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EEE 241
ANALOG ELECTRONICS 1
Lecture 16

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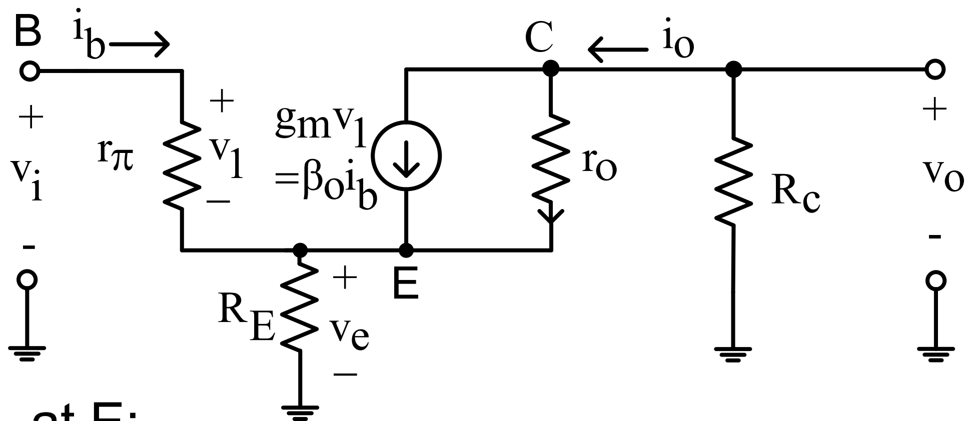
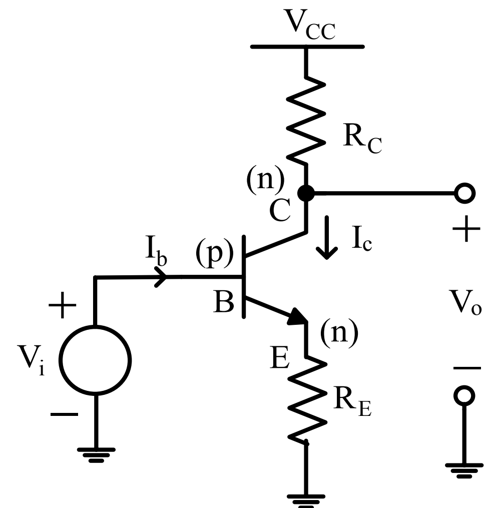
CE with Emitter Degeneration





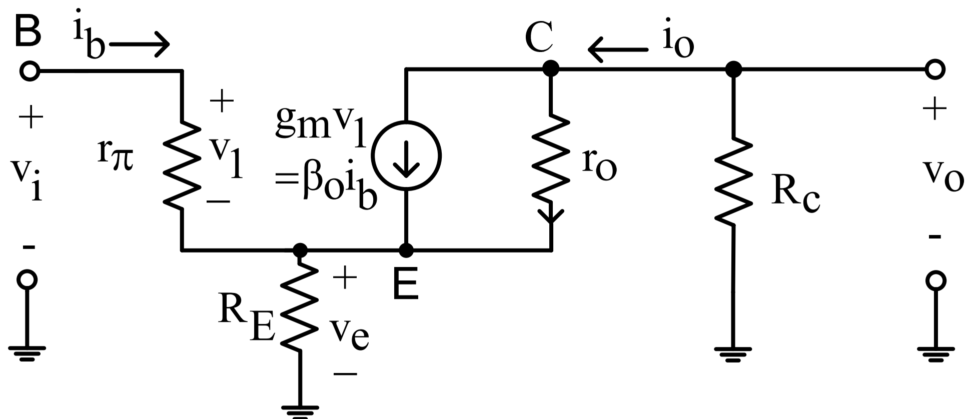
KCL at E:

$$i_b + \beta_o i_b + \frac{v_o - v_e}{r_o} = \frac{v_e}{R_E}$$

$$(1+\beta_o) i_b = \frac{v_e}{R_E} - \frac{-i_o R_C - v_e}{r_o} = \frac{v_e}{R_E} + \frac{i_o R_C + v_e}{r_o}$$

$$(1+\beta_o) i_b = \frac{v_e}{R_E} + \frac{v_e}{r_o} + \frac{i_o R_C}{r_o}$$

$$i_o = \left[(1+\beta_o) i_b - \left(\frac{1}{R_E} + \frac{1}{r_o}\right) v_e\right] \frac{r_o}{R_C}$$

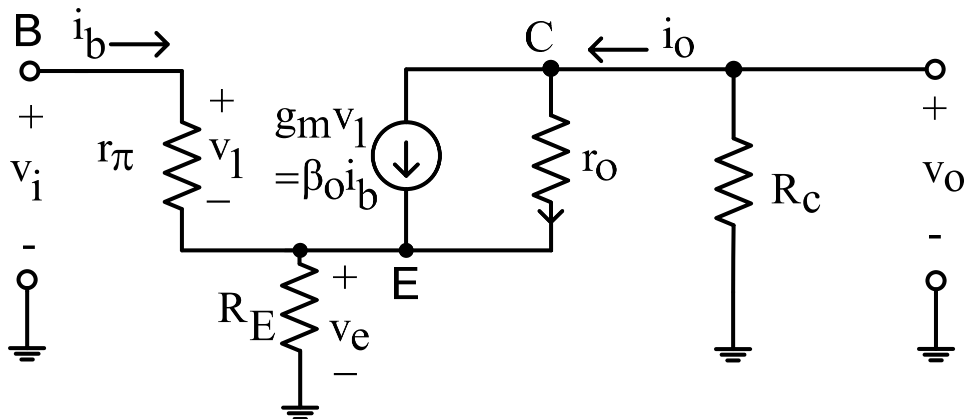


KCL at C:

