CHAPTER 1

Signals and Amplifiers

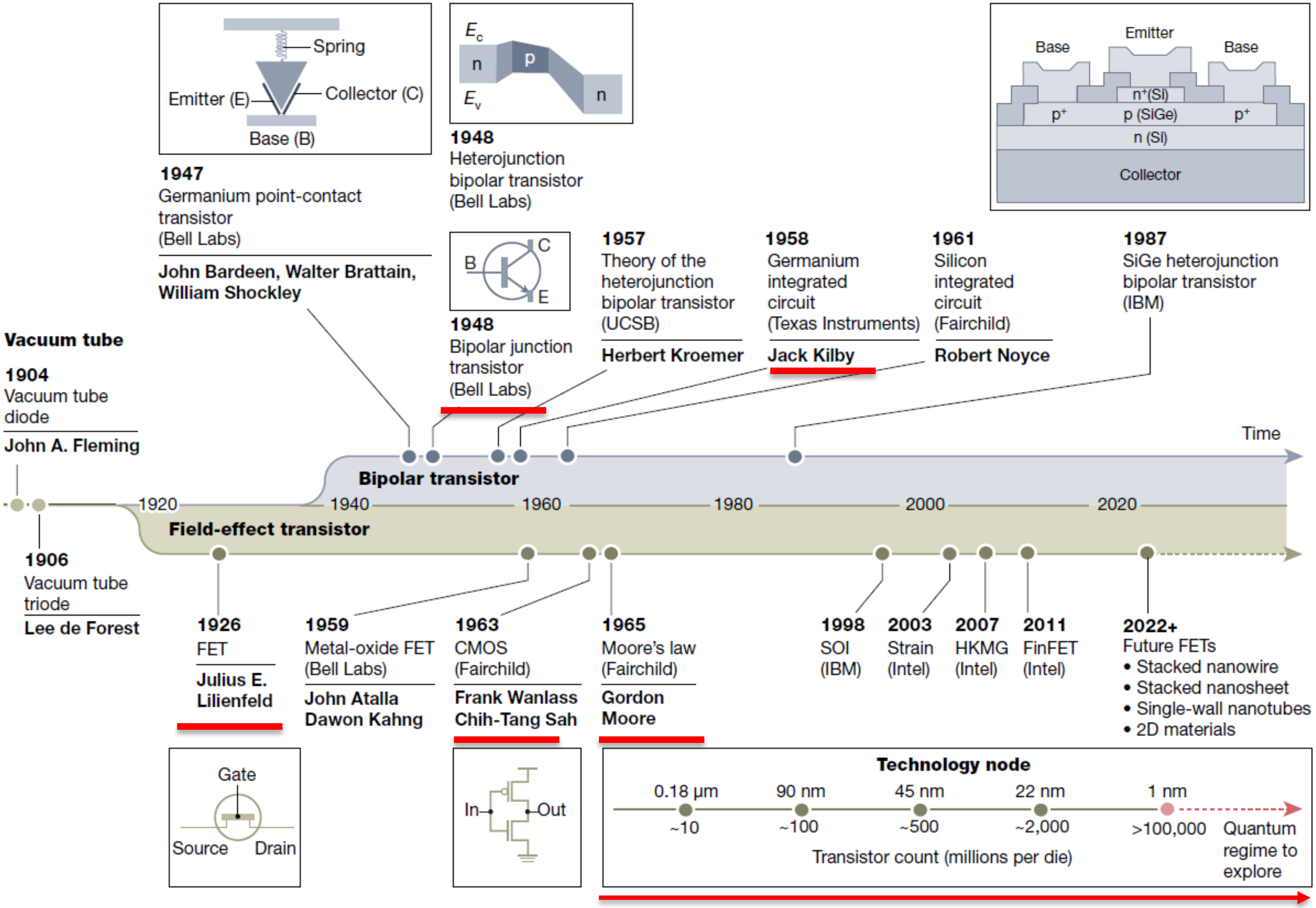


Fig. 1 | The history of transistor technology. All major transitions from vacuum tubes to BJTs, and eventually to MOSFETs, have been primarily driven by the need to reduce power consumption. Four major non-traditional FET scaling technologies, that is, SOI, strained channel, HKMG and FinFET are shown according to their commercialization time, corresponding to the 0.18-μm, 90-nm, 45-nm and 22-nm technology nodes, respectively. It is noted that beginning from the 22-nm node, the technology node becomes increasingly smaller than the FET physical dimension. E_c, conduction band minima; E_v, valence band maxima; IBM, International Business Machines; UCSB, University of California, Santa Barbara. Transistor count data are from https://en.wikipedia.org/wiki/Transistor_count.

Cao W, Bu H, Vinet M, Cao M, Takagi S, Hwang S, Ghani T, Banerjee K. The future transistors. Nature. 2023 Aug; 620(7974):501-515. doi: 10.1038/s41586-023-06145-x. Epub 2023 Aug 16. PMID: 37587295.

Outlines

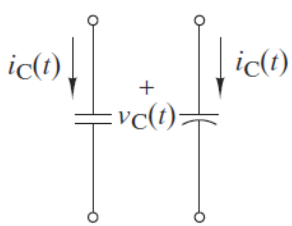
- 1.1 Signals and Overview
- 1.2 Amplifiers
- 1.3 Circuit Models for Amplifiers
- 1.4 Frequency Response of Amplifier

1.1 Signals

- Resistance (R, Ω): $Z_R = R$
- Capacitance RT PP.274
  - C, F-Farad
  - Resistance: $Z_C = \frac{1}{j\omega C}$, $\omega = 2\pi f$

    Angular frequency in radians/s (ω); Frequency in Hz (f)
- Inductance RT PP.282
  - L, H-Henry
  - Resistance: $Z_L = j\omega L$, $\omega = 2\pi f$

Linear circuit textbook: Roland E Thomas (RT), e.g. the analysis and design of linear circuit, 8th edition

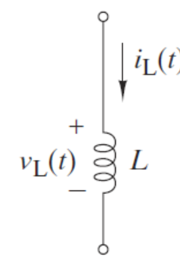


(b)

$$i_c(t) = C\frac{dv_c(t)}{dt}$$

FIGURE 6–1 *The capacitor: (a) Parallel plate device. (b) Circuit symbols.*

$$v_L(t) = L\frac{di_L(t)}{dt}$$



(b)

FIGURE 6–9 *(a) Magnetic flux surrounding a current-carrying coil. (b) Circuit symbol showing inductor current and voltage.*

- Things will be used from linear circuit class
  - KCL, KVL: RT PP.23
  - Equivalent circuit: RT PP.41, Fig. 2-37
  - Voltage and current division: RT PP.42
  - Thévenin and Norton Equivalent Circuits: RT PP.107
  - … Catch up the 1~4 chapters

