Lecture 19

Transistor Amplifiers (II)

Common-Emitter Amplifier

Outline

- Common-source amplifier (summary)
- Common-emitter amplifier
- Common-emitter amplifier with current-source supply
- Common-emitter amplifier with emitter degeneration resistor

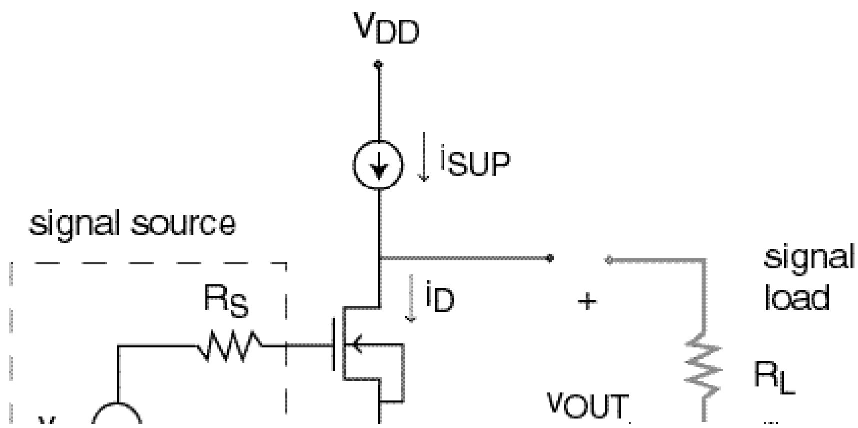
Reading Assignment:
Howe and Sodini; Chapter 8, Sections 8.4-8.6

Announcement:
Quiz #2: Wednesday, November 15, 7:30-9:30 PM at Walker Memorial. Lectures #10 - #17. Calculator Required. Open book & notes.
No Recitation on Wednesday: Instructors will be available in their offices during recitation times

Summary of Key Concepts

- Common-emitter amplifier with resistive supply
  - To maximize gain, large power supply required
  - High power consumption
- Performance improved by using common-emitter amplifier with current source supply.
- Two-port network computation of voltage gain, input resistance and output resistance of amplifier.

1. Common Source Amplifier:
with current source supply



Summary of small-signal results (unloaded):

- Voltage gain: $A_{vo} = -g_m (r_o // r_{oc})$.
- Input resistance :$R_{in} = \infty$
- Output resistance: $R_{out} = r_o // r_{oc}$.

Relationship between circuit figures of merit and device parameters

Remember:

$$g_m = \sqrt{2 I_D \frac{W}{L} \mu_n C_{ox}}$$

$$r_o \approx \frac{1}{\lambda_n I_D} \quad \frac{L}{I_D}$$

Then:

Device* Parameters	Circuit Parameters		
	$\lvert A_{vo} \rvert$	R_{in}	R_{out}
	$g_m(r_o//r_{oc})$		$r_o//r_{oc}$
I_{SUP} ↑	↓	-	↓
W ↑	↑	-	-
$\mu_n C_{ox}$ ↑ `	↑	-	-
L ↑	↑	-	↑

* adjustments are made to V_{GG} so that none of the other parameters change

CS amplifier with current source supply is a good voltage amplifier (R_{in} high and $\lvert A_{vo} \rvert$ high), but R_{out} high too voltage gain degraded if $R_L << r_o//r_{oc}$.

2. Common-Emitter Amplifier:

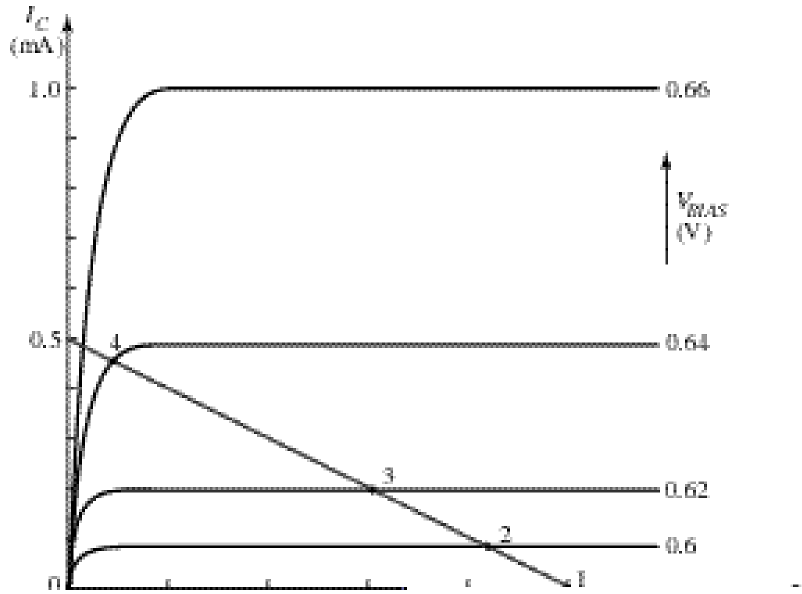
Circuit Topology:

Consider it first unloaded by R_L. How does it work?

