ECE 342
Electronic Circuits

Lecture 30
Operational Amplifiers - 1

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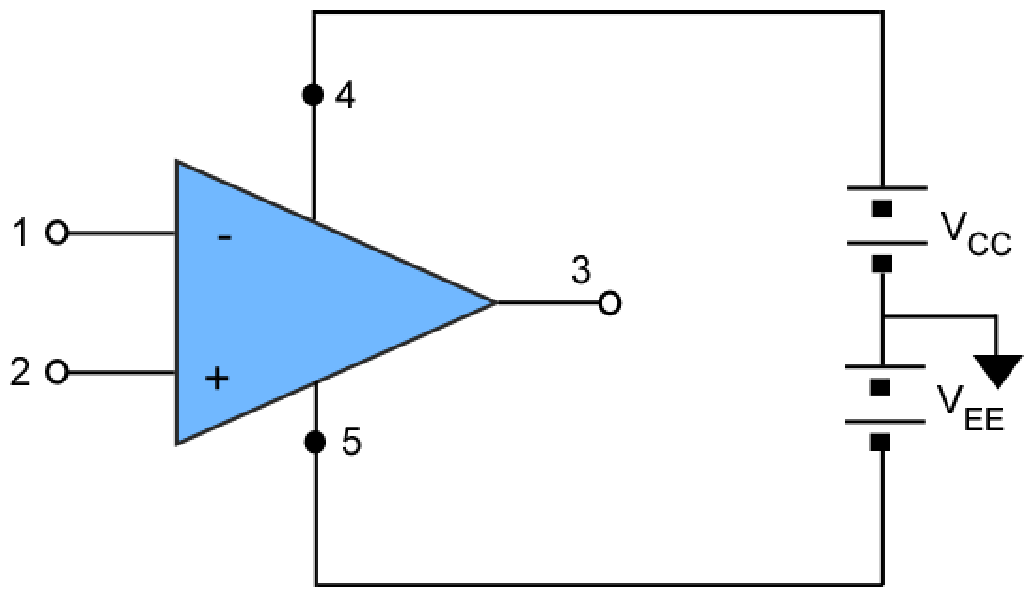
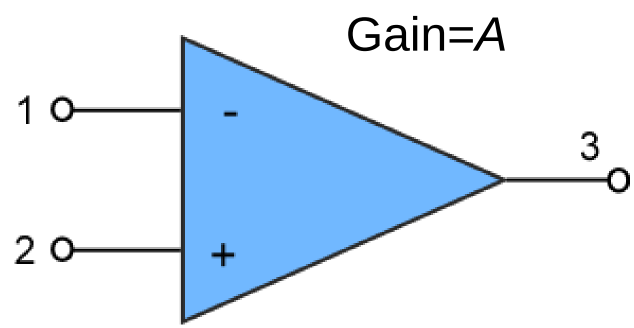
Operational Amplifiers

- **Universal importance (e.g. amplification from microphone to loudspeakers)**



General terminal configuration with bias

Operational Amplifiers



$$v_{out} = A(v_2 - v_1)$$

Common configuration with bias implied but not shown

- **Signaling**
  1. Differential input stage
  2. Difference between input is amplified

Operational Amplifiers

- **Ideal Op Amp**

1. Infinite input impedance
2. Zero output impedance
3. Infinite open-loop gain A➔inf
4. Infinite CMRR or zero common-mode gain
5. Infinite bandwidth

