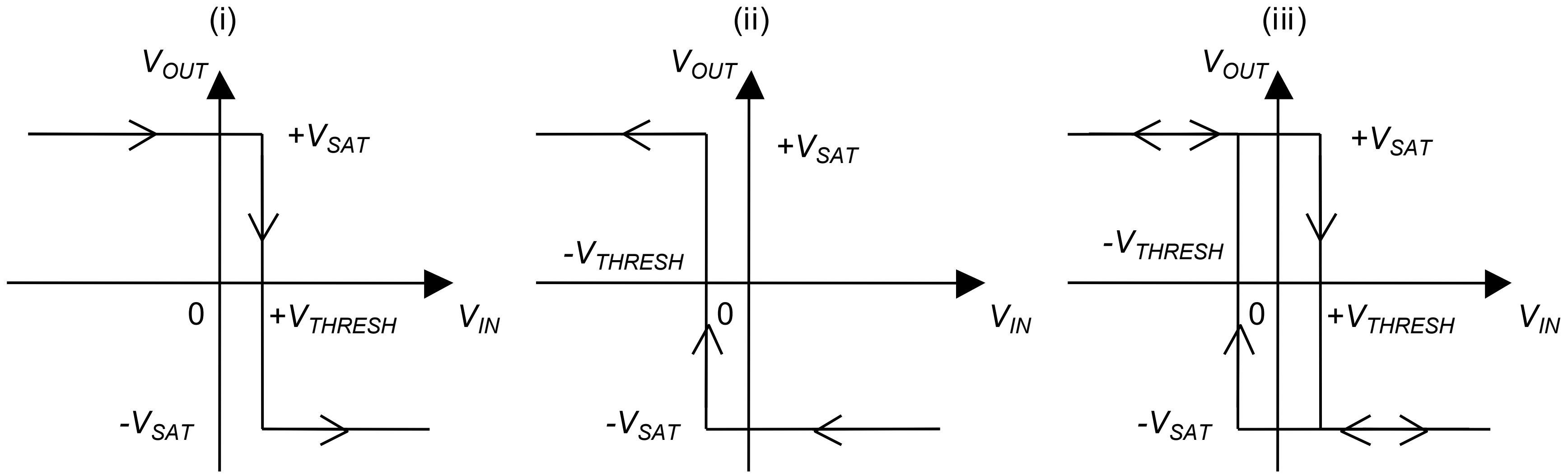
Input–Output Relationship



V_{IN} increasing V_{IN} decreasing   (i) & (ii) combined

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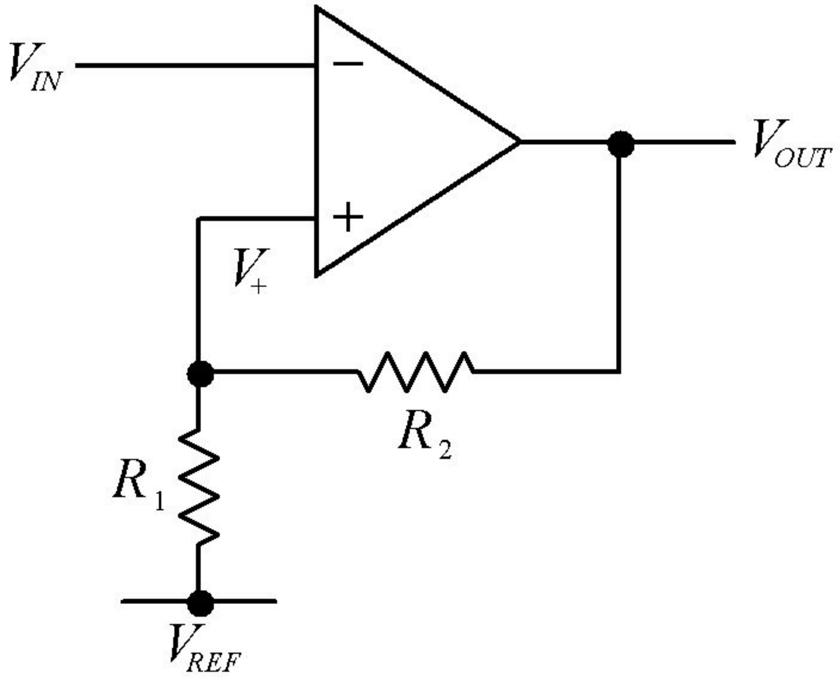
Asymmetrical Thresholds



- We don't always want the threshold levels to be symmetrical around 0 V.
- More general configuration features an arbitrary reference level.

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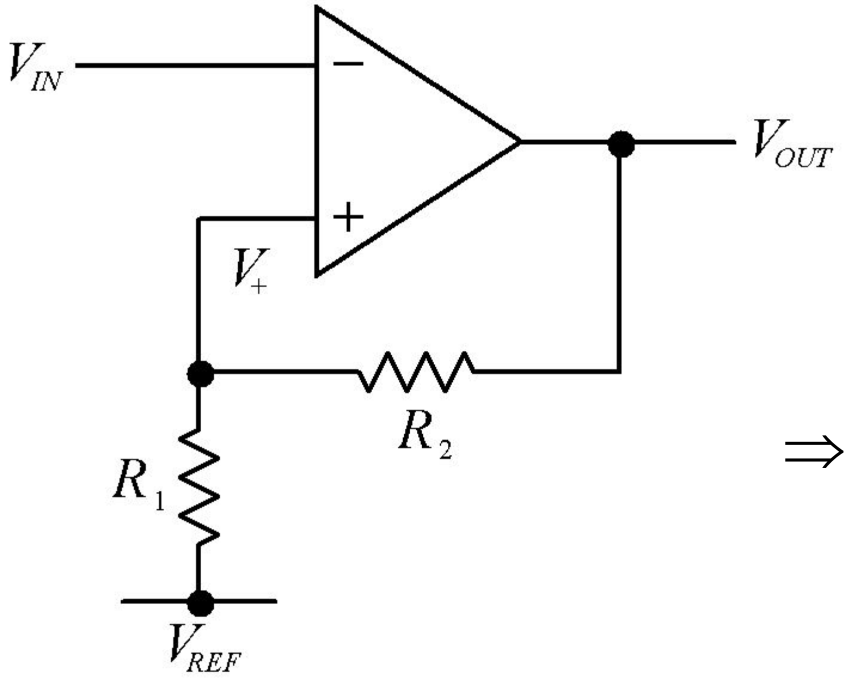
Analysis



Using Kirchoff's current law:

$$\frac{V_{OUT} - V_+}{R_2} + \frac{V_{REF} - V_+}{R_1} = 0$$

$$\Rightarrow \frac{V_{OUT}}{R_2} + \frac{V_{REF}}{R_1} = \frac{V_+}{R_2} + \frac{V_+}{R_1} = V_+ \frac{R_1 + R_2}{R_1 R_2}$$

$$\Rightarrow V_+ = V_{OUT} \frac{R_1}{R_1 + R_2} + V_{REF} \frac{R_2}{R_1 + R_2}$$

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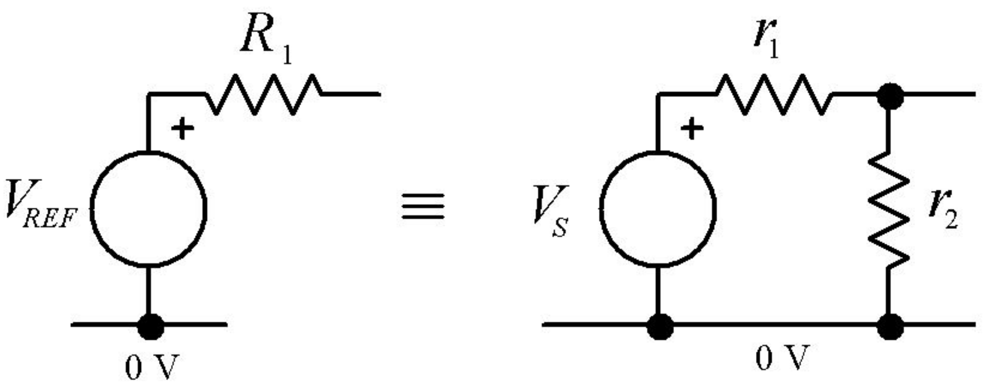
Realising V_{REF}

Solving $$V_{THRESH} = \pm V_{SAT} \frac{R_1}{R_1 + R_2} + V_{REF} \frac{R_2}{R_1 + R_2}$$

often gives a value of V_{REF} that isn't available.

