EEE225: Analogue and Digital Electronics

Lecture II

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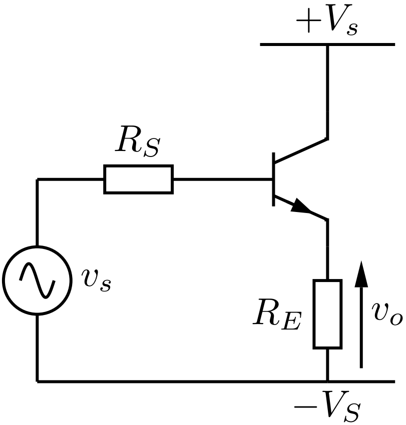
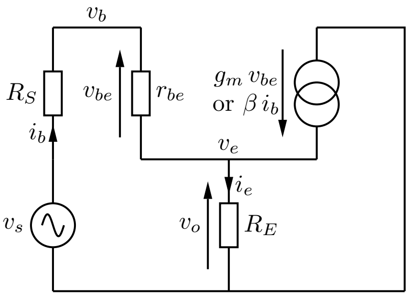
This Lecture

Emitter Follower / Common Collector

- A kind of "voltage follower" or "buffer"
- Approximately unity voltage gain
- pnp or npn versions possible
- High current gain
- May be thought of as impedance transformer (so can all transistor circuits...)



In this figure the biasing circuitry is contained as an effective resistance within R_S



$$v_o = v_{be}\, R_E \left(\frac{1}{r_{be}} + g_m \right) \qquad (1)$$

$$\approx v_{be}\, R_E\, g_m \qquad (2)$$

and a relation between v_{be}, v_s and v_o is given by summing voltages around the input loop.

$$v_s = i_b\, R_S + v_{be} + v_o \qquad (3)$$

$$= v_{be} \left(1 + \frac{R_S}{r_b e} \right) + v_o \qquad (4)$$

using the result in (2) to eliminate v_{be},

$$\frac{v_o}{v_s} = \frac{r_{be}\, g_m\, R_E}{r_{be}\, g_m\, R_E + R_S + r_{be}} \qquad (5)$$

$$= \frac{R_E}{\frac{1}{g_m} + \frac{R_S}{\beta} + R_E} \qquad (6)$$

1. The gain is non-inverting
2. Gain ≈ 1 if $R_E >> R_S/\beta$ and $R_E >> 1/g_m$

The input resistance is given by considering v_b/i_b, recall (1)

$$v_e = v_{be}\, R_E \left(\frac{1}{r_{be}} + g_m \right) \quad (7)$$

and summing up the voltages...

$$v_b = v_{be} + v_e \quad (8)$$

$$= v_{be} + v_{be}\, R_E \left(\frac{1}{r_{be}} + g_m \right) \quad (9)$$

$$= v_{be} \left(1 + R_E \left(\frac{1}{r_{be}} + g_m \right) \right) \quad (10)$$

since $v_{be} = i_b\, r_{be}$ and $g_m\, r_{be} = \beta$ we can write,

$$r_i = \frac{v_b}{i_b} = r_{be} + (\beta + 1)\; R_E \quad (11)$$

Generally $(\beta + 1)\, R_E >> r_{be}$ so the input resistance is dominated by the $(\beta + 1)\, R_E$ term. By comparing this result with the input resistance of the non-degenerated common emitter amplifier we could show negative feedback can be used to increase the input resistance of a transistor stage.

To obtain the output resistance inject a test current i_t with the input grounded and find v_o/i_t. Summing currents at v_e

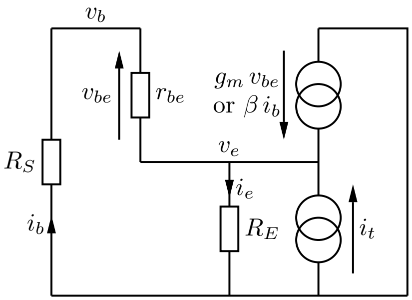
$$(1+\beta)\ i_b + i_t = \frac{v_e}{R_E} \qquad (12)$$

and summing up the voltages in the base loop

$$v_e = -i_b\,(R_S + r_{be}) \qquad (13)$$

substituting (13) into (12) and solving for v_e/i_t,

$$r_o = \frac{1}{\frac{1+\beta}{R_S+r_{be}}} + \frac{1}{R_E} \qquad (14)$$

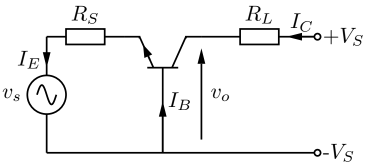


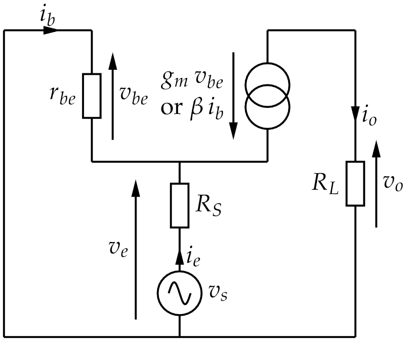
$$r_o \approx \frac{1}{g_m} + \frac{R_S}{\beta} \qquad (15)$$

If $\beta >> 1$, the first term becomes $\frac{R_S+r_{be}}{\beta}$ and if R_E is large, we can ignore the $\frac{1}{R_E}$ term.

