ECE/ENGRD 2100

Introduction to Circuits for ECE

Lecture 15

Input and Output Resistance,
Differential and Common Mode Signals
and Op-Amp Non-Idealities

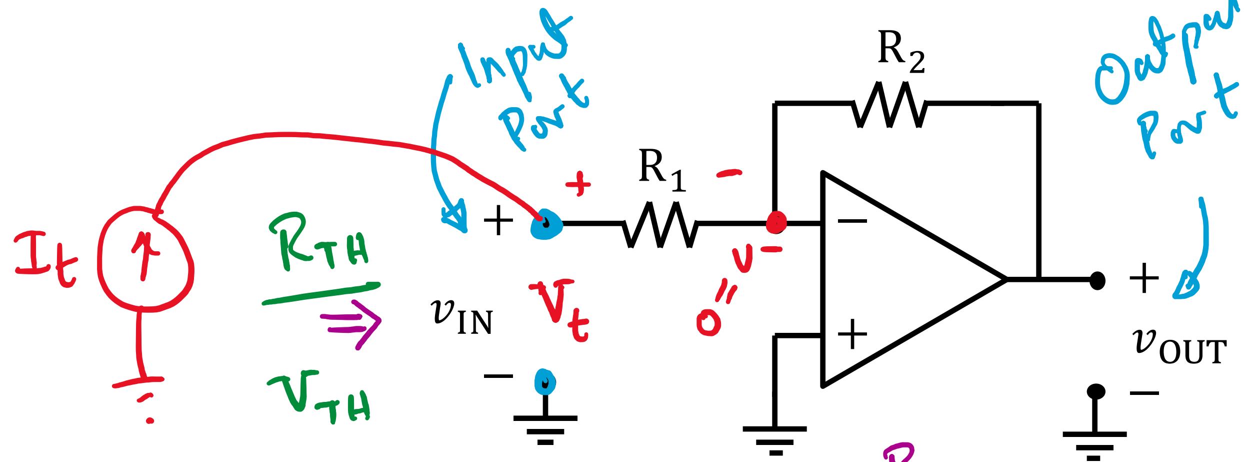
Announcements

- Recommended Reading:
  - Textbook Chapter 5

- Upcoming due dates:
  - Lab report 2 due by 11:59 pm on Wednesday 27, 2019
  - Prelab 3 due by 12:20 pm on Tuesday March 5, 2019
  - Homework 3 due by 11:59 pm on Friday March 8, 2019
  - Lab report 3 due by 11:59 pm on Friday March 15, 2019

- Lab 3 is next week (starting Tuesday March 5, 2019)

