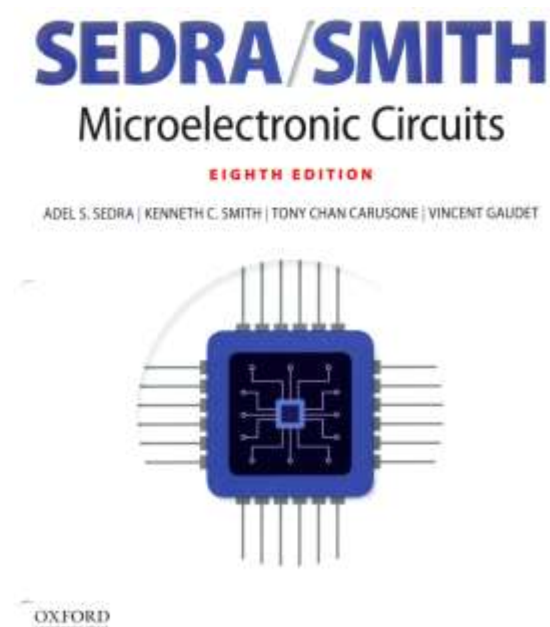

SEDRA/SMITH
Microelectronic Circuits
EIGHTH EDITION
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OXFORD

Chapter #1: Signals and Amplifiers

from **Microelectronic Circuits** Text
by Sedra and Smith
Oxford Publishing

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Introduction

- **IN THIS CHAPTER YOU WILL LEARN…**
  - That electronic circuits process signals, and thus **understanding electrical signals** is essential to appreciating the material in this book.处理信号的电路，因此，理解“什么是电信号”是基础
  - The Thevenin and Norton **representations of signal sources**.信号源的戴维南和诺顿表示
  - The representation of a signal as sum of sine waves.信号可以由一些列的正弦信号叠加而构成
  - The analog and digital representations of a signal.模拟信号与数字信号

Introduction

- **IN THIS CHAPTER YOU WILL LEARN…**
  - The most basic and pervasive signal-processing function: signal amplification, and correspondingly, the **signal amplifier**. 最为基础和普遍的信号处理——信号放大，以及相应的电路——信号放大器
  - How amplifiers are characterized (modeled) as circuit **building blocks** independent of their internal circuitry. 理解放大器的行为模型，不**care**内部实现
  - How the frequency response of an amplifier is measured, and how it is calculated, especially in the simple but common case of a **single-time-constant (STC)** type response.放大器的频率响应

1.1. **Signals**

- **signal** – contains information 信号——包含有用信息
  - e.g. voice of radio announcer reading the news
- **process** – an operation which allows an observer to understand this information from a signal (extract information from signal) 处理——从信号从提取信息的运算
  - generally done electrically
- **transducer** – device which converts signal from non-electrical to electrical form 换能器——将非电信号转换为电信号
  - e.g. microphone (sound to electrical)

1.1: **Signals**

- **Q:** How are signals represented? 信号表示形式
  - **A: thevenin form** – voltage source $\mathbf{v}_s(t)$ with series resistance R_S
    - **preferable when R_S is low**
  - **A: norton form** – current source $\mathbf{i}_s(t)$ with parallel resistance R_S
    - **preferable when R_S is high**
  - 电压信号一般内阻较小，用戴维南；
  - 电流信号一般内阻较大，用诺顿；

1.1. Signals

信号源的两种表示形式

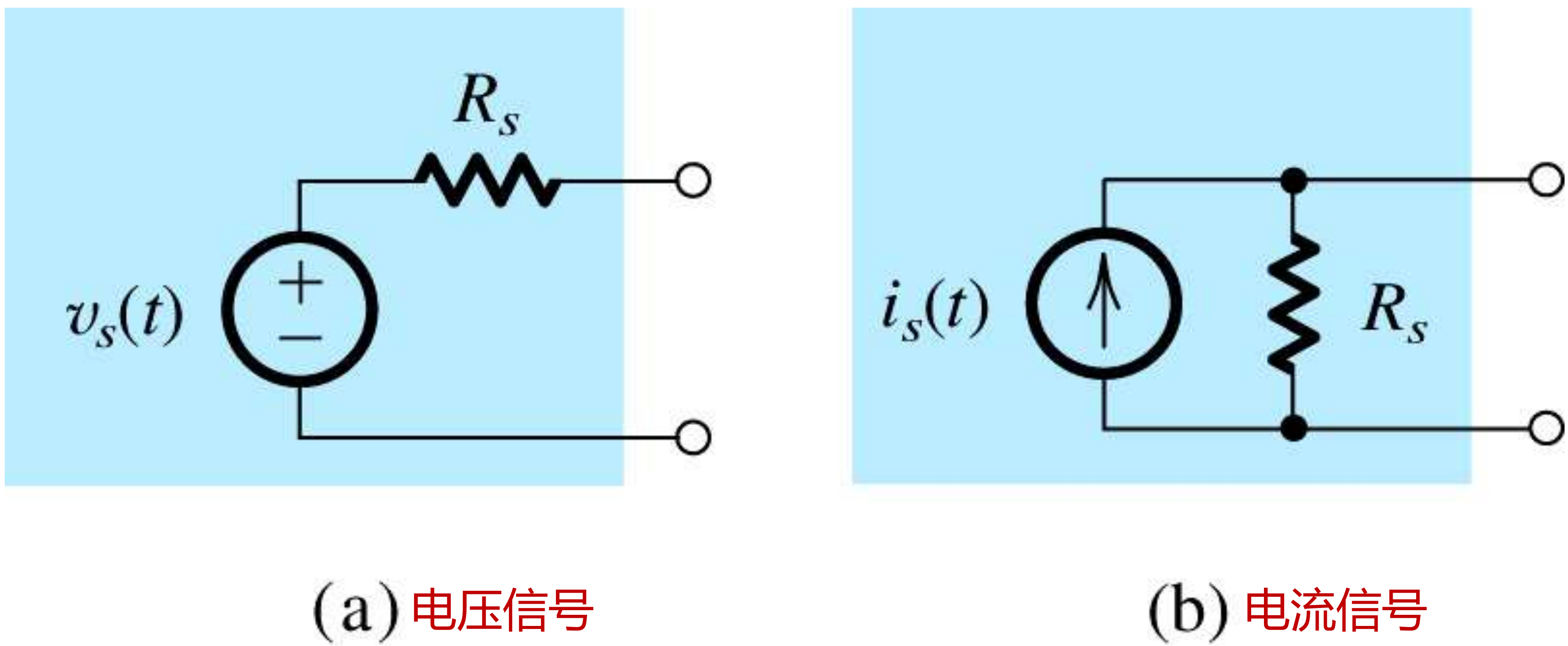
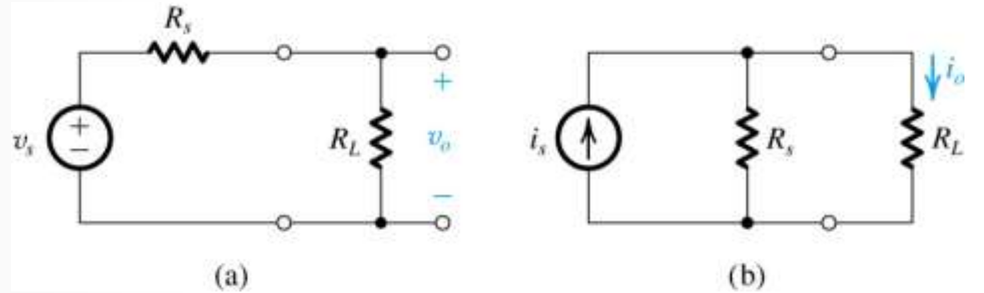


Figure 1.1: Two alternative representations of a signal source: **(a)** the Thévenin form; **(b)** the Norton form.

Example 1.1: Thevenin and Norton Equivalent Sources



输出电阻：从输出端看进去的等效电阻，限制着信号实际到达负载的多少

- Consider two source / load combinations to upper-right.
  - note that **output resistance** of a source limits its ability to deliver a signal at full strength (分压/分流)
- **Q(a):** what is the relationship between the source and output when maximum power is delivered?
  - 共轭匹配
- **Q(b):** what are ideal values of R_S for norton and thevenin representations?
  - 电压源~小内阻；电流源~大内阻

$v_o \simeq v_s \implies R_s \ll R_L$ $\qquad$ $i_o \simeq i_s \implies R_s \gg R_L$

并不是所有情况，我们都希望最大功率传输。对于原本就比较微弱的信号，我们更关心电压（或电流）强度衰减的最小化，或者说更关心电压/电流强度的放大

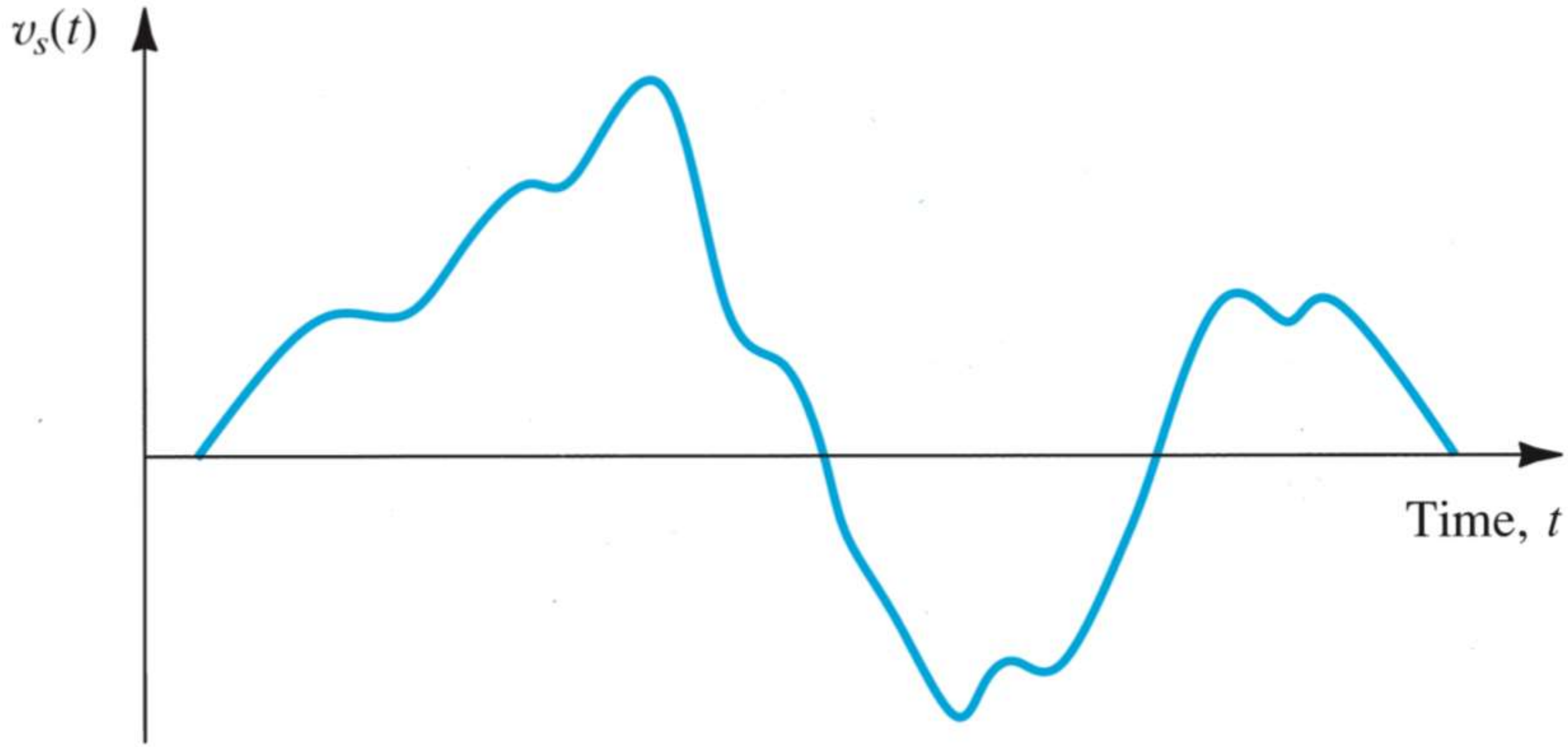


Figure 1.3 An arbitrary voltage signal $v_s(t)$.

一个任意的电压信号

- 幅度的变化包含了信息
- 难以写出解析表达式
- 一个信号可以有两个 views：
  - 时域 ←→ 频域

1.2. Frequency Spectrum of Signals

- **frequency spectrum** 频谱 – The frequency spectrum of an electrical signal is the **distribution** of the amplitudes and phases of each frequency component against frequency. 时域信号在频域里的表达
- **Q:** What is a Fourier Series? 傅里叶级数
  - **A:** An expression of a **periodic function** as the sum of an infinite number of sinusoids whose frequencies are harmonically related 周期信号可以表达成无限个正弦信号的和，且这些正弦信号的频率呈谐波关系

Fourier Series Example

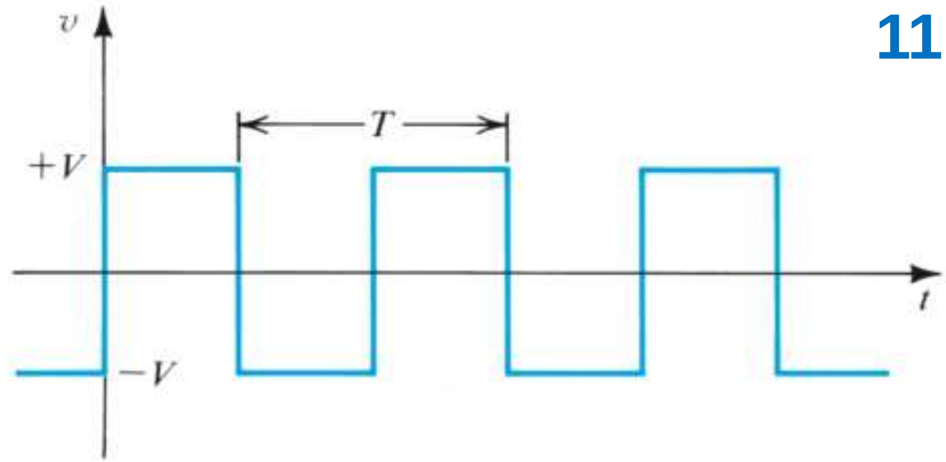
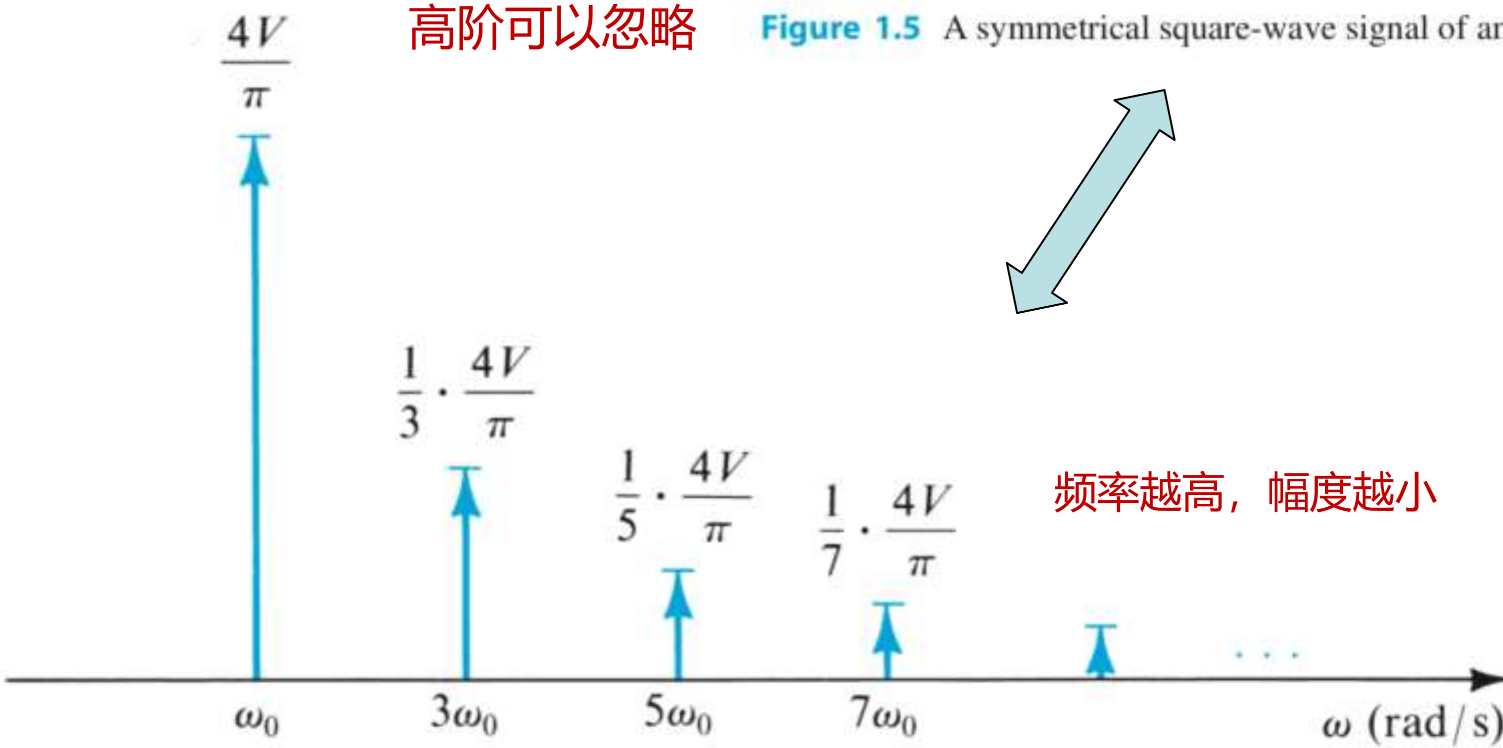


Figure 1.5 A symmetrical square-wave signal of amplitude V.

$$v(t) = \frac{4V}{\pi}\left(\sin \omega_0 t + \frac{1}{3}\sin 3\omega_0 t + \frac{1}{5}\sin 5\omega_0 t + \cdots\right)$$

高阶可以忽略



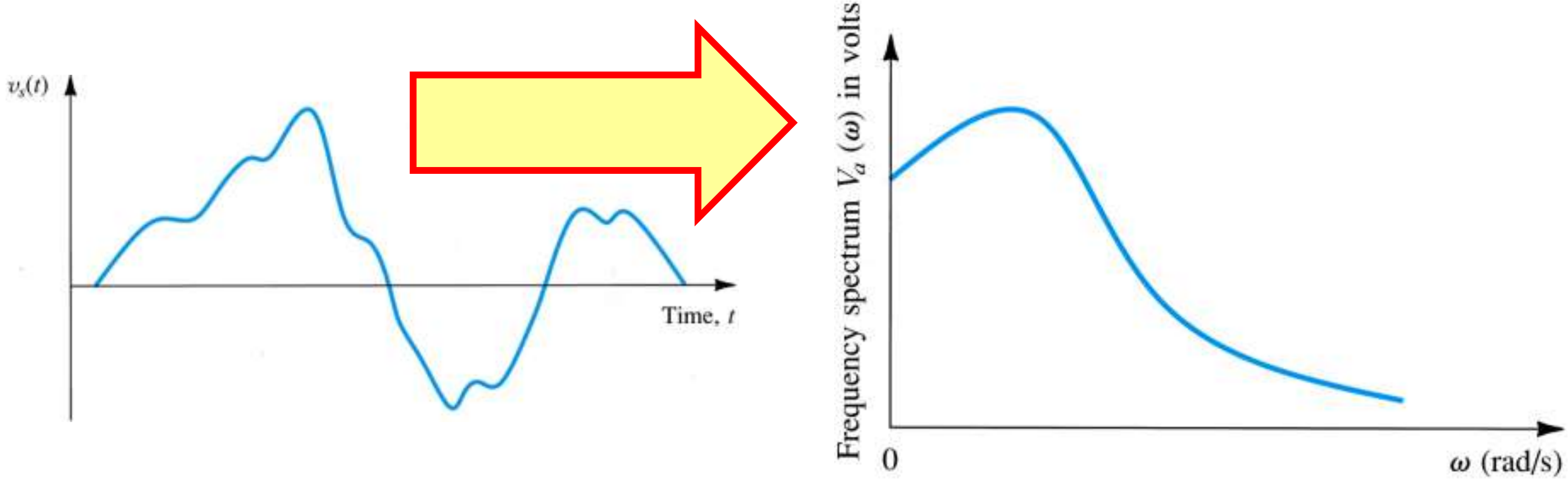
频率越高，幅度越小

Figure 1.6 The frequency spectrum (also known as the **line spectrum**) of the periodic square wave of Fig. 1.5.

