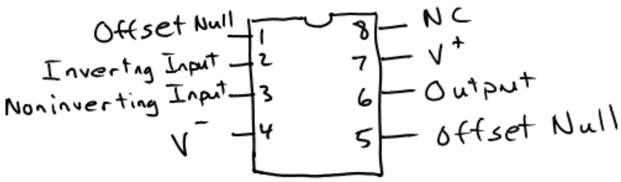
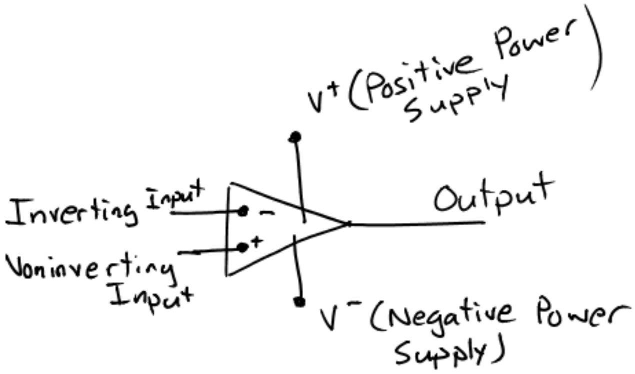
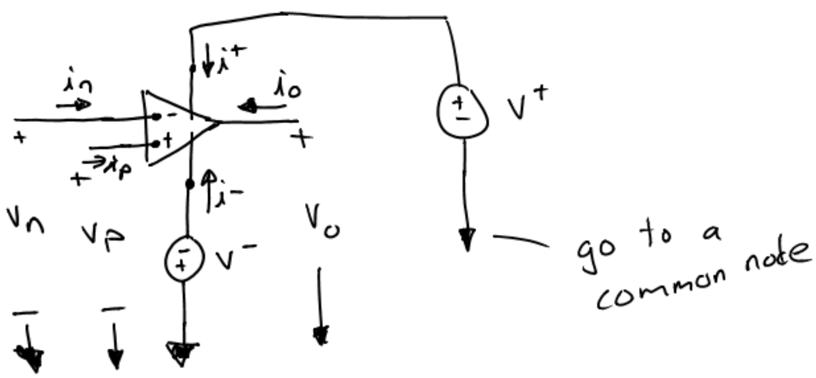
The Operational Amplifier (Op Amp)

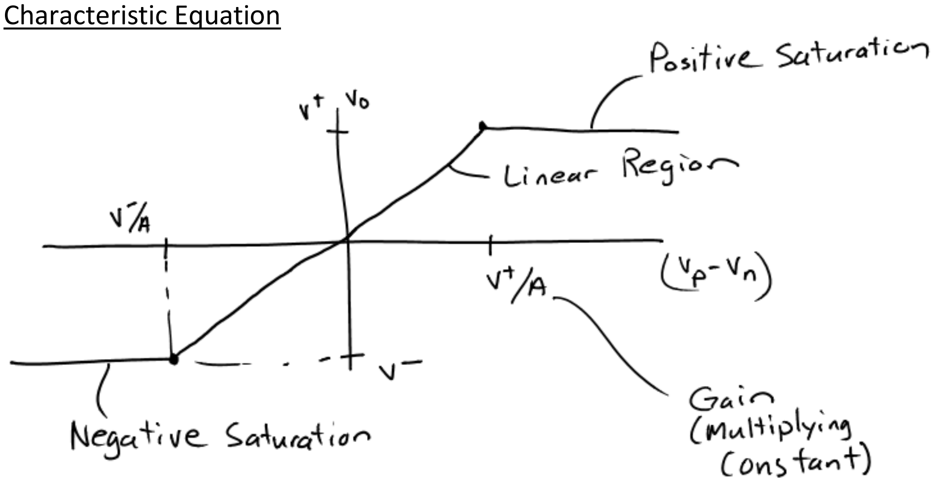
- Electronic Circuit
- Used for scaling, summing, sign changing, subtracting, integrating, etc.