Common Base Connection

Generally used in conjunction with other transistors in "circuit blocks", but sometimes alone[1]. i_e is the input current (flowing from v_s), since $i_e = i_o + i_b$ the current gain (i_o / i_e) is slightly less than 1 (actually it's $= \alpha$).





summing currents,

$$i_e + i_b + g_m\, v_{be} = 0 \qquad (16)$$

[1] http://dx.doi.org/10.1088/0957-0233/23/12/125901

$$\frac{v_s - v_e}{R_S} + \frac{v_{be}}{rbe} + g_m\, v_{be} = 0 \quad (17)$$

$v_e + v_{be} = 0$ so $v_e = -v_{be}$ therefore (17) can be solved for v_{be}

$$v_{be} = -\frac{v_s}{R_S\left(\frac{1}{R_S} + \frac{1}{r_{be}} + g_m\right)} \quad (18)$$

$$\approx -\frac{v_s}{1 + g_m\, R_S} \quad (19)$$

approximation is because $1/r_{be} = g_m/\beta$ and $\beta >> 1$

At the output,

$$v_o = i_o\, R_L = -g_m\, v_{be}\, R_L \quad (20)$$

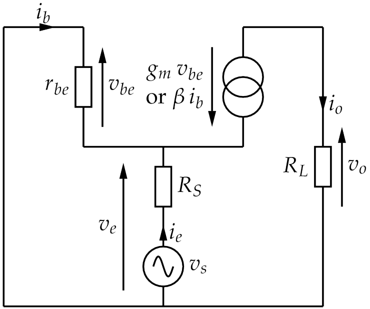
combining this with (19) to eliminate v_{be}

$$\frac{v_o}{v_s} = \frac{g_m\, R_L}{1 + g_m\, R_S} = \frac{R_L}{r_e + R_S} \quad (21)$$

where $r_e = 1/g_m$.

- The gain is non-inverting
- Gain $\propto R_L$
- If $R_S >> r_e$ gain controlled by ratio R_L/R_S

Common Base Input Resistance



The resistance looking into the emitter,

$$r_i = \frac{v_e}{i_e} = \frac{v_e}{\frac{-v_{be}}{r_{be}} - g_m\, v_{be}} \qquad (22)$$

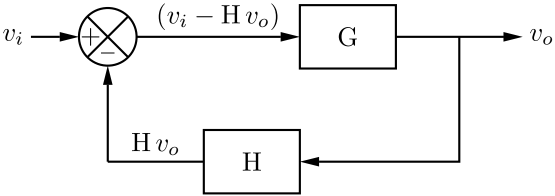
Since $v_e = -v_{be}$ and $g_m >> 1/r_{be}$ this reduces to $r_i \approx \frac{1}{g_m} = r_e$ The value is small 10s - 100s Ω

There is another model of the transistor called "T Model" in which r_e plays a much bigger role. However hybid-π is the only model we will use. The original π paper is by Giacolletto[2].

[2] http://dx.doi.org/10.1109/JSSC.1969.1049963

Feedback Systems (Quick reminder)

In EEE118 we discussed the opamp in terms of a general feedback system.



So $v_o = G\,(v_i - H\,v_o)$ (23)

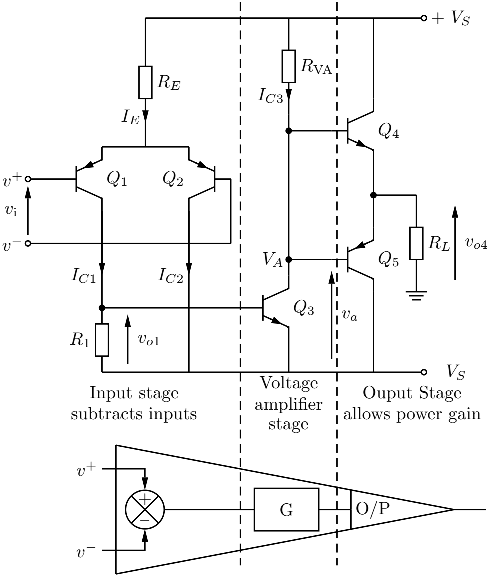
or $v_o\,(1 + G\,H) = G\,v_i$ (24)

$$\frac{v_o}{v_i} = \frac{G}{1 + G\,H} \qquad (25)$$

If $|G\,H| >> 1$,

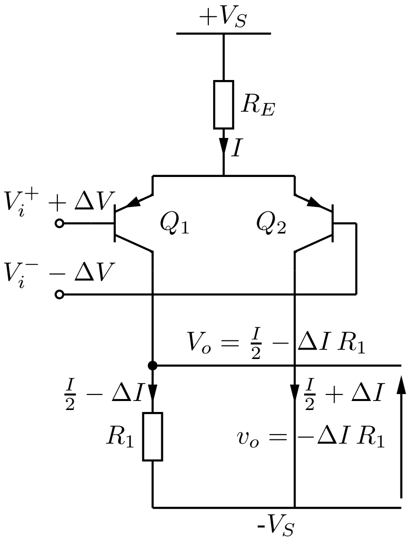
$$\frac{v_o}{v_i} = \frac{G}{G\,H} = \frac{1}{H} \qquad (26)$$

System dependent on H, designer controls H with ratio of resistors.

