MW 3-4p7 OH

EE 351 Electronics I
Spring Quarter 1992

Chapter I Introduction to electronics p1-45 Sections 1.4-1.6.

Goals: Signal amplifiers / linear amplifiers.

transducers: transforms signals into voltages or current.
voice → electrical signal (using microphones).
wall power supply: 120V (rms) → $120\sqrt{2}$ volts peak value.

1.4 Amplifiers.

- transducers provide signals that are weak. (μV, mV) and with little energy.
- Amplifiers must preserve the details of the signal waveform

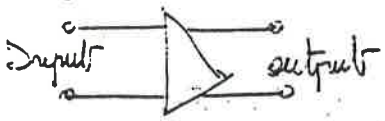
$$v_o(t) = A\, v_i(t)$$

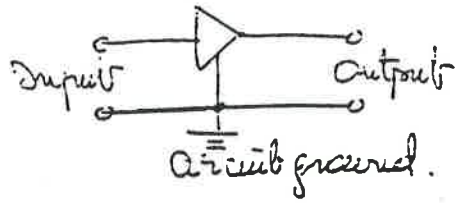
(linear) amplifier gain

If relation is not linear → distortion is said to be introduced in the signal.

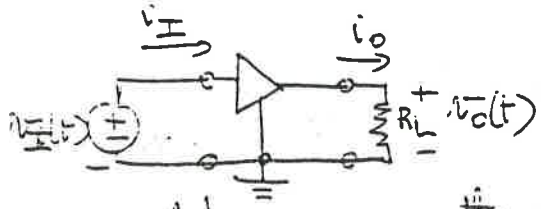
Power amplifier: provides only a modest amount of voltage gain but substantial current gain (home stereo system: you need enough power to drive the loudspeaker).

Amplifier Circuit Symbol two-port network.





Voltage Gain



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

Power Gain an amplifier increases the signal power, (contrary to a transformer for instance).

$$\boxed{\text{Power gain } (A_p) = \frac{\text{load power } (P_L)}{\text{input power } (P_I)}}$$

$$A_P = \frac{v_O i_O}{v_I i_I}$$

Current Gain : $(A_i) = \frac{i_O}{i_I}$

$$A_P = A_v A_i$$

For historical reasons

volt. gain in dB = $20 \log_{10} |A_v|$ dB

Cur. gain " " = $20 \log_{10} |A_i|$ dB

Power. " = $10 \log_{10} |A_P|$ dB

negative gain A_v means that there is a 180° phase difference between input and output signals.

Amplifier Power Supplies

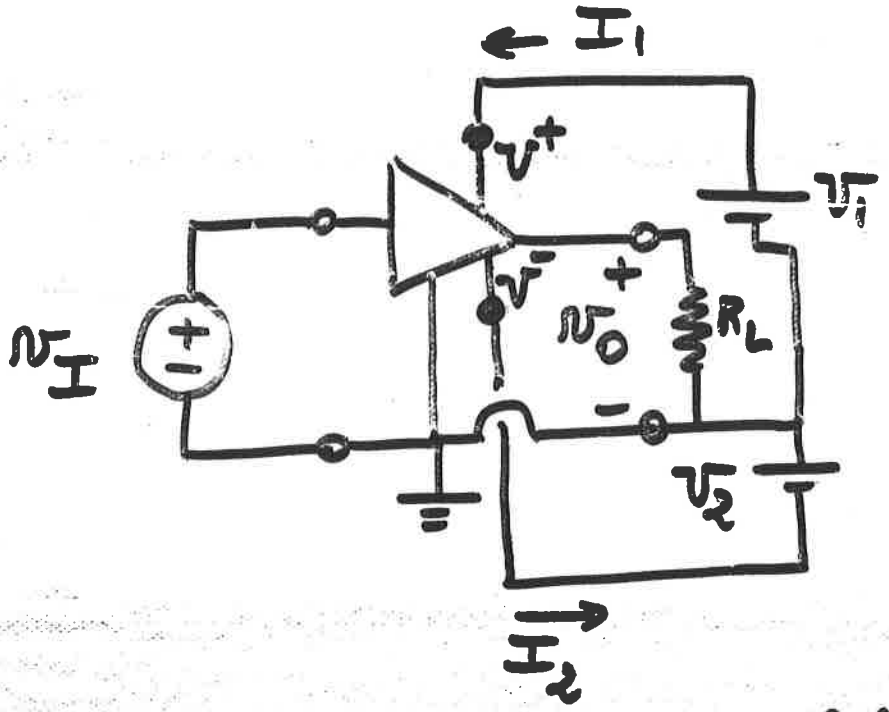
Power delivered to load is > power drawn from the signal.

Source of additional power? Amplifiers need DC power supplies.

AC signals (sine waves)

$$P_L = V_{rms} I_{rms} = \frac{V_{ampl}}{\sqrt{2}} \cdot \frac{I_{ampl}}{\sqrt{2}}$$

P_L^{out}, P_L^{in} → $\boxed{A_P = \frac{P_L}{P_I}}$



DC Power delivered to amplifier

$$P_{dc} = V_1 I_1 + V_2 I_2$$

$P_{dissipated}$ = Power dissipated in amplifier circuit.

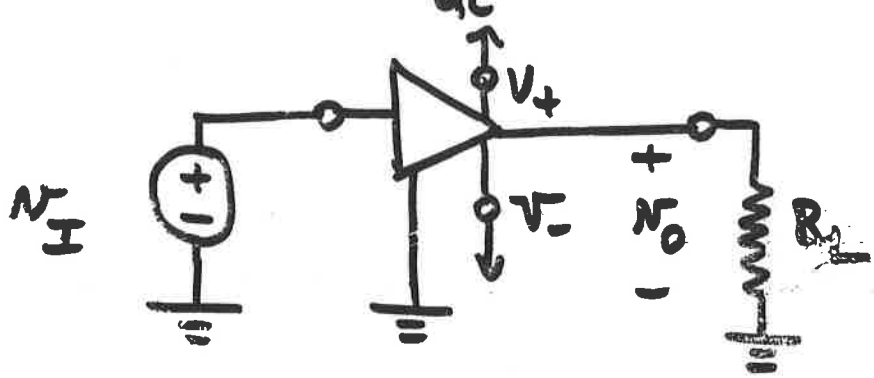
P_I = Power drawn from signal source

Balance Eq. $P_{dc} + P_I = P_L + P_{dissipated}$

usually small

to load

<u>Efficiency:</u> $\eta = \dfrac{P_L}{P_{dc}} \times 100$



work out Example 1.1 on page 13

EXAMPLE 1.1

Consider an amplifier operating from ±10-V power supplies. It is fed with a sinusoidal voltage having 1 V peak and delivers a sinusoidal voltage output of 9 V peak to a 1-kΩ load. The amplifier draws a current of 9.5 mA from each of its two power supplies. The input current of the amplifier is found to be sinusoidal with 0.1 mA peak. Find the voltage gain, the current gain, the power gain, the power drawn from the dc supplies, the power dissipated in the amplifier, and the amplifier efficiency.

Solution

$$A_v = \frac{9}{1} = 9 \text{ V/V}$$

or

$$A_v = 20 \log 9 \simeq 19.1 \text{ dB}$$

$$\hat{I}_o = \frac{9 \text{ V}}{1 \text{ k}\Omega} = 9 \text{ mA}$$

$$A_i = \frac{\hat{I}_o}{\hat{I}_i} = \frac{9}{0.1} = 90 \text{ A/A}$$

or

$$A_i = 20 \log 90 = 39.1 \text{ dB}$$

$$P_L = V_{o_{\text{rms}}} I_{o_{\text{rms}}} = \frac{9}{\sqrt{2}} \frac{9}{\sqrt{2}} = 40.5 \text{ mW}$$

$$P_I = V_{i_{\text{rms}}} I_{i_{\text{rms}}} = \frac{1}{\sqrt{2}} \frac{0.1}{\sqrt{2}} = 0.05 \text{ mW}$$

$$A_p = \frac{P_L}{P_I} = \frac{40.5}{0.05} = 810 \text{ W/W}$$

or

$$A_p = 10 \log 810 = 29.1 \text{ dB}$$

$$P_{\text{dc}} = 10 \times 9.5 + 10 \times 9.5 = 190 \text{ mW}$$

$$P_{\text{dissipated}} = P_{\text{dc}} + P_I - P_L$$

$$= 190 + 0.05 - 40.5 = 149.6 \text{ mW}$$

$$\eta = \frac{P_L}{P_{\text{dc}}} \times 100 = 21.3\%$$

Figure 1.11 A linear amplifier with output saturation.

