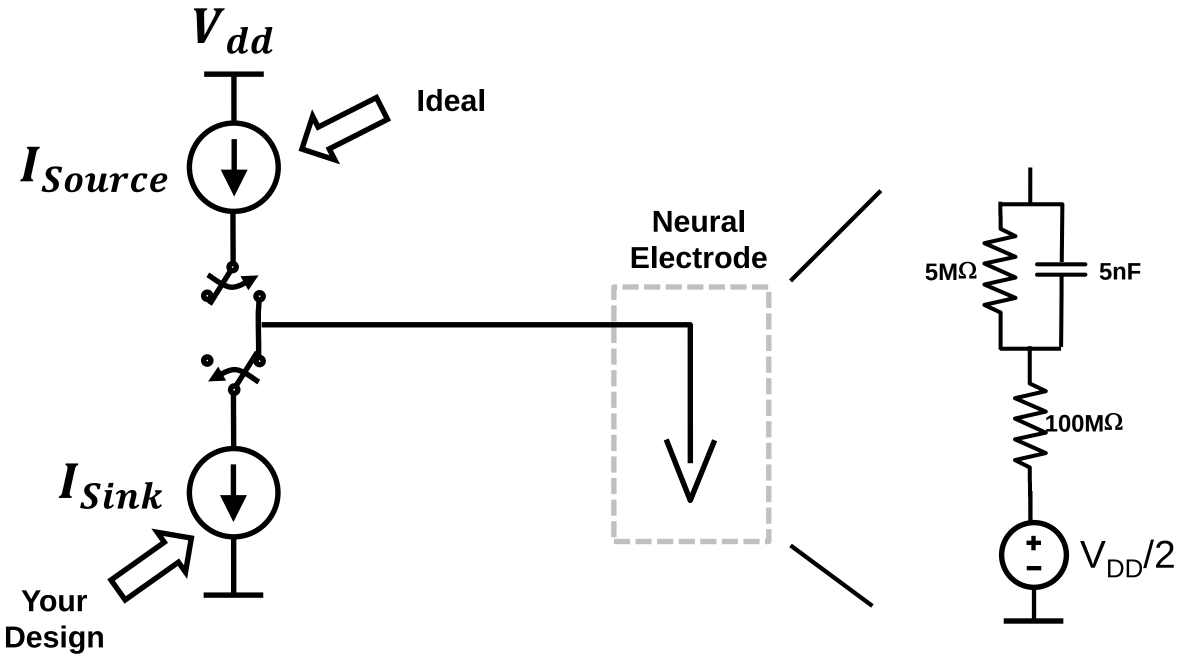
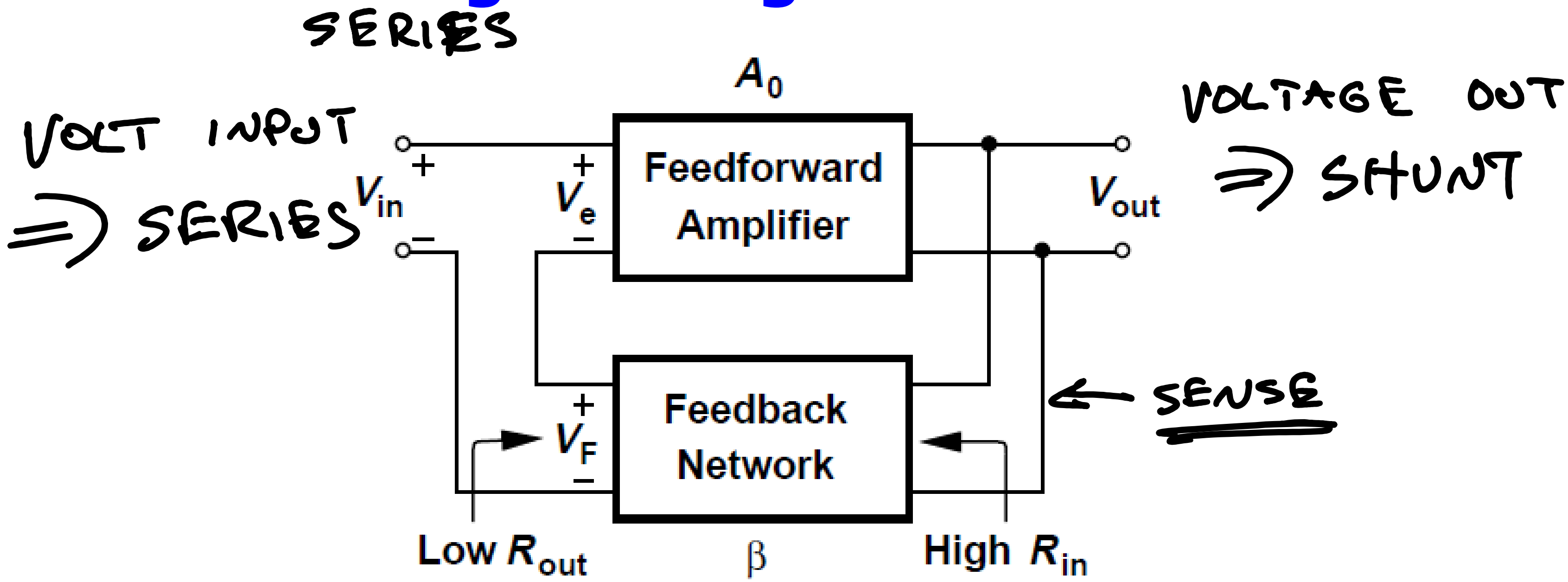
Lecture #21, March 2nd, 2022

