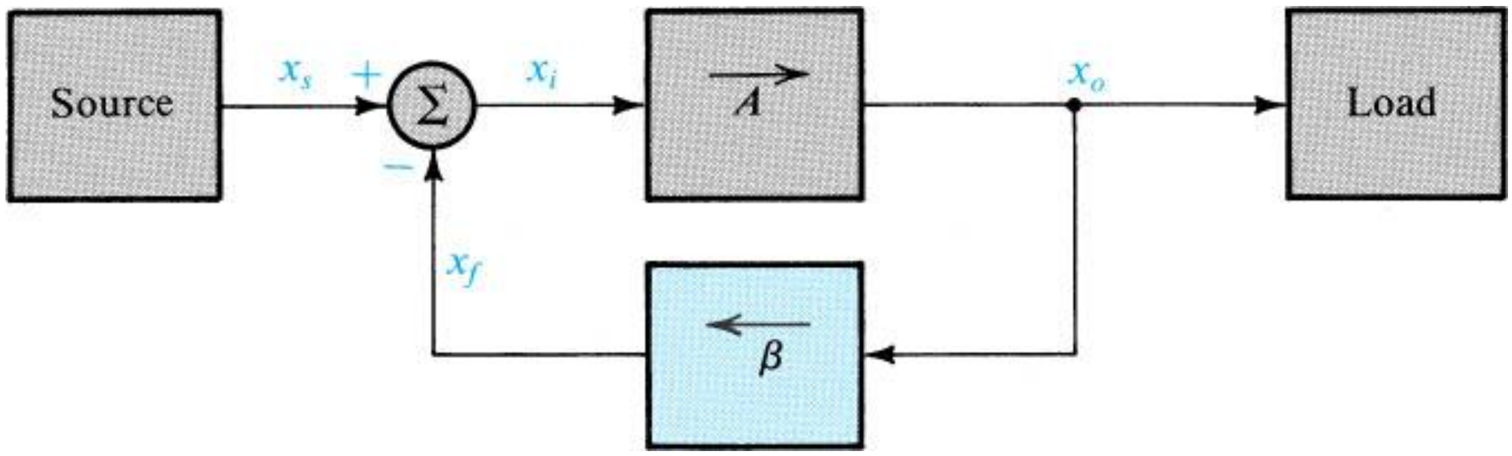
CHAPTER 10



# Feedback

- Consists of returning part of the output of a system to the input
- Negative Feedback: a portion of the output signal is returned to the input in opposition to the original input signal
- Positive Feedback: the feedback signal aids the original input signal
- Negative Feedback Effects:
  - Reduces gain
  - Stabilizes gain
  - Reduces non linear distortion
  - Reduces certain types of noise
  - Controls input and output impedances
  - Extends bandwidth

- The disadvantage of reducing the gain can be overcome by adding few more stages of amplification

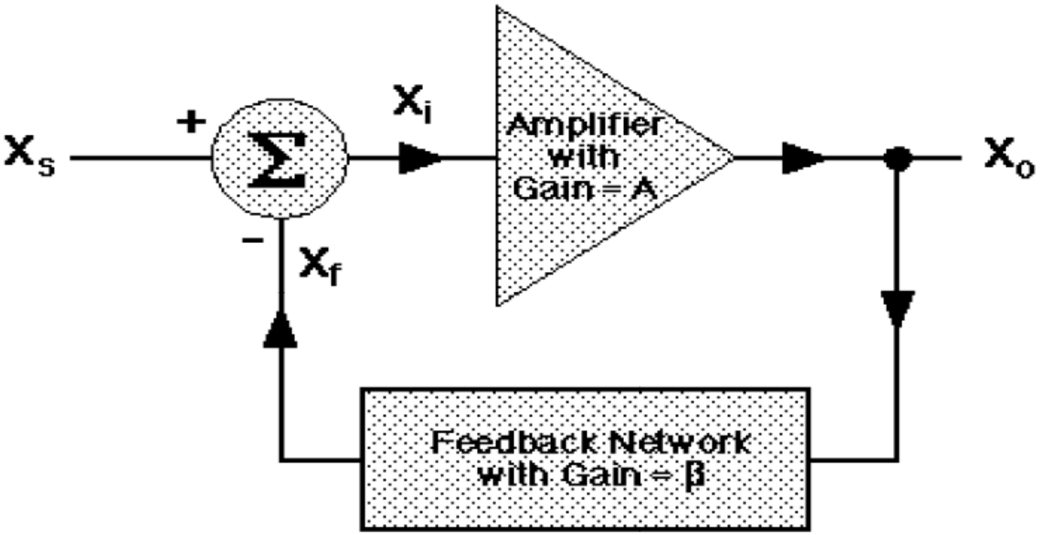
## Advantages of Negative Feedback

1. **Gain Sensitivity – variations in gain is reduced**
2. **Bandwidth Extension – larger than that of basic amplifier**
3. **Noise Sensitivity – may increase S/N ratio**
4. **Reduction of Nonlinear Distortion**
5. **Control of Impedance Levels – input and output impedances can be increased or decreased**

## Disadvantages of Negative Feedback

1. **Circuit Gain – reduced compared to that of basic amplifier**
2. **Stability – possibility that feedback circuit will become unstable and oscillate at high frequencies**

# THE BASIC FEEDBACK CIRCUIT




- Input to the amplifier is:

$$x_i = x_s - x_f$$

- Output of the amplifier is:

$$x_o = Ax_i$$

- Output signal in terms of input and feedback gain:

$$x_o = A\left(x_s - x_f\right) = A\left(x_s - \beta x_o\right)$$

- Rearranging: $x_o = Ax_s - A\beta x_o \quad \rightarrow \quad x_o\left(1 + A\beta\right) = Ax_s$

- From which we obtain the negative feedback equation by solving for the overall gain:

$$A_{fb} \equiv \frac{x_o}{x_s} = \frac{A}{1 + A\beta}$$

$$A_{fb} \equiv \frac{x_o}{x_s} = \frac{A}{1 + A\beta} \approx \frac{1}{\beta} \qquad \text{for large A}$$

# Example

How good is the $1/\beta$ approximation?

Assume open-loop gain is $A = 1\times10^5$, and the closed-loop gain is $A_f = 50$. Then

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

$$50 = \frac{1\times10^5}{1+\beta\times10^5}$$

$$\beta = 0.01999$$

$$A_f \cong 1/\beta = 50.025$$

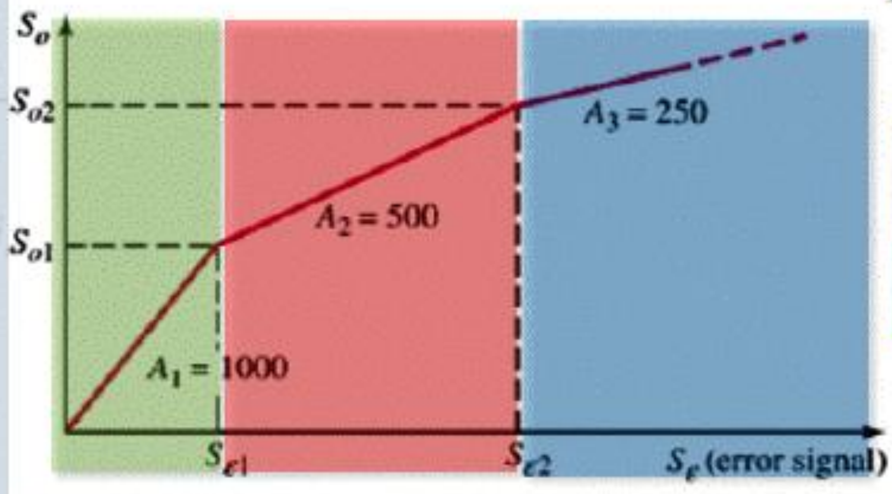
Assume open-loop gain is $A = 10^6$, with the same $\beta$

$$A_f = \frac{A}{1+\beta A} = \frac{1\times10^6}{1+\beta 10^6} = 50.025$$

Practically the same closed-loop gain

# Reduction of Nonlinear Distortion

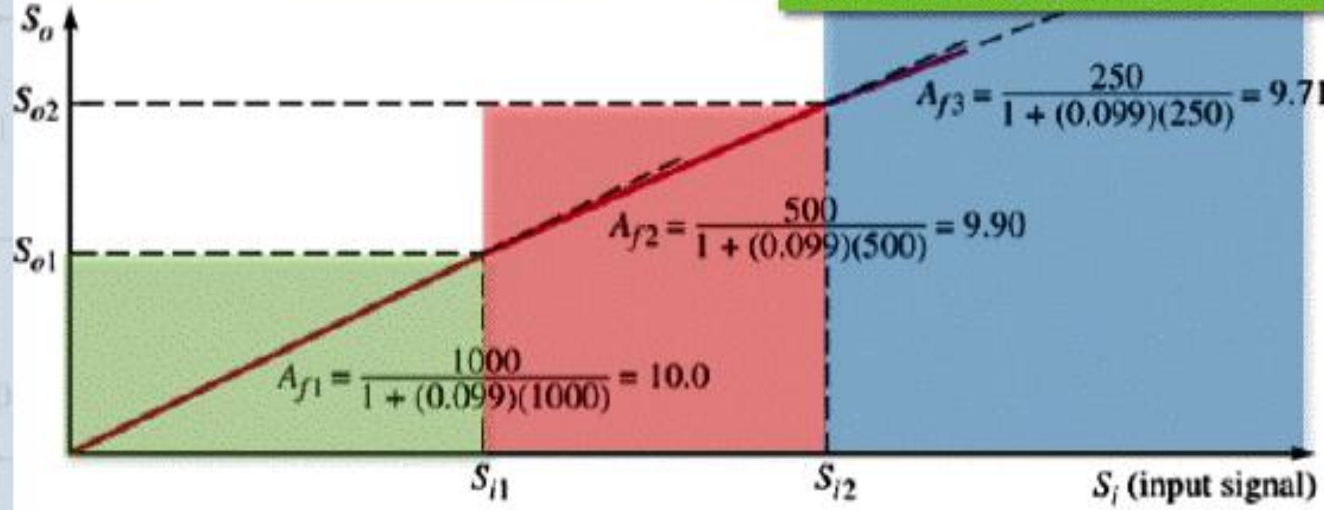
Open-Loop Gain




Non-linear because the gain depends on the signal

Closed-loop gain, $\beta = 0.099$

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



# Gain Sensitivity

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

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

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

Dividing both sides with closed-loop gain yields

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

$$\frac{\left(\frac{dA_f}{A_f}\right)}{\left(\frac{dA}{A}\right)} = \frac{1}{1+\beta A}$$

This shows that the % change in closed-loop gain is smaller, by a factor $1+\beta A$, than the % change in open-loop gain.

# Gain Sensitivity

An engineer designed a feedback amplifier $\beta = 0.01999$, and $A = 1\times10^5$. By how much does the closed-loop gain change when the same feedback network is used, but an amplifier with open-loop gain $A = 1\times10^6$ is used?

$$\frac{dA_f}{A_f} = \frac{1}{1+\beta A}\frac{dA}{A} = \frac{1}{1+(0.01999)\times10^5}\frac{10^6-10^5}{10^5}$$

$$= 4.5\times10^{-3}$$

$$= 0.45\%$$

In other words, the open-loop gain changed by a factor 10, while the closed loop gain changed about 0.5%.

# Gain Versus Frequency

Assume we can characterize the frequency response of an amplifier with a single pole

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

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

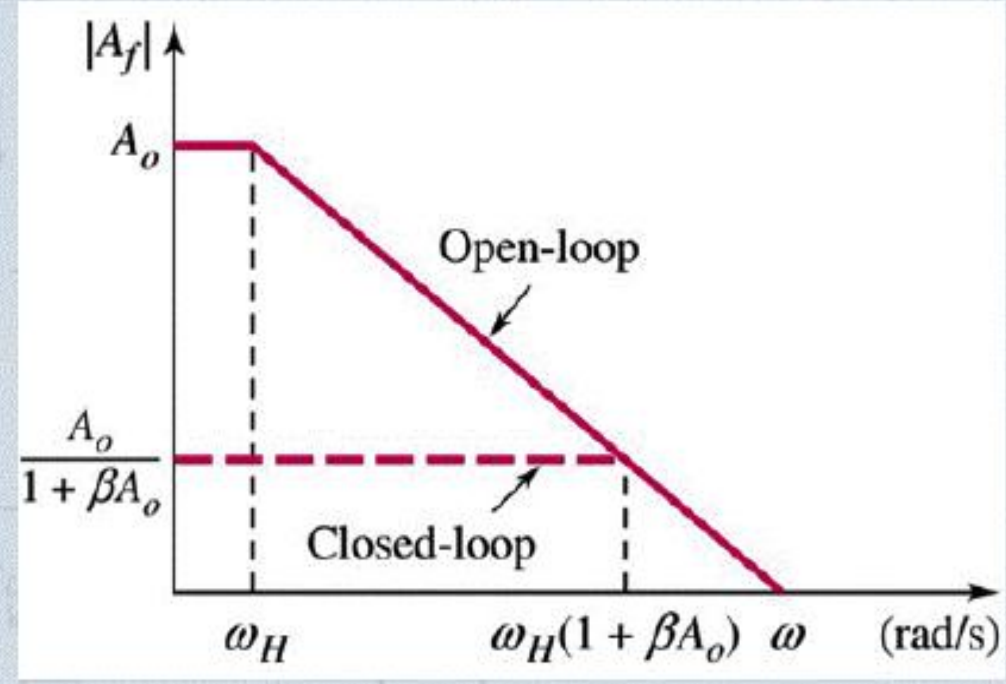
$$A_f(s) = \frac{\frac{A_M}{(1 + A_M\beta)}}{1 + \frac{s}{\omega_H(1 + A_M\beta)}}$$

The closed-loop gain is smaller than the open-loop gain by a factor $(1+\beta A)$

The 3 dB bandwidth is larger by a factor $(1+\beta A)$

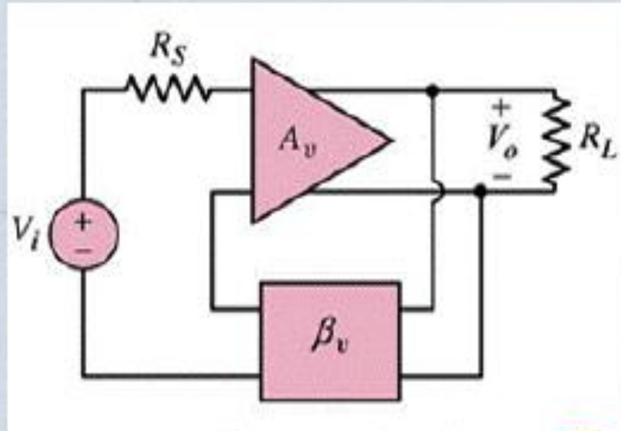
# Gain-Bandwidth Product

Gain-bandwidth product of a feedback amplifier is constant



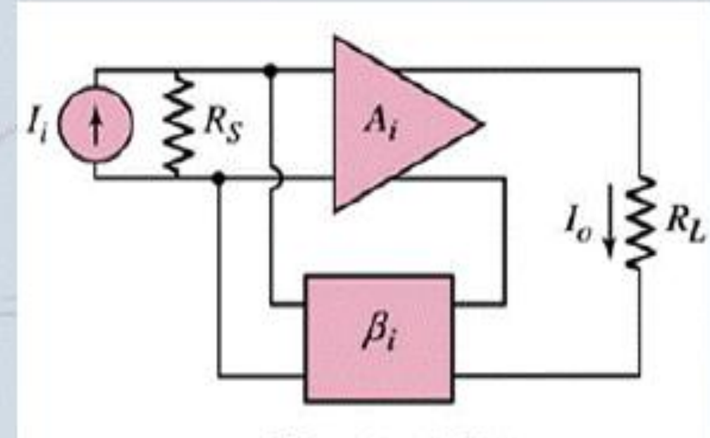

We can increase bandwidth at the expense of gain

# Ideal Basic Feedback Configurations



Series–shunt

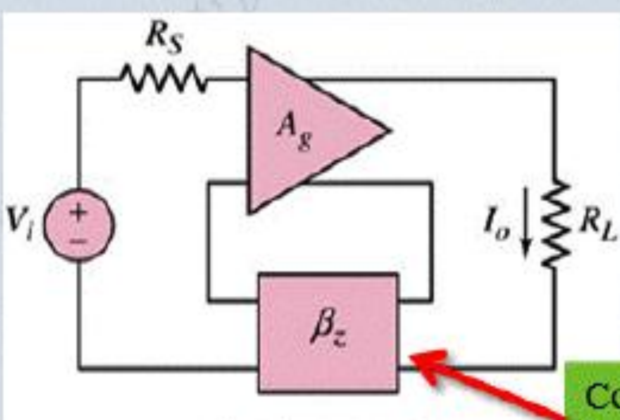
Voltage Amplifier



Shunt–series

Current Amplifier

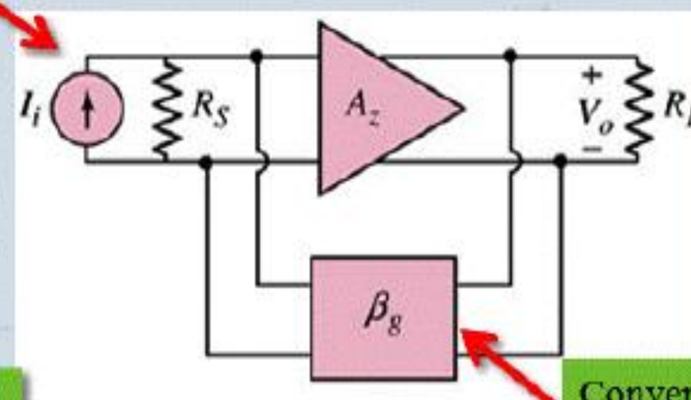
Very Common



Series–series

Converts current to voltage

Transconductance Amplifier (voltage in-current out)

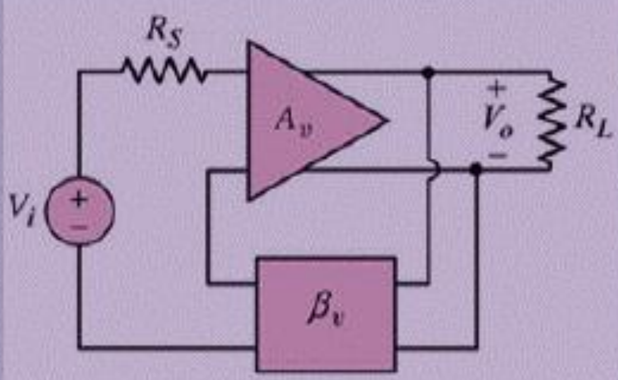


Shunt–shunt

Converts voltage to current

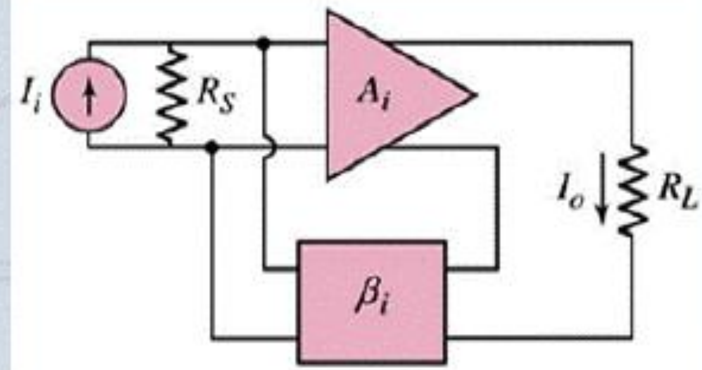
Transresistance Amplifier (current in-voltage out)

# Recap-Ideal Basic Feedback Configurations



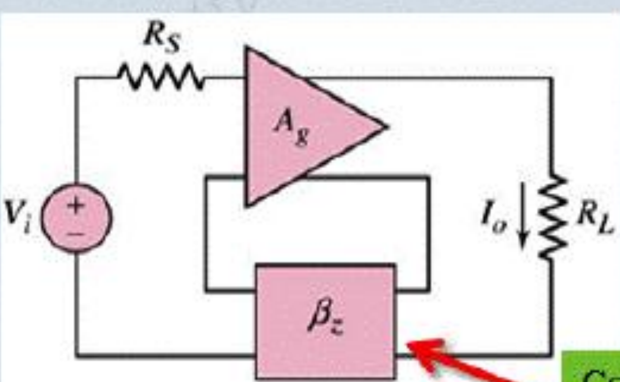

**Series–shunt**

Voltage Amplifier




**Shunt–series**

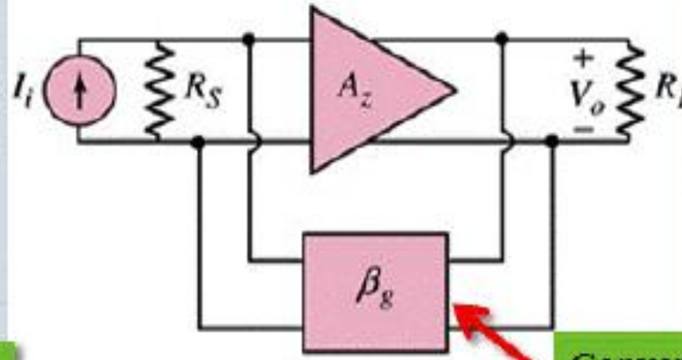
Current Amplifier




**Series–series**

Converts current to voltage

Transconductance Amplifier
(voltage in-current out)

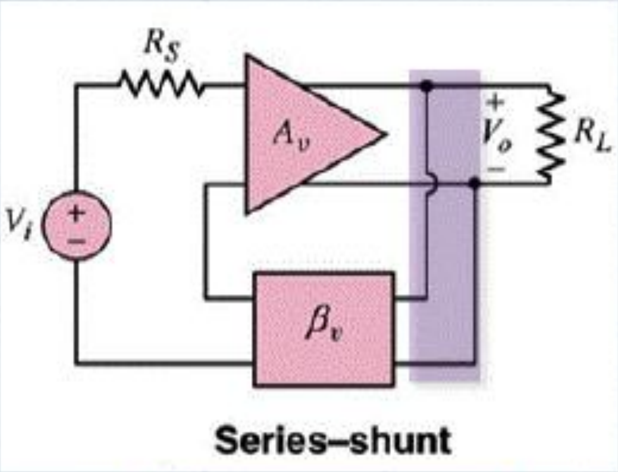



**Shunt–shunt**

Converts voltage to current

Transresistance Amplifier
(current in-voltage out)

# Ideal Series-Shunt Feedback




$$A_{vf} = \frac{A_v}{1+\beta_v A_v}$$

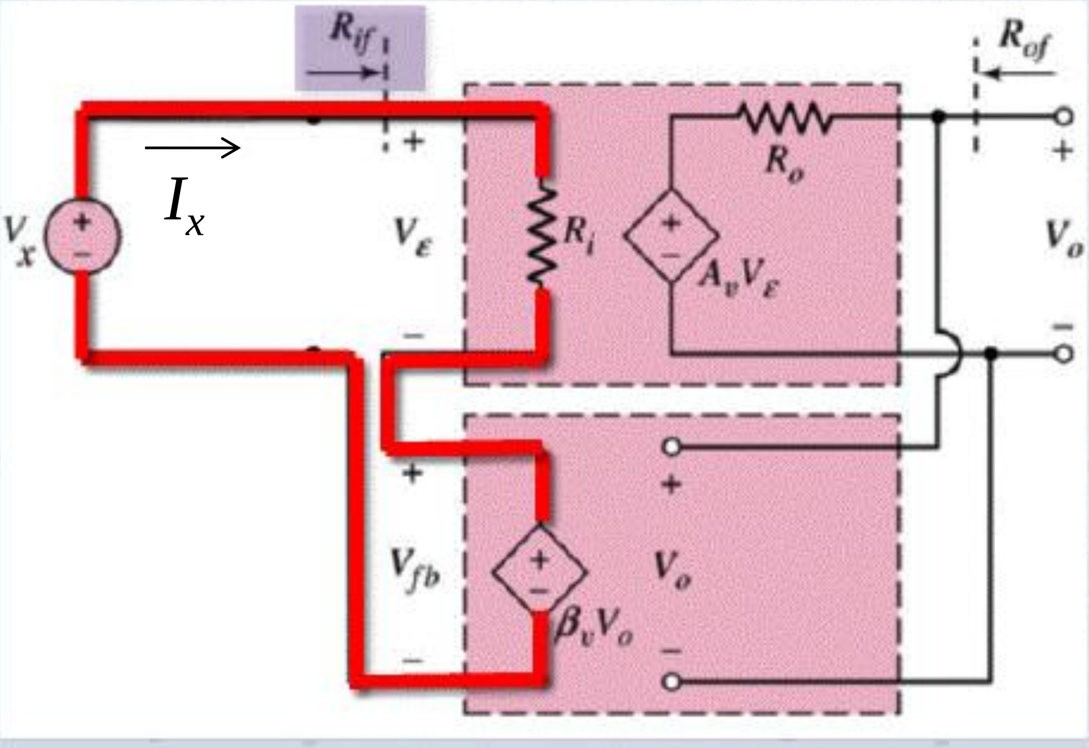
Sample output voltage and feed it back to input

Ideal: assume feedback network does not load output/input

Voltage Amplifier

$$V_x = I_x R_i + \beta_v V_o$$
$$= I_x R_i + \beta_v A_v V_\varepsilon$$
$$= I_x R_i + \beta_v A_v I_x R_i$$
$$= I_x R_i (1+\beta_v A_v)$$

$$R_{if} = \frac{V_x}{I_x} = R_i(1+\beta_v A_v)$$



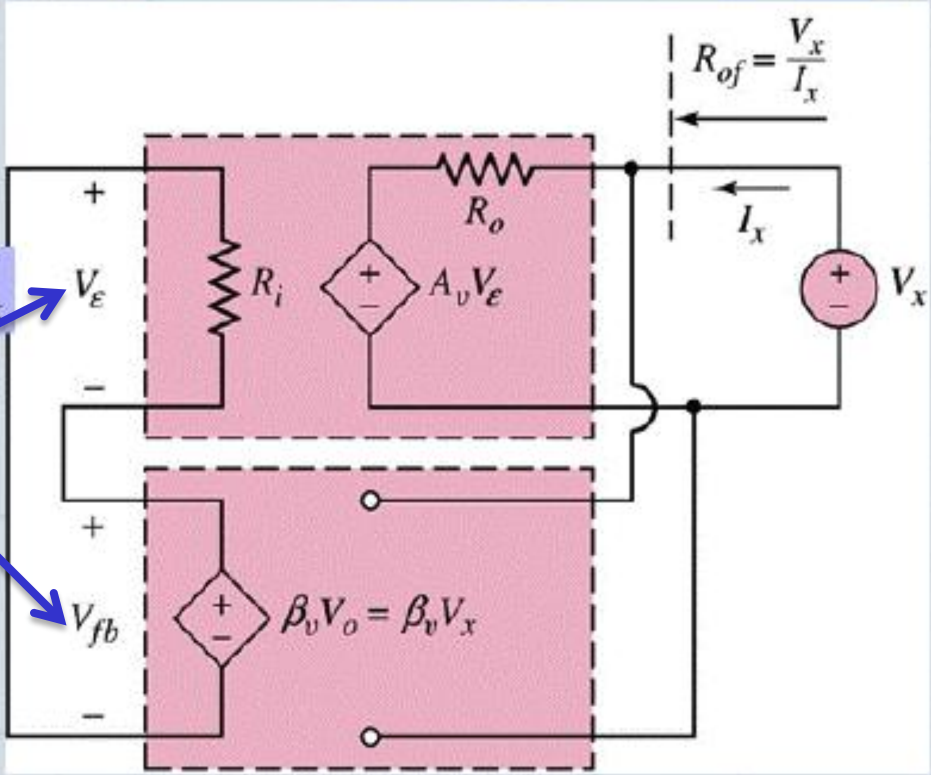
# Series-Shunt Feedback Output Resistance

How do we determine output resistance?

1. Turn off independent sources
2. Add test voltage $V_x$
3. See what test current $I_x$ flows
4. Determine $V_x/I_x$

$V_\varepsilon = -\beta_v V_x$

$+ \quad = 0$



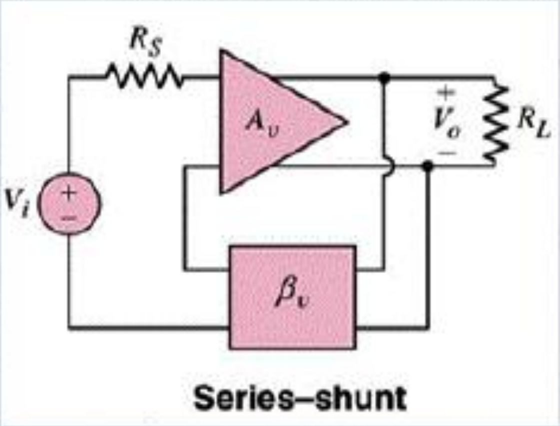

$$I_x = \frac{V_x - A_v V_\varepsilon}{R_o}$$

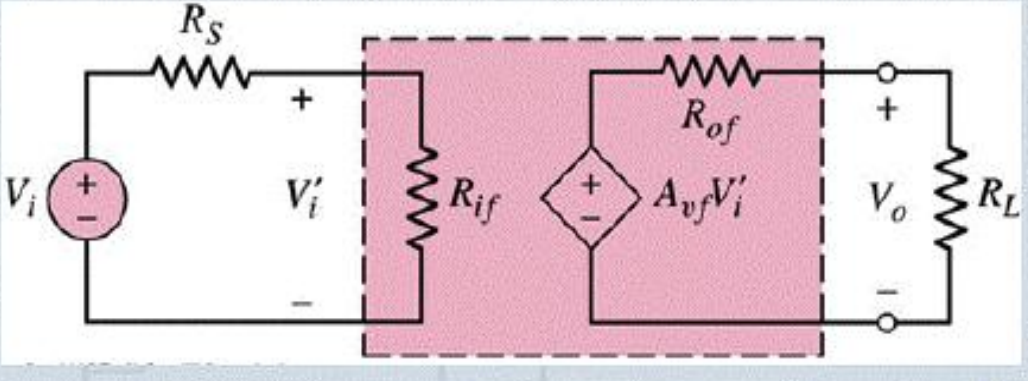
$$= \frac{V_x - A_v(-\beta_v V_x)}{R_o}$$

$$= \frac{V_x(1+\beta_v A_v)}{R_o}$$

$$R_{of} = \frac{V_x}{I_x} = \frac{R_o}{(1+\beta_v A_v)}$$

# Equivalent Circuit: Series-Shunt Feedback Circuit



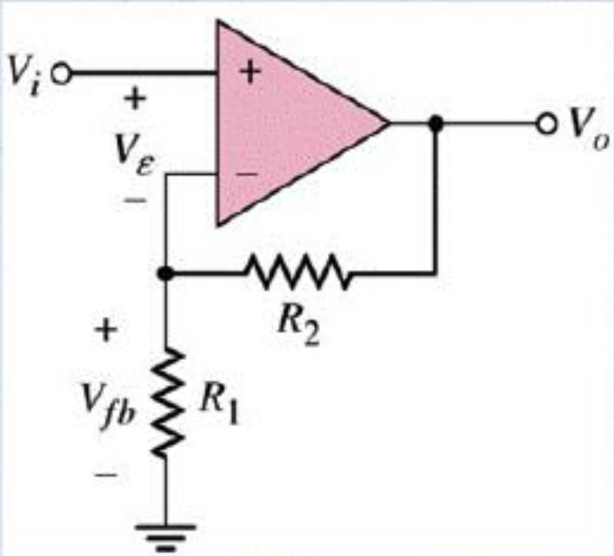

$$R_{if} = R_i\left(1+\beta_v A_v\right)$$

$$A_{vf} = \frac{A_v}{1+\beta_v A_v}$$

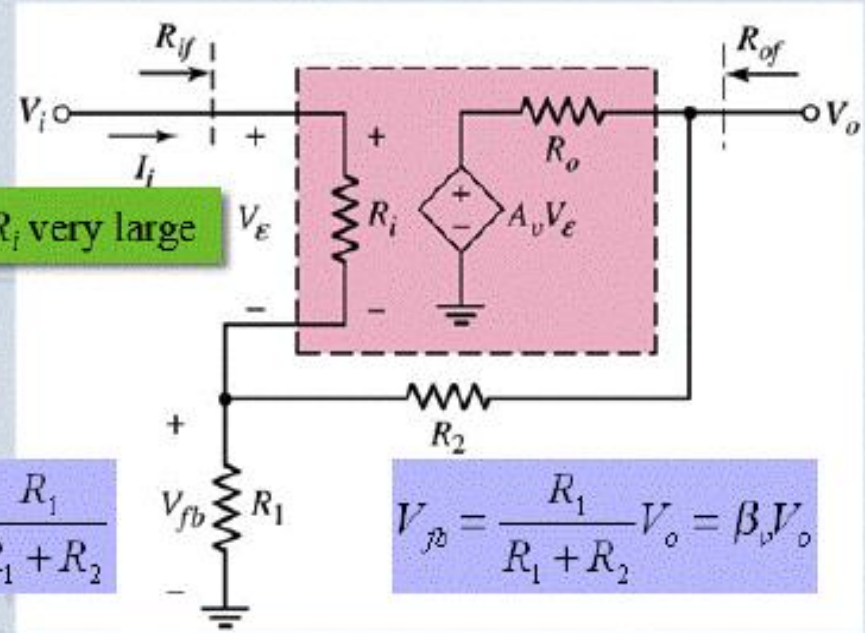
$$R_{of} = \frac{R_o}{\left(1+\beta_v A_v\right)}$$

$$\mathrm{BW}_f = \left(1+\beta_v A_v\right)\mathrm{BW}$$

# Op-Amp Series-Shunt Feedback Circuit




Assume $R_i$ very large




$$\beta_v = \frac{R_1}{R_1 + R_2}$$

$$V_{fb} = \frac{R_1}{R_1 + R_2} V_o = \beta_v V_o$$

**Series-shunt feedback**

- Take some of the output voltage
- Feed it back in series with input

$$A_{vf} \cong \frac{1}{\beta_v}$$

**Series-shunt feedback**

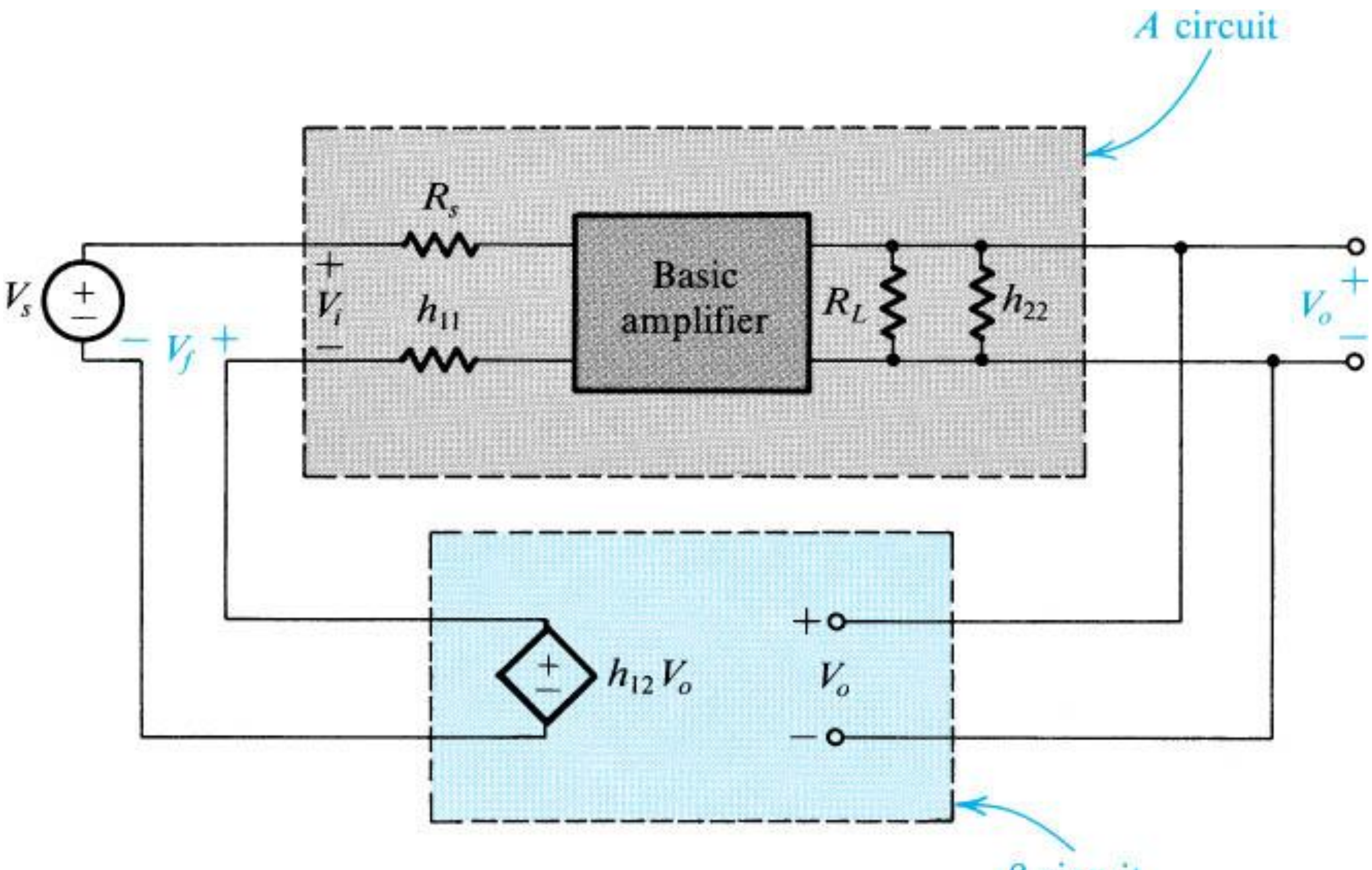
- Input impedance will increase
- Output impedance will decrease
- Bandwidth will increase

$$A_{vf} \cong \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

$$R_{if} = R_i(1 + \beta_v A_v) = R_i\left(1 + A_v \frac{R_1}{R_1 + R_2}\right)$$

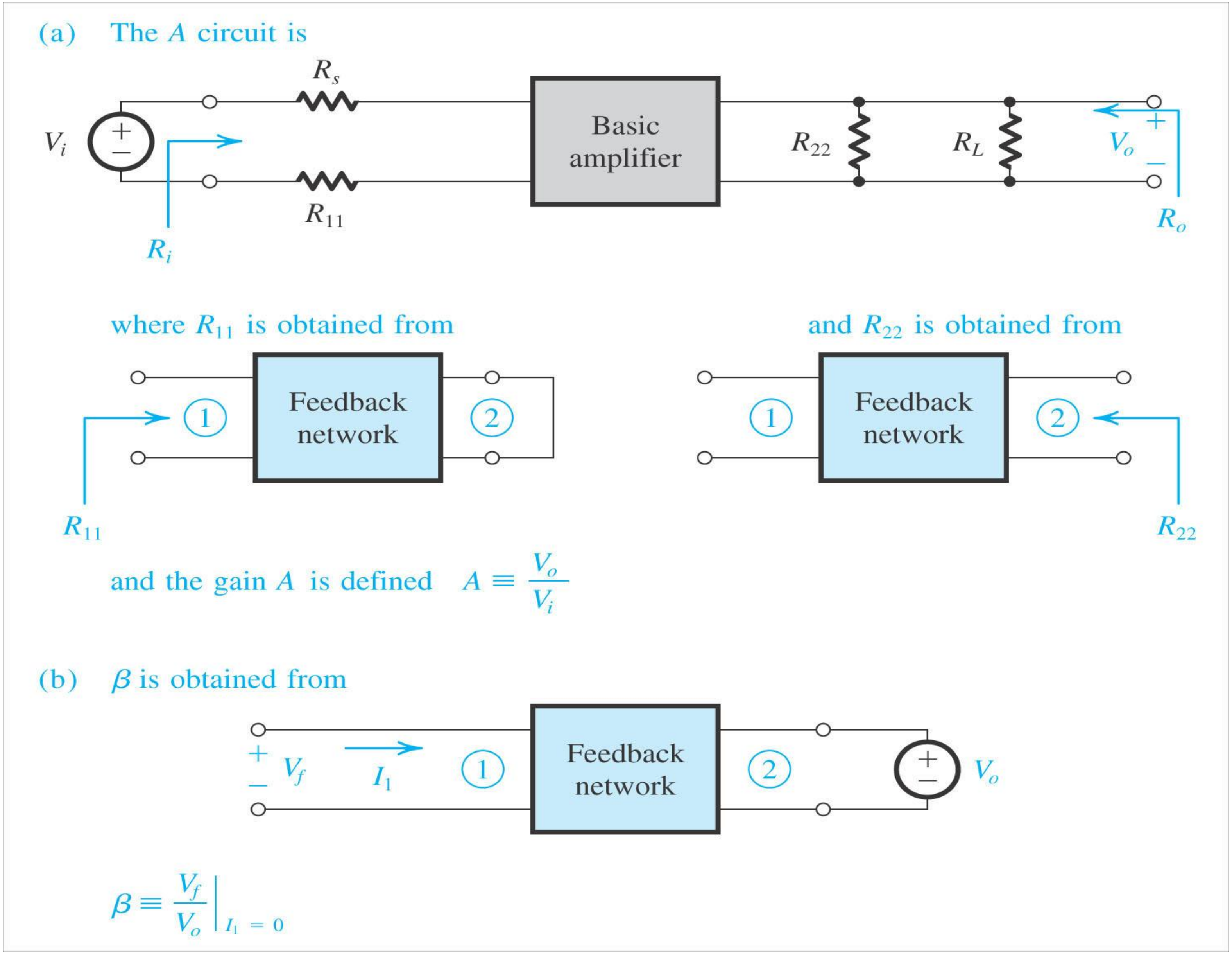
$$R_{of} = R_o / (1 + \beta_v A_v) = R_o \Big/ \left(1 + A_v \frac{R_1}{R_1 + R_2}\right)$$

