2007 Fall: Electronic Circuits 2

CHAPTER 8

Feedback

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Introduction

- In this chapter, we will be covering…
  - Negative Feedback
  - The General Feedback Structure
  - The Four Basic Feedback Topologies
  - Feedback in relation with Stability
  - Feedback in relation with Frequency Response

Introduction

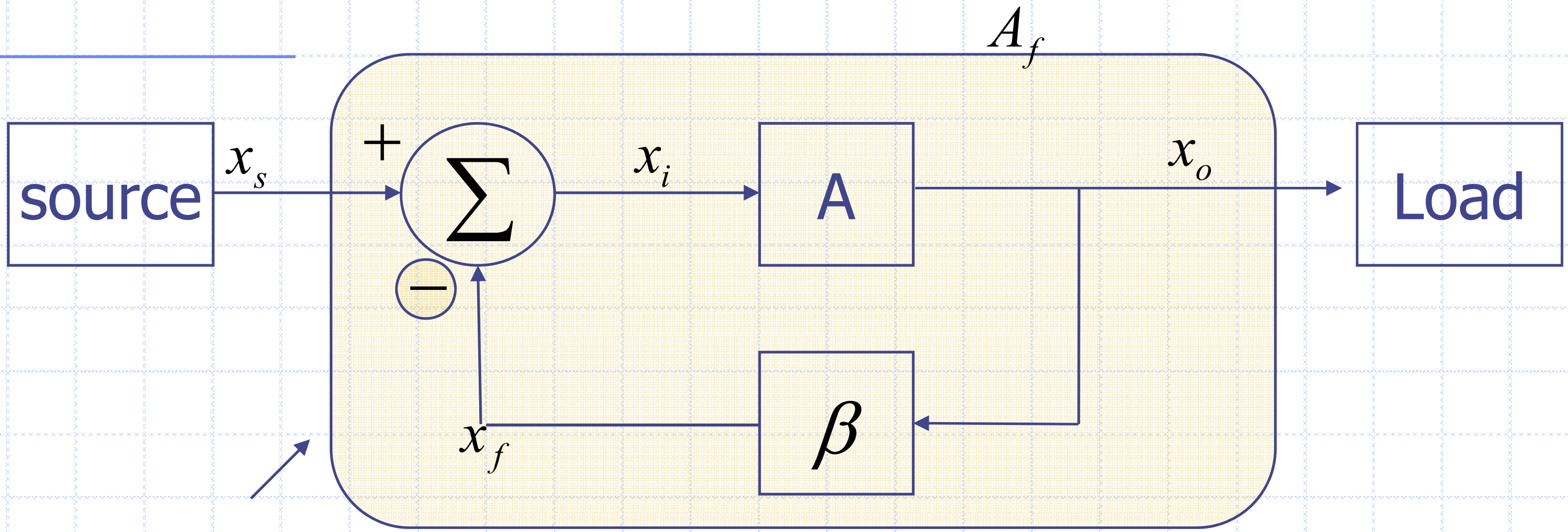
- Two types of Feedback
  - Positive (Regenerative) Feedback
  - Negative (Degenerative) Feedback

- This chapter will focus on Negative Feedback

Introduction – Negative FB

- Negative Feedback – Trades off gain for other desired properties, such as…
  - Desensitized gain
  - Reduced non-linear distortion
  - Reduced effect of noise
  - Controlled input and output impedance
  - Extended bandwidth
- These trade-offs take place under the influence of a numeric factor called ‘amount of feedback’.

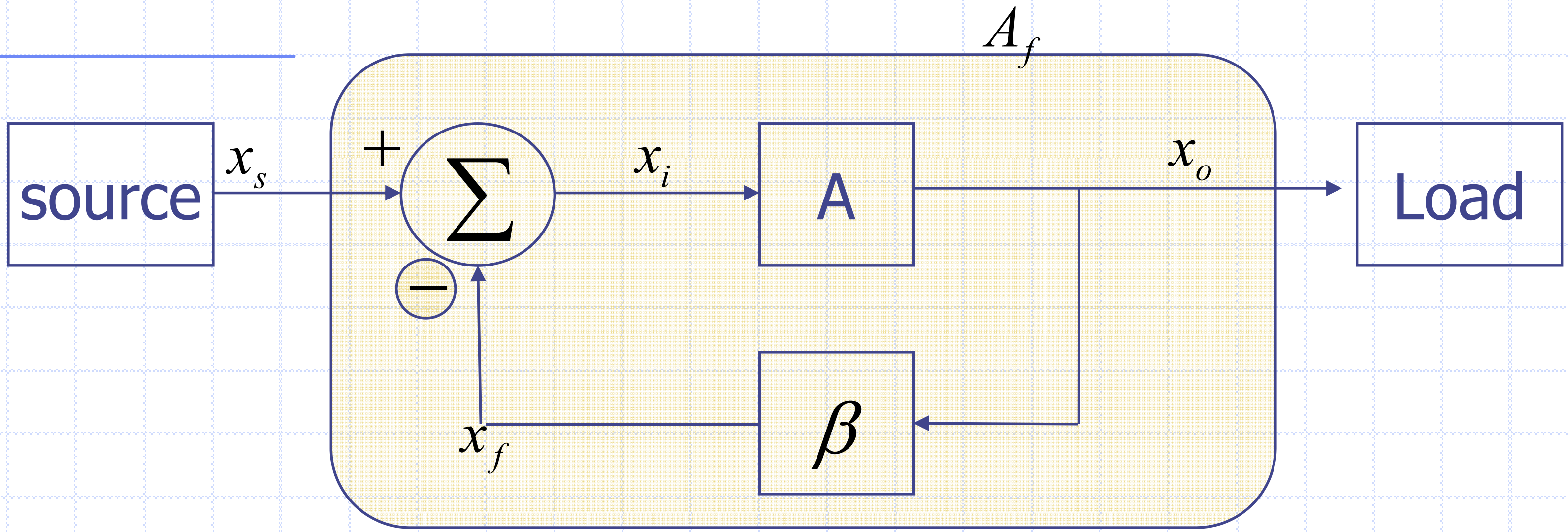
1. The General Feedback Structure



This is a signal-flow diagram of the general negative feedback structure.

$$\begin{cases} x_o = A \cdot x_i \\ x_f = \beta \cdot x_o \\ x_i = x_s - x_f \end{cases} \longrightarrow \begin{cases} x_o = A \cdot x_i \\ \quad = A \cdot (x_s - x_f) \\ \quad = A \cdot (x_s - \beta \cdot x_o) \\ A_f \equiv \dfrac{x_o}{x_s} = \dfrac{A}{1 + A \cdot \beta} \end{cases}$$

1. The General Feedback Structure



A : open loop gain

β : feedback factor

$A \cdot \beta \Rightarrow$ loop gain

$1 + A \cdot \beta \Rightarrow$ amount of feedback

A_f : closed loop gain

$$A_f \equiv \frac{x_o}{x_s} = \frac{A}{1 + A \cdot \beta}$$

$$A_f = \frac{1}{\beta} \quad \text{as A} \rightarrow \infty$$

Note that A and β are in fact transfer functions.

2. Some Properties of Negative Feedback

- As mentioned in the introduction, negative FB trades off gain for some other desired properties.

- It will become apparent explicitly in this section.

2. Some Properties of Negative Feedback

- Gain Desensitivity

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

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

$$\longrightarrow \boxed{\frac{dA_f}{A_f} = \frac{1}{1+A\beta}\cdot\frac{dA}{A}}$$

The percentage change in A_f is smaller than the percentage change in A by the amount of feedback ($\equiv 1+A\beta$).

2. Some Properties of Negative Feedback

Bandwidth Extension

Consider an amplifier with a single pole, then

$$\text{open-loop TF}: A(s) = \frac{A_M}{1 + s / w_H}$$

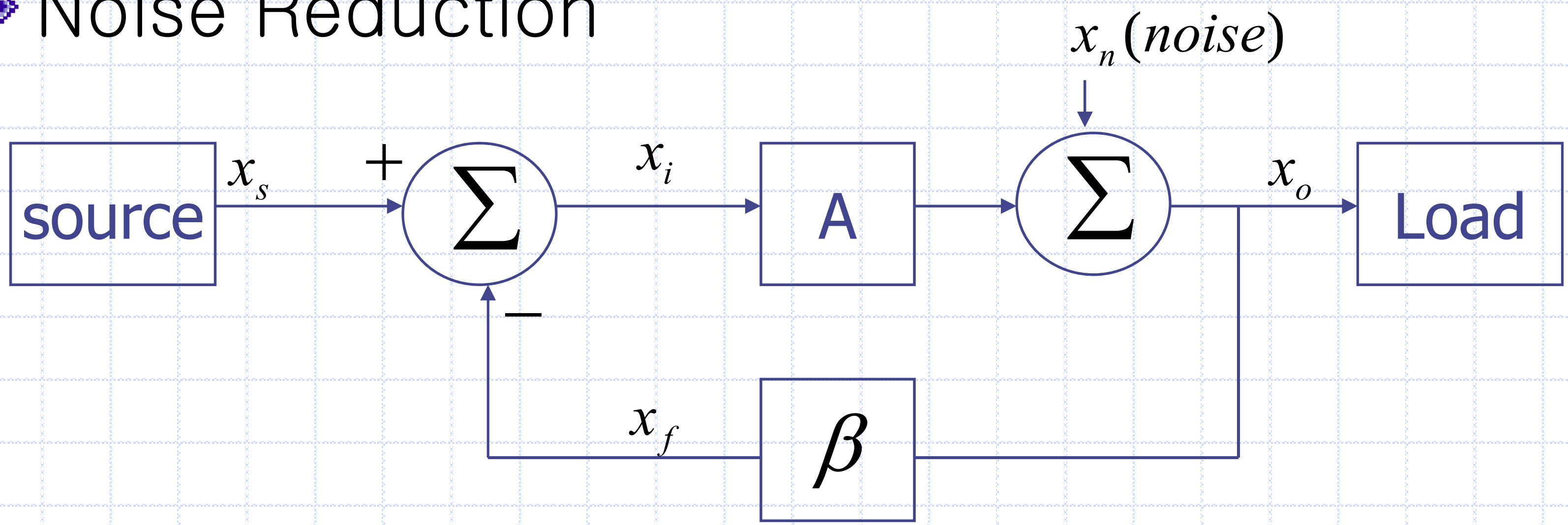
$$A_f(s) = \frac{A(s)}{1 + A(s)\beta} \longrightarrow A_f(s) = \frac{\dfrac{A_M}{1 + s / w_H}}{1 + \dfrac{A_M}{1 + s / w_H} \cdot \beta} = \frac{A_f}{1 + s / \boxed{(1 + A_M \beta) w_H}}$$

$$\boxed{\therefore\ w_{Hf} = w_H (1 + A_M \beta)}$$

The upper 3-dB frequency is increased by a factor equal to the amount of feedback ($\equiv 1 + A\beta$), where A_M denotes the midband gain and ω_H is the upper 3-dB frequency. However, the gain-bandwidth product remains constant.

2. Some Properties of Negative Feedback

- Noise Reduction



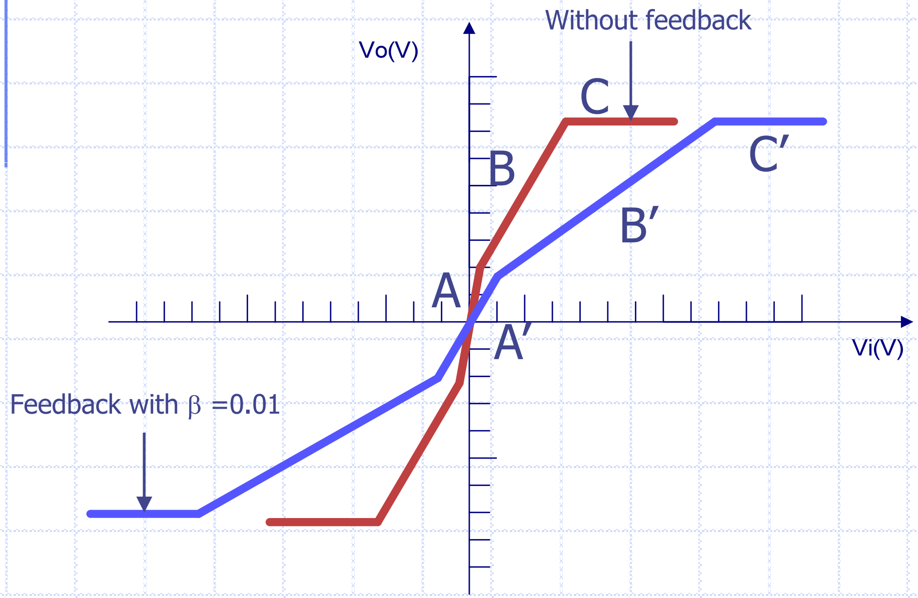
$$\left\{ \begin{aligned} x_o &= A \cdot x_i + x_n \\ x_f &= \beta \cdot x_o \\ x_i &= x_s - x_f \end{aligned} \right\} \longrightarrow \left\{ \begin{aligned} x_o &= A \cdot (x_s - x_f) + x_n \\ &= A \cdot x_s - A \cdot \beta \cdot x_o + x_n \\ \therefore x_o &= \frac{A \cdot x_s}{1 + A\beta} + \frac{x_n}{1 + A\beta} = A_f \cdot x_s + \boxed{\frac{x_n}{1 + A\beta}} \end{aligned} \right.$$

The magnitude of noise seen at the output is reduced by the amount of feedback.

2. Some Properties of Negative Feedback

◆ Reduction in Nonlinear Distortion

Consider an amplifier with the gain of 1000 in region A, 100 in region B, and 0 in region C.



Under feedback,

by $A_f = \dfrac{A}{1 + A\beta}$ $(\beta = 0.01)$

- Gain in region A′ is 90.9
- Gain in region B′ is 50
- Gain in region C′ is 0

The amplifier transfer characteristic is considerably linearized.

3. The Four Basic Feedback Topologies

- There are four basic feedback topologies, namely,
  - Series-Shunt
  - Shunt-Series
  - Series-Series
  - Shunt-Shunt

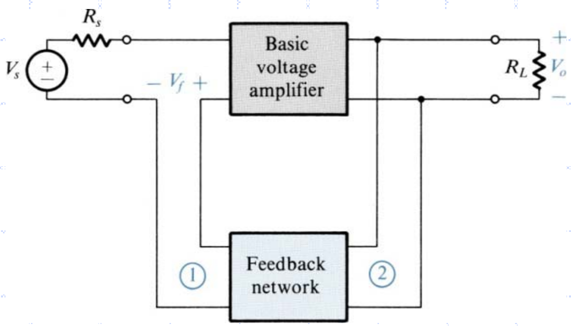
- Each has an aptitude on four different kinds of amplifiers discussed in Chapter 1. Correct application of feedback topology idealizes the amplifier's input/output impedance.

3. The Four Basic Feedback Topologies

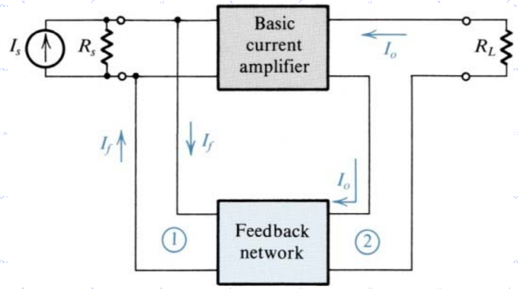
- The term ‘shunt’ is an another expression for ‘parallel’.
- Why are the names like that?
  - The word before the dash describes how the feedback signal is ‘mixed’ into the input.
  - The word after the dash describes how the feedback signal is ‘sampled’ from the output.
  - Voltage is mixed in series and sampled in parallel.
  - Current is mixed in parallel and sampled in series.
  - Ex) Series-shunt mixes in series and samples in parallel. So both input and output has to be a voltage.

3. The Four Basic Feedback Topologies

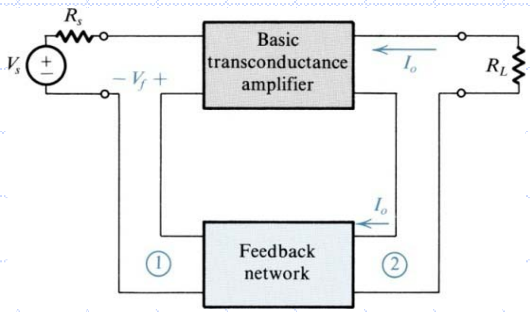
- Four kinds of amplifier paired with its most effective feedback topology.



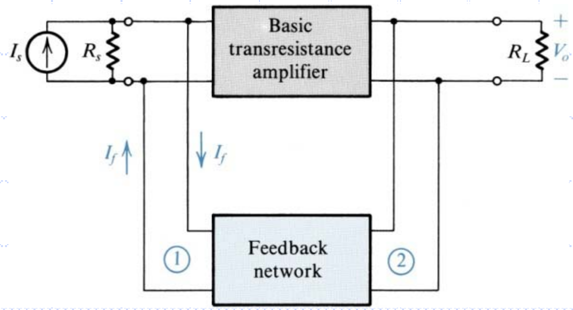
(a) Voltage Amp.(series-shunt)



(b) Current Amp.(shunt-series)



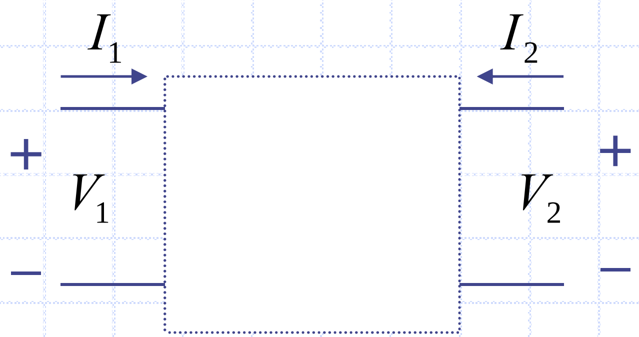
(c) Transconductance Amp. (series-series)



(d) Transresistance Amp. (shunt-shunt)

Appendix B – Two Port Network Parameters

Review of Two Port Network



1) h param.(series-shunt)

$$V_1 = h_{11} I_1 + h_{12} V_2$$
$$I_2 = h_{21} I_1 + h_{22} V_2$$

2) z param.(series-series)

$$V_1 = z_{11} I_1 + z_{12} I_2$$
$$V_2 = z_{21} I_1 + z_{22} I_2$$

3) y param.(shunt-shunt)

$$I_1 = y_{11} V_1 + y_{12} V_2$$
$$I_2 = y_{21} V_1 + y_{22} V_2$$

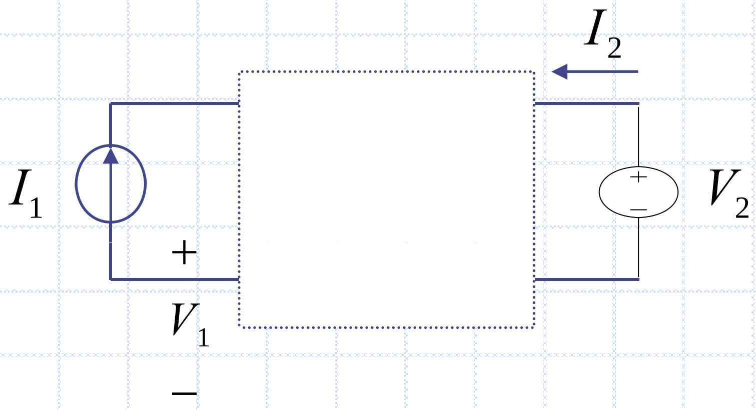
4) g param.(shunt-series)

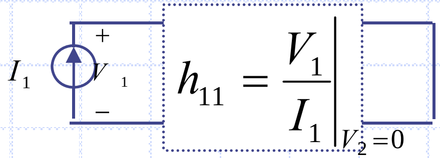
$$I_1 = g_{11} V_1 + g_{12} I_2$$
$$V_2 = g_{21} V_1 + g_{22} I_2$$

Appendix B – Two Port Network Parameters

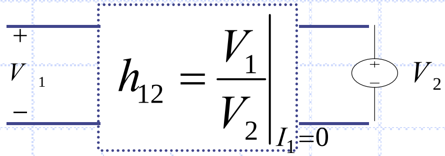
1) h param.(series-shunt) – I_1 and V_2 are the stimuli

$$V_1 = h_{11} I_1 + h_{12} V_2$$
$$I_2 = h_{21} I_1 + h_{22} V_2$$

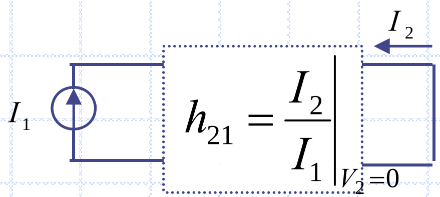




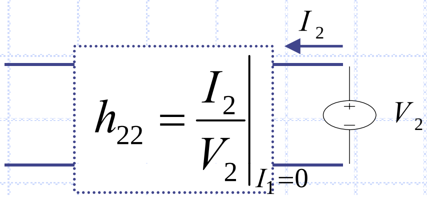
$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$