- Kirchhoff's Voltage Law (KVL)
  - The **algebraic** sum of all the voltages around a loop is zero at every instant.
- Kirchhoff's Current Law (KCL)
  - The sum of the currents entering a node equals the sum of the currents leaving the node.
- RT PP. 23

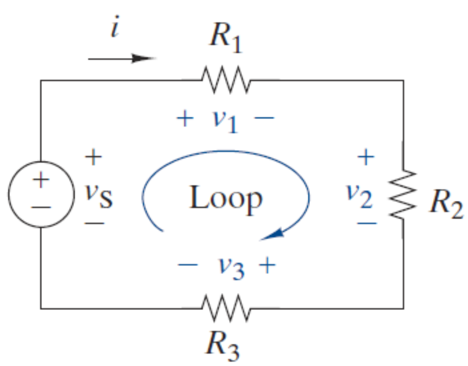


FIGURE 2–38 *A voltage divider circuit.*

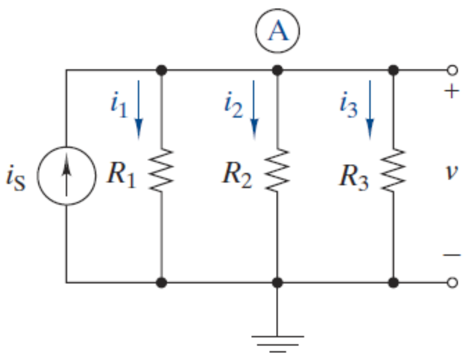


FIGURE 2–44 *A current divider circuit.*

- Equivalent circuit RT PP.41, Fig. 2-37

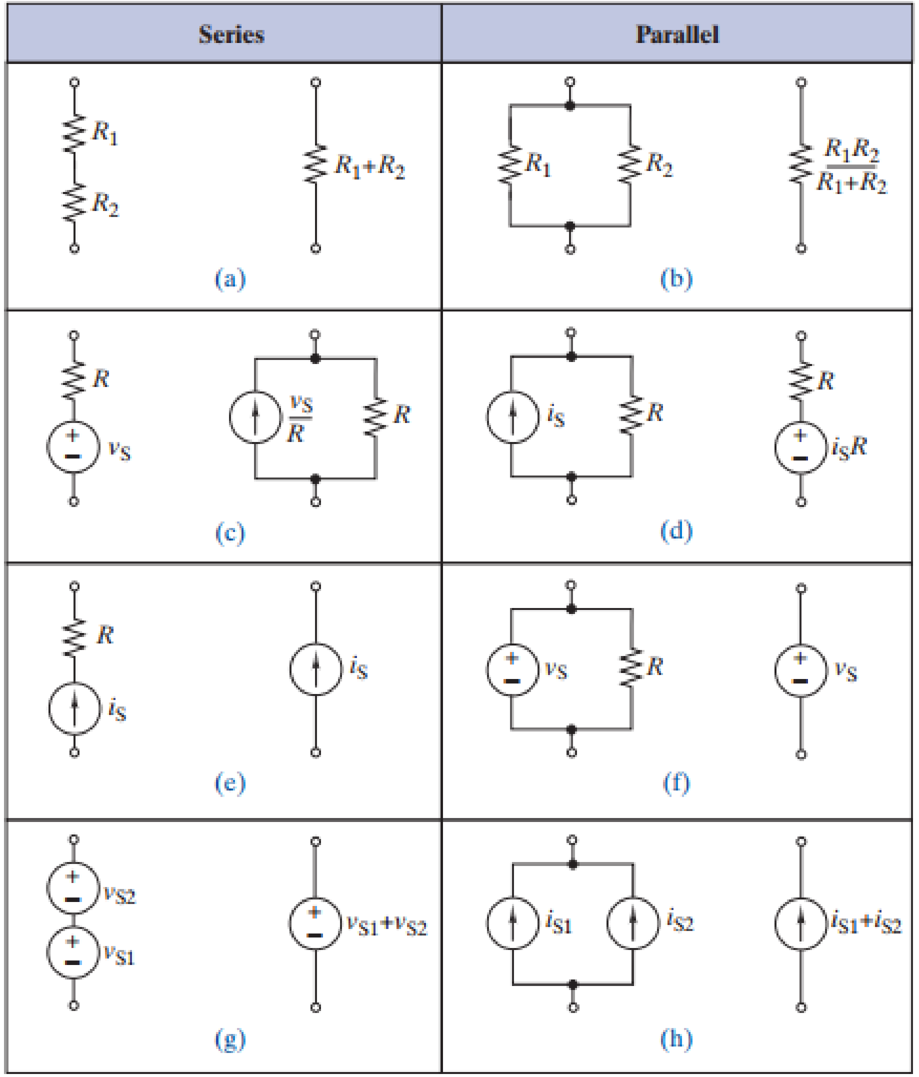


FIGURE 2–37 *Summary of two-terminal equivalent circuits.*

Consider one resistor in series/parallel with one capacitor?

- In series: $Z = R + 1/jwC$
- In parallel: $Z = \frac{1}{\frac{1}{R}+jwc}$

- Voltage division RT PP.42
  - In a **series** connection, the voltage across each resistor is equal to its **resistance** divided by the equivalent series **resistance** of the connection times the voltage across the series circuit.

$v_s = v_1 + v_2 + v_3$ (KVL)

$v_s = R_1 i + R_2 i + R_3 i$ (Ohm's law)

$$i = \frac{v_s}{R_1+R_2+R_3}$$

thus $v_1 = R_1 i = \left(\frac{R_1}{R_1+R_2+R_3}\right) v_s$

$$v_2 = R_2 i = \left(\frac{R_2}{R_1+R_2+R_3}\right) v_s$$

$$v_{13} = R_3 i = \left(\frac{R_3}{R_1+R_2+R_3}\right) v_s$$

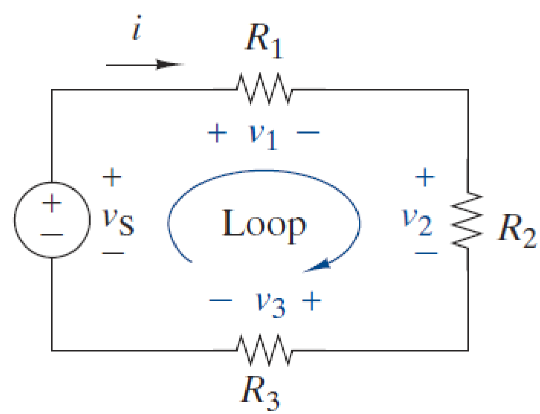


FIGURE 2–38 *A voltage divider circuit.*

- Current division RT PP.42
  - In a **parallel** connection, the current through each resistor is equal to its **conductance** divided by the equivalent parallel **conductance** of the connection times the current through the parallel circuit.