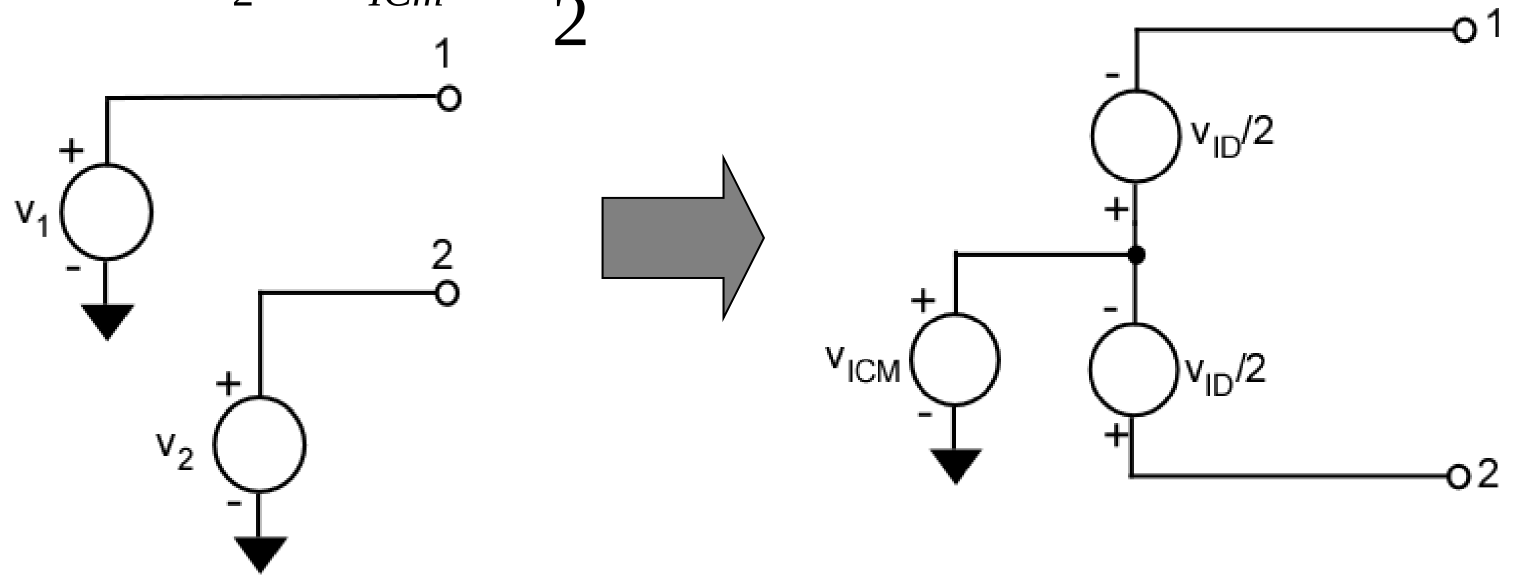
Also, op amps are dc (or direct coupled) amplifiers since they are expected to amplify signals with frequency as low as DC.

Differential & Common-Mode Signals

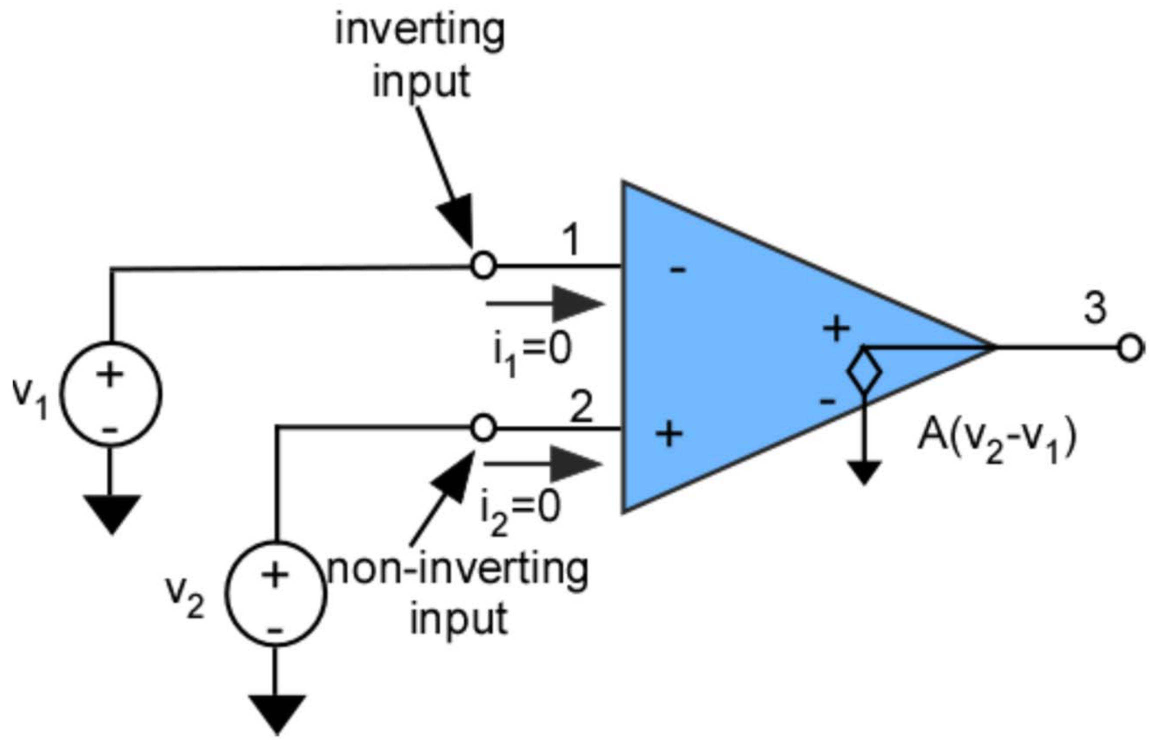
- Differential input signal $v_{ID}=v_2-v_1$
- Common-mode input signal $v_{ICm}=0.5(v_1+v_2)$

