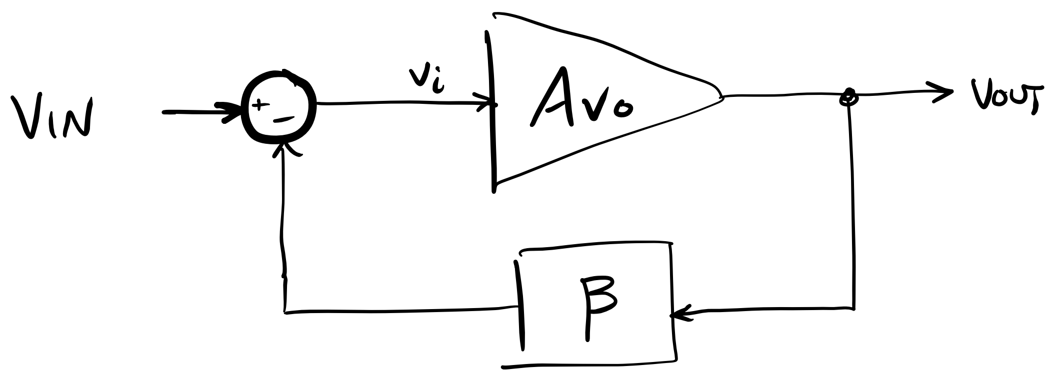
Negative Feedback

- real-world amplifiers almost always use <u>some</u> type of negative feedback; you almost never see a basic transistor amplifier by itself, for <u>any</u> application!

- discovered by Harold Black at Bell Labs in August 1927, the essential mechanism of negative feedback is <u>subtracting</u> a portion of the <u>output</u> of an amplifier from its <u>input</u>, to correct <u>errors</u> in amplification, at the expense of <u>gain</u>.

  - unbelievably huge development!!!
  - reduces non-linear distortion, corrects frequency response, improves input and output impedances, reduces noise, and a host of related benefits

System block diagram; voltage amplifier example



A_{vo} : open-loop gain of amplifier (i.e., with no feedback)
β : feedback factor (a/k/a feedback fraction)

∵ V_{OUT} with no feedback applied is

input to amplifier

$$V_{OUT} = v_i \cdot A_{vo}$$

open-loop gain

∵ v_i comprises the system V_{IN}, minus a fraction of V_{OUT};

$$v_i = V_{IN} - V_{OUT} \cdot \beta$$

$$\therefore \quad V_{OUT} = (V_{IN} - V_{OUT} \cdot \beta) A_{vo}$$

$$V_{OUT} = V_{IN} \cdot A_{vo} - V_{OUT} \cdot \beta \cdot A_{vo}$$

$$V_{OUT} (1 + \beta A_{vo}) = V_{IN} \cdot A_{vo}$$

∴ define closed-loop system gain; i.e., the final gain of the system <u>with</u> negative feedback

$$A_v = \frac{V_{OUT}}{V_{IN}};$$

then $$\boxed{A_v = \frac{A_{vo}}{1 + \beta A_{vo}}}$$

∴ magical negative feedback equation!

∴ impossible to overestimate the importance of this!

∴ there are four principal methods of applying a negative feedback loop to an amplifier:

1.) shunt-derived / series-applied

- ∴ feedback network is connected in <u>parallel</u> (shunt!) w/ output and in <u>series</u> with input
- ∴ this tends to <u>lower</u> output impedance of an amplifier (closer to ideal voltage source) and <u>raise</u> input impedance (ideally infinite like an ideal voltmeter)

2.) shunt-derived / shunt-applied

∴ feedback network in parallel w/ output
<u>and</u> in parallel w/ input

∴ this tends to lower both input <u>and</u> output impedances; so voltage-source output and <u>current</u> input (remember, ideal ammeter is a <u>short</u>)

less common:

3.) series-derived / series-applied

∴ feedback network is in <u>series</u> with amplifier output, which samples output <u>current</u> rather than voltage, raising output impedance, and in series with the input, raising input impedance

