Introduction to Analog Integrated Circuit Design

Fall 2022

Feedback

Yung-Hui Chung

MSIC Lab

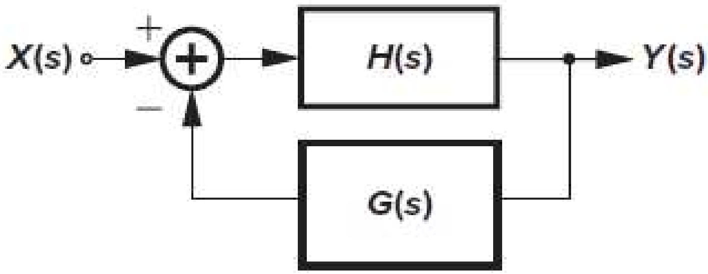
DECE, NTUST

Mixed-Signal IC Laboratory NTUST

Outline

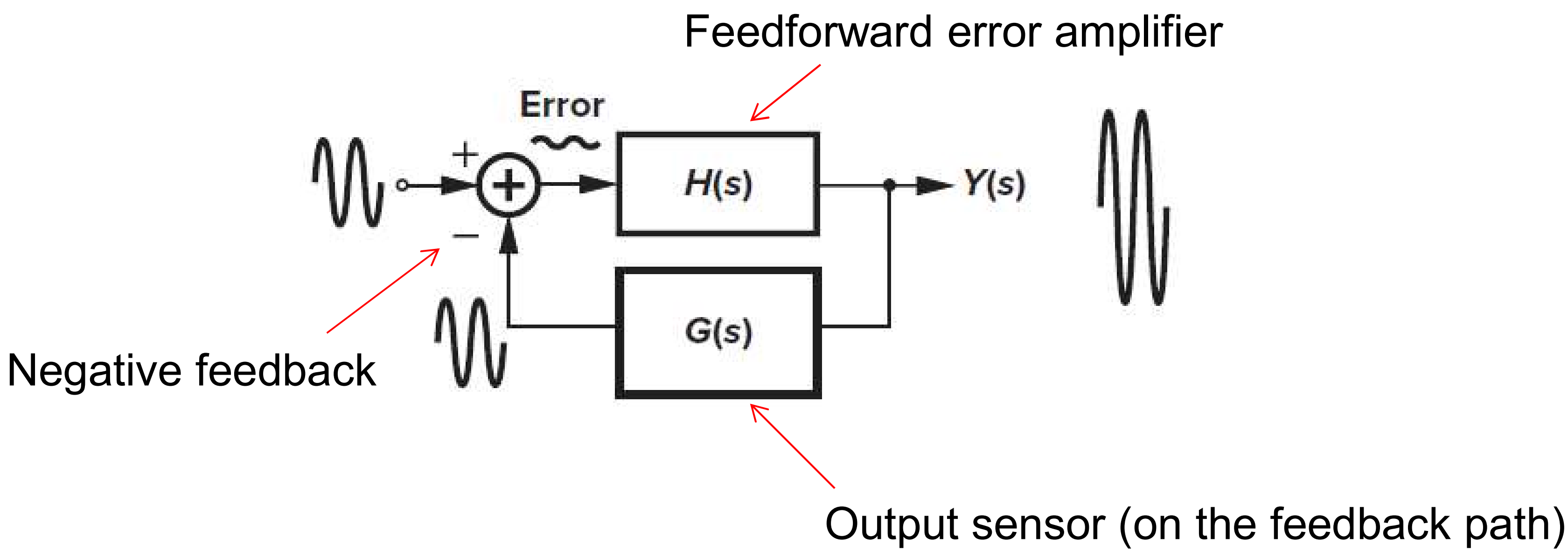
- Benefits of Feedback Systems
- Feedback Topologies
- Difficulties of Feedback Analysis
- Two-Port Network Models
- Loop Gain Calculation

A Feedback System



$$Y(s) = H(s)[X(s) - G(s)Y(s)]$$

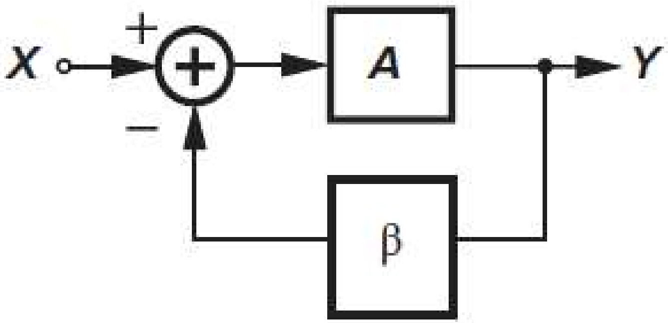
$$\frac{Y(s)}{X(s)} = \frac{H(s)}{1 + G(s)H(s)}$$



Properties of Feedback Circuits

- Gain Desensitization
  - Using feedback to stabilize the gain accuracy
- Terminal Impedance Modification
  - Using feedback to approach ideal impedance
- Bandwidth Modification
  - Using feedback to extend the -3dB bandwidth
- Nonlinearity Reduction
  - Using feedback to improve the output nonlinearity

Gain Desensitization



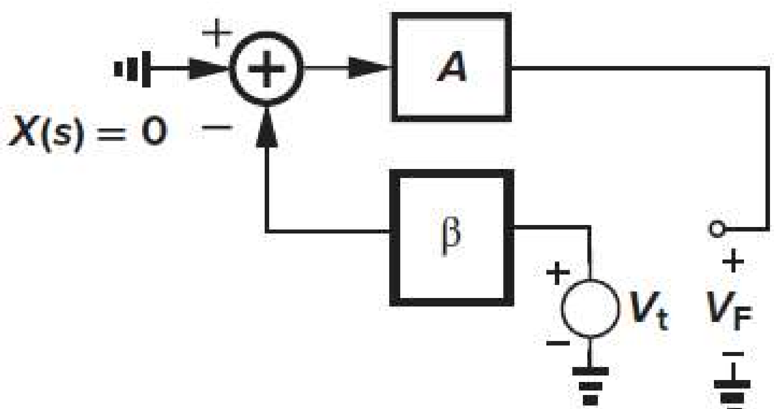
$$\frac{Y}{X} = \frac{A}{1+\beta A}$$

$$\approx \frac{1}{\beta}\left(1 - \frac{1}{\beta A}\right)$$ if $\beta A >> 1$

Cap. Ratio or Resistor ratio

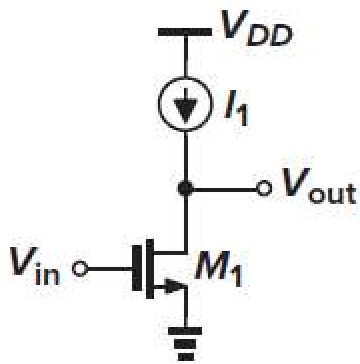
High-gain opamp

Loop Gain

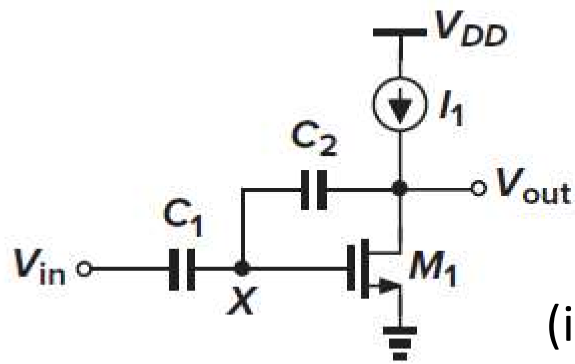


$$V_F / V_t = -\beta A$$

Gain Desensitization



(a)



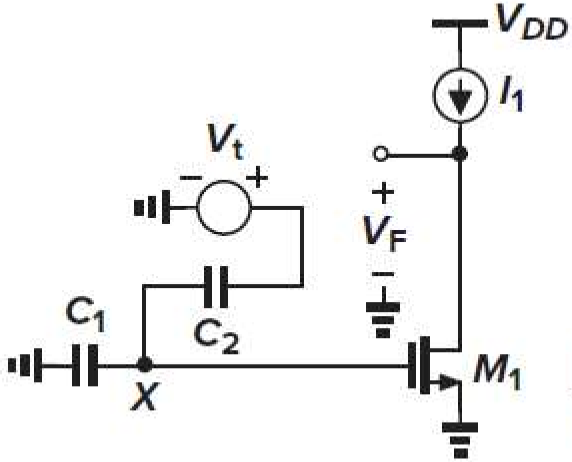
(b)

(if $g_{m1}r_{O1}$ >> 1)

$$\frac{V_{out}}{V_{in}} = -g_{m1}r_{O1}$$

$$\frac{V_{out}}{V_{in}} = -\frac{1}{\left(1+\frac{1}{g_{m1}r_{O1}}\right)\frac{C_2}{C_1}+\frac{1}{g_{m1}r_{O1}}}$$

$$= -\frac{C_1}{C_2}\frac{1}{1+\frac{1}{g_{m1}r_{O1}}\frac{C_1+C_2}{C_2}} = -\frac{C_1}{C_2}\frac{1}{1+\frac{1}{\beta A}}$$



$$V_t\frac{C_2}{C_1+C_2}(-g_{m1}r_{O1}) = V_F$$

$$\frac{V_F}{V_t} = -\frac{C_2}{C_1+C_2}g_{m1}r_{O1}$$

$A = g_{m1}r_{O1}$

$\beta = C_2/(C_1+C_2)$

Terminal Impedance Modification

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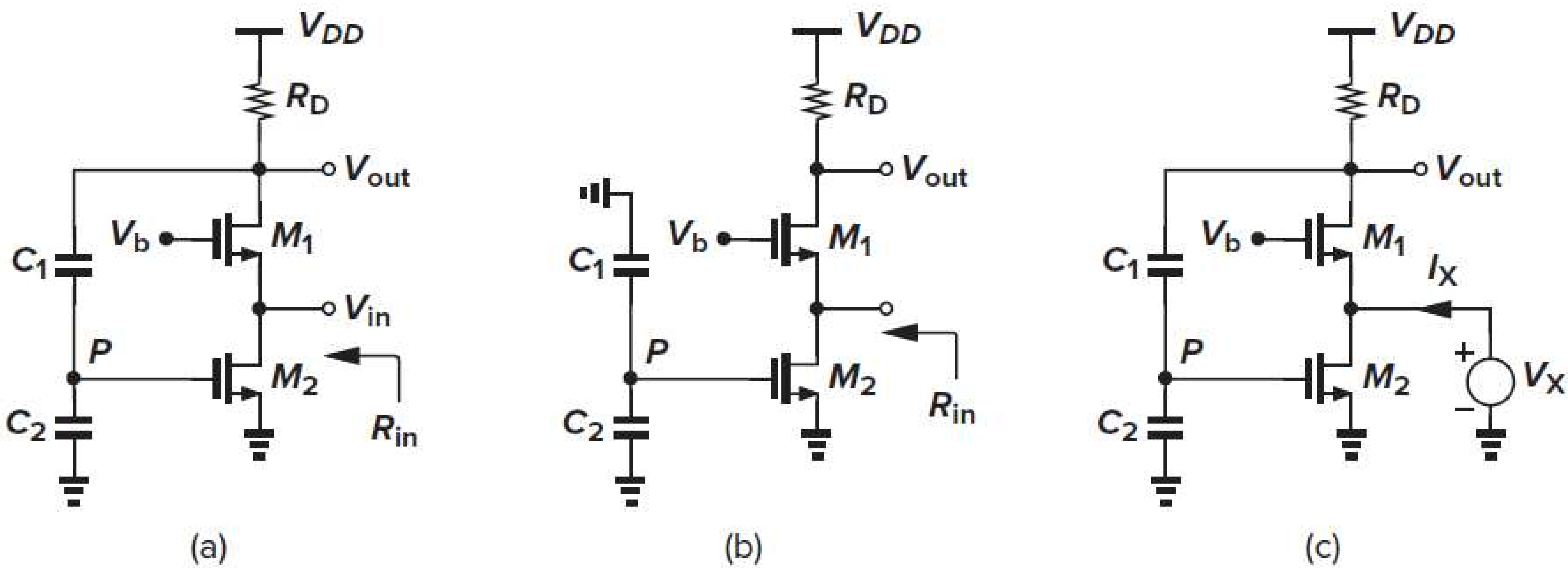


$$R_{in,open} = \frac{1}{g_{m1} + g_{mb1}}$$

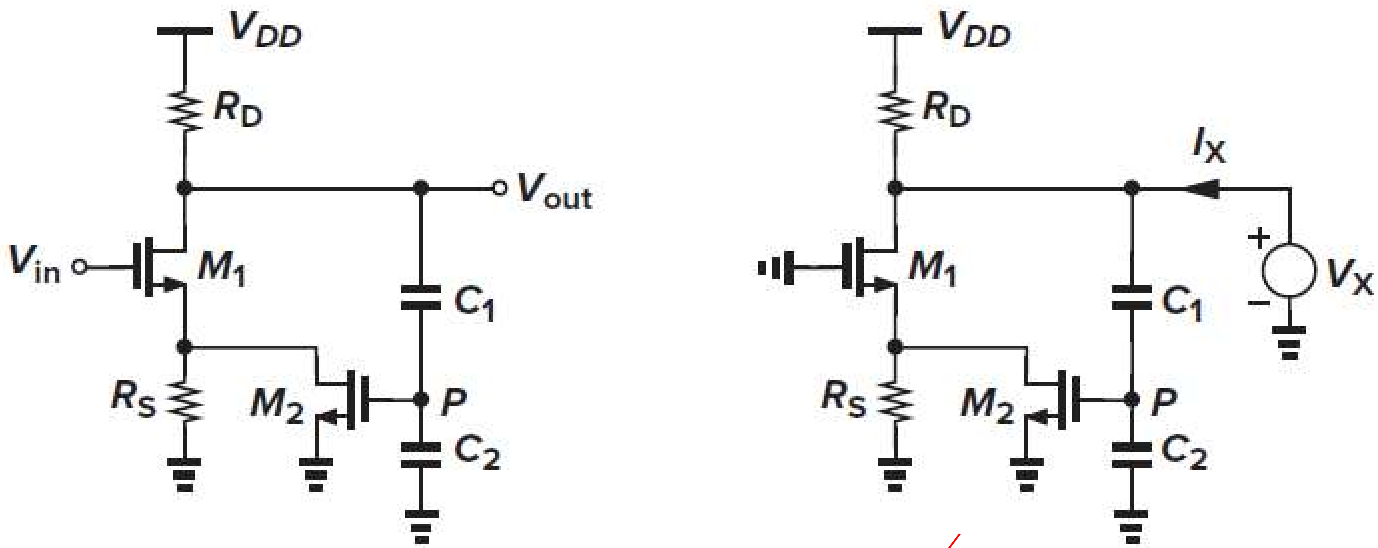
$$R_{in,closed} = V_X / I_X$$

$$= \frac{1}{g_{m1} + g_{mb1}} \frac{1}{1 + g_{m2} R_D \dfrac{C_1}{C_1 + C_2}}$$

(The detail is on p.278, textbook)

$$Z_{in,open} \to \frac{Z_{in,open}}{1 + \beta A}$$

Terminal Impedance Modification



(a) (b)

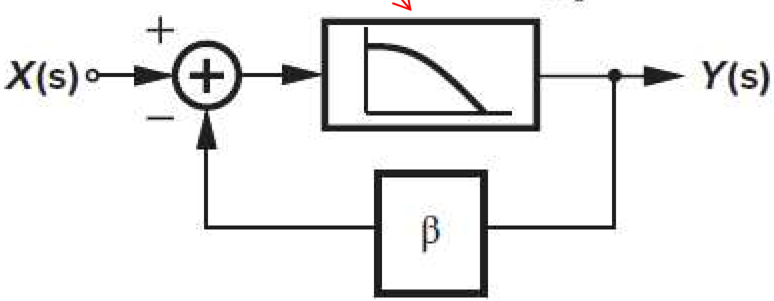
$$\frac{V_X}{I_X} = \frac{R_D}{1 + \underbrace{\frac{g_{m2} R_S (g_{m1} + g_{mb1}) R_D}{(g_{m1} + g_{mb1}) R_S + 1}}_{A} \underbrace{\frac{C_1}{C_1 + C_2}}_{\beta}}$$

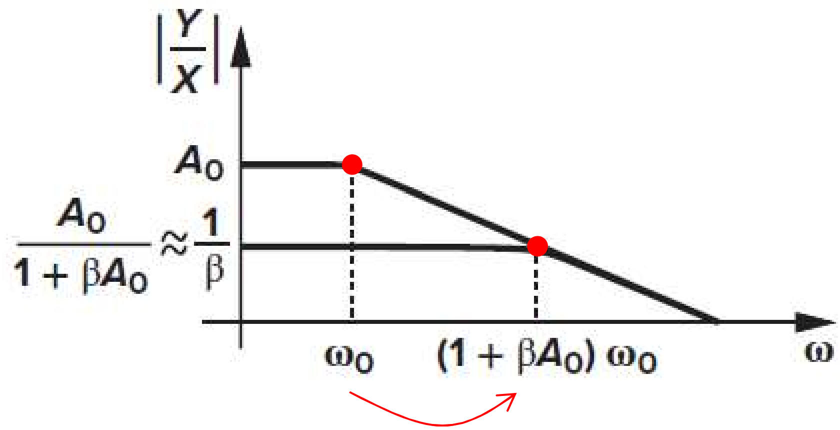
$\longrightarrow$?

Bandwidth Modification

Open-loop T. F.

$$A(s) = \frac{A_0}{1 + \frac{s}{\omega_0}}$$





Closed-loop T. F.

$$\frac{Y}{X}(s) = \frac{\frac{A_0}{1 + \frac{s}{\omega_0}}}{1 + \beta \frac{A_0}{1 + \frac{s}{\omega_0}}} = \frac{A_0}{1 + \beta A_0 + \frac{s}{\omega_0}}$$

$$= \frac{\frac{A_0}{1 + \beta A_0}}{1 + \frac{s}{(1 + \beta A_0)\omega_0}}$$

Q: For the closed-loop T. F.,

- What is the DC gain?
- What is the -3dB bandwidth?

