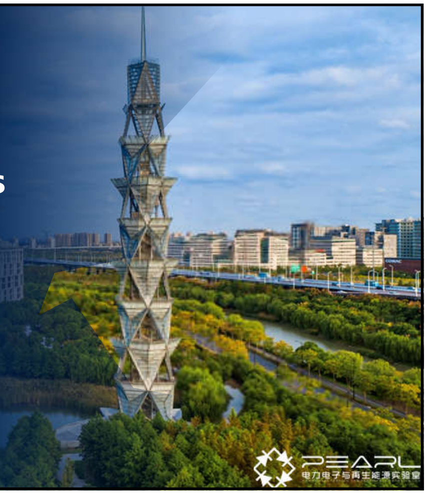

EE115 Analog Circuits
OP AMP Basics

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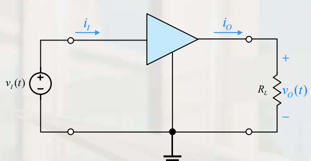
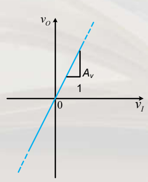
Outline

- OP AMP Basics
  - Amplifiers
  - Circuit Models for Amplifiers
  - Frequency Response of Amplifiers
- Reading: Sedra/Smith Book Pages 16-45

Amplifier Gain





- Voltage Gain:

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

- Current Gain:

$$A_i = \frac{i_o}{i_I}$$

- Power Gain:

$$A_p = \frac{p_L}{p_I} = \frac{v_o i_o}{v_I i_I} = A_v A_i$$

- Note: A_v and A_i can be **positive**, **negative**, or even **complex** numbers. Nagative gain means the output is 180° out of phase with input. However, A_p should always be **positive**.
- Gain is usually expressed in **Decibel (dB)**

$$A_p(dB) = 10\log|A_p|$$

$$A_v(dB) = 10\log|A_v|^2 = 20\log|A_v|$$

$$A_v(dB) = 10\log|A_i|^2 = 20\log|A_i|$$

Amplifier Power Supply and Dissipation

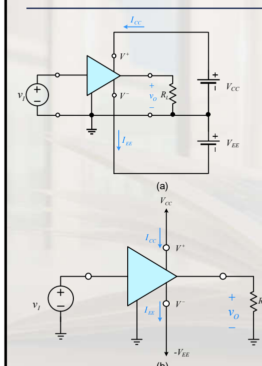


Fig. An amplifier with dual dc supplies.

- Circuit needs dc **power supplies** to function
- Typical power supplies are denoted as V_{CC} (or V_{DD})and $-V_{EE}$ (or V_{SS})
- Total **dc power dissipation**

$$P_{dc} = V_{CC}I_{CC} + V_{EE}I_{EE}$$

- Power balance

$$P_{dc} + P_I = P_L + P_{diss}$$

  - P_I: power drawn from signal source
  - P_L: power delivered to the load
  - P_{diss}: power dissipated in the amplifier circuit
- Power efficiency

$$\eta = \frac{P_L}{P_{dc}}$$

  - Important for power amplifiers: stereo output, transmitters

Amplifier Power Supply and Dissipation

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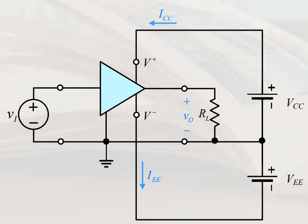
- A microphone outputs a 0.4 V peak sinusoidal signal and delivers 100 μA peak to an amplifier powered by ±1V supplies. The amplifier drives a 32 Ω speaker with a 0.8 V peak output and draws 30 mA from each supply.
- Find：Voltage gain; current gain; power gain; DC power supplied; power dissipation; and efficiency.