$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$



$$h_{21} = \left.\frac{I_2}{I_1}\right|_{V_2=0}$$

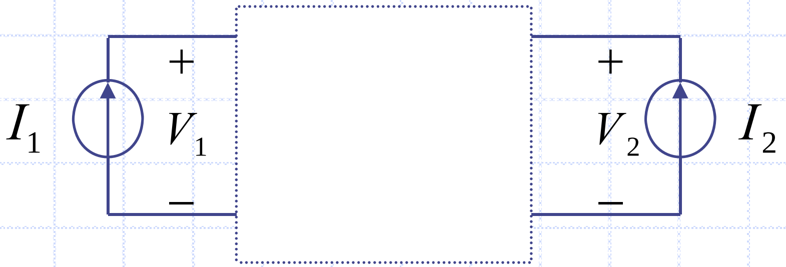


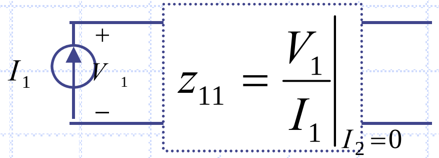
$$h_{22} = \left.\frac{I_2}{V_2}\right|_{I_1=0}$$

Appendix B – Two Port Network Parameters

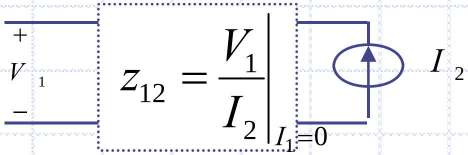
2) z param.(series-series) – I_1 and I_2 are the stimuli

$$V_1 = z_{11} I_1 + z_{12} I_2$$
$$V_2 = z_{21} I_1 + z_{22} I_2$$

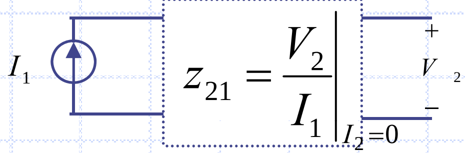




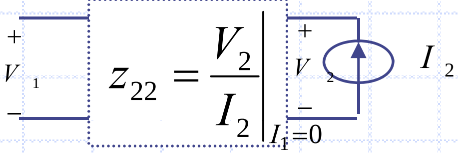
$$z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0}$$



$$z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0}$$



$$z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0}$$

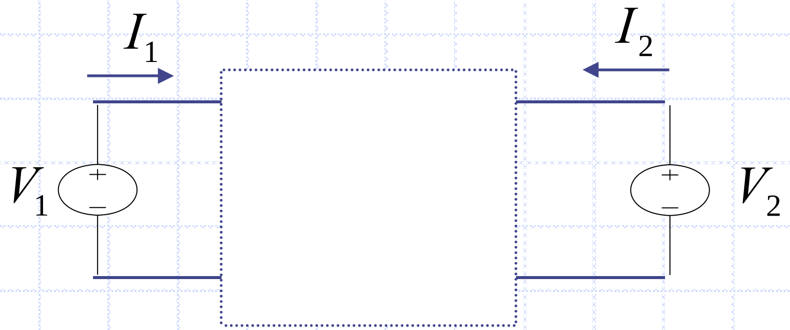


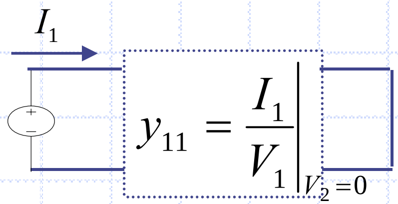
$$z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

Appendix B – Two Port Network Parameters

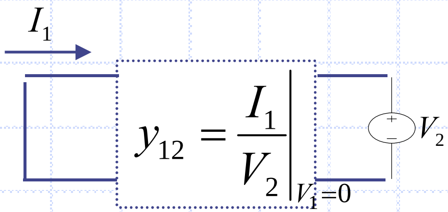
3) y param.(shunt-shunt) – V_1 and V_2 are the stimuli

$$I_1 = y_{11}V_1 + y_{12}V_2$$
$$I_2 = y_{21}V_1 + y_{22}V_2$$

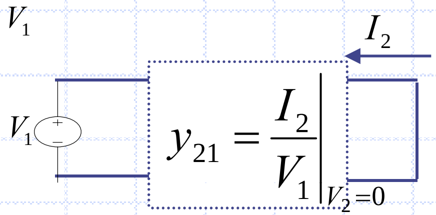




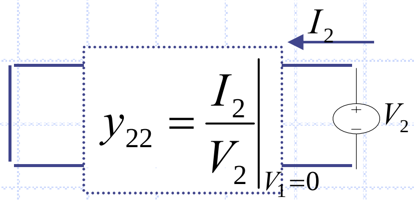
$$y_{11} = \left.\frac{I_1}{V_1}\right|_{V_2=0}$$



$$y_{12} = \left.\frac{I_1}{V_2}\right|_{V_1=0}$$



$$y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2=0}$$

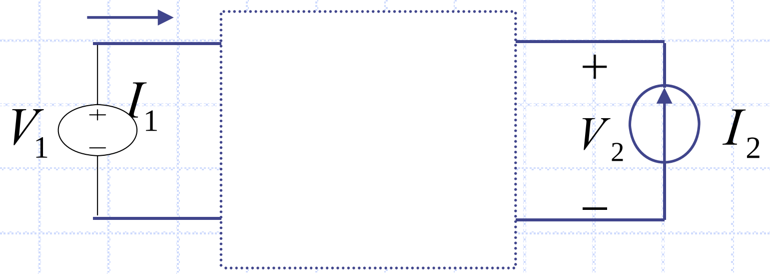


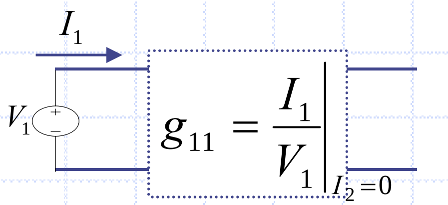
$$y_{22} = \left.\frac{I_2}{V_2}\right|_{V_1=0}$$

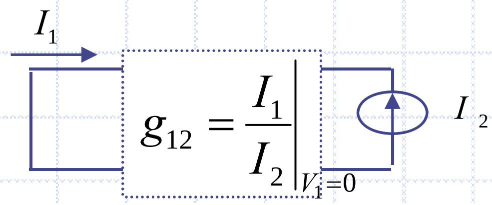
Appendix B – Two Port Network Parameters

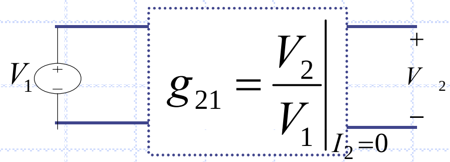
4) g param.(shunt-series) – V_1 and I_2 are the stimuli

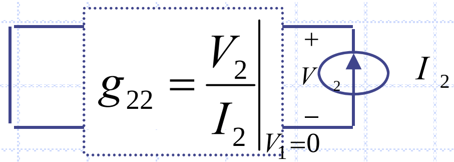
$$I_1 = g_{11}V_1 + g_{12}I_2$$
$$V_2 = g_{21}V_1 + g_{22}I_2$$









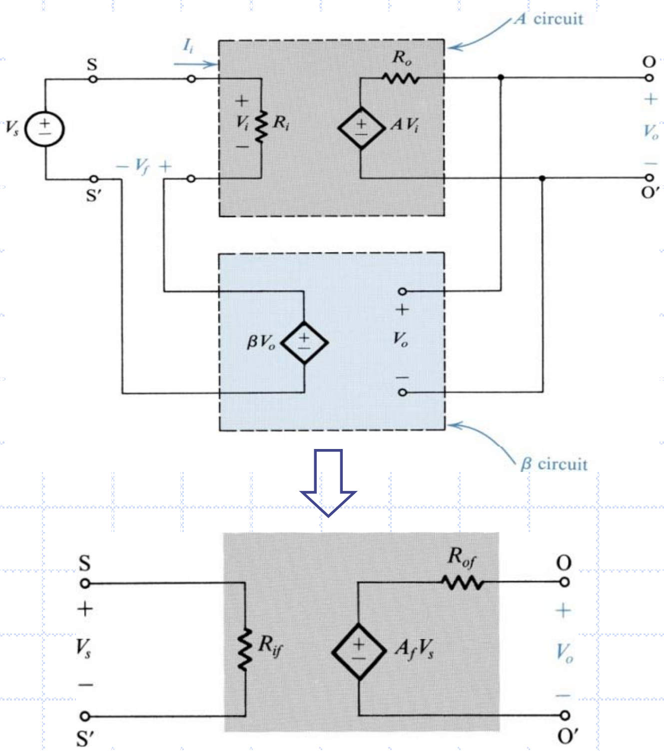


4. The Series-Shunt Feedback Amplifier

- Series-Shunt (voltage amp)
  => Input is mixed in voltage(series), and output is sampled in voltage(shunt).
  - Whenever voltage is mixed, the input impedance is increased by the amount of feedback.
  - Whenever voltage is sampled, the output impedance is reduced by the amount of feedback.

4. The Series-Shunt Feedback Amplifier

- Ideal Situation (w/o load and source res.)



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

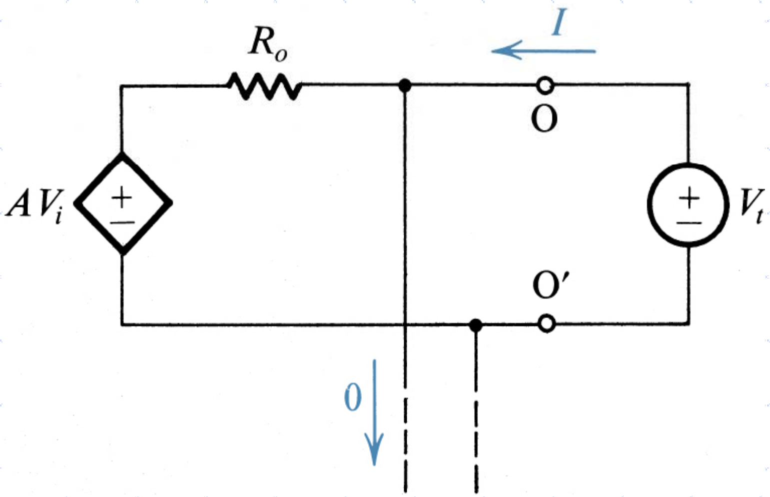
$$R_{if} \equiv \frac{V_s}{I_i} = \frac{V_s}{V_i / R_i} = R_i \frac{V_s}{V_i} = R_i \frac{V_i + A\beta V_i}{V_i}$$

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

$$\boxed{Z_{if} = Z_i(1 + A(s)\beta(s))}$$

4. The Series-Shunt Feedback Amplifier

◆ Ideal Situation(Cont'd)



To find R_{of}, Set V_S=0, apply test voltage V_t

$$R_{of} \equiv \frac{V_t}{I}$$

$$I = \frac{V_t - AV_i}{R_o}$$

$$V_i = -V_f = -\beta V_o = -\beta V_t$$

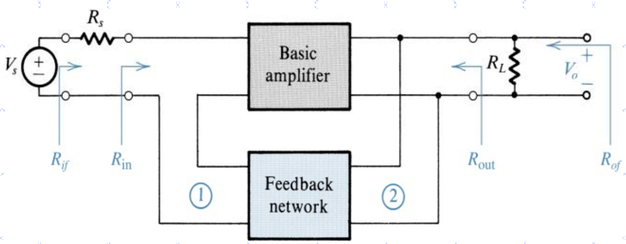
$$I = \frac{V_t + A\beta V_t}{R_o}$$

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

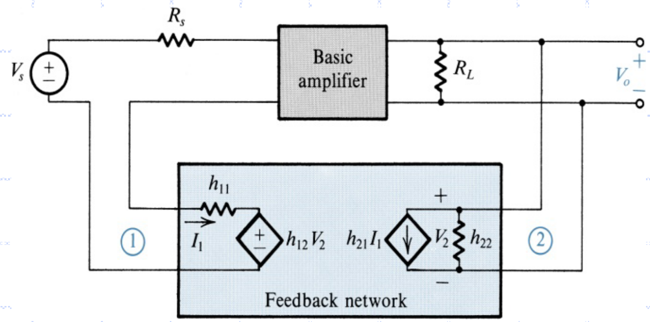
$$Z_{of} = \frac{Z_i(s)}{1 + A(s)\beta(s)}$$

4. The Series-Shunt Feedback Amplifier

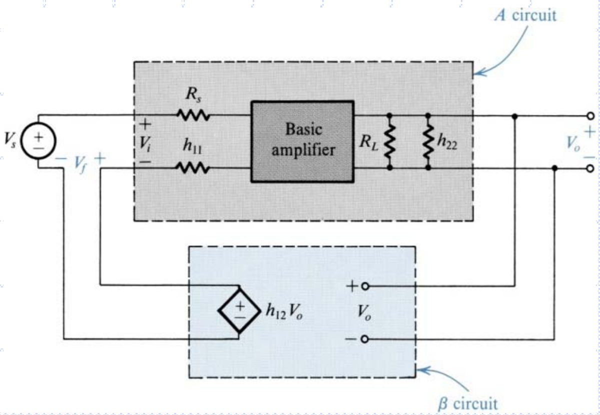
◆ Practical Situation



(a) Practical series-shunt amp.



(b) Represented by h parameters

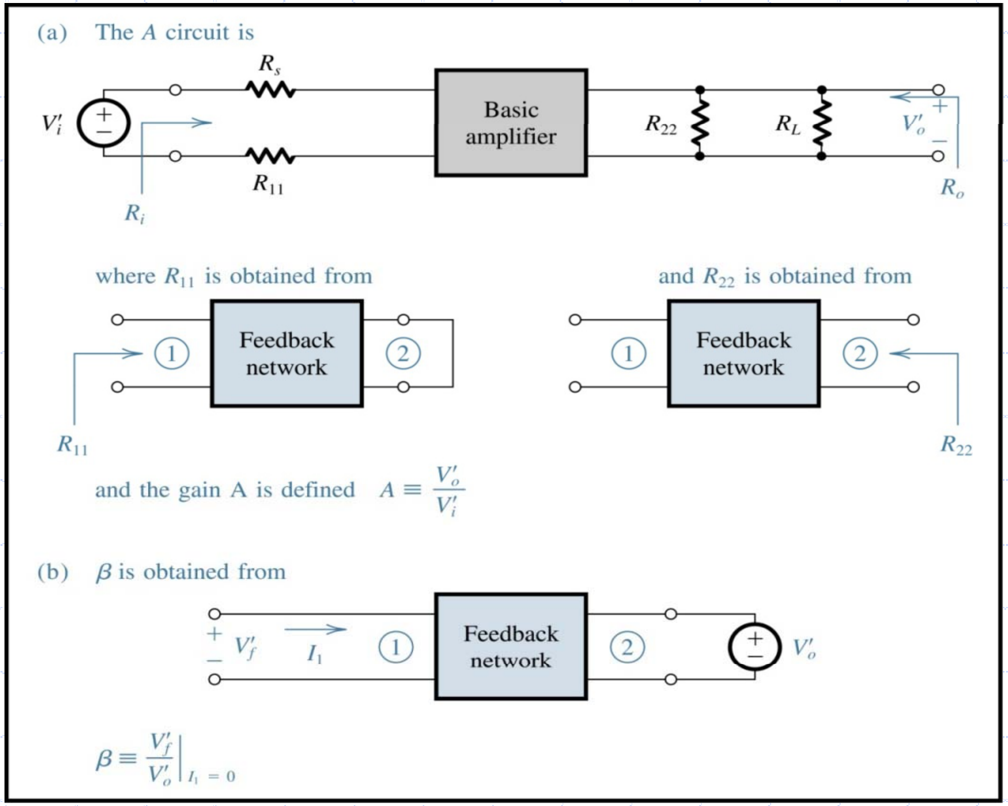


$$\beta = h_{21} \equiv \left. \frac{V_1}{V_2} \right|_{I_1=0}$$

(c) Neglecting h21 (similar to ideal case)

4. The Series-Shunt Feedback Amplifier

Summary



$$R_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$

$$R_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

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

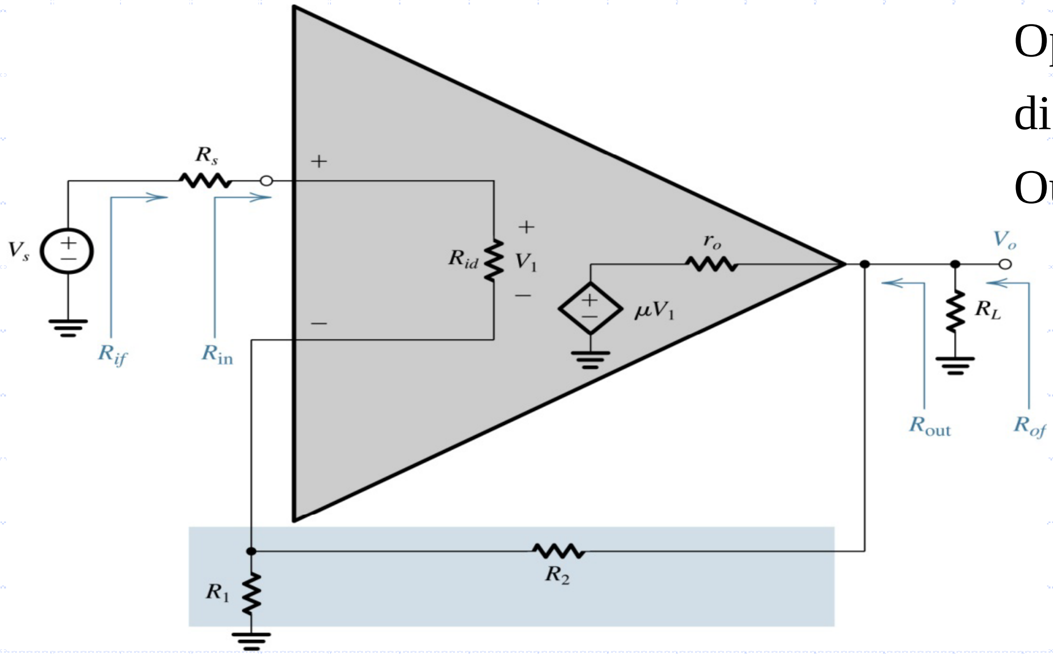
$$R_{out} = 1/\left(\frac{1}{R_{of}} - \frac{1}{R_L}\right)$$

(in Fig. 8.10(a))

4. The Series-Shunt Feedback Amplifier

Example 8.1

Q : find the expressions for $A, \beta, V_o / V_s, R_{in}$ and R_{out}.



Open loop gain : $\mu = 10^4$

diff. input resistance : $R_{id} = 100\ k\Omega$

Ouput resistance : $r_o = 1 k\Omega$

$R_1 = 1 k\Omega$

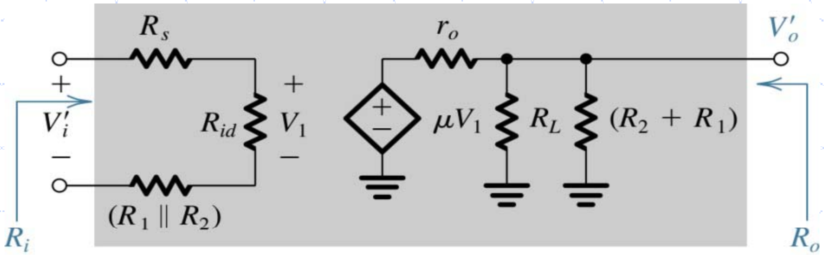
$R_2 = 1 M\Omega$

$R_s = 10\ k\Omega$

4. The Series-Shunt Feedback Amplifier

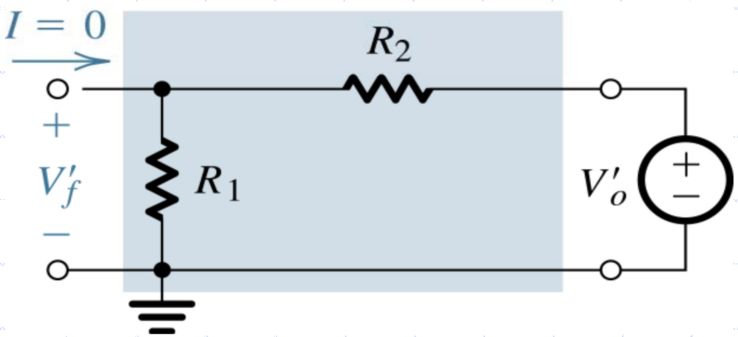
◆ Example 8.1(Cont'd)

It sample voltage and mixes voltage, so series-shunt…



$$A \equiv \frac{V_o'}{V_i'} = \mu \frac{R_L //(R_1 + R_2)}{[R_L //(R_1 + R_2)] + r_o} \cdot \frac{R_{id}}{R_{id} + R_s + (R_1 // R_2)}$$

$$\approx 6000(V/V)$$

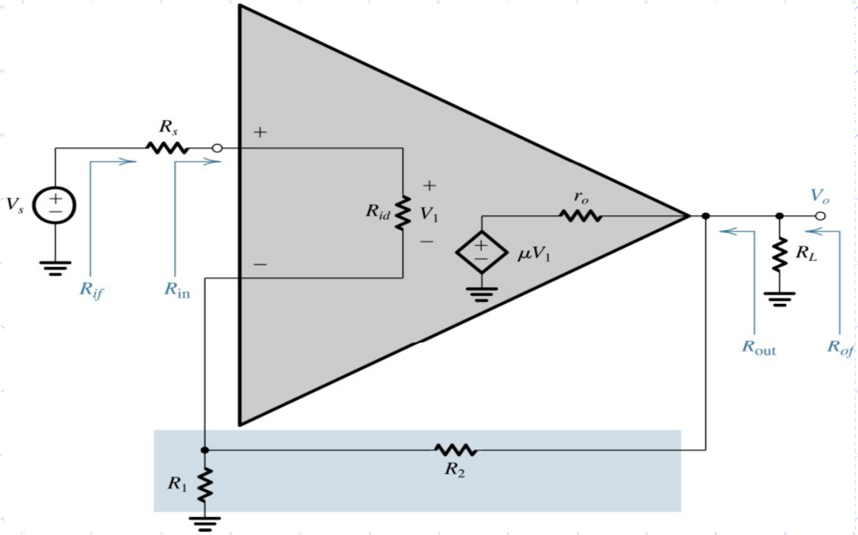


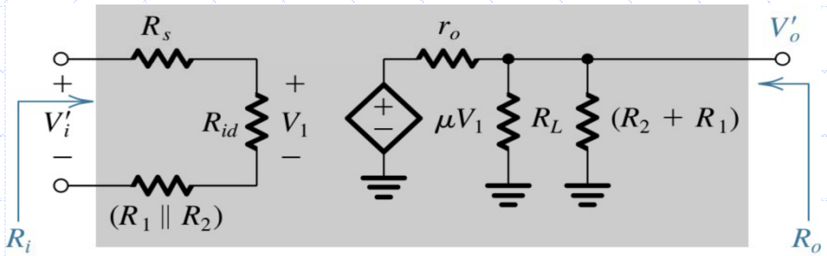
$$\beta \equiv \frac{V_f'}{V_o'} = \frac{R_1}{R_1 + R_2} \approx 10^{-3}(V/V)$$