1.2. **Frequency Spectrum of Signals**

- **周期**信号 → **离散**频谱
- **非周期**信号 → **连续**频谱

- **Q:** Can the Fourier Transform be applied to a non-periodic function of time?
  - **A:** Yes, however (as opposed to a discrete frequency spectrum) it will yield a continuous…



1.3. Analog and Digital Signals

- **analog signal (模拟信号)** – is continuous with respect to both value and time 时间和数值都连续变化
- **discrete-time signal (离散时间信号)** – is continuous with respect to value but sampled at discrete points in time 在离散的时间点上对模拟信号进行抽样
- **digital signal (数字信号)** – is quantized (applied to values) as well as sampled at discrete points in time 对离散时间信号的数值进行量化/数字化

时间和幅度上都是离散

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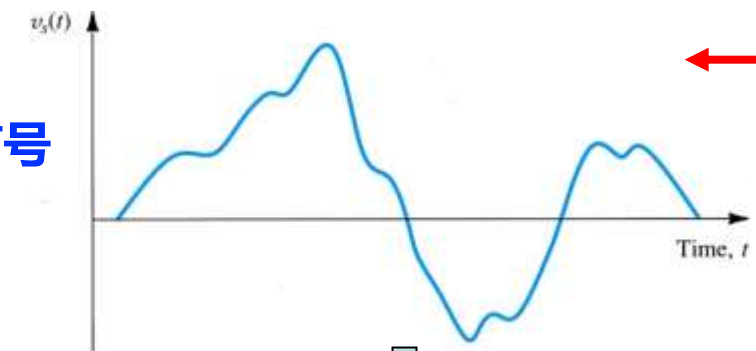
1.3. Analog and Digital Signals

analog signal

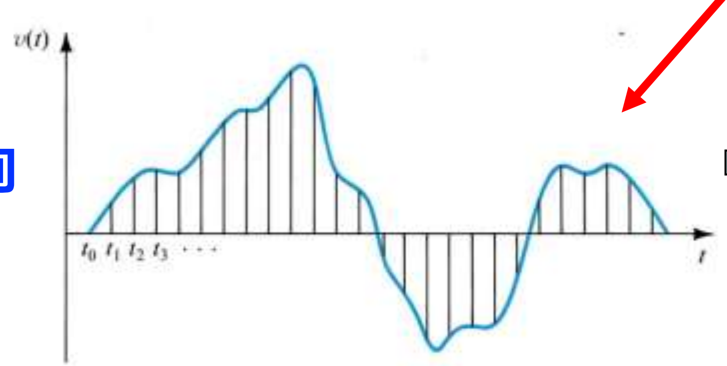
discrete-time signal

digital signal

模拟信号

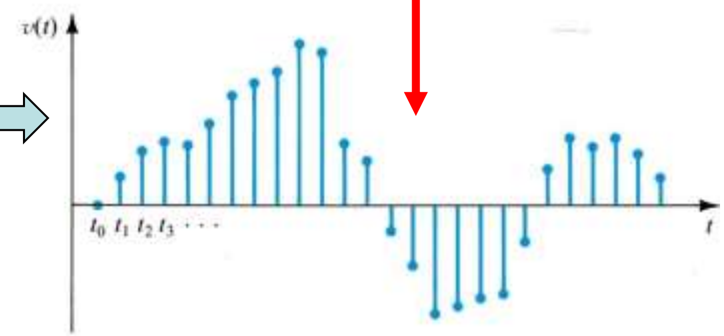


离散时间信号



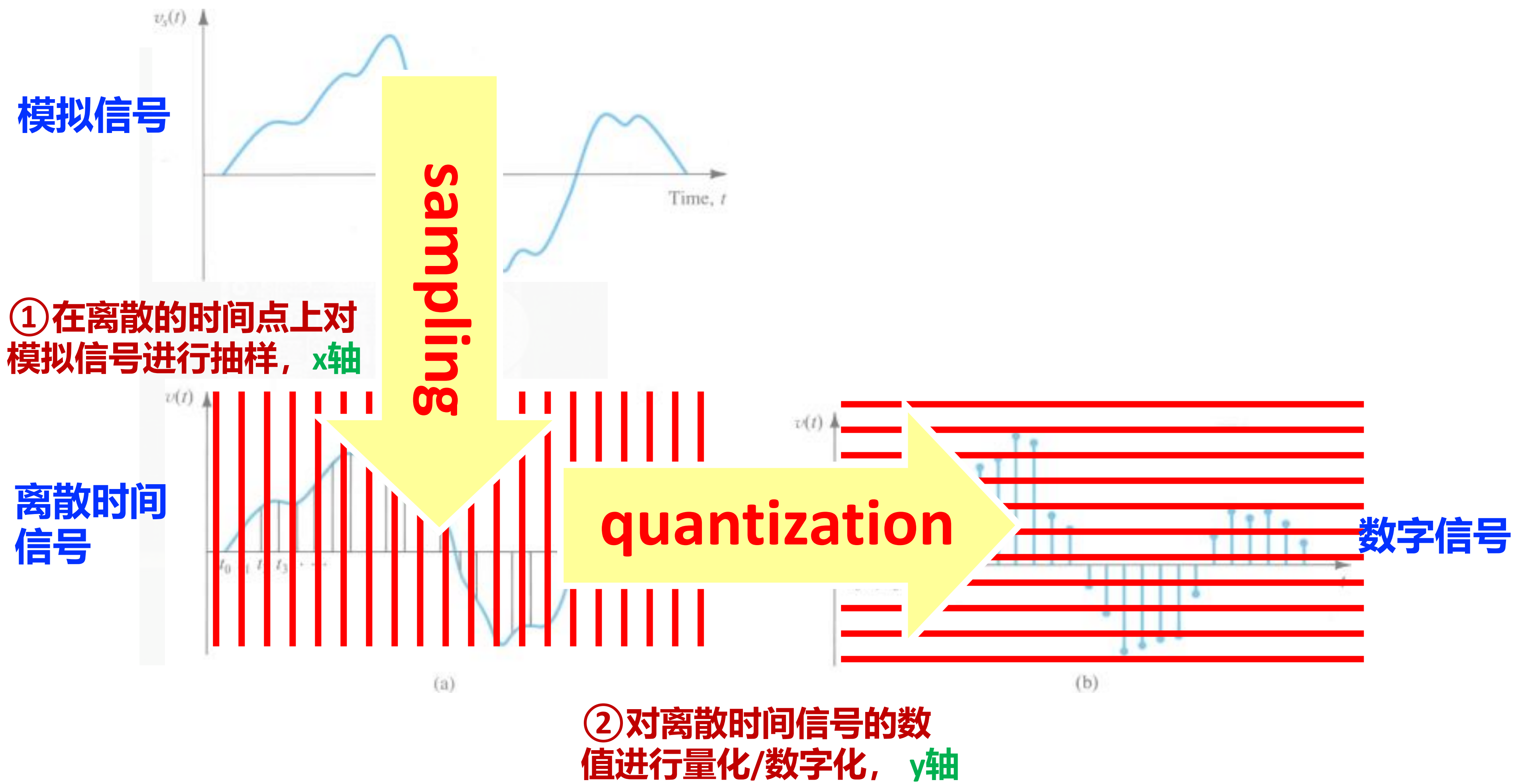
(a)

数字信号

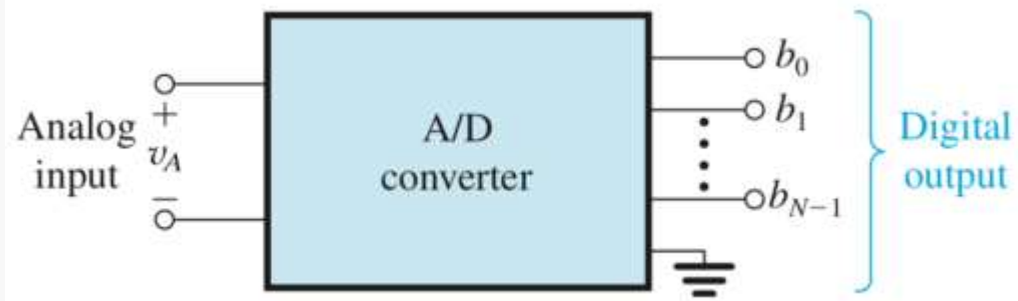


(b)

1.3. Analog and Digital Signals

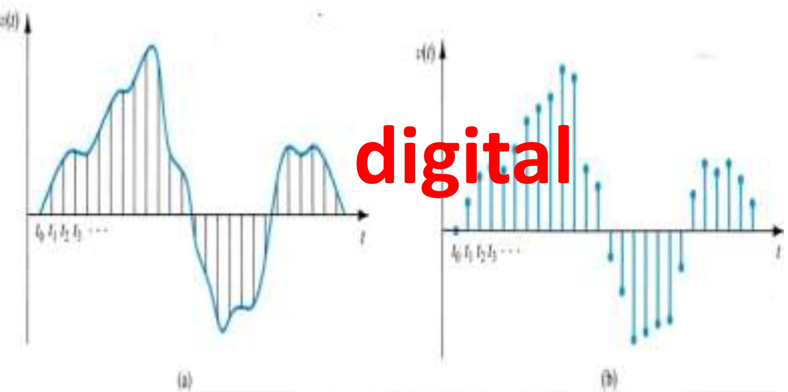


1.3. **Analog and Digital Signals**

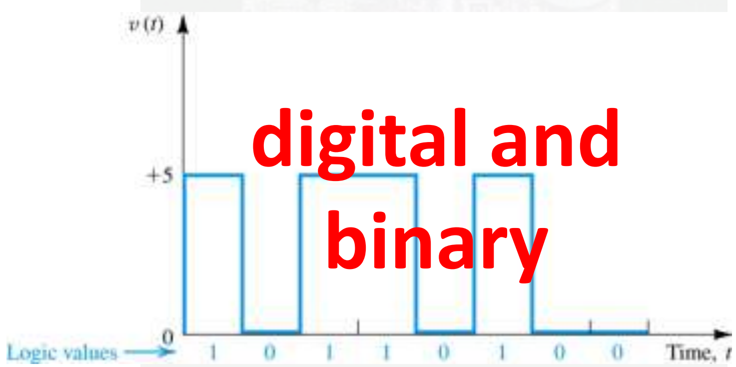


“数字信号”和“二进制信号”是同义词吗？

- **Q:** Are digital and binary synonymous?
  - **A: No.** The binary number system ($base_2$) is one way to represent digital signals.



digital



digital and binary

“二进制信号”是“数字信号”的特例

Representation of a Binary Number

Most Significant Bit
最高位

Least Significant Bit
最低位

MSB	Binary Digit							LSB
2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
256	128	64	32	16	8	4	2	1

Decimal Digit Value	256	128	64	32	16	8	4	2	1
Binary Digit Value	1	0	1	1	0	0	1	0	1

101100101_2

⇩

$(256) + (64) + (32) + (4) + (1) = 357_{10}$

$$\overbrace{y = b_0 2^0 + b_1 2^1 + b_2 2^2 + \ldots}^{\text{base 10} \leftarrow \text{base 2}}$$

LSB

$$\ldots + b_3 2^3 + \ldots b_{n-1} 2^{n-1}$$

MSB

二进制数值 → 十进制数值

1.4. **Amplifiers 放大器**

- **Q:** Why is signal amplification needed?为何需要信号放大?
  - **A:** Because many transducers yield output at low power levels (*mW*) 信号源（换能器产生的电信号）的初始信号往往幅度很小
- **linearity (线性度)**– is property of an amplifier which ensures a signal is not “altered” from amplification
- **Distortion (失真)** – is any unintended change in output

1.4.1. Signal Amplification

- **voltage amplifier** – is used to boost voltage levels 目的是增加信号的电压幅度

$$\overbrace{\mathbf{v}_o(t) = A_v \mathbf{v}_i(t)}^{\text{output / input relationship for amplifier}}$$

voltage gain

- **power amplifier** – is used to boost power levels 目的是增加信号的功率，提供中等程度的电压增益，但提供大幅的电流增益

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1.4.2. **Amplifier Circuit Symbol** 放大器的符号

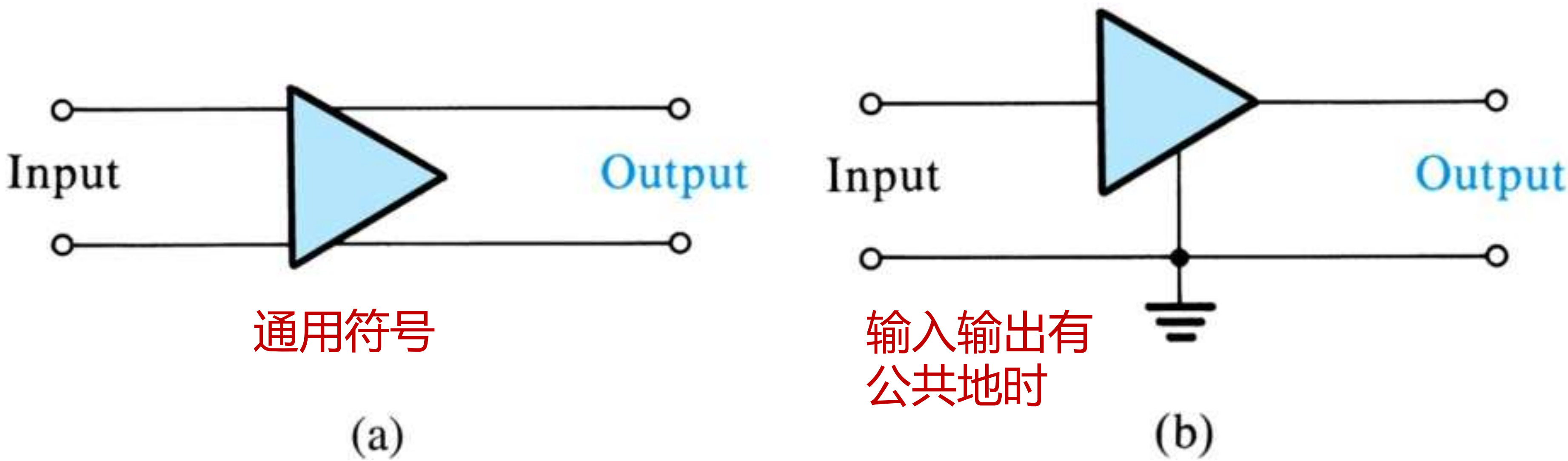


Figure 1.11: (a) Circuit symbol for amplifier. **(b)** An amplifier with a common terminal (ground) between the input and output ports.

1.4.4. **Power and Current Gain**

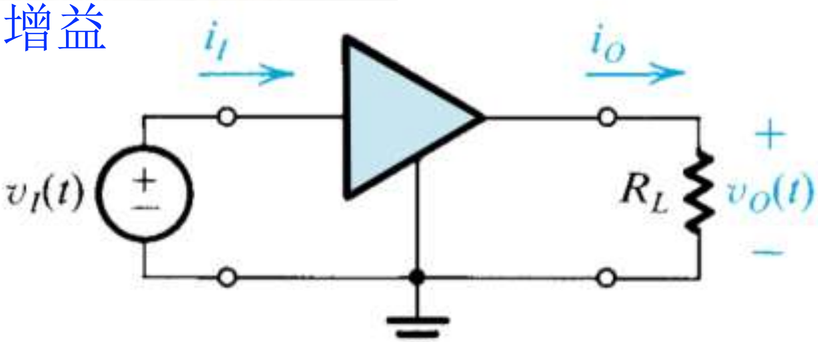
放大器和变压器的主要区别是什么？两者都能改变电压幅度

- **Q:** What is one main difference between an amplifier and transformer? …Because both alter voltage levels.
  - **A:** Amplifier may be used to **boost** power delivery.

$$power\ gain\ (A_p) = \frac{load\ power\ (P_L)}{input\ power\ (P_I)} = \frac{v_o i_o}{v_i i_i}$$

power delivers to the load / power draws from the signal source

变压器没有功率增益



$$\text{Current gain } (A_i) \equiv \frac{i_O}{i_I}$$

$$A_p = A_v A_i$$

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1.4.5. Expressing Gain in Decibels

- **Q:** How may gain be expressed in **decibels**?