Input Resistance of Inverting Amplifier

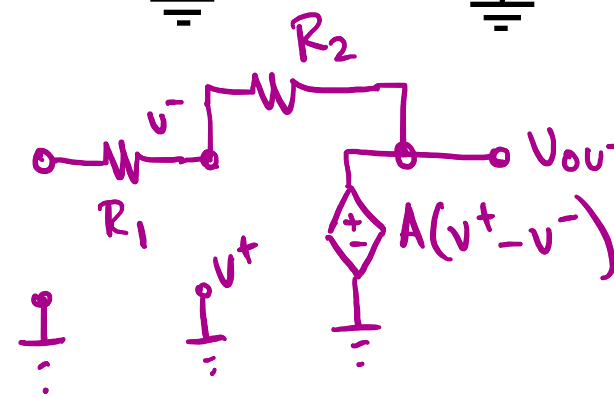


$V_t = R_1 I_t$

$\Rightarrow R_{TH} \equiv \frac{V_t}{I_t} = R_1$

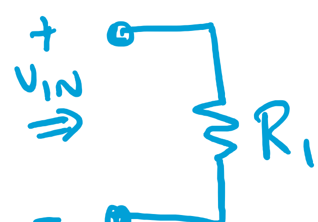
$$R_{TH} = R_1$$

$V_{TH} = V_{OC} = 0$

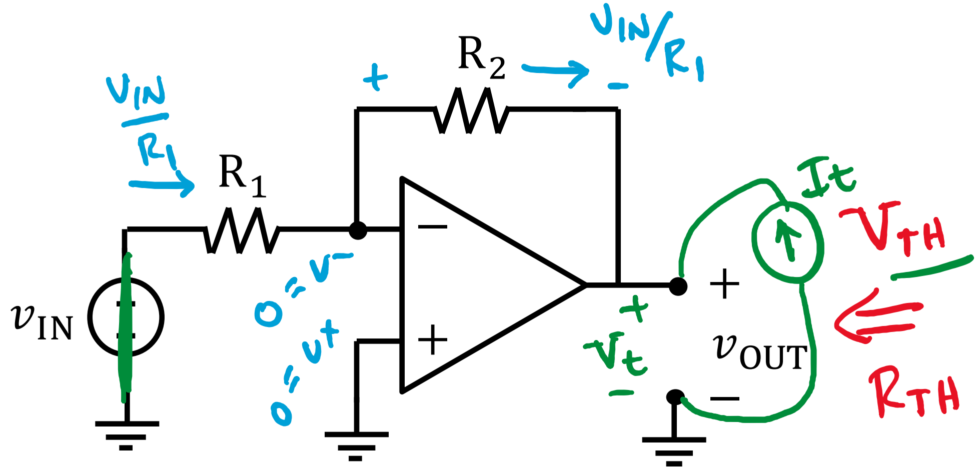


$v^- \approx v^+ = 0$

Input Port

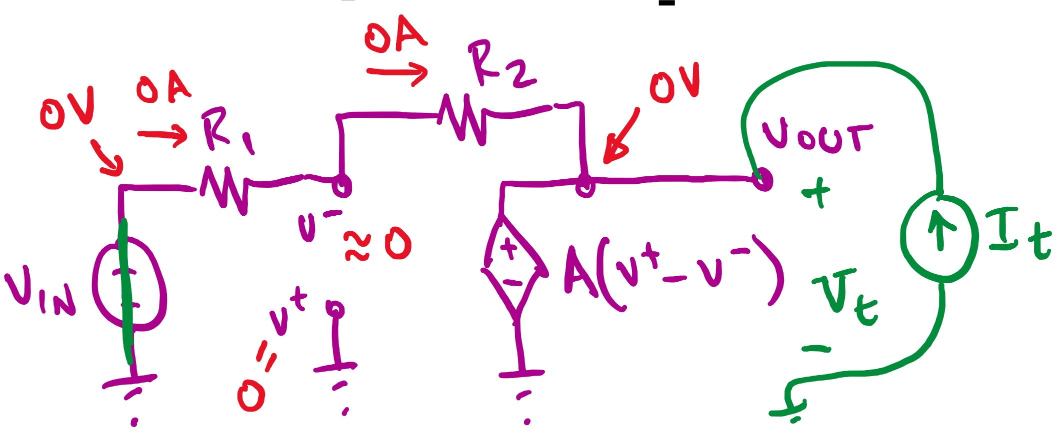


Output Resistance of Inverting Amplifier



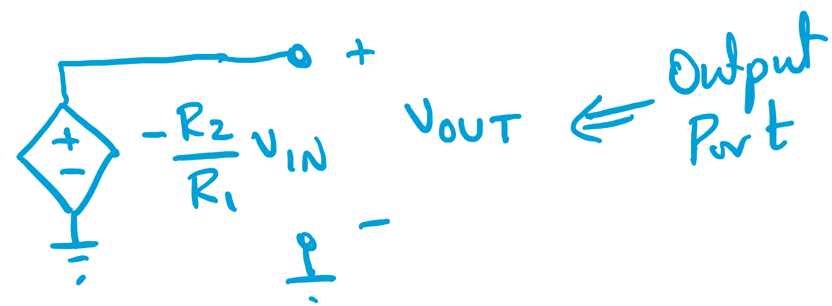
$$v_{OUT} = 0 - \frac{v_{IN}}{R_1} R_2$$

