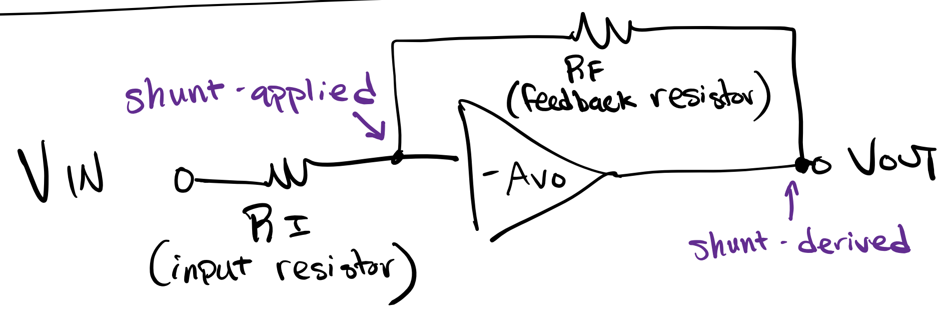
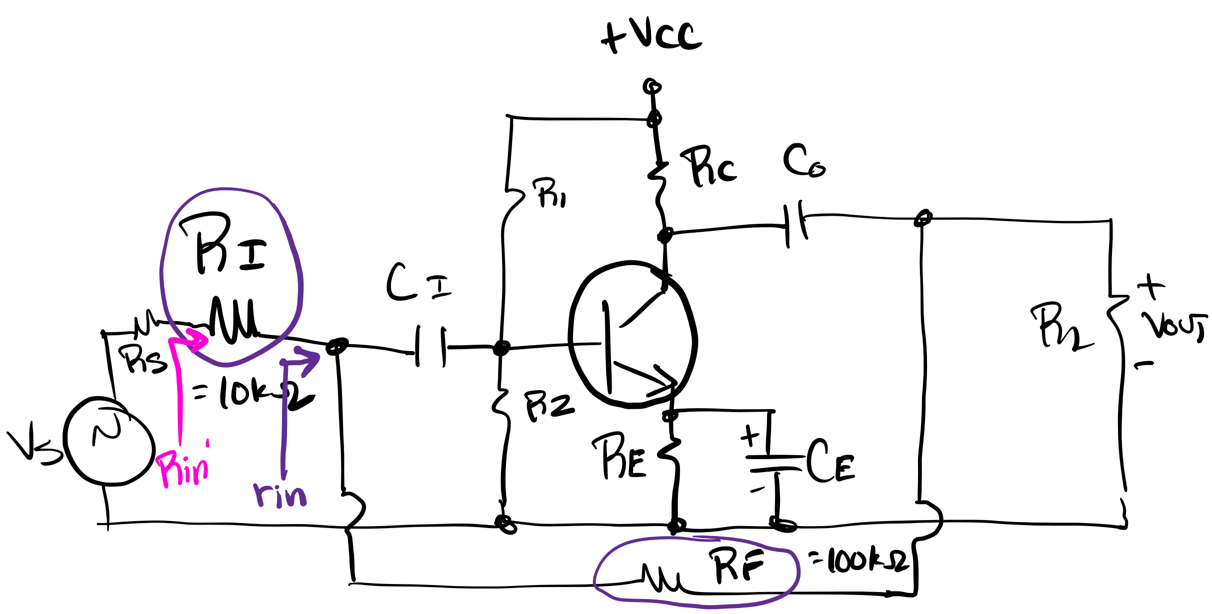
Shunt/Shunt Feedback Voltage Amplifier



- we can apply a shunt-derived/shunt-applied external feedback loop around any inverting amplifier
- thus, it works with single-transistor amplifiers (common-emitter, common-source), cascodes, etc.

ex: common-emitter example



·· the β network for this amplifier is the ratio of input and output resistors; $\boxed{\beta = \frac{R_I}{R_F}}$

·· recall from our analysis that the CE amplifier has an A_{v_2} of -271.5; thus, $A_{vo} = 271.5$ (inverting)

·· the closed loop gain, using the feedback equation, is:

✓ inherently inverting!