But,



Providing $R_1 = r_1 \parallel r_2$ and $V_{REF} = V_S \frac{r_2}{r_1 + r_2}$

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Summary

- Saturation of op-amps is exploited by comparator circuits.
- Their function is to decide whether an input voltage is greater or less than a reference level.
- Hysteresis is often applied to provide some resilience against noise.

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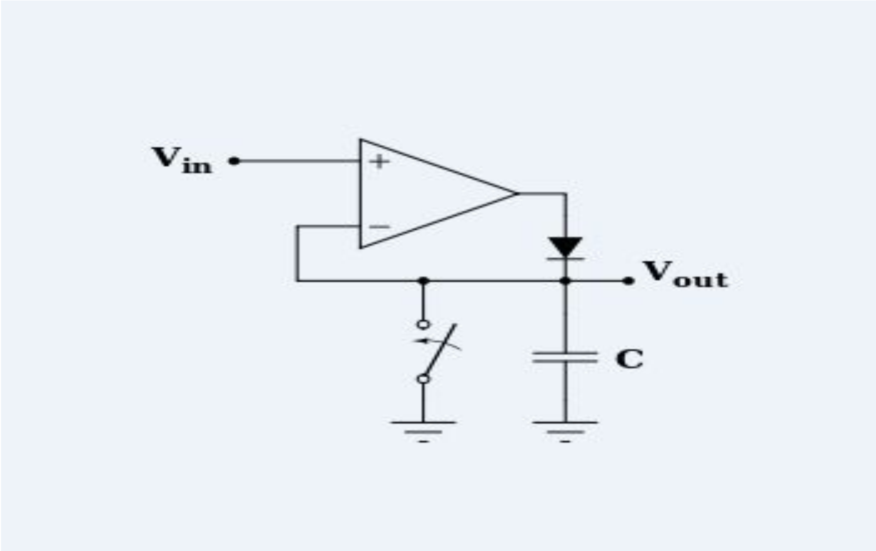
Peak Detector

Peak detector detects and holds the most positive value of attained by the input signal prior to the time when the switch is closed.



$V_{out} < V_{in}$; D ON and C charges to peak value of input,
$V_{out} < V_{in}$; D OFF and C holds the peak value of input

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- a)$V_{out} < V_{in}$ the op amp output V' is positive so that the diode conducts and the capacitor charges to the input value at that instant as it forms a voltage follower circuit.
- b) When $V_{out} > V_{in}$, op amp output V ' is negative and the diode becomes reverse biased.
- Thus the capacitor charges to the most positive value of input.

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Op amp zero crossing detector

- In opamp zero crossing detectors the output responds almost discontinuously every time the input passes through zero. It consists of a comparator circuit followed by differentiator and diode arrangement.

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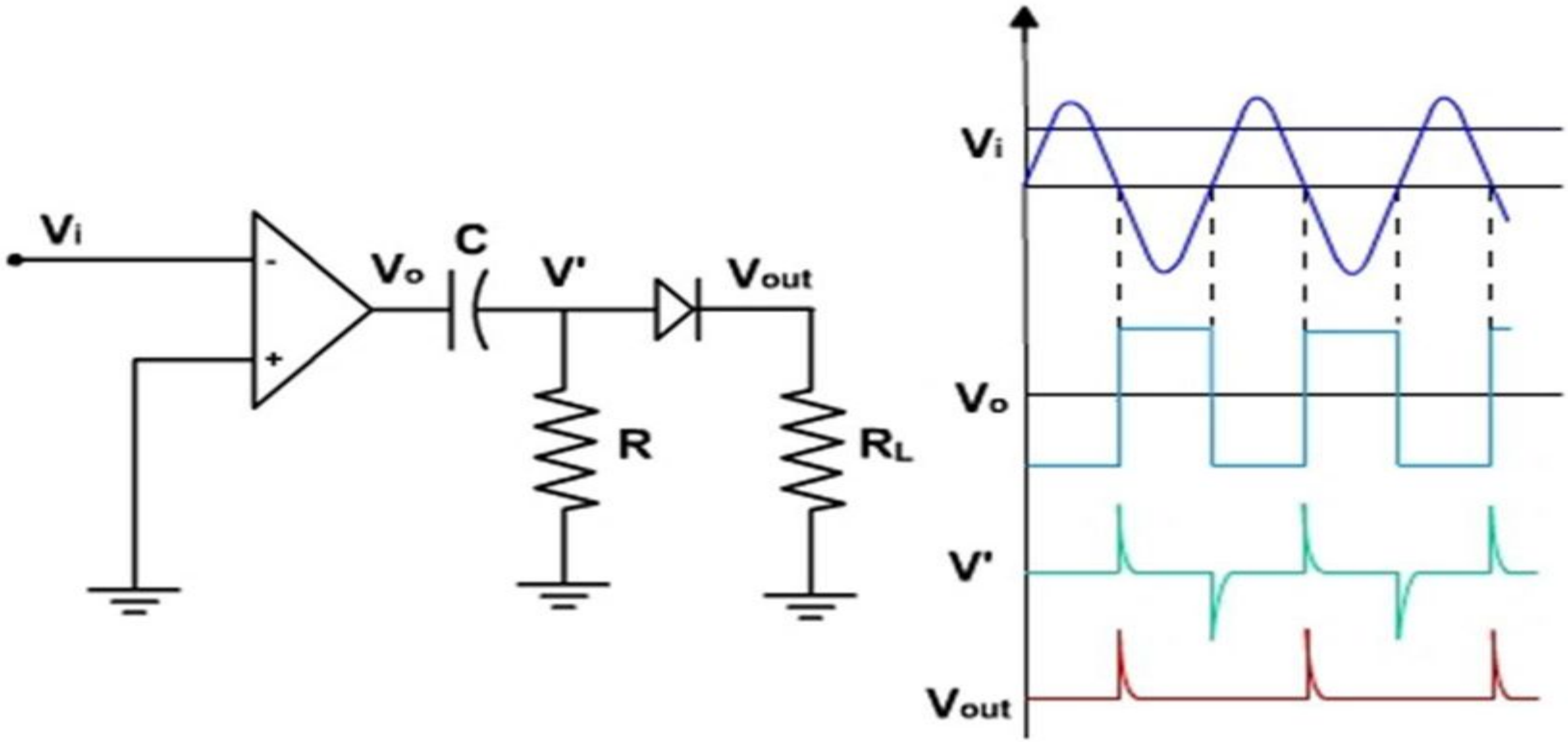
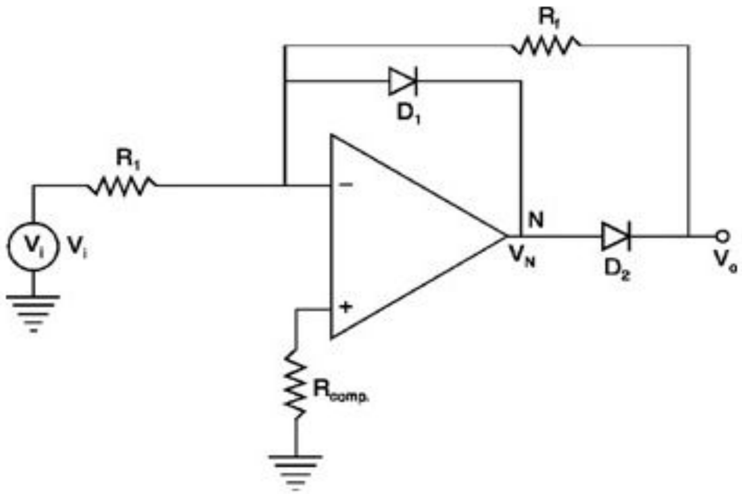
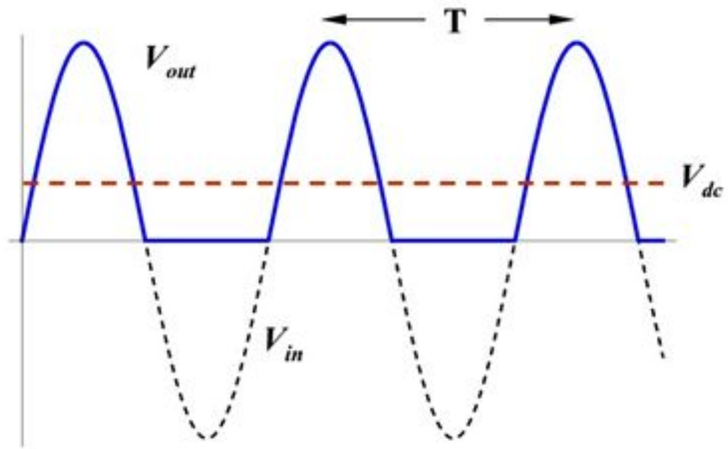


