Lecture 11:

Single-Stage BJT Amplifiers

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Overview

- **Reading**
  - S&S: Chapter 4.11
- **Supplemental Reading**

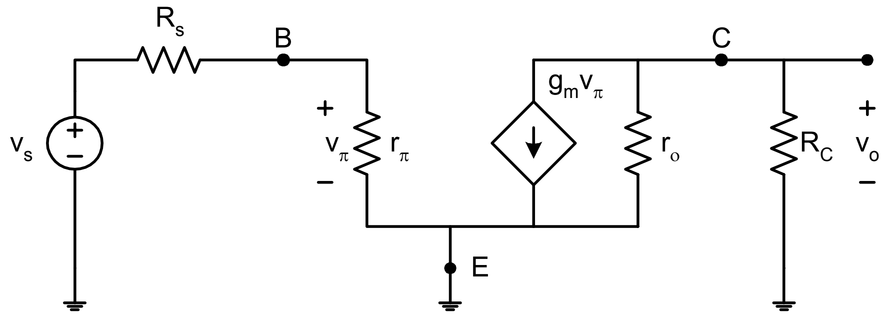
- **Background**
  - Given our understanding of small-signal models and analysis, we continue our investigation of BJT circuits by looking at single-stage BJT amplifiers of various configurations. While there is a lot more detail we can discuss in terms of BJTs and their large signal behavior, we will stop with the discussion of BJT amplifiers and continue next lecture with MOSFETs which we will focus on for the rest of the semester.
  - For more information on BJT circuits, read S&S 4.12~15

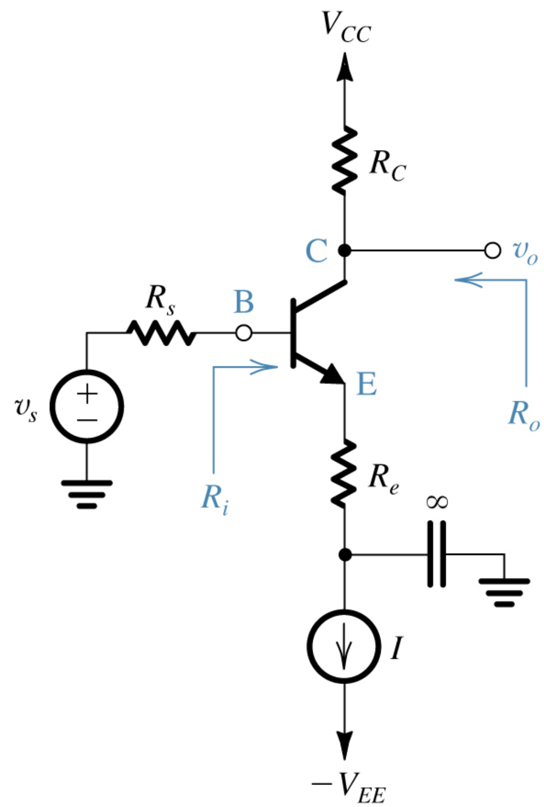
Single-Stage Amplifier Configurations

- There are three basic configurations for single-stage BJT amplifiers:
  – Common-Emitter
  – Common-Base
  – Common-Collector
- Let's look at these amplifier configurations and their small-signal operation

Common-Emitter Amplifier

- First, assume R_e = 0 (this is not r_e, but an explicit resistor)
- The BJT is biased with a current source (with high output impedance) and a capacitor connects the emitter to ground.
  - Cap provides an AC short at the emitter for small time-varying signals but is an open circuit for DC signals
- Can redraw the circuit with an equivalent circuit that replaces the BJT with its hybrid-π model





$$\frac{v_\pi}{v_s} = \frac{r_\pi}{R_s + r_\pi} \qquad v_o = -g_m v_\pi \left(R_C \| r_o\right) \qquad \frac{v_o}{v_\pi} = -g_m \left(R_C \| r_o\right)$$

$$\frac{v_o}{v_s} = \frac{v_o}{v_\pi}\frac{v_\pi}{v_s} = -\frac{r_\pi}{R_s + r_\pi} g_m \left(R_C \| r_o\right) = -\frac{\beta\left(R_C \| r_o\right)}{R_s + r_\pi}$$