Solution:

$A_v = \frac{0.8V}{0.4V} = 2V/V$, or $A_v = 20\log 2 = 6$ dB

$\hat{I}_o = \frac{0.8V}{32\Omega} = 25$ mA

$A_i = \frac{\hat{I}_o}{\hat{I}_i} = \frac{25\text{ mA}}{0.1\text{ mA}} = 250$ A/A, or A_i
$= 20\log 250 = 47.9$ dB

$P_L = V_{Orms} I_{Orms} = \frac{0.8\text{ V}}{\sqrt{2}} \frac{25\text{ mA}}{\sqrt{2}} = 10$ mW

$P_I = V_{irms} I_{irms} = \frac{0.4\text{ V}}{\sqrt{2}} \frac{0.1\text{ mA}}{\sqrt{2}} = 20\ \mu$W

$A_p = \frac{P_L}{P_I} = \frac{10\text{ mW}}{20\ \mu\text{W}} = 500$ W/W, or A_p
$= 10\log 500 = 29.9$dB

$P_{dc} = 1V \times 30\text{ mA} + 1V \times 30\text{ mA} = 60$ mW

$P_{dissipated} = P_{dc} + P_I - P_L$
$= 60\text{ mW} + 0.02\text{ mW} - 10\text{ mW} \simeq 50$ mW

$\eta = \frac{P_L}{P_{dc}} \times 100 = 16.7\%$

Linear Range vs. Saturation Range

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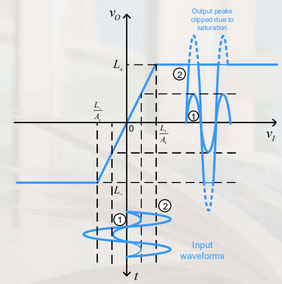

Fig. Typical amplifier transfer characteristics.

- **Within** linear range, the output voltage (or current) is **proportional** to the input voltage (or current)
- **Beyond** linear range, the output voltage (or current) waveforms **saturates**, resulting in distortions
  - Lose fidelity in stereo system

Symbol Notation

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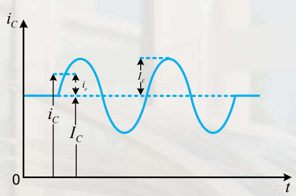

Fig. Symbol notation convention

$$i_C(t) = I_C + i_c(t)$$

where

- $i_C(t)$: Lowercase-uppercase→ **total** current
- I_C: Uppercase-uppercase→ **dc** current
- $i_c(t)$: Lowercase-lowercase → **small signal ac** current

$$i_c = I_c \sin(\omega t)$$

where,

- I_c : Uppercase-lowercase→ **amplitude** of ac current (sinwave)

Circuit Model of Voltage Amplifiers

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(Two-Port Model)

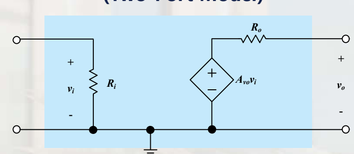


Fig. Circuit model for the voltage amplifier.

- A_{vo}: open-circuit voltage gain
- R_i: input resistance
- R_o: output resistance
- R_s: source resistance
- R_L: load resistance

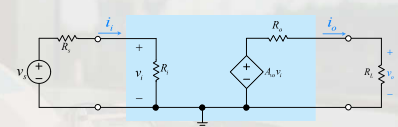


Fig. Voltage amplifier with input signal source and load.

For ideal op-amp, why we prefer large R_i and Small R_o?