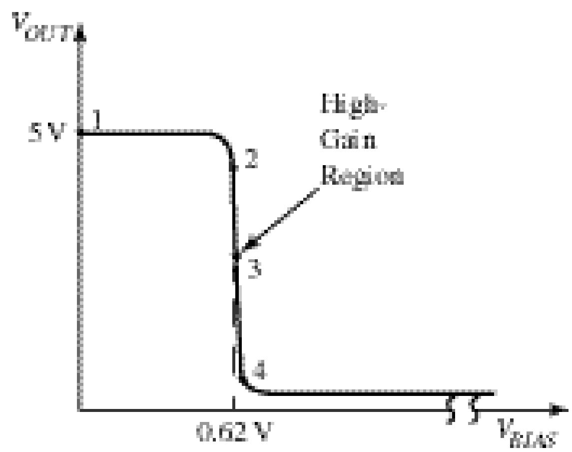
- V_{BIAS}, R_C and A_E of npn-BJT selected to bias transistor in forward active region (FAR) and obtain desired output bias point (i.e. $V_{OUT} = 0$).
- $v_S \uparrow$ $v_{BE} \uparrow$ $i_B \uparrow$ $i_C \uparrow$ $v_{OUT} \downarrow$
- $A_v = v_{out} / v_s < 0$; output out of phase from input, but if amplifier is well designed, $|A_v| > 1$.

Watch notation: $v_{OUT}(t) = V_{OUT} + v_{out}(t)$

Load line of Common Emitter Amplifier:

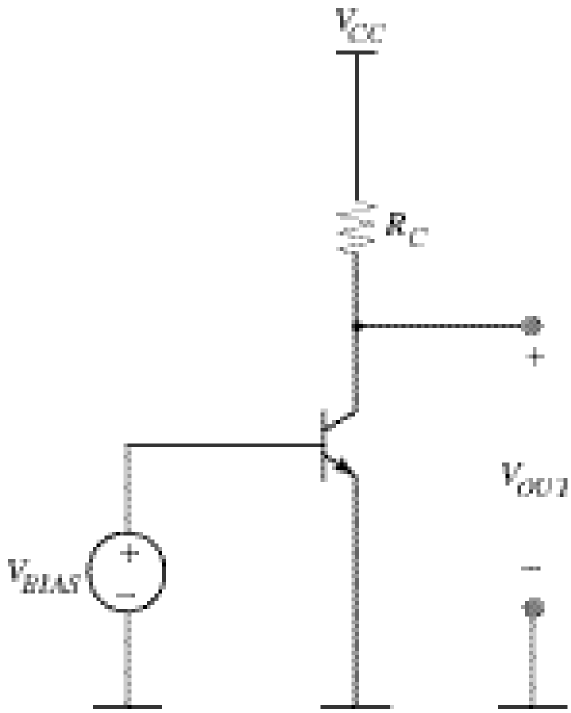


Transfer characteristics of amplifier:



- Graphical approach
  - Plot I_C as a function of the DC base-emitter voltage V_{BIAS}
  - Note that normally we plot I_C vs. I_B, so we have to return to Ebers-Moll equations
- We can plot the forward active current for
  - $V_{CE} = V_{OUT} > V_{CE(sat)}$
  - Note that the range of V_{BIAS} is only 600-660 mV

Biasing the CE Amplifier



The collector current is given by the Ebers-Moll Equation:

$$\mathbf{I_C} = \mathbf{I_S}\left(\exp\left(\frac{\mathbf{V_{BE}}}{\mathbf{V_{th}}}\right) - 1\right) - \frac{\mathbf{I_S}}{\beta_R}\left(\exp\left(\frac{\mathbf{V_{BC}}}{\mathbf{V_{th}}}\right) - 1\right)$$

