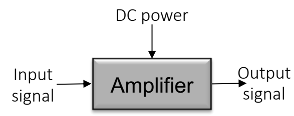
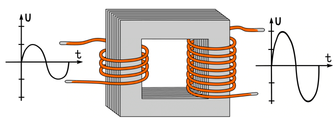
An Amplifier



- Voltage gain, $A_v = \dfrac{output\ voltage}{input\ voltage} = \dfrac{v_o}{v_{in}}$
- Current gain, $A_i = \dfrac{output\ current}{input\ current} = \dfrac{i_o}{i_{in}}$
- Power gain, $A_p = A_v \times A_i$

since $P = VI$

- Additional power is supplied by the DC source; conservation of energy



- A step-up transformer is not a voltage amplifier
- There is no power gain
- $V_p \times I_p = V_s \times I_s$

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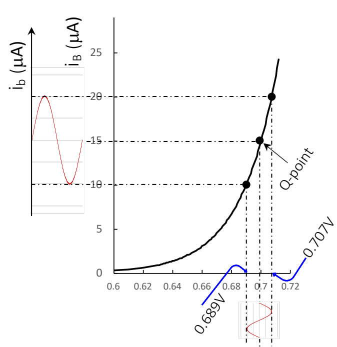
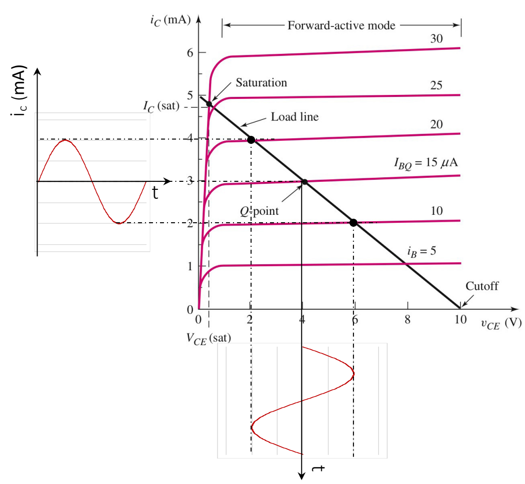
Transistor as an Amplifier: Graphical Illustration





$$A_i = \frac{(4-2)\times 10^{-3}}{(20-10)\times 10^{-6}} = 200 = \beta$$

$$A_v = \frac{(2-6)}{(0.707-0.689)} = -222$$

$$A_p = |A_v| \times |A_i| = 44{,}400$$

- A CE amplifier provides enormous power gain
- The negative voltage gain indicates 180° phase difference between input and output voltages

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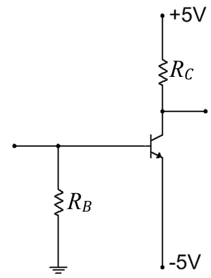
Coupling Capacitors



- You wanted to design an audio amplifier, where the operating point had to be almost at the middle of the load-line
- You obtained $R_C = 2\ k\Omega$ and $R_B = 200\ k\Omega$, where it was given that $\beta = 100$

Without any signal and load being connected to this amplifier, the operating point was set to

$$I_B = \frac{(5-0.7)}{200\times10^3}$$

$$\boxed{I_B = 21.5\ \mu A}$$

$$I_C = \beta I_B$$

$$\boxed{I_C = 2.15\ mA}$$

$$V_{CE} = 5-(-5)+I_C R_C$$

$$\boxed{V_{CE} = 5.7\ V}$$

Perfect design-great job!

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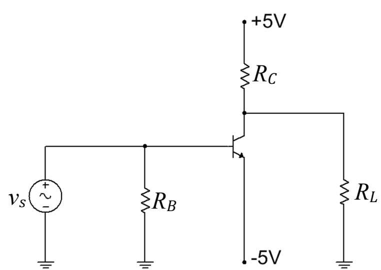
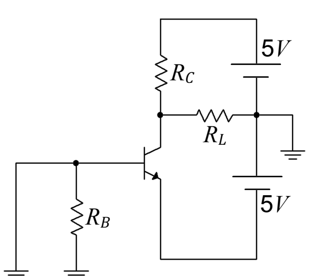
Coupling Capacitors (Continued …)



- Now connect a very low-impedance (assume zero) microphone to the amplifier input with v_s input voltage
- Also, connect an 8 Ω speaker at the output (assume $R_L \approx 0$)
- The DC equivalent circuit will become as shown in the left-bottom corner



With the mic and speaker connected, the Q-point will change to

$V_{BE} = 0$ $\boxed{I_B = 0}$ $\boxed{I_C = 0}$

$V_C = 5\times\frac{R_L}{R_C+R_L} = 0.02\ V$ $\boxed{V_C \approx 0}$

The biasing is completely lost, and the Q-point is set to cut-off!

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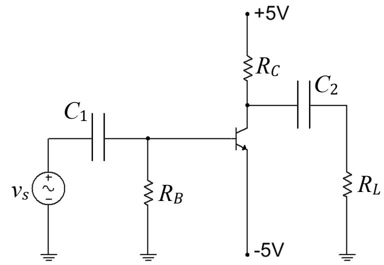
Voltage division

Coupling Capacitors (Continued …)



Question: How to apply input signal and connect a load without changing transistor biasing or Q-point?

Eureka!! We have capacitors, which is an open circuit for DC, but for a suitable selection it becomes a short circuit for the signal.