# Actual Series-Shunt Feedback

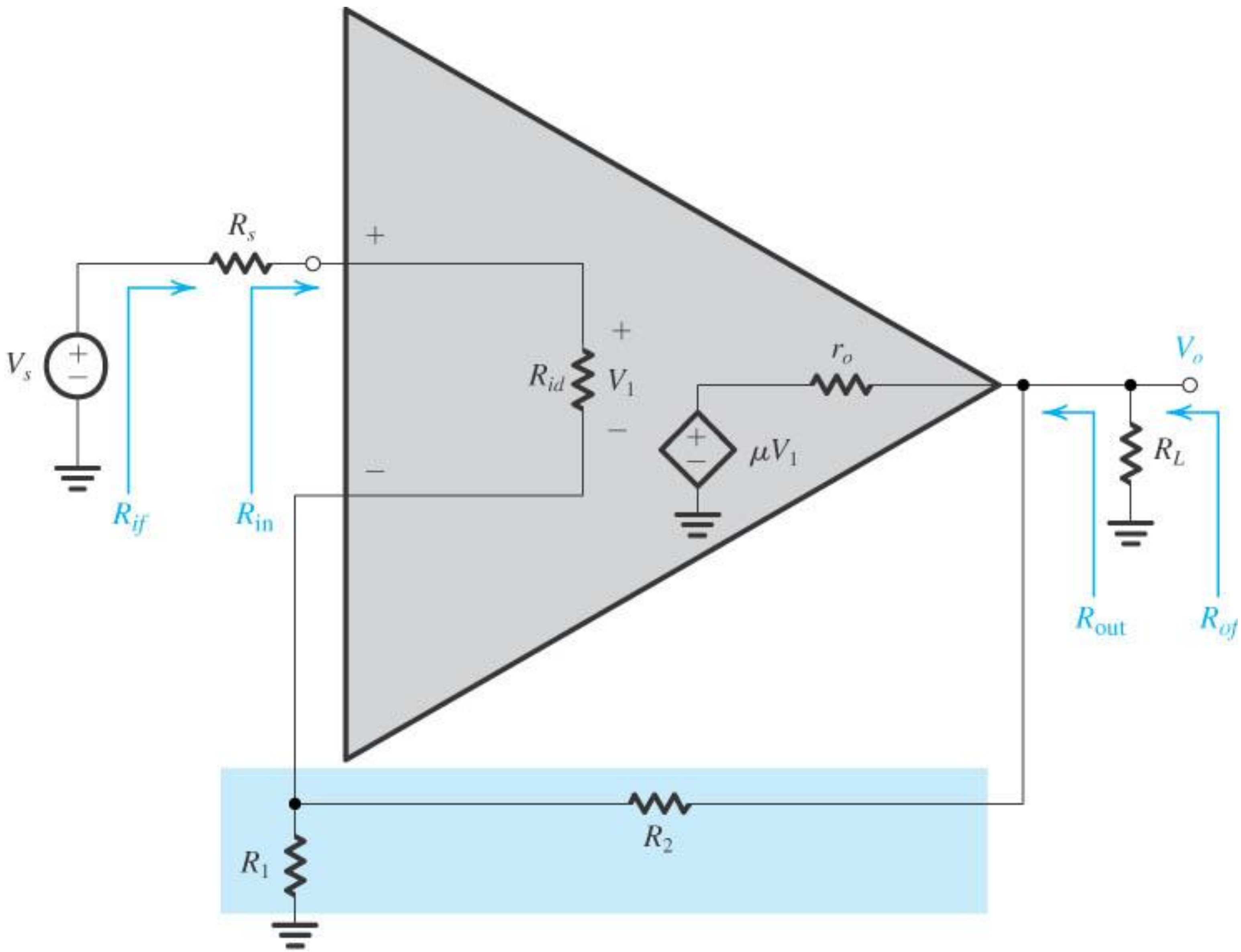



(c)

# Analysis Procedure – Rules to Determine Parameters

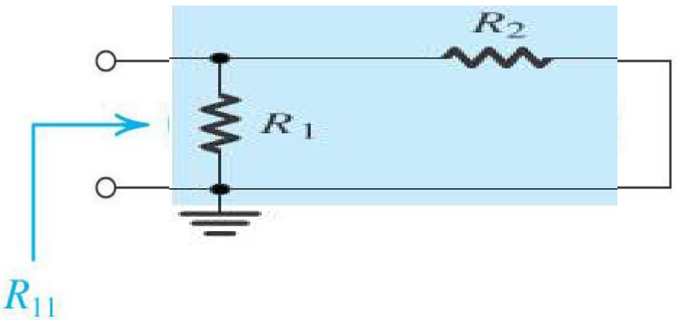


# Example 8.1

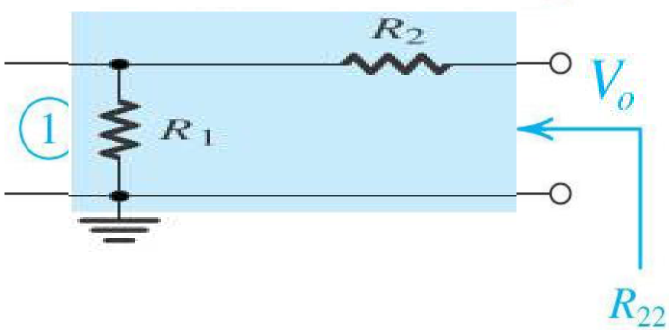


(a)

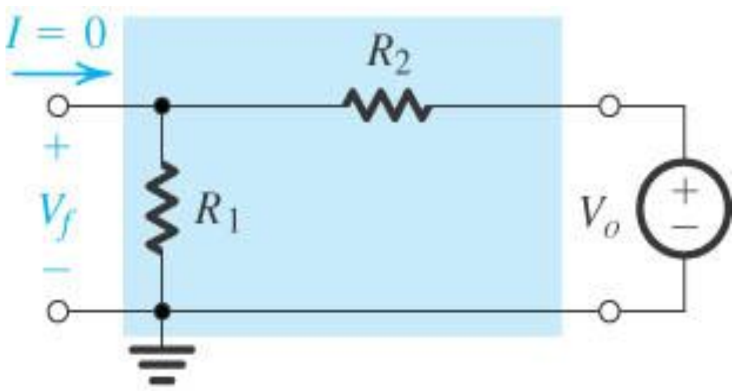
# Step 1 : Determine β and the Loading Effects




$$R_{11} = \frac{V_f}{I_1}\bigg|_{V_o=0} = R_1 \,//\, R_2$$



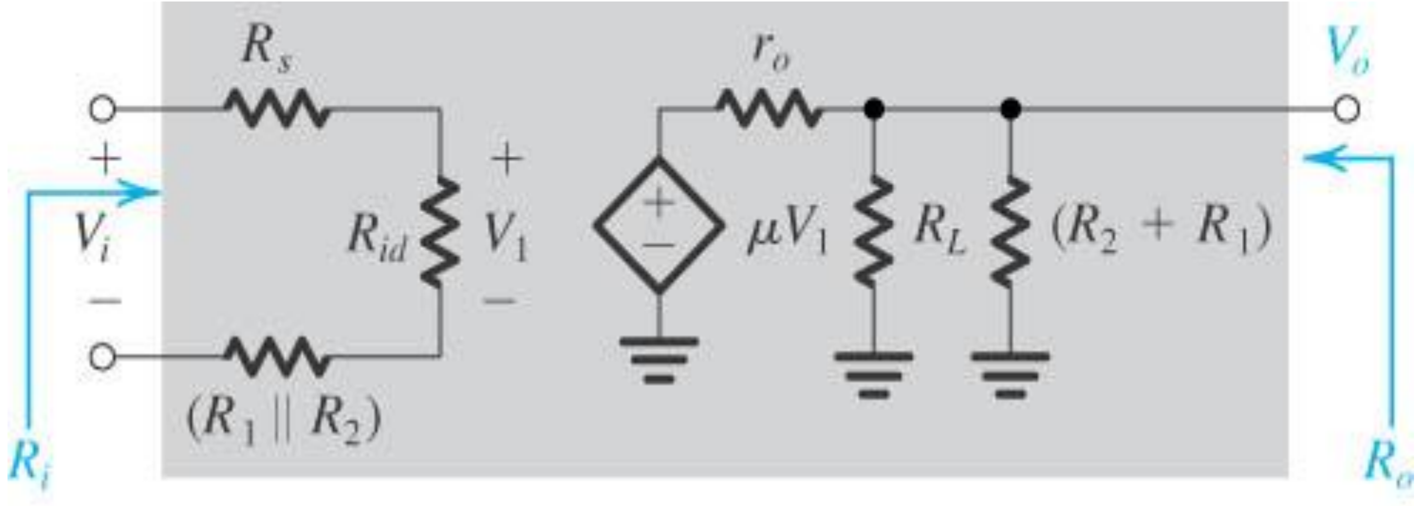

$$R_{22} = \frac{V_o}{I_o}\bigg|_{I_1=0} = R_1 + R_2$$




(c)

$$\frac{V_f}{V_o}\bigg|_{I_1=0} = \frac{R_1}{R_1 + R_2} = \beta$$

# Step 2 : Form the A-Circuit to Determine Gain and Resistances




(b)

$$R_{if} = (1+\beta A)(R_s + R_{id} + R_{11}) = (1+\beta A)(R_s + R_{id} + (R_1 // R_2)) = R_s + R_{in}$$

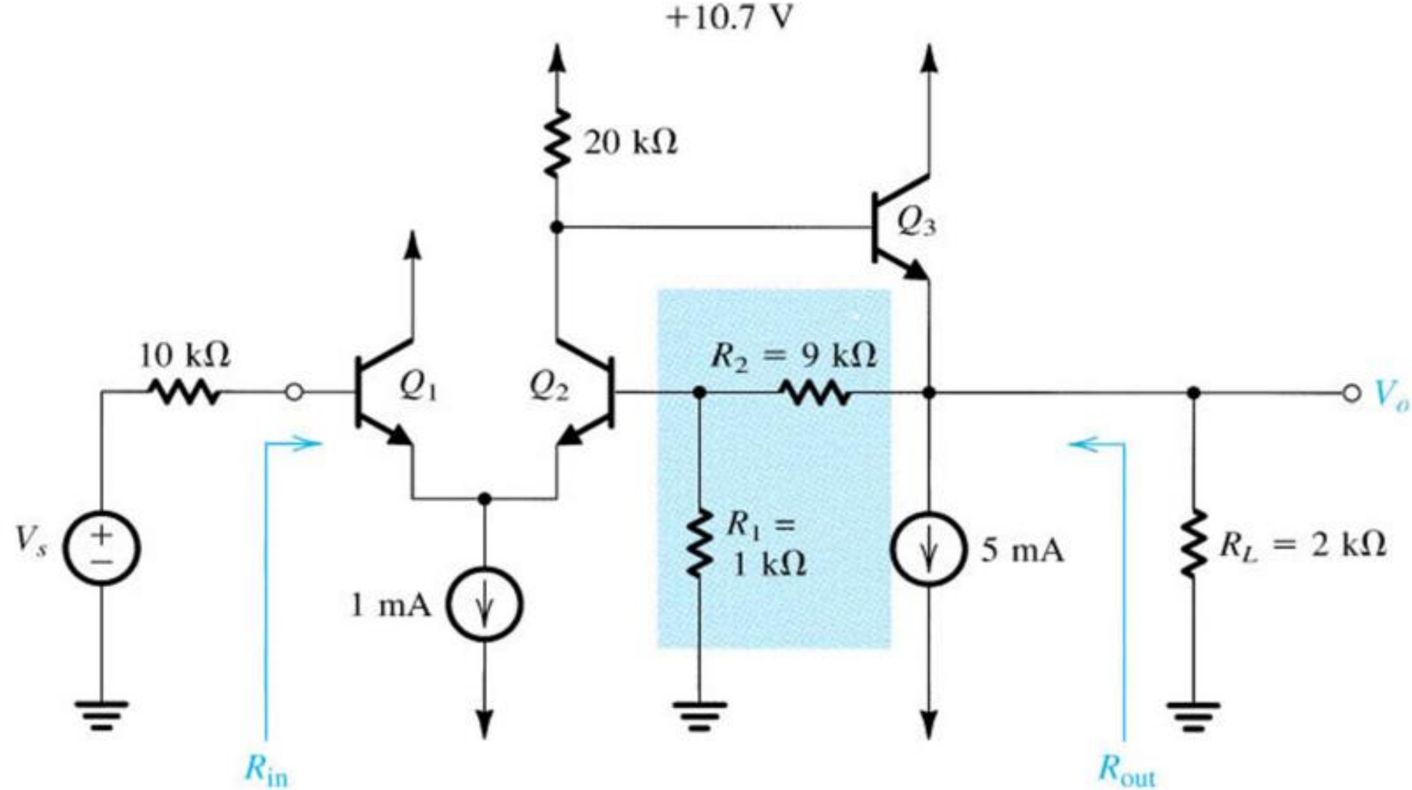
$$R_{in} = R_s - R_{if}$$

$$R_{of} = \frac{r_o // R_{22} // R_L}{(1+\beta A)} = \frac{r_o //(R_1 + R_2) // R_L}{(1+\beta A)} = R_{out} // R_L$$

$$R_{out} \Rightarrow find$$

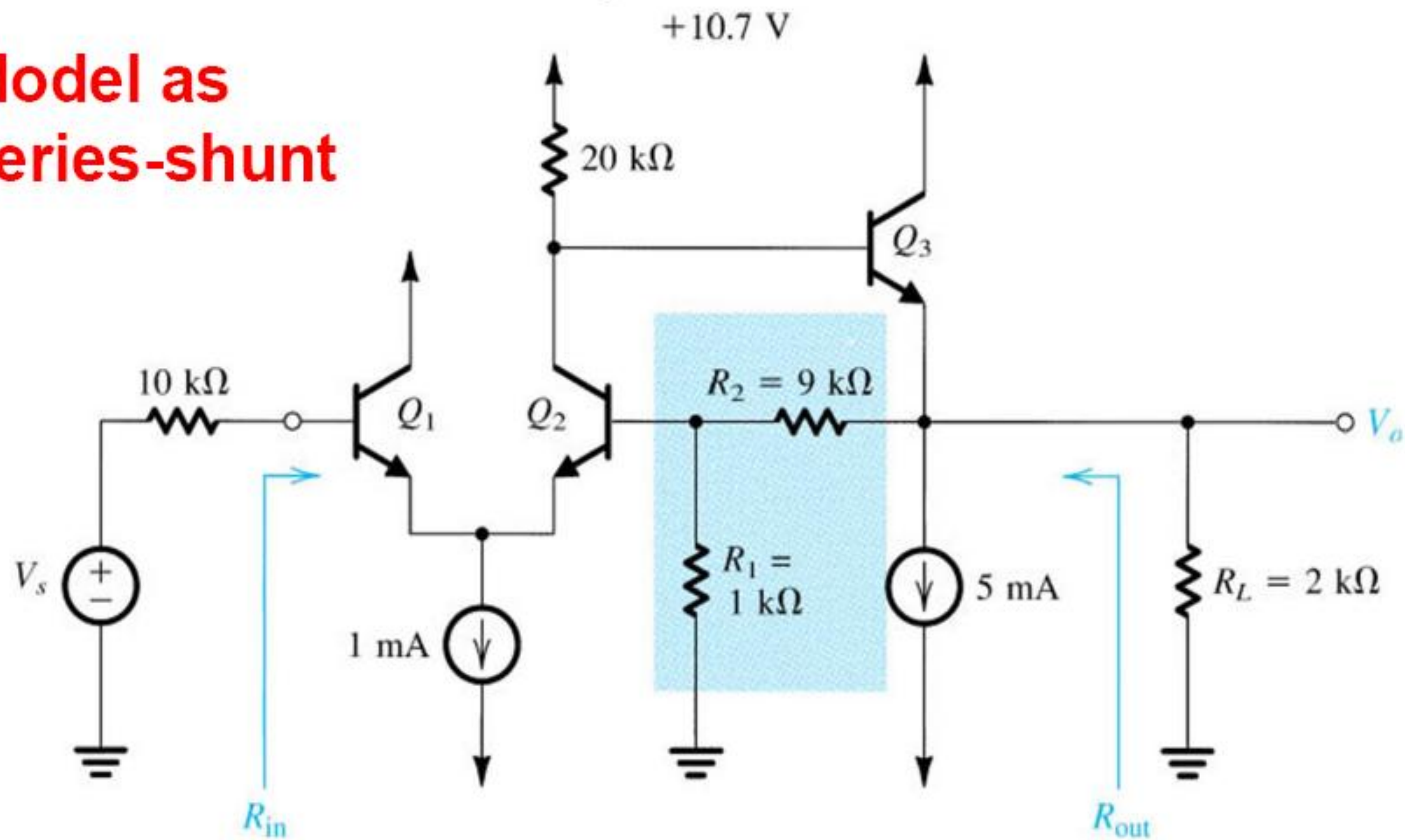
$$A_f = \frac{A}{1+\beta A}, \qquad A = \frac{V_o}{V_i} = \mu \frac{(R_L // R_{22})}{(R_L // R_{22}) + r_o} \frac{R_{id}}{R_{id} + R_s + R_{11}}$$

# Example - Feedback




**Differential stage followed by an emitter follower, with series-shunt feedback supplied by the resistors $R_1$ and $R_2$. Perform DC analysis and find $A$, $\beta$, $A_f$, $R_{in}$ and $R_{out}$**

**Model as series-shunt**




$$I_{E1} = I_{E2} = 0.5\,mA$$

$$V_{c2} = 10.7 - 0.5 \times 20 = +0.7\,V$$

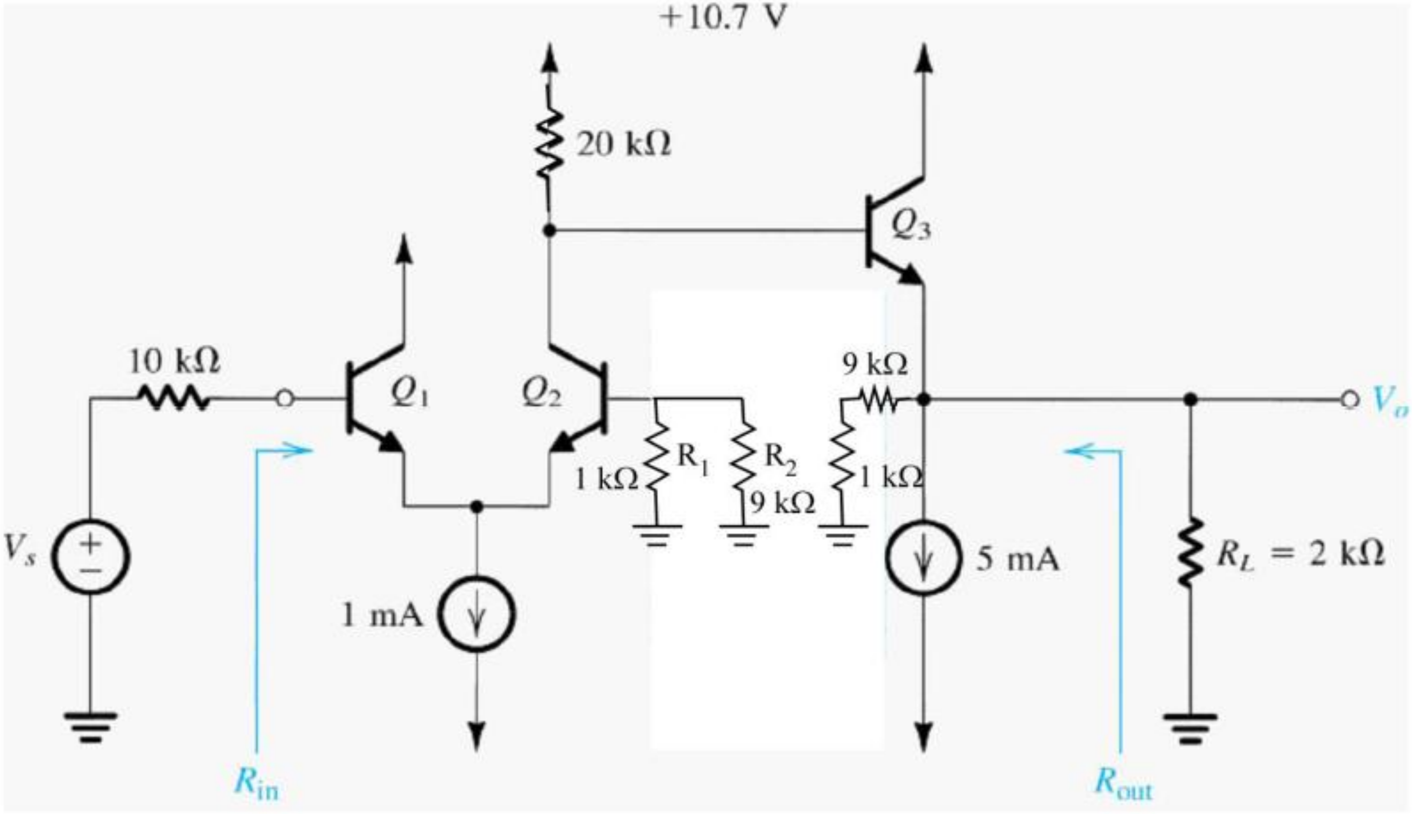
$$V_o = 0.7 - V_{BE3} = 0$$

$$I_{E3} = 5\,mA$$

$$r_{e1} = r_{e2} = \frac{V_T}{I_C} = 50\,\Omega$$

$$r_{e3} = 5\,\Omega$$

# A - Circuit




$$A=\frac{V_o}{V_s}=\frac{\left[20\,||\left(\beta_2+1\right)\left(r_{e3}+(2\,||\,10)\right)\right]}{r_{e1}+r_{e1}+\dfrac{10}{\beta_1+1}+\dfrac{(1\,||\,9)}{\beta_2+1}}\times\frac{(2\,||\,10)}{r_{e3}+(2\,||\,10)}=85.7\,V/V$$

# A - Circuit – cont’

$$R_i = R_s + (\beta + 1)(r_{e1} + r_{e2}) + R_E \parallel R_4$$

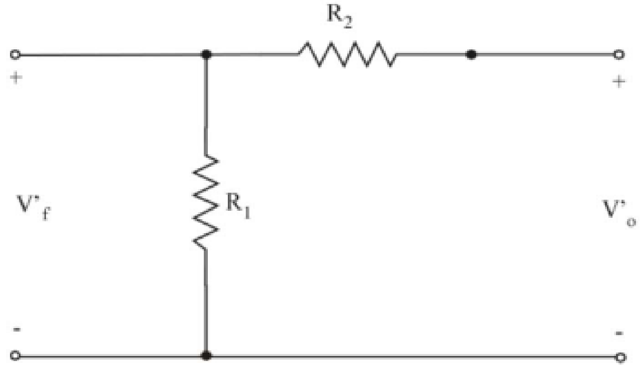
$$R_i = 10 + 101(50 + 50) + \left(1 \parallel 9\right) = 21\,k\Omega$$

$$R_o = 2 \parallel 10 \parallel \left[ r_{e3} + \frac{20}{\beta_2 + 1} \right] = 181\,\Omega$$

# β - Circuit

$$\beta = V_f^{'} / V_o^{'} = \frac{1}{9+1} = 0.1\,V$$

$$A_f = \frac{V_o}{V_s} = \frac{A}{1+A\beta} = \frac{85.7}{1+85.7\times 0.1} = 8.96\,V/V$$



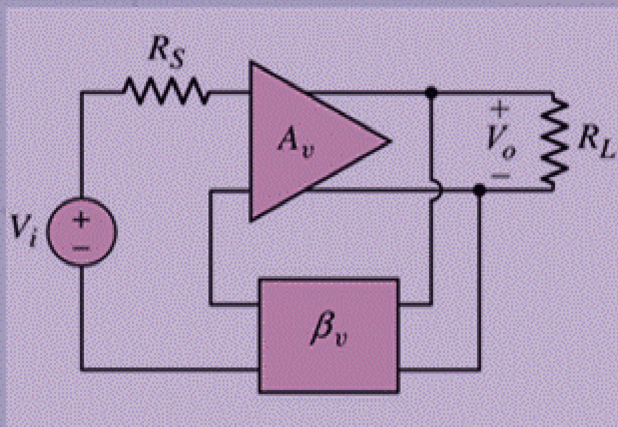

$$R_{if} = R_1\left(1+A\beta\right) = 21\times 9.37 = 201\,k\Omega$$

$$R_{IN} = R_{if} - R_s = 201 - 10 = 191\,k\Omega$$

$$R_{of} = \left(R_{out} \,\|\, R_L\right) = \frac{R_o}{1+A\beta} = \frac{181}{9.57} = 18.8\,\Omega$$

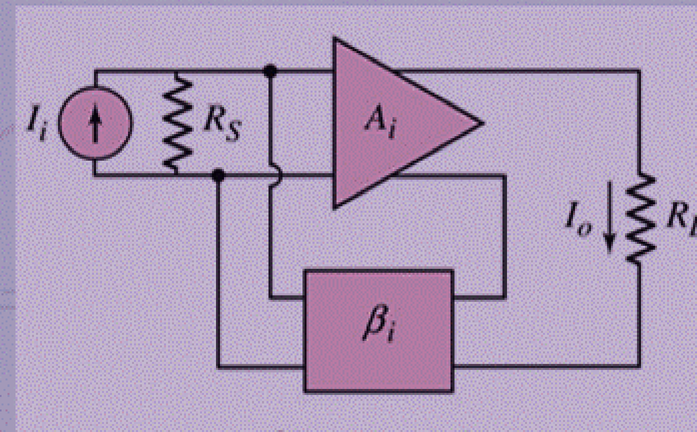
$$R_{out} = 19.1\,\Omega$$

# Ideal Basic Feedback Configurations



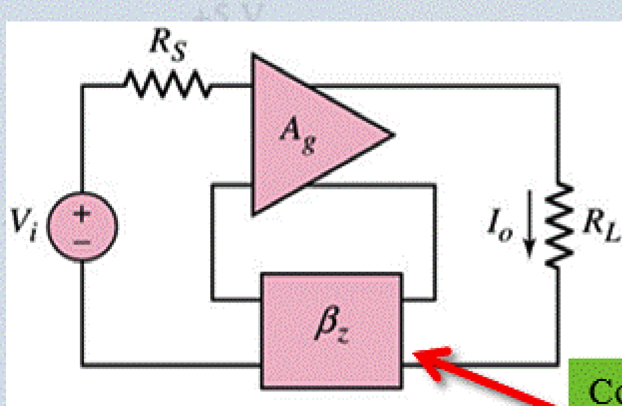
Series–shunt

Voltage Amplifier



Shunt–series

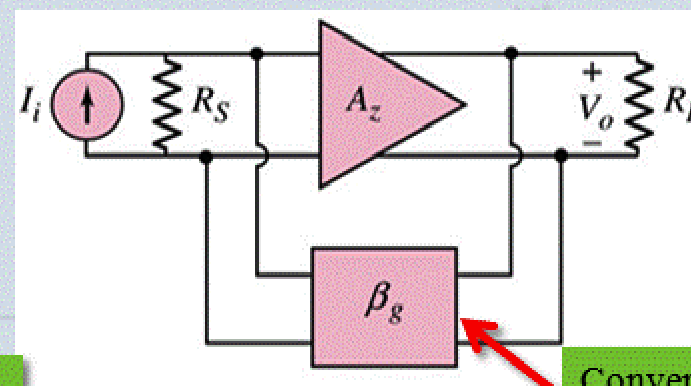
Current Amplifier



Series–series

Converts current to voltage

Transconductance Amplifier (voltage in-current out)

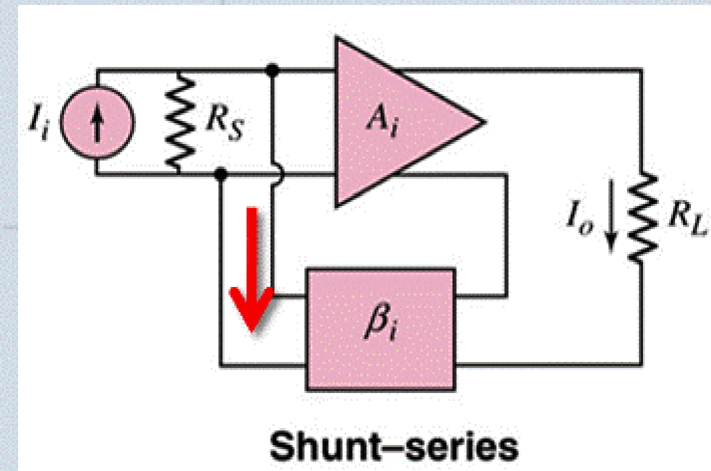


Shunt–shunt

Converts voltage to current

Transresistance Amplifier (current in-voltage out)

# Ideal Shunt-Series Feedback




Current Amplifier

Sample output current and feed it back to input

Ideal: assume feedback network does not load output, so that $I_o$ is unaffected

$$A_{if} = \frac{A_i}{1+\beta_i A_i}$$

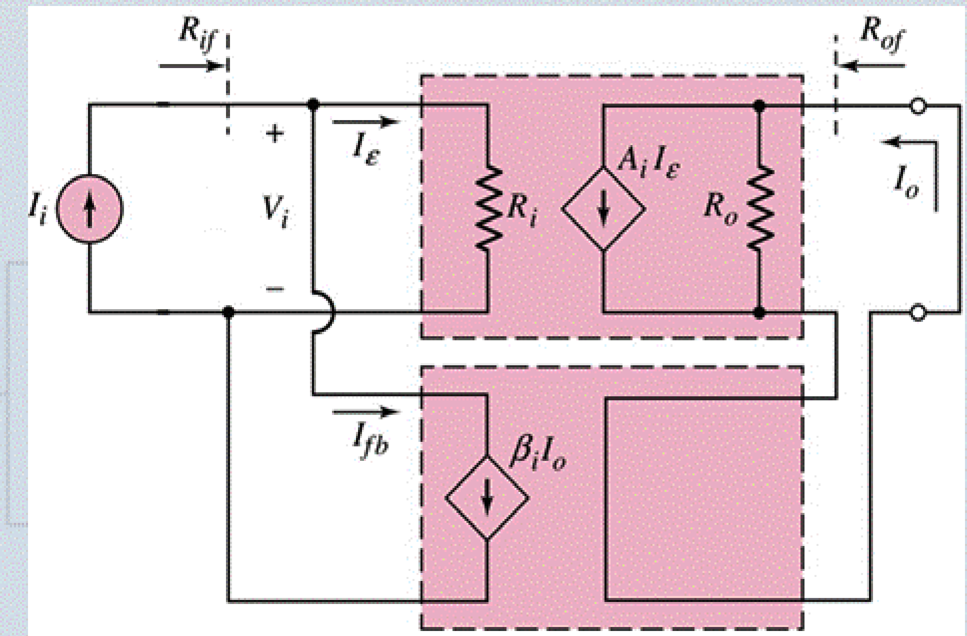
"Feedback" = "Subtract", "Reduce", "Steal From"

$$I_i = I_\varepsilon + \beta I_o$$
$$= I_\varepsilon + \beta\left(A_i I_e\right)$$

$$I_\varepsilon = \frac{I_i}{\left(1+\beta_i A_i\right)}$$

$$V_i = I_\varepsilon R_i = \frac{I_i R_i}{\left(1+\beta_i A\right)_i}$$

$$R_{if} = \frac{V_i}{I_i} = \frac{R_i}{\left(1+\beta_i A_i\right)}$$



# Ideal Shunt-Series Feedback

How do we determine output resistance?

1. Turn off independent sources
2. Add test current $I_x$ output
3. See what test current $V_x$ results
4. Determine $V_x/I_x$

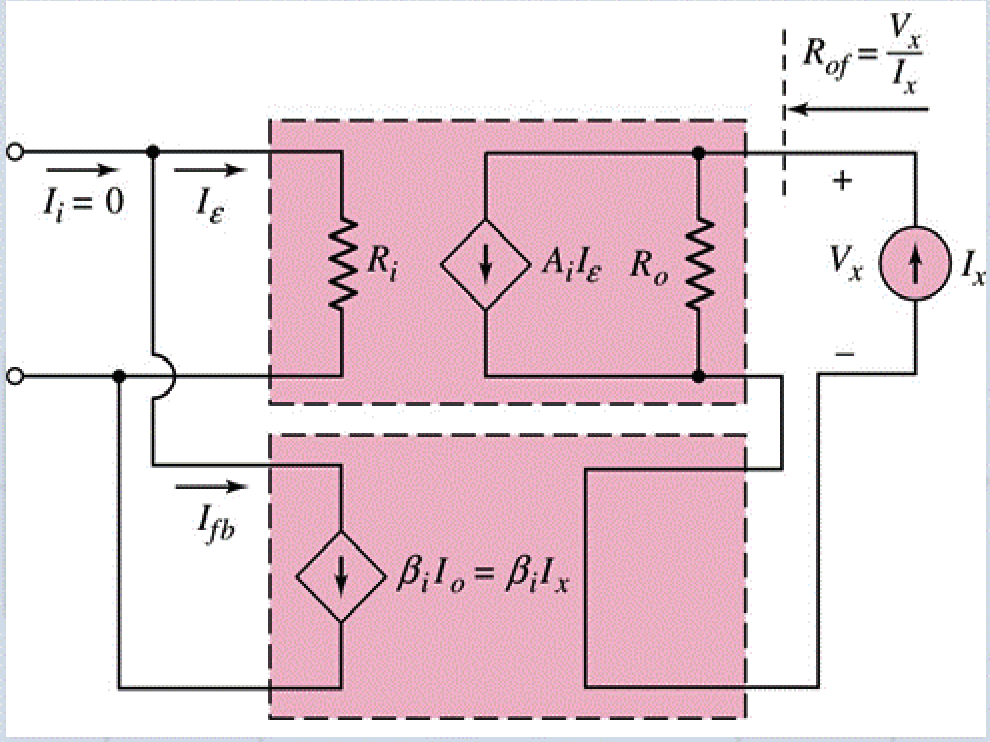
$$I_\varepsilon = -\beta I_x$$

$$V_x = (I_x - A_i I_\varepsilon)R_o$$

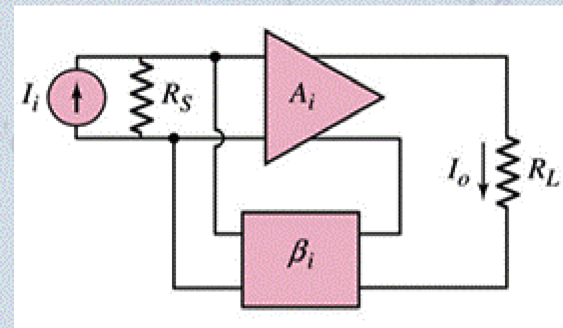
$$= (I_x - A_i(-\beta_i I_x))R_o$$

$$= I_x(1+\beta_i A_i)R_o$$

$$R_{of} = \frac{V_x}{I_x} = (1+\beta_i A_i)R_o$$

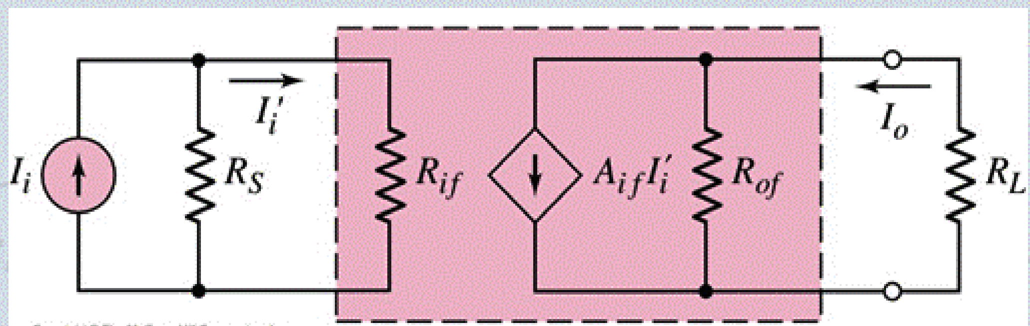


# Equivalent Circuit: Shunt-Series Feedback Circuit




Shunt–series

Current Amplifier

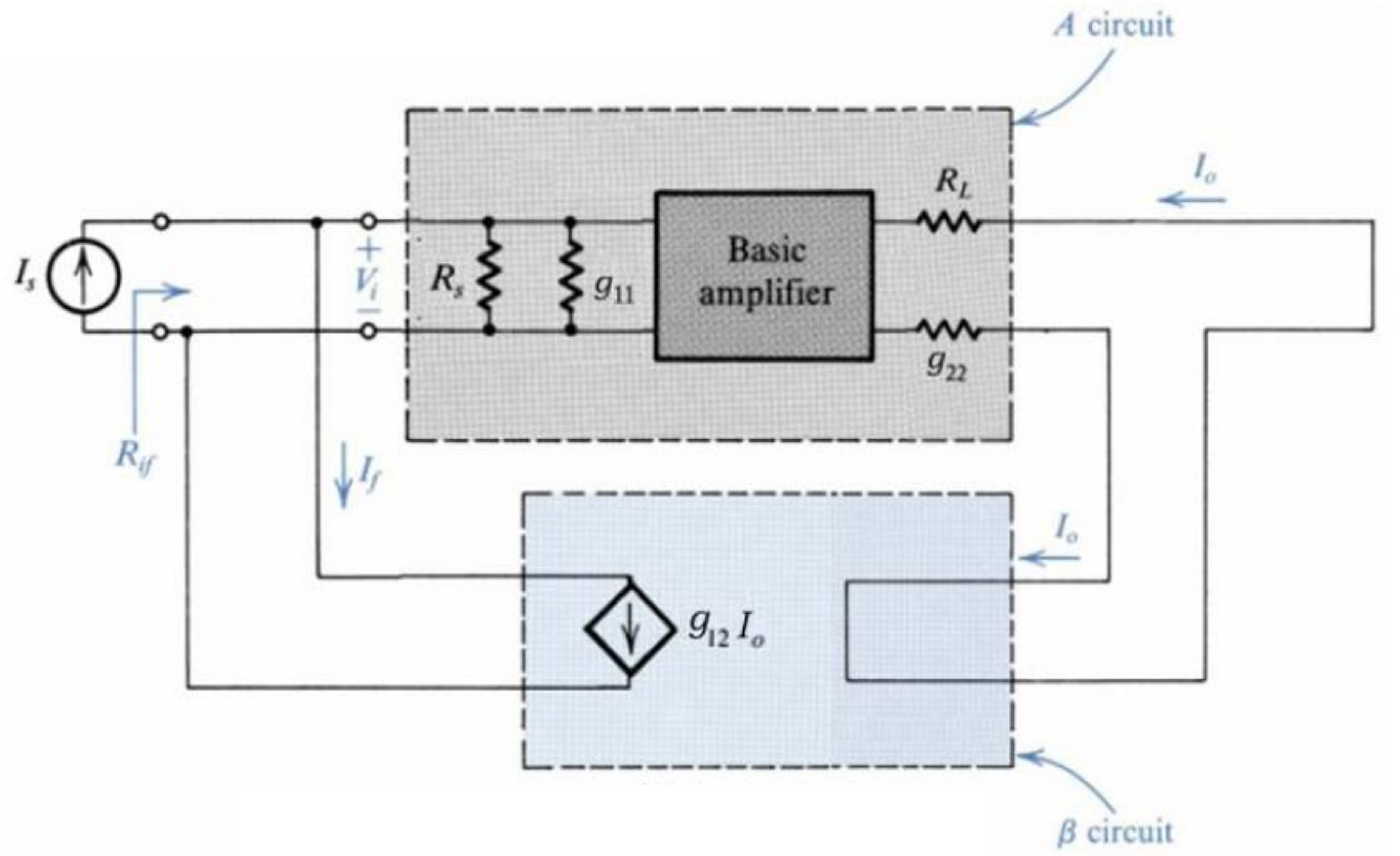



$$R_{if} = \frac{R_i}{(1 + \beta_i A_i)}$$

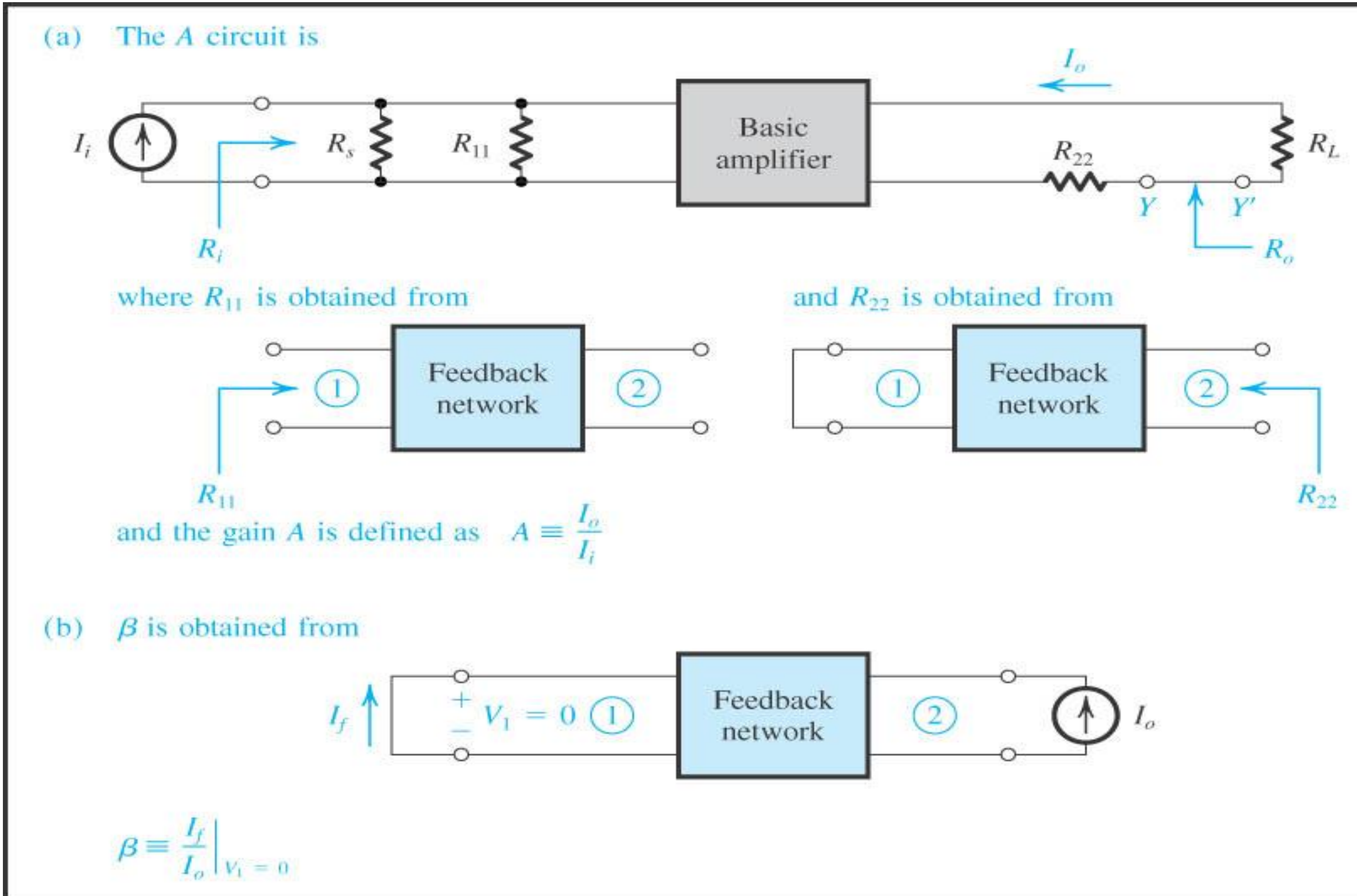
$$A_{if} = \frac{A_i}{1 + \beta_i A_i}$$