$$R_{in} = r_\pi \qquad R_o = r_o \| R_C$$

CE Amp with Emitter Degeneration

- Now, assume $R_e \neq 0$. First, find R_i…
  - voltage applied to the base is across r_e and R_e

$$v_b = i_e\left(r_e + R_e\right)$$

  - base current is

$$i_b = \frac{i_e}{1+\beta}$$

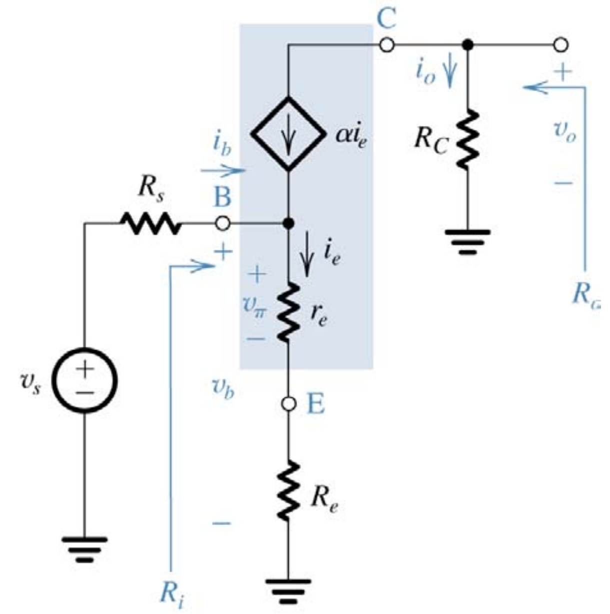
  - and let's us find R_i

$$R_i \equiv \frac{v_b}{i_b} = \left(\beta+1\right)\left(r_e + R_e\right)$$

  - this tells us that adding R_e increases the input resistance

$$\frac{R_i\,(\text{w/ } R_e)}{R_i(\text{w/o } R_e)} = 1 + \frac{R_e}{r_e} = 1 + g_m R_e$$

  - Can design the desired R_i by setting R_e



(c)

- To determine the voltage gain, first find the gain from the base to the collector (ignore r_o b/c it complicates the analysis considerably)

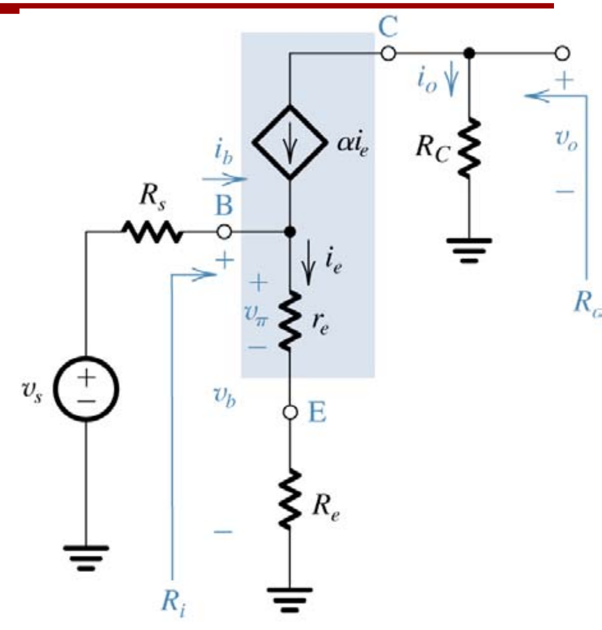
$$v_o = -\alpha i_e R_C \qquad v_b = i_e\left(r_e + R_e\right)$$

$$\frac{v_o}{v_b} = \frac{-\alpha R_C}{r_e + R_e} \cong \frac{-R_C}{r_e + R_e}$$

  – **NOTE:** *Voltage gain between base and collector is equal to ratio of total resistance in the collector to the total resistance in the emitter.*
- To find the total gain,

$$\frac{v_o}{v_s} = \frac{v_o}{v_b}\frac{v_b}{v_b} = \frac{R_i}{R_i + R_s}\frac{-R_C}{r_e + R_e} = -\frac{\beta R_C}{R_s + (\beta+1)(r_e + R_e)}$$

- Characteristics with R_e:
  – gain is less with but less dependent on β
  – input resistance is higher
  – allows higher input signal voltage