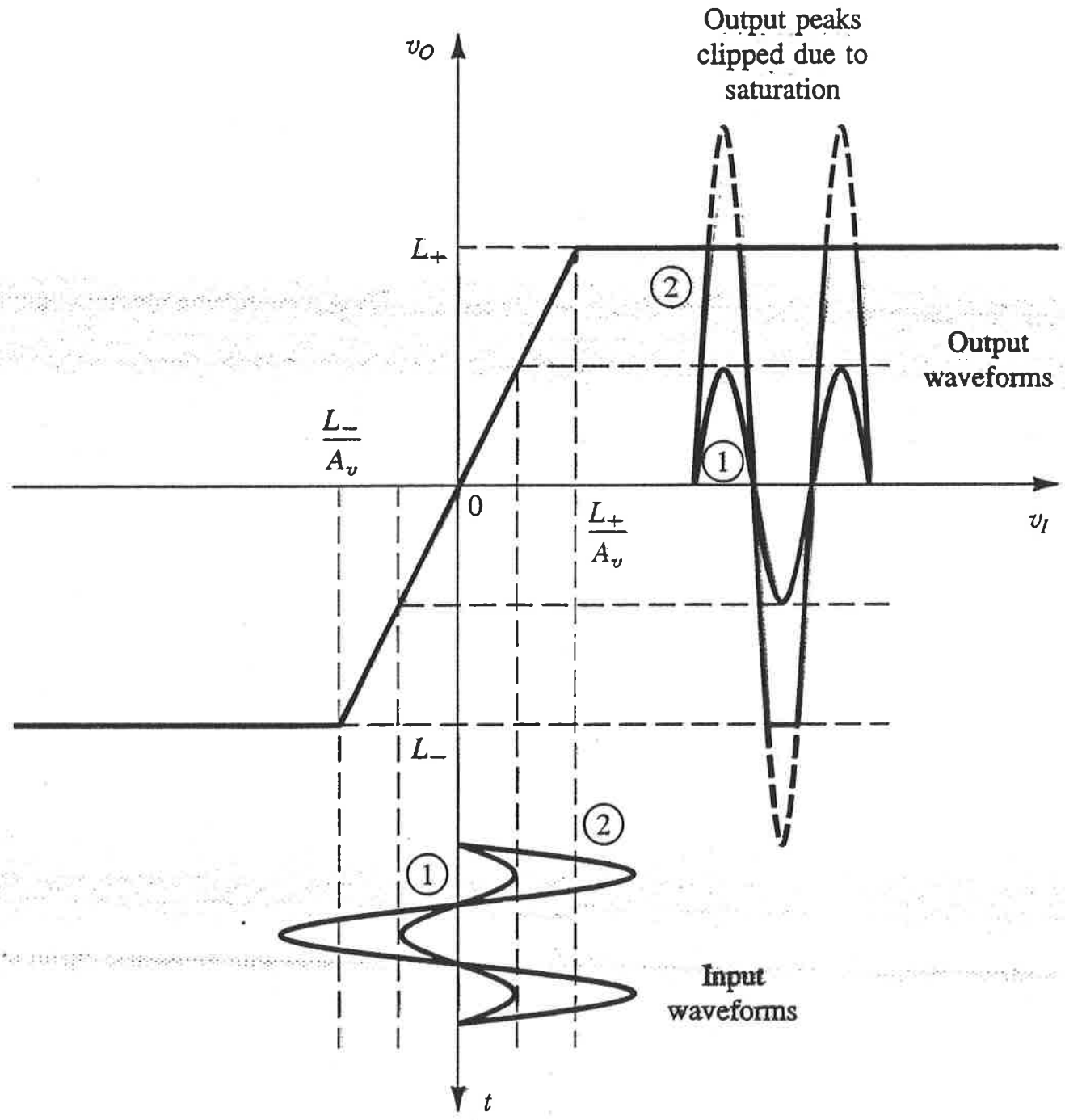


Fig. 1.11

Figure 1.12 Obtaining linear operation from a nonlinear amplifier.

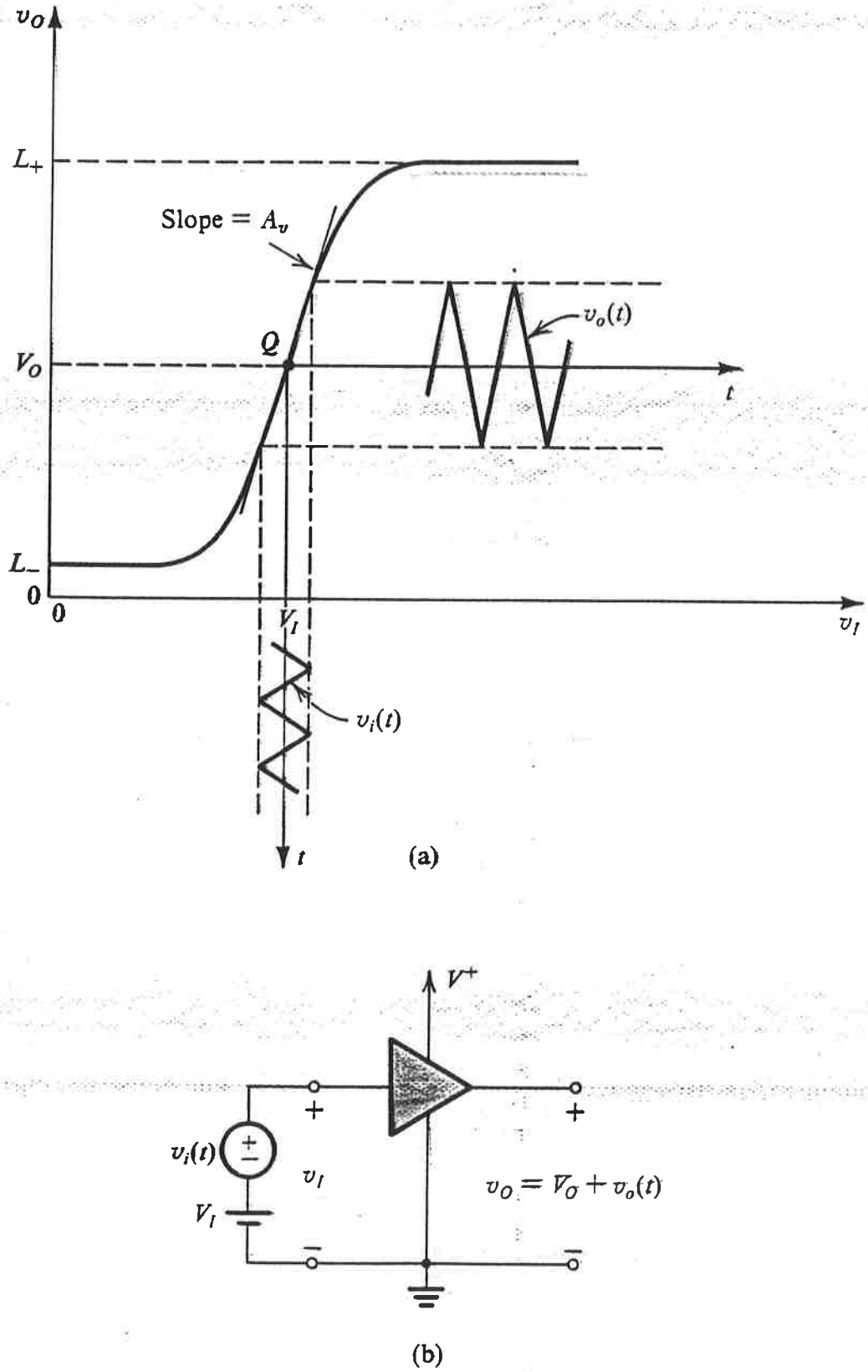
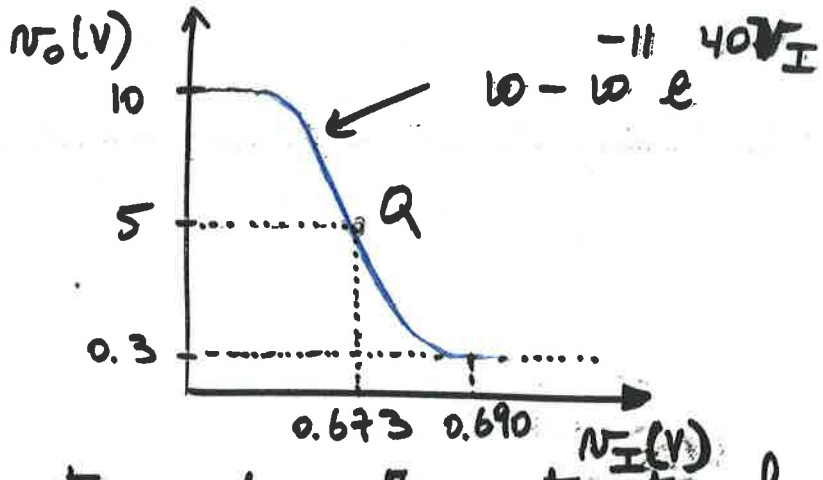


