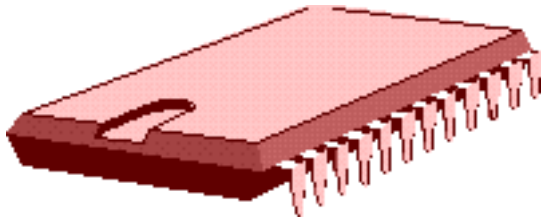


## Operational Amplifier



The operational amplifier is an integrated circuit (IC) composed of about thirty transistors, a dozen resistors and several capacitors manufactured on a single piece of silicon crystal called a chip. The Op amps are used in many electronic circuits for both linear and nonlinear operations. The circuit symbol for an op amp with its five essential terminals is shown in Figure 4.1.

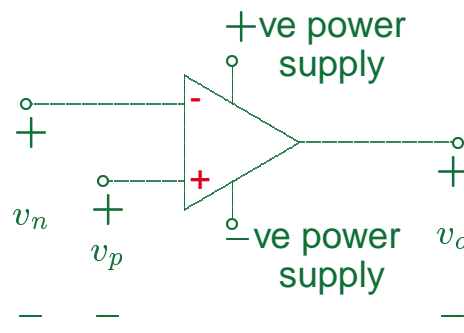


Figure 4.1 Circuit symbol for an op amp.

There are more terminals in a typical op amp, but we are not concerned with the remaining terminals. Our focus is on the terminal behavior of the amplifier as a circuit element and not on the internal structure.

Thus, we treat the op amp as a black box with the following essential terminals:

- The inverting terminal designated by - sign.
- The noninverting terminal designated by + sign.
- The output terminal.
- The positive power supply.
- The negative power supply.

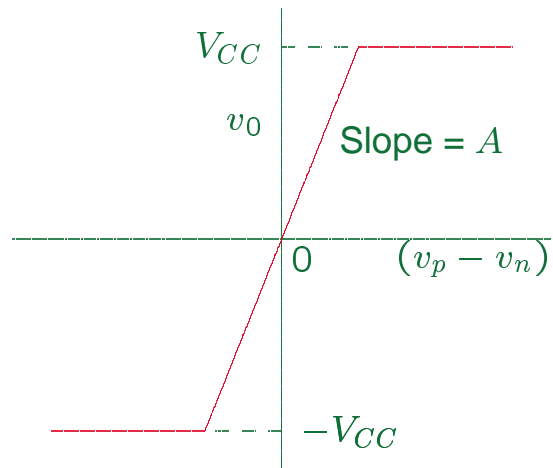
When a voltage  $v_n$  is applied to the inverting terminal the output voltage is an inverted amplified signal of the input  $v_n$ . The voltage  $v_p$  applied to the noninverting terminal is amplified without inversion. Thus, with both input voltages the output voltage is

$$\begin{aligned}v_0 &= -Av_n + Av_p \\ &= -A(v_n - v_p)\end{aligned}$$

Where  $A$  is the open-loop gain of the op amp.  $A$  is very large, typically in the order of  $10^5$ – $10^6$  for DC and low frequency signals. The gain drops with increase in the frequency and approaches unity with frequency in the range of 50 MHz.

## Voltage transfer characteristic

The transfer characteristics describes how the output voltage varies as a function of the input voltage as shown in Figure 4.2.



When  $|v_p - v_n|$  is small the op amp behaves as a linear device. Outside this linear range the op amp saturates and behaves as a nonlinear device. For operation in the linear range the net input voltage is constrained to the voltage  $V_{CC}$  applied to the power terminals. The op amp output is given by

$$v_0 = \begin{cases} -V_{CC} & A(v_p - v_n) < -V_{CC} \\ A(v_p - v_n) & -V_{CC} \leq A(v_p - v_n) \leq V_{CC} \\ V_{CC} & A(v_p - v_n) > V_{CC} \end{cases}$$

For a typical op amp operating on its linear region, the voltage difference between the two inputs is very small, less than 2 mV.