Nonlinearity Reduction

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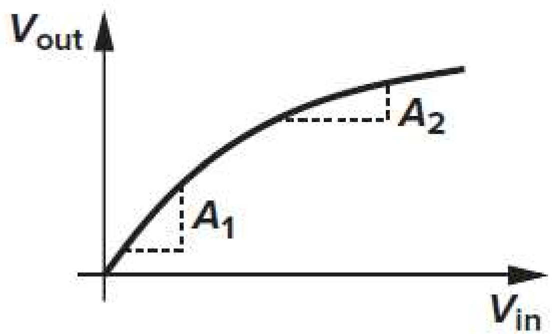
Open-loop



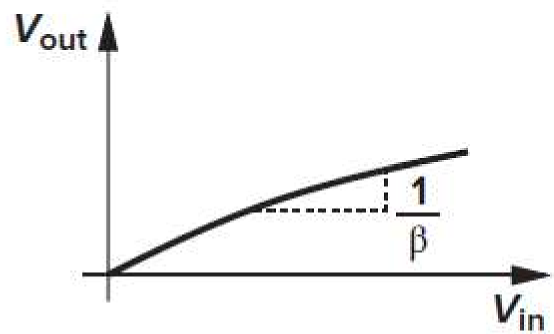
$$r_{open} = \frac{A_2}{A_1}$$

$$r_{open} = 1 - \underbrace{\frac{\Delta A}{A_1}}_{Err_{OL}}$$

For ICs, $A \approx k\left(g_m r_O\right)^N$

Close-loop

r: gain ratio



$$r_{closed} = \frac{\dfrac{A_2}{1+\beta A_2}}{\dfrac{A_1}{1+\beta A_1}} = \frac{1+\dfrac{1}{\beta A_1}}{1+\dfrac{1}{\beta A_2}}$$

$$r_{closed} \approx 1 - \frac{\dfrac{1}{\beta A_2} - \dfrac{1}{\beta A_1}}{1+\dfrac{1}{\beta A_2}}$$

$$\approx 1 - \frac{A_1 - A_2}{1+\beta A_2}\frac{1}{A_1}$$

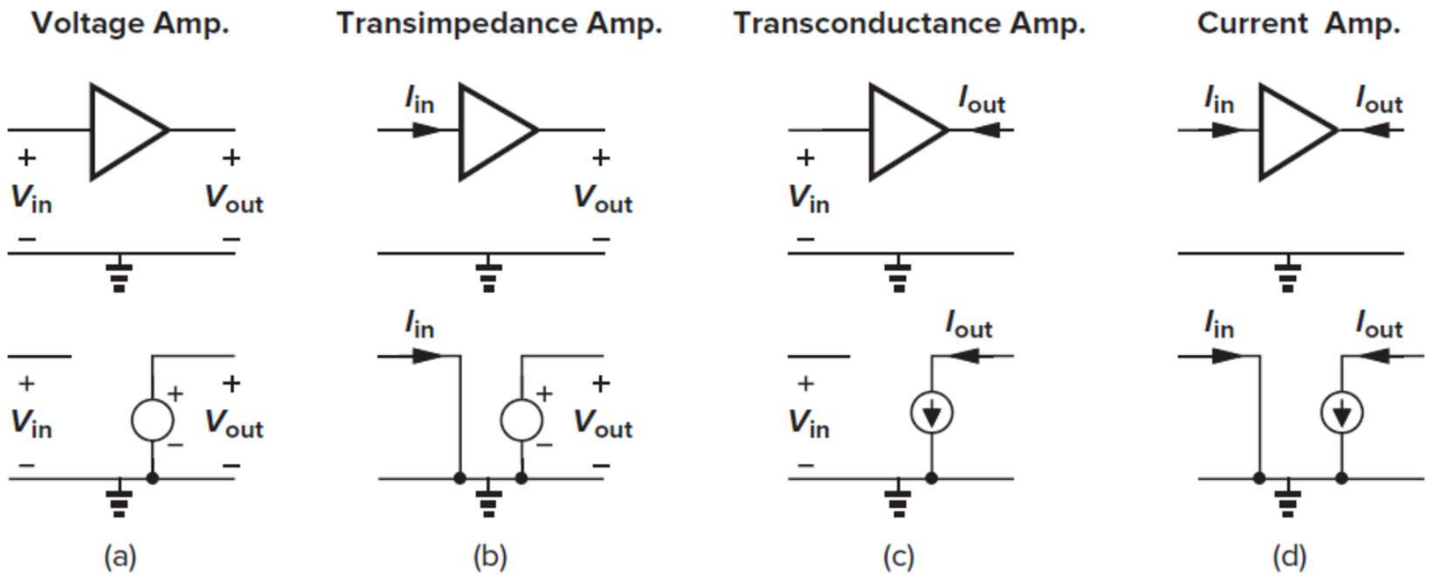
$$\approx 1 - \underbrace{\frac{\Delta A}{1+\beta A_2}\frac{1}{A_1}}_{Err_{CL}}$$

$Err_{CL} = Err_{OL} / (1+\beta A)$

Properties of Feedback Circuits: Recall

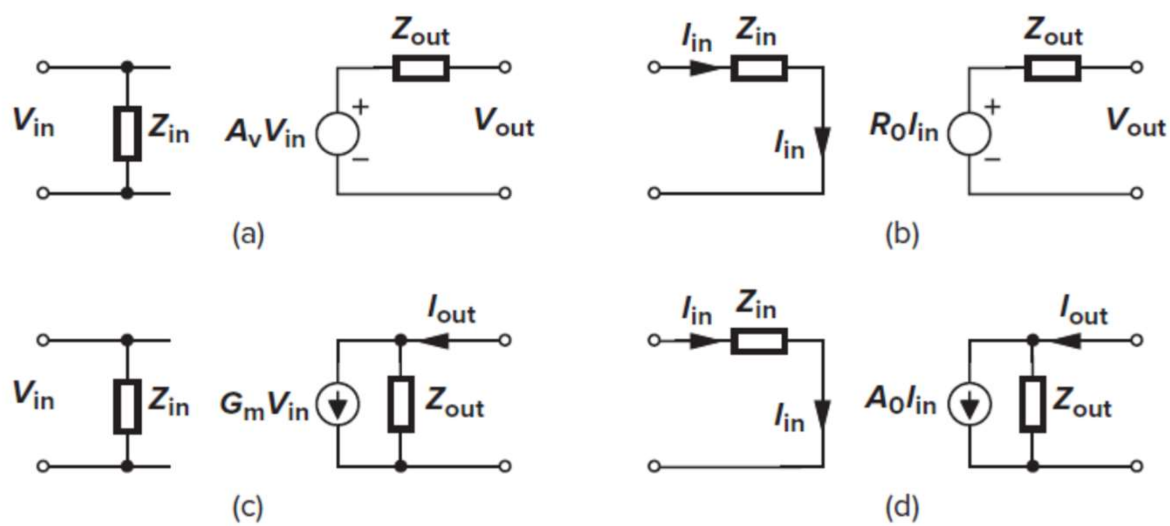
- Gain Desensitization
  - Using feedback to stabilize the gain accuracy
- Terminal Impedance Modification
  - Using feedback to approach ideal impedance
- Bandwidth Modification
  - Using feedback to extend the -3dB bandwidth
- Nonlinearity Reduction
  - Using feedback to improve the output nonlinearity

Types of Amplifiers

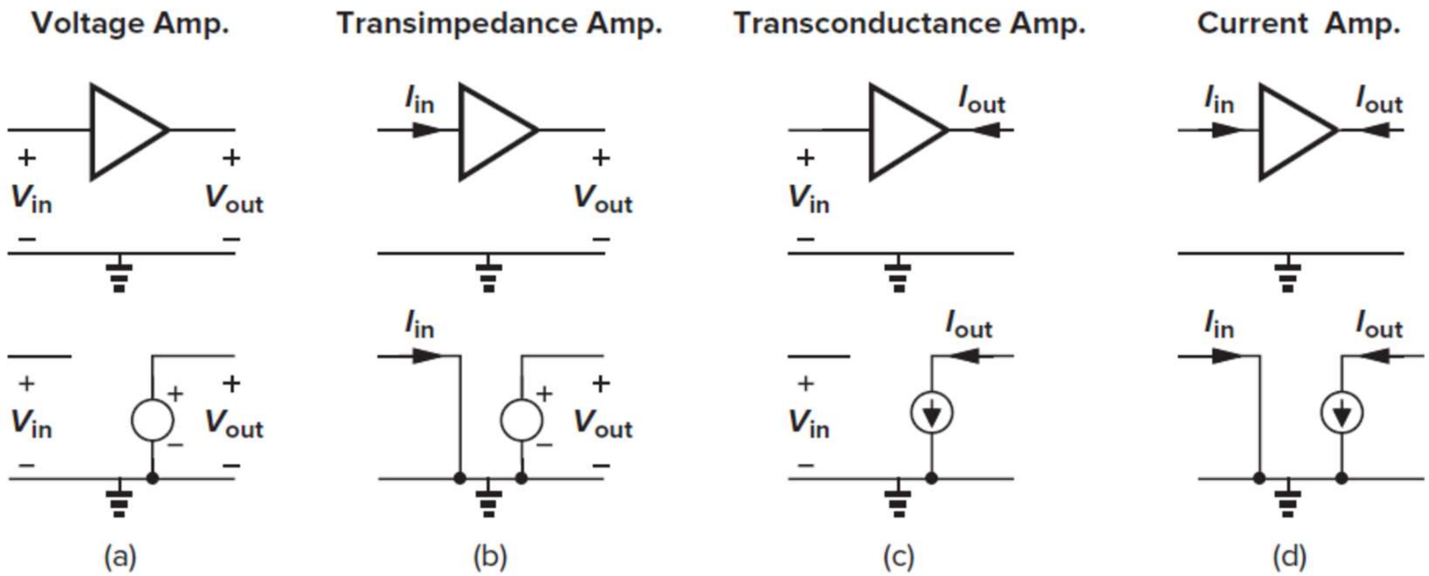


輸入阻抗的連接:
- 電壓輸入是並聯
- 電流輸入是串聯

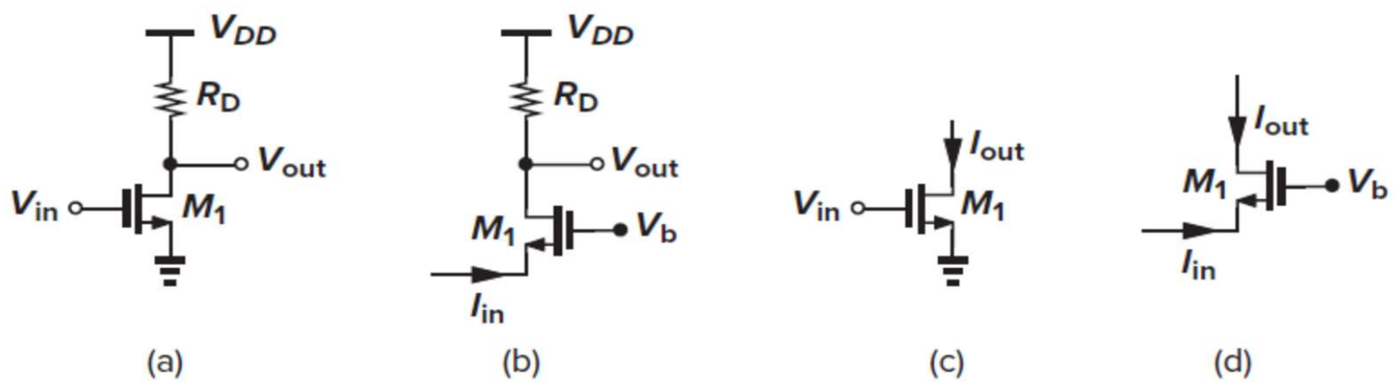
輸出等效電路:
- 電壓是戴維寧
- 電流是諾頓



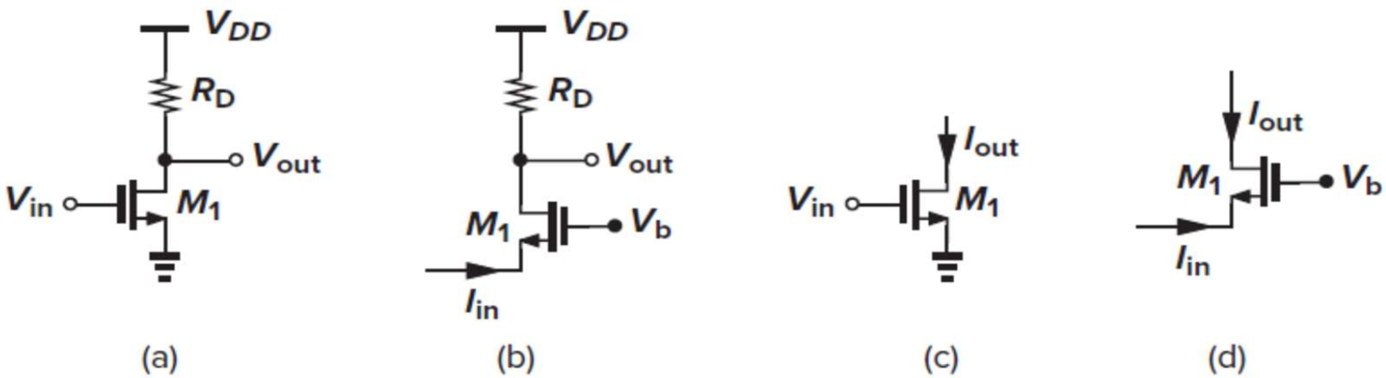
Types of Amplifiers



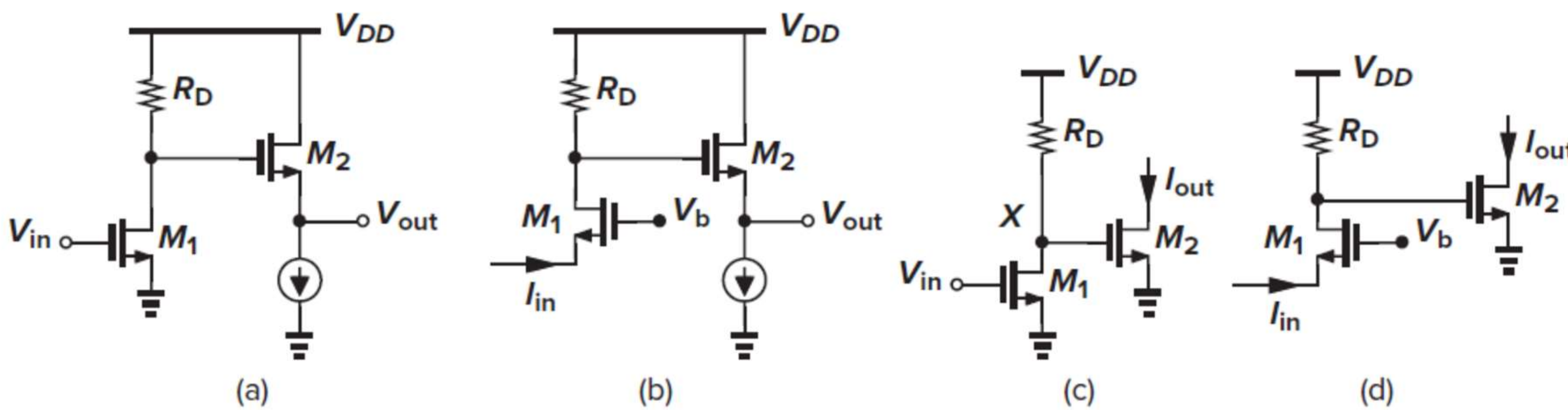
Four circuit examples



Types of Amplifiers

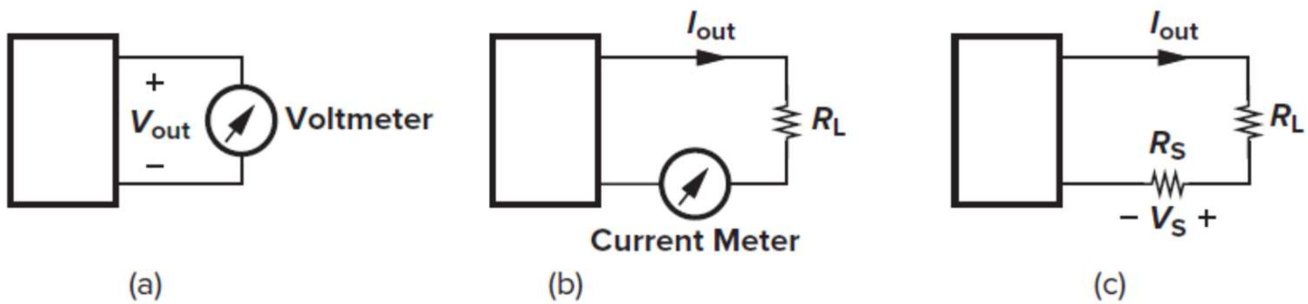


Four improved circuit examples: key issue is the output terminal

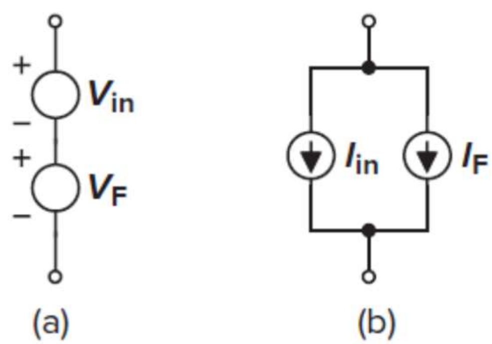


Sense and Return Mechanisms

Sensing

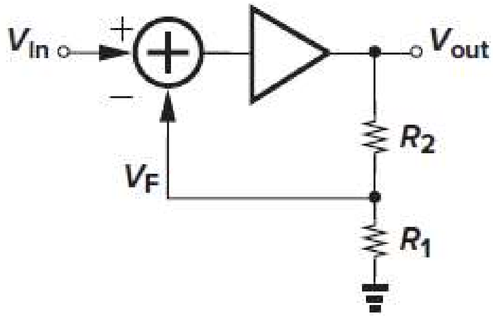


Addition

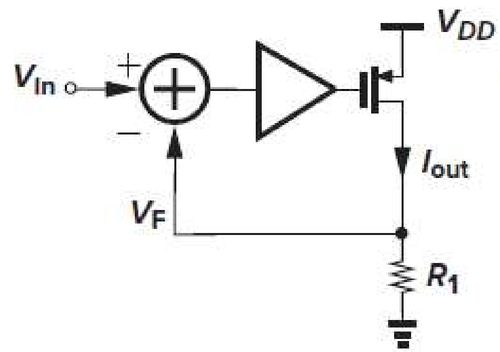


- In general, sensing and return circuits will change the original circuitry!!
- It's hard not to change, but we may reduce the effect reasonably!!

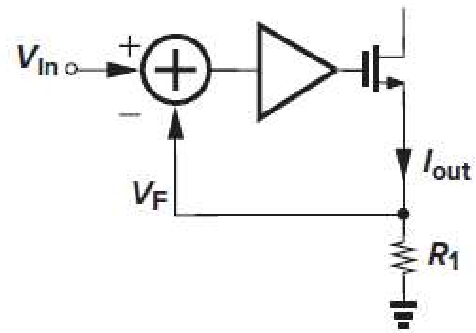
Practical Sensing/Feedback Circuits



(a)

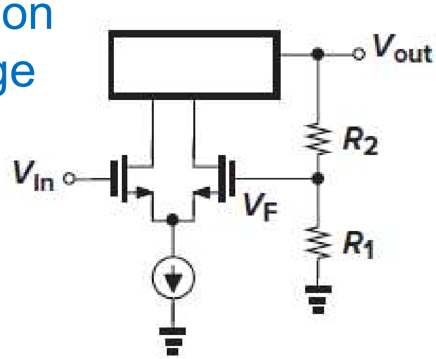


(b)

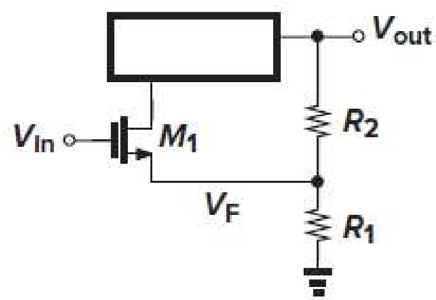


(c)

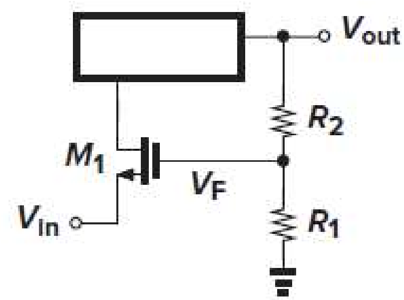
Subtraction
by Voltage



(d)

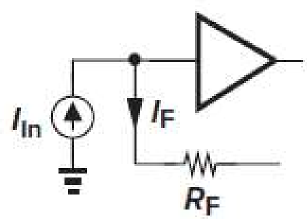


(e)

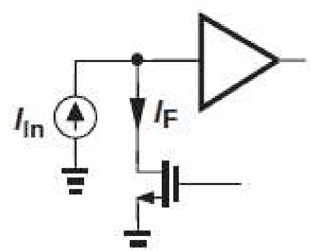


(f)

Subtraction
by Current



(g)

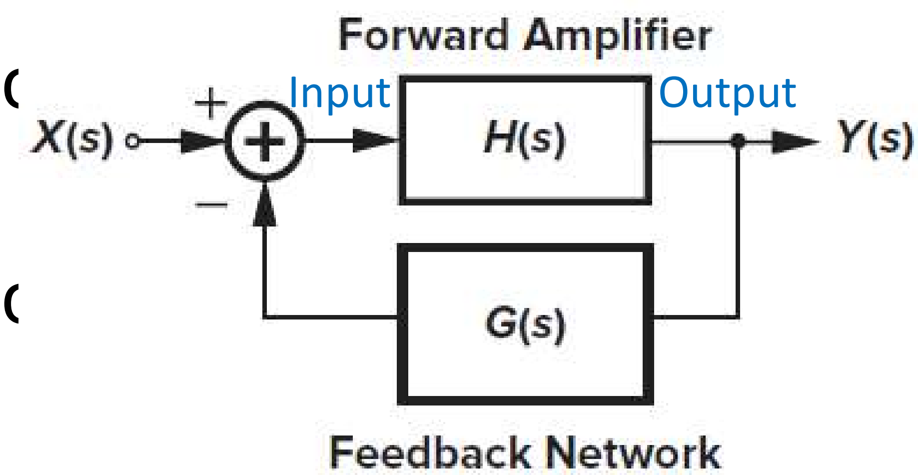


(h)