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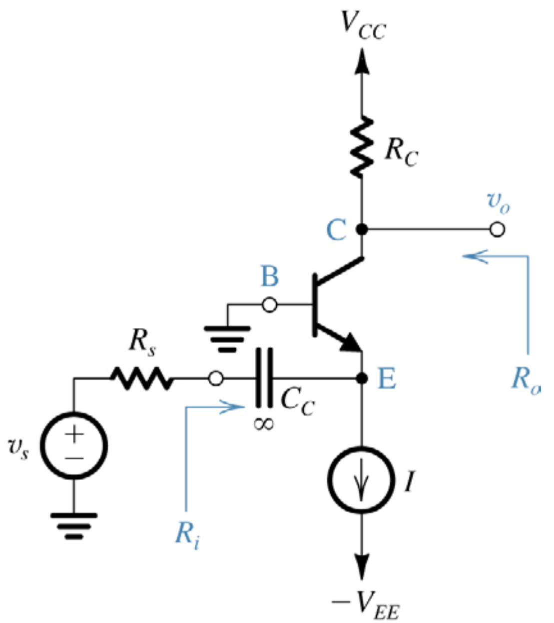
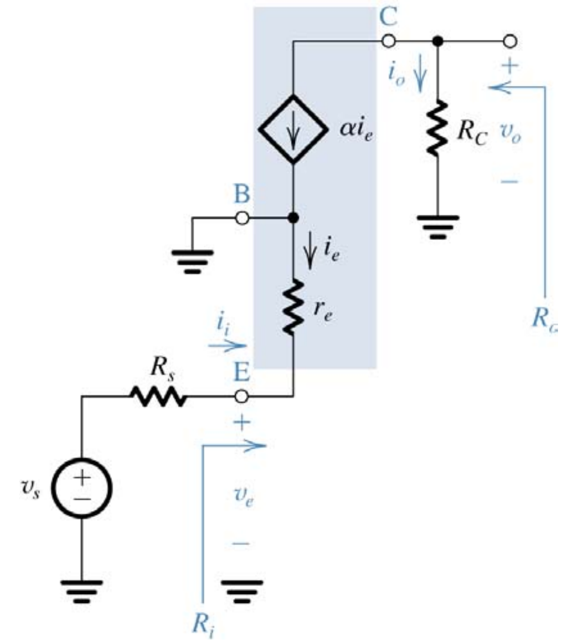
Common-Base Amplifier

- This time, ground the base and drive the input signal into the emitter through a coupling capacitor (only passes ac signals)





- Model the small signal approximation with a T-model
  - current source is an AC open and C_C is an AC short