$$v_{OUT} = -\frac{R_2}{R_1} v_{IN}$$

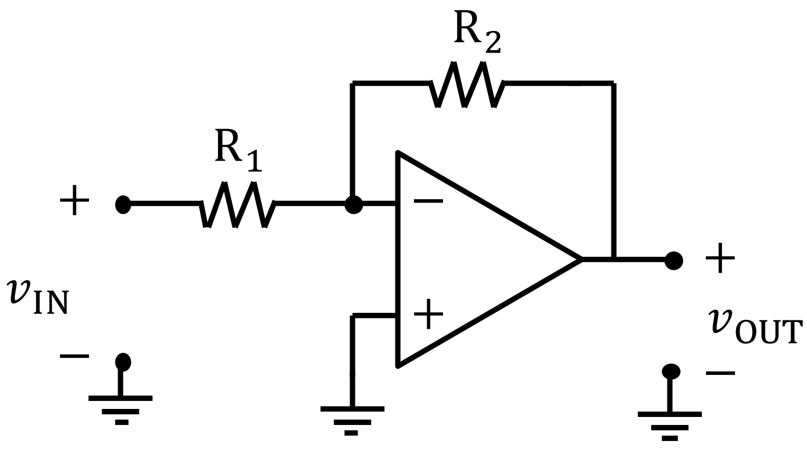


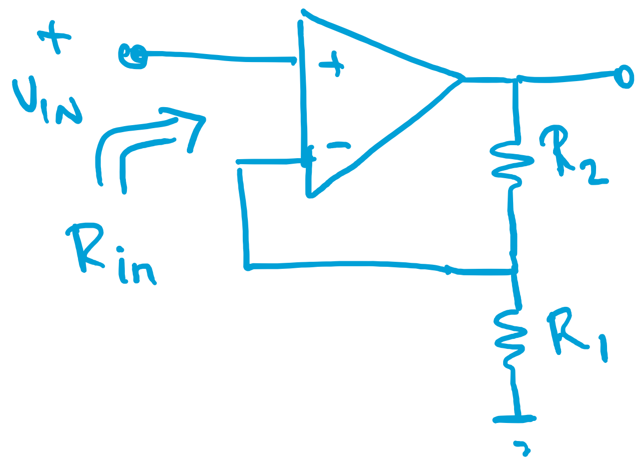
$$V_t = 0$$

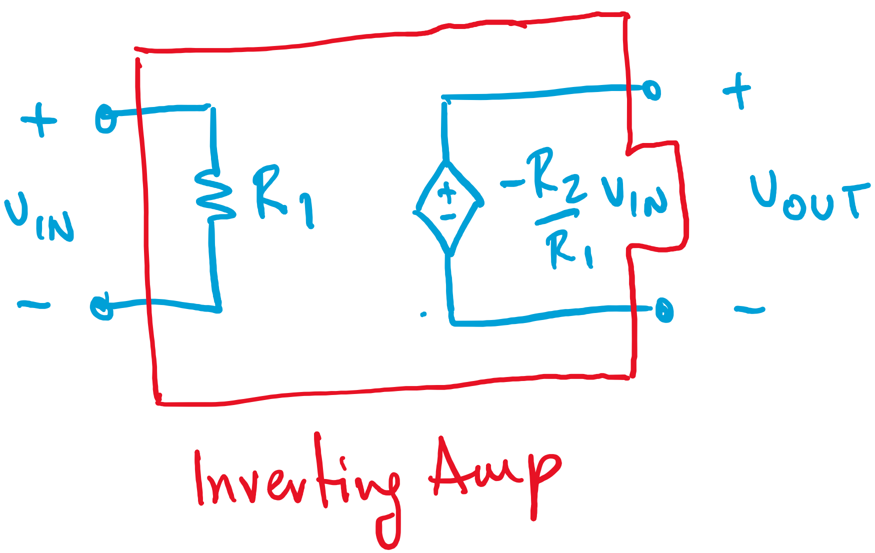
$$\Rightarrow R_{TH} \equiv \frac{V_t}{I_t} = 0$$



