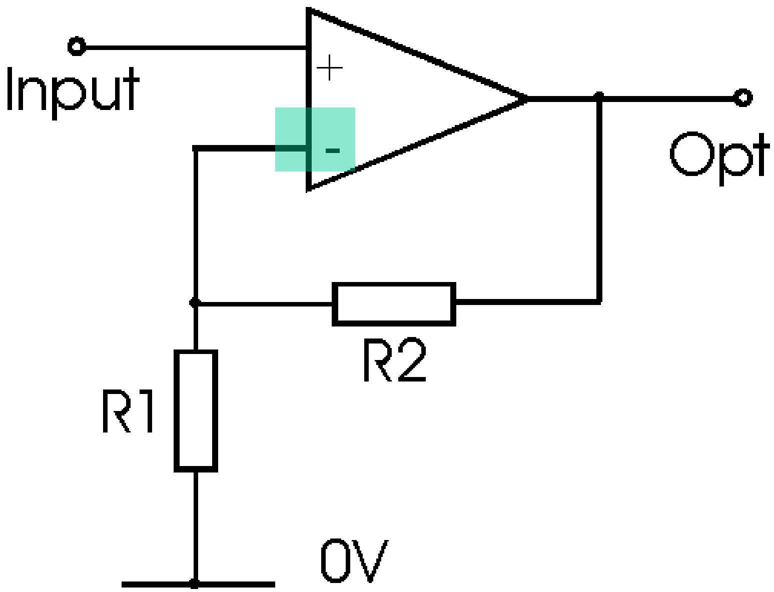
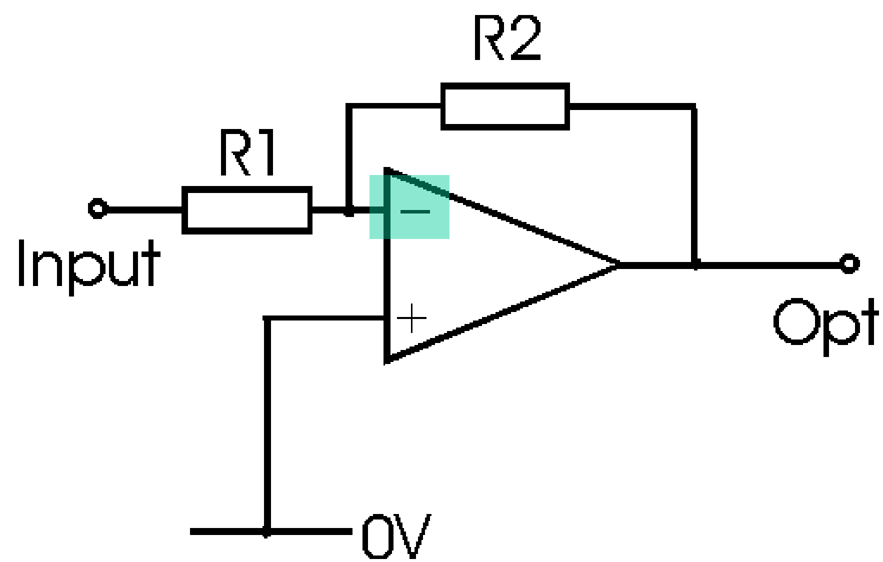
AE 242
Aerospace Measurements Laboratory


Input
+
-
Opt
R2
R1
0V


R2
R1
Input
−
+
Opt
0V

Operational Amplifier

Operational Amplifier

Integrated circuit many stages of matched transistor amplifiers

Very high gain differential amplifier

High input impedance and low output impedance

Initially designed for mathematical operations: multiplication, division, addition, subtraction etc

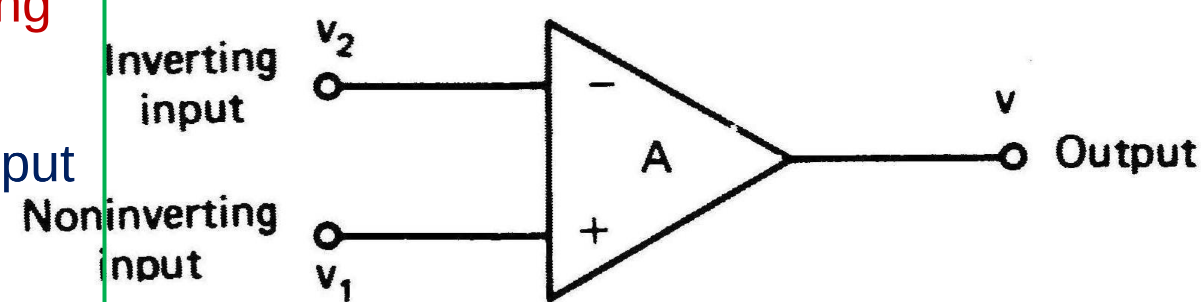
v_1 - voltage at non-inverting input

v_2 - voltage at inverting input

v - Output voltage

A – Open loop gain

All are measured wrt ground



$$v = A(v_1 - v_2)$$

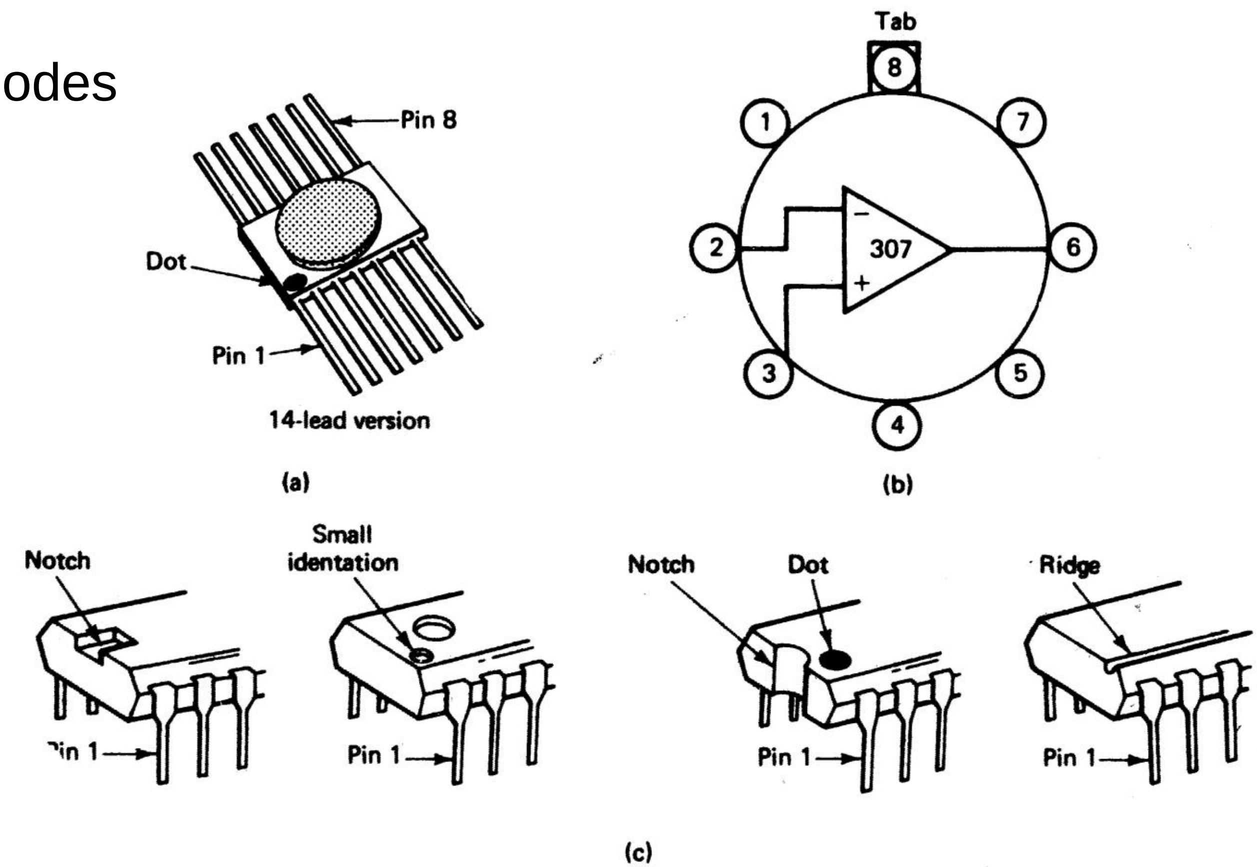
Output is amplification of difference at input terminals

Operational Amplifier

Simple to use and understand as compared to transistors. Large number of applications. Most popular is 741 (8 pin dip).

Can be used in many modes

- Differential
- Single ended
- Open loop
- Feed back



Operational Amplifier

Pin assignment

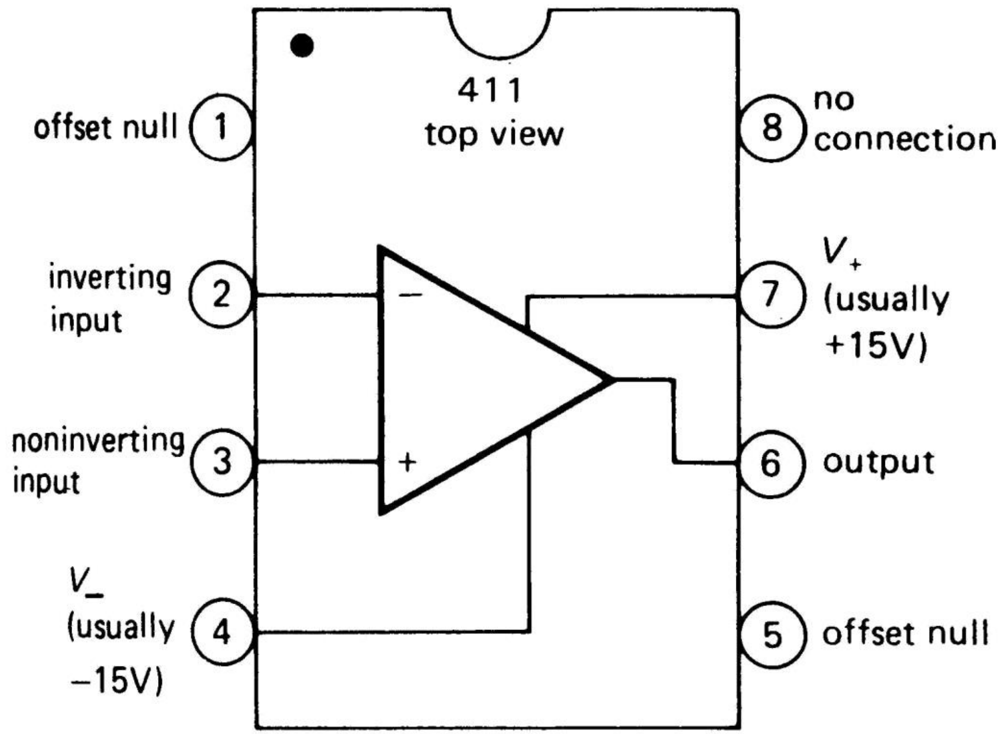
Generally in circuit diagram connection are pointed to pin number 2, 3, 4, 7 and 6.