$$i_o = \beta_o i_b + \frac{v_o - v_e}{r_o} = \beta_o i_b + \frac{-i_o R_C - v_e}{r_o}$$

$$\left[(1+\beta_o)i_b - \left(\frac{1}{R_E} + \frac{1}{r_o}\right)v_e\right]\frac{r_o}{R_C} = \beta_o i_b + \frac{-\left[(1+\beta_o)i_b - \left(\frac{1}{R_E} + \frac{1}{r_o}\right)v_e\right]\frac{r_o}{R_C} R_C - v_e}{r_o}$$

$$v_e = \left[\frac{(1+\beta_o)\frac{r_o}{R_C} + 1}{\frac{r_o}{R_E R_C} + \frac{1}{R_C} + \frac{1}{R_E}}\right] i_b$$



KVL of the input loop: $-v_i + v_1 + v_e = 0$. Thus, $-v_i + i_b r_\pi + v_e = 0$

$$v_i = r_\pi i_b + \left[\frac{(1+\beta_o)\frac{r_o}{R_C}+1}{\frac{r_o}{R_E R_C}+\frac{1}{R_C}+\frac{1}{R_E}}\right] i_b$$

$$R_i = \frac{v_i}{i_b} = r_\pi + \left[\frac{(1+\beta_o)\frac{r_o}{R_C}+1}{\frac{r_o}{R_E R_C}+\frac{1}{R_C}+\frac{1}{R_E}}\right] \leftarrow \text{enough}$$

$$R_i = r_\pi + \frac{R_E R_C\left[1+(1+\beta_o)\frac{r_o}{R_C}\right]}{r_o+R_C+R_E} = r_\pi + \frac{(1+\beta_o)R_E\left[\frac{R_C}{(1+\beta_o)}+r_o\right]}{r_o+R_C+R_E}$$

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$$R_i = r_\pi + \frac{(1+\beta_o)R_E\left[\dfrac{R_C}{(1+\beta_o)} + r_o\right]}{r_o + R_C + R_E}$$

If $r_o >> R_C$ and $r_o >> R_E$ (in the case of $r_o \to \infty$), then

$$R_i = r_\pi + \frac{(1+\beta_o)R_E[r_o]}{r_o} = r_\pi + (1+\beta_o)R_E$$

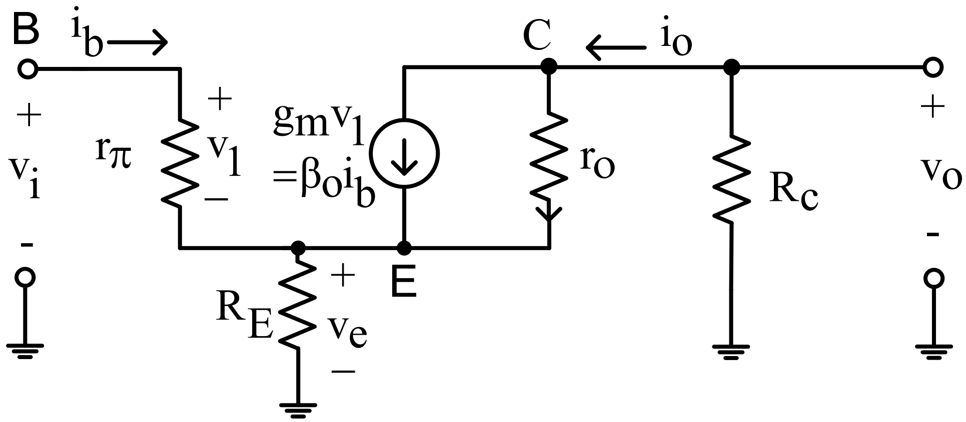
For a finite r_o, $\dfrac{\dfrac{R_C}{(1+\beta_o)} + r_o}{r_o + R_C + R_E} < 1.$

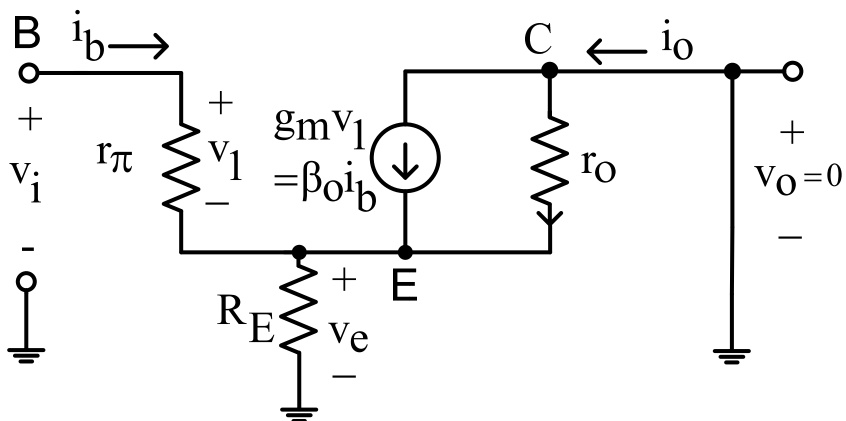
Hence, a finite r_o will reduce the R_i when compared to the R_i when $r_o \to \infty$.