$$v_1 = v_{ICm} - \frac{v_{ID}}{2}$$

$$v_2 = v_{ICm} + \frac{v_{ID}}{2}$$



Operational Amplifiers

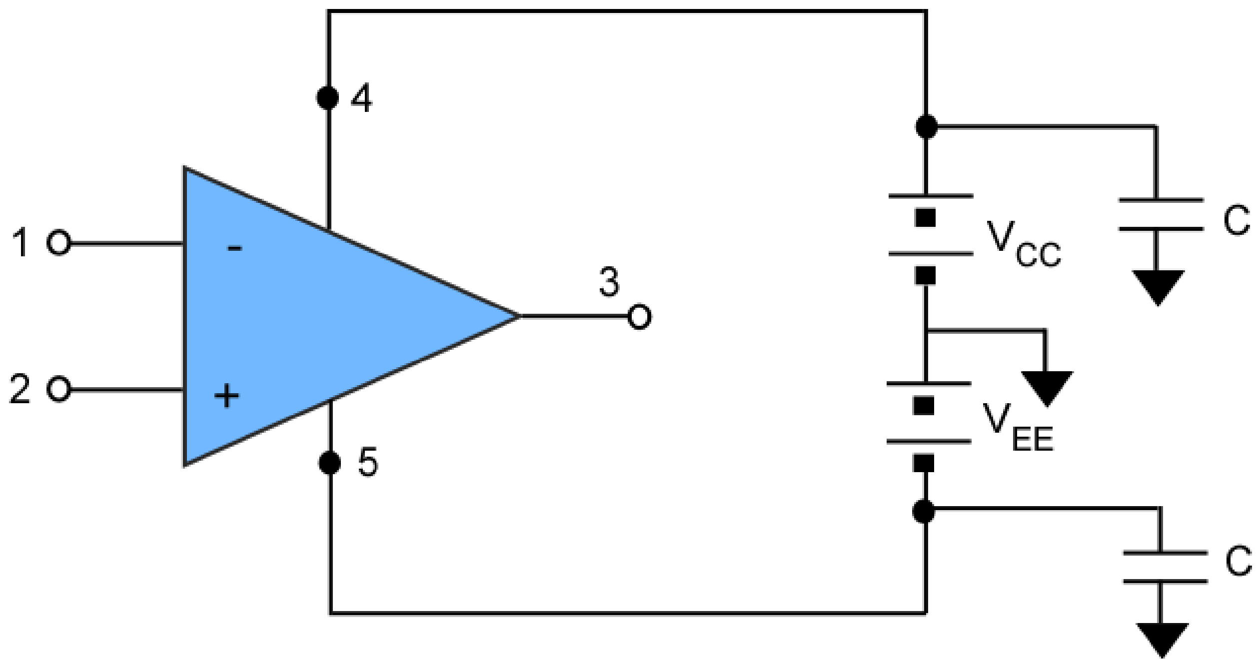


Ideally, v_{ICM} should be zero to achieve high CMRR.