- Will focus on chapters 8 (Feedback) and 10 (Stability and Compensation).
- Homework #4 due next Monday – don’t wait until the day before to start the homework.
- Project 2 due this Friday March 4th.
- Comments on the Project
- Today
  - Regulated Cascode
  - Common-Mode Feedback.
  - Different forms of Feedback
    - Series – Series
    - Series – Shunt
    - Shunt – Shunt
    - Shunt - Series

Project Discussion



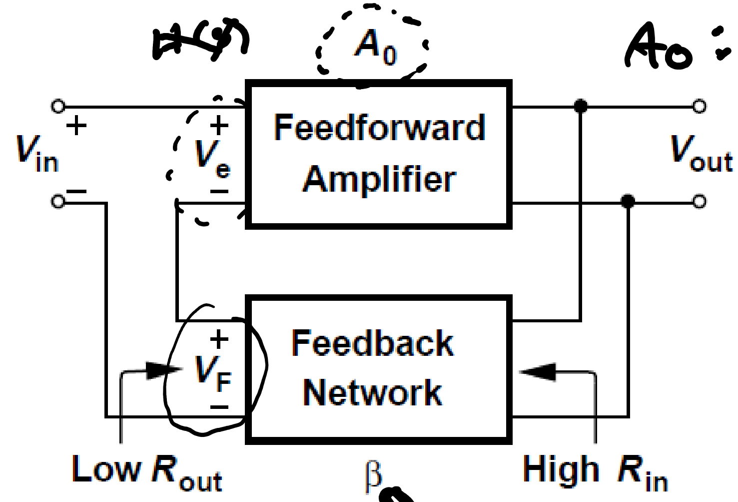
Voltage-Voltage Feedback



- **This topology senses the output voltage and returns the feedback signal as a voltage**
- **Feedback network is connected in *parallel* with the output and in *series* with the input. Sometimes referred to as Series – Shunt Feedback**
- **An ideal feedback network in this case has infinite input impedance (ideal voltmeter) and zero output impedance (ideal voltage source)**

