EE 332: Devices and Circuits II

Lecture 7: Feedback

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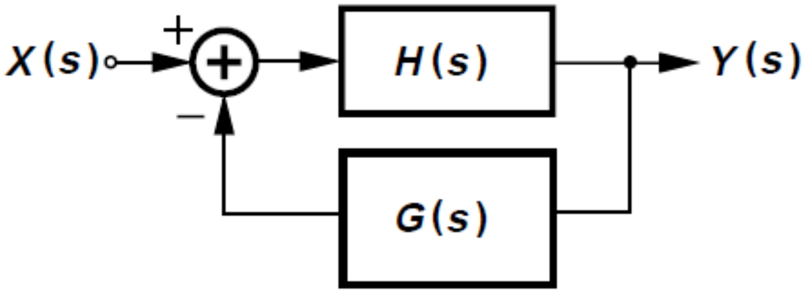
ELECTRICAL & COMPUTER ENGINEERING

Feedback Systems

- Feedback Examples?

- Positive vs. Negative Feedback

General Considerations



- Above figure shows a negative feedback system
- *H*: Feedforward network & *G: F*eedback network
- Feedback error is given by *X(s) – G(s)Y(s)*

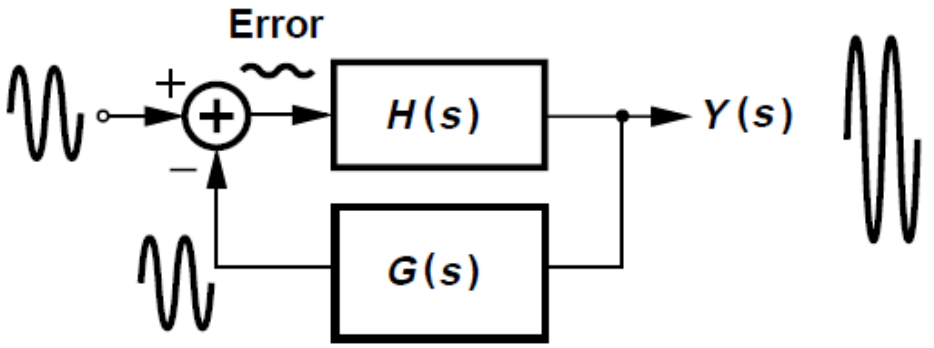
$$Y(s) = H(s)[X(s) - G(s)Y(s)]$$

- Thus

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

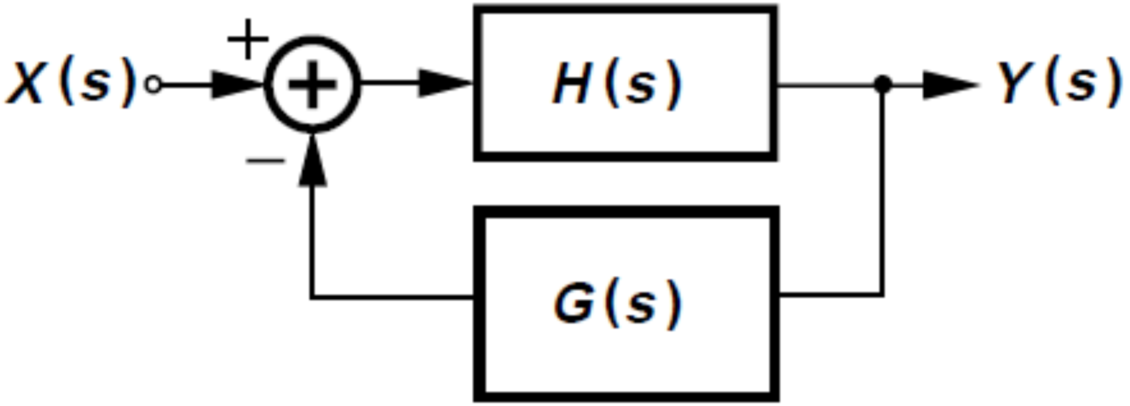
- *H(s)* is called the “open-loop” transfer function, *Y(s)/X(s)* is called the “closed-loop” transfer function, and G(s)H(s) is the “loop-gain”

General Considerations



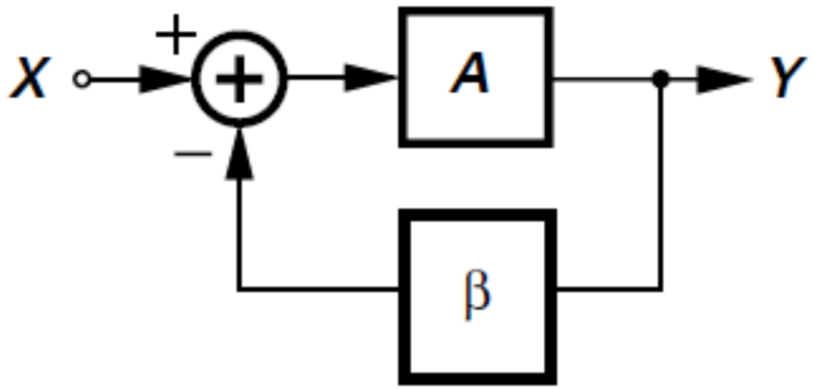
- In most cases, *H(s)* represents an amplifier and *G(s)* is a frequency-independent quantity
- In a well-designed negative feedback system, the error term is minimized, making the output of *G(s)* an "accurate" copy of the input and hence the output of the system a faithful (scaled) replica of the input
- In subsequent developments, *G(s)* is replaced by a frequency-independent quantity *β* called the *feedback factor*

General Considerations



- Four elements of a feedback system
    - The feedforward amplifier
    - A means of sensing the output
    - The feedback network
    - A means of generating the feedback error, i.e., a subtractor (or an adder)