Characteristic Equation



$$v_o = \begin{cases} -V^- & (v_p - v_n) < \frac{V^-}{A} \\ A(v_p - v_n) & \frac{-V^-}{A} \leq v_p - v_n \leq \frac{V^+}{A} \\ V^+ & v_p - v_n > \frac{V^+}{A} \end{cases}$$

- Typically, the magnitude of v^+ and v^- is no more than 20 V, and A is more than 10,000

Linear Operating Region

$$|v_p - v_n| \leq \left| \frac{V^+, V^-}{A} \right|$$

$$\leq \frac{20V}{10{,}000}$$

$$\leq 0.002V$$

$\Rightarrow$ Small ≈ 0

$A \to \infty$

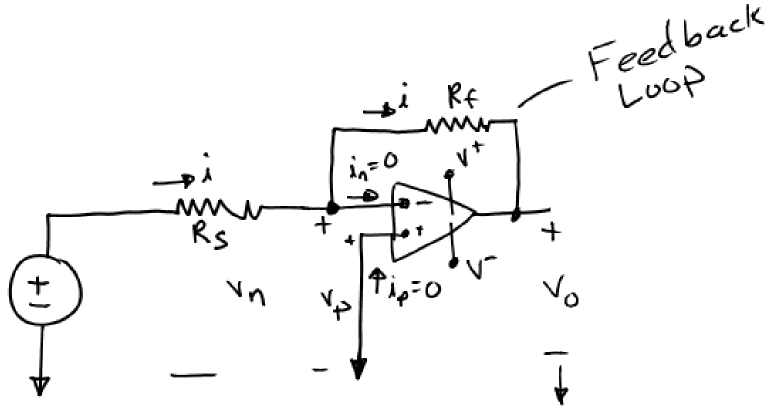
$v_p - v_n = 0$

$\boxed{v_p = v_n}$ Ideal Op Amp

Assume $\boxed{i_p = i_n = 0}$ Ideal Op Amp

Standard Op Amp Circuits

- Inverting Amplifier



$$v_p = 0 \quad \Rightarrow \quad v_n = v_p = 0$$

KVL (Left, CW)

$$-v_s + i R_s + v_n = 0 \quad \Rightarrow \quad i = \frac{v_s - v_n^{\nearrow 0}}{R_s}$$

KVL (Perimeter)

$$-v_n^{\nearrow 0} + i R_f + v_o = 0$$

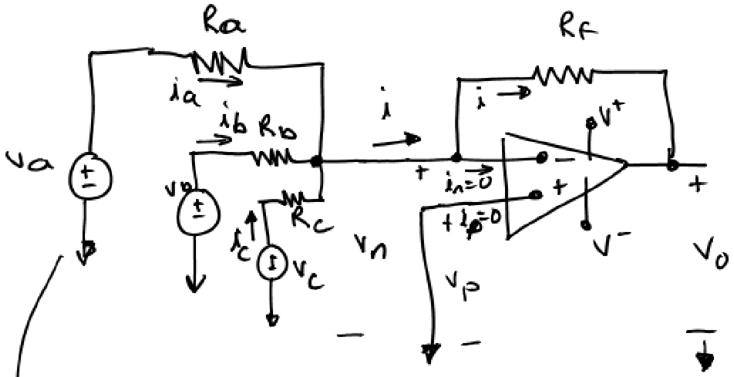
$$\left(\frac{v_s}{R_s}\right) R_f + v_o = 0$$

$$\boxed{v_o = -\frac{R_f}{R_s} v_s}$$

Also must check for saturation

$$\boxed{-V^- \leq v_o \leq V^+}$$

- Summing Amplifier



$i = i_a + i_b + i_c$

$v_p = 0 \qquad v_n = v_p = 0$

KVL

$-v_a + i_a R_a + v_n \to 0 \qquad i_a = \frac{v_a}{R_a}$

Similarly, $\quad i_b = \frac{v_b}{R_b}$

$i_c = \frac{v_c}{R_c}$

$$\boxed{i = \frac{v_a}{R_a} + \frac{v_b}{R_b} + \frac{v_c}{R_c}}$$

KVL (Perimeter, cw)

