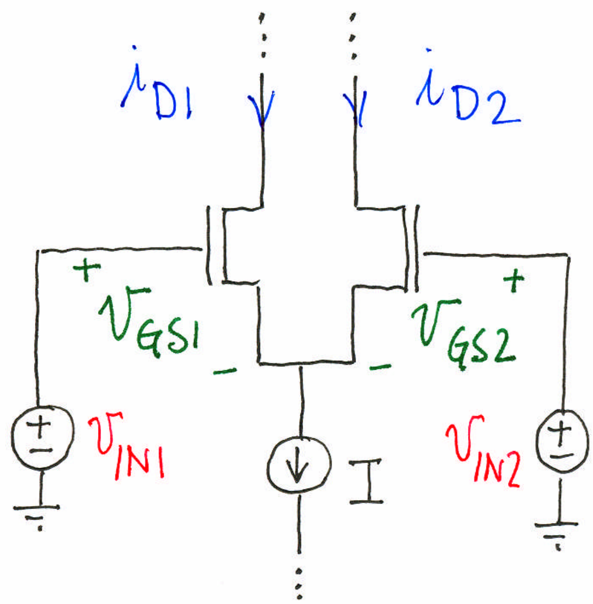
6.002 - Lecture 22

Op Amp Details

- MOSFET Review
- Differential Amplifier
- An Operational Amplifier
- Small-Signal Analysis

Differential Amplifier



$$i_{D1} + i_{D2} = I$$

$$i_{D1} = \frac{K}{2}(v_{GS1} - V_T)^2$$

$$i_{D2} = \frac{K}{2}(v_{GS2} - V_T)^2$$

$$v_{IN1} - v_{GS1} + v_{GS2} - v_{IN2} = 0$$

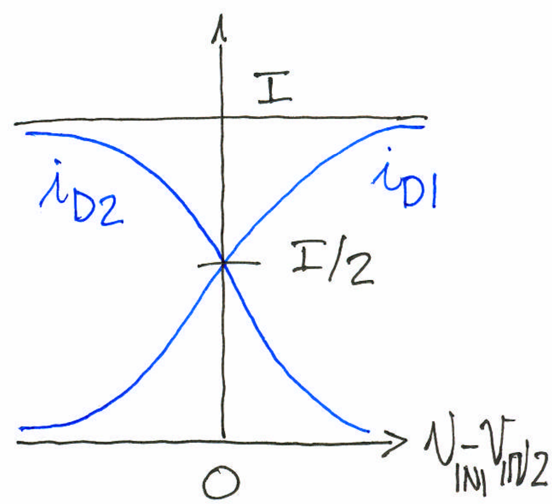
$$i_{D1} + \frac{K}{2}(v_{GS2} - V_T)^2 = I$$