In Forward Active Region

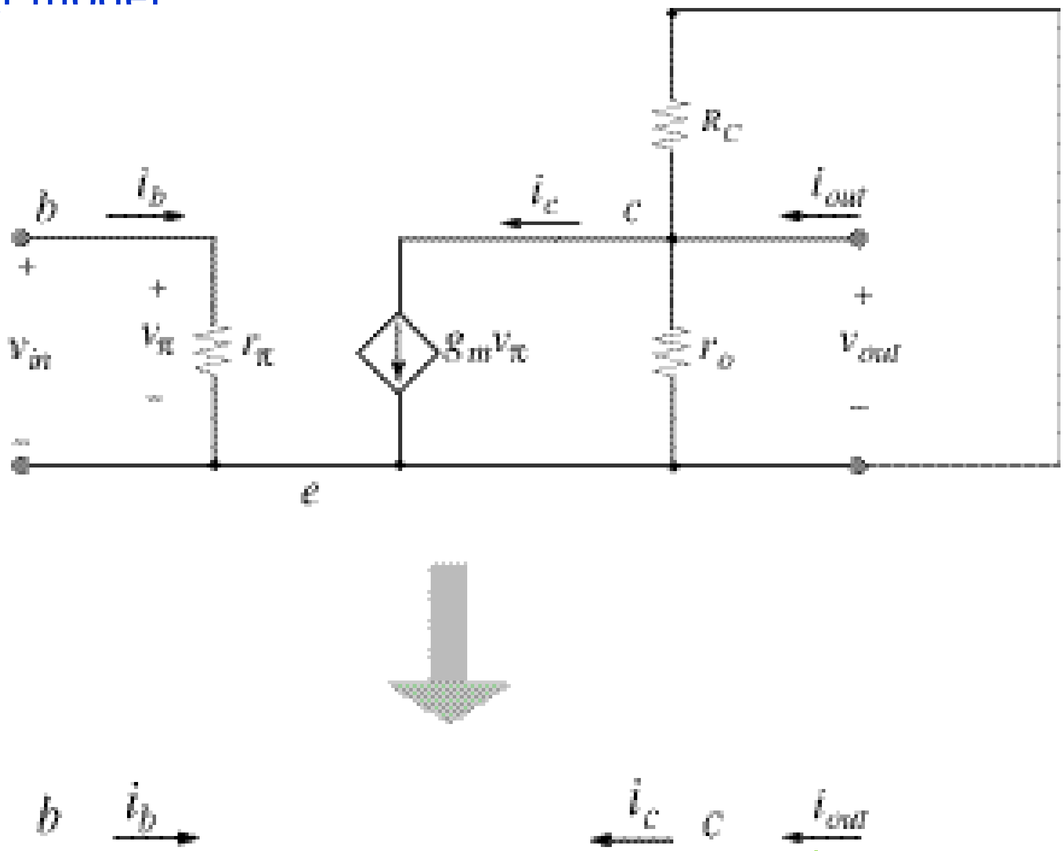
$$\mathbf{I_C} \approx \mathbf{I_S} \cdot \exp\left(\frac{\mathbf{V_{BE}}}{\mathbf{V_{th}}}\right) = \mathbf{I_S} \cdot \exp\left(\frac{\mathbf{V_{BIAS}}}{\mathbf{V_{th}}}\right)$$

Output Voltage

$$V_{OUT} = V_{CE} = V_{CC} - I_C R_C$$

Typically select $V_{OUT} = 1/2\ V_{CC}$

Small-signal voltage gain: draw small-signal equivalent circuit model:



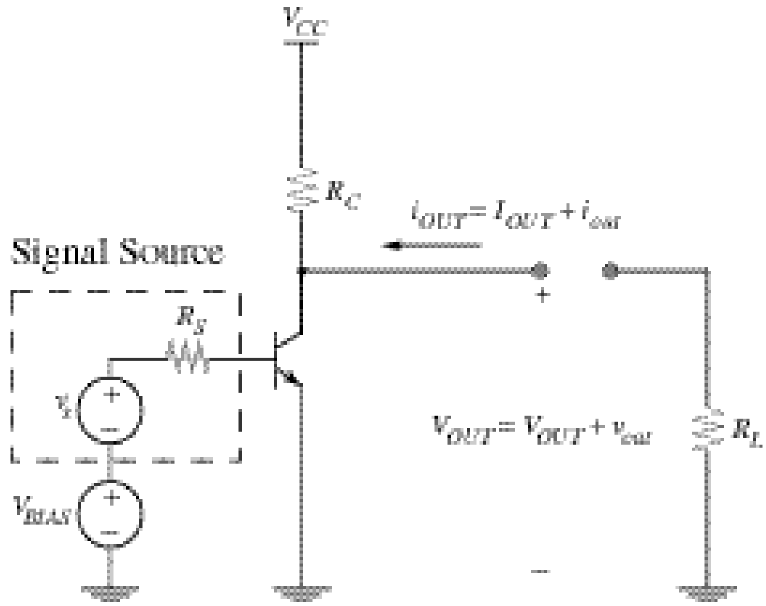
$$v_{out} = -g_m v_{in} \left(r_o // R_C \right)$$

$$g_m = \frac{qI_C}{kT}$$

Then unloaded voltage gain:

$$A_{vo} = \frac{v_{out}}{v_{in}} = -g_m \left(r_o // R_C \right)$$

Signal Swing and Effect of input/output loading:



- Upswing limited by resistive divider:

$$v_{OUT,max} = V_{CC} \frac{R_L}{R_L + R_C}$$

- Downswing not affected by loading $V_{OUT,min} = V_{CE,sat}$
- Voltage swing

$$\mathbf{\Delta v_{OUT} = \Delta v_{out} = V_{CC} \frac{R_L}{R_L + R_C} - V_{CE,sat}}$$