$$R_{of} = \frac{V_x}{I_x} = (1 + \beta_i A_i) R_o$$

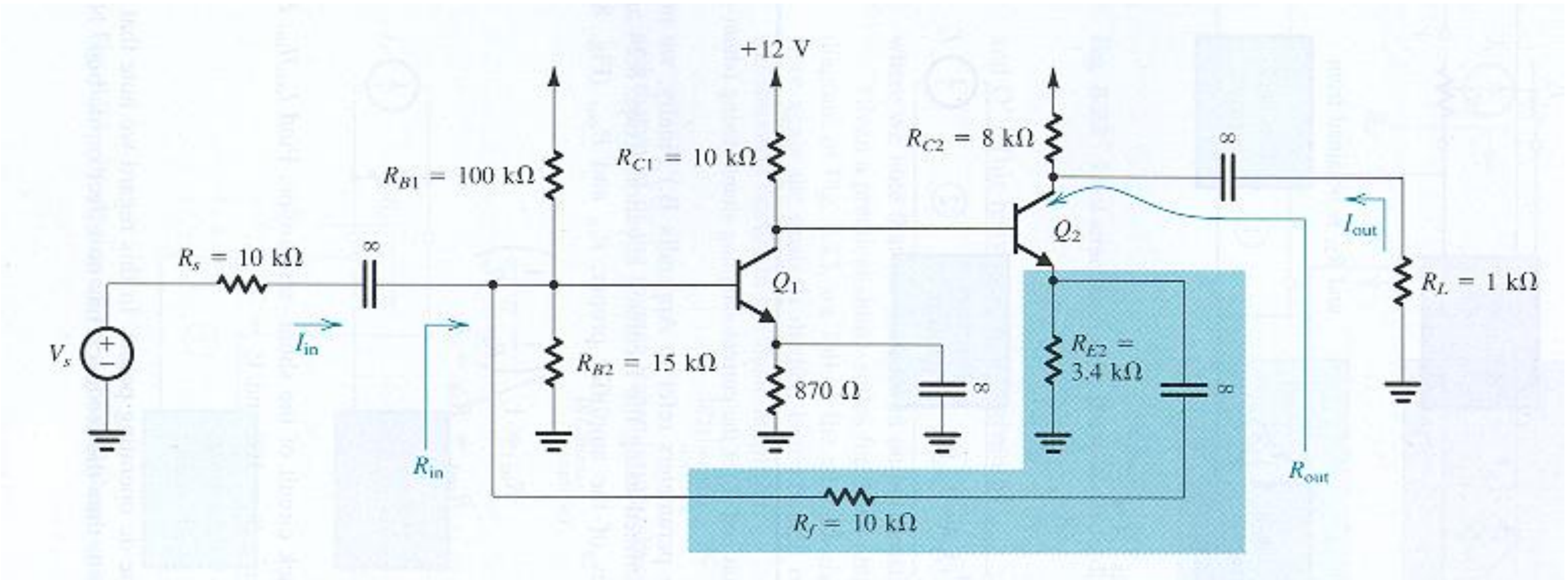
# Actual Shunt-Series Feedback



# Analysis Procedure – Rules to Determine Parameters

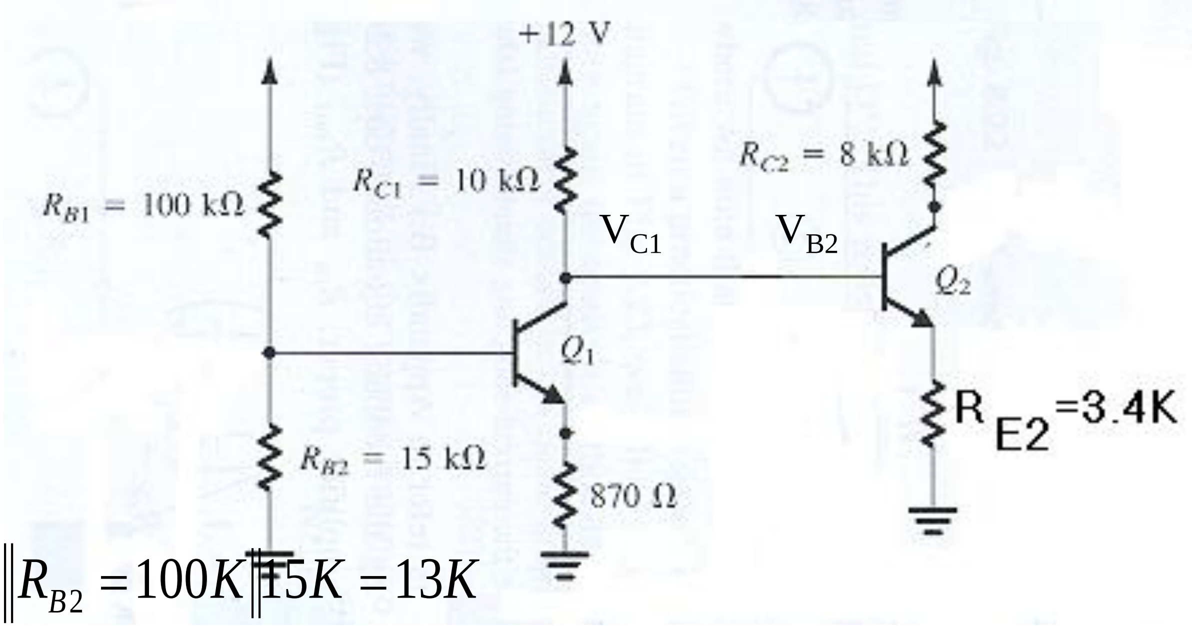


# Example - Shunt-Series Feedback Amplifier




- **Two stage [CE+CE] amplifier**
- **Transistor parameters Given: β=100, $r_x$= 0**
- **Input and output coupling and emitter bypass capacitors, but direct coupling between stages**
- **Capacitor in feedback connection removes $R_f$ from DC bias**
- **DC bias of two stages is coupled (bias of one affects the other)**

# DC Bias Analysis




Given:

$\beta_1 = \beta_2 = 100$

$r_{x1} = r_{x2} = 0$

$$R_{B1}\|R_{B2} = 100K\|15K = 13K$$

$$\frac{R_{B2}}{R_{B1}+R_{B2}}12V = \frac{15K}{15K+100K}12V = 1.6V$$

$$\frac{V_{TH1}-V_{BE1}}{R_{TH1}+(\beta+1)R_{E1}} = \frac{1.6V-0.7V}{13K+(101)0.87K} = 8.7\ \mu A$$

$$I_{C1} = \beta I_{B1} = 100(8.7\ \mu A) = 0.87\ mA$$ (neglecting $I_{B2}$)

$$g_{m1} = \frac{I_{C1}}{V_T} = \frac{0.87\ mA}{0.0256\ V} = 34\ mA/V \qquad r_{\pi 1} = \frac{\beta}{g_{m1}} = \frac{100}{34mA/V} = 2.9K$$

$$V_{C1} = 12\ V - I_{C1}R_{C1} = 12\ V - (0.87\ mA)10K = 3.3\ V$$

$$V_{B2} = V_{C1} = V_{BE2} + I_{E2}R_{E2} = 0.7V + (\beta+1)I_{B2}R_{E2}$$

$$I_{B2} = \frac{3.3V-0.7V}{(\beta+1)R_{E2}} = \frac{2.6V}{101(3.4K)} = 7.6\ \mu A$$ ($<<I_{C1}$ =870 µA)

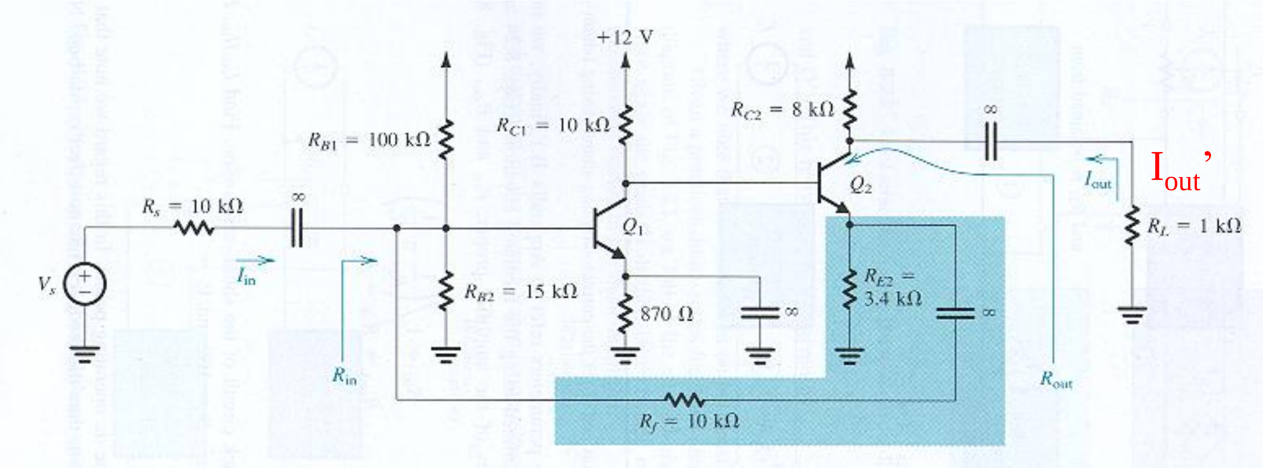
$$I_{C2} = \beta I_{B2} = 100(7.6\ \mu A) = 0.76\ mA$$

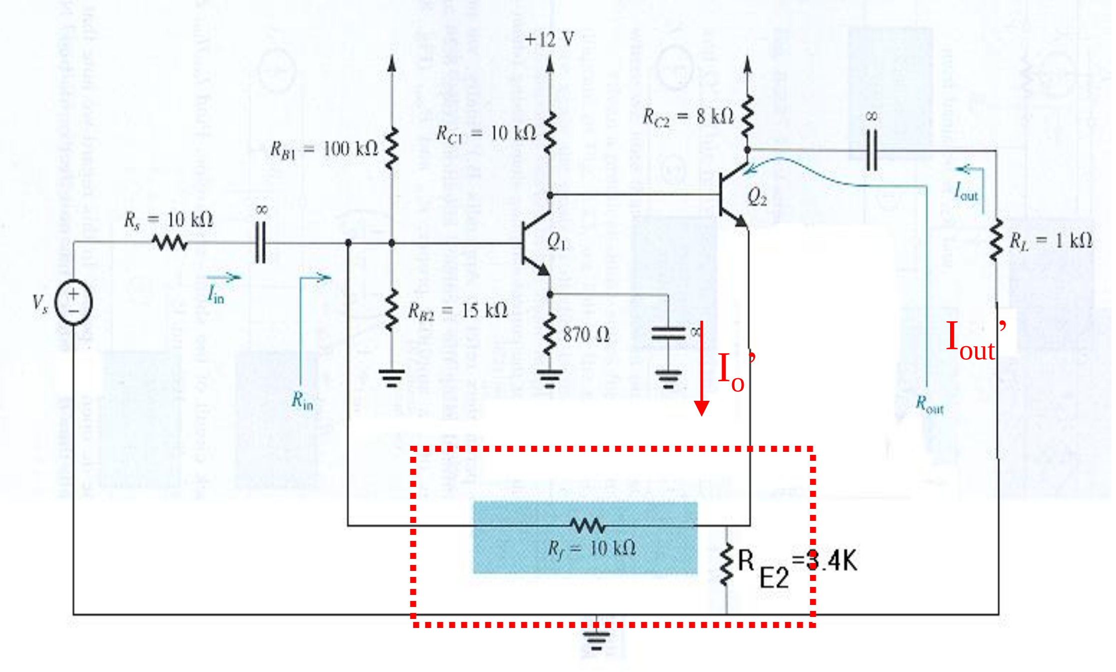
$$g_{m2} = \frac{I_{C2}}{V_T} = \frac{0.76\ mA}{0.0256V} = 30\ mA/V$$

$$r_{\pi 2} = \frac{\beta}{g_{m2}} = \frac{100}{30\ mA/V} = 3.3K$$

# Example - Shunt-Series Feedback Amplifier

- Redraw circuit to show
  - Feedback circuit
  - Type of output sampling (current in this case = $I_o$)
  - Type of feedback signal to input (current in this case = $I_f$)



# Example - Shunt-Series Feedback Amplifier

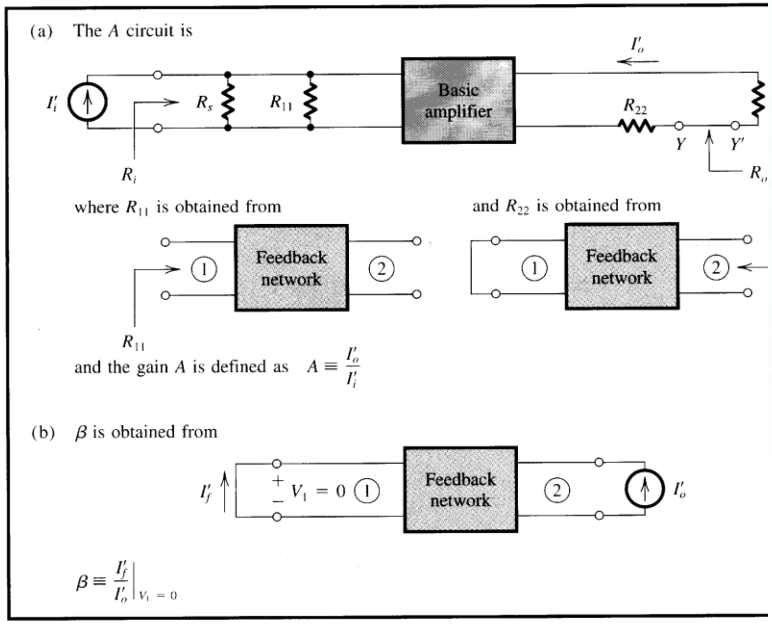
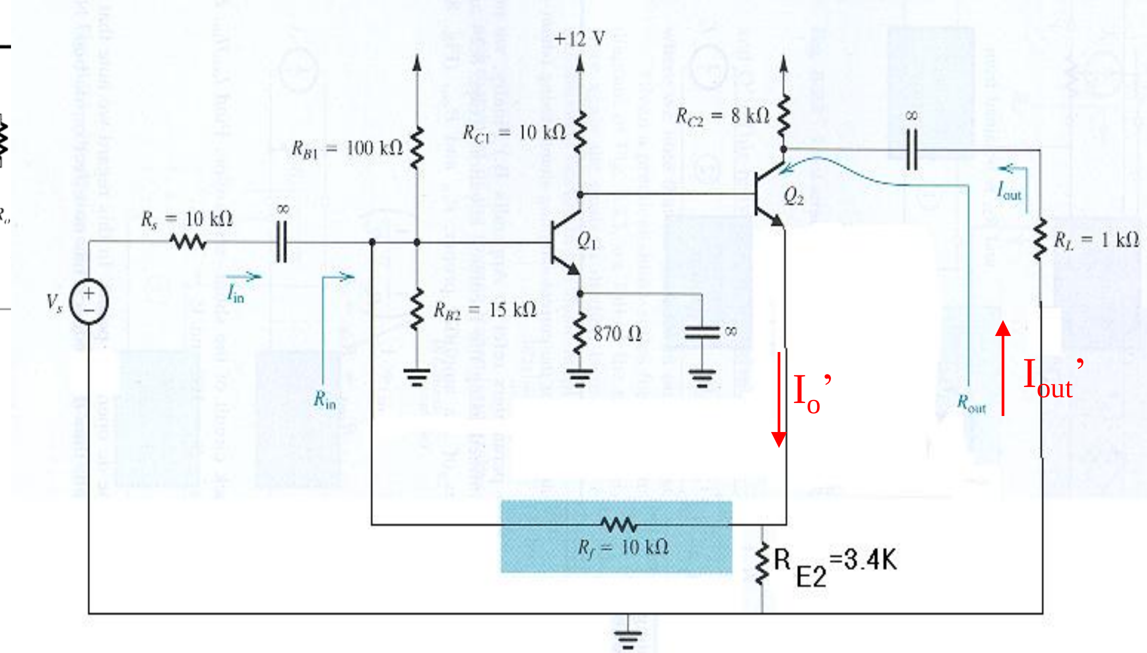
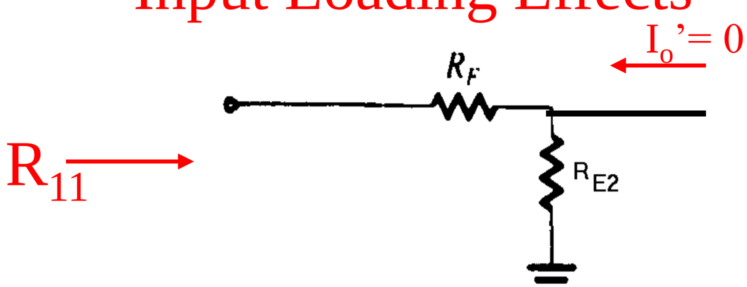


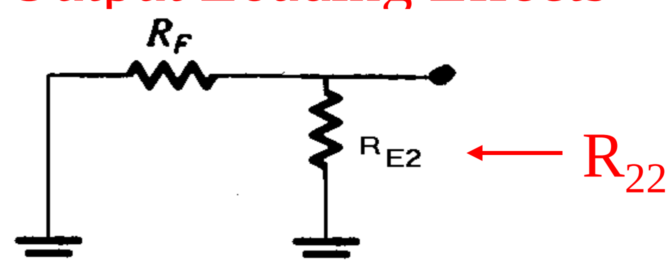

Fig. 8.24 Finding the $A$ circuit and $\beta$ for the current-sampling shunt-mixing (shunt–series) c




## Input Loading Effects



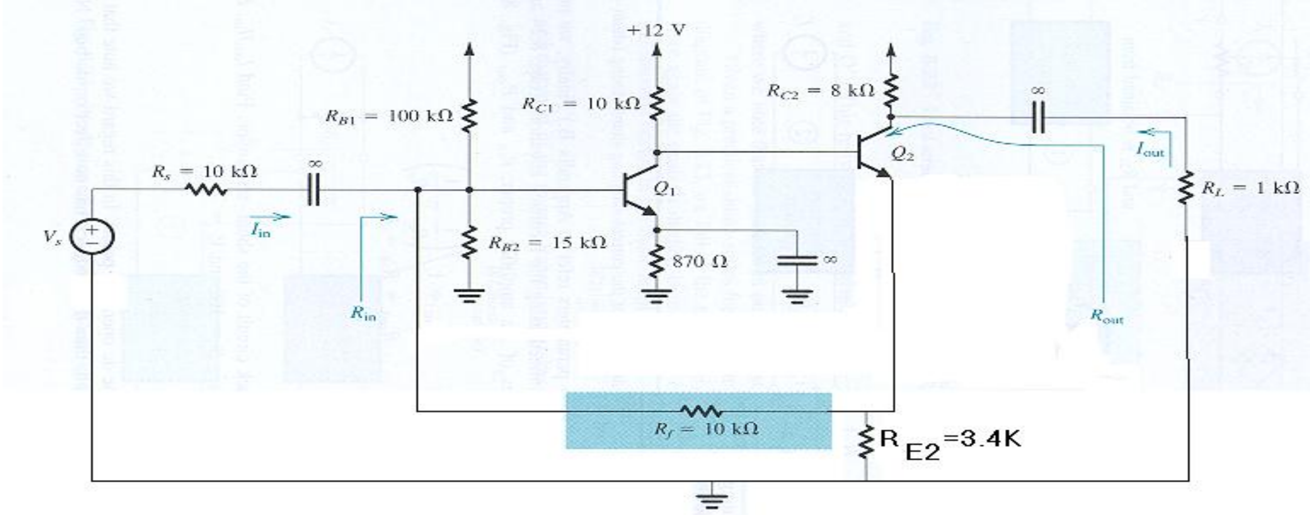

## Output Loading Effects



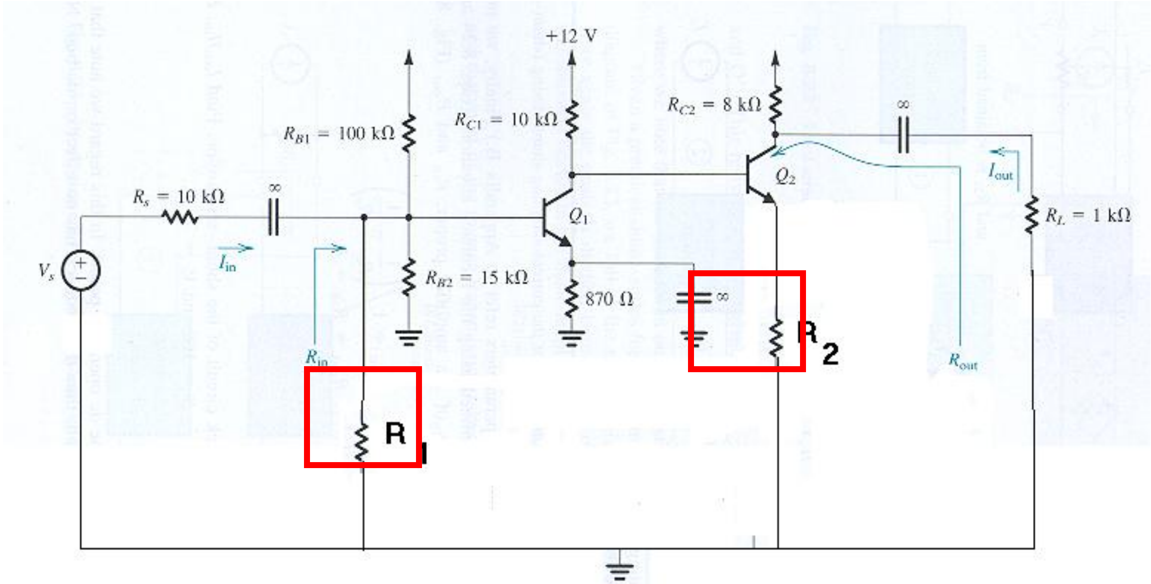

$$R_{22} = R_F \| R_{E2} = 10K \| 3.4K = 2.5K$$

$$R_{11} = R_F + R_1 = 10K + 3.4K = 13.4K$$

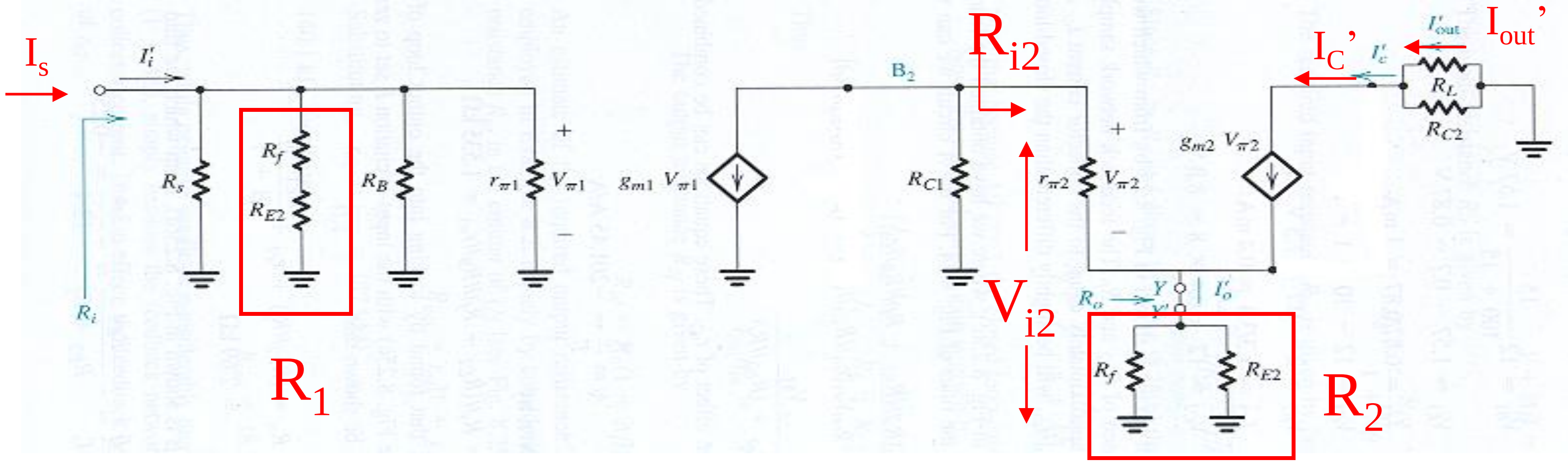
# Example - Shunt-Series Feedback Amplifier




## Amplifier with Loading Effects but Without Feedback



# Example - Shunt-Series Feedback Amplifier
## Midband Gain Analysis




$$A_{Io} = \frac{I_{out}'}{I_s} = \left(\frac{I_{out}'}{I_c'}\right)\left(\frac{I_c'}{V_{\pi 2}}\right)\left(\frac{V_{\pi 2}}{V_{i2}}\right)\left(\frac{V_{i2}}{V_{\pi 1}}\right)\left(\frac{V_{\pi 1}}{I_s}\right)$$

$$\frac{I_{out}'}{I_c'} = \frac{R_{C2}}{R_{C2}+R_L} = \frac{8K}{8K+1K} = 0.89$$

$$\frac{I_c'}{V_{\pi 2}} = \frac{g_{m2}V_{\pi 2}}{V_{\pi 2}} = g_{m2} = 30 \;\; mA/V$$

$$\frac{V_{\pi 2}}{V_{i2}} = \frac{I_{\pi 2}r_{\pi 2}}{I_{\pi 2}r_{\pi 2} + I_{\pi 2}(1+g_{m2}r_{\pi 2})R_2} = \frac{r_{\pi 2}}{R_{i2}} = \frac{r_{\pi 2}}{r_{\pi 2}+(1+g_{m2}r_{\pi 2})R_2} = \frac{3.3K}{3.3K+101(2.5K)} = 0.013$$

$$\frac{V_{i2}}{V_{\pi 1}} = -g_{m1}R_{C1}\|R_{i2} = -g_{m1}\left(R_{C1}\|[r_{\pi 2}+(1+g_{m2}r_{\pi 2})R_2]\right) = -34 \;\; mA/V\left(10K\|[3.3K+101(2.5K)]\right) = -327$$

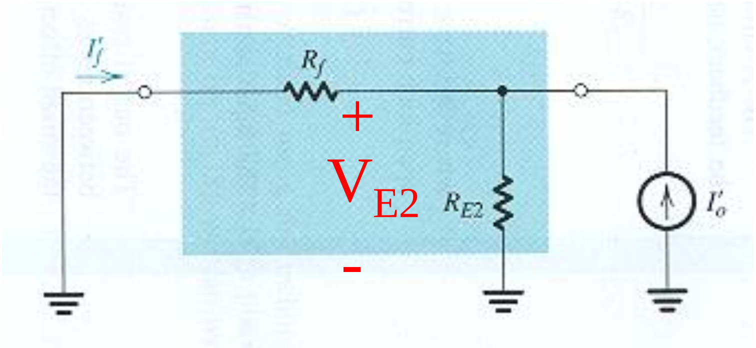
$$\frac{V_{\pi}}{I_S} = \left(R_S\|R_1\|r_{\pi 1}\|R_{B1}\right) = \left(10K\|13.4K\|2.9K\|13K\right) = 1.7K$$

$$A_{Io} = \frac{I_{out}'}{I_s} = (0.89)(30 \;\; mA/V)(0.013)(-327)(1.7K) = -193$$

# Midband Gain with Feedback

- **Determine the feedback factor $\beta_f$**

$$\beta_f = \frac{X_f}{X_o} = \frac{I_f'}{I_o'} = \frac{-R_{E2}}{(R_{E2}+R_f)} = \frac{-3.4K}{3.4K+10K} = -\,0.25$$




- **Calculate gain with feedback $A_{Ifo}$**

$$\beta_f A_{Io} = -193(-0.25) = 48$$

$$A_{Ifo} = \frac{A_{Io}}{1+\beta_f A_{Io}} = \frac{-193}{1+48} = -3.9$$

$$A_{Ifo}(dB) = 20\log 3.9 = 11.8\ dB$$

$$V_{E2} = -I_f' R_f = (I_o' + I_f')R_{E2}$$

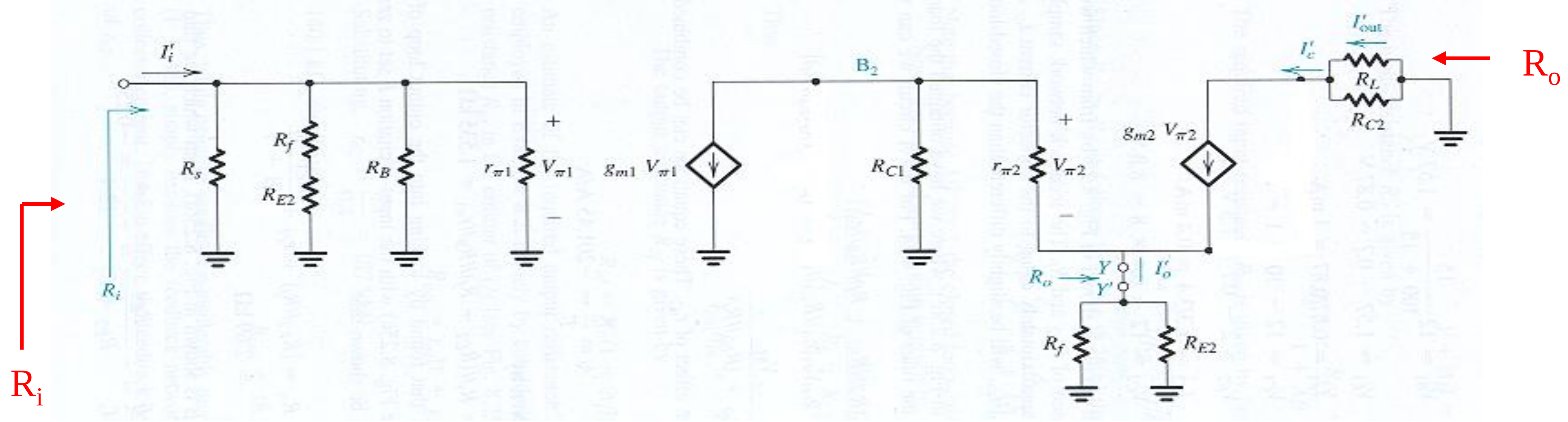
$$-I_f'(R_f + R_{E2}) = I_o' R_{E2}$$

$$\frac{I_f'}{I_o'} = \frac{-R_{E2}}{R_f' + R_{E2}}$$

- **Note**
  - **$\beta_f < 0$ and $A_{Io} < 0$**
  - **$\beta_f A_{Io} > 0$ as necessary for negative feedback and dimensionless**
  - **$\beta_f A_{Io}$ is large so there is significant feedback.**
  - **Can change $\beta_f$ and the amount of feedback by changing $R_F$.**
  - **Gain is determined by feedback resistance**

$$A_{Ifo} \approx \frac{1}{\beta_f} = -\frac{R_{E2}+R_f}{R_{E2}} = -\,4.0$$

# Input and Output Resistances with Feedback




- **Determine input $R_i$ and output $R_o$ resistances with loading effects of feedback network.**

$$R_i = R_S \| R_1 \| R_{B1} \| r_{\pi_1} = 10K \| 13.4K \| 13K \| 2.9K = 1.7K$$

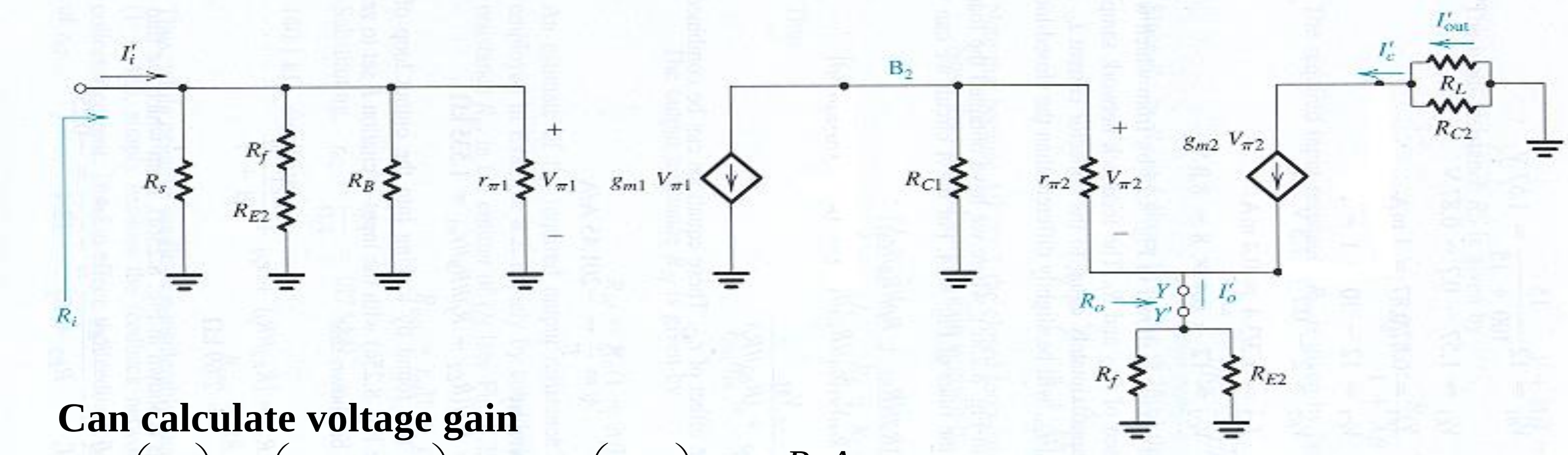
$$R_o = R_{C2} \| R_L + \infty = \infty$$

- **Calculate input $R_{if}$ and output $R_{of}$ resistances for the complete feedback amplifier.**

$$R_{if} = \frac{R_i}{(1+\beta_f A_{Io})} = \frac{1.7K}{49} = 0.035K$$

$$R_{of} = R_o (1+\beta_f A_{Io}) = \infty(49) = \infty$$

# Voltage Gain for Current Gain Feedback Amplifier




- **Can calculate voltage gain**

$$A_{Vfo} = \left(\frac{V_o}{V_s}\right)_f = \left(\frac{-I_{out}'R_L}{I_s R_s}\right)_f = \frac{-R_L}{R_s}\left(\frac{I_{out}'}{I_s}\right)_f = \frac{-R_L A_{Ifo}}{R_s} = \frac{-1K}{10K}(-4.2) = +\ 0.42\ V/V$$

$$A_{Vfo}(dB) = 20\log(0.42) = -7.5\ dB$$

- **Note - can't calculate the voltage gain as follows:**

$$Assume\quad A_{Vfo} = \frac{A_{Vo}}{1+\beta_f A_{Vo}}$$

$$Find\quad A_{Vo} = \frac{V_o}{V_s} = \frac{-I_o R_L}{I_s R_s} = \frac{-A_{Io} R_L}{R_s} = \frac{-(-193)(1K)}{10K} = +19.3\ V/V$$

$$Calculate\quad \beta_f A_{Vo} = (-0.25)(19.3\ V/V) = -4.8$$

Calculate voltage gain with feedback from $A_{Vfo} = \dfrac{A_{Vo}}{1+\beta_f A_{Vo}} = \dfrac{-19.3\ V/V}{1-4.8} = +5.8\ V/V$

Magnitude is off by nearly a factor of ten!

