Lecture 25--Feedback, part I

Chapter 11, from **Microelectronic Circuits**

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课程纲要

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Introduction

- **IN THIS CHAPTER YOU WILL LEARN** 主要学习负反馈
  - The general structure of the negative-feedback amplifier and the basic principle that underlies its operation.通用结构与基本原理
  - The advantages of negative feedback, how these come about, and at what cost. 优点及代价
  - The appropriate feedback topology to employ with each of the four amplifier types: voltage, current, trans-conductance, and trans-resistance.四种基本组态
  - Why and how negative-feedback amplifiers may be unstable (i.e. oscillate) and how to design the circuit to ensure stable performance. 稳定性问题

Introduction

- Most physical systems incorporate some sort of feedback. 许多物理系统包含着各种各样的反馈
- Although theory of negative feedback was developed by electrical engineers. 但负反馈最早是电子工程师的发明
  - Harold Black with Western Electric Company
- Feedback can be negative (degenerative) or positive (regenerative). 反馈可以是正反馈，也可以是负反馈

Introduction

- Negative feedback may be used to: 负反馈的作用
  - desensitize the gain 减小增益对温度、电阻阻值等因素的敏感度
  - reduce nonlinear distortion 减小非线性失真
  - reduce the effect of noise 减小噪声的影响
  - control the input and output resistances 改变I/O阻抗
  - extend bandwidth 扩大带宽
- These characteristics result, however, in loss of gain.
  - “The basic idea of negative feedback is to trade-off gain for other desirable properties.” 代价是牺牲增益

Introduction

- Under certain conditions, negative feedback can be come positive. 但是，负反馈也可能会转变成正反馈→振荡
  - This causes oscillation.

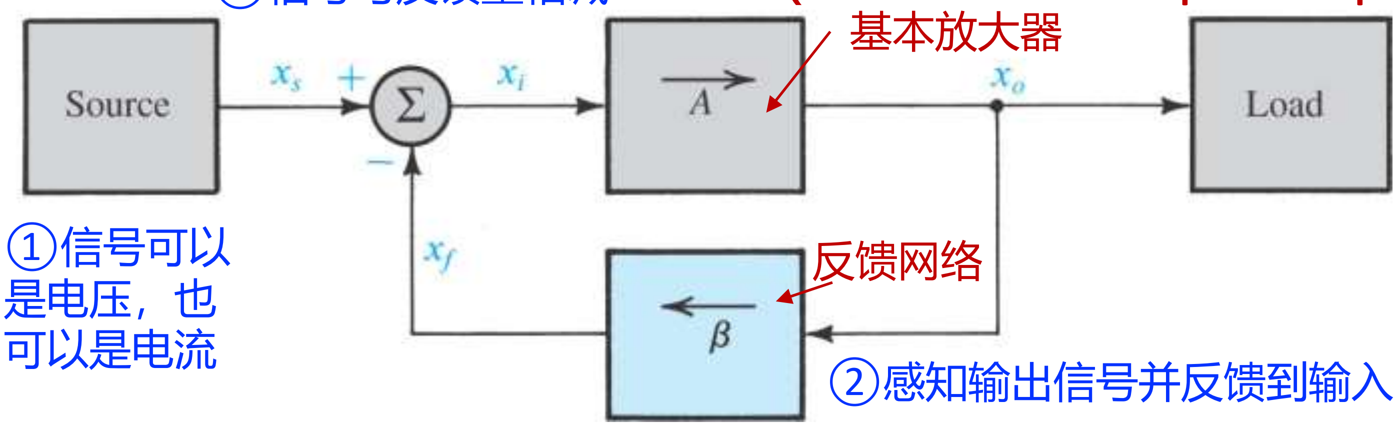
11.1. 反馈的基本结构

反馈结构的**基本参数**:

- Open-loop amplifier has gain A ($x_o = Ax_i$). 参数①开环增益A
  也即基本放大器的增益
- Output (x_o) is fed to load as well as feedback network.
- Feedback factor (β.) defines feedback signal (x_f). 参数② 反馈因子β
- Feedback signal (x_f) is subtracted from input (x_i).
  - This characterizes negative feedback.

假设反馈网络β对基本放大器的增益A没影响
(does not load the amplifier output & input)

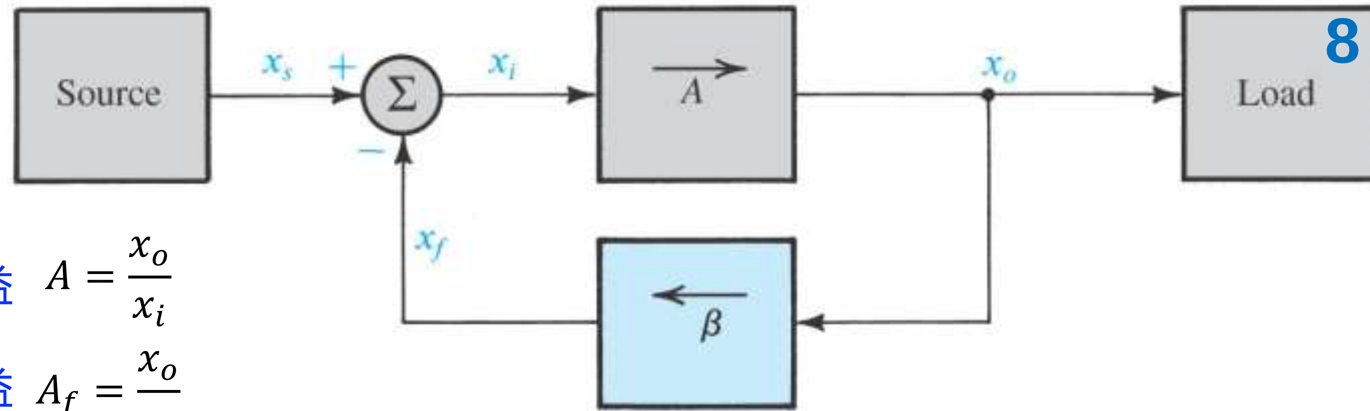
③信号与反馈量相减



①信号可以是电压，也可以是电流

②感知输出信号并反馈到输入

Figure 11.1: General structure of the feedback amplifier. This is a **signal-flow diagram**, and the quantities ***x* represent either voltage or current signals**.



两个增益

- 开环增益 $A = \dfrac{x_o}{x_i}$
- 闭环增益 $A_f = \dfrac{x_o}{x_s}$

- Gain of feedback amplifier is defined in (10.4).
  - Note that (10.4) may be approximated at $1/\beta$.深度反馈
  - As such, gain of feedback amplifier is almost entirely determined by feedback network.

(eq10.4) gain with feedback: $$A_f \equiv \frac{x_o}{x_s} = \frac{A}{\underbrace{\left[1+\left(A\beta\right)\right]}_{\text{amount of feedback}}}$$

③ 闭环增益

④ loop gain

⑤ amount of feedback

$$x_o = Ax_i$$
$$x_f = \beta x_o$$
$$x_i = x_s - x_f$$

深度反馈时，闭环增益只与反馈系数β有关，与开环增益A无关

(eq10.5) if assumed that $A\beta >> 1$: $A_f = \dfrac{1}{\beta}$

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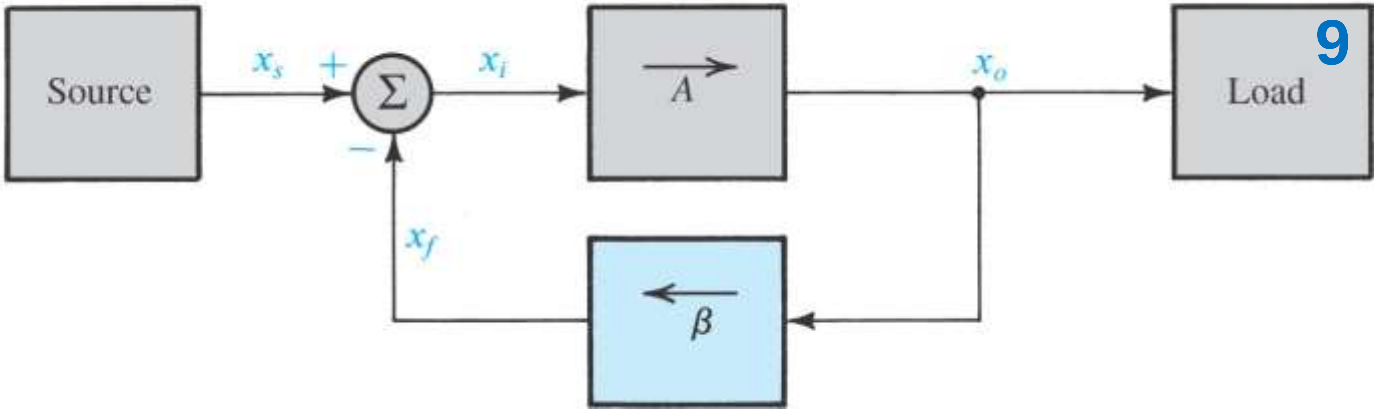

(eq10.6) feedback signal: $x_f = \dfrac{A\beta}{1+A\beta} x_s$

(eq10.7) input signal: $x_i = x_s - x_f = x_s - \dfrac{A\beta}{1+A\beta} x_s$

(eq10.6) input signal: $x_i = \left(1 - \dfrac{A\beta}{1+A\beta}\right) x_s$

(eq10.6) input signal: $x_i = \left(\dfrac{1}{1+A\beta}\right) x_s$

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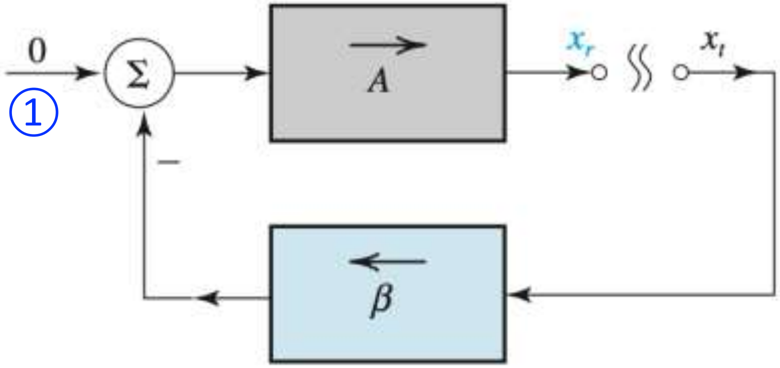
loop gain Aβ 是负反馈里最重要的参数

$$A_f = \frac{A}{1 + A\beta}$$

1. The sign of $A\beta$ determines the polarity of the feedback; the loop gain $A\beta$ must be positive for the feedback to be negative. Aβ 决定了反馈的极性：Aβ为正，则为负反馈
2. The magnitude of $A\beta$ determines how close the closed-loop gain A_f is to the ideal value of $1/\beta$. Aβ 决定了闭环增益与理想深反馈的接近程度：Aβ >> 1, 则 $A_f \approx {}^{1}/_{\beta}$
3. The magnitude of $A\beta$ determines the amount of feedback $(1 + A\beta)$ and hence, as we shall see in the next section, the magnitude of the various improvements in amplifier performance resulting from the negative feedback. 放大器的各种性能都按（1+Aβ）缩放
4. As we shall see in later sections, the inevitable variation of $A\beta$ with frequency can cause $A\beta$ to become negative, which in turn can cause the feedback amplifier to become unstable. It follows that the design of a stable feedback amplifier may involve modifying the frequency behaviors of its loop gain $A\beta$ appropriately (Section 11.10).

Aβ 是频率相关量，所以当频率变化时，负反馈可能会不稳定。设计稳定的负反馈放大器，需要考虑Aβ的频率特性



那么，如何计算 Aβ 呢?

Figure 11.2 Determining the loop gain by breaking the feedback loop at the output of the basic amplifier, applying a test signal x_t, and measuring the returned signal x_r: $A\beta \equiv -x_r/x_t$.

The significance of the loop gain requires us to consider its determination. Reference to Fig. 11.1 indicates that the value of the loop gain $A\beta$ can be determined as follows:

计算步骤:

1. Set $x_s = 0$. ①信号源置零
2. Break the feedback loop at a convenient location, ensuring that the values of A and β *do not change*. Since we assumed that the feedback network does not load the amplifier output, we can break the loop at the amplifier output (see Fig. 11.2) without causing A to change. ②在合适的地方将反馈环断开（确保A和β不受影响）
3. Apply a test signal x_t to the input of the loop (where the break has been made) and determine the *returned signal* x_r at the loop output (i.e., at the other side of the break). From Fig. 11.2 we see that

③在断点处施加测试信号 x_t，求通过回路返回到断点处的信号 x_r

$$x_r = -A\beta x_t$$

and the loop gain $A\beta$ is obtained as

负反馈系统，Aβ为正，所以 x_r 和 x_t 相位相反，这也是判断反馈是否为负反馈的方法

$$A\beta = -\frac{x_r}{x_t} \tag{11.8}$$

The noninverting op-amp configuration shown in Fig. 11.3(a) provides a direct implementation of the feedback loop of Fig. 11.1.

$\boxed{\beta \equiv \frac{V_f}{V_o} = \frac{R_1}{R_1+R_2}}$ $\boxed{A_f = \frac{A}{1+A\beta}}$ $\boxed{A\beta \gg 1}$ $\boxed{A_f \simeq \frac{1}{\beta} = 1 + \frac{R_2}{R_1}}$

(a) Assume that the op amp has infinite input resistance and zero output resistance. Find an expression for the feedback factor β.

(b) Find the condition the open-loop gain A must satisfy so that the closed-loop gain A_f is almost entirely determined by the feedback network. Also, give the value of A_f in this case.

(c) If the open-loop gain $A = 10^4$ V/V, find R_2/R_1 to obtain a closed-loop gain A_f of 10 V/V.

(d) What is the amount of feedback in decibels?

(e) If $V_s = 1$ V, find V_o, V_f, and V_i.

(f) If A decreases by 20%, what is the corresponding decrease in A_f?

$\boxed{A_f = \frac{A}{1+A\beta}}$ $\boxed{\beta = 0.0999}$ $\boxed{\frac{R_2}{R_1} = 9.01}$

$\boxed{1 + A\beta = \frac{A}{A_f} = \frac{10^4}{10} = 1000}$ $\boxed{60\text{ dB}}$

$$V_o = A_f V_s = 10 \times 1 = 10\text{ V}$$
$$V_f = \beta V_o = 0.0999 \times 10 = 0.999\text{ V}$$
$$V_i = \frac{V_o}{A} = \frac{10}{10^4} = 0.001\text{ V}$$

$\boxed{A = 0.8 \times 10^4\text{ V/V}}$

$$A_f = \frac{0.8 \times 10^4}{1 + 0.8 \times 10^4 \times 0.0999} = 9.9975\text{ V/V}$$

it decreases by 0.025%

Example 11.1 continued

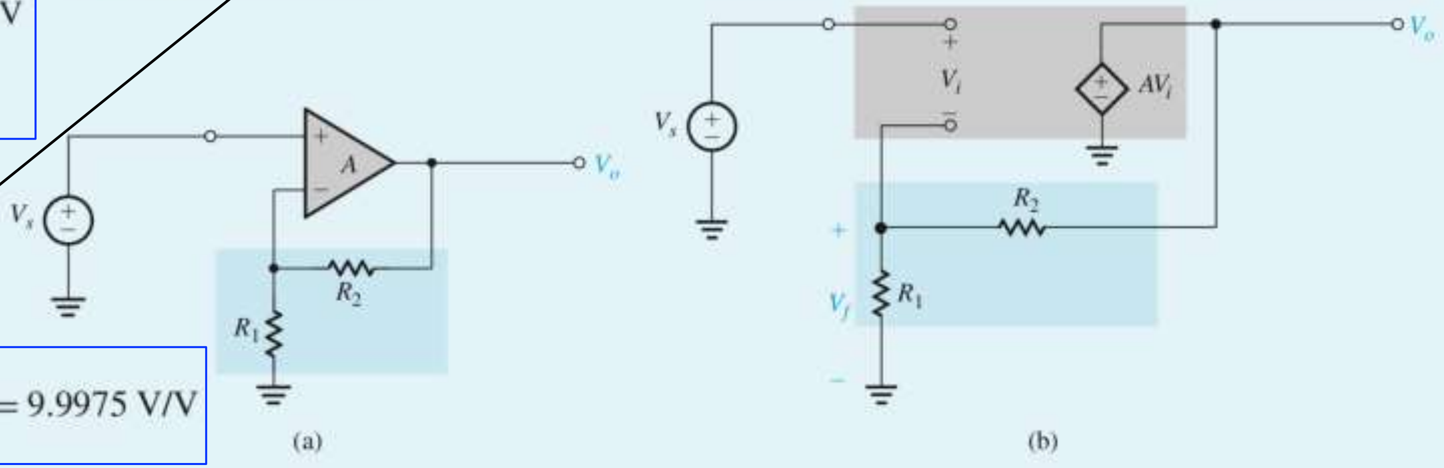


Figure 11.3 (a) A noninverting op-amp circuit for Example 11.1. (b) The circuit in (a) with the op amp replaced with its equivalent circuit.