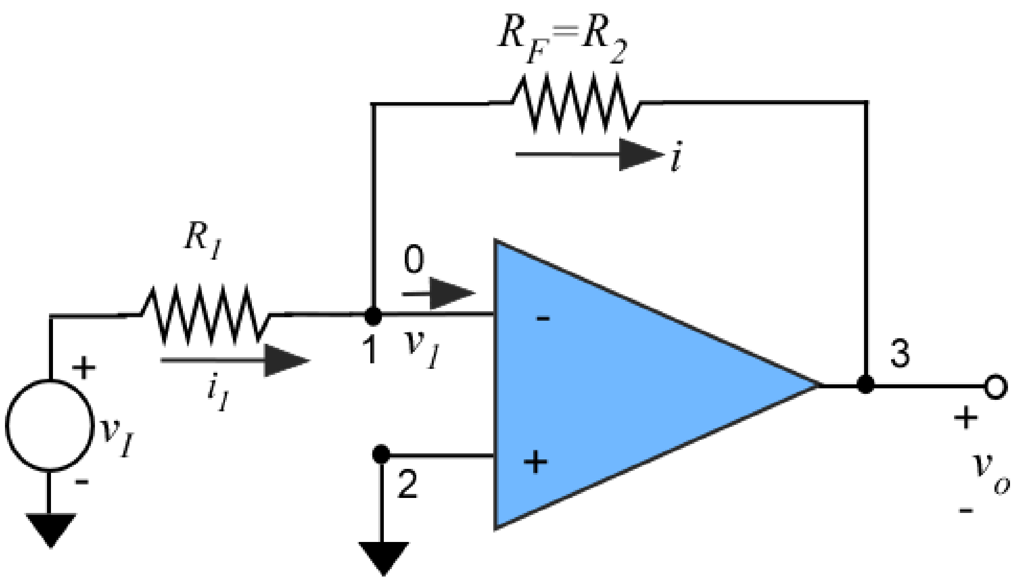
- **Amplifier will amplify the <u>difference</u> between the two input signals**

Practical Considerations

The output voltage swing of an op amp is limited by the DC power supply. Since op amp can exhibit high gain, power supply voltage fluctuations must be minimized ➔ use decoupling capacitors from power supply



Inverting Configuration



Terminal 2 is tied to ground

We introduce R_F (or R_2) to reduce gain (from inf)

- **When R_F is connected to terminal 1, we talk about negative feedback. If R_F is tied to terminal 2, we have positive feedback**

Inverting Configuration

Need to evaluate v_o/v_I

Assume ideal Op-Amp

Since gain is infinite: $$\frac{v_o}{A}=(v_2-v_1)=0$$

$$Thus,\, v_1=v_2=0$$ **Note: *A* is <u>open-loop gain</u>**

v_1 is virtual ground

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

Inverting Configuration

Since input impedance of OP amp is infinite, current through R_F is i_1

$$i = i_1 = \frac{v_I}{R_1}$$

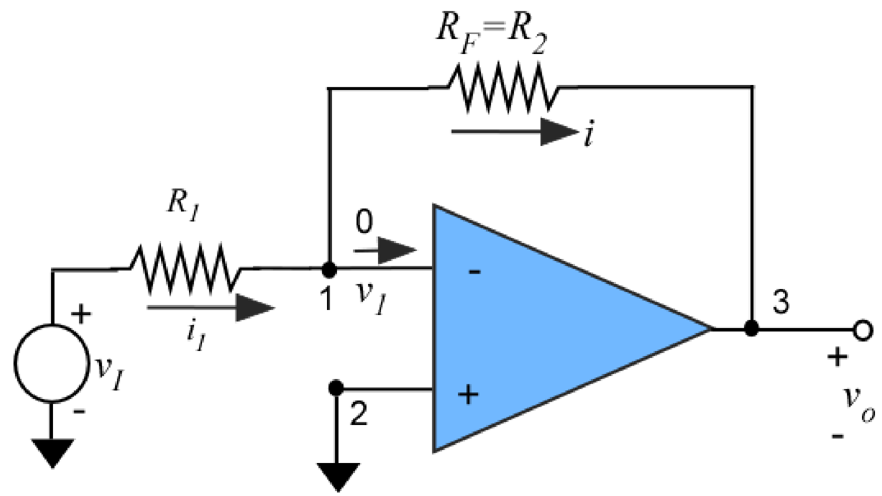
$$\frac{v_1 - v_o}{R_F} = \frac{0 - v_o}{R_F} = i = \frac{v_I}{R_1}$$

$$\frac{-v_o}{R_F} = \frac{v_I}{R_1} \Rightarrow v_o = -v_I \frac{R_F}{R_1}$$

Inverting Configuration

Closed-Loop gain

$$\frac{v_o}{v_I} = -\frac{R_F}{R_1} = G$$



Observe that the closed-loop gain is the ratio of external components ➔ we can make the closed-loop as accurate as we want. Gain is smaller but more accurate.