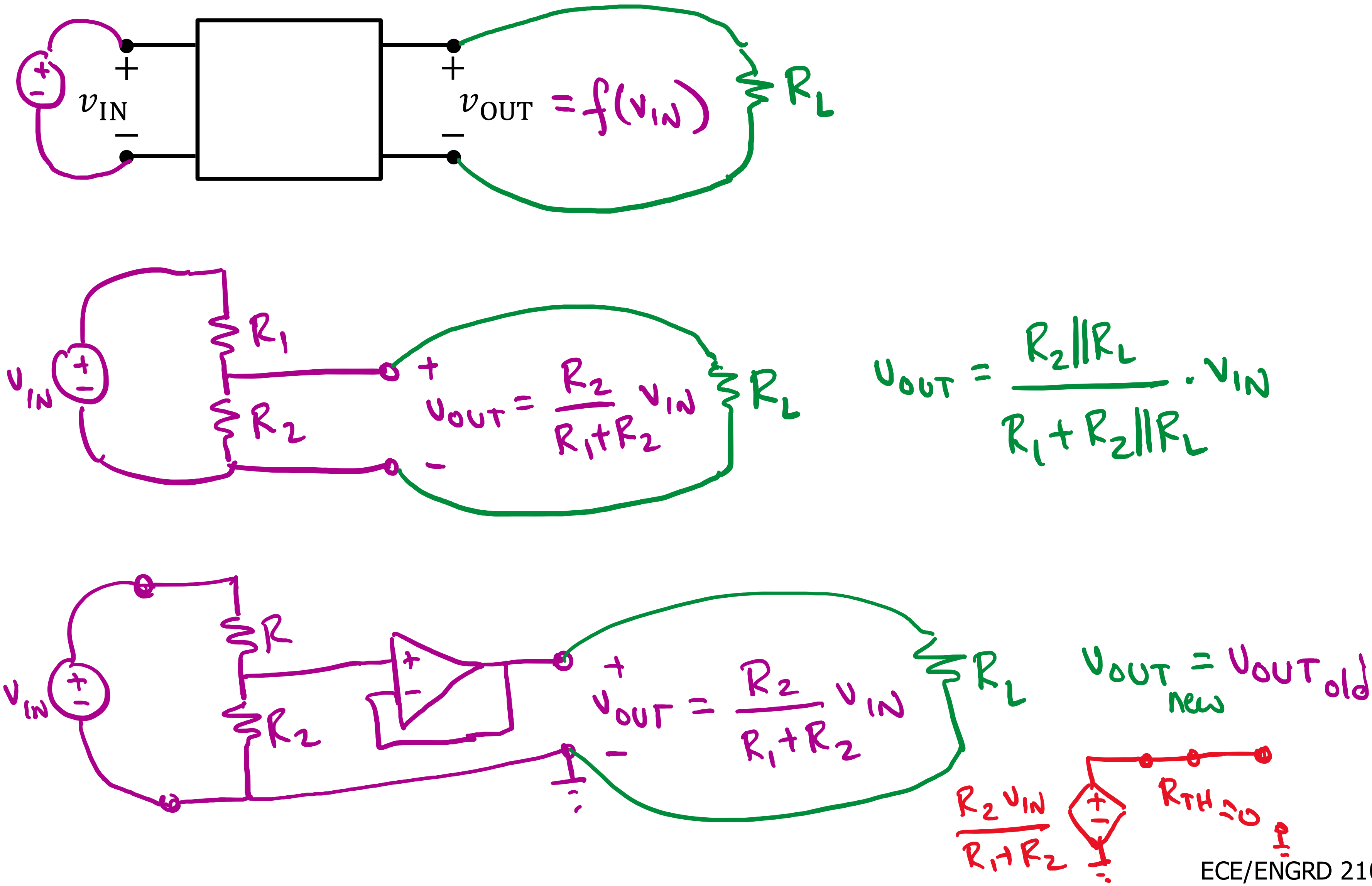
Two-Port Model of Inverting Amplifier



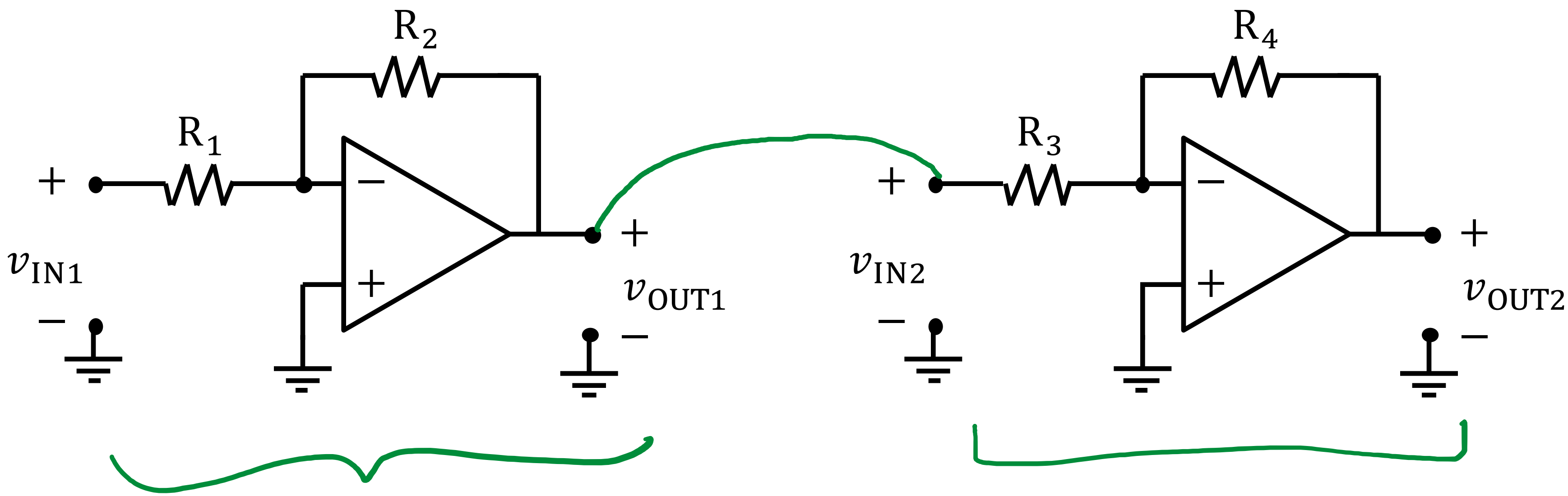




Loading Effect



Cascaded Op-Amp Circuits



$$v_{OUT_1} = g(v_{IN_1})$$

$$v_{OUT_2} = f(v_{IN_2})$$

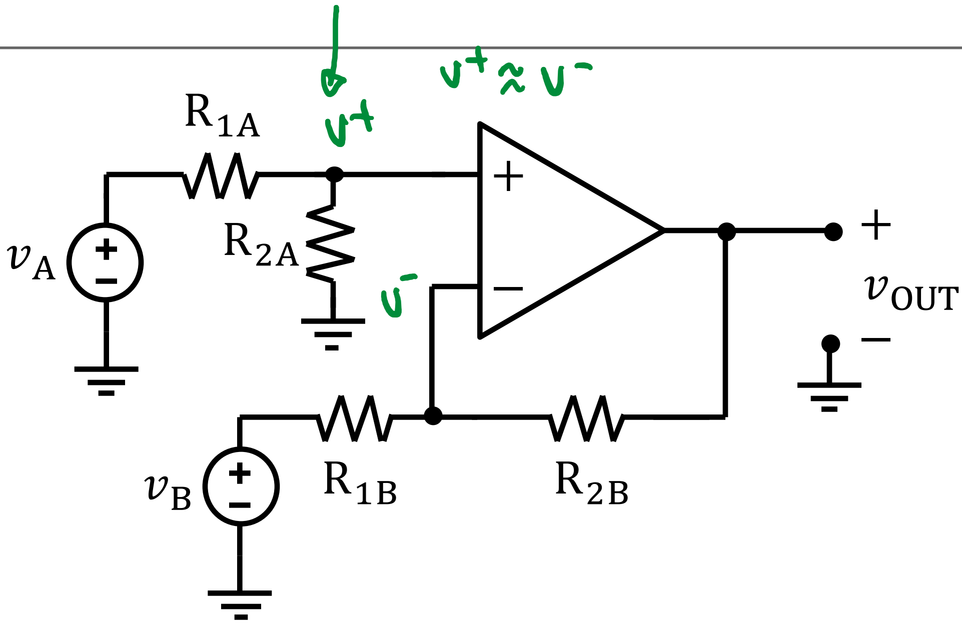
$$v_{OUT_1} = -\frac{R_2}{R_1} v_{IN_1}$$