$$A_v = \frac{-A_{vo}}{1 + \beta A_{vo}} = \frac{-A_{vo}}{1 + \frac{R_I}{R_F} \cdot A_{vo}}$$

$$A_v = \frac{-271.5}{1 + \frac{10k}{100k} \cdot 271.5} = -9.645$$

or 19.68 dB (inverting)

·· note that if βA_{vo} is a sufficiently large value, $1 + \beta A_{vo} \approx \beta A_{vo}$

$$A_v \approx \frac{-\cancel{A_{vo}}}{\beta \cancel{A_{vo}}} = \frac{-1}{\beta} = \frac{-1}{R_I / R_F}$$

$$\boxed{A_v \approx \frac{-R_F}{R_I}}$$

Look familiar? (inverting op-amp equation!)

·· using the approximation:

$$A_v \approx \frac{-100k}{10k} = -10 \text{ or } 20\,dB$$

(inverting)

·· close enough? yep!!!

·· note that if $R_F = R_I$, the gain is approximately -1;

·· thus, it can be a <u>unity-gain inverter</u> and in the vacuum tube era it was commonly referred to as an <u>anode follower</u>

[rather than cathode follower, analogous to emitter/source follower]

→ Charles Boegli <u>greatly</u> expanded on this ca. early 60's

<u>Output Resistance of Shunt/Shunt Amplifier</u>

·· CE output resistance ($R_C \| r_o \approx R_C$) will be <u>reduced</u> by shunt-derived feedback to:

$$R_{out}' = \frac{R_{out}}{1 + \beta A_{vo}}$$

← denominator of feedback equation

$$R_{out}' = \frac{4.185k}{1 + \frac{10k}{100k} \cdot 271.5} = 0.1487\ k\Omega$$ ← check that lecture!

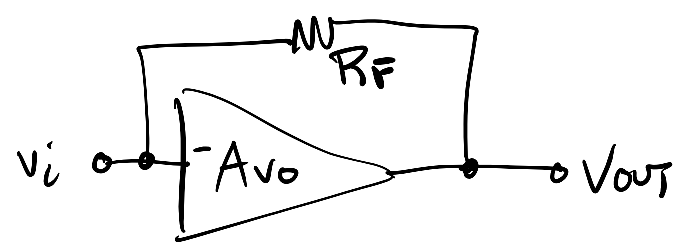
or $\underline{148.7\ \Omega}$

∴ <u>usefully low</u> for driving kΩ-range loads and cable capacitance

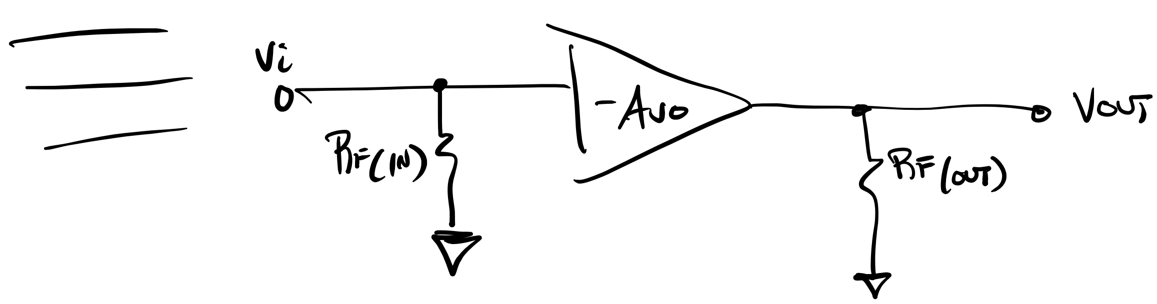
Input Resistance of Shunt/Shunt Amplifier

∴ this is a bit trickier to analyze!

∴ first, consider the effect of R_F on the impedance of the input of the amplifier:



∴ we would like to determine equivalent <u>shunt</u> impedances at the input and output terminals



.. that's right, it's Miller Time!