For a CE without degeneration, $R_i = \dfrac{v_i}{i_i} = r_\pi = \dfrac{\beta_o}{g_m}$.

Thus, a CE with degeneration will increase the R_i.

Normally, the R_i for a CE with emitter degeneration is taken as $r_\pi + (1+\beta_o)R_E$





Transconductance,

$$G_m = \left.\frac{i_o}{v_i}\right|_{v_o=0}$$

At node E,

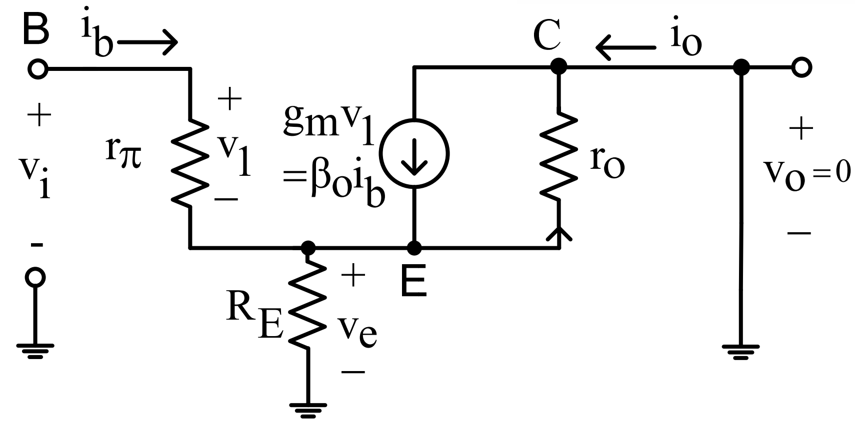
$$i_b + \beta_o i_b = \frac{v_e}{R_E} + \frac{v_e}{r_o}$$

$$(1+\beta_o)\frac{v_i - v_e}{r_\pi} = \left(\frac{1}{R_E} + \frac{1}{r_o}\right) v_e$$

$$v_e = \frac{(1+\beta_o) v_i}{r_\pi \left[\frac{1}{R_E} + \frac{1}{r_o} + \frac{(1+\beta_o)}{r_\pi}\right]}$$

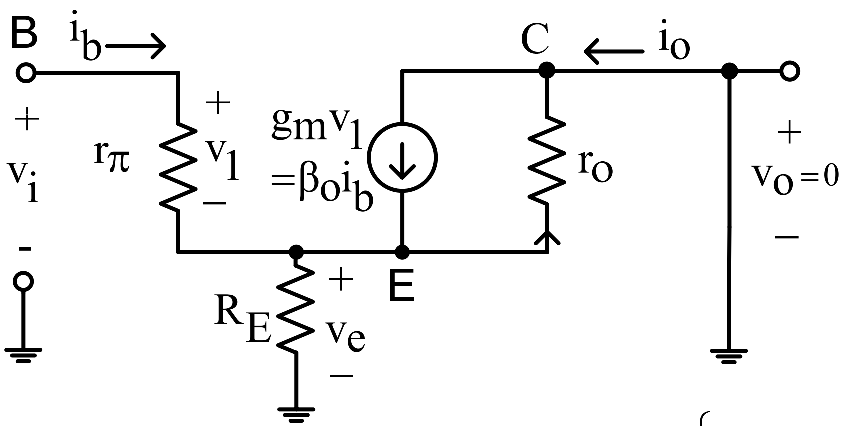
At node C,

$$i_o + \frac{\dfrac{(1+\beta_o)v_i}{r_\pi\left[\dfrac{1}{R_E}+\dfrac{1}{r_o}+\dfrac{(1+\beta_o)}{r_\pi}\right]}}{r_o} = \beta_o i_b$$



$$i_o + \frac{\dfrac{(1+\beta_o)v_i}{r_\pi\left[\dfrac{1}{R_E}+\dfrac{1}{r_o}+\dfrac{(1+\beta_o)}{r_\pi}\right]}}{r_o}$$

$$=\beta_o \frac{\left\{v_i - \dfrac{(1+\beta_o)v_i}{r_\pi\left[\dfrac{1}{R_E}+\dfrac{1}{r_o}+\dfrac{(1+\beta_o)}{r_\pi}\right]}\right\}}{r_\pi} = \beta_o \frac{\left\{1 - \dfrac{(1+\beta_o)}{r_\pi\left[\dfrac{1}{R_E}+\dfrac{1}{r_o}+\dfrac{(1+\beta_o)}{r_\pi}\right]}\right\}v_i}{r_\pi}$$



$$i_o + \frac{\dfrac{(1+\beta_o)v_i}{r_\pi\left[\dfrac{1}{R_E}+\dfrac{1}{r_o}+\dfrac{(1+\beta_o)}{r_\pi}\right]}}{r_o} = \beta_o \frac{\left\{1-\dfrac{(1+\beta_o)}{r_\pi\left[\dfrac{1}{R_E}+\dfrac{1}{r_o}+\dfrac{(1+\beta_o)}{r_\pi}\right]}\right\}v_i}{r_\pi}$$

$$G_m = \left.\frac{i_o}{v_i}\right|_{v_o=0}$$

$$i_o + \frac{(1+\beta_o)v_i}{r_o r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]} = \beta_o \frac{\left\{1-\frac{(1+\beta_o)}{r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}\right\}v_i}{r_\pi}$$

