EE105
Microelectronic Devices and Circuits

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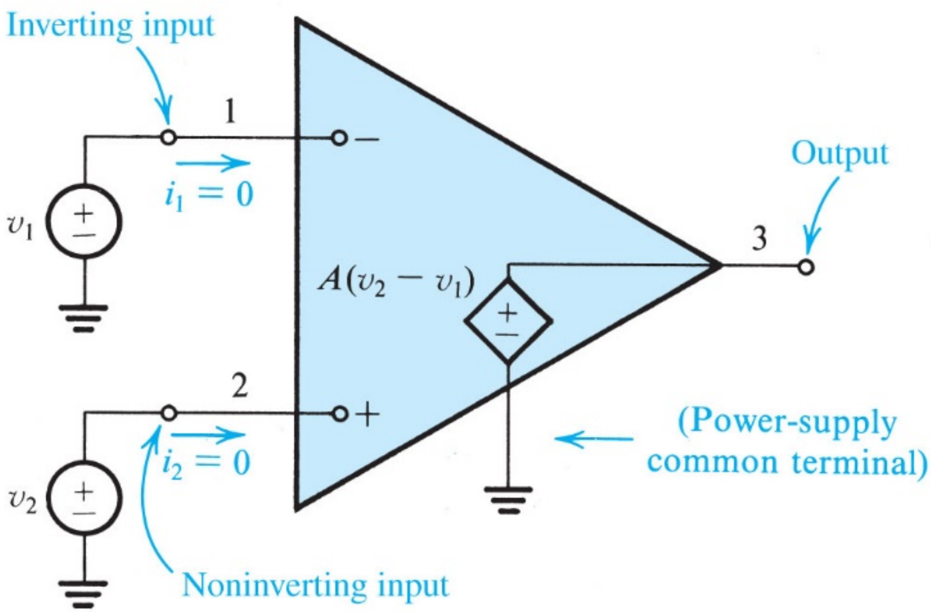
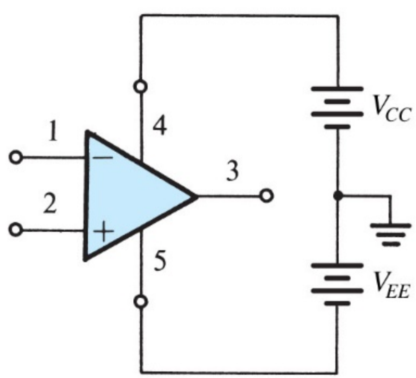
Ideal Op Amp



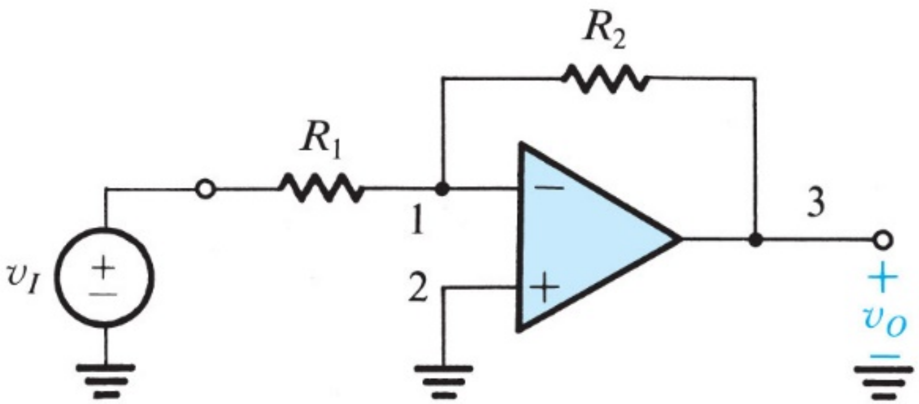
- **Infinite open-loop gain, $A = \infty$**
- **Infinite input impedance**
  - **No current goes in**
- **Zero output impedance**
- **$V_- = V_+$ with feedback circuit**