.. we already know $R_{F(IN)} = \dfrac{R_F}{1-A_V}$

$R_{F(OUT)} = \dfrac{R_F}{1-\frac{1}{A_V}}$ } Miller's Theorem

$$R_{F(IN)} = \frac{100k}{1-(-271.5)} = 0.3670\ k\Omega$$

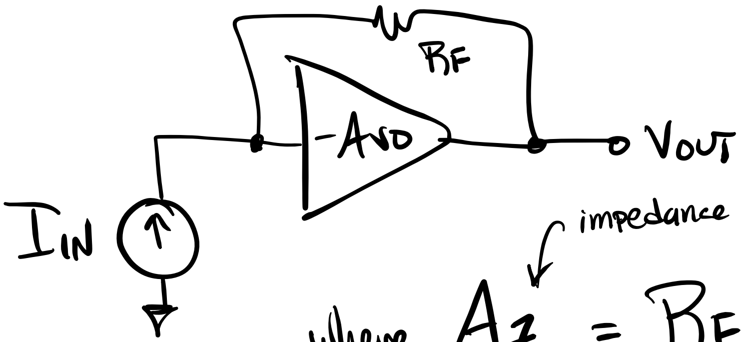
or $\underline{367\Omega}$

.. this is a quite low value that reinforces the notion that shunt-applied negative feedback lowers input resistance and creates current input [ideal ammeter: short]

$$R_{F(OUT)} = \frac{100k}{1-\frac{1}{-271.5}} \approx 100k$$ (treat like output load)

.. very high open-loop gain will make $R_{F(IN)}$ even lower → virtual ground

.. in fact, the feedback transimpedance amplifier omits R_I and is used as a current-to-voltage converter



impedance!

where $A_Z = R_F$

$= 100\ V/mA$

note unit! not $k\Omega$!

∴ back to the shunt/shunt voltage amplifier, the net input (shunt) resistance is:

$$r_{in} = R_{F(IN)} \parallel R_{in}$$

$\hookrightarrow R_1 \parallel R_2 \parallel r_b$ for CE

$$= 0.367k \parallel 1.735k = 0.3029\ k\Omega$$

∴ the input resistance of the whole amplifier, as seen by V_s, is thus:

$$R_{in}' = r_{in} + R_I$$

∴ if $R_I \ggg r_{in}$,

$$\boxed{R_{in}' \approx R_I}$$

.. this example: $R_{in}' \approx 10k\Omega$

.. not great, but not unuseable for many applications

High-Frequency Response of Shunt/Shunt Amplifier

.. the net HF input capacitance is computed the usual way; in this example,

$$C_{BE} + \underset{\substack{\uparrow \\ \text{Miller Time!}}}{C_{BC(IN)}} = 1102\ pF$$

.. this forms a low-pass filter with $R_I \parallel r_{in}$

.. since $R_I \ggg r_{in}$, we can neglect R_I (and R_S)

thus, $$f_{H(IN)} \cong \frac{1}{2\pi \cdot (C_{BE} + C_{BC(IN)}) \cdot r_{in}}$$

$$= \frac{1}{2\pi \cdot 1102 \times 10^{-12} \cdot 302.9}$$

$$f_{H(IN)} = 476.8\ kHz$$

.. note: compared to open-loop bandwidth of 2.97 MHz, high-frequency response is actually <u>worse</u>, despite the application of negative feedback!

.. why??

.. <u>open-loop</u> $f_{H(IN)}$ assumed $R_S = 50\,\Omega$ in parallel with $R_b' = 1.735\,k\Omega$