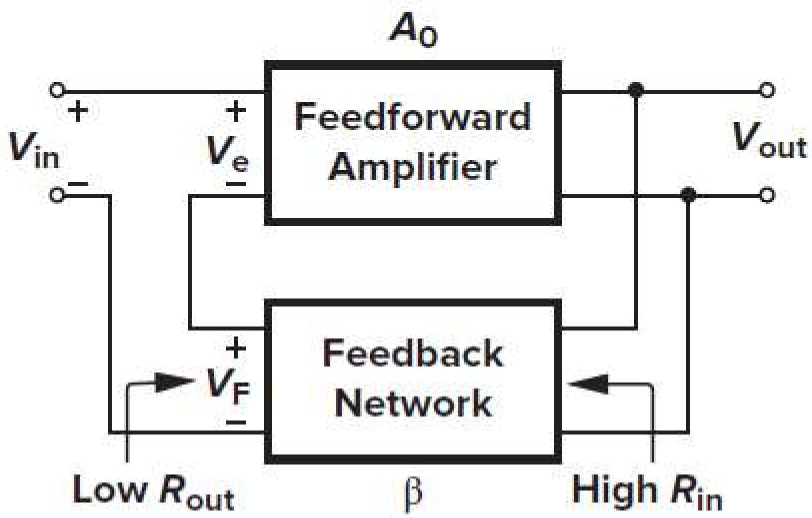
Feedback Topologies

(Output – Input)

- Voltage-Voltage Feedback
- Current-Voltage Feedbac
- Voltage-Current Feedbac
- Current-Current Feedback



Voltage-Voltage Feedback



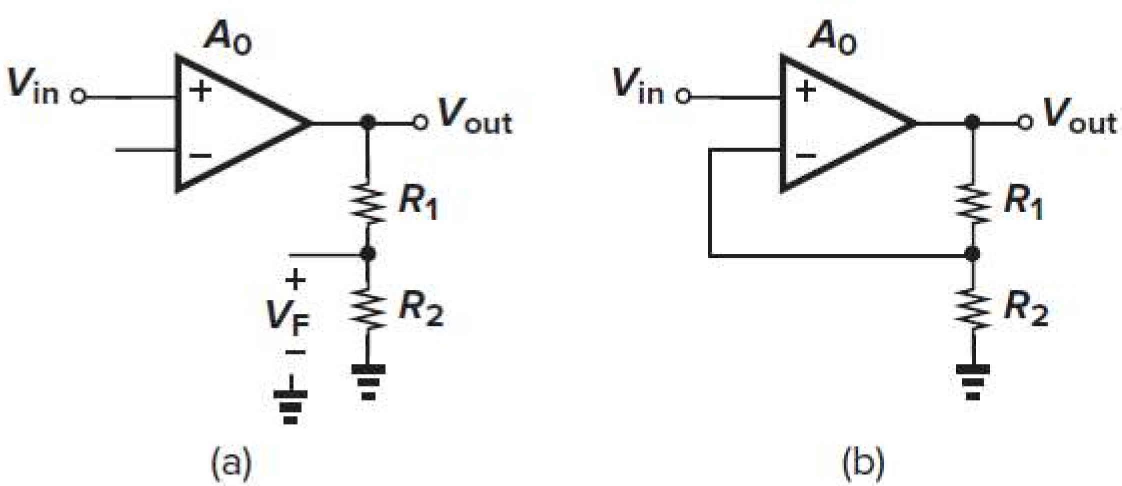
$$V_F = \beta V_{out}$$

$$V_e = V_{in} - V_F$$

$$V_{out} = A_0(V_{in} - \beta V_{out})$$

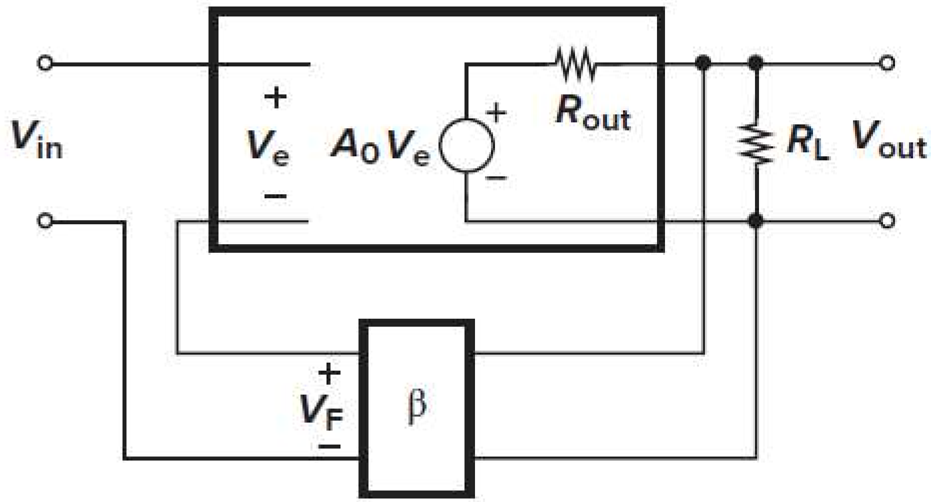
$$A_{CL} = \frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \beta A_0}$$

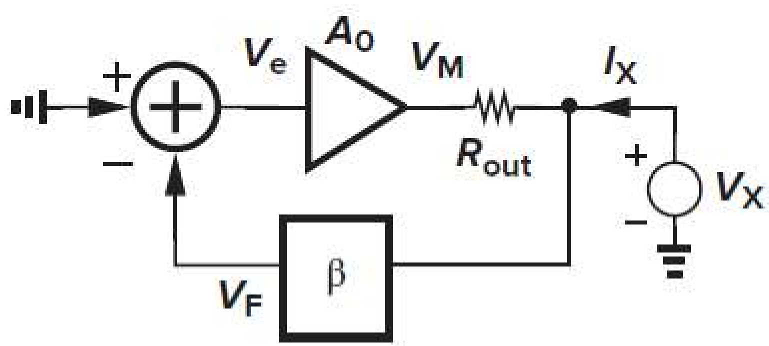
Example



$$\beta = \frac{V_F}{V_{out}} = \frac{R_2}{R_1 + R_2}$$

Output Resistance Modification





$$V_F = \beta V_X$$

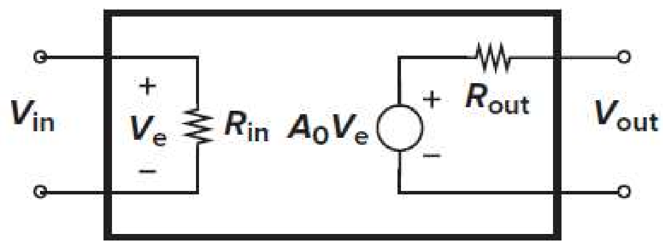
$$V_e = 0 - V_F = -\beta V_X$$

$$V_M = A_0 V_e = -\beta A_0 V_X$$

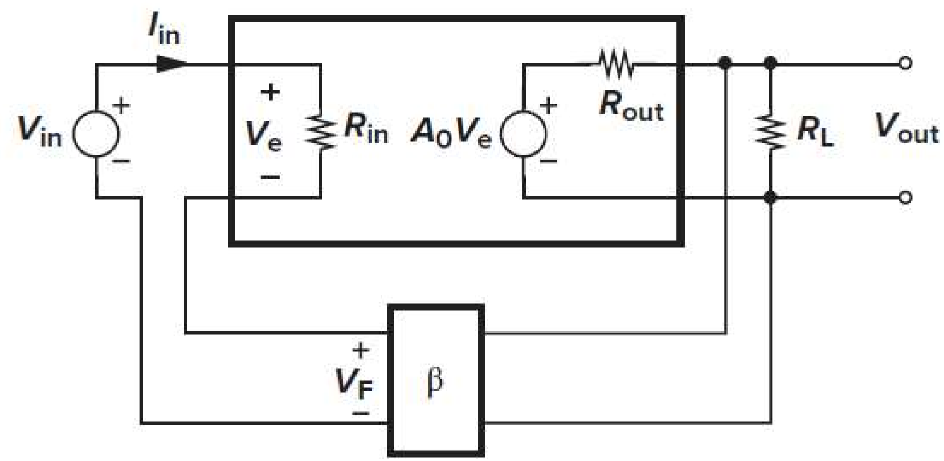
$$I_X = \frac{V_X - V_M}{R_{out}}$$

$$R_{out,CL} = \frac{V_X}{I_X} = \frac{R_{out}}{1 + \beta A_0}$$

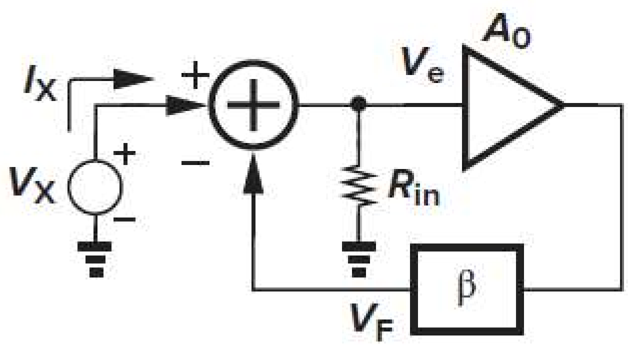
Input Resistance Modification



(a)



(b)



$$V_F = \beta A_0 V_e \text{ and } V_e = I_X R_{in}$$

$$V_e = V_X - V_F = V_X - \beta A_0 I_X R_{in}$$

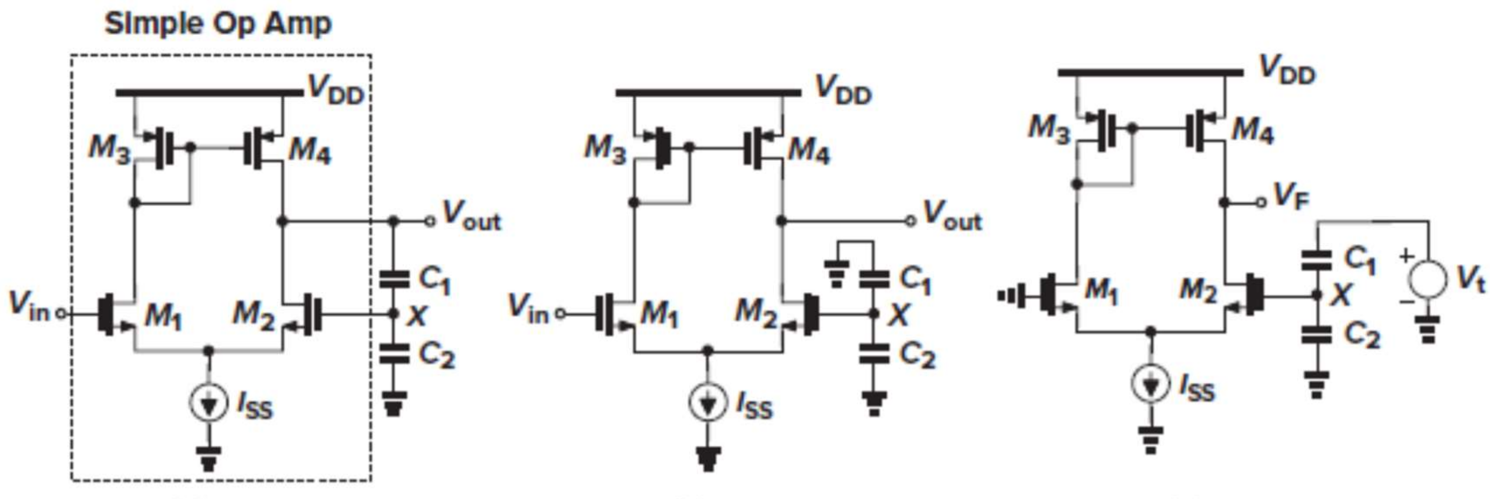
$$I_X R_{in} = V_X - \beta A_0 I_X R_{in}$$

$$R_{in,CL} = \frac{V_X}{I_X} = R_{in}(1 + \beta A_0)$$

Example 8.4

Mixed-Signal IC Laboratory

Calculate the closed-loop gain and output resistance of the amplifier at relatively low frequencies.



(a) (b) (c)

$$V_F = -V_t \frac{C_1}{C_1 + C_2} g_{m1}(r_{O2} \| r_{O4})$$

$$A_{closed} = \frac{g_{m1}(r_{O2} \| r_{O4})}{1 + \frac{C_1}{C_1 + C_2} g_{m1}(r_{O2} \| r_{O4})}$$

$$\beta A_0 = \frac{C_1}{C_1 + C_2} g_{m1}(r_{O2} \| r_{O4})$$

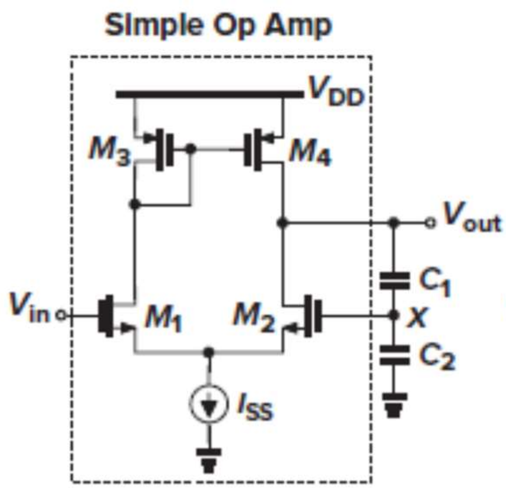
$$R_{out,closed} = \frac{r_{O2} \| r_{O4}}{1 + \frac{C_1}{C_1 + C_2} g_{m1}(r_{O2} \| r_{O4})} \approx \left(1 + \frac{C_2}{C_1}\right) \frac{1}{g_{m1}}$$

$$R_{out,CL} \approx \frac{1}{\beta g_m}$$

Example 8.4 (at high frequencies)

Mixed-Signal IC Laboratory

Calculate the closed-loop gain and output resistance of the amplifier at high frequencies.



(a)

Example 8.6

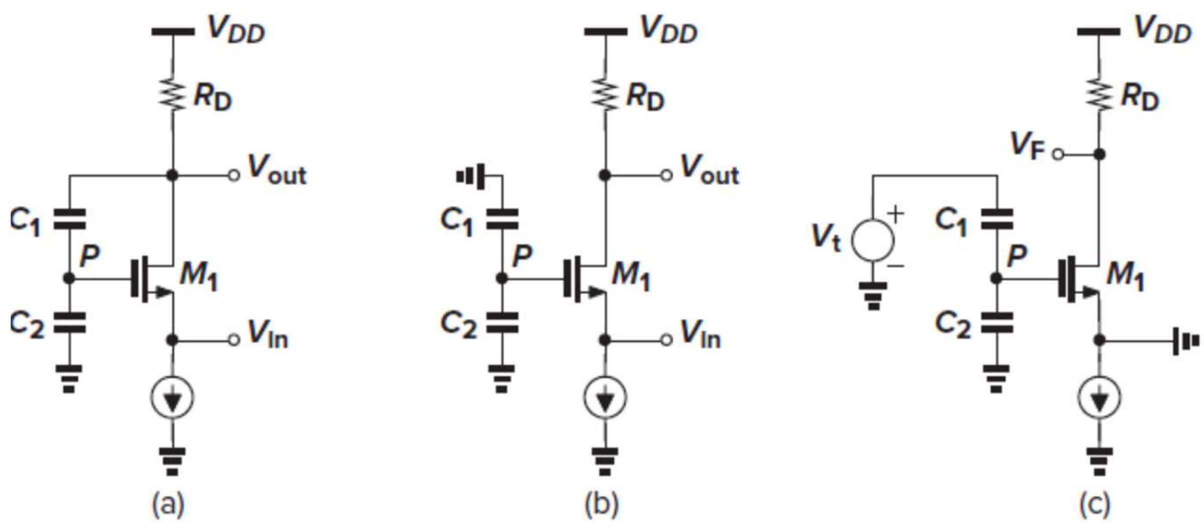
Mixed-Signal IC Laboratory

In textbook, Figure 8.29(a) shows a common-gate topology placed in a voltage-voltage feedback configuration. Note that the summation of the feedback voltage and the input voltage is accomplished by applying the former to the gate and the latter to the source (Vgs = Vg - Vs).

- Calculate the input resistance at low frequencies if channel-length modulation is negligible

[Solution]

As shown in Fig.(b), breaking the loop at output feedback path



Example 8.6

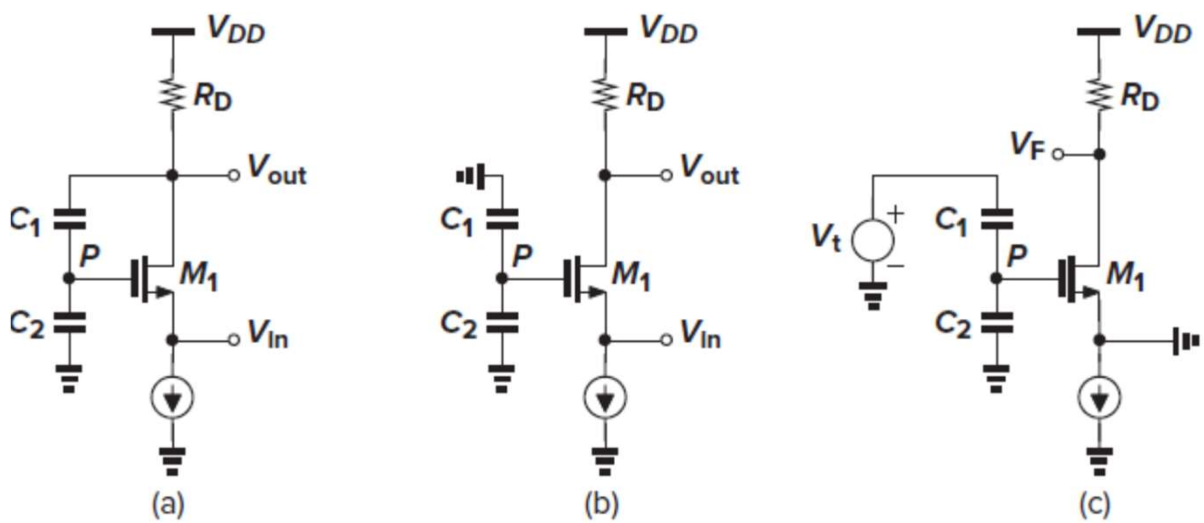
$$R_{in} = \frac{1}{g_{m1} + g_{mb1}}$$

$$R_{in,CL} = R_{in}(1 + \beta A_0)$$

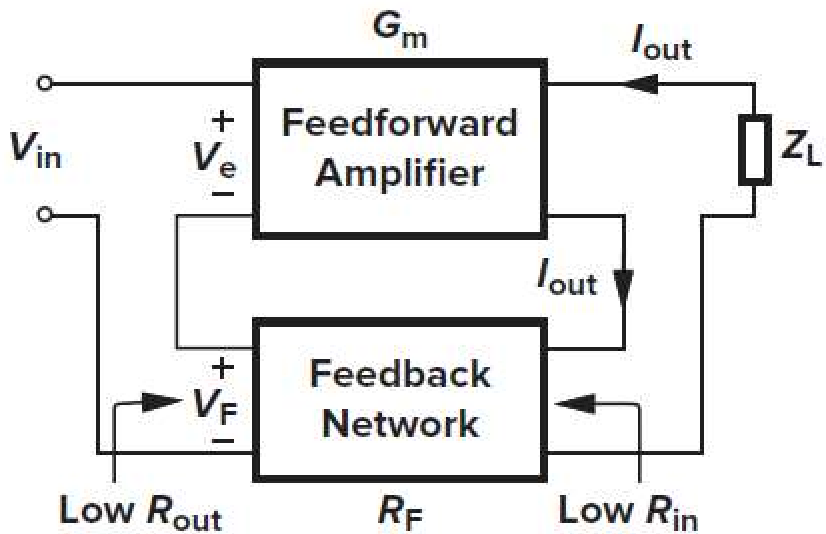
$$\beta A_0 = -\frac{V_F}{V_t} = -\frac{C_1}{C_1 + C_2}(-g_{m1}R_D)$$

$$\beta A_0 = \frac{C_1}{C_1 + C_2} g_{m1}R_D$$

$$R_{in,CL} = \frac{1}{g_{m1} + g_{mb1}}\left(1 + \frac{C_1}{C_1 + C_2}\, g_{m1}R_D\right)$$



Current-Voltage Feedback



$$\left(V_{in} - I_{out}R_F\right)G_m = I_{out}$$

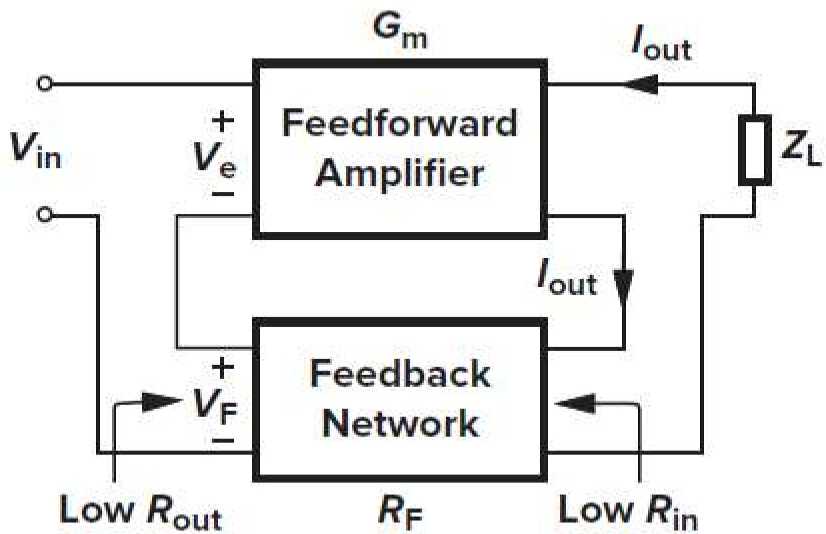
$$\frac{I_{out}}{V_{in}} = \frac{G_m}{1 + G_m R_F}$$

$$\Rightarrow \quad A_0 = G_m \text{ and } \beta = R_F$$

Feedforward Amplifier:

- Input is Voltage
- Output is Current

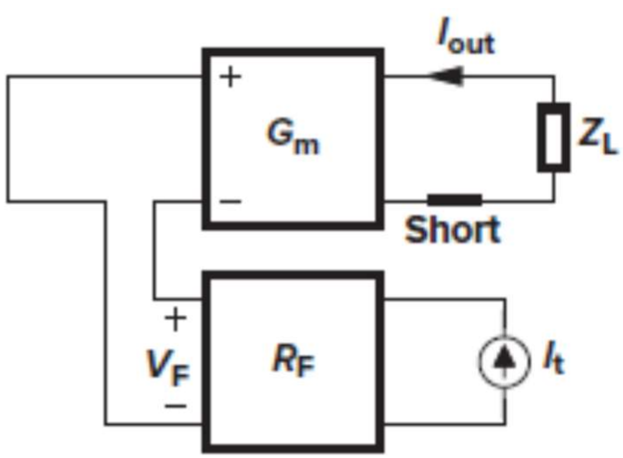
Current-Voltage Feedback



$$\left(V_{in} - I_{out} R_F\right) G_m = I_{out}$$

$$\frac{I_{out}}{V_{in}} = \frac{G_m}{1 + G_m R_F}$$

Calculation of loop gain



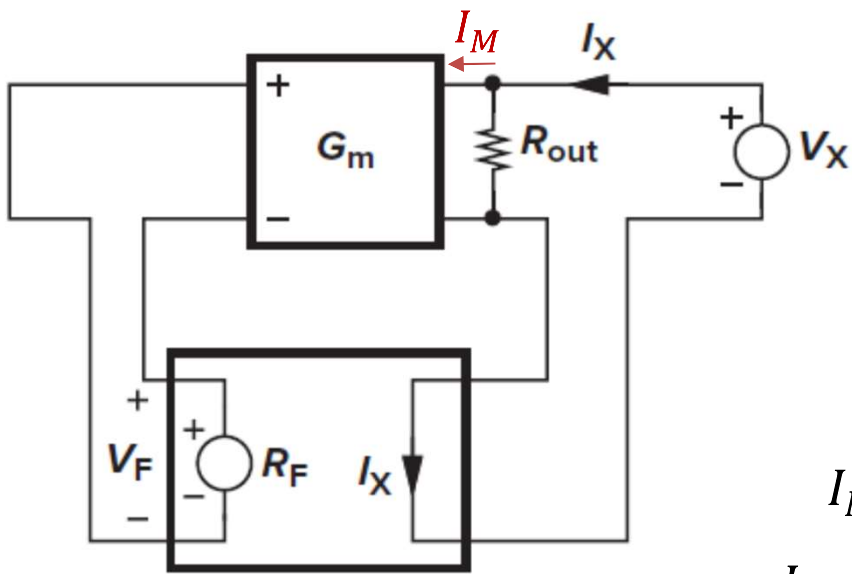
$$V_F = R_F I_t$$

$$I_{out} = G_m(0 - R_F I_t)$$

Loop gain = $-\dfrac{I_{out}}{I_t} = G_m R_F$

Closed-loop gain: $\dfrac{I_{out}}{V_{in}} = \dfrac{G_m}{1+G_m R_F}$

Output Resistance Modification



$$V_F = R_F I_X$$

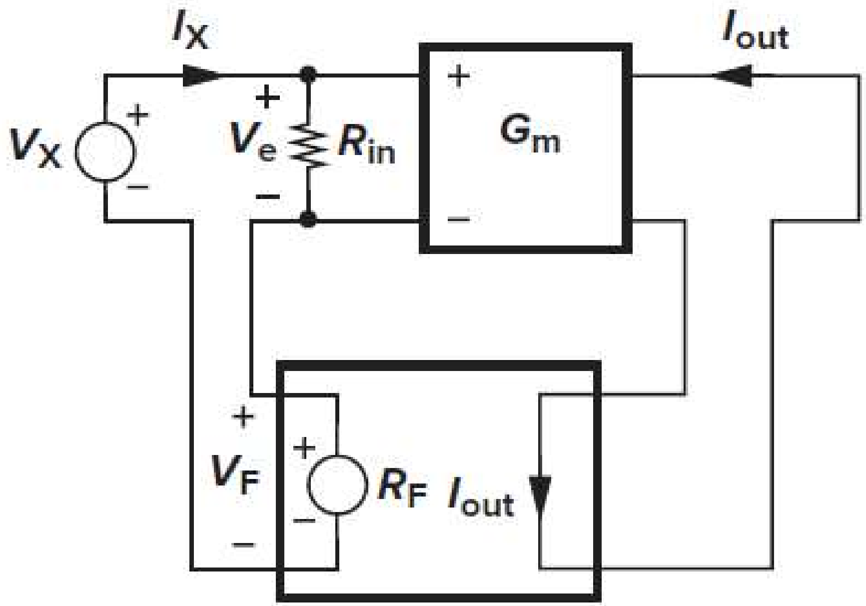
$$I_M = G_m(0 - V_F) = -G_m R_F I_X$$

$$I_M = I_X - V_X/R_{out}$$

$$-G_m R_F I_X = I_X - V_X/R_{out}$$

$$R_{out,CL} = \frac{V_X}{I_X} = R_{out}(1 + G_m R_F)$$

Input Resistance Modification



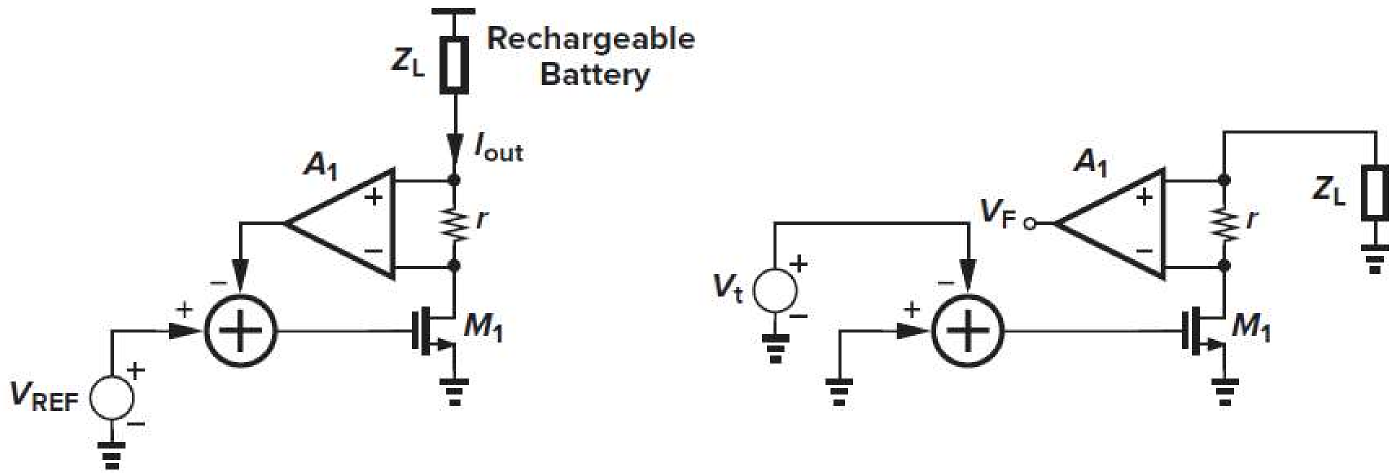
$V_F = R_F I_{out} = R_F G_m V_e$

$V_e = V_X - V_F = V_X - R_F G_m V_e$

$V_e = V_X/(1 + G_m R_F) = I_X R_{in}$

$R_{in,CL} = \frac{V_X}{I_X} = R_{in}\,(1 + G_m R_F)$

Example 8.7



(a) (b)

$$\left(V_{REF} - A_1 I_{out} r\right) \cdot g_{m1} = I_{out}$$

$$g_{m1} V_{REF} = \left(1 + A_1 g_{m1} r\right) I_{out}$$

$$\frac{I_{out}}{V_{REF}} = \frac{g_{m1}}{1 + A_1 g_{m1} r}$$

$$V_F = A_1 I_{M1} r$$

$$I_{M1} = g_{m1}(0 - V_t) = -g_{m1} V_t$$

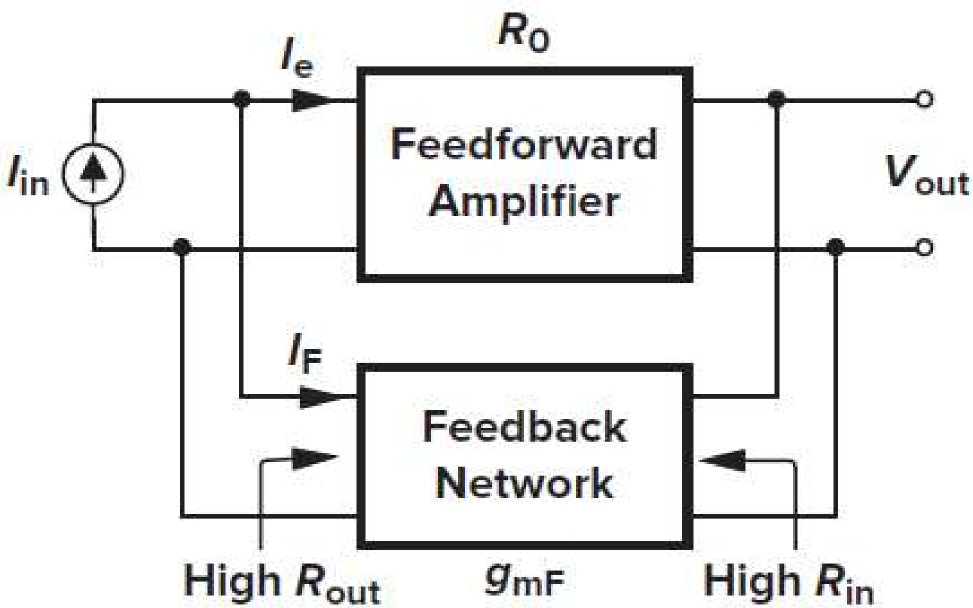
$$V_F = -A_1 g_{m1} r V_t$$

$$Loop\ gain = -\frac{V_F}{V_t} = A_1 g_{m1} r$$

$$R_{out,CL} = (r_o + r)(1 + A_1 g_{m1} r)$$

Voltage-Current Feedback

Mixed-Signal IC Laboratory



$$V_{out} = I_e R_O$$

$$I_e = I_{in} - I_F = I_{in} - g_{mF} V_{out}$$

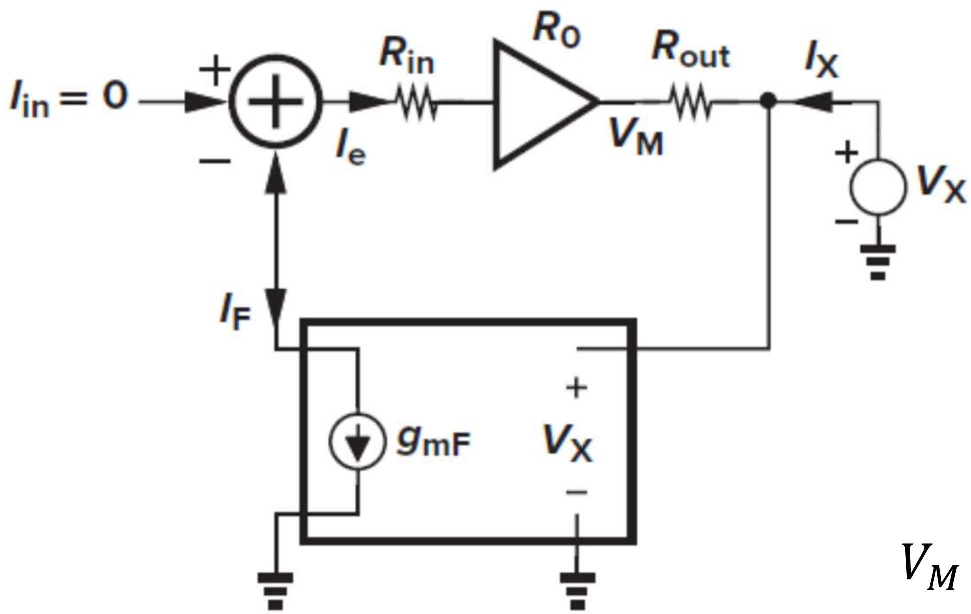
$$V_{out} = R_O \left(I_{in} - g_{mF} V_{out} \right)$$

$$\frac{V_{out}}{I_{in}} = \frac{R_0}{1 + g_{mF} R_0}$$

Feedforward Amplifier:

- Input is Current
- Output is Voltage

Output Impedance Modification



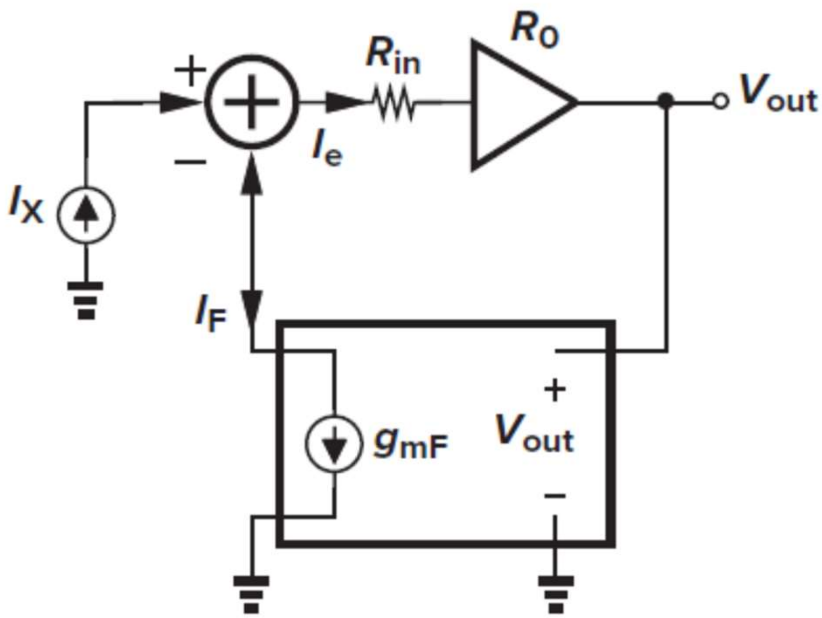
$$I_F = g_{mF} V_X = -I_e$$

$$V_M = I_e R_0 = -\, g_{mF} R_0 V_X$$

$$I_X = \frac{V_X - V_M}{R_{out}} = \frac{V_X + g_{mF} R_0 V_X}{R_{out}}$$

$$R_{out,CL} = \frac{R_{out}}{1 + g_{mF} R_0}$$

Input Impedance Modification



$$I_e = \frac{V_X}{R_{in}}$$

$$I_F = I_X - I_e = I_X - \frac{V_X}{R_{in}}$$

$$I_F = g_{mF} R_0 I_e = g_{mF} R_0 \frac{V_X}{R_{in}}$$

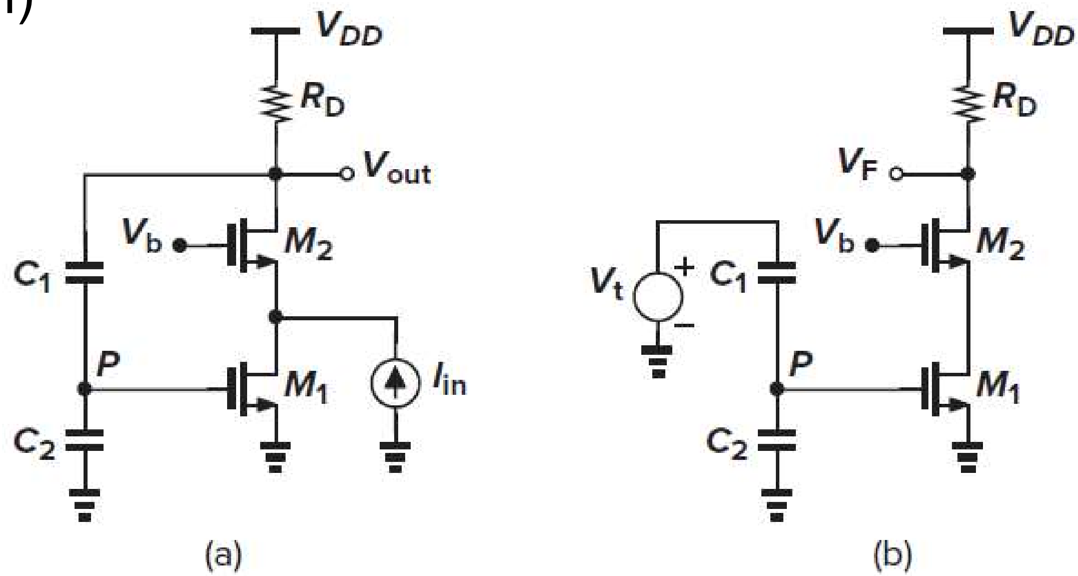
$$I_X - \frac{V_X}{R_{in}} = g_{mF} R_0 \frac{V_X}{R_{in}}$$

$$I_X = \frac{V_X + g_{mF} R_0 V_X}{R_{in}}$$

$$R_{in,CL} = \frac{R_{in}}{1 + g_{mF} R_0}$$

Example 8.8

Calculate the transimpedance, V_{out}/I_{in}, of the circuit shown in Fig. 8.36(a) at relatively low frequencies. Assume that $\lambda = 0$. (The bias network of M_1 is not shown)



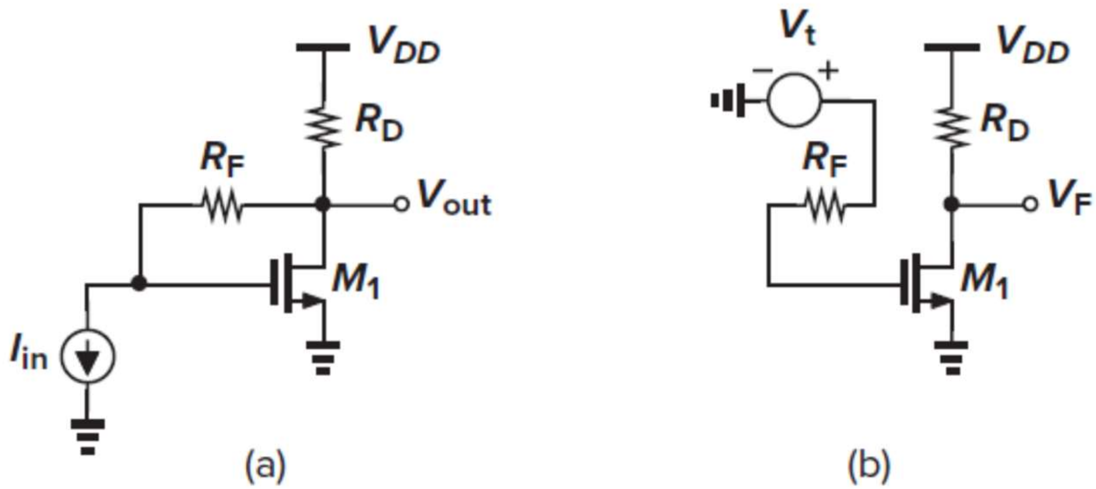
$$R_{0,CL} = \frac{V_{out}}{I_{in}} = \frac{R_D}{1 + \frac{C_1}{C_1 + C_2} g_{m1} R_D}$$

$$-\left(V_t \frac{C_1}{C_1 + C_2} g_{m1} R_D\right) = V_F$$

$$\beta A_0 = -\frac{V_F}{V_t} = \frac{C_1}{C_1 + C_2} g_{m1} R_D$$

Example 8.10

Calculate the input and output impedances, assume that R_F>>R_D.