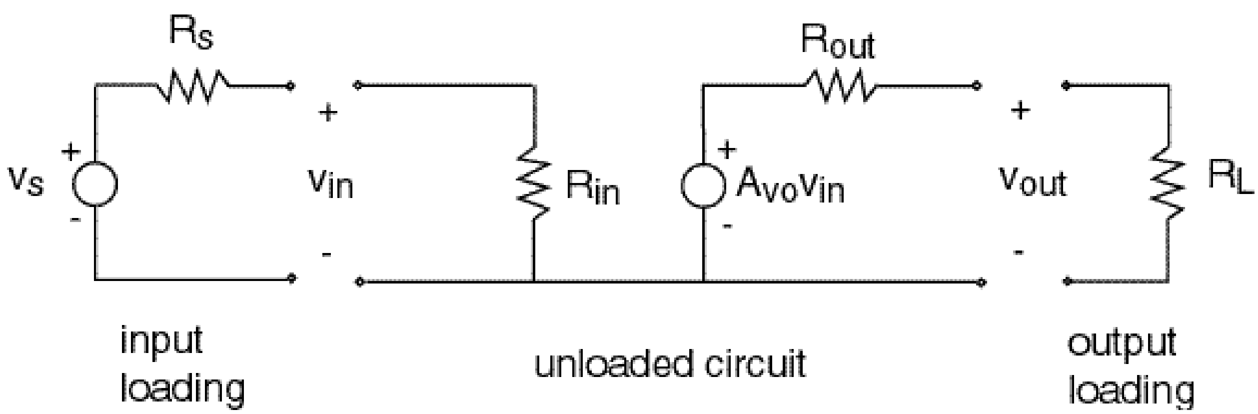
- Voltage gain:
  - Input loading (R_S): R_S reduces voltage gain because it forms a resistor divider with r_π;
  - Output loading (R_L): R_L reduces voltage gain because it draws current.

$$|A_v| = \frac{r_\pi}{r_\pi + R_S} g_m (r_o // R_C // R_L) < g_m (r_o // R_C)$$

Effect of loading on small-signal operation

Two-port network view of small-signal equivalent circuit model of amplifier:

R_{in} is ***input resistance***
R_{out} is ***output resistance***
A_{vo} is ***unloaded voltage gain***



Voltage divider at input: $$v_{in} = R_{in}\frac{v_s}{R_{in}+R_s}$$

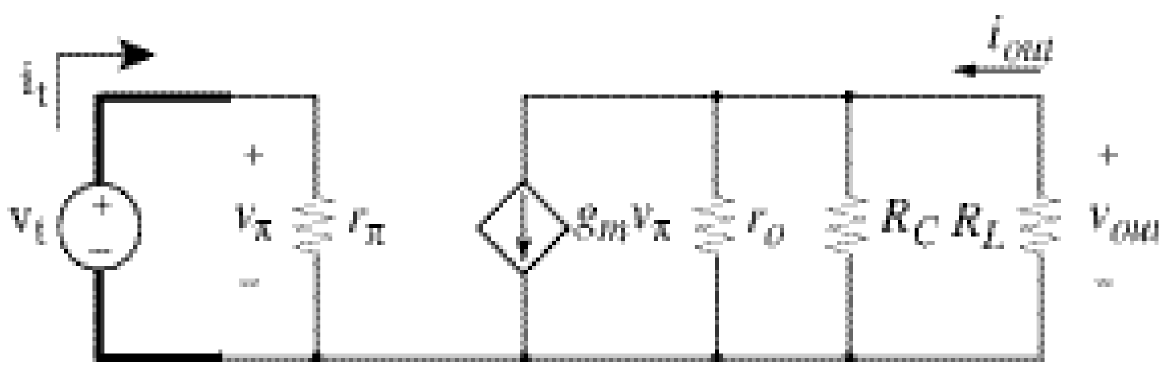
Voltage divider at output: $$v_{out} = R_L\frac{A_{vo}v_{in}}{R_{out}+R_L}$$

Loaded voltage gain: $$\frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in}+R_S}A_{vo}\frac{R_L}{R_L+R_{out}}$$

Input Resistance

- Calculation of input resistance, R_{in}:
  - Load amplifier with R_L
  - Apply test voltage (or current) at input, measure test current (or voltage).

For common-emitter amplifier:



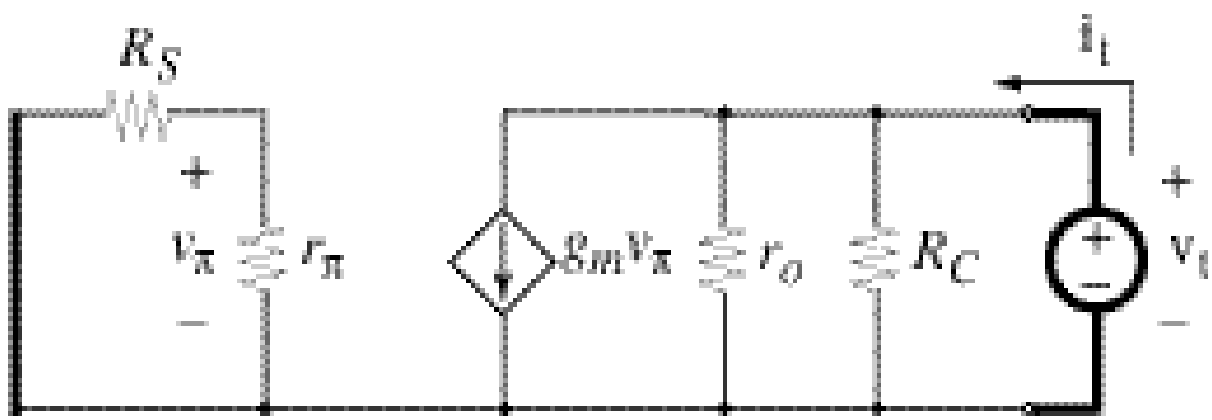
$$v_t = i_t r_\pi \qquad R_{in} = \frac{v_t}{i_t} = r_\pi$$

No effect of loading at input.

Output Resistance

- Calculation of input resistance, R_{out}:
  - Load amplifier with R_S
  - Apply test voltage (or current) at output, measure test current (or voltage).

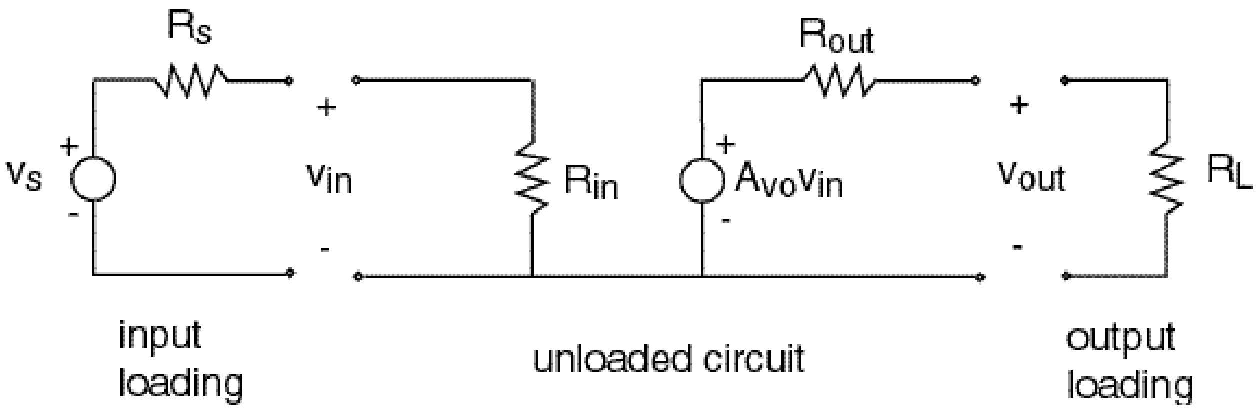
For common-emitter amplifier:



$$v_\pi = 0 \qquad g_m v_\pi = 0 \qquad v_t = i_t \left(r_o // R_C \right)$$

$$R_{out} = \frac{v_t}{i_t} = r_o // R_C$$

Two-port network view of common-source amplifier



$$\frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_S} A_{vo} \frac{R_L}{R_L + R_{out}}$$

$$= -\frac{r_\pi}{r_\pi + R_S} g_m \left(r_o // R_C\right) \frac{R_L}{R_L + r_o // R_C}$$

Or:

$$\frac{v_{out}}{v_s} = -\frac{r_\pi}{r_\pi + R_S} g_m \left(r_o // R_C // R_L\right)$$

$$R_{out} = r_o // R_C$$

$$R_{in} = r_\pi$$

Design issues of common-emitter amplifier (unloaded)

- To maximize the output swing, set $V_{OUT} = V_{CC}/2$.
  The load resistor value is coupled with the collector current through the load line equation

$$I_C = \frac{V_{CC} - V_{OUT}}{R_C} \approx \frac{V_{CC}}{2R_C}$$

- The transconductance is therefore

$$g_m = \frac{I_C}{V_{th}} = \frac{V_{CC}}{2R_C V_{th}}$$

- The small signal gain voltage gain (for $r_o >> R_C$)