$$i_{D1} + \frac{K}{2}(v_{IN2} - v_{IN1} + v_{GS1} - V_T)^2 = I$$

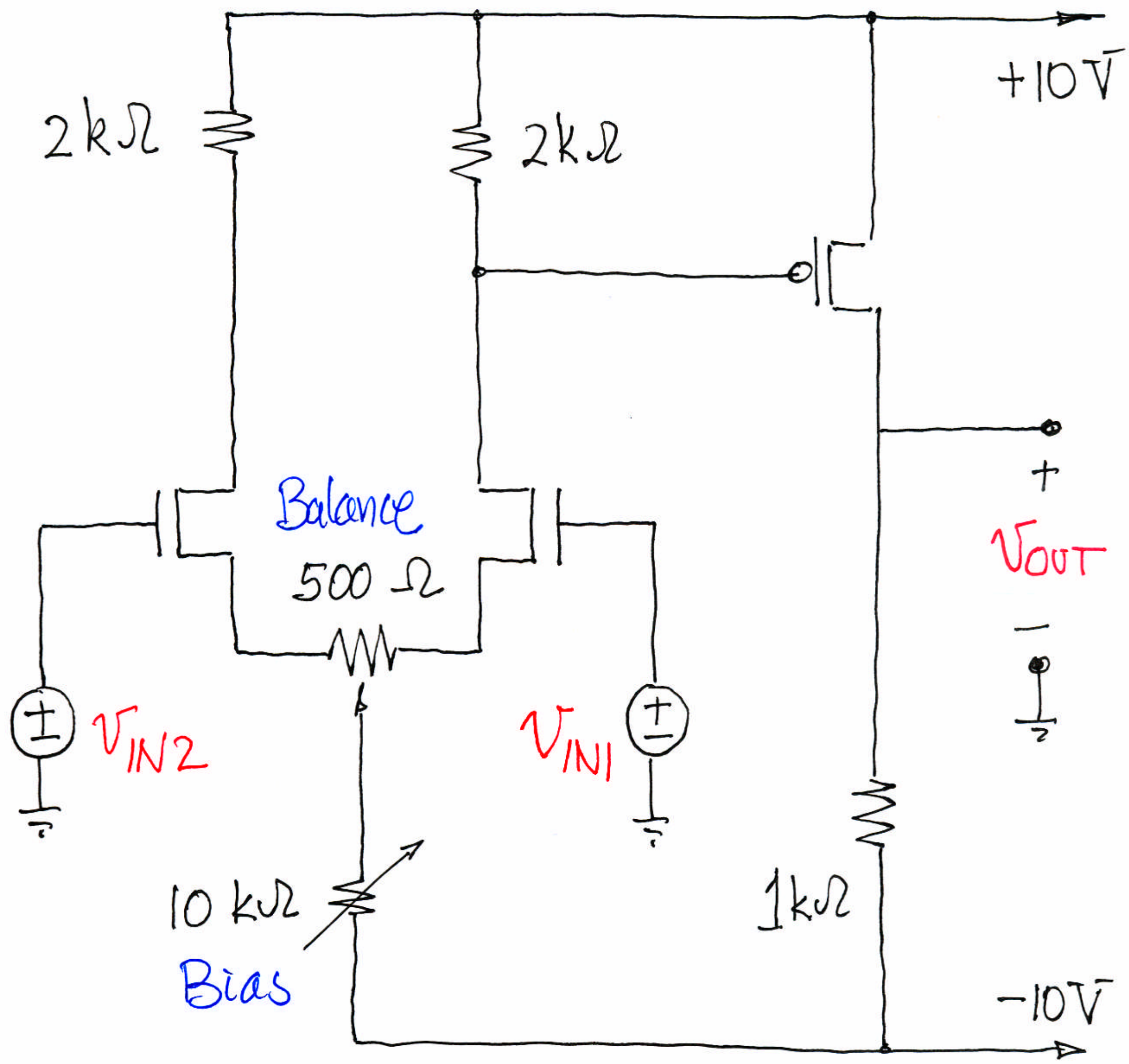
$$i_{D1} + \frac{K}{2}\left(v_{IN2} - v_{IN1} + \sqrt{\frac{2 i_{D1}}{K}}\right)^2 = I$$