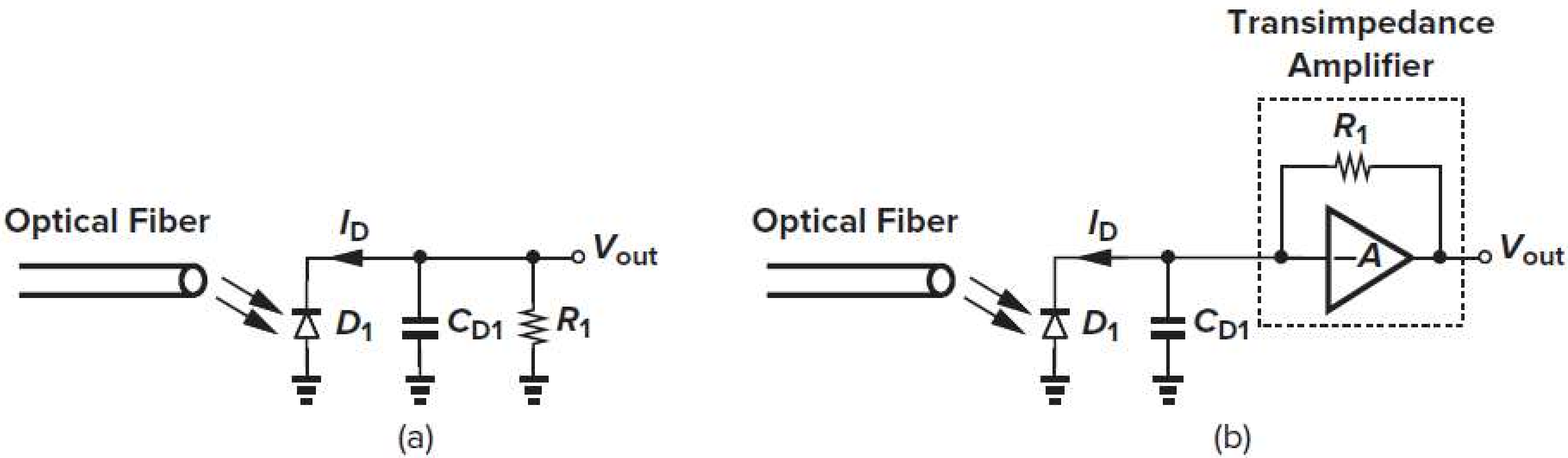
$$-(V_t g_{m1} R_D) = V_F \;\; => \;\beta A = -\frac{V_F}{V_t} = g_m R_D$$

$$R_{in,CL} = \frac{R_F}{1 + g_m R_D}$$

$$R_{out,CL} = \frac{R_D}{1 + g_m R_D}$$

$$R_{out,CL} = \frac{1}{g_m} || R_D$$

Optical Fiber Example

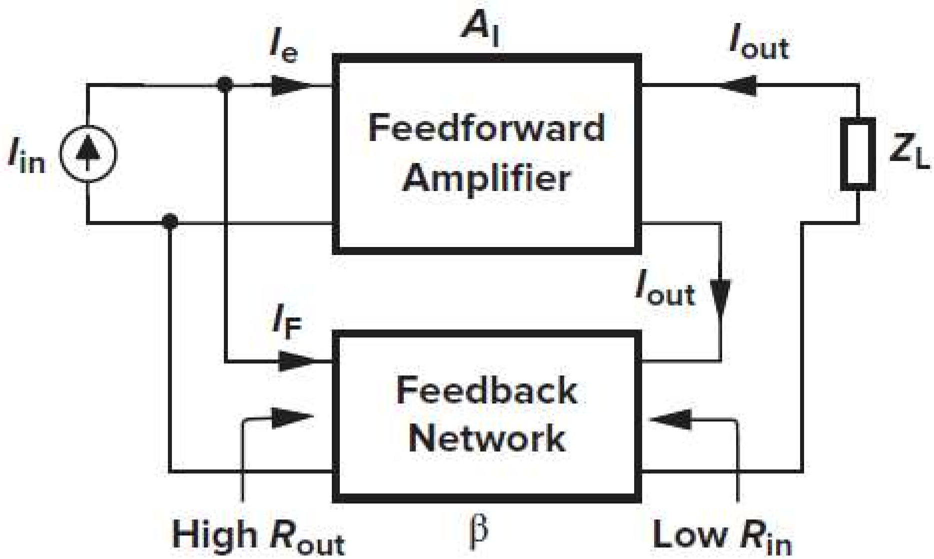


Bandwidth issue??

We need to get a small R_1 but keep a large amplitude of V_{out}

$$R_{in} = \frac{R_1}{1+A}$$

Current-Current Feedback

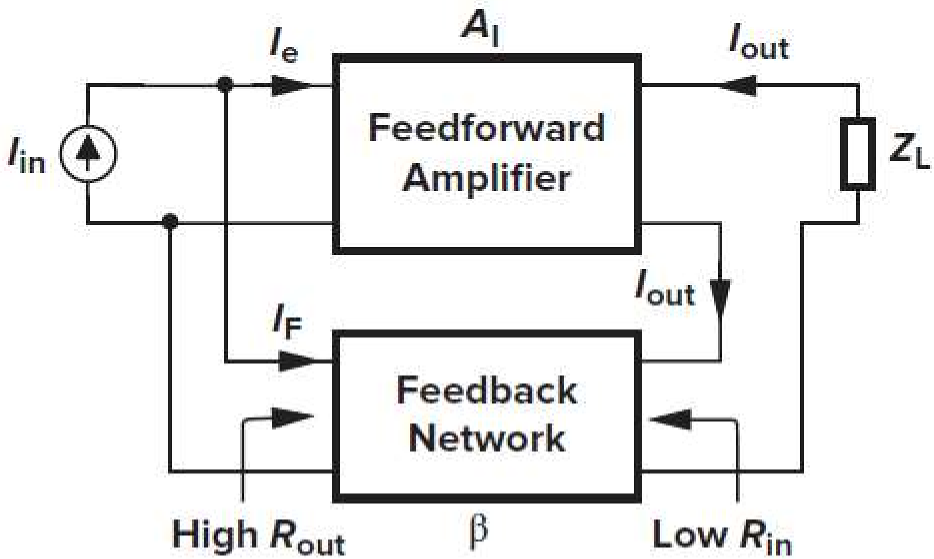


$$\frac{I_{out}}{I_{in}} = \frac{A_I}{1+\beta A_I}$$

Feedforward Amplifier:

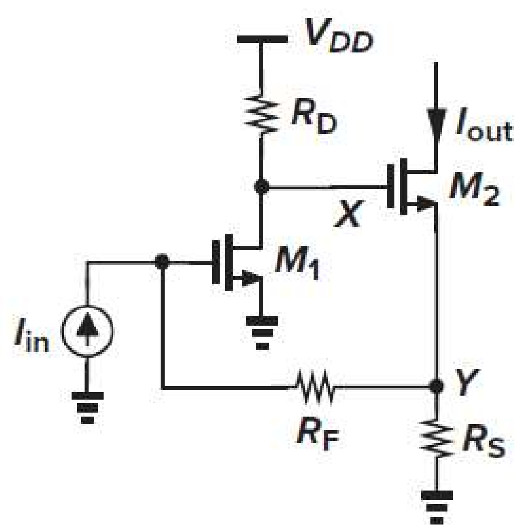
- Input is Current
- Output is Current

Current-Current Feedback



$$\frac{I_{out}}{I_{in}} = \frac{A_I}{1+\beta A_I}$$

Example



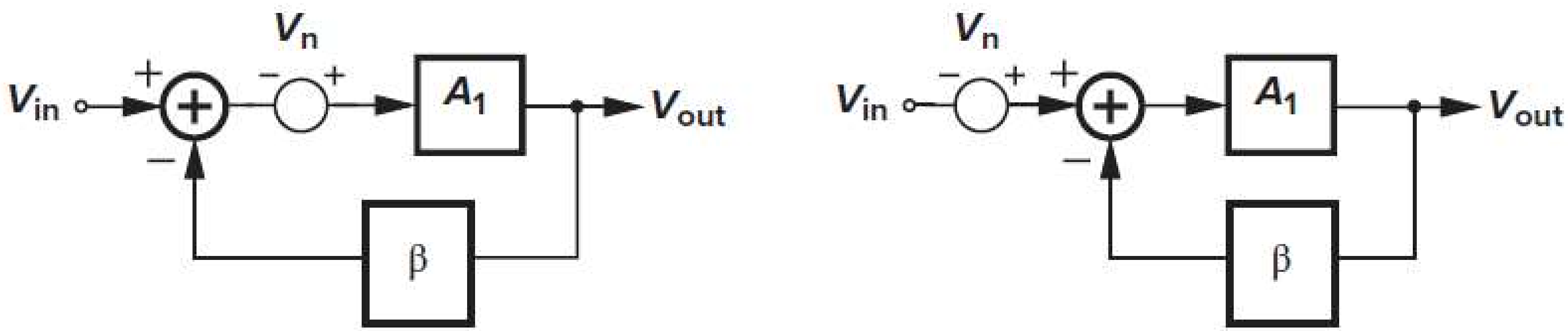
$R_{in,CL} = ?$

$R_{out,CL} = ?$

Effect of Feedback on Noise

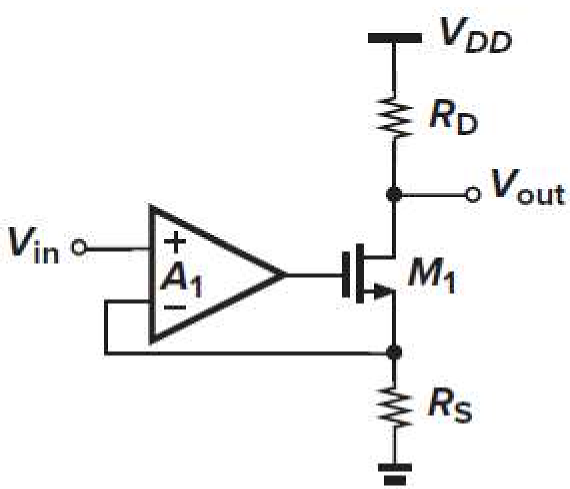
Mixed-Signal IC Laboratory

- Feedback does not improve the noise performance of circuits?



(a) (b)

$$V_{out} = (V_{in} + V_n)\frac{A_1}{1 + \beta A_1}$$



$$|V_{n,in,open}| = \frac{|V_{n,RD}|}{A_1 R_D}\left[\frac{1}{g_m} + R_S\right]$$

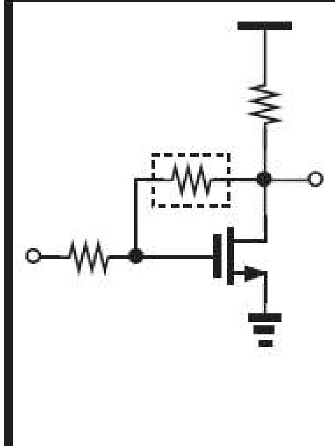
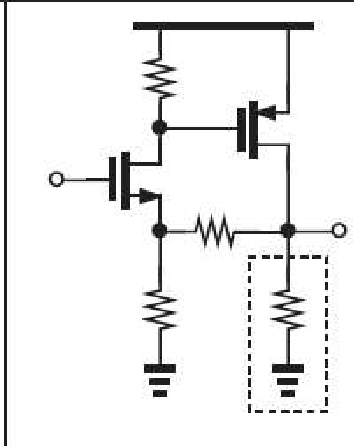
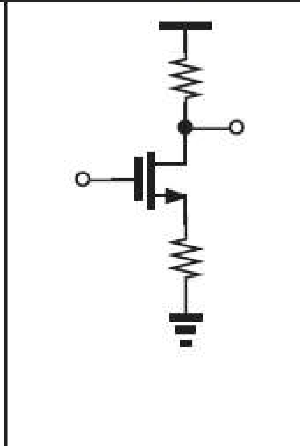
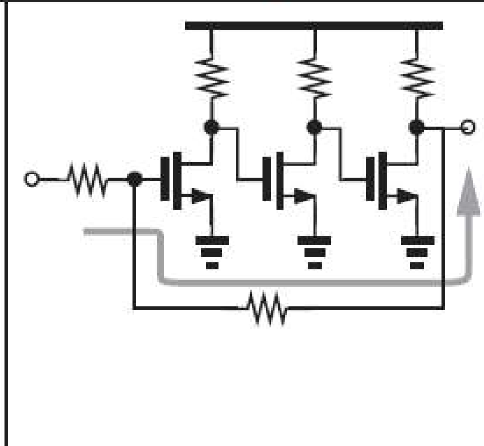
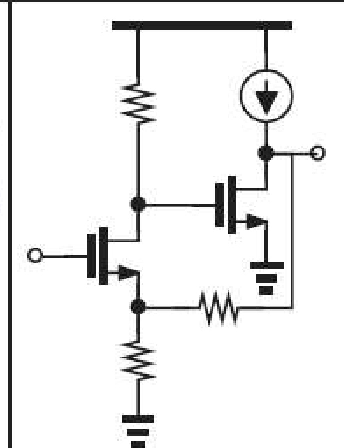
if the feedback network is noiseless

$$|V_{n,in,closed}| = \frac{|V_{n,RD}|}{A_1 R_D}\left[\frac{1}{g_m} + (1 + A_1)R_S\right]$$

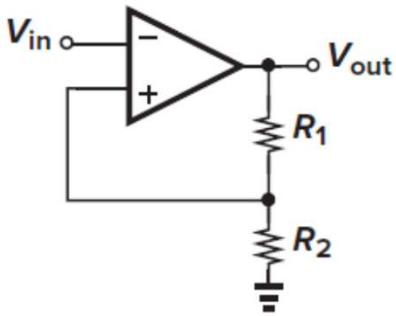
Feedback Analysis Difficulties

Mixed-Signal IC Laboratory

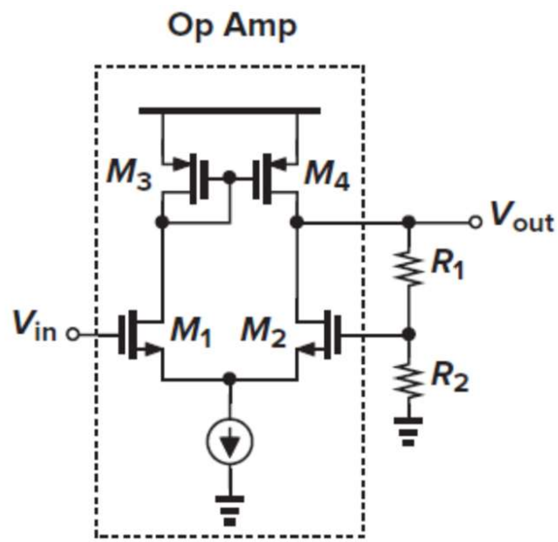
1. Breaking the loop with loading effect
2. Circuits cannot be clearly decomposed
3. Circuits cannot be mapped into four topologies
4. Bilateral Circuits
5. Multiple Feedback Circuits

Loading	Ambiguous Decomposition	Noncanonical Topologies	Nonunilateral Loop	Multiple Feedback Mechanisms
				

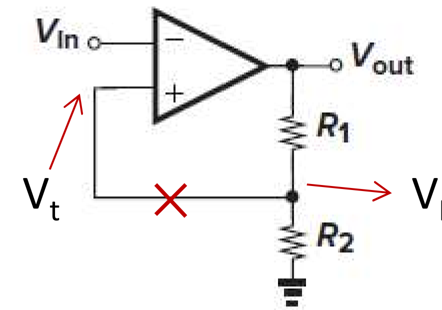
Breaking the loop with loading effect



(a)



(b)



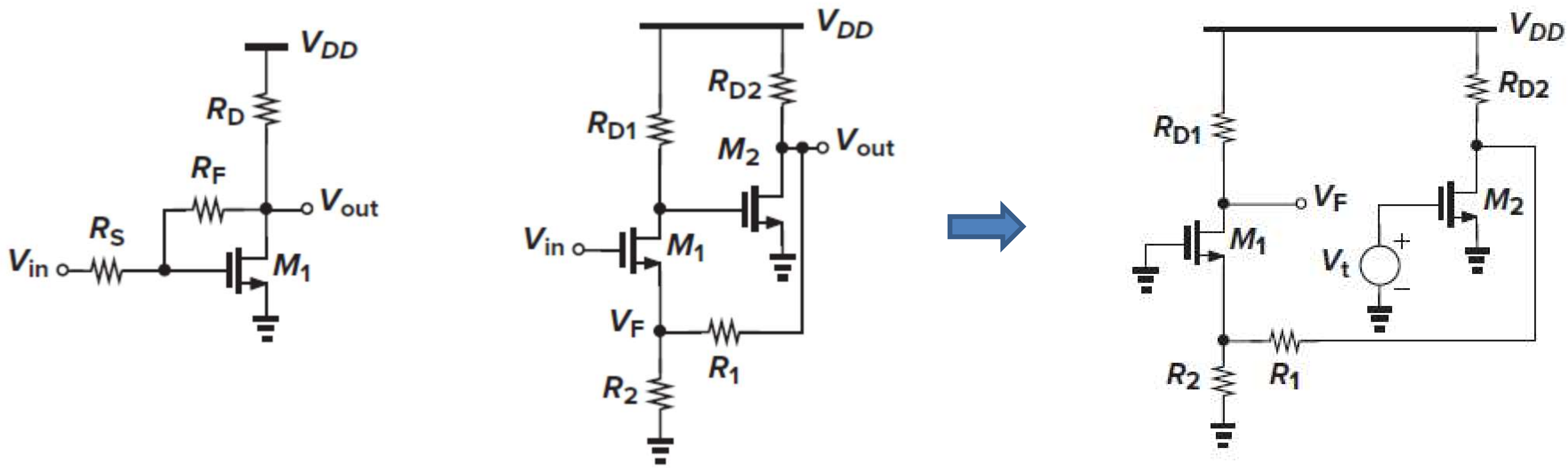
The feedback branch consisting of R_1 and R_2 may draw a significant signal current from the op amp, reducing its *open-loop* gain

So, what is the real feedforward output resistance?

=> The answer is $Ro,amp \,||\, (R_1+R_2)$

Breaking the loop with loading effect

Mixed-Signal IC Laboratory



(c) (d) (e)

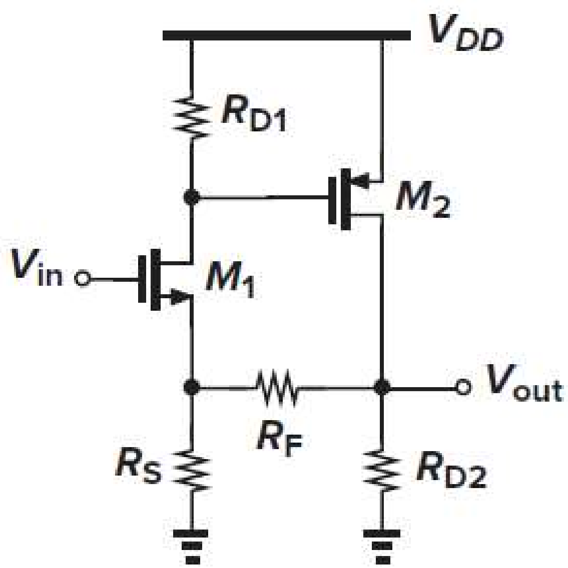
Fig.(c) shows the open-loop gain of the forward CS stage falls if R_F is not very large. (R_F must be as large as possible!!)

The “output” loading results from the nonideal input impedance of the feedback network.

Fig.(d) has similar condition for R_1 and R_2

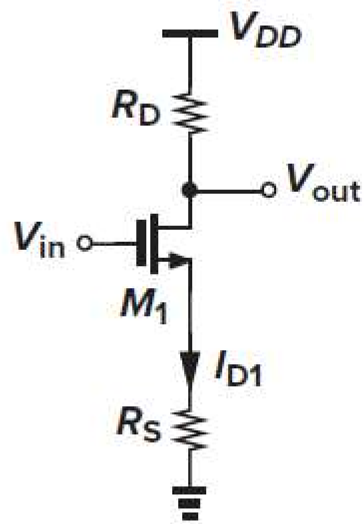
Loop broken as “Fig.(e)” is good for loading effect. But, what is Ro?