Properties of Feedback Circuits



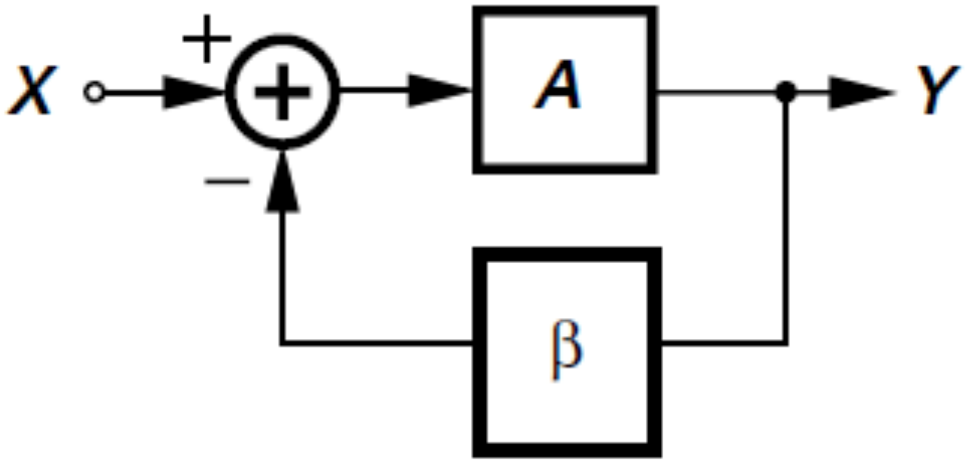
- For a more general case, gain desensitization is quantified by writing

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

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

- It is assumed *βA* >> 1; even if open-loop gain *A* varies by a factor of 2, *Y*/*X* varies by a small percentage since 1/(*βA*) << 1

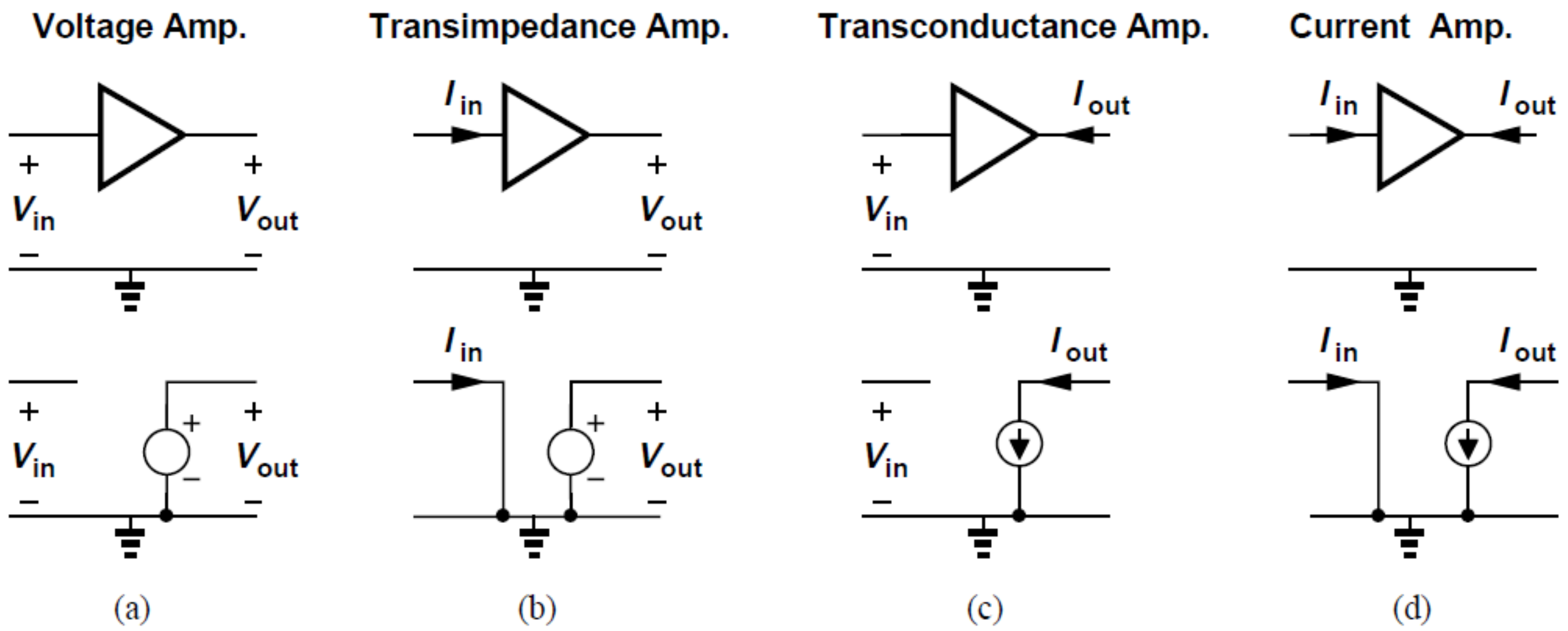
Properties of Feedback Circuits



- The quantity βA is called the "loop gain"
- The output of the feedback network is equal to $\beta Y = X \cdot \beta A/(1+\beta A)$ approaching X as βA becomes much greater than unity

