EE105 – Fall 2015
Microelectronic Devices and Circuits

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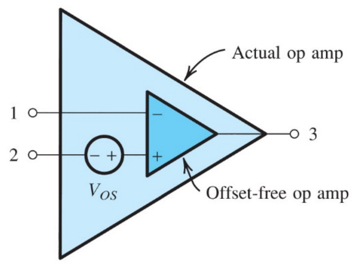
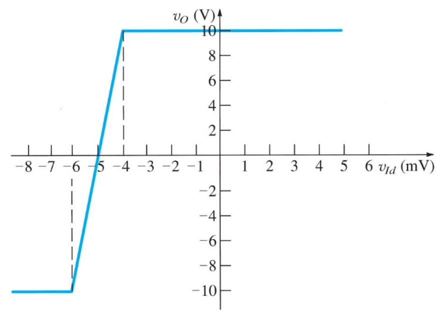
Imperfections in Practical Op-Amps

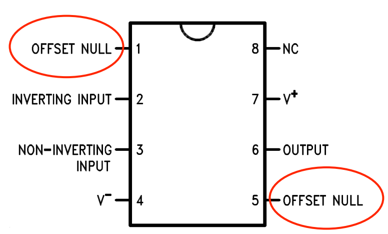
- **Finite open-loop gain ($A_0 < \infty$)**
- **Finite input resistance ($R_i < \infty$)**
- **Non-zero output resistance ($R_o > 0$)**
- **Finite bandwidth**
- **Offset voltage**
- **Input bias and offset currents**

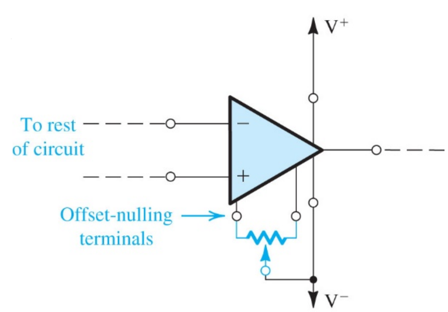
Offset Voltage

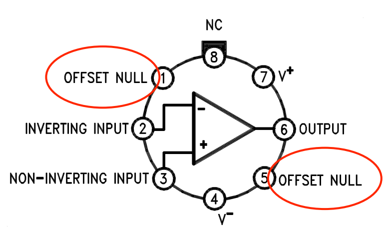




Trimming of Offset Voltage

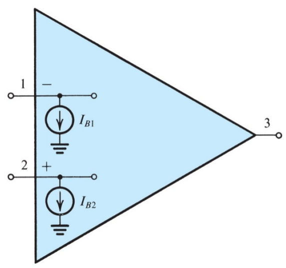






The output dc offset voltage of an op amp can be trimmed to zero by connecting a potentiometer to the two offset-nulling terminals. The wiper of the potentiometer is connected to the negative supply of the op amp.

Input Bias Currents and Offset Currents



The input terminals need to be supplied with bias currents, I_{B1} and I_{B2}, for Op Amp to function. (This will become clear towards the end of the semester).

Input bias current: $I_B = \dfrac{I_{B1} + I_{B2}}{2}$

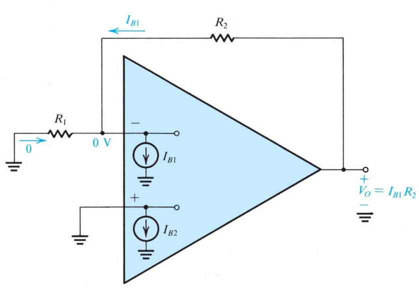
Input offset current: $I_{OS} = |I_{B1} - I_{B2}|$

Typical bipolar transistor Op amps:

$I_B \sim 100$ nA

$I_{OS} \sim 10$ nA

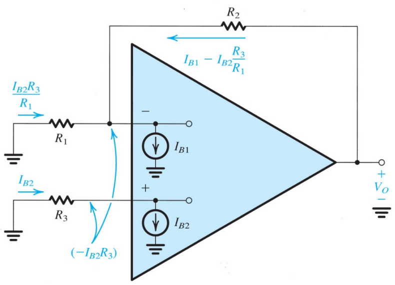
Effect of Input Bias Current in Amplifier Circuit



In the absence of input voltage, the output should be zero for ideal Op Amp. However, with non-zero I_B,

$$V_O = I_{B1}R_2 \approx I_B R_2$$

Reducing the Effect of Input Bias Currents



$$V_O = -I_{B2}R_3 + R_2\left(I_{B1} - \frac{I_{B2}R_3}{R_1}\right)$$

First approximate $I_{B1} = I_{B2} = I_B$

$$V_O = -I_B R_3 + I_B R_2 - \frac{I_B R_3}{R_1}R_2 = I_B\left(R_2 - R_3\left(1 + \frac{R_2}{R_1}\right)\right)$$

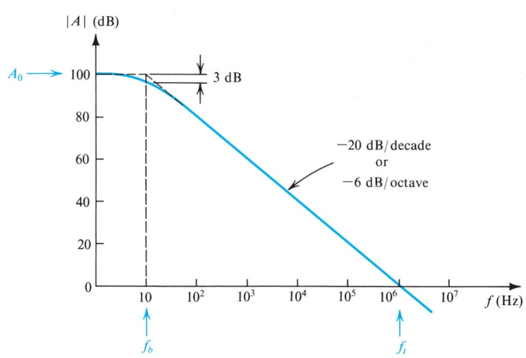
Choose $R_3 = \dfrac{R_2}{1 + \dfrac{R_2}{R_1}}$, $V_O = 0$