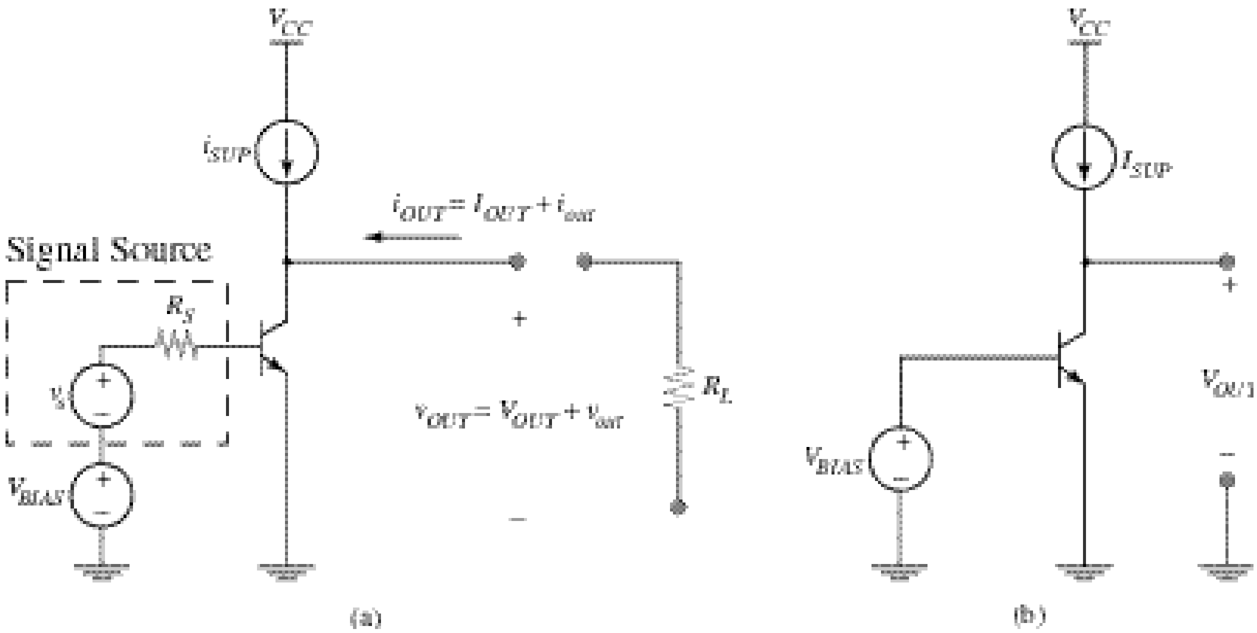
$$A_v \approx g_m R_C = \frac{-V_{CC}}{2\ V_{th}}$$

Issue:

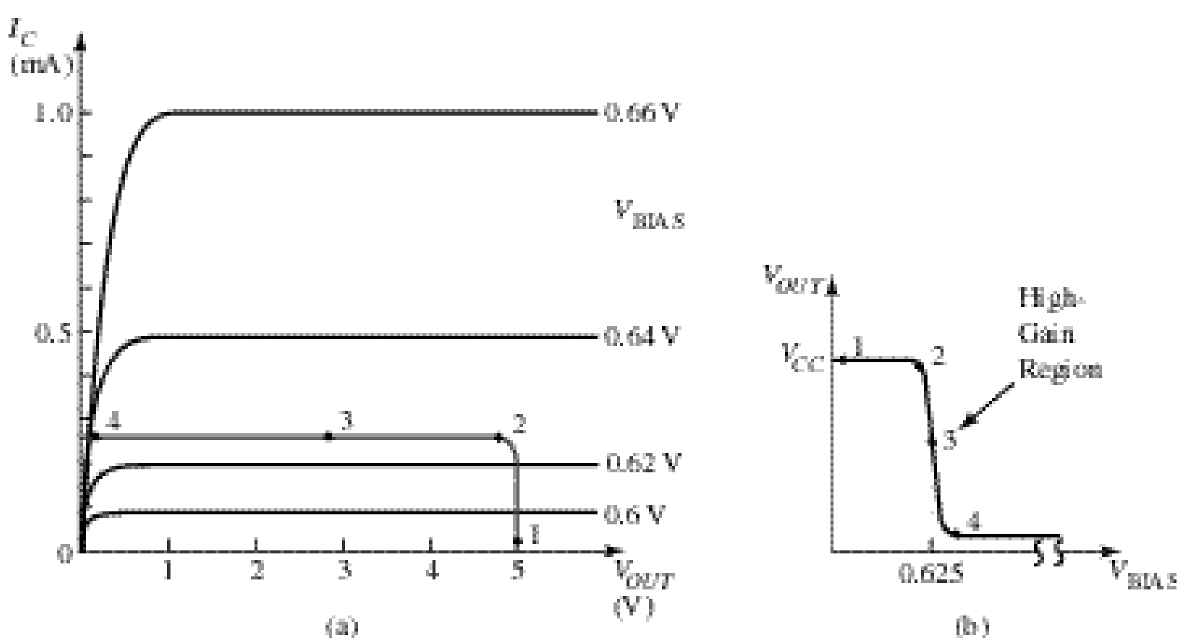
- To increase the voltage gain, the only option is to increase the supply voltage which wastes power