Voltage-Voltage Feedback

Also called "Series-Shunt" Feedback



A_0 : DC, LOW-FREQ GAIN

β : RETURN PATH GAIN

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

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

$$V_{OUT} = A_0 \cdot (V_{IN} - \beta \cdot V_{out})$$

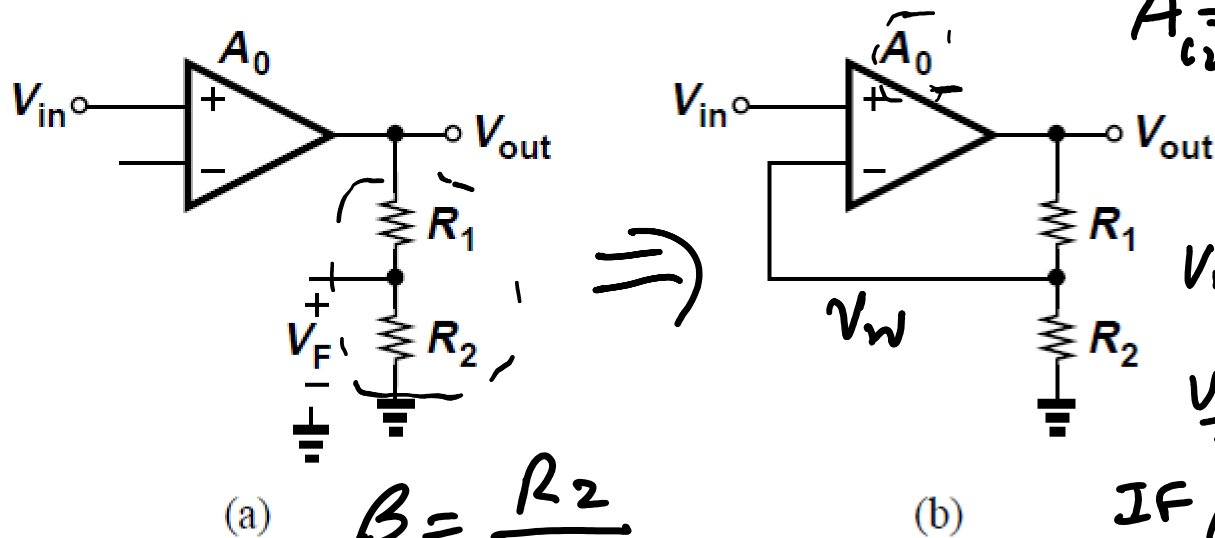
$$V_{out}(1+\beta A_0) = A_0 V_{IN}$$

$$\frac{V_{out}}{V_{IN}} = \frac{A_0}{1+\beta A_0} \approx 1/\beta$$

, IF A_0 LARGE & $1 \ll \beta A_0$

Voltage-Voltage Feedback

$A_{CL} = \left(1+\frac{R_1}{R_2}\right)$



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

$V_{out} = V_{IN} + \frac{V_{IN}}{R_2} R_1$

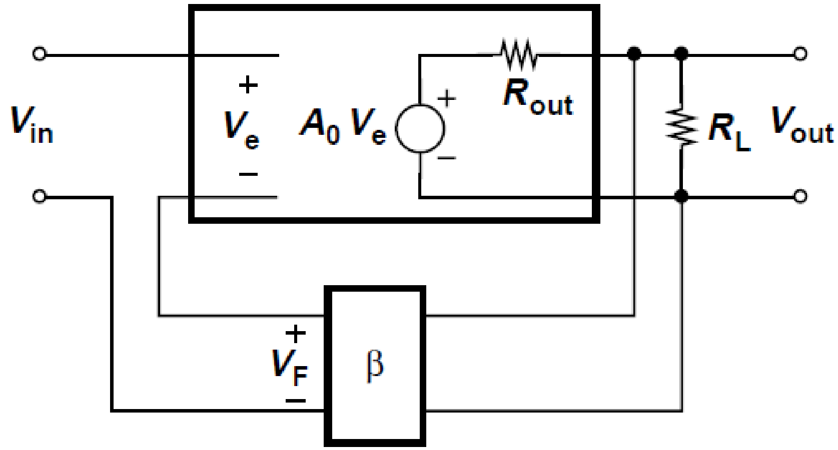
$\frac{V_{out}}{V_{IN}} = \left(1+\frac{R_1}{R_2}\right)$

IF $A_0 \to \infty$

$A \cong 1/\beta = \frac{R_1+R_2}{R_2} \cong 1+\frac{R_1}{R_2}$

- **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**

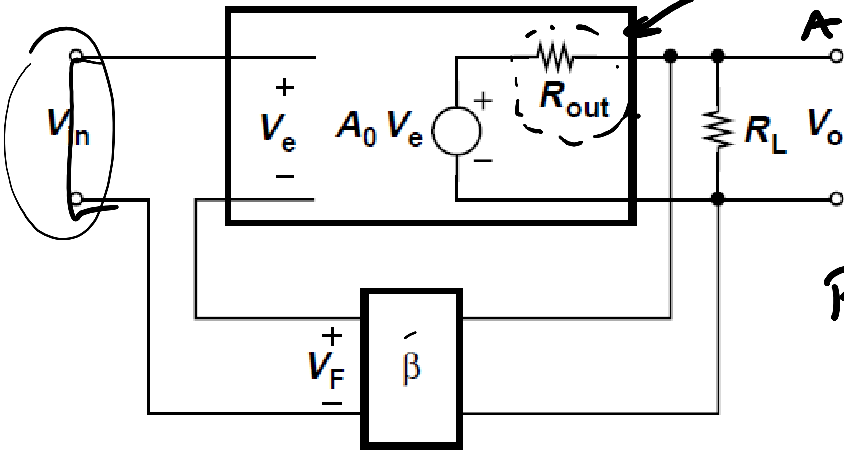
Voltage-Voltage Feedback: Output Resistance



