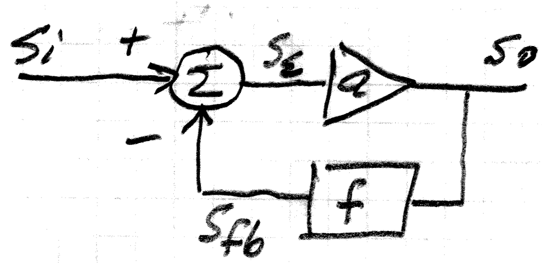
Feedback:



$S_o = a S_\varepsilon$

S_ε = error signal $= S_i - S_{fb}$

$$\therefore \frac{S_o}{S_i} = A = \frac{a}{\underbrace{1+af}_{\text{loop transmission}}}$$

- **Benefits of negative FB:**

① Stabilizes closed-loop gain, A, against parameter changes and active device variations.

$$A = \frac{a}{1+af} \Rightarrow \frac{dA}{da} = \frac{(1+af) - af}{(1+af)^2} = \frac{1}{(1+af)^2}$$

For a change in open-loop gain, δa:

$$\frac{\delta A}{\delta a} = \frac{1}{(1+af)^2} \Longrightarrow \delta A = \frac{\delta a}{(1+af)^2} \quad \text{(much smaller than } \delta a\text{)}$$

So, the fractional change is:

$$\boxed{\frac{\delta A}{A} = \frac{\frac{\delta a}{a}}{(1+af)}}$$

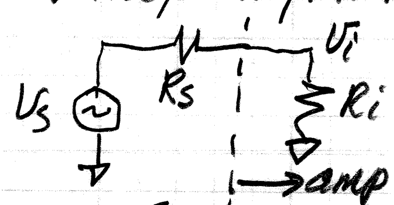
$\therefore$ gain sensitivity decreased by $\frac{1}{1+af} \simeq \frac{1}{af} = \frac{1}{T}$

Generally, closed-loop gain values are very accurate!

② Modifies R_i and R_o — i.e., improves these values according to the type of amplifier implemented.

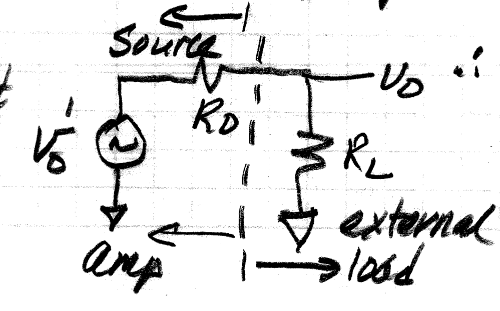
Example: Voltage amplifier; i.e., voltage in → voltage out

@ input:



$\therefore V_i = \frac{R_i V_s}{R_i + R_s} \simeq V_s$ if $R_i \gg R_s$

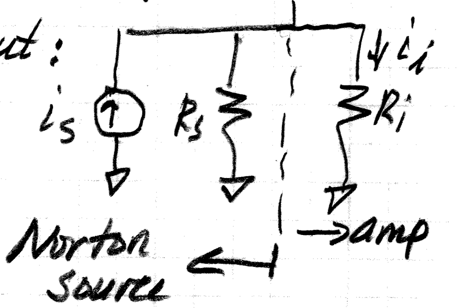
@ output



$\therefore V_o = \frac{R_L V_o'}{R_o + R_L} \simeq V_o'$ if $R_o \ll R_L$

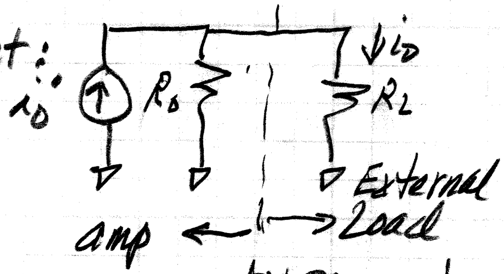
Another example: Current amplifier, i.e., current in → current out

@ input:



$\therefore\ i_i = \dfrac{R_s\, i_s}{R_i + R_s} \simeq i_s$ if $R_i \ll R_s$

@ output:



$\therefore\ i_o = \dfrac{R_o}{R_o + R_L}\, i_o' \simeq i_o'$ if $R_o \gg R_L$

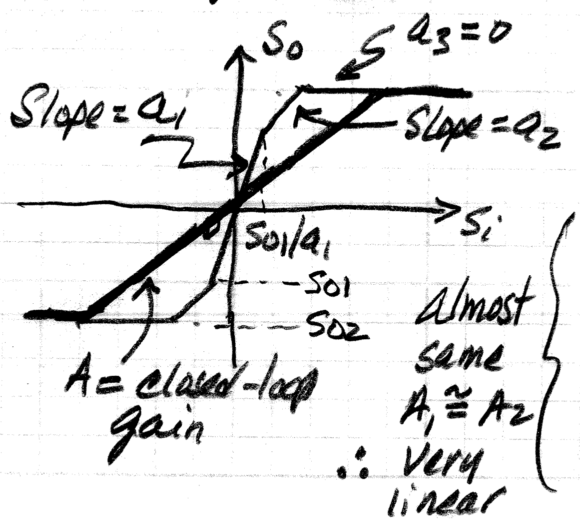
Summary:

type	R_i	R_o
V–V (Voltage Amp)	High	Low
V–I (transconductance)	High	High
I–V (transresistance)	Low	Low
I–I (current amp)	Low	High

- **Key Point: Negative FB can be used to taylor R_i and R_o for a specific type of amplifier**

(3) Negative FB to reduce distortion, increase linearity

- Consider a general open-loop transfer function:



- Two gain ranges in this example:

For $0 < S_o < |S_{o1}|$

$A_1 = \dfrac{a_1}{1 + a_1 f} \simeq \dfrac{1}{f}$ (e.g., $a_1 = 20k$)

For $|S_{o1}| < S_o < |S_{o2}|$

$A_2 = \dfrac{a_2}{1 + a_2 f} \simeq \dfrac{1}{f}$ (e.g., $a_2 = 1000$)

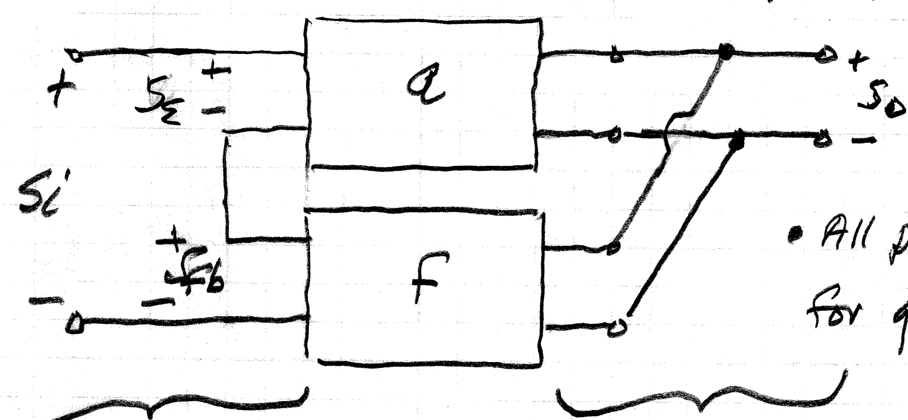
Almost same $A_1 \cong A_2$ $\therefore$ Very linear

④ Use negative FB to increase Bandwidth

① Gain is reduced — reduction factor ≈ equal to the amount of gain stabilization, distortion reduction, etc.; i.e., gain reduced by $(1+af)$.

② Feedback causes stability problems (if not compensated properly).

- <u>Inspection Analysis of Feedback Circuits</u>
    - <u>Identification of Feedback Types</u>



• All ports shown for generality

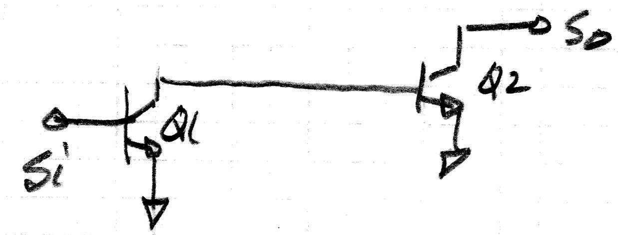
Series Connection	Shunt connection
• Feedback network port in <u>series</u> with amplifier port	• Feedback network port in <u>shunt</u> with amplifier port
• must go through both the FB port and the amplifier port to get from the (+) input to the (−) input (often ground)	• can go from the (+) output to the (−) output either through the amplifier port or the feedback network port