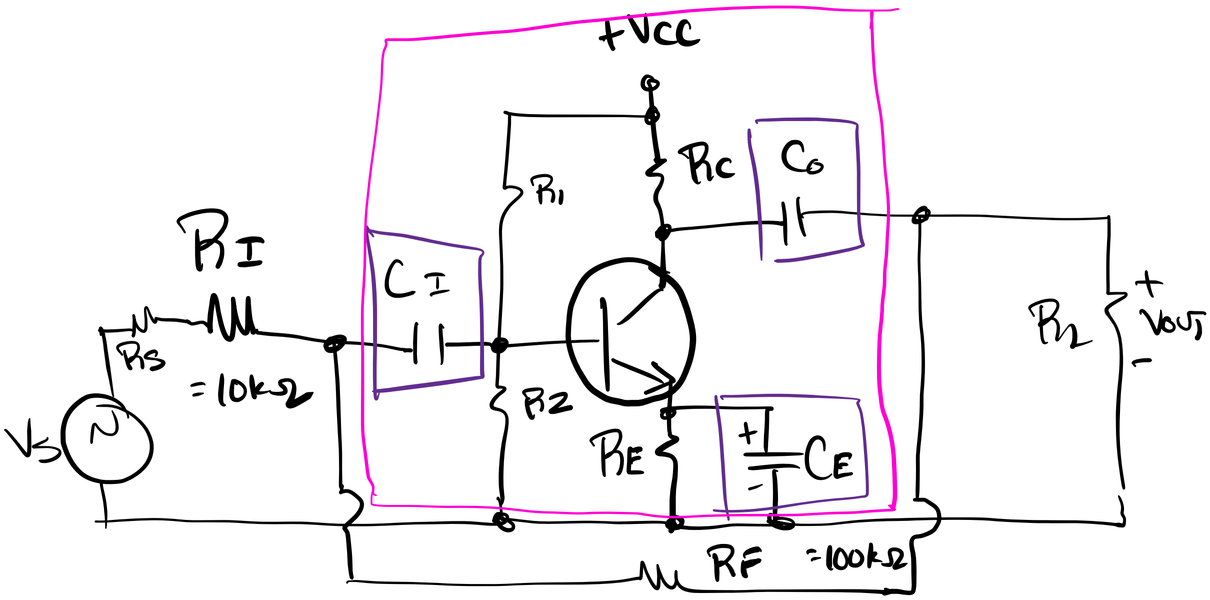
.. now response is dominated by $r_{in} = \frac{R_F}{1 - A_v}$

.. we can reduce R_F to get a lower r_{in}, extending bandwidth; but then to maintain the same β and thus overall gain, we'd have to also lower R_I, lowering R_{in}'!

.. classic engineering tradeoff!!!...

Low-Frequency Response of Shunt/Shunt

.. this is also a bit tricky to analyze!



∴ because C_I, C_o, and C_E are all inside the negative feedback loop, the final low-frequency cutoff f_L is subject to negative feedback and will be lowered by $1 + \beta A_{vo}$ (good!)

∴ but since we have three low-frequency poles inside a negative feedback loop, we are likely to have problems

∴ each pole has a max. phase shift of +90° [1st-order high-pass filter!]

∴ two poles inside a negative feedback loop will approach +180°, which is equivalent to a polarity inversion

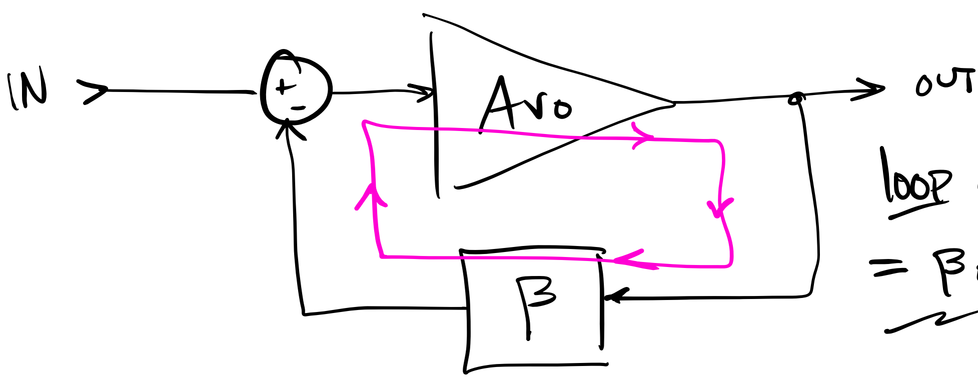
- this is starting to turn negative feedback into positive feedback (oscillator!)

- three poles approaches +270°, almost certain to cause LF instability

Mitigation strategies :