电子工程中，常常将一个无量纲的比值，如电压增益、功率增益等，用对数的形式（以10为底）表述。这是工程惯例, **功率乘以10，电压电流乘以20**

$$\text{voltage gain in decibels} = 20\ \mathbf{log}\left|A_v\right| dB$$

$$\text{current gain in decibels} = 20\ \mathbf{log}\left|A_i\right| dB$$

$$\text{power gain in decibels} = 10\ \mathbf{log}(A_p) dB$$

A_V为负表示相位相差180度，并非表示信号衰减；
而dB值若为负，则表示信号衰减！ **1:1 ~ 0 dB**

Using dB

Commonly used (and easy to remember) dB values:

+10 dB = 10 times the power
-10 dB = one tenth power
+3 dB = double power
-3 dB = half the power

For example:

some power + 10 dB = 10 times the power
some power - 10 dB = one tenth power
some power + 3 dB = double power
some power - 3 dB = half the power

dBm and mW

- What if we want to measure an absolute power with dB? We **have to define a reference**. 指定一个参考功率作为分母，就可以用 dB 来表示功率的绝对值（常常用1mW作为参考值）
- The reference point that relates the logarithmic dB scale to the linear watt scale may be for example this:

m 指以 1mW 为参考功率

$$1\ \text{mW} \rightarrow 0\ \text{dBm}$$

- The new **m** in dBm refers to the fact that the reference is one **m**W, and therefore a **dBm** measurement is a measurement of absolute power with reference to 1 mW. dBm表示以1mW为参考值的功率绝对值

dBm and mW

- To convert power in mW to dBm:

$$P_{dBm} = 10 \log_{10} P_{mW}$$

10 times the *logarithm in base 10* of the "Power in mW"

- To convert power in dBm to mW:

$$P_{mW} = 10^{\,P_{dBm}/10}$$

10 *to the power of* ("Power in dBm" divided by 10)

dBm and mW

- Example: mW to dBm

  Radio power: 100mW

  $P_{dBm} = 10 \log_{10}(100)$

  100mW → 20dBm

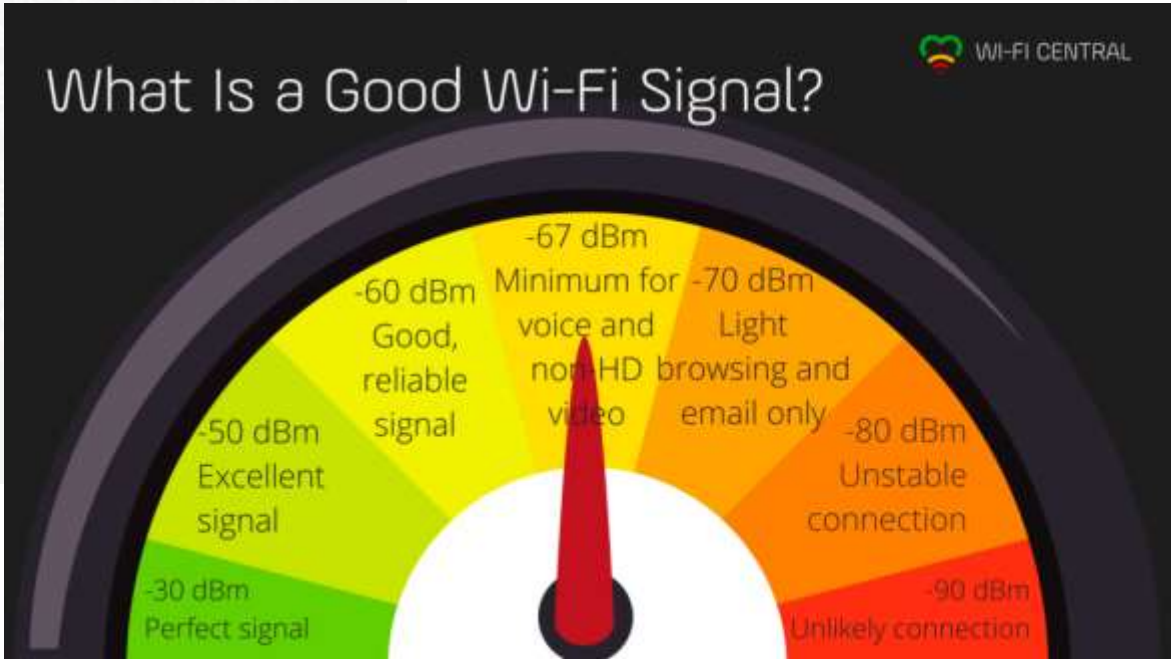
- Example: dBm to mW

  Signal measurement: 17dB

  $P_{mW} = 10^{17/10}$

  17dBm → 50 mW

26



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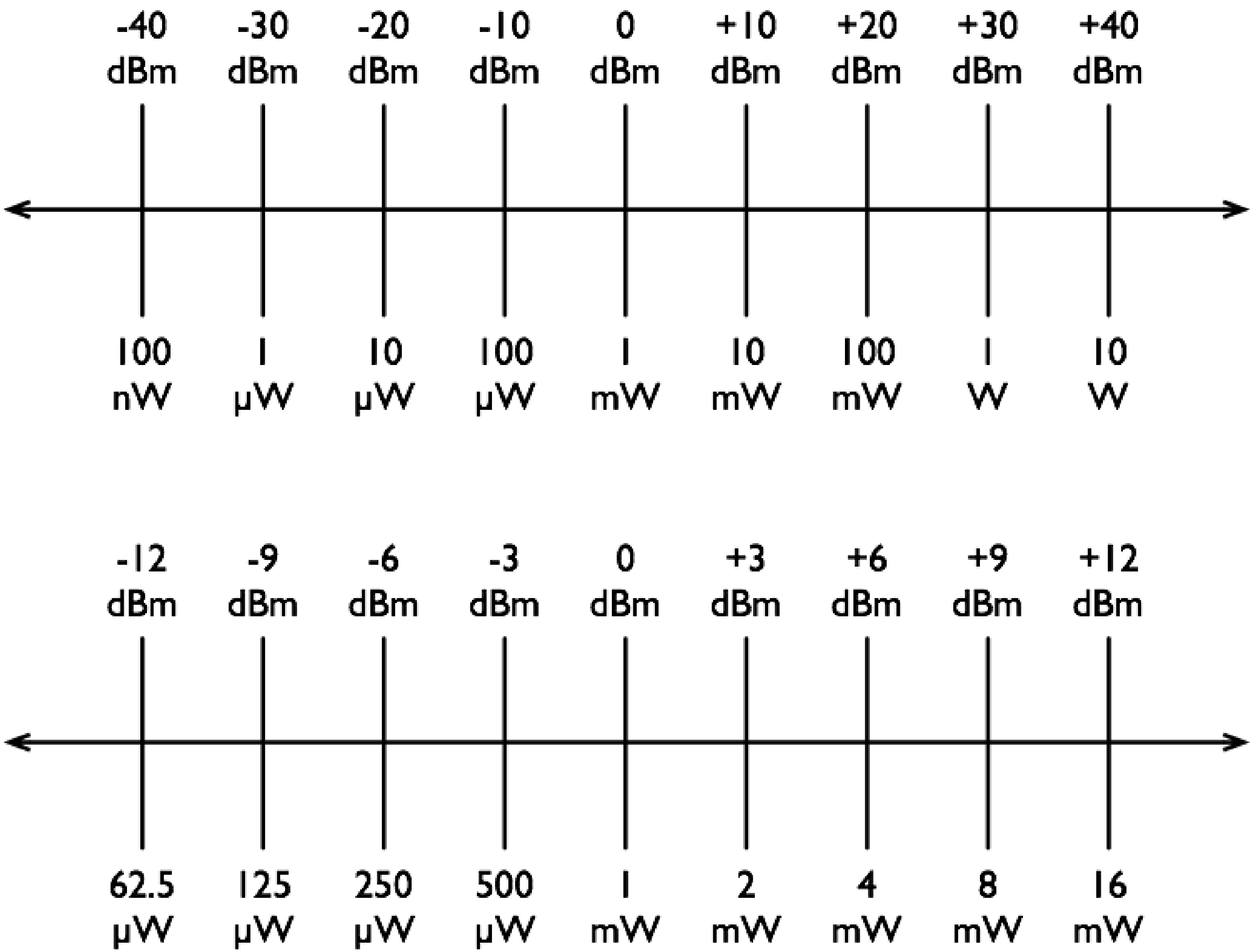
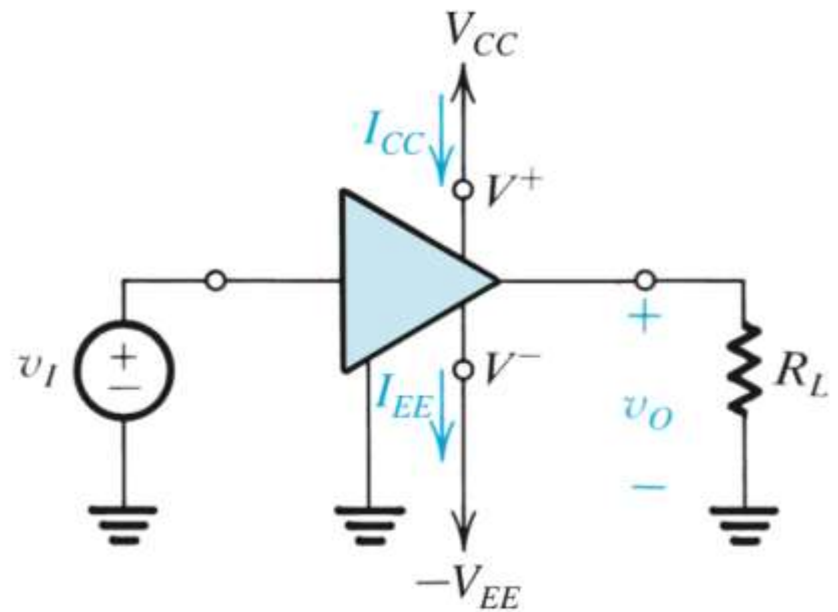
Using dB



1.4.6. **Amplifier Power Supply** 放大器供电

- **supplies** – an amplifier has two power supplies
  - V_{CC} is **positive**, current I_{CC} is drawn
  - $-V_{EE}$ is **negative**, current I_{EE} is drawn
- **power draw** – from these supplies is defined below
  - $P_{dc} = V_{CC} I_{CC} + V_{EE} I_{EE}$

The "CC" relates to the "**c**ollector" of an npn, bipolar transistor.
Similarly, "EE" relates to the **e**mitter of an npn, bipolar transistor.

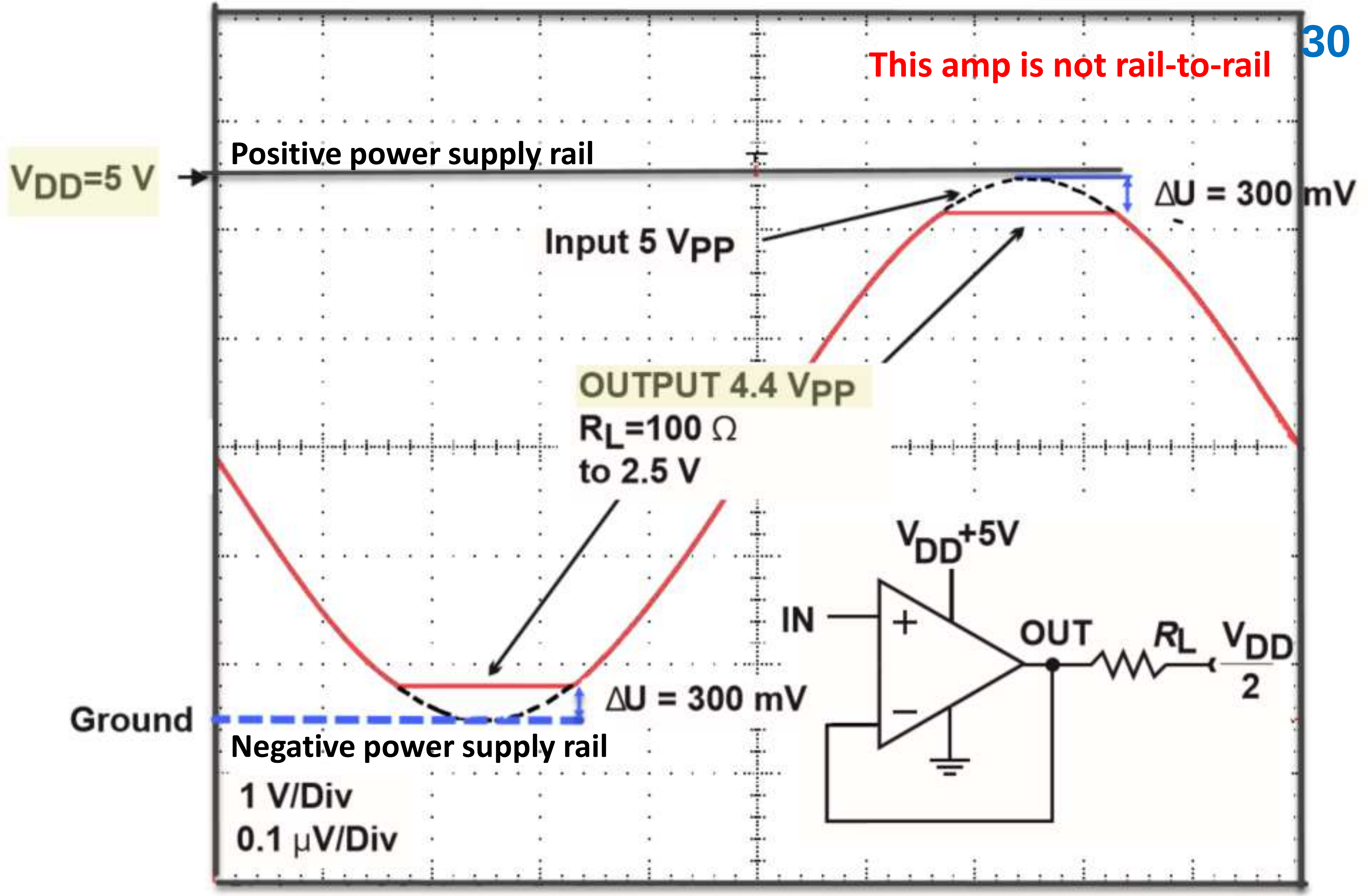


1.4.6. Amplifier Power Supply

- **conservation of power** （功率守恒） – dictates that power input (P_i) plus that drawn from supply (P_{dc}) is equal to output (P_L) plus that which is dissipated (P_{dis}).
  - $P_i + P_{dc} = P_L + P_{dissapated}$
- **efficiency** （效率） – is the ratio of power output to input.
  - efficiency = $P_L / (P_i + P_{dc})$
  - 因为**P_i往往非常小**，所以：

$$\eta \equiv \frac{P_L}{P_{\mathrm{dc}}} \times 100$$

Efficiency η = (Power delivered to the load)/(Power supplied to Amplifier).



swing: 电压摆幅

rail: 电源轨； **rail-to-rail**: 轨到轨，输入/输出电压摆幅非常接近于电源轨

1.4.6. **Amplifier Power Supply**

Symmetric ± power supplies allow the inputs/outputs to swing symmetrically +/- and signals can approach the “rails”.

对称的正负电源供电，可以使输入输出信号围绕“0 V”有对称的摆幅

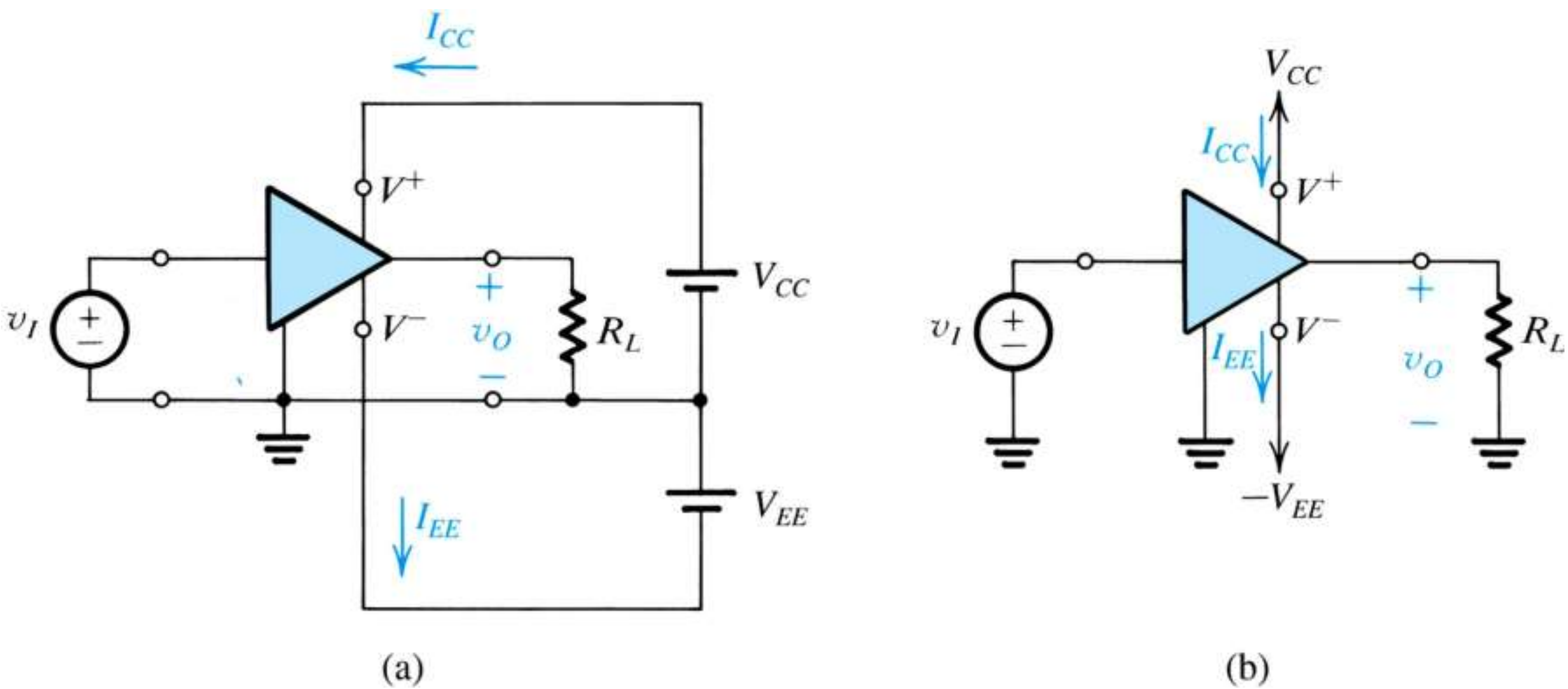


Figure 1.13: An amplifier that requires two dc supplies (shown as batteries) for operation.

Consider a microphone producing a sinusoidal signal that is 400-mV peak. It delivers 10-μA peak sinusoidal current to an amplifier that operates from ±1-V power supplies. The amplifier delivers a 0.8-V peak sinusoid to a speaker load with 32-Ω resistance. The amplifier draws a current of 30 mA from each of its two power supplies. 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.