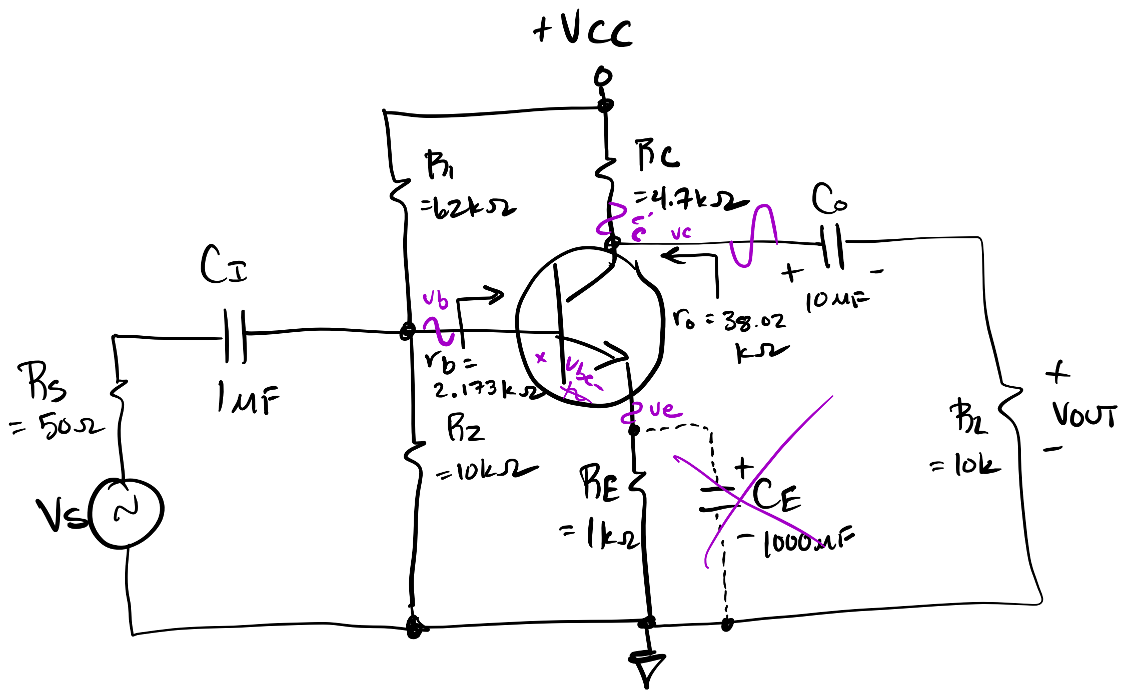
4.) series-derived / shunt-applied

∴ network samples current, raising output impedance, and shunts the input, lowering input impedance

∴ <u>current</u> amplifier

∴ We'll start with a mechanism that can be implemented on an amplifier with which we're already familiar;
<u>local feedback</u> caused by an <u>unbypassed</u> emitter or source resistor in a common-emitter or common-source amplifier

CE amplifier w/ bypassed R_E:



∴ we already performed small-signal analysis on this amplifier with C_E in place:

$$A_v = -263.3 \quad \text{or } 48.4\text{ dB, inverting}$$

- now let's investigate how removing C_E creates a series-derived / series-applied negative feedback loop

  - AC collector current [gm Vbe!], which also flows through R_E, is now allowed to drop a small-signal voltage ve

  - since the transistor amplifies the small-signal base-to-emitter voltage Vbe, this Ve subtracts from the input signal Vb, self-creating negative feedback!
    - hence, local feedback

  - Since it's output current that is sampled

    $$\left(\text{AC collector current} = \frac{V_{OUT}}{R_C \| r_o \| R_L} \right),$$

    small-signal model!

    it is series-derived

  - since this same current develops an AC emitter voltage that subtracts from the input voltage, it is series-applied.

    $$v_e = \text{AC collector current} \cdot R_E$$

    $$\therefore \quad v_e = \frac{V_{OUT}}{R_C \| r_o \| R_L} \cdot R_E$$

-- therefore, for this feedback mechanism, the **feedback factor β** is :

$$\boxed{\beta = \frac{R_E}{R_C \| r_o \| R_L}}$$

-- we can show that for a field-effect transistor common-source amplifier,

$$\boxed{\beta = \frac{R_S}{R_D \| r_o \| R_L}}$$

-- let's plug some numbers into the feedback equation

$$R_C \| r_o \| R_L = 4.7k \| 38.02k \| 10k = \underline{2.949 \, k\Omega}$$

$$\beta = \frac{R_E}{R_C \| r_o \| R_L} = \frac{1k}{2.949k}$$

$$\underline{\beta = 0.3391}$$

$$A_v = \frac{A_{vo}}{1 + \beta A_{vo}} = \frac{263.3}{1 + 0.3391 \cdot 263.3}$$

open-loop gain

$$\underline{A_v = 2.916 \text{ or } 9.3 \text{ dB}}$$ [still inverting, of course!]