Solution: CE amplifier with current source supply

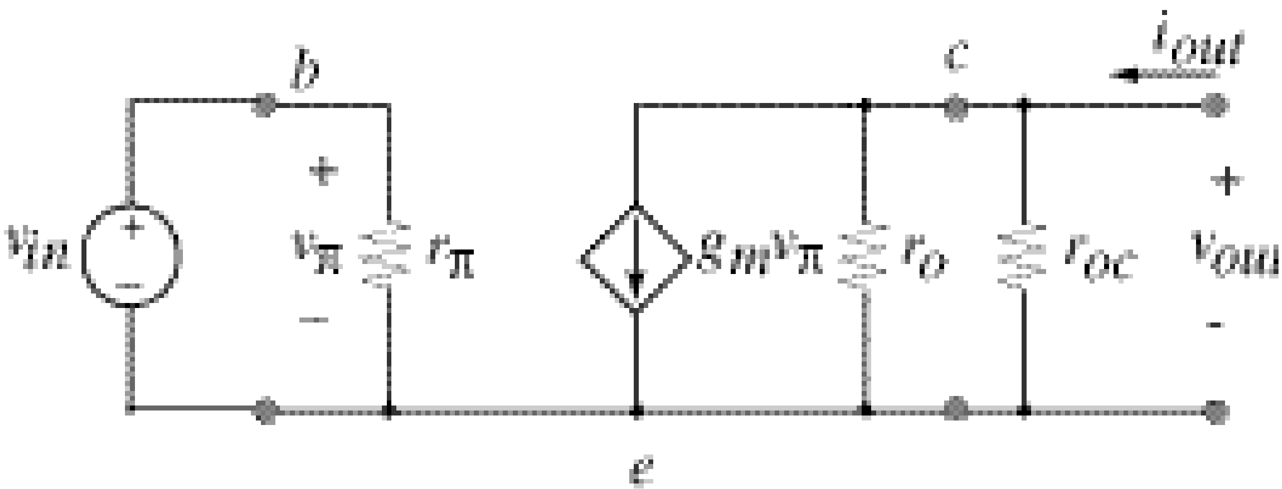
3. Common-source amplifier with current-source supply



CE Amplifier with Idealized Current Source Loadline :



Small-Signal Model for CE Amplifier with Current Source Supply



- Voltage Gain (unloaded)

$$\mathbf{A_{vo} = \frac{v_{out}}{v_{in}} = -g_m(r_o // r_{oc})}$$

- For a well designed current source, $r_{oc} >> r_o$, hence common emitter amplifier gain reduces to:

$$\mathbf{A_{vo} \approx g_m r_o = -\left(\frac{I_C}{V_{th}}\right)\left(\frac{V_A}{I_C}\right) = -\frac{V_A}{V_{th}}}$$

- Final expression depends on device dimensions and parameters
  - (e.g., base width and the ratio of base doping to collector doping)

Relationship between common emitter amplifier circuit figures of merit and device parameters

Remember:

$$g_m = \frac{I_C}{V_{th}}$$

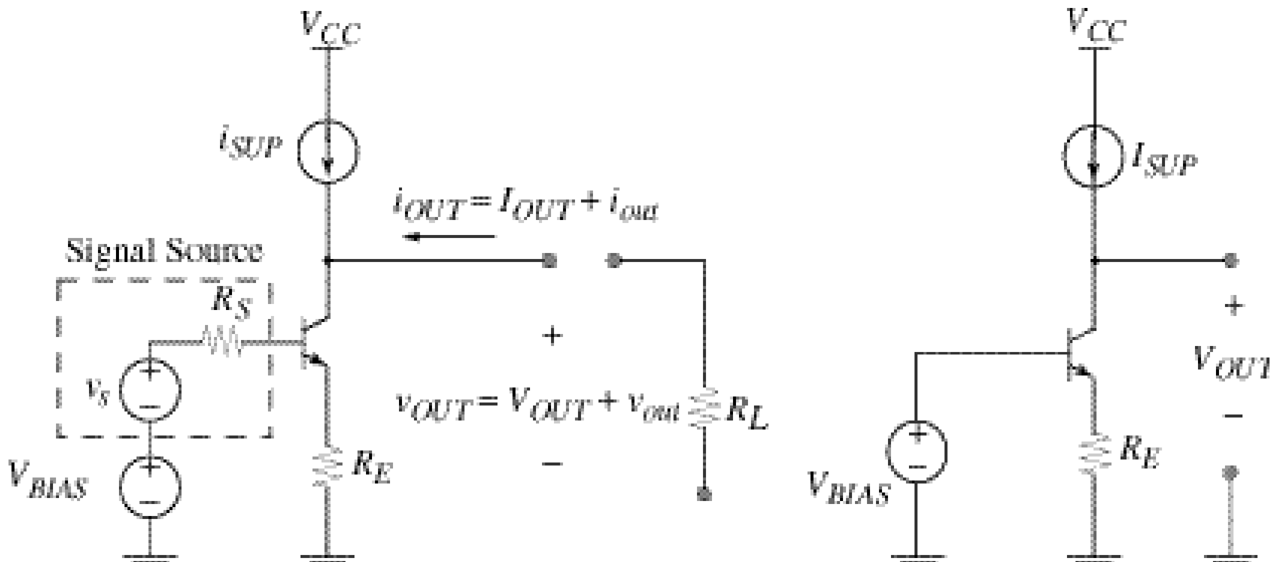
$$r_o \approx \frac{V_A}{I_C}$$

Then:

Device Parameters	Circuit Parameters		
	$\lvert A_{vo} \rvert$	R_{in}	R_{out}
	$g_m(r_o//r_{oc})$	r_π	$r_o//r_{oc}$
I_{SUP} ↑	-	↓	↓
β_o ↑ `	-	↑	-
V_A ↑	↑	-	↑

CE amplifier with current source supply is a good voltage amplifier (R_{in} medium and $\lvert A_{vo} \rvert$ high), but R_{out} high too   voltage gain degraded if $R_L << r_o//r_{oc}$.