Recall that $Z_C = \dfrac{1}{2\pi f C}$

impedence

The coupling capacitors:

- keep the DC biasing unchanged
- create an almost shorted path for the AC signal

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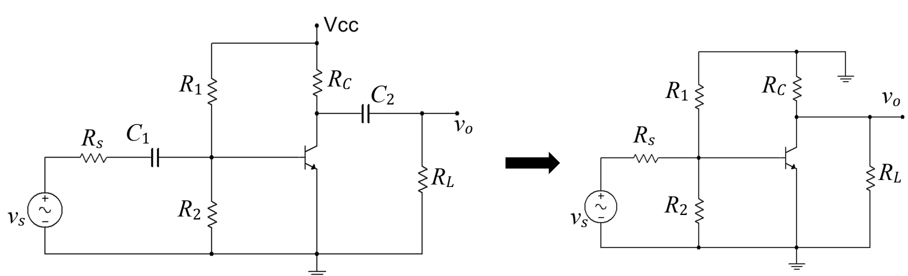
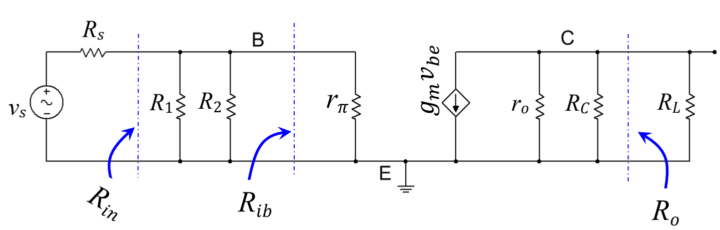
Small-Signal Analysis of a CE Amplifier



Given CE amplifier
(R_s = signal resistance)

AC equivalent circuit of the CE amplifier



Small-signal π-model

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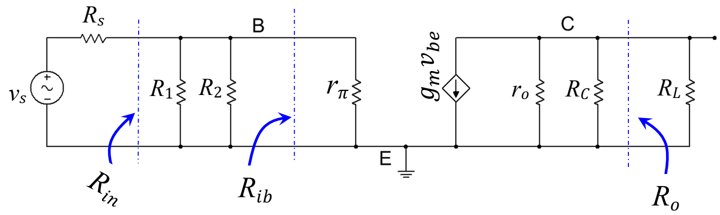
Small-Signal Analysis of a CE Amplifier: Input Resistance



Input resistance at the base, R_{ib}, is

$$\boxed{R_{ib} = r_\pi}$$

Input resistance seen by the source, R_{in}, is

$$R_{in} = R_1||R_2||R_{ib}$$

or, $$\boxed{R_{in} = R_B||R_{ib}}$$

Where, $R_B = R_1||R_2$

Note

- $R_{in} < r_\pi$
- If $R_B \gg r_\pi$, $R_{in} \approx r_\pi$
- The input resistance of a CE amplifier without emitter resistor (R_E) is low

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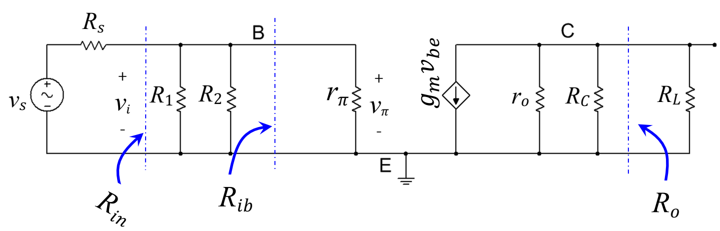
Small-Signal Analysis of a CE Amplifier: Input Voltage

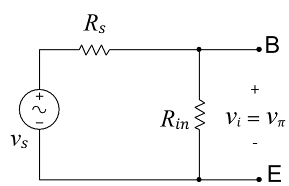


Input voltage at the base is

$$v_i = v_\pi = v_{be} = v_{in} \neq v_s$$

$$v_i = v_s \frac{R_{in}}{R_{in} + R_s}$$

or, $$v_i \approx v_s \frac{r_\pi}{r_\pi + R_s}$$ [If $R_B \gg r_\pi$]



What would you expect in your design, higher R_S or lower R_S?

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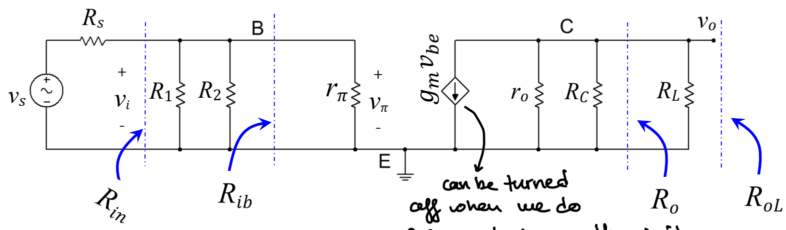
Small-Signal Analysis of a CE Amplifier: Output Resistance



can be turned off when we do A.C. analysis, eventhough it is a dependent source, because we know it's internal Resistance

Output resistance R_o is

$$R_o = R_C || r_o$$

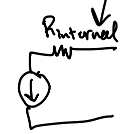
Typically, $r_o \gg R_C$, which gives

$$R_o \approx R_C$$

Output resistance R_{oL} is

$$R_{oL} = R_o || R_L$$

Thus, $R_{oL} < R_o$



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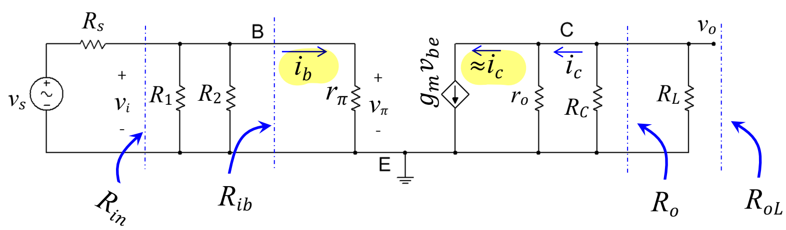
Small-Signal Analysis of a CE Amplifier: Current Gain



Current gain A_i is

$$A_i = \frac{i_c}{i_b} \approx \frac{g_m v_{be}}{\left(\frac{v_\pi}{r_\pi}\right)}$$

or, $A_i = g_m r_\pi$ [Since $v_{be} = v_\pi$]

But $r_\pi = \frac{V_T}{I_B} = \frac{V_T \beta}{I_C} = \frac{\beta}{g_m}$

or, $r_\pi g_m = \beta$

Thus, we can write,

$$\boxed{A_i = \beta}$$

Therefore β is called common-emitter current gain, this is an inherent parameter.