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

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

$$A_i = \frac{\hat{I}_o}{\hat{I}_i} = \frac{25\ \text{mA}}{0.01\ \text{mA}} = 2500\ \text{A/A, or } A_i = 20\log 2500 = 68\ \text{dB}$$

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

$$P_I = V_{i\text{rms}} I_{i\text{rms}} = \frac{0.4\ \text{V}}{\sqrt{2}}\,\frac{0.01\ \text{mA}}{\sqrt{2}} = 2\ \mu\text{W}$$

$$A_p(\text{dB}) \neq A_v(\text{dB}) + A_i(\text{dB})$$

Why?

$$A_p = \frac{P_L}{P_I} = \frac{10\ \text{mW}}{2\ \mu\text{W}} = 5000\ \text{W/W, or } A_p = 10\log 5000 = 37\ \text{dB}$$

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

$$A_p(\text{dB}) = \frac{1}{2}[A_v(\text{dB}) + A_i(\text{dB})]$$

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

注意，加减还要把Pi算入

$$= 60\ \text{mW} + 0.002\ \text{mW} - 10\ \text{mW} \simeq 50\ \text{mW}$$

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

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1.4.7. Amplifier Saturation

- **limited linear range** – practically, amplifier operation is linear over a limited input range.
- **saturation (饱和)**– beyond this range, saturation occurs.
  - output remains constant as input varies

$$\underbrace{\frac{L_{minus}}{A_v} \leq v_i \leq \frac{L_{plus}}{A_v}}_{\text{or...}}$$

输入范围 = 输出范围/增益

or...

$L_{minus} \leq v_o \leq L_{plus}$

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1.4.7. Amplifier Saturation

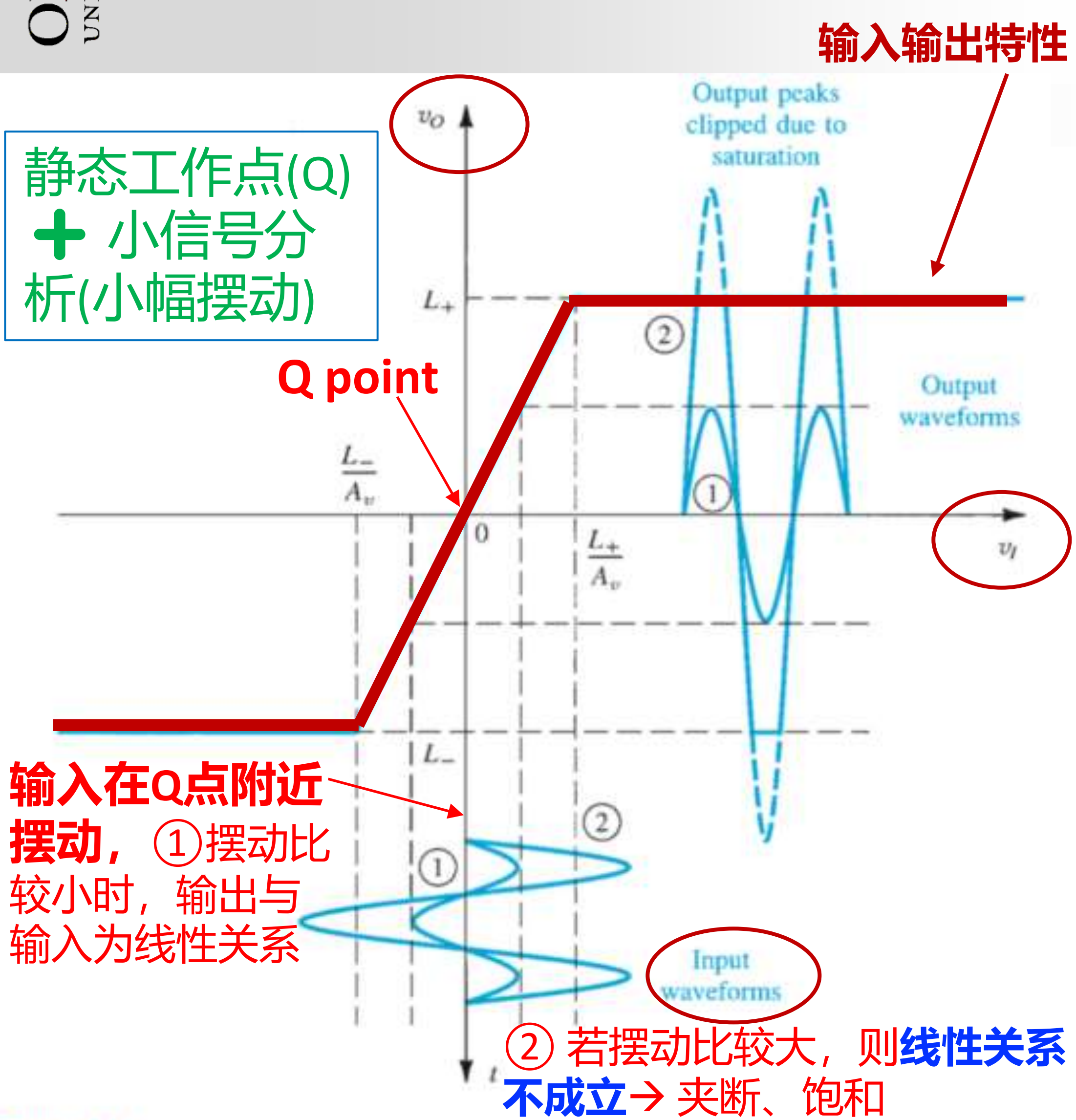


Figure 1.14 An amplifier transfer characteristic that is linear except for output saturation.

In our previous work (LTI systems), the world was **assumed to be linear** so that "superposition" could be used.

The **real world is non-linear** and we must learn to deal with it.

We can always do a "**Small Signal Analysis**" where an **assumption of linearity is still reasonably accurate.**

The slope of the device operational curve(s) at the "**Quiescent Point**" **determines the small signal parameters**.

This set of curves indicate that there would be "soft clipping" of the signal as the output signal approached the "rails".

符号规范

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

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

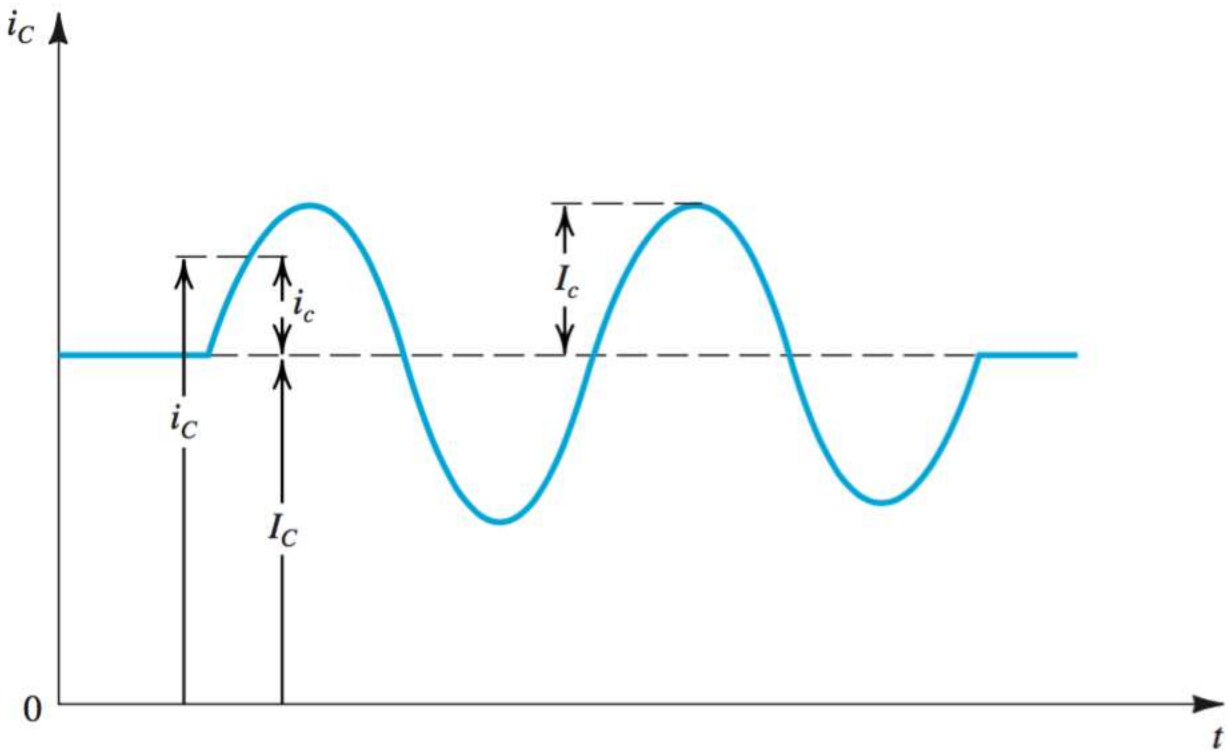


Figure 1.15 Symbol convention employed throughout the book.

- ① 小写$_{大写}$：瞬时总量
- ②大写$_{大写}$：直流量
- ③小写$_{小写}$：瞬时增量（交流量）
- ④大写$_{小写}$：正弦量的幅度

1.5. Circuit Models for Amplifiers 放大器的电路模型

- **model** – is the description of component's (e.g. amplifier) terminal behavior
  - neglecting internal operation / transistor design

Modelling is about building representations of things in the 'real world', and it is a way of expressing a particular view of an identifiable system of some kind.

物理模型：从器件背后的物理机理出发，推导出具有物理意义的数学表达式，用来表征该器件的特性；

等效电路模型：用电路的形式来等效器件的特性，电路参数不一定要具有物理意义。

1.5.1. **Voltage Amplifiers**

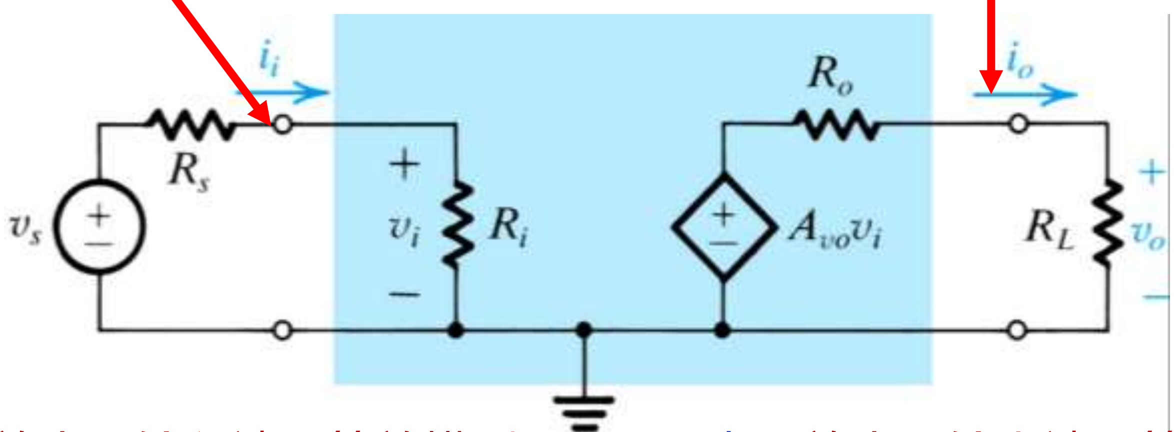
This assumes linear behavior. Amplifiers can exhibit non-linear behavior as well.

model of amplifier input terminals

$$\text{input voltage} = v_i = \underbrace{(v_s)}_{\text{source volt.}} \underbrace{\frac{R_i}{R_i + R_s}}_{\text{source and input resistances}}$$

model of amplifier output terminals

$$\text{output voltage} = v_o = \underbrace{(A_{vo} v_i)}_{\text{open-ckt output voltage}} \underbrace{\frac{R_L}{R_L + R_o}}_{\text{output and load resistances}}$$



(b)

Turn off 独立源v_s

电压放大器输入端口等效模型

输入端口看进去的等效电阻? R_i

电压放大器输出端口等效模型

输出端口看进去的等效电阻? R_o

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1.5.1. **Voltage Amplifiers**

- **Q:** How can one model the amplifier behavior from previous slide?
  - **A:** Model which is function of: v_s, A_{vo}, R_i, R_s, R_o, R_L

$$v_o = \underbrace{\left(\underbrace{A_{vo} (v_s)}_{\text{source volt.}} \underbrace{\frac{R_i}{R_i + R_s}}_{\text{source and input resistances}} \right)}_{\text{open-ckt output voltage}} \underbrace{\frac{R_L}{R_L + R_o}}_{\text{output and load resistances}} = A_{vo} v_s \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o}$$

1.5.1. **Voltage Amplifiers**

- **Q:** What is one "problem" with this behavior?
  - **A:** Gain (ratio of v_o and v_s) is not constant, and dependent on input and load resistance.电压增益受输入电阻**R$_i$**和输出电阻**R$_o$**的影响

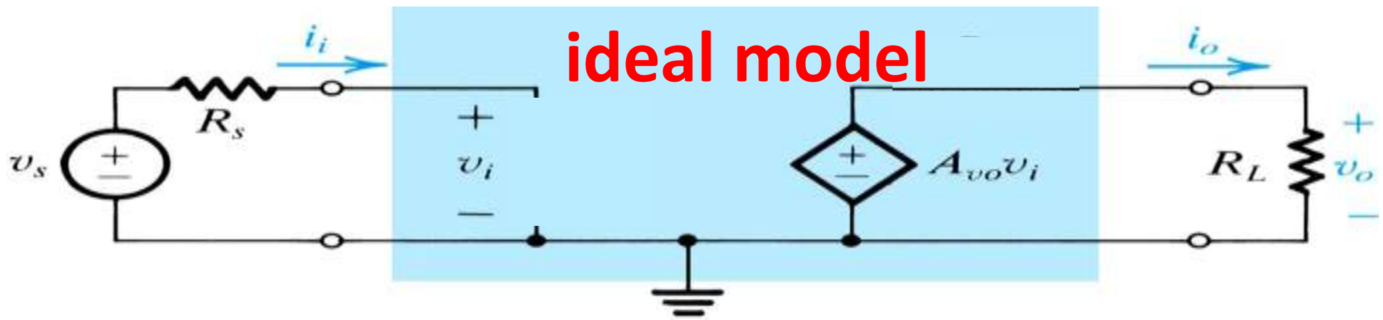
$$v_o = \underbrace{\left(\underbrace{A_{vo}\,(v_s)}_{\text{source volt.}} \underbrace{\frac{R_i}{R_i + R_s}}_{\text{source and input resistances}} \right)}_{\text{open-ckt output voltage}} \underbrace{\frac{R_L}{R_L + R_o}}_{\text{output and load resistances}} = A_{vo} v_s \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o}$$

1.5.1. **Voltage Amplifiers**

- **ideal amplifier model** – is function of v_s and A_{vo} only!!
  - It is assumed that $R_o << R_L$…
  - It is assumed that $R_s << R_i$…

$$\frac{v_o}{v_s} = A_{vo}$$

理想电压放大器的电压增益



key characteristics of ideal voltage amplifier model = high input impedance, low output impedance理想电压放大器：输入电阻∞，输出电阻为0

1.5.1. **Voltage Amplifiers**

- **ideal amplifier model** – is function of v_s and A_{vo} only!!
  - It is assumed that $R_o << R_L$...
  - It is assumed that $R_s << R_i$...

$$v_o = \underbrace{A_{vo} v_s \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o}}_{\text{non-ideal model}} = \underbrace{A_{vo} v_s}_{\text{ideal model}}$$

key characteristics of ideal voltage amplifier model = source resistance R_S and load resistance R_L have no effect on gain

Buffer amplifier
缓冲放大器

如果R_L较小，而信号的R_s较大，则不能直接将两者相连（直接驱动），Why?

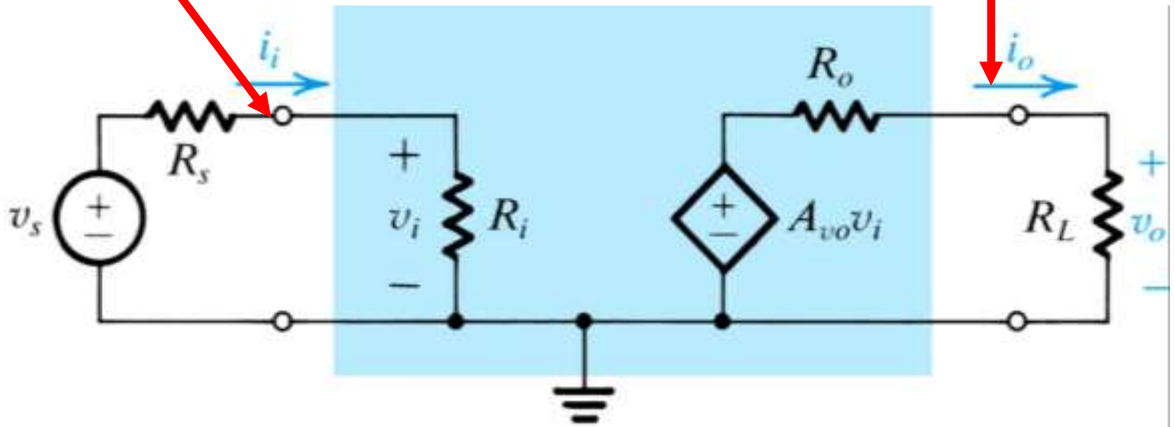
我们可以插入一个 **buffer amplifier**，其输入阻抗=∞；输出阻抗=0，而增益Av并不作要求。

model of amplifier input terminals

$$\text{input voltage} = v_i = \underbrace{(v_s)}_{\text{source volt.}} \frac{R_i}{\underbrace{R_i + R_s}_{\text{source and input resistances}}}$$

model of amplifier output terminals

$$\text{output voltage} = v_o = \underbrace{(A_{vo} v_i)}_{\text{open-ckt output voltage}} \frac{R_L}{\underbrace{R_L + R_o}_{\text{output and load resistances}}}$$



(b)

1.5.2. **Cascaded Amplifiers 放大器级联**

- In real life, an amplifier is not ideal and will not have infinite input impedance or zero output impedance. 实际情况，输入阻抗可能不是∞，输出阻抗也可能不是**0** → 可以通过级联来解决
- **Cascading** of amplifiers, however, may be used to emphasize desirable characteristics.
  - first amplifier – high R_i, medium R_o
  - last amplifier – medium R_i, low R_o
  - aggregate – high R_i, low R_o

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Example 1.3: Cascaded Amplifier Configurations

- Examine system of cascaded amplifiers on next slide.
- **Q(a):** What is overall voltage gain?
- **Q(b):** What is overall current gain?
- **Q(c):** What is overall power gain?

aggregate amplifier

with gain

$$A_v = \frac{v_L}{v_s - i_i R_s}$$

Example 1.3

Figure 1.17 depicts an amplifier composed of a cascade of three stages. The amplifier is fed by a signal source with a source resistance of 100 kΩ and delivers its output into a load resistance of 100 Ω. The first stage has a relatively high input resistance and a modest gain factor of 10. The second stage has a higher gain factor but lower input resistance. Finally, the last, or output, stage has unity gain but a low output resistance. We wish to evaluate the overall voltage gain, that is, v_L/v_s, the current gain, and the power gain.