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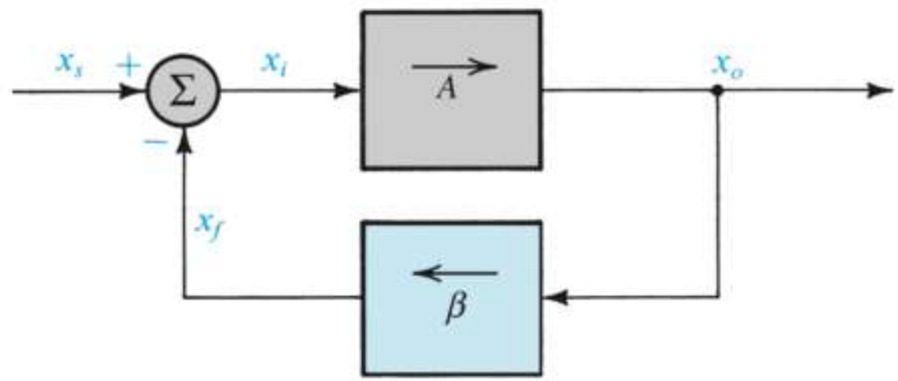
Table 11.1 Summary of the Parameters and Formulas for the Ideal Feedback-Amplifier Structure of Fig. 11.1



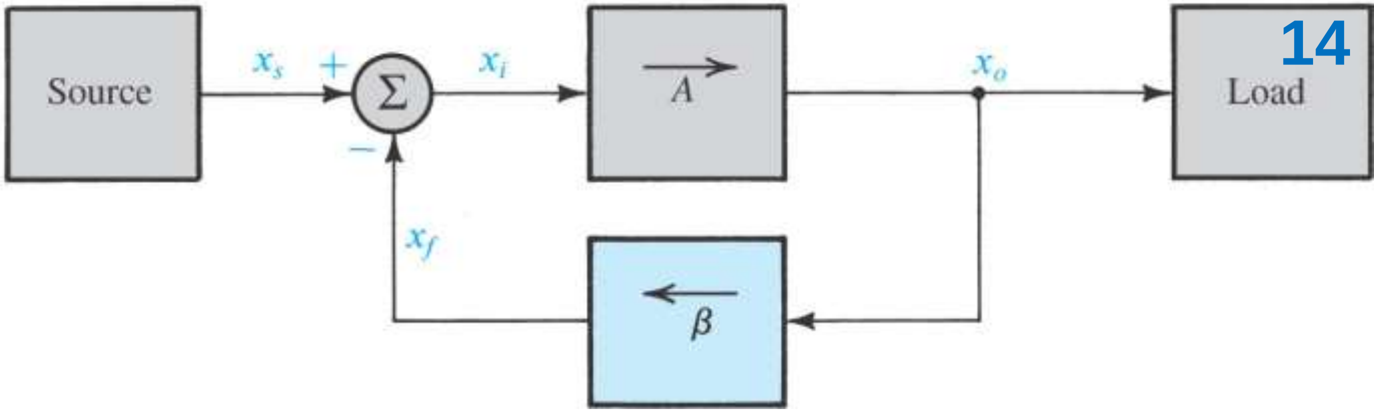
- Open-loop gain $\equiv A$
- Feedback factor $\equiv \beta$
- Loop gain $\equiv A\beta$ (positive number)
- Amount of feedback $\equiv 1 + A\beta$
- Closed-loop gain $\equiv A_f = \dfrac{x_o}{x_s} = \dfrac{A}{1 + A\beta}$
- Feedback signal $\equiv x_f = \dfrac{A\beta}{1 + A\beta} x_s$
- Input signal to basic amplifier $\equiv \boxed{x_i = \dfrac{1}{1 + A\beta} x_s}$

基本放大器的输入信号缩小了（1+Aβ）倍

- Closed-loop gain as a function of the ideal value $\dfrac{1}{\beta}$: $A_f = \left(\dfrac{1}{\beta}\right)\dfrac{1}{1 + 1/A\beta}$
- For large loop gain, $A\beta \gg 1$,

$$A_f \simeq \frac{1}{\beta} \qquad x_f \simeq x_s \qquad x_i \simeq 0$$

11.2. Some Properties of Negative Feedback



- **11.2.1. Gain De-sensitivity 负反馈的作用之一：增益去敏**
  - Equations (10.8) and (10.9) define de-sensitivity factor of $(1+A\beta)$.

闭环增益
$$A_f \equiv \frac{x_o}{x_s} = \frac{A}{1+A\beta} \qquad (10.4)$$

$$\frac{d\frac{f}{g}}{dx} = \frac{\frac{df}{dx}g - f\frac{dg}{dx}}{g^2} \quad (g \neq 0)$$

两边求微分

$$dA_f = \frac{dA}{(1+A\beta)^2} \qquad (10.8)$$

$$\frac{dA_f}{A_f} = \frac{1}{(1+A\beta)}\frac{dA}{A} \qquad (10.9)$$

若因各种因素导致基本放大器的增益（开环增益）A有p%的变化，则形成负反馈后闭环增益 A_f 的变化显著降低，缩放因子是（1 + Aβ）

11.2. Some Properties of Negative Feedback

- **11.2.2. Bandwidth Extension** 负反馈的作用之二：带宽增加
  - Equations (10.10) through (10.13) demonstrate how 3-*dB* frequencies may be shifted via negative feedback.

引入负反馈前（开环增益）

$$A(s) = \frac{A_M}{1 + s/\omega_H} \qquad (10.10)$$

一个高频极点，ω_H 为上限截止频率

引入负反馈后（闭环增益）

$$A_f(s) = \frac{A(s)}{1 + \beta A(s)}$$

$$A_f(s) = \frac{A_M/(1 + A_M\beta)}{1 + s/\omega_H(1 + A_M\beta)} \qquad (10.11)$$

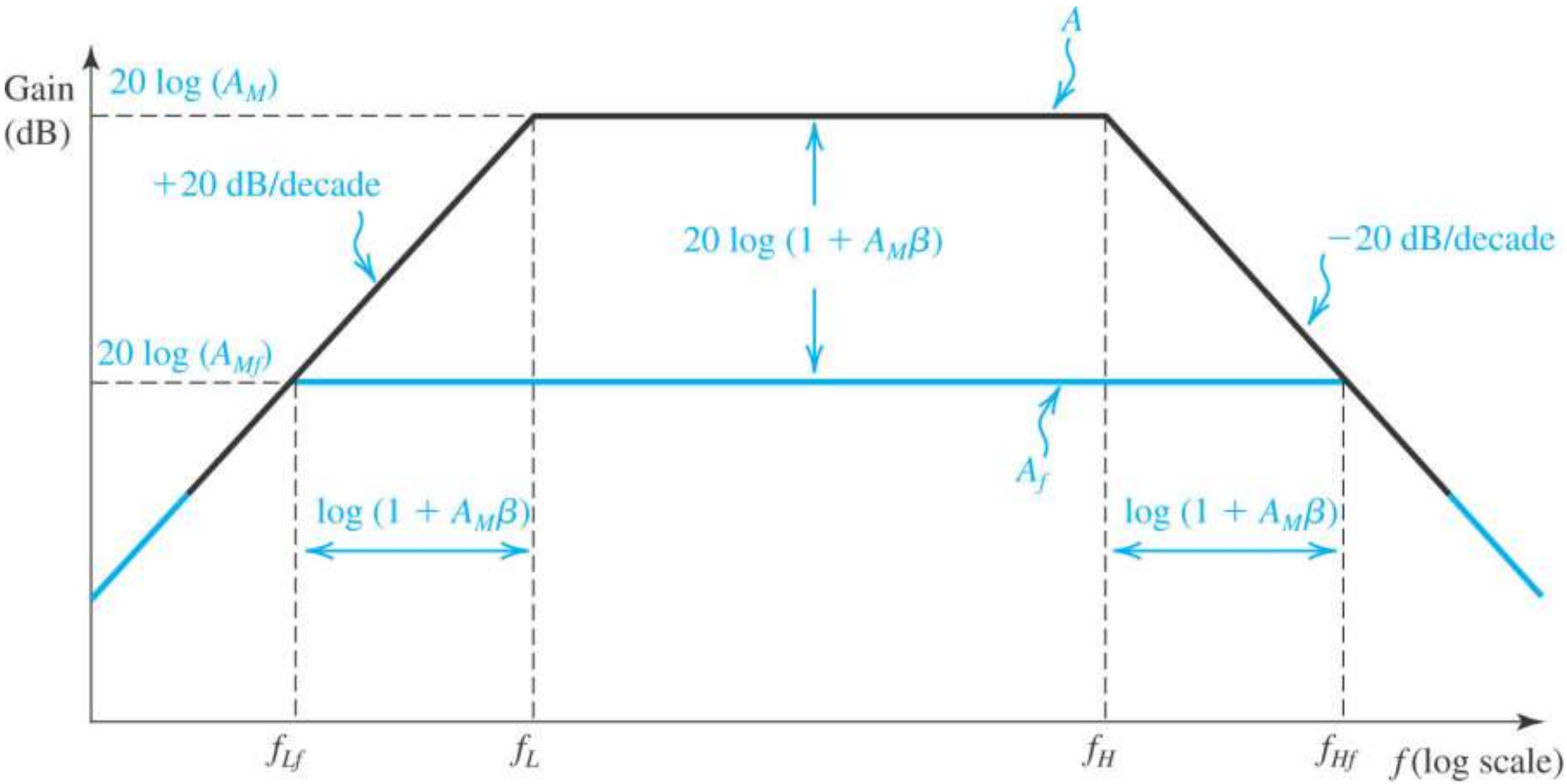
中频增益减小（$1+A_M\beta$）倍

$$\omega_{Hf} = \omega_H(1 + A_M\beta) \qquad (10.12)$$

上限截止频率扩大（$1+A_M\beta$）倍

增益×带宽 = constant

③因 $f_L << f_H$，所以负反馈使得放大器的带宽展宽（1+Aβ）倍



②同理，下限截止频率缩小（1+A_Mß）倍

①上限截止频率扩大（1+A_Mß）倍

$$f_{Lf} = \frac{f_L}{1 + A_M\beta} \qquad A_{Mf} = \frac{A_M}{1 + A_M\beta} \qquad f_{Hf} = f_H(1 + A_M\beta)$$

Figure 10.3 Application of negative feedback reduces the midband gain, increases f_H, and reduces f_L, all by the same factor, (1+$A_M\beta$), which is equal to the amount of feedback.

- **11.2.4. Reduction in Nonlinear Distortion**
  - Negative feedback may facilitate linearization.

负反馈的作用之三：增加线性度

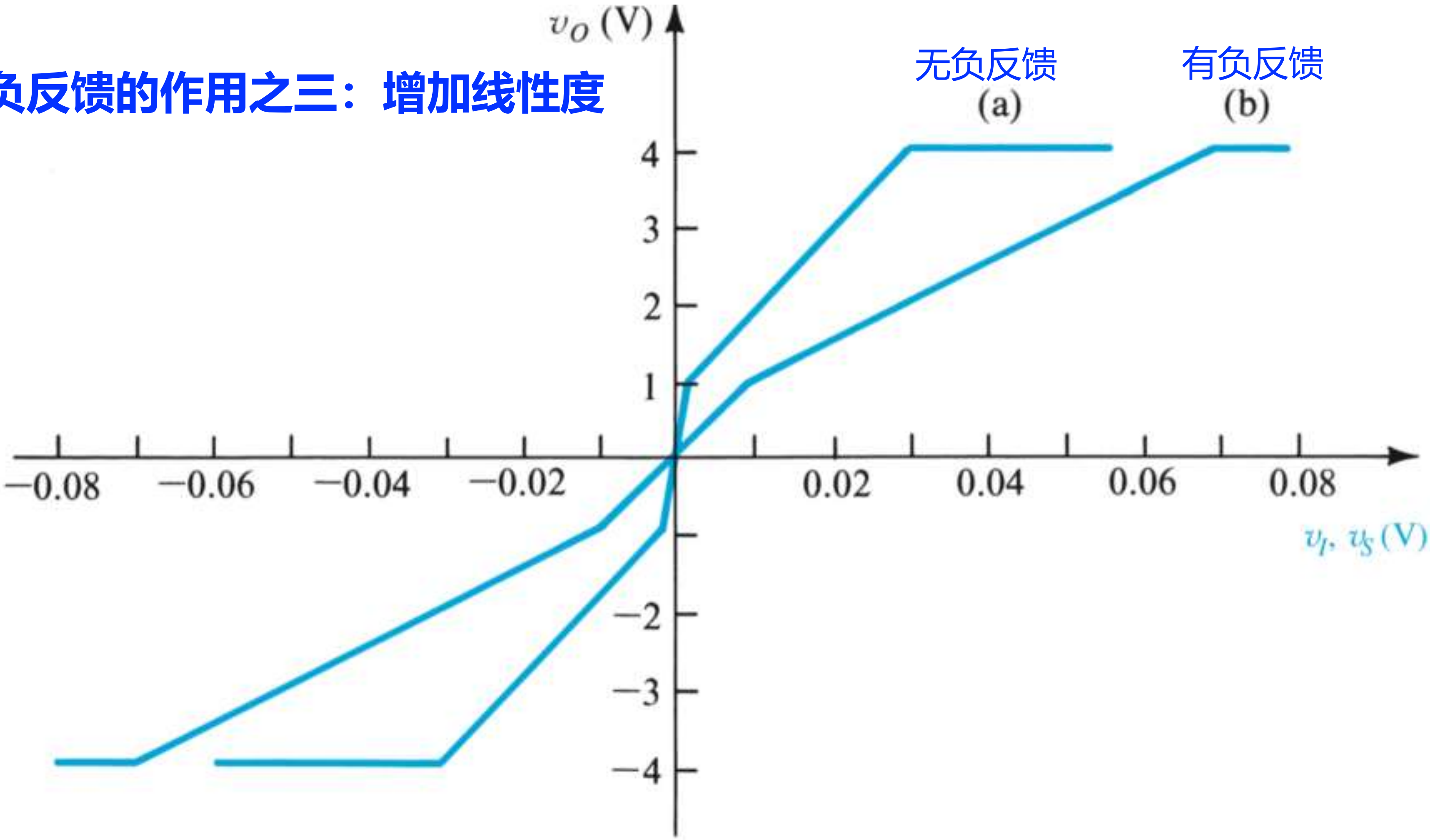


Figure 11.6 Illustrating the application of negative feedback to reduce the nonlinear distortion in amplifiers. Curve (a) shows the amplifier transfer characteristic (v_O versus v_I) without feedback. Curve (b) shows the characteristic (v_O versus v_S) with negative feedback ($\beta = 0.01$) applied.

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Four Types of Amplifiers （放大器的四种类型）

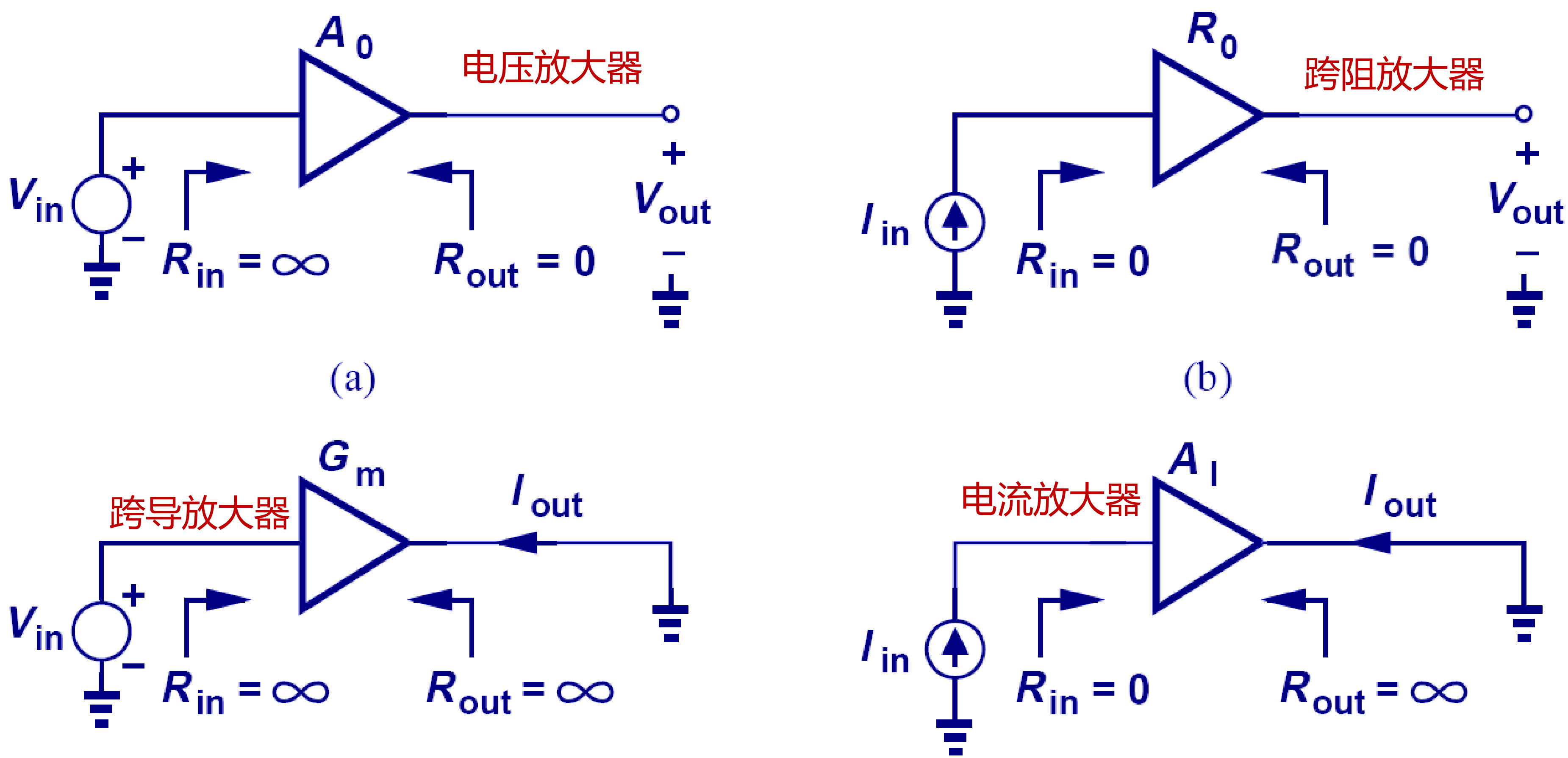

Figure 12.14 (a) Voltage, (b) transimpedance, (c) transconductance, and (d) current amplifiers.

Ideal Models of the Four Amplifier Types （理想模型）

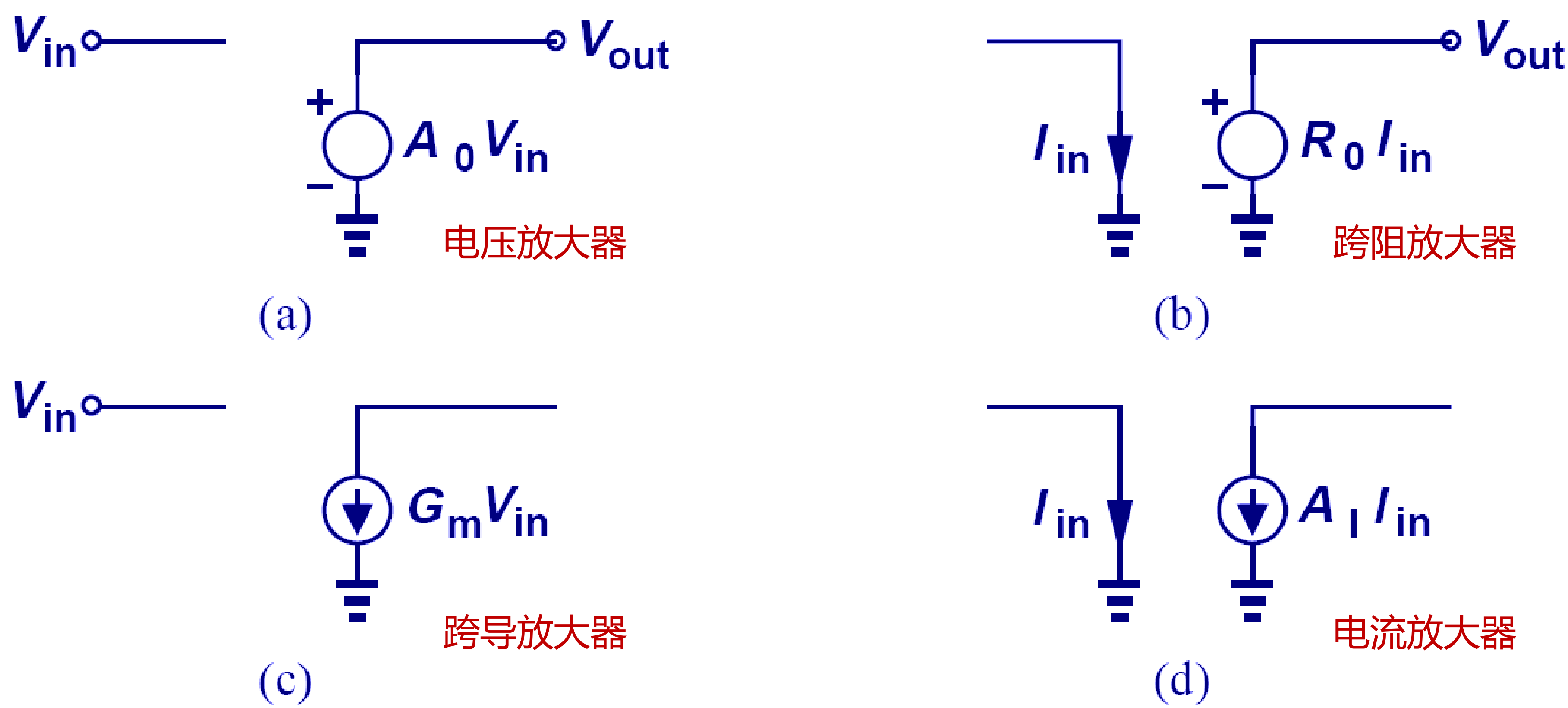

Figure 12.15 Ideal models for (a) voltage, (b) transimpedance, (c) transconductance, and (d) current amplifiers.