$$v_{OUT_2} = -\frac{R_4}{R_3} v_{IN_2}$$

$$v_{IN_2} = v_{OUT_1}$$

$$\Rightarrow \quad v_{OUT_2} = -\frac{R_4}{R_3}\left(-\frac{R_2}{R_1}\right) v_{IN_1} = \frac{R_4 R_2}{R_3 R_1} v_{IN_1}$$

Differential Amplifier



$R_{1A} = R_{1B}$ & $R_{2A} = R_{2B}$

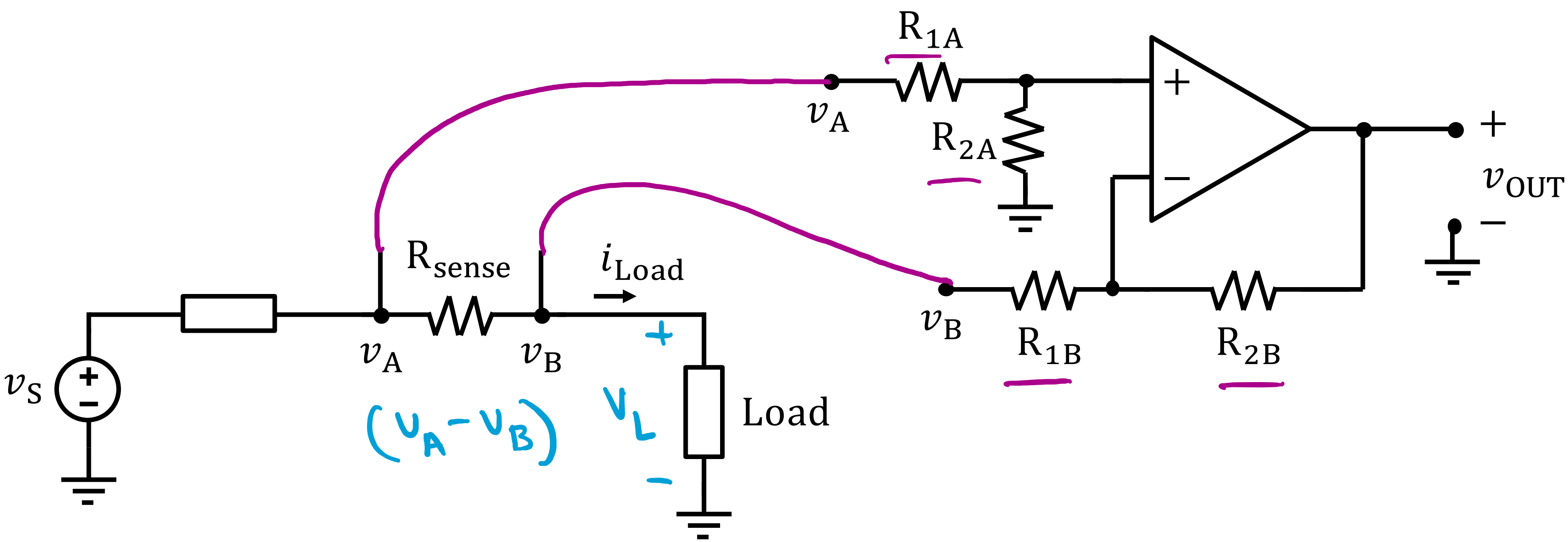
$\quad\;\; = R_1 \qquad\qquad\quad = R_2$