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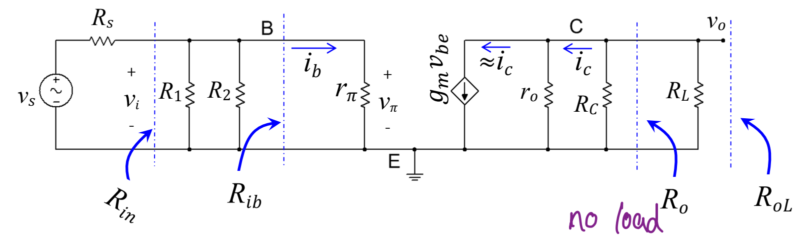
Small-Signal Analysis of a CE Amplifier: Voltage Gain



Voltage gain A_v is

$$A_v = \frac{v_o}{v_i} = \frac{v_o}{v_\pi}$$

why?

or, $A_v = \dfrac{-(g_m v_\pi)(r_o||R_C||R_L)}{v_\pi}$

or, $A_v = -g_m\ (r_o||R_C||R_L) = -g_m R_{oL}$

The negative sign indicates
180° phase difference in CE amp

The open circuit voltage gain is

$A_{vo} = -g_m\ (r_o||R_C) = -g_m R_o$

- If $r_o \gg R_C$

  $A_{vo} \approx -g_m R_C$
- Lower value of V_A (r_o) reduces the voltage gain

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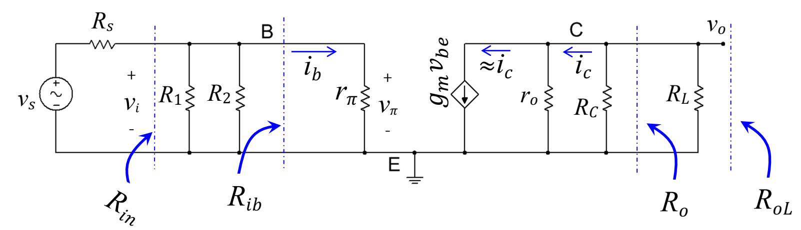
Small-Signal Analysis of a CE Amplifier: Voltage Gain (continued ...)



The voltage gain with load R_L is

or, $A_v = -g_m\ (r_o||R_C||R_L)$

or, $A_v = -g_m\ (R_C||R_L)$

or, $A_v = -g_m R_o \dfrac{R_L}{R_o + R_L}$

or, $\boxed{A_v = A_{vo} \dfrac{R_L}{R_o + R_L}}$

A load can significantly reduce the voltage gain

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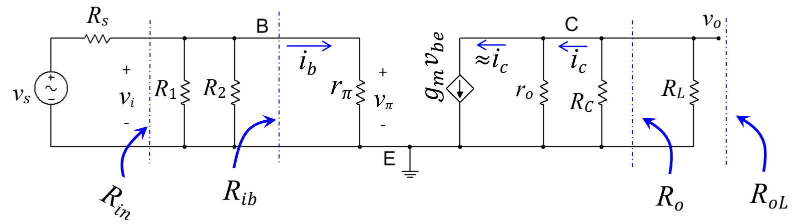
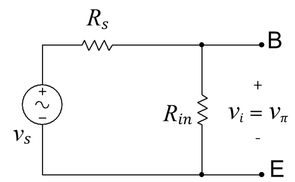
Small-Signal Analysis of a CE Amplifier: Effect of Source Resistance



We have just obtained voltage gain using the definition

$$A_v = \frac{v_o}{v_i} = \frac{v_o}{v_\pi}$$

Notice that the actual input signal is v_s, where v_i is the signal that appears at the base.



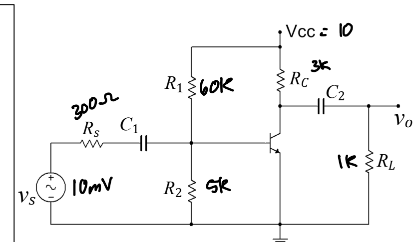
and, $v_i = v_s \dfrac{R_{in}}{R_{in} + R_s}$

Thus, the overall voltage gain is further dropped by source resistance

Small-Signal Analysis: CE Amplifier Example

Example: In the given circuit, $V_{CC} = 10$ V, $R_1 = 60$ kΩ, $R_2 = 5$ kΩ, $R_C = 3$ kΩ, $R_L = 1$ kΩ, $R_s = 300$ Ω, $v_s = 10$ mV, $\beta = 100$, and $V_A = 80$ V. Determine:

a) Small-signal parameters
b) Signal voltage at the base
c) Voltage gain without load
d) Voltage gain with load
e) Output voltage



Soln:

In order to determine the small-signal parameters, DC analysis is required

DC analysis

$I_{R2} = V_{BE(on)}/R_2$

$I_{R2} = 0.7/5\text{x}10^3$

$I_{R2} = 140\ \mu A$

$I_{R1} = [V_{CC}\text{-}V_{BE(on)}]/R_1$

$I_{R1} = (10\text{-}0.7)/60\text{x}10^3$

$I_{R1} = 155\ \mu A$

$I_B = I_{R1} - I_{R2}$

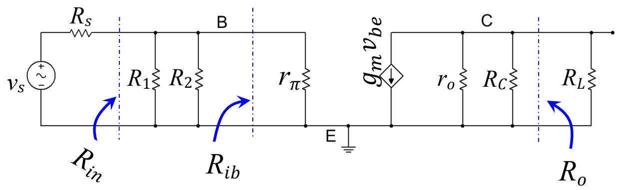
$I_B = 15\ \mu A$

$I_C = \beta \times I_B = 1.50$ mA

$I_E = (\beta+1) I_B = 1.52$ mA

Small-Signal Analysis: CE Amplifier Example (Continued …)

Given: $V_{CC} = 10$ V, $R_1 = 60$ kΩ, $R_2 = 5$ kΩ, $R_C = 3$ kΩ, $R_L = 1$ kΩ $R_s = 300$ Ω, $v_s = 10$ mV, $\beta = 100$, and $V_A = 80$ V



Solution to part (a): small-signal parameters

$r_\pi = V_T/I_B$

$r_\pi = 25\text{x}10^{-3}/15\text{x}10^{-6}$

$r_\pi = 1.67\ \text{k}\Omega$

$r_o = V_A/I_C$

$r_o = 80/1.5\text{x}10^{-3}$

$r_o = 53.3\ \text{k}\Omega$

$g_m = I_C/V_T$

$g_m = 1.5\text{x}10^{-3}/25\text{x}10^{-3}$

$g_m = 60\ \text{mA/V}$

$r_e = V_T/I_E$

$r_e = 25\text{x}10^{-3}/1.52\text{x}10^{-3}$

$r_e = 16.45\ \Omega$

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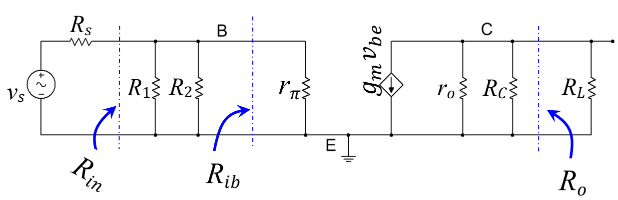
Small-Signal Analysis: CE Amplifier Example (Continued …)

Given: $V_{CC} = 10$ V, $R_1 = 60$ kΩ, $R_2 = 5$ kΩ, $R_C = 3$ kΩ, $R_L = 1$ kΩ $R_s = 300$ Ω, $v_s = 10$ mV, $\beta = 100$, and $V_A = 80$ V



Solution to part (b): signal voltage at the base

$$v_\pi = v_{be} = v_{ib} = v_s \frac{R_{in}}{R_{in} + R_s}$$

or, $$v_{ib} = 10\times10^{-3}\times\frac{(60\,//\,5\,//\,1.67)\times10^3}{300 + (60\,//\,5\,//\,1.67)\times10^3}$$

or, $$v_{ib} = 10\times10^{-3}\times\frac{1226}{300 + 1226}$$

or, $$v_{ib} = 10\times10^{-3}\times\mathbf{0.803} = 8.03\ mV$$

Notice that only 80.3% of the input signal appears at the base. This is only because of R_s.

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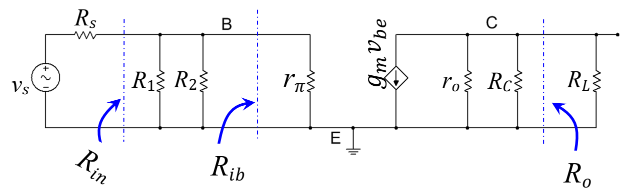
Small-Signal Analysis: CE Amplifier Example (Continued ...)

Given: $V_{CC} = 10$ V, $R_1 = 60$ kΩ, $R_2 = 5$ kΩ, $R_C = 3$ kΩ, $R_L = 1$ kΩ $R_s = 300$ Ω, $v_s = 10$ mV, $\beta = 100$, and $V_A = 80$ V



Solution to part (c): no-load voltage gain

$$A_{vo} = -g_m (r_o // R_C)$$

or, $$A_{vo} = -60\times10^{-3}\times\frac{53.3\times3\times10^6}{(53.3+3)\times10^3}$$

or, $$A_{vo} = 60\times10^{-3}\times\mathbf{0.947}\times3\times10^3$$

or, $\boxed{A_{vo} = -170.5}$ or, $\boxed{|A_{vo}| = 170.5}$

- Had we ignored r_o ($r_o=\infty$), the voltage gain would have been **180**.
- The no load gain has dropped by a factor 0.947 because of considering r_o.
- Had we had $R_C = 1$ kΩ, the voltage gain would have been three times lower, i.e., $|A_{vo}| = 56.8$

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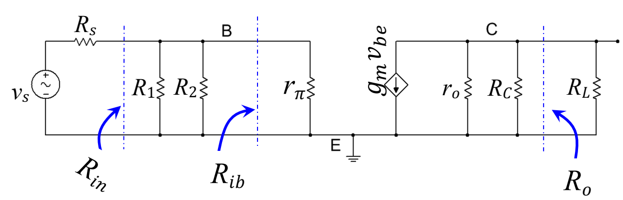
Small-Signal Analysis: CE Amplifier Example (Continued ...)

Given: $V_{CC} = 10$ V, $R_1 = 60$ kΩ, $R_2 = 5$ kΩ, $R_C = 3$ kΩ, $R_L = 1$ kΩ $R_s = 300$ Ω, $v_s = 10$ mV, $\beta = 100$, and $V_A = 80$ V



Solution to part (d): voltage gain with load

$$A_v = -g_m (r_o // R_C // R_L)$$

or, $$A_v = -60\times10^{-3}\times(53.3 // 3 // 1)\times10^3$$

or, $$A_v = 60\times10^{-3}\times739.6$$

or, $\boxed{A_v = -44.4}$ or, $\boxed{|A_v| = 44.4}$

- Had we ignored r_o ($r_o=\infty$), the voltage gain would have been **45**.
- That would have been only 1.4% error.
- Had we had $R_C = 1$ kΩ, the voltage gain would have been $|A_v| = 29.7$ instead of 44.4.