Cascaded Amplifier

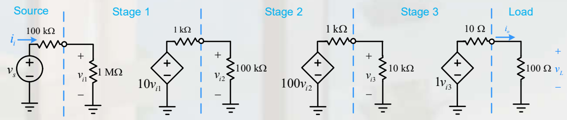
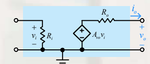
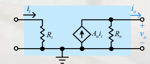
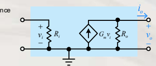
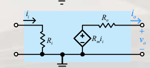


Fig. Three-stage amplifier

- For most practical applications, multiple stages of amplifiers are cascaded to
  - Provide sufficient **gain**
  - Provide adequate input and output **resistances/impedances**
- For example, in a voltage amplifier
  - The **input stage** is designed to have **high input impedance**
  - The **output stage** is designed to have **low output impedance**
  - **Middle stage** provides the necessary **gain**

Amplifier Types

Table The Four Amplifier Types

Type	Circuit Model	Gain Parameter	Ideal Characteristics
Voltage Amplifier		Open-Circuit Voltage Gain $A_{vo} \equiv \left.\frac{v_o}{v_i}\right\|_{i_o=0}$ (V/V)	$R_i = \infty$ $R_o = 0$
Current Amplifier		Short-Circuit Current Gain $A_{is} \equiv \left.\frac{i_o}{i_i}\right\|_{v_o=0}$ (A/A)	$R_i = 0$ $R_o = \infty$
Transconductance Amplifier		Short-Circuit Transconductance $G_m \equiv \left.\frac{i_o}{v_i}\right\|_{v_o=0}$ (A/V)	$R_i = \infty$ $R_o = \infty$
Transresistance Amplifier		Open-Circuit Transresistance $R_m \equiv \left.\frac{v_o}{i_i}\right\|_{i_o=0}$ (V/A)	$R_i = 0$ $R_o = 0$

- Depending on the nature of the source signals and output loads, different types of amplifiers are needed:
  - **Voltage** amplifier
  - **Current** amplifier
  - **Transconductance** amplifier
    - Voltage to current
  - **Transimpedance** amplifier
    - Current to voltage

Amplifier Frequency Response

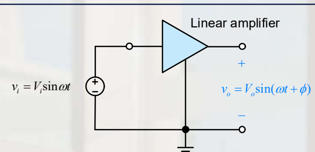


Fig. Measuring the frequency response of a linear amplifier

- When a sinusoidal signal is applied to a linear amplifier, the output is sinusoidal:
  - With **identical frequency** as input
  - But **different amplitude** and **phase**
- **Transfer function:** $T(\omega)=V_o(\omega)/V_i(\omega)$
- Amplitude response $|T(\omega)|=V_o/V_i$
- Phase response $\angle T(\omega)=\phi$

Frequency Response

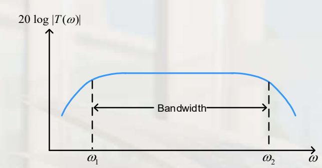


Fig. Typical magnitude response of an amplifier.

- **Bode Plot: log-log** plot of the **transfer function** vs. **angular frequency**, ω
  - Vertical axis: $20\log|T(\omega)|$
  - Horizontal axis: $10\log\omega$
- **Bandwidth**
  - Band of frequencies over which the gain response falls by **3dB**

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Frequency Response of Low-Pass Filters

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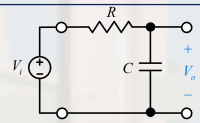

Fig. a low-pass network.

- Transfer function:

$$T(\omega) = \frac{1/(j\omega C)}{R + 1/(j\omega C)} = \frac{1}{1 + j\omega RC} = \frac{1}{1 + j\omega/\omega_o}$$

where $\omega_o = \frac{1}{RC}$

$$|T(\omega)| = \frac{1}{\sqrt{1 + (\omega/\omega_0)^2}}$$

$$\angle T(\omega) = -\tan^{-1}(\omega/\omega_0)$$

$$\omega_{3dB} = \omega_0$$

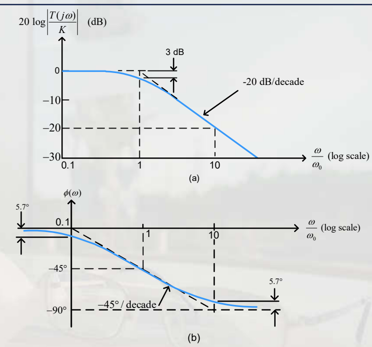

Fig. (a) Magnitude and **(b)** phase response of STC networks of the low-pass type.