$$v^+ = \frac{R_{2A}}{R_{1A}+R_{2A}} v_A \qquad v^- = \frac{R_{2B}}{R_{1B}+R_{2B}} v_B + \frac{R_{1B}}{R_{1B}+R_{2B}} v_{OUT}$$

$v^+ \approx v^-$

$$\Rightarrow \quad v_{OUT} = \frac{R_{1B}+R_{2B}}{R_{1B}} \left(\frac{R_{2A}}{R_{1A}+R_{2A}} \cdot v_A - \frac{R_{2B}}{R_{1B}+R_{2B}} \cdot v_B \right)$$

Differential Mode and Common Mode Signals



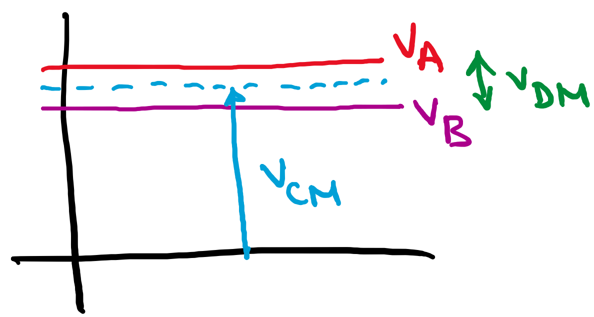
$v_L \gg (v_A - v_B)$

Differential mode signal

$$v_{DM} = v_A - v_B$$

Common mode signal

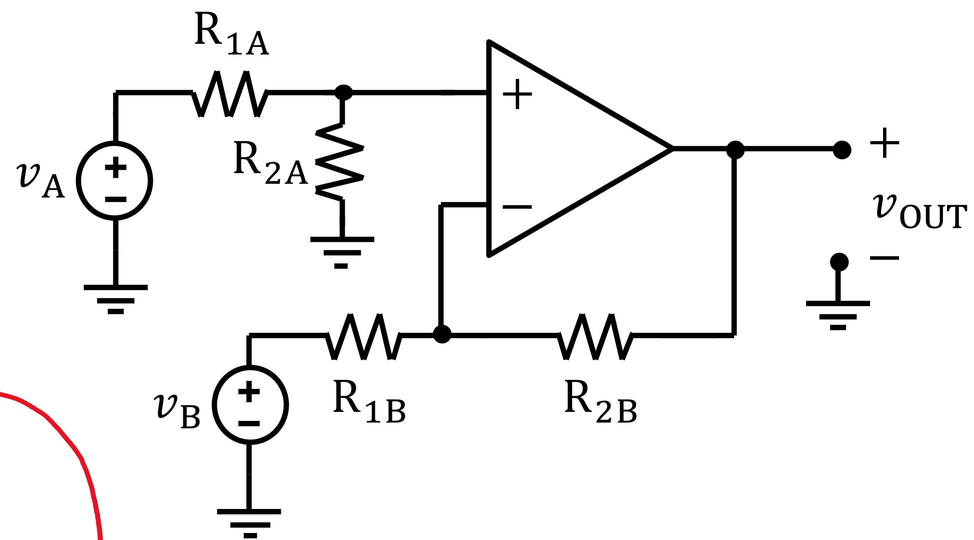
$$v_{CM} = \frac{v_A + v_B}{2}$$



$$v_A = v_{CM} + \frac{v_{DM}}{2}$$

$$v_B = v_{CM} - \frac{v_{DM}}{2}$$

Differential Mode and Common Mode Gain



$$v_A = v_{CM} + \frac{v_{DM}}{2}$$

$$v_B = v_{CM} - \frac{v_{DM}}{2}$$

$$v_{OUT} = \frac{R_{1B}+R_{2B}}{R_{1B}}\left[\frac{R_{2A}}{R_{1A}+R_{2A}}v_A - \frac{R_{2B}}{R_{1B}+R_{2B}}v_B\right]$$