$i_s = i_1 + i_2 + i_3$ (KCL)

$i_s = v/R_1 + v/R_2 + v/R_3$ (Ohm's law)

$$v = i_s \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

thus $i_1 = v/R_1 = \left(\frac{1/R_1}{1/R_1 + 1/R_2 + 1/R_3}\right) i_s$

$$i_2 = v/R_2 = \left(\frac{1/R_2}{1/R_1 + 1/R_2 + 1/R_3}\right) i_s$$

$$i_3 = v/R_3 = \left(\frac{1/R_3}{1/R_1 + 1/R_2 + 1/R_3}\right) i_s$$

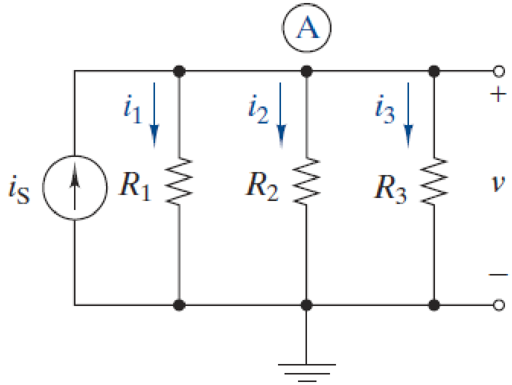


FIGURE 2–44 *A current divider circuit.*

- Thévenin and Norton Equivalent Circuits
  - If the source circuit in a **two-terminal** interface is **linear**, the interface signals **v and i don't change** when the source circuit is **replaced by its T/N equivalent circuit**
- RT PP. 107

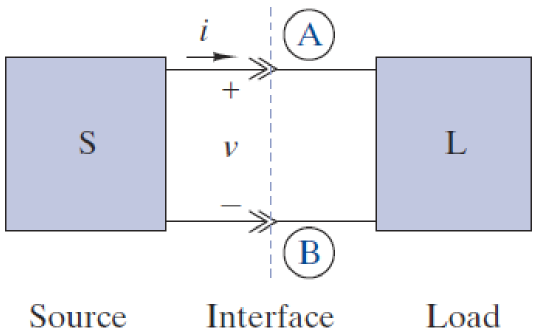


FIGURE 3–41 *A two-terminal interface.*

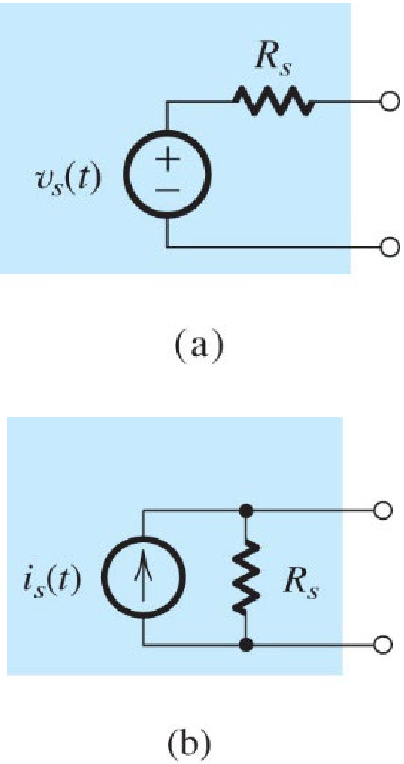


Figure 1.1 Two alternative representations of a signal source: **(a)** the Thévenin form; **(b)** the Norton form.

- How to find v_T / i_N and R?
  - Open circuit for Thévenin v_T
  - Short circuit for Norton i_N

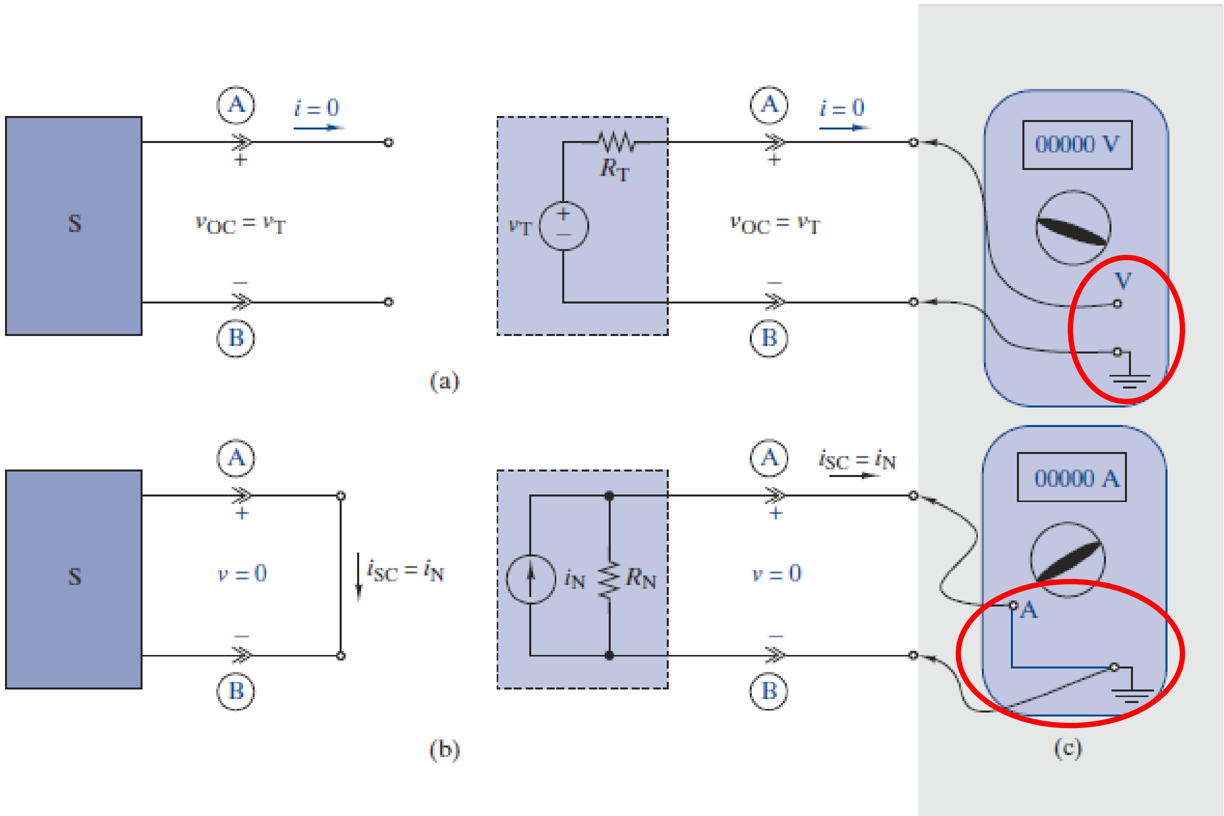


FIGURE 3–43 *Loads used to find Thévenin and Norton equivalent circuits: (a) Open circuit yields the Thévenin voltage. (b) Short circuit yields the Norton current. (c) Measuring v_{OC} and i_{SC} using a DMM.*

