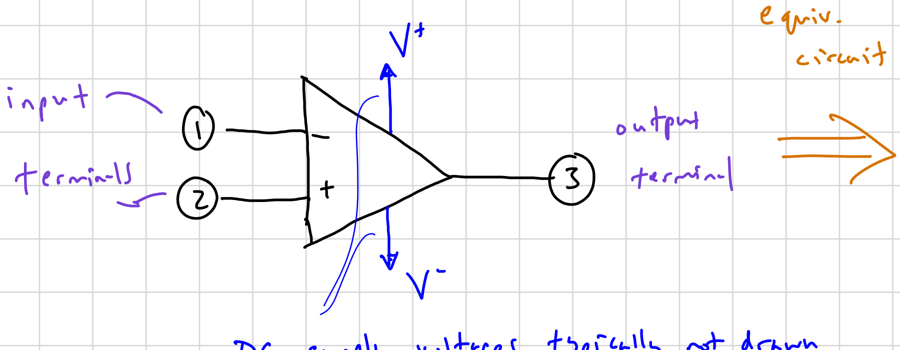
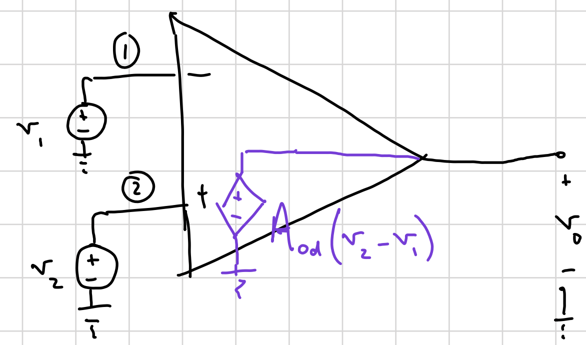
# Lecture #22 — The Operational Amplifier (Op-Amp)

- **Intro to Op-Amp**
  - → Integrated circuit that amplifies the difference between two input voltages, producing a single output.
  - → Function/use changes depending on how it is connected and what it is connected to.



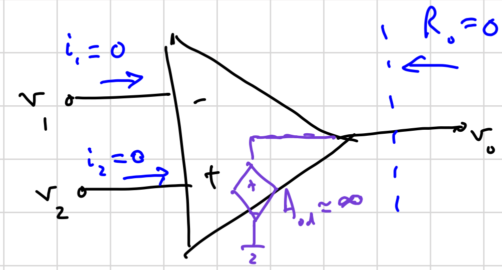




★ No coupling capacitors, so inputs can be pure DC or AC voltages

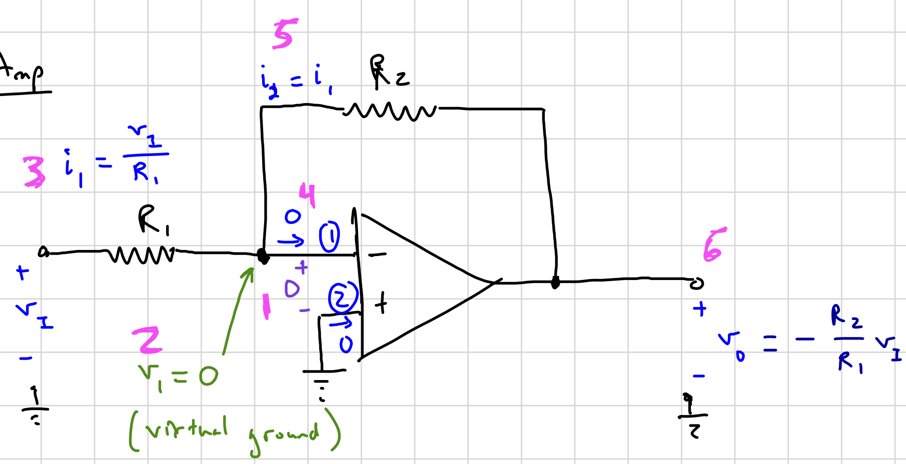
$A_{od}$ ≡ open-loop differential voltage gain
① ≡ inverting input terminal
② ≡ noninverting input terminal

- **Ideal Op-Amp with "Negative Feedback"** → output connected to inverting input terminal

Ideal op-Amp means:
1) $A_{od}$ is $\infty$
2) Differential input voltage, $v_2 - v_1 = 0$
3) Input resistances $= \infty$, $i_1 = i_2 = 0$
4) Output resistance, $R_o = 0 \Rightarrow v_o$ connected directly to $A_{od}(v_2 - v_1)$ and independent of any load on output.




- **Basic Inverting Op-Amp**




What will the closed-loop voltage gain be?

$$A_v = \frac{v_o}{v_I}$$

1 − $v_2 - v_1 = \frac{v_o}{A_{od}} = 0$

2 − $v_1 = v_2 \equiv v_1$ is "virtual ground"

★ Has zero voltage but is not physically connected to ground.