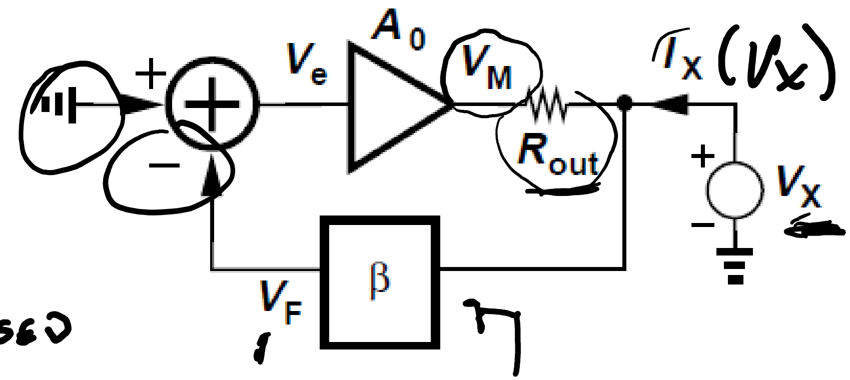
- **If output is loaded by resistor R_L, in open-loop configuration, output decreases in proportion to $R_L/(R_L+R_{out})$**
- **In closed-loop V_{out} is maintained as a constant replica of V_{in} regardless of R_L as long as loop gain is much greater than unity**
- **Circuit "stabilizes" output voltage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

Voltage-Voltage Feedback: Output Resistance

ROUT OF FORWARD AMP



$R_{o_{CLOSED}}$



$R_{w,b} \to \infty$

FIND $R_{o_{CLOSED}}$ (R_{OUT}, β, A)

$$V_F = \beta V_x$$

$$V_e = -V_F = -\beta V_x$$

$$V_m = -A_0 \beta V_x$$

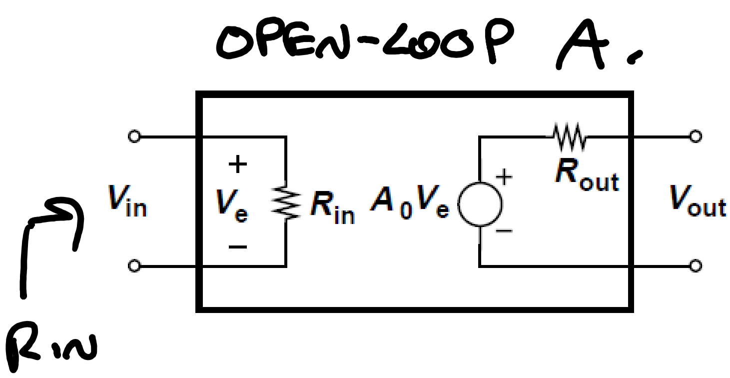
$$I_x = \frac{V_x - V_m}{R_{OUT}} = \left(V_x - (-A_0 \beta V_x)\right) / R_{OUT}$$

SHUNT IN/OUT DROPS ROUT BY $(1 + A_0\beta)$

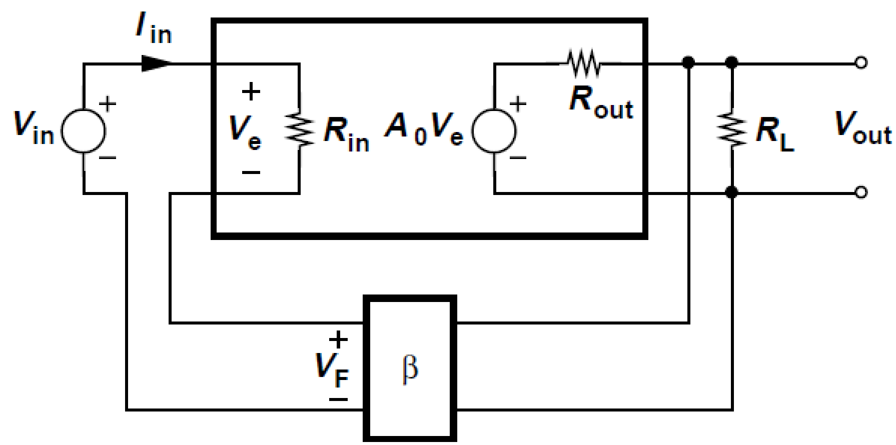
$$\frac{V_x}{I_x} = R_{o_{CLOSED}} = \frac{R_{out}}{1 + A_0 \beta}$$

- OPEN-LOOP ROUT
- CLOSED-LOOP IS ROUT ÷ $1 + A_0\beta$

Voltage-Voltage Feedback: Input Resistance



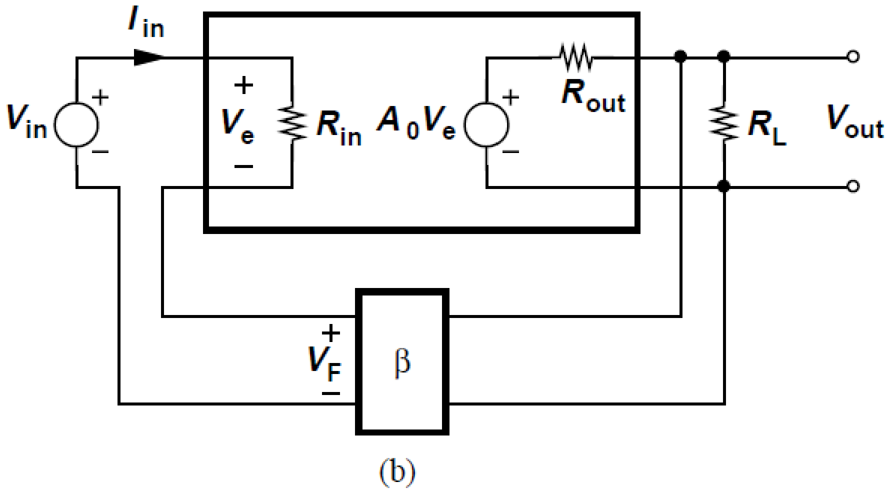
(a)