Fig. 1.12 (a)

Example: p. 12



L_+, L_-? (positive and negative saturation levels).
v_I? so that $v_O = 5V$ and voltage gain at the corresponding operating point.

$L_- = 0.3V \rightarrow v_I = 0.69V$

$L_+ = 10V \rightarrow v_I = 0V$

$v_O = 5V \rightarrow v_I = 0.673V$

$$\boxed{A_v = \left.\frac{dv_O}{dv_I}\right]_{v_I = 0.673V} = -200\,V/V}$$

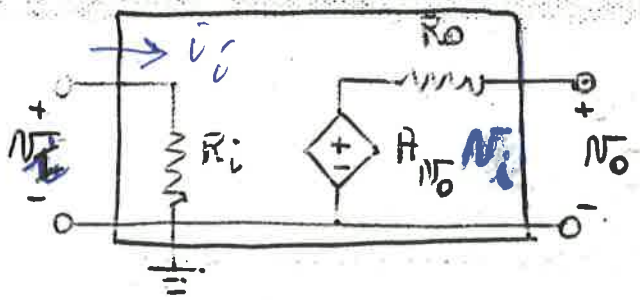
Notation:

Instantaneous quantities: $i_A(t)$, $v_C(t)$

Direct-current (DC) " : I_A, V_C

incremental signal quantities: $i_a(t)$, $v_c(t)$

§1.5 Circuit Model for Amplifiers

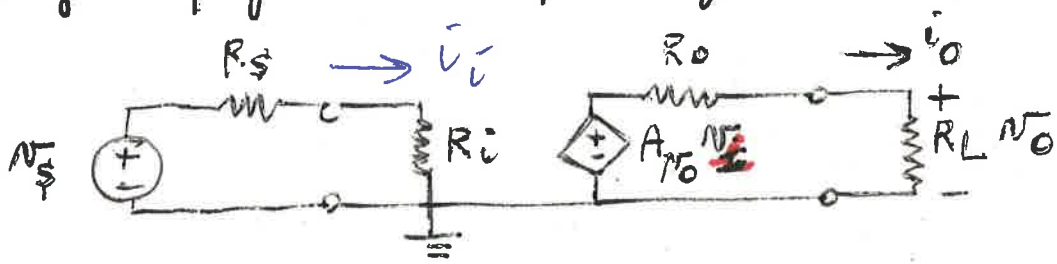


Circuit Model for Voltage Amplifier

$R_i \triangleq$ input resistance (amplifier draws input current from source)

$R_o \triangleq$ Output resistance (accounts for change in output voltage as the amplifier supplies output current to load)

Voltage amplifier with input signal source & load



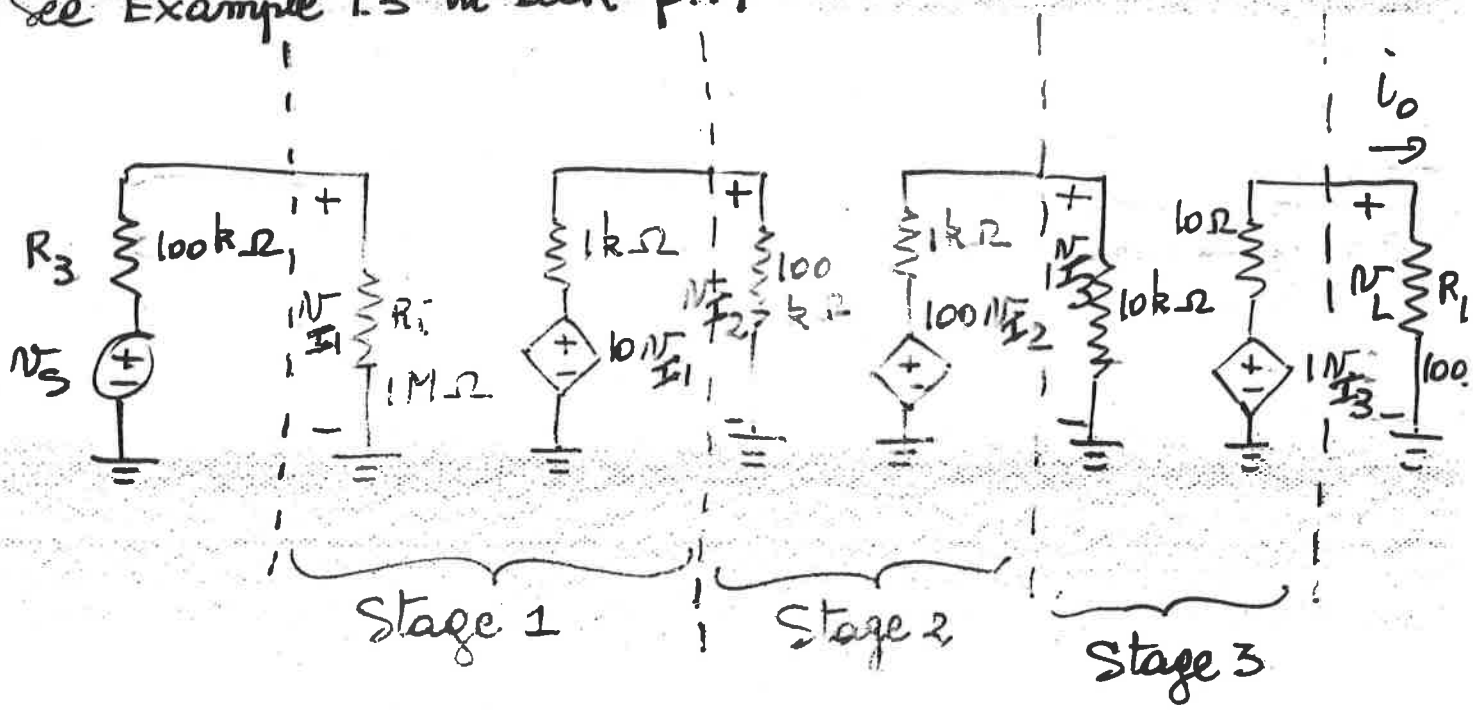
$$v_o = A_{v_o} v_i \left(\frac{R_L}{R_L + R_o}\right) \qquad v_i = \left(\frac{R_i}{R_i + R_s}\right) v_s$$

$$\frac{v_o}{v_i} = A_v = A_{v_o}\left(\frac{R_L}{R_L + R_o}\right)$$

- To Not kill A_v, R_o should be much smaller than R_L
  Ideal Voltage amplifier is one with $R_o = 0$.
- For $R_L = \infty$ $\quad A_v = A_{v_o} \rightarrow A_{v_o} \triangleq$ Open circuit voltage gain.
- Design amplifier such that $R_i \gg R_s$
  Ideal Voltage amplifier has $R_i = \infty$ (current & Power gains become infinite).