Inverting Configuration

We assumed that the OP-amp was ideal. If we assume that the gain *A* is finite = *A*

$$\left(v_2 - v_1\right)A = v_o \Rightarrow v_1 = -v_o / A$$

$$i_1 = \frac{v_{in} - (-v_o / A)}{R_1} = \frac{v_{in} + v_o / A}{R_1}$$

Inverting Configuration

Still assume infinite input impedance

$$v_o = -\frac{v_o}{A} - iR_F = -\frac{v_o}{A} - \frac{\left(v_i + v_o / A\right) R_F}{R_1}$$

$$G = \frac{v_o}{v_I} = \frac{-R_F / R_1}{\left(1 + R_F / R_1\right) / A} = \frac{-AR_F}{R_1\left(1 + A\right) + R_F}$$

$$\boxed{G = \frac{-AR_F}{R_1\left(1 + A\right) + R_F}}$$

Closed-loop gain for inverting configuration

Inverting Configuration

The reflected impedance of R_F is given by

$$R_R = \frac{v_1}{i_1} = \frac{-\left(v_o / A\right) R_1}{\dfrac{v_o}{G} + v_o / A}$$

$$R_R = \frac{-R_1}{1 + \dfrac{A}{G}} \quad \text{since} \quad \frac{A}{G} = -1 - \frac{-R_1}{R_F}(1 + A)$$

$$\boxed{R_R = \frac{R_F}{1 + A}}$$ ➔ small

Inverting Configuration

Since the reflected impedance is so small, v_1 is thus very small and the inverting terminal is said to be a virtual ground in this configuration

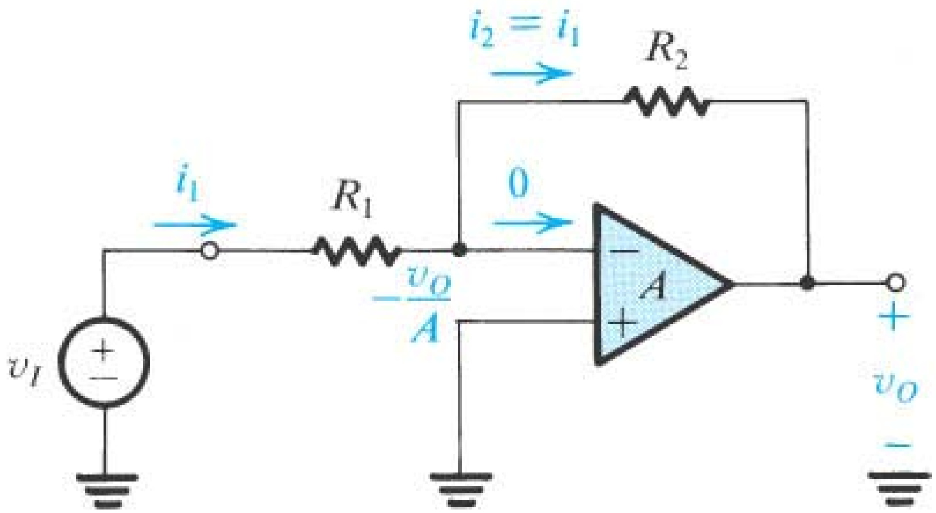
We see that $$as\ A \rightarrow \infty,\ G \rightarrow -\frac{R_F}{R_1}$$

$$as\ A \rightarrow \infty,\ R_R \rightarrow 0$$

Note: To minimize the closed-loop gain (*G*) on the value of the open-loop gain (*A*), make $1+R_F/R_1 \ll A$

Input and Output Impedances

Inverting Configuration



$$R_i \equiv \frac{v_I}{i_1} = \frac{v_I}{v_I / R_1} = R_1$$

- If high gain is required, input impedance will be low
- Output impedance is zero