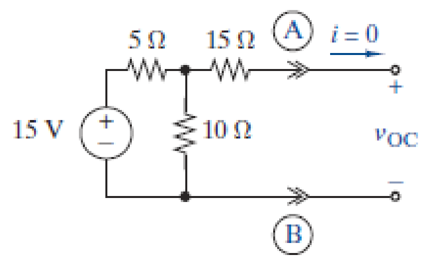
- Find the Thévenin and Norton Equivalent Circuits.

$$v_T = \frac{10}{10+5} \times 15V = 10V \text{ (OPEN LOAD)}$$

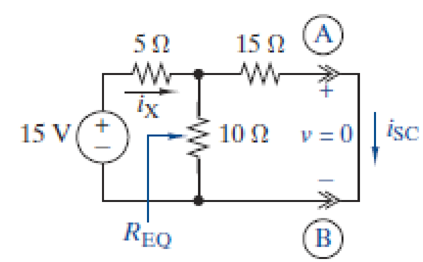
$$i_N = \frac{\frac{1}{15}}{\frac{1}{15}+\frac{1}{10}+\frac{1}{5}} \times 3A = 0.5454\text{A} \text{ (SHORT LOAD)}$$

$$R = \frac{v_T}{i_N} = 18.3\Omega$$

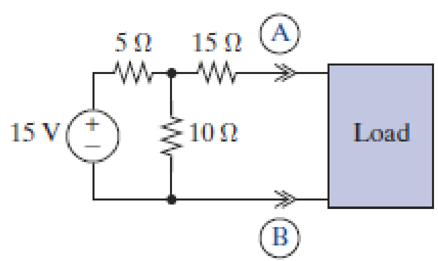
- Lookback resistance :
  - Turnoff all the sources （RT PP. 115）
  - Grab terminals and walk into



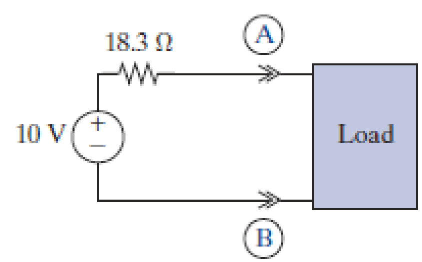
(b)



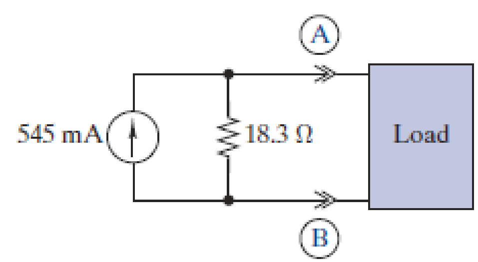
(c)



(a)



(d)



(e)

1.4 Amplifiers

- Linear amplifier
  - Voltage gain $A_v = \frac{v_O}{v_I}$ $(\frac{V}{V})$
  - Current gain $A_i = \frac{i_O}{i_I}$ $(\frac{A}{A})$
  - Power gain $A_p = \frac{v_O i_O}{v_I i_I}$ $(\frac{W}{W})$

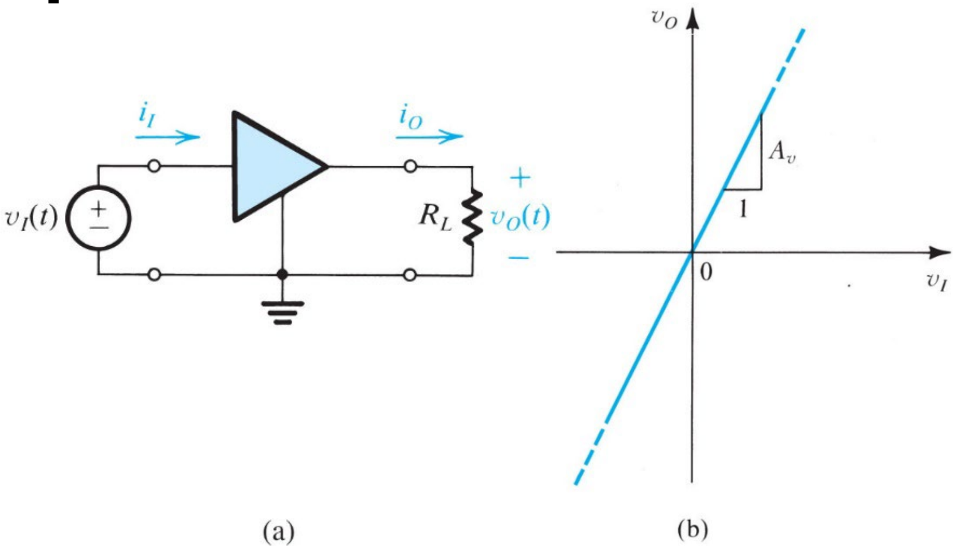


Figure 1.12 (a) an amplifier fed with a signal v_I(t) (b) Transfer characteristic f a linear voltage amplifier with a voltage gain A_v

- Gain in decibels
  - Voltage gain in decibel: $20 \log A_v \; dB$
  - Current gain in decibel: $20 \log A_i \; dB$
  - Power gain in decibel: $10 \log A_p \; dB$

- Exercise 1.10
  - An amplifier has a voltage gain of 100V/V, and a current gain of 1000A/A. Express the voltage and current gains in decibels and find the power gain

(a) $\text{voltage gain} = 20\log 100 = 40\text{db}$

(b) $\text{current gain} = 20\log 1000 = 60\text{db}$

(c) $\text{power gain} = 10\log A_P = 10\log(A_v A_i) = 50\text{db}$

1.5 Circuit Models for Amplifiers

- Voltage amplifier – voltage-controlled (v_i,A_{vo})

Open loop gain (A_{vo}) = the gain of the component all by itself, with all other components removed. Ideally, infinite gain can be obtained by an ideal amplifier!

Closed loop gain (A_v)= the gain of the amplifier circuit as a whole, from circuit-input to circuit-output, with all components intact.