$$i_{D1} = \text{Function}(v_1 - v_2)$$

Currents

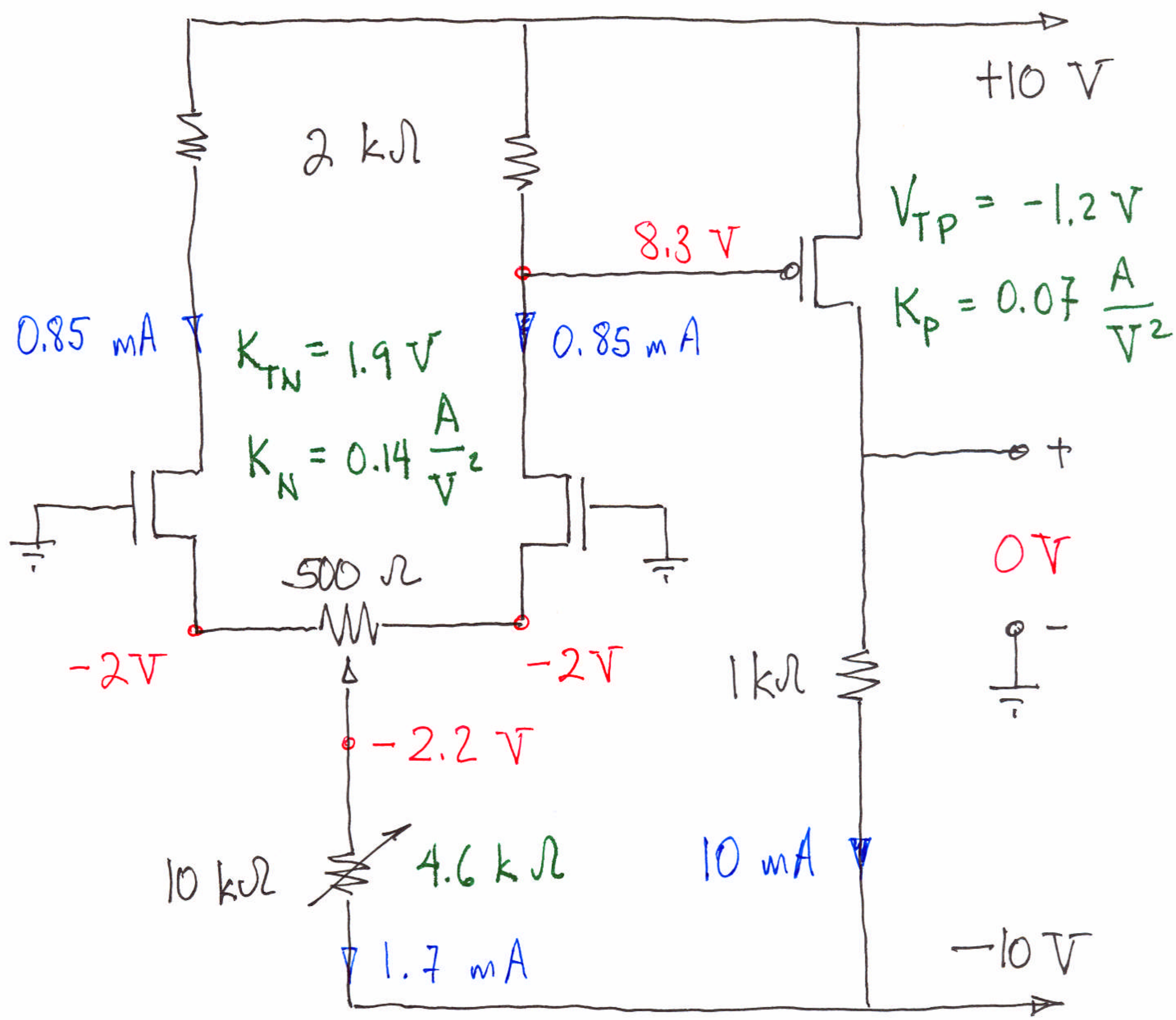


An Op-Amp

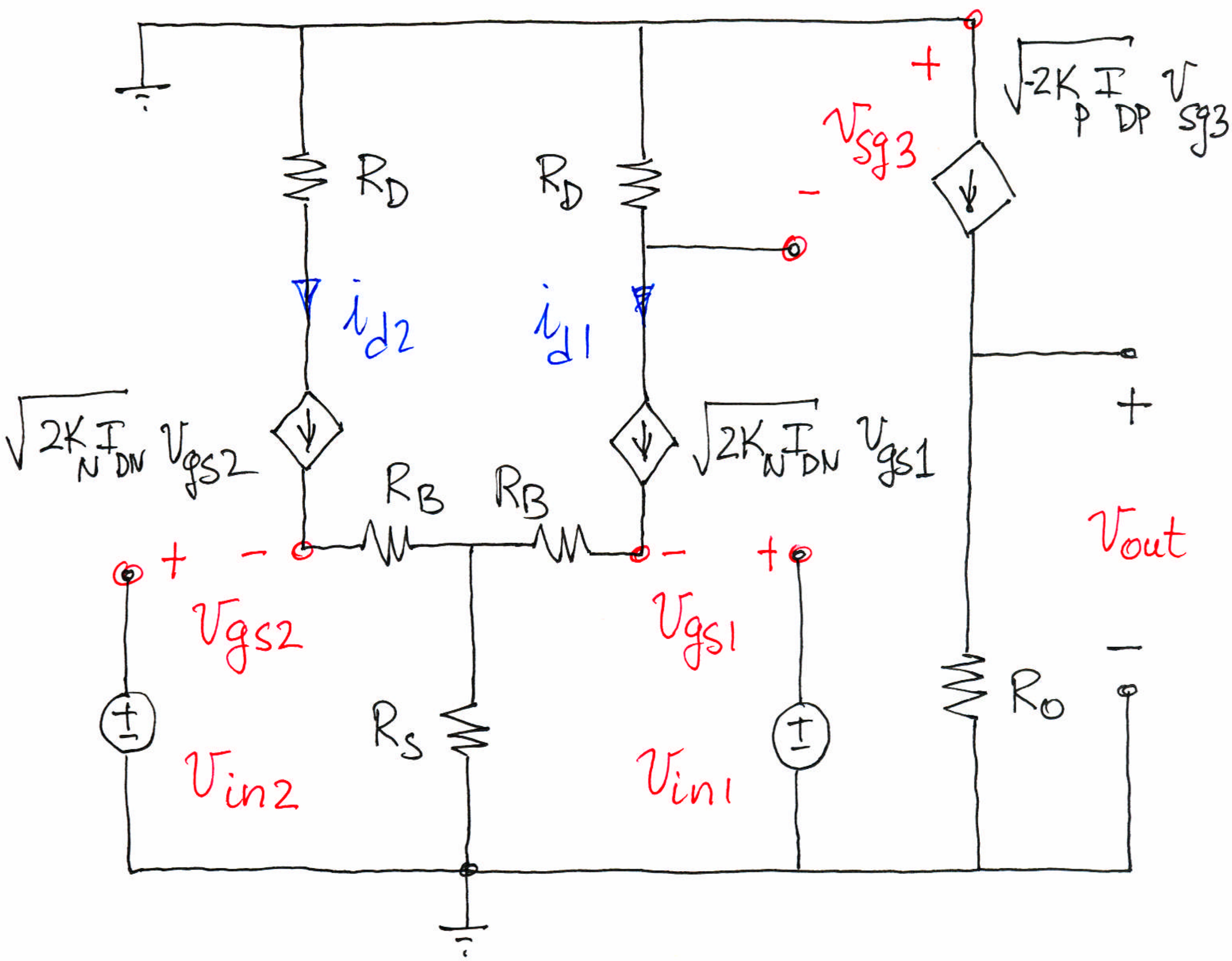


Adjust balance and bias for balanced currents and zero output when $v_{IN1} = v_{IN2} = 0$.

Approximate Biasing



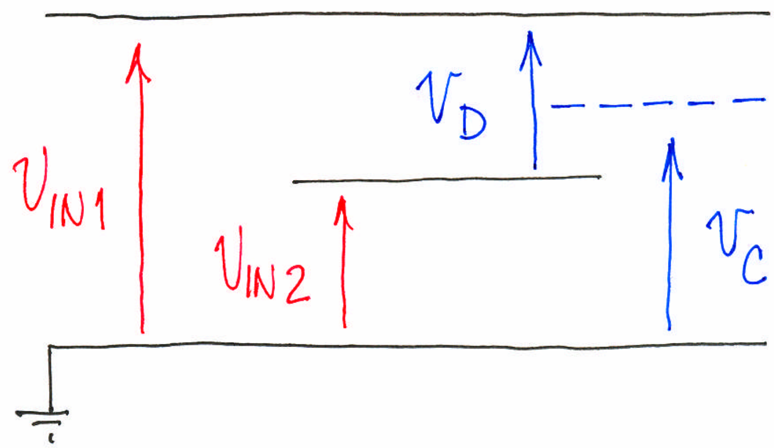
Small-Signal Model



(N) $i_D = \frac{K_N}{2}(V_{GS} - V_{TN})^2 \Rightarrow i_d = K_N(\bar{V}_{GS} - \bar{V}_{TN})\, v_{gs} = \sqrt{2K_N I_D}\, v_{gs}$

(P) $-i_D = \frac{K_P}{2}(V_{SG} + V_{TP})^2 \Rightarrow -i_d = K_p(\bar{V}_{SG} + \bar{V}_{TP})\, v_{sg} = \sqrt{-2K_p I_D}\, v_{sg}$