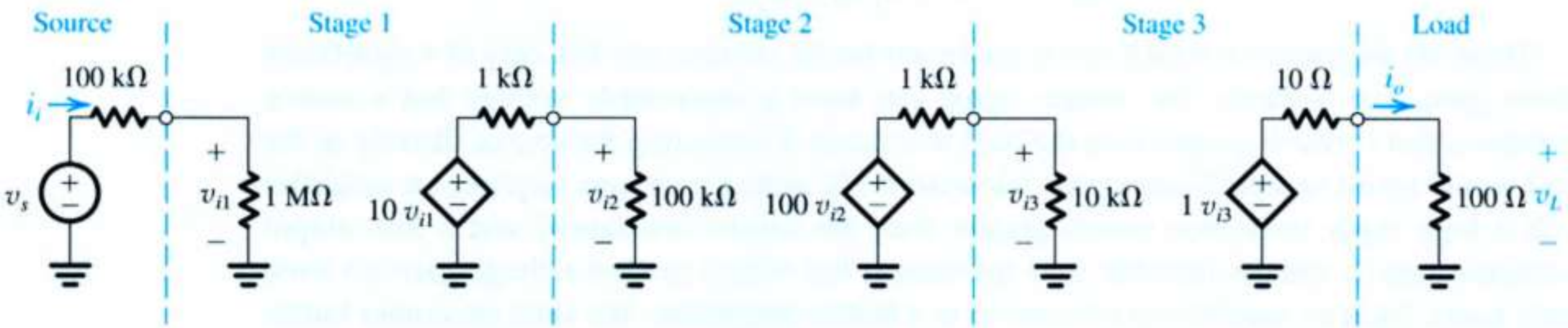
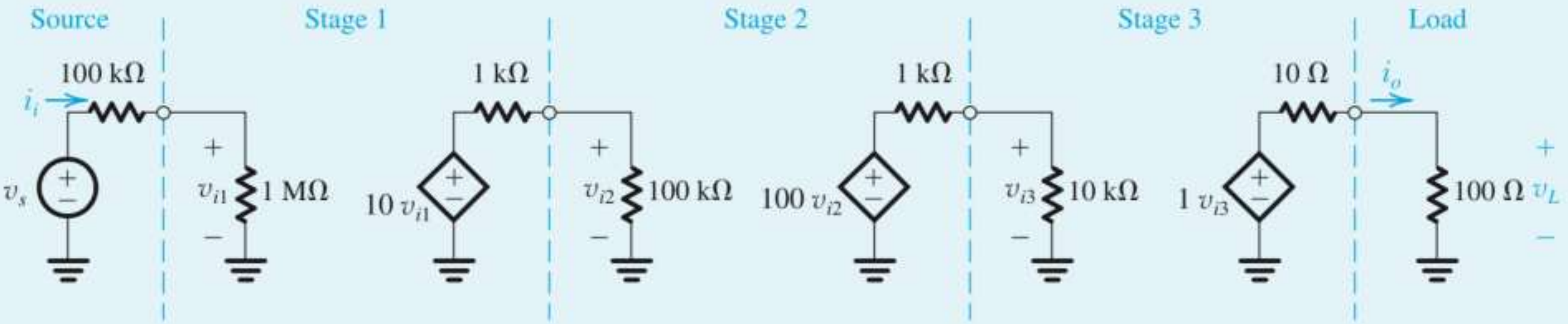


Figure 1.17 Three-stage amplifier for Example 1.3.

Example 1.3 *continued*



$$\frac{v_{i1}}{v_s} = \frac{1\ \text{M}\Omega}{1\ \text{M}\Omega + 100\ \text{k}\Omega}$$

$$A_{v1} \equiv \frac{v_{i2}}{v_{i1}} = 10\frac{100\ \text{k}\Omega}{100\ \text{k}\Omega + 1\ \text{k}\Omega}$$

$$A_{v2} \equiv \frac{v_{i3}}{v_{i2}} = 100\frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 1\ \text{k}\Omega}$$

$$A_{v3} \equiv \frac{v_L}{v_{i3}} = 1\frac{100\ \Omega}{100\ \Omega + 10\ \Omega} = 0.909\ \text{V/V}$$

$$A_v \equiv \frac{v_L}{v_{i1}} = A_{v1}A_{v2}A_{v3} = 818\ \text{V/V}$$

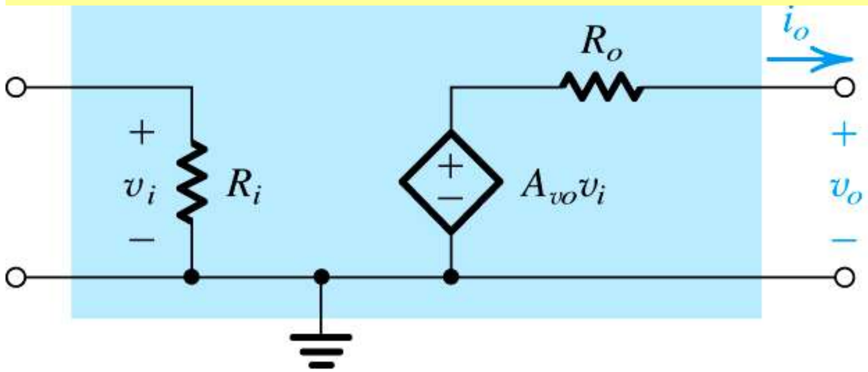
$$\frac{v_L}{v_s} = \frac{v_L}{v_{i1}}\frac{v_{i1}}{v_s} = A_v\frac{v_{i1}}{v_s}$$

$$A_i \equiv \frac{i_o}{i_i} = \frac{v_L/100\ \Omega}{v_{i1}/1\ \text{M}\Omega}$$

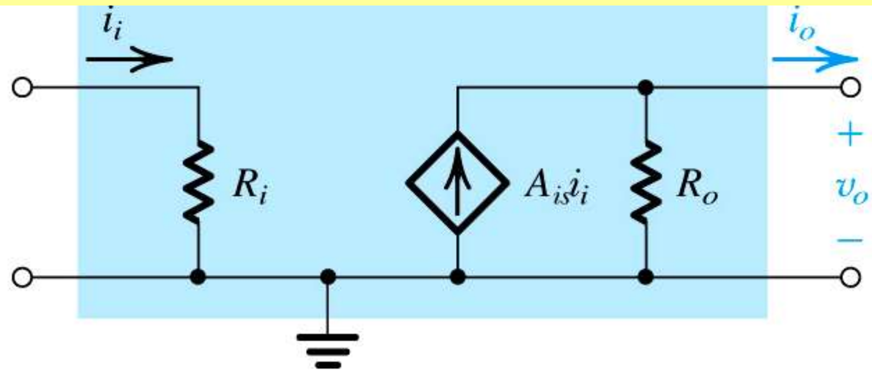
$$A_p \equiv \frac{P_L}{P_I} = \frac{v_L i_o}{v_{i1} i_i}$$

1.5.3. **Other Amplifier Types**

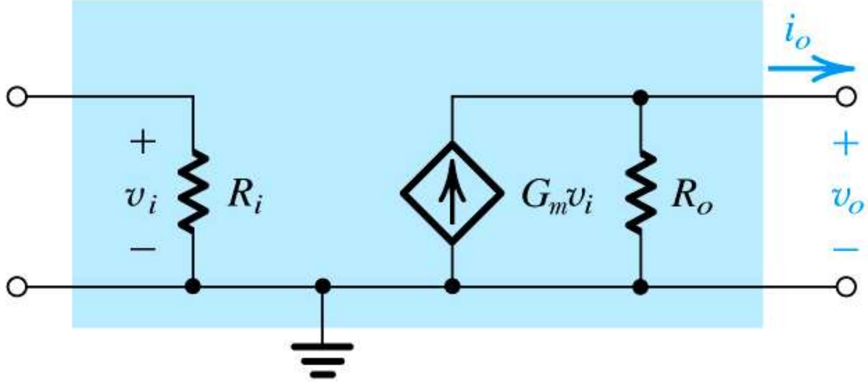
voltage amplifier



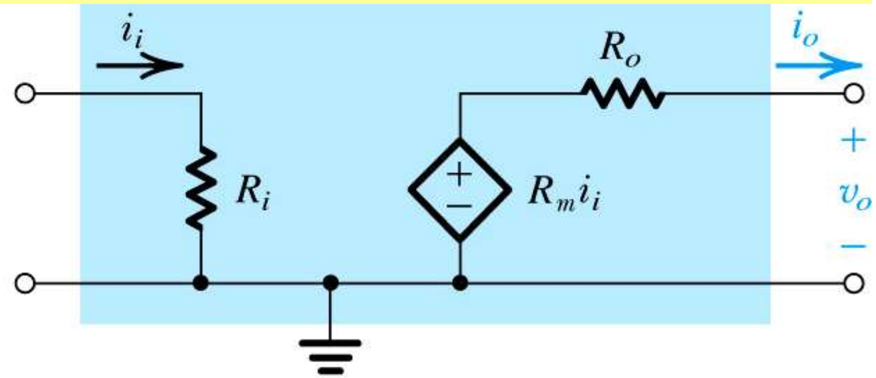
current amplifier



transconductance amp.

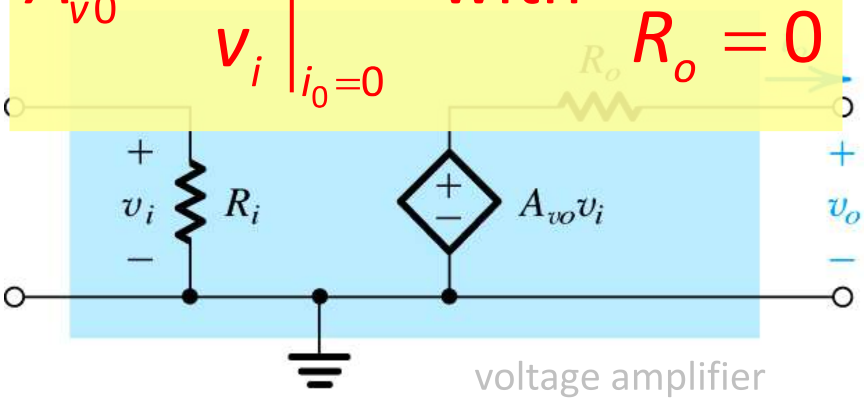


transresistance amp.



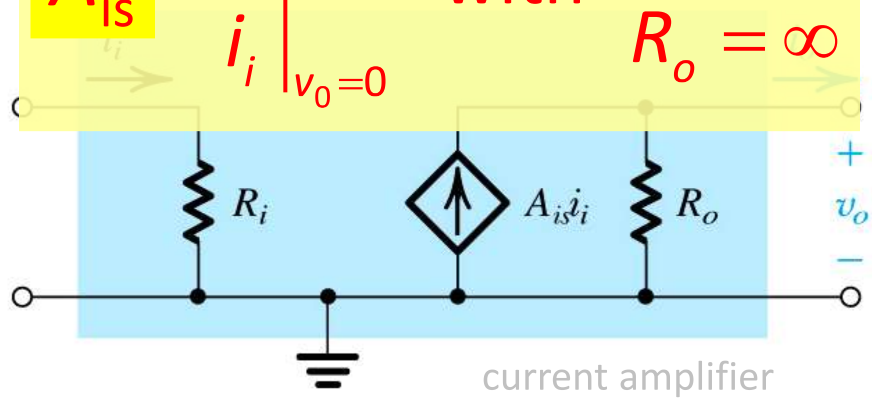
1.5.3. **Other Amplifier Types**

$$A_{v0} = \left.\frac{v_0}{v_i}\right|_{i_0=0} \quad \text{with} \quad \begin{matrix} R_i = \infty \\ R_o = 0 \end{matrix}$$



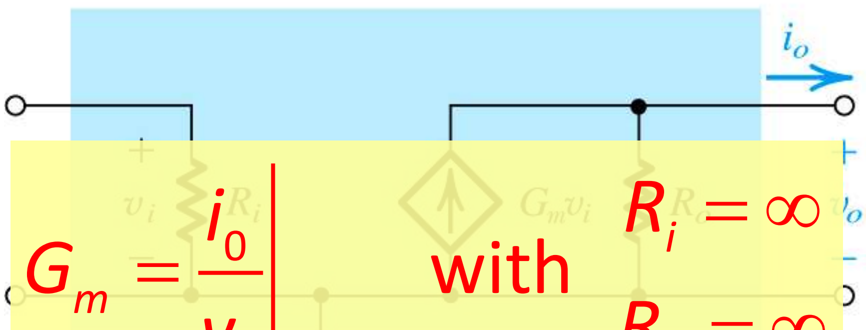
voltage amplifier

$$A_{is} = \left.\frac{i_0}{i_i}\right|_{v_0=0} \quad \text{with} \quad \begin{matrix} R_i = 0 \\ R_o = \infty \end{matrix}$$



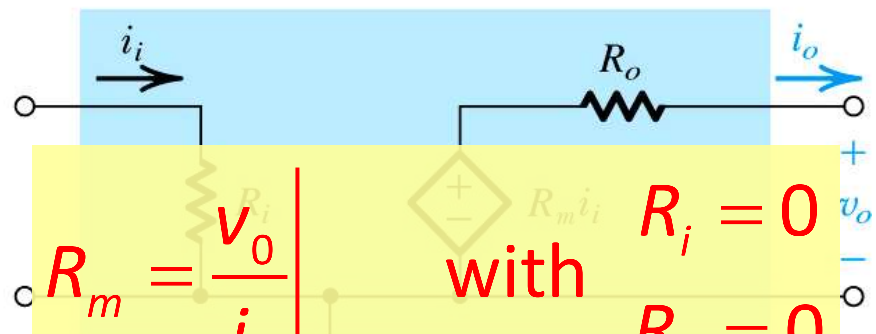
current amplifier

transconductance amplifier



$$G_m = \left.\frac{i_0}{v_i}\right|_{v_0=0} \quad \text{with} \quad \begin{matrix} R_i = \infty \\ R_o = \infty \end{matrix}$$

transresistance amplifier



$$R_m = \left.\frac{v_0}{i_i}\right|_{i_0=0} \quad \text{with} \quad \begin{matrix} R_i = 0 \\ R_o = 0 \end{matrix}$$

1.5.4. Relationship Between Four Amp Models

- interchangeability – although these four types exist, any of the four may be used to model any amplifier
  - they are related through A_{vo} (open circuit gain)

电路等效：
①开路电压相等；
②短路电流相等

$$A_{vo} = \underbrace{A_{is}\left(\frac{R_o}{R_i}\right)}_{\text{current to voltage amplifier}} = \underbrace{G_m R_o}_{\text{transcond. to voltage amplifier}} = \underbrace{\frac{R_m}{R_i}}_{\text{transres. to voltage amplifier}}$$

基于 Source Transformation

1.5.5. **Determining** ***R_i* and *R_o***

输入输出电阻的计算
就是 戴维南等效电阻的计算

- **Q:** How can one calculate input resistance from terminal behavior?
  - **A:** Observe v_i and i_i, calculate via $R_i = v_i / i_i$
- **Q:** How can one calculate output resistance from terminal behavior?
  - **A:** 输出电阻也可以用 "开路电压/短路电流" 计算

    ~ Trun off 独立源
    - Remove source voltage (such that $v_i = i_i = 0$)
    - Apply voltage to output (v_x)
    - Measure negative output current ($-i_o$)
    - Calculate via $R_o = -v_x / i_o$