V_{in}>0,V_o=+V_{cc}, V' = R*C*dVo/dt positive spike, D ON and C charges through R and R_L to +V_{cc};
V_{in}>0,V_o=-V_{cc},V' = R*C*dVo/dt negative spike, D OFF and C discharges through R to +V_{cc}

Opamp Half wave rectifier





Vi > 0 v ; D1, D2 ON ;Vo = 0
Vi < 0 v ; D1, D2 OFF ;Vo = –(Rf/R1)*Vi

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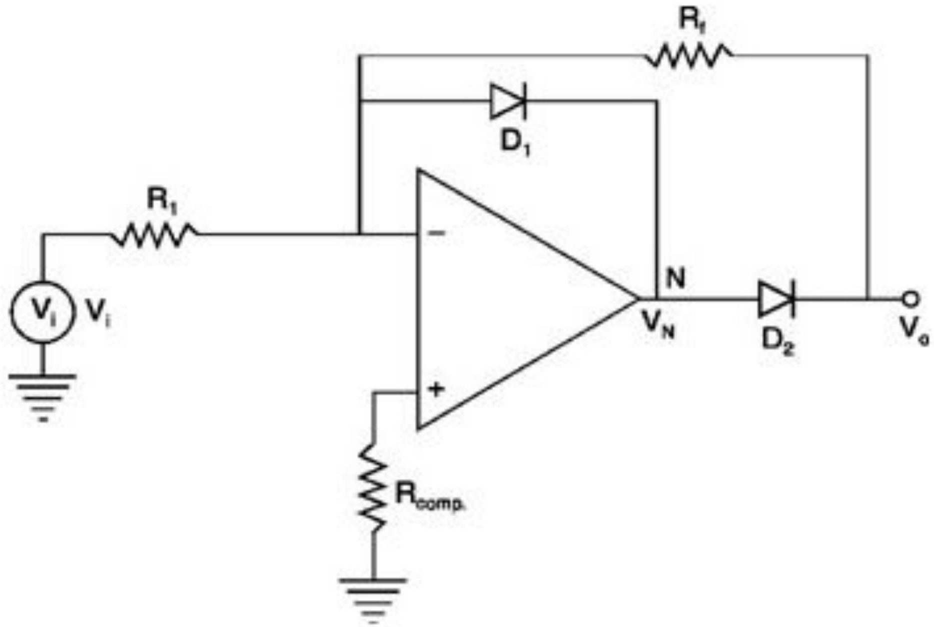
HWR Using Opamp



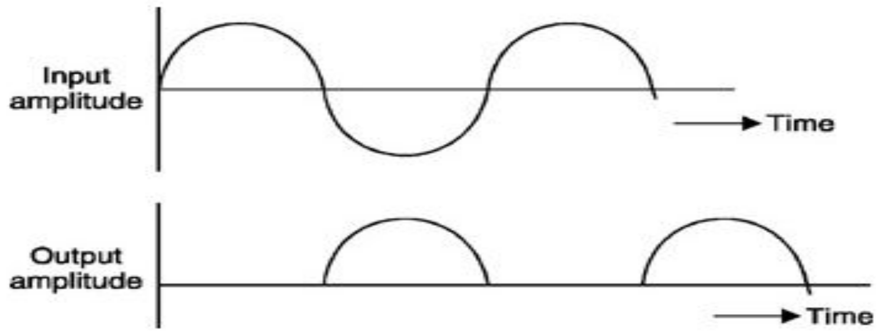


Figure 4.17: Input-output relationship for a half-wave rectifier.

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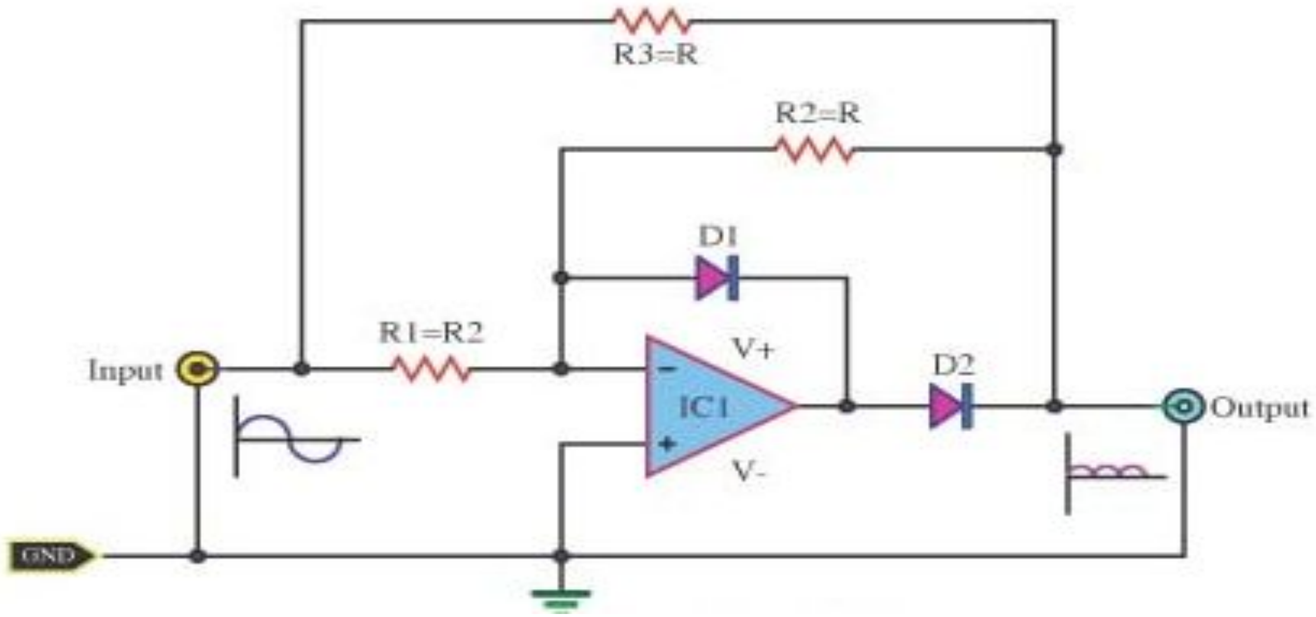
Full wave rectifier with an op amp



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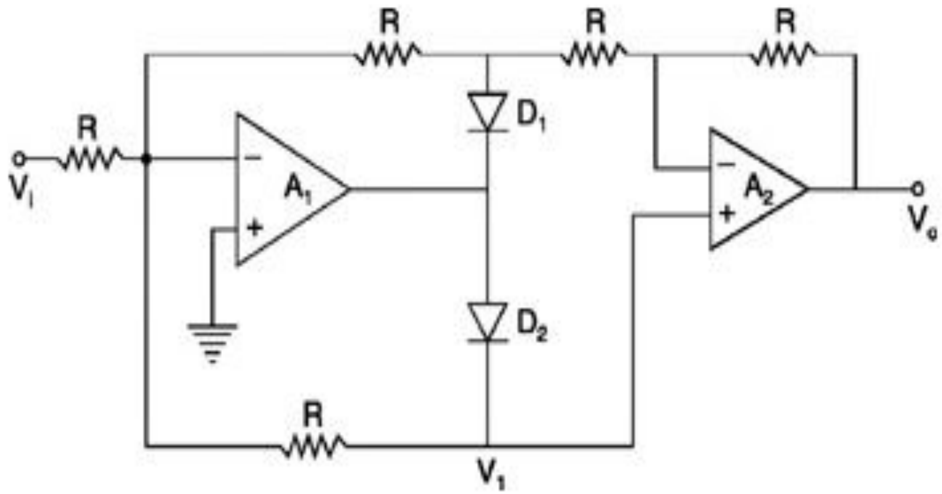
Full wave rectifier with two op-amps