$$i_o = \beta_o \frac{\left\{1-\frac{(1+\beta_o)}{r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}\right\}v_i}{r_\pi} - \frac{(1+\beta_o)v_i}{r_o r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}$$

$$i_o = \left\{ \beta_o \frac{\left\{ 1 - \dfrac{(1+\beta_o)}{r_\pi \left[\dfrac{1}{R_E} + \dfrac{1}{r_o} + \dfrac{(1+\beta_o)}{r_\pi} \right]} \right\}}{r_\pi} - \frac{(1+\beta_o)}{r_o r_\pi \left[\dfrac{1}{R_E} + \dfrac{1}{r_o} + \dfrac{(1+\beta_o)}{r_\pi} \right]} \right\} v_i$$

$$\frac{i_o}{v_i} = \left\{ \frac{\beta_o r_o \left[\frac{1}{R_E} + \frac{1}{r_o} + \frac{(1+\beta_o)}{r_\pi} \right] \left\{ 1 - \frac{(1+\beta_o)}{r_\pi \left[\frac{1}{R_E} + \frac{1}{r_o} + \frac{(1+\beta_o)}{r_\pi} \right]} \right\}}{r_\pi r_o \left[\frac{1}{R_E} + \frac{1}{r_o} + \frac{(1+\beta_o)}{r_\pi} \right]} - \frac{(1+\beta_o)}{r_o r_\pi \left[\frac{1}{R_E} + \frac{1}{r_o} + \frac{(1+\beta_o)}{r_\pi} \right]} \right\}$$

$\rightarrow$ enough

$$\frac{i_o}{v_i}=\left\{\frac{\left\{\beta_o r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]-\frac{\beta_o r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right](1+\beta_o)}{r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}\right\}}{r_\pi r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}-\frac{(1+\beta_o)}{r_o r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}\right\}$$

$$\frac{i_o}{v_i}=\left\{\frac{\left\{\beta_o r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]-\frac{\beta_o r_o(1+\beta_o)}{r_\pi}\right\}}{r_\pi r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}-\frac{(1+\beta_o)}{r_o r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}\right\}$$

$$\frac{i_o}{v_i} = \frac{\beta_o r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]-\frac{\beta_o r_o(1+\beta_o)}{r_\pi}-(1+\beta_o)}{r_o r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}$$

$$\frac{i_o}{v_i} = \frac{\beta_o r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]-\frac{\beta_o r_o(1+\beta_o)}{r_\pi}-(1+\beta_o)}{r_o r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}$$

$$G_m = \frac{g_m r_\pi r_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]-\frac{\beta_o r_o(1+\beta_o)}{r_\pi}-(1+\beta_o)}{r_o r_\pi\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)}{r_\pi}\right]}$$

$$G_m = \frac{g_m\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}\right]-\frac{g_m(1+\beta_o)g_m}{\beta_o}-\frac{g_m}{r_o\beta_o}(1+\beta_o)}{\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}\right]}$$

$$= \frac{g_m\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}-\frac{(1+\beta_o)g_m}{\beta_o}-\frac{1}{r_o\beta_o}(1+\beta_o)\right]}{\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}\right]}$$

$$= \frac{g_m\left[\frac{1}{R_E}+\frac{1}{r_o}-\frac{(1+\beta_o)}{r_o\beta_o}\right]}{\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}\right]}$$

$$G_m = \frac{g_m\left[\frac{1}{R_E}+\frac{1}{r_o}-\frac{(1+\beta_o)}{r_o\beta_o}\right]}{\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}\right]}$$

$$= \frac{g_m\left[\frac{r_o\beta_o}{R_E}+\beta_o-(1+\beta_o)\right]}{r_o\beta_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}\right]}$$

$$= \frac{g_m\left[\frac{r_o\beta_o}{R_E}-1\right]}{r_o\beta_o\left[\frac{1}{R_E}+\frac{1}{r_o}+\frac{(1+\beta_o)g_m}{\beta_o}\right]}$$

$$G_m = \frac{g_m\left[\frac{r_o\beta_o}{R_E} - 1\right]}{\left[\frac{r_o\beta_o}{R_E} + \beta_o + (1+\beta_o)g_m r_o\right]} = \frac{g_m\left[\frac{r_o\beta_o}{R_E} - 1\right]}{\frac{1}{R_E}\left[r_o\beta_o + R_E\beta_o + (1+\beta_o)g_m r_o R_E\right]}$$

$$G_m = \frac{g_m\left[\frac{r_o\beta_o - R_E}{R_E}\right]}{\frac{1}{R_E}\left[r_o\beta_o + R_E\beta_o + (1+\beta_o)g_m r_o R_E\right]} = \frac{g_m\left[r_o\beta_o - R_E\right]}{\left[r_o\beta_o + R_E\beta_o + (1+\beta_o)g_m r_o R_E\right]}$$

$$G_m = \frac{g_m\left[r_o\beta_o - R_E\right]}{r_o\beta_o + R_E\beta_o + g_m r_o R_E + \beta_o g_m r_o R_E} = \frac{g_m\left[r_o\beta_o - R_E\right]}{r_o\beta_o\left(1 + \frac{R_E}{r_o} + \frac{g_m R_E}{\beta_o} + g_m R_E\right)}$$