- <u>Steps to identification:</u>

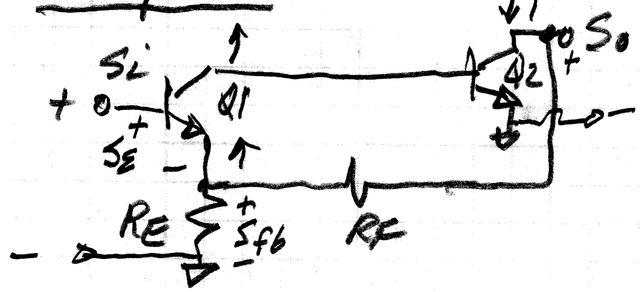
    (i) Check for negative feedback

    (ii) Identify type of feedback at input and output

- **Examples of Feedback Circuits:**
- First, a basic amplifier: (Two CE stages)



Example 1:



Type?

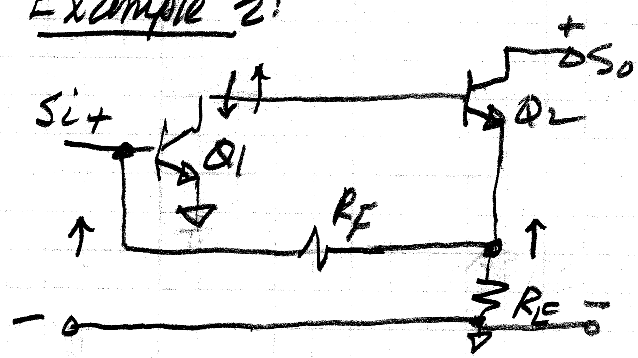
Series at input – must go through Q_1 and R_E to go from (+) to (–) input terminals

Shunt at output — Either from (+) output terminal to (–) through Q_2 or R_F and R_E

Negative FB?

Yes, follow around loop

Example 2:



Shunt at input – Either from (+) input to ground (emitter) or from (+) to (–) (ground) through R_F and R_E

Series at output – must go through Q_2 and R_E to go from (+) output terminal to (–) output terminal.

Negative FB?

Yes, follow around loop

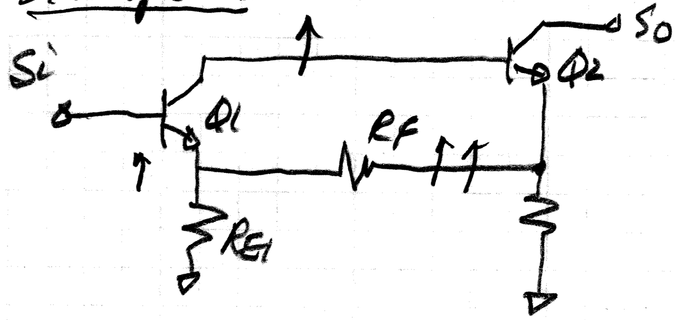
Example 3:

Same circuit except take output between R_F and R_E.

Shunt at input – same as above

Shunt at output

Example 4:



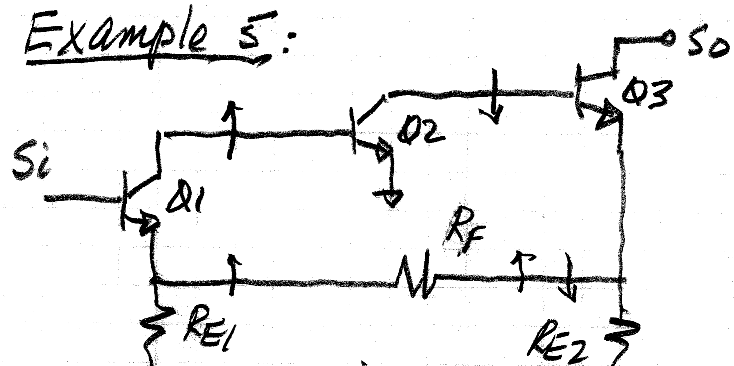
Series at input

Series at output

But, what about feedback?