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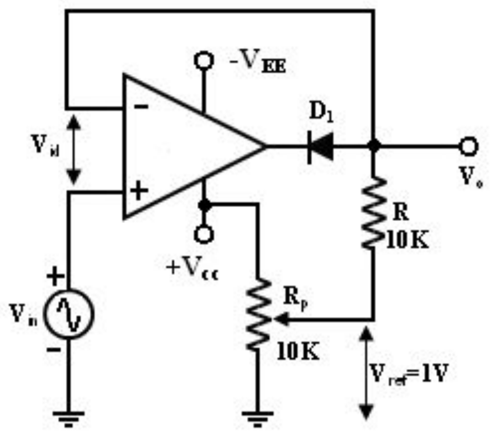
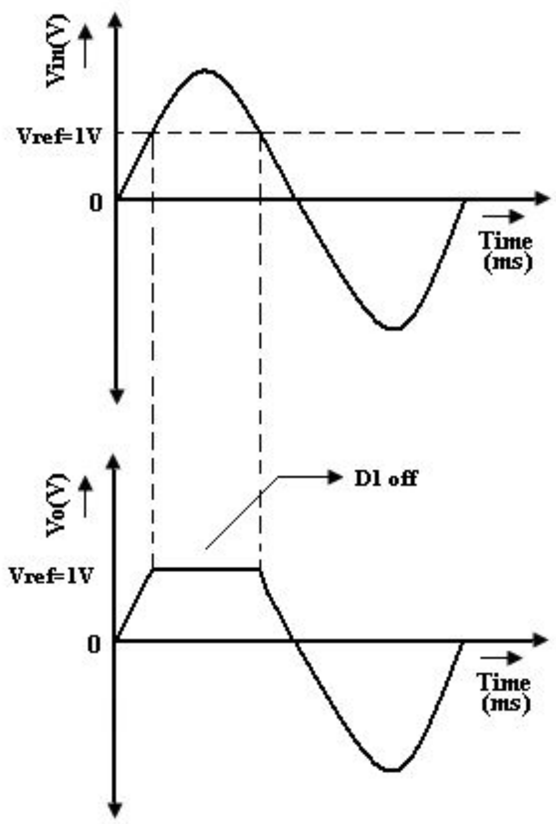
Positive and Negative Clipper:





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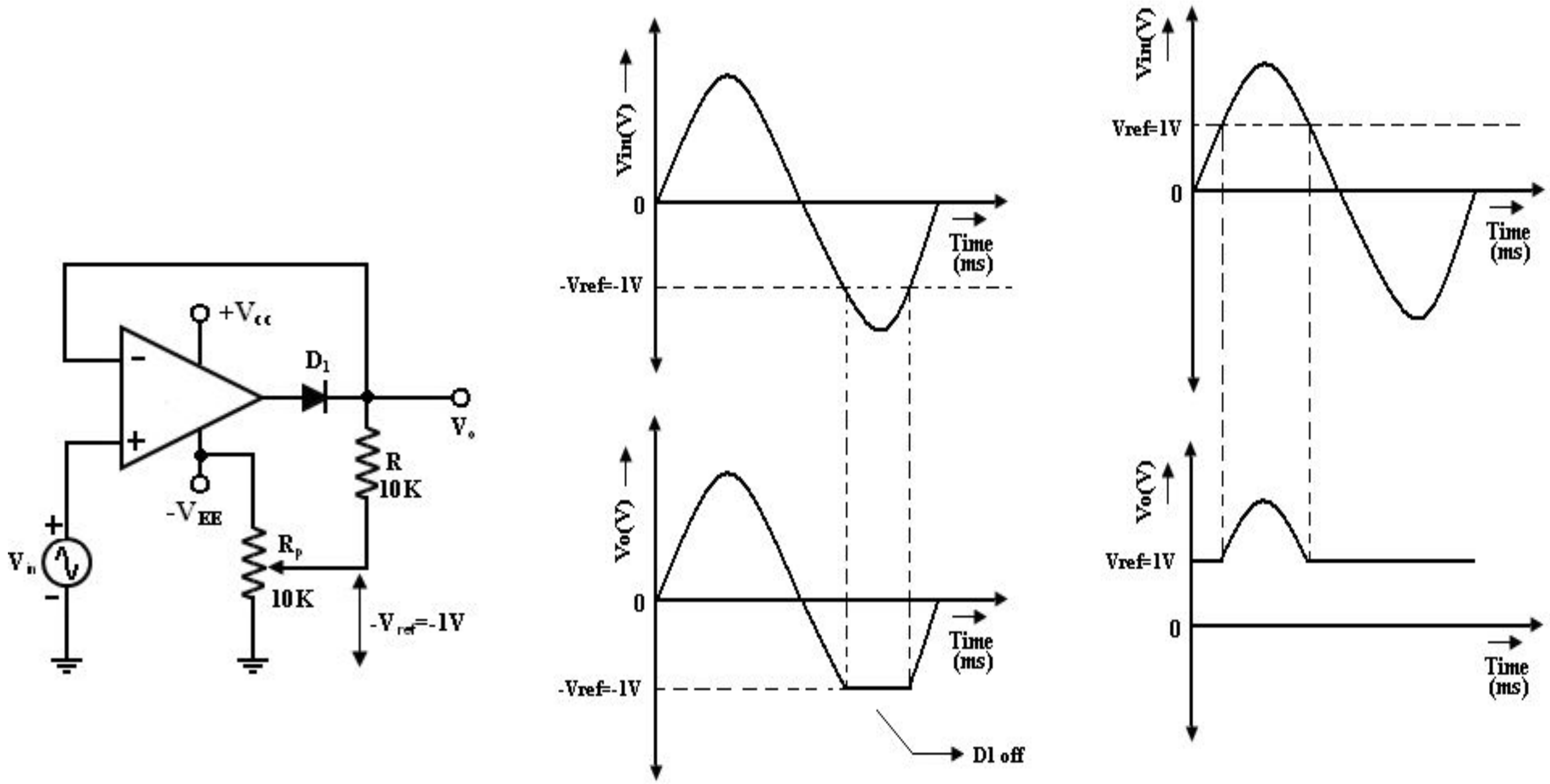
Negative Clipper:



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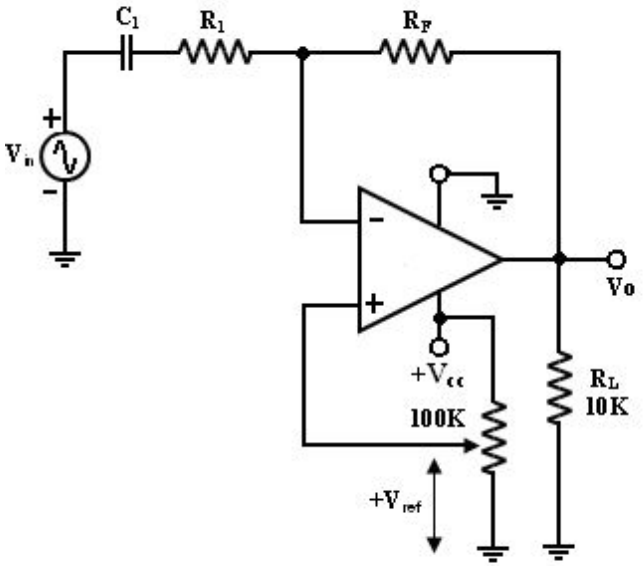
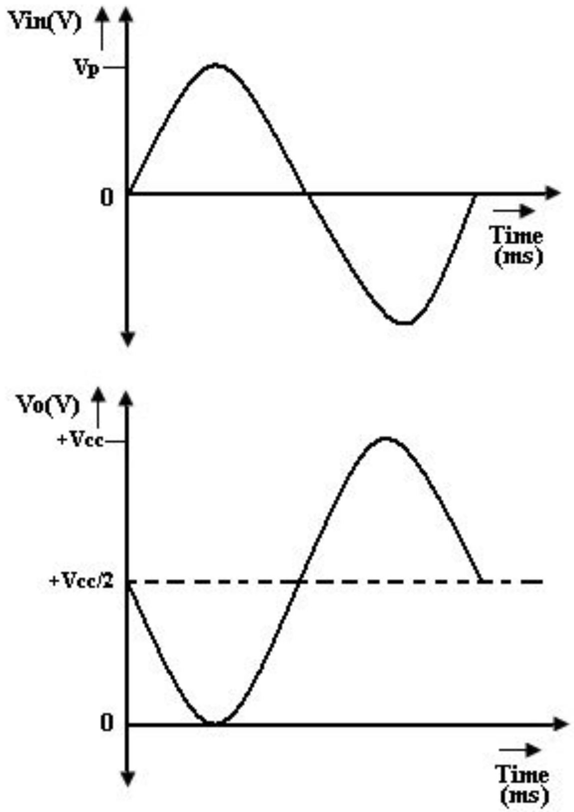
Positive and Negative Clampers:





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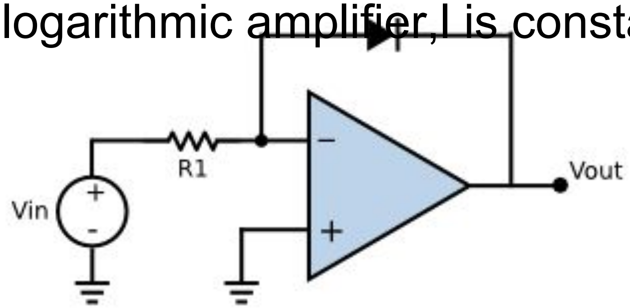
Logarithmic Amplifier

- Logarithmic amplifier gives the output proportional to the logarithm of input signal.