Common Emitter Amplifier
(with emitter degeneration resistor)



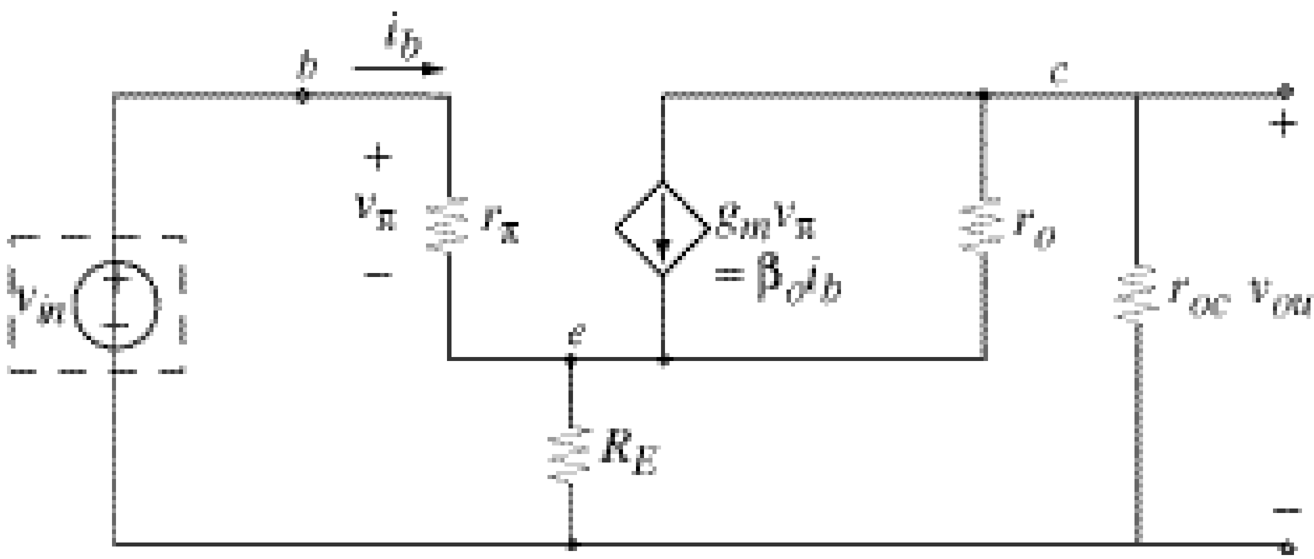
- Addition of emitter resistance leads to increase in input and output resistance
- Voltage gain depends predominantly on the emitter resistance resulting in a well controlled gain
  - Gain relatively independent of temperature and process variations

$$\mathbf{V_{BIAS}} = \mathbf{V_{BE}} + \frac{(\beta_F + 1)\mathbf{I_C}}{\beta_F}\mathbf{R_E} \approx \mathbf{V_{BE}} + \mathbf{I_C R_E}$$

$$\mathbf{V_{BE}} = \mathbf{V_{th}} \ln\left(\frac{\mathbf{I_C}}{\mathbf{I_S}}\right)$$

$$\mathbf{I_C} = \mathbf{I_{SUP}}$$

Small Signal Model
(CE Amplifier with R_E)



- Addition of emitter resistance leads to increase in input and output resistance by a factor $(1 + g_m R_E)$
- Voltage gain reduced by a factor $(1 + g_m R_E)$

$$\mathbf{A_v} \approx -\frac{\mathbf{g_m}\left[\mathbf{r_{oc}} // \mathbf{r_o}\left(1+\mathbf{g_m R_E}\right)\right]}{1+\mathbf{g_m R_E}} \approx \frac{\mathbf{g_m r_{oc}}}{1+\mathbf{g_m R_E}}$$

$$\mathbf{R_{in}} = \mathbf{r_\pi}\left(1+\mathbf{g_m R_E}\right)$$

$$\mathbf{R_{out}} \approx \mathbf{r_{oc}} // \mathbf{r_o}\left(1+\mathbf{g_m R_E}\right)$$

What did we learn today?

Summary of Key Concepts

- Common-emitter amplifier with resistive supply
  - To maximize gain, large power supply required
  - High power consumption
- Performance improved by using common-emitter amplifier with current source supply.
- Two-port network computation of voltage gain, input resistance and output resistance of amplifier.