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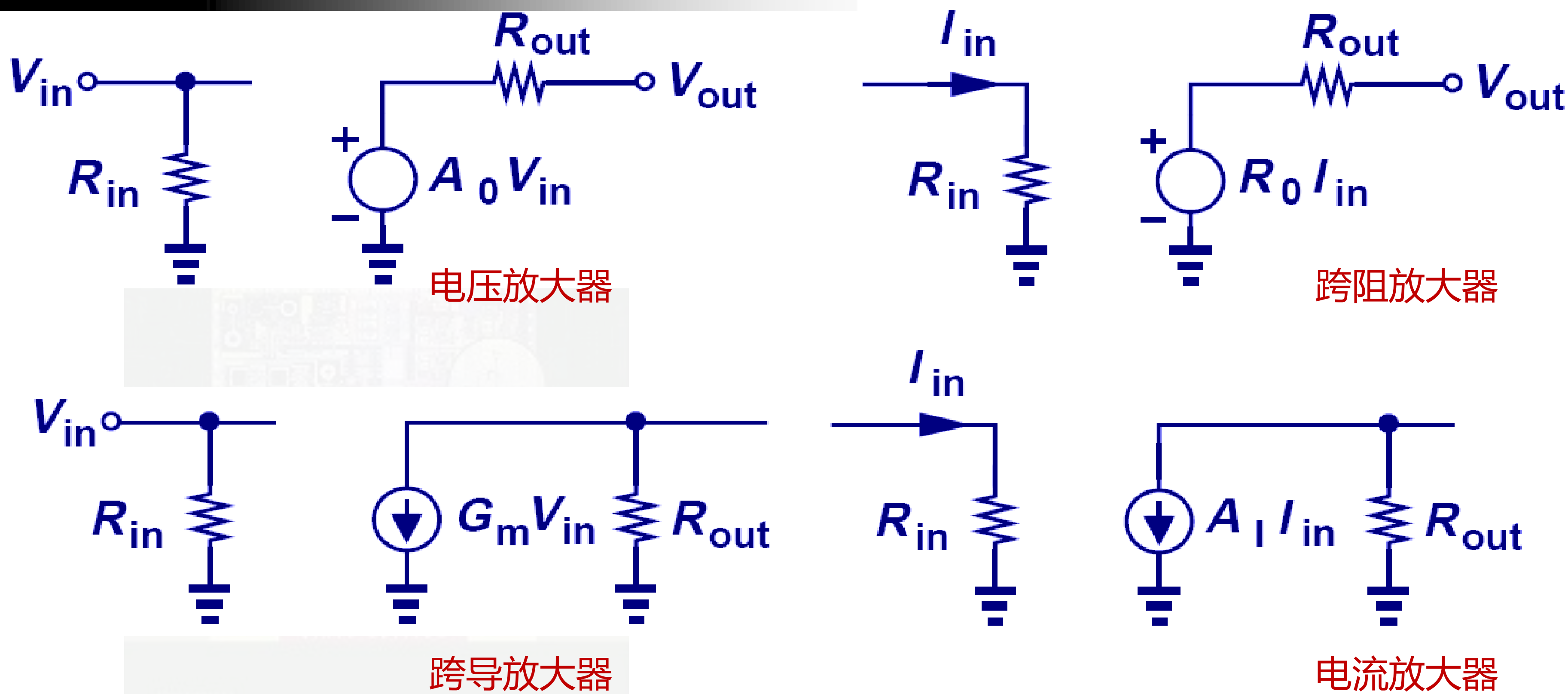
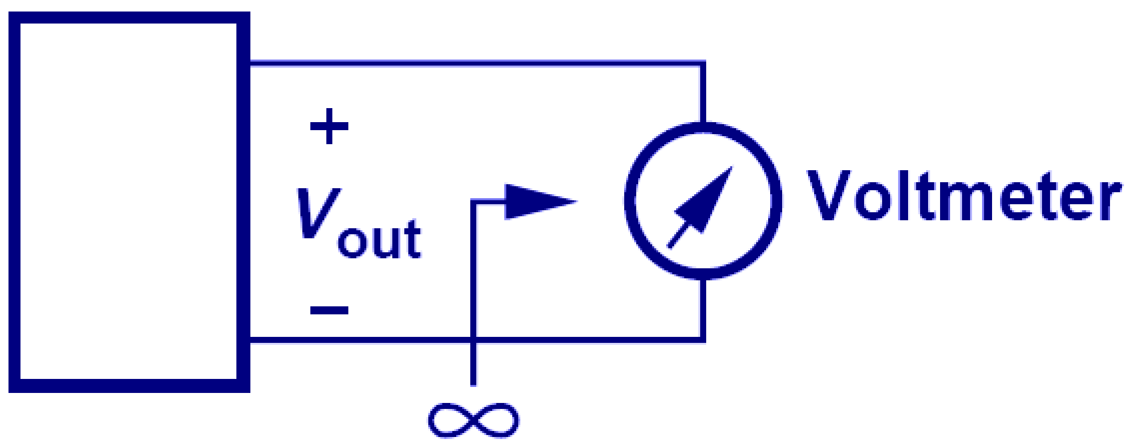
Realistic Models of the Four Amplifier Types（实际模型）



输出电压：用戴维南等效；
输出电流：用诺顿等效；

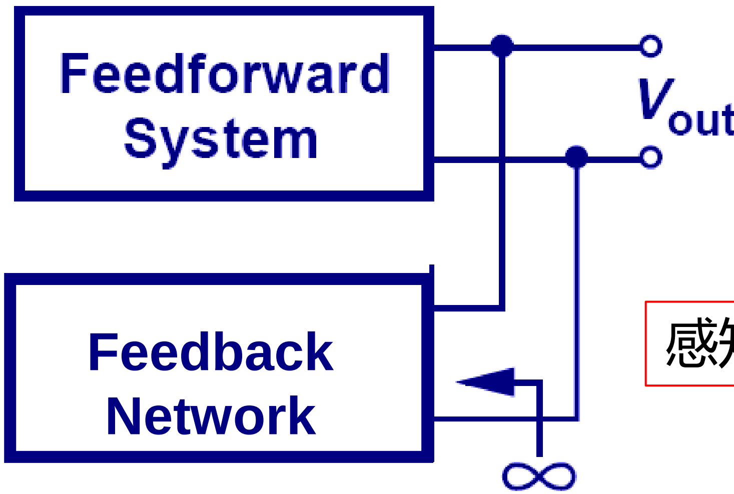
Sensing a Voltage（电压感知）

负反馈系统需要从输出感知信号（电压或电流），那么，感知是如何实现的?

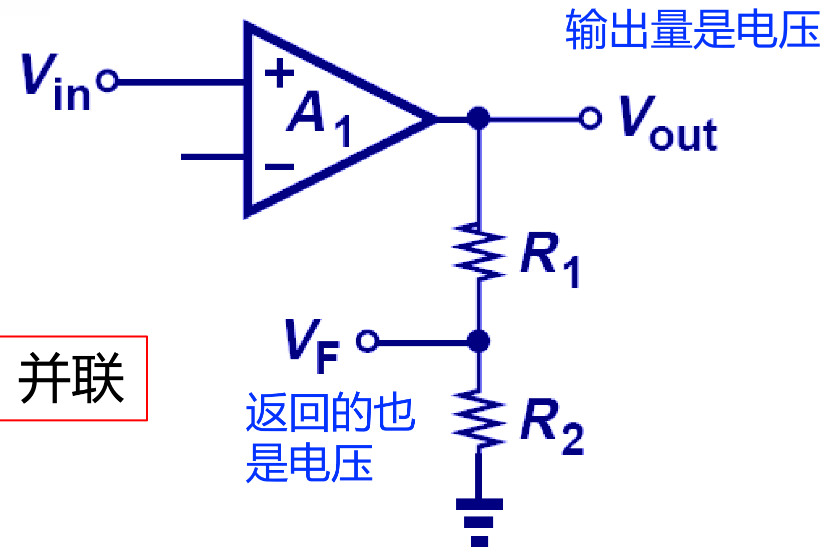


- 理想的电压表（阻抗无穷大）可以用来感知电压（与输出信号并联）

Sensing and Returning a Voltage
（感知和返回电压）



感知电压：并联

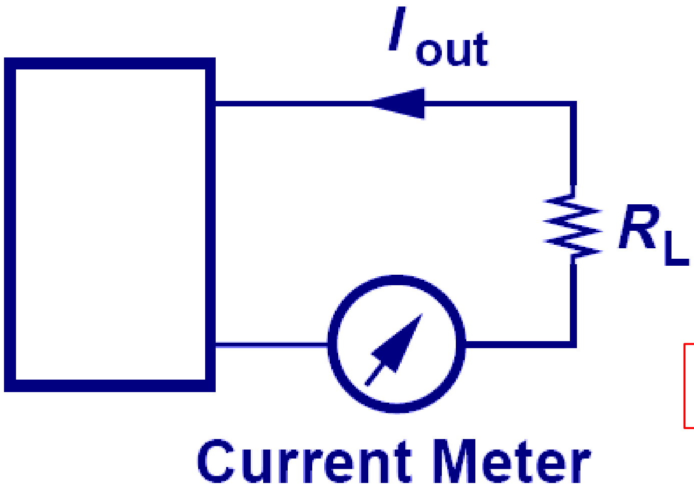


$$R_1 + R_2 \approx \infty$$

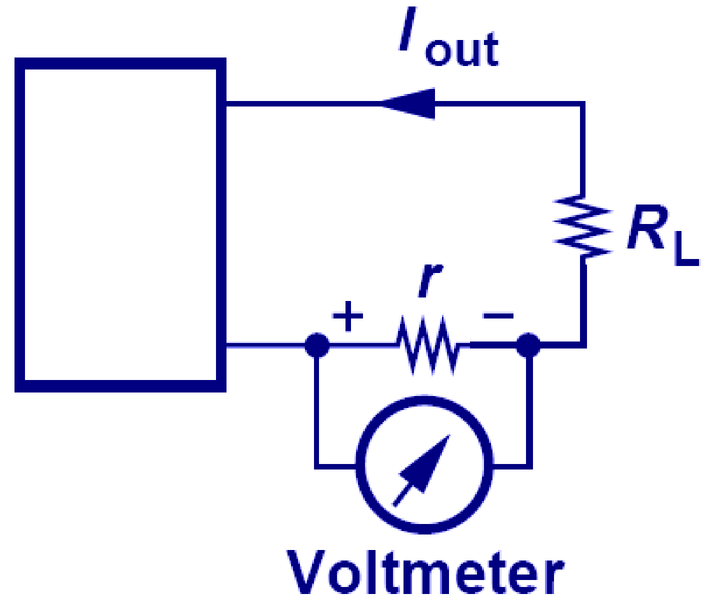
感知电压用大电阻并联

- 同样的，要使反馈网络能正确地感知输出电压，反馈网络的输入阻抗需要足够大（模拟一个电压表），并且并联到输出上
- R_1 and R_2 同时也返回了电压V_F到输入端

Sensing a Current（感知电流）

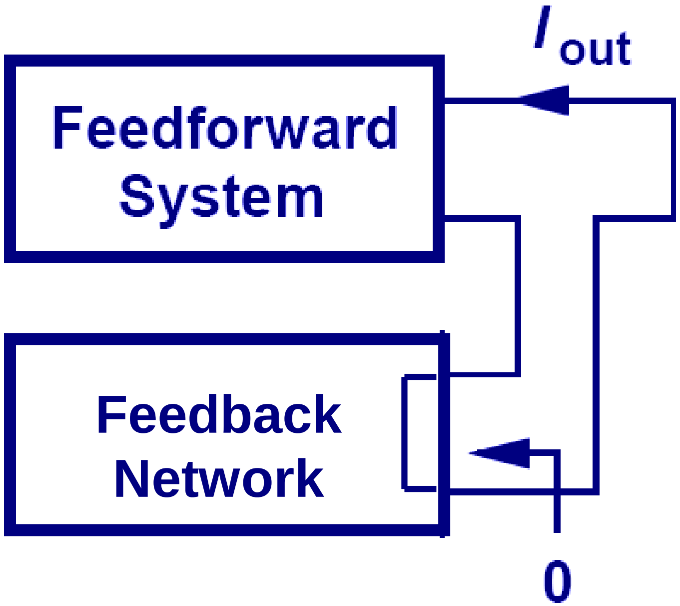


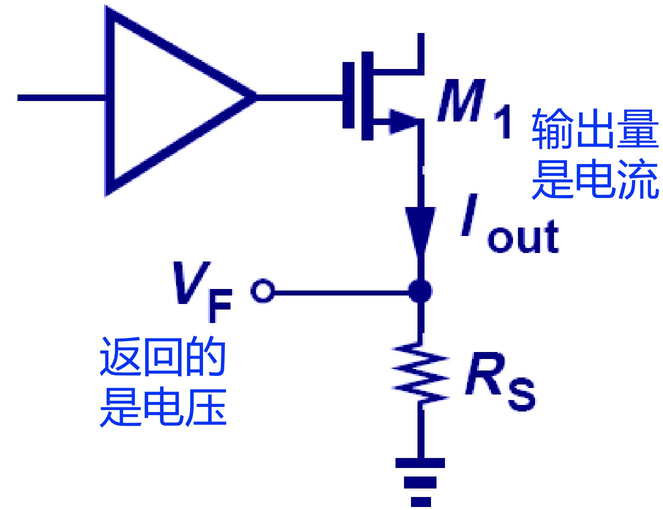
感知电流：串联



- 理想电流表（零阻抗）可用来感知电流（与输出信号串联）
- 电流表实际上是由一个小电阻和并联的电压表构成；

Sensing and Returning a Current（感知和返回电流）





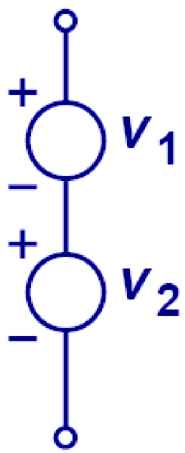
$$R_S \approx 0$$

感知电流用小电阻串联

- 同样，要使反馈网络能正确地感知输出电流，其输入阻抗应该足够小（模拟一个电流表），且串联到输出
- R_S 必须足够小，以保证其电压降不会对 I_{out} 产生影响.

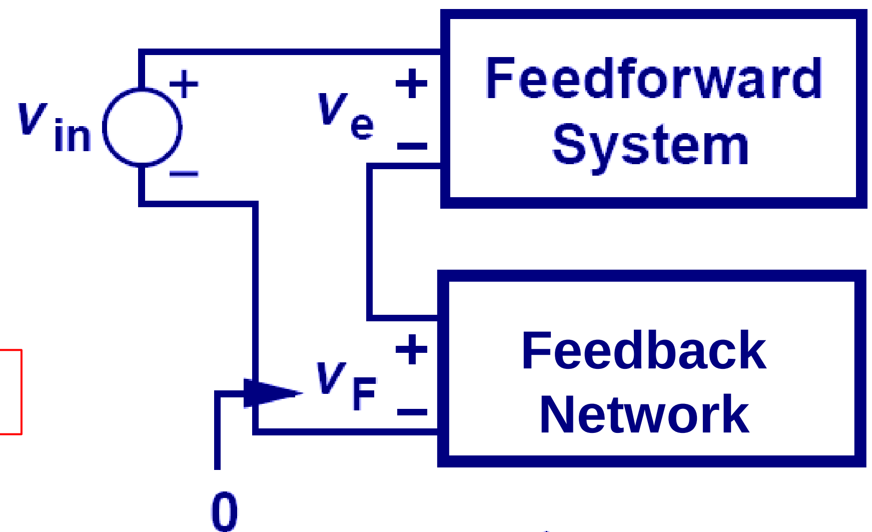
Addition of Two Voltage Sources（电压相加/减）

反馈网络从输出端感知到的信号要返回到输入端，并与信号源相减，如何实现的?