Frequency Response of High-Pass Filters

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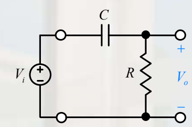

Fig. A high-pass network.

- Transfer function:

$$T(\omega) = \frac{R}{R + 1/(j\omega C)} = \frac{1}{1 + 1/(j\omega RC)}$$

$$= \frac{1}{1 - j\omega_o/\omega}$$

Where, $\omega_o = \frac{1}{RC}$

$$|T(\omega)| = \frac{1}{\sqrt{1 + (\omega_0/\omega)^2}}$$

$$\angle T(\omega) = \tan^{-1}(\omega_0/\omega)$$

$$\omega_{3dB} = \omega_0$$

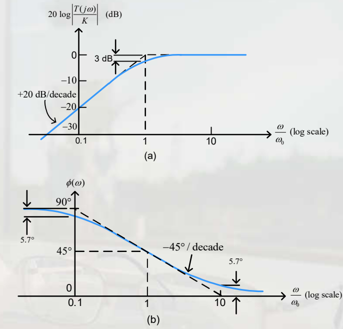

Fig. (a) Magnitude and **(b)** phase response of STC networks of the high-pass type.

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Example: Amplifier Frequency Response

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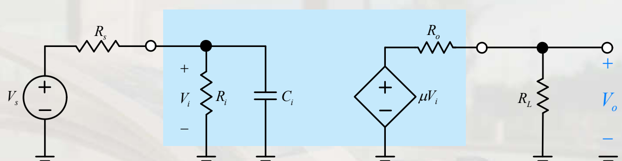
Given a voltage amplifier (input resistance R_i, input capacitance C_i, gain μ, output resistance R_o) driven by a source V_s with resistance R_s. A load R_L is connected to the output.



Solution(a): Amplifier Frequency Response

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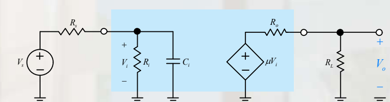
- (a) Derive V_o/V_s as a function of frequency. Find dc gain and 3-dB frequency.



Solution:

(a)

$$V_i = V_s \frac{Z_i}{Z_i + R_s}$$

$$V_i = V_s \frac{1}{1 + R_s Y_i} = V_s \frac{1}{1 + R_s[(1/R_i) + sC_i]}$$

$$\Rightarrow \frac{V_i}{V_s} = \frac{1}{1 + (R_s/R_i) + sC_i R_s}$$

$$\frac{V_i}{V_s} = \frac{1}{1 + (R_s/R_i)} \cdot \frac{1}{1 + sC_i/\left(\frac{1}{R_s} + \frac{1}{R_i}\right)}$$

$$= \frac{1}{1 + (R_s/R_i)} \cdot \frac{1}{1 + sC_i[(R_s R_i)/(R_s + R_i)]}$$

$$V_o = \mu V_i \frac{R_L}{R_L + R_o}$$

$$\frac{V_o}{V_s} = \mu \frac{1}{1 + (R_s/R_i)} \cdot \frac{1}{1 + (R_o/R_L)} \frac{1}{1 + sC_i[(R_s R_i)/(R_s + R_i)]}$$

$$\tau = C_i \frac{R_s R_i}{R_s + R_i} = C_i(R_s||R_i)$$

$$\boldsymbol{T(j\omega) \equiv \frac{V_o}{V_s}(s) = \frac{K}{1 + \left(\frac{s}{\omega_0}\right)}}$$

$$K \equiv \frac{V_o}{V_s}(s = 0) = \mu \frac{1}{1 + \left(\frac{R_s}{R_i}\right)} \frac{1}{1 + \left(\frac{R_o}{R_L}\right)}$$

$$\omega_0 = \frac{1}{\tau} = \frac{1}{C_i(R_s||R_i)}$$

Solution(b): Amplifier Frequency Response

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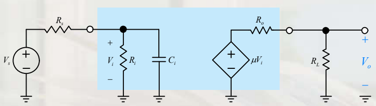
- (b) Given R_s = 20 kΩ, R_i = 100kΩ, C_i=60pF, μ = 144V/V, R_o = 200 Ω, and R_L = 1kΩ. Calculate the dc gain, and the 3-dB frequency.