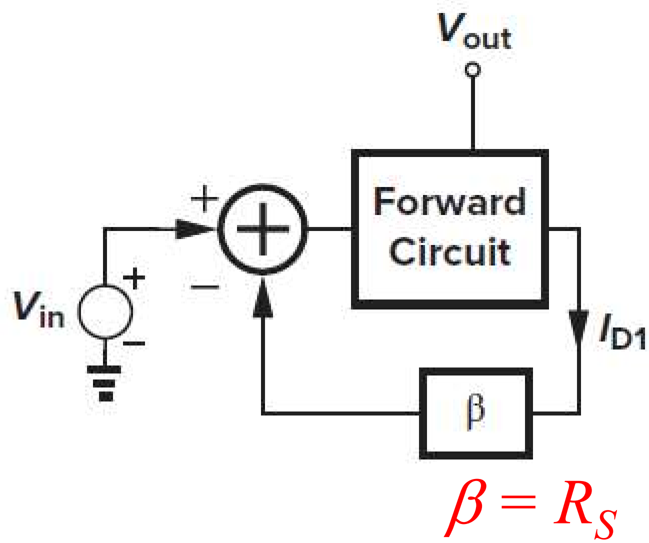
Circuits cannot be clearly decomposed



- Is R_{D2} a feedback element? The answer can be yes or no!!
- How about R_S and R_F?
- Actually, these three resistors are both in a feedforward circuit.
  $\Rightarrow$Voltage-Voltage topology

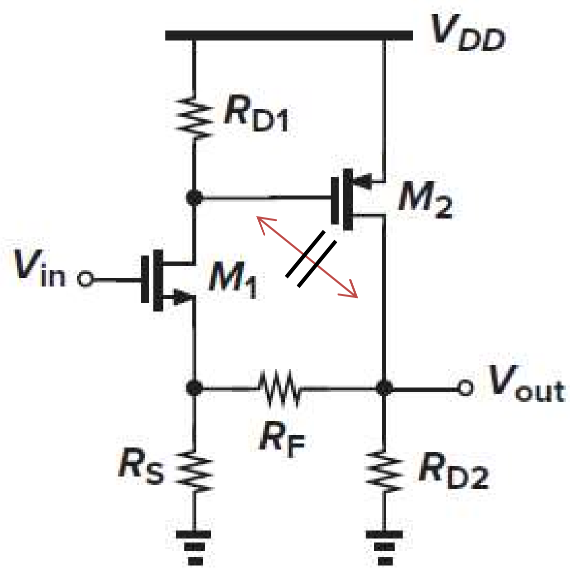
Circuits cannot be mapped into four topologies





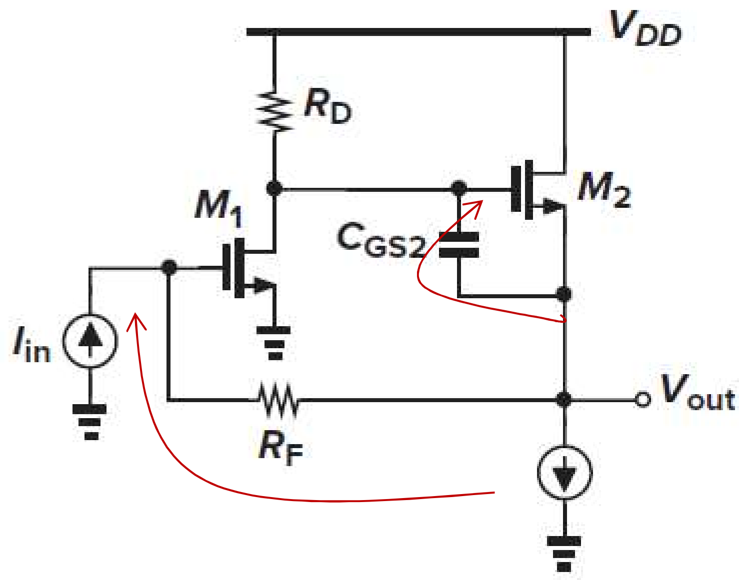
- R_S is used as both feedforward and feedback elements
- This is a "Current-Voltage" topology

Bilateral circuits in the feedback path



- It is a bilateral circuit
- For example, the signal leaks from the drain of *M*2 to its gate through C_{GD2} at high frequencies

Multiple Feedback Circuits

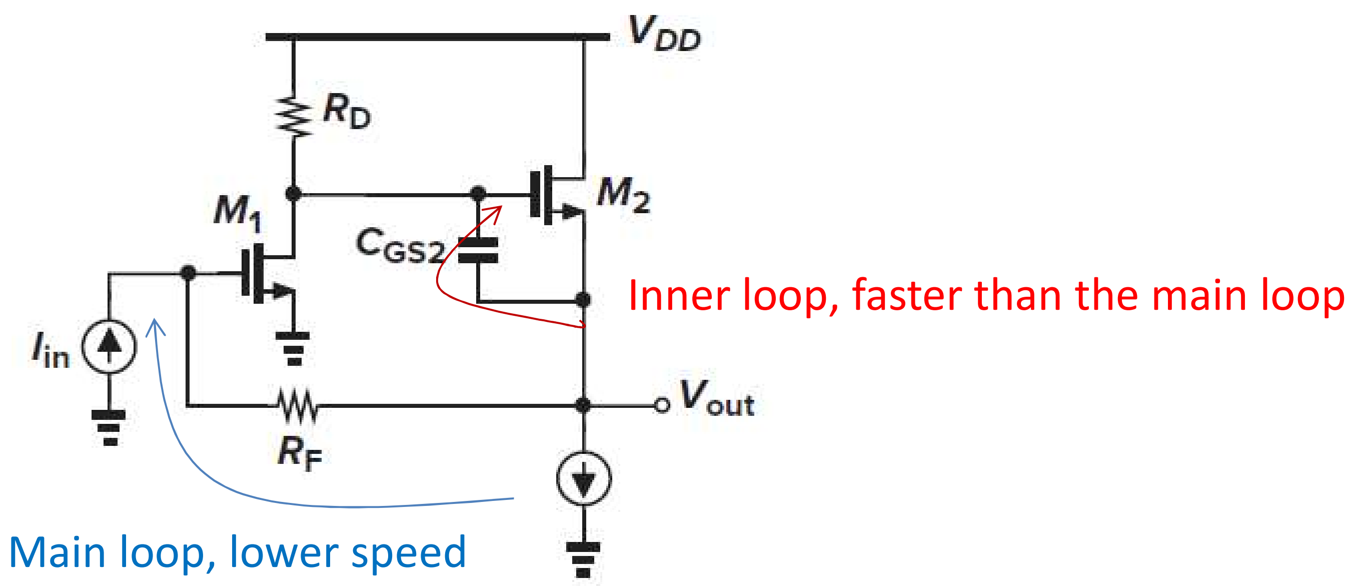


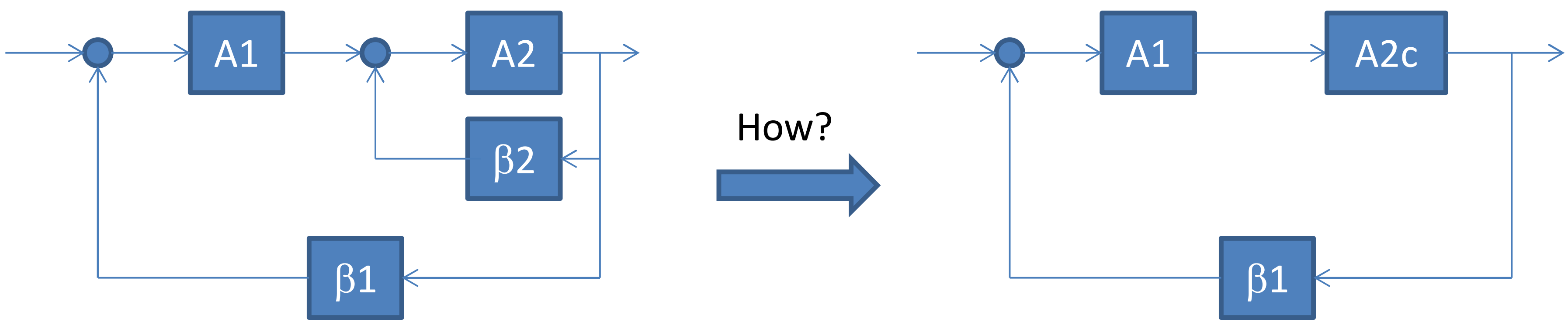
Q: How to analyze this circuit?

⇒Two feedback loops

⇒Then, …

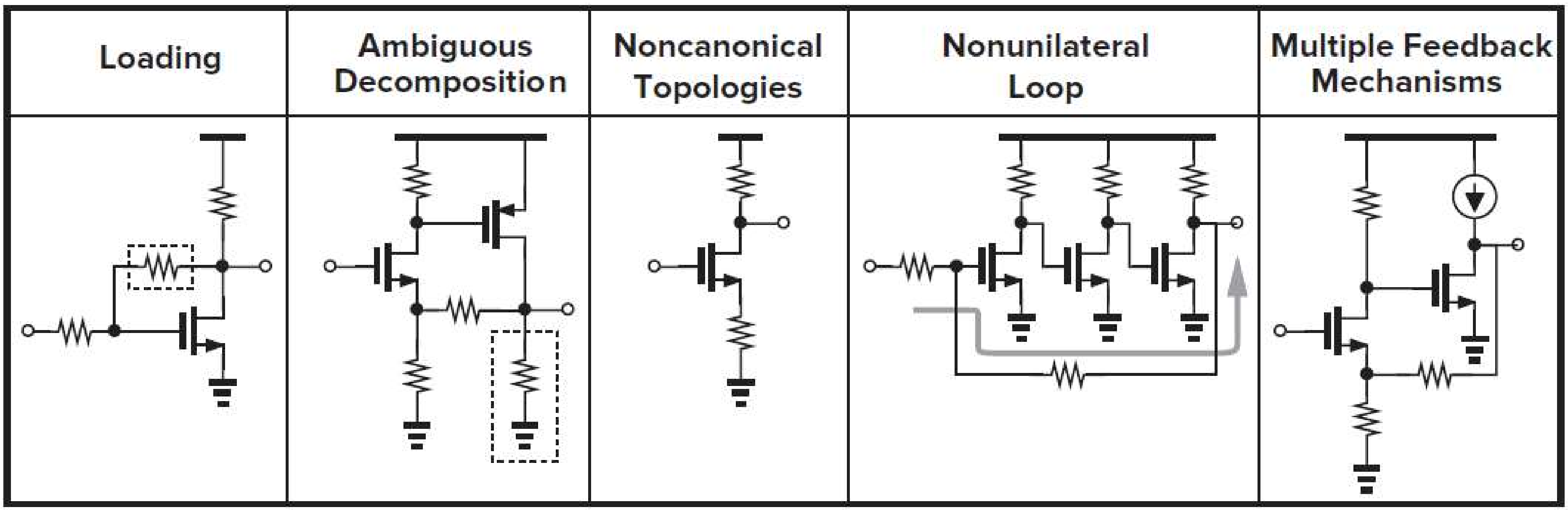
Multiple Feedback Circuits





Feedback Analysis Difficulties: Recall

1. Breaking the loop with loading effect
2. Circuits cannot be clearly decomposed
3. Circuits cannot be mapped into four topologies
4. Bilateral Circuits
5. Multiple Feedback Circuits

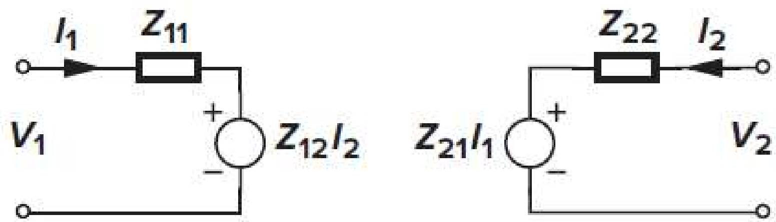


Analysis Methods of Feedback Circuits

Two-Port Method	Bode's Method	Middlebrook's Method
• Computes open-loop and closed-loop quantities and the loop gain. • Includes loading effects. • Neglects feedforward through feedback network. • Can be applied recursively to multiple feedback mechanisms. • Does not apply to noncanonical topologies.	• Computes closed-loop quantities without breaking the loop. • Applies to any topology. • Provides loop gain only if one feedback mechanism is present.	• Computes closed-loop quantities without breaking the loop. • Applies to any topology. • Provides loop gain only if local and global loops are distinguishable. • Reveals effect of reverse loop gain in nonunilateral loops.

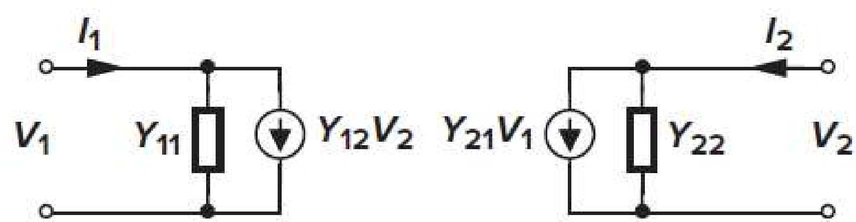
Not mentioned in this lecture

Two-Port Network Models



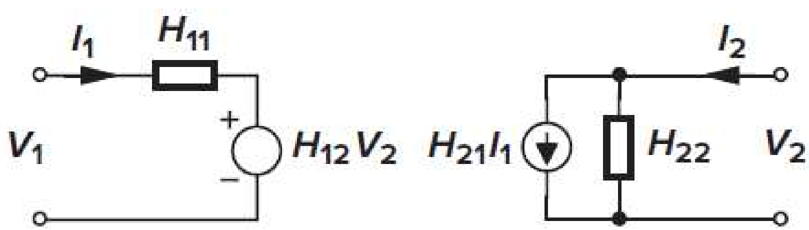
(a)

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



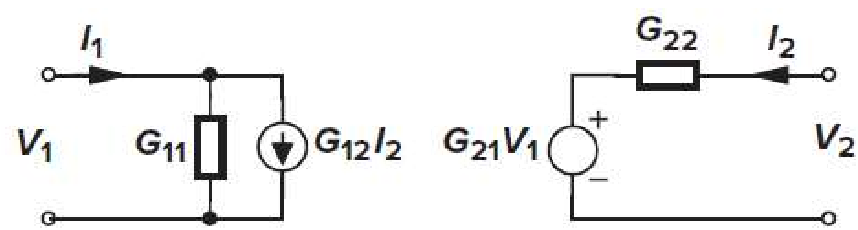
(b)

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



(c)

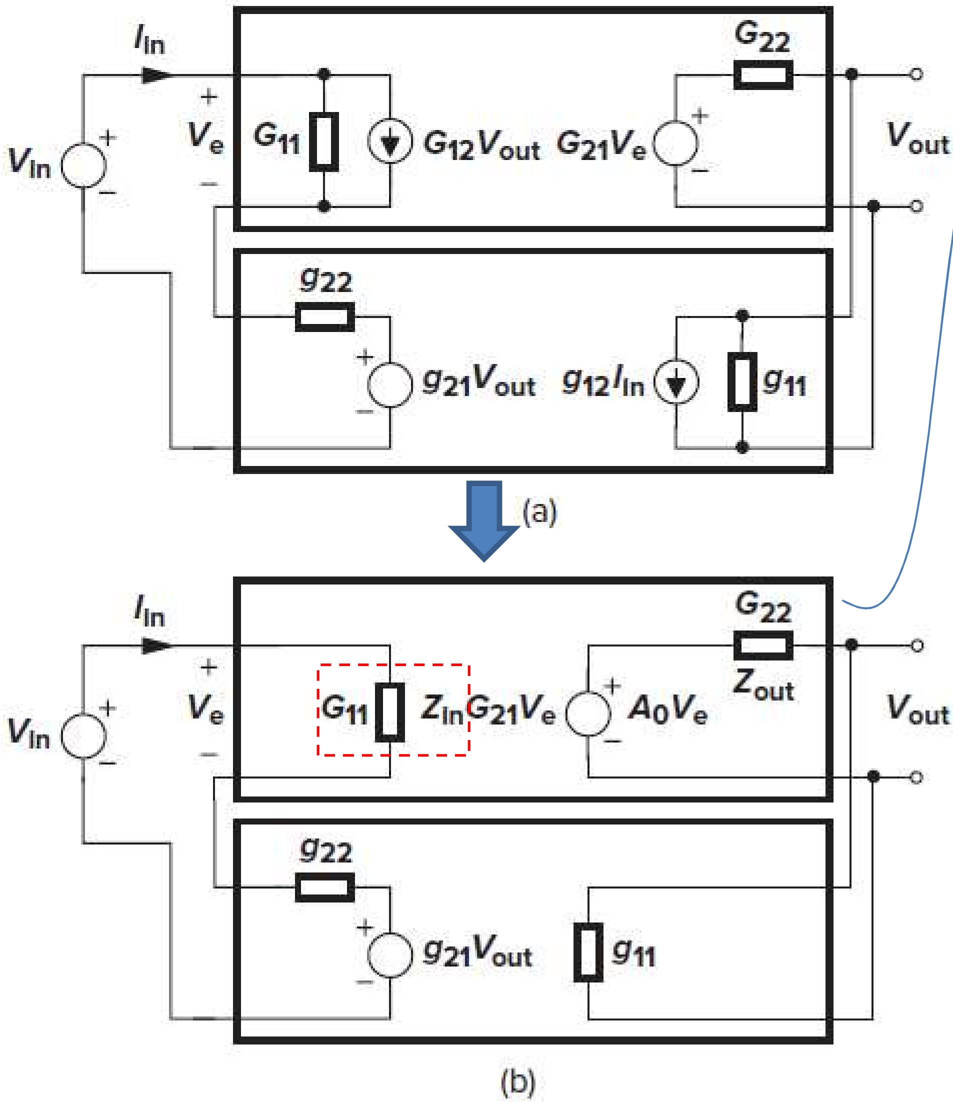
$$V_1 = H_{11}I_1 + H_{12}V_2$$
$$I_2 = H_{21}I_1 + H_{22}V_2$$



(d)

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

Voltage-Voltage Feedback



$$V_{in} = V_e + g_{22}\frac{V_e}{Z_{in}} + g_{21}V_{out}$$

$$g_{11}V_{out} + \frac{V_{out} - A_0V_e}{Z_{out}} = 0$$

$$\frac{V_{out}}{V_{in}} = \frac{A_0}{(1+\frac{g_{22}}{Z_{in}})(1+g_{11}Z_{out}) + g_{21}A_0}$$

$$\frac{V_{out}}{V_{in}} = \frac{\frac{A_0}{(1+\frac{g_{22}}{Z_{in}})(1+g_{11}Z_{out})}}{1+g_{21}\frac{A_0}{(1+\frac{g_{22}}{Z_{in}})(1+g_{11}Z_{out})}}$$

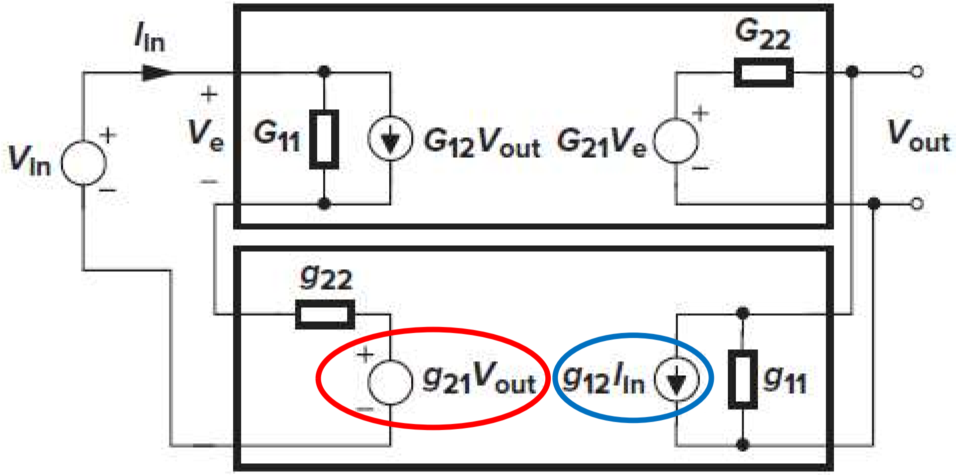
where

$$A_{v,open} = \frac{A_0}{\underbrace{(1+\frac{g_{22}}{Z_{in}})}(1+\underbrace{g_{11}Z_{out})}}$$