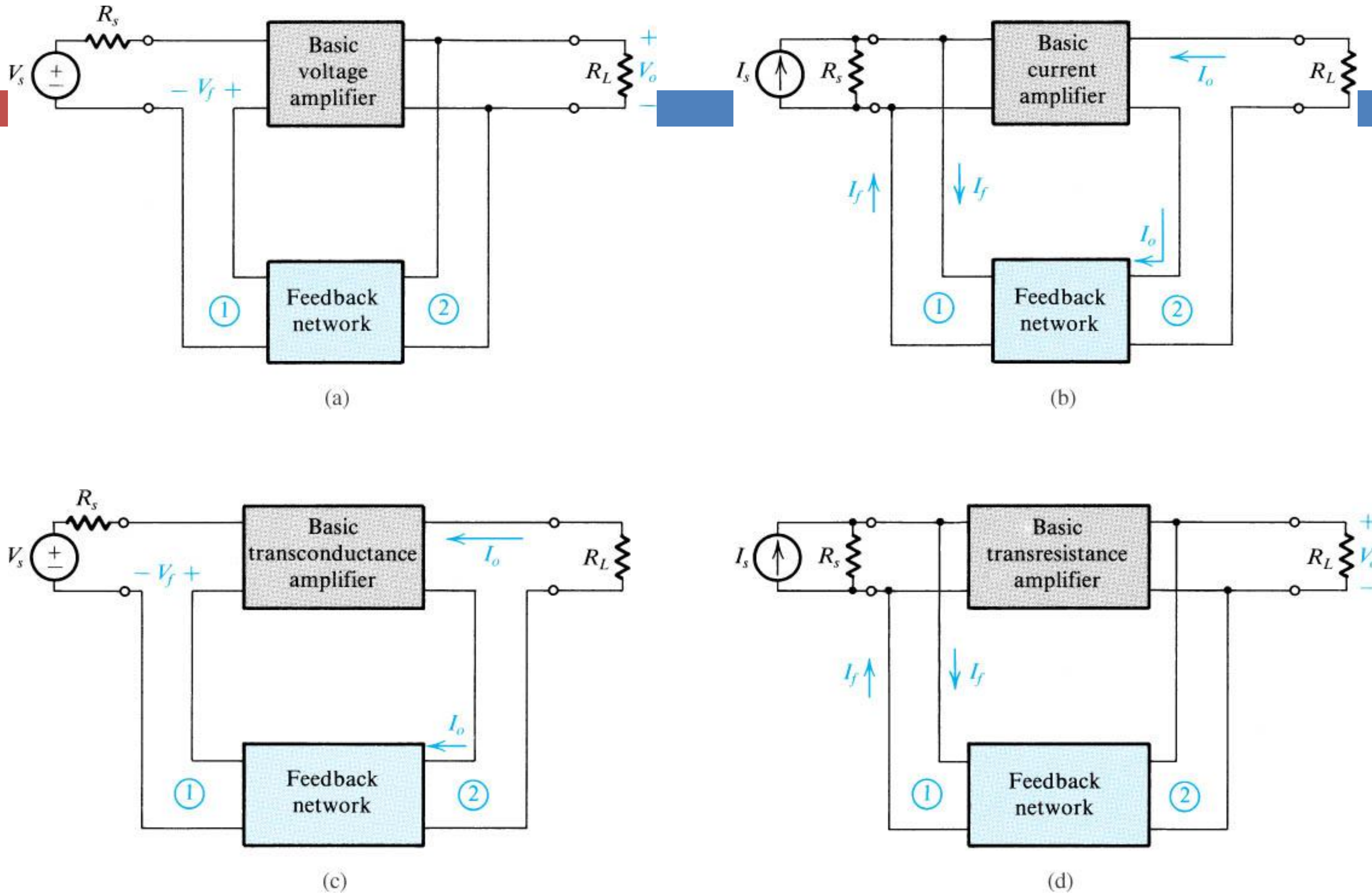



**Figure 8.4** The four basic feedback topologies: **(a)** voltage-mixing voltage-sampling (series–shunt) topology; **(b)** current-mixing current-sampling (shunt–series) topology; **(c)** voltage-mixing current-sampling (series–series) topology; **(d)** current-mixing voltage-sampling (shunt–shunt) topology.

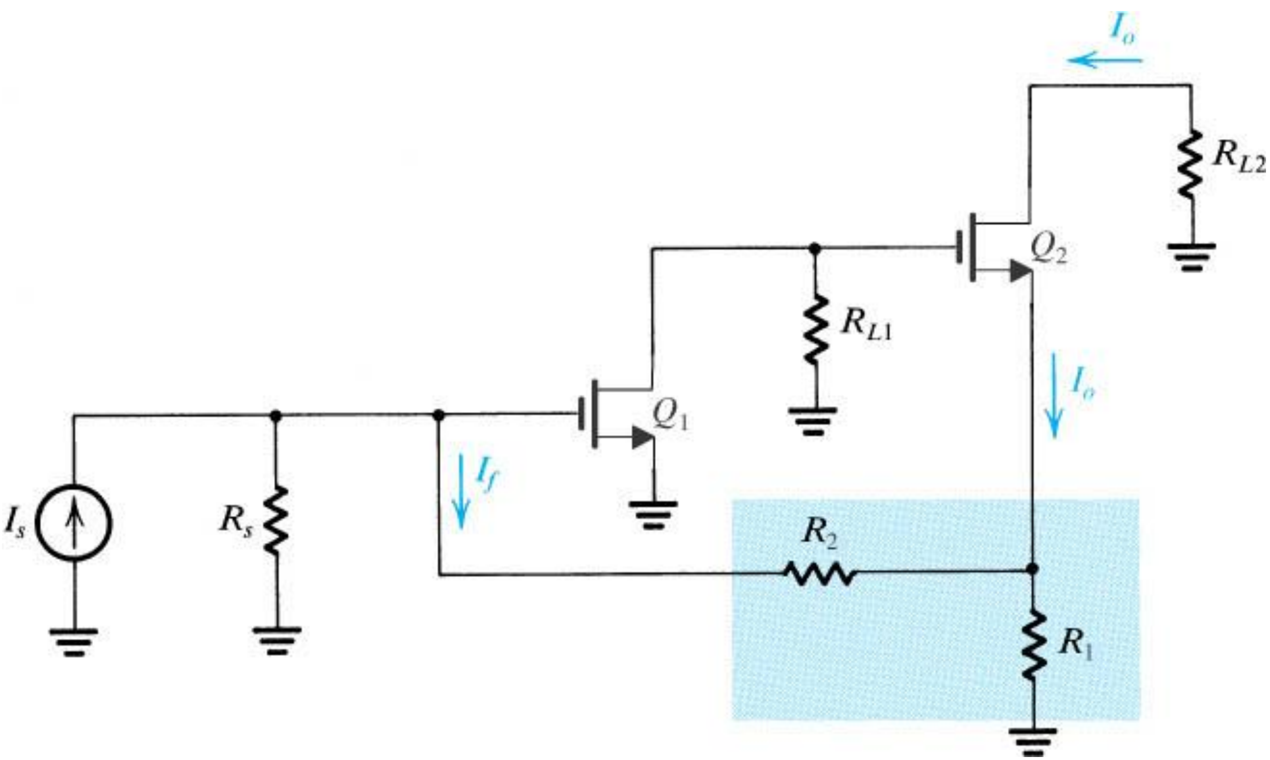



**Figure 8.5** A transistor amplifier with shunt–series feedback. (Biasing not shown.)

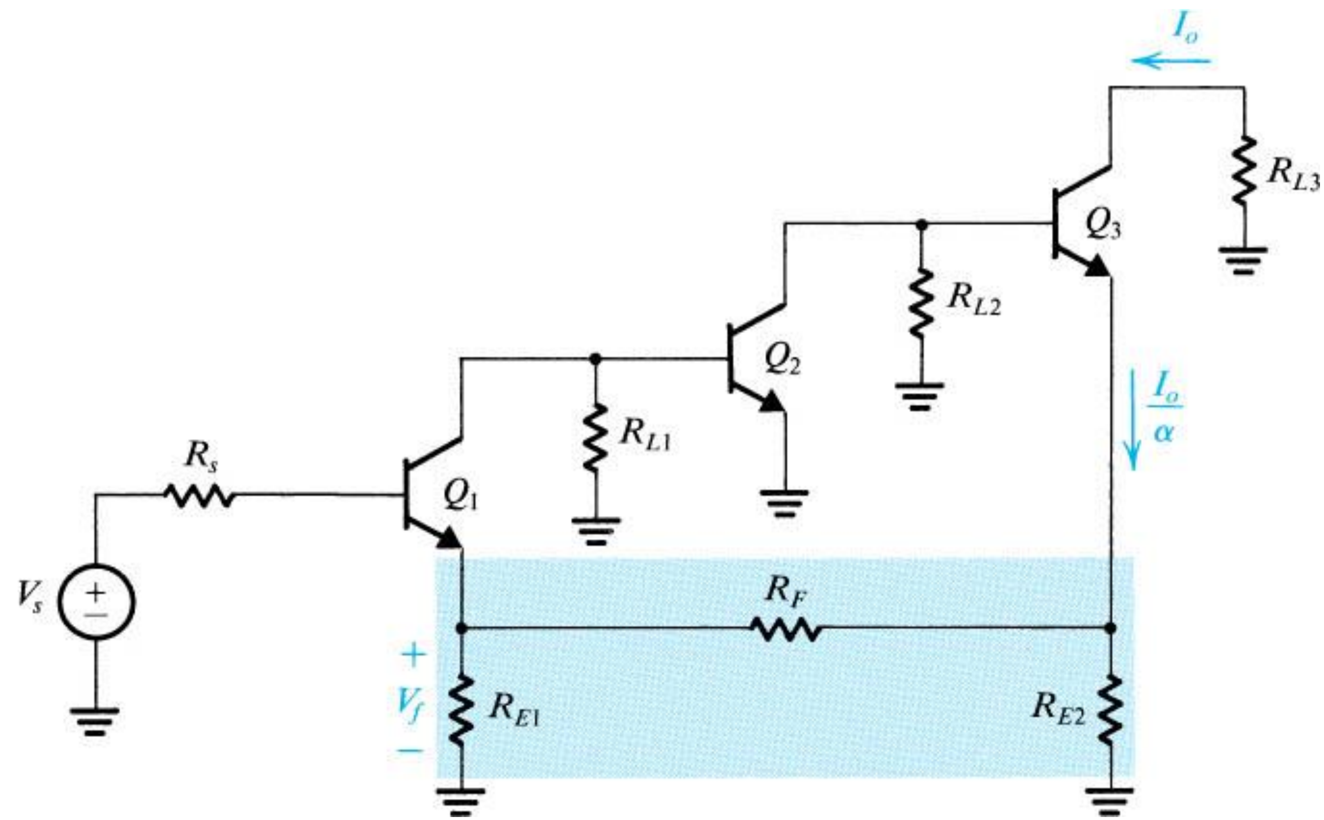



**Figure 8.6** An example of the series–series feedback topology. (Biasing not shown.)

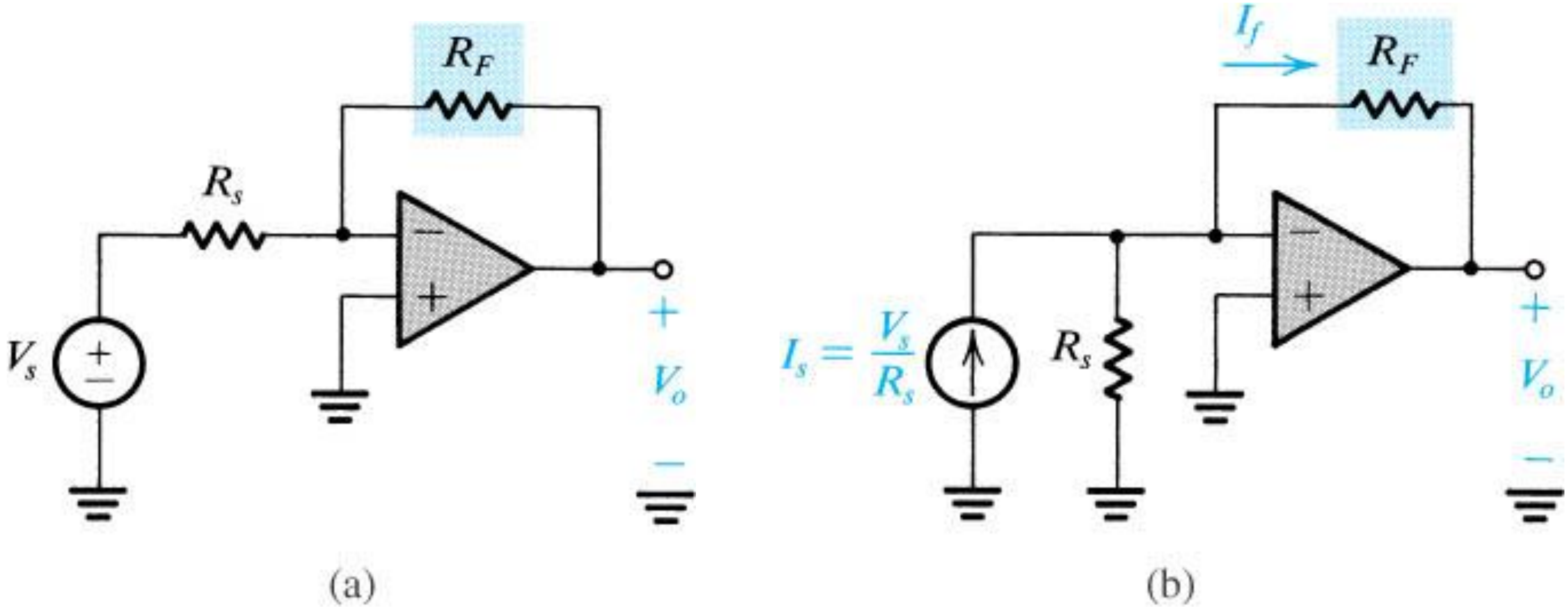



**Figure 8.7** **(a)** The inverting op-amp configuration redrawn as **(b)** an example of shunt–shunt feedback.

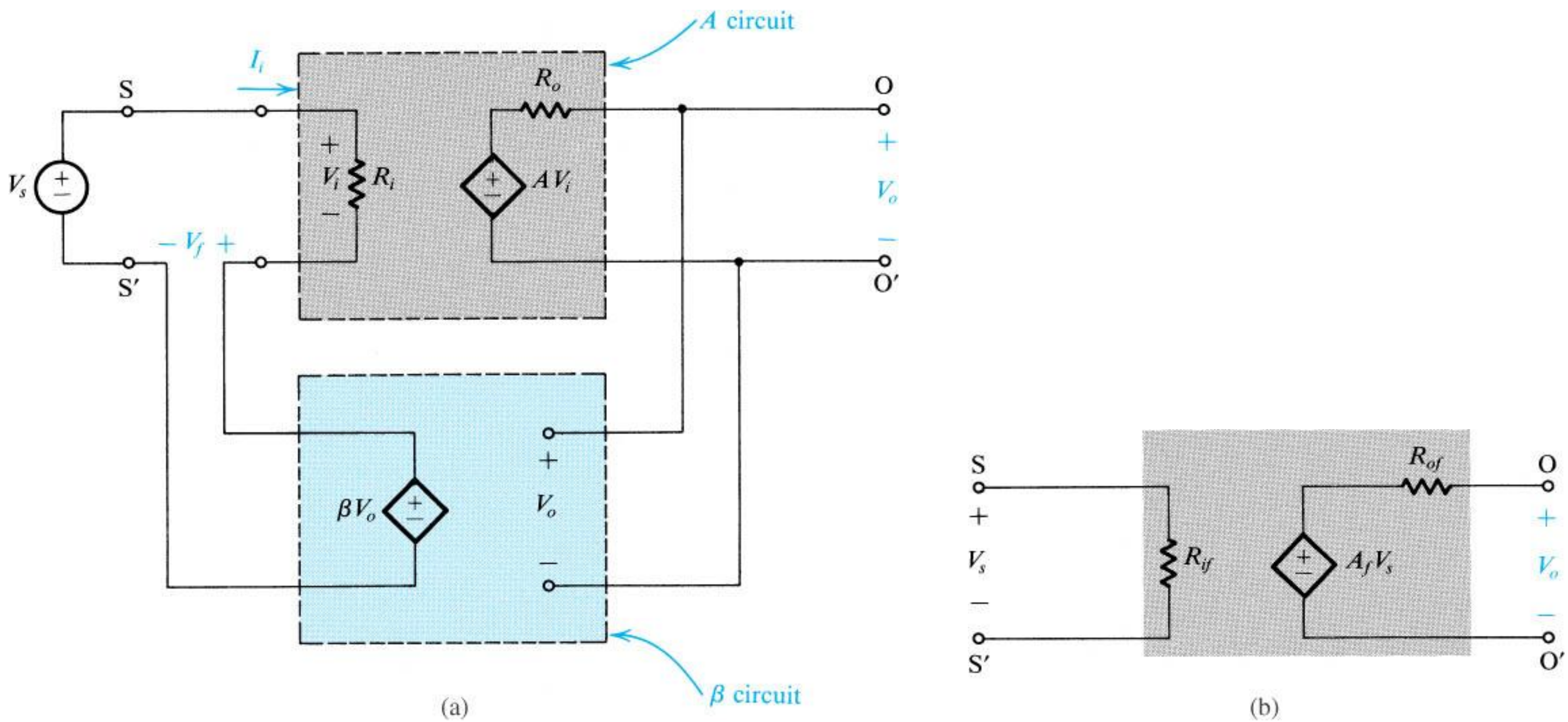



**Figure 8.8** The series–shunt feedback amplifier: **(a)** ideal structure and **(b)** equivalent circuit.

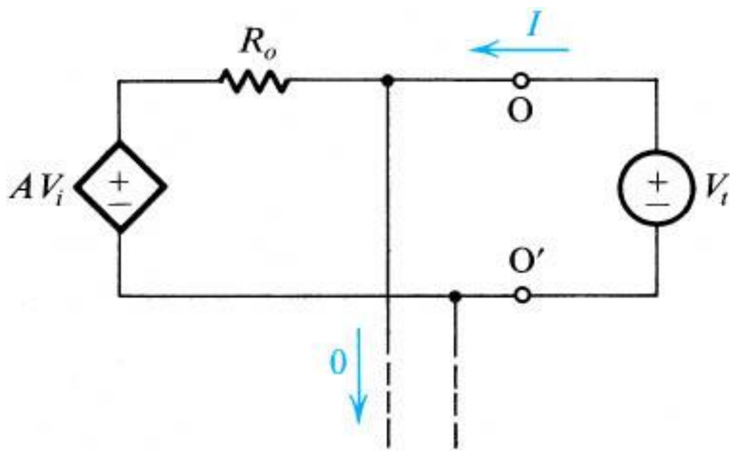
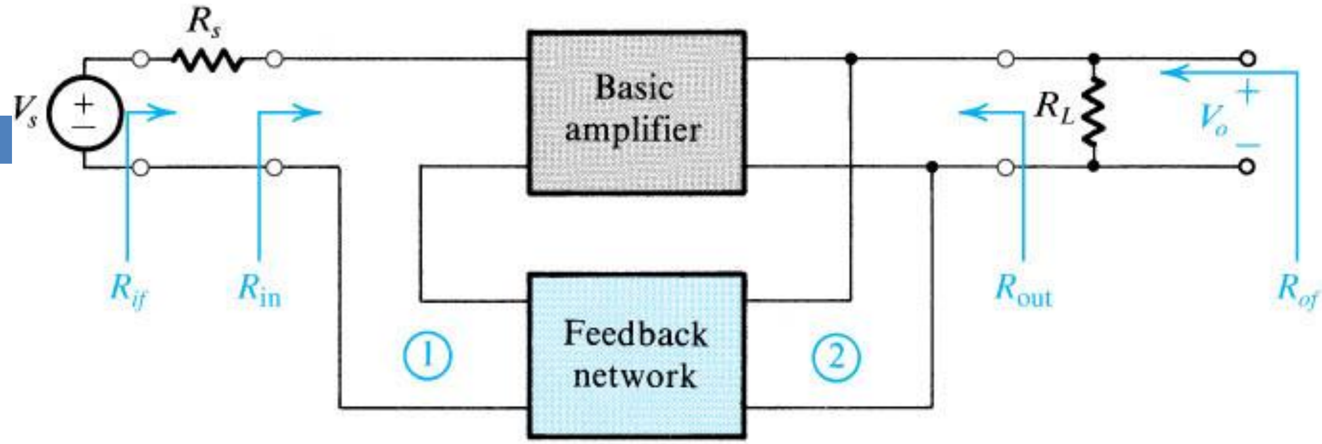
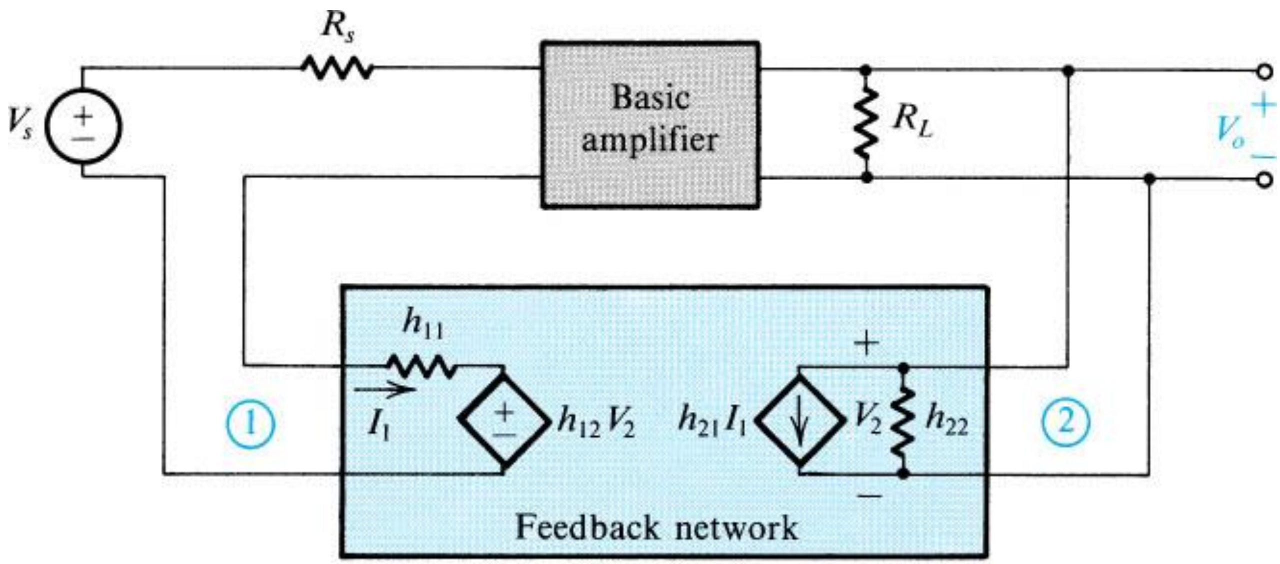



**Figure 8.9** Measuring the output resistance of the feedback amplifier of Fig. 8.8(a): $R_{of} = V_t/I$.




(a)




(b)

**Figure 8.10** 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.

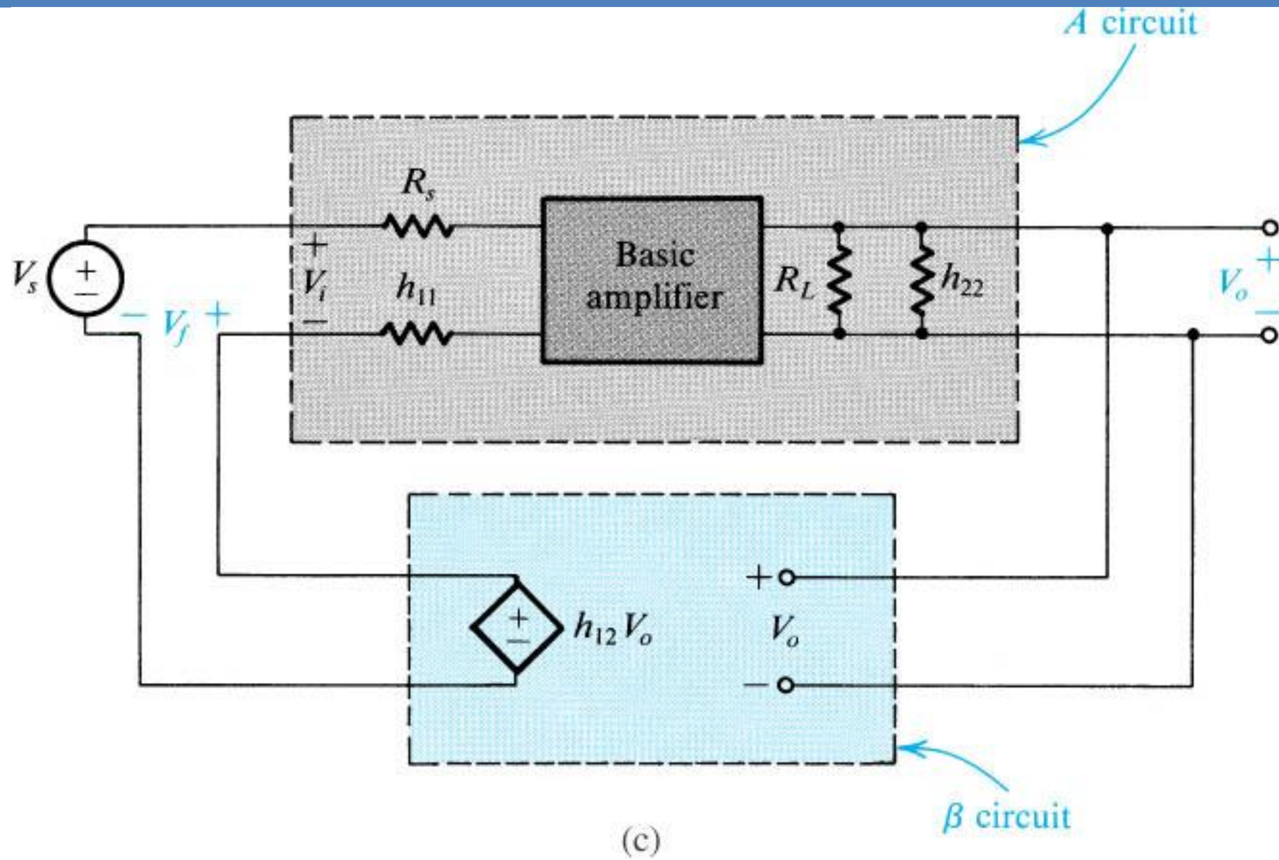



**Figure 8.10** *(Continued)* **(c)** The circuit in (b) with $h_{21}$ neglected.

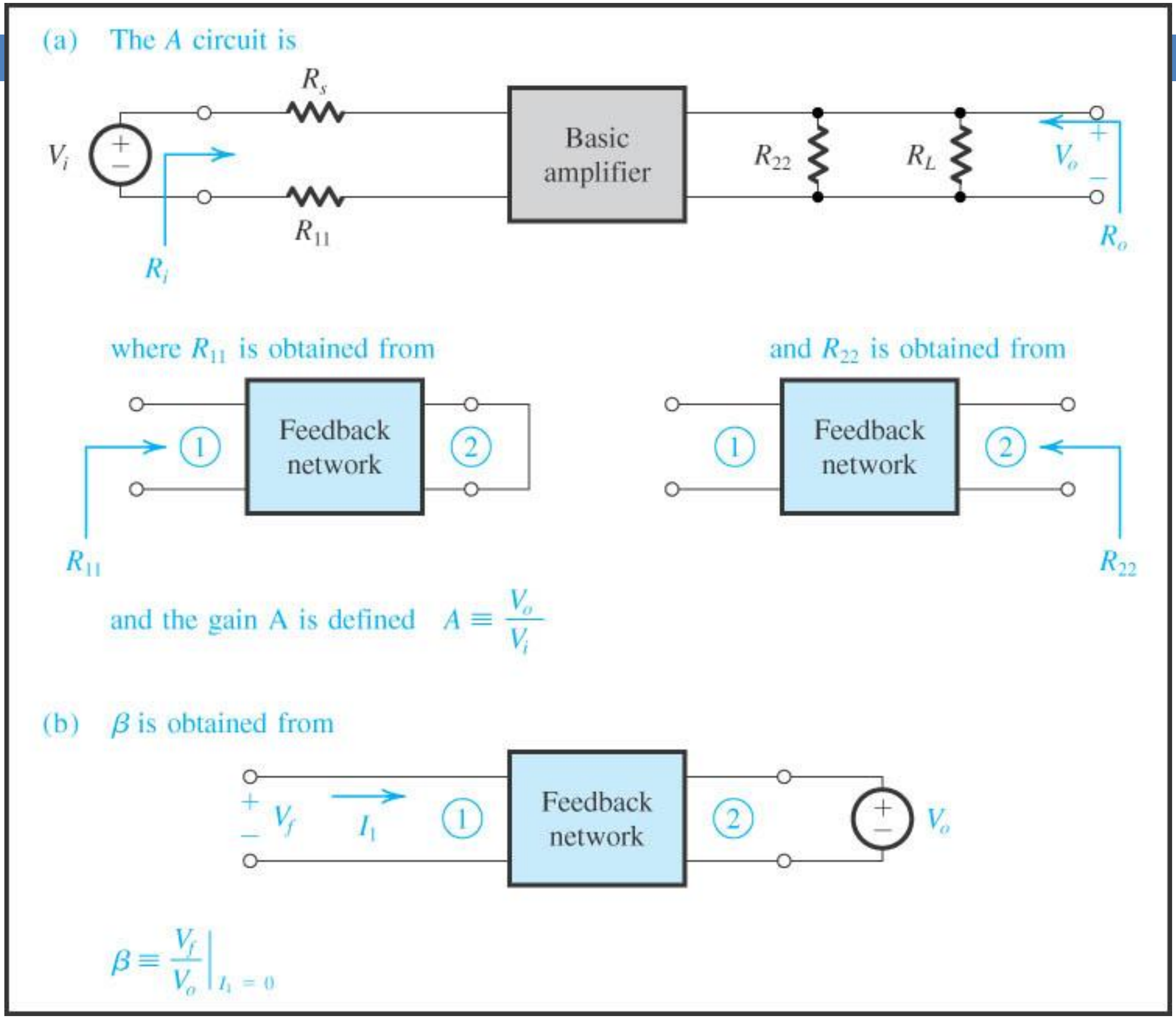



**Figure 8.11** Summary of the rules for finding the *A* circuit and $\beta$ for the voltage-mixing voltage-sampling case of Fig. 8.10(a).

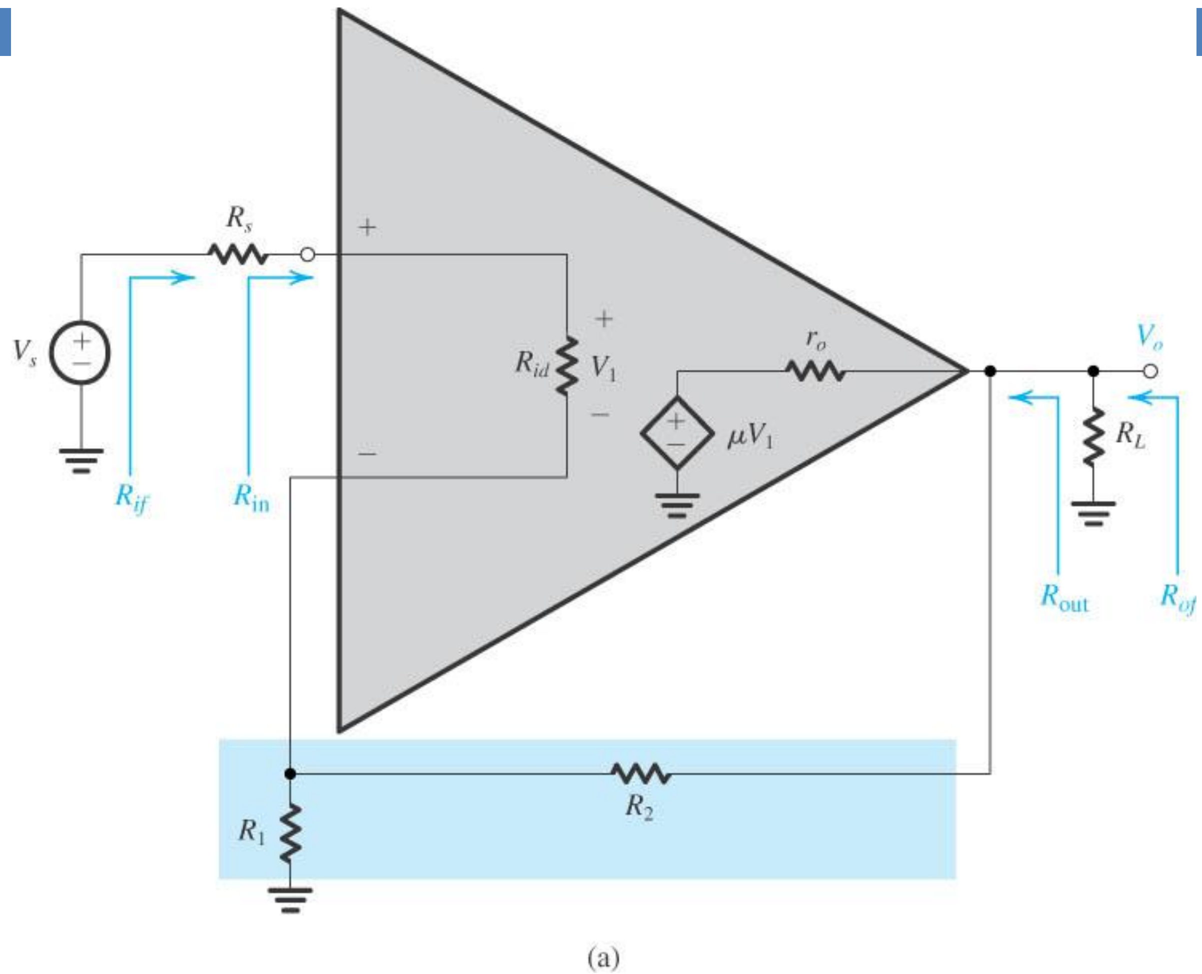
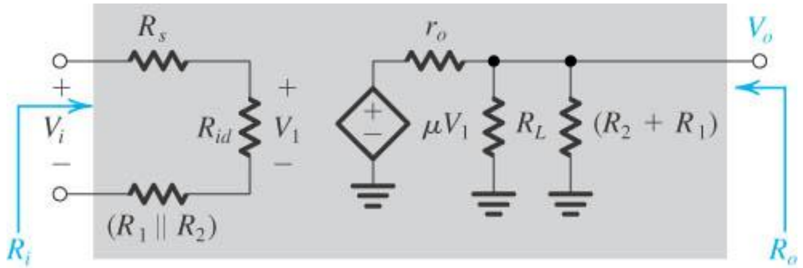
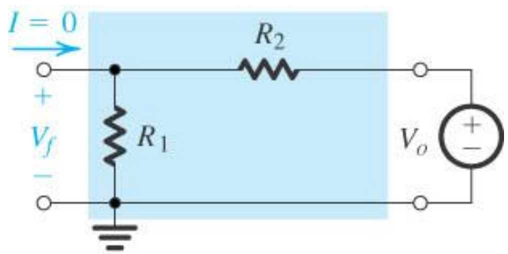



**Figure 8.12** Circuits for Example 8.1.




(b)




(c)

**Figure 8.12** *(Continued)*

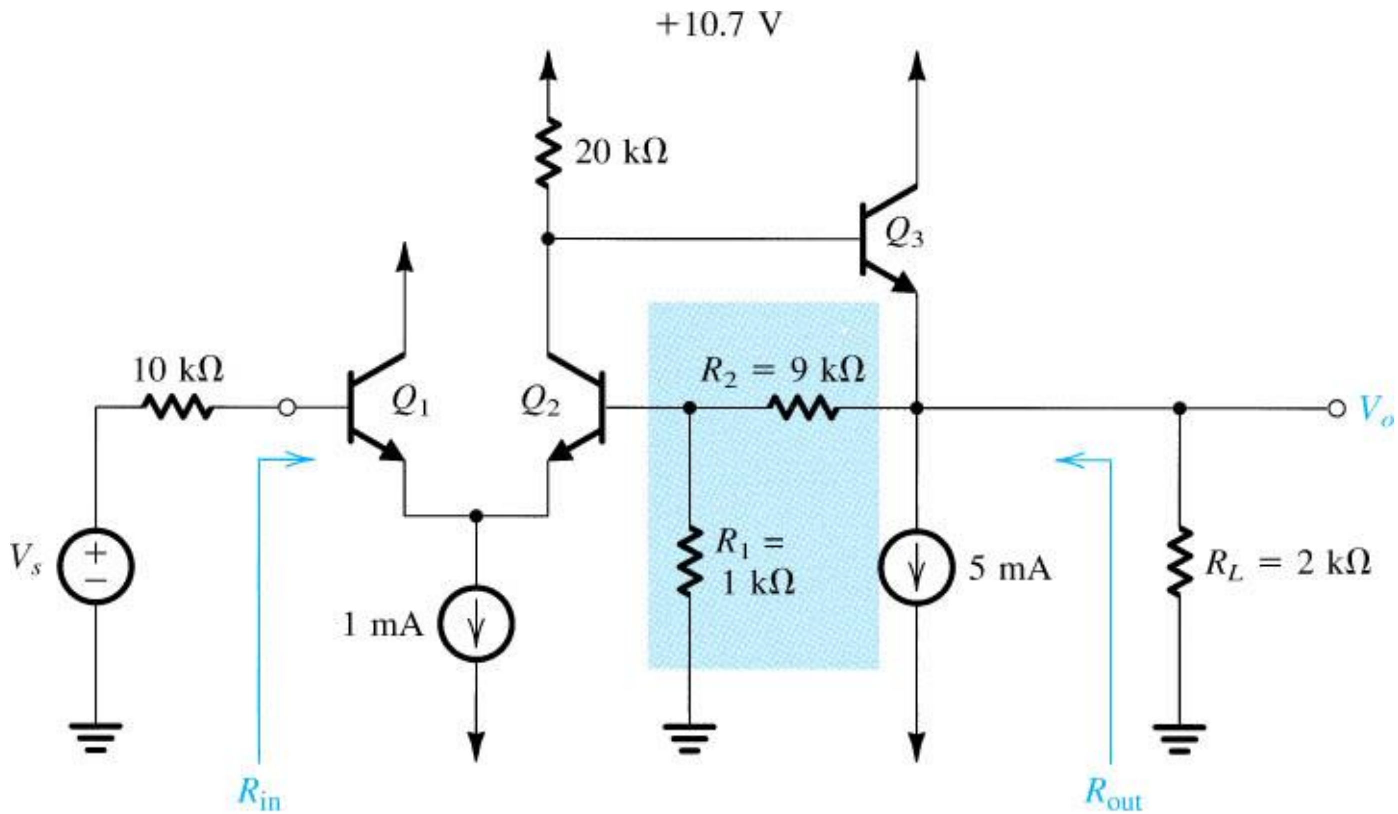

+10.7 V
20 kΩ
$Q_3$
10 kΩ
$Q_1$
$Q_2$
$R_2$ = 9 kΩ
$V_o$
$V_s$
$R_1$ =
1 kΩ
5 mA
$R_L$ = 2 kΩ
1 mA
$R_{in}$
$R_{out}$

**Figure E8.5**

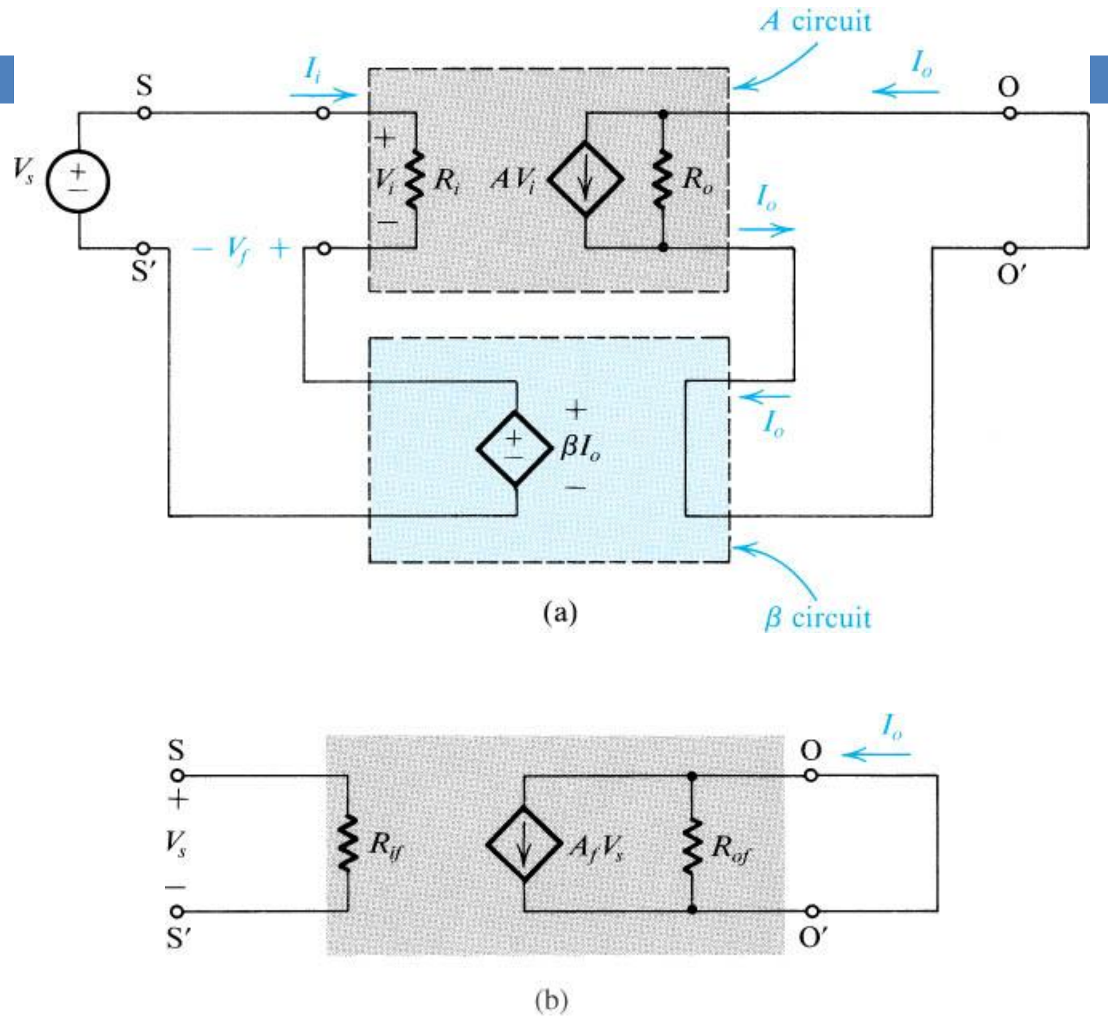



**Figure 8.13** The series–series feedback amplifier: **(a)** ideal structure and **(b)** equivalent circuit.

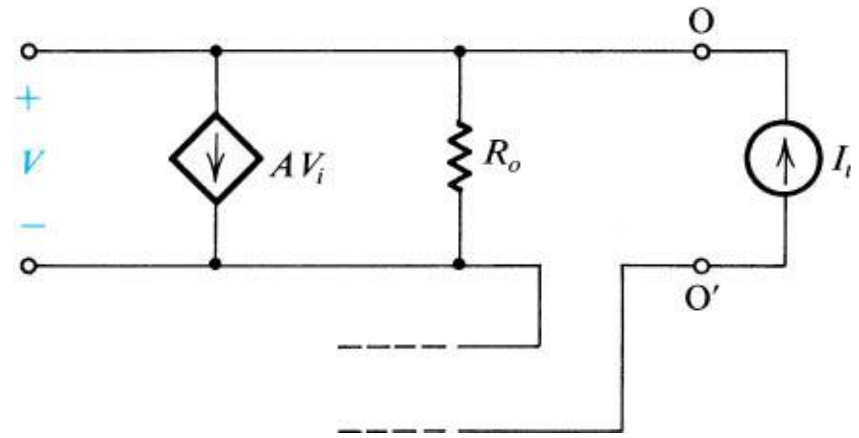



**Figure 8.14** Measuring the output resistance $R_{of}$ of the series–series feedback amplifier.

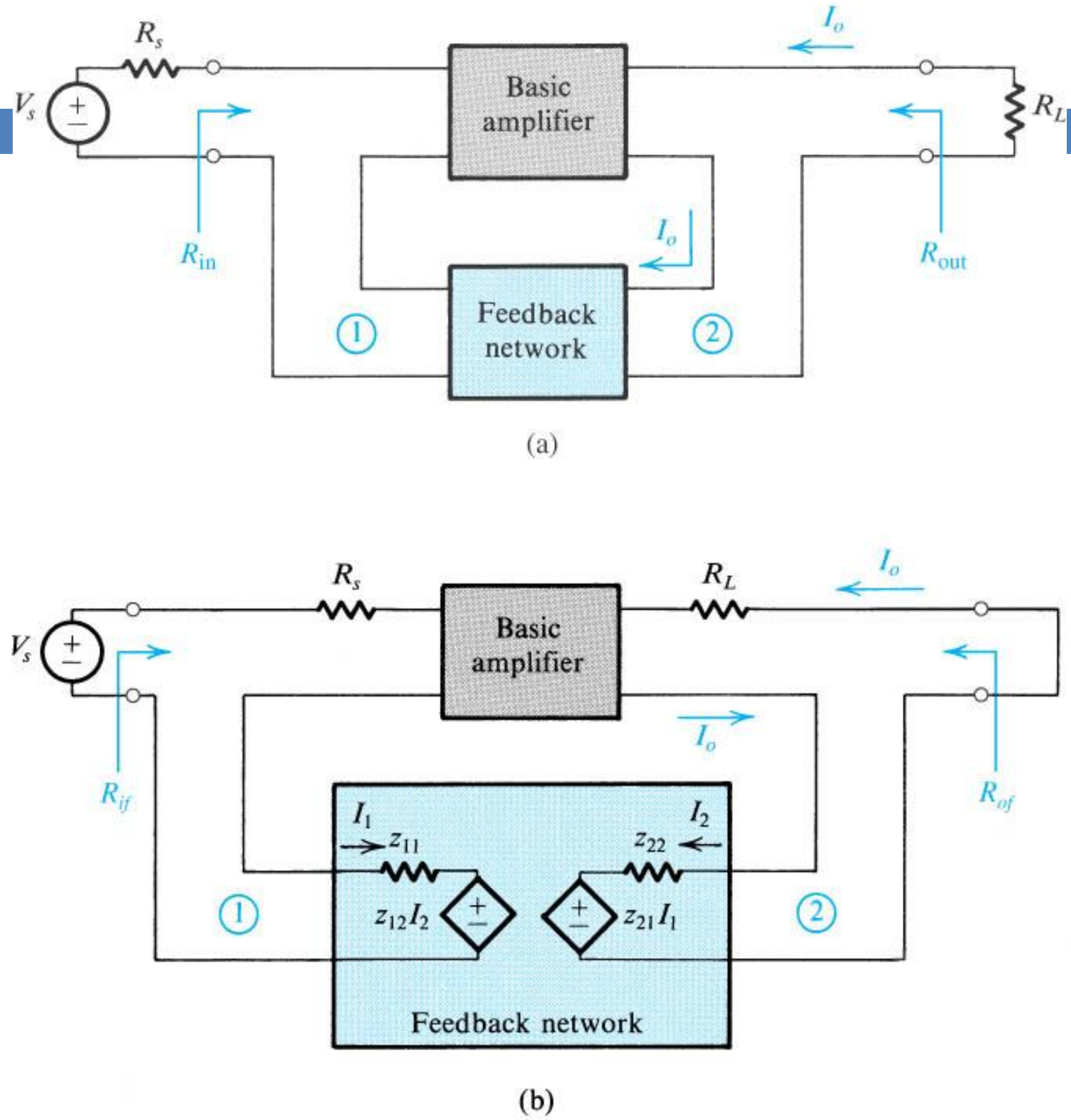



**Figure 8.15** Derivation of the $A$ circuit and the $\beta$ circuit for series–series feedback amplifiers. **(a)** A series–series feedback amplifier. **(b)** The circuit of (a) with the feedback network represented by its $z$ parameters.