$$K \equiv \frac{V_o}{V_s}(s=0) = \mu \frac{1}{1+\left(\frac{R_s}{R_i}\right)} \frac{1}{1+\left(\frac{R_o}{R_L}\right)}$$

$$\omega_0 = \frac{1}{\tau} = \frac{1}{C_i(R_s||R_i)}$$

Solution:

(b)

$$K = 144\frac{1}{1+(20/100)} \cdot \frac{1}{1+(200/1000)} = 100 \text{ V/V}$$

$$\omega_0 = \frac{1}{60 \text{ pF} \times (20 \text{ k}\Omega||100 \text{ k}\Omega)}$$

$$= \frac{1}{60\times10^{-12}\times[20\times100/(20+100)]\times10^3}$$

$$f_0 = \frac{10^6}{2\pi} = 159.2 \text{ kHz}$$

Solution(c): Amplifier Frequency Response

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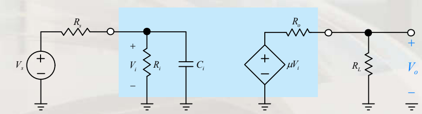
(c) Find $v_i(t)$ for each of the following inputs:

(i) $v_i = 0.1 \sin 10^2 t\ V$

(ii) $v_i = 0.1 \sin 10^5 t\ V$

(iii) $v_i = 0.1 \sin 10^6 t\ V$

(iv) $v_i = 0.1 \sin 10^8 t\ V$



Solution: (c)

$$T(j\omega) \equiv \frac{V_o}{V_s}(j\omega) = \frac{100}{1+j\left(\frac{\omega}{10^6}\right)}$$

(i) For $\omega=10^2$ rad/s,

$|T| \simeq 100$ and $\phi = -\tan^{-1}10^{-4} \simeq 0°$.

$v_o(t) = 10\sin 10^2 t V$

(ii) For $\omega=10^5$ rad/s,

$|T| = 99.5$ and $\phi = -\tan^{-1}0.1 = -5.7°$.

$v_o(t) = 9.95\sin(10^5 t - 5.7°)$V

(iii) For $\omega=10^6$ rad/s,

$|T| = 100/\sqrt{2}$=70.7 V/V or 37dB and $\phi = -45°$.

$v_o(t) = 7.07\sin(10^6 t - 45°)$V

(iv) For $\omega=10^8$ rad/s,

$|T| \simeq 1$ and $\phi = -\tan^{-1}100 = -89.4°$.

$v_o(t) = 0.1\sin(10^8 t - 89.4°)$V

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Typical Frequency Responses

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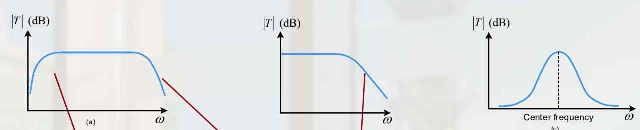

Fig. Frequency response for **(a)** a capacitively coupled amplifier, **(b)** a direct-coupled amplifier, **(c)** a tuned or bandpass amplifier.

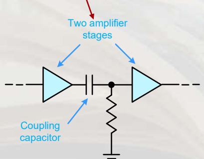

Fig. Use of a capacitor to couple amplifier stages.

High frequency cut-off due to **intrinsic capacitors** of the transistors

Low frequency roll-off due to **coupling capacitor**