- If V_i is the input signal applied to a differentiator then output is $V_o = K*\ln(V_i)+I$
- where K is gain of logarithmic amplifier,I is constant.



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- The current equation of diode
- $I_d = I_{do}*(\exp(V/V_t)-1)$ -----------(1)
- where I_{do} is reverse saturation current,
- V is voltage applied across diode;
- V_t is the voltage equivalent of temperature
- $(0-V_{in})/R_1 + I_d = 0$
- $I_d = V_{in}/R_1$ ---------(2)
- (1)=(2)

$I_{do}*(\exp(V/V_t)-1) = V_{in}/R_1$.

Assuming $\exp(V/V_t) >> 1$ i.e. $V>>V_t$ and $V = -V_o$, $I_{do}*\exp(-V_o / V_t) = V_{in}/R_1$.

Applying Antilog on both sides we get

- $V_o = -V_t * \ln(V_{in}/(R_1*I_{do}))$.

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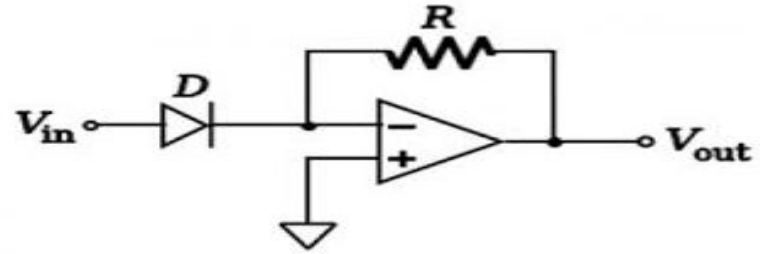
Anti log amplifier

- Anti log amplifier is one which provides output proportional to the anti log i.e. exponential to the input voltage.
- If V_i is the input signal applied to a Anti log amplifier then the output is V_o=K*exp(a*V_i) where K is proportionality constant, a is constant.



The current equation of diode is given as $I_d = I_{do}*(\exp(V/V_t)-1)$

I_{do} is reverse saturation current,

V is voltage applied across diode;

V_t is the voltage equivalent of temperature

Applying KCL at inverting node of opamp

$$I_d = (0-V_o)/R = I_o*(\exp(V_{in}/V_t)) \text{ (assumed } V_{in}/V_t >> 1)$$

$$V_o = -I_o*R*(\exp(V_{in}/V_t)).$$

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Filter

- Filter is a frequency selective circuit that passes signal of specified Band of frequencies and
- attenuates the signals of frequencies outside the band
- **Type of Filter**
- 1. Passive filters
- 2. Active filters

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- **Passive filters**
- Passive filters works well for high frequencies. But at audio frequencies, the inductors become problematic, as they become large, heavy and expensive.
- For low frequency applications, more number of turns of wire must be used which in turn adds to the series resistance degrading inductor’s performance ie, low Q,resulting in high power dissipation
- **Active filters**
- Active filters used op- amp as the active element and resistors and capacitors as passive elements.
- By enclosing a capacitor in the feed back loop , inductor less active filters can be obtained

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- Active filters use op-amp(s) and RC components.
- Advantages over passive filters:

– op-amp(s) provide gain and overcome circuit losses
– increase input impedance to minimize circuit loading
– higher output power
– sharp cutoff characteristics **some commonly used active filters**

1. Low pass filter
2. High pass filter
3. Band pass filter
4. Band reject filter

Active Filters

can be produced simply and efficiently without bulky inductors

Review of Filter Types & Responses

- 4 major types of filters: low-pass, high-pass, band pass, and band-reject or band-stop
- 0 dB attenuation in the pass band (usually)
- 3 dB attenuation at the *critical or cutoff frequency, fc (for Butterworth filter)*
- Roll-off at 20 dB/dec (or 6 dB/oct) per *pole outside the passband (# of poles = # of* reactive elements).

Attenu

$$atten.(dB)\,at\,f = \log\left(\frac{f}{f_c}\right) x\,atten.(dB)\,at\,f_{dec}$$

- Bandwidth of a filter: BW = fcu – fcl
- Phase shift: 45°/pole at fc; 90°/pole at >> fc
- 4 types of filter responses are commonly used:

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Types of filters

- Butterworth - maximally flat in passband; highly non-linear phase response with frequency
- – Bessel - gentle roll-off; linear phase shift with freq.
- – Chebyshev - steep initial roll-off with ripples in passband
- – Cauer (or elliptic) - steepest roll-off of the four types but has ripples in the passband and in the stop band

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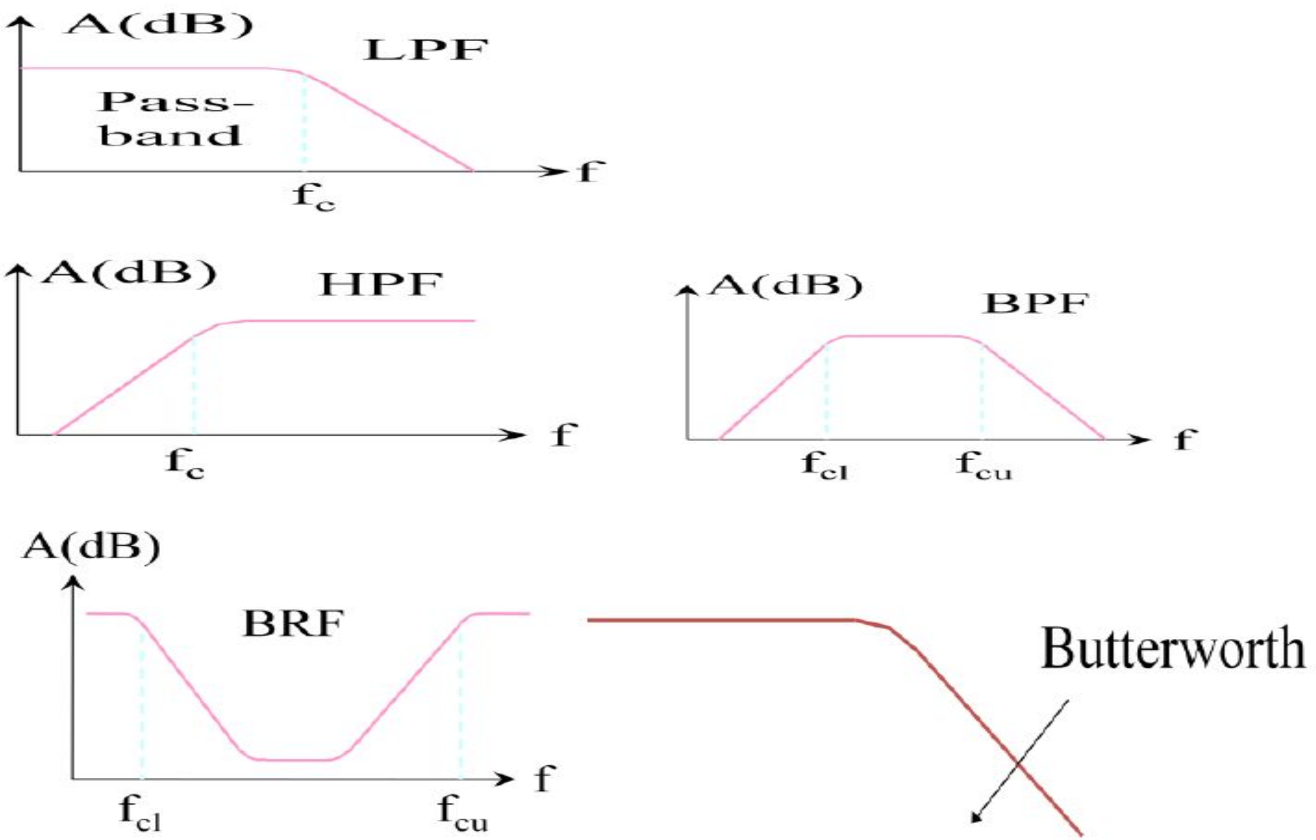
Frequency response of filters