Multiple stages

See Example 1.3 in book p.19



$$\frac{v_L}{v_{I_1}} = A_v = A_{v_1} A_{v_2} A_{v_3} \quad \& \quad \frac{v_L}{v_S} = \frac{v_L}{v_{I_1}} \cdot \frac{v_{I_1}}{v_S} = A_v \frac{v_{I_1}}{v_S}$$

$$A_i = \frac{i_o}{i_I} = \frac{v_L/R_L}{v_I/R_i}$$

$$A_p = \frac{P_L}{P_I} = \frac{v_L i_o}{v_{I_1} i_1} = A_v A_i$$

$$\frac{v_{I_1}}{v_S} = \frac{1\,M\Omega}{1\,M\Omega + 100\,k\Omega} = 0.909$$

$$A_{v_1} = \frac{v_{I_2}}{v_{I_1}} = 10 \left\{ \frac{100\,k\Omega}{100\,k\Omega + 1\,k\Omega} \right\} = 9.9$$

$$A_{v_2} = \frac{v_{I_3}}{v_{I_2}} = 100 \left\{ \frac{10\,k\Omega}{10\,k\Omega + 1\,k\Omega} \right\} = 90.9$$

$$A_{v_3} = \frac{v_L}{v_{I_3}} = 1 \left\{ \frac{100}{100 + 10} \right\} = 0.909 \simeq 1$$

Stage 3 is referred as <u>Buffer Amplifier</u>

$$A_v = \frac{v_L}{v_{I_1}} = A_{v_1} A_{v_2} A_{v_3} = 818 \text{ V/V} \quad (58.3 \text{ dB})$$

$$\Rightarrow \frac{v_L}{v_S} = A_v \left(\frac{v_{I_1}}{v_S}\right) = 818\,(0.909) = 743.6 \text{ V/V}$$

<u>Current gain</u> $\quad A_i = \dfrac{i_o}{i_I} = \dfrac{v_L/100\Omega}{v_{I_1}/10\Omega} = 10^4 A_v = 8.18\,10^6 \text{ A/A}$

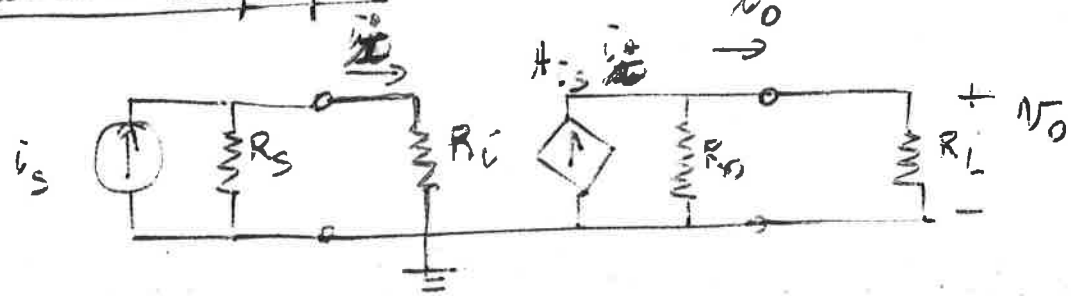
<u>Power gain</u> $\quad A_P = \dfrac{P_L}{P_I} = \dfrac{v_L i_o}{v_{I_1} i_I} = A_v A_i = 66.9\,10^8 \text{ W/W}$

(98.3 dB)

<u>Exercise:</u> Show that: $A_p(\text{dB}) = \frac{1}{2}\left[A_v(\text{dB}) + A_i(\text{dB})\right]$

<u>Other Amplifier Types</u>

<u>Current amplifier</u>



<u>Current divider rule:</u> $\quad i_o = A_{is}\, i_I \left(\dfrac{R_o}{R_o + R_L}\right)$

<u>Current gain of loaded amplifier</u>:

$$A_i = \frac{i_o}{i_i} = A_{is}\left(\frac{R_o}{R_o + R_L}\right)$$

- Best design $\quad R_o \gg R_L$

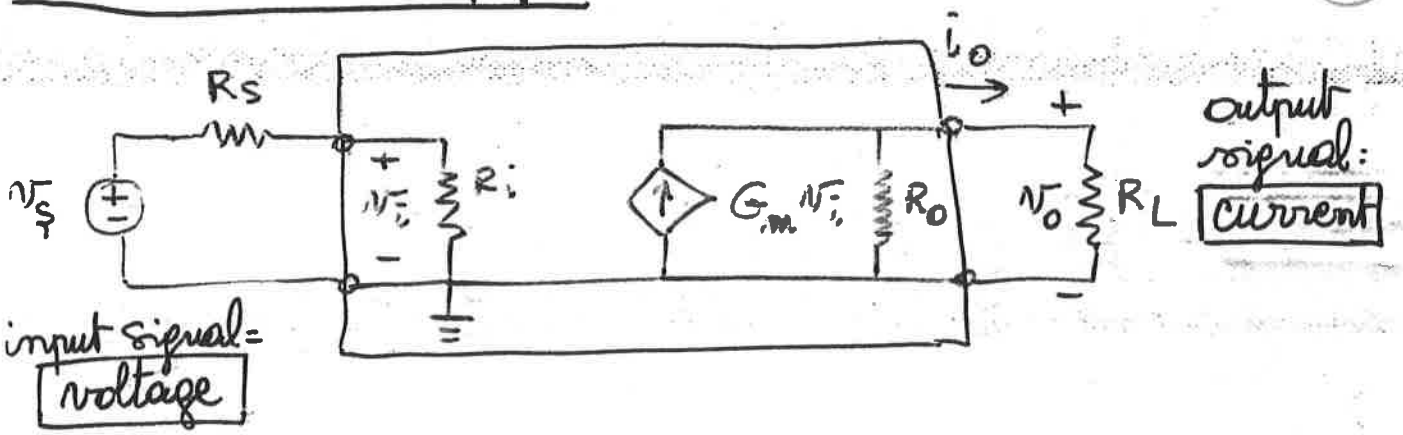
  Ideal current amplifier $\quad \boxed{R_o = \infty}$

- $i_I = i_s \left(\dfrac{R_s}{R_s + R_i}\right) \quad ; \quad R_i \ll R_s$

  Ideal current amplifier $\quad \boxed{R_i = 0}$

If $R_L = 0 \qquad A_i = A_{is} \triangleq$ Short-circuit current gain

Transconductance Amplifier:

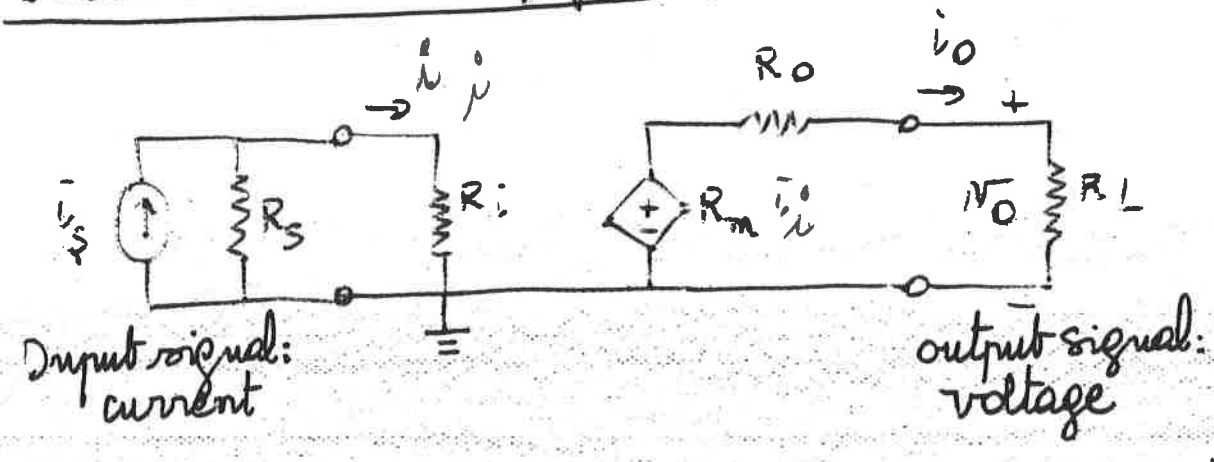


G_m = ratio of short-circuit output current to input voltage

$G_m \triangleq$ Short-circuit transconductance (A/V)

Ideal Transconductance amplifier? $R_i = \infty$; $R_o = \infty$

Transresistance Amplifier:



R_m = ratio of open-circuit output voltage to input current

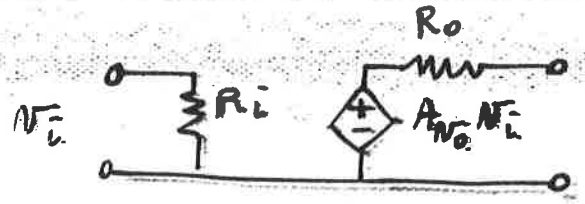
$R_m \triangleq$ Open-circuit Transresistance

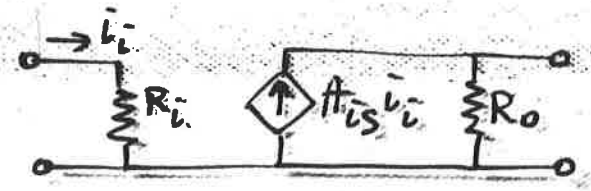
Ideal Transresistance Amplifier?