$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{1 + A\beta} \approx 857(V/V)$$

4. The Series-Shunt Feedback Amplifier

◆ Example 8.1(Cont'd)





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

$$R_i = R_s + R_{id} + (R_1 // R_2) \approx 111\ k\Omega$$

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

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

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

$$R_o = r_o // R_L //(R_2 + R_1) \approx 667\ \Omega$$

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

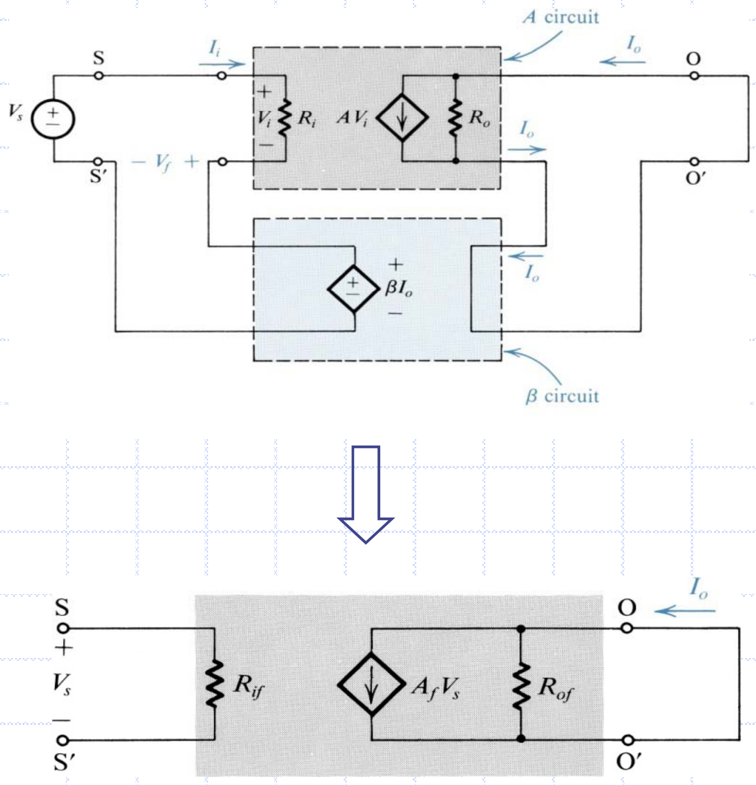
$$R_{out} = 1/(\frac{1}{R_{of}} - \frac{1}{R_L}) \approx 100\ \Omega$$

5. The Series-Series Feedback Amplifier

- Series–Series (transconductance amp.)
  => Input is mixed in voltage(series), and output is sampled in current(series).
  - Whenever voltage is mixed, the input impedance is increased by the amount of feedback.
  - Whenever current is sampled, the output impedance is increased by the amount of feedback.

5. The Series-Series Feedback Amplifier

◆ Ideal Situation



As shown previously,

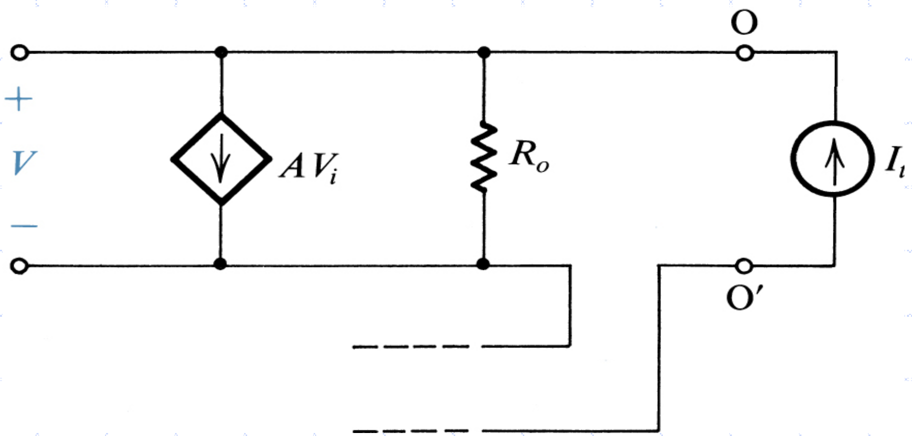
$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{1 + A\beta}$$

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

$$\boxed{Z_{if} = Z_i(1 + A(s)\beta(s))}$$

5. The Series-Series Feedback Amplifier

◆ Ideal Situation(Cont'd)



$$R_{of} \equiv \frac{V_t}{I}$$

$$V_i = -V_f = -\beta I_o = -\beta I_t$$

$$V = (I_t - AV_i)R_o = (I_t + A\beta I_t)R_o$$

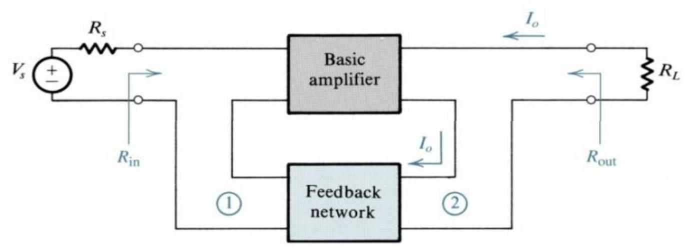
$$R_{of} = (1 + A\beta)R_o$$

To find R_{of}, Set V_S=0, apply test current V_t

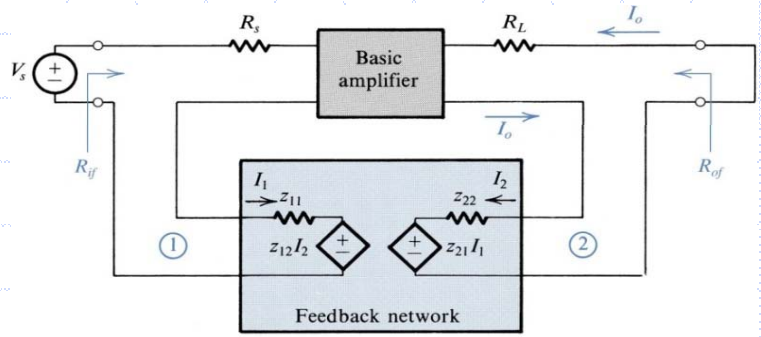
$$\boxed{Z_{of} = Z_o(1 + A(s)\beta(s))}$$

5. The Series-Series Feedback Amplifier

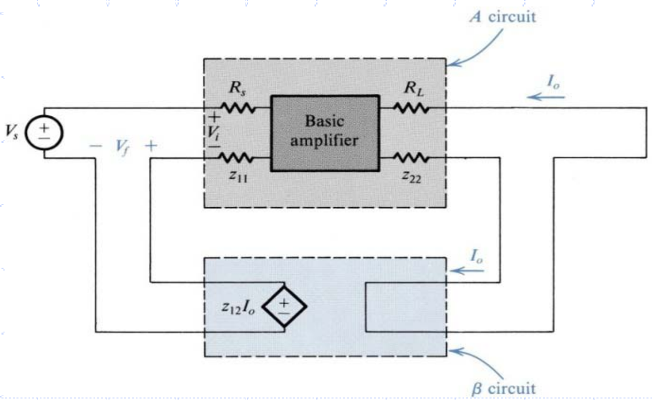
Practical Situation



(a) Practical series-series amp.



(b) Represented by z parameters

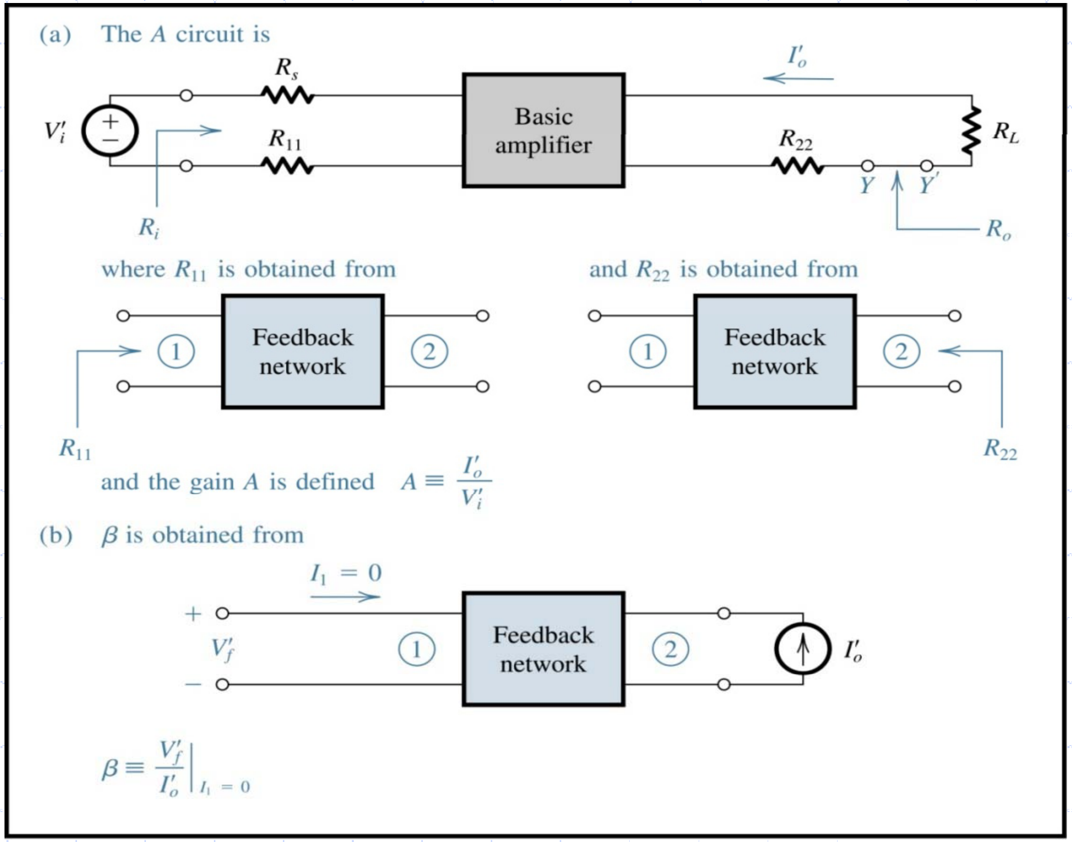


$$\beta = z_{21} \equiv \left.\frac{V_1}{I_2}\right|_{I_1=0}$$

(c) Neglecting z21 (similar to ideal case)

5. The Series-Series Feedback Amplifier

◆ Summary



$$R_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0}$$

$$R_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

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

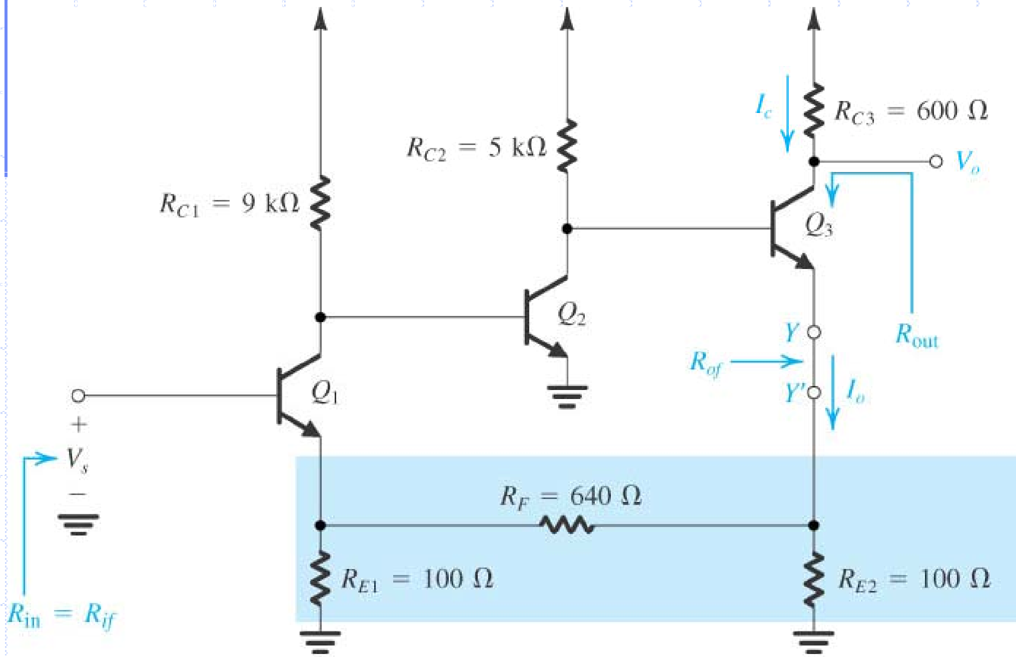
$$R_{out} = R_{of} - R_L$$

(in Fig. 8.15(b))

5. The Series-Series Feedback Amplifier

Example 8.2

Q : find the expression s for $A, \beta, A_f, V_o / V_s, R_{in}, R_{of}$, and R_{out}.



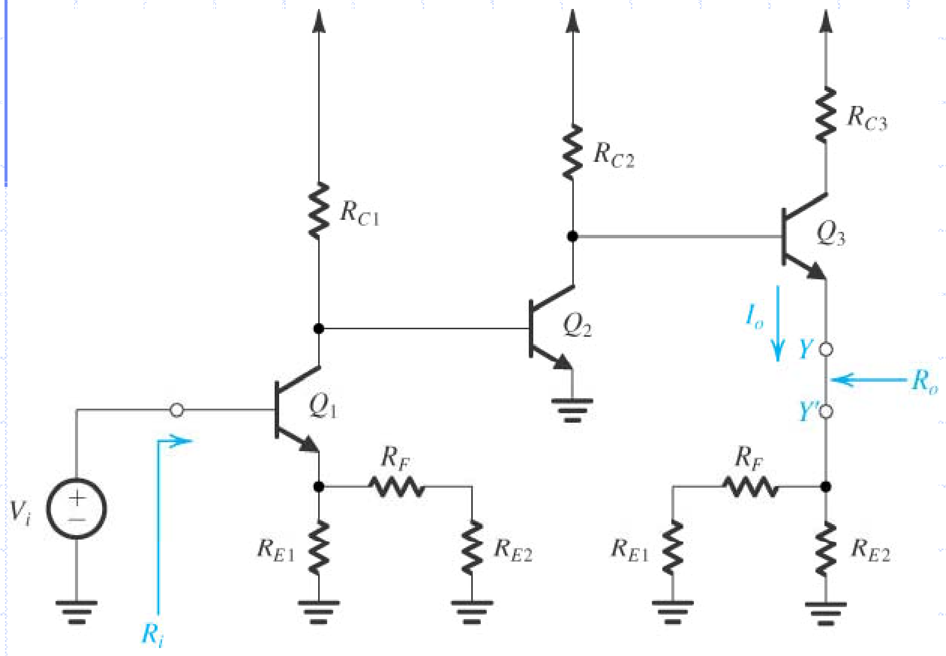
(a)

$$I_{C1} = 0.6\,mA$$
$$I_{C2} = 1\,mA$$
$$I_{C3} = 4\,mA$$
$$h_{fe} = 100$$
$$\text{assume} \quad r_0 = \infty$$

5. The Series-Series Feedback Amplifier

- Example 8.2(Cont'd)

  It samples current and mixes voltage, so series-series…



(b)

$$\frac{V_{c1}}{V_i} = \frac{-\alpha_1 (R_{C1} // r_{\pi 2})}{r_{e1} + [R_{E1} //(R_F + R_{E2})]}$$
$$\approx -14.92 (V/V)$$

$$\frac{V_{c2}}{V_{c1}} = -g_{m2}\{R_{C2} //(h_{fe}+1)[r_{e3} + (R_{E2} //(R_F + R_{E1}))]\}$$
$$\approx -131.2 (V/V)$$

$$\frac{I_o}{V_{c2}} = \frac{I_{e3}}{V_{b3}} = \frac{1}{r_{e3} + (R_{E2} //(R_F + R_{E1}))}$$
$$\approx 10.6 (mA/V)$$

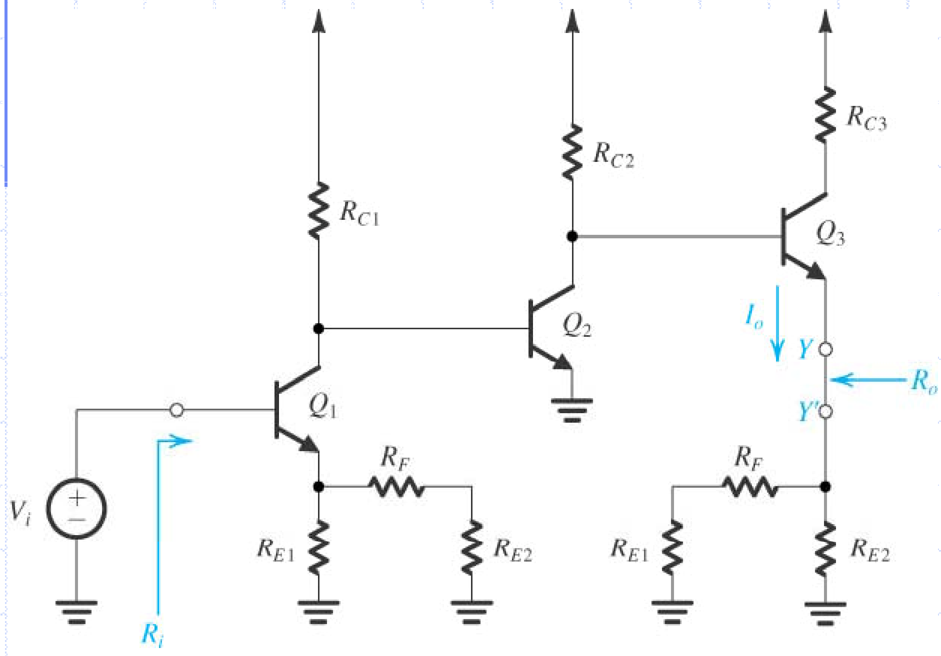
$$\Downarrow$$

$$A = \frac{I_o}{V_i} = \frac{V_{c1}}{V_i}\cdot\frac{V_{c2}}{V_{c1}}\cdot\frac{I_o}{V_{c2}}$$
$$\approx 20.7 (A/V)$$

$$\beta = \frac{V_f}{I_o} = \frac{R_{E2}}{R_{E2} + R_F + R_{E1}} \times R_{E1}$$
$$\approx 11.9 (\Omega)$$

5. The Series-Series Feedback Amplifier

Example 8.2(Cont'd)



(b)

$$A_f = \frac{I_o}{V_s} = \frac{A}{1 + A\beta} \approx 83.7\,(mA/V)$$

$$\frac{V_o}{V_s} = \frac{I_c R_{C3}}{V_s} \cong \frac{-I_o R_{C3}}{V_s} = -A_f R_{C3} \approx -50.2\,(V/V)$$

$$\begin{aligned} R_{if} &= R_i(1 + A\beta) \\ &= (h_{fe} + 1)[r_{e1} + (R_{E1} // (R_F + R_{E2}))](1 + A\beta) \\ &\approx 13.65 \times (1 + 20.5 \times 11.9) = 3.34\,(M\Omega) \end{aligned}$$

$$\begin{aligned} R_{of} &= R_o(1 + A\beta) \\ &= \{[R_{E2} // (R_F + R_{E1})] + r_{e3} + \frac{R_{C2}}{h_{fe} + 1}\}(1 + A\beta) \\ &\approx 143.9 \times (1 + 20.5 \times 11.9) = 35.6\,(k\Omega) \end{aligned}$$

if $r_o = 25\,k\Omega$

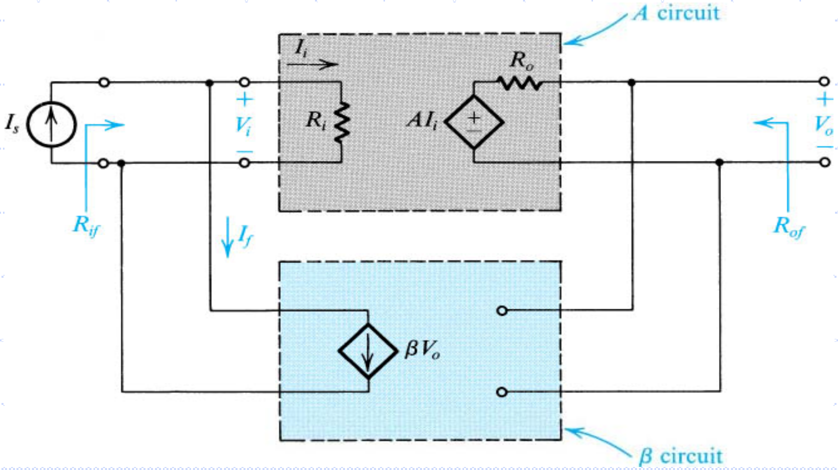
$$R_{out} = r_o + (1 + g_{m3} r_o)(R_{of} // r_{\pi 3}) \approx 2.5\,(M\Omega)$$

6.1 The Shunt-Shunt Feedback Amplifier

- Shunt–Shunt (transresistance amp)
  => Input is mixed in current(shunt), and output is sampled in voltage(shunt).
  - Whenever current is mixed, the input impedance is reduced by the amount of feedback.
  - Whenever voltage is sampled, the output impedance is reduced by the amount of feedback.