1.) Spacing LF poles

- we can ensure LF stability if the two most dominant poles are spaced apart by the loop gain.
  ↳ highest-f



loop gain $= \beta A_{vo}$

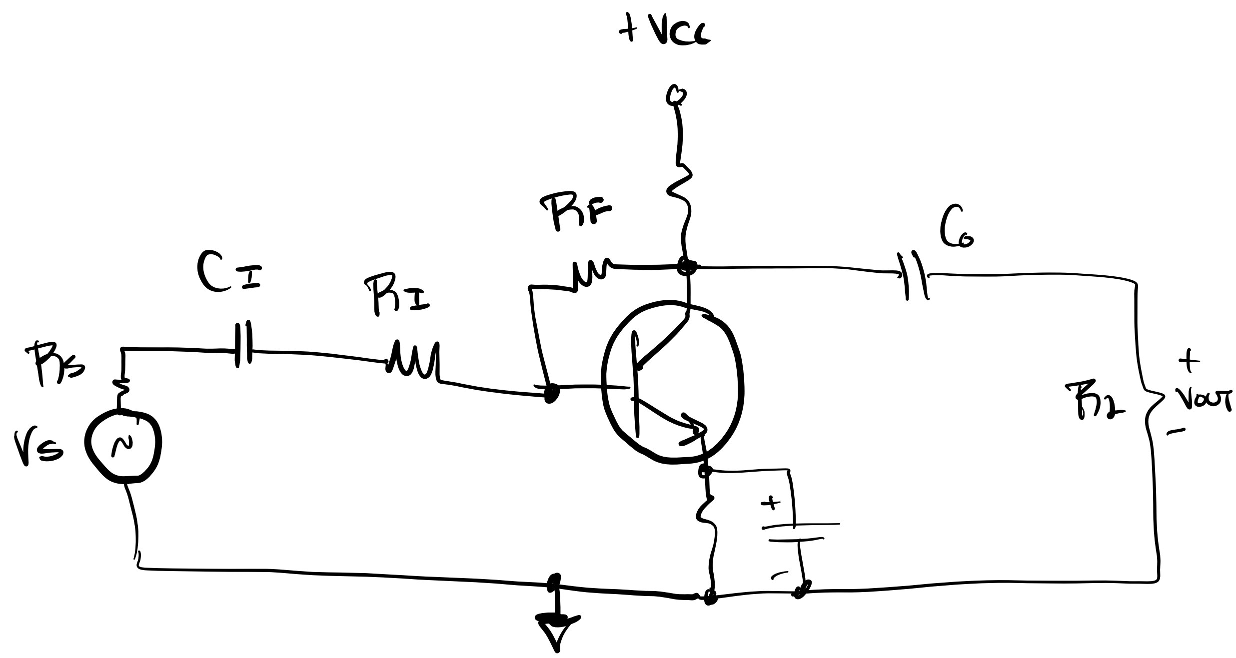
- in this amp, loop gain $= \frac{R_{II}}{R_F} \cdot A_{vo}$

$$= \frac{1}{10} \cdot 271.5 = 27.15$$

- thus, if the pole caused by C_O was 1 Hz, we could make the pole caused by C_E 27.15 Hz, and the pole at the input <<< 1 Hz (so the C_O and C_E poles dominate)

- could mean awkward component values, but feasible

2) reconfigure negative feedback loop to <u>not</u> include all three caps!



- note that R_F has replaced R_1 in the bias network, so R_2 will probably need to be recomputed for correct bias!

- now only C_E is inside the feedback loop; guaranteed to be stable, and its $f_{L(CE)}$ is reduced (a lot!) by feedback

- tradeoff: C_I and C_O are not subject to negative feedback

  ~ another engineering tradeoff!

- this does simplify some computations:

$$f_{L(IN)} \cong \frac{1}{2\pi \cdot C_I \cdot R_I}$$

↳ assuming $r_{in} \lll R_I$; "virtual ground"

$$= \frac{1}{2\pi \cdot 1\times10^{-6} \cdot 10k} = 15.92\ Hz$$

(better than 89 Hz!)

$$f_{L(OUT)} \cong \frac{1}{2\pi \cdot C_O \cdot R_L}$$

↳ assumes $R_L \lll R_{out}'$ due to neg. feedback

$$= \frac{1}{2\pi \cdot 10\times10^{-6} \cdot 10k} = 1.592\ Hz$$

- $f_{L(CE)}$ was previously determined to be 14.6 Hz
  - this is reduced by feedback to:

$$f_{L(CE)}' = \frac{f_{L(CE)}}{1+\beta A_{vo}} = \frac{14.6}{1+\frac{10k}{100k}\cdot 271.5}$$

$$= 0.5187 \text{ Hz}$$

- so the dominant pole is $f_{L(IN)}$;

$$f_L \cong 15.92 \text{ Hz}$$