Example

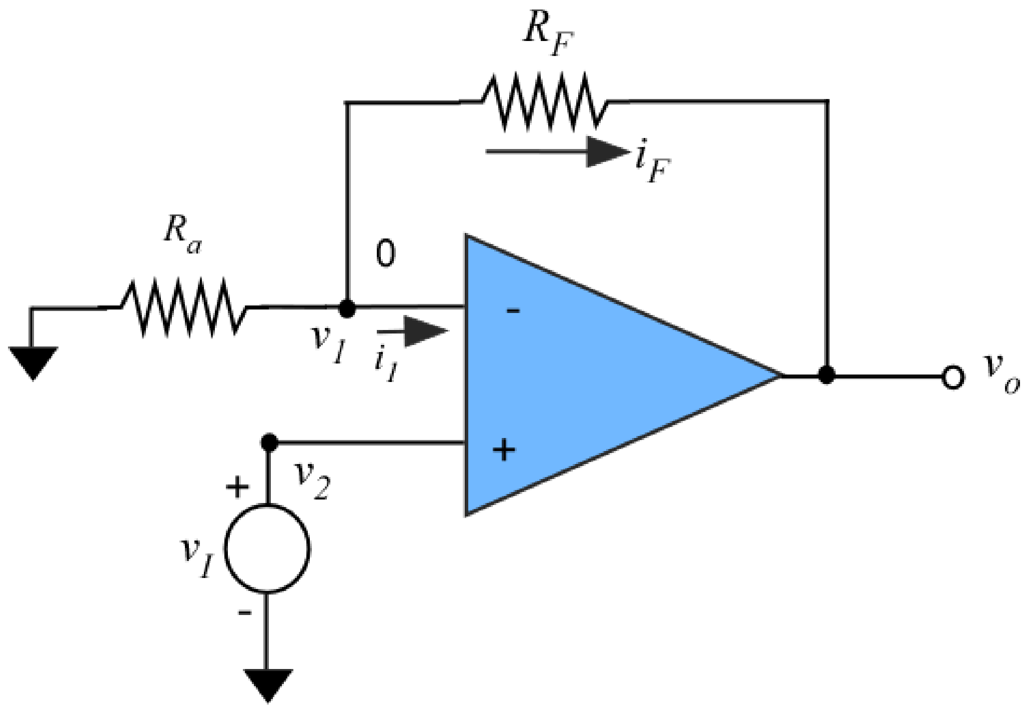
Find closed-loop gain for $A=10^3$, $A=10^4$ and $A=10^5$ assuming R_1=1 kΩ and R_F=100 kΩ. Assuming v_I=0.1 V, find v_1.

Using formulas

A	|G|	v_1
10^3	90.83	-9.08 mV
10^4	99.00	-0.99 mV
10^5	99.90	-0.1 mV

Note: Since output of inverting configuration is at terminal of VCVS, output impedance of closed-loop amp is zero.

Non-Inverting Configuration



$$\text{Assume gain is } \infty \Rightarrow v_{ID} = \frac{v_o}{A} \rightarrow 0$$