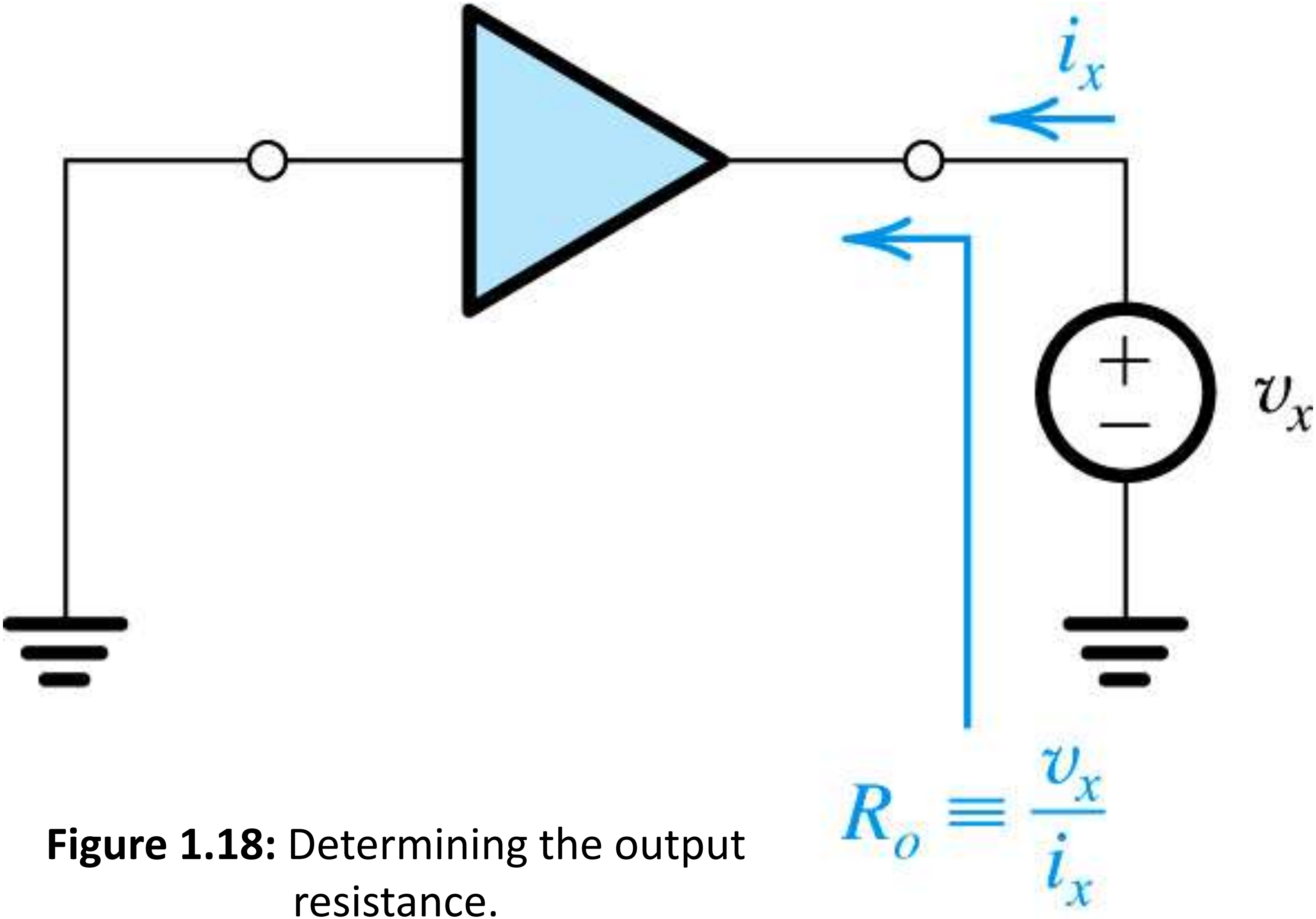


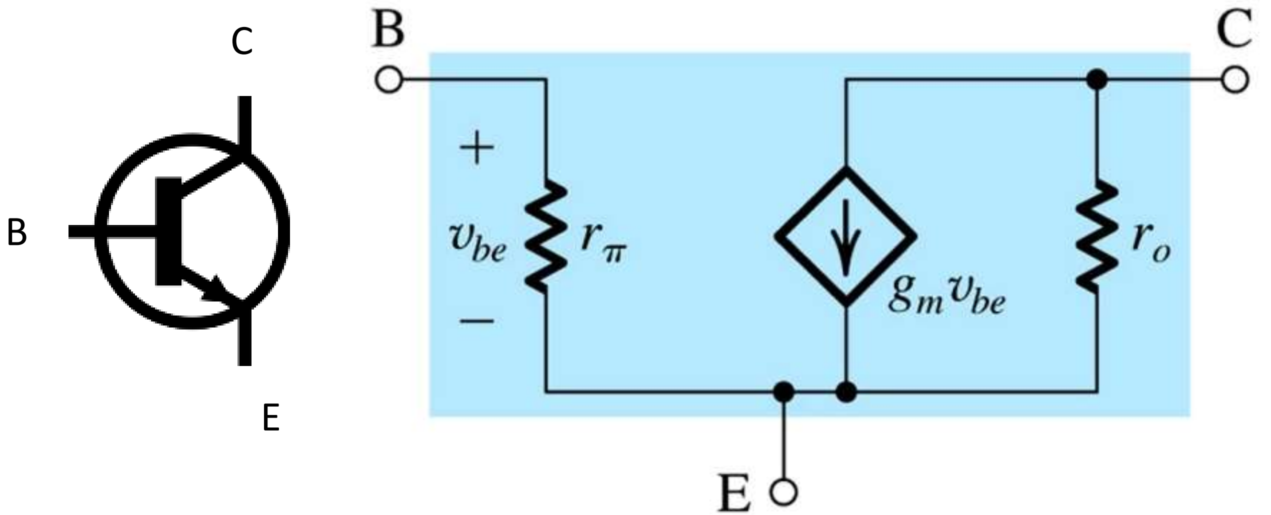
Figure 1.18: Determining the output resistance.

1.5.6. **Unilateral Models**

- **unilateral model** (单向模型) – is one in which signal flows only from input to output (not reverse)
  - However, most practical amplifiers will exhibit some reverse transmission…

Example 1.4: Common-Emitter Circuit

- Examine the **bipolar junction transistor** (BJT).
  - three-terminal device
  - when powered up with dc source and operated with small signals, may be modeled by linear circuit below.



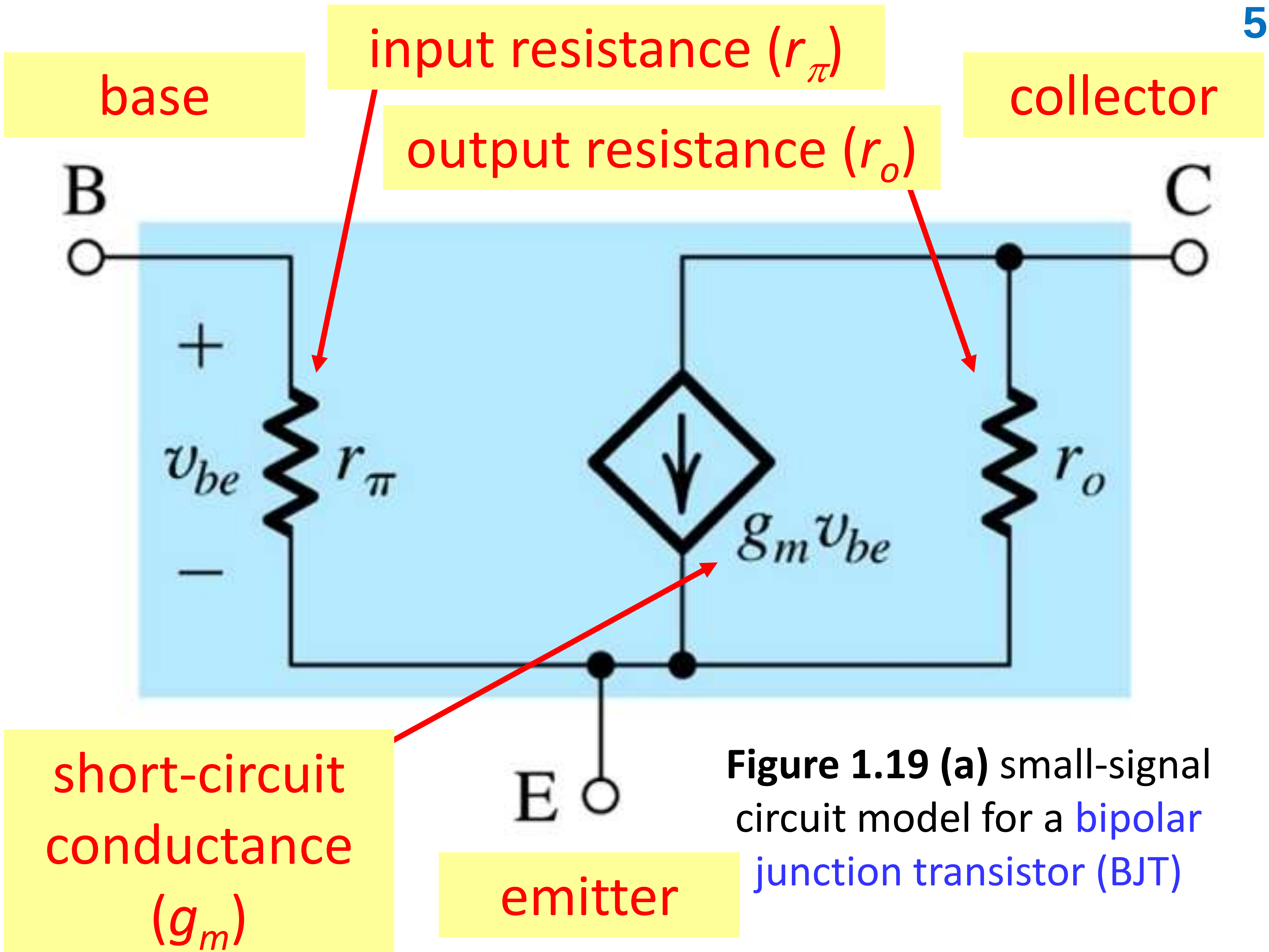
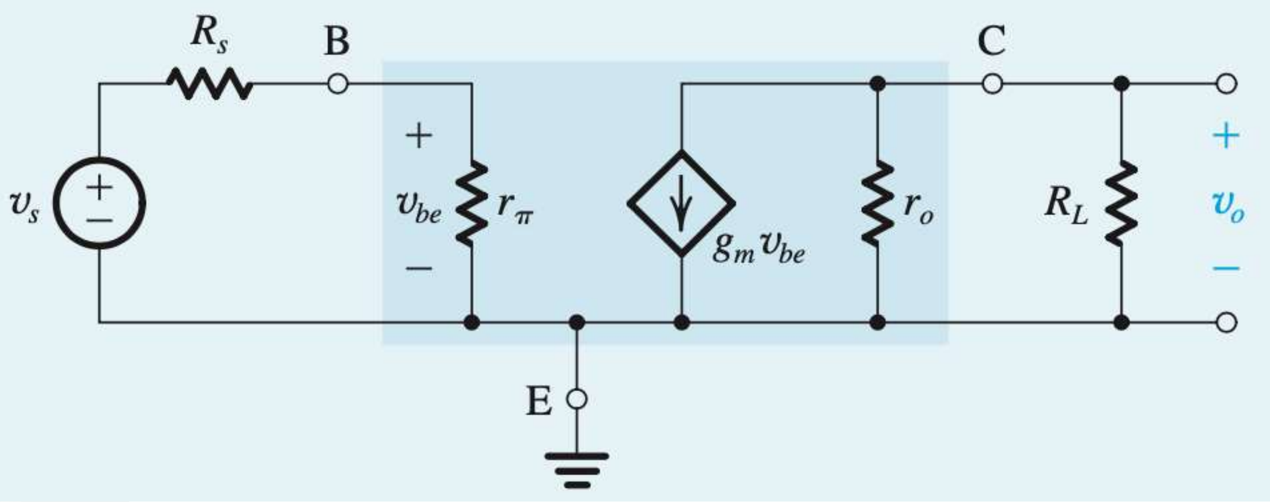


Figure 1.19 (a) small-signal circuit model for a bipolar junction transistor (BJT)

Example 1.4: Common-Emitter Circuit

- **Q(a):** Derive an expression for the voltage gain v_o / v_s of common-emitter circuit with:
  - $R_s = 5kohm$
  - $r_\pi = 2.5kohm$
  - $g_m = 40mA/V$
  - $r_o = 100kohm$
  - $R_L = 5kohm$



input and output share common terminal

$v_{be} = v_s * r_\pi/(R_s + r_\pi)$

$v_o = g_m * v_{be} * r_o/(R_L + r_o) * R_L$

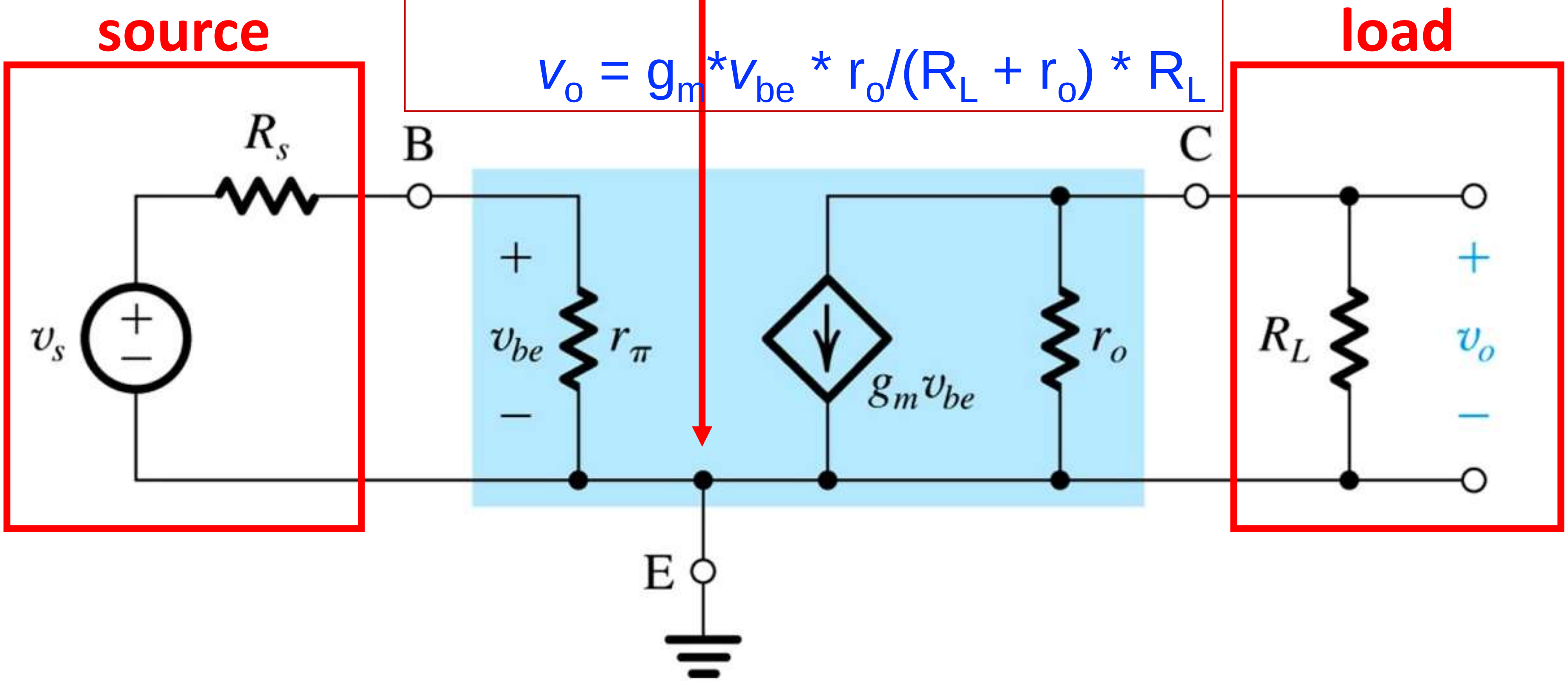


Figure 1.19(b): The BJT connected as an amplifier with the emitter as a common terminal between input and output (called a common-emitter amplifier).

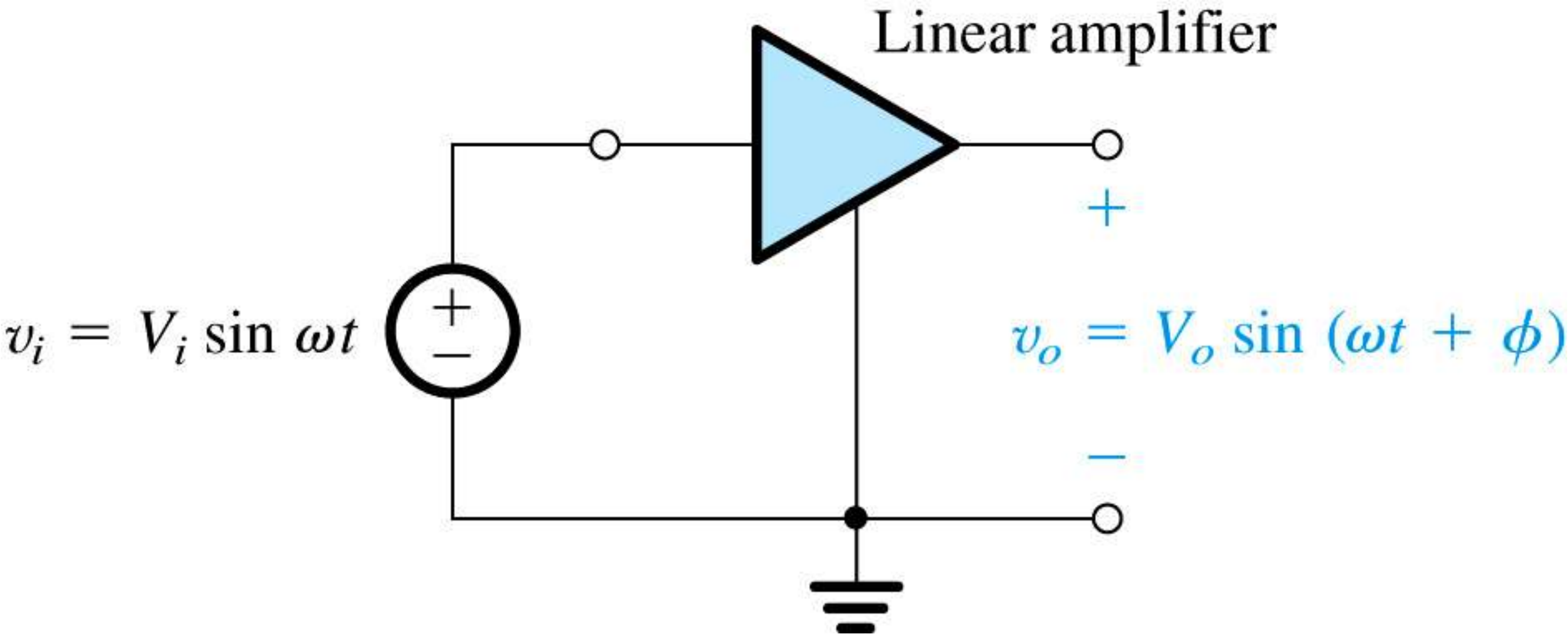
1.6.1. **Measuring the Amplifier Frequency Response**

- **Q:** How does one examine frequency response?
  - **A:** By applying sine-wave input of amplitude V_i and frequency ω.
- **Q:** Why?
  - **A:** Because, although its amplitude and phase may change, its shape and frequency will not.

this characteristic of sine wave applied to linear circuit is unique

1.6.1: Measuring the Amplifier Frequency

input and output are similar for linear amplifier



1.6.1. **Measuring the Amplifier Frequency Response 放大器频率响应**

- **amplifier transfer function** (**T**) – describes the input-output relationship of an amplifier – or other device – with respect to various parameters, including frequency of input applied.
  - It is a complex value, often defined in terms of magnitude and phase shift.