No, positive feedback - follow around loop

Example 5:



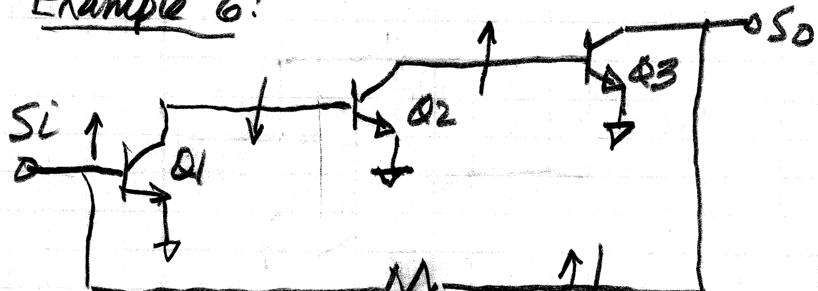
Negative FB

(add extra stage to get negative feedback)

Series at input

Series at output

Example 6:

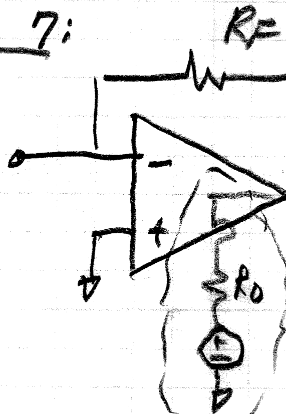


Yes, negative FB

Shunt at input

Shunt at output

Example 7:



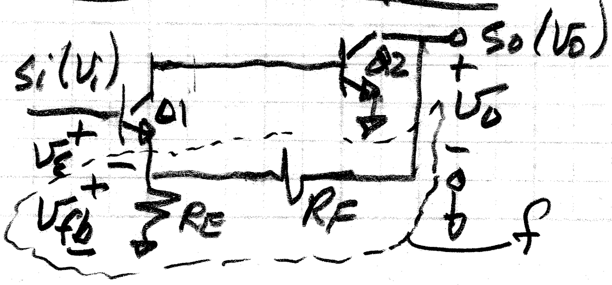
Shunt at input

Shunt at output

Yes, negative FB

Path to ground through opamp.

Back to Example 1:



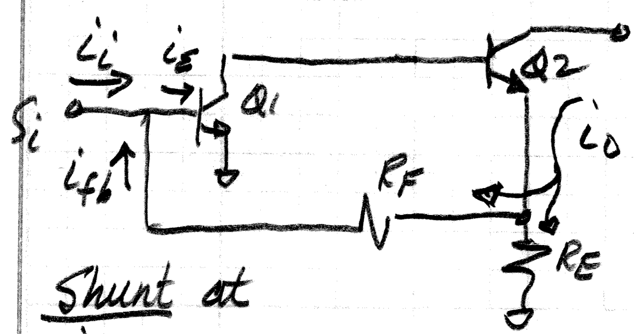
Series - Shunt: i.e., Voltage - Voltage Amp

$$V_{fb} = \frac{R_E}{R_E + R_F} V_O$$

$$V_E = V_i - V_{fb}$$

$$V_i = V_{fb} + V_E$$

Back to Example 2:



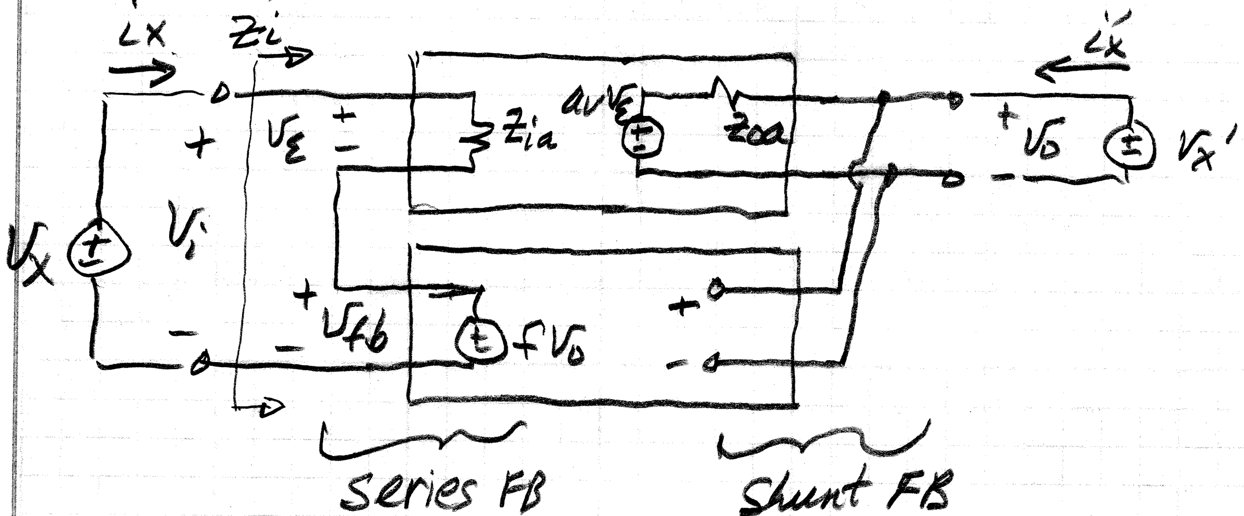
Series at output ∴ current as shown

Shunt at input ∴ current as shown

- **Effect of Feedback on Z_i and Z_o:**

Example: Series-shunt feedback

Assumption (for now): Feedback network has ideal impedances; i.e., does not load basic amplifier



