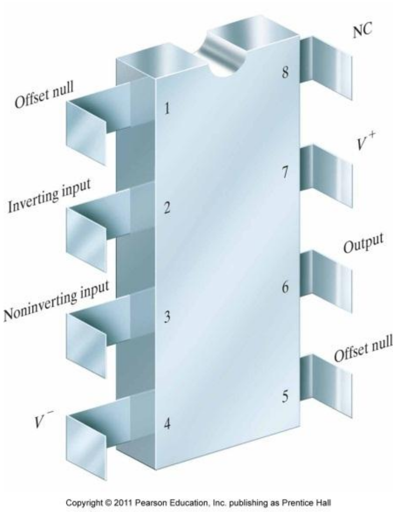
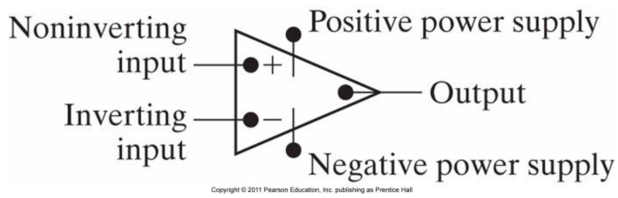
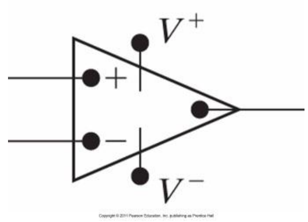
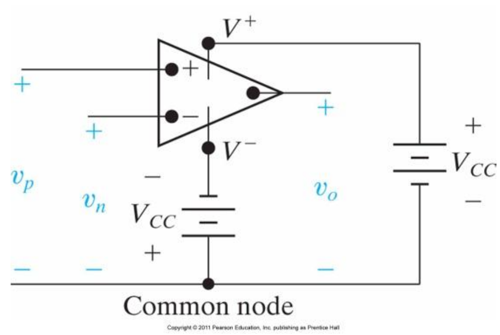
5.1 Operational Amplifier Terminals

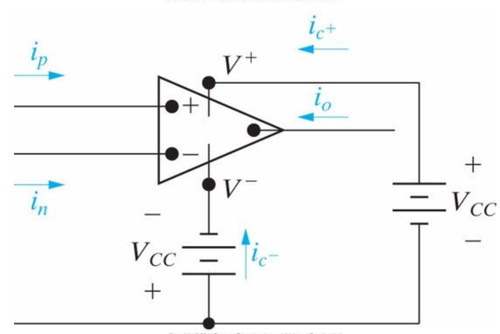


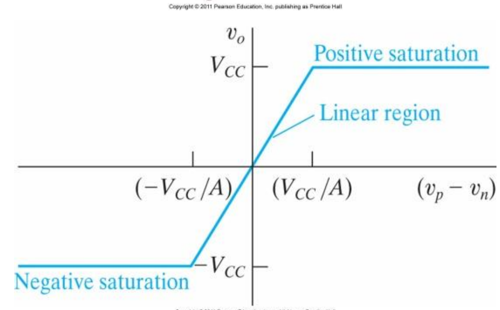




5.2 Terminal Voltages and Currents







All voltages are considered as a voltage rise from the common node.

V_{CC} = positive voltage supply $-V_{CC}$ = negative voltage supply

v_n = voltage between inverting terminal and common node

v_p = voltage between noninverting terminal and common node

v_o = voltage between output terminal and common node

i_n = current into the inverting terminal

i_p = current into the noninverting terminal

i_o = current into the output terminal

i_{c^+} = current into the positive power supply terminal

i_{c^-} = current into the positive power supply terminal

Characteristics:

$$v_o = \begin{cases} -V_{CC}, & A(v_p - v_n) < -V_{CC} \\ A(v_p - v_n), & -V_{CC} \le A(v_p - v_n) \le +V_{CC} \\ +V_{CC}, & A(v_p - v_n) > +V_{CC} \end{cases}$$

Where A is the **gain**

Input voltage constraint for an ideal op-amp $\boldsymbol{v_p = v_n}$; when in its linear range

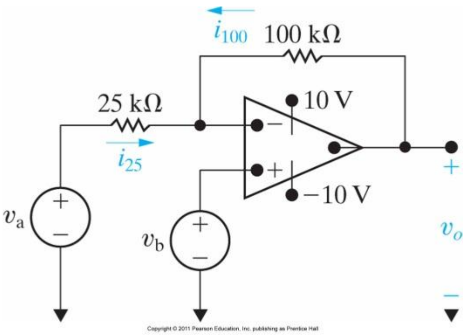
<u>Negative feedback:</u> output signal fed back into the inverted output (w/out neg. fb op-amp usually saturates)