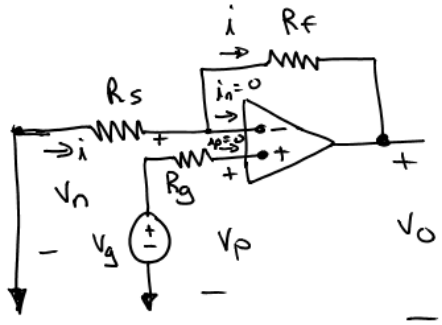
$-v_n \to 0 + i R_f + v_o = 0$

$\left(\frac{v_a}{R_a} + \frac{v_b}{R_b} + \frac{v_c}{R_c}\right) R_f + v_o = 0$

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

Check for saturation

- Noninverting Amplifier



$$v_p = v_g \Rightarrow v_n = v_g$$

KVL (Left, cw)

$$i R_s + v_n = 0 \quad (v_n = v_g)$$

$$i = -\frac{v_g}{R_s}$$

KVL (Perimeter, cw)

$$-v_n + i(R_f) + v_o = 0$$

$$-v_g + \left(\frac{-v_g}{R_s}\right)R_f + v_o = 0$$

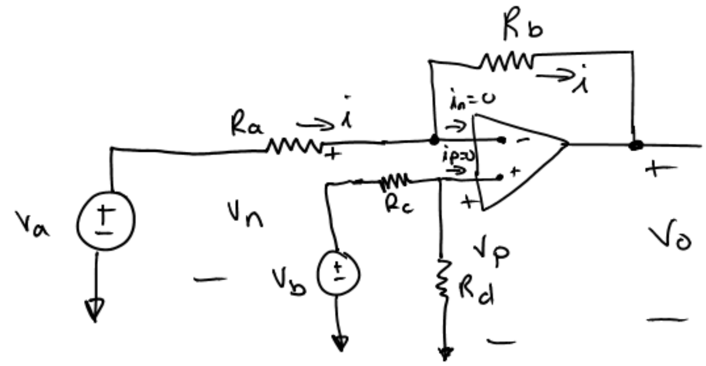
$$v_o = v_g\left(1 + \frac{R_f}{R_s}\right)$$

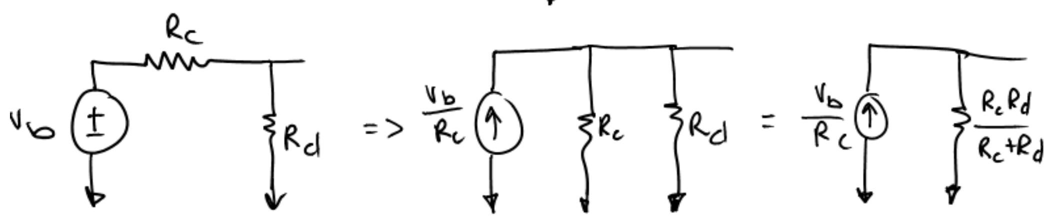
$$v_o = v_g\left(\frac{R_f + R_s}{R_s}\right)$$

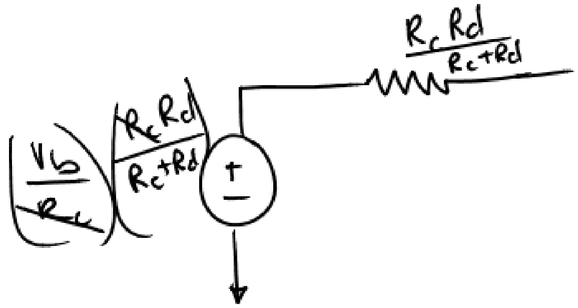
$$\boxed{v_o = \left(\frac{R_s + R_f}{R_s}\right) v_g}$$

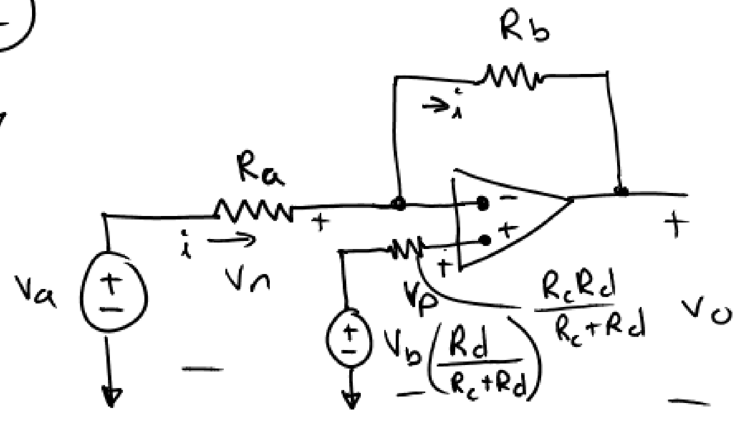
Check for saturation

- Difference Amplifier









$$V_p = \left(\frac{R_d}{R_c+R_d}\right) V_b = V_n$$

KVL (Left, cw)