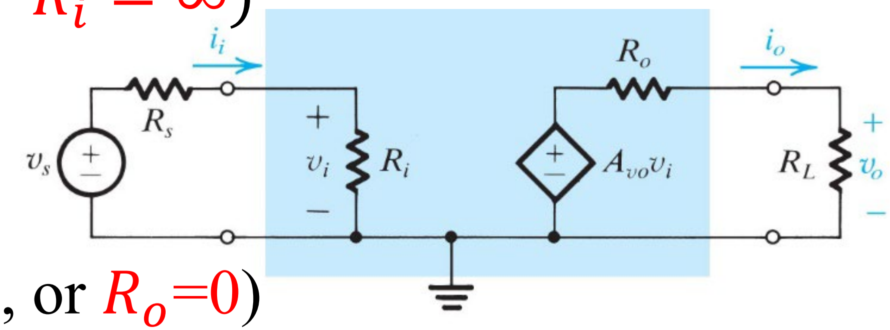
General gain (G_v)= the gain of the amplifier from voltage source to load.

$$v_i = v_s \times \frac{R_i}{R_i + R_s} \quad (R_i >> R_s, or\ R_i = \infty)$$

$$v_o = A_{vo} v_i \times \frac{R_L}{R_L + R_o}$$

$$A_v = \frac{v_o}{v_i} = A_{vo} \frac{R_L}{R_L + R_o} \quad (R_L >> R_o, \text{ or } R_o = 0)$$

$$G_v = \frac{v_o}{v_s} = A_{vo} \frac{R_L}{R_L + R_o} \frac{R_i}{R_i + R_s}$$

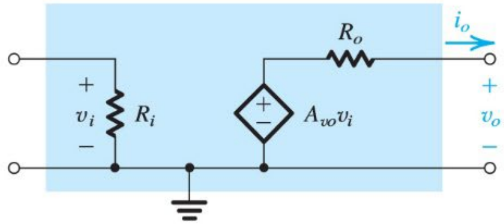
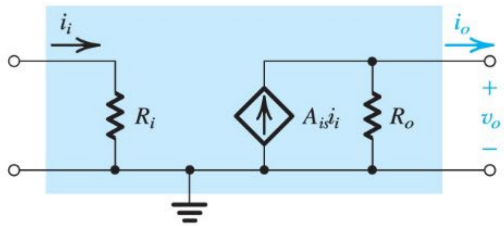
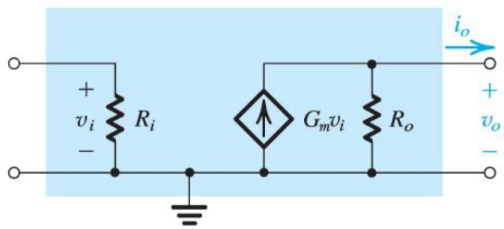
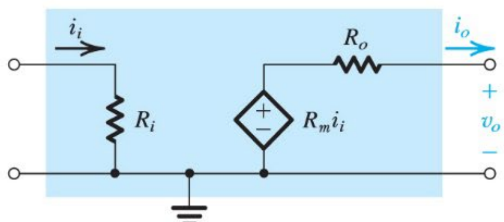


(b)

Figure 1.16 (b) The voltage amplifier with input signal source and load.

• The four amplifier models

Table 1.1 The Four Amplifier Types

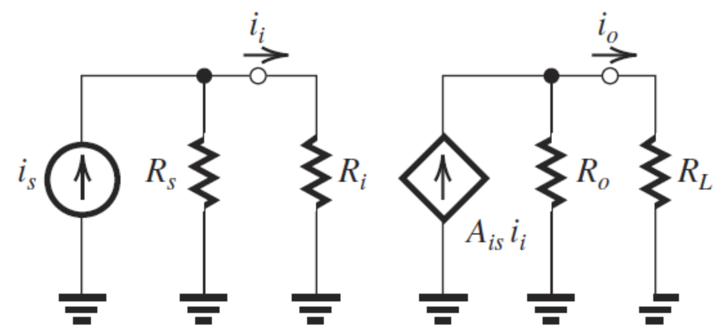
Type	Circuit Model	Gain Parameter	Ideal Characteristics
Voltage Amplifier		Open-Circuit Voltage Gain $A_{vo} \equiv \left.\frac{v_o}{v_i}\right\|_{i_o=0}$ (V/V)	$R_i = \infty$ $R_o = 0$
Current Amplifier		Short-Circuit Current Gain $A_{is} \equiv \left.\frac{i_o}{i_i}\right\|_{v_o=0}$ (A/A)	$R_i = 0$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

- # Exercise 1.18

Consider $\frac{i_o}{i_s}$ of a current-controlled current amplifier. Let the amplifier be fed with a current-source i_s having a resistance R_s, and let the output be connected to a load resistance R_L.

$i_i = \frac{R_s}{R_s+R_i} i_s$ $\qquad$ $i_o = \frac{R_o}{R_o+R_L} A_{is}\, i_i$

Thus, $\frac{i_O}{i_S} = A_{is} \frac{R_O}{R_O+R_L} \frac{R_S}{R_S+R_i}$

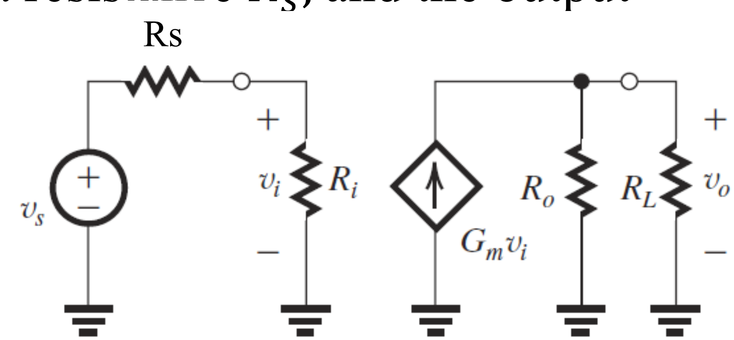


- # Exercise 1.19

Consider $\frac{v_o}{v_s}$ of a transconductance amplifier (voltage-controlled current amplifier). Let the voltage-source v_s having a resistance R_s, and the output be connected to a load resistance R_L.

$v_i = \frac{R_i}{R_s+R_i} v_s$ $\qquad$ $v_o = G_m\, v_i\, (R_o \,||\, R_L)$

Thus, $\frac{v_O}{v_S} = G_m \frac{R_i}{R_s+R_i} (R_o \,||\, R_L)$

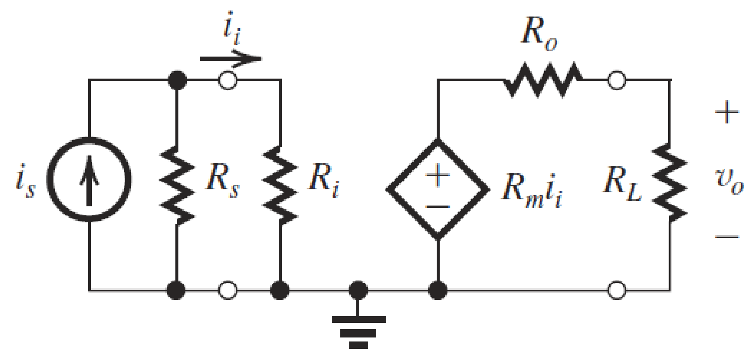


- # Exercise 1.20

Consider $\frac{v_o}{i_s}$ of a transresistance amplifier (current-controlled voltage amplifier). Let the amplifier be fed with a current-source i_s having a resistance R_s, and let the output be connected to a load resistance R_L.