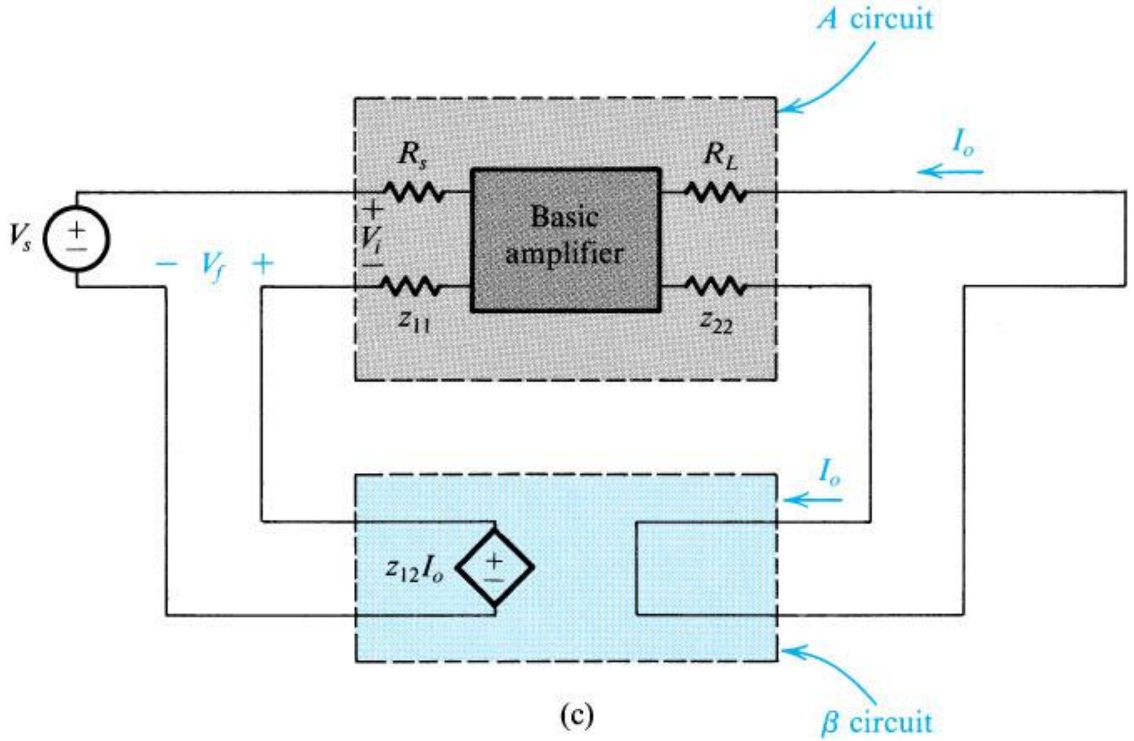



**Figure 8.15** *(Continued)* **(c)** A redrawing of the circuit in (b) with $z_{21}$ neglected.

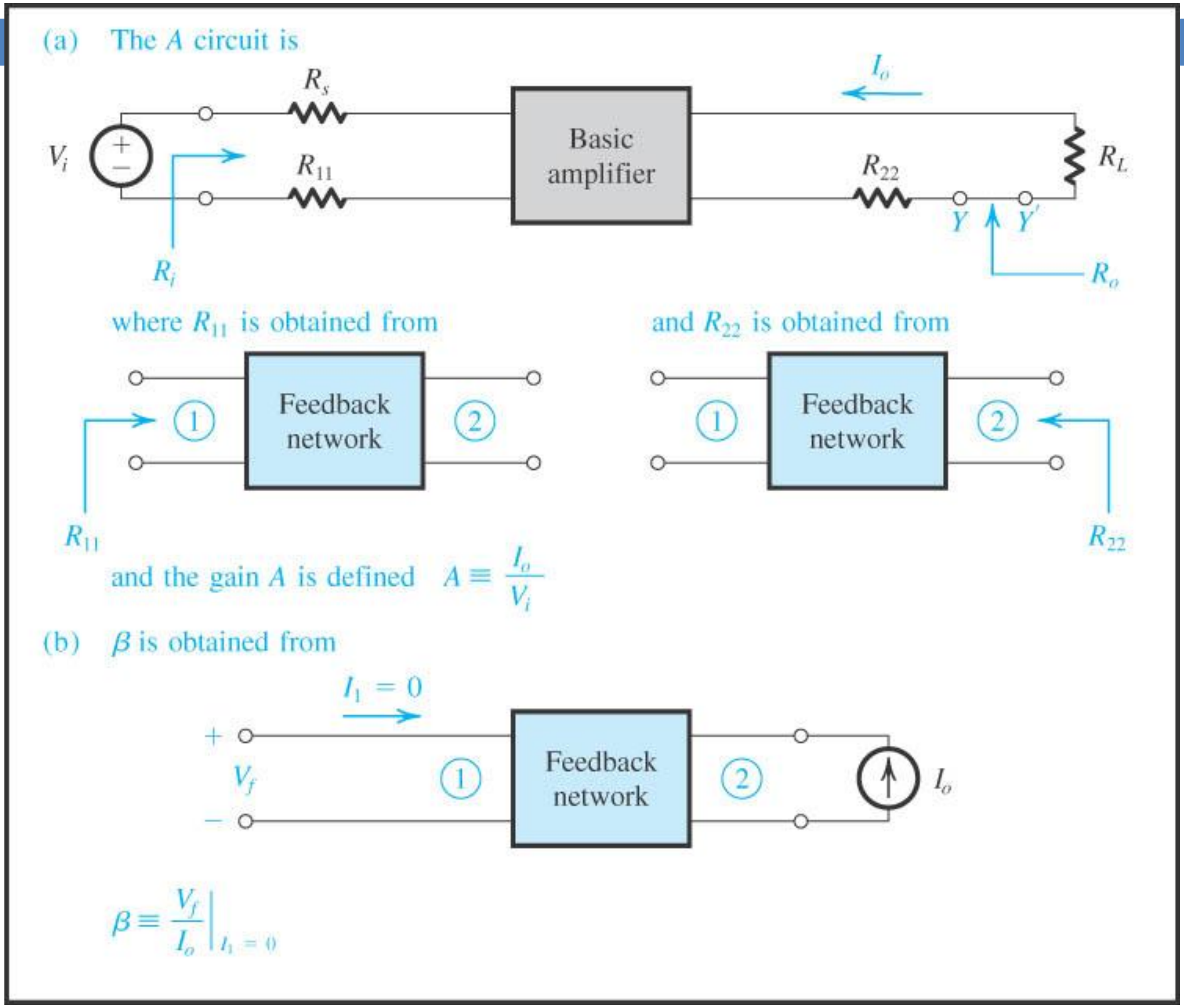



**Figure 8.16** Finding the $A$ circuit and $\beta$ for the voltage-mixing current-sampling (series–series) case.

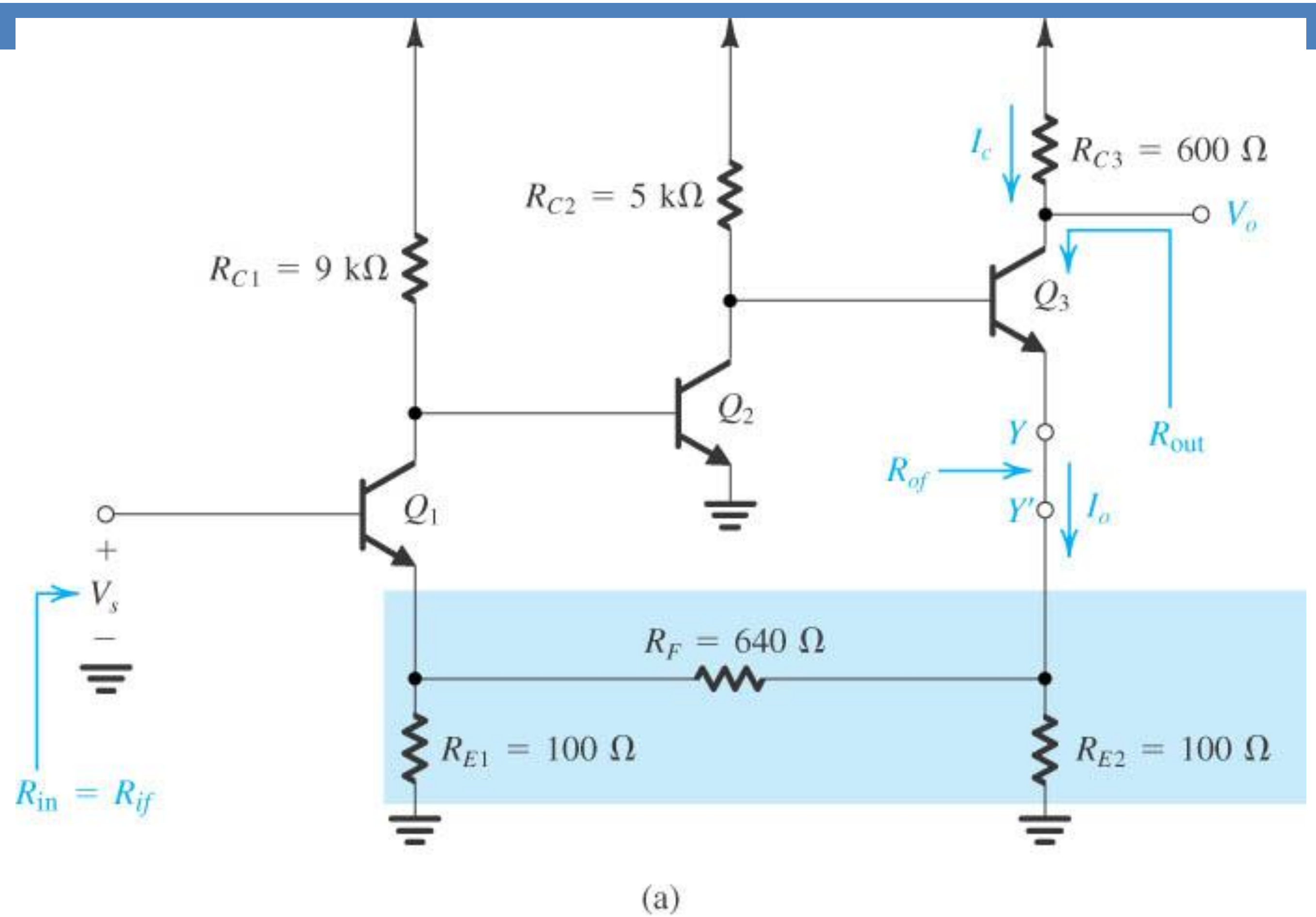



**Figure 8.17** Circuits for Example 8.2.

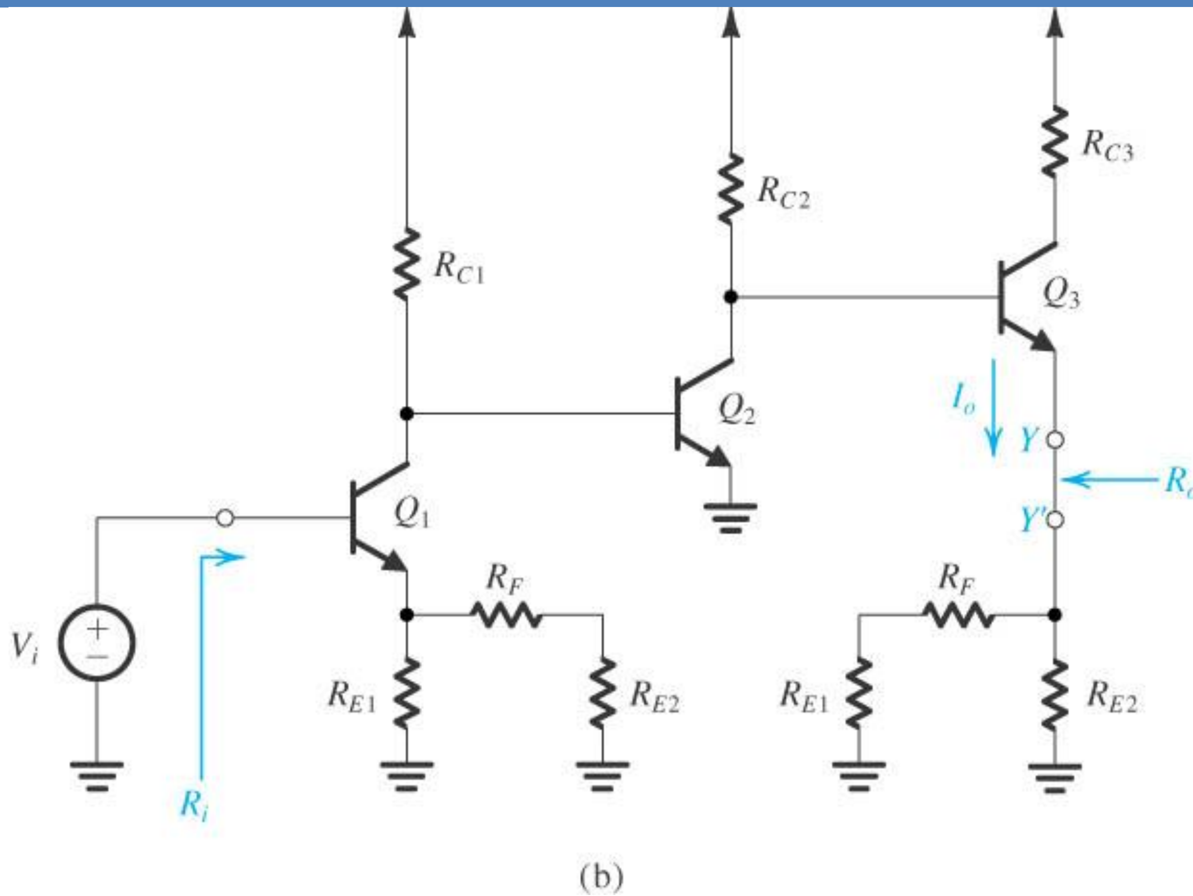



**Figure 8.17** *(Continued)*

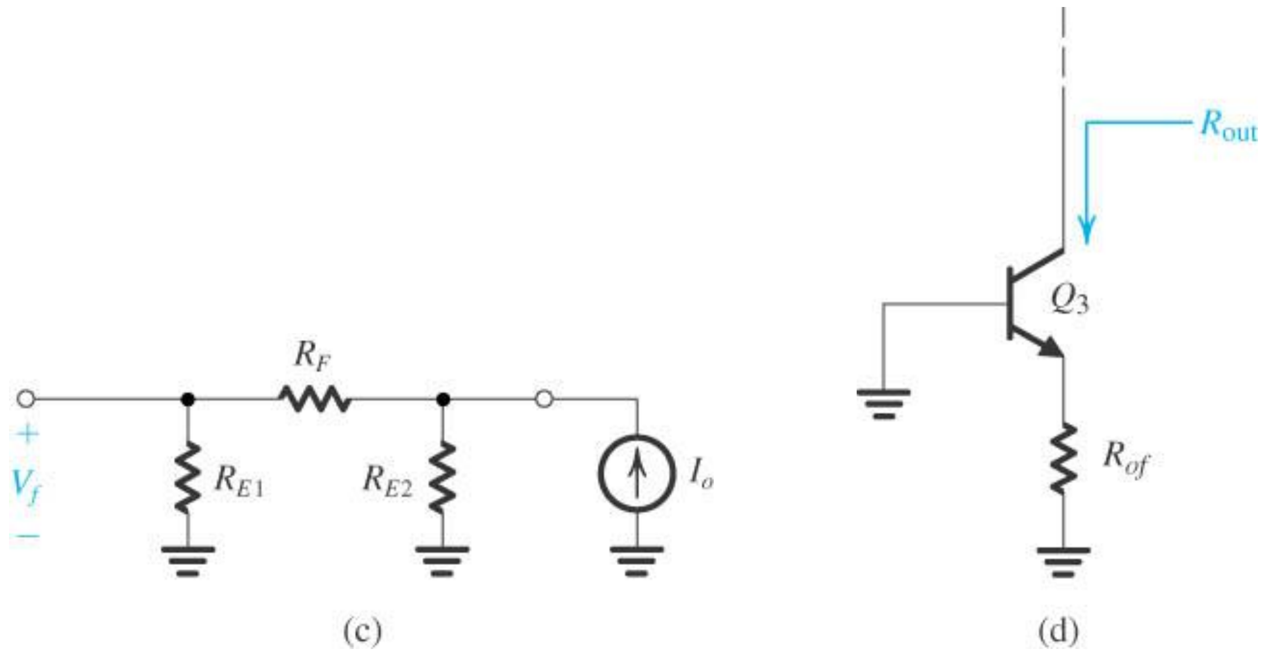



**Figure 8.17** *(Continued)*.

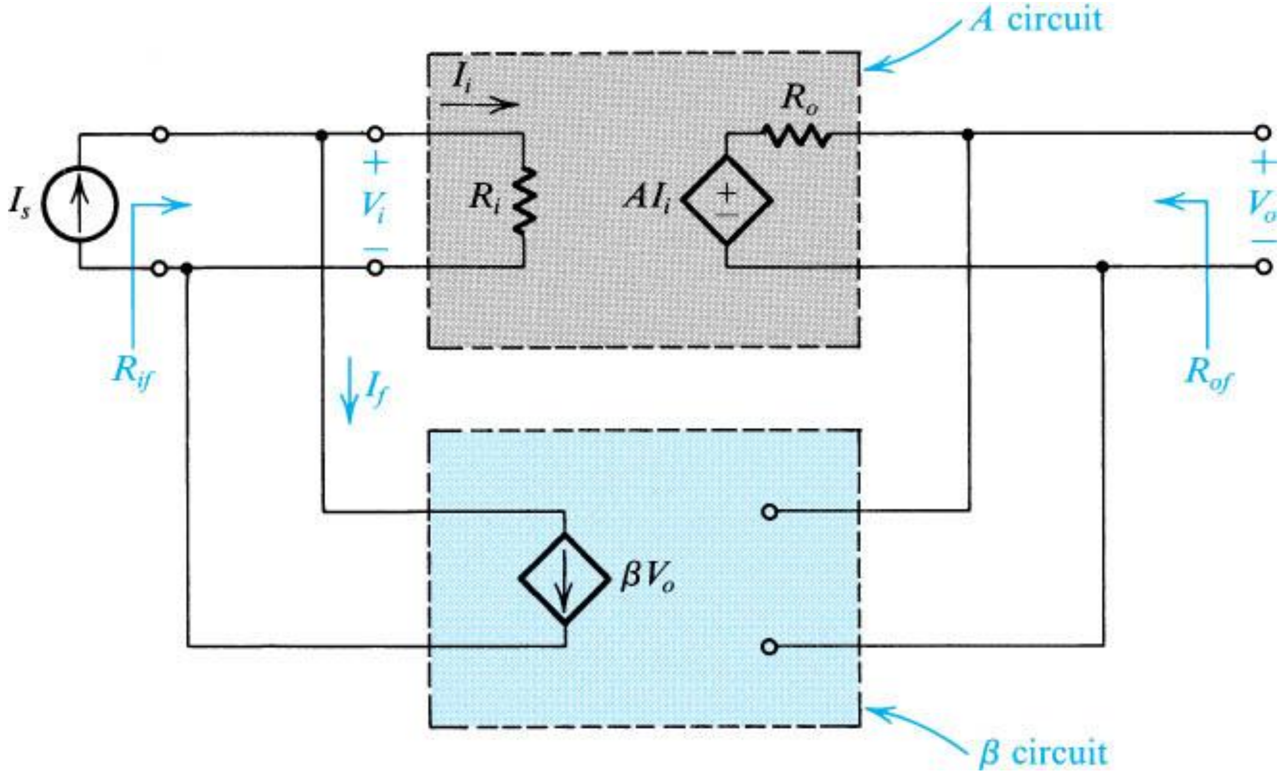



**Figure 8.18** Ideal structure for the shunt–shunt feedback amplifier.

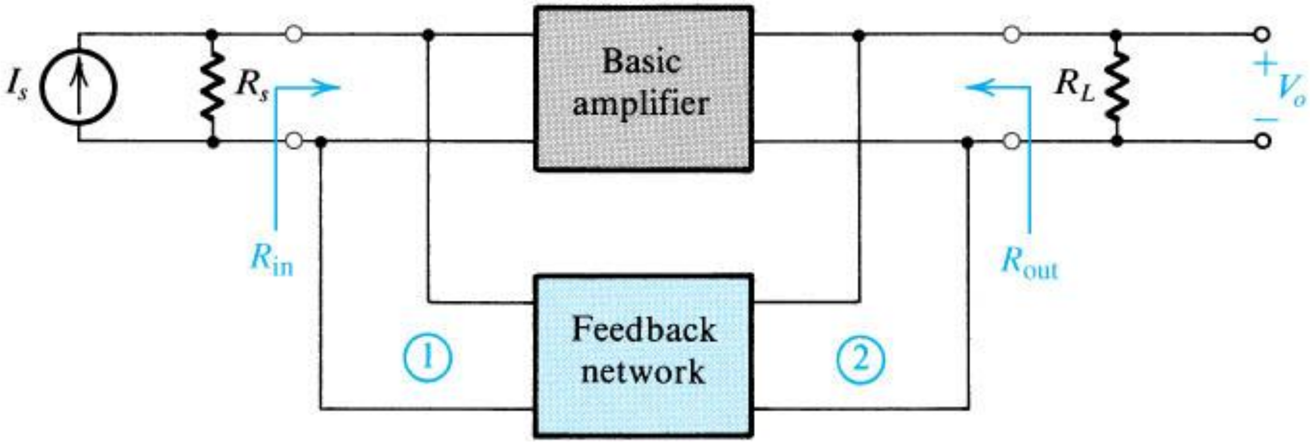



**Figure 8.19** Block diagram for a practical shunt–shunt feedback amplifier.

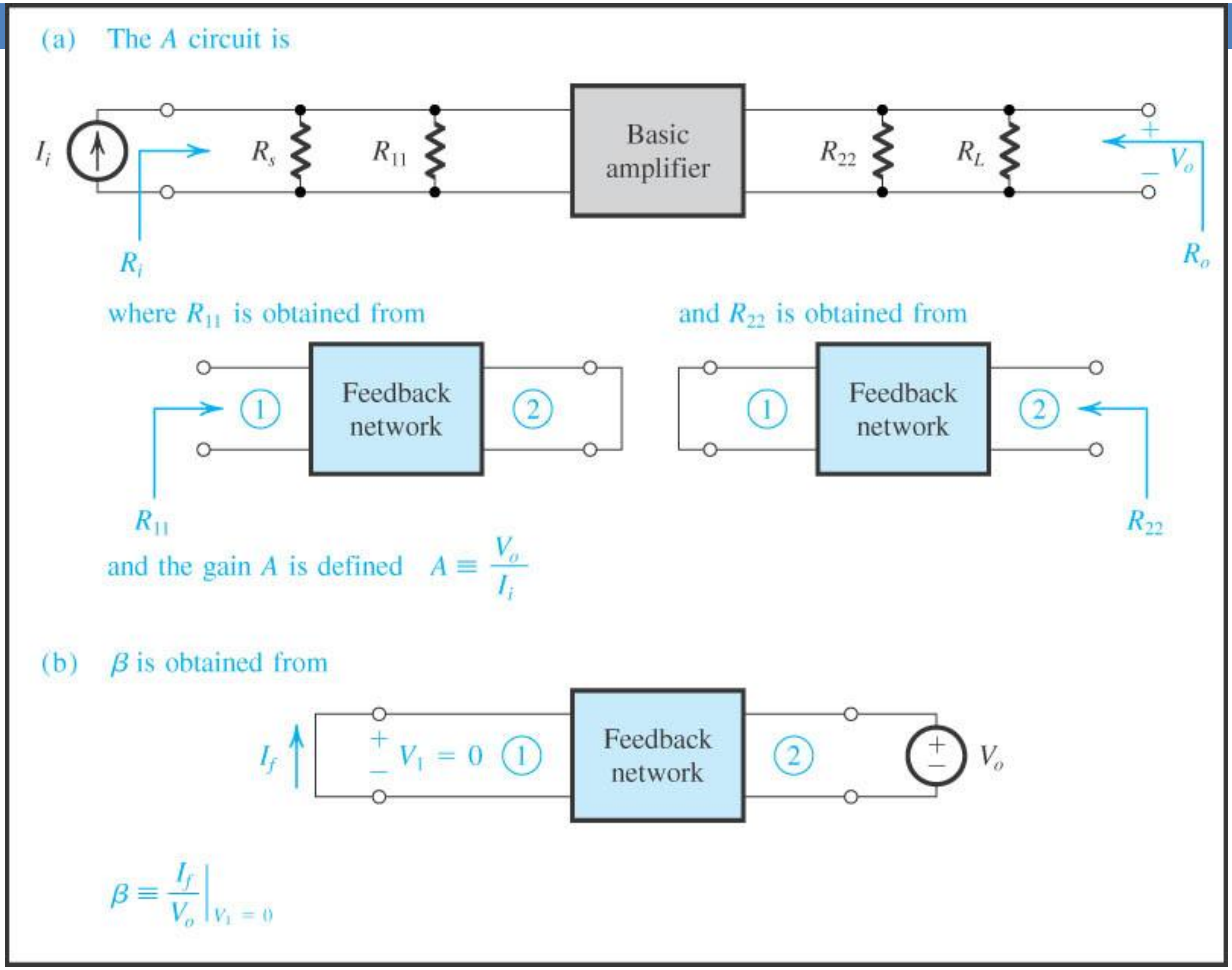



**Figure 8.20** Finding the *A* circuit and $\beta$ for the current-mixing voltage-sampling (shunt–shunt) feedback amplifier in Fig. 8.19.