- **Infinite bandwidth**
- **Infinite common-mode rejection**

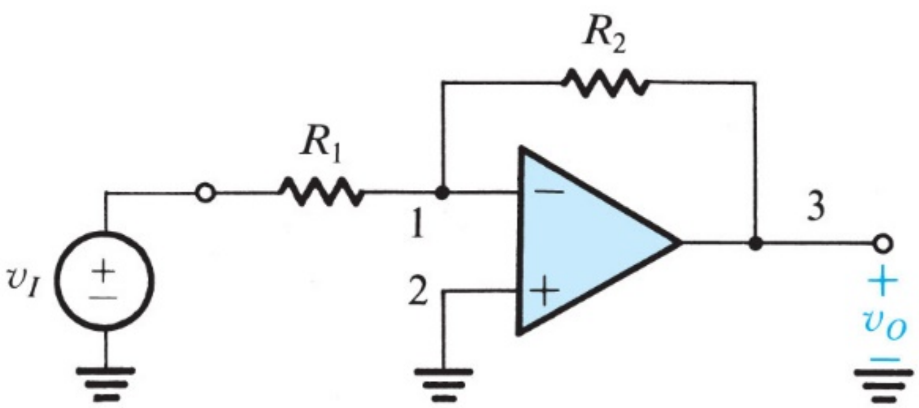
Op-Amp with dc bias



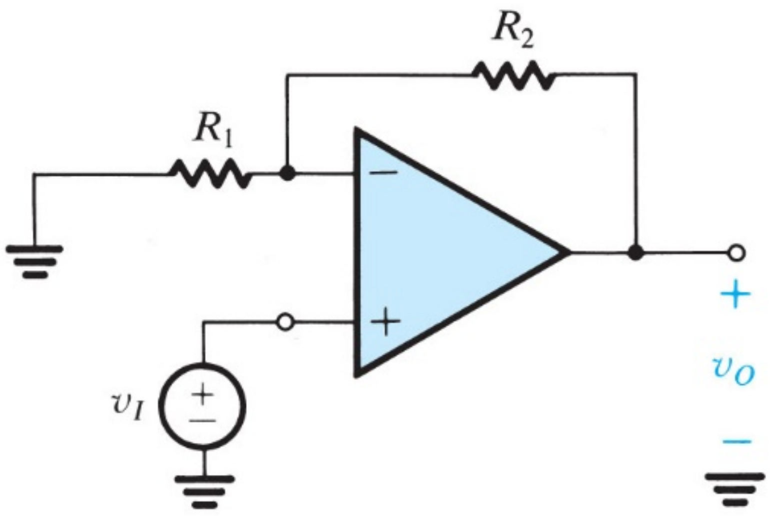
Inverting Amplifier



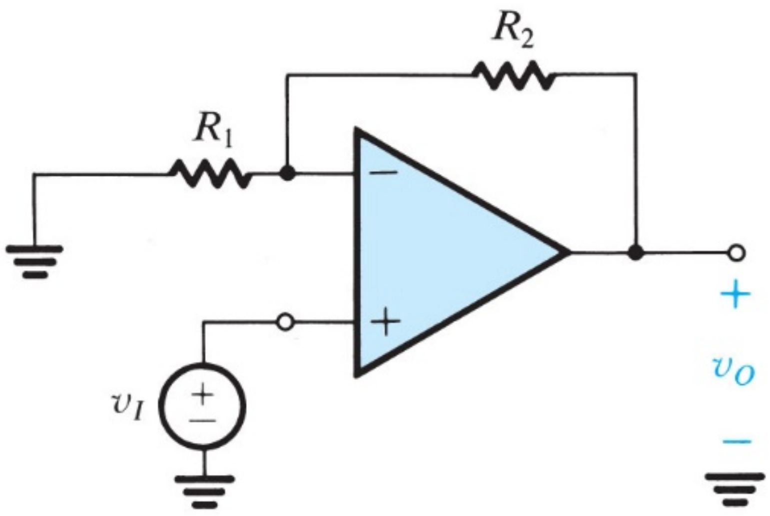
Inverting Amplifier: Input and Output Resistances



Non-Inverting Amplifier



Non-Inverting Amplifier: Input and Output Resistances



Practical Op-Amps

- **Linear Imperfections:**
  - **Finite open-loop gain ($A_0 < \infty$)**
  - **Finite input resistance ($R_i < \infty$)**
  - **Non-zero output resistance ($R_o > 0$)**
  - **Finite bandwidth / Gain-BW Trade-off**

- **Other (non-linear) imperfections:**
  - **Slew rate limitations**
  - **Finite swing**
  - **Offset voltage**
  - **Input bias and offset currents**
  - **Noise and distortion**