$$v_{OUT} = \frac{R_{1B}+R_{2B}}{R_{1B}}\left(\frac{R_{2A}}{R_{1A}+R_{2A}} - \frac{R_{2B}}{R_{1B}+R_{2B}}\right)v_{CM} + \frac{R_{1B}+R_{2B}}{R_{1B}}\left(\frac{R_{2A}}{R_{1A}+R_{2A}} + \frac{R_{2B}}{R_{1B}+R_{2B}}\right)\frac{v_{DM}}{2}$$

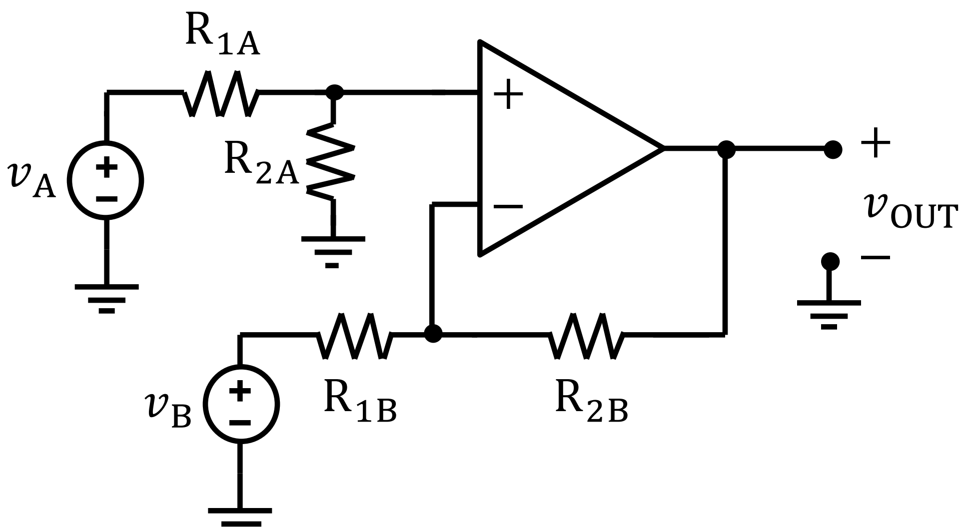
want to keep

want to reject

$\equiv G_{CM}$ common-mode gain

$\equiv G_{DM}$ differential-mode gain

Common Mode Rejection Ratio



Common mode rejection ratio

$$\text{CMRR} \equiv \frac{G_{DM}}{G_{CM}}$$

$$v_{OUT} = \underbrace{\frac{R_{1B}+R_{2B}}{R_{1B}}\left(\frac{R_{2A}}{R_{1A}+R_{2A}} - \frac{R_{2B}}{R_{1B}+R_{2B}}\right)}_{G_{CM}} v_{CM} + \underbrace{\frac{R_{1B}+R_{2B}}{R_{1B}}\left(\frac{R_{2A}}{R_{1A}+R_{2A}} + \frac{R_{2B}}{R_{1B}+R_{2B}}\right)}_{G_{DM}} \frac{v_{DM}}{2}$$

$$G_{DM} \equiv \left.\frac{v_{OUT}}{v_{DM}}\right|_{v_{CM}=0} = \frac{R_2}{R_1}$$