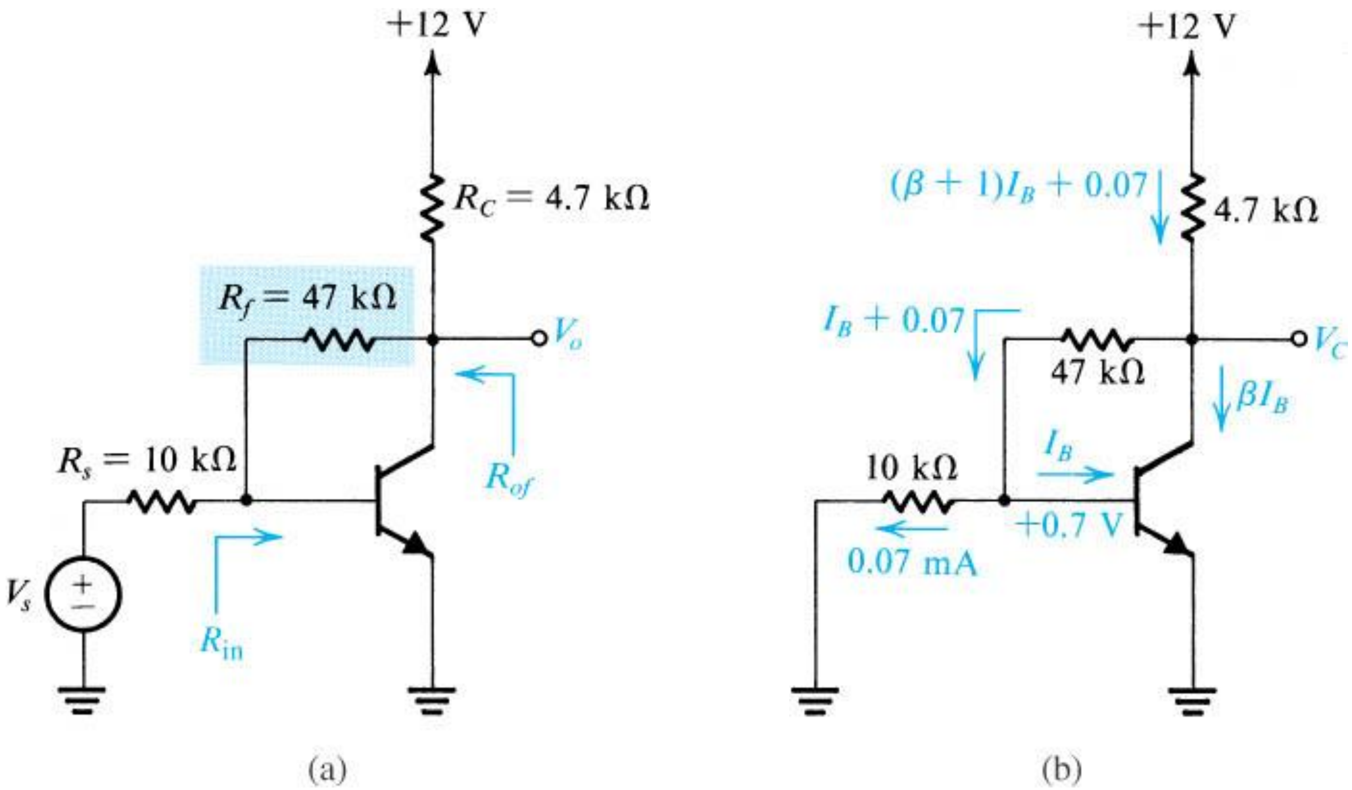



**Figure 8.21** Circuits for Example 8.3.

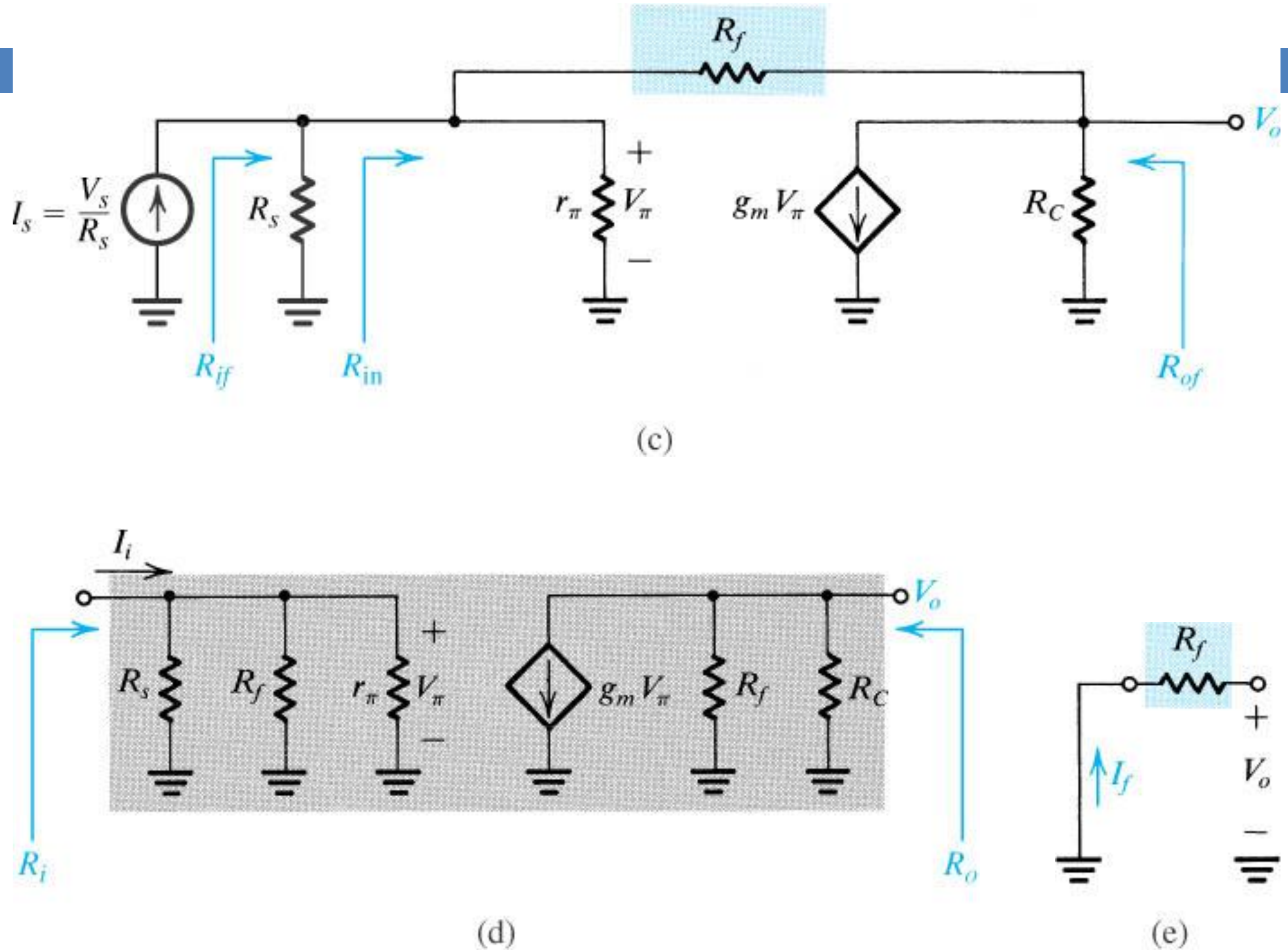



**Figure 8.21** *(Continued)*

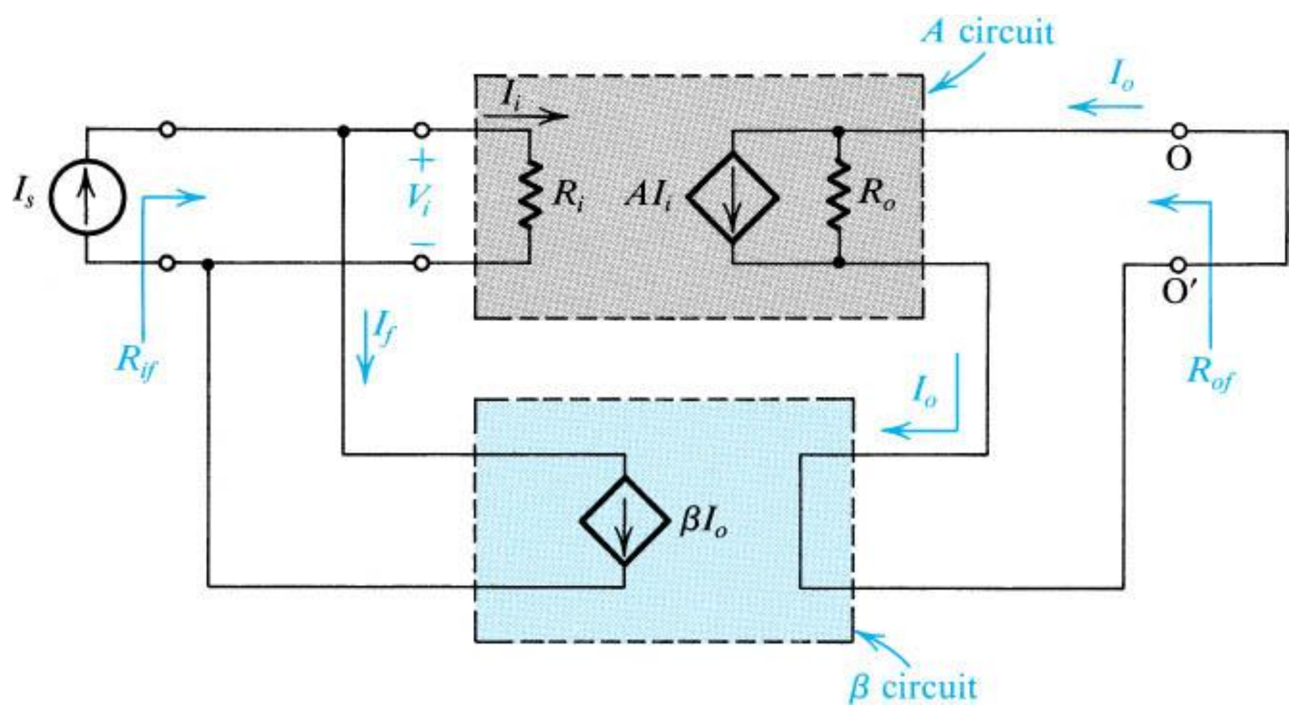



**Figure 8.22** Ideal structure for the shunt–series feedback amplifier.

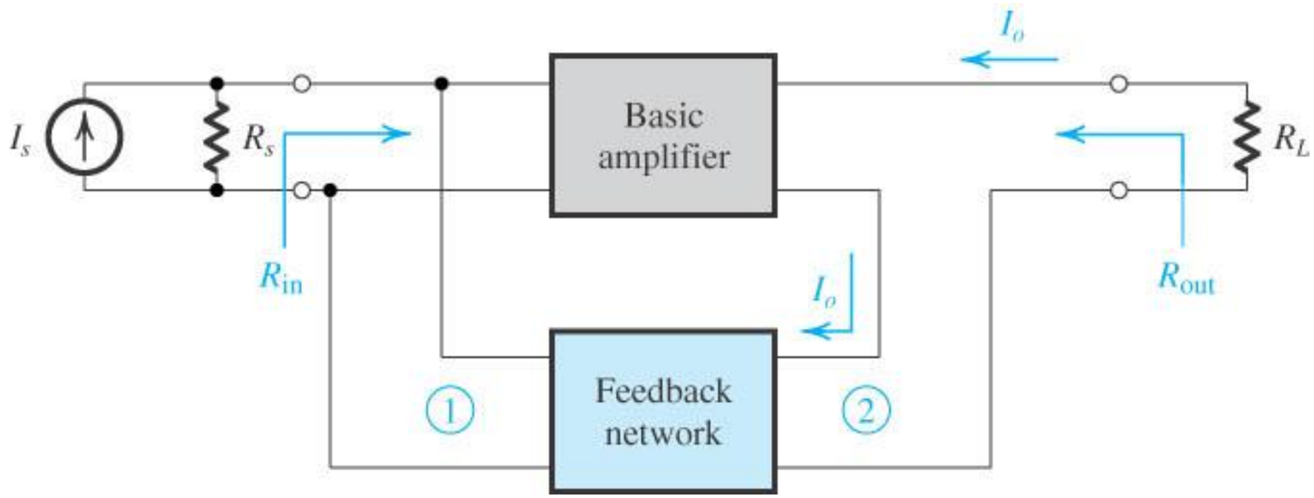



**Figure 8.23** Block diagram for a practical shunt–series feedback amplifier.

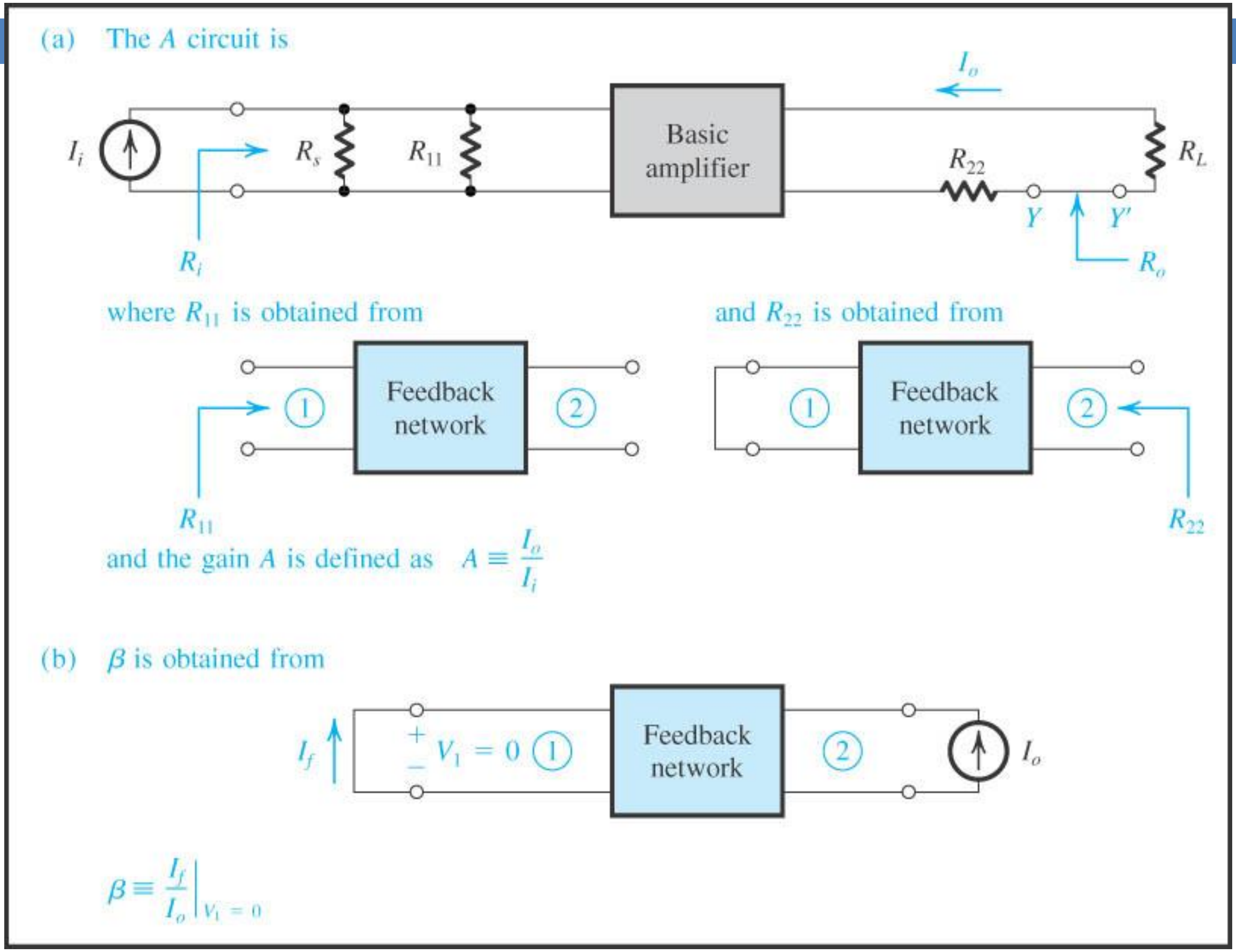



**Figure 8.24** Finding the *A* circuit and *β* for the current-mixing current-sampling (shunt–series) feedback amplifier of Fig. 8.23.

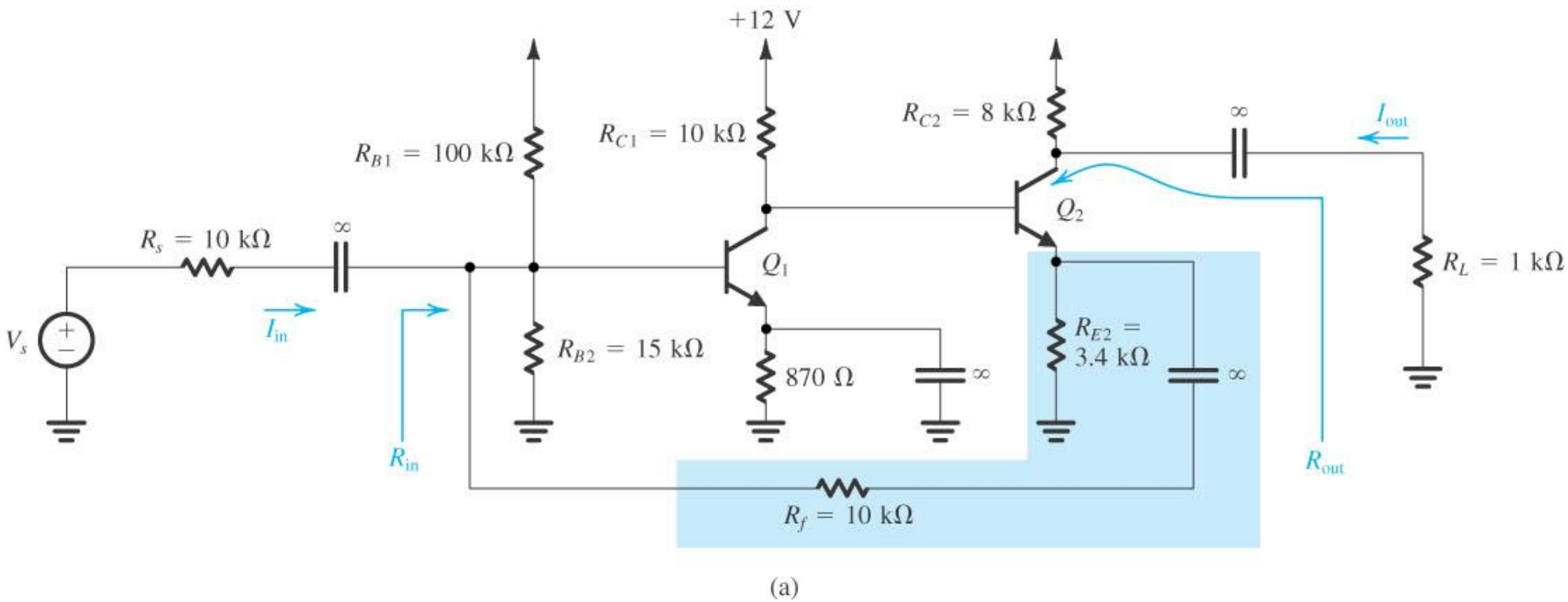



**Figure 8.25** Circuits for Example 8.4.

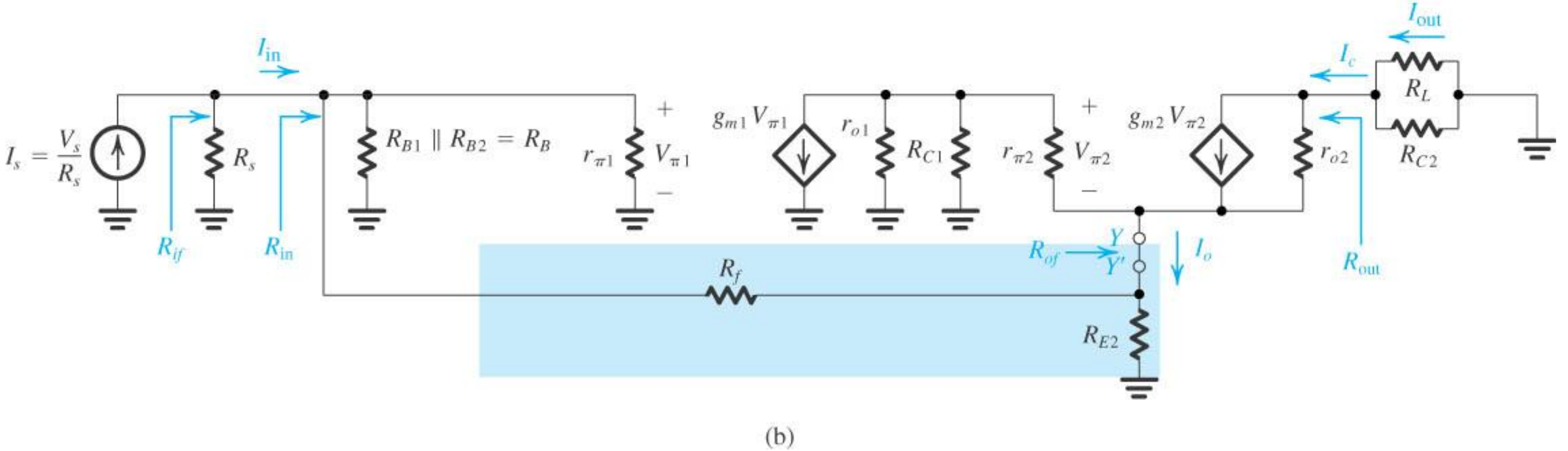
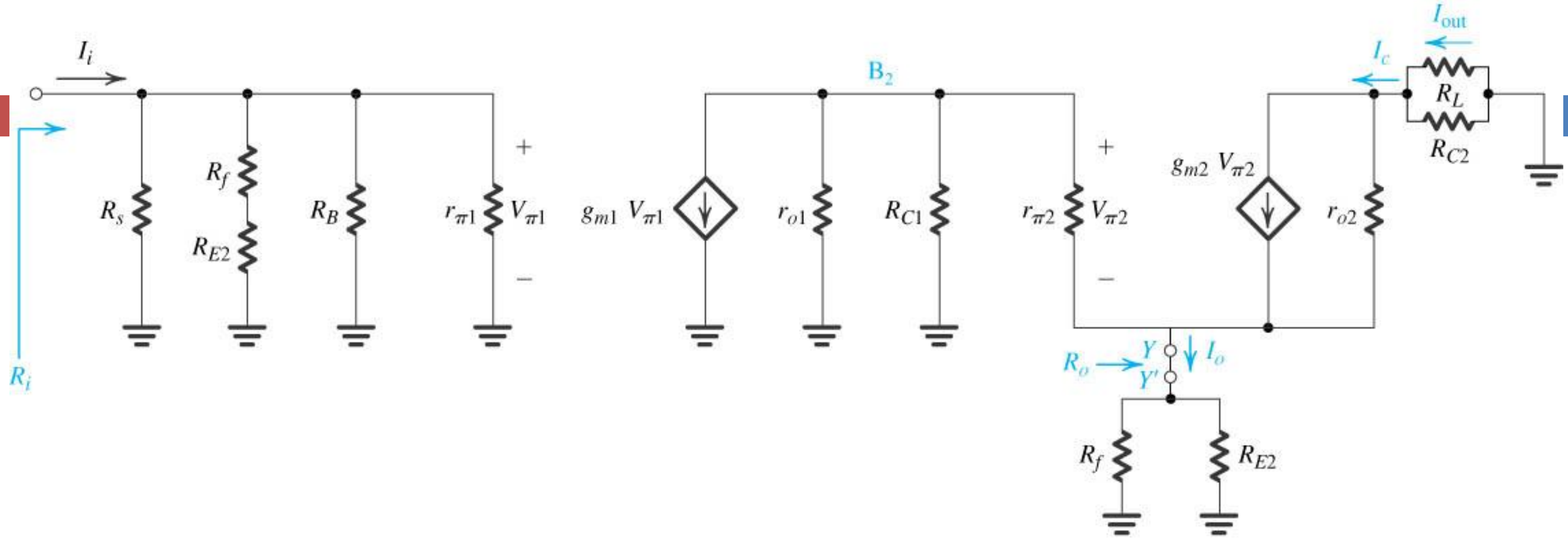
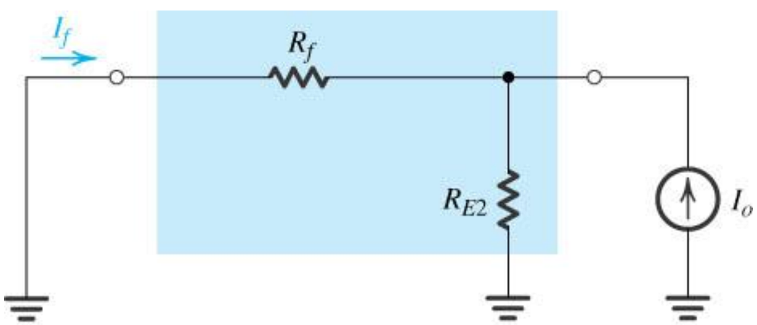


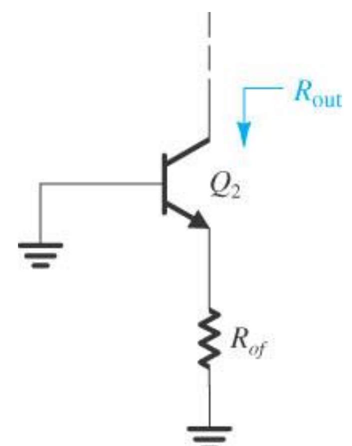

**Figure 8.25** *(Continued)*




(c)




(d)




(e)

**Figure 8.25** *(Continued)*

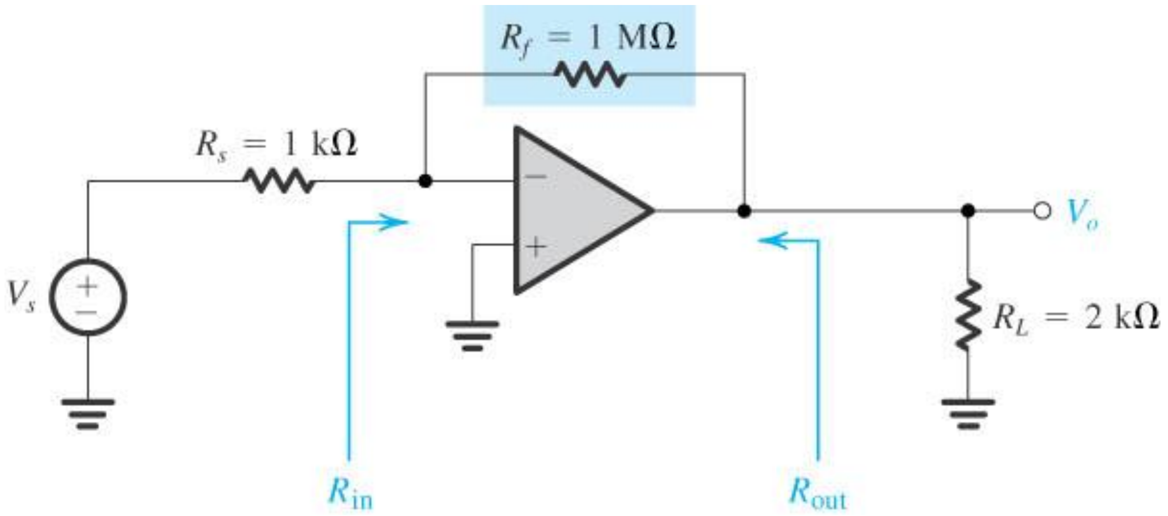



**Figure E8.7**

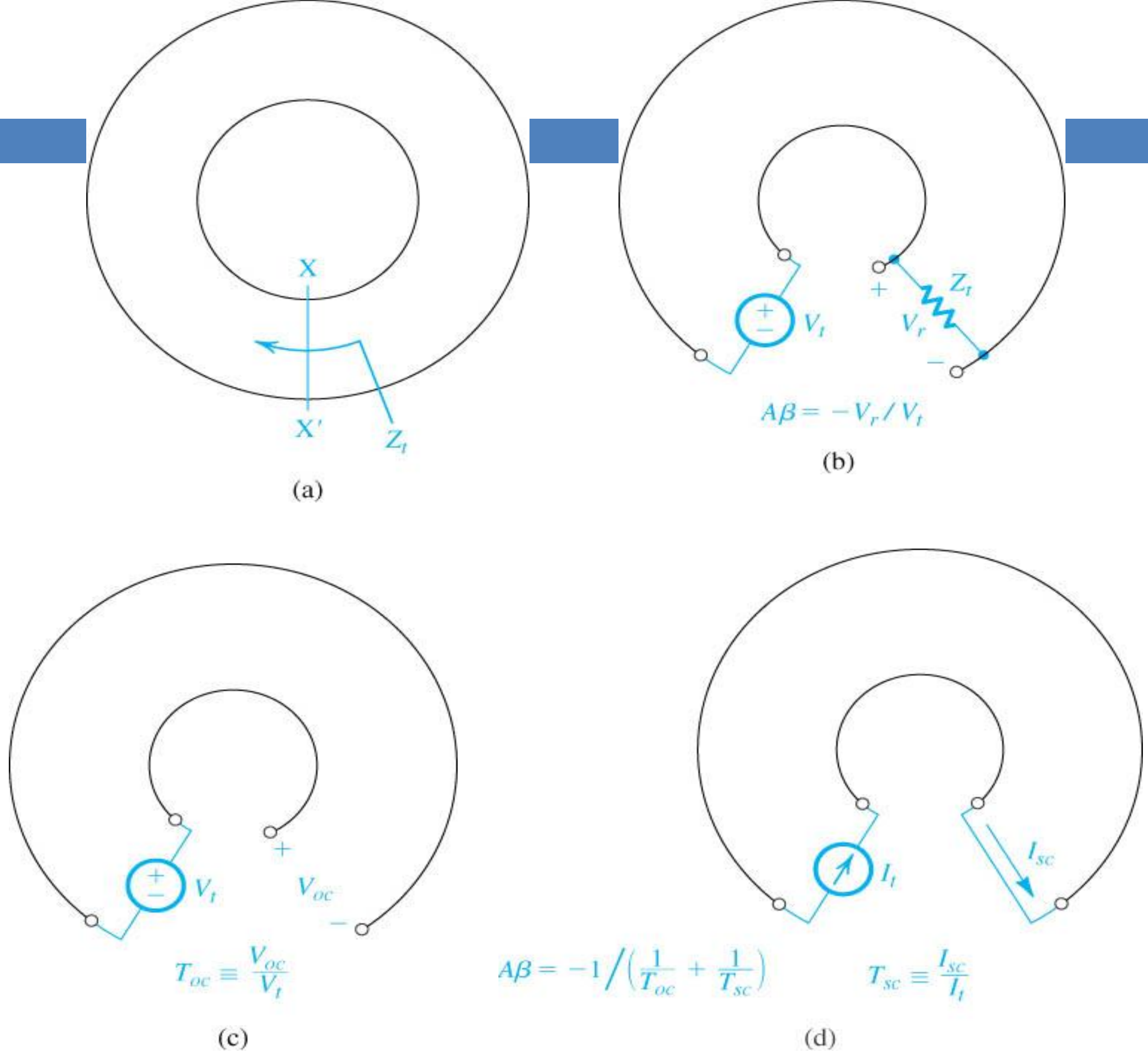



**Figure 8.26** A conceptual feedback loop is broken at XX′ and a test voltage $V_t$ is applied. The impedance $Z_t$ is equal to that previously seen looking to the left of XX′. The loop gain $A\beta = -V_r/V_t$, where $V_r$ is the *returned* voltage. As an alternative, $A\beta$ can be determined by finding the open-circuit transfer function $T_{oc}$, as in (c), and the short-circuit transfer function $T_{sc}$, as in (d), and combining them as indicated.

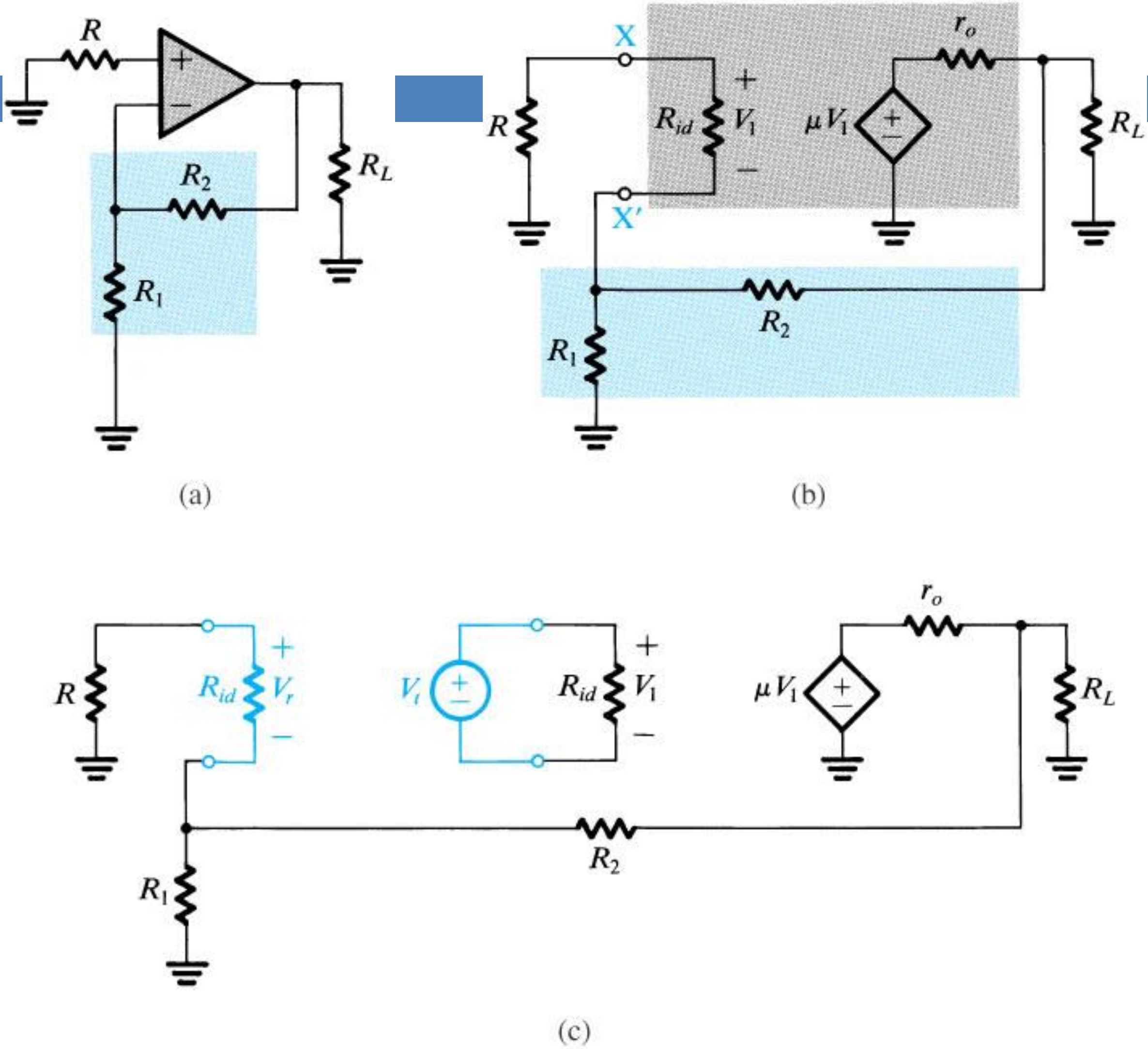



**Figure 8.27** The loop gain of the feedback loop in (a) is determined in (b) and (c).

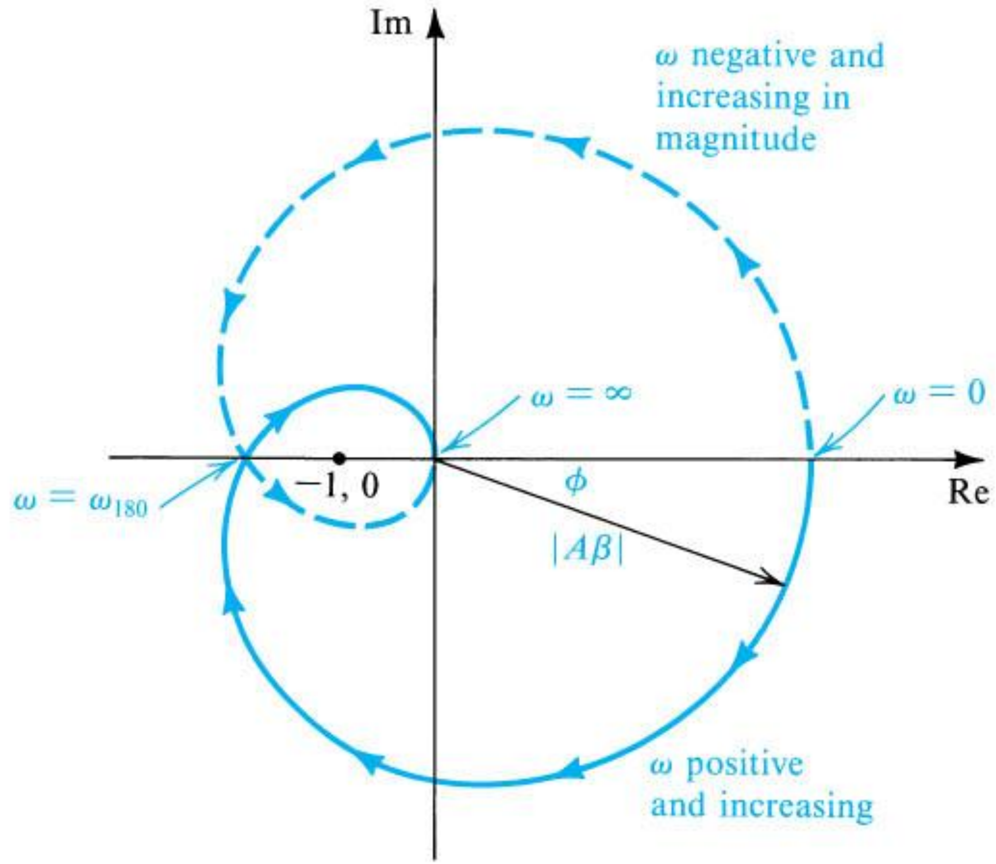



**Figure 8.28** The Nyquist plot of an unstable amplifier.

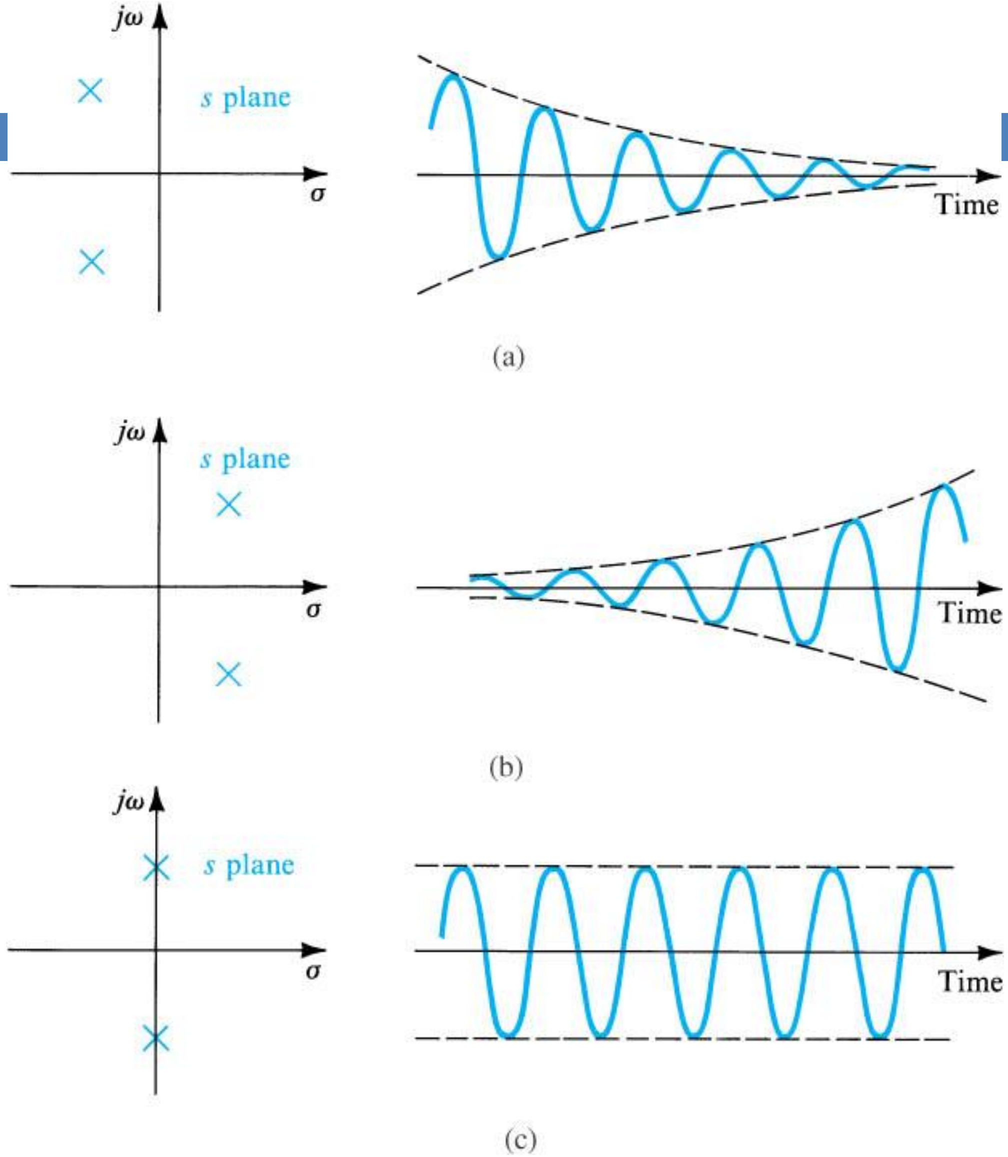



**Figure 8.29** Relationship between pole location and transient response.

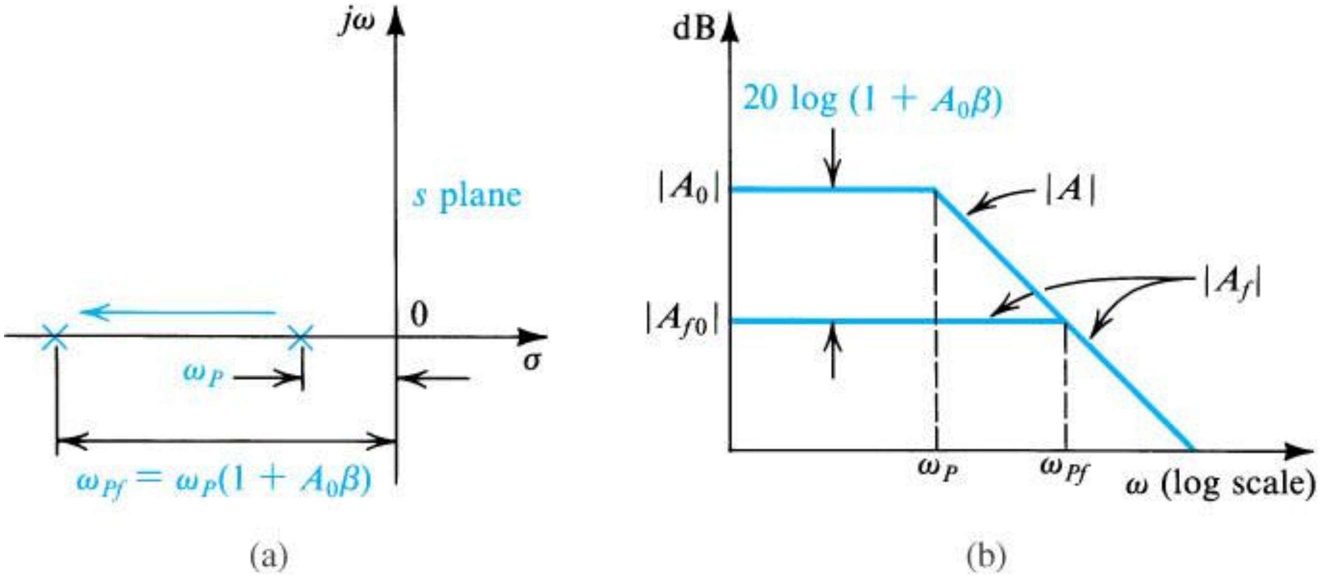



**Figure 8.30** Effect of feedback on **(a)** the pole location and **(b)** the frequency response of an amplifier having a single-pole open-loop response.

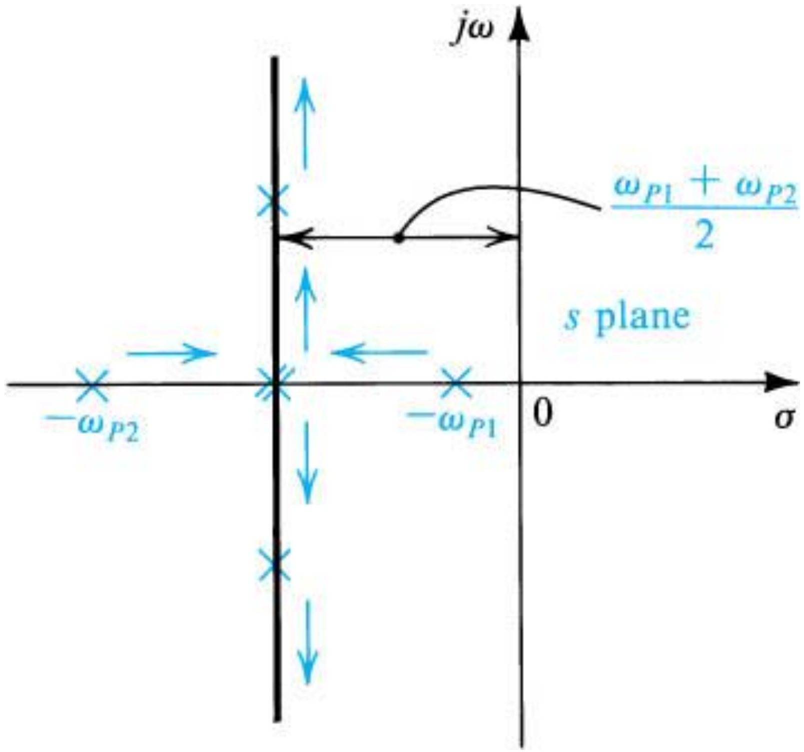



**Figure 8.31** Root-locus diagram for a feedback amplifier whose open-loop transfer function has two real poles.

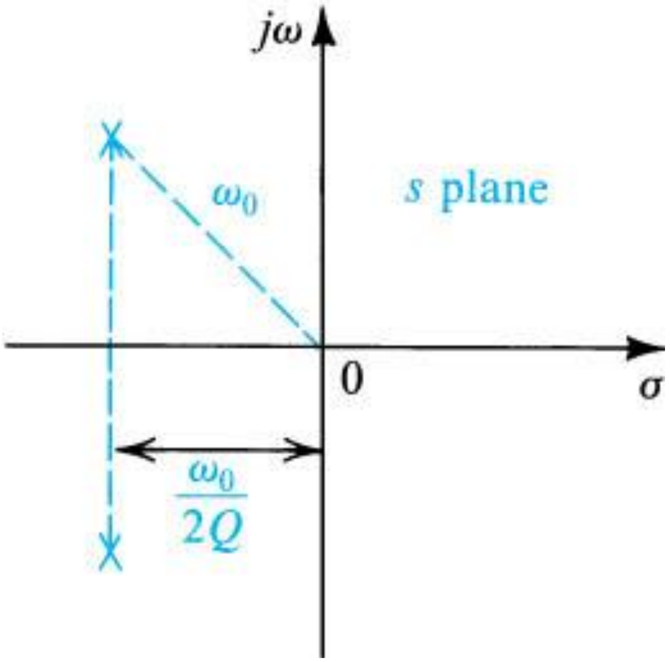



**Figure 8.32** Definition of $\omega_0$ and $Q$ of a pair of complex-conjugate poles.

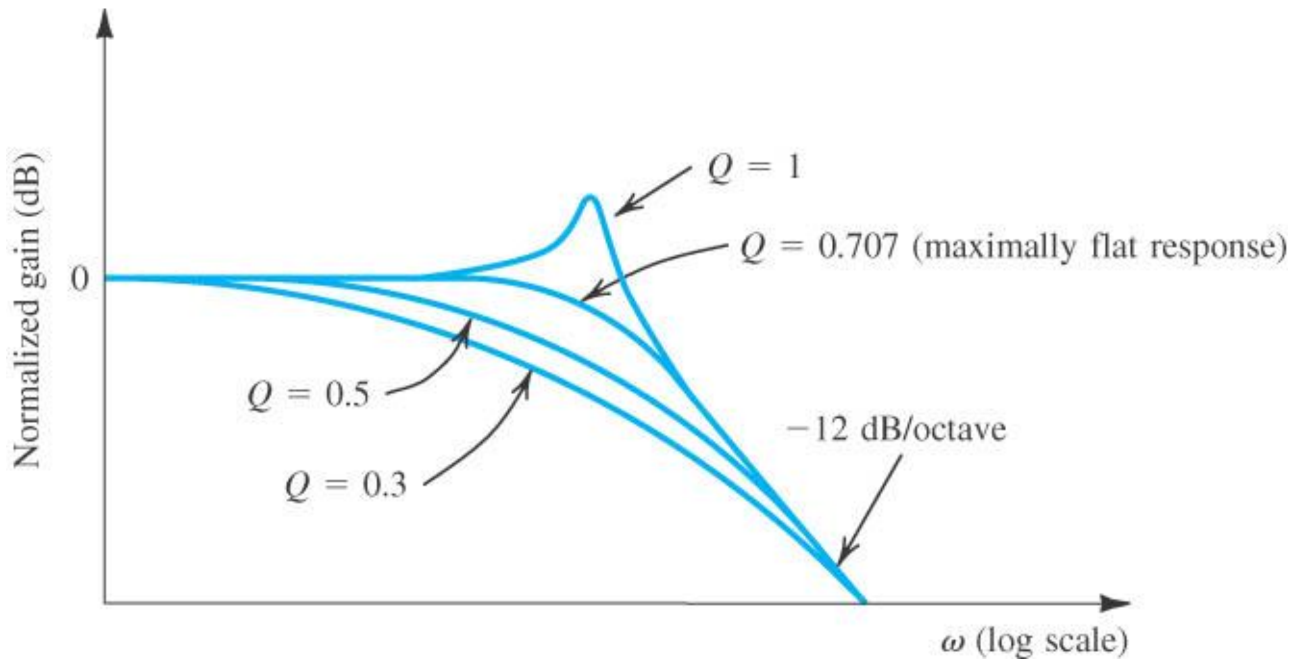



**Figure 8.33** Normalized gain of a two-pole feedback amplifier for various values of $Q$. Note that $Q$ is determined by the loop gain according to Eq. (8.65).