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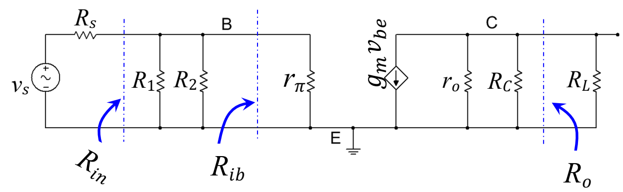
Small-Signal Analysis: CE Amplifier Example (Continued ...)

Given: $V_{CC} = 10$ V, $R_1 = 60$ kΩ, $R_2 = 5$ kΩ, $R_C = 3$ kΩ, $R_L = 1$ kΩ $R_s = 300$ Ω, $v_s = 10$ mV, $\beta = 100$, and $V_A = 80$ V



Solution to part (e): Output voltage

The output voltage without load is

$$v_o = A_{vo} \times v_{ib}$$

or, $v_o = -170.5 \times 8.03 \times 10^{-3}$

or, $v_o = -1.37\ V$

or, $\boxed{|v_o| = 1.37\ V}$

The output voltage with load is

$$v_o = A_v \times v_{ib}$$

or, $v_{oL} = -44.4 \times 8.03 \times 10^{-3}$

or, $v_o = -356.5\ mV$

or, $\boxed{|v_o| = 0.357\ V}$

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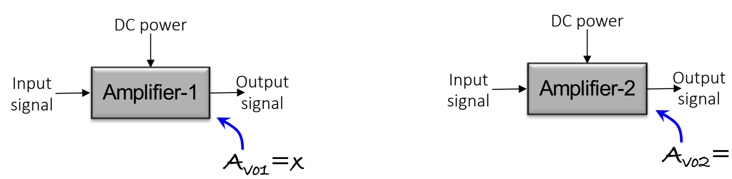
Small-Signal Analysis of a CE Amplifier: Voltage Gain (continued ...)



$$A_{v,12} = \frac{v_{o2}}{v_{i1}} = \frac{v_{o2}}{v_{01}} \times \frac{v_{o1}}{v_{i1}} = A_{vo1} \times A_{vo2} = xy$$

Is this valid?

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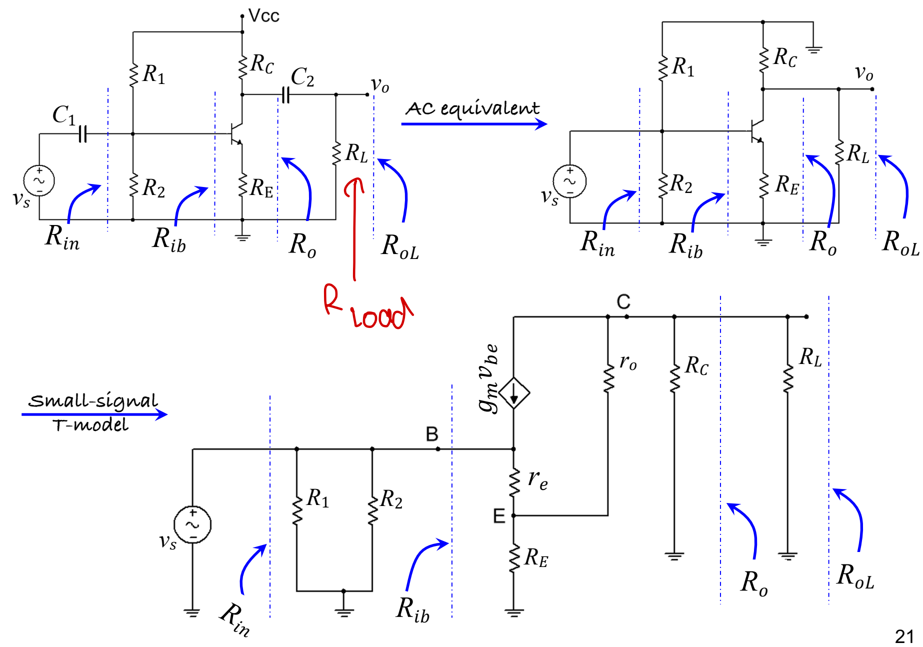
Quiz 2, ends here

Small-Signal Analysis of a CE Amplifier With Emitter Resistor R_E



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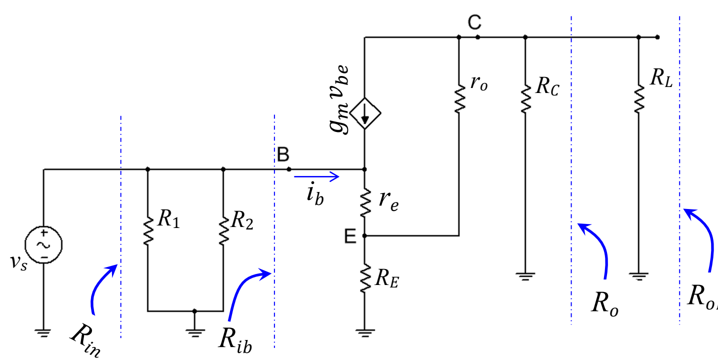
CE Amplifier With Emitter Resistor R_E: Input Resistance



Input resistance at the base is

$$R_{ib} = \frac{v_b}{i_b}$$

or, $R_{ib} = \dfrac{(\beta + 1)v_b}{i_e}$

[Since $i_e = (\beta + 1)i_b$]

Typically $r_o \gg (r_e$ and $R_E)$

Setting $r_o = \infty$ we have,

$$R_{ib} = (\beta + 1)(r_e + R_E)$$

Notice how the factor $(\beta+1)$ is introduced in the input resistance. We'll use it frequently.