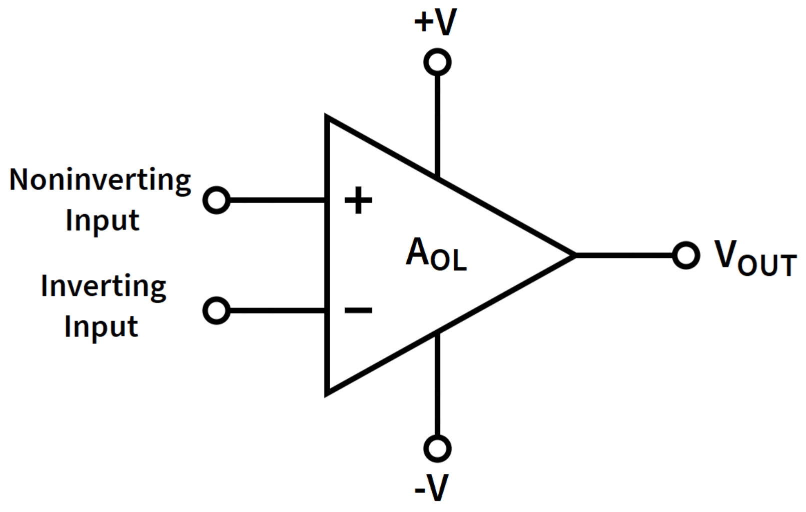
Types of Amplifiers

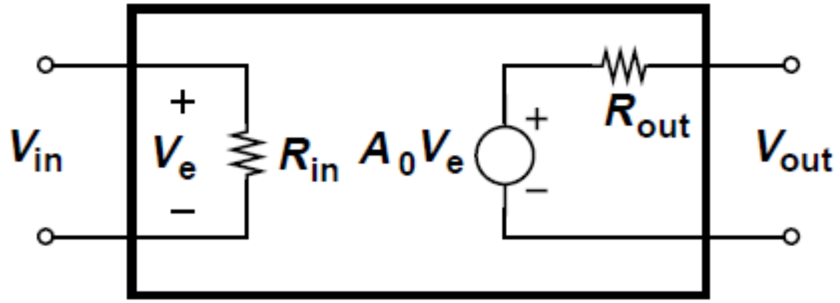
- Four possible amplifier configurations depending on whether the input and output signals are voltage or current quantities



- Figs. (a) – (d) show the four amplifier types with the corresponding idealized models

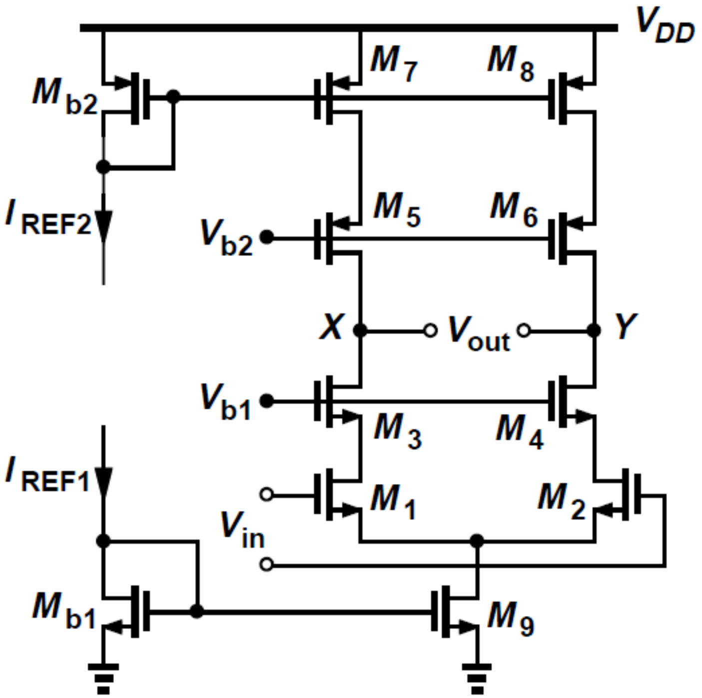
OpAmp

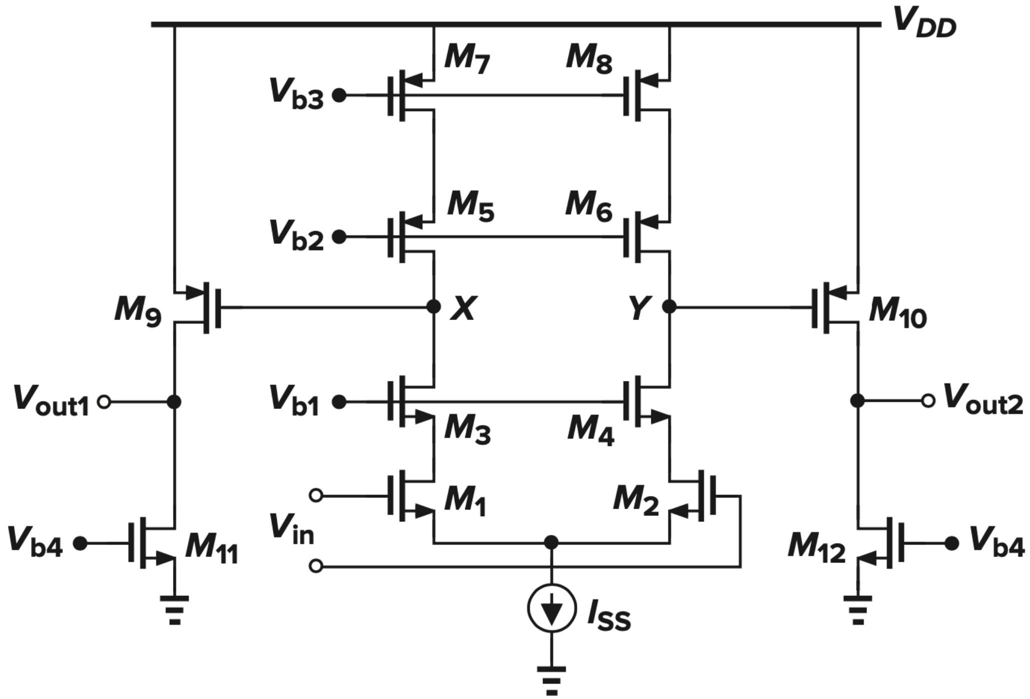

+V
Noninverting Input
Inverting Input
+
−
A_{OL}
V_{OUT}
-V


V_{in}
+
V_e
−
R_{in}
A_0V_e
+
−
R_{out}
V_{out}

OpAmp

- ***Providing large-gain by:***
  - Cascoding technique
  - Cascading multiple stages
  - etc.