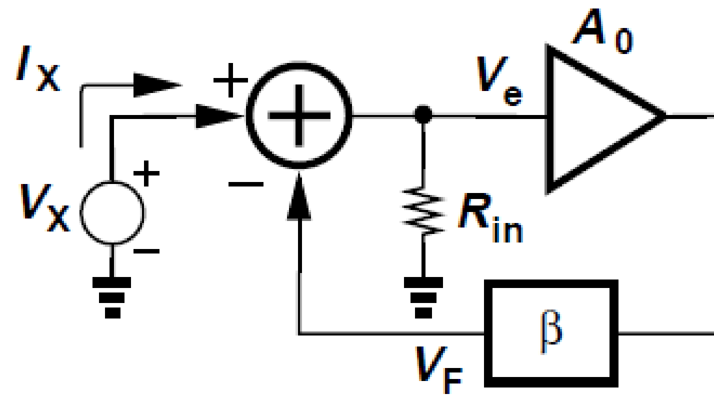
(b)

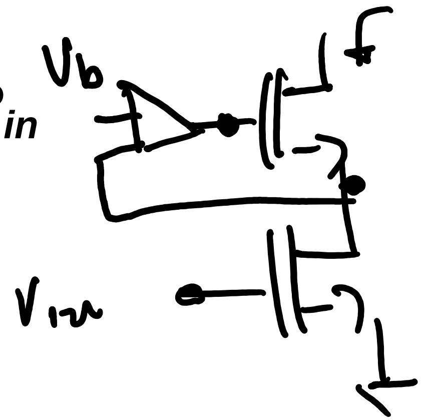
- **Voltage-voltage feedback also modifies input impedance**
- **In Fig. (a) [open-loop], R_{in} of the forward amplifier sustains the entire V_{in}, whereas only a fraction in Fig. (b) [closed-loop]**
- **I_{in} is less in the feedback topology compared to open-loop system, suggesting increase in the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

Voltage-Voltage Feedback: Input Resistance



(b)



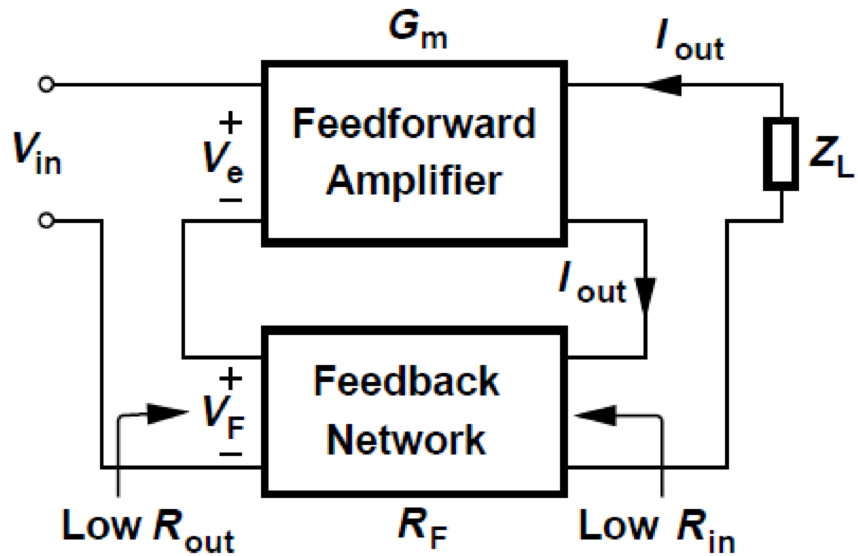


- In the above model, $V_e = I_X R_{in}$ and $V_F = \beta A_0 I_X R_{in}$
- Thus, we have $V_e = V_X - V_F = V_X - \beta A_0 I_X R_{in}$
- Hence, $I_X R_{in} = V_X - \beta A_0 I_X R_{in}$ and