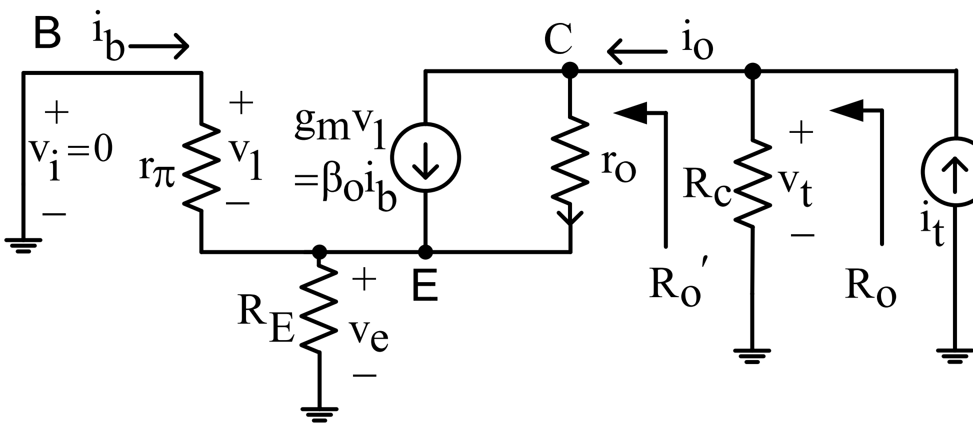
$$G_m = \frac{g_m\left[1 - \frac{R_E}{r_o\beta_o}\right]}{1 + g_m R_E\left(1 + \frac{1}{g_m r_o} + \frac{1}{\beta_o}\right)}$$

$$G_m = \frac{g_m\left[1 - \frac{R_E}{r_o\beta_o}\right]}{1 + g_m R_E\left(1 + \frac{1}{g_m r_o} + \frac{1}{\beta_o}\right)}$$

Practically, $\beta_o >> 1$, $r_o >> R_E$ and $g_m r_o >> 1$

$$G_m = \frac{g_m}{1 + g_m R_E}$$

This expression is often used to calculate the transconductance of the CE with emitter degeneration amplifier. Practically, $G_{m\_CE\_emitter\ degen} < G_{m\_CE}$ as $G_{m\_CE} = g_m$.



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$$R_o = \left.\frac{v_t}{i_t}\right|_{v_i=0} = R_c // R_o'$$

$$v_1 = -i_t\left(r_\pi // R_E\right)$$

$$i_1 = i_t - g_m v_1 = i_t + g_m\left[i_t\left(r_\pi // R_E\right)\right]$$

$$-v_t + i_1 r_o - v_1 = 0$$

$$-v_t + \left[1 + g_m\left(r_\pi // R_E\right)\right] i_t r_o + i_t\left(r_\pi // R_E\right) = 0$$

$$R_o' = \frac{v_t}{i_t} = \left[1 + g_m\left(r_\pi // R_E\right)\right] r_o + \left(r_\pi // R_E\right)$$

$$\left(r_\pi // R_E\right) << \left[1 + g_m\left(r_\pi // R_E\right)\right] r_o$$

$$R_o' = \frac{v_t}{i_t} = \left[1+g_m\left(r_\pi // R_E\right)\right]r_o + \left(r_\pi // R_E\right)$$

$$\left(r_\pi // R_E\right) << \left[1+g_m\left(r_\pi // R_E\right)\right]r_o$$

$$R_o' = \left[1+g_m\left(r_\pi // R_E\right)\right]r_o = \left[1+g_m\frac{r_\pi R_E}{r_\pi+R_E}\right]r_o$$

$$R_o' = \left[1+\frac{g_m R_E}{\frac{1}{r_\pi}\left(r_\pi+R_E\right)}\right]r_o = \left[1+\frac{g_m R_E}{1+\frac{R_E}{r_\pi}}\right]r_o = \left[1+\frac{g_m R_E}{1+\frac{g_m R_E}{\beta_o}}\right]r_o$$

If $g_m R_E << \beta_o, R_o' = \left[1+g_m R_E\right]r_o$

$$R_o = R_c // \left[1+g_m R_E\right]r_o$$

If $g_m R_E >> \beta_o, R_o' = \left[1+\frac{g_m R_E}{\frac{g_m R_E}{\beta_o}}\right]r_o = \left[1+\beta_o\right]r_o$

$$R_o' = \left[1+\frac{g_m R_E}{\frac{g_m R_E}{\beta_o}}\right]r_o = \left[1+\beta_o\right]r_o.$$