$R_i =$?

$R_o =$?

Relationship between the 4 amplifier Models





Open-circuit output voltage?

For voltage amplifier $= A_{v_o} v_i$
For current amplifier $= A_{is} i_i R_o$ } MUST be equal

$$A_{v_o} v_i = A_{is} i_i R_o = A_{is}\left(\frac{v_i}{R_i}\right) R_o$$

$$\Rightarrow \boxed{A_{v_o} = A_{is} \frac{R_o}{R_i}}$$

These 3 equations can be used to relate any two of the gain parameters.

Similarly $\boxed{A_{v_o} = G_m R_o}$, and $\boxed{A_{v_o} = \frac{R_m}{R_i}}$

Measurement:

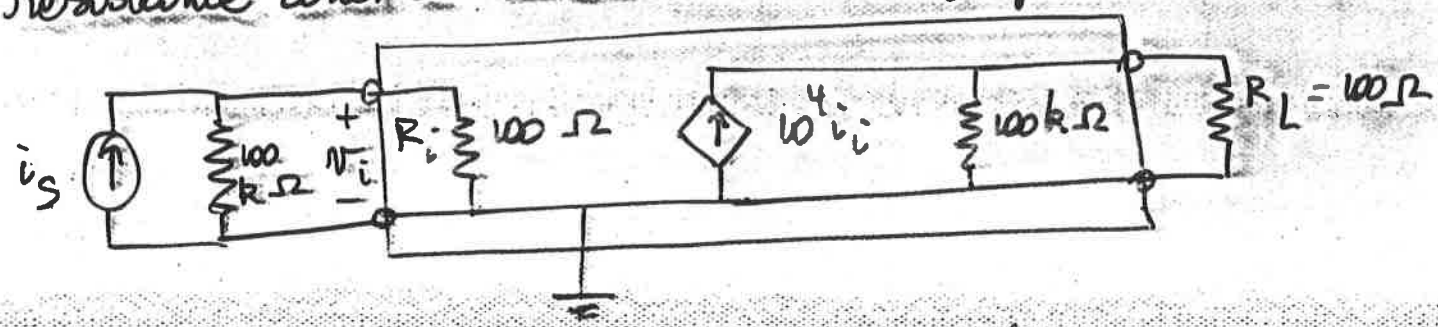
R_i? Apply v_i, measure $i_i = \frac{v_i}{R_i}$

R_o? ① Ratio of open-circuit output voltage to short-circuit output current

② Eliminate input signals (i_i & $v_i = 0$)
Apply test voltage v_x to output of amplifier

$$\rightarrow \boxed{R_o = \frac{v_x}{i_x}}$$

Ex 1.10 Current amplifier $\left\{\begin{array}{l} R_i = 100\,\Omega \\ R_o = 100\,k\Omega \\ \text{gain} = 10^4 = A_{is} \end{array}\right\}$ is connected between a signal current source with 100 kΩ source resistance and a 100 Ω load. Voltage gain? power gain?

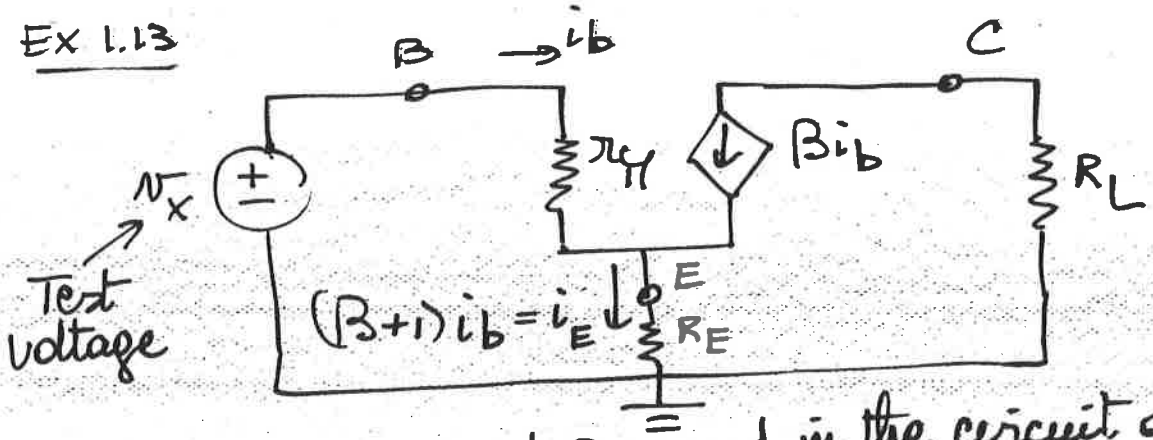


$$\left.\begin{array}{l} v_o = 10^4 i_i \,(100\,k\Omega \,//\, 100\,\Omega) \\ v_i = R_i i_i \rightarrow i_i = \dfrac{v_i}{100\,\Omega} \end{array}\right\} \Rightarrow v_o = \frac{10^6 v_i}{100} = 10^4 v_i$$

Voltage gain $= 10^4\,V/V$
$= 80\,dB$

$$A_p = \frac{P_L}{P_i} = \frac{v_o^2/100}{v_i^2/100} = 10^8\,W/W \rightarrow 10 \log A_p = 80\,dB$$

Ex 1.13



R_i between B and Ground in the circuit above

$$R_i = \frac{v_x}{i_x} \; ; \qquad v_x = v_{BG} = r_\pi i_b + R_E(\beta+1) i_b$$

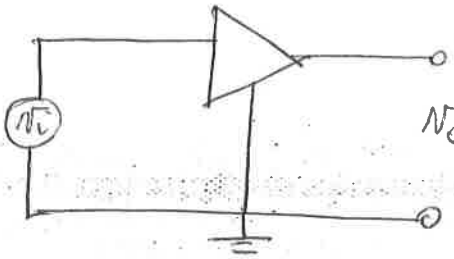
$$v_x = \left[r_\pi + (\beta+1) R_E\right] i_b = \left[r_\pi + (\beta+1) R_E\right] i_x$$

So, $\boxed{R_i = r_\pi + (\beta+1) R_E}$

Section 1.6

Linear Amplifier
Phasors
Transfer Function

$V_i \sin \omega t =$



$v_o = V_o \sin(\omega t + \phi)$

$$|T(\omega)| = |V_o / V_i|$$

$$\angle T(\omega) = \phi$$

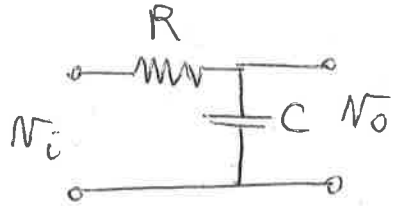
$$T = |T| e^{j\phi} = \mathrm{Re}\,T + j\,\mathrm{Im}\,T$$

$$e^{j\phi} = \cos\phi + j \sin\phi$$

$$\left.\begin{aligned} \mathrm{Re}\,T &= |T| \cos\phi \\ \mathrm{Im}\,T &= |T| \sin\phi \end{aligned}\right\} \rightarrow \frac{\sin\phi}{\cos\phi} = \frac{\mathrm{Im}\,T}{\mathrm{Re}\,T}$$

$$\boxed{\phi = \tan^{-1}\left\{\frac{\mathrm{Im}\,T}{\mathrm{Re}\,T}\right\}}$$

Example:



$$\frac{v_o}{v_i} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{1}{1 + j\omega RC} = T$$

$$T = \frac{1 - j\omega RC}{\sqrt{1 + (\omega RC)^2}} = \mathrm{Re}\,T + j\,\mathrm{Im}\,T$$

$$\phi = \tan^{-1}\{-\omega RC\} \quad ; \quad |T| = \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}}$$