Simple Model of Amplifier

- Input and output capacitances are added
- Any amplifier has input capacitance due to transistors and packaging / board parasitics
- Output capacitance is usually dominated by load
  - Driving cables or a board trace

Transfer Function

- **Using the concept of impedance, it's easy to derive the transfer function**

Operational Transconductance Amp

- **Also known as an "OTA"**
  - **If we "chop off" the output stage of an op-amp, we get an OTA**
- **An OTA is essentially a G_m amplifier. It has a current output, so if we want to drive a load resistor, we need an output stage (buffer)**
- **Many op-amps are internally constructed from an OTA + buffer**

Op-Amp Model

- The model closely resembles the insides of an op-amp
- The input OTA stage drives a high Z node to generate a very large voltage gain
- The output buffer then can drive a low impedance load and preserve the high voltage gain

Op-Amp Gain / Bandwidth

- **The dominant frequency response of the op-amp is due to the time constant formed at the high-Z node**

$$G = G_m R_x$$

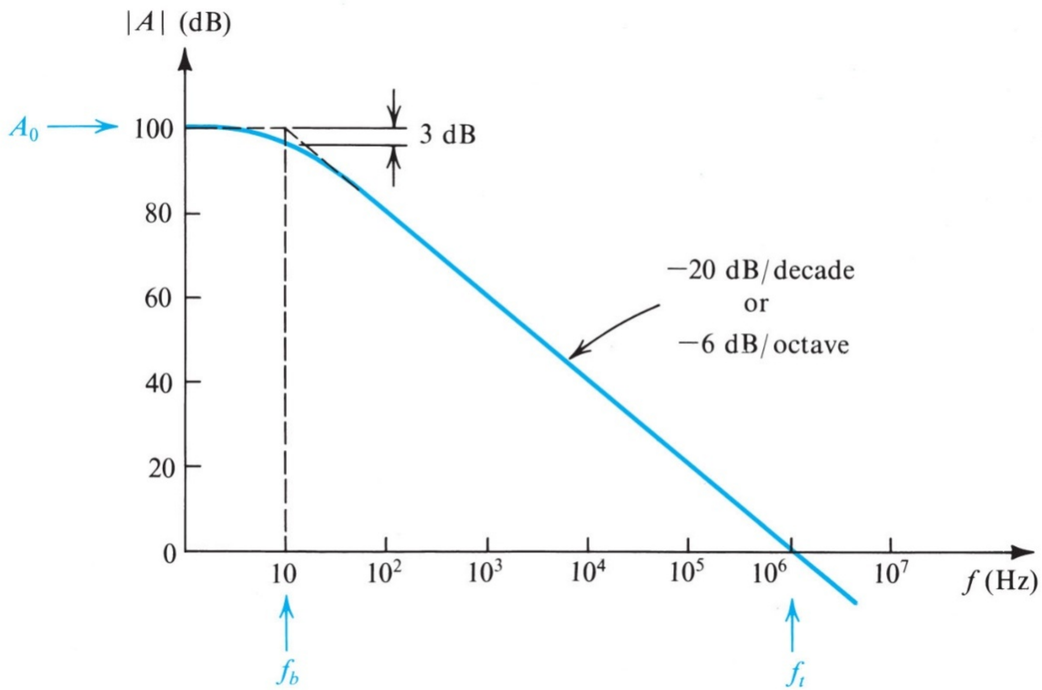
$$\omega_{3dB} = \omega_b = \frac{1}{R_x C_x}$$

- **An interesting observation is that the gain-bandwidth product depends on G_m and C_x only**

$$G \times \omega_{3dB} = G_m R_x \frac{1}{R_x C_x} = \frac{G_m}{C_x}$$

Gain-Bandwidth Trade-off

Frequency Response of Open-Loop Op Amp



$$A(j\omega) = \frac{A_0}{1 + j\omega / \omega_b}$$

A_0 : dc gain

ω_b : 3dB frequency

$\omega_t = A_0 \omega_b$: unity-gain bandwidth

(or "gain-bandwidth product")

For high frequency, $\omega >> \omega_b$

$$A(j\omega) = \frac{\omega_t}{j\omega}$$

Single pole response with a dominant pole at ω_b

Bandwidth Extension with Feedback

- **Overall transfer function with feedback:**

$$v_o = A(j\omega)(v_i - \beta v_o); \qquad A(j\omega) = \frac{A_o}{1 + j\dfrac{\omega}{\omega_b}}$$