6.1 The Shunt-Shunt Feedback Amplifier

- Ideal Situation

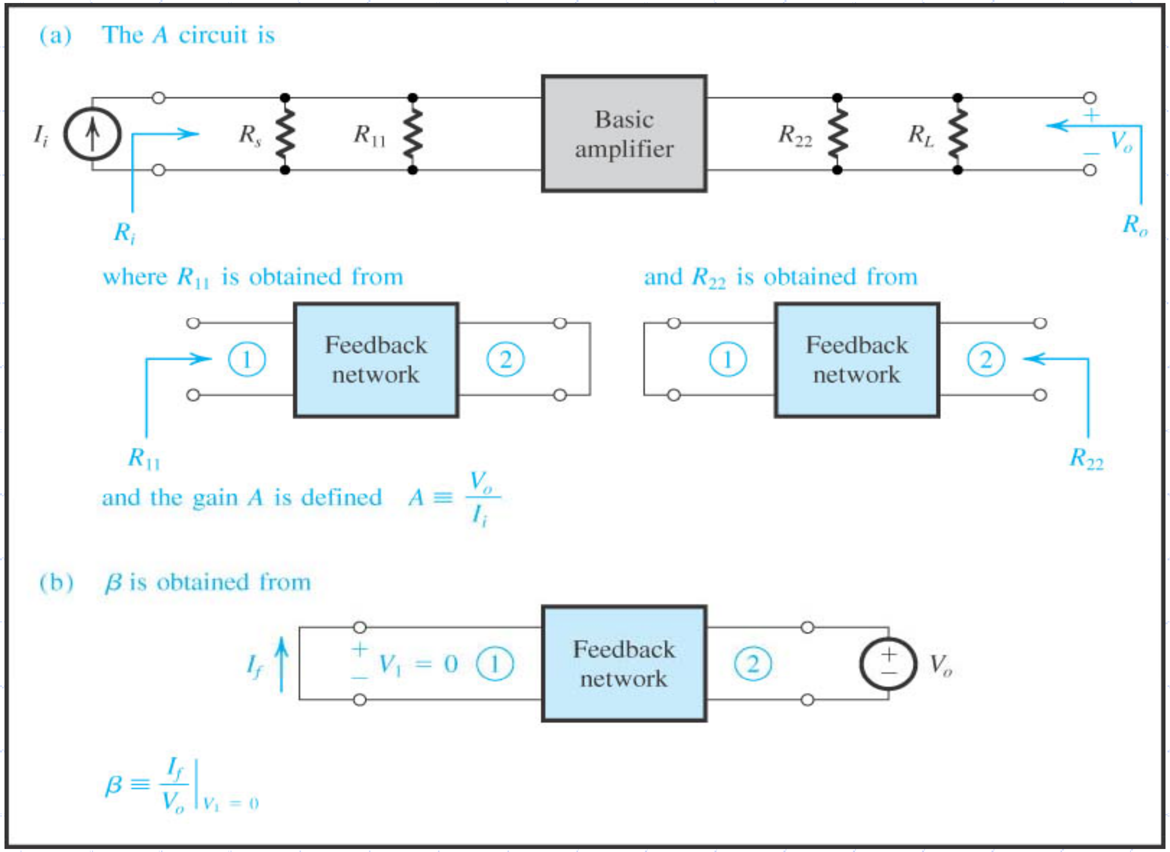


$$Z_{if} = \frac{Z_i(s)}{1 + A(s)\beta(s)}$$

$$Z_{of} = \frac{Z_o(s)}{1 + A(s)\beta(s)}$$

6.1 The Shunt-Shunt Feedback Amplifier

Summary



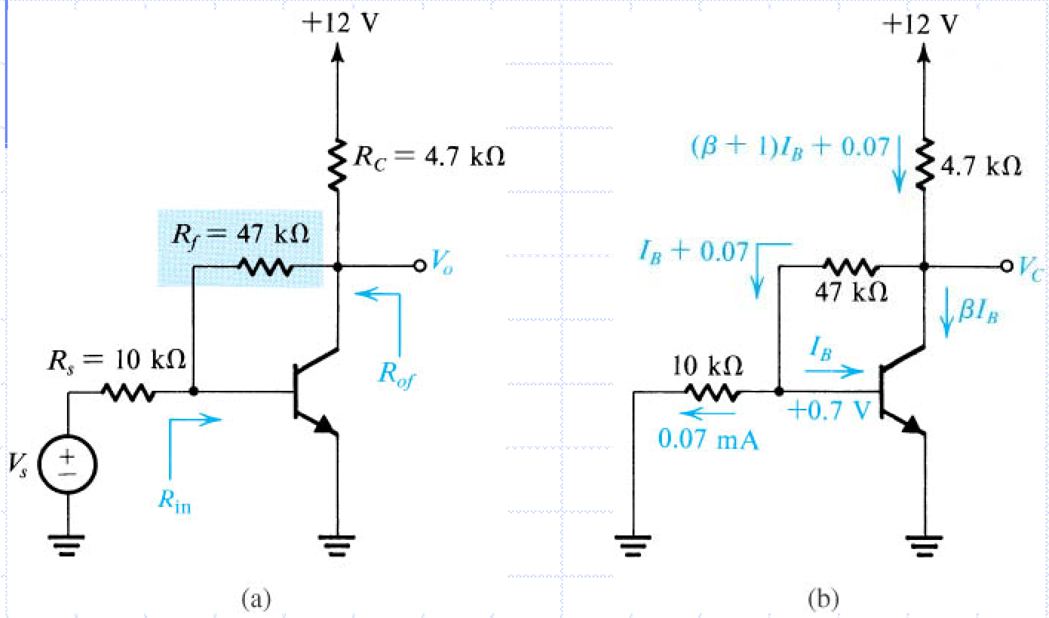
$$R_{in} = 1/(\frac{1}{R_{if}} - \frac{1}{R_s})$$

$$R_{out} = 1/(\frac{1}{R_{of}} - \frac{1}{R_L})$$

6.1 The Shunt-Shunt Feedback Amplifier

- **Example 8.3**

Q : Determine $V_o / V_s, R_{in}, R_{of}$.($\beta = 100$)



$$V_C = 0.7 + (I_B + 0.07)47 = 3.99 + 47 I_B$$

$$\frac{12 - V_C}{4.7} = (\beta + 1) I_B + 0.07$$

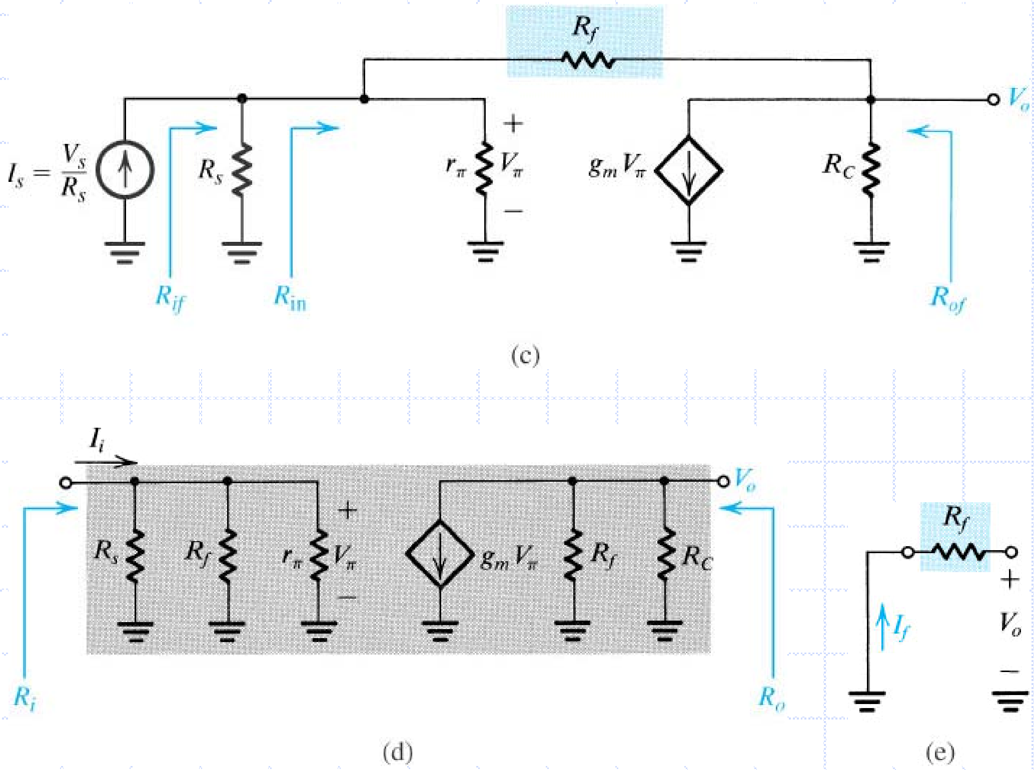
$$I_B \approx 0.015\ (mA)$$

$$I_C \approx 1.5 (mA)$$

$$V_C \approx 4.7 (V)$$

6.1 The Shunt-Shunt Feedback Amplifier

- Example 8.3(Cont'd)



It samples voltage and mixes current, so shunt-shunt…

$$V_\pi = I_i (R_s // R_f // r_\pi)$$

$$V_o = -g_m V_\pi (R_f // R_C)$$

$$\Downarrow$$

$$A = \frac{V_o}{I_i} = -g_m (R_f // R_C)(R_s // R_f // r_\pi)$$

$$= -358.7 (k\Omega)$$

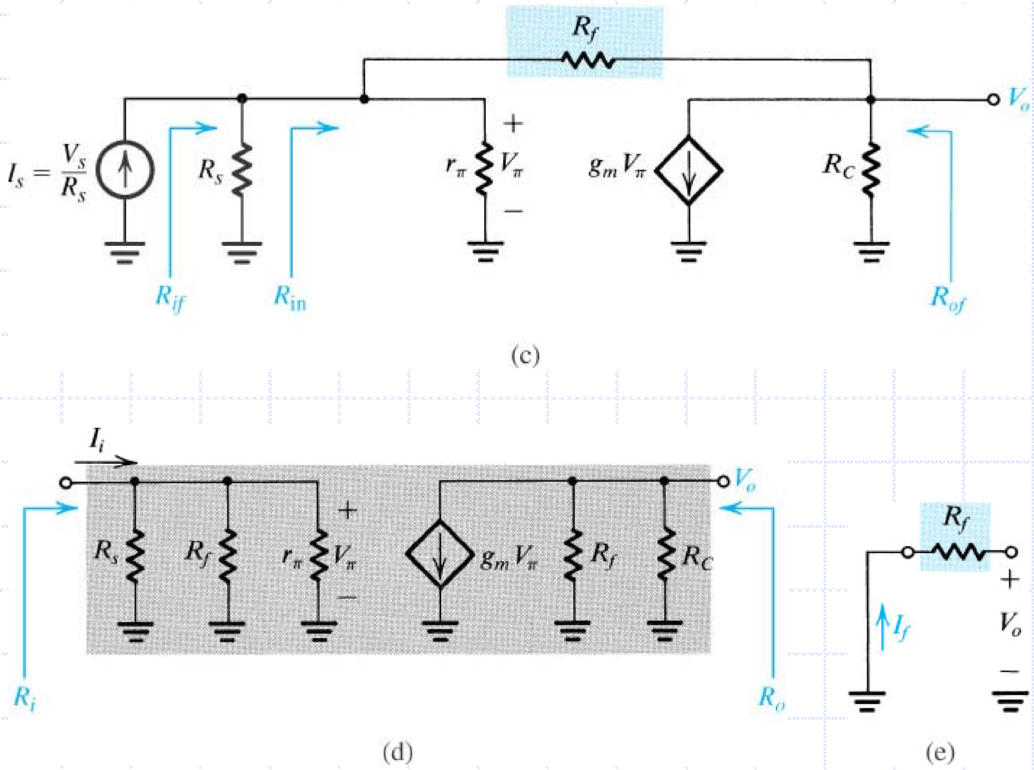
$$\beta = \frac{I_f}{V_o} = -\frac{1}{R_f} = -\frac{1}{47 (k\Omega)}$$

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

$$= -41.6 (k\Omega)$$

6.1 The Shunt-Shunt Feedback Amplifier

- Example 8.3(Cont'd)



$$\frac{V_o}{V_s} = \frac{V_o}{I_s R_s} = \frac{A_f}{R_s} = -4.16\,(V/V)$$

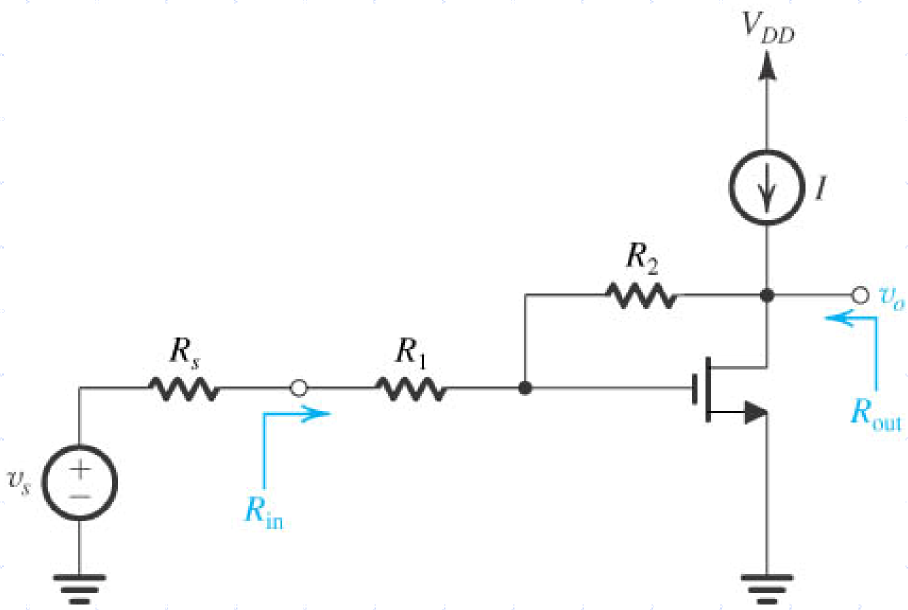
$$R_{if} = \frac{R_i}{1 + A\beta} = \frac{R_s \,//\, R_f \,//\, r_\pi}{1 + A\beta}$$
$$= 162.2\,(\Omega)$$

$$R_{of} = \frac{R_o}{1 + A\beta} = \frac{R_C \,//\, R_f}{1 + A\beta}$$
$$= 495\,(\Omega)$$

6.1 The Shunt-Shunt Feedback Amplifier

Problem 8.42(p.866)

Q : Identify the type of feedback used and find V_o/V_s, R_{in}, and R_{out}.



Given

$I = 1(mA)$

$V_{GS} = 0.8(V)$

$V_t = 0.6(V)$

$V_A = 30\,(V)$

$R_S = 10\,(k\Omega)$

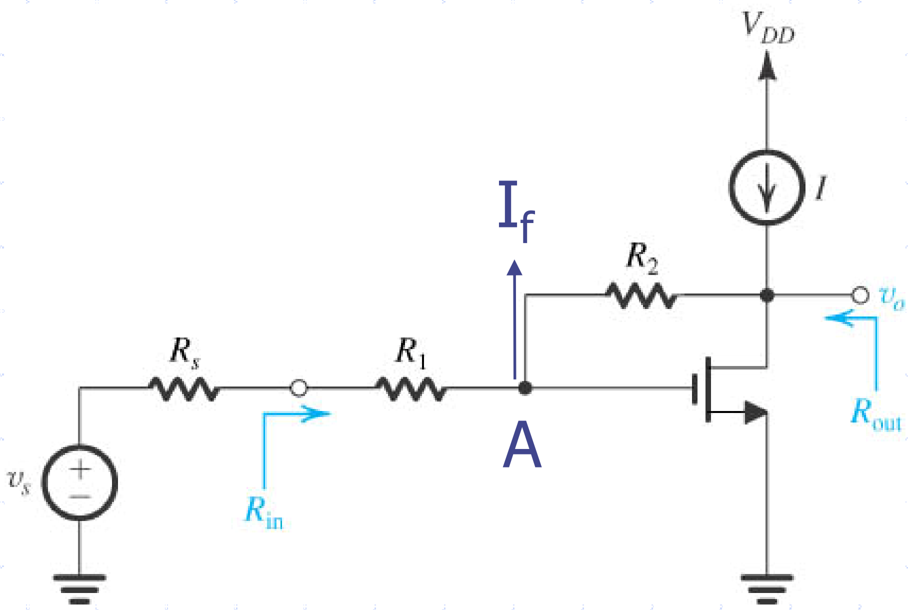
$R_1 = 10\,(M\Omega)$

$R_2 = 4.7(M\Omega)$

6.1 The Shunt-Shunt Feedback Amplifier

- Problem 8.42(p.866) (Cont'd)

Voltage is sampled, and current is mixed.
So shunt-shunt feedback amplifier.



$$A = \frac{V_o}{I_S} = \frac{V_A}{I_s}\frac{V_o}{V_A}$$

$$= -[(R_s + R_1) // R_2](R_2 // r_o) g_m$$

$$= -2.4 \times 10^7 (V / A)$$

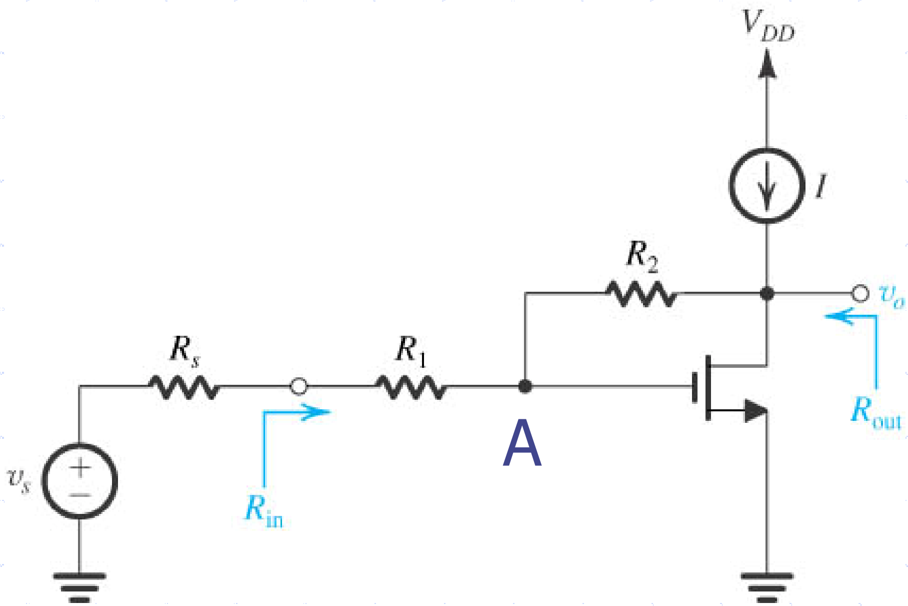
$$\beta = \frac{I_f}{V_o} = -\frac{1}{R_f} = -2.1 \times 10^{-7} (A / V)$$

$$A_f = \frac{A}{1 + A\beta} = -3.9 \times 10^3 (V / A)$$

$$\frac{V_o}{V_s} = \frac{A_f}{R_s + R_1} = -3.89 (V / V)$$

6.1 The Shunt-Shunt Feedback Amplifier

◆ Problem 8.42(p.866) (Cont'd)



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

$$= 126\ (k\Omega)$$

$$R_{out} = R_{of} = \frac{r_o // R_2}{1 + A\beta}$$

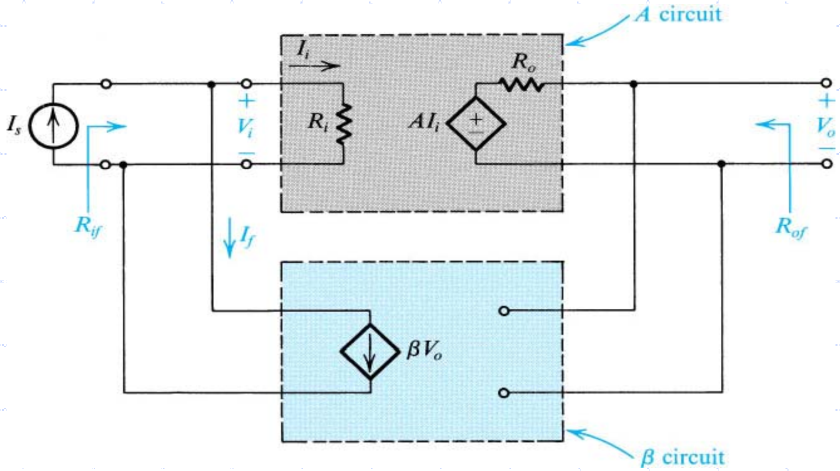
$$= 4.86\ (k\Omega)$$

6.2 The Shunt-Series Feedback Amplifier

- Shunt–Series (current amp)
  => Input is mixed in current(shunt), and output is sampled in current(series).
  - Whenever current is mixed, the input impedance is reduced by the amount of feedback.
  - Whenever current is sampled, the output impedance is increased by the amount of feedback.