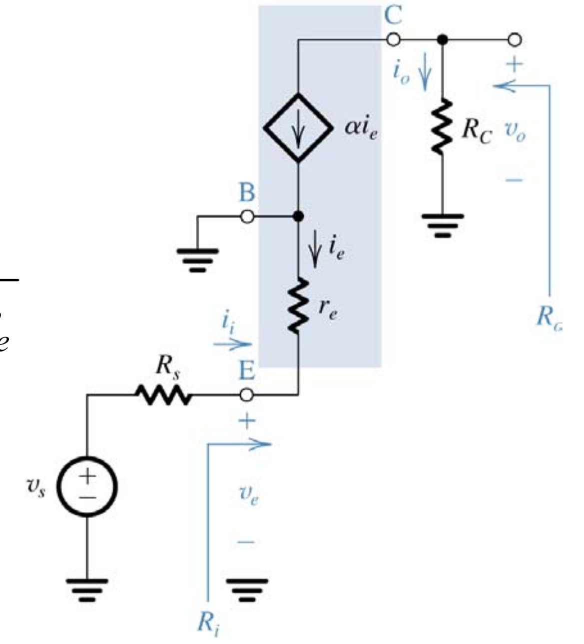
- First, we can see that…

$$R_i = r_e$$

- To find the gain, solve for v_o

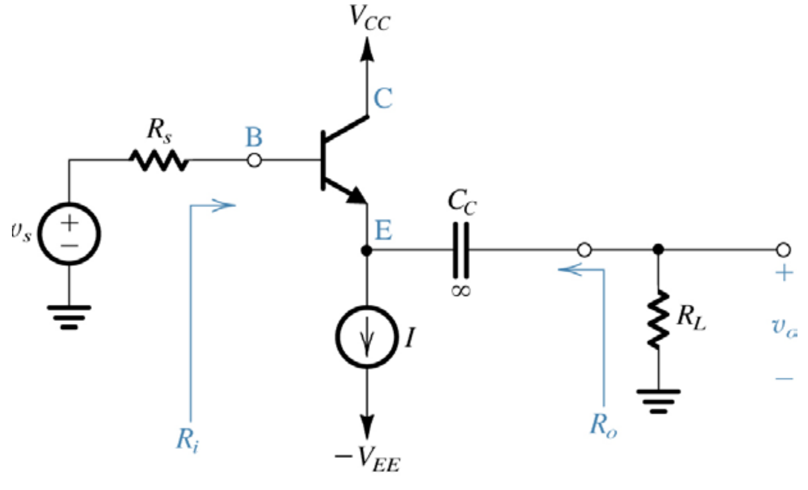
$$v_o = -\alpha i_e R_C \qquad i_e = -\frac{v_s}{R_s + r_e} \qquad A \equiv \frac{v_o}{v_s} = \frac{\alpha R_C}{R_s + r_e}$$

- The output impedance is just $R_o = R_C$
- CB amp characteristics:
  - voltage gain has little dependence on β
  - gain depends critically on R_s
  - is non-inverting
  - most commonly used as a unity-gain current amplifier or current buffer and not as a voltage amplifier: accepts an input signal current with low input resistance and delivers a nearly equal current with impedance
  - most significant advantage is its excellent frequency response



Common-Collector Amplifier (Emitter Follower)

- The last basic configuration is to tie the collector to a fixed voltage, drive an input signal into the base and observe the output at the emitter



(a)

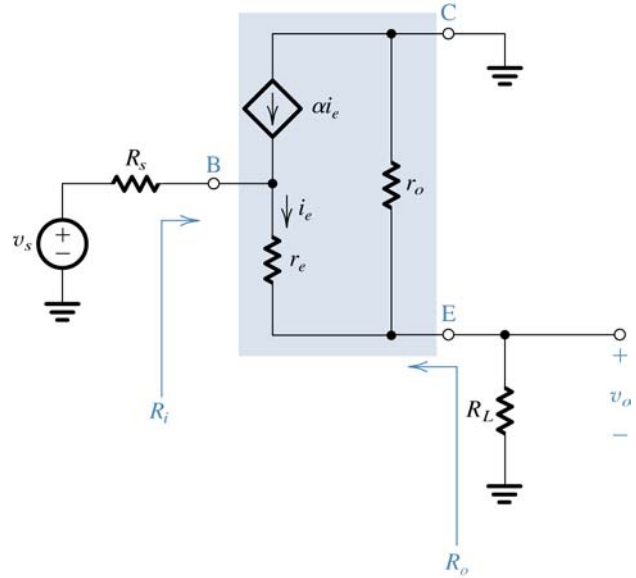
- Also called an emitter follower since the emitter follows the input signal
- Used for connecting a source with a large R_s to a load with low resistance

- Redraw the circuit to have r_o in parallel with R_L
  - now, find R_i $$R_i = (\beta+1)\left[r_e + (r_o \| R_L)\right]$$
  - when $r_e \ll R_L \ll r_o$ $$R_i \cong (\beta+1)R_L$$
  - notice the amplifier has large input resistance
- Find the gain with two voltage dividers

$$\frac{v_b}{v_s} = \frac{(\beta+1)\left[r_e + (r_o \| R_L)\right]}{R_s + (\beta+1)\left[r_e + (r_o \| R_L)\right]} \qquad \frac{v_o}{v_b} = \frac{r_o \| R_L}{r_e + r_o \| R_L}$$

$$A_v \equiv \frac{v_o}{v_s} = \frac{(\beta+1)(r_o \| R_L)}{R_s + (\beta+1)\left[r_e + (r_o \| R_L)\right]} = \frac{r_o \| R_L}{\frac{R_s}{\beta+1} + r_e + (r_o \| R_L)}$$