Bandwidth Extension and Gain Reduction

- **Bandwidth increase:**

$$BW = (1 + A_o\beta)\omega_b$$

- **Gain reduces:**

$$G = \frac{A_o}{1 + A_o\beta}$$

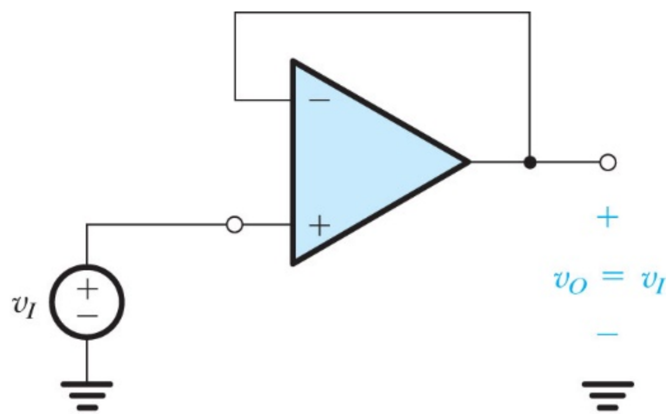
- **Gain-Bandwidth Product remains constant:**

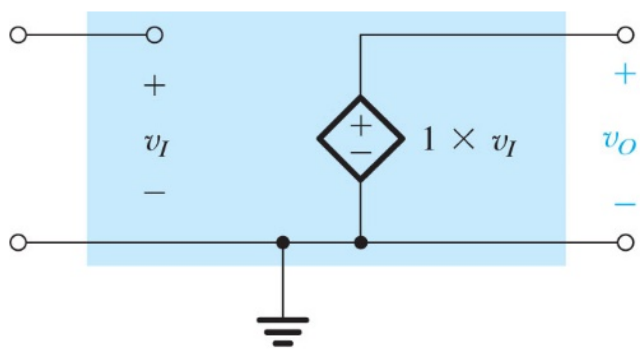
$$G \times BW = A_o\omega_b$$

Gain – Bandwidth Trade-off

Unity Gain Feedback Amplifier

- **An amplifier that has a feedback factor β = 1, such as a unity gain buffer, has the full GBW product frequency range**

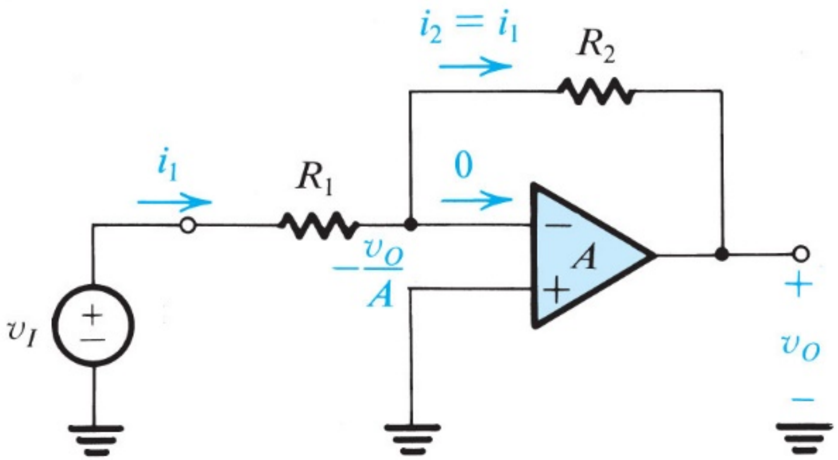




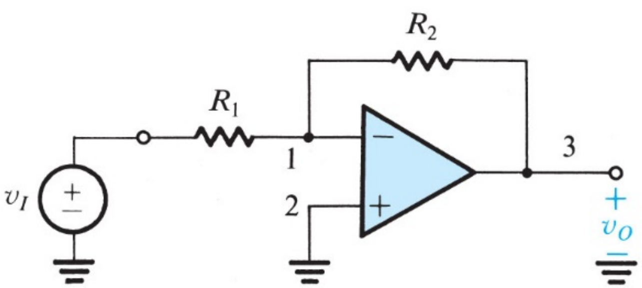
$$G = \frac{A_o}{1 + A_o\beta} = \frac{A_o}{1 + A_o} \approx 1$$

$$BW = (1 + A_o\beta)\omega_b = (1 + A_o)\omega_b \approx A_o\omega_b$$

Voltage Gain of Inverting Amplifier with Finite Open-Loop Gain



Frequency Response of Closed-Loop Op Amp



Steps to find frequency response of closed-loop amplifiers:

1. Find the transfer function with finite open-loop gain. For example, for inverting amplifier:

$$G = \frac{v_o}{v_I} = \left(-\frac{R_2}{R_1}\right)\frac{1}{1+\dfrac{(1+R_2/R_1)}{A}}$$

2. Substitute A with $A(j\omega) = \dfrac{A_0}{1+j\omega/\omega_b}$

3. Simplify the expression

$$G(\omega) = \left(-\frac{R_2}{R_1}\right)\frac{1}{1+(1+R_2/R_1)\dfrac{1+j\omega/\omega_b}{A_0}}$$

$$= \left(-\frac{R_2}{R_1}\right)\frac{1}{1+\dfrac{(1+R_2/R_1)}{A_0}+\dfrac{j\omega}{\left(\dfrac{A_0\omega_b}{1+R_2/R_1}\right)}}$$

Frequency Response of Closed-Loop Inverting Amplifier Example

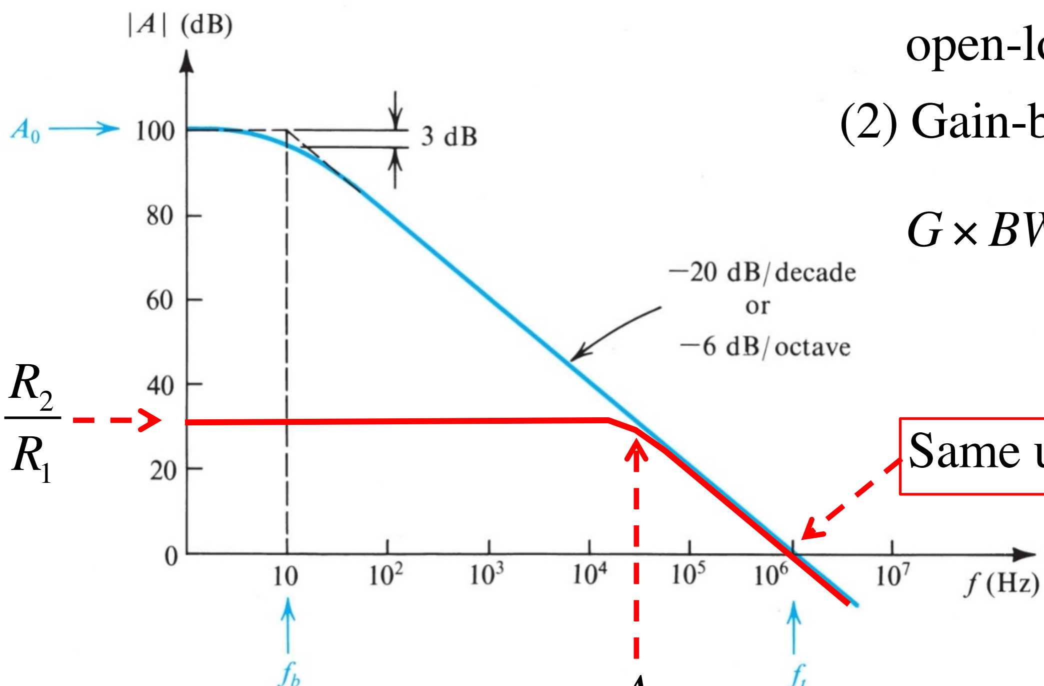
$$G(\omega) \approx \left(-\frac{R_2}{R_1}\right)\frac{1}{1+\dfrac{j\omega}{\omega_{3dB}}} \qquad \text{where } \omega_{3dB} = \frac{A_0\omega_b}{1+R_2/R_1}$$

Note:

(1) 3-dB frequency is higher than open-loop bandwidth, ω_b

(2) Gain-bandwidth product remains unchanged:

$$G \times BW = \frac{R_2}{R_1}\frac{A_0\omega_b}{1+R_2/R_1} \approx \frac{R_2}{R_1}\frac{A_0\omega_b}{R_2/R_1} = A_0\omega_b = \omega_t$$



Same unity-gain frequency: f_t

$$f_{3dB} \approx \frac{A_0}{R_2/R_1} f_b$$