Pin 2 & 3 are input

Pin 4 & 7 are power supply

Pin 6 is output

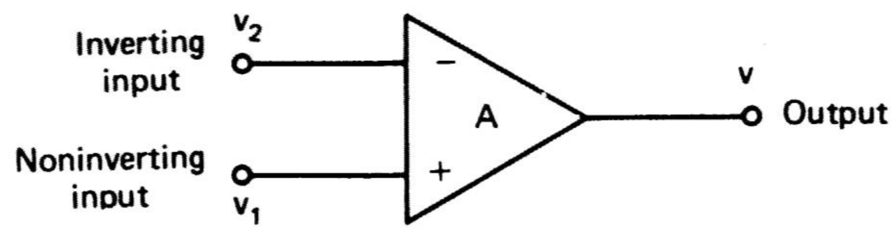
Pin 1 & 5 for offset null



Operational Amplifier

Common mode rejection ratio (CMRR): Ratio of common mode differential voltage gain A_d to common mode voltage gain A_{cm}.

$$\mathrm{CMRR} = \frac{A_d}{A_{cm}}$$



Generally A_d is very large compared to A_{cm} and CMRR is a very large number. Typically 90dB ~ 31.6 k Higher the number it is better. This quality is important when the OpAmp is used in differential mode. Helps in noise reduction. Generally noise is common to both the input terminals and the applied signal is voltage difference at the input terminals. For precision opamp it is as high as 120 dB.

$$\boxed{dB = 20 \log_{10} x}$$

dB values

dB	Power ratio	Amplitude ratio
100	10 000 000 000	100 000
90	1 000 000 000	31 623
80	100 000 000	10 000
70	10 000 000	3 162
60	1 000 000	1 000
50	100 000	316.2
40	10 000	100
30	1 000	31.62
20	100	10
10	10	3.162
6	3.981 ≈ 4	1.995 ≈ 2
3	1.995 ≈ 2	1.413 ≈ $\sqrt{2}$
1	1.259	1.122
0	1	1
−1	0.794	0.891
−3	0.501 ≈ ½	0.708 ≈ $\sqrt{1/2}$
−6	0.251 ≈ ¼	0.501 ≈ ½
−10	0.1	0.316 2
−20	0.01	0.1
−30	0.001	0.031 62
−40	0.000 1	0.01
−50	0.000 01	0.003 162
−60	0.000 001	0.001
−70	0.000 000 1	0.000 316 2
−80	0.000 000 01	0.000 1
−90	0.000 000 001	0.000 031 62
−100	0.000 000 000 1	0.000 01

An example scale showing power ratios x, amplitude ratios $\sqrt{x}$, and dB equivalents $10 \log_{10} x$.

$$dB = 20 \log_{10} x$$

Operational Amplifier

Large-signal voltage gain: Ratio of output voltage to difference of input voltage. It is very high 20 k. It means that 0.05 mV differential voltage at input will give one volt output.

Output voltage swing: This is the saturation voltage of output in positive and negative range. This will always be less than supply voltage, generally 1 to 2 volts. Opamp with rail to rail output are also available.

Output resistance : Equivalent resistance at output i.e. measured between output terminal and ground. It is ~ 75 ohms.

Gain bandwidth product : The bandwidth of the op-amp when the voltage gain is one. This can be obtained from open loop voltage gain and frequency characteristics.

Slew rate : Maximum rate of change of output volt per second, important for high frequency signal. V/ μS This is a measure of how rapidly output will change in response to input signal. Perfect square wave is not possible.

Operational Amplifier

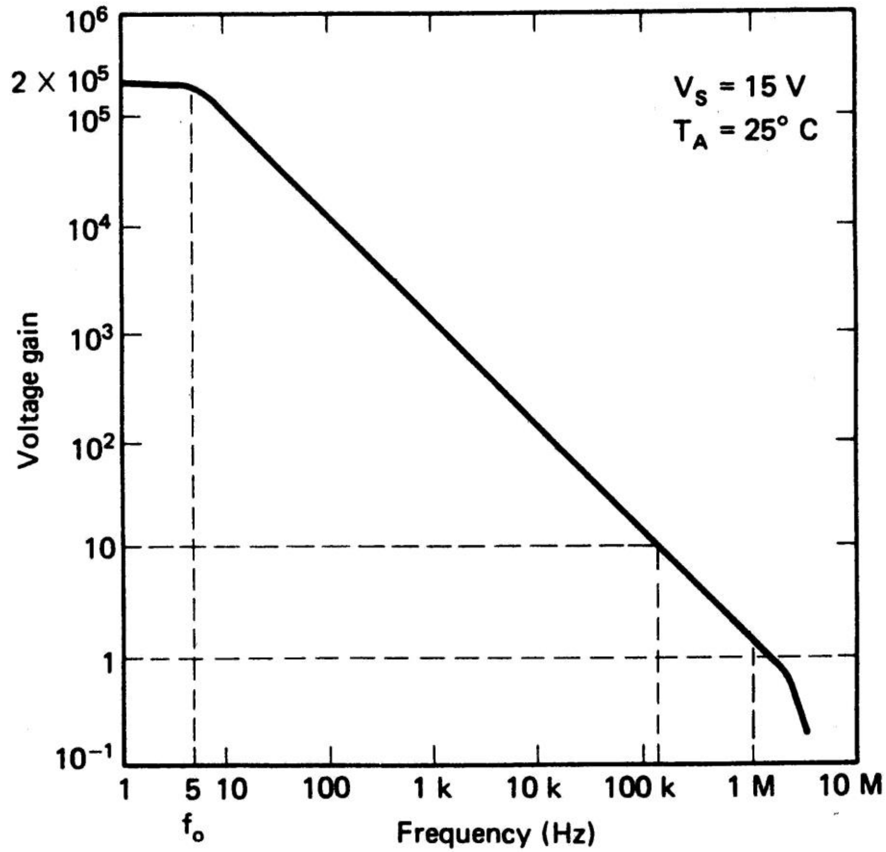
Bandwidth with feed back

Bandwidth of an amplifier is defined as the band of frequencies for which the gain remain constant

f_0 is break frequency (5 Hz)

$f_F = f_0\,(1 + AB)$

f_F is bandwidth with feed back, B is feed back gain



Open loop gain versus frequency

Operational Amplifier

<u>Ideal op-amp</u>

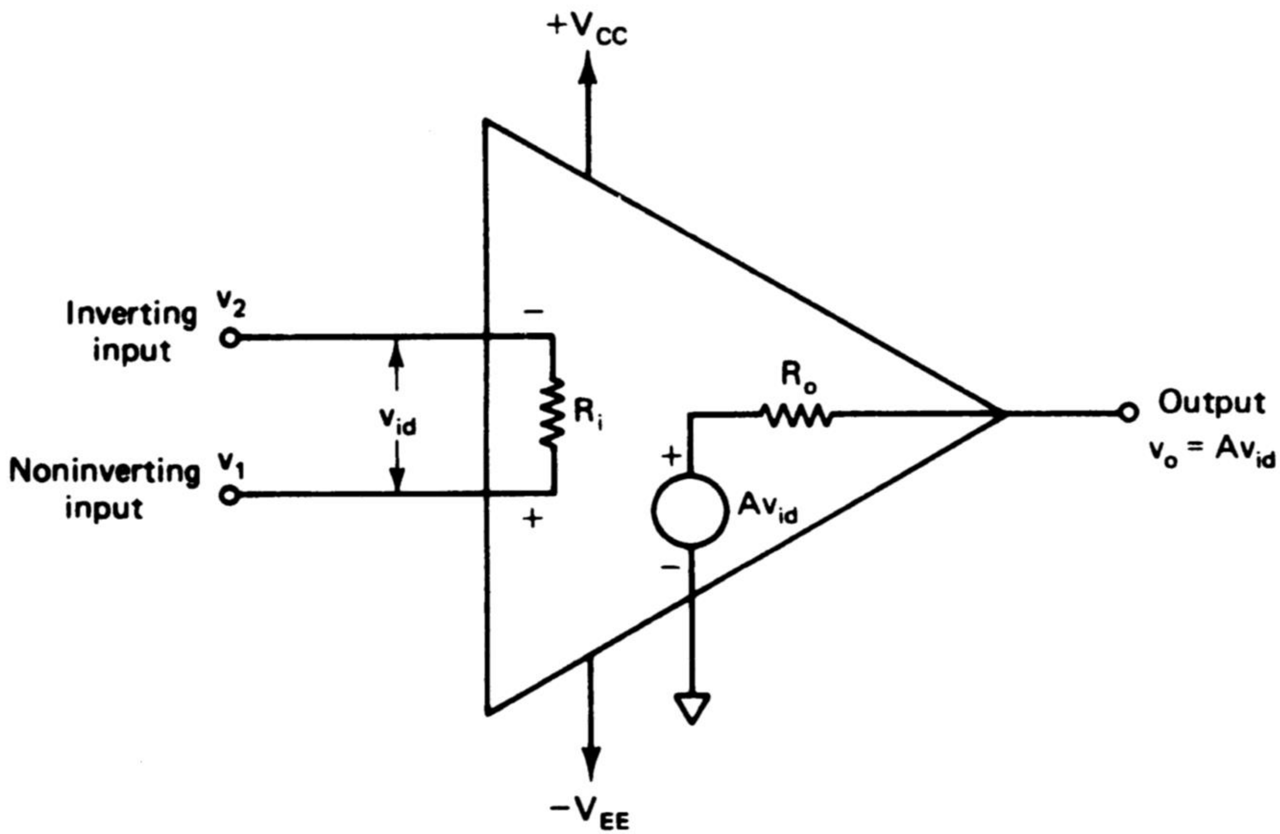
- Infinite voltage gain
- Infinite input resistance - no loading on source
- Zero output resistance - so that output can drive any number of devices
- Zero output voltage when input voltage is zero
- Infinite bandwidth
- Infinite CMRR
- Infinite slew rate

Characteristic	Ideal value	Typical real-world value
Open-loop gain A	∞	100,000 V/V
Offset voltage V_{os}	0	± 1 mV @ 25°C
Bias currents i_A, i_B	0	10^{-6} to 10^{-14} A
Input impedance Z_D	∞	10^5 to 10^{11} Ω
Output impedance Z_o	0	1 to 10 Ω

For practical opamps and practical use many of the characteristic can be approximated to above mentioned characteristics.

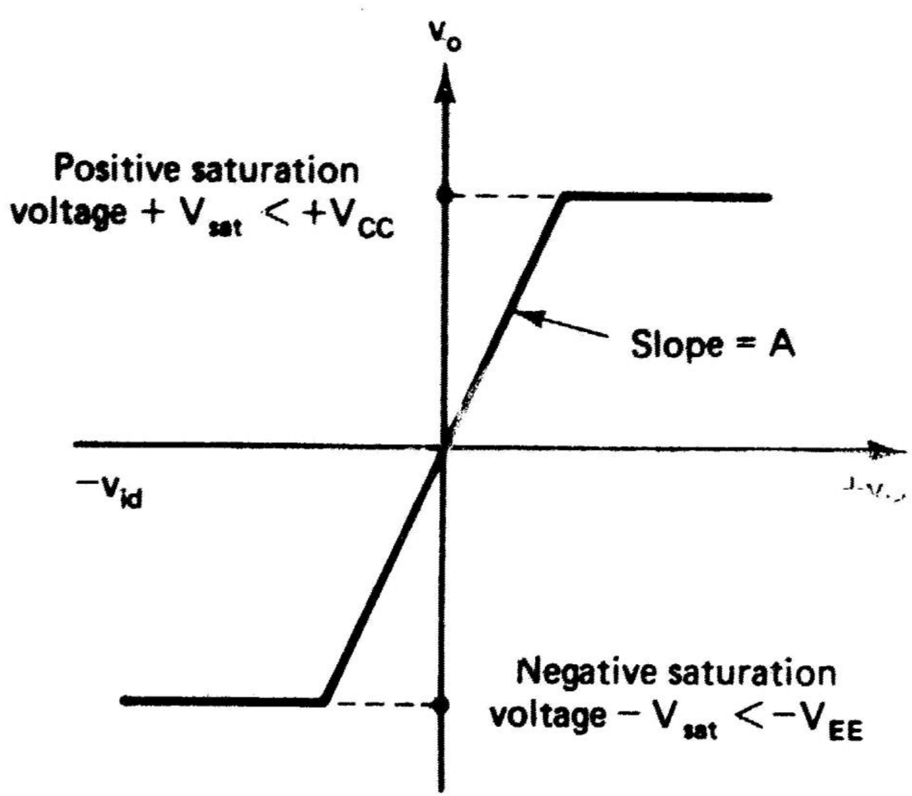
Equivalent circuit of an op-amp

Equivalent circuit is shown using input resistance, output resistance, and open loop gain. Input resistance will load the source and output resistance will drive the output.



Operational Amplifier

Ideal Voltage transfer curve : Output voltage cannot exceed the positive and negative saturation voltages. Offset voltage is zero. Slope is generally very large (almost vertical). Amplifies the difference in input voltages not the individual voltages.