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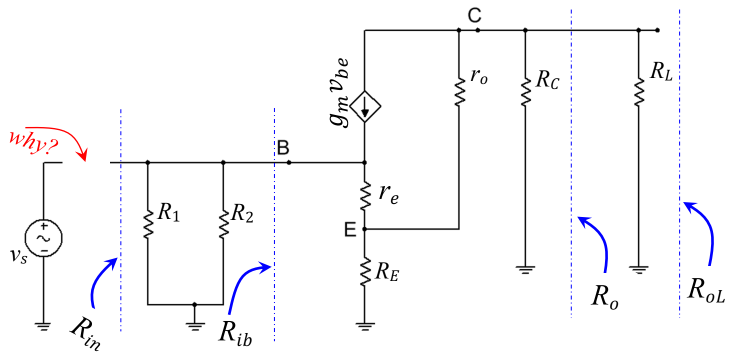
CE Amplifier With Emitter Resistor R_E: Output Resistance



Output resistance R_o is

$$R_o = R_C || \left[r_o + \left\{ R_E || \left(r_e + \frac{R_1 || R_2}{\beta + 1} \right) \right\} \right]$$

Where would R_S go in this equation if it was not ignored?

If $r_o \gg (r_e$ and $R_E)$

Setting $r_o = \infty$ we have,

$$R_o = R_C$$

and $R_{oL} = R_o || R_L$

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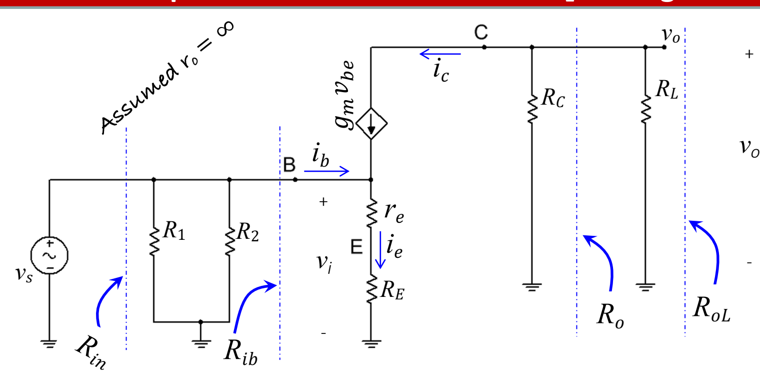
we have this because we are not adding Resistors that have same Current passing through, $R_1||R_2$ have i_b rest have i_e or derivations of i_e

CE Amplifier With Emitter Resistor R_E: Voltage Gain



The voltage gain A_v is

$$A_v = \frac{v_o}{v_i} = \frac{-i_c (R_C || R_L)}{i_e (r_e + R_E)}$$

or, $$A_v = \frac{-\alpha (R_C || R_L)}{(r_e + R_E)} \; \ldots \ldots \ldots (1)$$

or, $$A_v = -\frac{\alpha}{r_e} \times \frac{(R_C || R_L)}{\left(1 + \frac{1}{r_e} \times R_E\right)}$$

using $g_m = \frac{\alpha}{r_e} \cong \frac{1}{r_e}$ we have,

$$A_v \cong -\frac{g_m (R_C || R_L)}{(1 + g_m R_E)}$$

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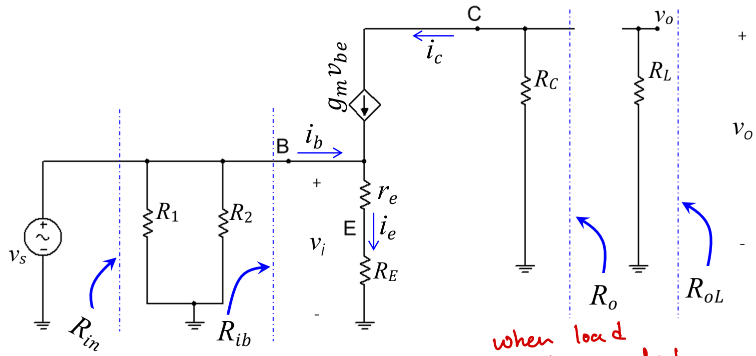
CE Amplifier With Emitter Resistor R_E: No-Load Voltage Gain



The no-load voltage gain A_{vo} is

$$A_{vo} \cong -\frac{g_m R_C}{(1 + g_m R_E)}$$

The voltage gain is reduced by a factor $(1+g_m R_E)$.
What if $R_E = 0$?

when load is not connected
For open circuit, eq (1) becomes

$$A_{vo} \cong -\frac{R_C}{r_e + R_E}$$

or, $A_{vo} = \frac{\text{Total resistance in the collector}}{\text{Total resistance in the emitter}}$

used when modelling Resistors

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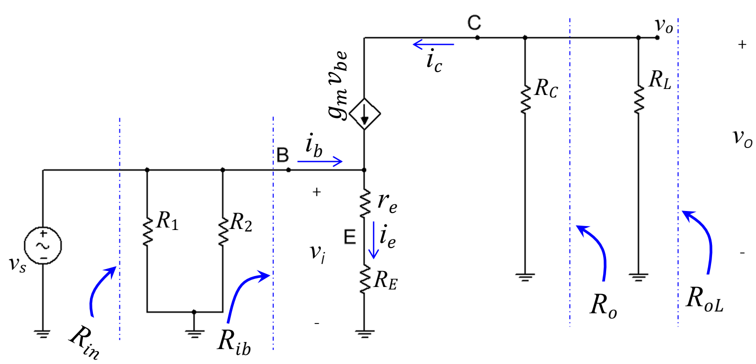
CE Amplifier With Emitter Resistor R_E: Current Gain