Low pass filter

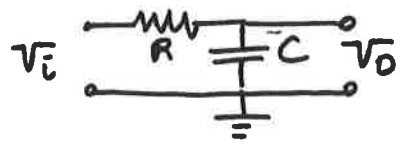
Review

STC Networks
(Single-Time Constant)

See Appendix F

$$\frac{v_o(s)}{v_i(s)} = T(s) = \frac{K}{1+\left(\frac{s}{\omega_0}\right)}$$

Example



$K=1$

$\omega_0 = \frac{1}{RC} = \omega_{3dB}$

$s = j\omega$

$$T(j\omega) = \frac{1}{1+j\left(\frac{\omega}{\omega_0}\right)}$$

BODE PLOT

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

$$20\log_{10}|T(j\omega)| = 20\log_{10}\left(1+\left(\frac{\omega}{\omega_0}\right)^2\right)^{-1/2}$$

if $\omega \to 0$ $(\omega \ll \omega_0)$ $\longrightarrow$ $20\log_{10}|T(j\omega)| \to 0$ (dB)

if $\omega > \omega_0$ $\left(\frac{\omega}{\omega}\right)^2 \gg 1$ $\longrightarrow$ $\underbrace{20\log_{10}|T(j\omega)|}_{y} = -20\underbrace{\log\left(\frac{\omega}{\omega_0}\right)}_{x}$

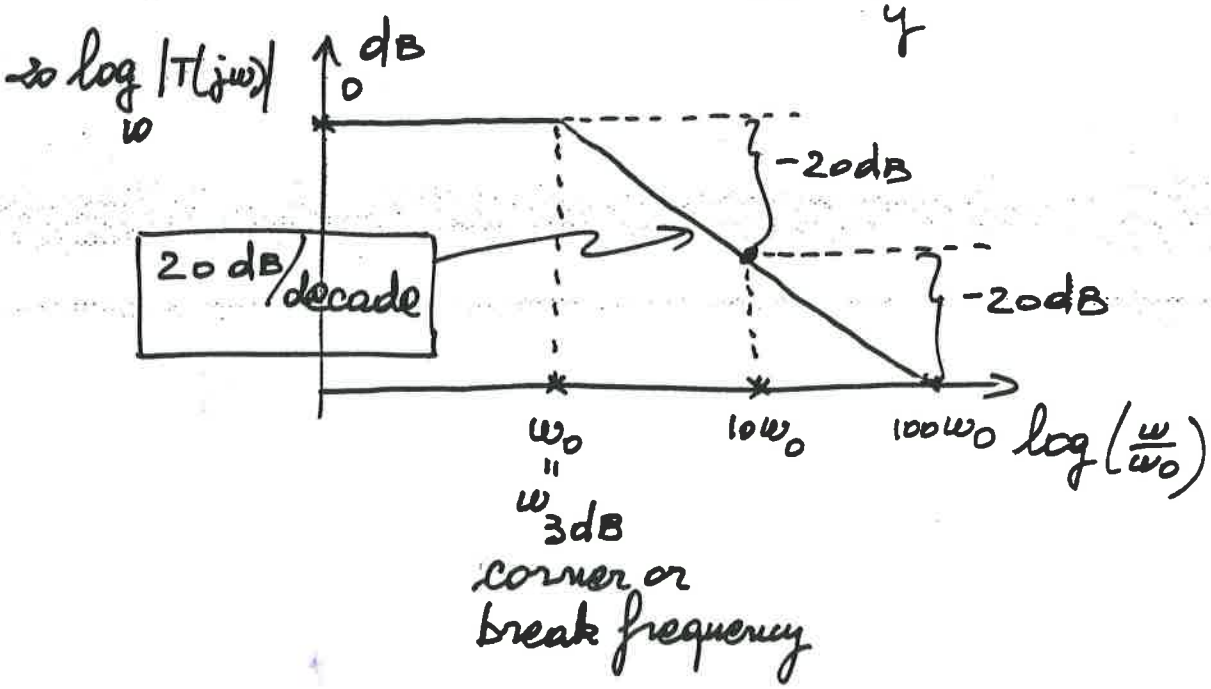


Figure 1.24 (a) Magnitude and (b) phase response of low-pass STC networks.

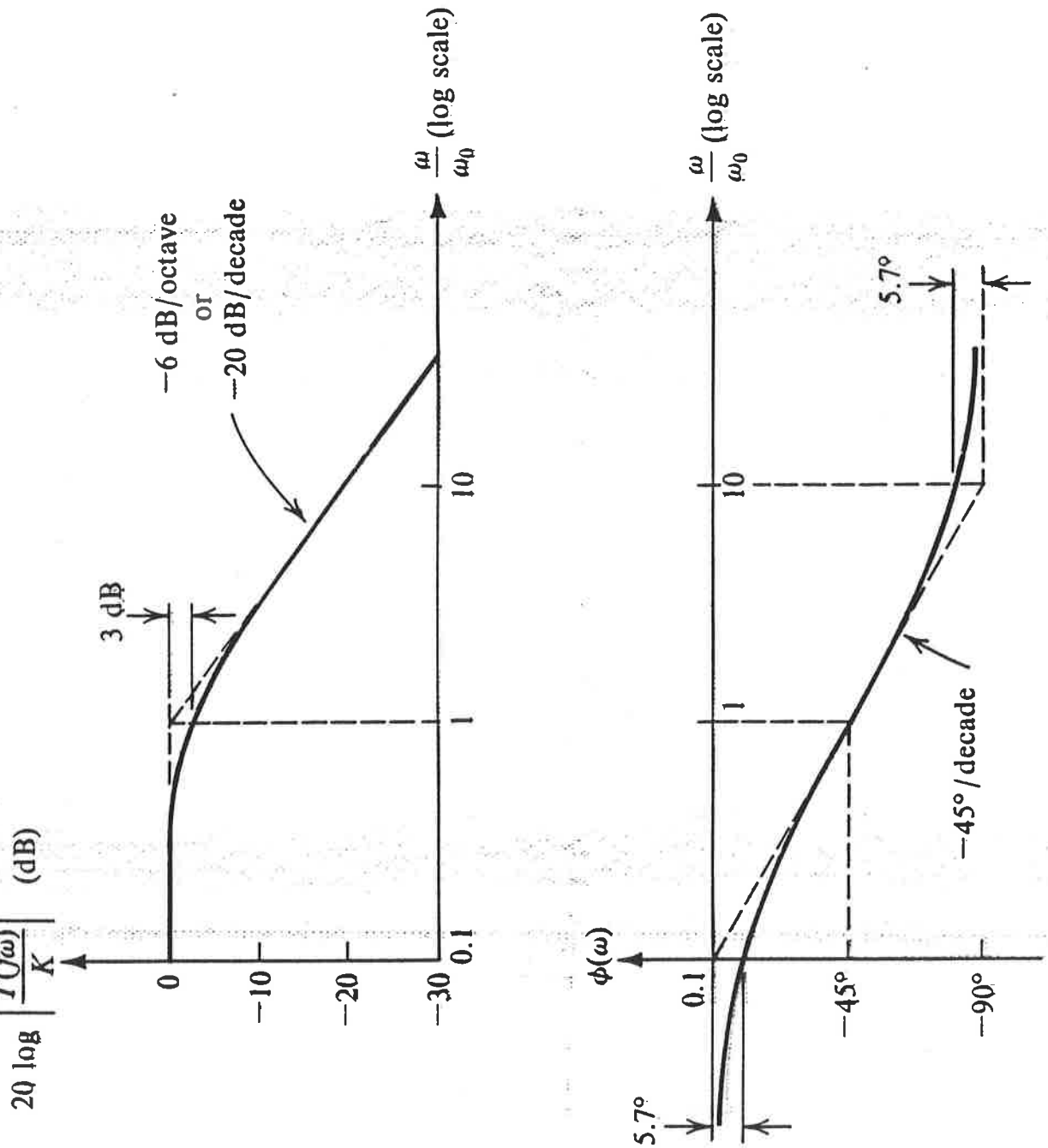


Fig. 1.24

Figure 1.25 (a) Magnitude and (b) phase response of high-pass STC networks.