Now consider $I_{B1} = I_B + \dfrac{I_{OS}}{2}$

and $I_{B2} = I_B - \dfrac{I_{OS}}{2}$

$$V_O = I_{OS}R_2$$

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

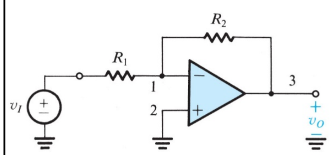
$\omega_t = A_0\omega_b$: unity-gain bandwidth (or "gain-bandwidth product")

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

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

Single pole response with a dominant pole at ω_b

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

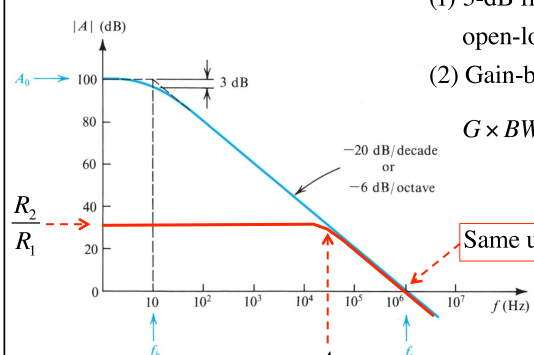
$$G(\omega) \approx \left(-\frac{R_2}{R_1}\right)\frac{1}{1+\dfrac{j\omega}{\omega_{3dB}}} \quad \text{where } \omega_{3dB} = \frac{A_0\omega_b}{1+R_2/R_1}$$

Note:

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

(2) Gain-bandwidth product remains unchanged:

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

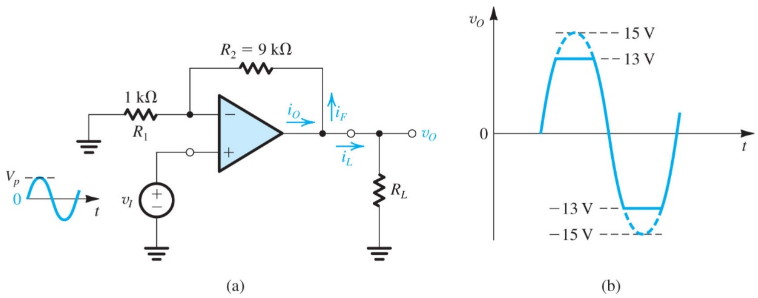


Same unity-gain frequency: f_t

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

Output Saturation

- **The output voltage swing is limited by**
  1. **Saturation voltage (usually a volt or two lower than power supply voltage)**
  2. **Maximum output current (in case of small load resistance)**
- **Output waveform appears to be "clipped" when either condition happens**



Slew Rate

Amplifier output is limited by "slew rate": maxium rate of change possible at output

$$SR = \left.\frac{dv_o}{dt}\right|_{\max}$$

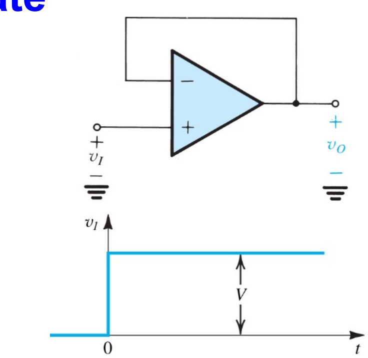
SR is specified in datasheet in V/μs.

Note

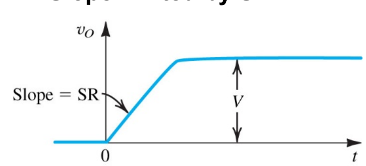
SR limit is different from bandwidth limit:

• Limited bandwidth is a linear phenomenon, it does not change the shape of input sinusoid

• SR limitation can cause nonlinear distortion to input sinusoidal signal



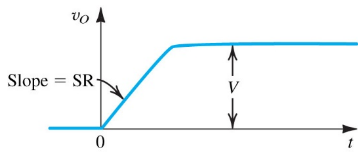
Output not able to follow input; Slope limited by SR



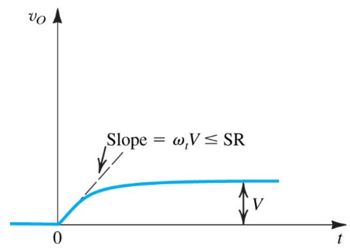
(c)

Comparison of Slew Rate and Bandwidth Limits

For step function input waveform, both SR and bandwidth limits cause the output to rise with a finite slope, but there is an important difference:



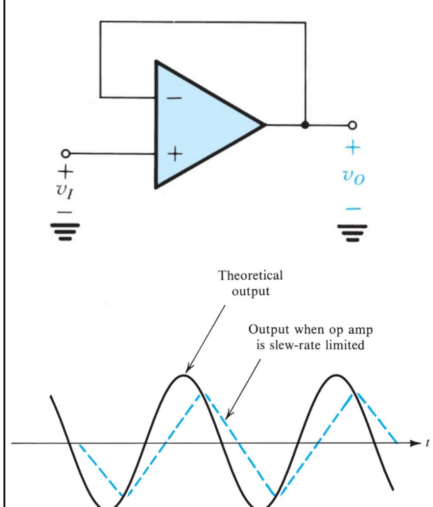
Slew rate limited output:
Slope = SR



Bandwidth limited output:
Slope = ω_tV < SR
(V is the steady state output voltage)

BSAC

Full-Power Bandwidth



For sinusoidal input to unity-gain follower:

$v_I = V_i \sin \omega t$

Rate of change:

$$\frac{dv_I}{dt} = V_i \omega \cos \omega t \le \text{ SR}$$

Full-power bandwidth:

The frequency at which SR-limited distortion starts to occur for an output sinusoid with maximum rated output voltage, $V_{o\max}$,

$$\omega_M V_{o\max} = SR$$

$$f_M = \frac{SR}{2\pi V_{o\max}}$$

BSAC