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

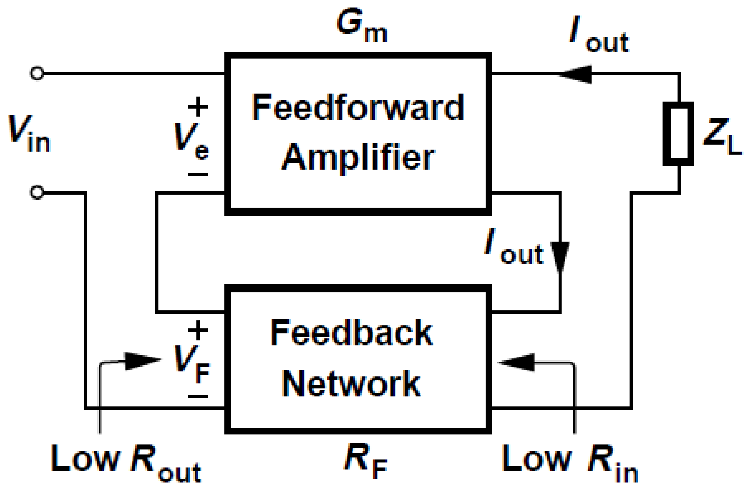
- Input impedance increases by the factor $1+\beta A_0$, bringing the circuit closer to an ideal voltage amplifier
- Voltage-voltage feedback decreases output impedance and increases input impedance, useful as a buffer stage

Current-Voltage Feedback



- This topology senses the output current and returns a voltage as the feedback signal
- The current is sensed by measuring the voltage drop across a (small) resistor placed in series with the output
- Feedback factor β has the dimension of resistance and is hence denoted by R_F

Current-Voltage Feedback



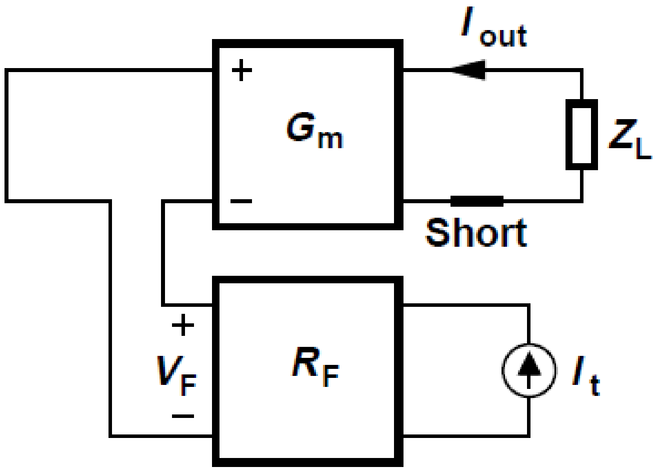
- A G_m stage must be terminated by a finite impedance to ensure it can deliver its output current
- If $Z_L = \infty$, an ideal G_m stage would sustain an infinite output voltage

- We write $V_F = R_F I_{out}$, $V_e = V_{in} - R_F I_{out}$ and hence $I_{out} = G_m(V_{in} - R_F I_{out})$
- It follows that

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

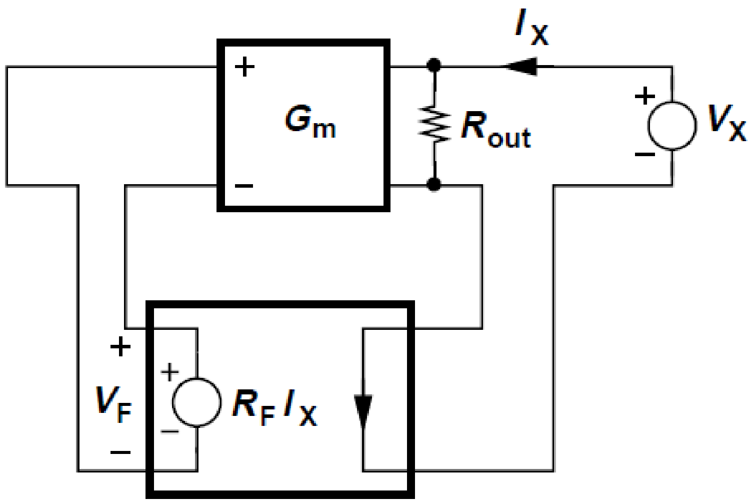
- Ideal feedback network in this case exhibits zero input and output impedances