Operational Amplifier

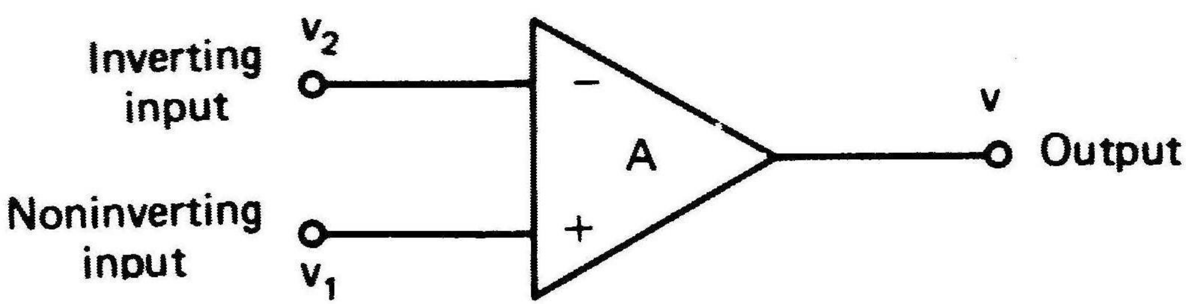
Open-loop op-amp configuration

No connection between output and input

1 Differential amplifier

2 Inverting amplifier

3 Noninverting amplifier



Operational Amplifier

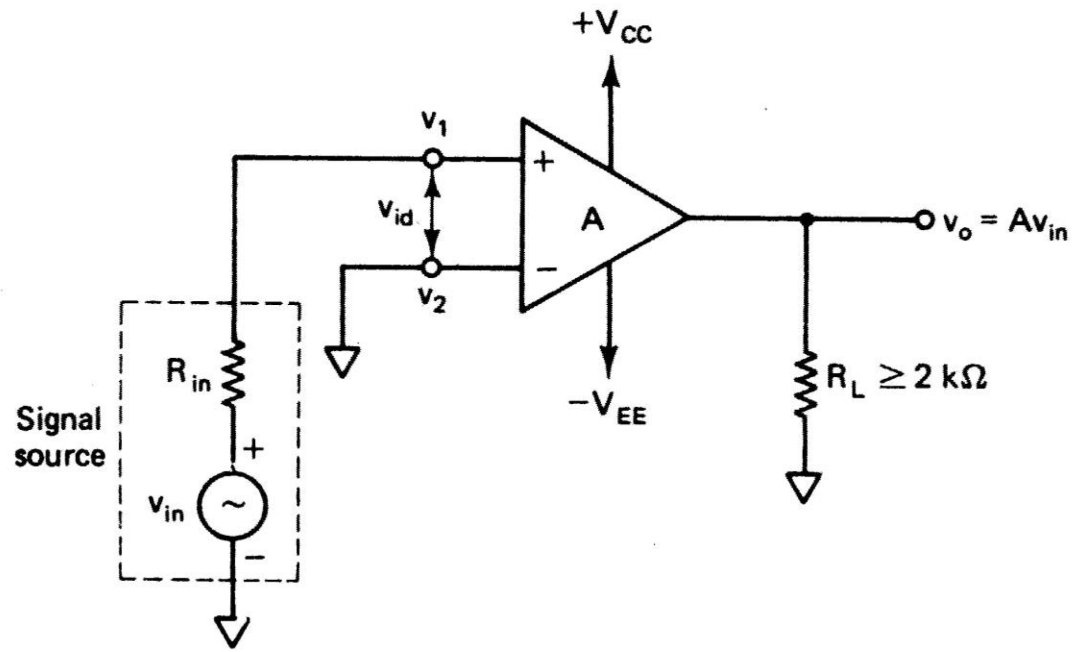
Non-inverting amplifier

Signal is applied to non-inverting (positive) terminal. Inverting terminal is grounded.

$v_0 = A\,(v_1 - v_2) = A\,v_1$, where A is open loop gain

Output is in phase with input, it will have same polarity as input.

In open loop configurations any input signal of few milli volts will saturate the output due to high open loop gain



Operational Amplifier

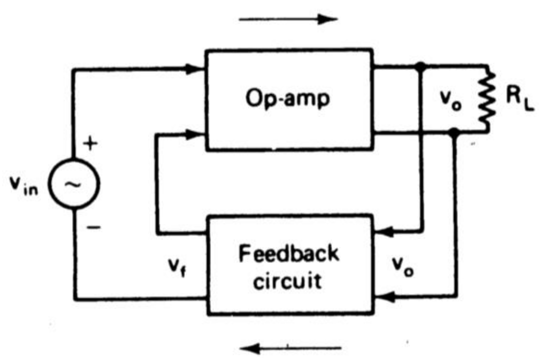
Difference input voltage ideally zero   Opamp equation $$V_{id} = \frac{V_0}{A}$$

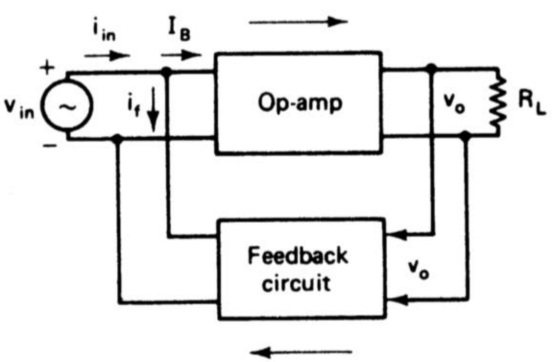
A is very large and ideally infinite. $V_{id} = 0$

$v_1 = v_2$, inverting and non-inverting terminal are at same voltage

__Golden rule 1 :__ opamp will work in such a way that it will drive the two inputs to same level

__Golden rule 2 :__ No current can flow into opamp





Using above two rules op-amp circuit analysis becomes easy.

Applicable for negative feedback

Operational Amplifier

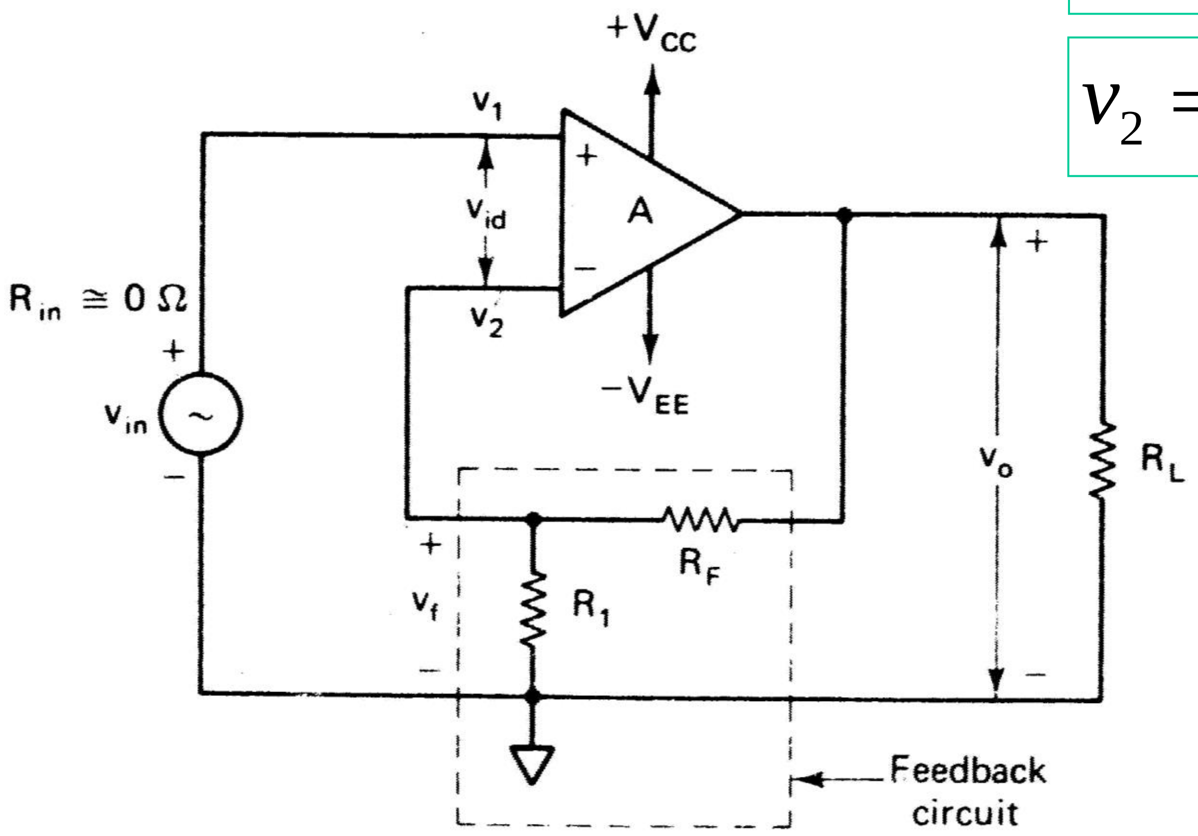
Voltage series feed back - Noninverting amplifier

Input - noninverting terminal (positive)

Feedback - inverting terminal

$$\boxed{v_o = ?}$$

$$\boxed{v_2 = v_f = ?}$$



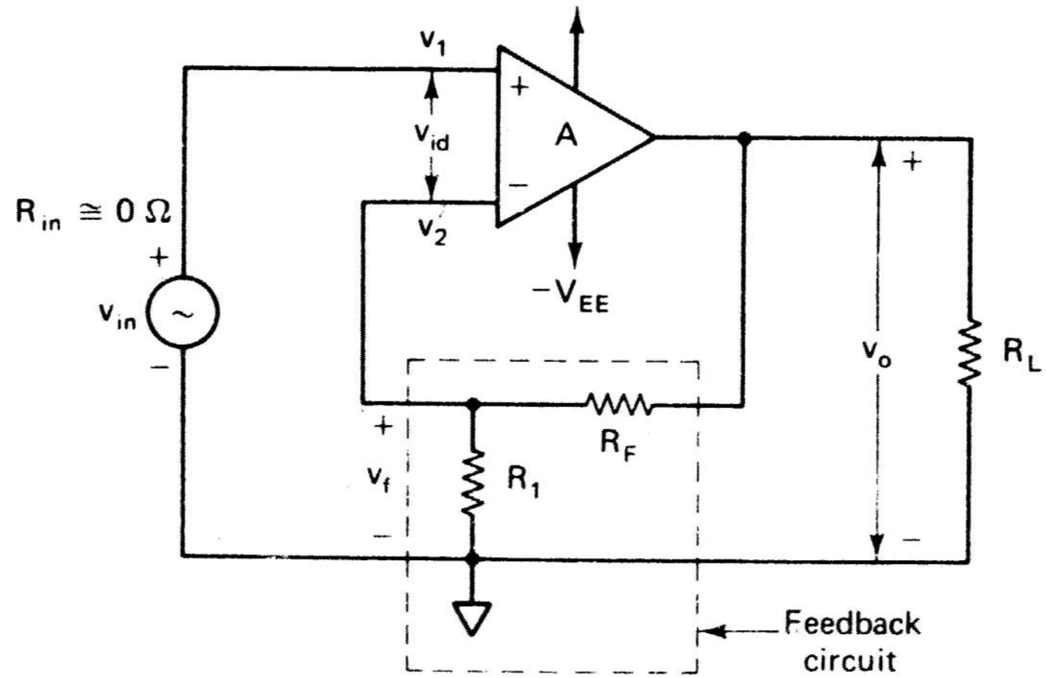
Operational Amplifier

Closed loop voltage gain $\mathbf{A_F = \frac{v_0}{v_{in}}}$

$$\mathbf{v_o = A(v_1 - v_2)} \qquad \mathbf{v_1 = v_{in}} \qquad \mathbf{v_2 = v_f = \frac{R_1 v_o}{R_1 + R_F}}$$

$$\mathbf{v_o = \frac{A(R_1 + R_F)v_{in}}{R_1 + R_F + AR_1}}$$

$$A_F = \frac{v_0}{v_{in}} = \frac{A(R_1 + R_F)}{R_1 + R_F + AR_1}$$



Exact gain, involves open loop gain and generally not known correctly

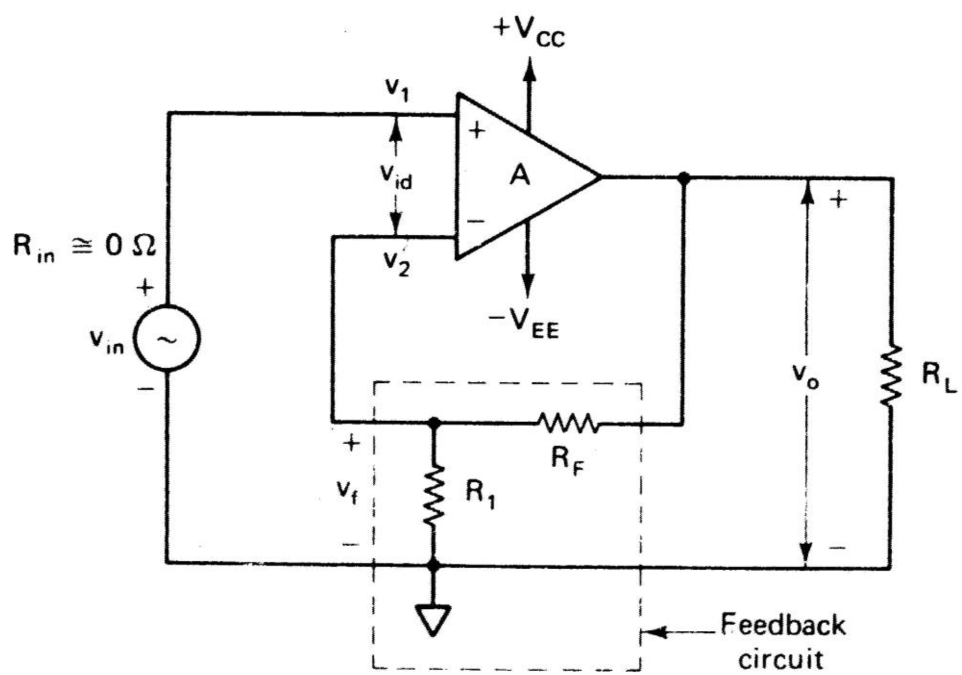
Operational Amplifier

Closed loop voltage gain $$A_F = \frac{v_0}{v_{in}} = \frac{A(R_1 + R_F)}{R_1 + R_F + AR_1}$$ Exact