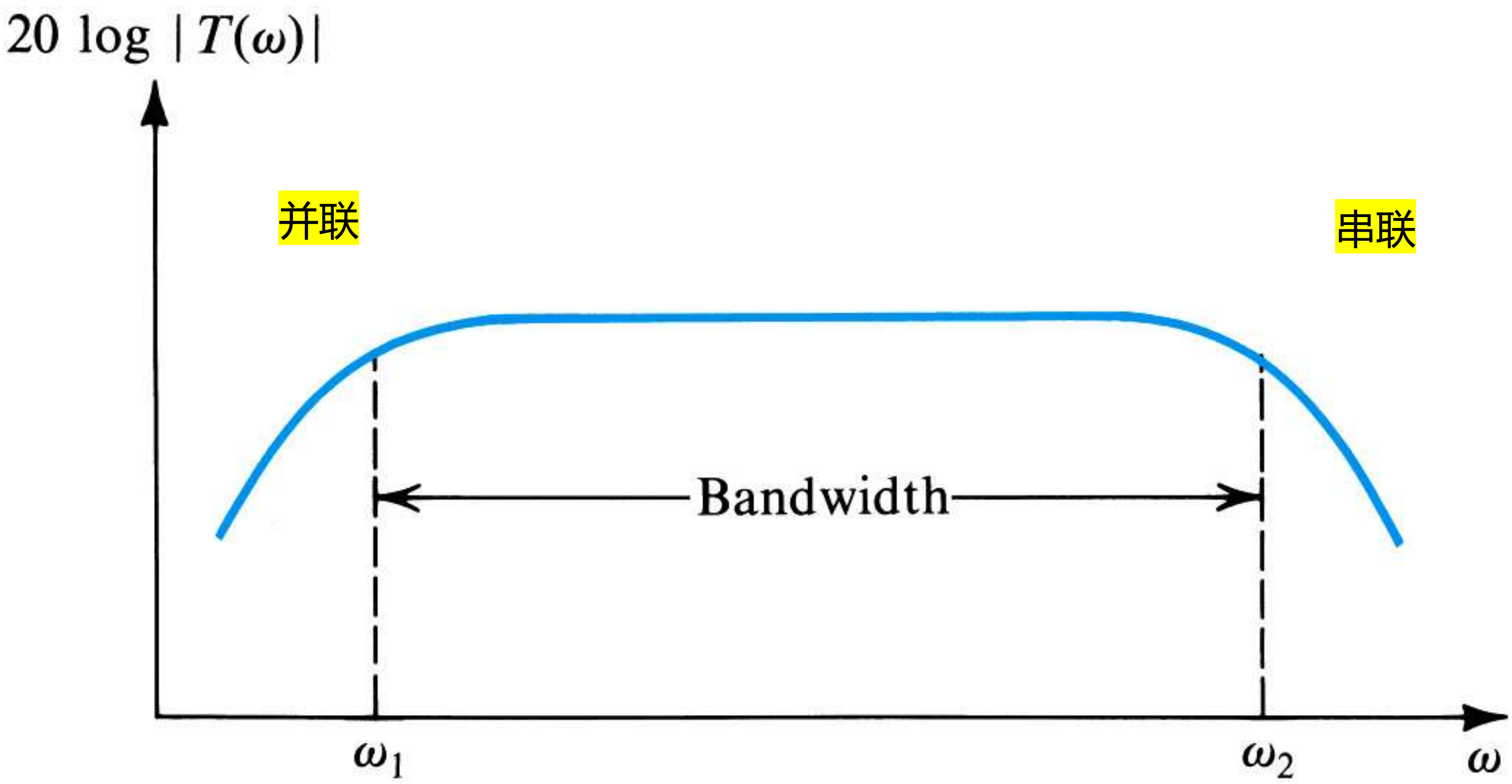
$$\underbrace{|\mathbf{T}(\omega)| = \frac{V_o}{V_i}}_{\text{magnitude gain}} \quad \text{and} \quad \underbrace{\angle \mathbf{T}(\omega) = \phi}_{\text{phase shift}}$$

1.6.2. **Amplifier Bandwidth 放大器带宽**

- **Q:** What is **bandwidth** of a device?
  - **A:** The range of frequencies over which its magnitude response is constant (within 3dB).
- **Q:** For an amplifier, what is main bandwidth concern?
  - **A:** That the bandwidth extends beyond range of frequencies it is expected to amplify.

1.6.2. Amplifier Bandwidth

The 3dB points are the "half power" points of the frequency response curve.



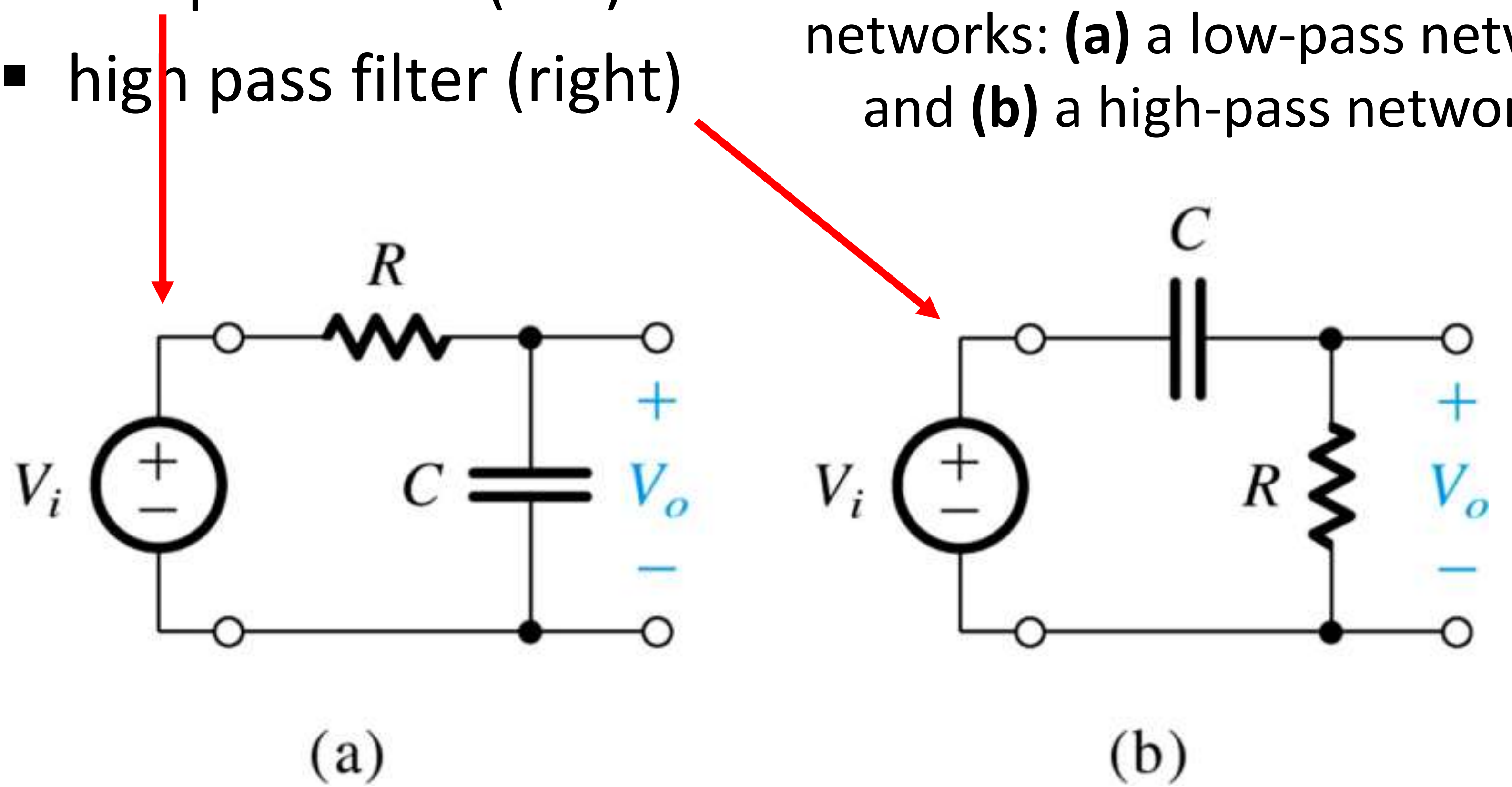
1.6.4. Single Time-Constant Networks 单时间常数网络

- **single time–constant (STC) network** – is composed of (or may be reduced to) **one reactive component** and **one resistance**. **RC或RL电路**
  - **low pass filter** – attenuates output at high frequencies, allow low to pass
  - **high pass filter** – attenuates output at low frequencies, allow high to pass
- **time constant (τ)** – describes the length of time required for a network transient to settle from step change ($\tau = L / R = RC$)

1.6.4. **Single Time-Constant Networks**

- low pass filter (left)
- high pass filter (right)

Figure 1.22: Two examples of STC networks: **(a)** a low-pass network and **(b)** a high-pass network.



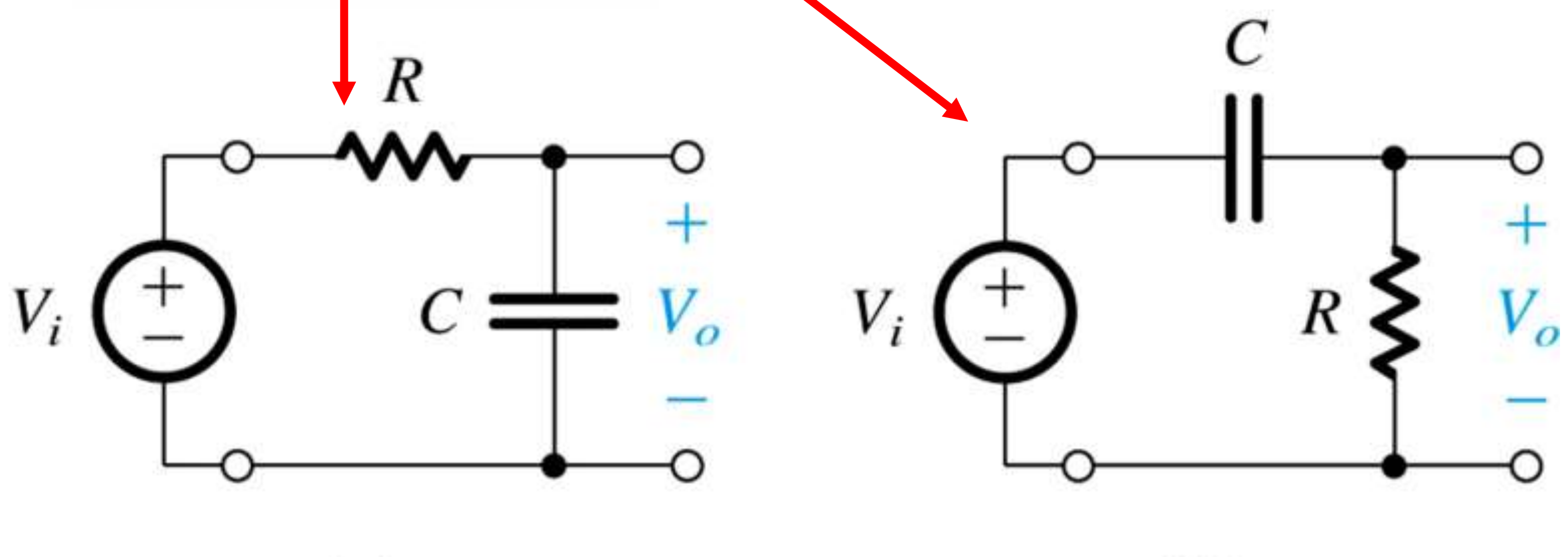
1.6.4. Single Time-Constant Networks

low-pass:

$$\frac{v_o}{v_i} = \frac{Z_o}{Z_i + Z_o} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} \propto k\frac{1}{\omega}$$

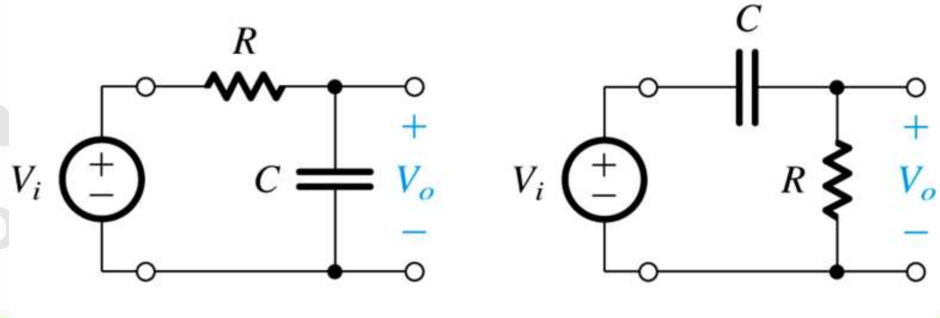
high-pass:

$$\frac{v_o}{v_i} = \frac{Z_o}{Z_i + Z_o} = \frac{R}{R + \frac{1}{j\omega C}} \propto k\omega$$



(a) (b)

1.6.4. Single Tin
Constant Netwo



(a) (b)

Table 1.2 Frequency Response of STC Networks

$\boxed{s = j\omega}$

	低通STC Low-Pass (LP)	高通STC High-Pass (HP)
Transfer Function $T(s)$ 传递函数标准形式	$\boxed{\dfrac{K}{1+(s/\omega_0)}}$	$\boxed{\dfrac{Ks}{s+\omega_0}}$
Transfer Function (for physical frequencies) $T(j\omega)$	$\dfrac{K}{1+j(\omega/\omega_0)}$	$\dfrac{K}{1-j(\omega_0/\omega)}$
Magnitude Response $\|T(j\omega)\|$	$\dfrac{\|K\|}{\sqrt{1+(\omega/\omega_0)^2}}$	$\dfrac{\|K\|}{\sqrt{1+(\omega_0/\omega)^2}}$
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

$$\frac{\frac{1}{j\omega C}}{R+\frac{1}{j\omega C}}$$

$$\frac{R}{R+\frac{1}{j\omega C}}$$

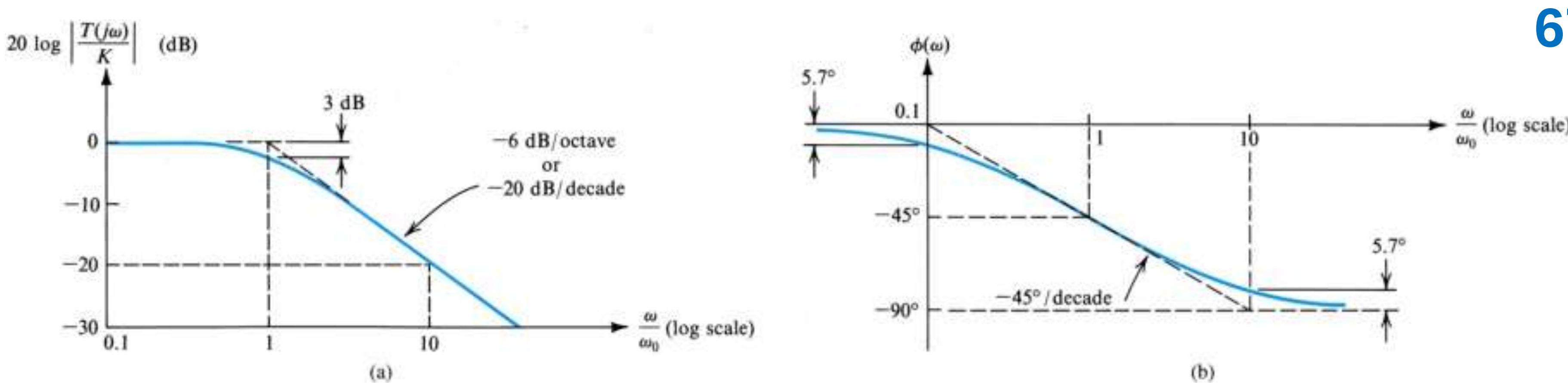
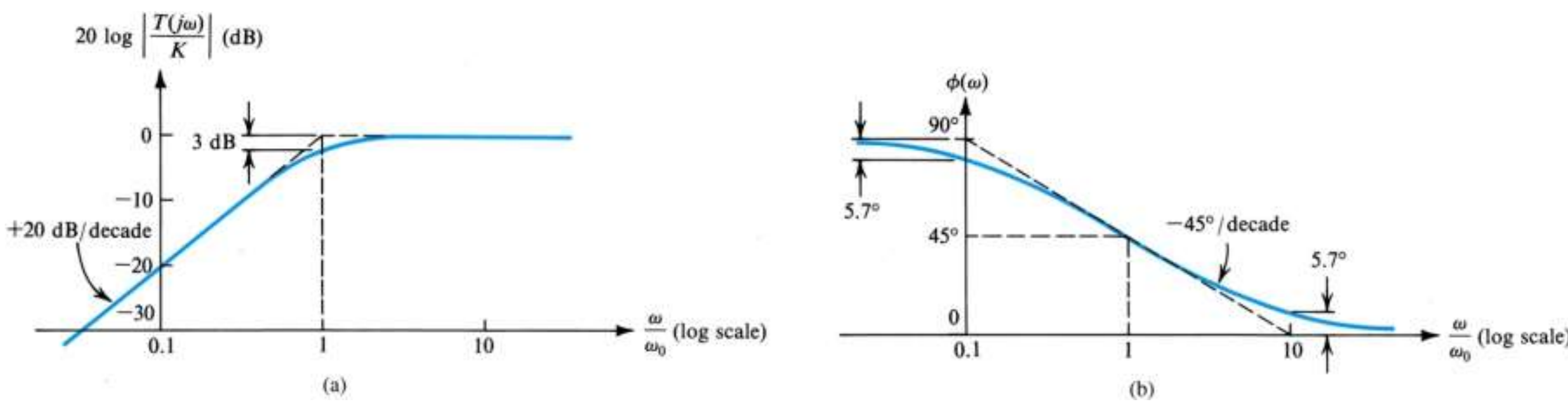
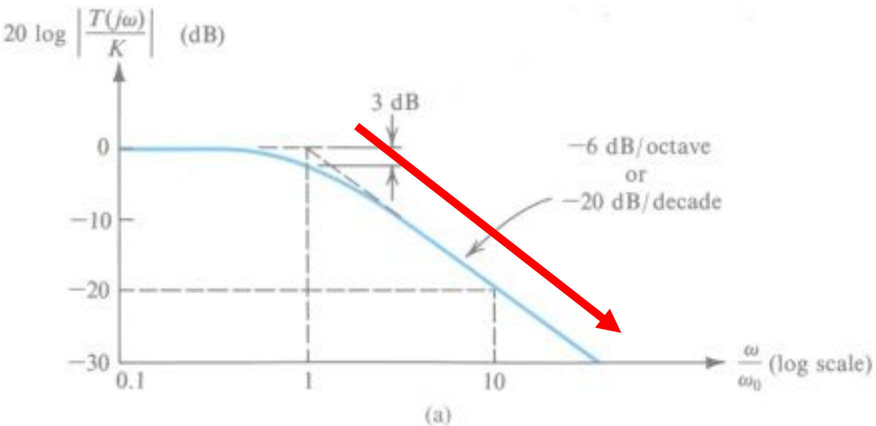
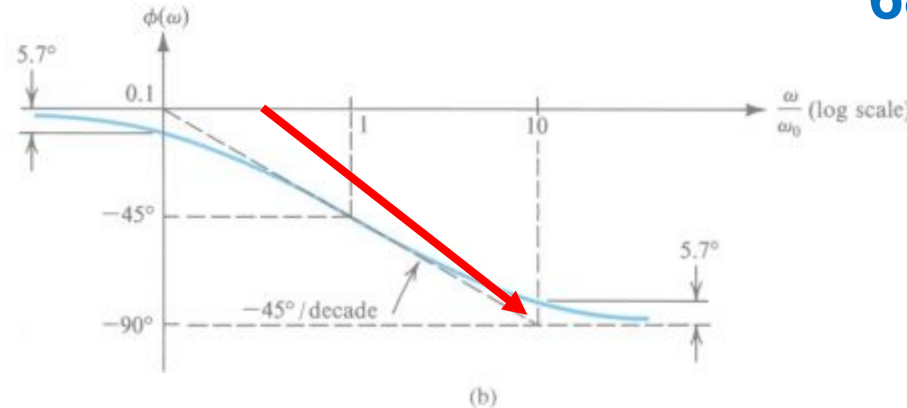