Input current constraint for an ideal op-amp $\boldsymbol{i_p = i_n = 0}$

KCL around the op-amp

$$i_p + i_n + i_o + i_{c^+} + i_{c^-} = 0$$
$$i_o = -(i_{c^+} + i_{c^-})$$

Example 5.1



For ideal, $i_p = i_n = 0$ and $v_p = v_n$ if in linear range

a) $v_a = 1\,V$ and $v_b = 0\,V$
b) $v_a = 1\,V$ and $v_b = 2\,V$
c) $v_a = 1.5\,V$ and $v_b = ??$

Note: negative feedback so assume linear region

Part a. KCL

$$i_n - i_{25} - i_{100} = 0 \xrightarrow{yields} i_n = i_{25} + i_{100} = 0$$

Ohm's

$$i_{25} = \frac{v_a - v_n}{25k} = \frac{1-0}{25k} = \frac{1}{25} mA$$

$$i_{100} = \frac{v_0 - v_n}{100k} = \frac{v_0 - 0}{100k} = \frac{v_0}{100k} = -\frac{1}{25} mA$$

$$v_0 = -4V$$

Part b.

$$i_{25} = \frac{v_a - v_n}{25k} = \frac{1-2}{25k} = -\frac{1}{25} mA$$

$$i_{100} = \frac{v_0 - v_n}{100k} = \frac{v_0 - 2}{100k} = -\frac{1}{25} mA$$

$$v_0 = 6V$$

Part c.

$$\frac{v_a - v_n}{25k} = -\frac{v_0 - v_n}{100k}$$

$$v_n = v_b = \frac{1}{5}(6 + v_0)$$

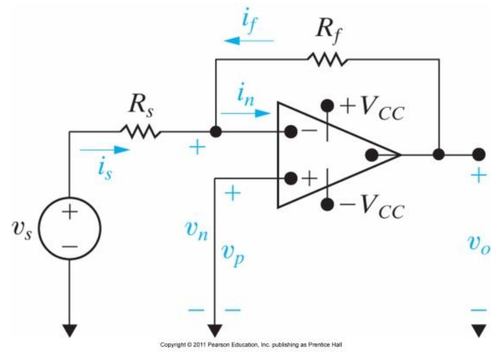
For linearity $-10V \le v_0 \le 10V$

Therefore

$$-0.8 \le v_b \le 3.2\,V$$

Review Assessment Problem 5.1

5.3 The Inverting-Amplifier Circuit



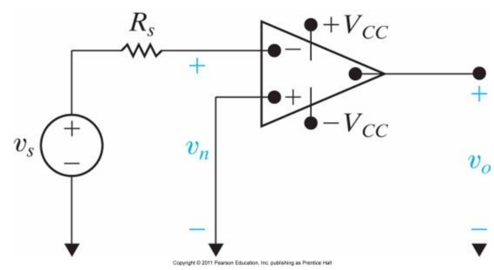
$$i_s + i_f = i_n = 0$$

$$i_s = \frac{v_s}{R_s} \qquad\qquad i_f = \frac{v_o}{R_f}$$

$$v_o = \frac{-R_f}{R_s} v_s \quad \textit{where } \frac{R_f}{R_s} \textit{ is the gain}$$

Assuming the power supply voltages are equal;

$$|v_o| \leq V_{CC}, \quad \left|\frac{R_f}{R_s} v_s\right| \leq V_{CC}, \quad \frac{R_f}{R_s} \leq \left|\frac{V_{CC}}{v_s}\right|$$



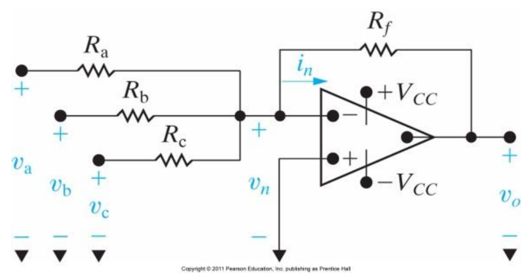
Open loop removing the feedback branch from the op amp

$$v_o = -Av_n \qquad \text{where} \qquad v_n \approx v_s$$

For linear operation $|v_s| < \frac{V_{CC}}{A}$

Review Example 5.2 and Assessment Problem 5.2

5.4 The Summing-Amplifier Circuit



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

Assuming an ideal op amp

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

If $R_a = R_b = R_c = R_s$

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

If $R_f = R_s$

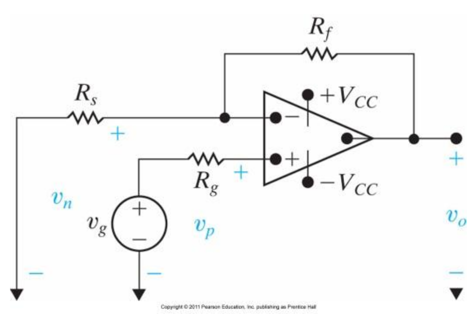
$$v_o = -(v_a + v_b + v_c)$$

Note: The summing op amp can have any number of input voltages applied to it for summing