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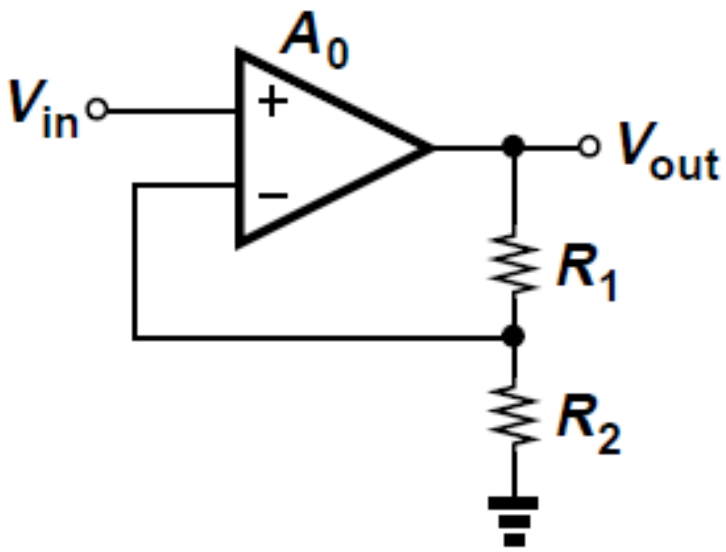
Properties of Feedback Circuits

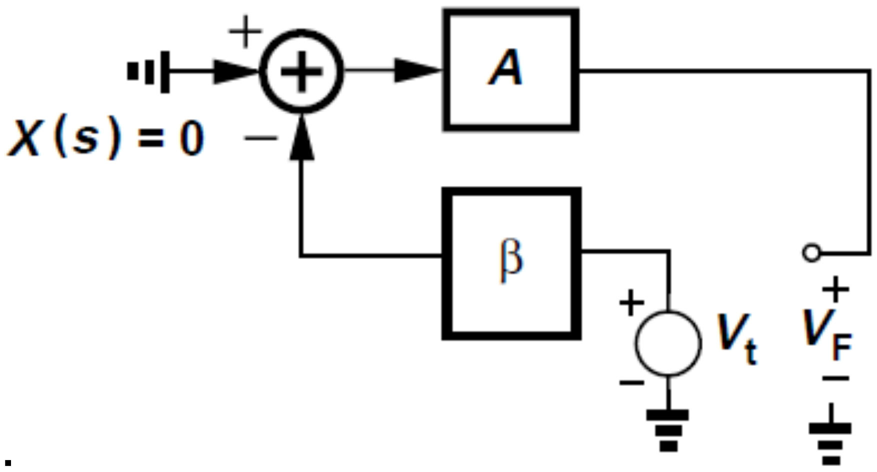
- **Gain Desensitization:** (Non-inverting feedback amplifier example)



•Gain can be controlled with higher accuracy unaffected by PVT variations

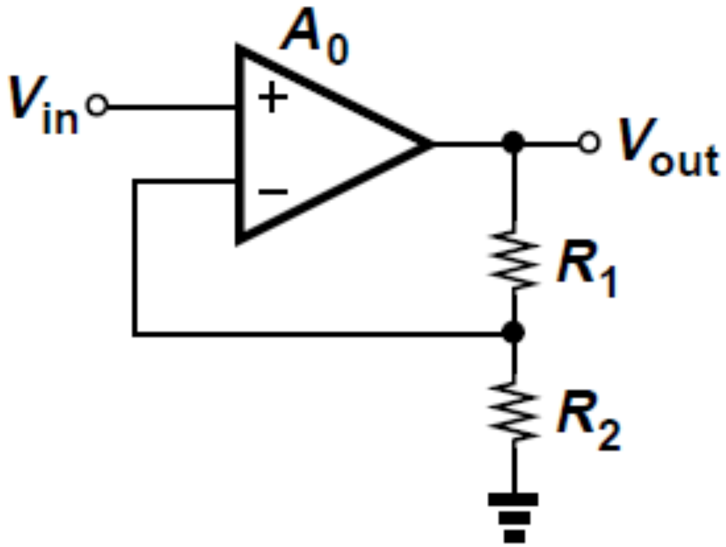
•Closed-loop gain is less sensitive to device parameters than the open-loop gain, hence called “gain desensitization”