A is open loop gain $AR_1 >> R_1 + R_F$ $$A_F = \frac{v_0}{v_{in}} = 1 + \frac{R_F}{R_1}$$ Ideal

Gain is decide by two resistance : R_1 and R_F independent of open loop gain

As a general rule R_1 and R_F should be less than 1 MΩ



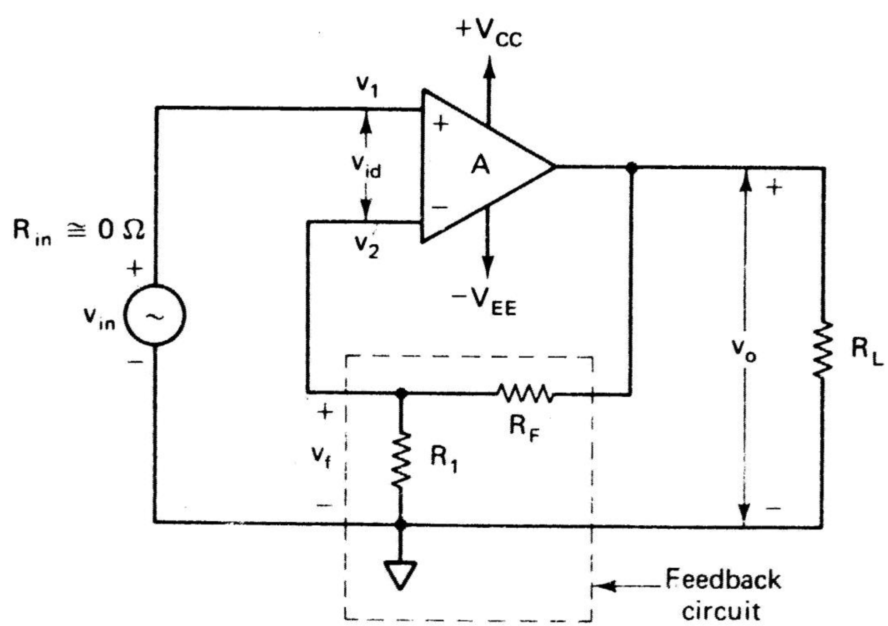
Operational Amplifier

Feedback gain $$\mathbf{B} = \frac{\mathbf{v_f}}{\mathbf{v_o}} = \frac{\mathbf{R_1}}{\mathbf{R_1 + R_F}}$$ $$\mathbf{A_F} = \frac{1}{\mathbf{B}}$$

$$A_F = \frac{v_0}{v_{in}} = \frac{A(R_1 + R_F)}{R_1 + R_F + AR_1}$$ $$\mathbf{A_F} = \frac{\mathbf{v_0}}{\mathbf{v_{in}}} = \frac{\mathbf{A(R_1 + R_F)/(R_1 + R_F)}}{\mathbf{(R_1 + R_F)/(R_1 + R_F) + AR_1/(R_1 + R_F)}}$$

$$\mathbf{A_F} = \frac{\mathbf{A}}{1 + \mathbf{AB}}$$ Exact

$$\mathbf{A_F} = \frac{\mathbf{v_0}}{\mathbf{v_{in}}} = \frac{1}{\mathbf{B}}$$ Ideal



Operational Amplifier

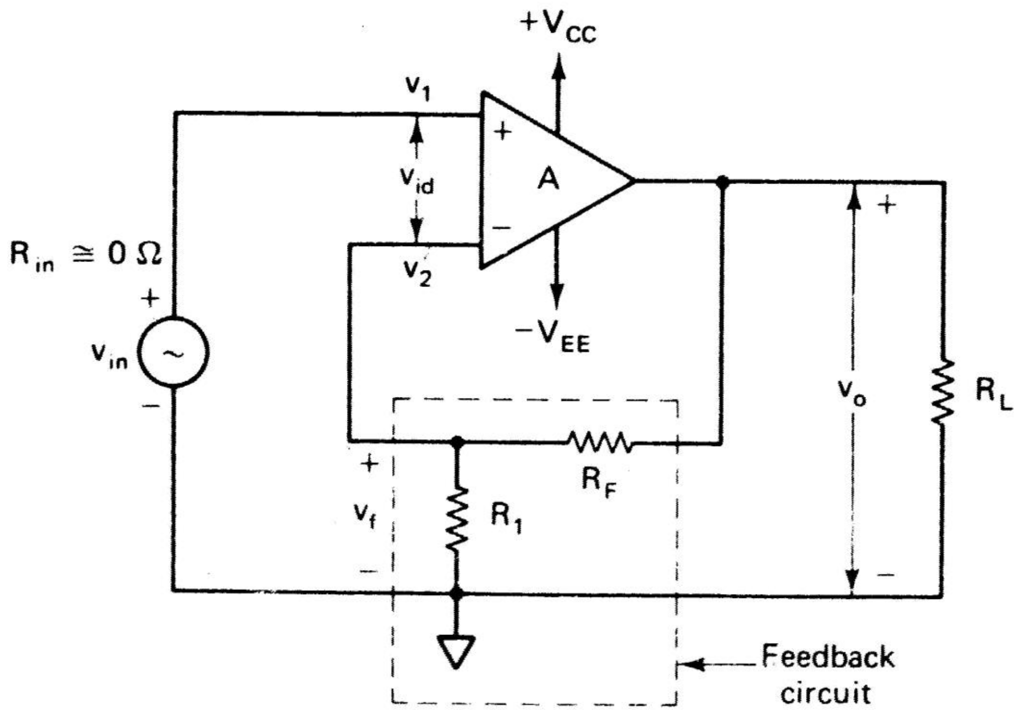
Using Golden rule

a) $v_1 = v_2$, b) No current flows in to opamp

$$V_2 = \frac{R_1}{R_F + R_1} V_0$$

$$V_1 = V_{in} = V_2$$

$$\frac{V_0}{V_{in}} = 1 + \frac{R_F}{R_1}$$



Operational Amplifier

Input resistance with feed back

$$R_{iF} = R_i\ (1+AB) \qquad B = 1/A_F$$

It means that input resistance in feed back is (1+AB) times than open loop input resistance R_i It means that input resistance increases.

Output resistance with feed back

$$R_{oF} = R_o\ /(1+AB)$$

It means that output resistance in feed back is 1/(1+AB) times open loop output resistance R_o It means that output resistance in feed back is much smaller compared to open loop.

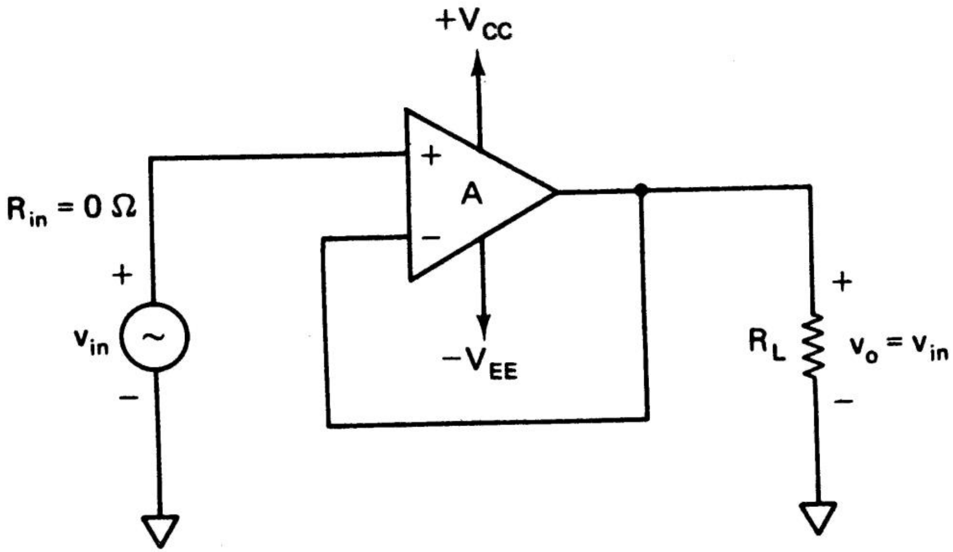
Operational Amplifier

<u>Voltage follower</u>

Lowest gain that can be obtained by a non-inverting amplifier is one, this configuration is called voltage follower. Output will follow the input.

Output is exactly equal to input and input resistance is very high.

Used as *isolator*. Any system connected on right side will obtain power from OpAmp. Power drawn from input will be almost zero, depends on the input resistance of OpAmp.



Operational Amplifier

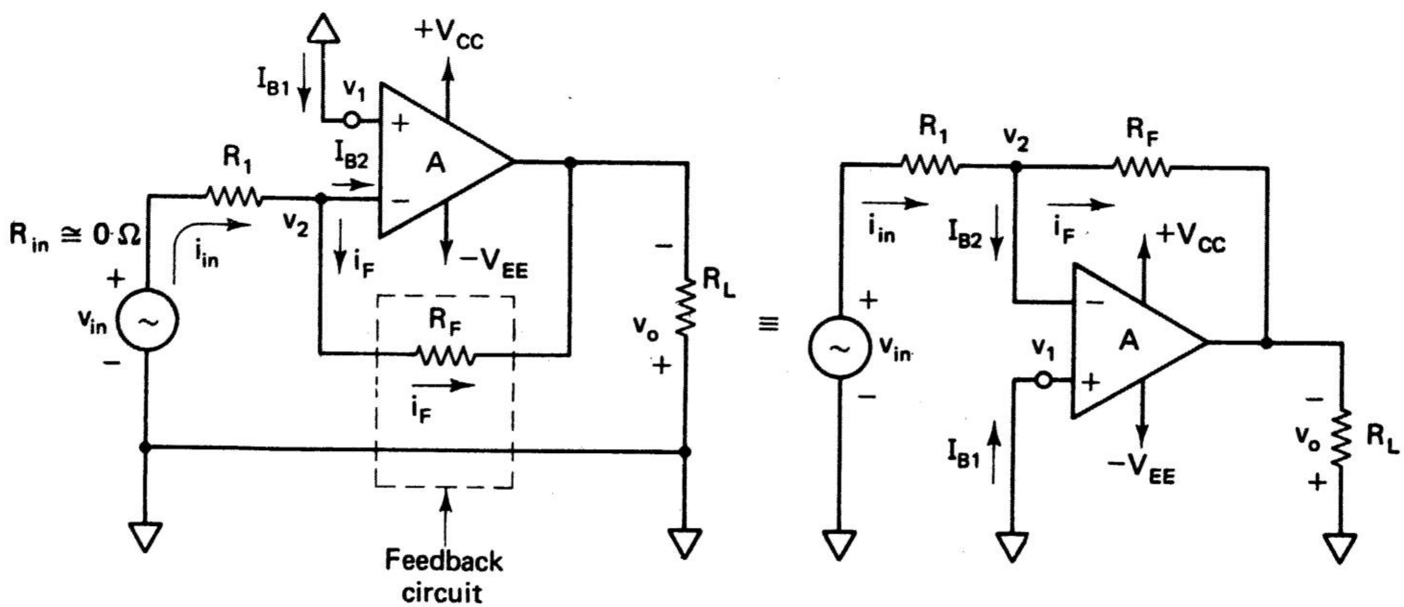
Voltage shunt feedback amplifier

Non-inverting terminal is grounded. Signal to inverting terminal in series with resistance R_1

$$i_{in} = i_F + I_{B2} \qquad I_{B2} \approx 0 \qquad I_{in} = \frac{v_{in} - v_2}{R_1} = \frac{v_2 - v_o}{R_F} \qquad \mathbf{v}_1 - \mathbf{v}_2 = \frac{\mathbf{v}_0}{\mathbf{A}}$$

$$\mathbf{A}_F = \frac{\mathbf{v}_0}{\mathbf{v}_{in}} = -\frac{\mathbf{A}\mathbf{R}_F}{\mathbf{R}_1 + \mathbf{R}_F + \mathbf{A}\mathbf{R}_1} \qquad \mathrm{V}_1 = 0 \qquad \mathbf{v}_2 = -\frac{\mathbf{v}_0}{\mathbf{A}}$$

$$\mathrm{A}_F = \frac{\mathrm{V}_0}{\mathrm{V}_{in}} = -\frac{\mathrm{R}_F}{\mathrm{R}_1}$$