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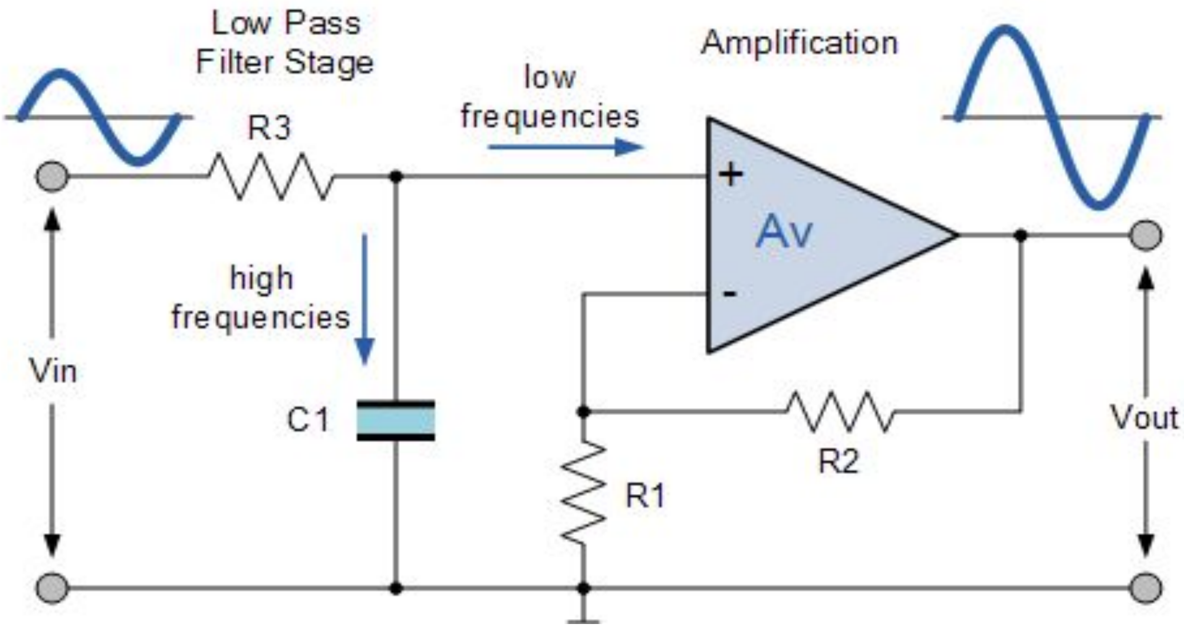
I order Active LPF



Gain of a first-order low pass filter

$$Voltage\ Gain,\ (Av) = \frac{Vout}{Vin} = \frac{A_F}{\sqrt{1 + \left(\frac{f}{fc}\right)^2}}$$

Where:

A_F = the pass band gain of the filter, (1 + R2/R1)

f = the frequency of the input signal in Hertz, (Hz)

fc = the cut-off frequency in Hertz, (Hz)

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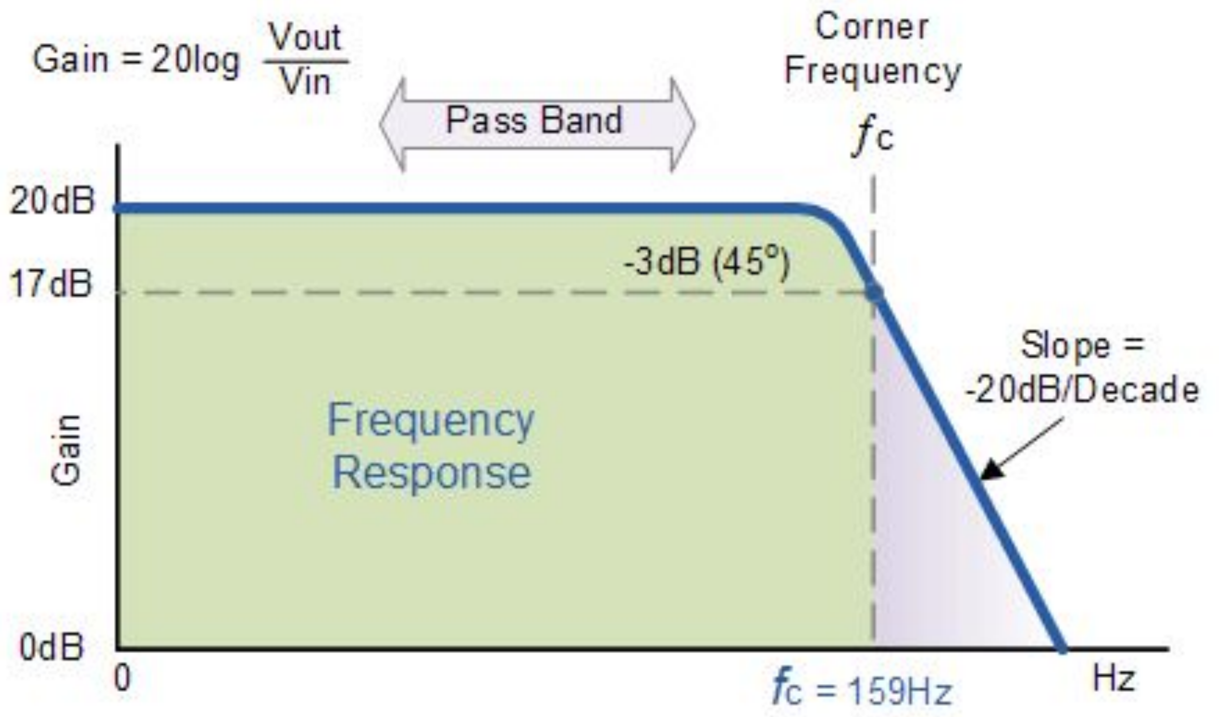
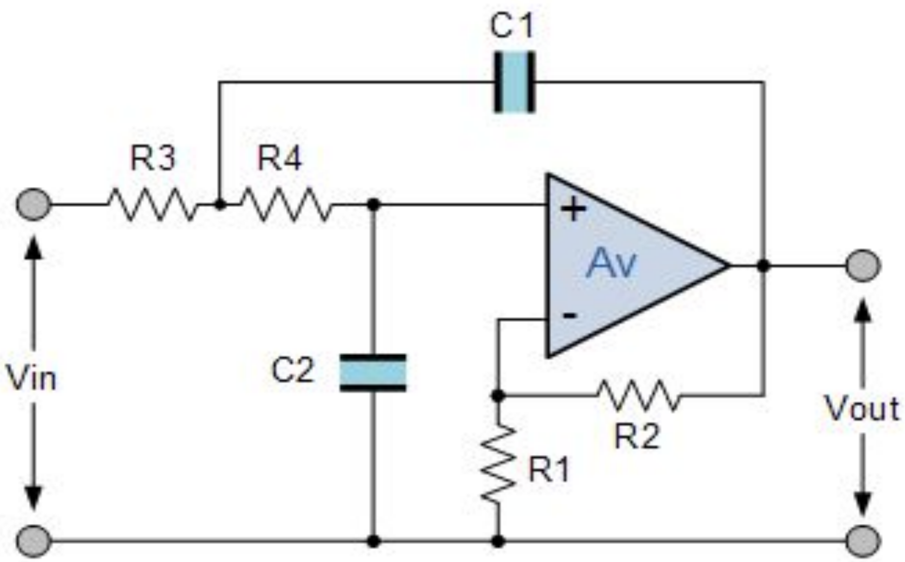

Gain = 20log Vout/Vin
Pass Band
Corner Frequency
fc
20dB
17dB
-3dB (45°)
Slope = -20dB/Decade
Gain
Frequency Response
0dB
0
fc = 159Hz
Hz

Second-order Low Pass Active Filter

As with the passive filter, a first-order Low Pass Active Filter can be converted into a second-order low pass filter simply by using an additional RC network in the input path. The frequency response of the second-order low pass filter is identical to that of the first-order type except that the stop band roll-off will be twice the first-order filters at 40dB/decade (12dB/octave). Therefore, the design steps required of the second-order active low pass filter are the same.