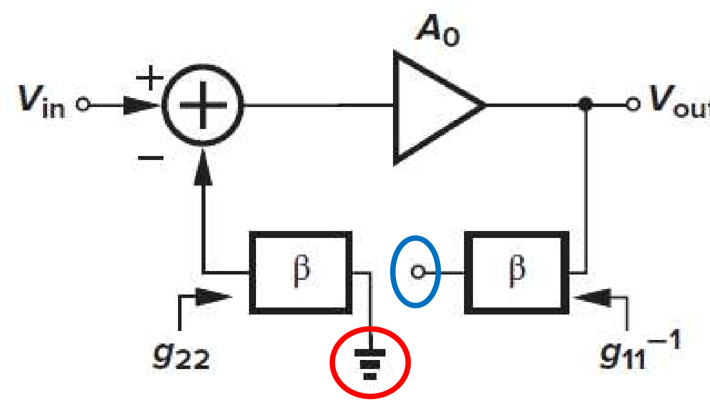
$$\beta = g_{21}$$

Loading effect from feedback ckt

Voltage-Voltage Feedback



FF: Feedforward amplifier



$$\frac{V_{out}}{V_{in}} = \frac{\dfrac{A_0}{(1+\dfrac{g_{22}}{Z_{in}})(1+g_{11}Z_{out})}}{1+g_{21}\dfrac{A_0}{(1+\dfrac{g_{22}}{Z_{in}})(1+g_{11}Z_{out})}}$$

where

$$A_{v,open} = \frac{A_0}{\underline{(1+\dfrac{g_{22}}{Z_{in}})}\underline{(1+g_{11}Z_{out})}}$$

$$\beta = g_{21}$$

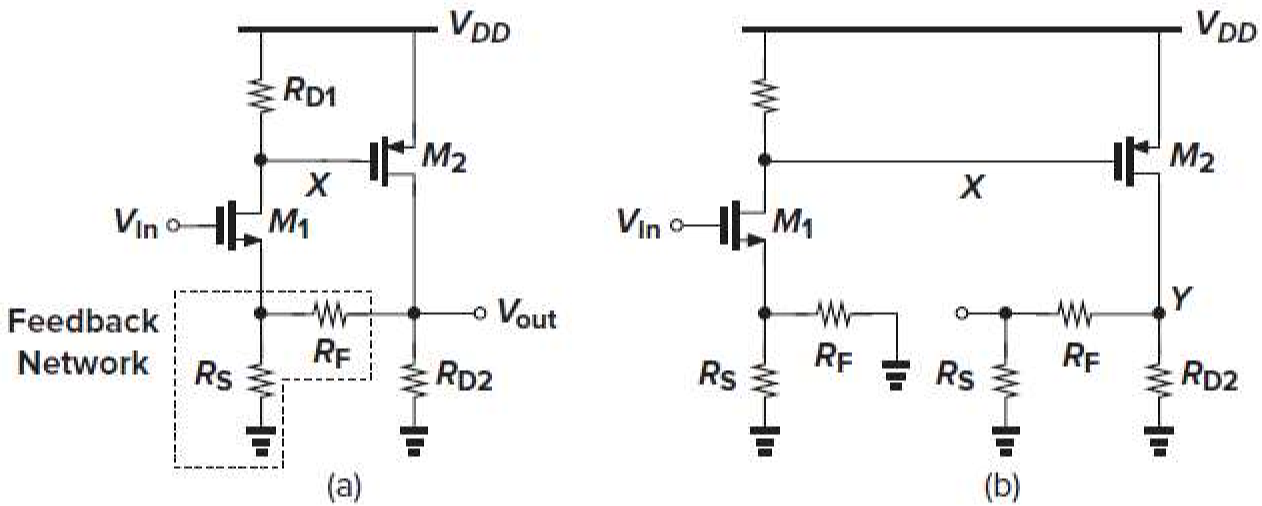
(1) Find out feedback (FB) network, and get "β"

(2) Find "$A_{0,OL}$" firstly w/ loading effect

Step-1: For FF's input, Vout=0 (connection is short)

Step-2: For FF's output, Iin=0 (connection is open)

Example 8.12



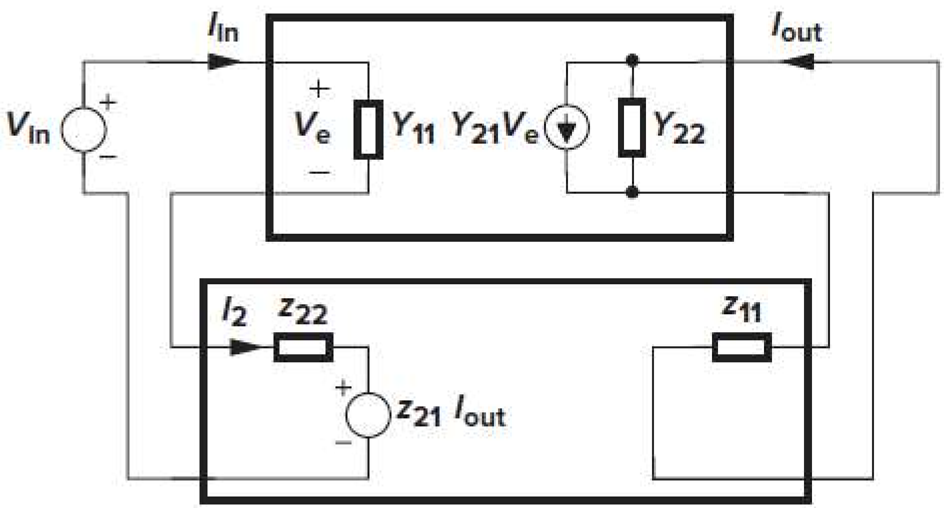
$$\lambda = \gamma = 0$$

$$g_{21} = R_S/(R_F + R_S)$$

$$A_{v,open} = \frac{V_Y}{V_{in}} = \frac{-R_{D1}}{R_F \| R_S + 1/g_{m1}}\{-g_{m2}[R_{D2}\|(R_F + R_S)]\}$$

$$A_{v,closed} = A_{v,open}/(1 + g_{21}A_{v,open})$$

Current-Voltage Feedback



$$V_{in} = V_e + Y_{11}V_e z_{22} + z_{21}I_{out}$$

$$-I_{out}z_{11} = \frac{I_{out} - Y_{21}V_e}{Y_{22}}$$

$$V_e = \frac{1 + z_{11}Y_{22}}{Y_{21}} I_{out}$$

$$V_{in} = V_e(1 + z_{22}Y_{11}) + z_{21}I_{out}$$

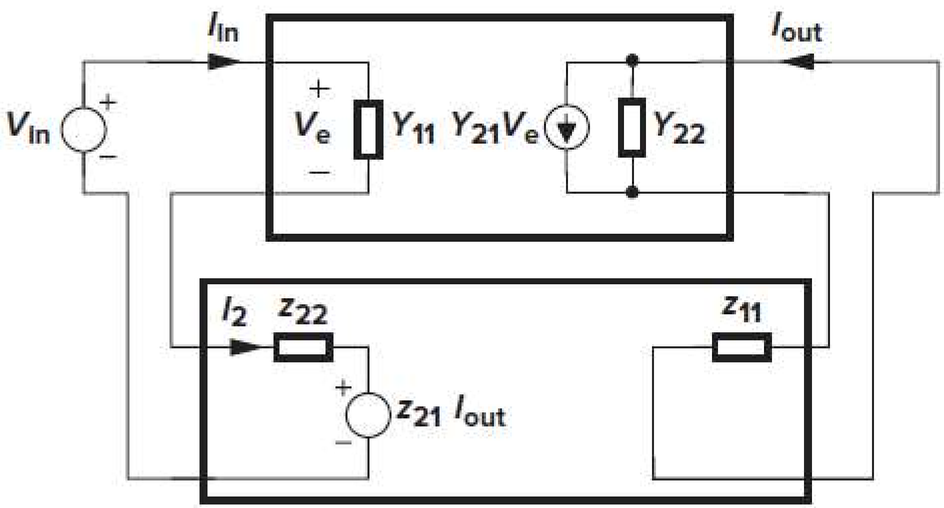
$$\frac{I_{out}}{V_{in}} = \frac{\dfrac{Y_{21}}{(1+z_{22}Y_{11})(1+z_{11}Y_{22})}}{1 + z_{21}\dfrac{Y_{21}}{(1+z_{22}Y_{11})(1+z_{11}Y_{22})}}$$

where

$$G_{m,open} = \frac{Y_{21}}{(1+z_{22}Y_{11})(1+z_{11}Y_{22})}$$

$$\beta = z_{21}$$

Current-Voltage Feedback



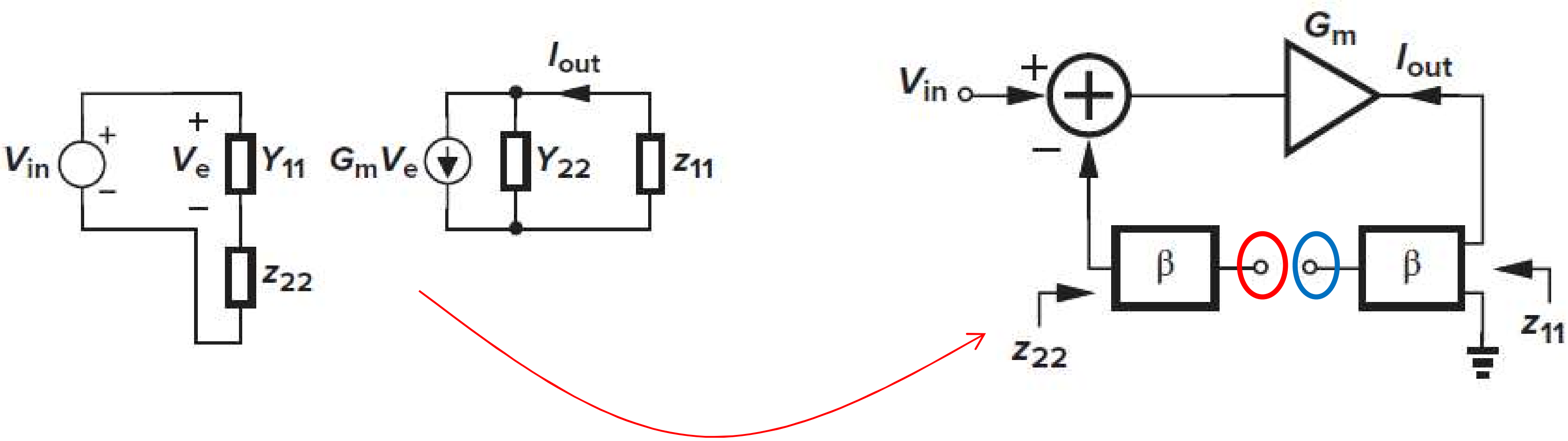
$$\frac{I_{out}}{V_{in}} = \frac{\dfrac{Y_{21}}{(1+z_{22}Y_{11})(1+z_{11}Y_{22})}}{1+z_{21}\dfrac{Y_{21}}{(1+z_{22}Y_{11})(1+z_{11}Y_{22})}}$$

where

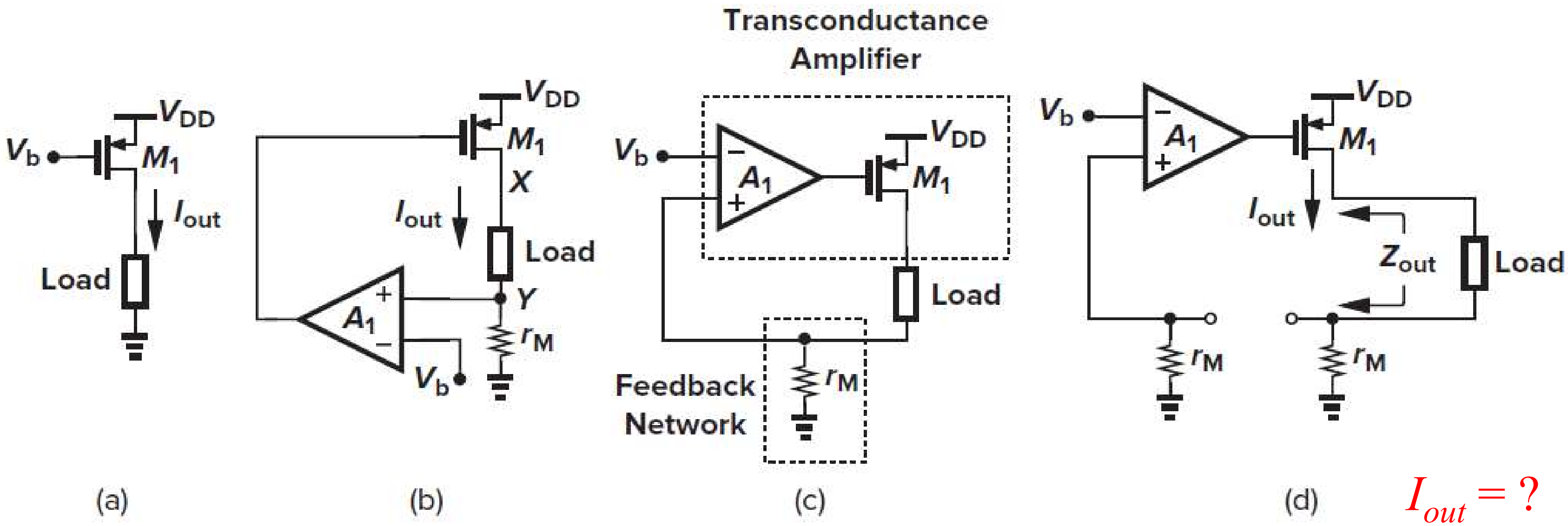
$$G_{m,open} = \frac{Y_{21}}{(1+z_{22}Y_{11})(1+z_{11}Y_{22})}$$

$$\beta = z_{21}$$

Breaking the loop



Example 8.14



$I_{out} \approx V_b / r_M$

$I_{out} = ?$
$Z_{out} = ?$

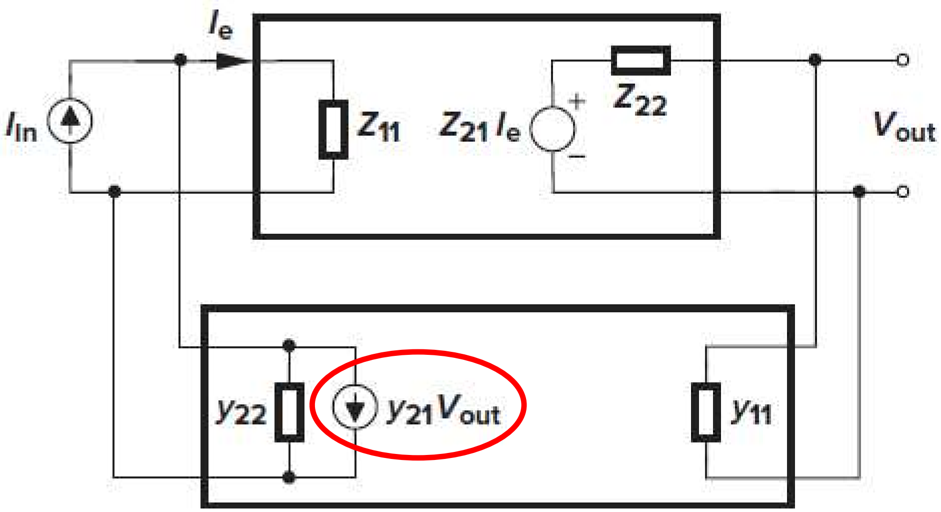
$$G_{m,open} = \frac{I_{out}}{V_b} \approx A_1 g_m$$

$$I_{out} = \frac{A_1 g_m}{1 + A_1 g_m r_M} V_b$$

$$\beta = r_M$$

$$r_O + r_M \Rightarrow Z_{out} = (1 + A_1 g_m r_M)(r_O + r_M)$$

Voltage-Current Feedback



$$I_{in} = I_e + I_e Z_{11} y_{22} + y_{21} V_{out}$$

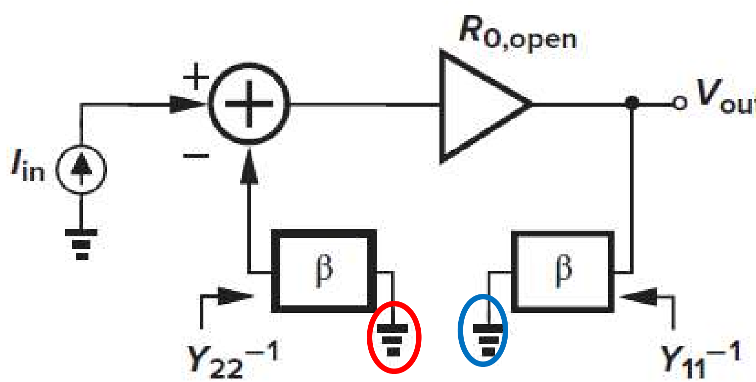
$$y_{11} V_{out} + \frac{V_{out} - Z_{21} I_e}{Z_{22}} = 0$$

$$\frac{V_{out}}{I_{in}} = \frac{\dfrac{Z_{21}}{(1 + y_{22} Z_{11})(1 + y_{11} Z_{22})}}{1 + y_{21} \dfrac{Z_{21}}{(1 + y_{22} Z_{11})(1 + y_{11} Z_{22})}}$$

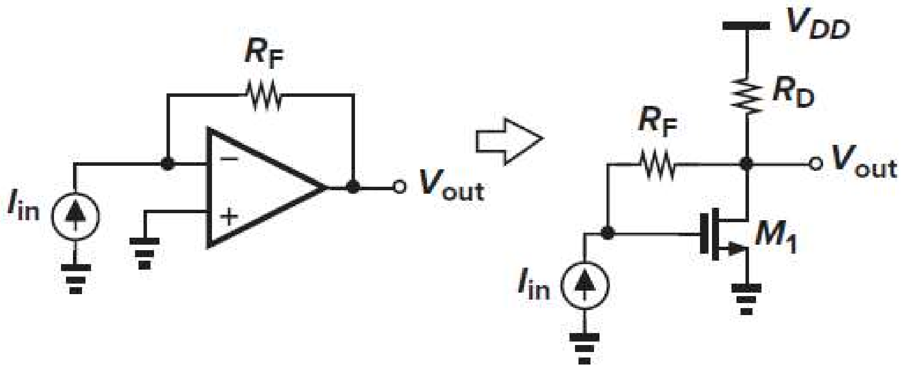
where

$$R_{0,open} = \frac{Z_{21}}{(1 + y_{22} Z_{11})(1 + y_{11} Z_{22})}$$

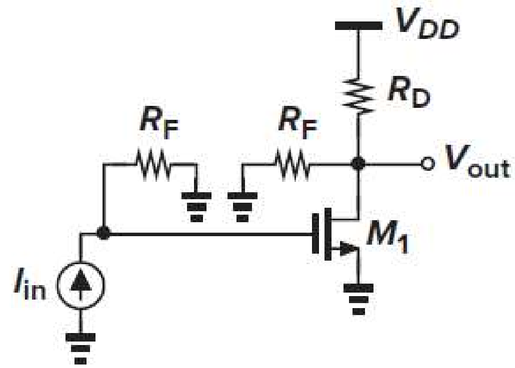
$$\beta = y_{21}$$



Example 8.15



(a)



(b) if $\lambda = 0$.

$$R_{0,open} = -R_F g_m (R_F || R_D)$$

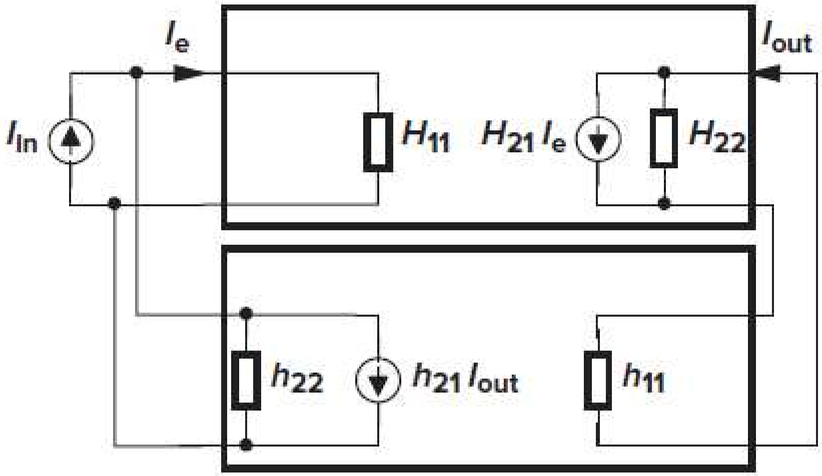
$$\beta = \frac{1}{R_F}$$

$$\frac{V_{out}}{I_{in}} = \frac{-R_F g_m (R_F || R_D)}{1 + g_m (R_F || R_D)}$$

$$R_{in} = \frac{R_F}{1 + g_m (R_F || R_D)}$$

$$R_{out} = \frac{R_F || R_D}{1 + g_m (R_F || R_D)}$$

Current-Current Feedback



$$I_{in} = I_e H_{11} h_{22} + h_{21} I_{out} + I_e$$

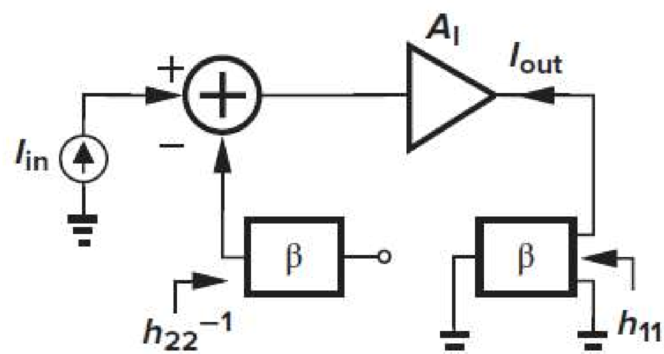
$$I_{out} = -I_{out} h_{11} H_{22} + H_{21} I_e$$

$$\frac{I_{out}}{I_{in}} = \frac{\dfrac{H_{21}}{(1+h_{22}H_{11})(1+h_{11}H_{22})}}{1 + h_{21}\dfrac{H_{21}}{(1+h_{22}H_{11})(1+h_{11}H_{22})}}$$