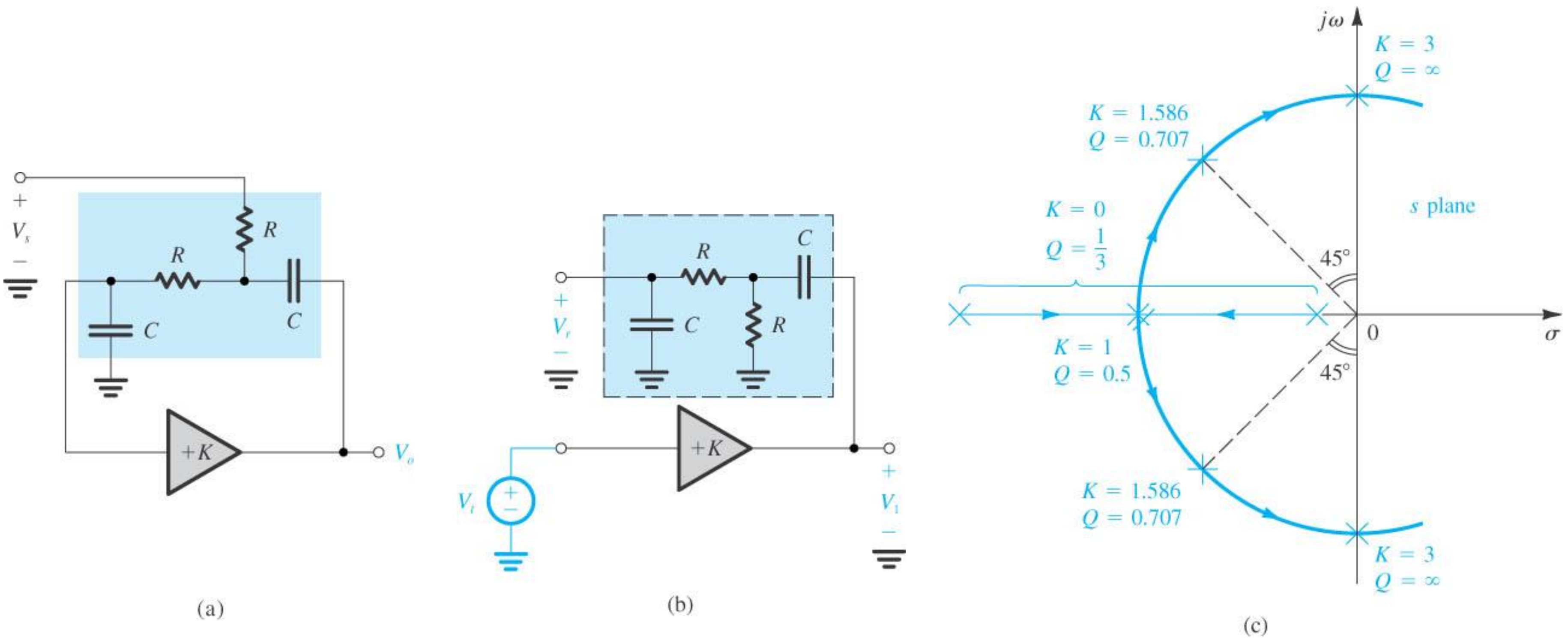



**Figure 8.34** Circuits and plot for Example 8.5.

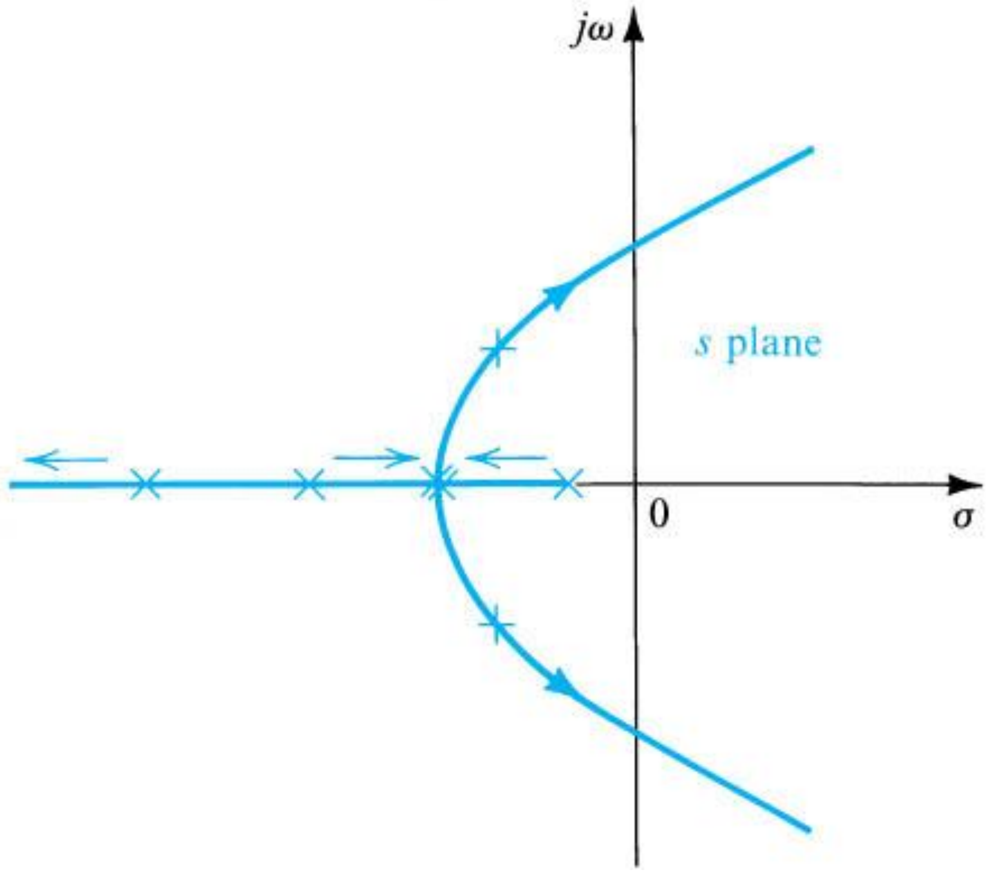



**Figure 8.35** Root-locus diagram for an amplifier with three poles. The arrows indicate the pole movement as $A_0\beta$ is increased.

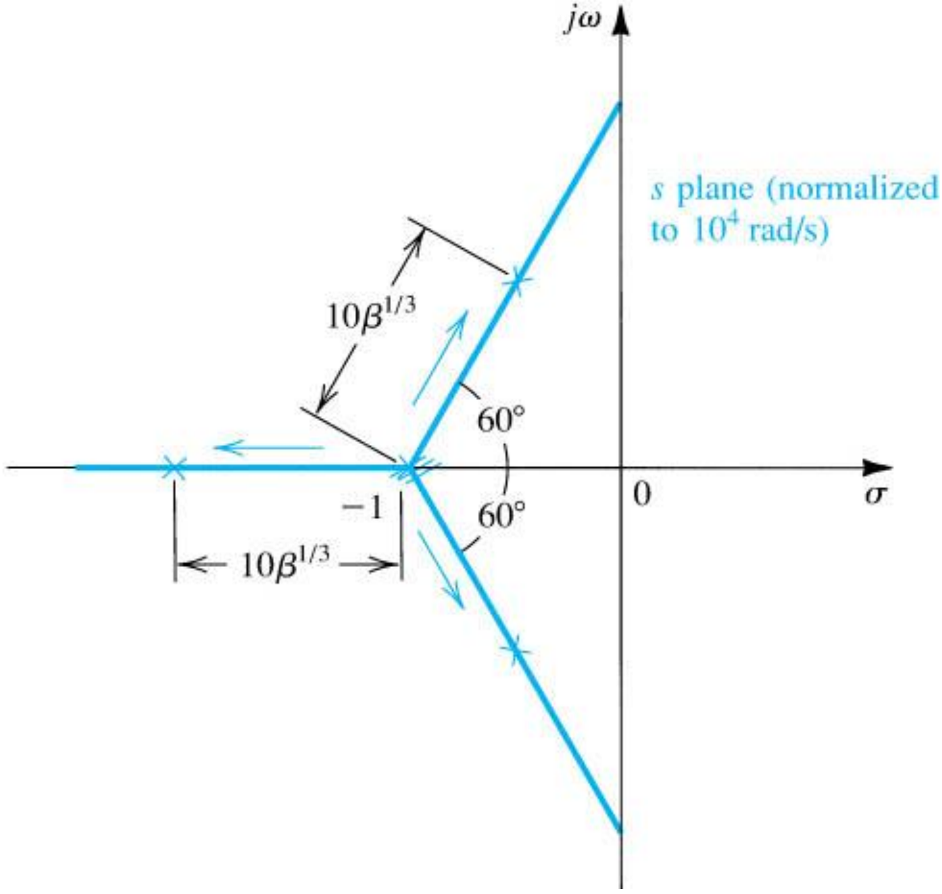



**Figure E8.13**

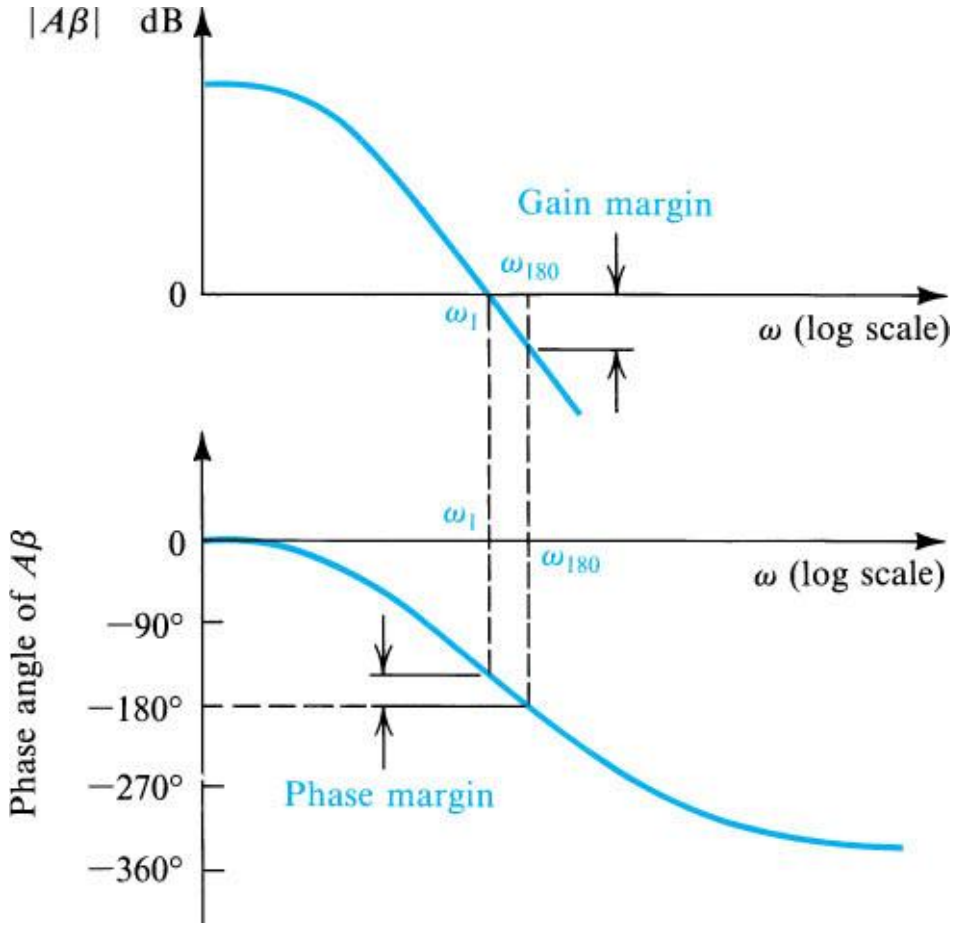



**Figure 8.36** Bode plot for the loop gain $A\beta$ illustrating the definitions of the gain and phase margins.

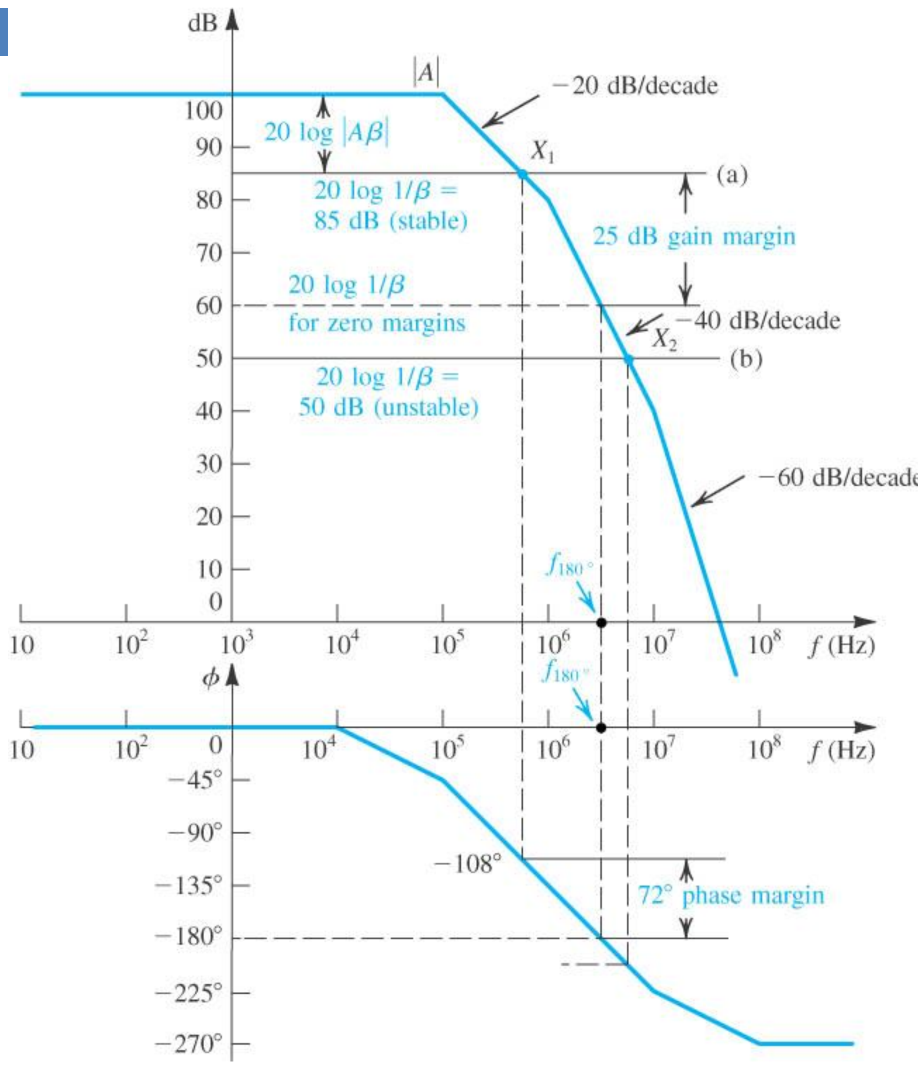



**Figure 8.37** Stability analysis using Bode plot of $|A|$.

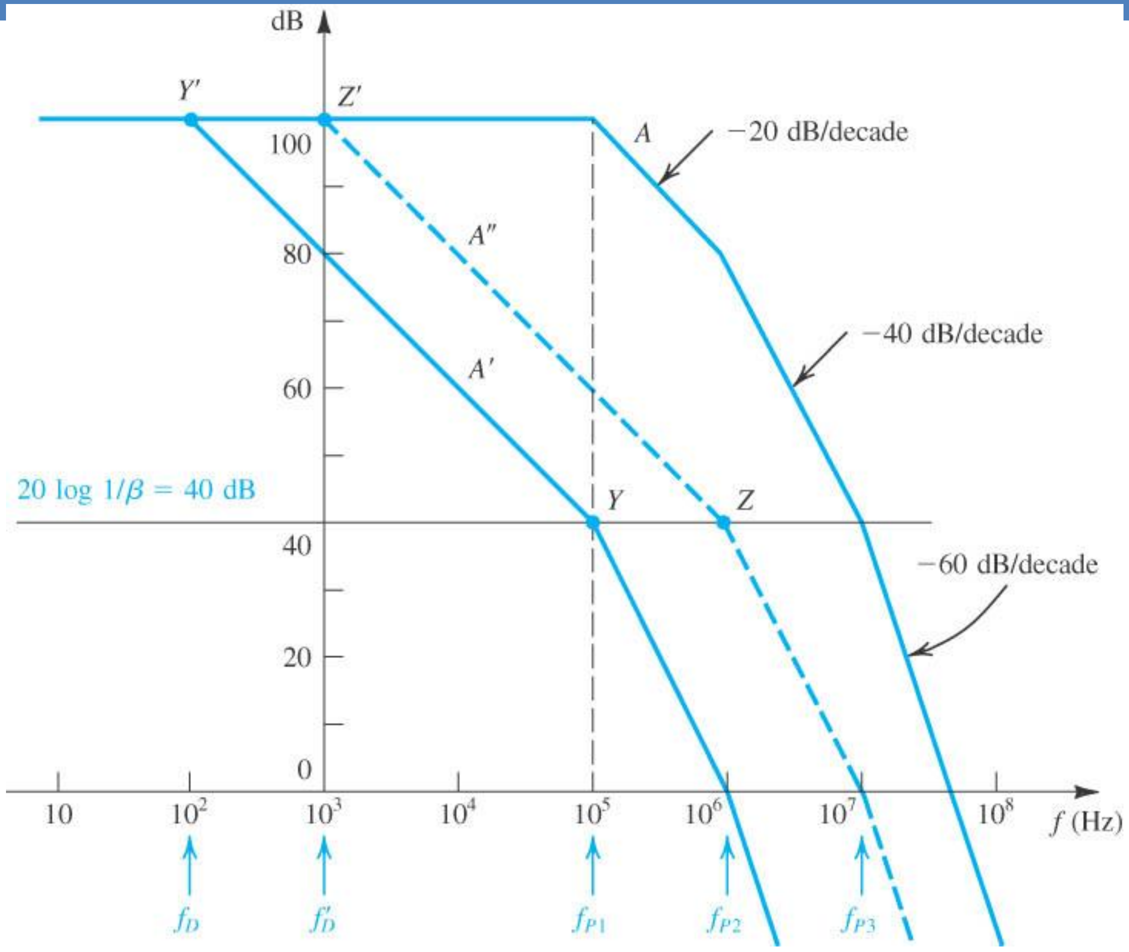



**Figure 8.38** Frequency compensation for $\beta = 10^{-2}$. The response labeled $A'$ is obtained by introducing an additional pole at $f_D$. The $A''$ response is obtained by moving the original low-frequency pole to $f'_D$.

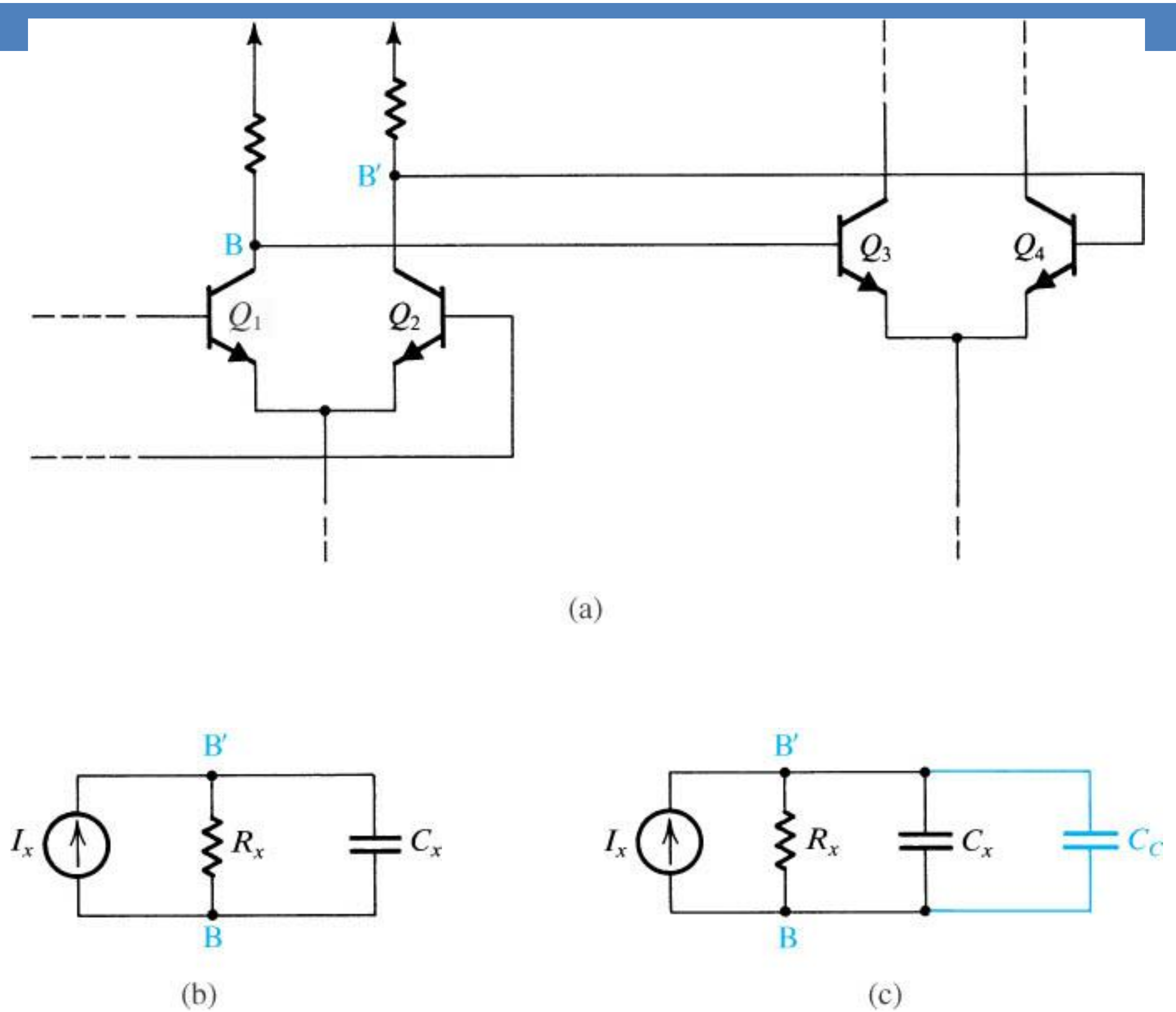



**Figure 8.39** **(a)** Two cascaded gain stages of a multistage amplifier. **(b)** Equivalent circuit for the interface between the two stages in (a). **(c)** Same circuit as in (b) but with a compensating capacitor $C_C$ added. Note that the analysis here applies equally well to MOS amplifiers.

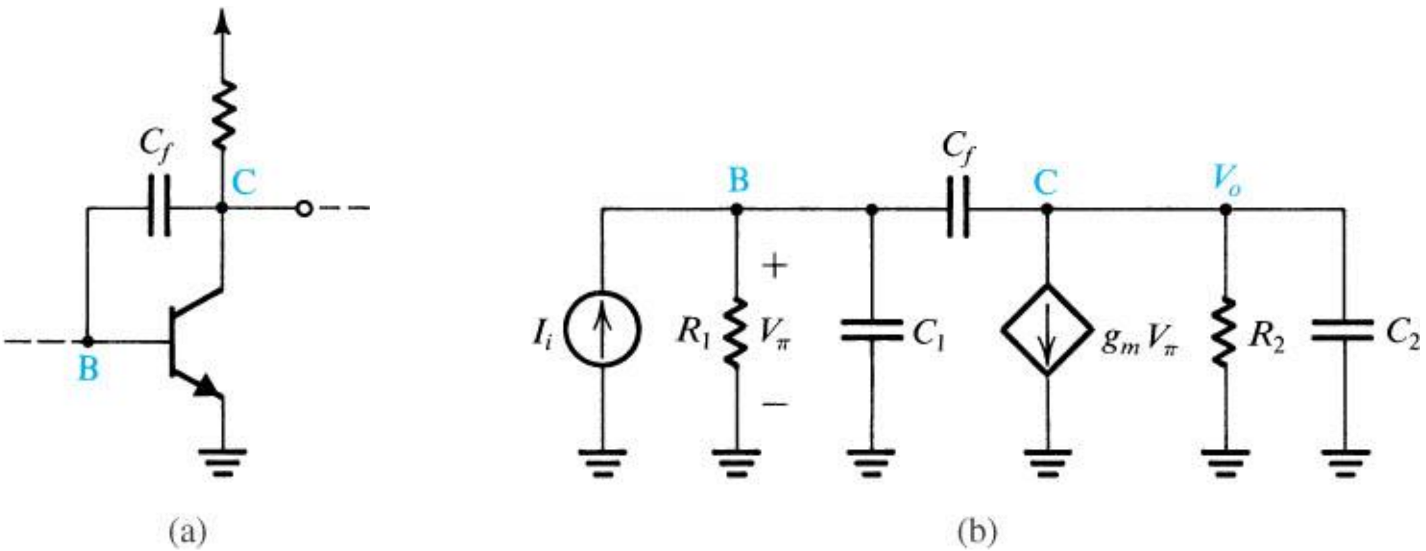



**Figure 8.40 (a)** A gain stage in a multistage amplifier with a compensating capacitor connected in the feedback path and **(b)** an equivalent circuit. Note that although a BJT is shown, the analysis applies equally well to the MOSFET case.

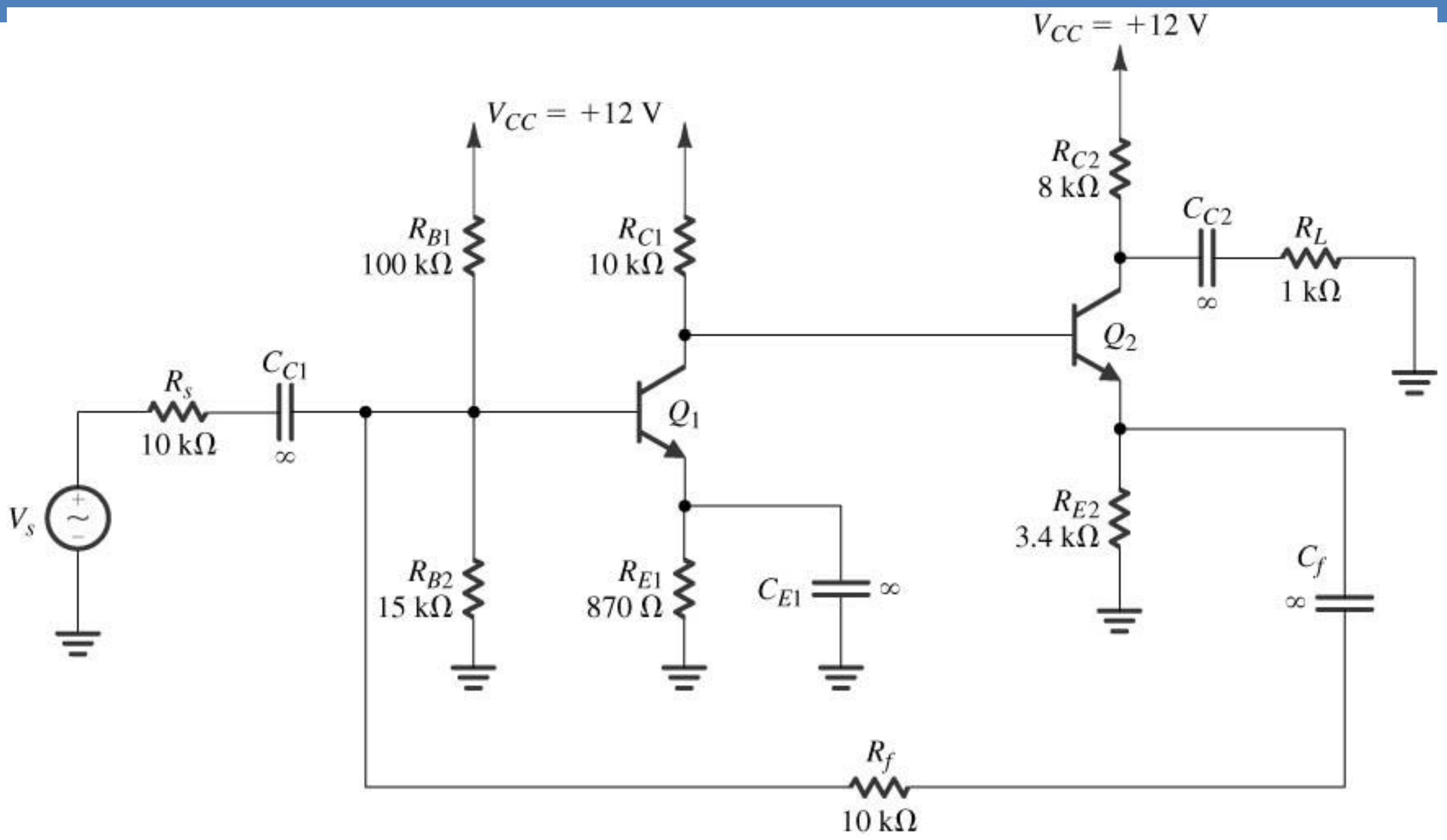



**Figure 8.41** Circuit of the shunt–series feedback amplifier in Example 8.4.

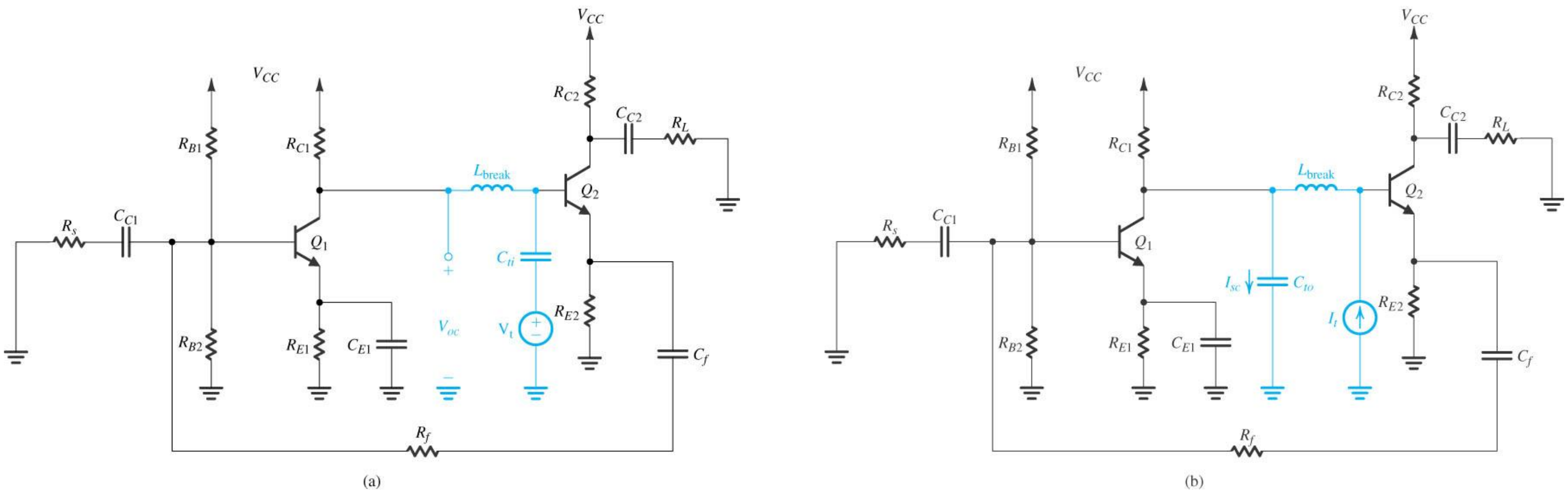



**Figure 8.42** Circuits for simulating **(a)** the open-circuit voltage transfer function $T_{oc}$ and **(b)** the short-circuit current transfer function $T_{sc}$ of the feedback amplifier in Fig. 8.41 for the purpose of computing its loop gain.

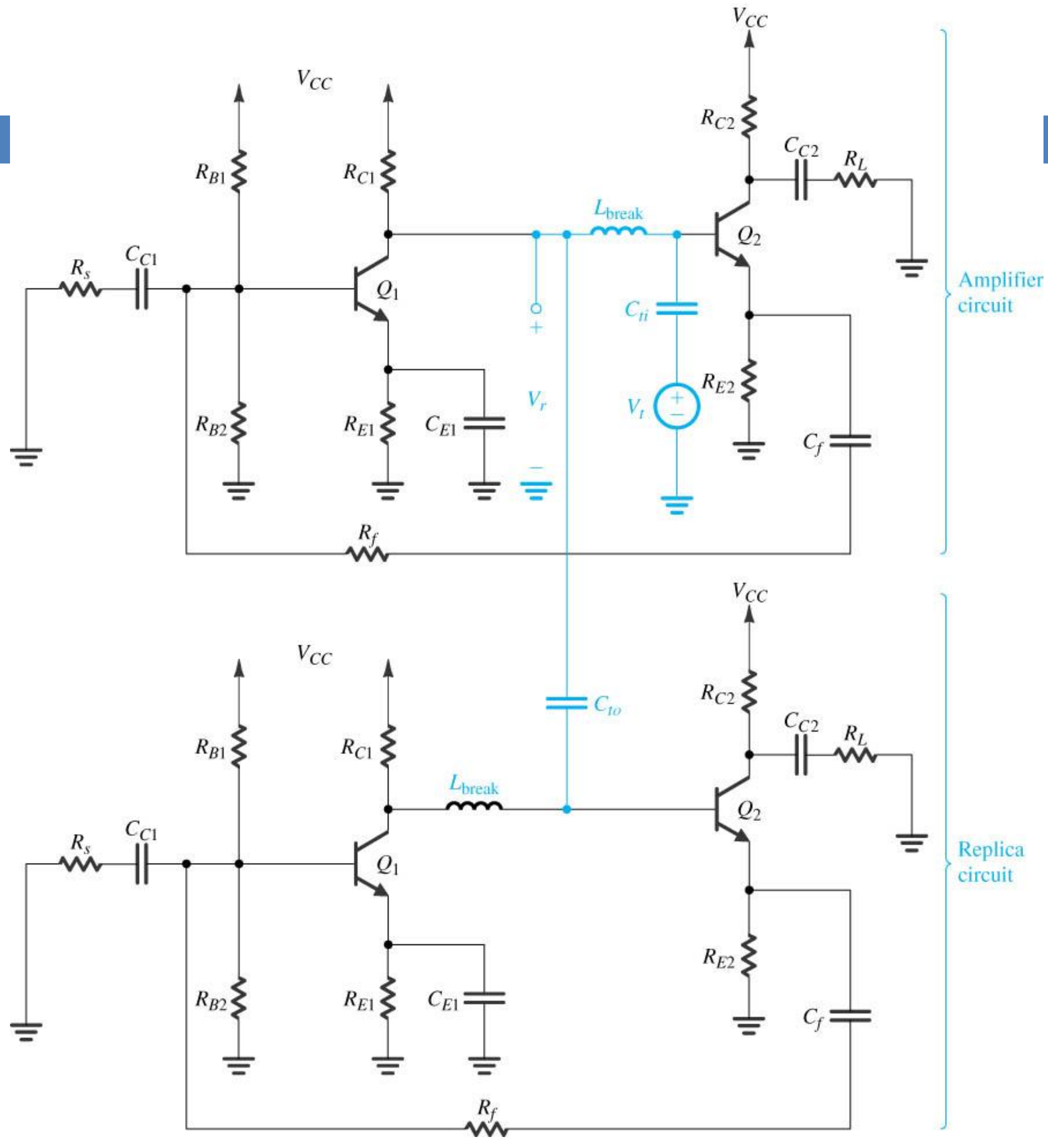



**Figure 8.43** Circuit for simulating the loop gain of the feedback amplifier circuit in Fig. 8.41 using the replica-circuit method.

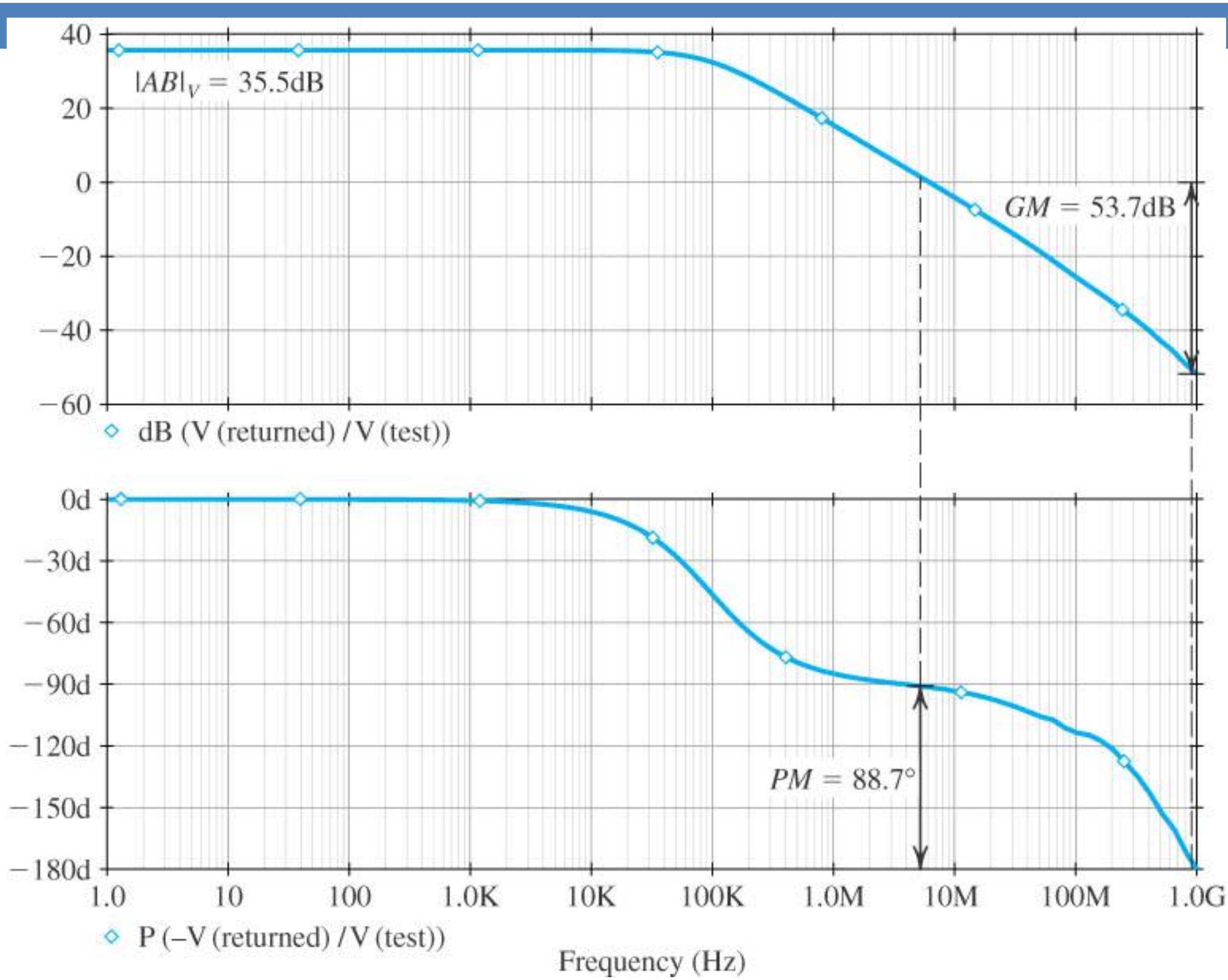



**Figure 8.44** **(a)** Magnitude and **(b)** phase of the loop gain $A\beta$ of the feedback amplifier circuit in Fig. 8.41.