3 − $i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I}{R_1}$

4 − $\infty$ input impedance of op-amp

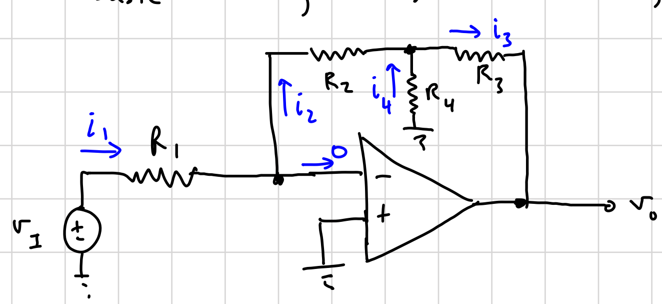
5/6 − $v_o = v_1 - i_2 R_2 = 0 - \left(\frac{v_I}{R_1}\right) R_2$

$\therefore A_v = -\frac{R_2}{R_1}$

- minus sign means op-amp leads to signal inversion
- $A_v$ depends entirely on external passive components
  - → can design very accurate $A_v$
  - → stable and predictable!
  - → works for AC or DC inputs!

- **Op-Amp with a T-network**

  → Basic inverting config is limited by difficulty of implementing very large resistors for $R_2$




$$\boxed{A_v = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)}$$

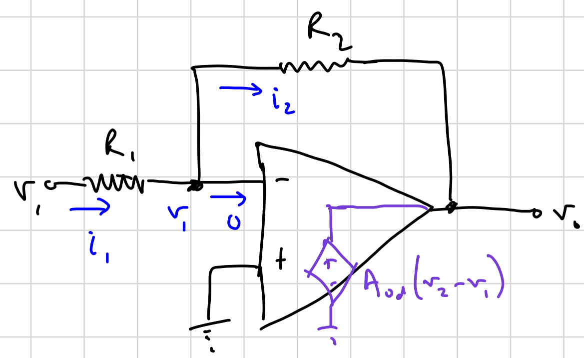
- **Effect of finite gain**

  → Key assumption thus far for "ideal op-amp" is $A_{od} = \infty$

  → What if it does not?

$$i_1 = \frac{v_I - v_1}{R_1} = i_2 = \frac{v_1 - v_o}{R_2}$$

For basic inverting config:

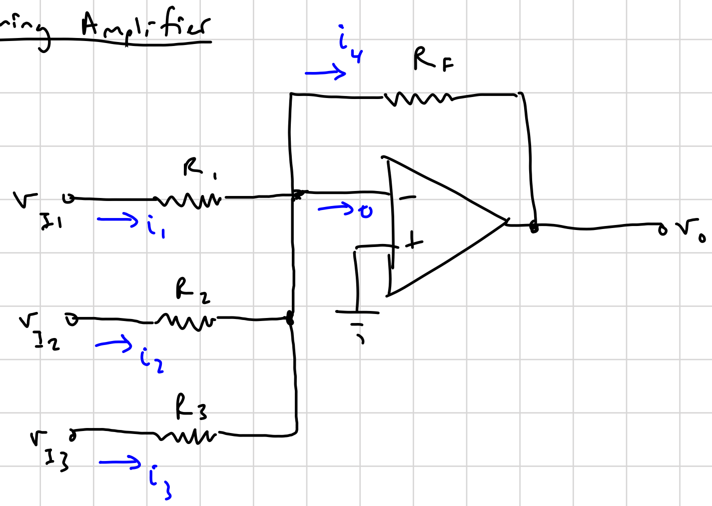



$$v_o = -A_{od} v_1 \rightarrow v_1 = -\frac{v_o}{A_{od}}$$

add this eqn to and solve for $v_o / v_I$:

$$\boxed{A_v = -\frac{R_2}{R_1}\left(\frac{1}{1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)}\right)}$$

- **Summing Amplifier**




☆ Can use superposition to analyze by summing up the different input contributions (set others to zero, solve, etc.)

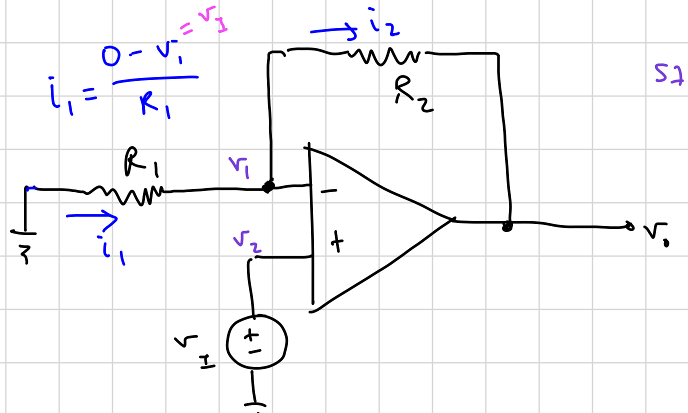
result: $\boxed{v_o = -\frac{R_F}{R_1}\left(v_{I1} + v_{I2} + v_{I3}\right)}$

if $R_1 = R_2 = R_3$

- **Non-inverting Amplifier**

  → apply input signal to non-inverting terminal (2)

$$i_1 = \frac{0 - v_1^{\,=v_I}}{R_1}$$

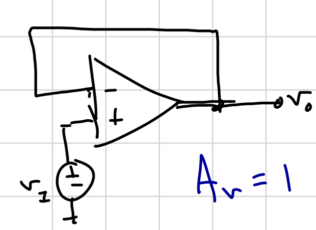



still have $v_1 = v_2$, now a "virtual short"

$$\boxed{A_v = 1 + \frac{R_2}{R_1}}$$

☆ in-phase output with input

used mostly as "voltage-follower" or impedance transformer:




$A_v = 1$

See book example