$$-v_a + i R_a + v_n = 0$$

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

$$i = \frac{v_a - \left(\frac{R_d}{R_c+R_d}\right)v_b}{R_a}$$

KVL (Perimeter, cw)

$$-v_n + i(R_b) + v_o = 0$$

$$v_n = \left(\frac{R_d}{R_c+R_d}\right)v_b \qquad i = \left(\frac{v_a - \left(\frac{R_d}{R_c+R_d}\right)v_b}{R_a}\right)$$

ASA

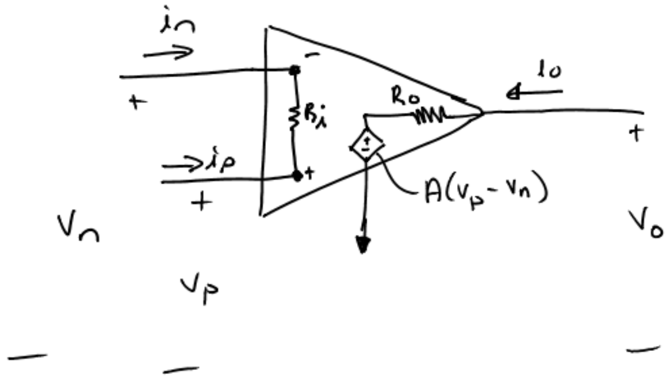
$$v_o = \frac{R_d(R_a+R_b)}{R_a(R_c+R_d)}v_b - \frac{R_b}{R_a}v_a$$

If $\frac{R_a}{R_b} = \frac{R_c}{R_d}$

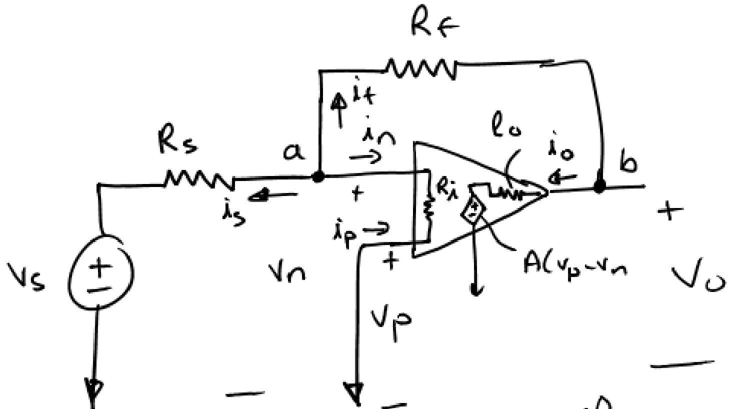
$$v_o = \frac{R_b}{R_a}(v_b - v_a)$$

Check for Saturation

A More Realistic Op Amp Model



- For the Inverting Amplifier



$$i_s = \frac{v_n - v_s}{R_s} \qquad i_n = \frac{v_n - \cancel{v_p}^{\,0}}{R_i}$$

$$i_f = \frac{v_n - v_o}{R_f} \qquad i_o = \frac{v_o - A(\cancel{v_p}^{\,0} - v_n)}{R_o}$$

a: $i_s + i_f + i_n = 0$

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

b: $-i_f + i_o = 0$

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

Eliminate v_n

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

- To get the Ideal Op Amp Model:

$$A \to \infty, \quad R_o \to 0, \quad R_i \to \infty$$

$$V_o = \frac{-A}{\frac{R_s}{R_f}(1+A) + \left(\frac{R_s}{R_i} + 1\right)} V_s$$

$$= \frac{-\cancel{A}}{\cancel{A}\left[\frac{R_s}{R_f}\left(\frac{1}{A}^{\to 0} + 1\right) + \cancel{\frac{1}{A}\left(\frac{R_s}{R_i}^{\to 0} + 1\right)}\right]} V_s$$

$$V_o = \frac{-1}{\frac{R_s}{R_f}} V_s$$

$$\boxed{V_o = -\frac{R_f}{R_s} V_s}$$