-- So the gain has been reduced by $1 + \beta A_{vo}$

or $1 + 0.3391 \cdot 263.3$

$= 90.29$ or 39.1 dB

check: $\underbrace{48.4 \text{ dB}}_{\text{open-loop gain}} - \underbrace{39.1 \text{ dB}}_{\text{negative feedback}} = \underbrace{9.3 \text{ dB}}_{\text{closed-loop gain}}$

-- note that if βA_{vo} is sufficiently high,

$1 + \beta A_{vo} \approx \beta A_{vo}$ (true here!)

-- then $A_v \approx \dfrac{\cancel{A_{vo}}}{\beta \cancel{A_{vo}}}$

$$A_v \approx \frac{1}{\beta}$$

-- remember, $\beta = \dfrac{R_E}{R_C \| r_o \| R_L}$

$$\therefore A_v \approx \frac{R_C \| r_o \| R_L}{R_E}$$

-- and if we can also assume $r_o \gg R_C \| R_L$,

$$\boxed{A_v \approx \frac{R_C \| R_L}{R_E}}$$

-- unreliable transistor characteristics have been removed from the equation!

∴ gain set by resistors!

check: $\frac{4.7k \parallel 10k}{1k} = 3.197$

or 10.1 dB;

off by 0.8 dB

(probably not a problem!)

∴ because this feedback loop is series-derived / series applied, we expect a 39.1 dB improvement in the following areas:

1.) increase in internal output impedance;

thus, $r_o' = r_o(1 + \beta A_{vo})$

$= 38.02k \cdot 90.29$

$= 3433\ k\Omega$ ← truly can be neglected compared to R_C and R_L!

∴ note: R_C is outside the negative feedback loop, so its effect on R_{out} is unchanged

thus, $R_{out}' = R_C \parallel r_o'$ ↳ huge!

$R_{out}' \approx R_C = 4.7\ k\Omega$

[slightly higher than $R_{out} = 4.7k \| 38.02k = 4.183k$]

∴ again, removes unreliable transistor r_o from R_{out}

2.) increases internal input impedance;

thus, $r_b' = r_b (1 + \beta A_{vo})$

$$r_b' = 2.173k \cdot 90.29 = \underline{196.2\ k\Omega}$$

∴ since R_{in} is dominated by r_b [$R_{in} = R_b \| R_1 \| R_2$], this constitutes a significant improvement!

$$R_{in}' = r_b' \| \boxed{R_1 \| R_2}$$

outside feedback loop; thus unchanged!

∴ now $r_b' \gg R_1 \| R_2$; thus,

$$\underline{R_{in}' \approx R_1 \| R_2} = \frac{1}{62k} \| \frac{1}{10k} = \underline{8.611\ k\Omega}$$

∴ Compared to $R_{in} = 2.173k \| 62k \| 10k = 1.735k$, this is way better; and removes unreliable BJT parameter r_b!

3.) increase in f_H caused by internal mechanisms

.. we found a dominant input pole of

$$f_{H(IN)} \approx 2.97\ \text{MHz} \quad \text{open-loop}$$

.. thus, we expect a 90.29-fold increase to:

$$f_{H(IN)}' = f_{H(IN)}(1 + \beta A_{vo}) = 2.97 \cdot 90.29$$

$$= 268.2\ \text{MHz}$$

.. in reality, this now makes the output pole of 13.5 MHz dominant, which will be unchanged because it mostly involves $R_C \parallel R_L$

4.) decrease in f_L caused by internal mechanisms

.. for starters, we simply remove f_{LCE}
↳ gone!

.. $f_{L(IN)}$ will decrease due to increased r_b', but since external $R_1 \parallel R_2$ are still in place, it won't be by the full $1 + \beta A_{vo}$!

$$f_{L(IN)}' = \frac{1}{2\pi C_{IN} (R_1 \| R_2)}$$

$$= \frac{1}{2\pi \cdot 1\times10^{-6} (8.611\,k)} = 18.48\ Hz$$

∴ a lot better than $f_{L(IN)} = 89.2$ Hz before!)

∴ $f_{L(OUT)} = 1.12$ Hz won't change much because r_o wasn't a significant factor; thus, $f_{L(IN)}$ still dominates and $f_L \approx 18.48$ Hz

5.) 39.1 dB decrease in distortion of small signals!

∴ much more linear amplification, up until we get close to clipping

∴ negative feedback is amazing and there are many more ways to implement it!