$$v_x = v_p - v_n \approx 0$$

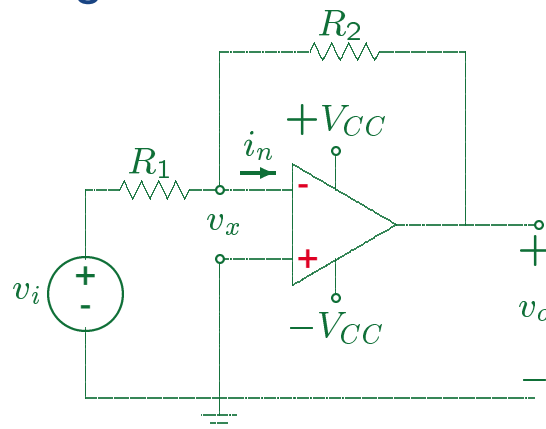
Also the input resistance is very large, and the output resistance is negligibly small. For example, the common 741 op amp has  $A \approx 10^5$ ,  $R_{in} \approx 2 \text{ M}\Omega$ , and  $R_{out} \approx 40\Omega$ . Because of the high input resistance, negligibly small current flows into the two op amp inputs, usually on the order of  $\mu\text{A}$ .

In most practical applications, the circuit analysis can be simplified with good accuracy by assuming the op amp to be ideal, i.e.,

- $A = \infty$ , so that  $v_n = v_p$
- $R_{in} = \infty$ , so that  $i_n = i_p = 0$
- $R_{out} = 0$

## Inverting Amplifier

Since the open-loop gain of an op amp is infinitely high to stabilize the operation a portion of the output signal is returned to the input inverting terminal, reducing the input voltage applied to this terminal which in turn reduces the output voltage, and the op amp operates on its linear region. Figure 4.3 shows the circuit configuration for an inverting op amp.



Applying KCL at the inverting node, we have

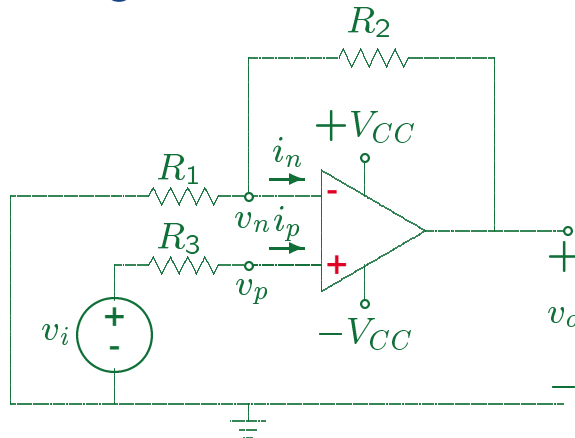
$$\frac{v_x - v_i}{R_1} + \frac{v_x - v_0}{R_2} + i_n = 0$$

Assuming ideal op amp  $i_n = 0$ , and  $v_x = 0$ , we get

$$\frac{-v_i}{R_1} + \frac{-v_0}{R_2} = 0 \quad \text{or} \quad v_0 = -\frac{R_2}{R_1}v_i$$

## Noninverting Amplifier

The circuit configuration for a noninverting op amp is shown in Figure 4.4



Applying KCL at the inverting node, we have

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

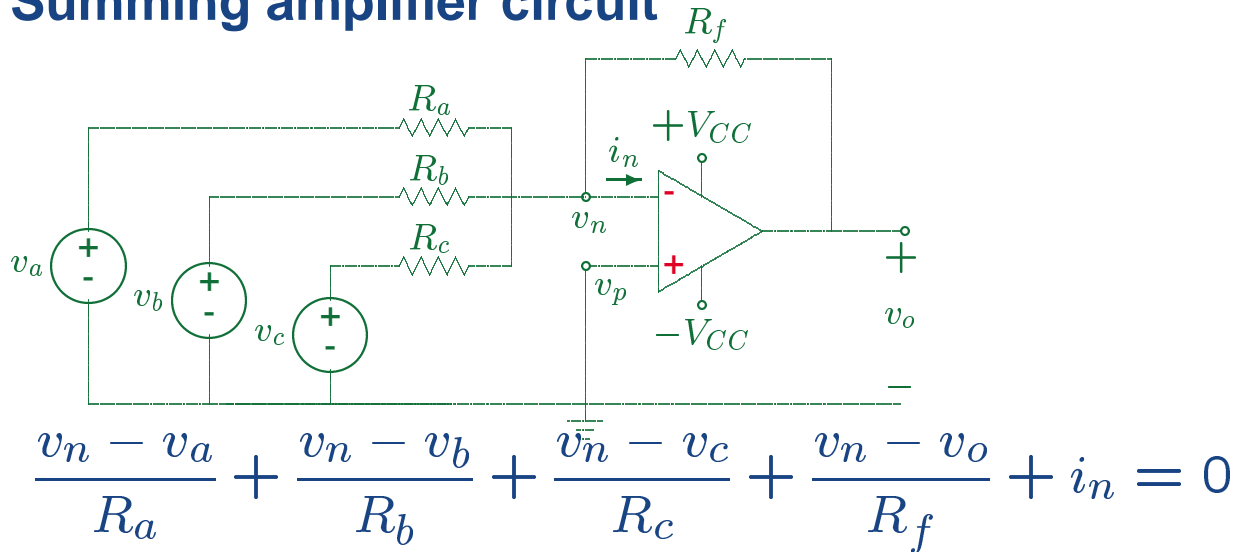
At the noninverting terminal  $v_p = v_i - R_3 i_p$ . Assuming ideal op amp  $i_n = i_p = 0$ , and  $v_n = v_p = v_i$ . Substituting in the first equation, we have