(a)

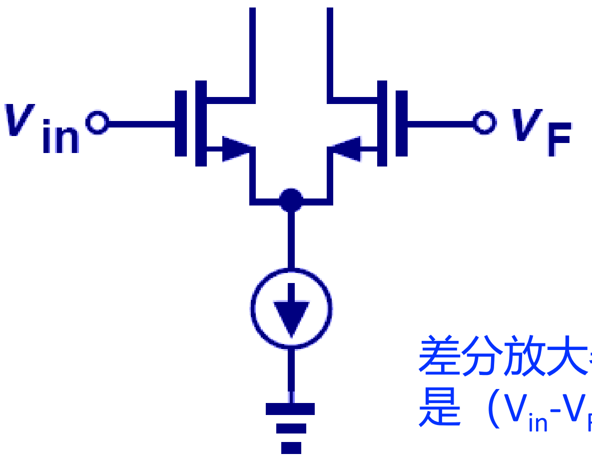
电压相减：串联



(b)

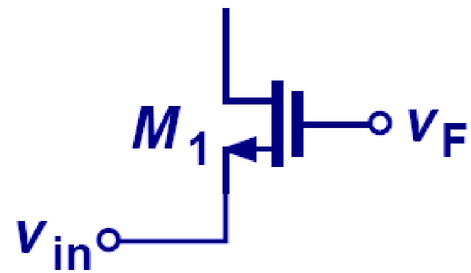
- 实现电压相加或相减：串联 → 反馈网络需与输入信号源相**串联**

Practical Circuits to Subtract Two Voltage Sources



差分放大器，输入是（V_{in}-V_F）

(c)

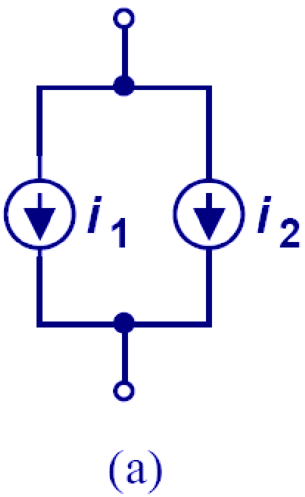


MOSFET，本质上是将v_{GS}（v_F-v_{in}）转换为i_D

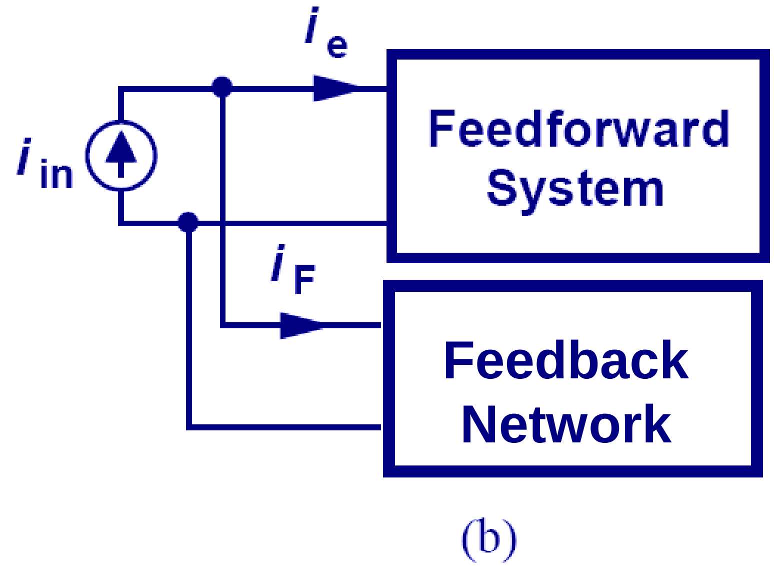
(d)

- 实用的、实现电压相减功能的电路

Addition of Two Current Sources（电流相加/减）



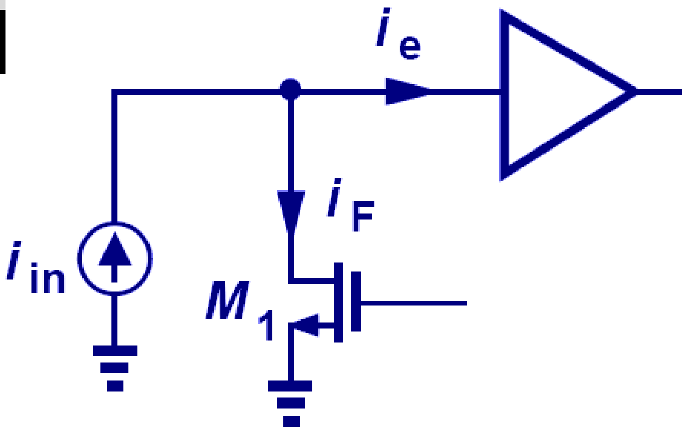
电流相减：并联



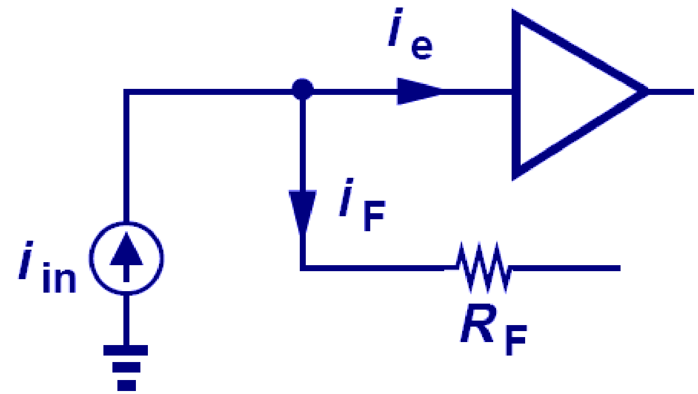
$$i_e = i_{in} - i_F$$

- 电流相加或相减：并联 → 反馈网络与输入信号源并联

Practical Circuits to Subtract Two Current Sources



(c)



(d)

- 实用的、实现电流相减功能的电路；

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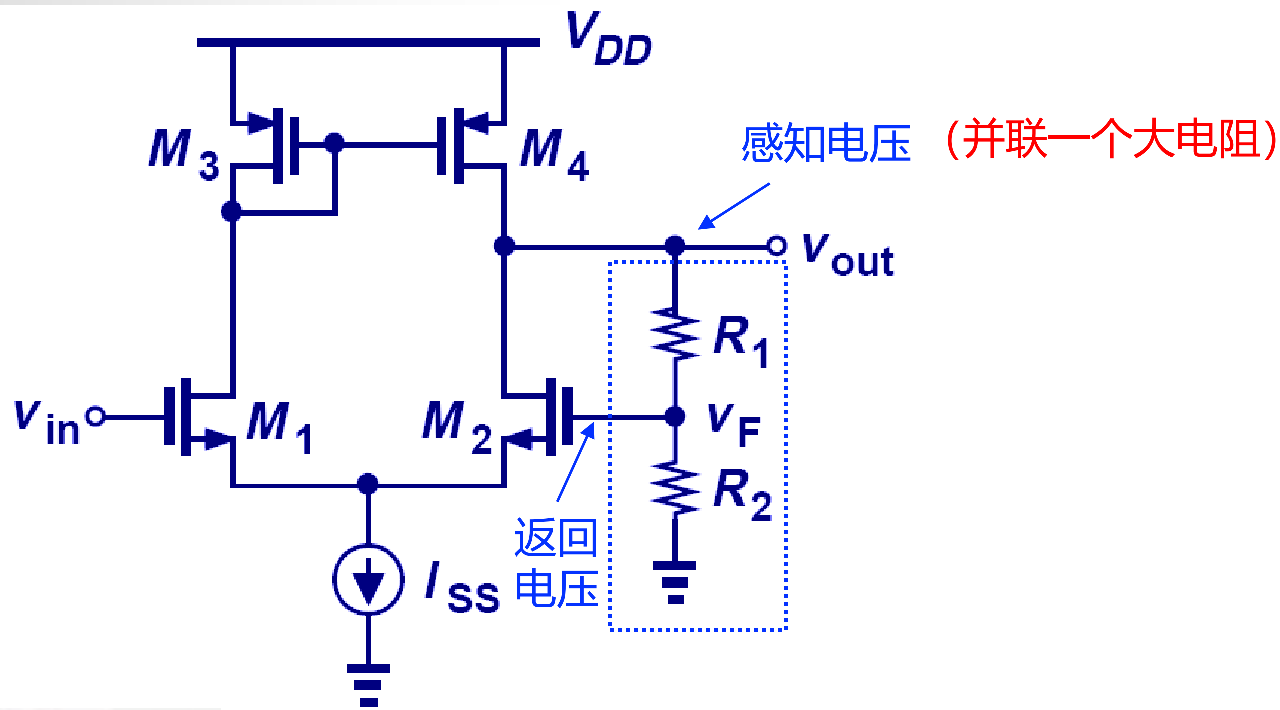
总结

	感知电压	感知电流
返回电压	输出并联大电阻 输入串联 (电压放大器)	输出串联小电阻 输入串联 (跨导放大器)
返回电流	输出并联大电阻 输入并联 (跨阻放大器)	输出串联小电阻 输入并联 (电流放大器)

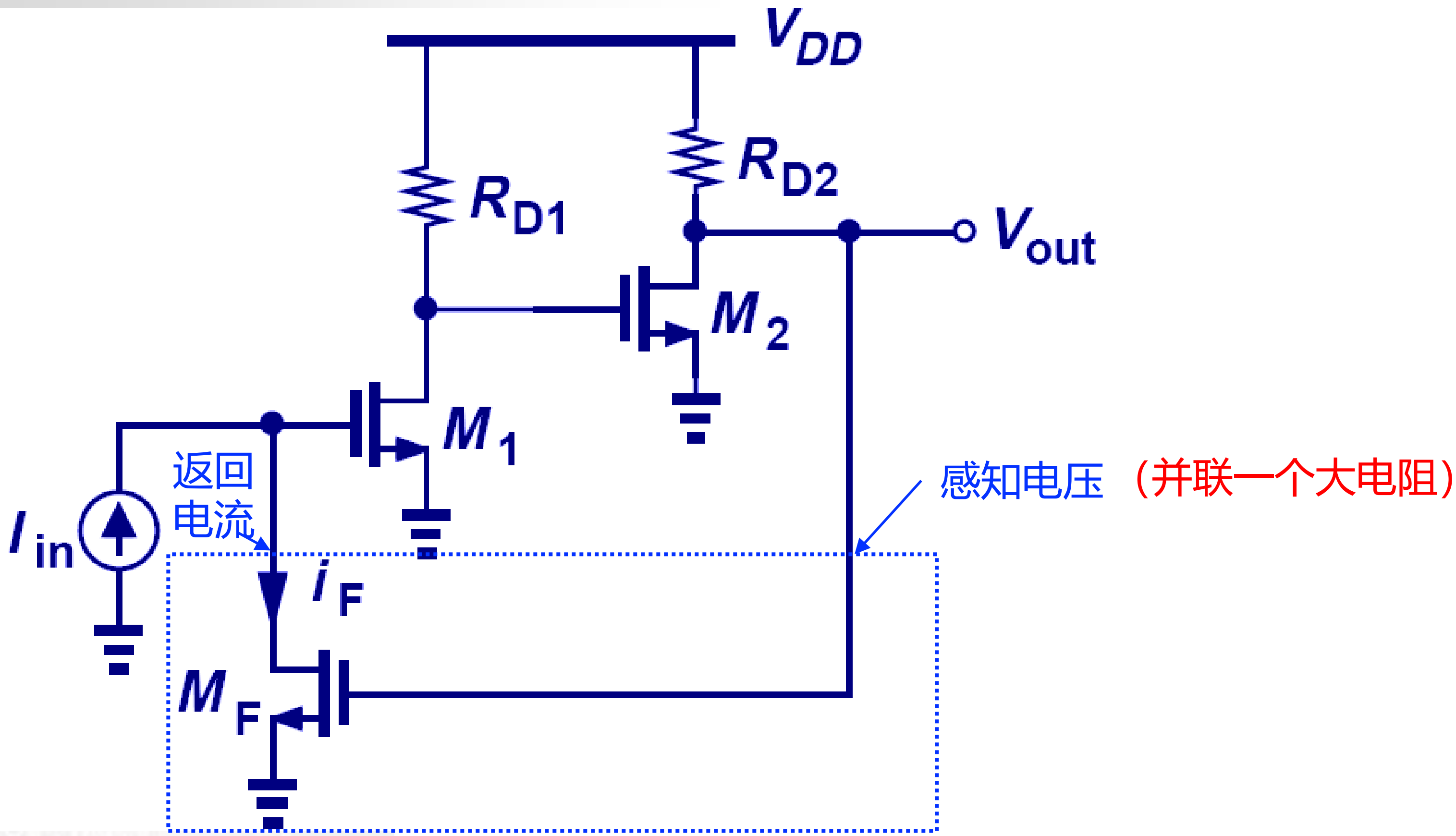
Example: Sense and Return
（感知电压，返回电压）



- R_1 and R_2 sense and return the output voltage to feedforward network consisting of M_1- M_4.
- M_1 and M_2 also act as a voltage subtractor.

Example: Feedback Factor（反馈因子“β或K”）

感知电压，返回电流



$$K = \frac{i_F}{v_{out}} = g_{mF}$$

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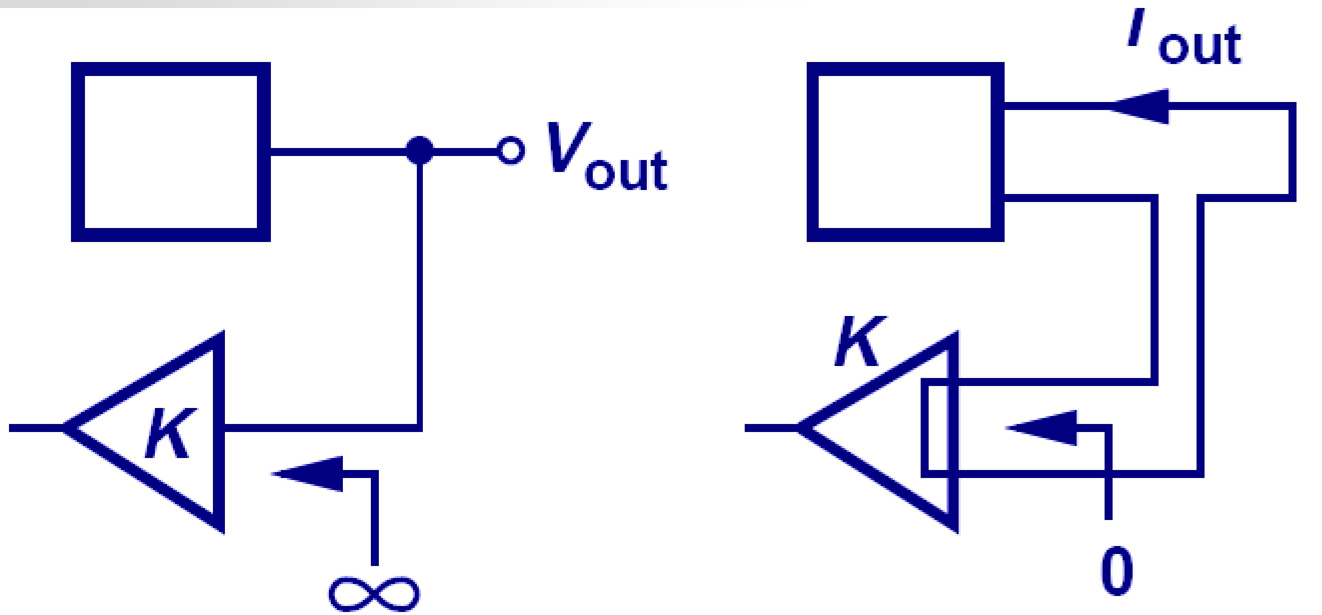
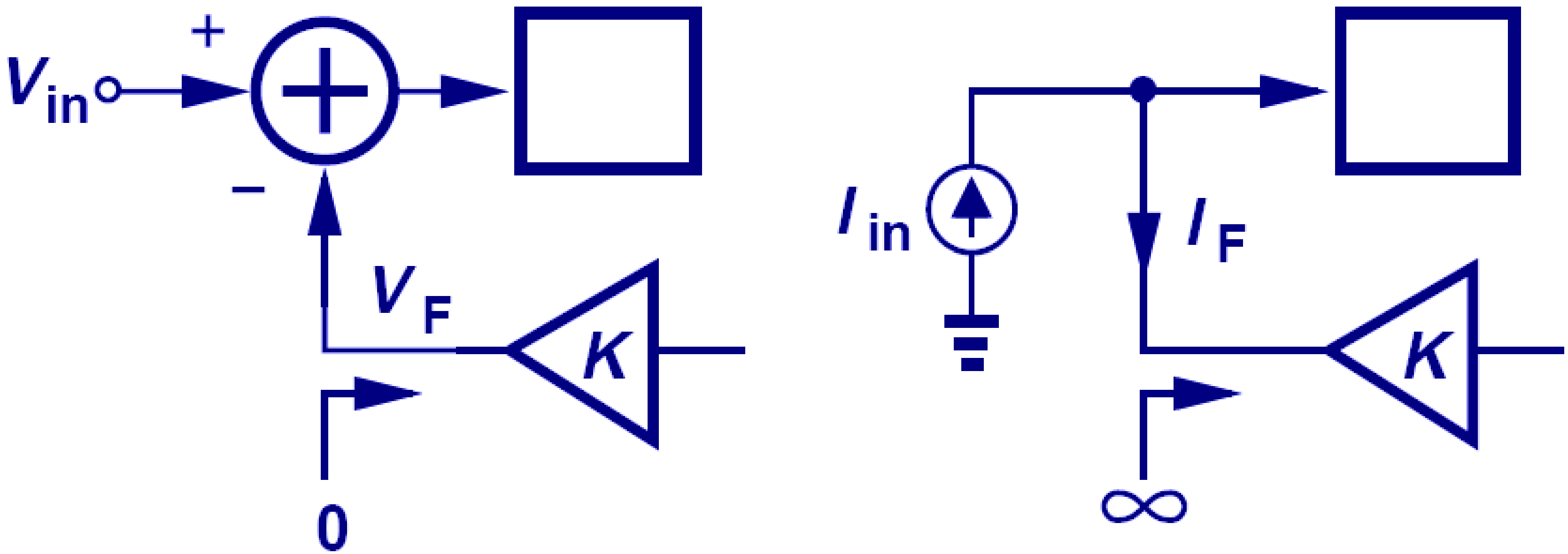
Input Impedance of an Ideal Feedback Network



- 对于电压感知的反馈网络，其理想的输入阻抗应该为无穷大（不影响原有电路），类似电压表；
- 对于电流感知的反馈网络，其理想的输入阻抗应该为零（不影响原有电路），类似电流表；

Output Impedance of an Ideal Feedback Network



- 对于返回电压量的反馈网络，串联，其理想的输出阻抗应该为零（不影响原有电路），不影响从信号源往右看的输入阻抗；
- 对于返回电流量的反馈网络，并联，其理想的输出阻抗应该为无穷大（不影响原有电路），不影响从信号源往右看的输入阻抗；

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Determining the Polarity of Feedback （如何判断反馈网络的极性）

- 1) Assume the input goes either up or down.假设输入信号上升或下降
- 2) Follow the signal through the loop.沿环路逐步分析信号
- 3) Determine whether the returned quantity enhances or opposes the original change.判断返回量是使初始假设增强（正反馈）还是使初始假设减弱（负反馈）