Second-order Active Low Pass Filter Circuit



$$A_V = 1 + \frac{R_2}{R_1}$$

$$f_C = \frac{1}{2\pi\sqrt{R_3 R_4 C_1 C_2}}$$

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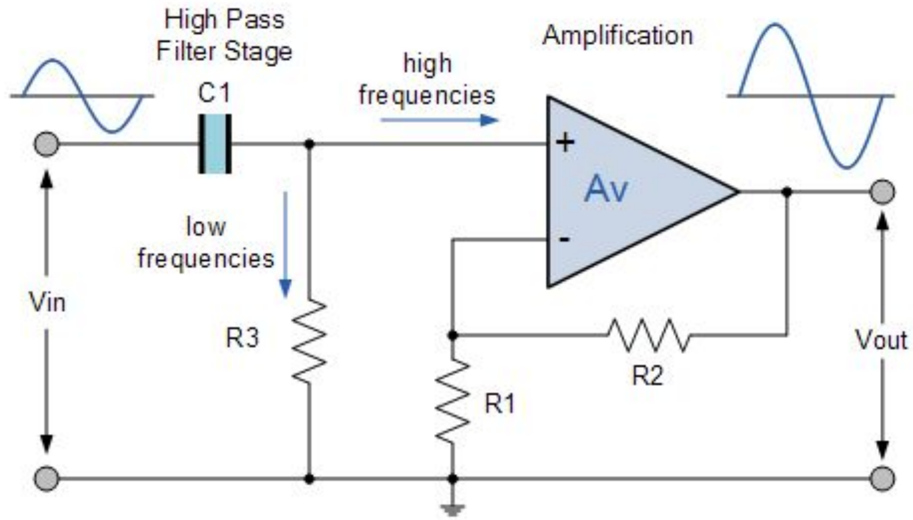
I order Active HPF



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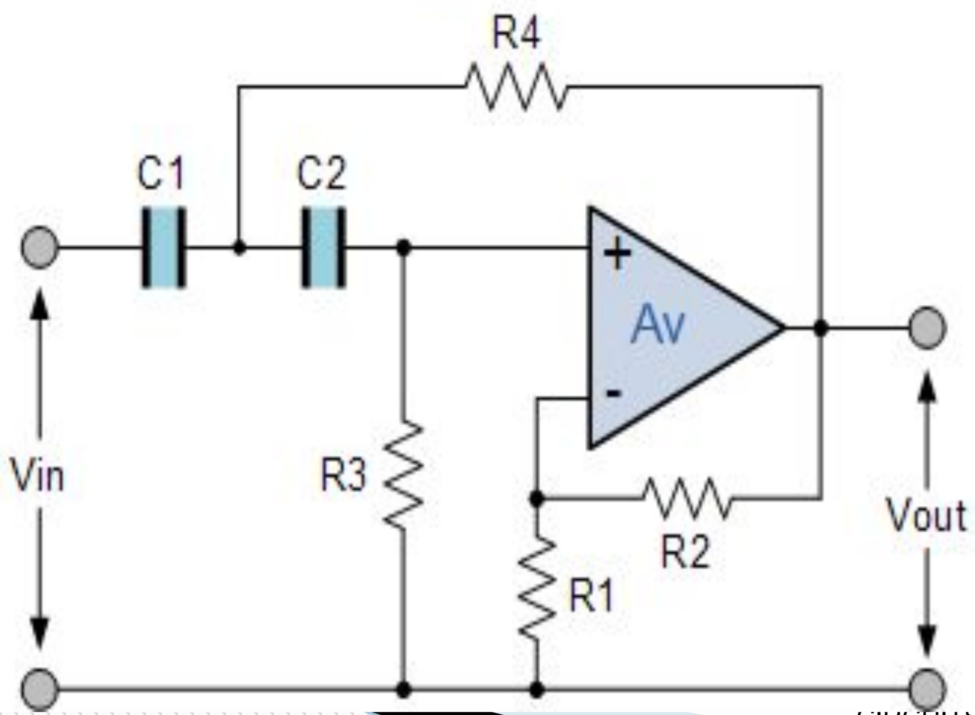
Second-order High Pass Active Filter

As with the passive filter, a first-order high pass active filter can be converted into a second-order high pass filter simply by using an additional RC network in the input path. The frequency response of the second-order high pass filter is identical to that of the first-order type except that the stop band roll-off will be twice the first-order filters at 40dB/decade (12dB/octave). Therefore, the design steps required of the second-order active high pass filter are the same.

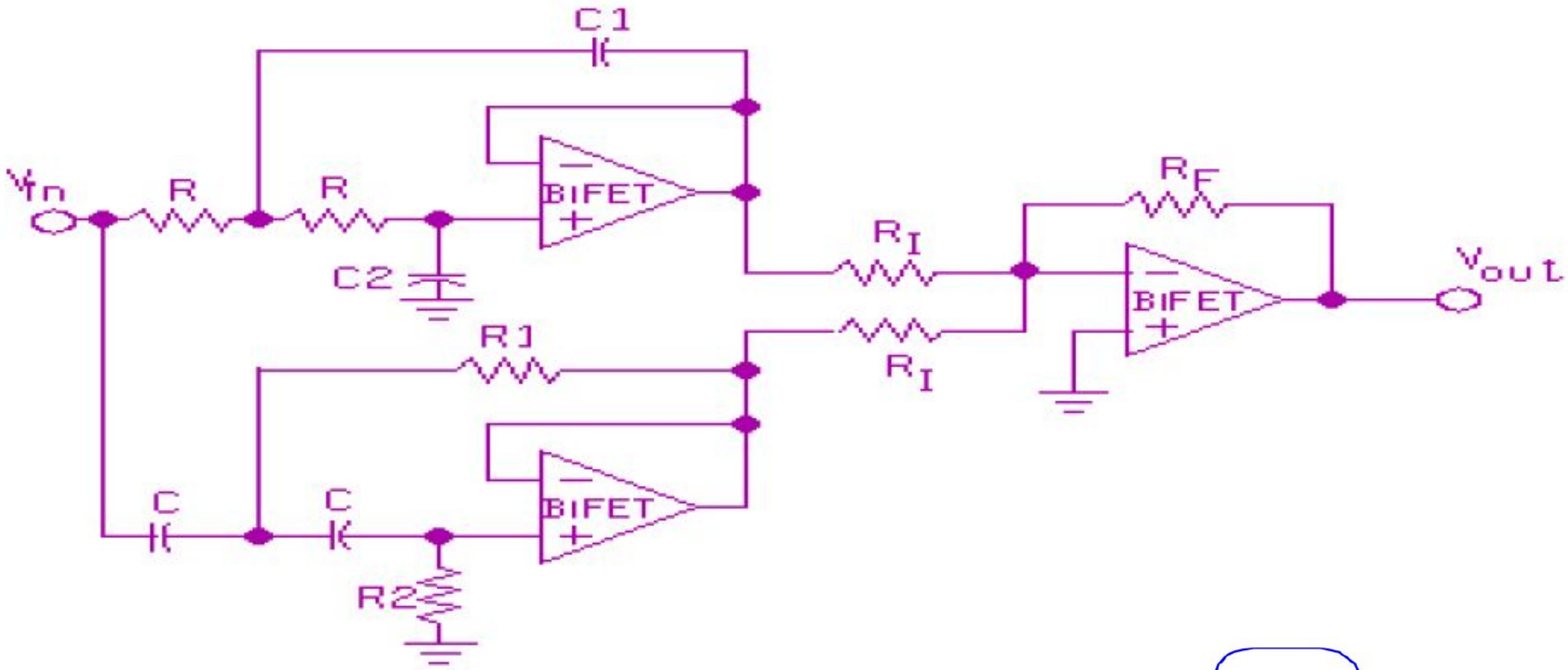
Second-order Active High Pass Filter Circuit



$$A_v = 1 + \frac{R_2}{R_1}$$

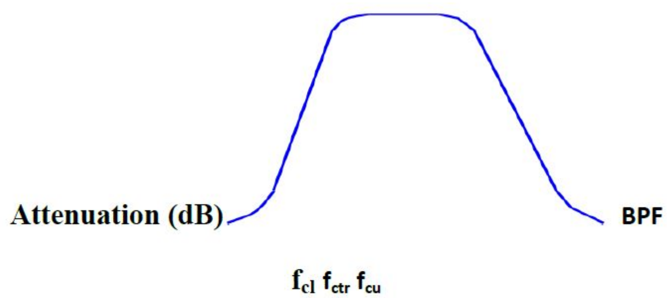
$$f_C = \frac{1}{2\pi\sqrt{R_3 R_4 C_1 C_2}}$$