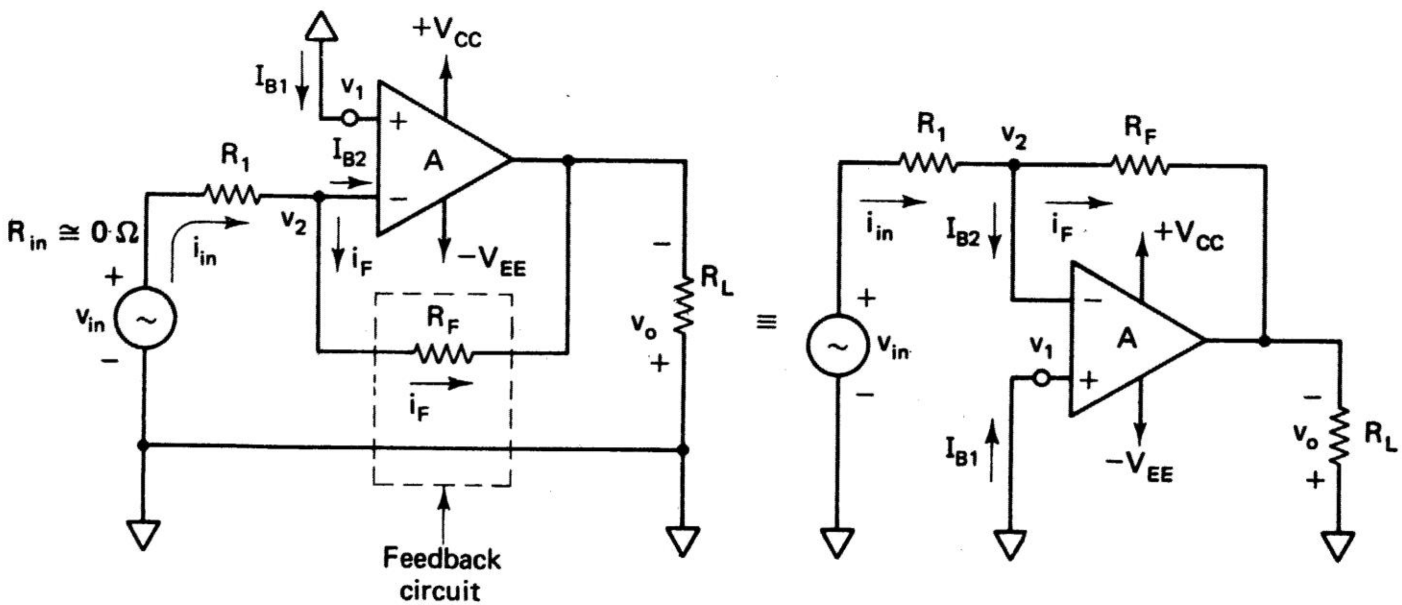
Operational Amplifier

Voltage shunt feedback amplifier

$$A_F = \frac{v_0}{v_{in}} = -\frac{R_F}{R_1}$$

Gain less than one possible

Gain is set by two resistance R_1 and R_F and independent of A



Operational Amplifier

Voltage shunt feedback amplifier

Using Golden rule

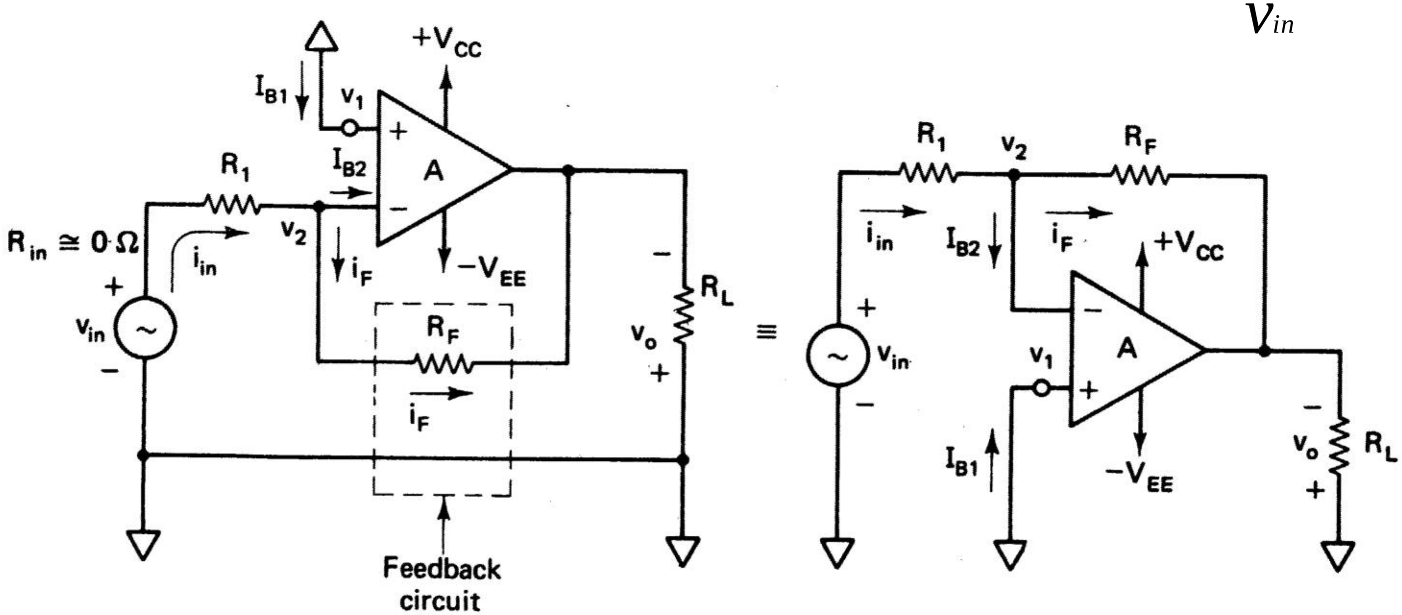
a) $v_1 = v_2$, b) No current flows in to opamp

$$\frac{V_{in} - V_2}{R_1} = \frac{V_2 - V_0}{R_F}$$

$$V_1 = 0 = V_2$$

$$A_F = \frac{v_0}{v_{in}} = -\frac{R_F}{R_1}$$

$$\frac{v_0}{v_{in}} = -\frac{R_F}{R_1}$$



Operational Amplifier

Input resistance with feed back

$$R_{iF} = R_1$$

It means that input resistance in feed back is ~ resistance R_1 much less compared to open loop input resistance R_i Input resistance reduces considerably.

Output resistance with feed back

$$R_{oF} = R_o /(1+AB)$$

It means that output resistance in feed back is 1/(1+AB) times open loop output resistance R_o Output resistance in feed back is much smaller compared to open loop. Same as non-inverting configuration.

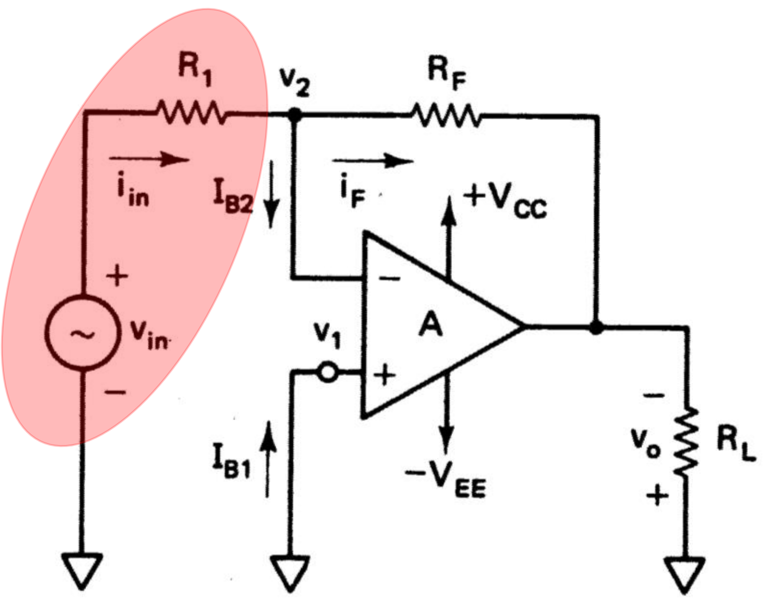
Operational Amplifier

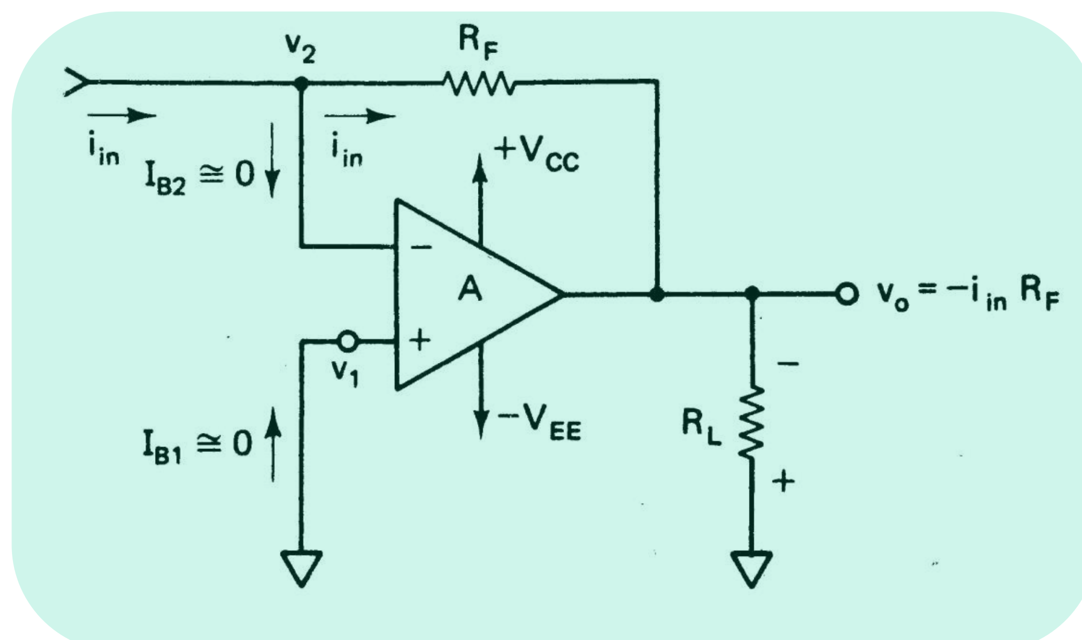
Current to voltage converter

$$v_0 = -\frac{v_{in}}{R_1} R_F$$

If replace v_{in} and R_1 combination by a current source, the output voltage will be proportional to current