The current gain remains the same, i.e.

$$A_i = \beta$$

} Regardless of whether $R_E > 0$ or $= 0$

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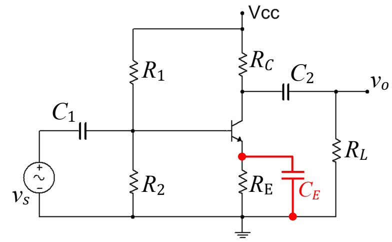
CE Amplifier With Emitter Resistor R_E: Bypass Capacitor

We have learned that the voltage gain of this circuit drops by a factor $(1+g_m R_E)$. Why do we use the emitter resistor, R_E?



R_E provides thermal stability – How?

- If I_C increases because of temp
- V_{RE} will increases
- Increase of V_{RE} will reduces V_{BE}
- The reduced V_{BE} will lower I_B
- The reduced I_B will lower I_C
- This is called negative feedback

How can we take the advantage of this thermal stability without loosing voltage gain?

Let the signal bypass RE but make the DC biasing current flow through R_E by using a capacitor. This capacitor is called emitter bypass capacitor.

Now, $A_v = -g_m(R_C||R_L)$

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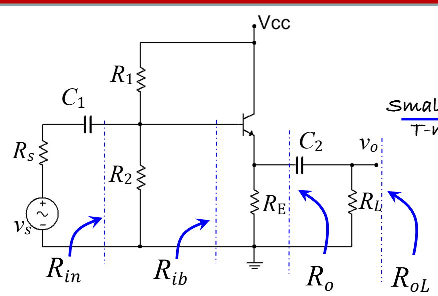
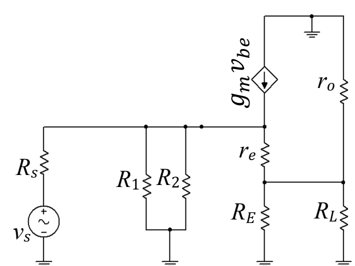
Small-Signal Analysis of a CC Amplifier

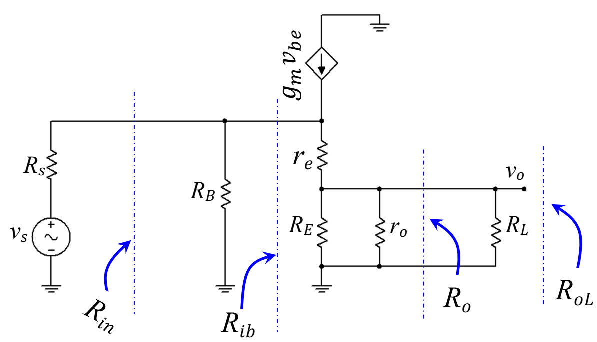


Small-signal T-model



Small-signal T-model

$R_B = R_1||R_2$



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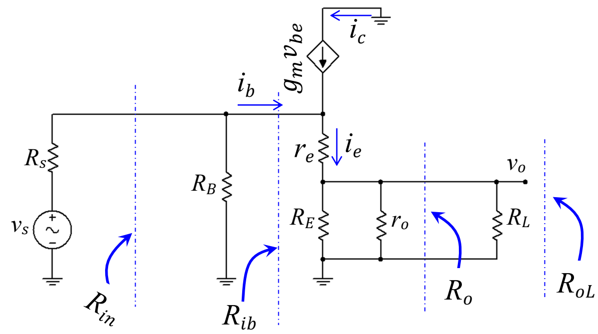
Small-Signal Analysis of a CC Amplifier: Input Resistance



Input resistance at the base is

$$R_{ib} = \frac{v_b}{i_b}$$

or, $R_{ib} = \dfrac{(\beta+1)v_b}{i_e}$

Here, $\dfrac{v_b}{i_e} = r_e + (R_E||r_o||R_L)$

Thus, $R_{ib} = (\beta+1)[r_e + (R_E||r_o||R_L)]$

Also, $R_{in} = R_B||R_{ib}$

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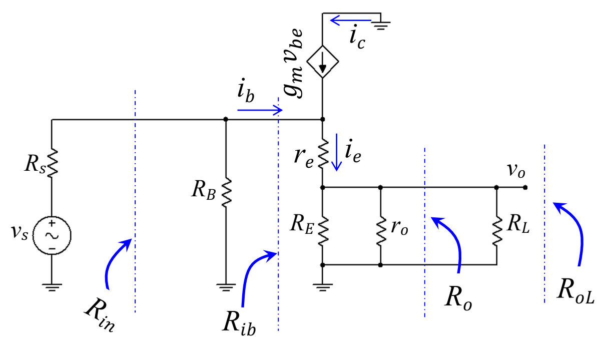
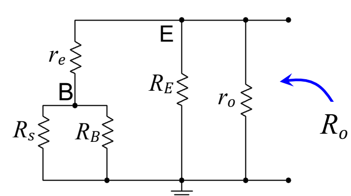
Small-Signal Analysis of a CC Amplifier: Output Resistance