Wide BPF

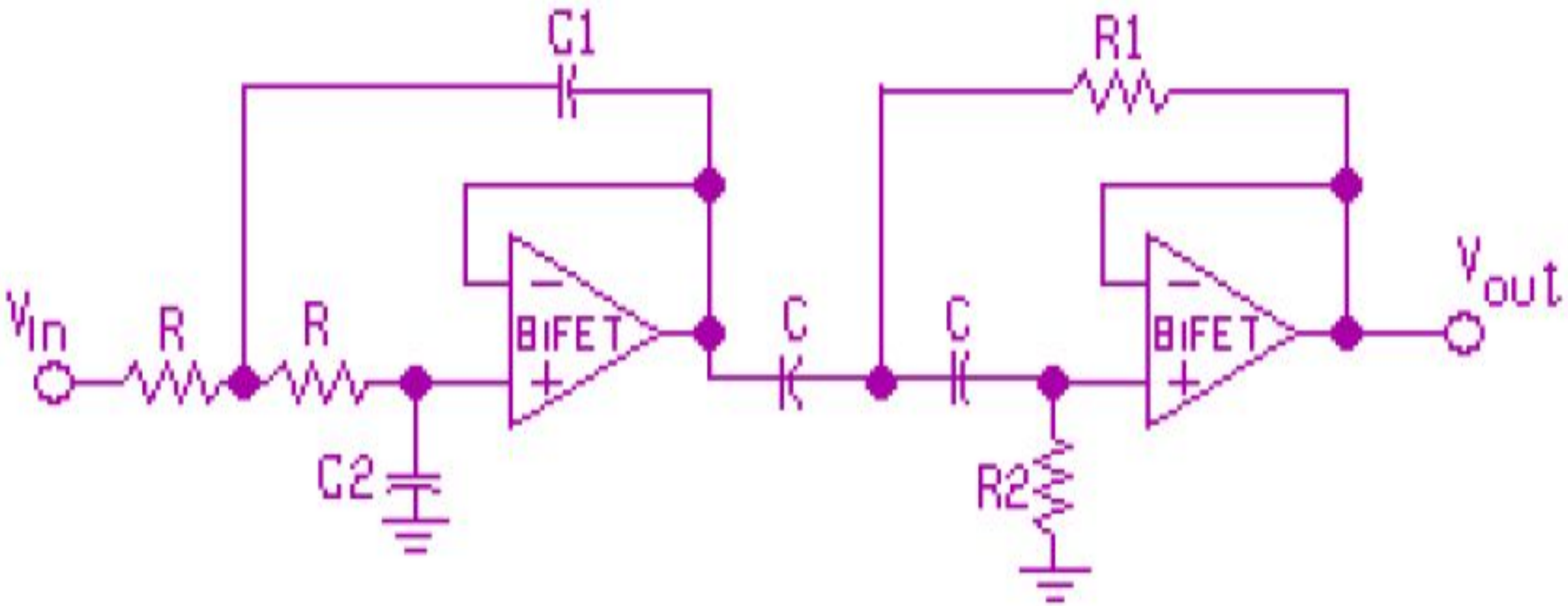


$$f_{ctr} = \sqrt{f_{cu} f_{cl}}$$

$$Q = \frac{f_{ctr}}{BW}$$



A *broadband* BPF can be obtained by combining a LPF and a HPF



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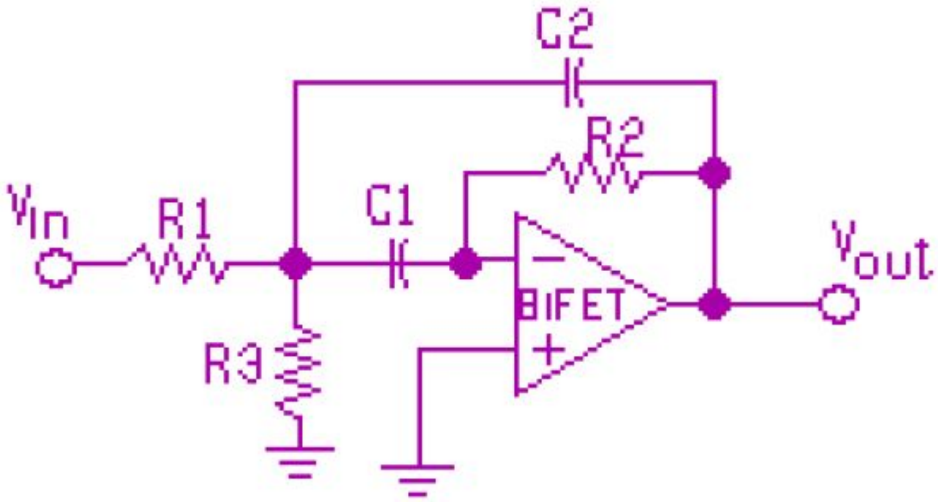
Narrow-band Bandpass Filter



$$f_{ctr} = \frac{1}{2\sqrt{2}\pi R_1 C}\sqrt{1+\frac{R_1}{R_3}}$$

$$BW = \frac{f_{ctr}}{Q} = \frac{1}{2\pi R_1 C}$$

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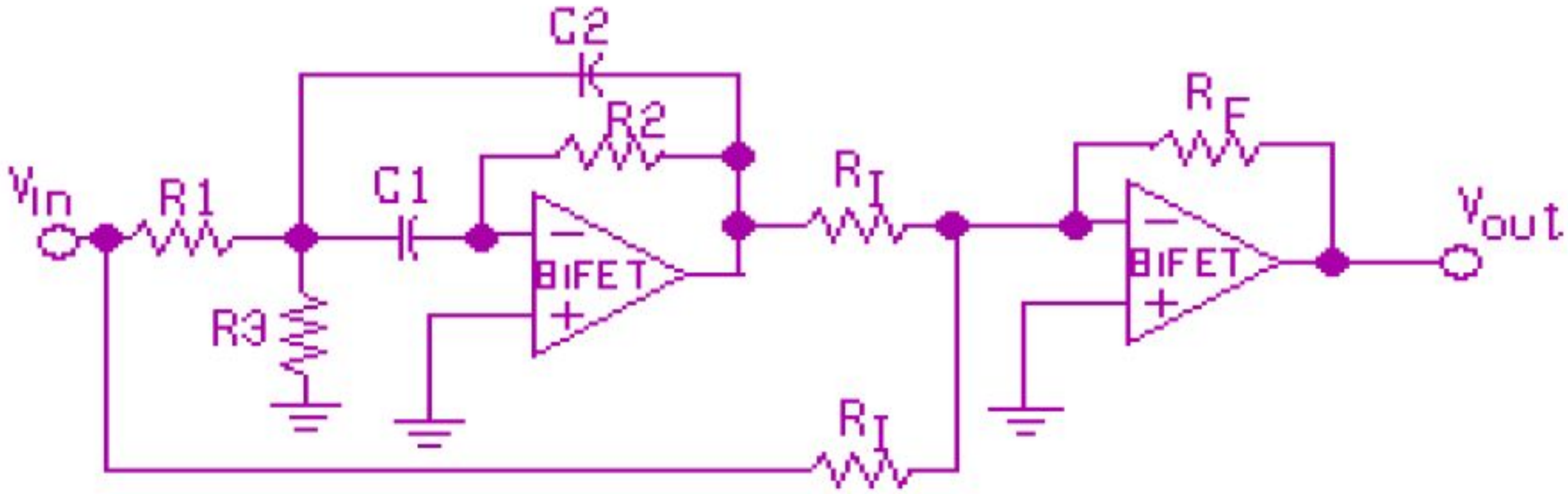
Narrow-band Band-Reject Filter

Easily obtained by combining the inverting output of a narrow-band BRF and the original signal



The equations for R1, R2, R3, C1, and C2 are the same as before.

$R_I = R_F$ for unity gain and is often chosen to be >> R1.

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