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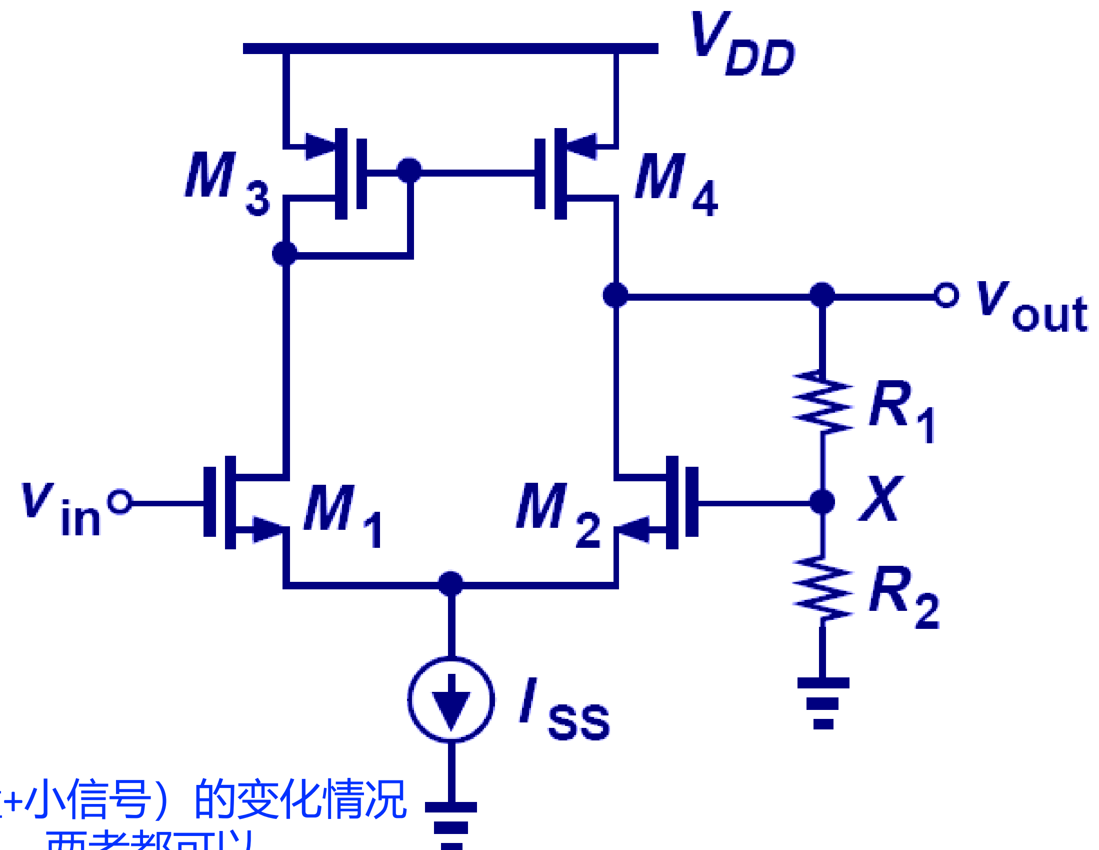
Polarity of Feedback Example I

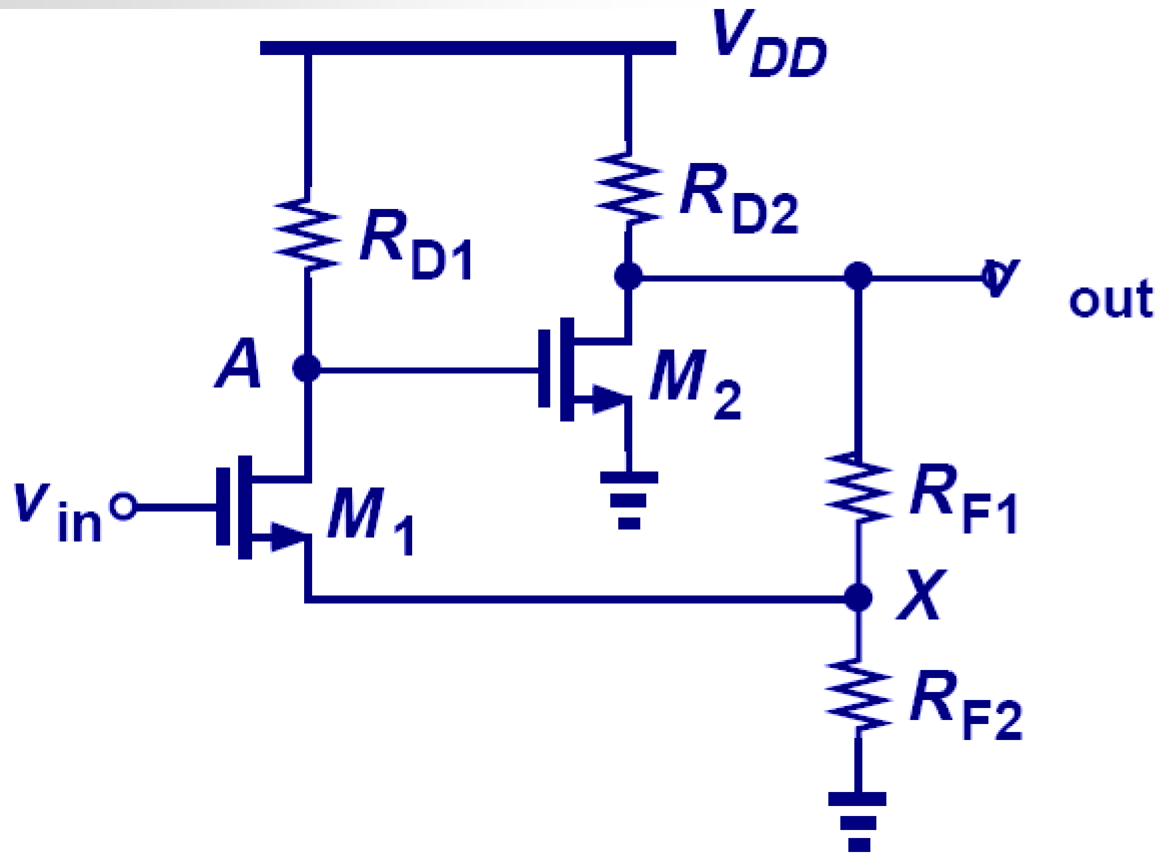


分析总量（直流偏置+小信号）的变化情况
或小信号的变化情况，两者都可以

$$V_{in}\uparrow \Rightarrow I_{D1}\uparrow, I_{D2}\downarrow \Rightarrow V_{out}\uparrow, V_x\uparrow \Rightarrow I_{D2}\uparrow, I_{D1}\downarrow$$

Negative Feedback

Polarity of Feedback Example II



$$V_{in}\uparrow \Rightarrow I_{D1}\uparrow, V_A\downarrow \Rightarrow V_{out}\uparrow, V_x\uparrow \Rightarrow I_{D1}\downarrow, V_A\uparrow$$

Negative Feedback

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The Four Basic Feedback Topologies

注意中英文术语的不同

中文先描述感知情况

感知 输出　反馈 输入

英文先描述返回情况

返回 输入　感知 输出

- 10.3.1. Voltage Amplifiers 电压串联负反馈电路 (series-shunt)
- 10.3.2. Current Amplifiers 电流并联负反馈电路(shunt-series)
- 10.3.3. Trans-conductance Amplifiers 电流串联负反馈电路 (series-series)
- 10.3.4. Trans-resistance Amplifiers 电压并联负反馈电路 (shunt-shunt)

反馈量若取自输出电压（电流），则称为电压（电流）反馈；

反馈量与输入量若以电压（电流）方式相叠加，则称为串联（并联）反馈；

11.3. **The Feedback Voltage Amplifiers** 电压串联负反馈电路

- **voltage amplifiers** – accept input voltage and yield output voltage.
  - VCVS
  - Thevenin Output
- **voltage-mixing(return,输入端叠加) / voltage-sampling(sense,输出端感知)** – is the topology most suitable for voltage amps.
  - Is also known as **series-shunt feedback.**
  - Provides high input resistance/low output resistance.

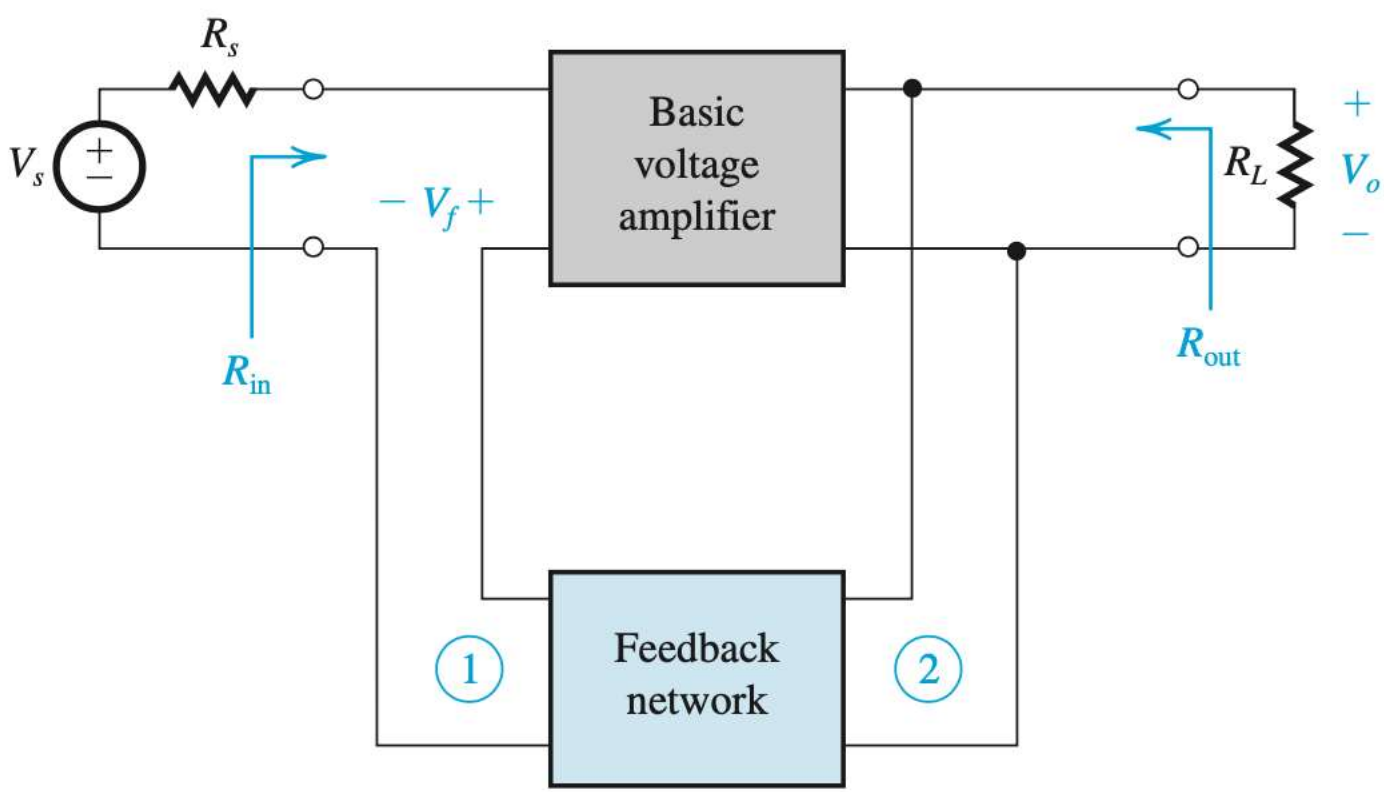
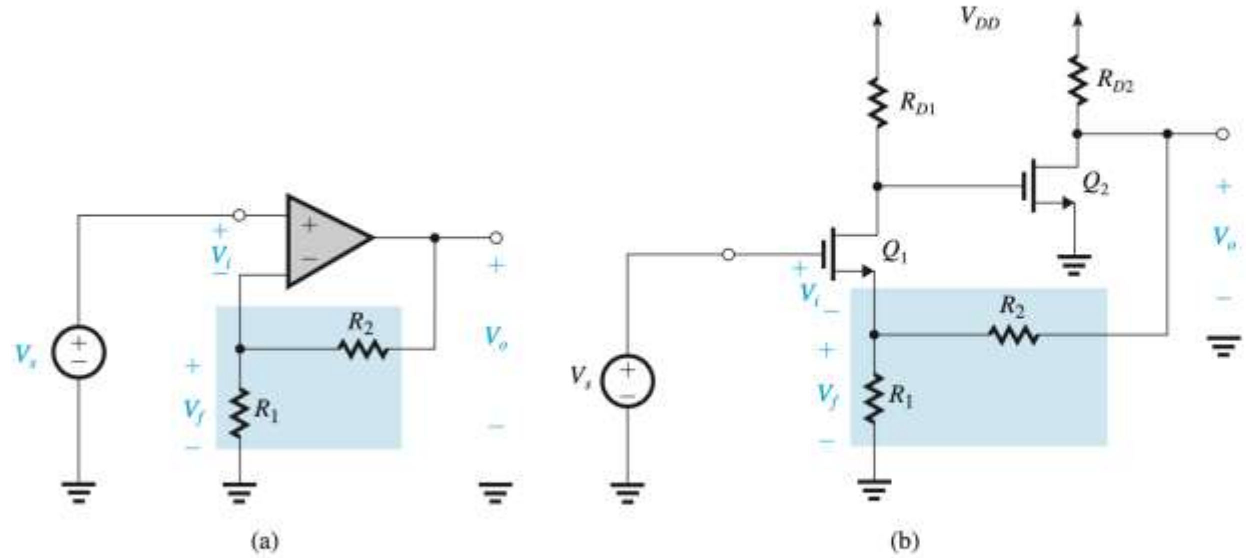


Figure 11.7 Block diagram of a feedback voltage amplifier. Here the appropriate feedback topology is series–shunt.

- Increased input resistance results because V_f subtracts from V_s, resulting in smaller signal V_i at the input.
  - Low V_i causes input current to be smaller.
  - This effects higher input resistance.
  - 输入串联，故输入阻抗增加；
- Decrease output resistance results because feedback works to keep V_o as constant as possible.
  - ΔV_o and ΔI_o change / vary together.
  - This effects lower output resistance.
  - 输出并联，故输出阻抗减小；



请判断反馈网络的极性，是正反馈，还是负反馈？

Tips：假设输入信号突然有一微小增加，再依信号流进行分析

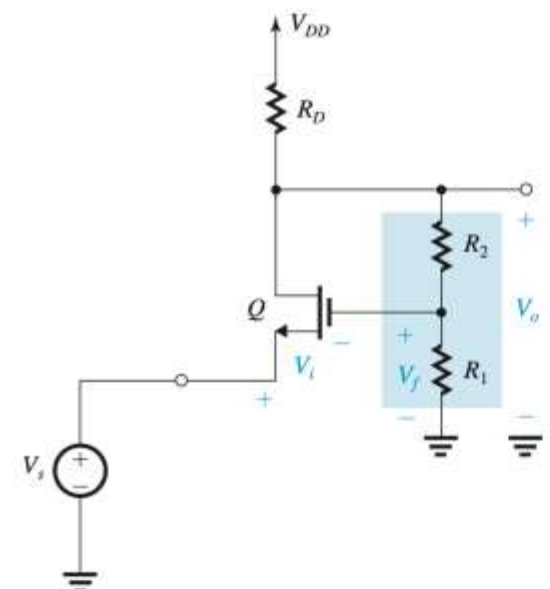


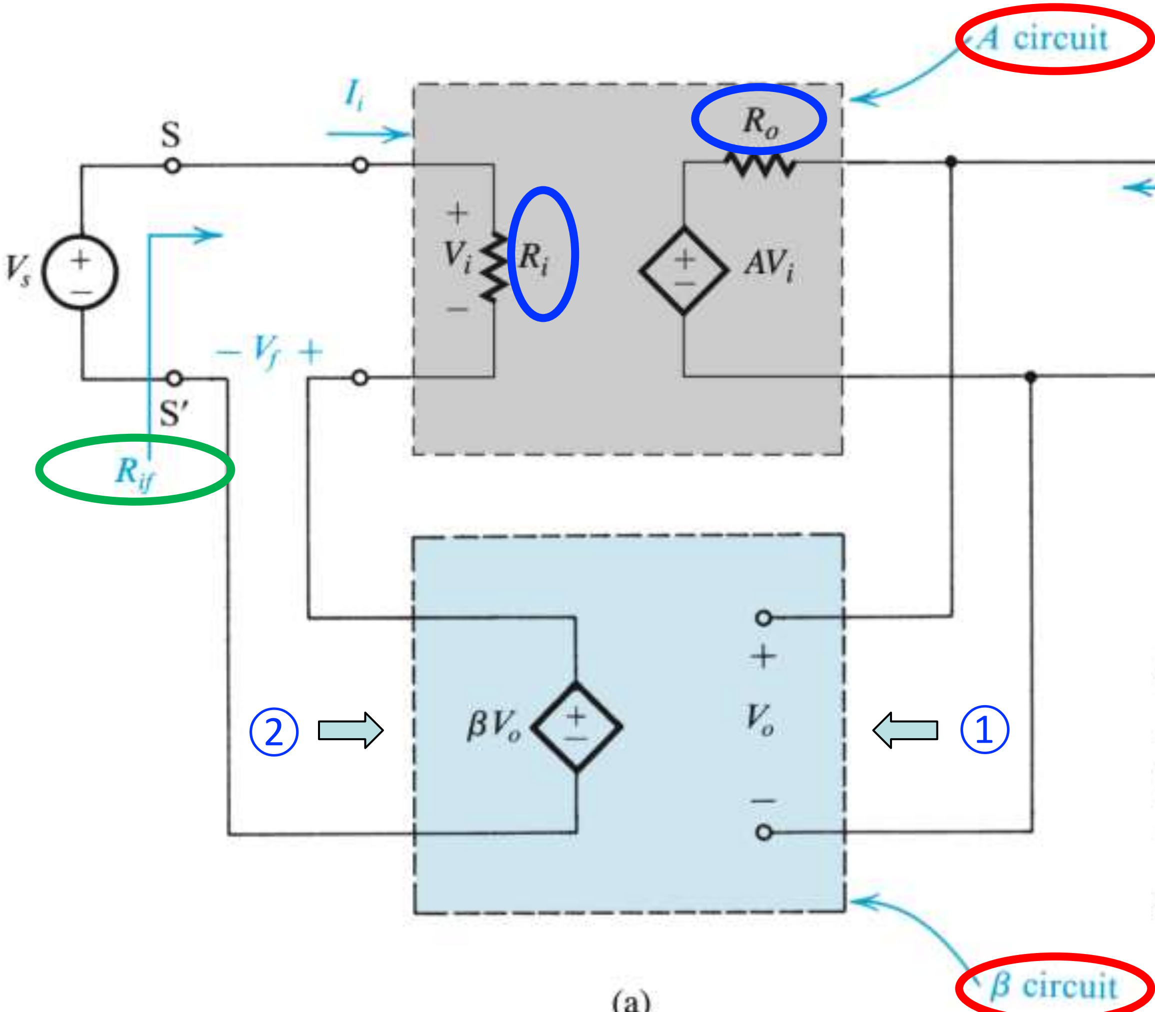
Figure 11.8 Examples of a feedback voltage amplifier. All these circuits employ series–shunt feedback. Note that the dc bias circuits are only partially shown.