Sensing current from photodiodes





Operational Amplifier

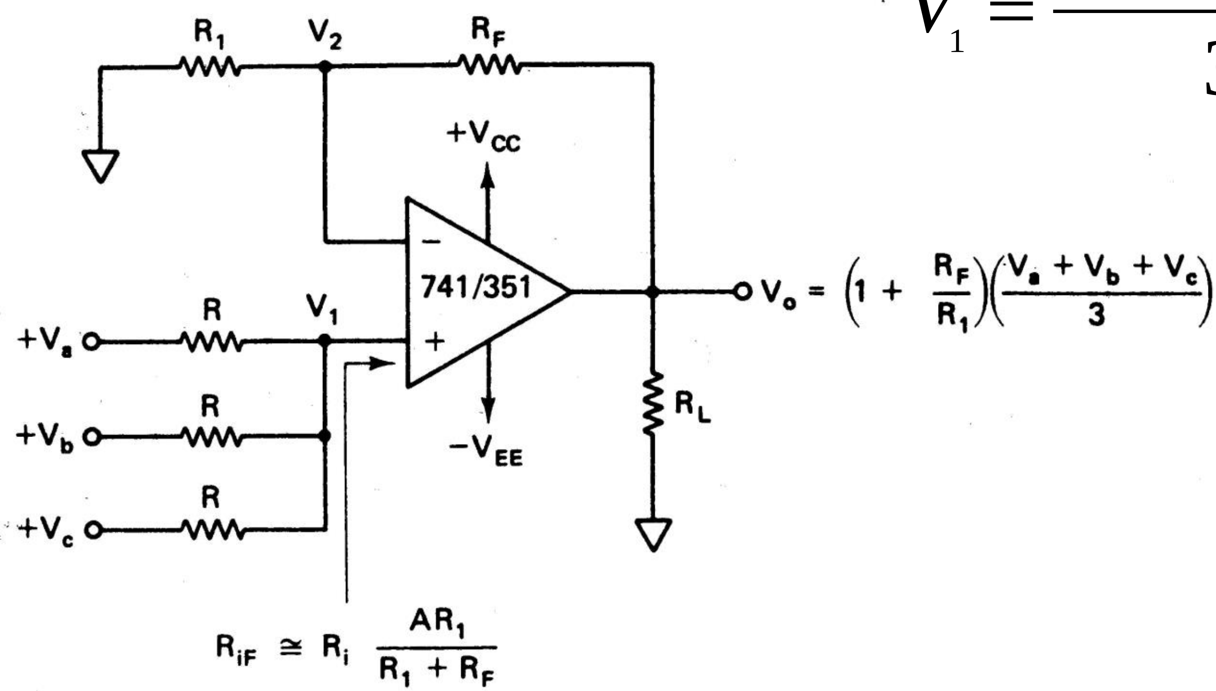
Summing amplifier - noninverting mode

Averaging of input signal

$$V_o = \left(1 + \frac{R_F}{R_1}\right)\frac{V_a + V_b + V_c}{3}$$

Summing, number of inputs = $\left(1 + \frac{R_F}{R_1}\right)$

$$V_1 = \frac{V_a + V_b + V_c}{3}$$



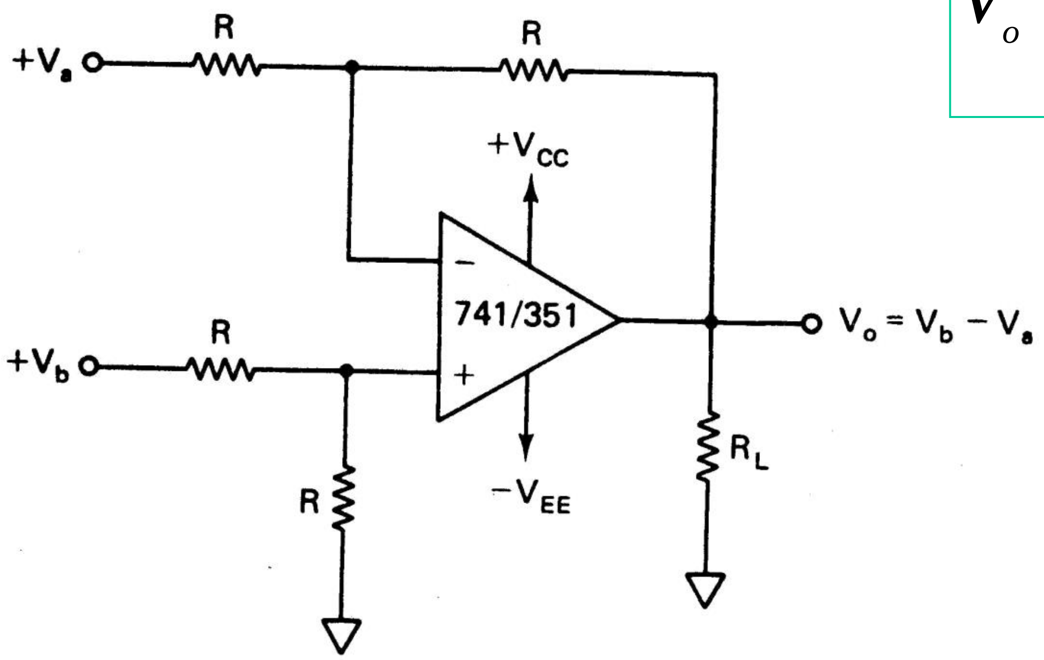
Operational Amplifier

Subtractor

Gain in inverting mode is 1

Gain in noninverting mode is 2

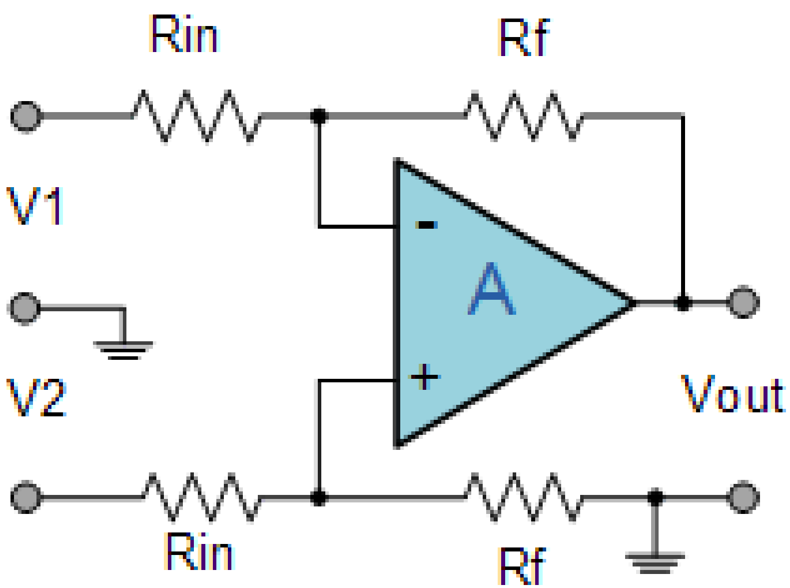
$$V_o = \frac{V_b}{2}\left(1+\frac{R}{R}\right) - V_a\frac{R}{R}$$



Output, $V_o = V_b - V_a$

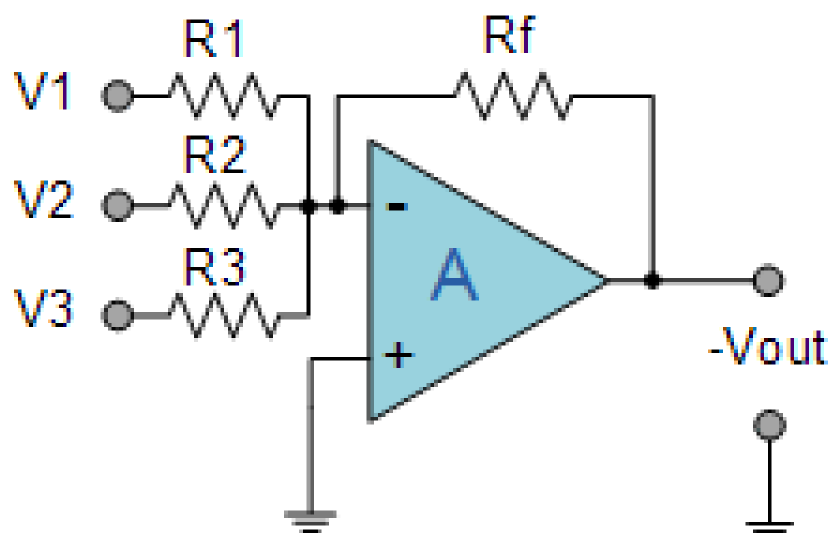
Operational Amplifier

Differential Op-amp



$$V_{out} = \frac{R_f}{R_{in}}(V2 - V1)$$

Summing Op-amp



$$V_{out} = -\left(\frac{R_f}{R1}V1 + \frac{R_f}{R2}V2 + \frac{R_f}{R3}V3\right)$$