Figure: Low-Pass Filter Magnitude (top-left) and Phase (top-right) Responses as well as High-Pass Filter (bottom-left) and Phase (bottom-right) Responses







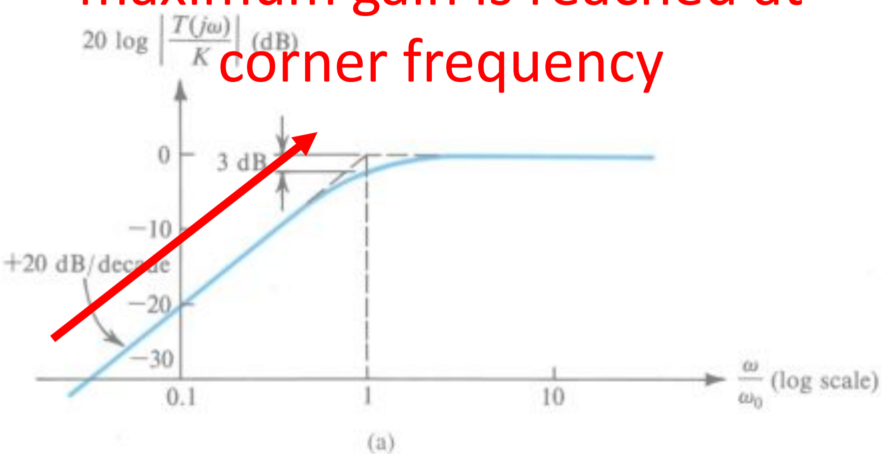
-20dB/decade drop, beginning from maximum gain at corner frequency

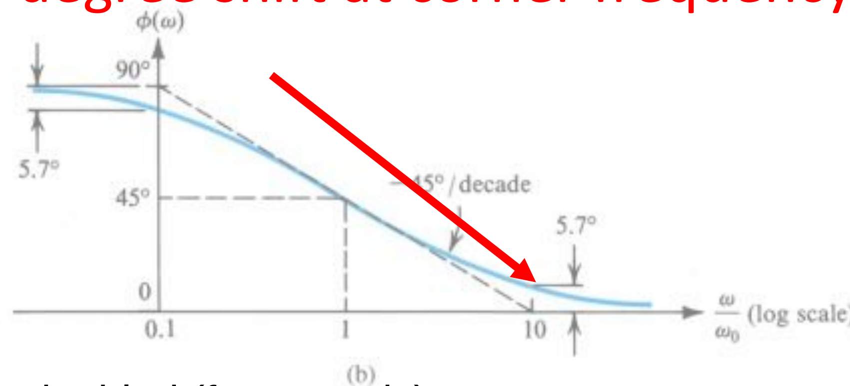
-45 degrees/decade drop, moving outward from -45 degree shift at corner frequency

Figure: Low-Filter Magnitude (top-left) and Phase (top-right) Responses as well as High-Pass Filter (bottom-left) and Phase (bottom-right) Responses

+20dB/decade incline, until maximum gain is reached at corner frequency

-45 degrees/decade drop, moving outward from +45 degree shift at corner frequency





An octave is the range over which the frequency is doubled (from music).

Figure 1.25 shows a voltage amplifier having an input resistance R_i, an input capacitance C_i, a gain factor μ, and an output resistance R_o. The amplifier is fed with a voltage source V_s having a source resistance R_s, and a load of resistance R_L is connected to the output.

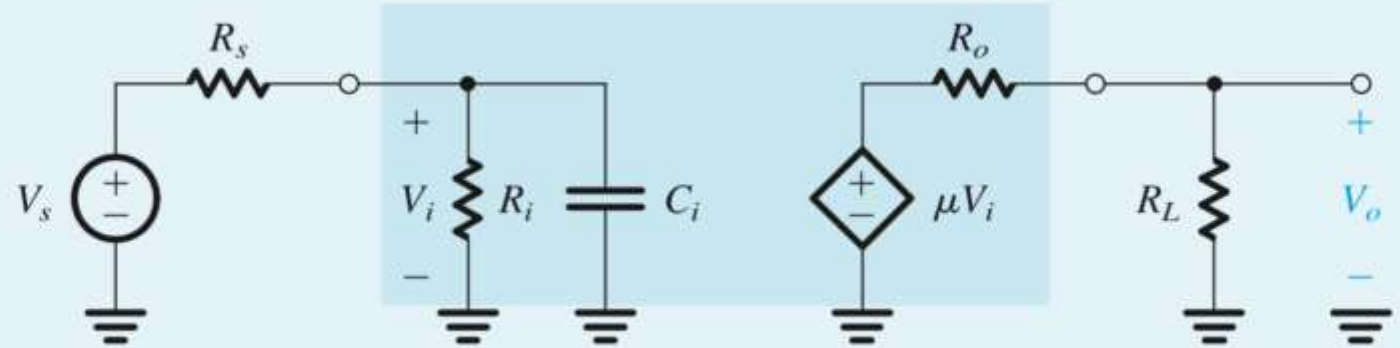


Figure 1.25 Circuit for Example 1.5.

(a) Derive an expression for the amplifier voltage gain V_o/V_s as a function of frequency. From this find expressions for the dc gain and the 3-dB frequency.

(b) Calculate the values of the dc gain, the 3-dB frequency, and the frequency at which the gain becomes 0 dB (i.e., unity) for the case $R_s = 20\ \text{k}\Omega$, $R_i = 100\ \text{k}\Omega$, $C_i = 60\ \text{pF}$, $\mu = 144\ \text{V/V}$, $R_o = 200\ \Omega$, and $R_L = 1\ \text{k}\Omega$.

(c) Find $v_o(t)$ 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

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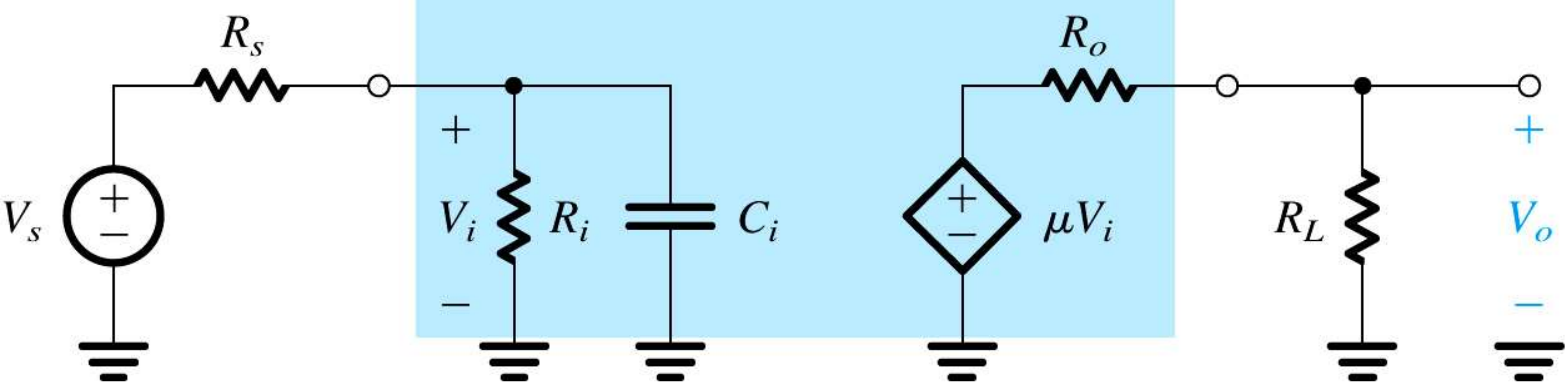
Example 1.5: Voltage Amplifier

Low-Pass (LP)

$$\frac{K}{1+(s/\omega_0)}$$



$$\frac{V_i}{V_s}=\frac{1}{1+(R_s/R_i)+sC_iR_s} \Rightarrow \frac{V_i}{V_s}=\frac{1}{1+(R_s/R_i)}\,\frac{1}{1+sC_i[(R_sR_i)/(R_s+R_i)]}$$

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

$$K\equiv\frac{V_o}{V_s}(s=0)=100\text{ V/V}$$

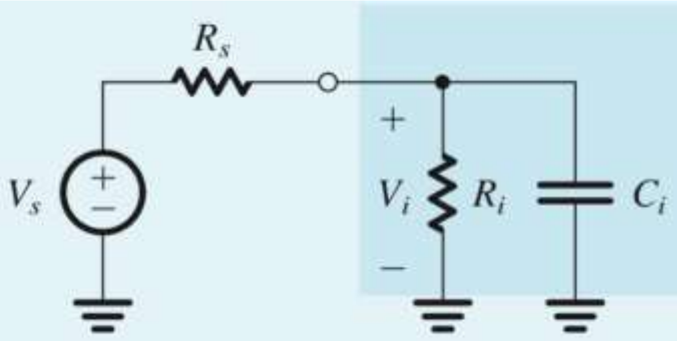
$$\omega_0=\frac{1}{\tau}=\frac{1}{C_i(R_s\parallel R_i)}=10^6\text{ rad/s}$$

Example 1.5:
Voltage Amplifier

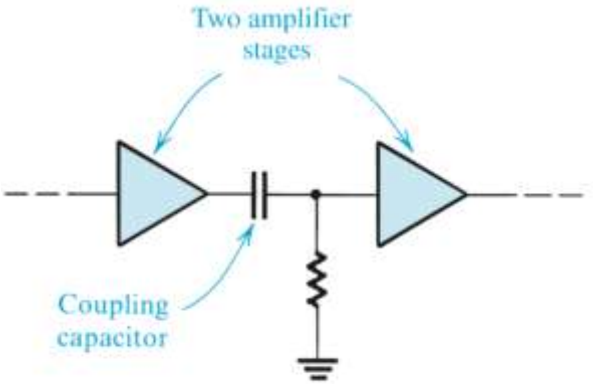
- **Q(b):** What is **unity-gain frequency**? How is it calculated?
  - **A:** Gain = 0dB
  - **A:** It is known that the gain of a low-pass filter drops at 20dB per decade beginning at ω_0. Therefore unity gain will occur two decades past ω_0 (40dB – 20dB – 20dB).
- **Q(c):** Find $v_o(t)$ for each of the following input: v_s = 0.1**sin**($10^2 t$), v_s = 0.1**sin**($10^5 t$)

$$\frac{V_o}{V_s}(j\omega) = \frac{100}{1 + j(\omega/10^6)}$$

1.6.5. **Classification of Amps Based on Frequency Response**



- **internal capacitances** – cause the falloff of gain at high frequencies **节点到地的寄生电容：高频时增益下降的原因**
  - like those seen in previous example
- **coupling capacitors** (隔直电容)– cause the falloff of gain at low frequencies **隔直电容：低频时增益下降的原因**
  - are placed in **between amplifier stages**
  - generally chosen to be large
  - 隔离不同 stages 放大器的直流



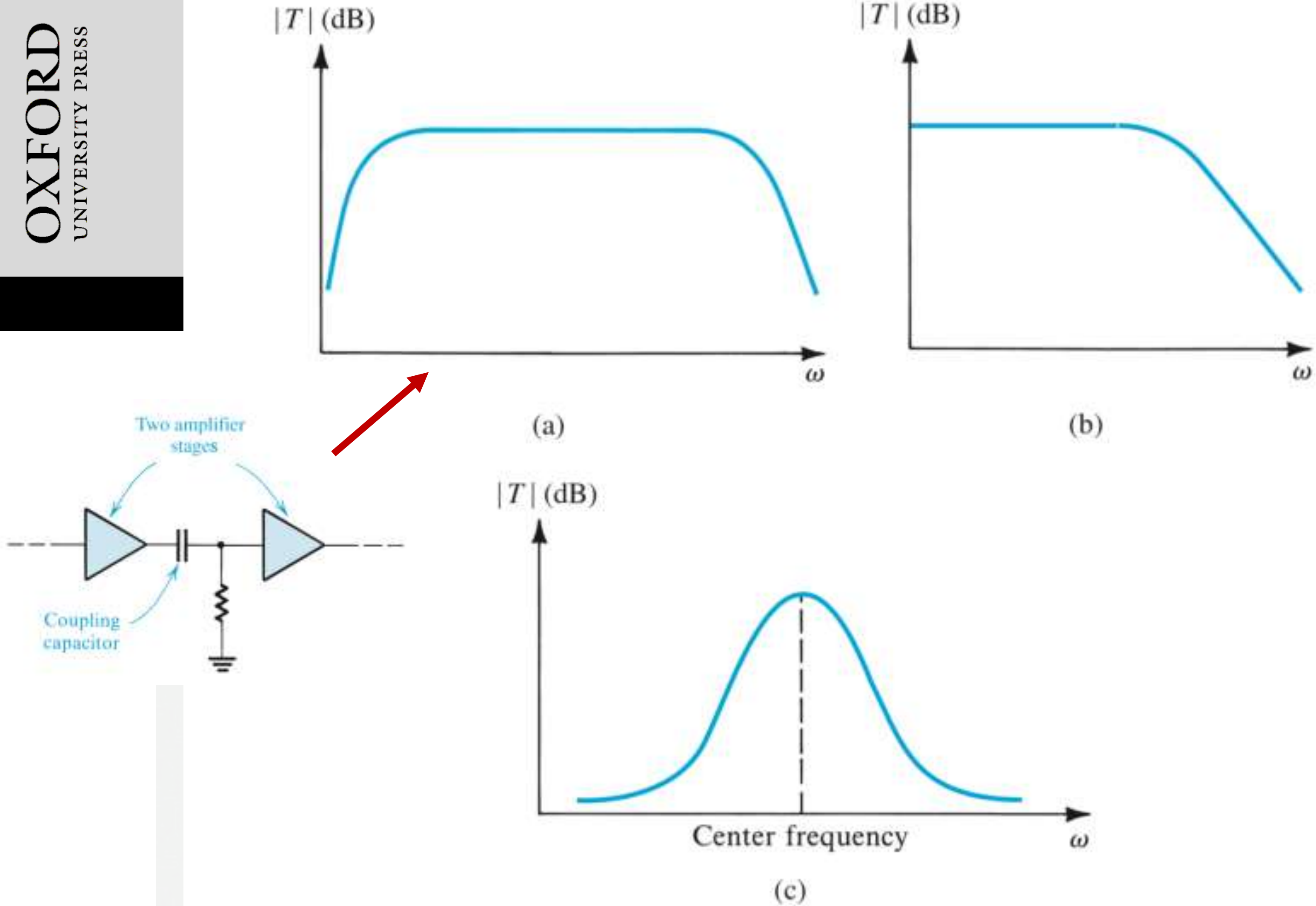


Figure 1.26 Frequency response for **(a)** a capacitively coupled amplifier, **(b)** a direct-coupled amplifier, and **(c)** a tuned or bandpass amplifier.

- **directly coupled / dc amplifiers** – allow passage of low frequencies
- **capacitively coupled amplifiers** – allow passage of high frequencies
- **tuned amplifiers** – allow passage of a “band” of frequencies

作业

1.3 A signal source that is most conveniently represented by its Thévenin equivalent has $v_s = 10$ mV and $R_s = 1$ kΩ. If the source feeds a load resistance R_L, find the voltage v_o that appears across the load for $R_L = 100$ kΩ, 10 kΩ, 1 kΩ, and 100 Ω. Also, find the lowest permissible value of R_L for which the output voltage is at least 80% of the source voltage.

Ans. 9.9 mV; 9.1 mV; 5 mV; 0.9 mV; 4 kΩ

1.12 A sensor producing a voltage of 1 V rms with a source resistance of 1 MΩ is available to drive a 10-Ω load. If connected directly, what voltage and power levels result at the load? If a unity-gain (i.e., $A_{vo} = 1$) buffer amplifier with 1-MΩ input resistance and 10-Ω output resistance is interposed between source and load, what do the output voltage and power levels become? For the new arrangement, find the voltage gain from source to load, and the power gain (both expressed in decibels).

Ans. 10 μV rms; 10^{-11} W; 0.25 V rms; 6.25 mW; −12 dB; 44 dB

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

1.22 Consider a voltage amplifier having a frequency response of the low-pass STC type with a dc gain of 60 dB and a 3-dB frequency of 1000 Hz. Find the gain in dB at $f = 10$ Hz, 10 kHz, 100 kHz, and 1 MHz.

Ans. 60 dB; 40 dB; 20 dB; 0 dB

D1.24 Consider the situation illustrated in Fig. 1.27. Let the output resistance of the first voltage amplifier be 1 kΩ and the input resistance of the second voltage amplifier (including the resistor shown) be 9 kΩ. The resulting equivalent circuit is shown in Fig. E1.24 where V_s and R_s are the output voltage and output resistance of the first amplifier, C is a coupling capacitor, and R_i is the input resistance of the second amplifier. Convince yourself that V_2/V_s is a high-pass STC function. What is the smallest value for C that will ensure that the 3-dB frequency is not higher than 100 Hz?

Ans. 0.16 μF

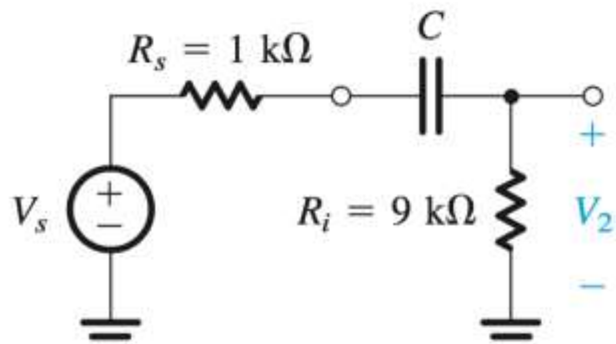


Figure E1.24

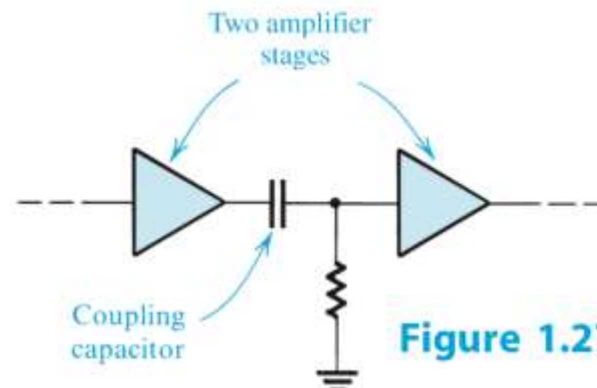


Figure 1.27