6.2 The Shunt-Series Feedback Amplifier

- Ideal Situation

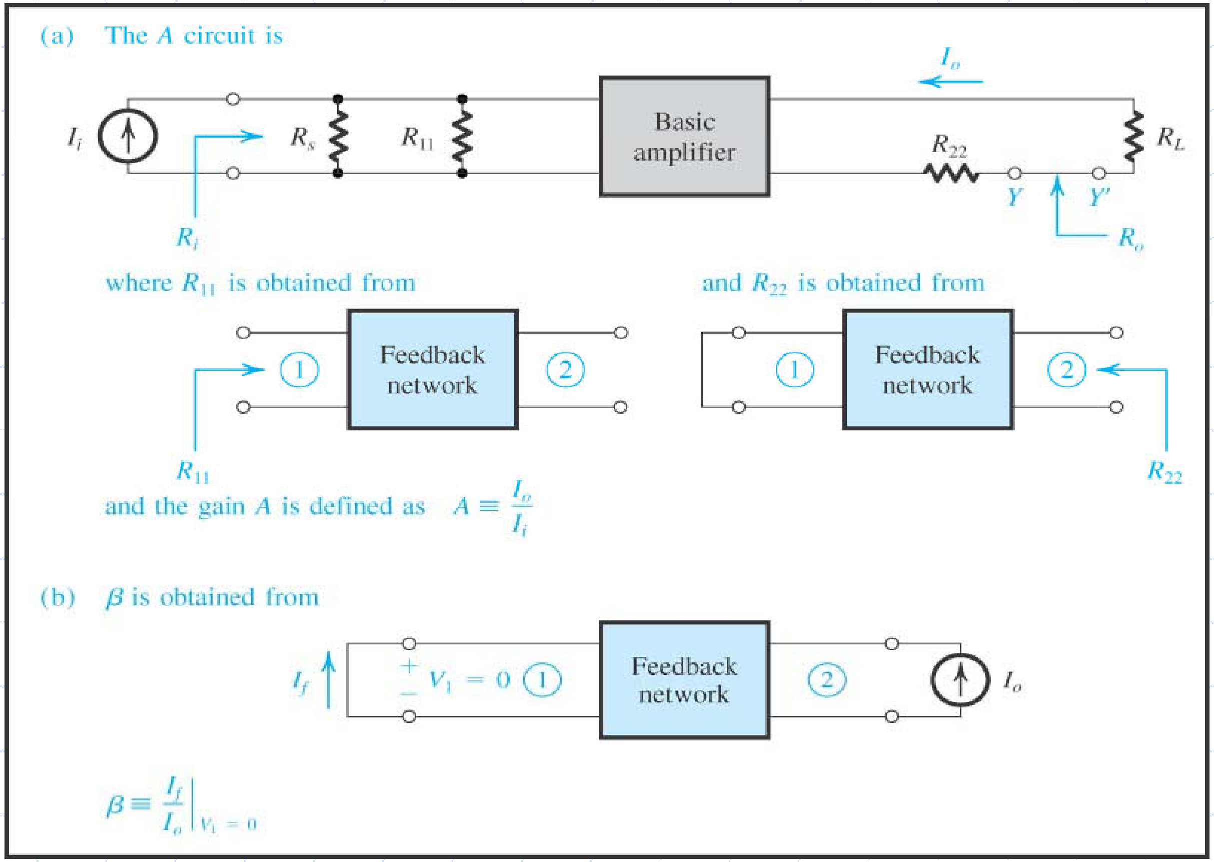


$$Z_{if} = \frac{Z_i(s)}{1 + A(s)\beta(s)}$$

$$Z_{of} = Z_o(1 + A(s)\beta(s))$$

6.2 The Shunt-Series Feedback Amplifier

◆ Summary



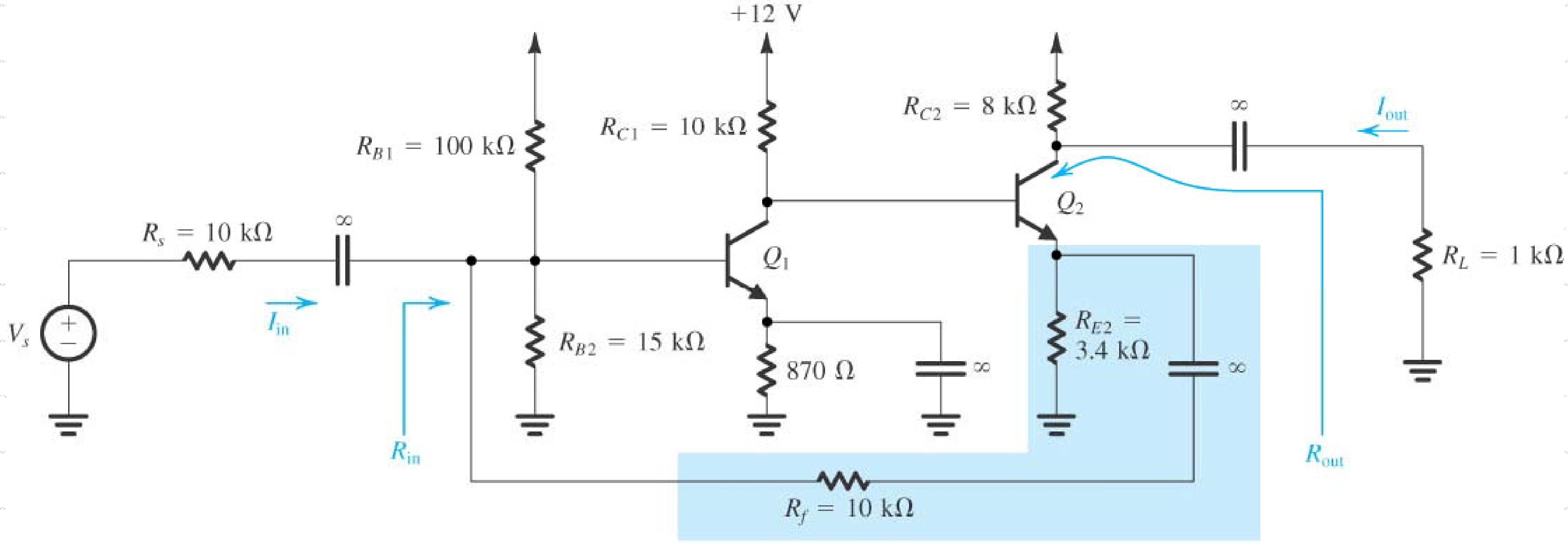
$$R_{in} = 1/(\frac{1}{R_{if}} - \frac{1}{R_s})$$

$$R_{out} = R_{of} - R_L$$

6.2 The Shunt-Series Feedback Amplifier

Example 8.4

Q : Find out I_{out}/I_{in}, R_{in}, and R_{out}. ($\beta = 100$, $V_A = 75$(V))

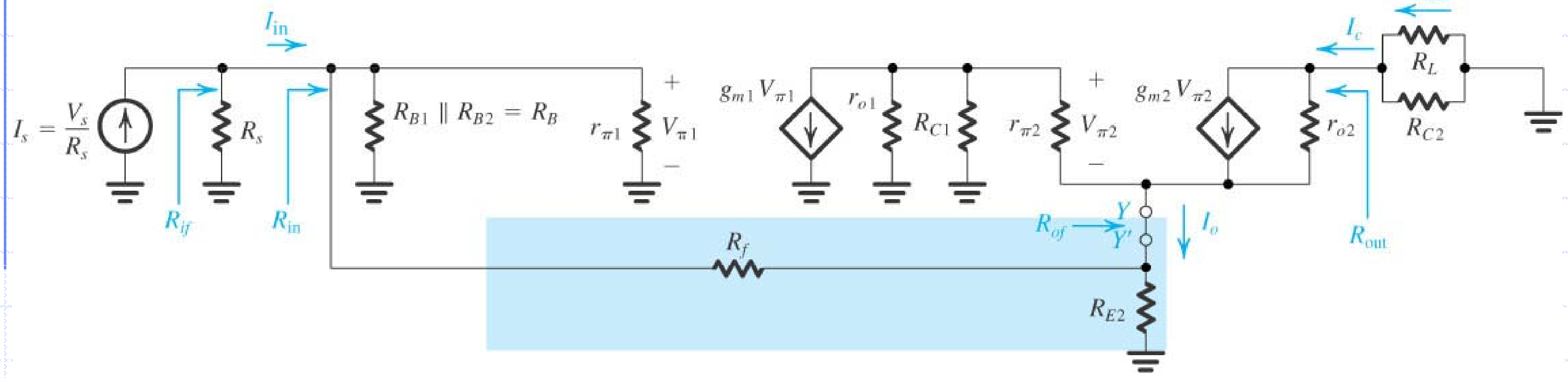


(a)

6.2 The Shunt-Series Feedback Amplifier

◆ Example 8.4(Cont'd)

It samples current and mixes current, so shunt-series…



(b)

$$V_{B1} \approx 12 \times [15/(100+15)] = 1.57\,(V)$$

$$V_{E1} \approx 1.57 - 0.7 = 0.87\,(V)$$

$$I_{E1} \approx 0.87/0.87 = 1(mA)$$

$$V_{C1} \approx 12 - 10 \times 1 = 2\,(V)$$

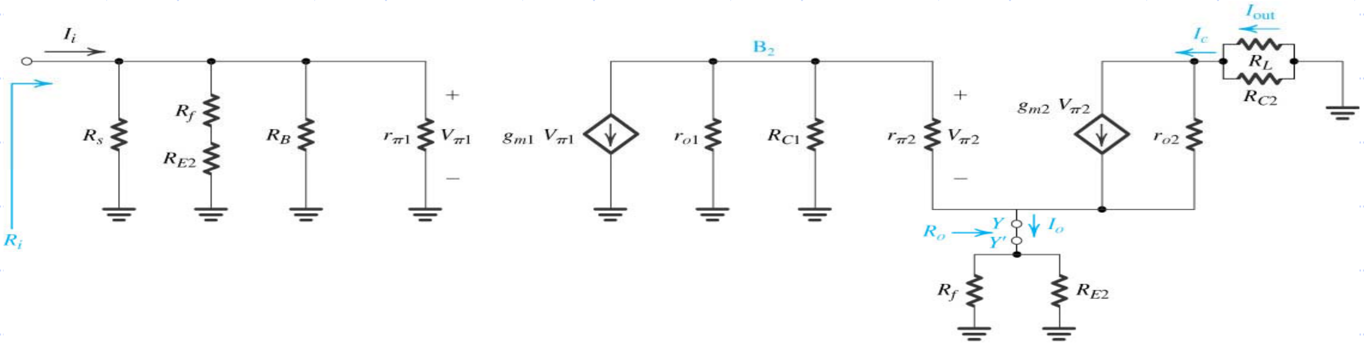
$$V_{E2} \approx 2 - 0.7 = 1.3(V)$$

$$I_{E2} \approx 1.3/3.4 = 0.4(mA)$$

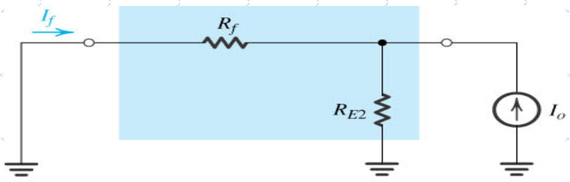
$$V_{C2} \approx 12 - 0.4 \times 8 = 8.8(V)$$

6.2 The Shunt-Series Feedback Amplifier

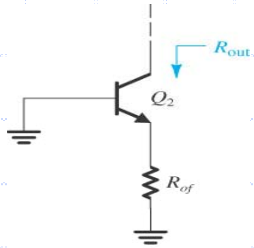
- Example 8.4(Cont'd)



(c)



(d)



(e)

$$V_{\pi1} = I_i[R_s //(R_{E2} + R_f)// R_B // r_{\pi1}]$$

$$V_{b2} = -g_{m1}V_{\pi1}\{r_{o1} // R_{C1} //[r_{\pi2} + (\beta+1)(R_{E2} // R_f)]\}$$

$$I_o = \frac{V_{b2}}{r_{e2} + (R_{E2} // R_f)}$$

$$A = \frac{I_o}{I_i} \approx -201.45\,(A/A)$$

$$\beta = \frac{I_f}{I_o} = -\frac{R_{E2}}{R_{E2} + R_f} = -0.254$$

6.2 The Shunt-Series Feedback Amplifier

Example 8.4(Cont'd)

$$1 + A\beta = 52.1$$

$$R_i = R_s //(R_{E2} + R_f) // R_B // r_{\pi 1}$$

$$= 1.535\ (k\Omega)$$

$$R_{if} = \frac{R_i}{1 + A\beta} = 29.5(\Omega)$$

$$R_{in} = \frac{1}{1/R_{if} - 1/R_s} = 29.5(\Omega)$$

$$R_o = (R_{E2} // R_f) + r_{e2} + \frac{R_{C1} // r_{o1}}{\beta + 1}$$

$$= 2.69\ (k\Omega)$$

$$R_{of} = R_o(1 + A\beta) = 140.1(k\Omega)$$

$$R_{out} = r_{o2}[1 + g_{m2}(r_{\pi 2} // R_{of})]$$

$$= 18.1(M\Omega)$$

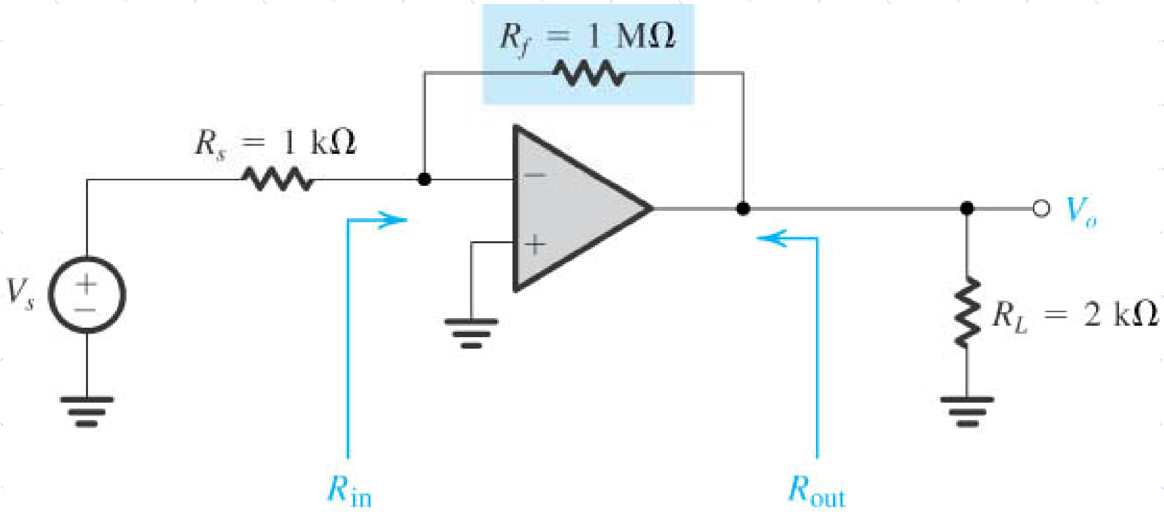
$$A_f = \frac{I_o}{I_s} = \frac{A}{1 + A\beta} = -3.87\ (A/A)$$

$$\frac{I_{out}}{I_{in}} \approx \frac{I_{out}}{I_s} = \frac{R_{C2}}{R_L + R_{C2}} \frac{I_c}{I_s} \approx \frac{R_{C2}}{R_L + R_{C2}} \frac{I_o}{I_s} = -3.44\ (A/A)$$

6.2 The Shunt-Series Feedback Amplifier

Exercise

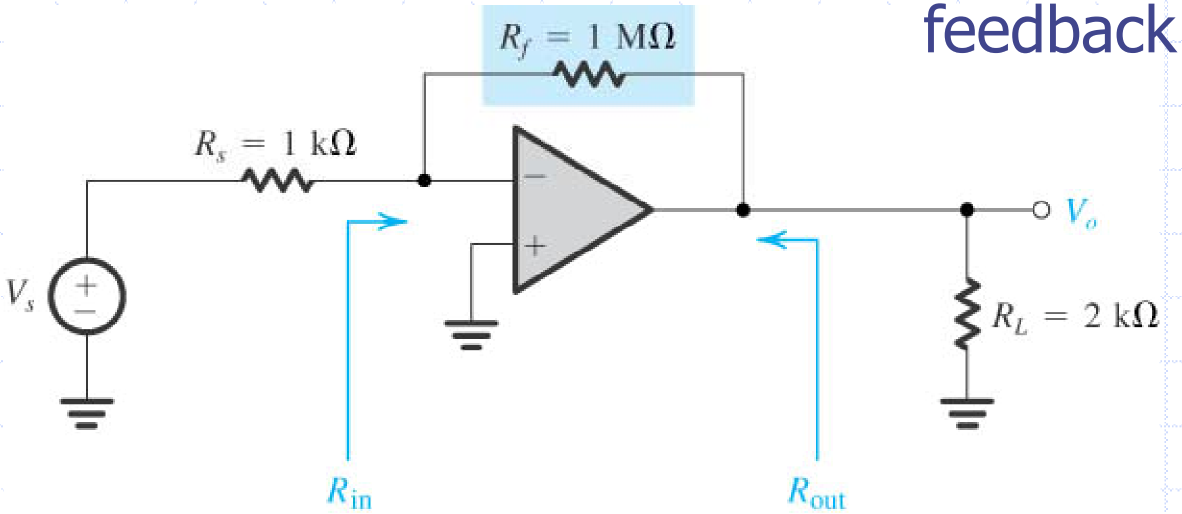
Q : Identify the type of feedback used.



6.2 The Shunt-Series Feedback Amplifier

◆ Exercise (Cont'd)

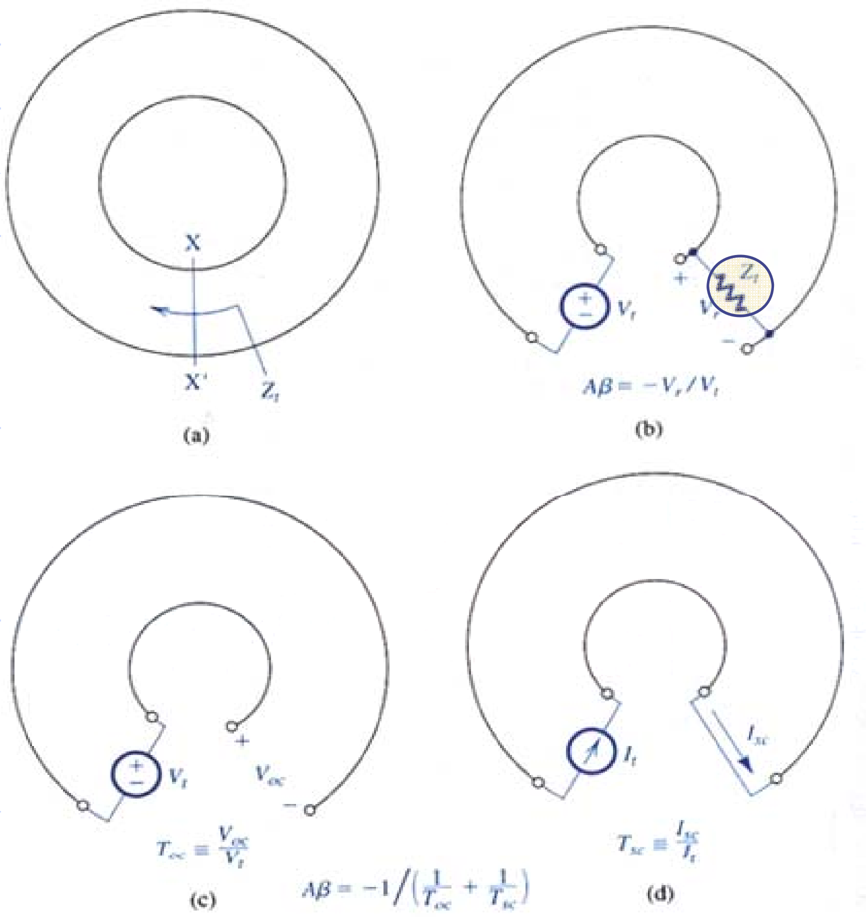
Voltage is sampled and current is mixed, so shunt-shunt feedback amplifier.



7. Determining The Loop Gain

Alternative Approaches

L(s)=A(s)β(s)=loop transmission



Approach 1.

$$A\beta = -\frac{V_r}{V_t}$$

Approach 2.