Calculation of Loop Gain



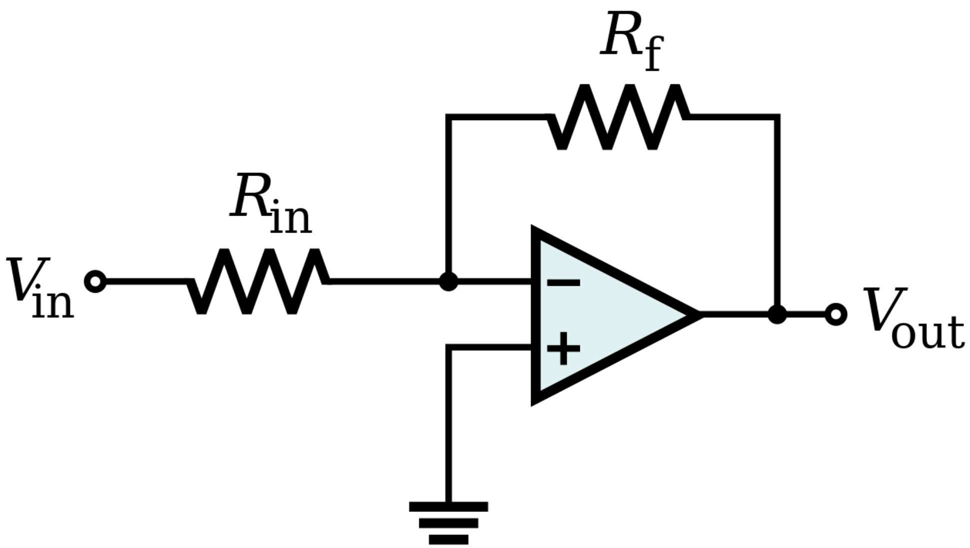
- To calculate the loop gain:
  - Set the main input to (ac) zero
  - Inject a test signal in the "right" direction
  - Follow the signal around the loop and obtain the value that returns to the break point
  - Negative of the transfer function thus obtained is the loop gain
- Loop gain is a dimensionless quantity
- In above figure, $V_t\beta(-1)A = V_F$ and hence $V_F/V_t = -\beta A$

Calculation of Loop Gain: Example



Calculation of Loop Gain: Example

(inverting feedback amplifier example)



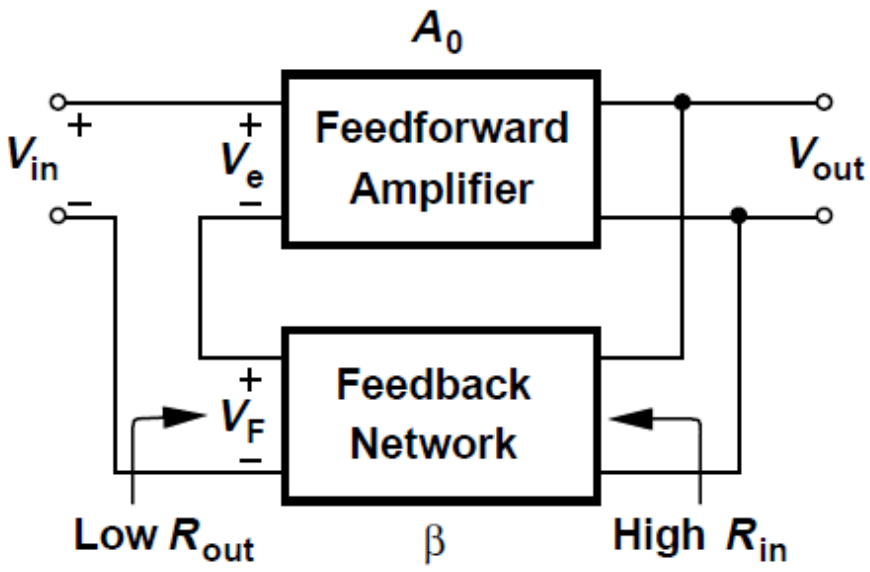
Sense and Return Mechanisms

- Placing a circuit in a feedback loop requires sensing an output signal and returning a fraction of it to the summing node at the input

- Four types of feedback:
  - Voltage-Voltage (*We only cover this type in our lecture, Sec. 8.2.1*)
  - Voltage-Current
  - Current-Current
  - Current-Voltage

- **First term is the quantity sensed at the output, and the second term is the type of signal returned to the input**

Voltage-Voltage Feedback

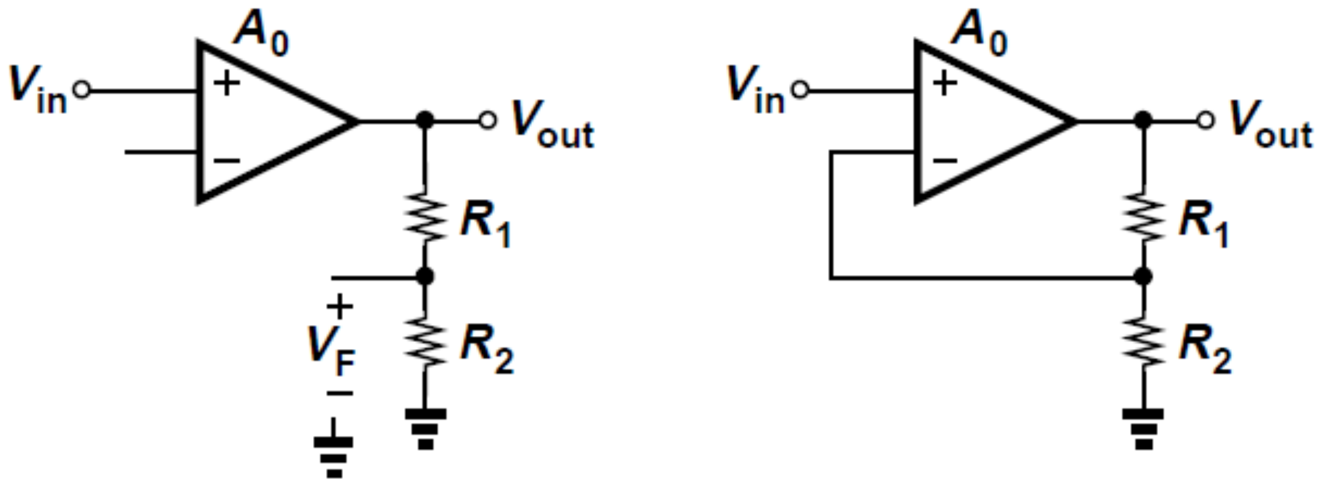


- Also called "series-shunt" feedback; first term refers to the *input* connection and second to the *output* connection
- We can write $V_F = \beta V_{out}$, $V_e = V_{in} - V_F$, $V_{out} = A_0(V_{in} - \beta V_{out})$, and hence