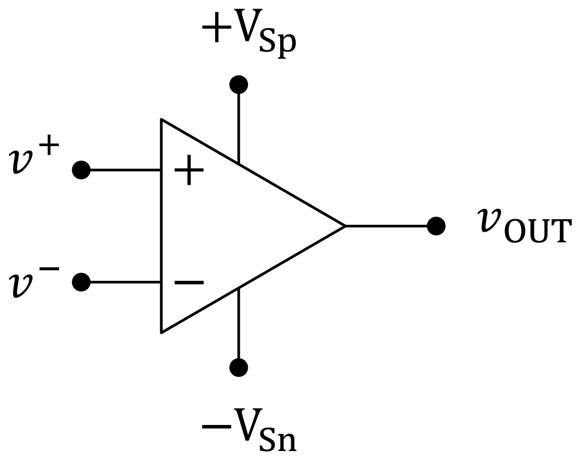
$$G_{CM} \equiv \left.\frac{v_{OUT}}{v_{CM}}\right|_{v_{DM}=0} = 0$$

if $R_{1A} = R_{1B} = R_1$, $R_{2A} = R_{2B} = R_2$

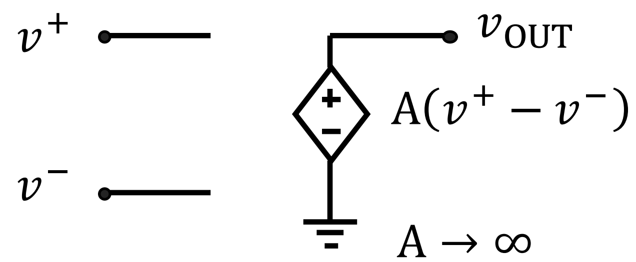
CMRR = ∞

$$G_{DM} = \frac{R_1+R_2}{R_1}\left(\frac{R_2}{R_1+R_2} + \frac{R_2}{R_1+R_2}\right)\frac{v_{DM}}{2} = \frac{R_2}{R_1} v_{DM}$$

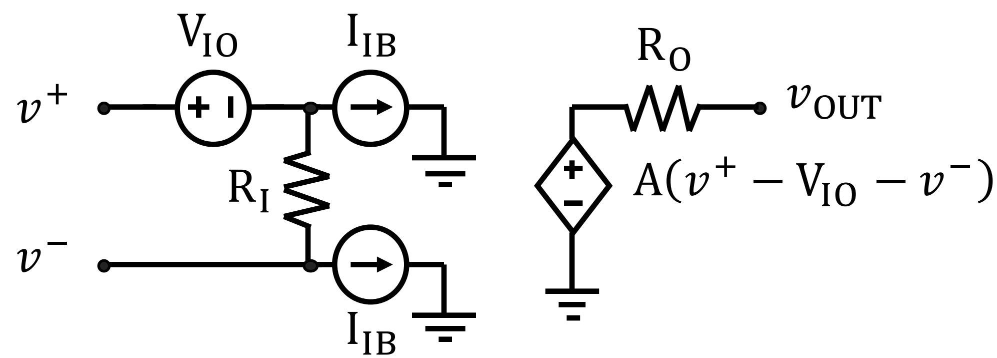
Op-Amp Non-Idealities



Ideal Op-Amp

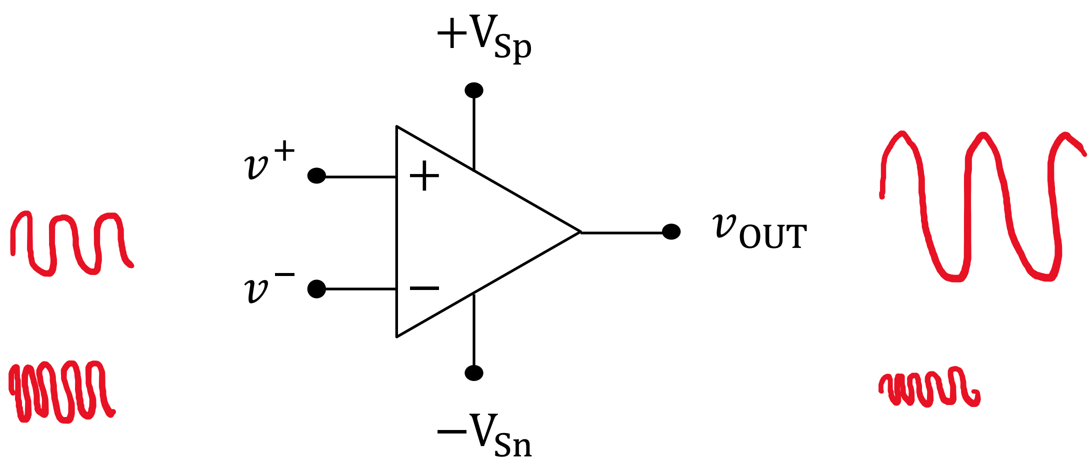


Real Op-Amp



$$-V_{Sn} + V_{Mn} \leq v_{OUT} \leq V_{Sp} - V_{Mp}$$

Op-Amp Bandwidth



Op-Amp gain starts decreasing beyond a certain frequency and crosses 1 at a frequency referred to as its bandwidth

This is caused by capacitive effects