15

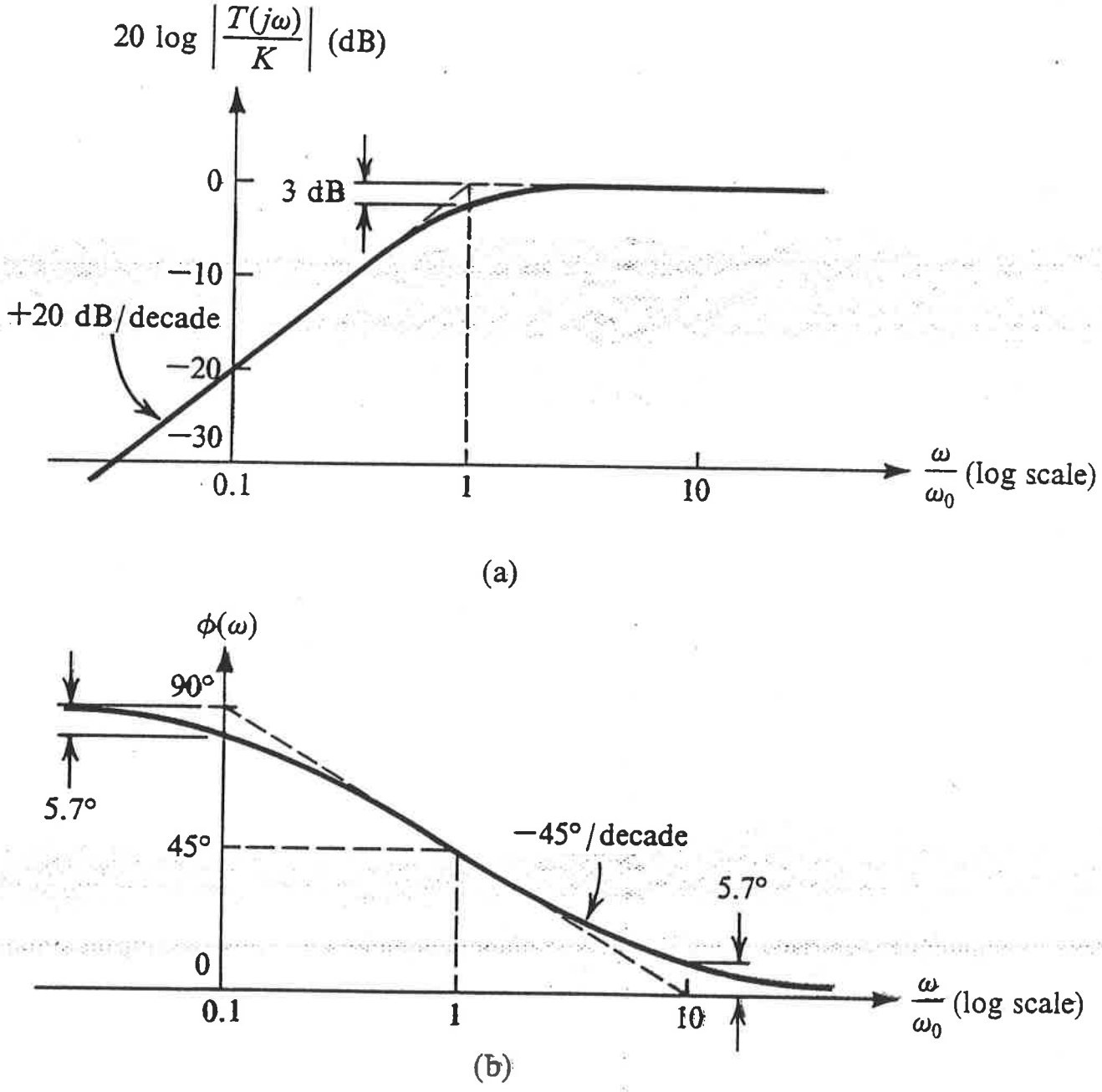
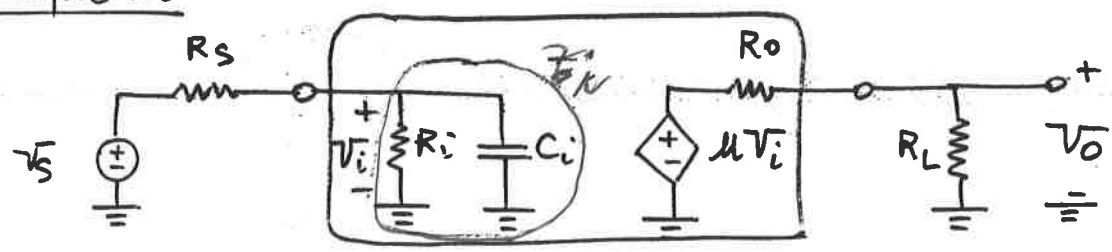


Fig. 1.25

ble 1.1 FREQUENCY RESPONSE OF STC NETWORKS

	Low-Pass (LP)	High-Pass (HP)
Transfer Function $T(s)$	$\dfrac{K}{1 + (s/\omega_0)}$	$\dfrac{Ks}{s + \omega_0}$
Transfer Function (for physical frequencies) $T(j\omega)$	$\dfrac{K}{1 + j(\omega/\omega_0)}$	$\dfrac{K}{1 - j(\omega_0/\omega)}$
Magnitude Response $\lvert T(j\omega)\rvert$	$\dfrac{\lvert K\rvert}{\sqrt{1 + (\omega/\omega_0)^2}}$	$\dfrac{\lvert K\rvert}{\sqrt{1 + (\omega_0/\omega)^2}}$
Phase Response $\angle T(j\omega)$	$-\tan^{-1}(\omega/\omega_0)$	$\tan^{-1}(\omega_0/\omega)$
Transmission at $\omega = 0$ (dc)	K	0
Transmission at $\omega = \infty$	0	K
3-dB Frequency	$\omega_0 = 1/\tau$, $\tau \equiv$ time constant $\tau = CR$ or L/R	
Bode Plots	in Fig. 1.24	in Fig. 1.25

Example 1.6



$\frac{v_o}{v_S}$? DC gain? 3dB frequency?

① Input Side

$$v_i = v_S \frac{Z_i}{Z_i + R_S} = v_S \frac{1}{1 + R_S Y_i} \qquad Y_i = \frac{1}{Z_i}$$

$$v_i = v_S \cdot 1 / \left[1 + R_S \left\{ \frac{1}{R_i} + sC_i \right\}\right]$$

We must write it in the form $K / \left[1 + \left(\frac{s}{\omega_0}\right)\right]$

$$\frac{v_i}{v_S} = \frac{1}{\left[1 + \frac{R_S}{R_i}\right]} \cdot \frac{1}{\left[1 + sC_i\left[(R_S R_i)/(R_S + R_i)\right]\right]}$$

② Output Side of Amplifier

$$v_o = \mu v_i \frac{R_L}{R_L + R_o}$$

⇒ Transfer Function

$$\frac{v_o}{v_S} = \underbrace{\mu \frac{1}{1 + (R_S/R_i)} \cdot \frac{1}{1 + (R_o/R_L)}}_{K} \frac{1}{1 + sC_i\left[R_S R_i/(R_S + R_i)\right]}$$

$$\omega_0 = \frac{1}{\tau}$$

$$\boxed{\tau = C_i \frac{R_S R_i}{R_S + R_i} = C_i (R_S // R_i)}$$

Quick way: $v_S = 0$ ➡ C_i discharges through the parallel combination of R_i and R_S