$$i_i = \frac{R_s}{R_s + R_i}\, i_s \qquad v_o = \frac{R_L}{R_L + R_o} R_m\, i_i$$

Thus, $\frac{v_O}{i_S} = R_m \frac{R_L}{R_L+R_O}\frac{R_S}{R_S+R_i}$

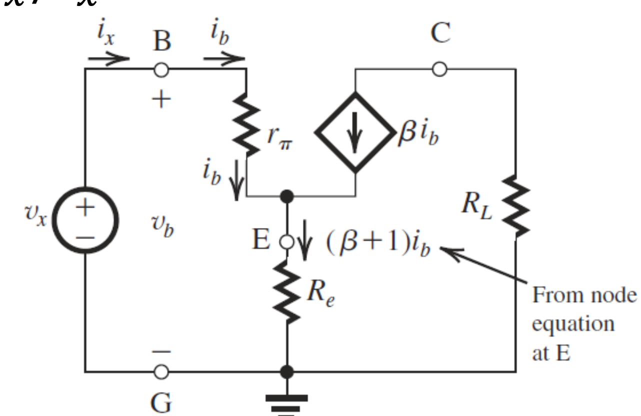


- # Exercise 1.21

Find the input resistance between B and G. The voltage v_x is a test voltage with the input resistance R_{in} defined as $R_{in} = v_x/i_x$.

$$v_x = v_b = i_b\, r_\pi + (\beta + 1)\, i_b R_e \quad i_x = i_b$$

Thus, $R_{in} = \frac{v_x}{i_x} = r_\pi + (\beta + 1)\, R_e$



1.6 Frequency Response of Amplifier

- Frequency response: (inductance, capacitance)
  - $T(j\omega) = \frac{V_o(j\omega)}{V_i(j\omega)}$
  - gain magnitude $|T(j\omega)| = |\frac{V_o(jw)}{V_i(jw)}|$ in V/V, $20\lg|T(j\omega)|$ in dB
- Low pass filter, high pass filter: the band of frequencies over which the gain is almost constant, to within 3dB.
- Single-time-constant (STC) network
  - Contains, or can be reduced to, one reactive component (inductance or capacitance) and one resistance

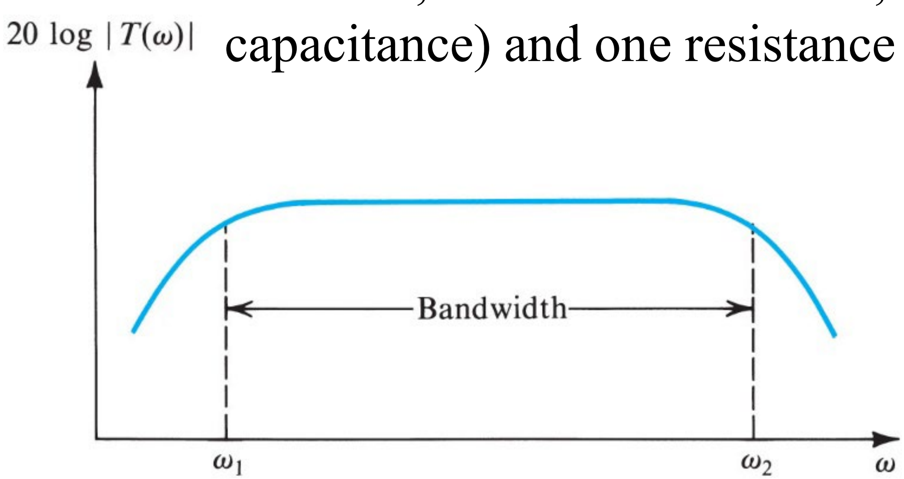
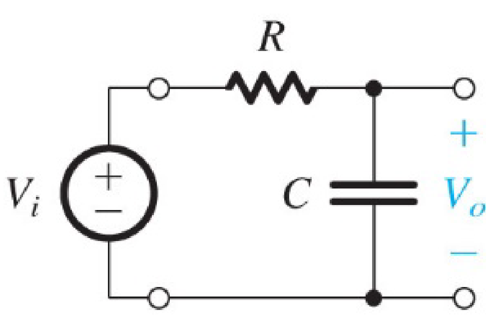


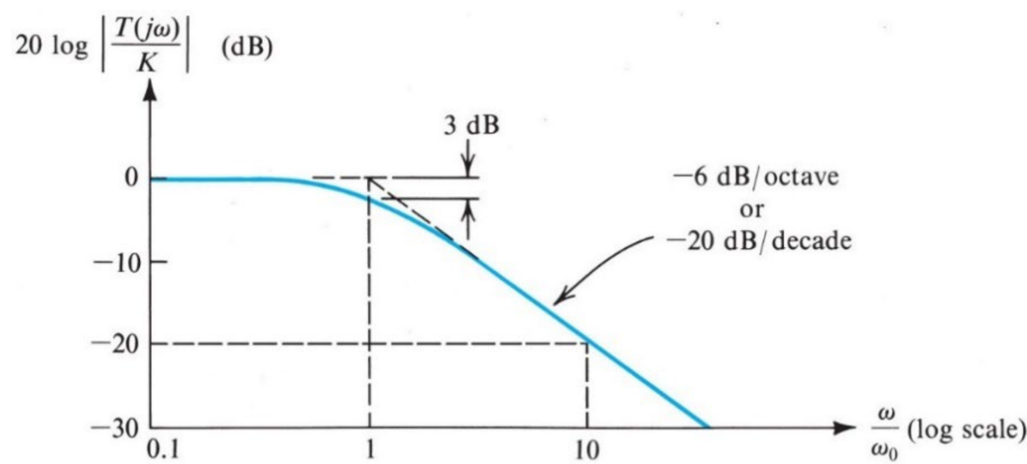
Figure 1.21 Typical magnitude response of an amplifier: $|T(\omega)|$ is the magnitude of the amplifier transfer function—that is, the ratio of the output $V_o(\omega)$ to the input $V_i(\omega)$.