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

- βA_0 is the loop gain and the overall gain has dropped by $1+ \beta A_0$

Voltage-Voltage Feedback

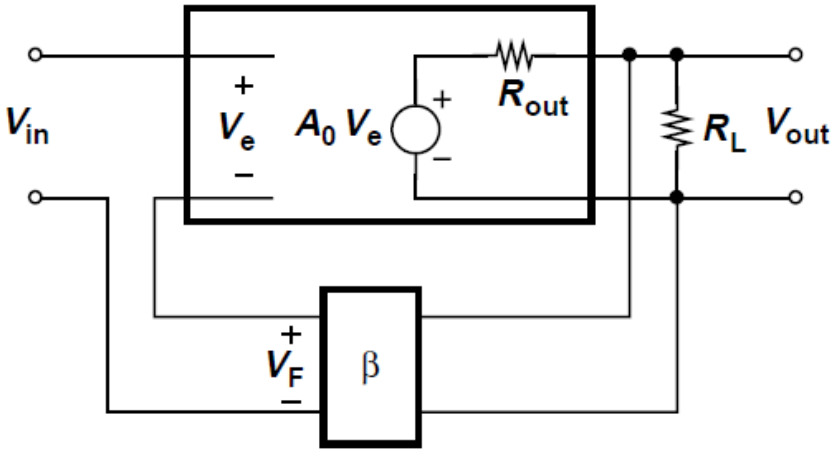


(a) (b)

- As an example of voltage-voltage feedback, a differential voltage amplifier with single-ended output can be used as the forward amplifier and a resistive divider as the feedback network [Fig. (a)]
- The sensed voltage V_F is placed in series with the input to perform subtraction of voltages

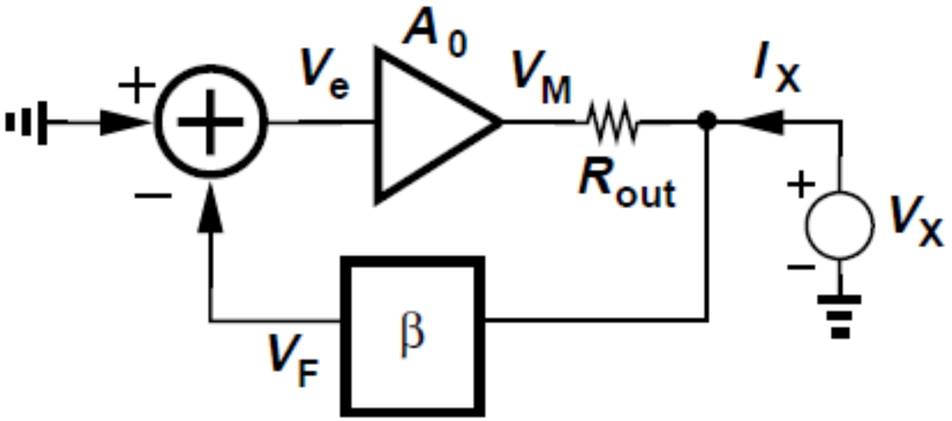
Properties of Feedback Circuits

- **Terminal Impedance Modification (output impedance)**



- If output is loaded by resistor R_L, in open-loop configuration, output decreases in proportion to $R_L/(R_L+R_{out})$
- In closed-loop V_{out} is maintained as a constant replica of V_{in} regardless of R_L as long as loop gain is much greater than unity
- Circuit "stabilizes" output voltage despite load variations, behaves as a voltage source and exhibits low output impedance

Voltage-Voltage Feedback: Output Resistance

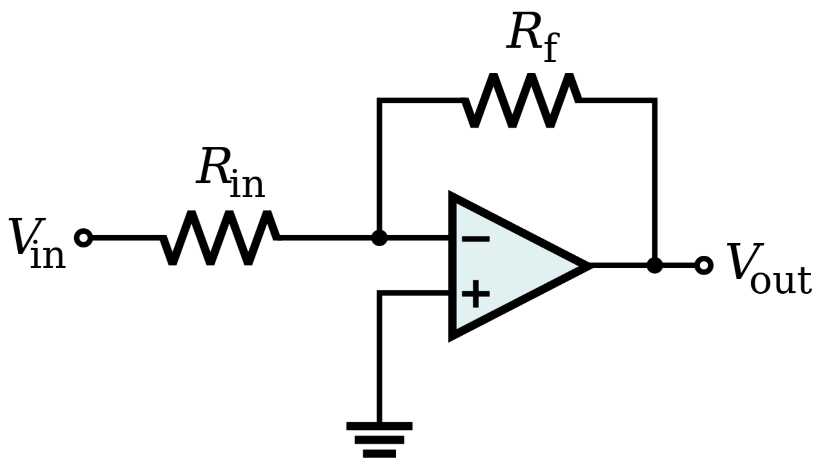


- In the above model, R_{out} represents the output impedance of the amplifier
- Setting input to zero and applying a voltage at the output, we write $V_F = \beta V_X$, $V_e = \beta V_X$, $V_M = \beta A_0 V_X$ and hence $I_X = [V_X - (-\beta A_0 V_X)]/R_{out}$ (*if current drawn by feedback network is neglected)