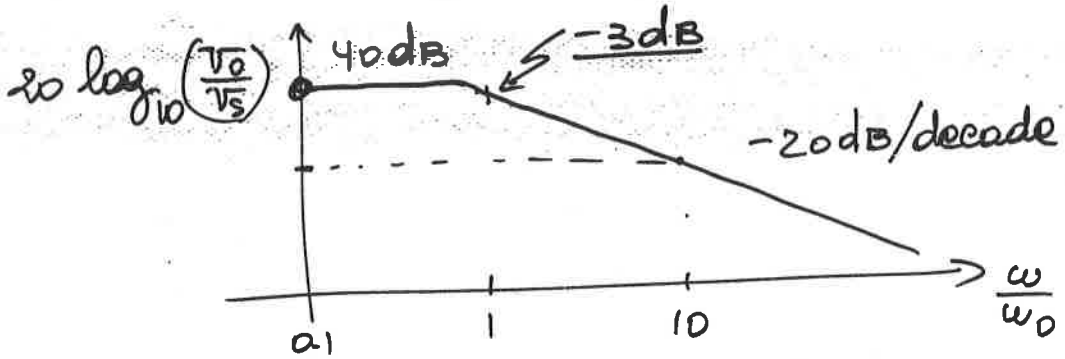
➡ $\boxed{\tau = C_i (R_S // R_i)}$

DC gain? 3dB frequency?
frequency at which gain becomes 0dB?

when $R_S = 20k\Omega$ $C_i = 60pF$ $R_o = 200\Omega$
$R_1 = 100k\Omega$ $\mu = 144$ $R_L = 1k\Omega$

$K = 100V/V = 40dB$

$\omega_o = 10^6 rad/s \rightarrow f_o = \frac{\omega_o}{2\pi} = 159.2kHz$

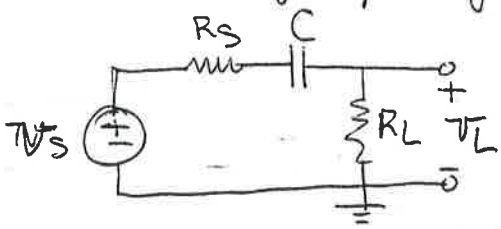


Gain falls off at the rate of -20dB/decade
starting at ω_o, the gain will fall at 0dB in two decades.

$\Rightarrow$ $\boxed{\text{unit gain frequency} = 15.92\ MHz}$

36

D1.27 It is required to couple a voltage source v_S having a resistance R_S to a load R_L via a capacitor C. Derive an expression for the transfer function from source to load (i.e., v_L/v_S) and show that it is of the high-pass STC type. For $R_S = 10\,k\Omega$ and $R_L = 40\,k\Omega$ find the smallest coupling capacitor that will result in a 3dB frequency no greater than 10 Hz.



$$\frac{v_L}{v_S} = \frac{R_L}{R_S + \frac{1}{sC} + R_L} = \frac{sR_L}{s(R_L+R_S) + \frac{1}{C}} = \frac{s\left[R_L/(R_S+R_L)\right]}{s + \frac{1}{C(R_S+R_L)}}$$

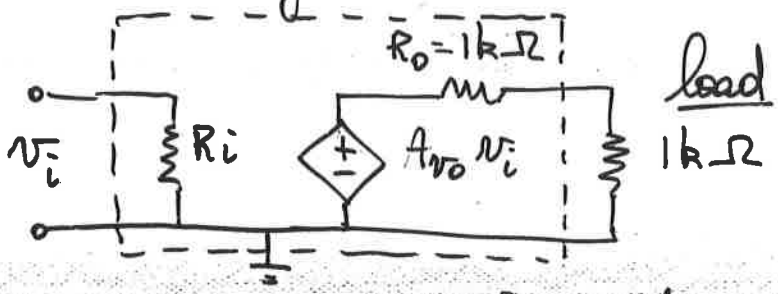
This transfer function is of the high-pass type with

$$K = \frac{R_L}{R_S+R_L} \quad \text{and} \quad \omega_0 = \frac{1}{C(R_S+R_L)}$$

For $R_S = 10\,k\Omega$, $R_L = 40\,k\Omega$ to obtain a 3dB frequency $\omega_0 \leq 2\pi \times 10$ rad/s

we must select $\boxed{C \geq \frac{1}{\omega_0(R_S+R_L)} = 0.318\,\mu F}$

1.9 An amplifier with a open voltage gain of +40 dB, $= A_{vo}$ (21)
an input resistance of 10 kΩ, and an output resistance of 1 kΩ is used to drive a load of 1 kΩ.
What is the value of A_{vo}? Find the value of power gain in dB



$A_{vo} = 40\,dB$

$$P_L = \frac{v_o^2}{R_L} = \frac{1}{R_L}\left(A_{vo} v_i \frac{R_L}{R_L + R_o}\right)^2$$

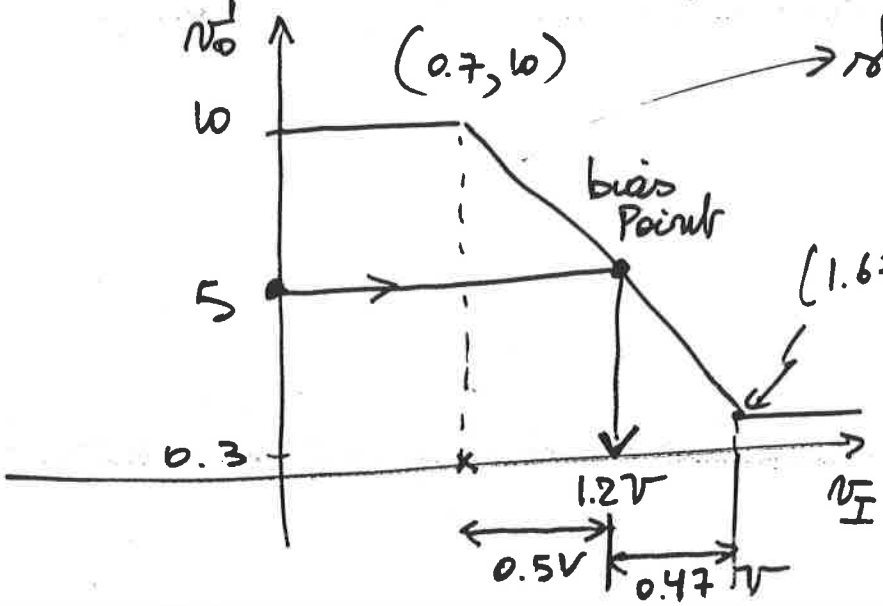
$$P_L = 2.5\, v_i^2$$

$$P_i = \frac{v_i^2}{R_i} = \frac{v_i^2}{10{,}000} \Longrightarrow A_p = \frac{P_L}{P_i} = 2.5\,10^4\ W/W$$

$$\boxed{10 \log A_p = 44\,dB}$$

D1.12 $v_o = 17 - 10 v_I$ for $0.3V \le v_o \le 10V$

v_I? so that DC output voltage is 5V.
v_i is superimposed on v_I; amplifier voltage gain?
If v_i is sinusoidal, find its largest possible amplitude without output clipping.



slope = gain = −10 V/V

To avoid clipping, the peak should be limited to 0.47V

Hwk 1

1.5 An amplifier operating from a single 15 V supply provides a 12 V p-p sine-wave signal to a 1kΩ load, and draws negligible input current from the signal source. The DC current drawn from the 15V supply is 8mA. What is the power dissipated in the amplifier and what is the power efficiency?

$$P_{dc} = 15 \times 8 = 120\,mW$$

$$P_L = \frac{1}{R} V_{eff}^2 = \frac{1}{1}\left(\frac{6}{\sqrt{2}}\right)^2 = 102\,mW$$

$$\Rightarrow \eta = \frac{P_L}{P_{dc}} \times 100 = 15\%$$

1.6. $v_O = 10 - 10^{-11} e^{40 v_I}$

$$v_I = V_I + v_i$$
$$v_O = V_O + v_o$$

$$\Rightarrow \underbrace{V_O}_{5V} + v_o = 10 - 10^{-11} e^{40(\underbrace{V_I}_{0.673V} + v_i)}$$

$$\Rightarrow \boxed{v_o = 5 - \left(10^{-11} e^{40 V_I}\right) e^{40 v_i}}$$

$v_i = 2mV \rightarrow v_o = -0.416V$ (208)/200 1.04

$v_i = 5mV \rightarrow v_o = -1.107V$ (221.4)/200 1.107

$v_i = 10mV \rightarrow v_o = -2.459V$ (245/200) 1.23

For small signal gain $\boxed{v_o = (-200\,V/V)\, v_i}$