Operational Amplifier

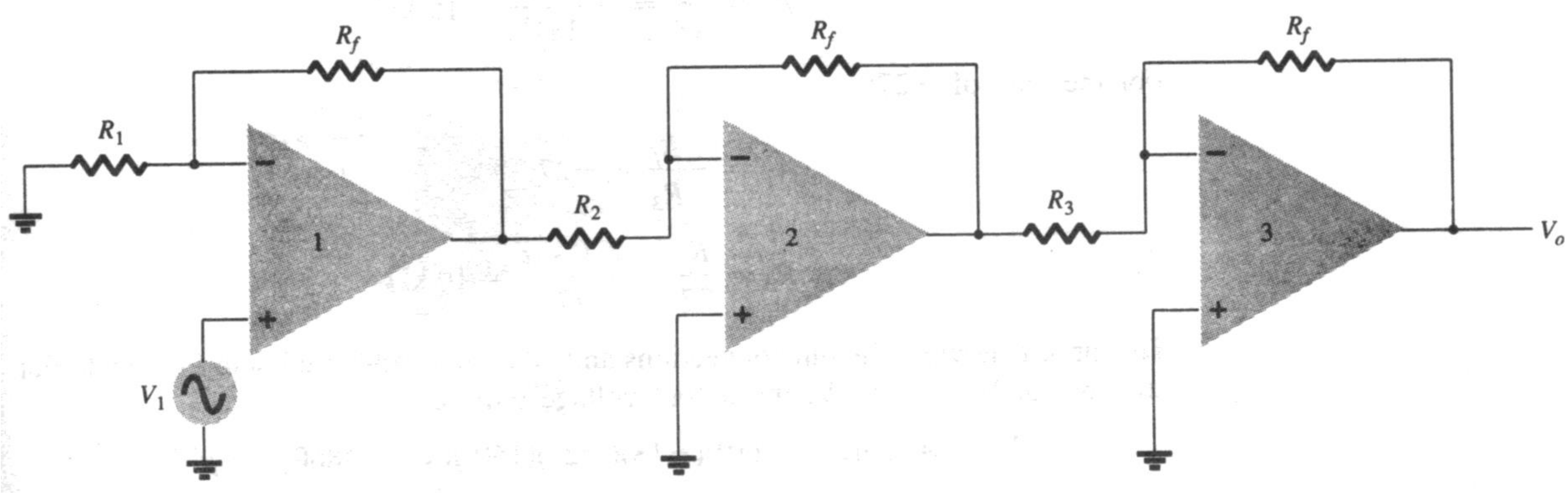
Multi stage amplifier

$$v_o = A\, V_1 \text{ where } A = A_1\, A_2\, A_3$$

A_1 = Amplification of first amplifier

A_2 = Amplification of second amplifier

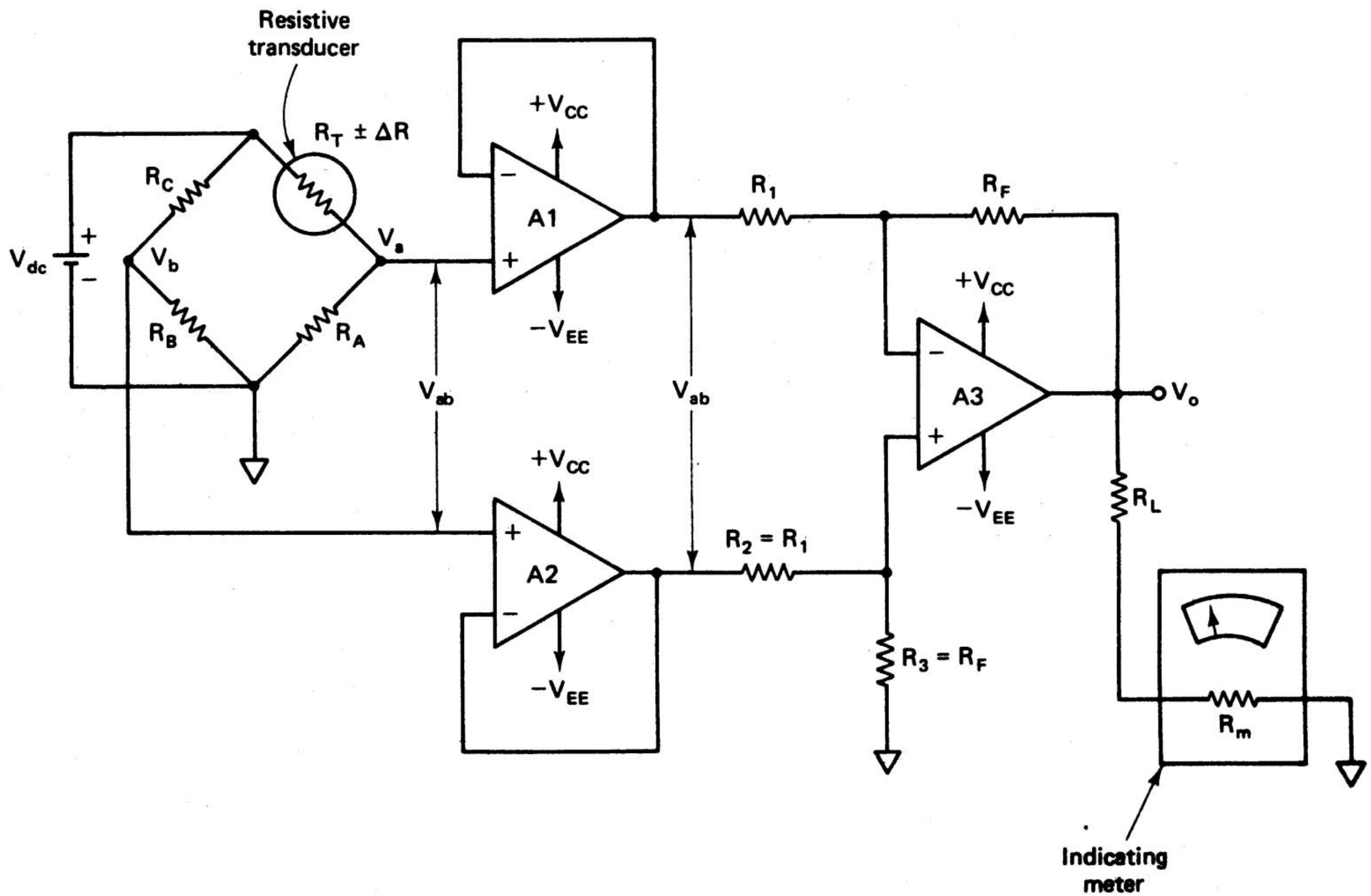
A_3 = Amplification of third amplifier



Operational Amplifier

Instrumentation amplifier

Two voltage follower output given to a differential amplifier



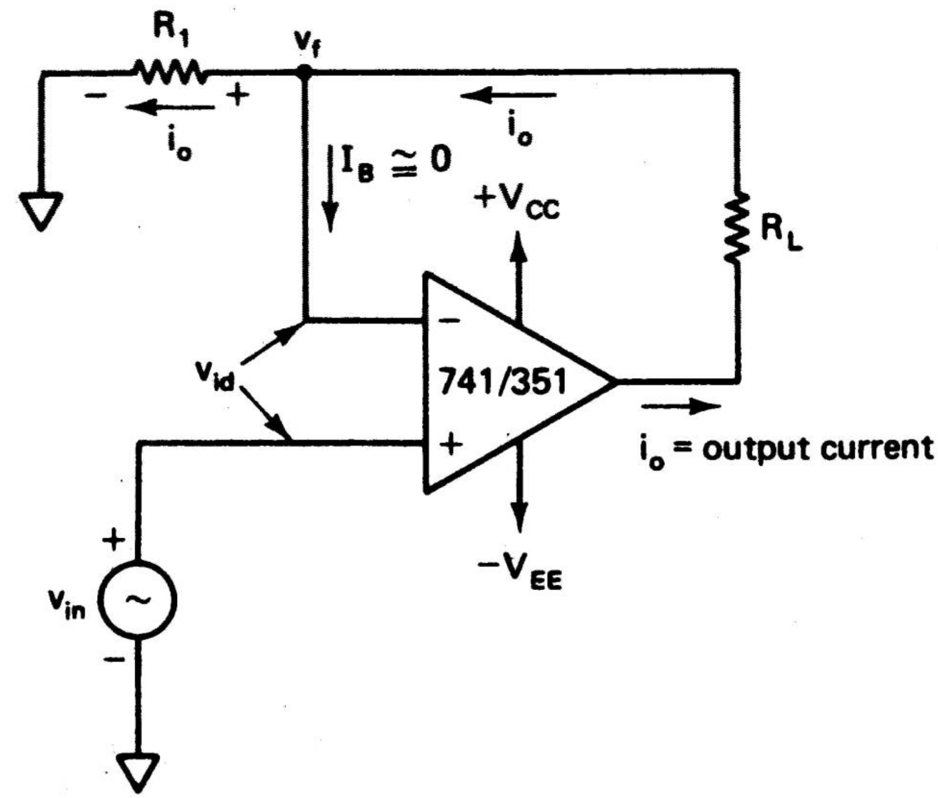
Operational Amplifier

Voltage to current converter

$$V_{id} = 0 \; ; V_f = V_{in}$$

$$\mathbf{i_o} = \frac{\mathbf{V_f}}{\mathbf{R}_1} \qquad i_o = \frac{V_{in}}{R_1}$$

Current is proportional to input voltage



Operational Amplifier

The integrator

The output is integral of the input signal is called integrator amplifier.

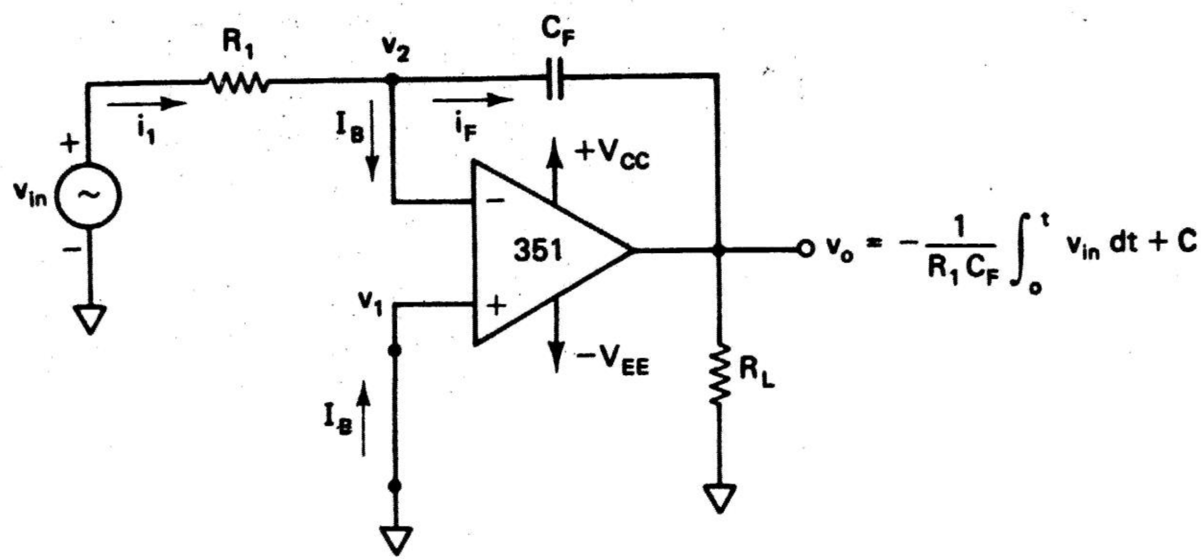
$$i_c = C\frac{dv_c}{dt}$$

$$\frac{V_{in} - V_2}{R_1} = C_F\frac{d}{dt}(V_2 - V_0)$$

$$V_2 = V_1 = 0$$

$$\frac{V_{in}}{R_1} = C_F\frac{dV_0}{dt}$$

$$V_0 = -\frac{1}{C_F R_1}\int_0^t v_{in}dt + C$$

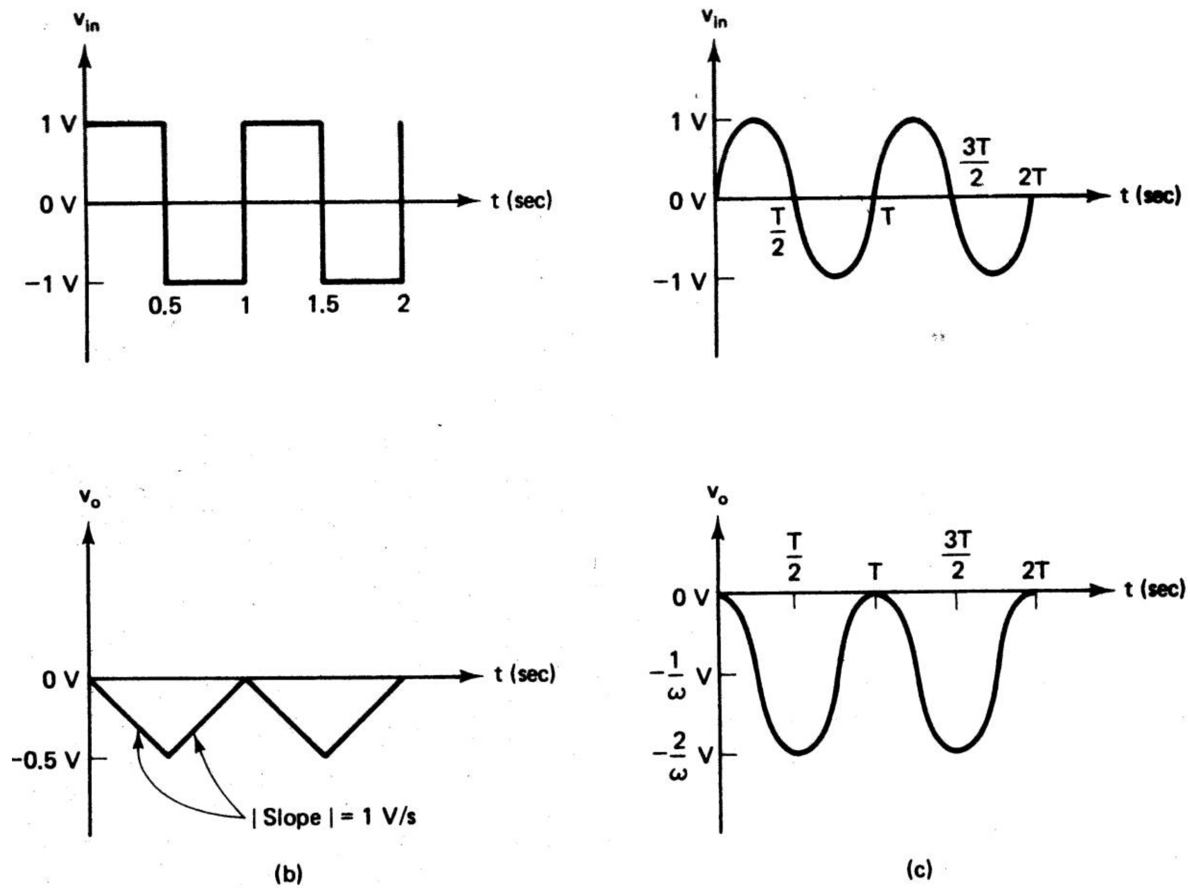


(a)

Operational Amplifier

The integrator

These are ideal waveforms integration errors due to constant bias is very common, which will increase linearly with time