Non-Inverting Configuration

$$v_{ID} = 0 \Rightarrow v_1 \approx v_2 \Rightarrow virtual\ short$$

Infinite input impedance $\Rightarrow i_1 = 0$

$$Therefore\ \frac{v_1 - v_o}{R_F} = \frac{0 - v_1}{R_a}$$

$$\frac{v_1\left(R_a + R_F\right)}{R_a} = v_o$$

Non-Inverting Configuration

Virtual short $\Rightarrow v_2 = v_I = v_1$

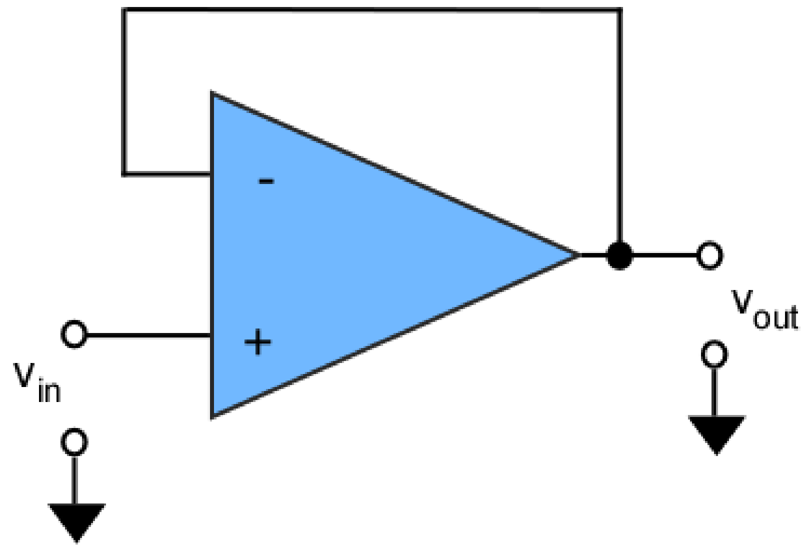
$$v_I \frac{(R_a + R_F)}{R_a} = v_o$$

$$G = \frac{v_o}{v_I} = 1 + \frac{R_F}{R_a}$$

$$\boxed{G = 1 + \frac{R_F}{R_a}}$$

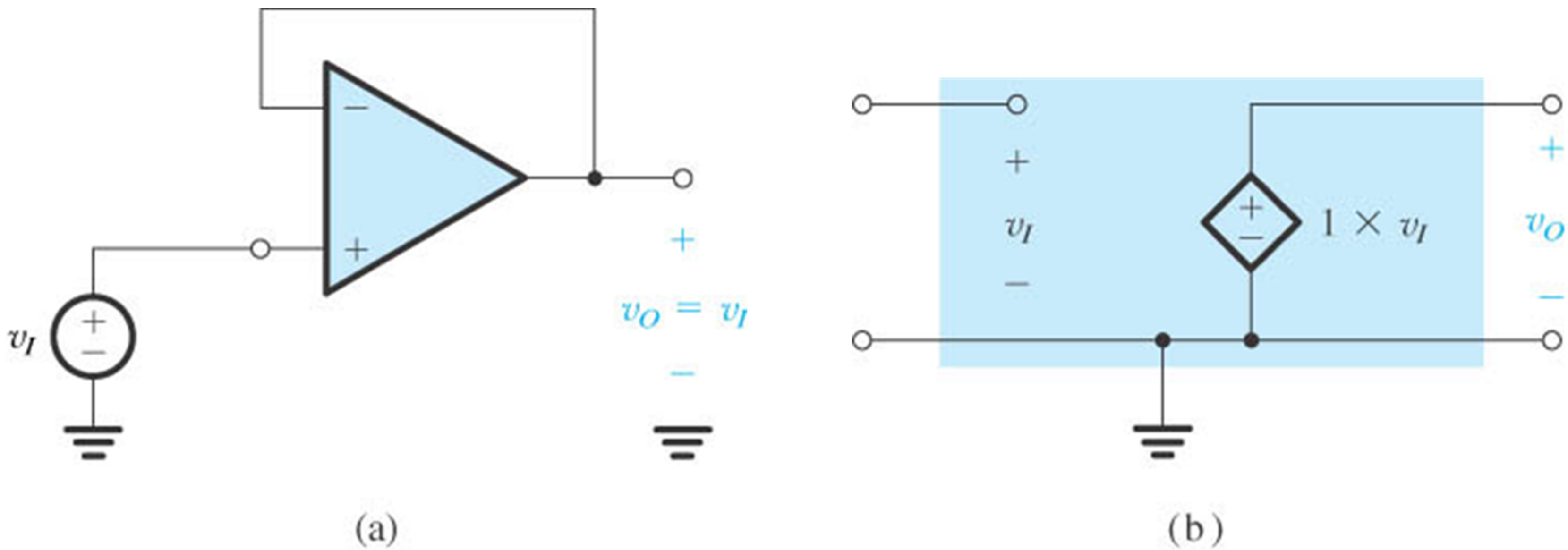
The Buffer Stage

$$If\ \ R_F \to 0,\ \ G = 1 + \frac{R_F}{R_a} \to 1$$



Although voltage gain is low, current gain can be quite high. Buffer stage can be used to interface between processors and switches.

The Voltage Follower



- Unity gain amplifier
- 100% negative feedback

$$R_{in} = \infty$$

$$R_{out} = 0$$