Output resistance R_o is

$$R_o = \left[r_o||R_E||\left(r_e + \frac{R_B||R_s}{\beta+1}\right)\right]$$

Also, $R_{oL} = R_L||R_o$



Notice that resistors in the base side are divided by $(\beta+1)$

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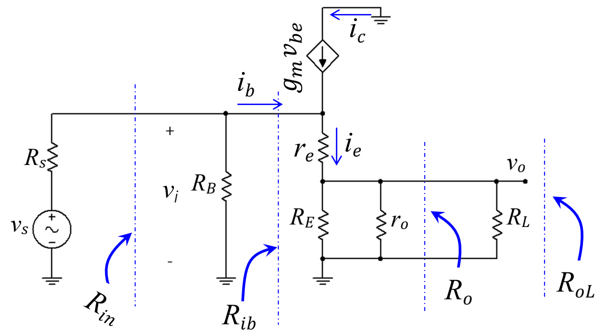
Small-Signal Analysis of a CC Amplifier: Voltage Gain



The voltage gain A_v is

$$A_v = \frac{v_o}{v_i} = \frac{v_o}{v_b}$$

or, $$A_v = \frac{i_e(R_L||r_o||R_E)}{i_e[r_e + (R_E||r_o||R_L)]}$$

If $r_e \ll R_L$, we can write

$$A_v = \frac{(R_L||r_o||R_E)}{r_e + (R_E||r_o||R_L)} \cong 1$$

- A_v cannot be higher than one
- If R_L is comparable with r_e, A_v can be significantly lower than one

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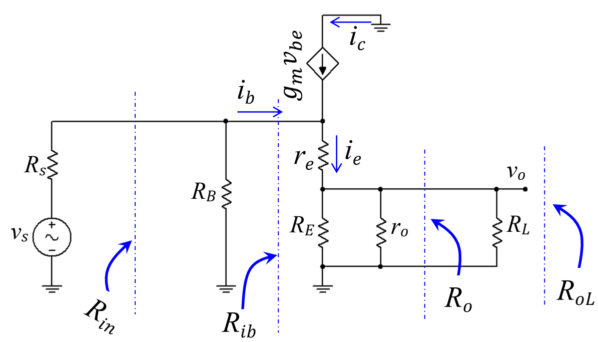
Small-Signal Analysis of a CC Amplifier: Current Gain



The current gain remains the same, i.e.

$$A_i = \beta$$

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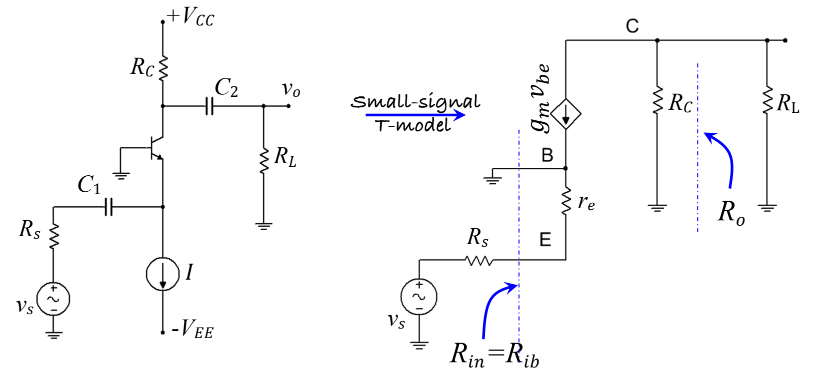
Small-Signal Analysis of a CB Amplifier



Input resistance

$R_{in} = r_e$

Output resistance

$R_o = R_C$

Open circuit voltage gain

$A_{vo} = g_m R_C$

Current gain

$A_i = \alpha \approx 1$

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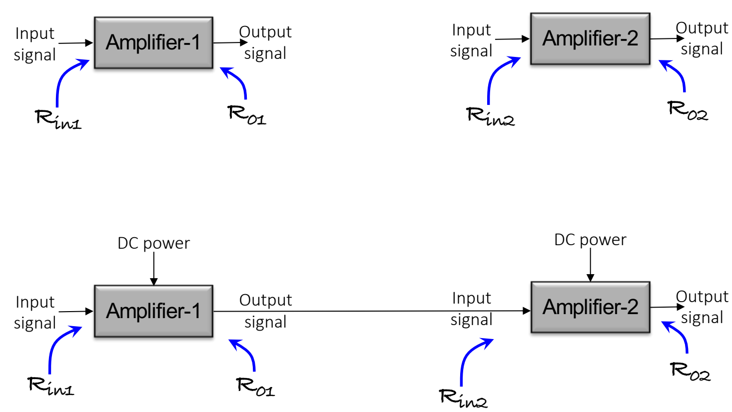
Impedance Matching



CE + CC

CE + CC + CE

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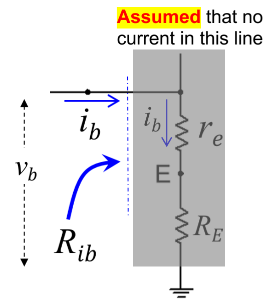
EXTRA Slide for Understanding $(\beta + 1)$ Factor in the Resistance

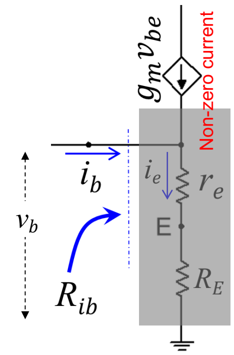


Here, the resistance R_{ib} is

$$R_{ib} = \frac{v_b}{i_b} = \frac{i_b(r_e + R_E)}{i_b}$$

or, $R_{ib} = r_e + R_E$

This is incorrect for a transistor



$$R_{ib} = \frac{v_b}{i_b} = \frac{i_e(r_e + R_E)}{i_b}$$

or, $R_{ib} = \dfrac{i_b(\beta + 1)(r_e + R_E)}{i_b}$

[Since $i_e = (\beta + 1)i_b$]

$$\boxed{R_{ib} = (\beta + 1)(r_e + R_E)}$$

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