Current-Voltage Feedback: Loop Gain



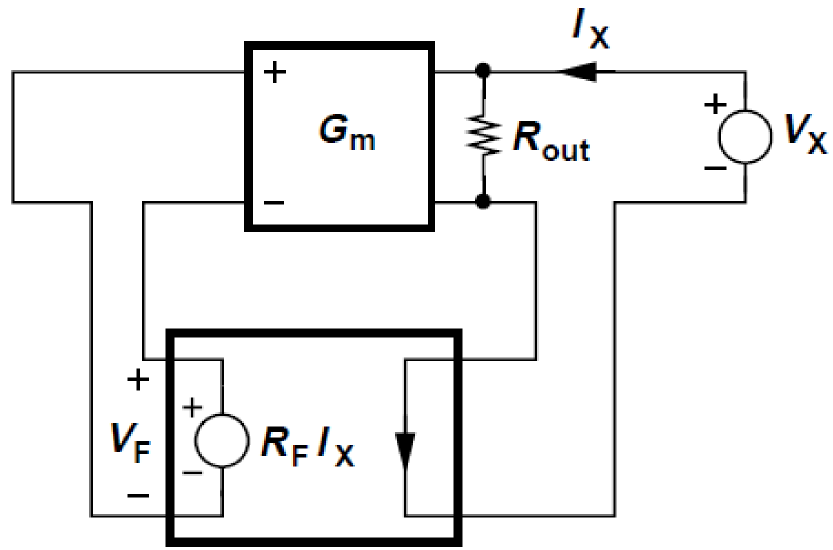
- To calculate the loop gain, the input is set to zero and the loop is broken by disconnecting the feedback network from the output and replacing it with a short at the output (if the feedback network is ideal)
- Test signal It is injected, producing $V_F = R_F I_t$ and hence $I_{out} = -G_m R_F I_t$
- Thus, loop gain is $G_m R_F$ and transconductance of the amplifier is reduced by $1+G_m R_F$ when feedback is applied

Current-Voltage Feedback: Output Resistance



- **Sensing the current at the output increases the output impedance**
- **System delivers the same current waveform as the load varies, approaching an ideal current source which exhibits a high output impedance**
- **In the above figure, R_{out} represents the finite output impedance of the feedforward amplifier**
- **Feedback network produces V_F proportional to I_X, i.e., $V_F = R_F I_X$**

Current-Voltage Feedback: Output Resistance

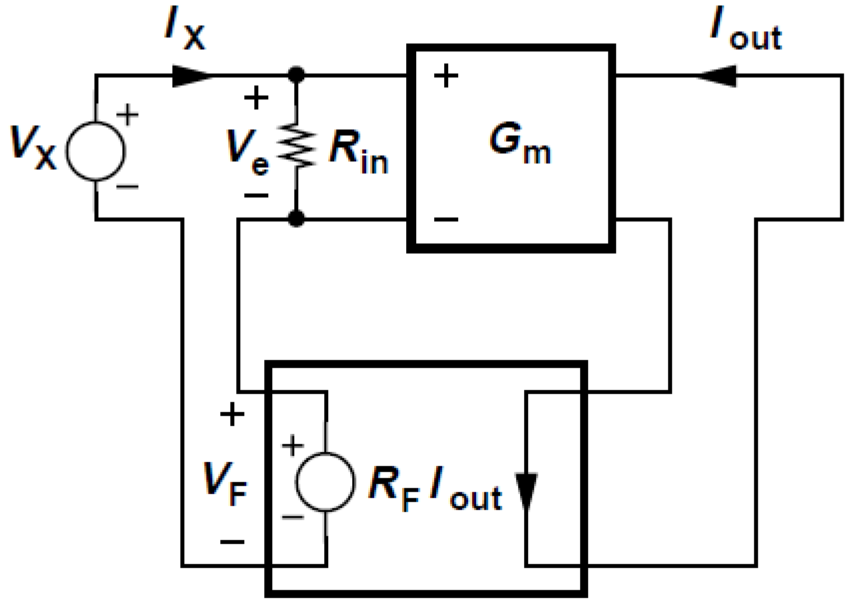


- **The current generated by G_m equals $-R_F I_X G_m$**
- **As a result, $-R_F I_X G_m = I_X - V_X/R_{out}$, yielding**

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

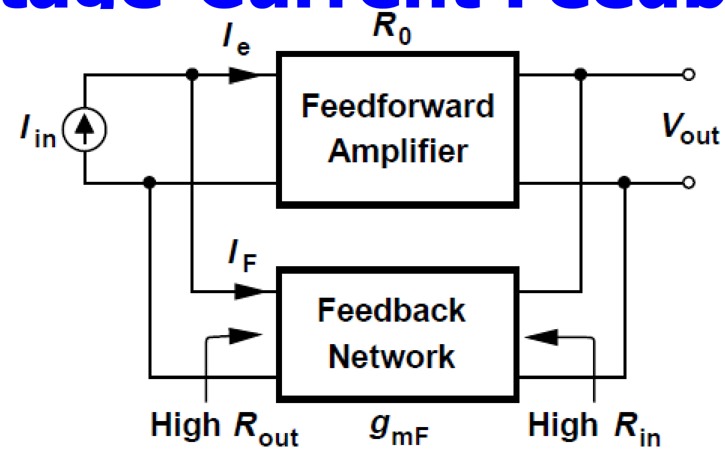
- **The output impedance therefore increases by a factor of $1+G_m R_F$**