11.4 Systematic Analysis of Feedback Voltage Amplifiers

11.4.1 The Ideal Case

理想情况：反馈网络（β circuit）的加入，对基本放大器（A circuit）的输入输出特性无影响，即

①反馈网络从电路输出端看，阻抗无穷大
②反馈网络从电路输入端看，阻抗为零

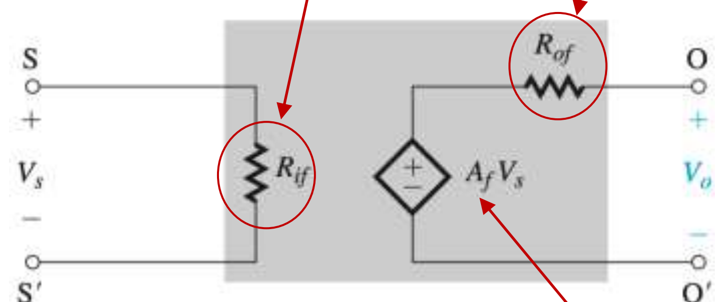


(a)

理想结构

含反馈网络后，电路的输入阻抗

含反馈网络后，电路的输出阻抗



闭环增益

(b)

等效电路

10.4.1. The Ideal Case

结论：输入输出阻抗的增大或减小，都是以（1+Aβ）因子缩放的；
且都变得更好了（输入阻抗增加、输出阻抗减小）

(10.17) closed-loop gain: $\boxed{A_f = \frac{V_o}{V_s} = \frac{A}{1+A\beta}}$

(10.18) input current: $I_i = \frac{V_i}{R_i} = \frac{V_s}{(1+A\beta)R_i}$

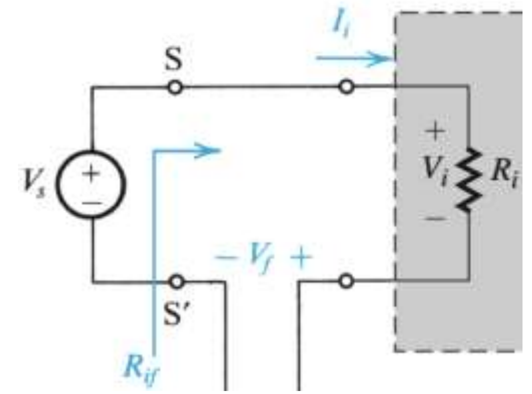
(10.19) input resistance: $\boxed{R_{if} = (1+A\beta)R_i}$

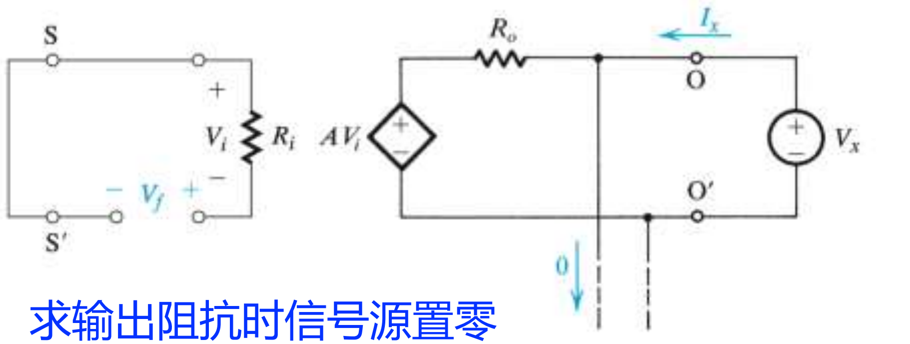
(10.20) output resistance: $R_{of} = \frac{V_x}{I_x}$

(10.21) current-x: $I_x = \frac{V_x - AV_i}{R_o}$

$V_f = \beta V_o = \beta V_x \Rightarrow V_i = -\beta V_x$

$\Rightarrow \boxed{R_{of} = \frac{R_o}{1+A\beta}}$





求输出阻抗时信号源置零

Figure 11.13 Determining the output resistance of the feedback amplifier of Fig. 11.12(a): $R_{of} = V_x/I_x$.

11.4.2 The Practical Case

- In practical case, feedback network will not be ideal VCVS. 实际上，反馈网络往往是由电阻构成的，做不到阻抗无穷大或阻抗为零
- Actually, it is resistive and will load the amplifier. 其对基本放大器的输入输出特性的影响不可忽略
- Source and load resistances will affect A, R_i, and R_o. 信号源内阻、负载电阻也会影响基本放大器的输入输出特性
- Source and load resistances should be lumped with basic amplifier.
- Expressed as two-port network. 反馈网络可用两端口网络来表述

所以我们的目的：将实际的负反馈电路等效成理想的 “A 电路” 和 “β 电路”

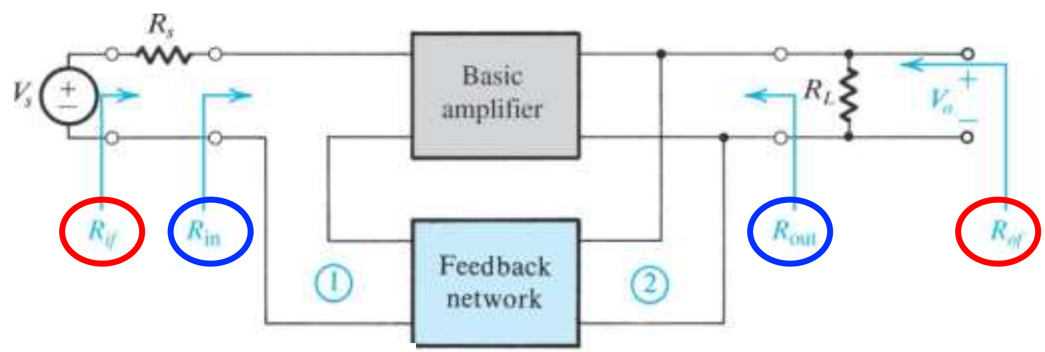
h_{11}， h_{22}表示实际非理想反馈网络对正向放大器的影响

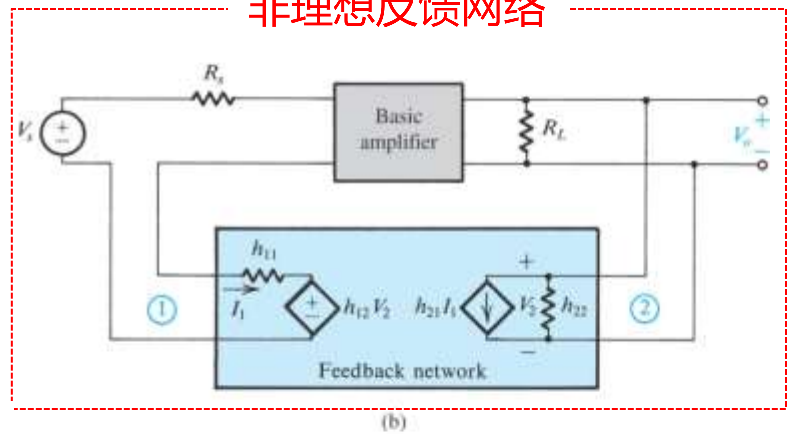
①若将h_{11}， h_{22}归纳到正向放大器中，则反馈网络就变为理想反馈网络；

②包含h_{11}， h_{22}后的正向放大器的增益为A；去除h_{11}， h_{22}后的反馈网络的反馈系数为β；A、β为理想

③根据上述等效后的理想的A和β，可以求得闭环增益A_f；

④ h_{11}和h_{22}的求法(simple rule)：另一端开路（串联）或短路（并联）so as to **destroy** the feedback





注1

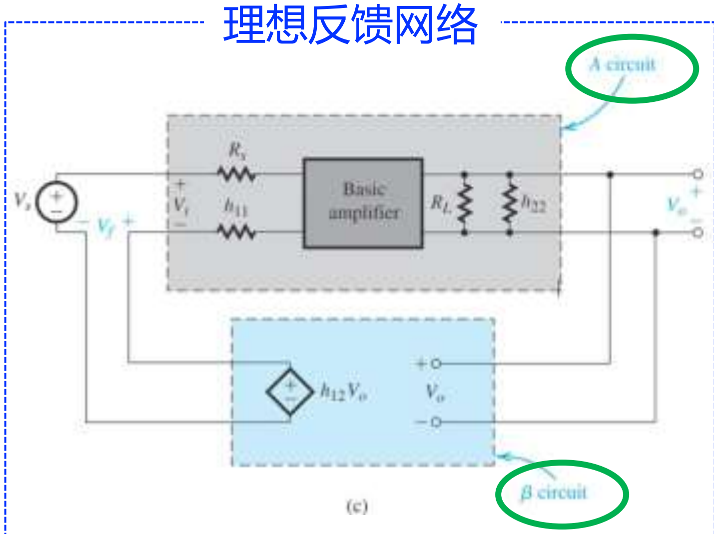
什么是destroy?

- 并联则短路
- 串联则开路

1）计算反馈网络在感知端②对主电路的影响h_{22}；（destroy①）

2)计算反馈网络在反馈端①对主电路的影响h_{11}；（destroy②）

3）计算ß（destroy①）



注2

h_{11}和h_{22}怎么加到A电路？

与反馈网络的接法一致：

若并联，则添加并联电阻；

若串联，则添加串联电阻

Figure 10.14 Derivation of the *A* circuit and *β* circuit for the series–shunt feedback amplifier. **(a)** Block diagram of a practical series–shunt feedback amplifier. **(b)** The circuit in **(a)** with the feedback network represented by its *h* parameters. **(c)** The circuit in **(b)** with h_{21} neglected.

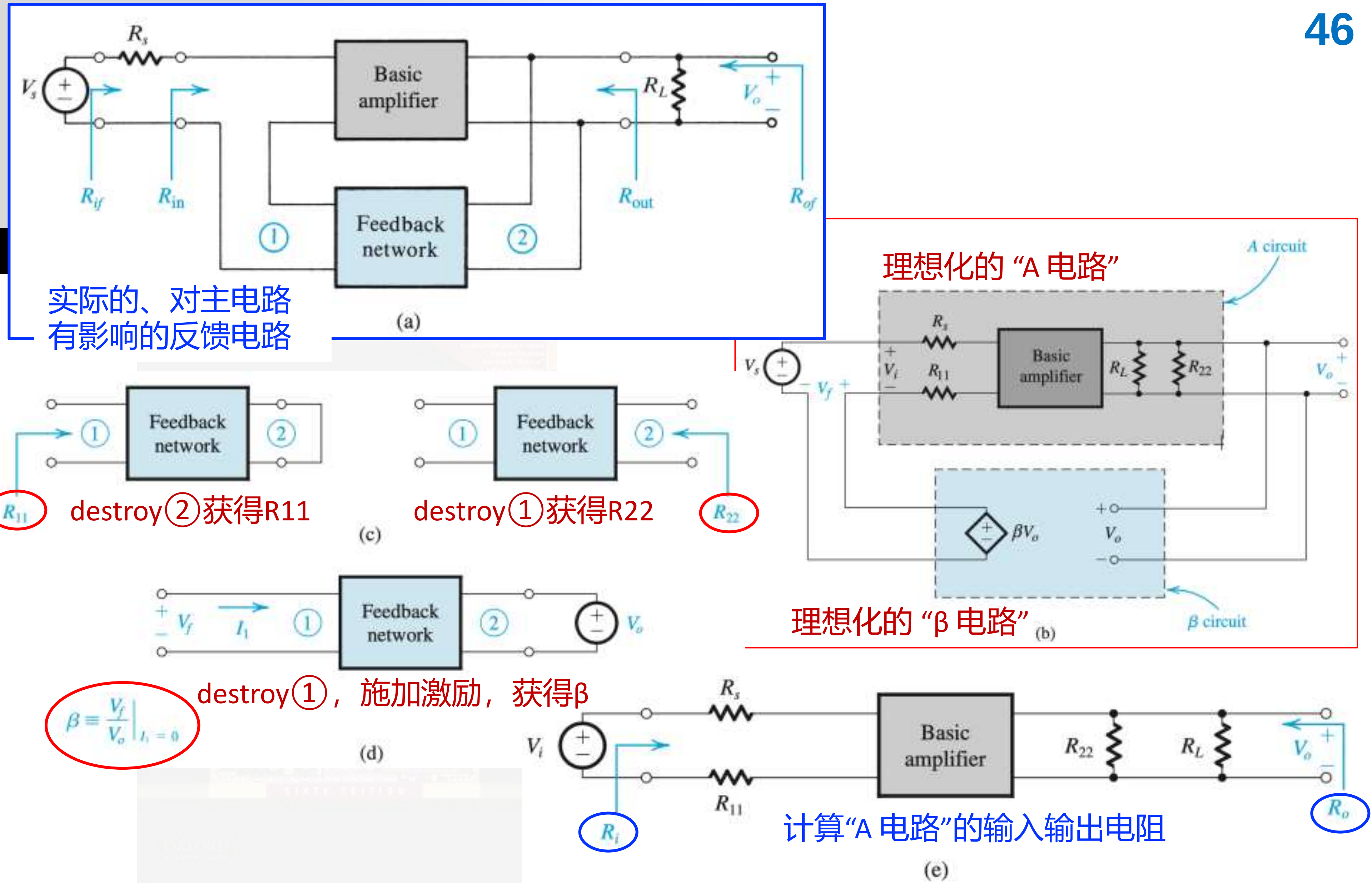


Figure 11.14 (a) Block diagram of a practical series–shunt feedback amplifier. (b) The circuit in (a) represented by the ideal structure of Fig. 11.12(a). (c) Definition of R_{11} and R_{22}. (d) Determination of the feedback factor β. (e) The A circuit, showing the open-loop resistances R_i and R_o.

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实际负反馈放大器的分析步骤

1. 根据上述等效拆分规则，将实际负反馈放大电路拆分成理想的A电路和理想的β电路
2. 求A电路的输入输出阻抗（包含R_s and R_L）： R_i and R_o
3. 求包含R_s and R_L的负反馈电路的输入输出阻抗：R_{if} and R_{of}，以及闭环增益，按（1+Aβ）比例缩放

$$R_{if} = R_i(1+A\beta)$$

$$R_{of} = R_o/(1+A\beta)$$

①

$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{1+A\beta}$$

4. 求实际负反馈电路的输入输出阻抗（不包含R_s and R_L）： R_{in} and R_{out}

②

$$R_{\text{in}} = R_{if} - R_s$$

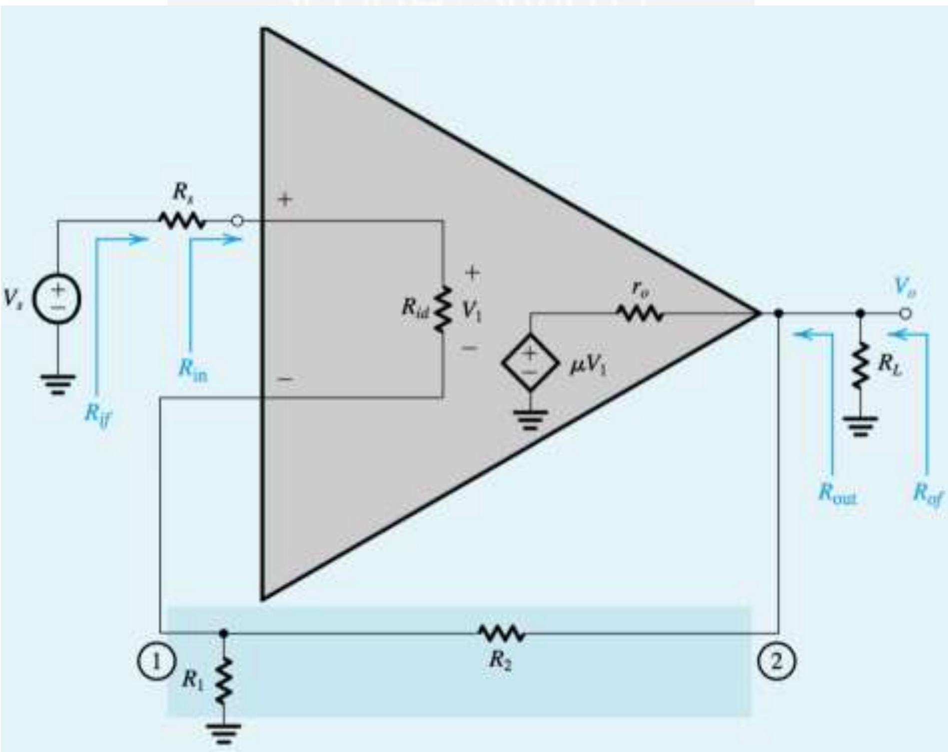
③

$$R_{\text{out}} = 1\Big/\left(\frac{1}{R_{of}} - \frac{1}{R_L}\right)$$

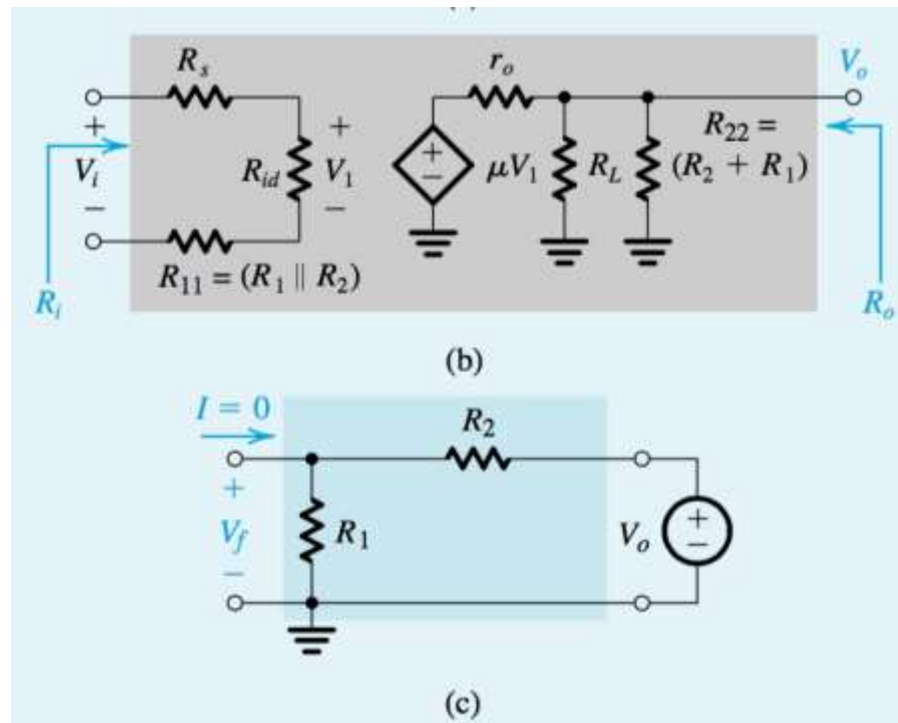
计算三个目标参数

Figure 11.15(a) shows an op amp connected in the noninverting configuration. The op amp has an open-circuit voltage gain μ, a differential input resistance R_{id}, and an output resistance r_o. Recall that in our analysis of op-amp circuits in Chapter 2, we neglected the effects of R_{id} (assumed it to be infinite) and of r_o (assumed it to be zero). Here we wish to use the feedback method to analyze the circuit taking both R_{id} and r_o into account. Find expressions for A, β, the closed-loop gain V_o/V_s, the input resistance R_{in} [see Fig. 11.15(a)], and the output resistance R_{out}. Also find numerical values, given $\mu = 10^4$, $R_{id} = 100\ \text{k}\Omega$, $r_o = 1\ \text{k}\Omega$, $R_L = 2\ \text{k}\Omega$, $R_1 = 1\ \text{k}\Omega$, $R_2 = 1\ \text{M}\Omega$, and $R_s = 10\ \text{k}\Omega$.