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

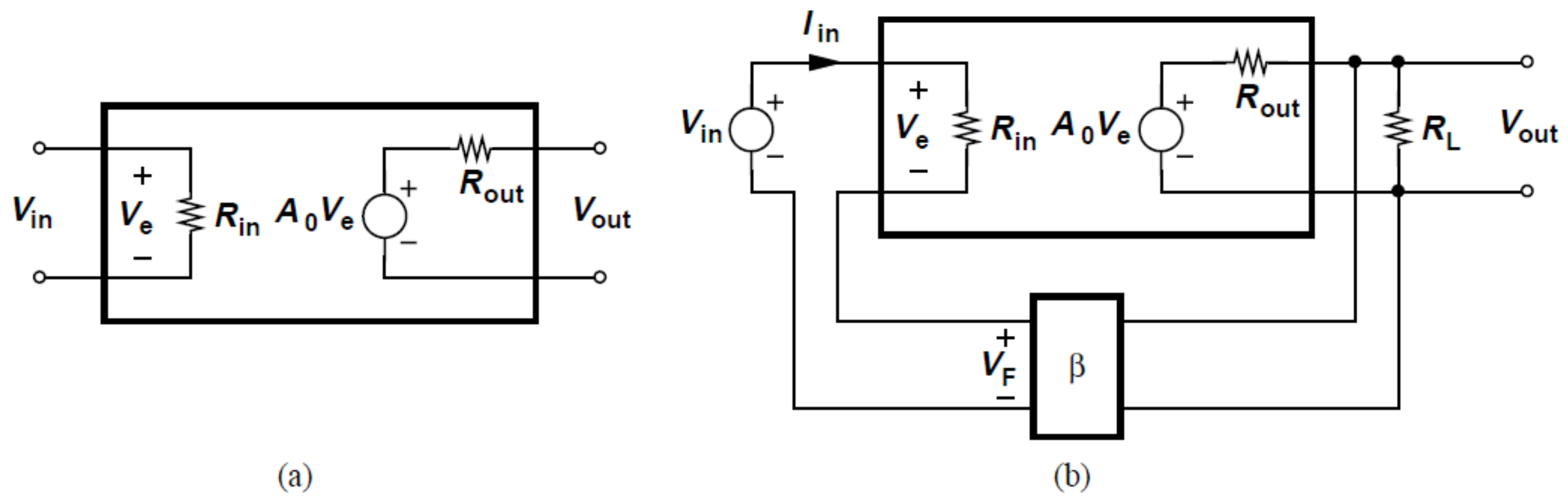
- Output impedance and gain are lowered by the same factor

Calculation of Output Impedance: Example



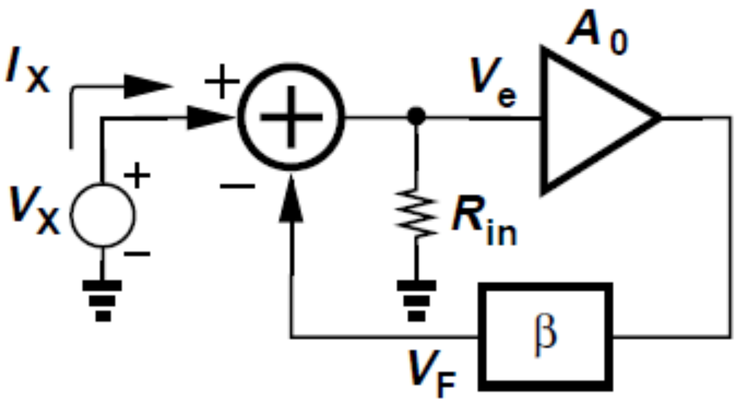
Properties of Feedback Circuits

- **Terminal Impedance Modification (input impedance)**



- Voltage-voltage feedback also modifies input impedance
- In Fig. (a) [open-loop], R_{in} of the forward amplifier sustains the entire V_{in}, whereas only a fraction in Fig. (b) [closed-loop]
- I_{in} is less in the feedback topology compared to open-loop system, suggesting increase in the input impedance

Voltage-Voltage Feedback: Input Resistance



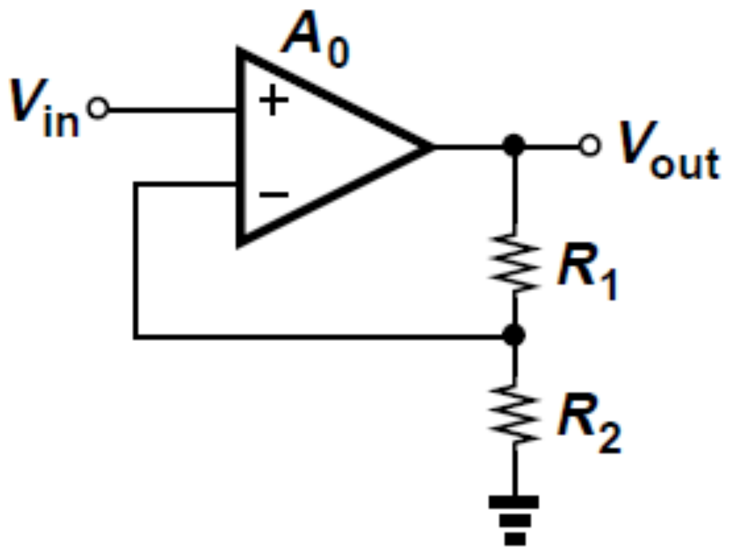
- $V_e = I_X R_{in}$ and $V_F = \beta A_0 I_X R_{in}$ => $V_e = V_X - V_F = V_X - \beta A_0 I_X R_{in}$
- Hence, $I_X R_{in} = V_X - \beta A_0 I_X R_{in}$ and

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

- Input impedance increases by the factor $1+\beta A_0$, bringing the circuit closer to an ideal voltage amplifier
- <u>Voltage-voltage feedback decreases output impedance and increases input impedance, useful as a buffer stage</u>