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

or

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

## Summing amplifier circuit



$v_n = v_p \approx 0$ , and  $i_n = 0$ , thus we have

$$-\frac{v_a}{R_a} - \frac{v_b}{R_b} - \frac{v_c}{R_c} - \frac{v_o}{R_f} = 0$$

$$v_o = -\left(\frac{R_f}{R_a}v_a + \frac{R_f}{R_b}v_b + \frac{R_f}{R_c}v_c\right)$$

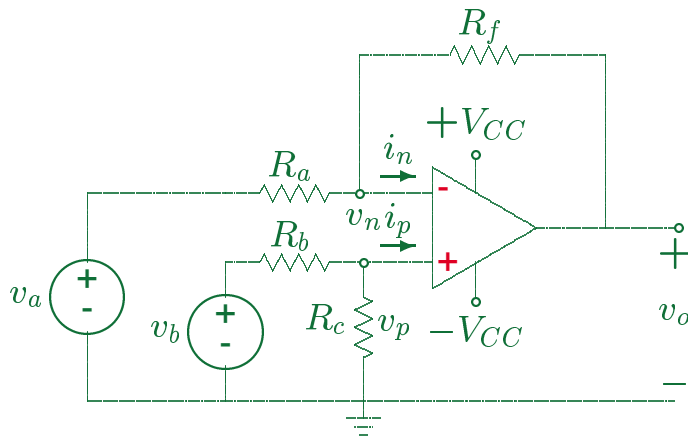
So the output voltage is an inverted scaled sum of the three input voltages. If  $R_a = R_b = R_c = R_s$ , then

$$v_o = -\frac{R_f}{R_s}(v_a + v_b + v_c)$$

and if  $R_f = R_s$ , we have

$$v_o = -(v_a + v_b + v_c)$$

## Difference amplifier circuit



$$\frac{v_n - v_a}{R_a} + \frac{v_n - v_o}{R_f} + i_n = 0$$

$i_n = 0 = i_p \approx 0$ , and  $v_n = v_p = \frac{R_c}{R_b + R_c}v_b$ , thus

$$\begin{aligned} v_o &= \frac{(R_a + R_f)}{R_a}v_n - \frac{R_f}{R_a}v_a \\ &= \frac{R_c(R_a + R_f)}{R_a(R_b + R_c)}v_b - \frac{R_f}{R_a}v_a \\ &= \frac{R_f(R_a/R_f + 1)}{R_a(R_b/R_c + 1)}v_b - \frac{R_f}{R_a}v_a \end{aligned}$$