SEDRA/SMITH

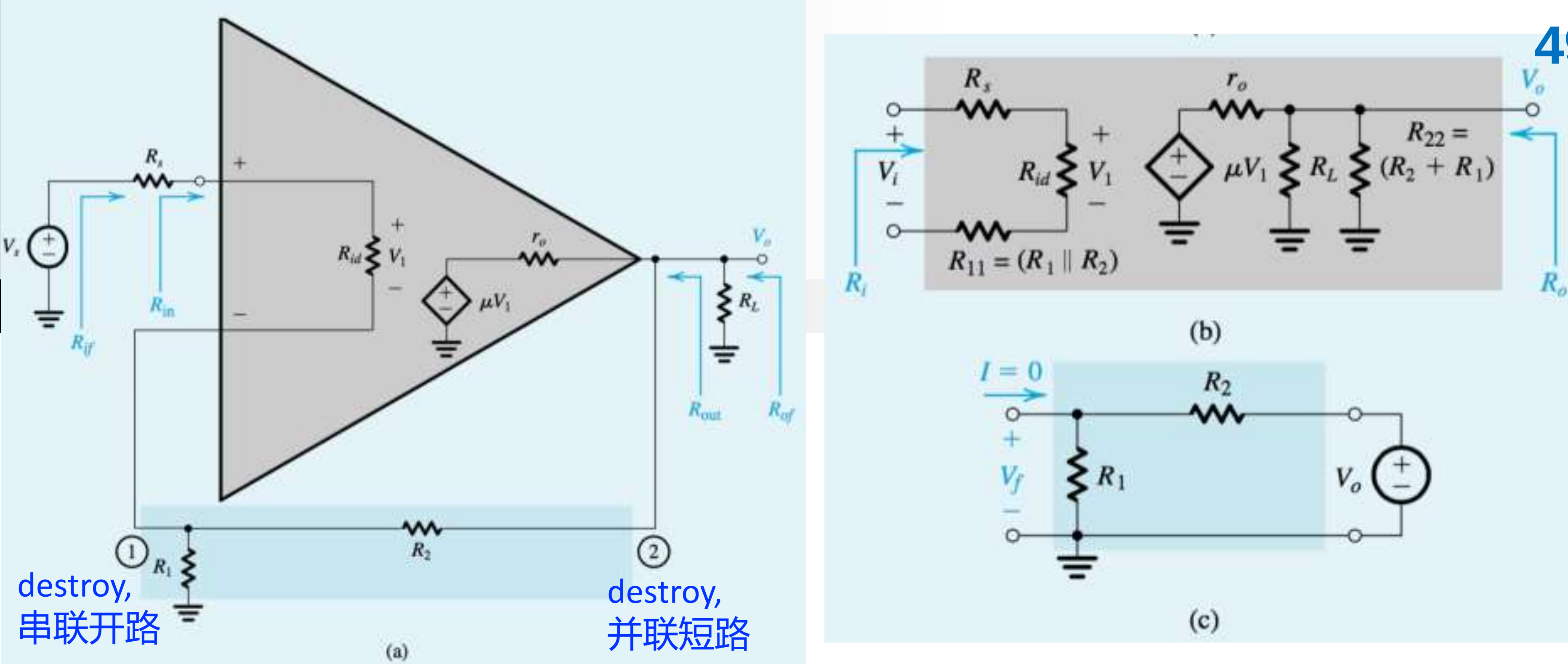


(a)



(b)

(c)



(a)
(b)
(c)

①判断反馈类型：感知电压，返回电压 → 电压串联负反馈电路

②计算反馈网络的h_{11}，h_{22}，并将其包含进正向放大器，计算A

$$R_{11} = R_1 \parallel R_2$$

$$R_{22} = R_2 + R_1$$

$$A \equiv \frac{V_o}{V_i} = \mu \frac{R_L \parallel (R_1 + R_2)}{[R_L \parallel (R_1 + R_2)] + r_o} \frac{R_{id}}{R_{id} + R_s + (R_1 \parallel R_2)} \simeq 6000 \text{ V/V}$$

③计算β

$$\beta \equiv \frac{V_f}{V_o} = \frac{R_1}{R_1 + R_2} \simeq 10^{-3} \text{ V/V}$$

④计算闭环增益

$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{1 + A\beta} = \frac{6000}{7} = 857 \text{ V/V}$$

⑤I/O阻抗

$$R_{if} = R_i(1 + A\beta)$$

$$R_i = R_s + R_{id} + (R_1 \parallel R_2)$$

$$R_{if} = 111 \times 7 = 777 \text{ k}\Omega$$

$$R_{in} = R_{if} - R_s = 739 \text{ k}\Omega.$$

$$R_{of} = \frac{R_o}{1 + A\beta}$$

$$R_o = r_o \parallel R_L \parallel (R_2 + R_1)$$

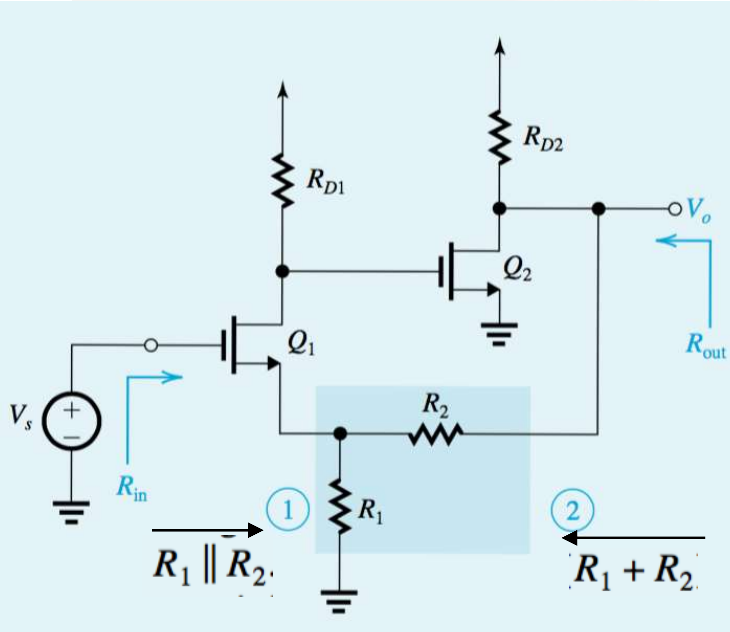
$$R_{of} = \frac{667}{7} = 95.3 \ \Omega$$

$$R_{of} = R_{out} \parallel R_L$$

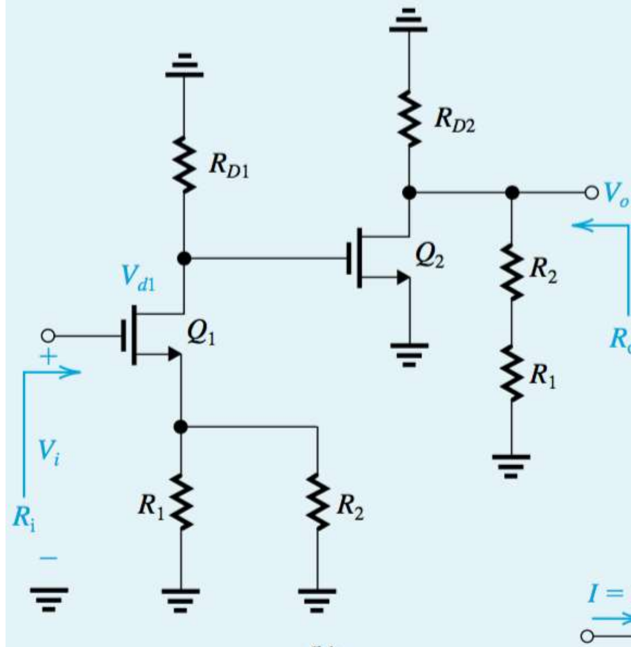
$$R_{out} \simeq 100 \ \Omega$$

①感知电压，返回电压：电压串联反馈电路 ②拆分A电路和β电路 ③分析计算

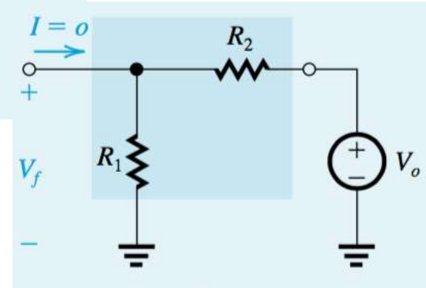
As another example of a series–shunt feedback amplifier, consider the circuit shown in Fig. 11.8(b), which we analyzed in Example 11.2 by determining the loop gain $A\beta$. In this example we wish to first analyze the circuit using our systematic procedure and then compare the results to those obtained in Example 11.2. For convenience, the circuit is repeated in Fig. 11.16(a). It is required to obtain the voltage gain V_o/V_s, input resistance R_{in}, and output resistance R_{out}. Find numerical values for the case $g_{m1} = g_{m2} = 4$ mA/V, $R_{D1} = R_{D2} = 10$ kΩ, $R_1 = 1$ kΩ, and $R_2 = 9$ kΩ. For simplicity, neglect r_o of each of Q_1 and Q_2.



(a)



(b)

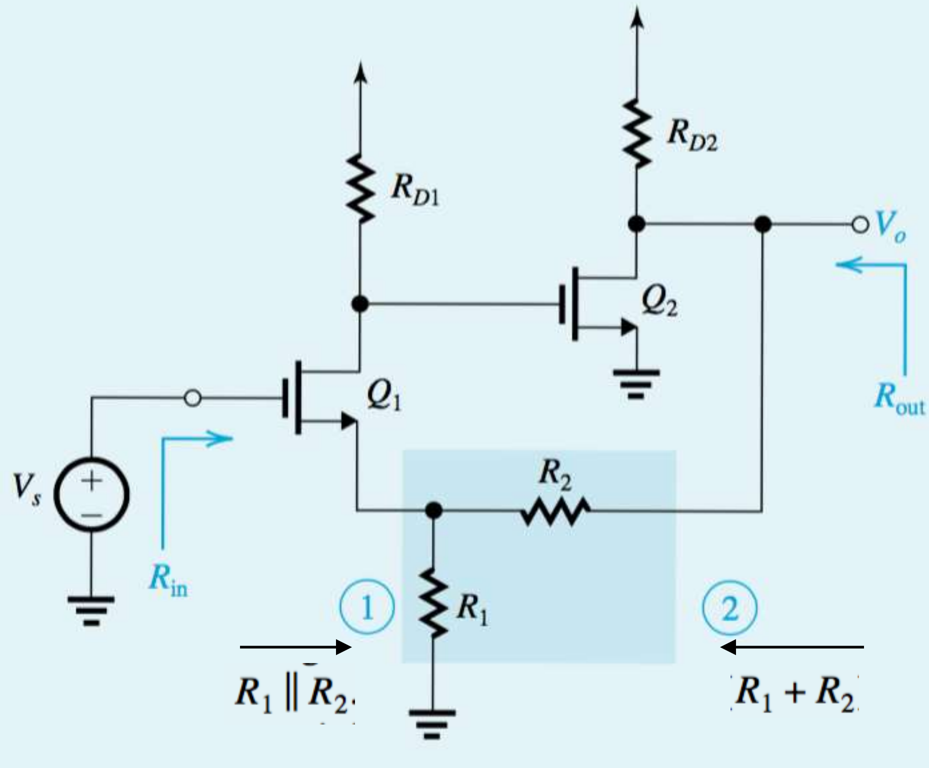


(c)

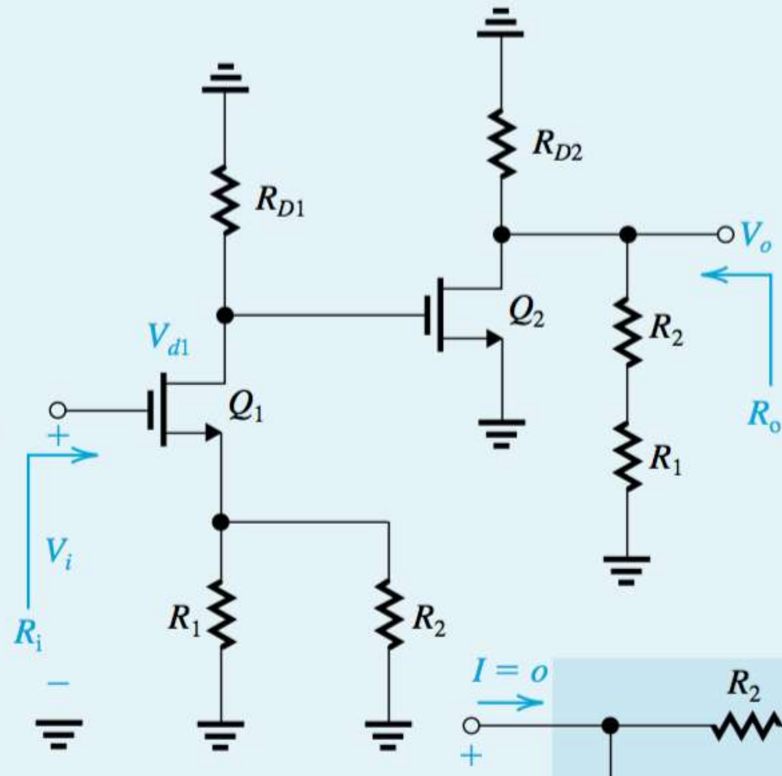
$$A = \frac{V_o}{V_i} = A_1 A_2 = \frac{g_{m1}R_{D1}g_{m2}[R_{D2} \| (R_1+R_2)]}{1+g_{m1}(R_1 \| R_2)} = 173.9 \quad \text{V/V}$$

$$\beta \equiv \frac{V_f}{V_o} = \frac{R_1}{R_1+R_2} = 0.1$$

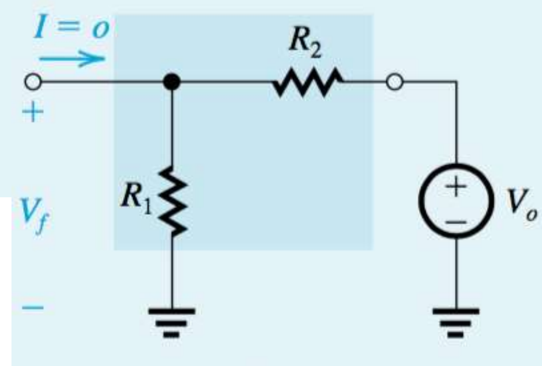
$$\frac{V_o}{V_s} = A_f = \frac{A}{1+A\beta} = \frac{173.9}{1+173.9\times 0.1} = 9.5 \quad \text{V/V}$$



(a)



(b)



(c)

$$R_o = R_{D2} \| (R_1 + R_2)$$
$$= 10 \| 10 = 5\ \mathrm{k\Omega}$$

$$R_{out} = R_{of} = \frac{R_o}{1 + A\beta}$$

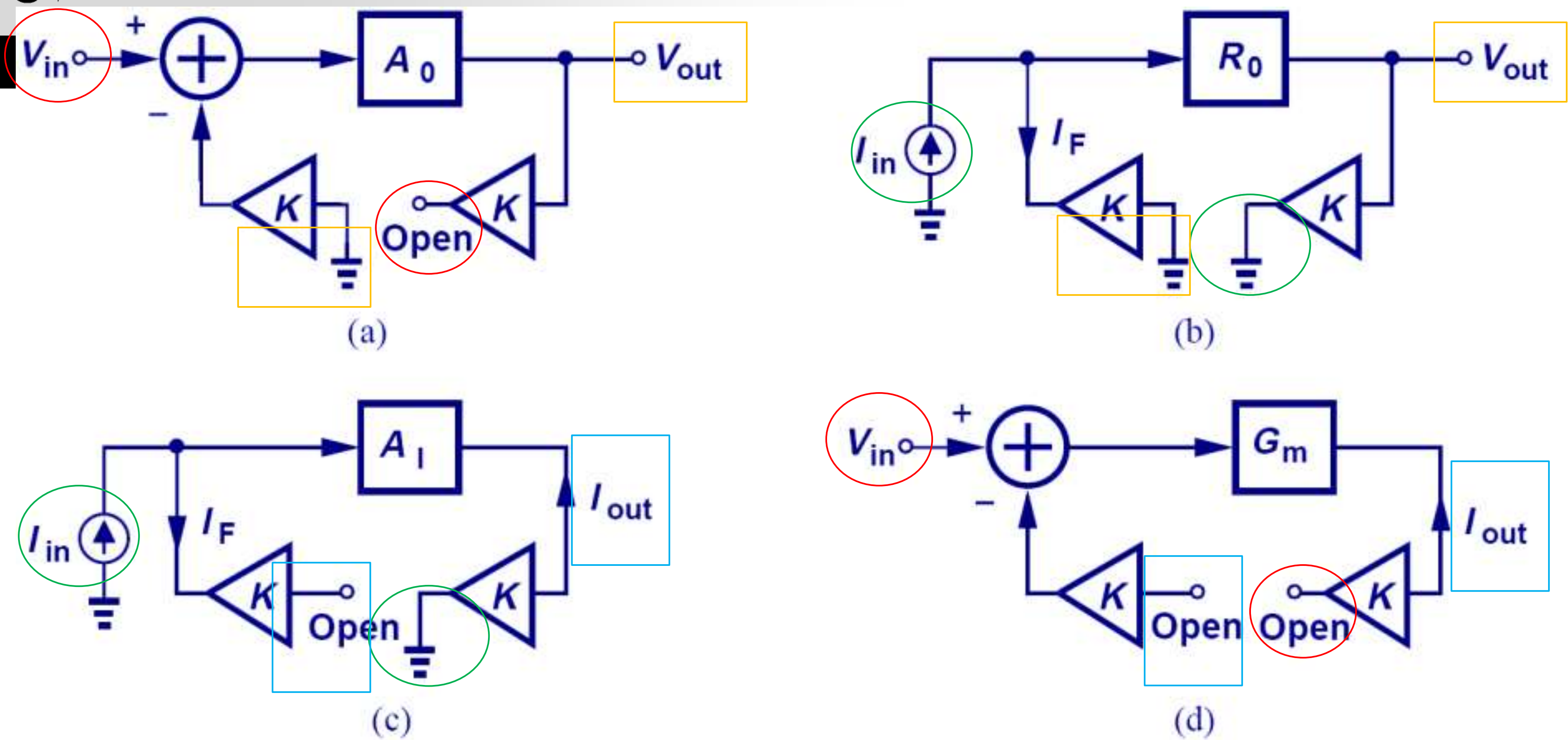
$$1 + A\beta = 1 + (173.9 \times 0.1) = 18.39$$

$$R_{out} = \frac{5000}{18.39} = 272\ \Omega$$

The input resistance is obviously infinite because of the infinite input resistance of the MOSFET.