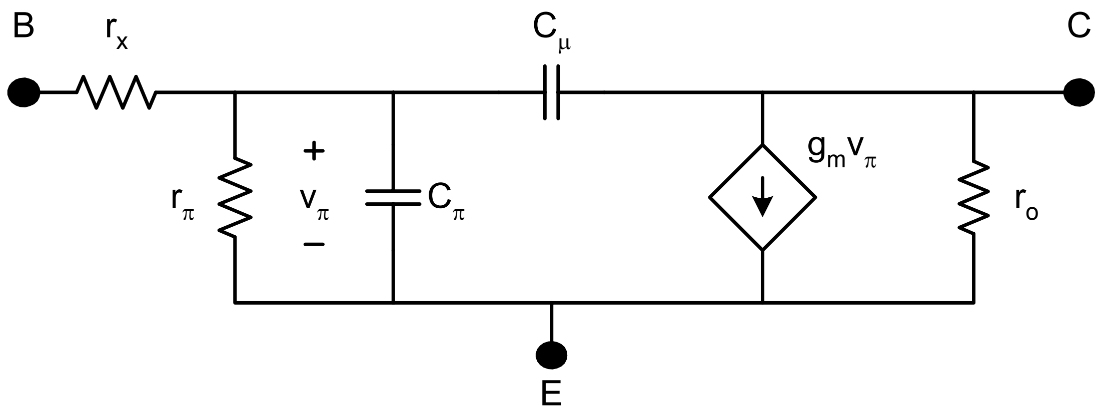
  - gain is less than unity, but close (to unity) since β is large and r_e is small



(b)

High-Frequency Model of BJTs

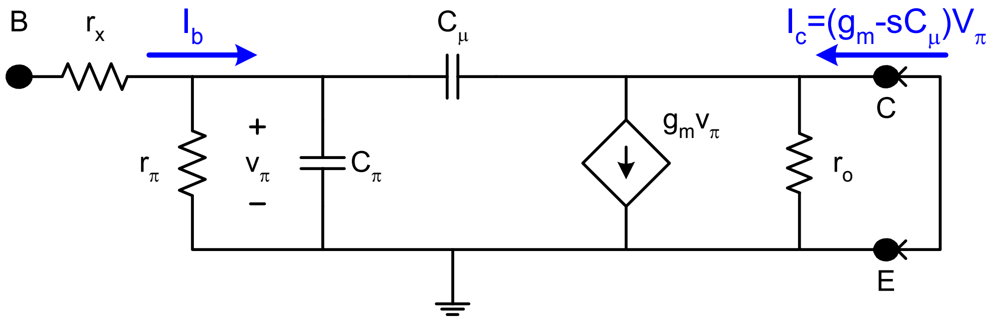
- When we looked at pn junctions, we found that the depletion regions can be modeled as capacitances. Let's see how these capacitances affect the performance of BJTs.
- There are two depletion regions and therefore two capacitors we need to include into our small-signal model. Also, a base resistance r_x is added because of current crowding at high frequencies (second-order effect in BJTs).



  - C_π and C_μ are bias dependent values which can be found (approximated) from the DC bias conditions of the circuit

f_T

- Transistor performance is often presented in terms of f_T which is a value that corresponds to its short-circuit current gain bandwidth product (or unity-gain bandwidth). Let's see how to solve for it…



- Find I_c/I_b

$$V_\pi = I_b\left(r_\pi \| C_\pi \| C_\mu\right) \qquad \frac{I_c}{I_b} = \frac{g_m - sC_\mu}{1/r_\pi + s\left(C_\pi + C_\mu\right)}$$

  – at frequencies over which the model is valid, $g_m >> \omega C_\mu$

$$\frac{I_c}{I_b} \cong \frac{g_m r_\pi}{1 + s\left(C_\pi + C_\mu\right)r_\pi} = \frac{\beta_0}{1 + s\left(C_\pi + C_\mu\right)r_\pi}$$

β_0 is the low-frequency value of β and current gain rolls off with a single pole at ω_β

$$\omega_\beta = \frac{1}{\left(C_\pi + C_\mu\right)r_\pi} \qquad \omega_T = \beta_0\omega_\beta = \frac{g_m}{C_\pi + C_\mu} \rightarrow f_T = \frac{g_m/2\pi}{C_\pi + C_\mu}$$