Modes



$$v_D \equiv v_{IN1} - v_{IN2} \equiv \text{Difference Mode}$$

$$v_C \equiv \frac{v_{IN1} + v_{IN2}}{2} \equiv \text{Common Mode}$$

$$v_{IN1} = v_C + \frac{v_D}{2}$$

$$v_{IN2} = v_C - \frac{v_D}{2}$$

Same for large and small signals

Difference Mode

$$v_C = 0 \qquad v_{in1} = -v_{in2} = v_d/2$$

$$\text{Symmetry} \Rightarrow \quad v_{gs2} = -v_{gs1} \qquad i_\Delta = 0$$

$$i_{d2} = -i_{d1} \qquad R_S\, i_s = 0$$

$$i_{d1} R_B + v_{gs1} = v_{in1}$$

$$i_{d1} = \sqrt{2K_N I_{DN}}\; v_{gs1}$$

$$i_{d1}\left(R_B + 1/\sqrt{2K_N I_{DN}}\right) = v_{in1} = v_d/2$$

$$i_{d1} = \frac{\sqrt{2K_N I_{DN}}\; v_d}{2\left(1 + R_B\sqrt{2K_N I_{DN}}\right)}$$

$$v_{out} = \underbrace{\frac{R_O\sqrt{-2K_P I_{DP}}\; R_D\sqrt{2K_N I_{DN}}}{2\left(1 + R_B\sqrt{2K_N I_{DN}}\right)}}_{\text{Difference Mode Gain} \;\equiv\; G_D}\; v_d$$

Common Mode

$v_d \equiv 0 \qquad v_{in1} = v_{in2} = v_c$

Symmetry $\Rightarrow$ $v_{gs1} = v_{gs2} \qquad i_{d1} = i_{d2}$

$$2R_S\, i_{d1} + R_B\, i_{d1} + v_{gs1} = v_{in1}$$

$$i_{d1} = \sqrt{2K_N I_{DN}}\; v_{gs1}$$

$$i_{d1}\left(2R_S + R_B + 1/\sqrt{2K_N I_{DN}}\right) = v_{in1} = v_c$$

$$i_{d1} = \frac{\sqrt{2K_N I_{DN}}\; v_c}{1 + (2R_S + R_B)\sqrt{2K_N I_{DN}}}$$

$$v_{out} = \underbrace{\frac{R_O \sqrt{-2K_P I_{DP}}\; R_D \sqrt{2K_N I_{DN}}}{1 + (2R_S + R_B)\sqrt{2K_N I_{DN}}}}_{\text{Common Mode Gain } \equiv\, G_C} v_c$$

Gain Summary

Combine difference and common mode analyses using superposition.

$$V_{out} = G_D (v_{IN1} - v_{IN2}) + G_C \frac{(v_{IN1} + v_{IN2})}{2}$$

$$= \underbrace{\left(G_D + \frac{G_C}{2}\right)}_{G_1} v_{IN1} - \underbrace{\left(G_D - \frac{G_C}{2}\right)}_{G_2} v_{IN2}$$

From Non-Inverting Input "v_+"

From Inverting Input "v_-"

Numbers

$R_B = 250\ \Omega$

$R_S = 4600\ \Omega$

$R_D = 2000\ \Omega$

$R_O = 1000\ \Omega$

$I_{DN} = 0.85\ mA$

$-I_{DP} = 10\ mA$

$K_N = 0.14\ A/V^2$

$K_P = 0.07\ A/V^2$

$\sqrt{2K_N I_{DN}} = 0.015\ A/V$

$\sqrt{-2K_P I_{DP}} = 0.037\ A/V$

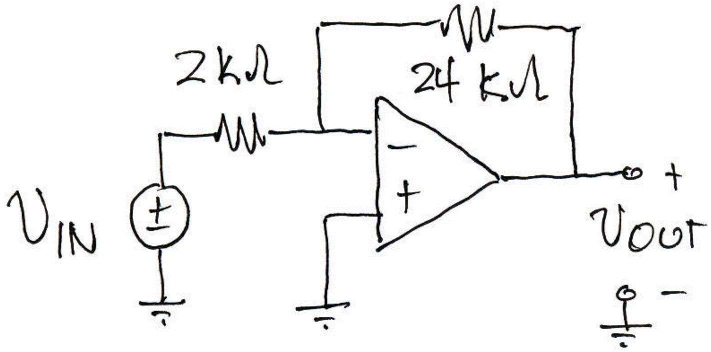
$G_D = 117$

$G_C = 8$

$G_1 = 121$ (From non-inverting input)

$G_2 = 113$ (From inverting input)

Applications



$$\frac{AG}{A+G} = \frac{121 \cdot 12}{121 + 12} = 10.9$$

Let $A = G_2$.