$R_{o\_CE} = R_c // r_o.$ $R_{o\_CE\_degen} > R_{o\_CE}.$

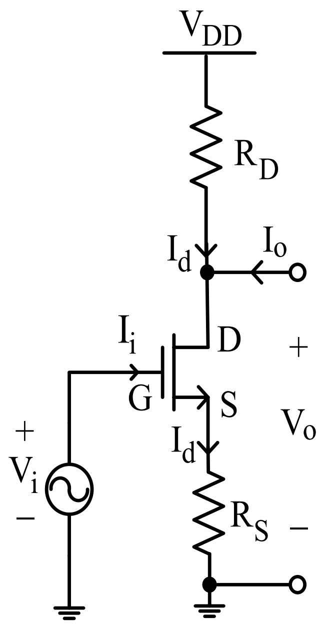
CS with Source Degeneration

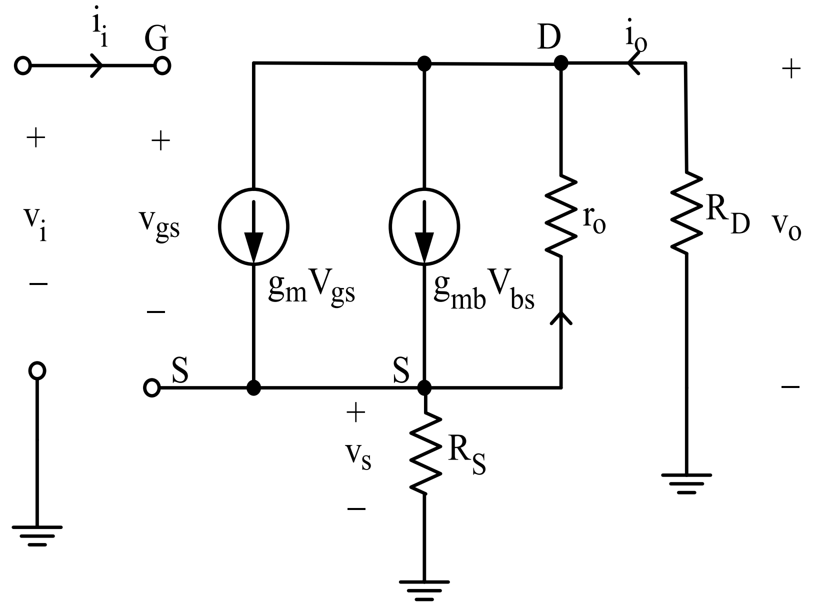
CS with S degeneration is not as typically implemented as the CE with E degeneration. The reasons are:

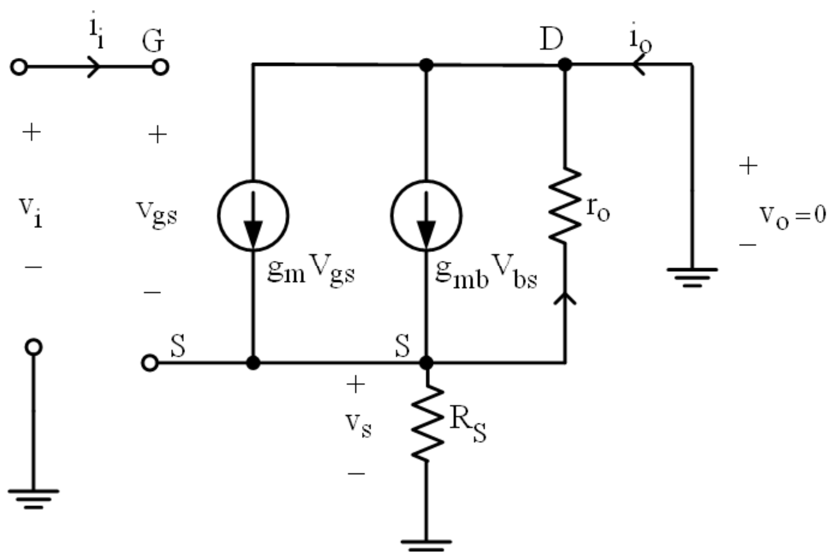
1. The transconductance of the MOS is far less than the transconductance of the BJT. When implementing S degeneration, the transconductance of the MOS will be reduced. This condition is undesired.
2. With E degeneration, R_i in CE is increased. However, $R_i \rightarrow \infty$ in the case of CS even without degeneration. Hence, the need for the degeneration circuit is not crucial.

CS with S degeneration is sometimes implemented to increase the R_o of the MOS.

CS with Source Degeneration







$$R_i = \frac{v_i}{i_i} = \infty$$

Now, S is not at ac gnd. Thus, $v_{bs} \neq 0$. g_{mb} generator cannot be omitted.

$$G_m = \left.\frac{i_o}{v_i}\right|_{v_o=0}$$

$$v_b = 0,\ v_{bs} = -v_s$$

KCL at S when $v_o = 0$:

$$g_m v_{gs} - g_{mb} v_s = \frac{v_s}{r_o} + \frac{v_s}{R_s}$$

$$g_m(v_i - v_s) - g_{mb} v_s = \frac{v_s}{r_o} + \frac{v_s}{R_s}$$

$$g_m v_i = \frac{v_s}{r_o} + \frac{v_s}{R_s} + g_m v_s + g_{mb} v_s$$

$$g_m v_i = v_s\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}\right)$$

$$g_m v_i = v_s\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}\right)$$

$$v_s = \frac{g_m v_i}{\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}\right)}$$

$$G_m = \left.\frac{i_o}{v_i}\right|_{v_o=0}$$

$$v_b = 0,\ v_{bs} = -v_s$$

KCL at D when $v_o = 0$:

$$g_m v_{gs} - g_{mb} v_s = \frac{v_s}{r_o} + i_o$$

Therefore,

$$g_m\left\{v_i - \left[\frac{g_m v_i}{\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}\right)}\right]\right\} - g_{mb}\left[\frac{g_m v_i}{\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}\right)}\right]$$

$$= \frac{\left[\frac{g_m v_i}{\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}\right)}\right]}{r_o} + i_o$$

$$g_m\left\{v_i-\left[\frac{g_m v_i}{\left(g_m+g_{mb}+\frac{1}{r_o}+\frac{1}{R_s}\right)}\right]\right\}-g_{mb}\left[\frac{g_m v_i}{\left(g_m+g_{mb}+\frac{1}{r_o}+\frac{1}{R_s}\right)}\right]$$