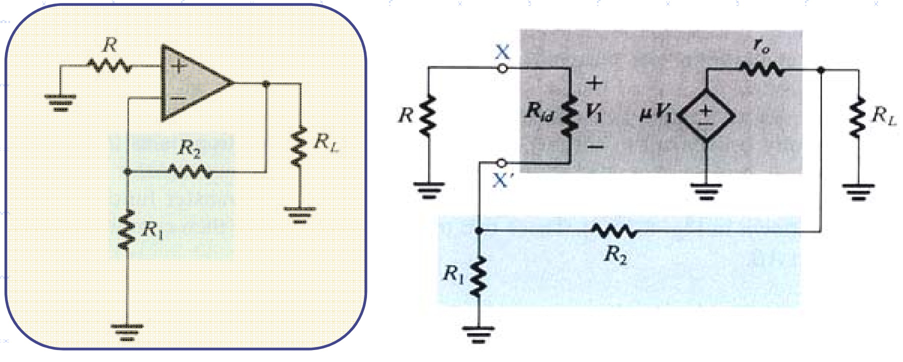
$$A\beta = \frac{-1}{\frac{1}{T_{oc}} + \frac{1}{T_{sc}}}$$

(Rosenstark, 1986)

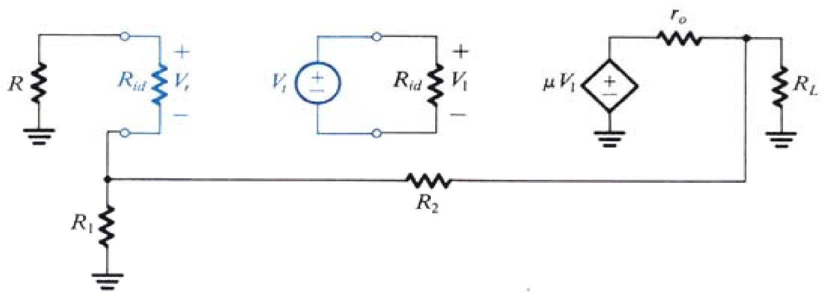
7. Determining The Loop Gain

◆ Example – Approach 1.

Q. Determine the loop gain of the following circuit.



(a) (b)



(c)

$$A\beta_1 = -\frac{R_{id}}{R_{id}+R}\cdot\mu$$

$$\cdot\frac{R_L \| [R_2 + R_1 \| (R_{id}+R)]}{r_o + R_L \| [R_2 + R_1 \| (R_{id}+R)]}$$

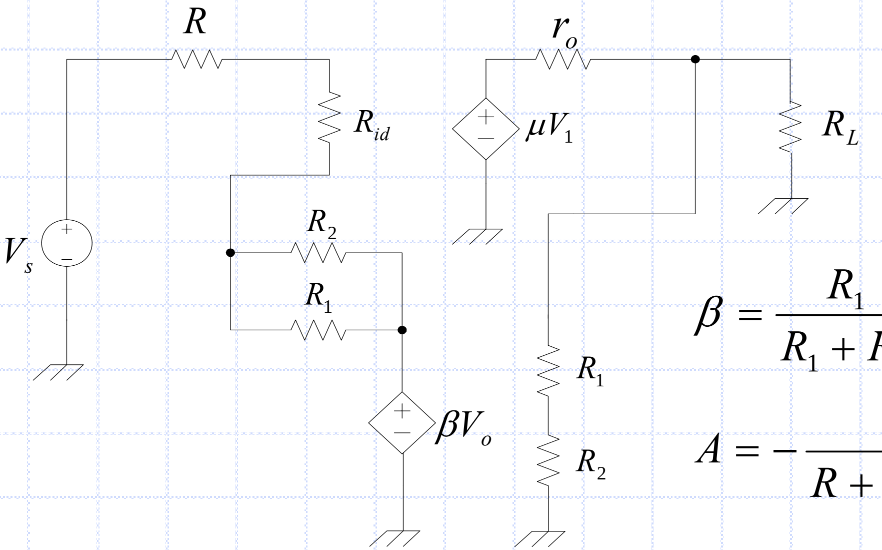
$$\cdot\frac{R_1 \| (R_{id}+R)}{R_2 + (R_1 \| (R_{id}+R))}$$

$$\approx -\frac{R_1}{R_1+R_2}\cdot\mu$$

$$when \quad R_{id} >> (R_1, R_2),\ r_0 \approx 0$$

7. Determining The Loop Gain

◆ Example – Approach 2.



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

$$A = -\frac{R_{id}}{R + R_{id} + (R_1 \| R_2)} \cdot \mu \cdot \frac{R_L \| (R_1 + R_2)}{r_o + R_L \| (R_1 + R_2)}$$

$$A\beta_2 = -\frac{R_{id}}{R + R_{id} + (R_1 \| R_2)} \cdot \mu \cdot \frac{R_L \| (R_1 + R_2)}{r_o + R_L \| (R_1 + R_2)} \cdot \frac{R_1}{R_1 + R_2}$$

$$\approx -\frac{\mu}{R_1 + R_2}$$

$$when \quad R_{id} >> (R_1, R_2), \quad r_0 \approx 0$$

7. Determining The Loop Gain

Comparison of the two results

$$A\beta_1 = \frac{R_{id}}{R_{id}+R} \cdot \mu \cdot \frac{R_L \| [R_2 + R_1 \| (R_{id}+R)]}{r_o + R_L \| (R_2 + R_1 \| (R_{id}+R))} \cdot \frac{R_L \| (R_{id}+R)}{R_2 + R_1 \| (R_{id}+R)}$$

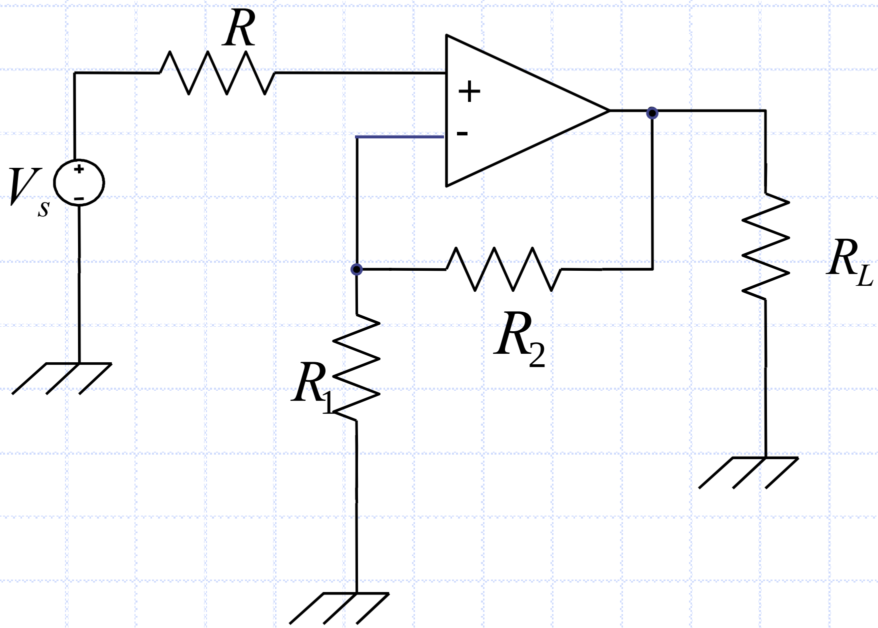
$$A\beta_2 = -\frac{R_{id}}{R + R_{id} + (R_1 \| R_2)} \cdot \mu \cdot \frac{R_L \| (R_1+R_2)}{r_o + R_L \| (R_1+R_2)} \cdot \frac{R_1}{R_1+R_2}$$

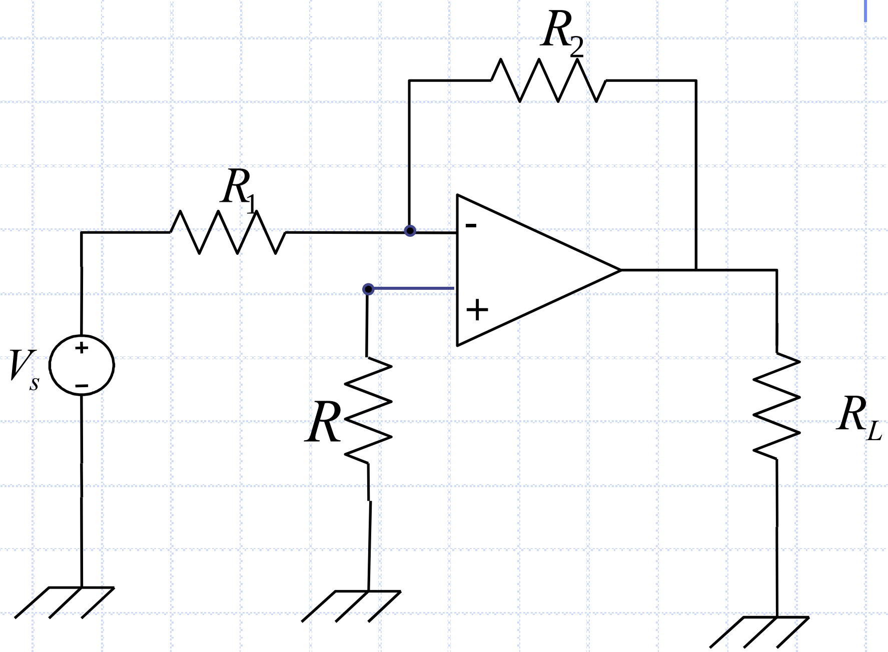
When $R_{id} >> (R_1, R_2)$, $r_0 \approx 0$, both values come to

$$A\beta_1 \cong A\beta_2 \cong -\frac{\mu}{R_1+R_2}$$

7. Determining The Loop Gain

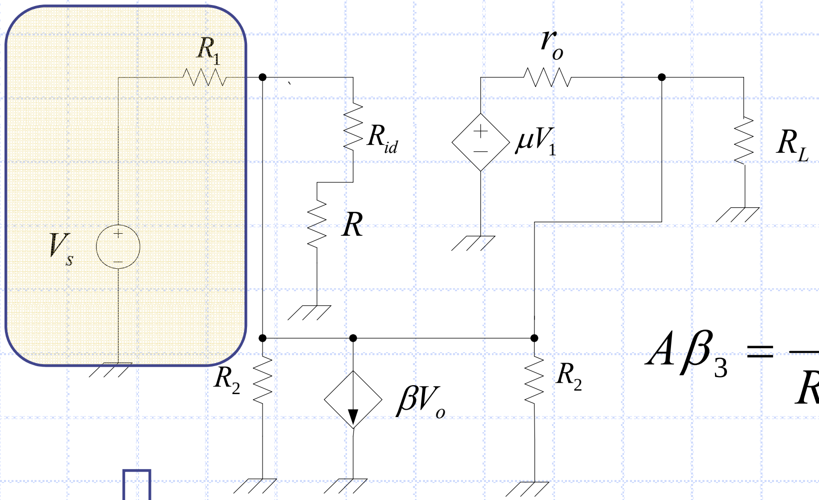
- Loop Equivalent with Different Op-Amp Circuits





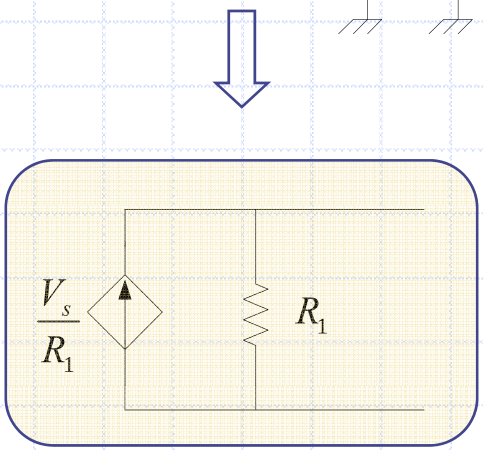
7. Determining The Loop Gain

◆ Example – Approach 3. Shunt-Shunt FB



$$A\beta_3 = \frac{R_{id}}{R + R_{id}} \cdot \frac{1}{R_1 \| R_2 \| (R_{id} + R)} \cdot \mu \cdot \frac{R_L \| R_2}{r_o + (R_L + R_2)} \cdot \frac{1}{R_2}$$

$$= \frac{R_{id}}{R + R_{id}} \cdot \frac{R_1 \| R_2}{R_2} \cdot \mu = \frac{R_{id}}{R + R_{id}} \cdot \frac{R_1}{R_1 + R_2} \cdot \mu$$



As $r_o \approx 0, R_{id} \approx \infty$,

$$A\beta_3 \approx -\frac{R_1}{R_1 + R_2} \cdot \mu$$

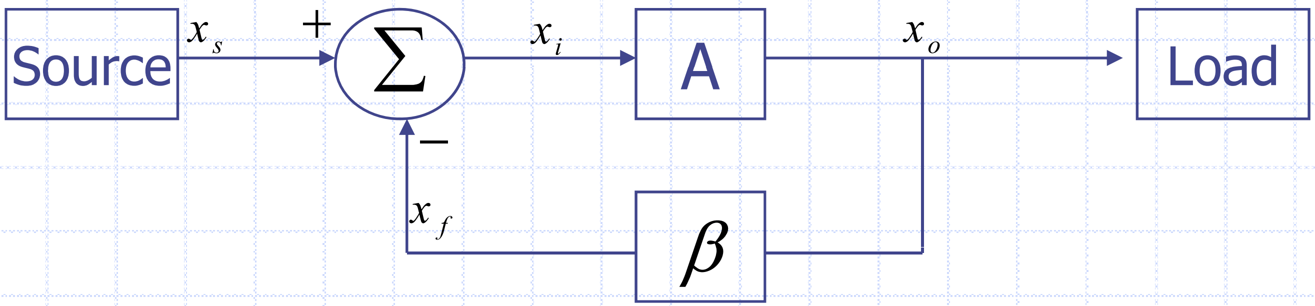
8. Stability Problem

- Feedback systems do not always have a tendency to stabilize.

- Under some conditions, the system will diverge and oscillate.

8. Stability Problem

- In an iterative process inside the loop…



x_s	1		
x_i	1	$1-A\beta$	$1-A\beta(1-A\beta)$
x_o	A	$A(1-A\beta)$	$A(1-A\beta(1-A\beta))$
x_f	$A\beta$	$A\beta(1-A\beta)$	$A\beta(1-A\beta(1-A\beta))$

$$
\begin{aligned}
x_o(\infty) &= A[1-A\beta(1-A\beta(1-A\beta\cdots\cdots \\
&= A[1-A\beta+(A\beta)^2-(A\beta)^3\cdots\cdots \\
&= A\cdot\frac{1-(-A\beta)^{\infty}}{1+A\beta}
\end{aligned}
$$

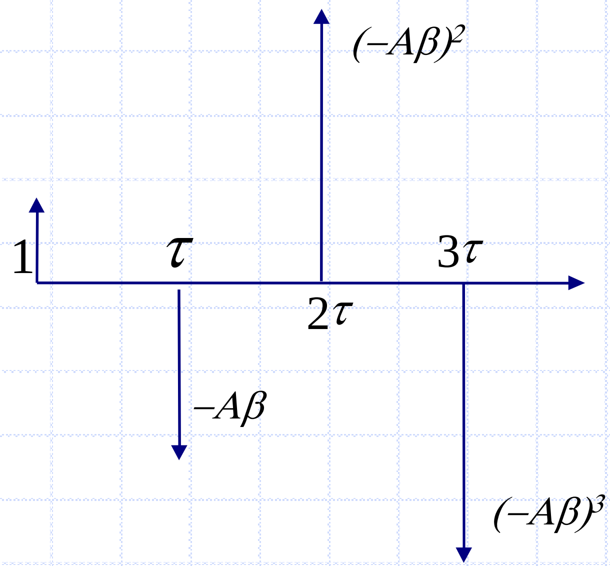
8. Stability Problem

- Conditions for stability under negative FB.
  - The system is stable IFF $x_0(\infty)$ converges.

All events occur simultaneously => stable

what if there is a delay in the loop => unstable

$$A(j\omega) = \frac{A(j\omega)}{1 + A(j\omega)\beta(j\omega)}$$



[unstable]

$$L(j\omega) = A(j\omega)\beta(j\omega)$$
$$= |A(j\omega)\beta(j\omega)| e^{j\Phi(w)}$$

if $A(j\omega)\beta(j\omega) \le -1$ => oscillation

when $\angle A(j\omega)\beta(j\omega) = -180^o$,

$|A(j\omega)\beta(j\omega)| > 1$ => oscillation

Magnitude of oscillation will grow until some nonlinearity eventually makes $|A\beta|=1$.

8. Stability Problem

- Problem 8.63(p.869)

  Q. Find the value of k above which the closed-loop amplifier becomes unstable.

Given $\Longrightarrow$ $A(s) = \dfrac{1000}{1 + \dfrac{s}{10^4}}$ $\quad \beta(s) = \dfrac{k}{(1 + \dfrac{s}{10^4})^2}$

8. Stability Problem

- Problem 8.63(p.869) (Cont'd)

$$Ang\,(A(s)\beta(s)) = -180^\circ = -3\tan^{-1}\frac{\omega_{180}}{10^4} \Longrightarrow \omega_{180} = \sqrt{3}\times 10^4 (rad\,/\,s)$$

If $|A\beta|_{\omega=\omega_{180}}$ <1 the system is stable.

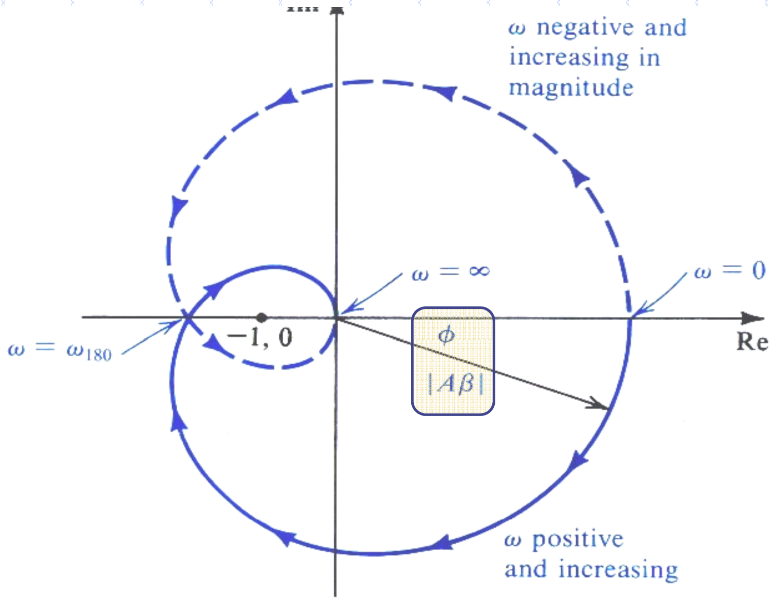
$$\Longrightarrow \frac{10^3}{\sqrt{1+(\sqrt{3})^2}} \cdot \frac{k}{1+(\sqrt{3})^2} < 1$$

$$\Longrightarrow k < 0.008$$

8. Stability Problem

◆ Nyquist plot example

$$A(s)\beta(s) = \frac{A_o}{(1+s/\omega_1)(1+s/\omega_2)(1+s/\omega_3)}$$



Because the magnitude of the loop gain is an even function and the phase is an odd function, the nyquist plot for negative frequency is a mirror image of nyquist plot of the positive frequency.

If the nyquist plot intersects the real axis on the left of (-1, 0), then the system is unstable.
-> The plot encircles the point (-1,0), thus the system is unstable.