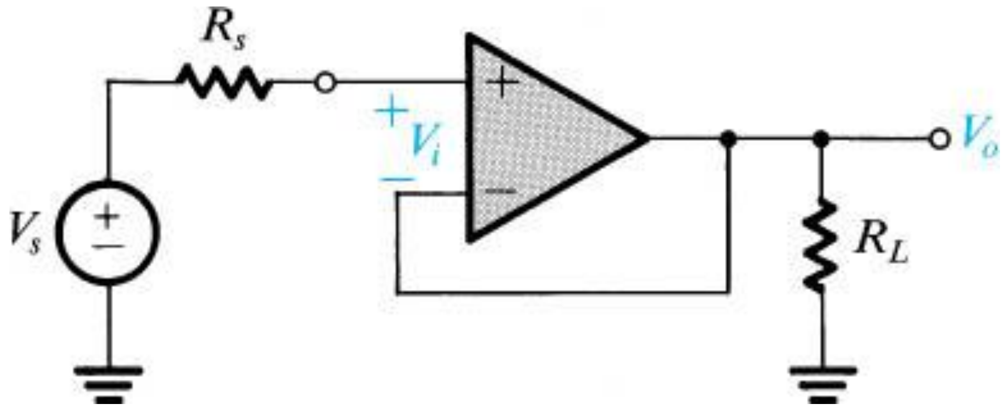



**Figure P8.4**

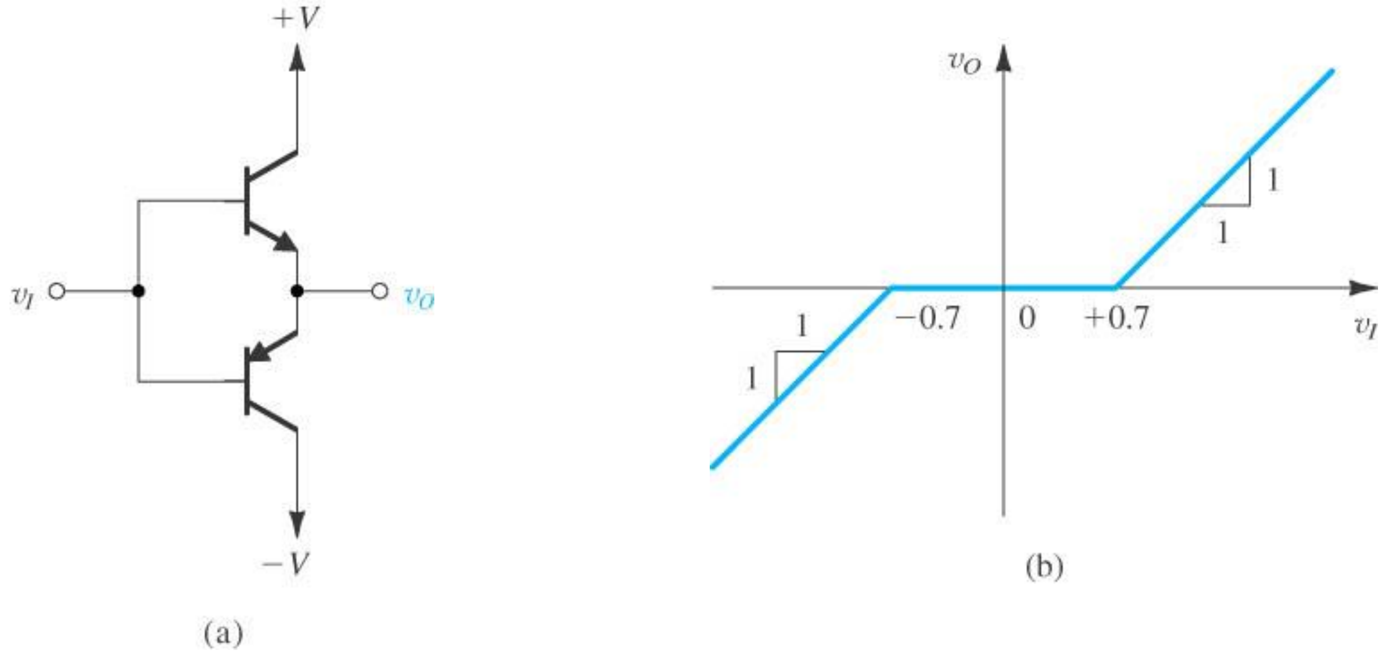



**Figure P8.19**

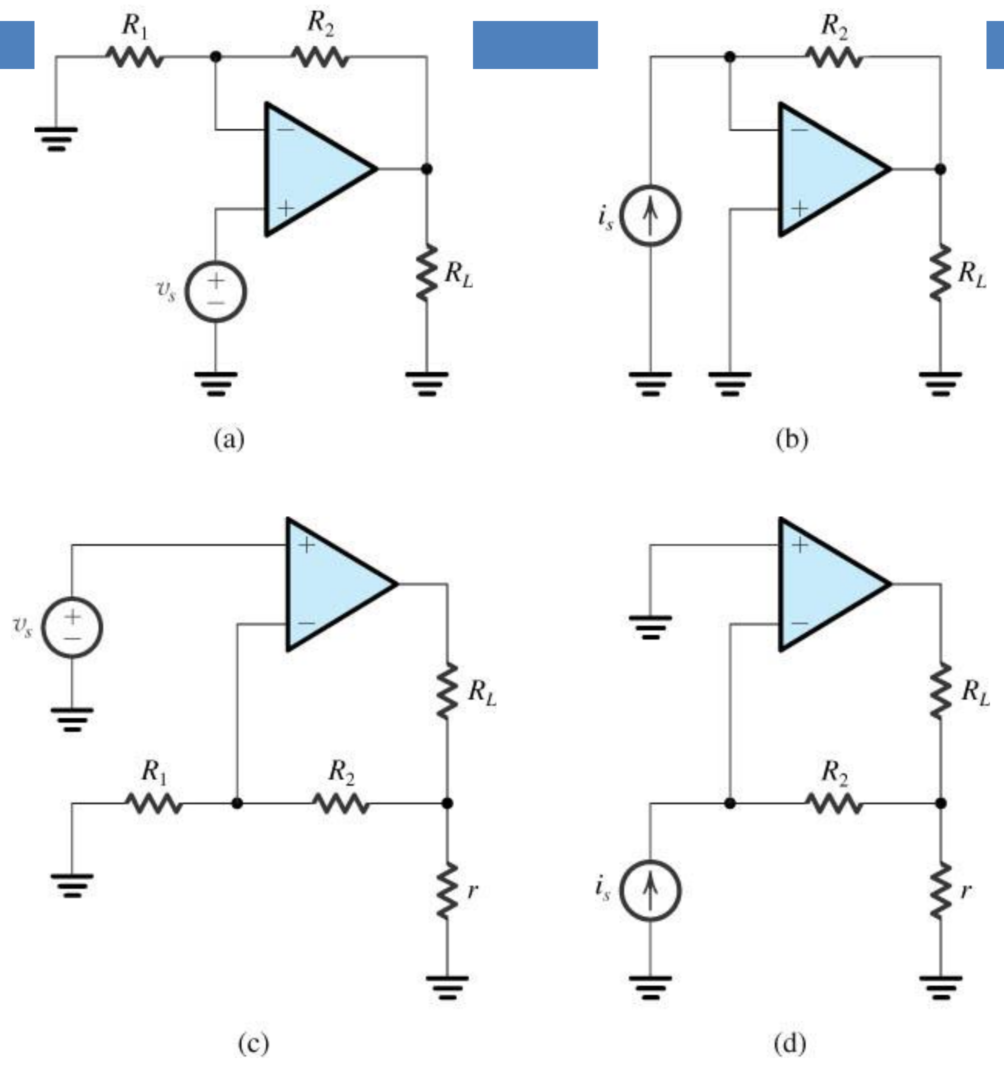



**Figure P8.26**

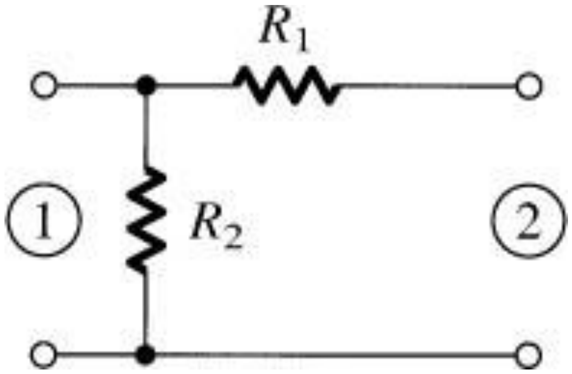



Figure P8.30

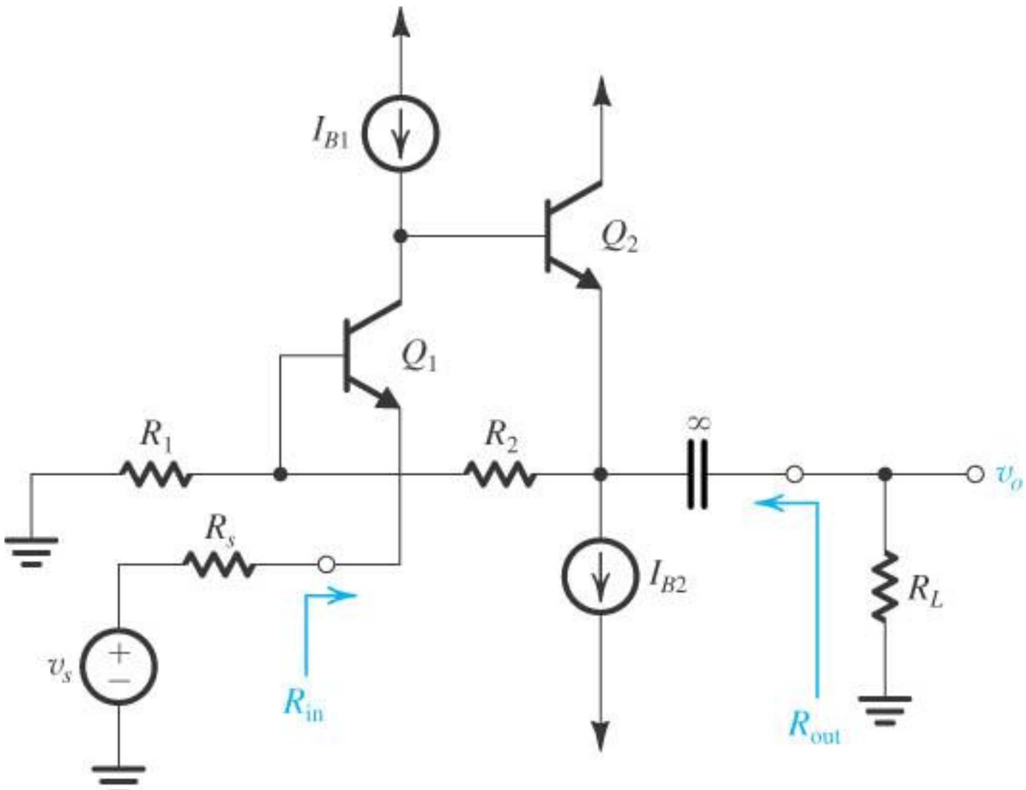



**Figure P8.32**

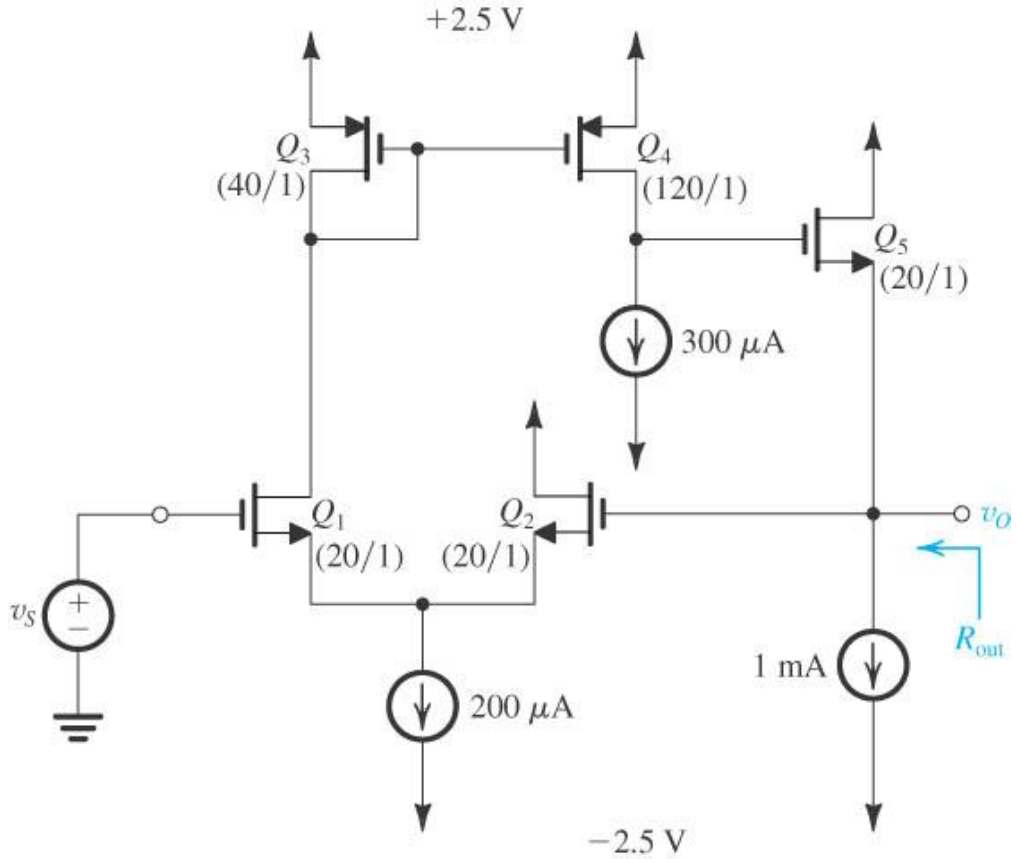

+2.5 V
Q3
(40/1)
Q4
(120/1)
Q5
(20/1)
300 μA
Q1
(20/1)
Q2
(20/1)
vO
vS
+
−
Rout
1 mA
200 μA
−2.5 V

**Figure P8.33**

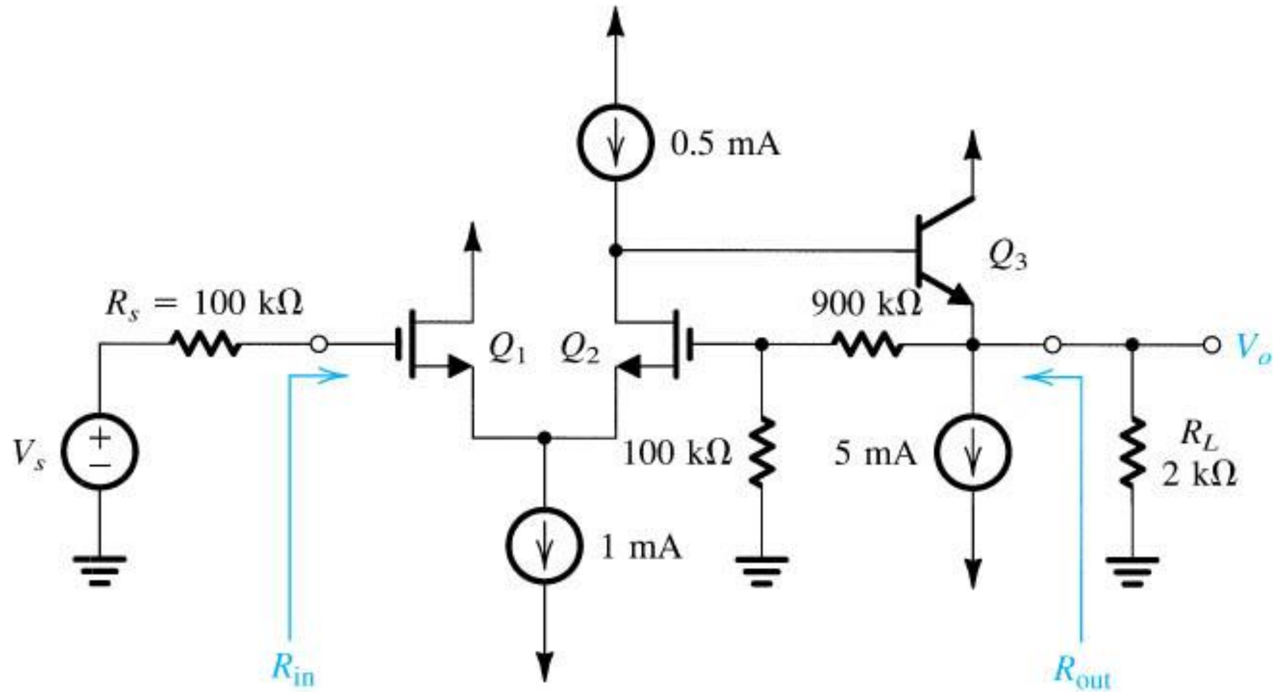



**Figure P8.34**

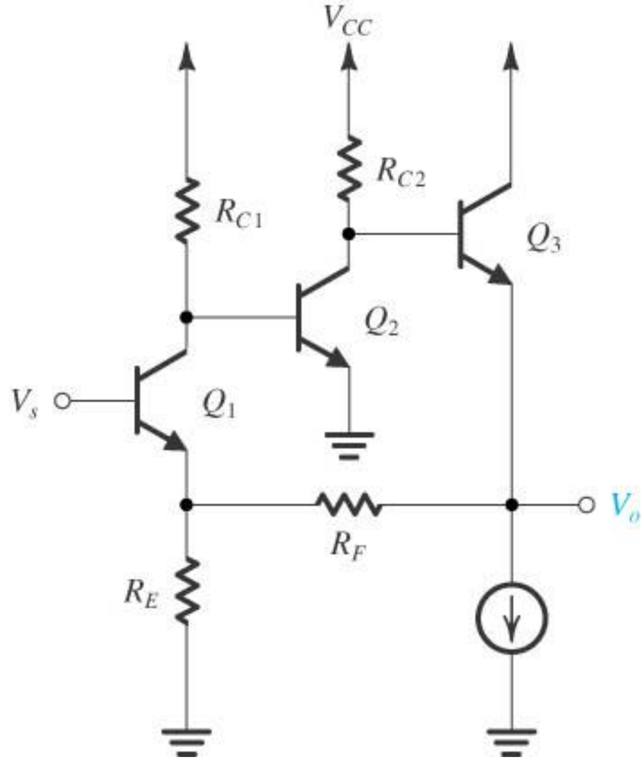



**Figure P8.35**

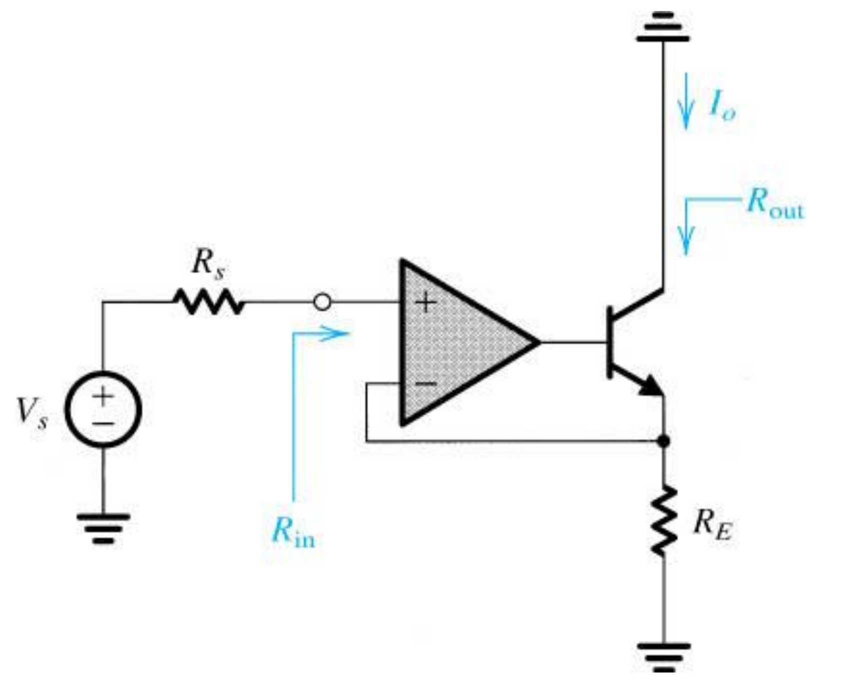



**Figure P8.38**

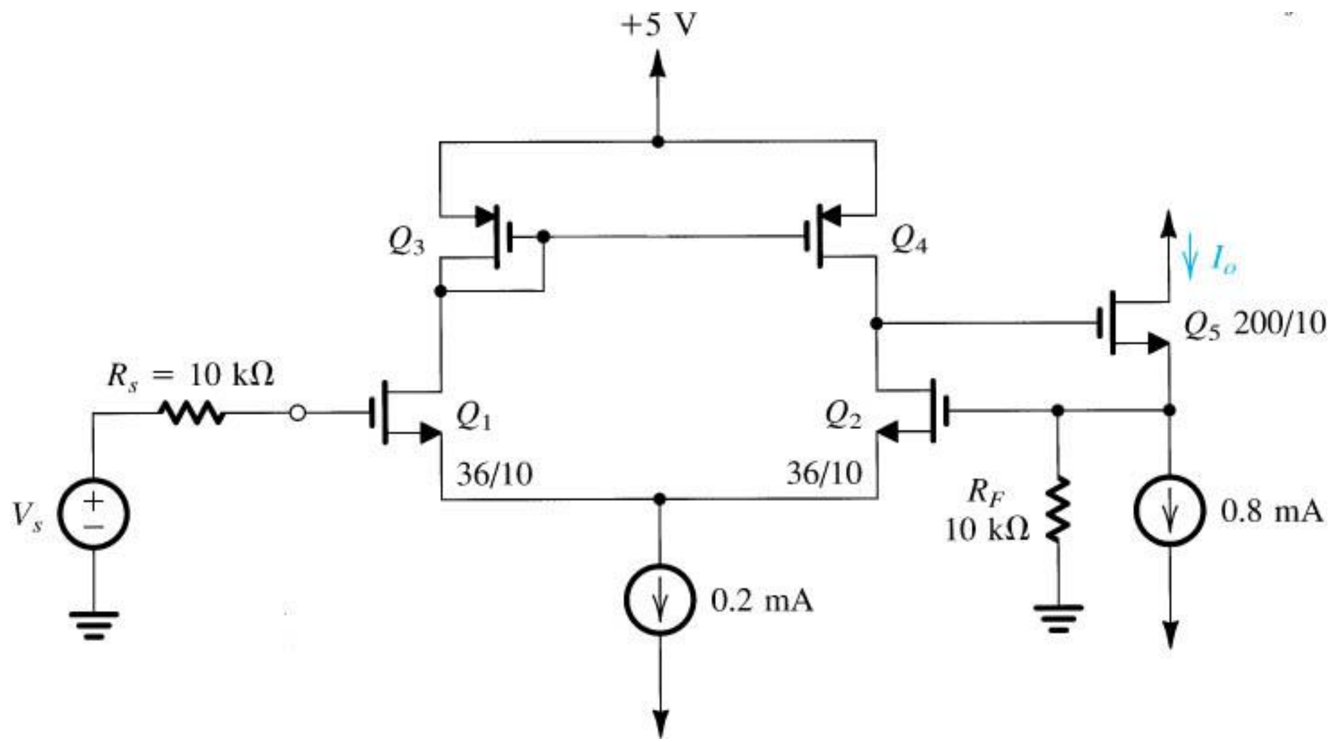



**Figure P8.39**

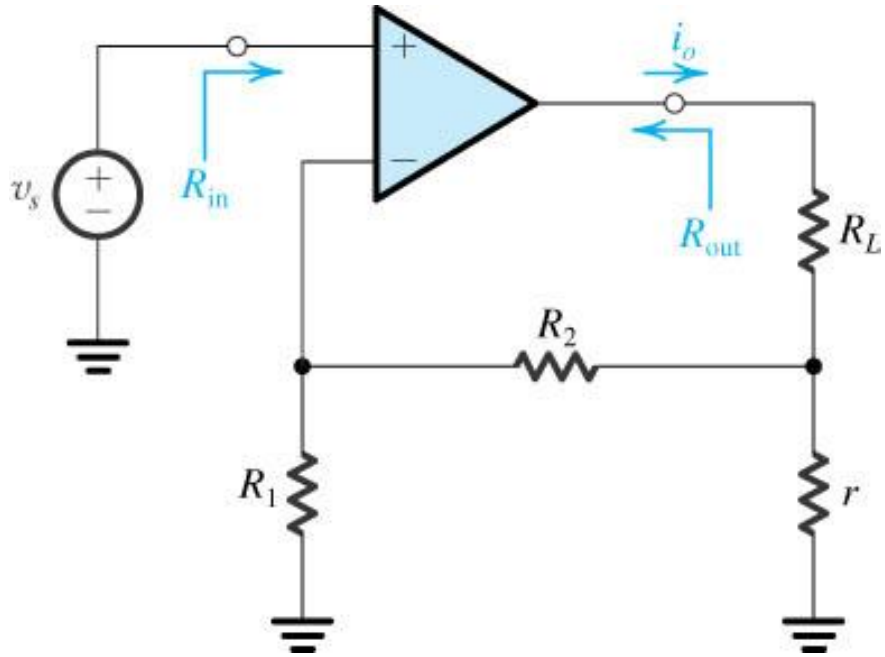



**Figure P8.40**

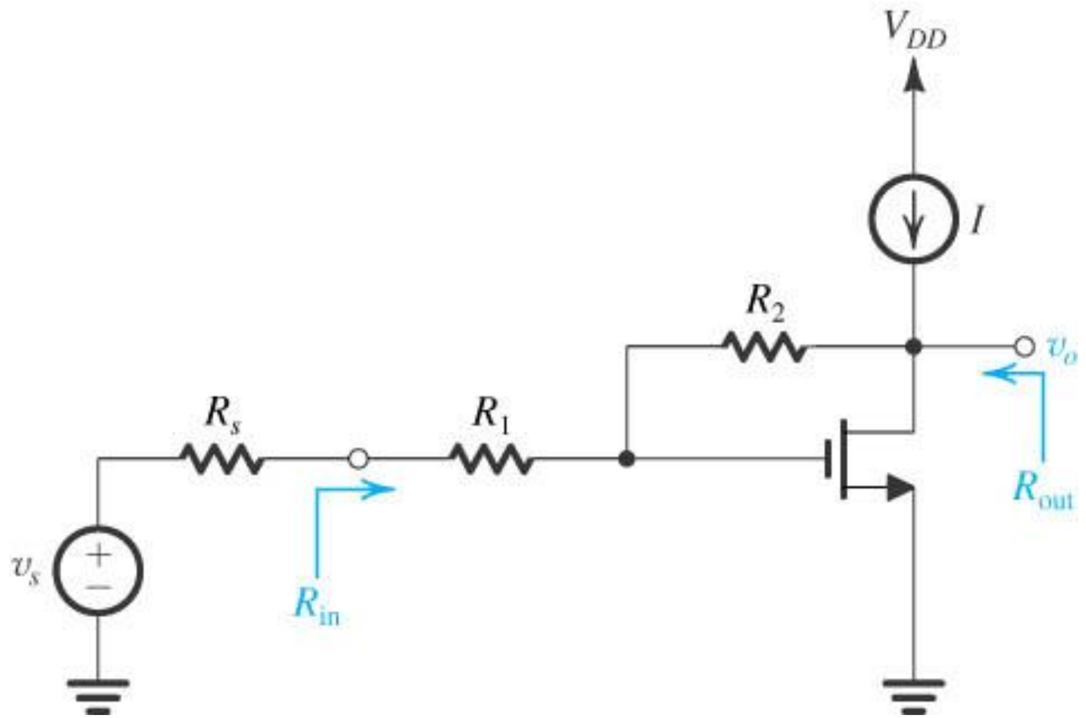



**Figure P8.42**

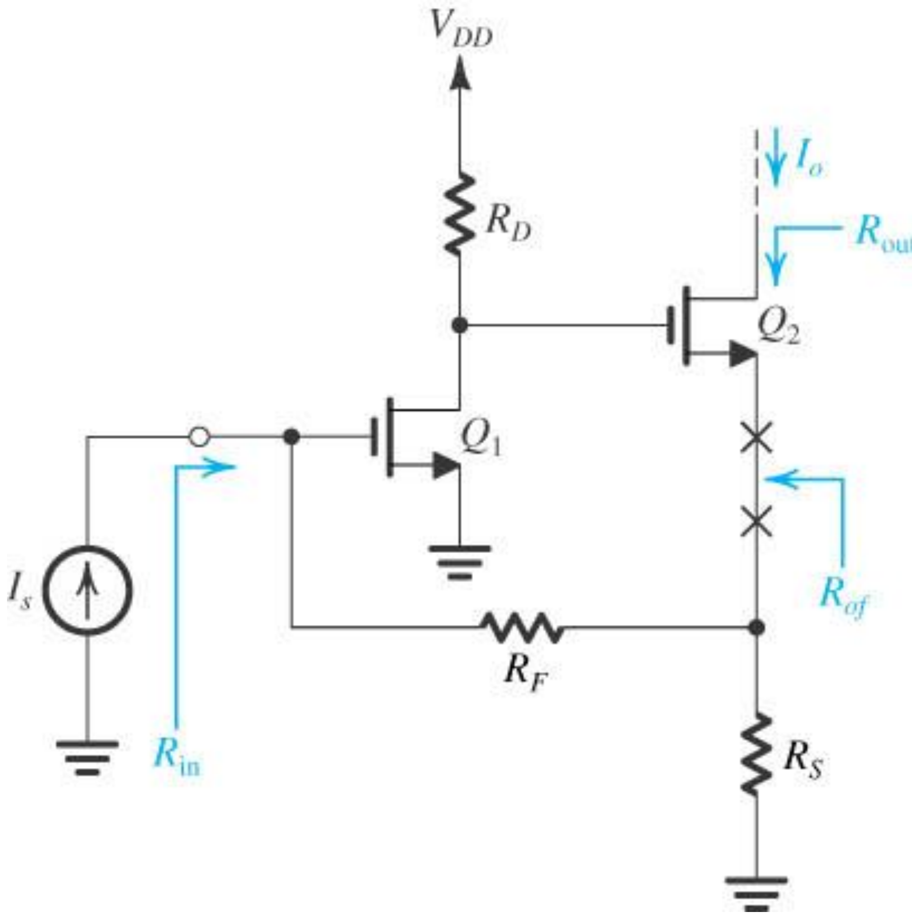



**Figure P8.44**

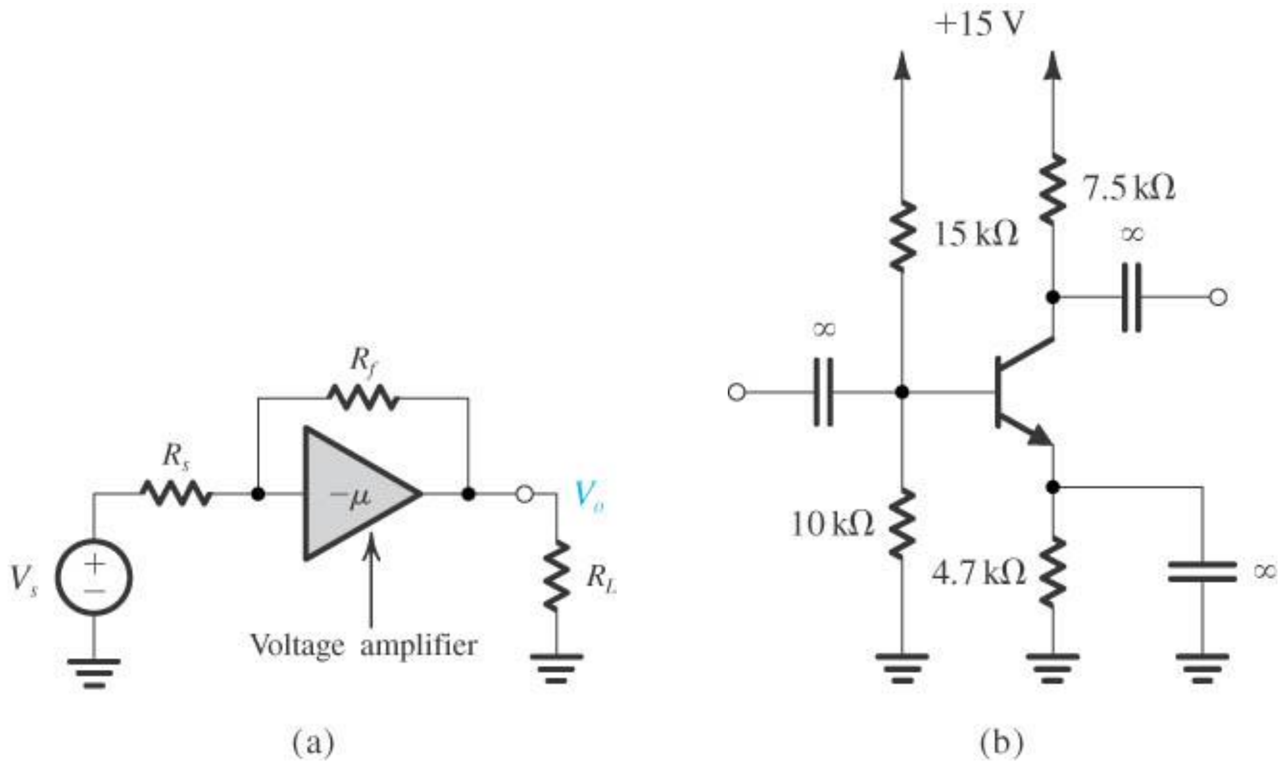



**Figure P8.46**

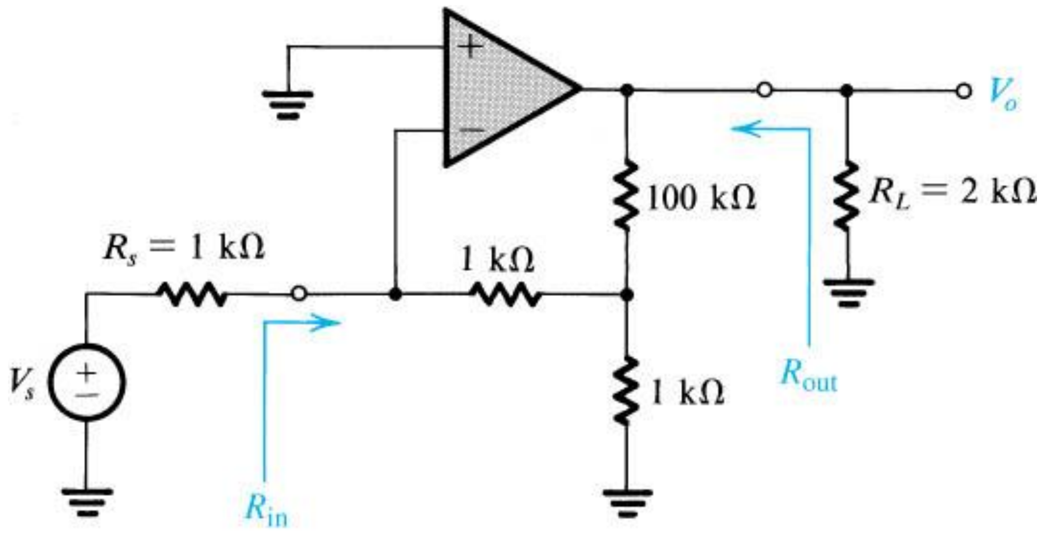



**Figure P8.48**

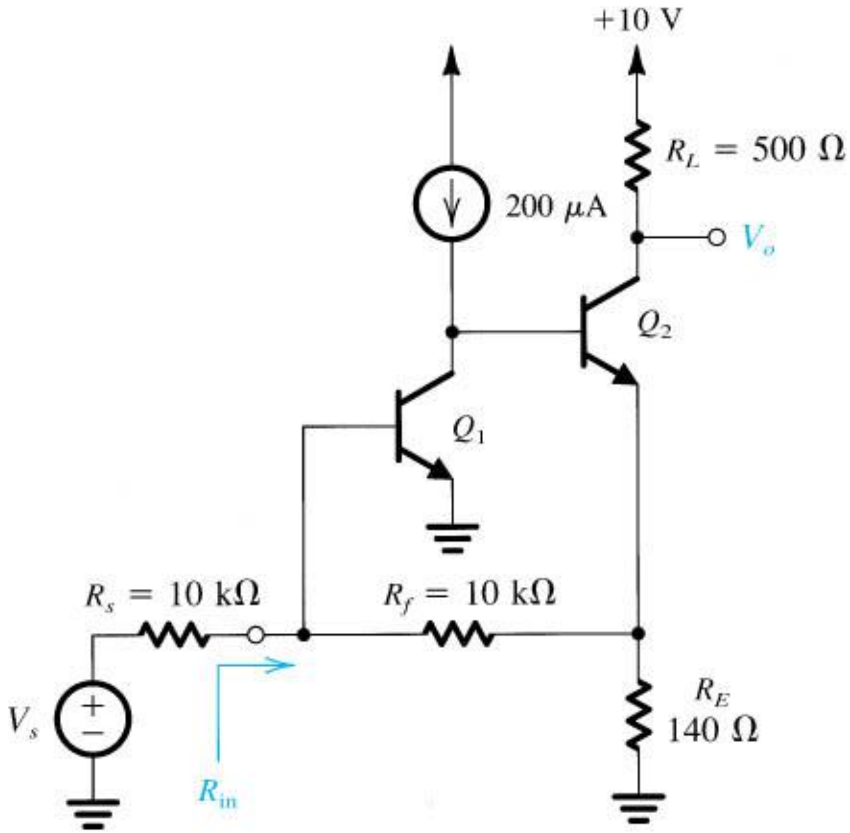



**Figure P8.51**

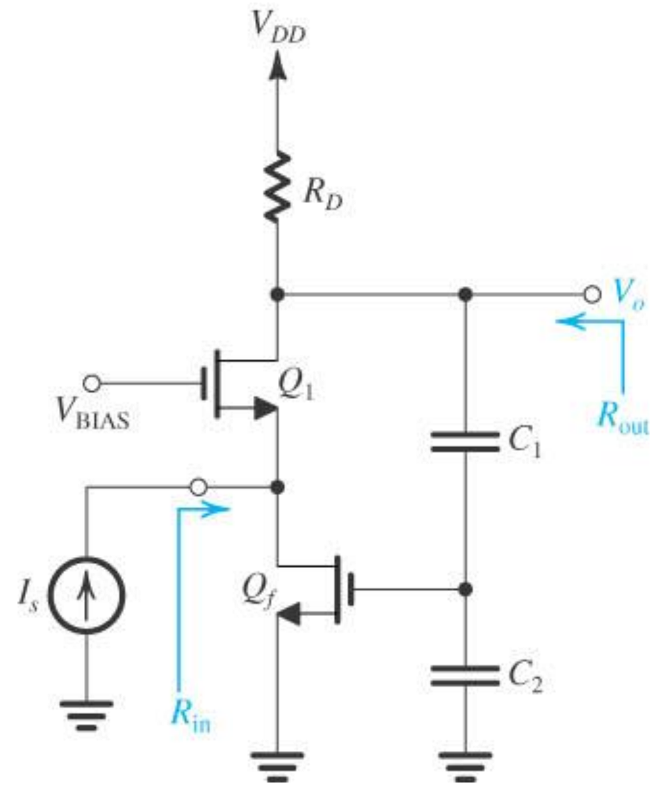



**Figure P8.52**

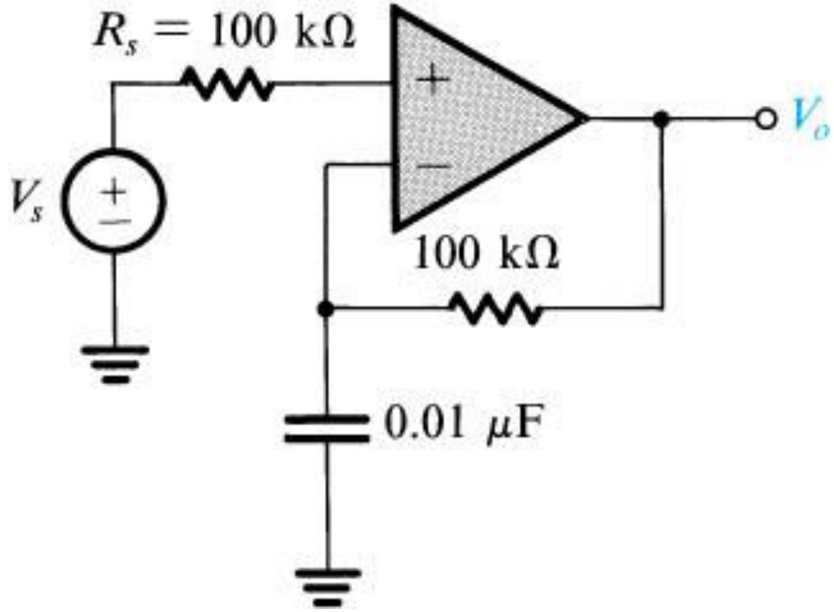



**Figure P8.81**