- Find the transfer function: (Ideal with no loading effects)

$$\left.\begin{aligned} v_\varepsilon &= v_i - v_{fb} \\ v_o &= a_v v_\varepsilon \\ v_{fb} &= f v_o \end{aligned}\right\} \Longrightarrow \frac{v_o}{v_i} = \frac{a_v}{1+a_v f}$$

(as expected)

- Find the input impedance, Z_i:

Apply a test source V_x as shown.

$$V_x = v_\varepsilon + v_{fb} = v_\varepsilon + f v_o = v_\varepsilon + f a_v v_\varepsilon = v_\varepsilon(1+\underbrace{a_v f}_{\text{loop gain}})$$

Now, $i_x = \dfrac{v_\varepsilon}{z_{ia}}$ $\Longrightarrow$ $z_i = \dfrac{v_x}{i_x} = \dfrac{v_\varepsilon(1+a_v f)}{v_\varepsilon / z_{ia}}$

- Open-loop opamp input impedance increased by $(1+a_v f)$ = loop gain when we use a series connection at the input. Thus, voltage input amp

$$\boxed{\therefore\ z_i = z_{ia}(1+a_v f)}$$

- Find the closed-loop output impedance z_o: (Short input)

$$z_o = \frac{v_x'}{i_x'} \qquad v_\varepsilon + v_{fb} = 0$$

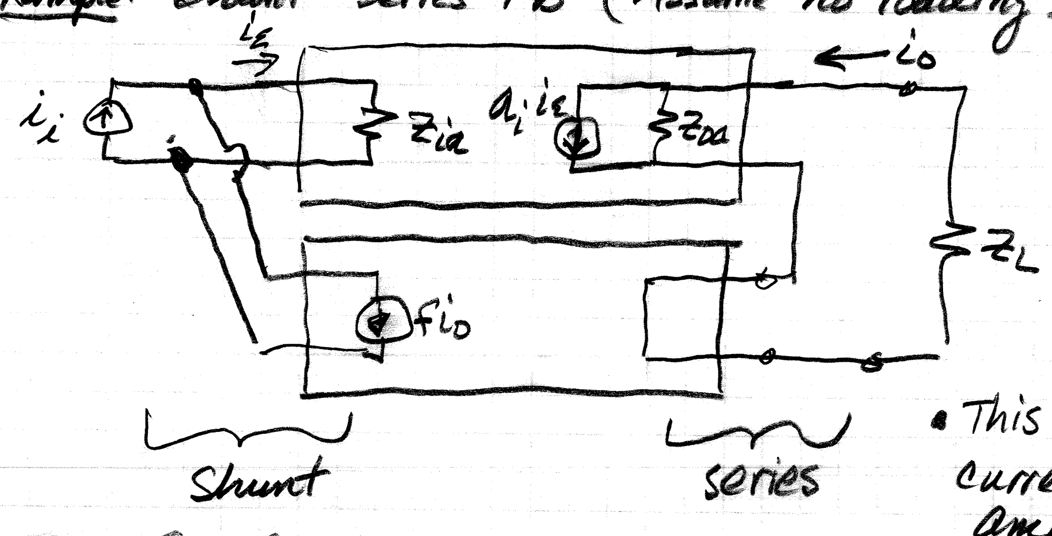
$$v_\varepsilon + f v_x' = 0 \qquad v_\varepsilon = -f v_x'$$

$$i_x' = \frac{v_x' - a_v v_\varepsilon}{z_{oa}} = \frac{v_x' + a_v f v_x'}{z_{oa}}$$

$$\therefore\ \boxed{z_o = \frac{v_x'}{i_x'} = \frac{z_{oa}}{1+a_v f}}$$ Closed-loop output impedance

- open-loop output impedance decreased by $(1+a_v f)$. Thus, voltage output amplifier.