9. Effect of Feedback on The Amplifier Poles

Stability and pole location

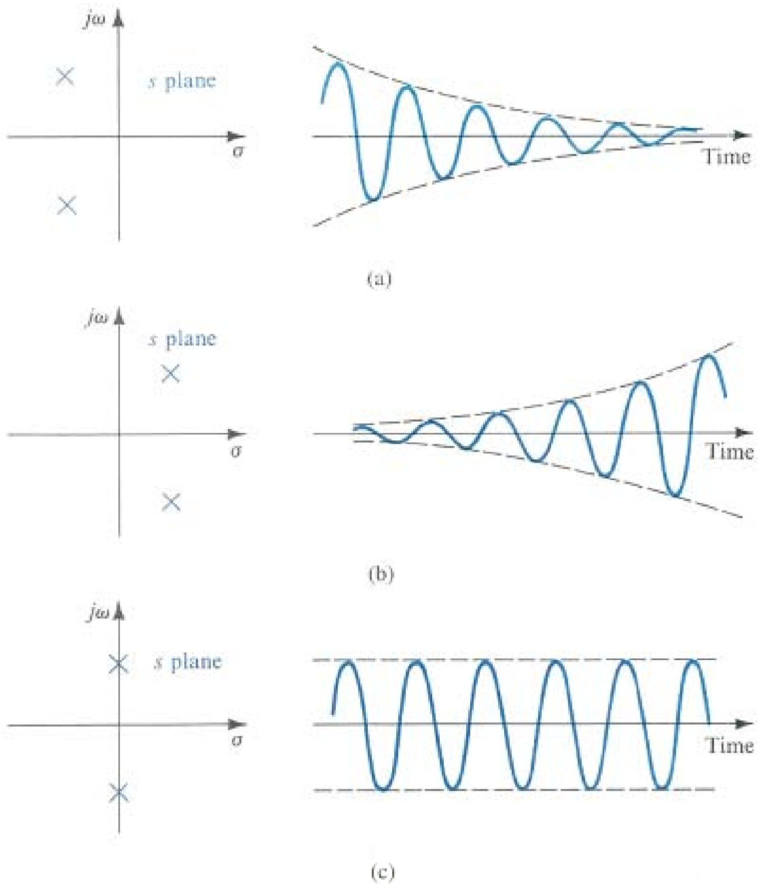


Fig. 8.29 Relationship between pole location and transient response.

$$v(t) = e^{\sigma t}\left(e^{j\omega_n t} + e^{-j\omega_n t}\right) = 2e^{\sigma t}\cos\omega_n t$$

$$\begin{cases} \sigma \geq 0 : unstable \\ \sigma < 0 : stable \end{cases}$$

Poles of FB system

$$V_O(s) = H(s)V_I(s)$$

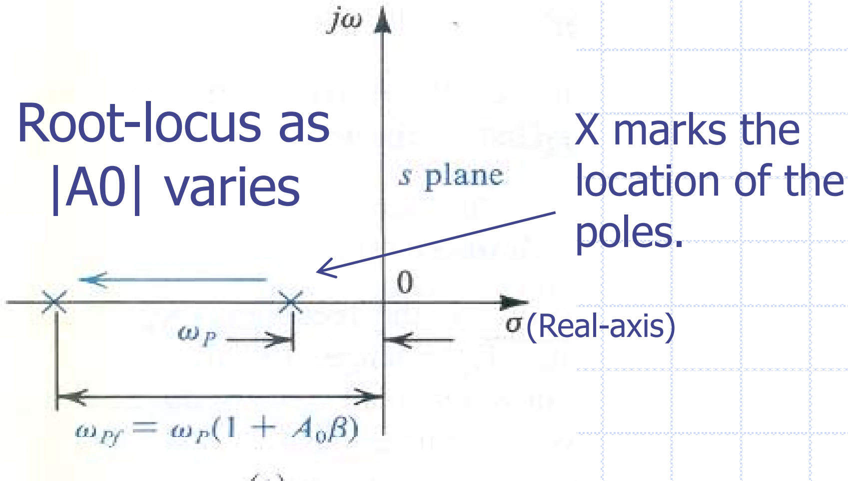
$$H(s) = \frac{A(s)}{1 + A(s)\beta(s)}$$

Characteristic equation

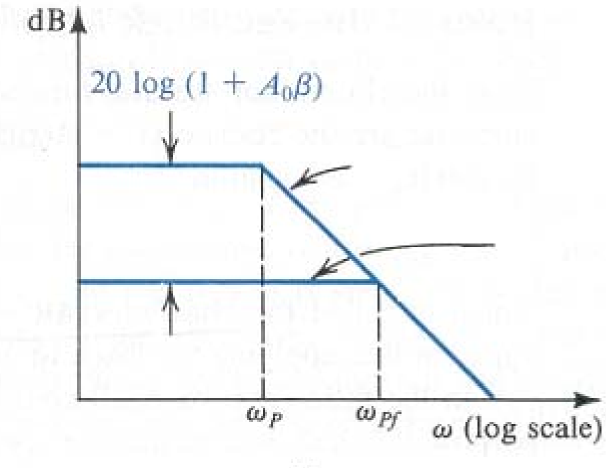
$$\boxed{1 + A(s)\beta(s) = 0}$$

9. Effect of Feedback on The Amplifier Poles

◆ Amplifier with one pole



(a)



(b)

$$A(s) = \frac{A_0}{1 + s/\omega_p}$$

Characteristc Eq. →

$$1 + A(s) \cdot \beta = 1 + \frac{\beta A_0}{1 + s/\omega_p} = 0$$

$$\boxed{\beta A_0 + 1 + s/\omega_p = 0}$$

Solve this to find where the pole is.

9. Effect of Feedback on The Amplifier Poles

Amplifier with two poles

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

$$= \frac{A_0/(1+s/\omega_{p1})(1+s/\omega_{p2})}{1+\beta A_0/(1+s/\omega_{p1})(1+s/\omega_{p2})}$$

$$= \frac{A_0\omega_{p1}\omega_{p2}}{s^2 + s(\omega_{p1}+\omega_{p2}) + (1+A_0\beta)\omega_{p1}\omega_{p2}}$$

$$= \boxed{\frac{A_{0f}\omega_0^2}{s^2 + s\cdot\frac{\omega_0}{Q} + \omega_0^2}}$$

$$|A_f(j\omega)| = \frac{A_{0f}\omega_0^2}{\sqrt{(\omega_0^2-\omega^2)^2 + \left(\frac{\omega\omega_0}{Q}\right)^2}}$$

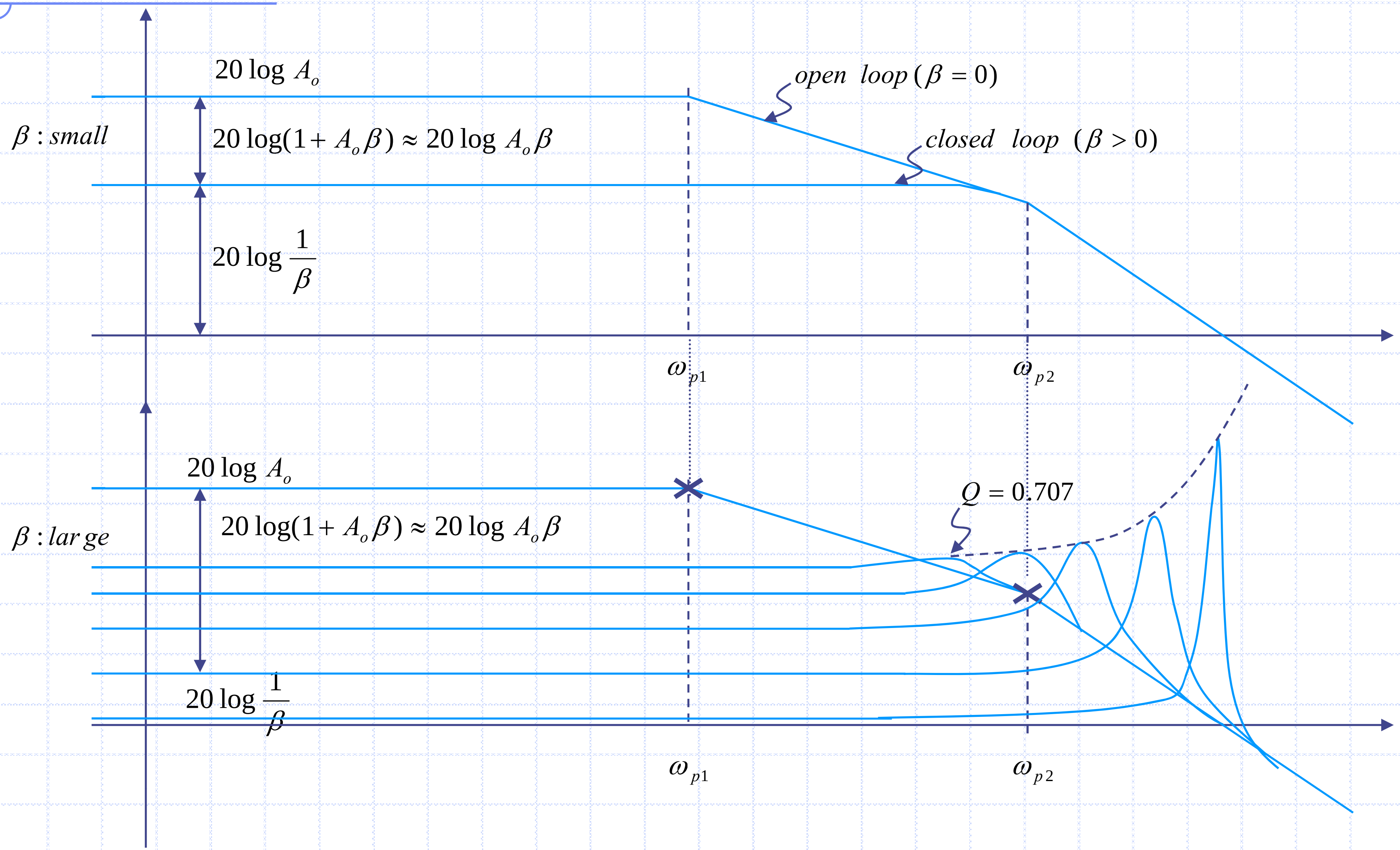
$$s^2 + s\frac{\omega_0}{Q} + \omega_0^2 = 0$$

ω_0 : *pole frequency* , Q : *pole Q factor*

$$\omega_0 = \sqrt{(1+A_0\beta)\omega_{p1}\omega_{p2}} \qquad Q = \frac{\sqrt{(1+A_0\beta)\omega_{p1}\omega_{p2}}}{\omega_{p1}+\omega_{p2}}$$

- Characteristic equation
  - Peaking starts to show in frequency domain at Q > 0.707.
  - Ringing starts to show in time domain at Q > 0.5.

9. Effect of Feedback on The Amplifier Poles



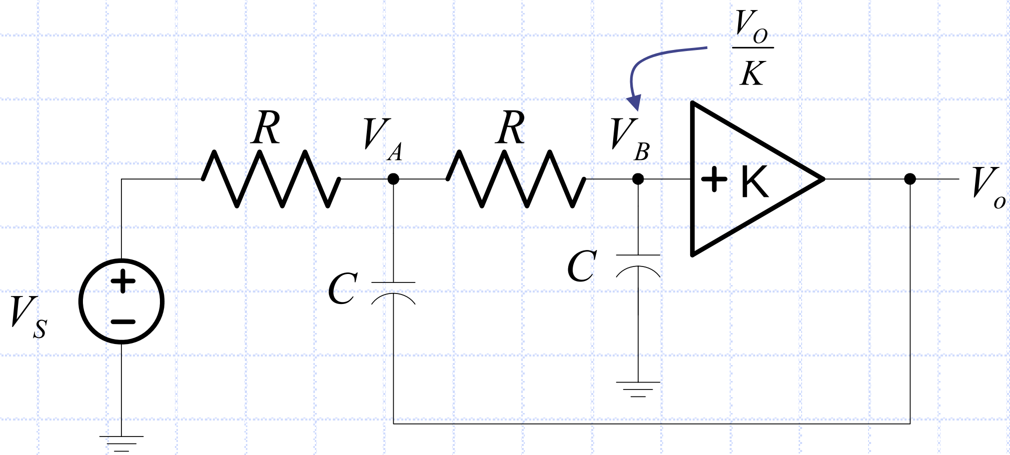
9. Effect of Feedback on The Amplifier Poles

- Amplifier with more poles or zeros
  - Too complex for hand analysis
  - Use CAD tool + Intuition

9. Effect of Feedback on The Amplifier Poles

◆ Example 8.5

Q: find k for maximally flat frequency response.



$KCL@V_A;$

$$\frac{V_A-V_S}{R}+sC(V_A-V_O)+\frac{V_A-V_B}{R}=0$$

$KCL@V_B;$

$$V_B=\frac{V_O}{K}=V_A\cdot\frac{\frac{1}{sC}}{R+\frac{1}{sC}}+sC\Rightarrow V_A=\frac{V_O}{K}\cdot(1+sCR)$$

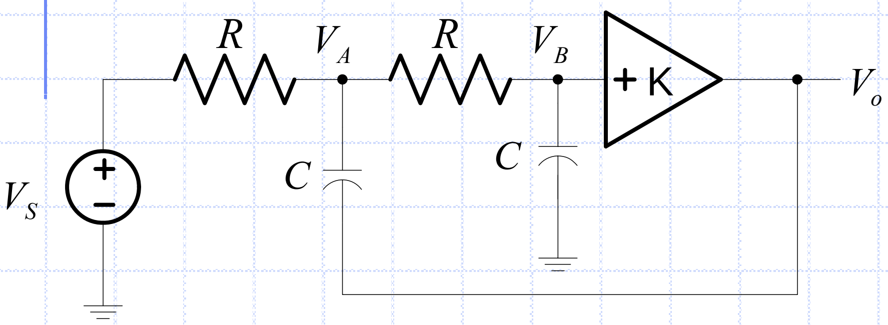
$$(\frac{1}{R}+sC+\frac{1}{R})V_A-\frac{V_S}{R}-sCV_O-\frac{V_O}{R\cdot K}=0$$

$$(\frac{2}{R}+sC)\cdot\frac{V_O}{K}\cdot(1+sCR)-sCV_O-\frac{V_O}{R\cdot K}=\frac{V_S}{R}$$

$$\left[(\frac{2}{R}+sC)\cdot\frac{1}{K}\cdot(1+sCR)-sC-\frac{1}{R\cdot K}\right]V_O=\frac{V_S}{R}$$

9. Effect of Feedback on The Amplifier Poles

- Example 8.5 (Cont'd)



$$\frac{V_O}{V_S} = \frac{\frac{1}{R}}{(\frac{2}{R}+sC)\cdot\frac{1}{K}\cdot(1+sCR)-sC-\frac{1}{R\cdot K}}$$

$$= \frac{\frac{1}{R}}{\frac{RC}{K}\cdot C\cdot S^2+\left[(\frac{1}{K}\cdot\frac{2}{R}\cdot C+\frac{C}{K})-C\right]S+\frac{1}{K}\cdot\frac{2}{R}-\frac{1}{R\cdot K}}$$

$$= \frac{\frac{1}{R}}{\frac{RC^2}{K}\cdot S^2+\left(\frac{3}{K}-1\right)C\cdot S+\frac{1}{KR}}$$

$$= \frac{\frac{K}{R^2C^2}}{S^2+\frac{1}{RC}\cdot(3-K)\cdot S+\frac{1}{R^2C^2}}$$

9. Effect of Feedback on The Amplifier Poles

◆ Example 8.5 (Cont'd)

$$\frac{V_O}{V_S} = \frac{K \cdot \omega_O^{\,2}}{s^2 + \omega_O/Q \cdot s + \omega_O^{\,2}} \qquad Q = \frac{1}{3-K}, \qquad \omega_o^{\,2} = \frac{1}{R^2C^2}$$

$Q = \dfrac{1}{\sqrt{2}}$ 일 때 maximally flat – no peaking !!

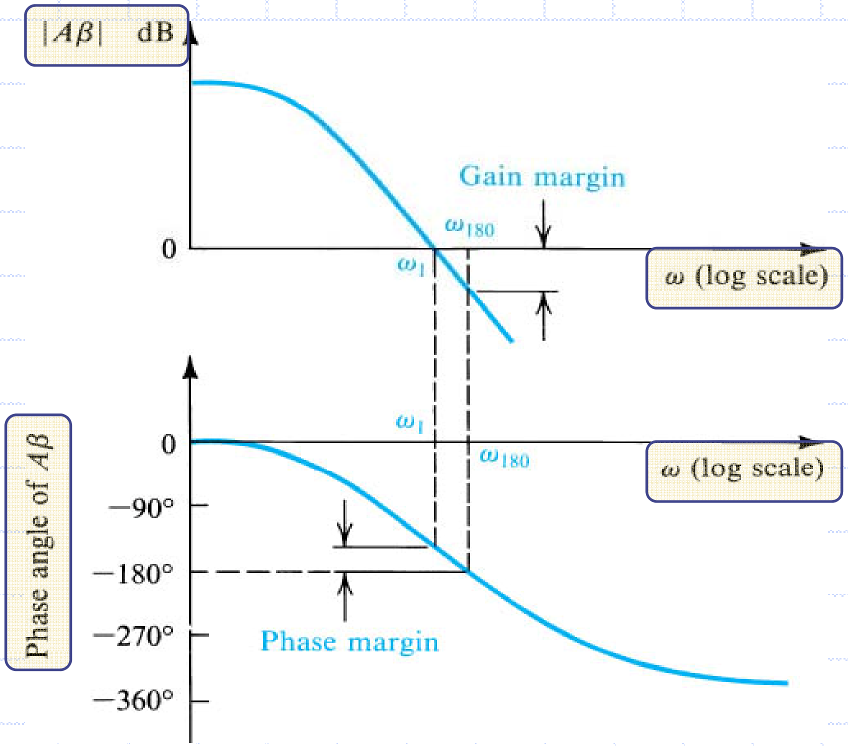
$$\therefore \ \frac{1}{3-K} = \frac{1}{\sqrt{2}}$$

$$3 - K = \sqrt{2}$$

$$K = 3 - \sqrt{2} = 1.586$$

10. Stability Study Using Bode Plots

Bode Plot

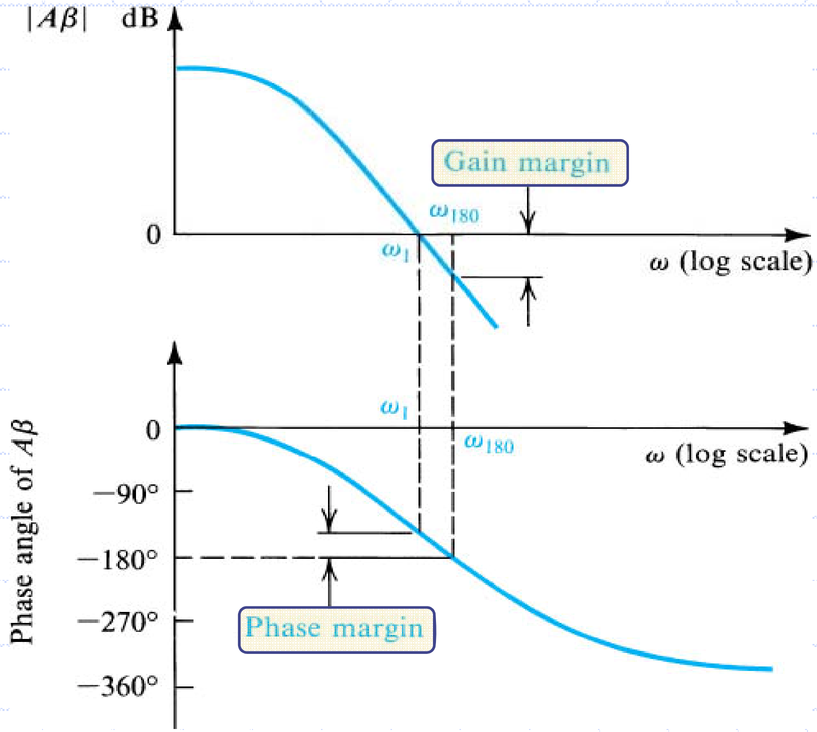


Every pole contributes to magnitude change of 20dB decrease per decade beyond its location.

Every pole contributes to phase change of 90˚ decrease through two consecutive decades where it is nested at the center.

10. Stability Study Using Bode Plots

Gain margin and phase margin



Gain margin is the difference between the value of |Aβ| at ω_{180} and unity(0dB).

Phase margin is the difference between the phase angle from the point where gain crosses unity(0dB) to 180˚.

10. Stability Study Using Bode Plots

- Conditions for Stability
  - Stable = Phase margin is greater than 0.
  - However, system with phase margin close to 0 suffers from severe peaking in its closed loop-gain. (freq. domain)
  - Typically, system with phase margin above 45˚ is well accepted to be stable.

10. Stability Study Using Bode Plots

- Phase margin of 45˚

$$loopgain = A(j\omega_1)\beta = 1 \times e^{-j\theta}$$ ← Loop gain is unity at ω_1.

(Where $\theta = 180^\circ$ - phase margin)

$$A_f(j\omega_1) = \frac{A(j\omega_1)}{1 + A(j\omega_1)\beta} \longrightarrow \left|A_f(j\omega_1)\right| = \frac{\frac{1}{\beta}}{\left|1 + e^{-j\theta}\right|}$$

$$= \frac{\frac{1}{\beta}e^{-j\theta}}{1 + e^{-j\theta}}$$

If the phase margin is 45˚
-> θ = 135˚

$$\boxed{\left|A_f(j\omega_1)\right| = 1.3\frac{1}{\beta}}$$

Closed loop gain peaks by 30% at ω_1 from the low frequency gain of 1/β.
Peaking would reach ∞ as phase margin approaches 0˚.

10. Stability Study Using Bode Plots

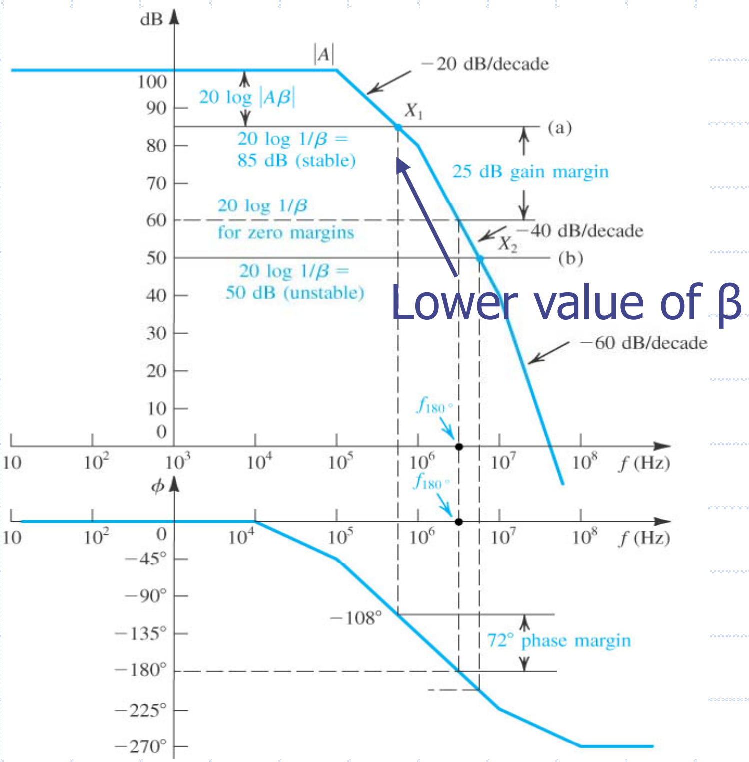
- Alternative approach for Investigating Stability
  - It would be very tiresome to find the best value for β by numerical iteration.
  - There is an alternative method to graphically estimate the value of β by using,

$$20\log|A(j\omega)| - 20\log\frac{1}{\beta} = 20\log|A\beta| = \text{loop gain in dB}$$

See next

10. Stability Study Using Bode Plots

- Q: System has poles at 10^5 Hz, 10^6Hz, and 10^7Hz. Find β that yields phase margin of 72˚?