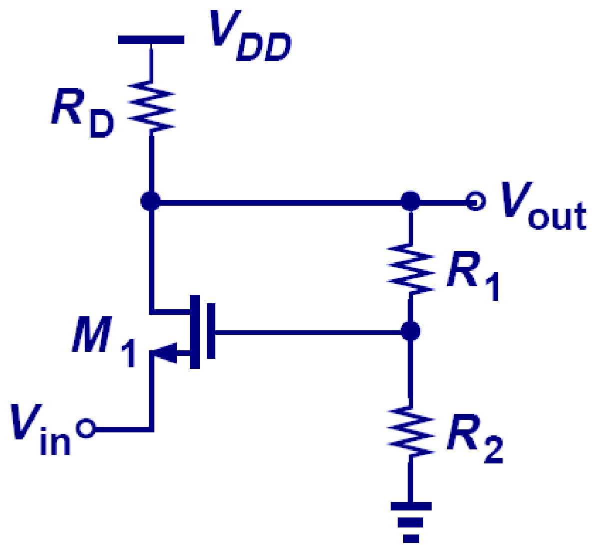
Rules for Breaking the Loop of Amplifier Types 另一种理解

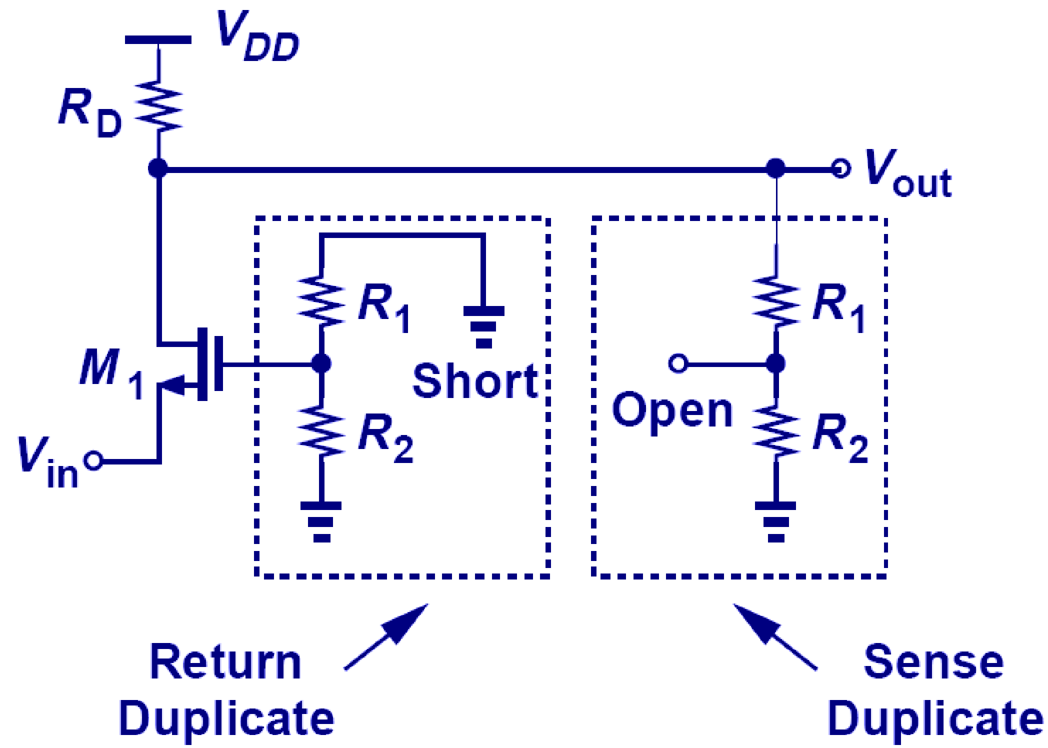
反馈网络符号用 β，也可用 K

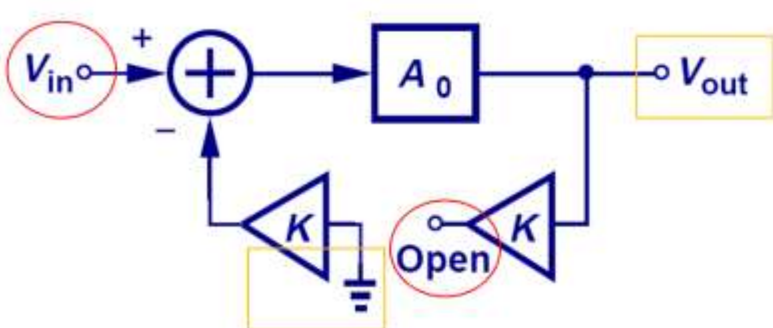


将反馈网络复制一遍，并断开，断点处开路或短路，参考destroy原则
- 并联（感知电压，或返回电流），则短路
- 串联（感知电流，或返回电压），则开路

Breaking the Loop Example I







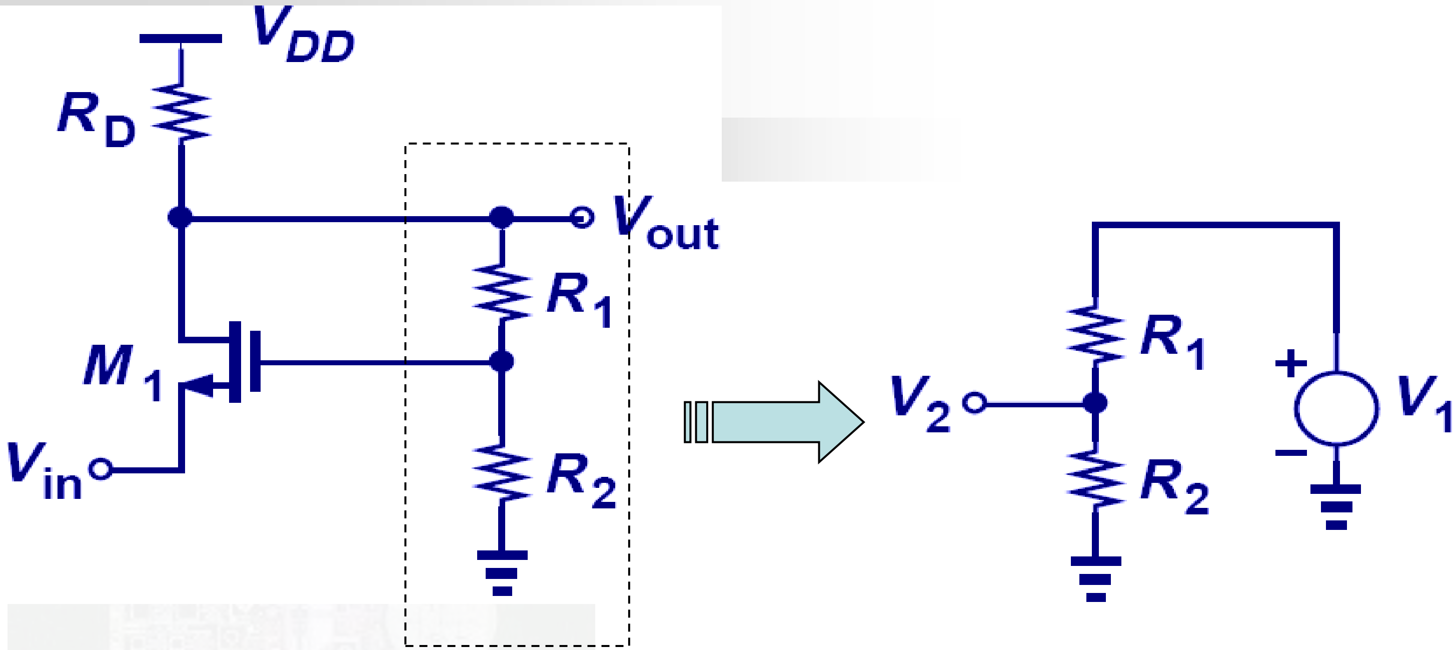
(a)

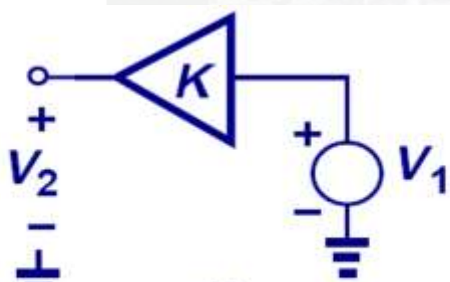
$$A_{v,open} = g_{m1}\left[R_D \parallel \left(R_1 + R_2\right)\right]$$

$$R_{in,open} = 1/g_{m1}$$

$$R_{out,open} = R_D \parallel \left(R_1 + R_2\right)$$

Feedback Factor Example I





$$K = \frac{V_2}{V_1}$$

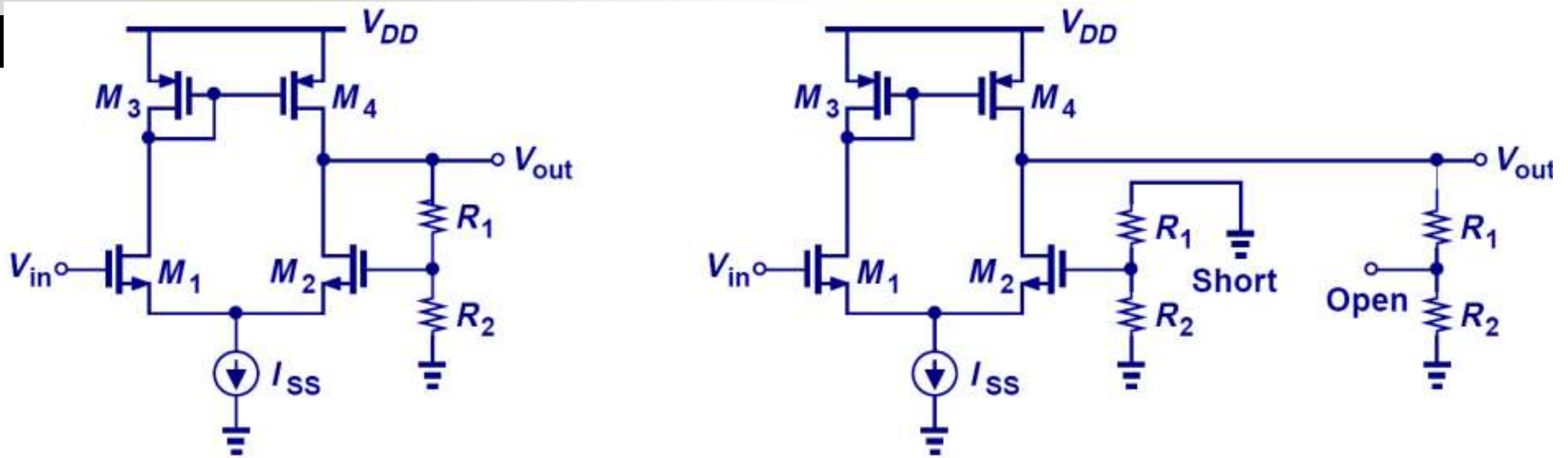
$$K = R_2/(R_1 + R_2)$$

$$A_{v,closed} = A_{v,open}/(1 + KA_{v,open})$$

$$R_{in,closed} = R_{in,open}(1 + KA_{v,open})$$

$$R_{out,closed} = R_{out,closed}/(1 + KA_{v,open})$$

Breaking the Loop Example II



$$A_{v,open} = g_{mN}\left[r_{ON} \parallel r_{OP} \parallel (R_1 + R_2)\right]$$

$$R_{in,open} = \infty$$

$$R_{out,open} = r_{ON} \parallel r_{OP} \parallel (R_1 + R_2)$$

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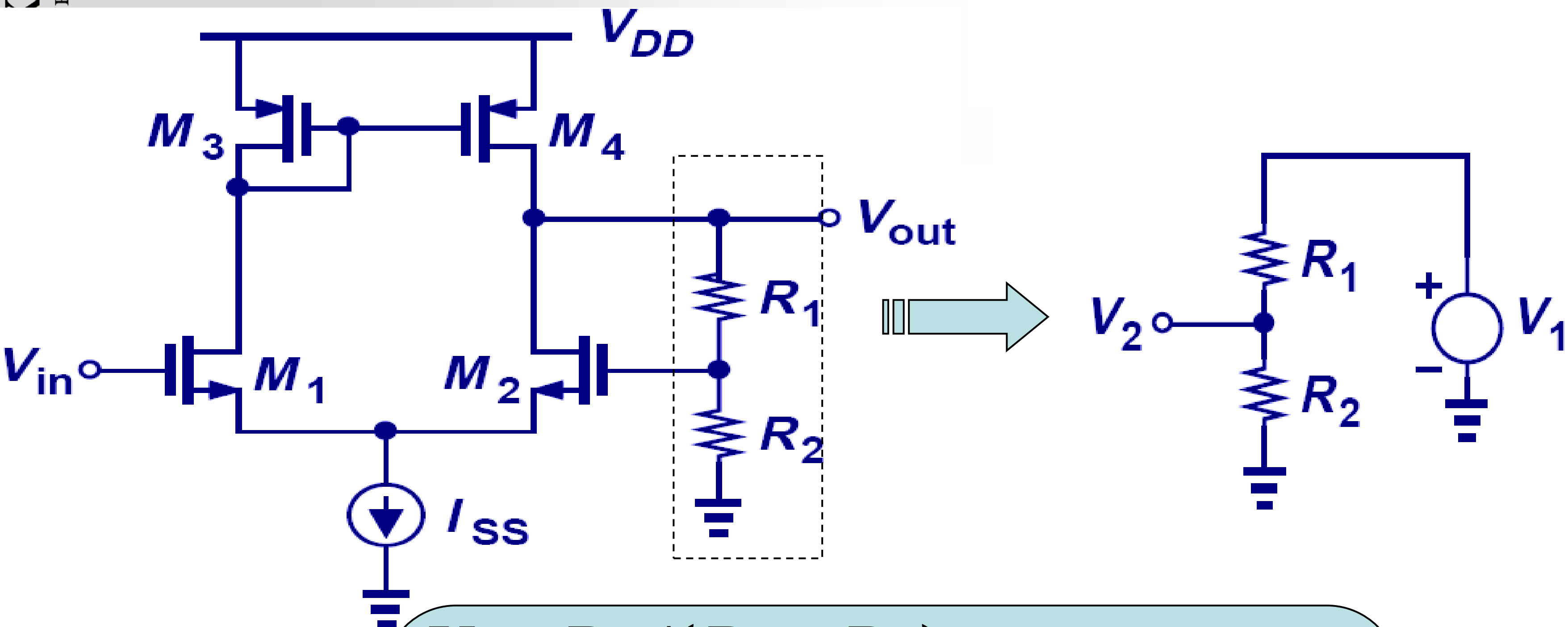
Feedback Factor Example II



$$K = R_2 / (R_1 + R_2)$$

$$A_{v,closed} = A_{v,open} / (1 + KA_{v,open})$$

$$R_{in,closed} = \infty$$

$$R_{out,closed} = R_{out,open} / (1 + KA_{v,open})$$

作业

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11.7 The circuit shown in Fig. E11.17 consists of a differential stage followed by an emitter follower, with series–shunt feedback supplied by the resistors R_1 and R_2. Assuming that the dc component of V_s is zero, and neglecting the base currents of the BJTs, show that the dc voltage at the output is approximately zero and find the dc operating current of each of the three transistors. Then find the values of A, β, $A_f \equiv V_o/V_s$, R_{in}, and R_{out}. Assume that the transistors have $\beta = 100$.

Ans. 0.5 mA, 0.5 mA, 5 mA; 85 V/V; 0.1 V/V; 8.95 V/V; 189.5 kΩ; 19.2 Ω.

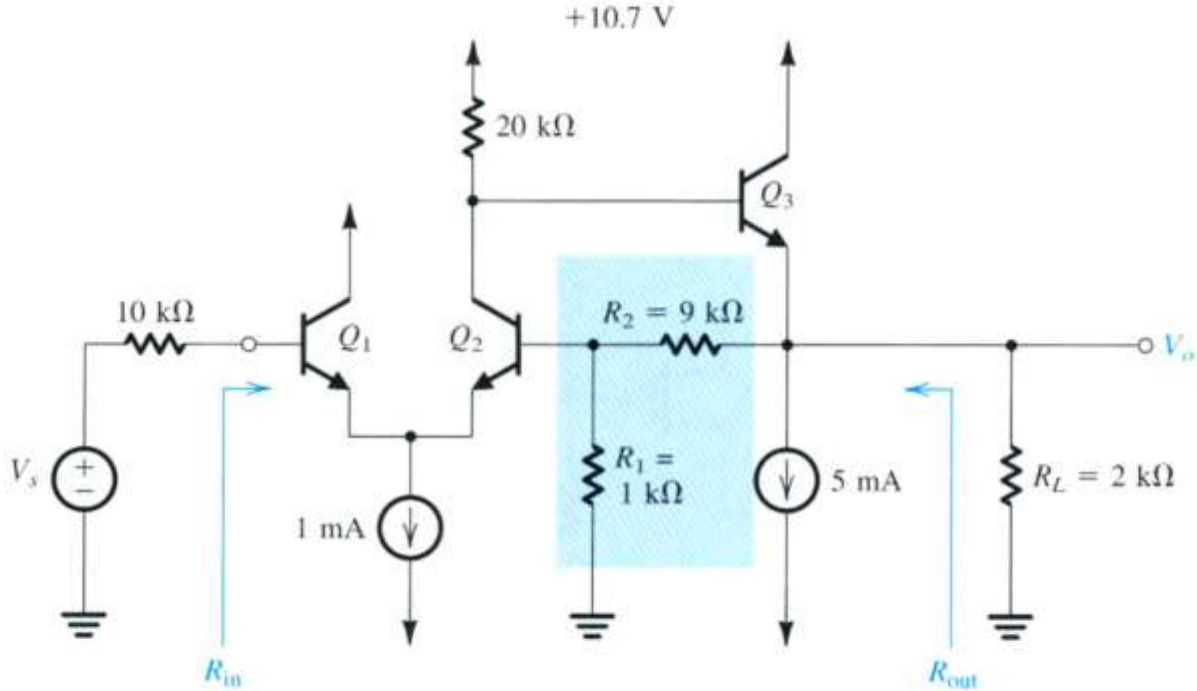

Figure E11.7