- Frequency response – low pass filter
  - $T(j\omega) = \frac{1}{1+j\frac{\omega}{1/CR}} = \frac{1}{1+j\frac{\omega}{\omega_0}}$
  - **Time constant: $\tau = CR$, 3dB/cutoff/coner frequence: $\omega_0 = 1/\tau$**
  - $|T(j\omega)| = \frac{1}{\sqrt{1+\omega^2/\omega_0^2}}$, then **$20\,log(|T(j\omega)/K|)$ is d.c. gain**, in this case K is 1.
    - $\omega = 0$, 0 dB
    - $\omega = \omega_0, -3dB$
    - $\omega = 10\omega_0, -20dB$
    - $\omega = 100\omega_0, -40dB$



(a)

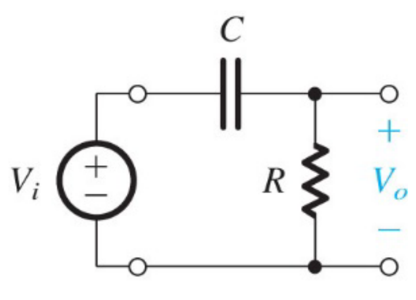
Figure 1.22 Examples of STC networks: **(a)** a low-pass filter



(a)

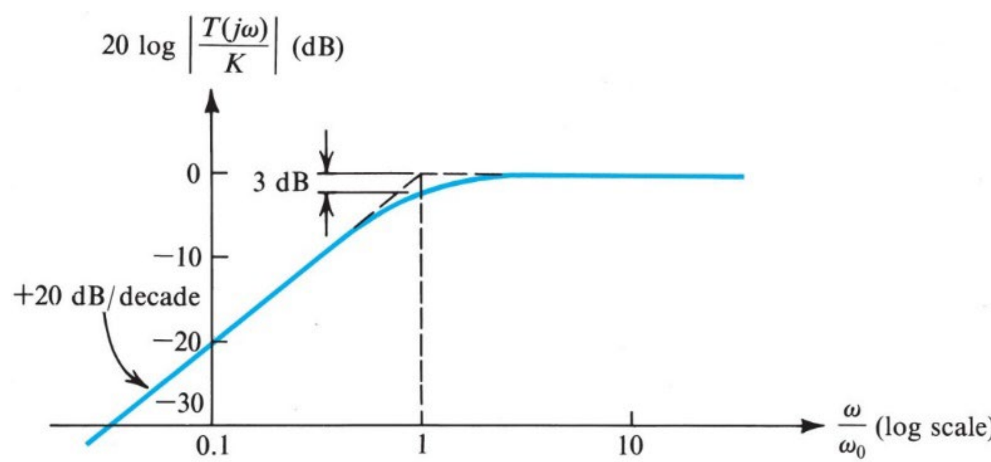
Figure 1.23 (a) Magnitude response of STC networks of the low-pass type.

- Frequency response – high pass filter
  - $T(j\omega) = \frac{1}{1 - j\frac{1/CR}{\omega}} = \frac{1}{1 - j\frac{\omega_0}{\omega}}$
  - **Time constant: $\tau = CR$, 3dB/cutoff/coner $frequence$: $\omega_0 = 1/\tau$**
  - $|T(j\omega)| = \frac{1}{\sqrt{1+\omega_0^2/\omega^2}}$, then **$20\,log(|T(j\omega)/K|)$ is d.c. gain (K=1)**
    - $\omega = \infty$, 0 dB
    - $\omega = \omega_0, -3dB$
    - $\omega = 0.1\omega_0, -20dB$
    - $\omega = 0.01\omega_0, -40dB$



(b)

Figure 1.22 Examples of STC networks: **(b)** a high-pass filter.



(a)

Figure 1.24 (a) Magnitude response of STC networks of the high-pass type.

- Procedure:
  - Find transfer function
    - Matching the function: LP or HP
    - Find the d.c gain: K (V/V) or **$20\,log(|T(j\omega)/K|)$ starting at 0 dB**
    - Find the 3dB ***frequence***: $\boldsymbol{\omega_0 = 1/\tau}$ in rads/s
  - Draw the magnitude response graph (the slop will be 20dB/decade)

Table 1.2 Frequency Response of STC Networks

	Low-Pass (LP)	High-Pass (HP)
Transfer Function $T(s)$	$\frac{K}{1+(s/\omega_0)}$	$\frac{Ks}{s+\omega_0}$
Transfer Function (for physical frequencies) $T(j\omega)$	$\frac{K}{1+j(\omega/\omega_0)}$	$\frac{K}{1-j(\omega_0/\omega)}$
Magnitude Response $\|T(j\omega)\|$	$\frac{\|K\|}{\sqrt{1+(\omega/\omega_0)^2}}$	$\frac{\|K\|}{\sqrt{1+(\omega_0/\omega)^2}}$
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. 1.23	in Fig. 1.24

Alternative way to find time constant $\boldsymbol{\tau}$:
1) Set voltage or current source to zero;
2) Grab hold two terminals of the capacitor or inductor
3) Equivalent resistance R between theses two terminals. Then, $\tau = \frac{L}{R}, or\ \tau = CR$

- # Example 1.5
  - Input resistance (R_i), capacitance (C_i), gain factor(μ), output resistance (R_O). Voltage source (V_S *and* R_S), load resistance (R_l)

(a) Find voltage gain ($\frac{V_o}{V_s}$) as a function of frequency. From this find expression for the dc gain and the 3-dB frequency.

$$Z_i = R_i || \frac{1}{jwC_i} = \frac{R_i}{1+jwC_iR_i}$$

$$\frac{V_i}{V_s} = \frac{Z_i}{Z_i + R_s} = \frac{\frac{R_i}{1 + jwC_iR_i}}{\frac{R_i}{1 + jwC_iR_i} + R_s} = \frac{R_i}{R_s + R_i} \frac{1}{1 + j\omega / \frac{R_s + R_i}{C_iR_sR_i}}$$

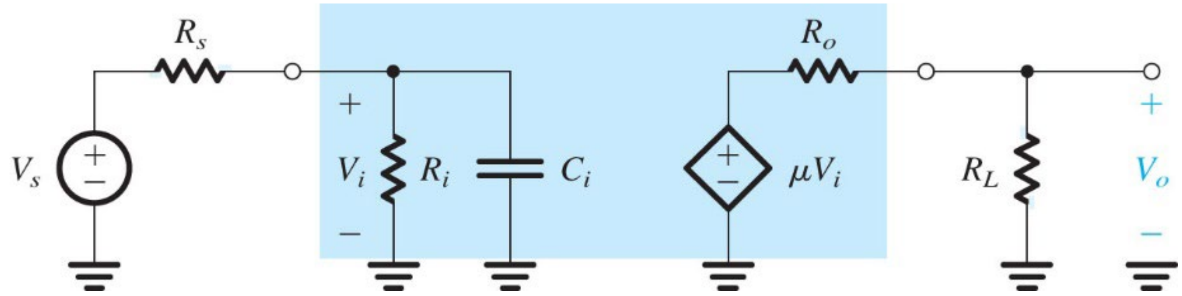


Figure 1.25 Circuit for Example 1.5.

• Example 1.5 Cont.