The output voltage is equal to the difference between scaled replica of the two inputs. If  $R_a/R_f = R_b/R_c$ , we get

$$v_o = \frac{R_f}{R_a}(v_b - v_a)$$

and if

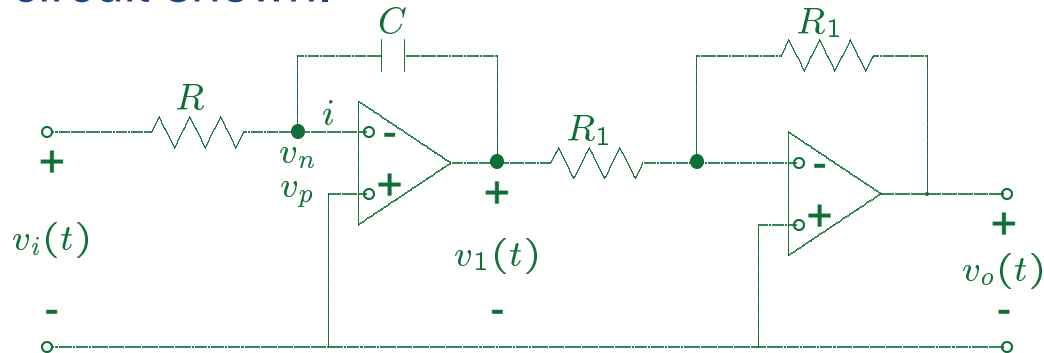
$$R_f = R_a$$

we obtain

$$v_o = v_b - v_a$$

## Integrating Op amp

In the Integrating op amp circuit the output is proportional to the integral of the input signal. Consider the circuit shown.



Applying KCL to node  $n$ , we have

$$\frac{v_n - v_i(t)}{R} + C \frac{d}{dt} (v_n - v_1(t)) = 0$$

For ideal op amps,  $v_n = v_p = 0$ ,  $i = 0$ , and we obtain

$$-\frac{v_i(t)}{R} - C \frac{dv_1(t)}{dt} = 0 \quad \text{or} \quad v_1(t) = -\frac{1}{RC} \int_0^t v_i(\lambda) d\lambda$$

The second stage is added to invert the signal

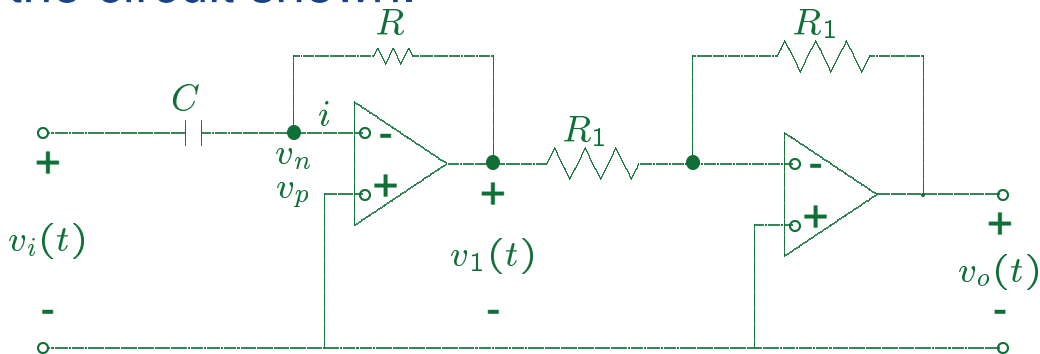
$$v_o(t) = -\frac{R_1}{R_1} v_1(t) \quad \text{or} \quad v_o(t) = \frac{1}{RC} \int_0^t v_i(\lambda) d\lambda$$

If  $R$  and  $C$  are selected such that  $RC = 1$ , then we get

$$v_o(t) = \int_0^t v_i(\lambda) d\lambda$$

## Differentiating Op amp

In the differentiating op amp circuit the output is proportional to the derivative of the input signal. Consider the circuit shown.



Applying KCL to node  $n$ , we have

$$C \frac{d}{dt} (v_n - v_i(t)) + \frac{v_n - v_1(t)}{R} = 0$$

For ideal op amps,  $v_n = v_p = 0$ ,  $i = 0$ , and we obtain

$$-C \frac{dv_i(t)}{dt} - \frac{1}{R} v_1(t) = 0 \quad \text{or} \quad v_1(t) = -RC \frac{dv_i(t)}{dt}$$

The second stage is added to invert the signal

$$v_o(t) = -\frac{R_1}{R_1} v_1(t) \quad \text{or} \quad v_o(t) = RC \frac{dv_i(t)}{dt}$$

If  $R$  and  $C$  are selected such that  $RC = 1$ , then we get

$$v_o(t) = \frac{dv_i(t)}{dt}$$