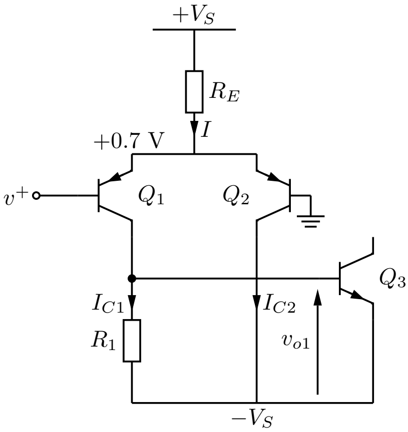


- Input stage: differential amplifier or "long tailed pair". Subtracts the inputs.
- Voltage amplifier stage (VAS): common emitter amplifier. Provides majority of voltage gain.
- Output stage: emitter follower. Increases current capability of VAS (voltage × current = power... hence "power gain".

- Opamp will not work properly without feedback. Feedback controls the gain of the circuit but also helps define the DC conditions. Feedback adjusts v_i in order to achieve the internal voltage drops required for proper operation. If $v_o = 0$, v_i will be at the value it needs to be in order to make $v_o = 0$. Feedback is *not* shown on prior slide.
- If $v^+ \approx v^- \approx 0$, V_{E1} and $V_{E2} \approx 0.7$ so $I_E \approx (+V_S - 0.7)/R_E$.
- I_E splits between Q_1 and Q_2 to form I_{C1} and I_{C2}.
- I_{C1} has two functions 1) create a voltage drop of 0.7 V across R_1 in order to bias Q_3 into conduction. 2) Provide the base current for Q_3. I_{C1} will be $0.7/R_1 + I_{C3}/h_{FE3}$.
- The value of I_{C3} varies with V_A and hence with V_{o4} but assuming $V_A = 0$, $I_{C3} = +V_S/R_{VA}$.
- I_{C2} is returned directly to the negative supply.
- In the case where $v^+ \approx v^- \neq 0$, there is a common mode input voltage, v_{cm}, and $I_E \approx (+V_S - v_{cm})/R_E$.

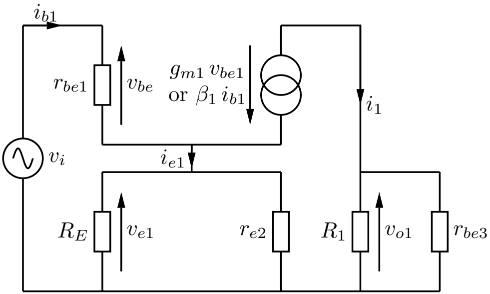


- If v^+ increases by Δv_i and v^- decreases by Δv_i, the average of v^+ and v^- is unchanged so I_E is unchanged because V_{be} is unchanged.
- If v^+ and v^- increase or decrease by Δv_i, v_i is called a "common mode signal" ideally the differential amplifier will not amplify any common mode component of the input.



We must consider the effects of three transistors. Q_1 and Q_2 are the input differential pair.

Q_3 must also be considered now because its input resistance forms part of Q_1's collector load resistance. If the input signal is regarded as v^+ with respect to ground, Q_2 looks like a common base connection and can be represented by its common base input resistance $1/g_{m2}$. The collector current of Q_1 sees two resistors in parallel, R_1 and the input resistance of Q_3. Q_3 is a common emitter amplifier *without* degeneration. Its input resistance is r_{be3}.



A small signal equivalent circuit describes the three transistor circuit block according to our simplifications.

This small signal model is very similar to the common emitter *with* degeneration from Lecture 1. In this case $R_S = 0$ and R_E and R_L are parallel combinations $R_E//r_{e2}$ and $R_1//r_{be3}$. Since $R_E >> r_{e2}$, r_{e2} dominates. The gain expression for the circuit is (based on the degenerated CE analysis)

$$\frac{v_{o1}}{v_i} = -\frac{R_1//r_{be3}}{r_{e1} + r_{e2}} \qquad (27)$$

Review

- Considered the emitter follower circuit (voltage gain, current gain, input and output resistances).
- Considered the common base circuit (voltage gain, current gain, input resistance).
- Recapped the idea of the opamp as a feedback system.
- Introduced a simplified schematic of an opamp.
- Developed some ideas around the DC conditions of the simplified opamp
- Looked at the combination of three transistors into a differential amplifier + common emitter stage and considered their combined effect.