Example: Shunt-Series FB (Assume no loading)



- This is a current amplifier

Transfer function:

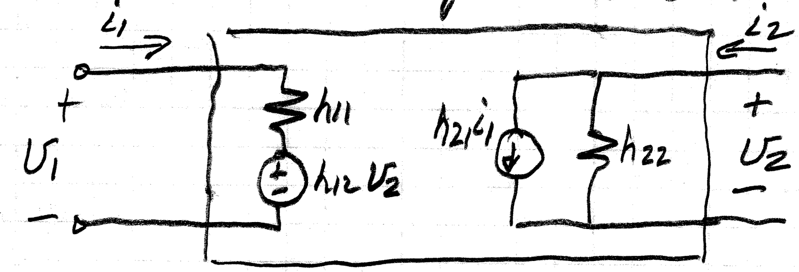
$$i_o = a_i i_\varepsilon = a_i (i_i - i_{fb}) = a_i (i_i + f i_o)$$

$$\therefore\ \frac{i_o}{i_i} = \frac{a_i}{1+a_i f} \quad \text{(as expected)}$$

Similarly, $\boxed{z_i = \dfrac{z_{ia}}{1 + a_i f}}$ and $\boxed{z_o = z_{oa}(1 + a_i f)}$

- Same approach to analyze transconductance ($V \rightarrow I$) and transresistance ($I - V$) closed-loop amplifiers

- <u>Now, consider the effects of loading impedances:</u>
- Take any nonidealities in the feedback network and move them into the forward amplifier: use h-parameter networks for a and f:



<u>Defining equations:</u>

$v_1 = h_{11} i_1 + h_{12} v_2$

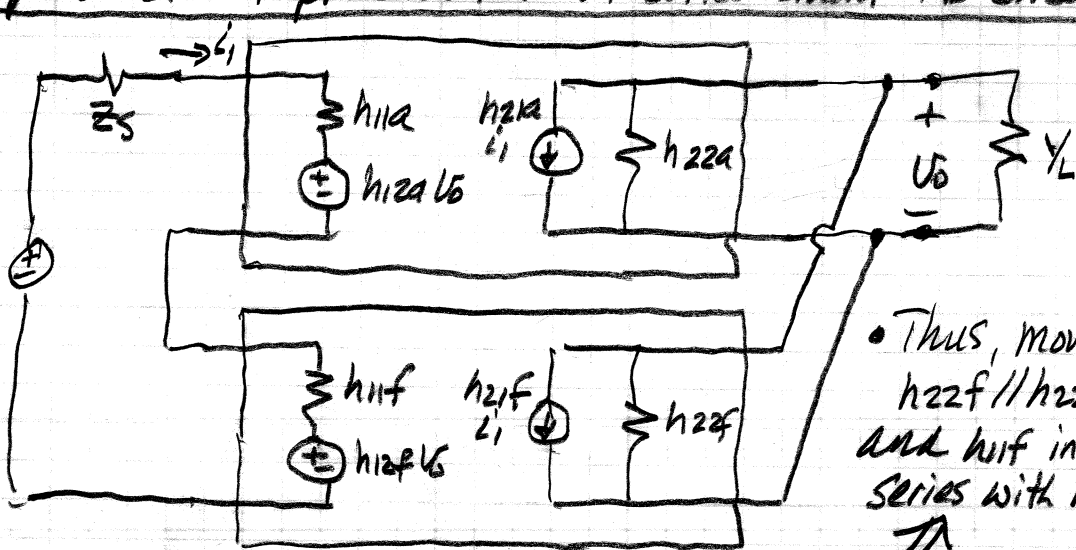
$i_2 = h_{21} i_1 + h_{22} v_2$

- For series-shunt closed-loop amp.

<u>Elements:</u> $h_{11} = \left.\dfrac{v_1}{i_1}\right|_{v_2=0}$ $\qquad h_{12} = \left.\dfrac{v_1}{v_2}\right|_{i_1=0}$

$h_{21} = \left.\dfrac{i_2}{i_1}\right|_{v_2=0}$ $\qquad h_{22} = \left.\dfrac{i_2}{v_2}\right|_{i_1=0}$

- <u>h-parameter representation of series-shunt FB circuit</u>



- Thus, move $h_{22f} // h_{22a}$ and h_{11f} in series with h_{11a}

- In general, amplifiers and feedback networks <u>uni-directional</u>:

$\therefore$ $|h_{12a}| \ll |h_{12f}|$ (neglect h_{12a}) and $|h_{21f}| \ll |h_{21a}|$ (neglect h_{21f})