Properties of Feedback Circuits

- **Terminal Impedance Modification**

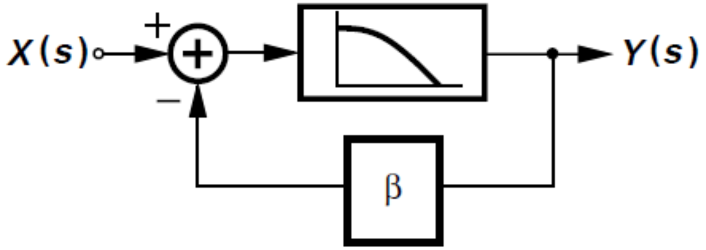


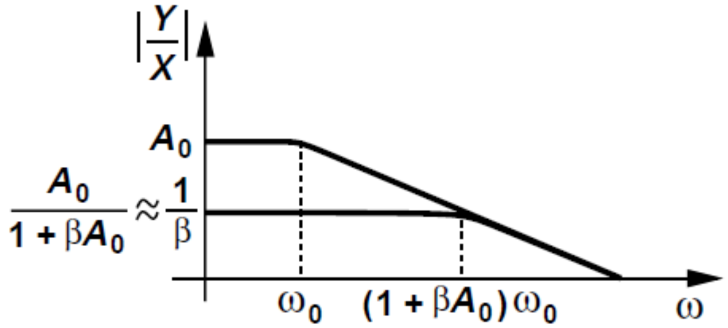
Feedback modifies input & output impedances (by a factor of 1+ *βA*)

- **increase or decrease of impedances depend on the feedback type**
  - **Feedback always improves the impedance …**

Properties of Feedback Circuits

- **Bandwidth Modification:**





- Suppose the feedforward amplifier above has a one-pole transfer function with A_0 as the low-frequency gain and ω_0 as the 3-dB bandwidth

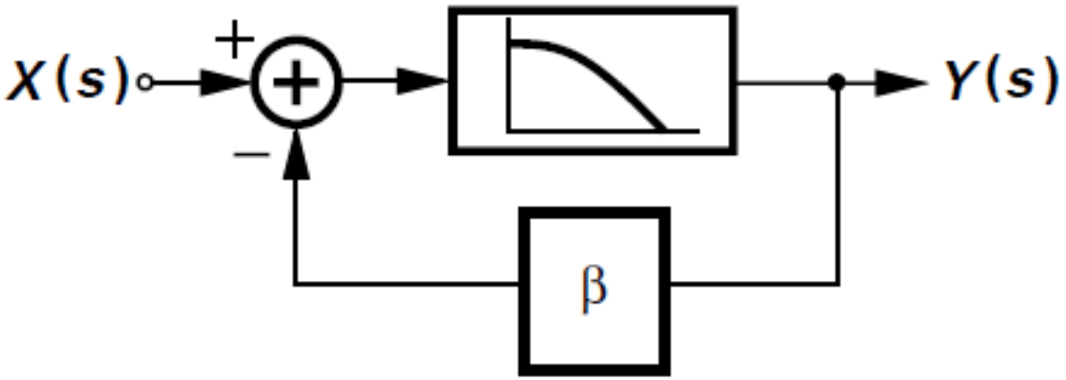
$$A(s) = \frac{A_0}{1 + \frac{s}{\omega_0}}$$

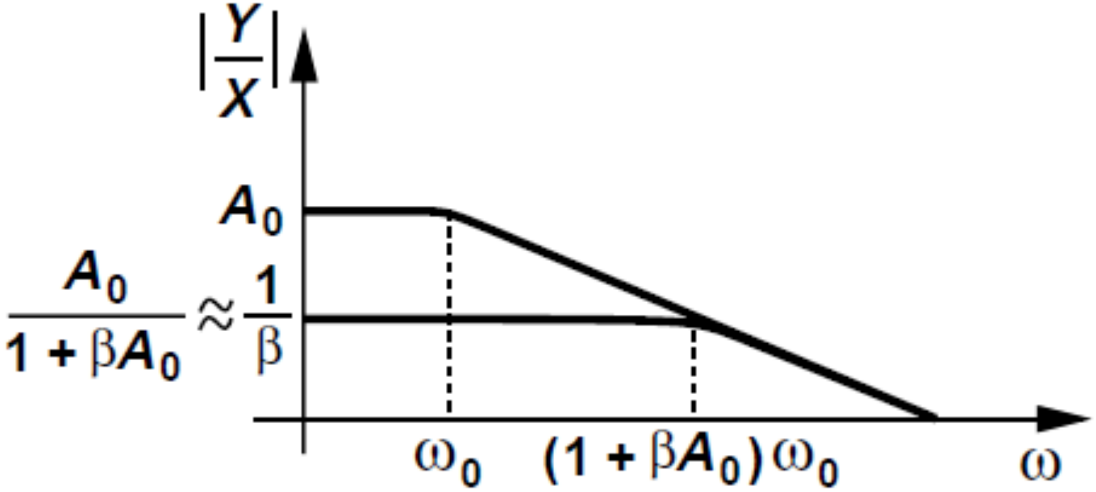
- Transfer function of the closed-loop system is

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

Properties of Feedback Circuits

- **Bandwidth Modification:**





- The closed-loop gain at low frequencies is reduced by a factor of $1+\beta A_0$, and the 3-dB bandwidth is increased by the same factor, revealing a pole at $(1+\beta A_0)\omega_0$.
- If A is large enough, closed-loop gain remains approximately equal to $1/\beta$
- At high frequencies, A drops so that βA is comparable to unity and closed-loop gain falls below $1/\beta$

Properties of Feedback Circuits

- **Bandwidth Modification:**