Operational Amplifier

The differentiator

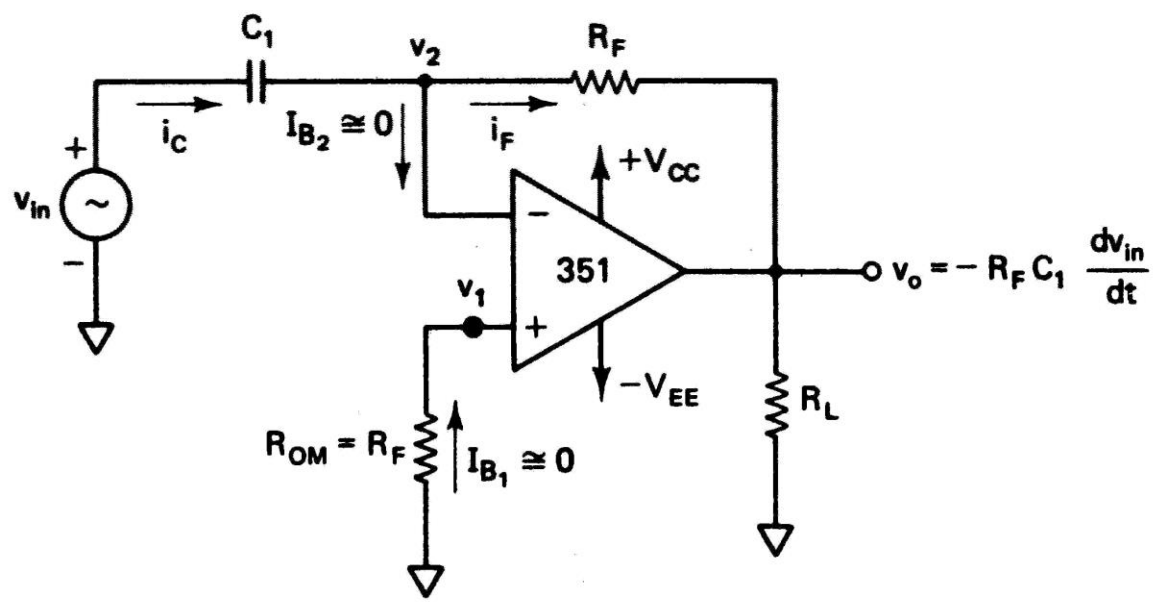
The output is differentiation of the input signal is called differentiator amplifier.

$$i_c = C\frac{dv_c}{dt}$$

$$C_F\frac{d}{dt}\left(V_{in} - V_2\right) = \frac{V_2 - V_0}{R_F}$$

$$V_2 = V_1 = 0$$

$$V_0 = -R_F C_1 \frac{dV_{in}}{dt}$$



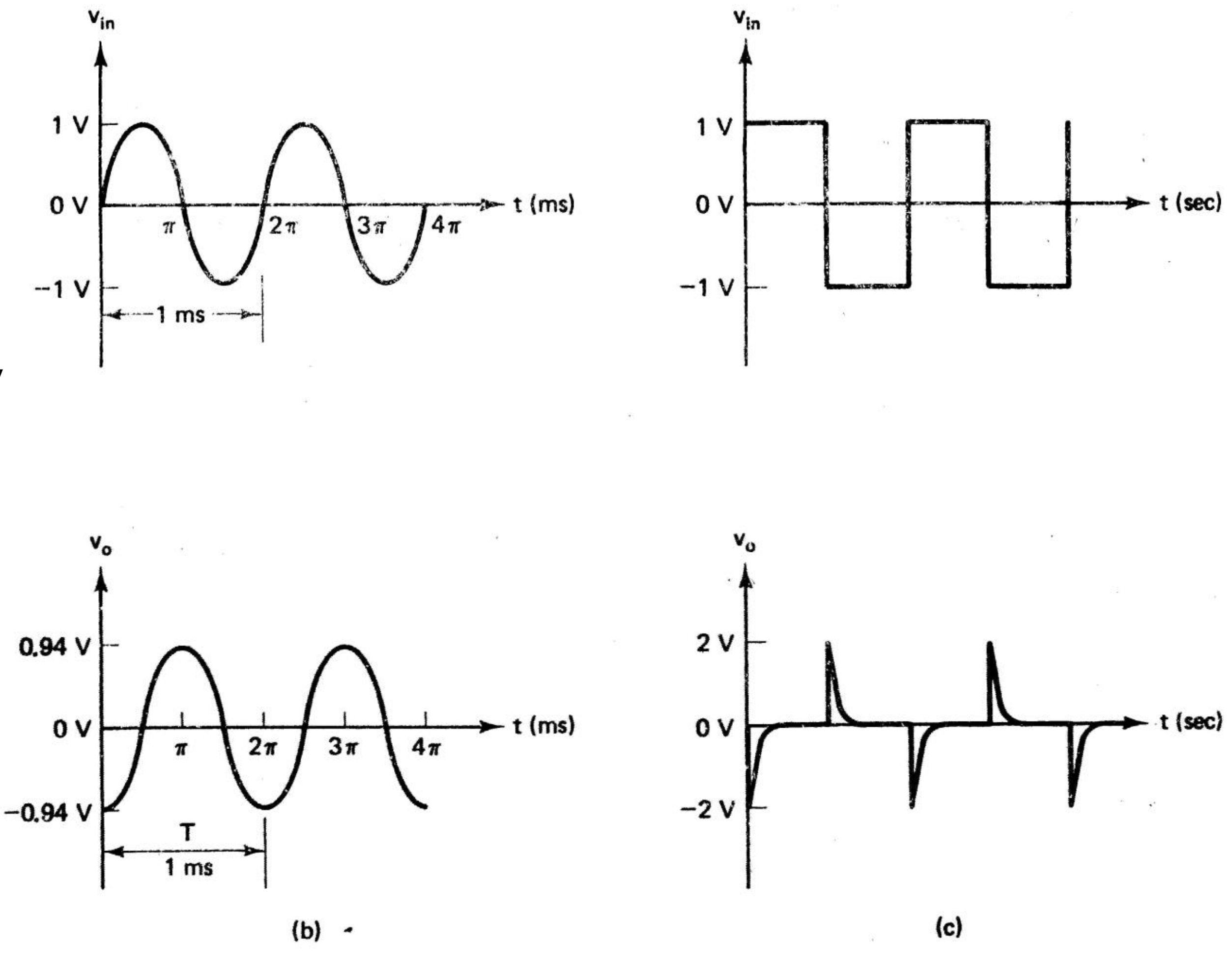
(a)

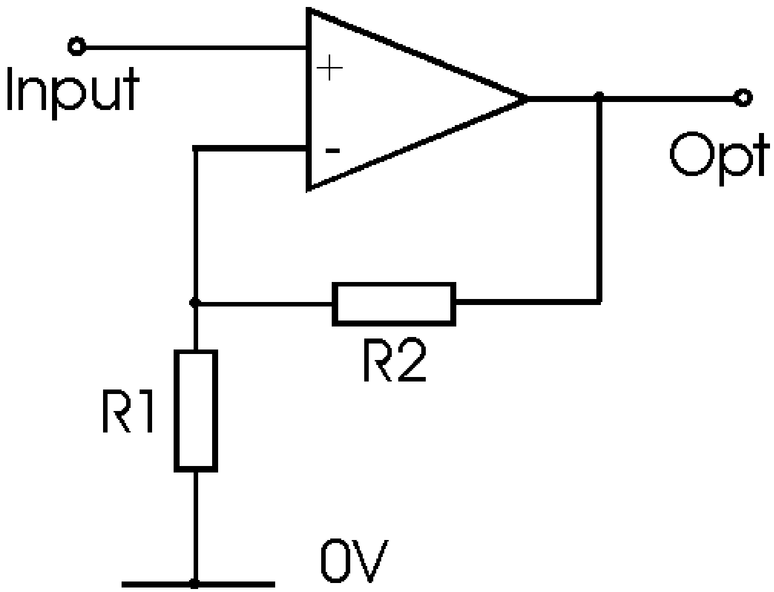
Operational Amplifier

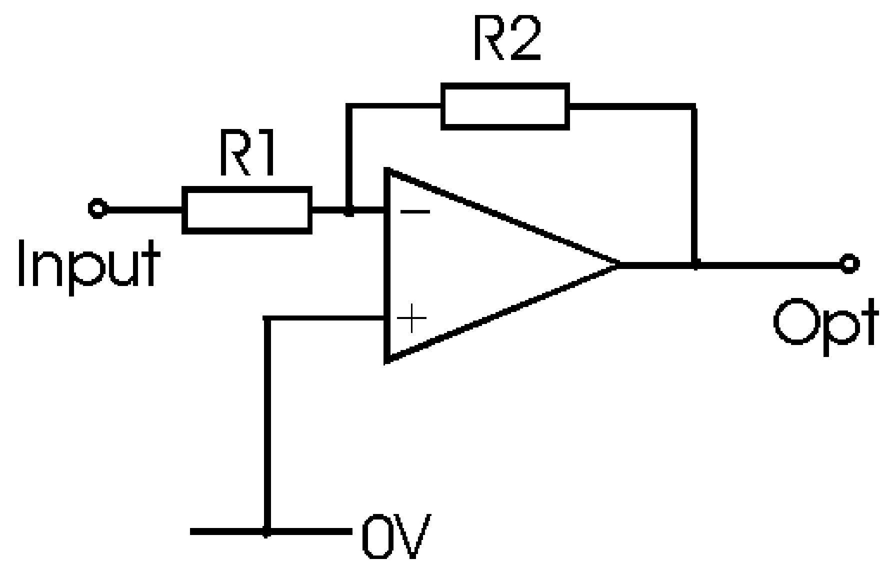
The differentiator

Sine wave into a cosine wave

Spikes (high frequency noise) in signal is generally a problem in such circuits




Input
+
-
Opt
R2
R1
0V


R2
R1
Input
−
+
Opt
0V

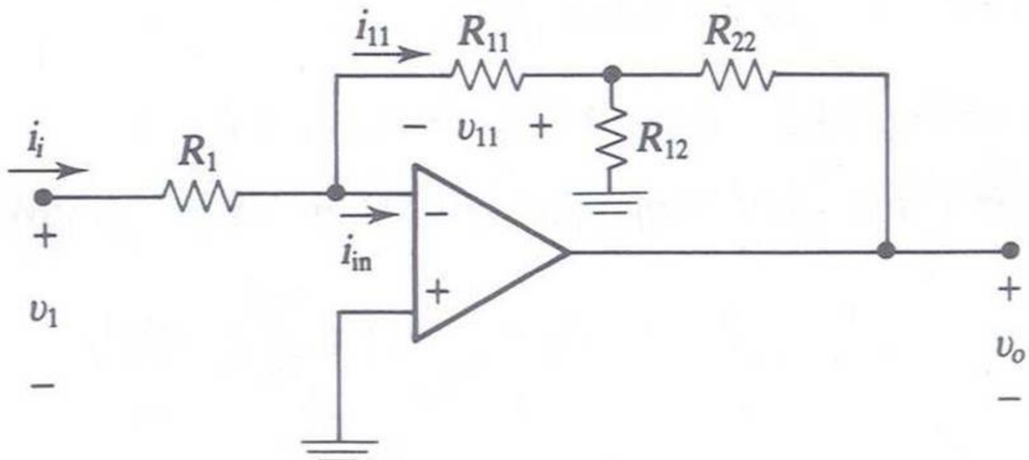


Fig. 13-23

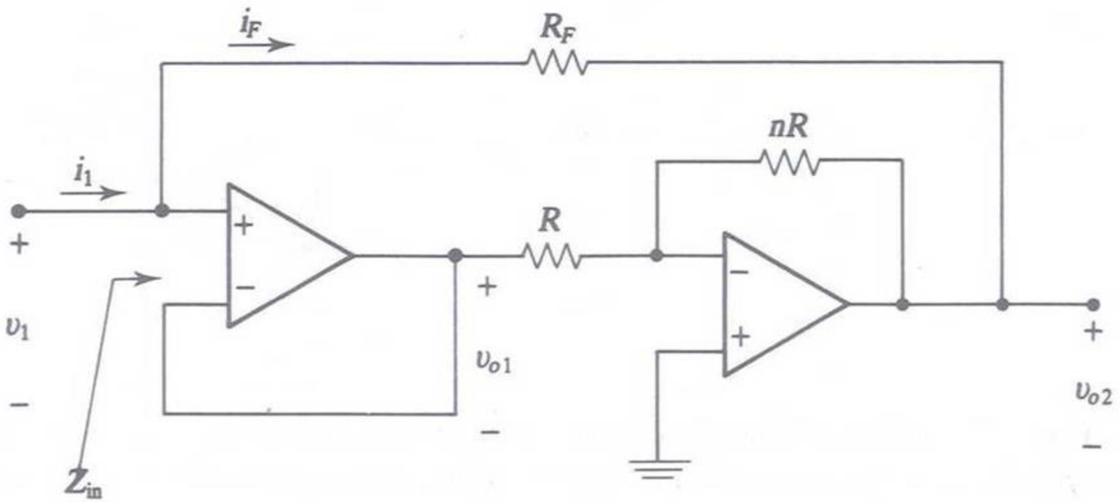


Fig. 13-25