1. Draw 20 log |A(jw)|
2. Draw the phase graph
3. Draw a line for 20 log 1/β so as it intersects 20 log|A(jw)| at the frequency that gives the needed phase margin.

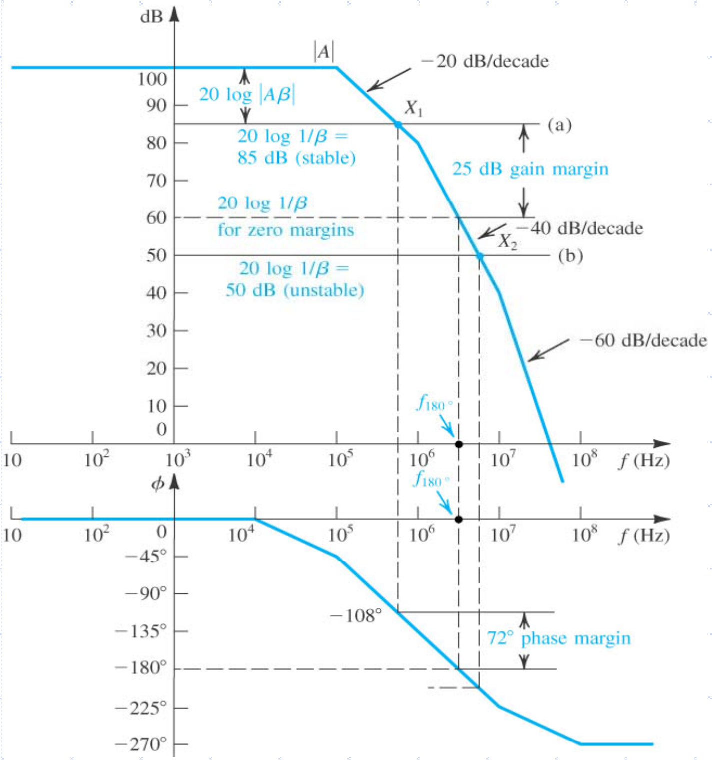
The area enclosed by 20 log |A(jw)| and 20 log 1/β redrawn with 20 log 1/β line as f-axis becomes the graph of the loop gain (20 log |A(jw)β|).

10. Stability Study Using Bode Plots

◆ Q: (Cont'd)

$$A = \frac{10^5}{(1+j\frac{f}{10^5})(1+j\frac{f}{10^6})(1+j\frac{f}{10^7})}$$

$$\phi = -[\tan^{-1}(\frac{f}{10^5}) + \tan^{-1}(\frac{f}{10^6}) + \tan^{-1}(\frac{f}{10^7})]$$



$f_{180} \fallingdotseq 3.2 \times 10^6$ Hz

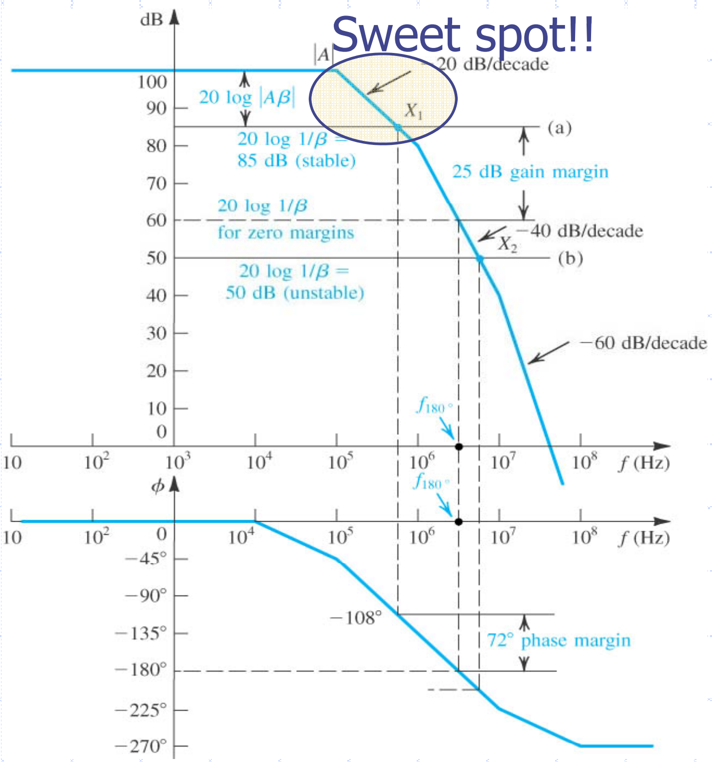
($f_{180} \fallingdotseq 3.34 \times 10^6$ Hz with more iteration)

$f_{108} \fallingdotseq 5.6 \times 10^5$ Hz → $|A(jw_{108})| = 85$ dB

$\boxed{\beta = 5.623 \times 10^{-5}}$

10. Stability Study Using Bode Plots

- Rule of thumb for stability



To guarantee stability,
the 20 log 1/β should intersect the 20 log |A| on its -20 dB/dec segment.
(then the phase margin > 45˙)

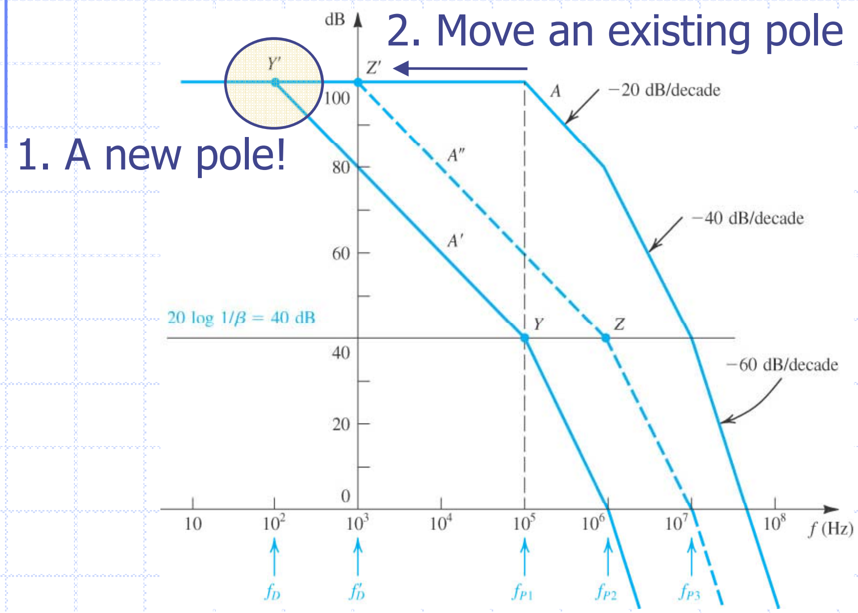
More generally, if β is a function of frequency…

The difference of slopes (= rate of closure) at the intersection of
20 log 1/β(jw) and 20 log |A(jw)| should not exceed 20dB/dec.

11. Frequency Compensation

◆ Theory

- A system can be made stable by introducing a new pole or moving the location of its existing pole.



1. Place a new pole so as to guarantee that the slope difference of 20 log |A(jw)| and 20 log 1/β does not exceed 20 dB/dec.

OR

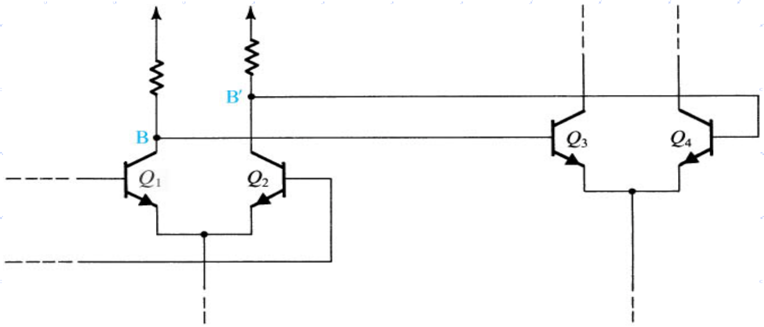
2. Move an existing pole the same way as 1. (preferred)

STABLE

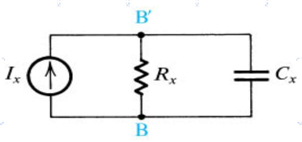
11. Frequency Compensation

Implementation

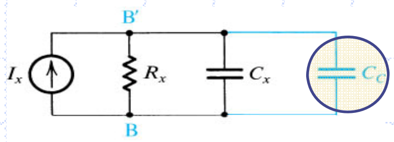
- Assume that the first pole f_{p1} is introduced at the interface between the two stages.



(a)



(b)



(c)

(a)'s small signal equivalent circuit can be simplified to the circuit shown in (b).

By adding Cc we are capable of moving the location of f_{p1} to a lower frequency.

$$f_{P1} = \frac{1}{2\pi C_x R_x}$$

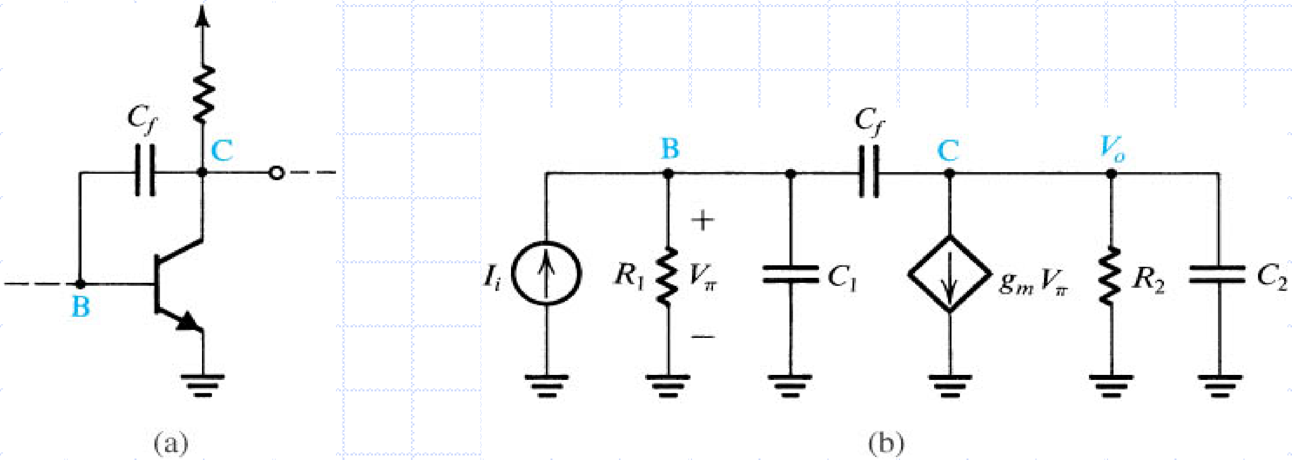
$$f_D' = \frac{1}{2\pi (C_x + C_c) R_x}$$

However, the required value of Cc is usually large and Cc has an secondary effect on poles other than f_{p1}.

11. Frequency Compensation

Miller compensation and pole splitting

- A miller effect is used in ICs to minimize C_c(C_f).



- Assume that C_1 includes the Miller component due to C_μ, C_2 includes the input capacitance of the subsequent stage.

11. Frequency Compensation

Miller comp.& pole splitting(Cont'd)

- Pole locations without C_f

$$f_{P1} = \frac{1}{2\pi C_1 R_1}, \quad f_{P2} = \frac{1}{2\pi C_2 R_2}$$

- Pole locations with Cf

$$\frac{V_o}{I_i} = \frac{(sC_f - g_m)R_1R_2}{1 + s[C_1R_1 + C_2R_2 + C_f(g_mR_1R_2 + R_1 + R_2)] + s^2[C_1C_2 + C_f(C_1 + C_2)]R_1R_2}$$

$$D(s) = (1 + \frac{s}{\omega_{P1}'})(1 + \frac{s}{\omega_{P2}'}) = 1 + s(\frac{1}{\omega_{P1}'} + \frac{1}{\omega_{P2}'}) + \frac{s^2}{\omega_{P1}'\omega_{P2}'}$$

$$\cong 1 + \frac{s}{\omega_{P1}'} + \frac{s^2}{\omega_{P1}'\omega_{P2}'} \qquad (\omega_{P1}' << \omega_{P2}')$$

The zero is usually at a much higher frequency, so we will neglect its effect.

$$\omega_{P1}' = \frac{1}{C_1R_1 + C_2R_2 + C_f(g_mR_1R_2 + R_1 + R_2)} \cong \frac{1}{g_mR_2C_fR_1} \qquad \omega_{P2}' \cong \frac{g_mC_f}{C_1 + C_2 + C_f(C_1 + C_2)}$$

11. Frequency Compensation

Miller comp.& pole splitting(Cont'd)

$$\omega_{P1}' = \frac{1}{C_1R_1 + C_2R_2 + C_f(g_mR_1R_2 + R_1 + R_2)} \cong \frac{1}{\boxed{g_mR_2C_f}R_1} \qquad \omega_{P2}' \cong \frac{g_mC_f}{C_1 + C_2 + C_f(C_1 + C_2)}$$

Miller effect

As $C_f\uparrow$, $\omega'_{p1}\downarrow$ and $\omega'_{p2}\uparrow$: Pole Splitting

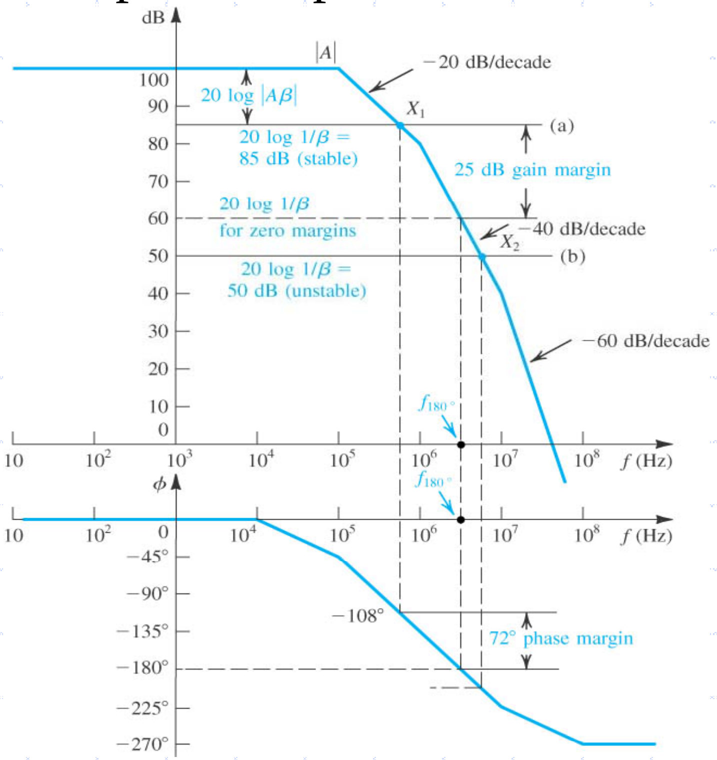
This method not only reduces the size of the needed compensation capacitance with miller effect, but also sends the second pole to a higher frequency.
-> Wider bandwidth.

Two goods in one package!!

11. Frequency Compensation

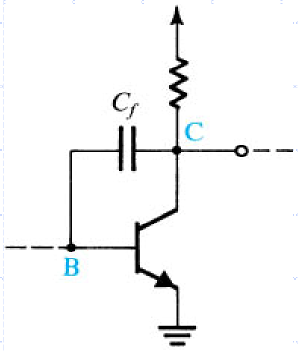
◆ Example 8.6

$$Q: \text{Find the value of } C_f \text{ needed to make the amplifier with following open-loop characteristic stable for } \beta \le 1.$$

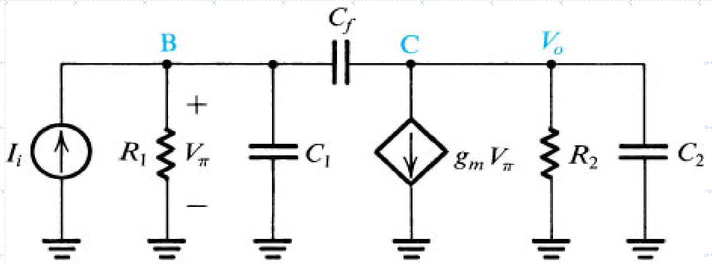


(Solve for two cases:

1. C_f placed between node B and ground.
2. C_f placed in the feedback path.)



(a)

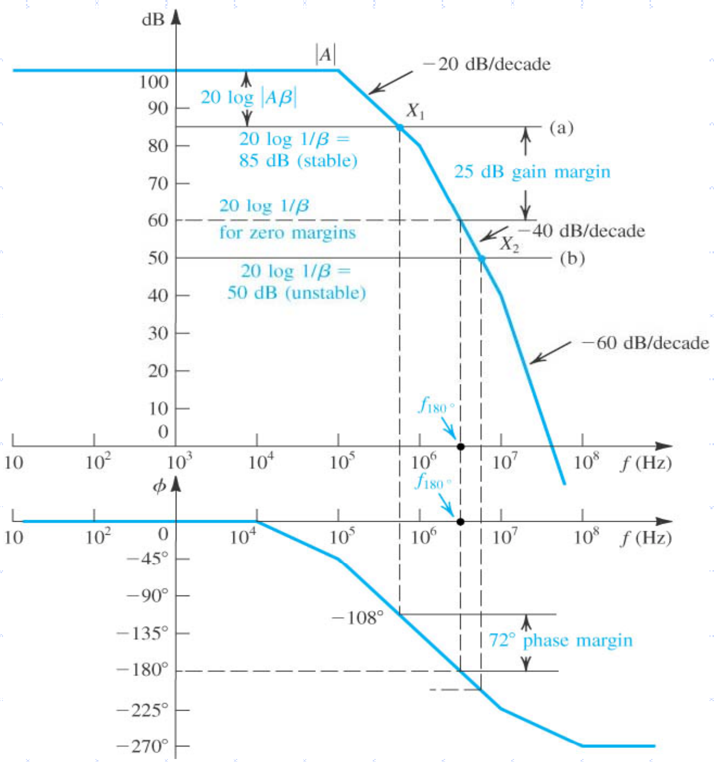


(b)

$$\text{Given } C_1 = 100\text{pF},\ C_2 = 5\text{pF, and } g_m = 40\text{mA/V}.$$

11. Frequency Compensation

◆ Example 8.6(Cont'd) – case 1.



$$f_p = \frac{1}{2\pi C_1 R_1} \Longrightarrow R_1 = \frac{1}{2\pi C_1 f_{p1}} = \frac{10^5}{2\pi}(\Omega)$$

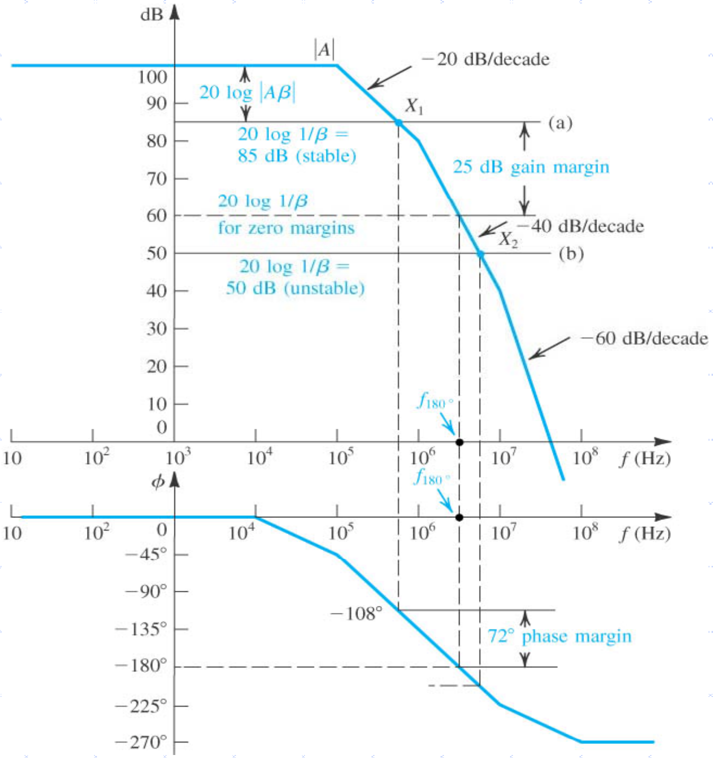
$$R_2 = \frac{1}{2\pi C_2 f_{p2}} = \frac{10^5}{\pi}(\Omega)$$

C_f moves f_{p1}. To make the amplifier stable, the first pole must be moved so that the 20 log |A(s)| intersects 0dB at f_{p2}(=1MHz).

$$f_{p1}' = \boxed{10Hz} = \frac{1}{2\pi(C_1 + C_f)R_1} \Longrightarrow \boxed{C_f \approx 1uF}$$

11. Frequency Compensation

- Example 8.6(Cont'd) – case 2.



$$f_{P1}' \cong \frac{1}{2\pi g_m R_2 C_f R_1}$$

$$f_{P2}' \cong \frac{g_m C_f}{2\pi(C_1 + C_2 + C_f(C_1 + C_2))}$$

Assume $C_f >> C_2$. Then,

$$f_{P2}' \cong \frac{g_m}{2\pi(C_1 + C_2)} = 60.6MHz$$

f_{P2}' is higher than f_{P3}, so the second pole of the system will be f_{P3}(=10MHz). Thus,

$$f_{P1}' \cong \boxed{100Hz} = \frac{1}{2\pi g_m R_2 C_f R_1} \Longrightarrow \boxed{C_f = 78.5pF}$$

$\Rightarrow$ Smaller C_f & higher f_{p1}'