Review Assessment Problem 5.3

5.5 The Noninverting-Amplifier Circuit

The voltage source is applied to the positive terminal of the op amp



$$v_n = v_p \approx v_g$$

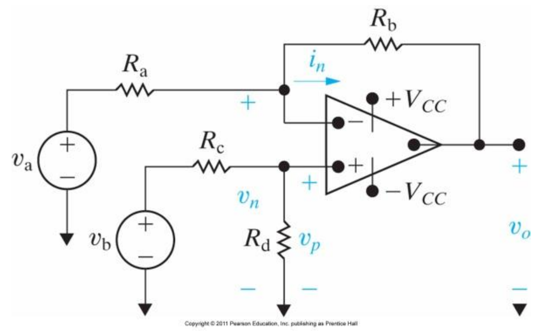
$$\frac{v_n}{R_s} + \frac{v_n - v_o}{R_f} + 0 = 0$$

$$v_o = \left(\frac{R_f + R_s}{R_s}\right) v_g$$

The op amp operates in the linear region when $\frac{R_f+R_s}{R_s} < \frac{V_{CC}}{v_g}$

Review Example 5.3 and Assessment Problem 5.4

5.6 The Difference-Amplifier Circuit



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

$$v_n = v_p = \left(\frac{R_d}{R_c + R_d}\right) v_b$$

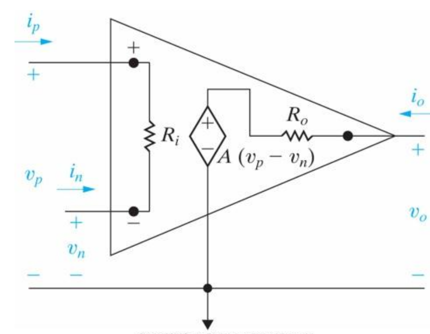
Substituting

$$v_o = \frac{R_d(R_a + R_b)}{R_a(R_c + R_d)} v_b - \frac{R_b}{R_a} v_a$$

$$v_o = \frac{R_b}{R_a}(v_b - v_a) \qquad \textit{when} \qquad \frac{R_a}{R_b} = \frac{R_c}{R_d}$$

Review Example 5.4 and Assessment Problem 5.5

5.7 A More Realistic Model for the Operational Amplifier

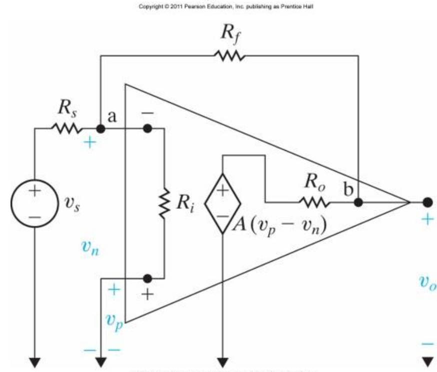


Differences from the ideal op amp model

1. A finite input resistance R_i
2. A finite open-loop gain, A
3. A non-zero output resistance R_o

Cannot assume that $i_p = i_n = 0$ or $v_p = v_n$ or the general equation for the voltage transfer characteristics.

Non-ideal inverting amplifier



Node a

$$\frac{v_n - v_s}{R_s} + \frac{v_n}{R_i} + \frac{v_n - v_o}{R_f} = 0$$

Node b

$$\frac{v_o - v_n}{R_f} + \frac{v_o - A(v_p - v_n)}{R_o} = 0$$

$$v_o = \frac{-A + \frac{R_o}{R_f}}{\frac{R_s}{R_f}\left(1 + A + \frac{R_o}{R_f}\right) + \left(\frac{R_s}{R_i} + 1\right) + \frac{R_o}{R_f}} v_s$$

Adding a load resistor R_L

$$v_o = \frac{-A + \frac{R_o}{R_f}}{\frac{R_s}{R_f}\left(1 + A + \frac{R_o}{R_i} + \frac{R_o}{R_L}\right) + \left(\frac{R_s}{R_i} + 1\right)\left(\frac{R_o}{R_L} + 1\right) + \frac{R_o}{R_L}} v_s$$

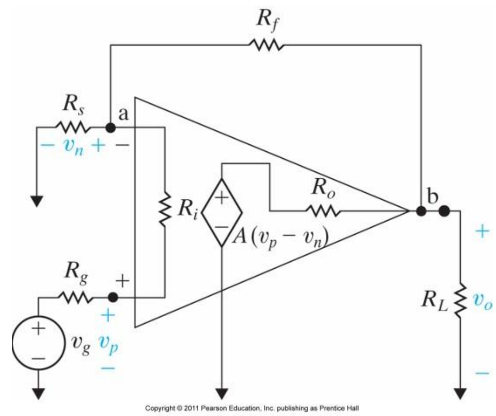
Non-ideal noninverting amplifier

Node a

$$\frac{v_n}{R_s} + \frac{v_n - v_g}{R_g + R_i} + \frac{v_n - v_o}{R_f} = 0$$

Node b

$$\frac{v_o - v_n}{R_f} + \frac{v_o}{R_L} + \frac{v_o - A\left(v_p - v_n\right)}{R_o} = 0$$



See book for remaining derivation and Assessment Problem 5.6