Current-Voltage Feedback: Input Resistance



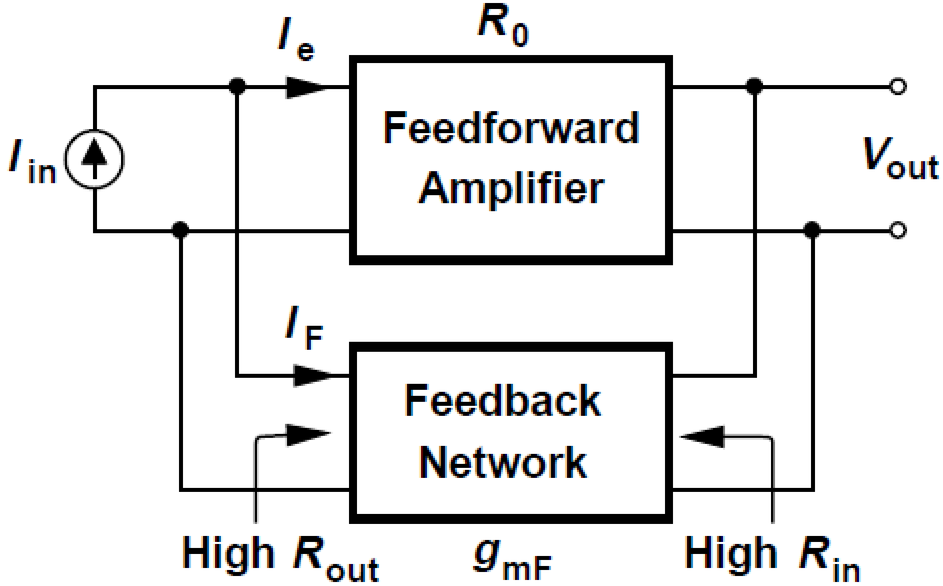
- Current-voltage feedback increases the input impedance by a factor of one plus the loop gain
- As shown in the above figure, we have $I_X R_{in} G_m = I_{out}$
- Thus, $V_e = V_X - G_m R_F I_X I_{in}$ and
- Current-voltage feedback increases both the input and output impedances while decreasing the feedforward transconductance

Voltage-Current Feedback



- **In this type of feedback, the output voltage is sensed and a proportional current is returned to the input summing point**
- **Feedforward path incorporates a transimpedance amplifier with gain R_0 and the feedback factor g_{mF} has a dimension of conductance**
- **Feedback network ideally exhibits infinite input and output impedances**
- **Also called "shunt-shunt" feedback**

Voltage-Current Feedback

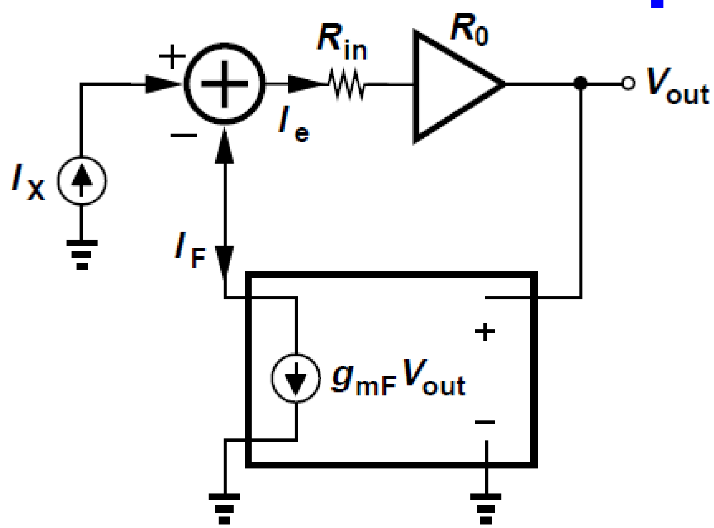


- **Since $I_F = g_{mF}V_{out}$ and $I_e = I_{in} – I_F$, we have $V_{out} = R_0I_e = R_0(I_{in} – g_{mF}V_{out})$**
- **It follows that**

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

- **This feedback lowers the transimpedance by a factor of one plus the loop gain**

Voltage-Current Feedback: Output Impedance



- **Voltage-current feedback decreases the output impedance**
- **Input resistance R_{in} of R_0 appears in series with the input port**
- **We write $I_F = I_X - V_X/R_{in}$ and $(V_X/R_{in})R_0 g_{mF} = I_F$**
- **Thus,**

$$\frac{V_X}{I_X} = \frac{R_{in}}{1 + g_{mF}R_0}$$