$$-\frac{\left[\frac{g_m v_i}{\left(g_m+g_{mb}+\frac{1}{r_o}+\frac{1}{R_s}\right)}\right]}{r_o}=i_o$$

$$i_o=v_i\left\{\begin{array}{l} g_m\left\{1-\left[\frac{g_m}{\left(g_m+g_{mb}+\frac{1}{r_o}+\frac{1}{R_s}\right)}\right]\right\}-\frac{g_{mb}g_m}{\left(g_m+g_{mb}+\frac{1}{r_o}+\frac{1}{R_s}\right)} \\ -\frac{g_m}{r_o\left(g_m+g_{mb}+\frac{1}{r_o}+\frac{1}{R_s}\right)} \end{array}\right\}$$

$$G_m = \frac{i_o}{v_i} = \left\{ \begin{aligned} & g_m \left\{ \frac{g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}}{g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}} - \left[\frac{g_m}{\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s} \right)} \right] \right\} - \frac{g_{mb} g_m}{\left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s} \right)} \\ & - \frac{g_m}{r_o \left(g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s} \right)} \end{aligned} \right\}$$

$$G_m = \left\{ g_m \left\{ \frac{g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s} - g_m - g_{mb} - \frac{1}{r_o}}{g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}} \right\} \right\}$$

$$G_m = \left\{ g_m \left[\frac{\frac{1}{R_s}}{g_m + g_{mb} + \frac{1}{r_o} + \frac{1}{R_s}} \right] \right\} = \frac{g_m}{R_s (g_m + g_{mb}) + \frac{R_s}{r_o} + 1}$$

$$G_m = \frac{g_m}{R_s(g_m+g_{mb})+\frac{R_s}{r_o}+1}$$

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$$\text{If } r_o >> R_s, G_m = \frac{g_m}{R_s(g_m+g_{mb})+1}$$

$$\text{If } R_s \text{ is large}, G_m = \frac{g_m}{R_s(g_m+g_{mb})} = \frac{1}{R_s\left(1+\frac{g_{mb}}{g_m}\right)} = \frac{1}{R_s(1+\chi)}$$

$$\chi = 0.1 \rightarrow 0.3$$

Without S degeneration, $G_m = g_m$. This shows that with source degeneration, G_m has reduced. $G_{m\_CS\_degen} < G_{m\_CS}$.

$$G_{m\_CS\_degen} = \frac{1}{R_s(1+\chi)} \text{ and } G_{m\_CE\_degen} = \frac{g_m\left[1-\frac{R_E}{r_o\beta_o}\right]}{1+g_m R_E\left(1+\frac{1}{g_m r_o}+\frac{1}{\beta_o}\right)}$$

$$\text{If } r_o >> R_E, \text{ and } R_E >> 1, \text{ then}$$

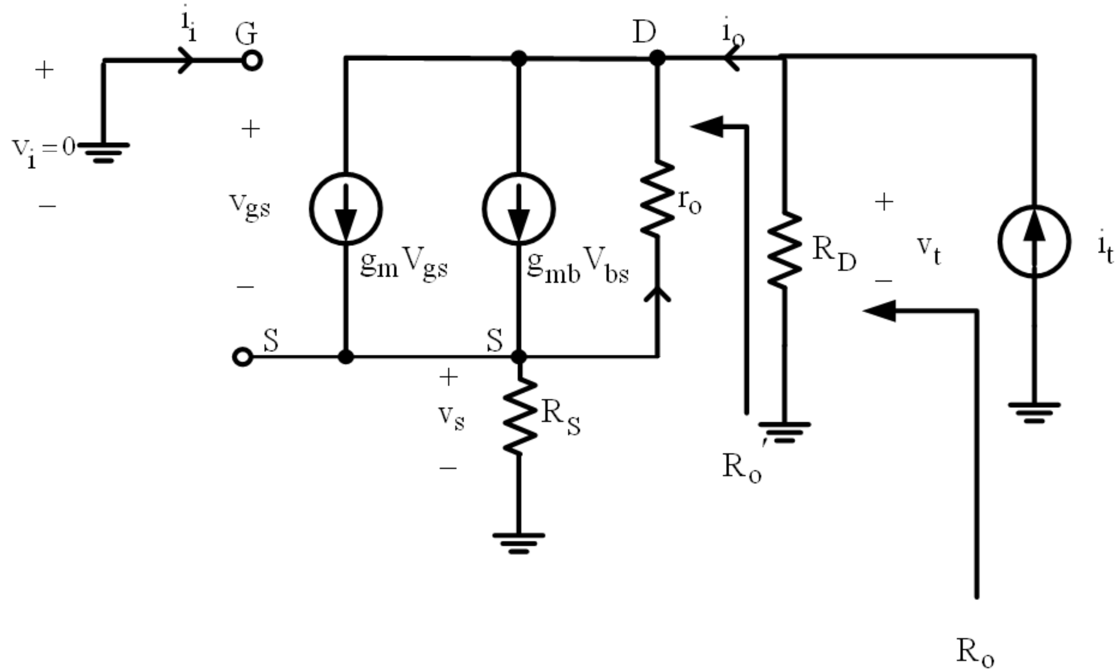
$$G_{m\_CE\_degen} = \frac{1}{R_E\left(1+\frac{1}{\beta_o}\right)} = \frac{\beta_o}{R_E(1+\beta_o)}$$

$$G_{m\_CS\_degen} = \frac{1}{R_S(1+\chi)}$$

$$G_{m\_CE\_degen} = \frac{1}{R_E\left(1+\frac{1}{\beta_o}\right)} = \frac{\beta_o}{R_E(1+\beta_o)}$$