At the load side, we have $V_o = \mu V_i \frac{R_L}{R_L+R_o}$, so

$$\frac{V_o}{V_s} = \mu \frac{R_L}{R_L + R_o} \frac{\frac{R_i}{R_s + R_i}}{1 + jwC_i \frac{R_s R_i}{R_s + R_i}} = \mu \frac{R_L}{R_L + R_o} \frac{R_i}{R_s + R_i} \frac{1}{1 + j\omega / \frac{R_s + R_i}{C_i R_s R_i}}$$

(Standard form for a low-pass filter/STC network)

Alternative way: Find equivalent resistance as $R_s // R_i$, $\tau = C_i (R_s // R_i)$

The DC gain is $\frac{V_o}{V_s}(w = 0) = \mu \frac{R_L}{R_L+R_o} \frac{R_i}{R_s+R_i}$

The 3-dB frequency $\omega_0 = 1/\tau = 1/C_i (R_s // R_i)$

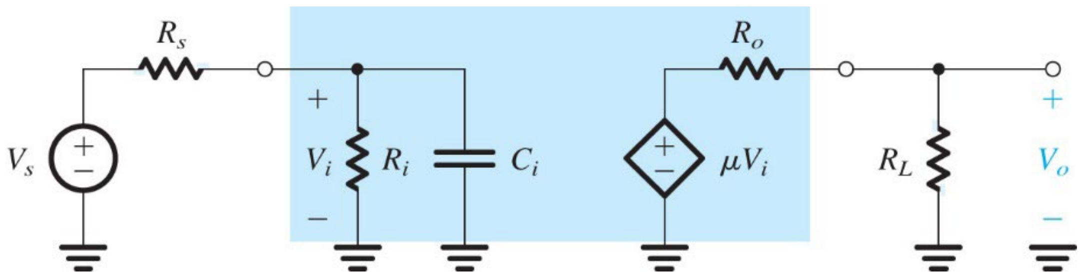


Figure 1.25 Circuit for Example 1.5.

- # Example 1.5 Cont.

(b) Find the values of the dc gain, the 3-dB frequency, and the frequency at which the gain becomes 0dB for the case $R_S = 20K\Omega, R_i = 100K\Omega, C_i = 60pF, \mu = 144, R_o = 200\Omega, R_L = 1K\Omega$

$$\frac{V_o}{V_s} = \mu \frac{R_L}{R_L + R_o} \frac{R_i}{R_s + R_i} \frac{1}{1 + j\omega / \frac{R_s + R_i}{C_i R_s R_i}}$$

(i) $\quad \text{k} = \frac{V_o}{V_s}(w = 0) = 144 \times \frac{1}{1+0.2} \times \frac{100}{100+20} = 100\ V/V$ (or 40dB)

(ii) $\omega_0 = \frac{20K\Omega + 100K\Omega}{60pF \times 20K\Omega \times 100K\Omega} = \frac{(20+100)\times 10^3}{60 \times 10^{-12} \times 20 \times 100 \times 10^6} = 10^6 rad/s$

Thus, $f_0 = 10^6/2\pi$=159.2kHz

(iii) Since the gain falls off at the rate of -20dB/decade, the gain will reach 0dB in 2 decades, thus, unity gain frequency =

$100\omega_0 = \frac{10^8 rad}{s}$ or15.92MHz

- Experiment 1

1) Do frequency sweep till change in A_V start to occur (using both oscilloscope and bode plotter)
2) At what frequency ($w_0 = 2\pi f_0$) does $A_V = 0.707$ (or -3db)

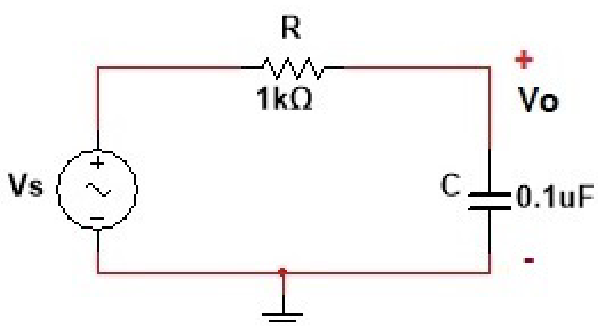


Table 1.2 Frequency Response of STC Networks

	Low-Pass (LP)	High-Pass (HP)
Transfer Function $T(s)$	$\frac{K}{1+(s/\omega_0)}$	$\frac{Ks}{s+\omega_0}$
Transfer Function (for physical frequencies) $T(j\omega)$	$\frac{K}{1+j(\omega/\omega_0)}$	$\frac{K}{1-j(\omega_0/\omega)}$
Magnitude Response $\lvert T(j\omega)\rvert$	$\frac{\lvert K\rvert}{\sqrt{1+(\omega/\omega_0)^2}}$	$\frac{\lvert K\rvert}{\sqrt{1+(\omega_0/\omega)^2}}$
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. 1.23	in Fig. 1.24

Frequency	100Hz	300Hz	1kHz	?	10kHz	100kHz	1MHz
$V_{o(P-P)}$							
A_V $(\frac{V}{V})$							
A_V (db)							

- # Experiment 2

1) Do frequency sweep till change in A_V start to occur (using both oscilloscope and bode plotter)
2) At what frequency does $A_V = 0.5 \times 0.707$ (or $-6db - 3db = -9db$)

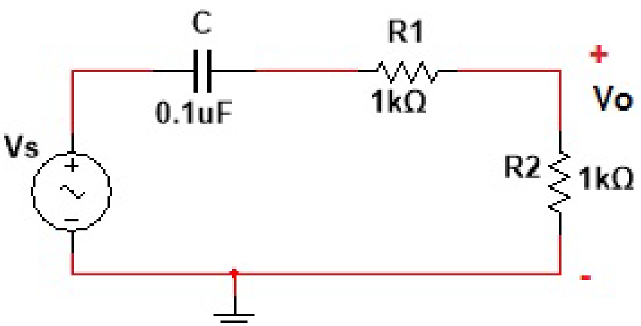


Table 1.2 Frequency Response of STC Networks

	Low-Pass (LP)	High-Pass (HP)
Transfer Function $T(s)$	$\frac{K}{1+(s/\omega_0)}$	$\frac{Ks}{s+\omega_0}$
Transfer Function (for physical frequencies) $T(j\omega)$	$\frac{K}{1+j(\omega/\omega_0)}$	$\frac{K}{1-j(\omega_0/\omega)}$
Magnitude Response $\lvert T(j\omega)\rvert$	$\frac{\lvert K\rvert}{\sqrt{1+(\omega/\omega_0)^2}}$	$\frac{\lvert K\rvert}{\sqrt{1+(\omega_0/\omega)^2}}$
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. 1.23	in Fig. 1.24

Frequency	100Hz	300Hz	1kHz	?	10kHz	100kHz	1MHz
$V_{o(P-P)}$							
$A_V\ (\frac{V}{V})$							
$A_V\ (db)$							

HW1

- Problems:
  - PP.47, 1.19 – Circuits analysis
  - PP.48, 1.21 – AC circuits
  - PP.50, 1.43 – Circuit models for amplifiers
  - PP.54, 1.68 – Frequency response of amplifiers

- Submission requirement:
  - Add the cover page!!!
  - Print the HW1.pdf out and answer all the questions (download on the blackboard)