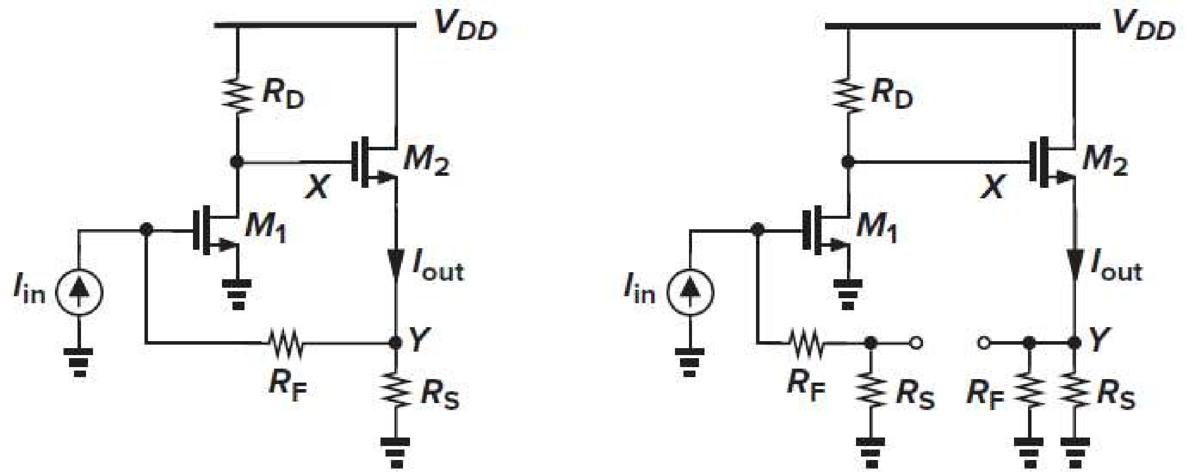
where

$$A_{I,open} = \frac{H_{21}}{(1+h_{22}H_{11})(1+h_{11}H_{22})}$$

$$\beta = h_{21}$$



Example 8.17



(a) (b)

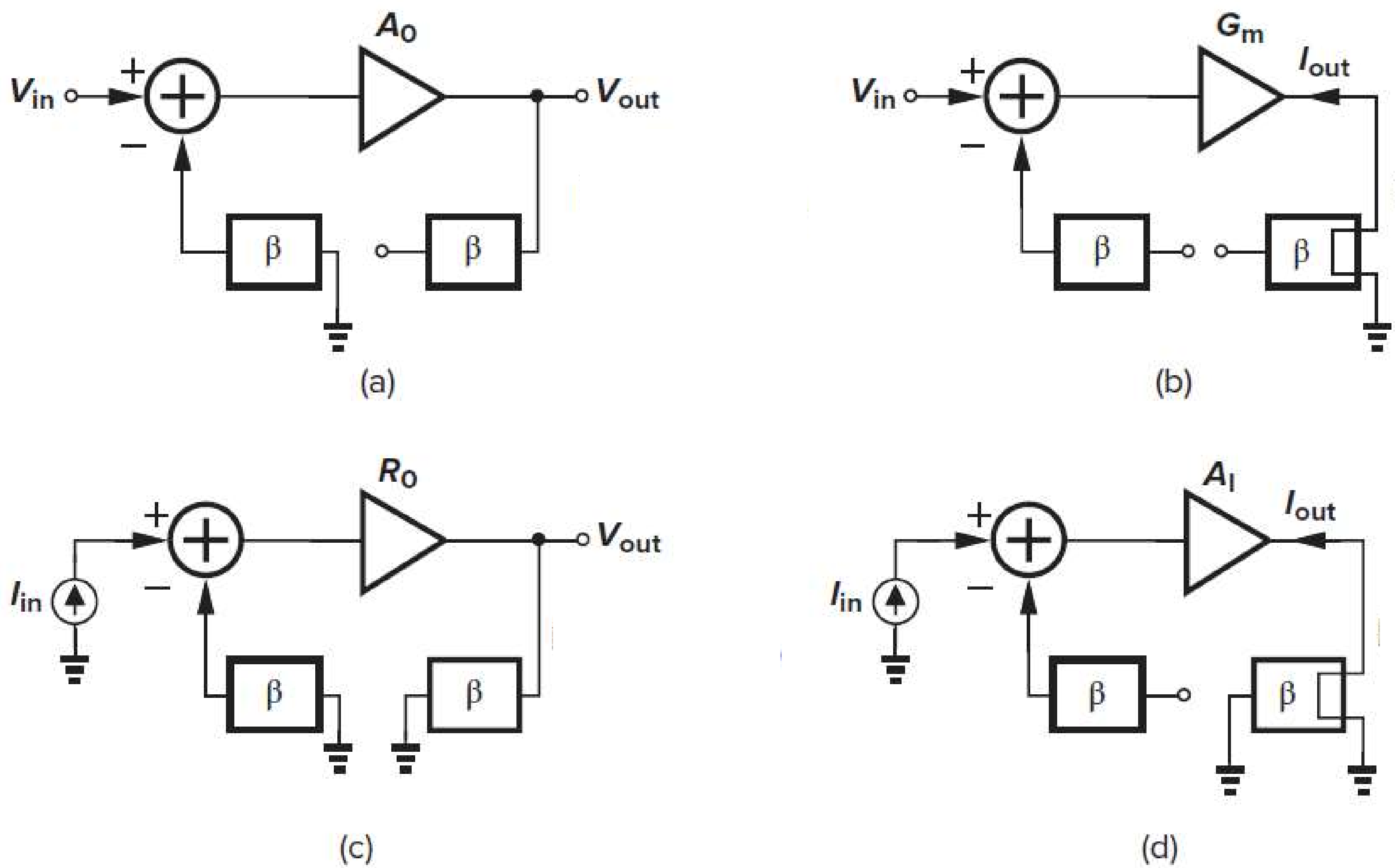
Solution

In this circuit, R_S and R_F sense the output current and return a fraction thereof to the input. Breaking the loop according to Fig. 8.65, we arrive at the circuit in Fig. 8.66(b), where we have

$$A_{I,open} = -(R_F + R_S) g_{m1} R_D \frac{1}{R_S \| R_F + 1/g_{m2}} \tag{8.106}$$

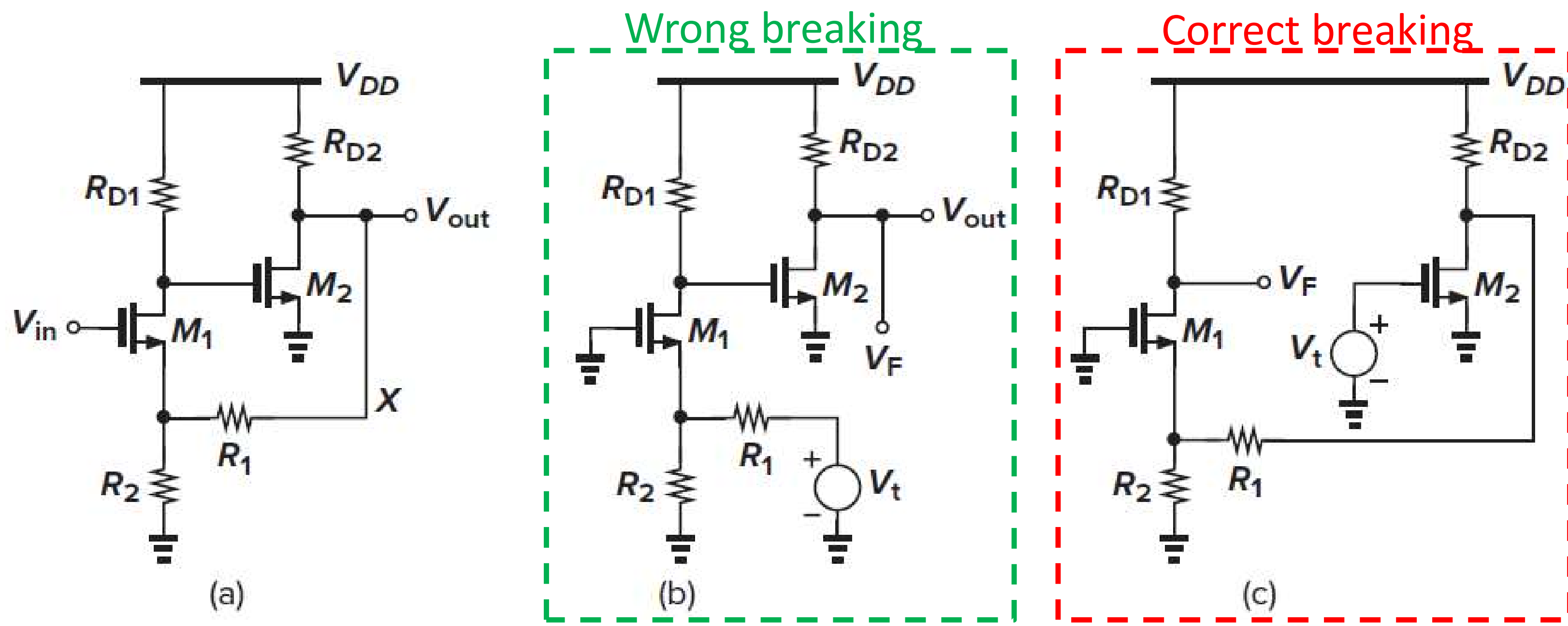
The loop gain is given by $h_{21} A_{I,open}$, where, from (8.62), $h_{21} = I_2/I_1$ with $V_2 = 0$. For the feedback network consisting of R_S and R_F, we have $h_{21} = -R_S/(R_S + R_F)$. The closed-loop gain equals $A_{I,open}/(1 + h_{21} A_{I,open})$.

Summary of Loading Effects



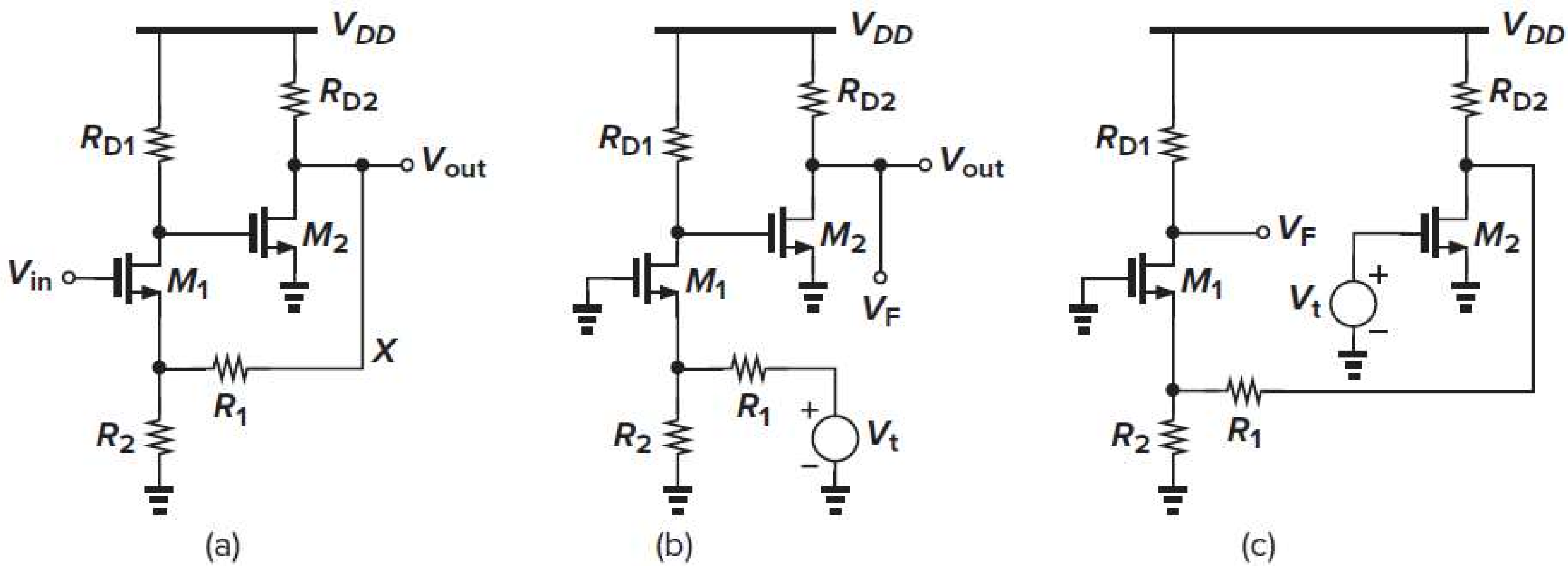
Loop Gain Calculation

Mixed-Signal IC Laboratory



Loop Gain Calculation

Mixed-Signal IC Laboratory



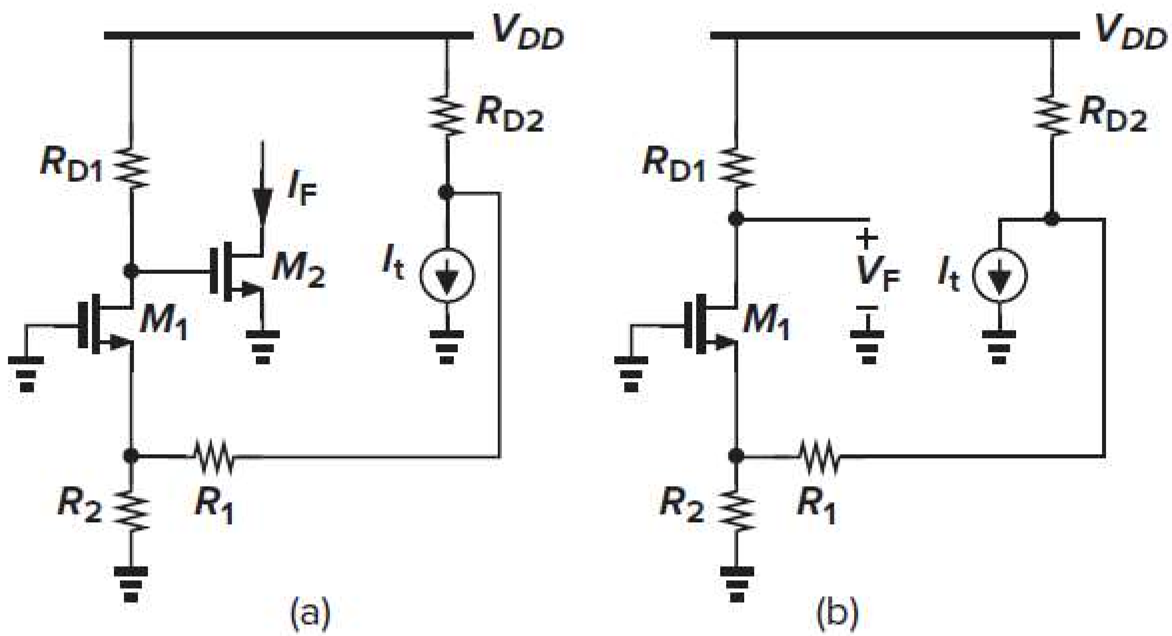
Q: Is it always possible to break the loop at the gate of a MOSFET?

⇒ **Yes, indeed** (at least at low frequencies).

⇒ For the feedback to be negative, the signal must be sensed by at least one gate in the loop because only the common-source topology inverts signals.

Loop Gain Calculation

Mixed-Signal IC Laboratory



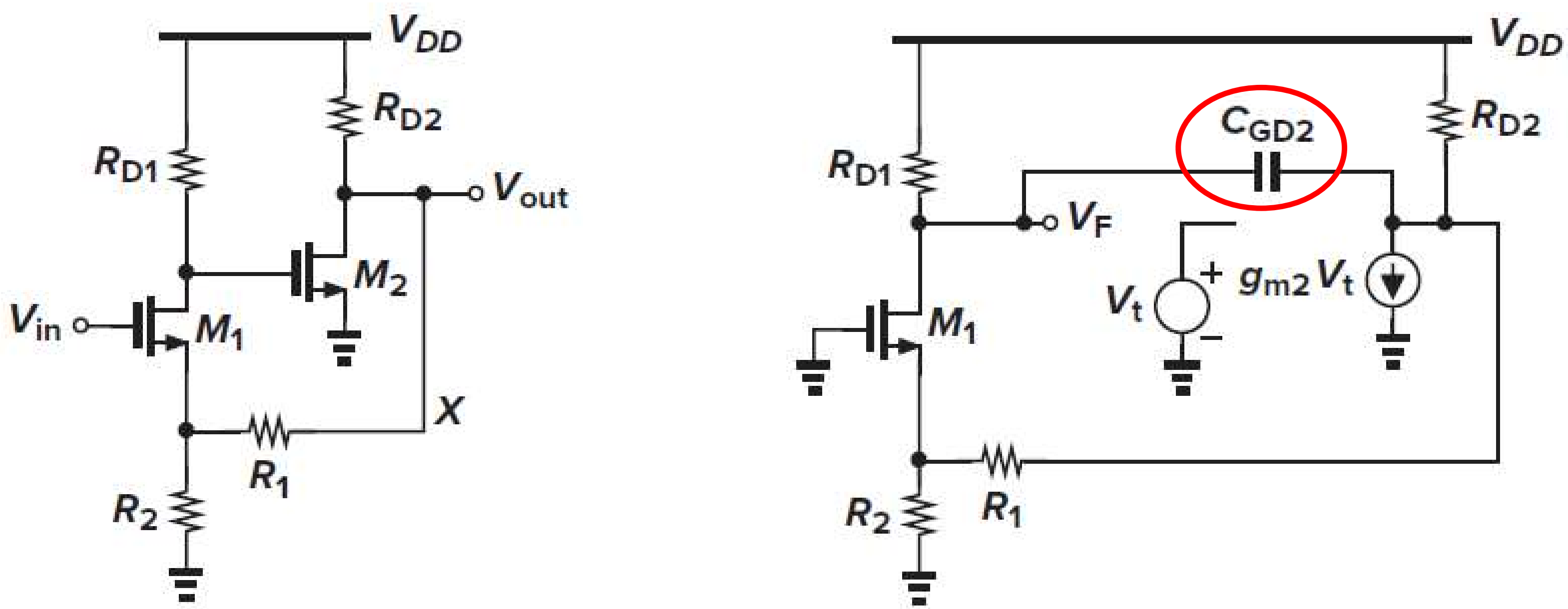
Under what condition can we apply a test current?

The reader can prove that I_F/I_t *in this case is the same as* V_F/V_t in Fig. 8.85(c) on the last page

Bode Analysis of Feedback Circuits

I want to skip this part because
it is not intuitive!!

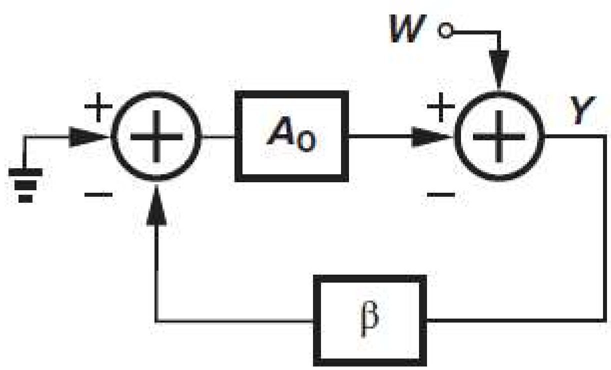
Loop Gain Calculation



As shown in Fig. 8.88, even though we provide the gate-source voltage by the independent source, V_t , C_{GD2} *still creates "local" feedback from the drain of M_2 to its gate, raising the* question of whether the loop gain should be obtained by nulling *all feedback mechanisms.*

Can you give a trial?

Loop Gain Calculation



$$Y/W = 1/(1+\beta A_0)$$

$$\text{Loop Gain} = \left(\frac{Y}{W}\right)^{-1} - 1$$

Example

Which one is right?