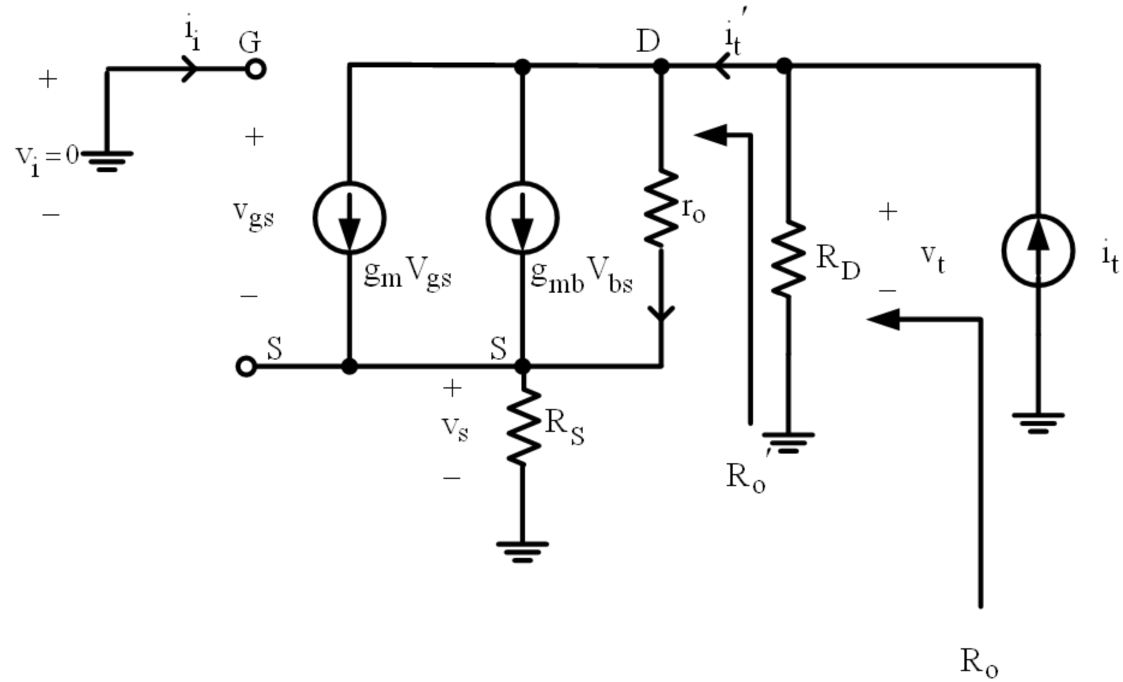
This shows that the G_m of the CS with S degeneration is more dependent on the device parameter when compared to the G_m of the CE with E degeneration.

$$R_o = \left.\frac{v_t}{i_t}\right|_{v_i=0}$$



$$R_o = \left.\frac{v_t}{i_t}\right|_{v_i=0}, R_o{}' = \left.\frac{v_t}{i_t{}'}\right|_{v_i=0}$$

$$v_{gs} = -v_s$$



KCL at node D:

$$i_t{}' = -g_{mb}v_s - g_m v_s + \frac{v_t - v_s}{r_o}$$

KCL at node S:

$$\frac{v_s}{R_s} + g_{mb}v_s + g_m v_s + \frac{v_s}{r_o} = \frac{v_t}{r_o}$$

$$v_s = \frac{v_t}{\left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right)r_o}$$

$$i_t{}' = -g_{mb}v_s - g_m v_s - \frac{v_s}{r_o} + \frac{v_t}{r_o}$$

$$= \left[\frac{\left(-g_{mb} - g_m - \frac{1}{r_o}\right)}{\left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right)r_o} + \frac{1}{r_o}\right]v_t$$

$$i_t' = -g_{mb}v_s - g_m v_s - \frac{v_s}{r_o} + \frac{v_t}{r_o}$$

$$= \left[\frac{\left(-g_{mb} - g_m - \frac{1}{r_o}\right)}{\left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right) r_o} + \frac{1}{r_o} \right] v_t$$

$$R_o' = \frac{v_t}{i_t'} = \frac{1}{\left[\frac{\left(-g_{mb} - g_m - \frac{1}{r_o}\right)}{\left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right) r_o} + \frac{1}{r_o} \right]} = \frac{1}{\left[\frac{\left(-g_{mb} - g_m - \frac{1}{r_o}\right) + \left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right)}{\left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right) r_o} \right]}$$

$$R_o' = \frac{1}{\left[\frac{\frac{1}{R_s}}{\left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right) r_o} \right]} = \frac{1}{\left[\frac{1}{R_s\left(\frac{1}{R_s} + g_{mb} + g_m + \frac{1}{r_o}\right) r_o} \right]} = r_o + r_o R_s g_{mb} + r_o R_s g_m + R_s$$

$$R_o' = r_o\left(1 + R_s\left(g_{mb} + g_m\right)\right) + R_s$$

$$R_o' = r_o\left(1 + R_s\left(g_{mb} + g_m\right)\right) + R_s$$

If $R_s \uparrow$, R_o' will also $\uparrow$.

For the CE with E degeneration:

$$R_o' = \left[1 + \beta_o\right] r_o.$$

Even though $R_E \to \infty$, R_o' will be limited to its maximum value of $r_o(1+ \beta_o)$.