EEE 51: Second Semester 2017 - 2018

Lecture 6

Single-Stage Amplifiers

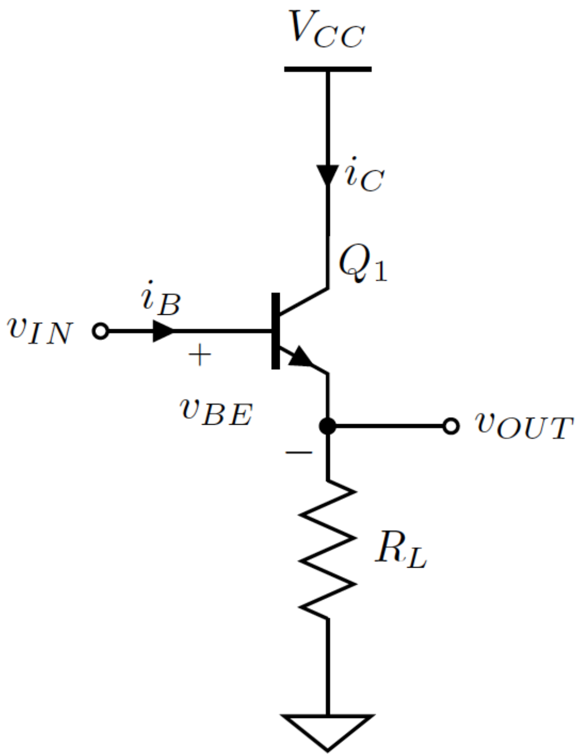
Current Sources

Today

- Wrap up single-stage amplifiers
- Current Sources

The Common-Collector Amplifier

- DC Analysis:



$$V_{IN} - V_{BE,Q} - I_{E,Q} R_L = 0$$

$$V_{IN} - V_T \ln\left(\frac{I_{C,Q}}{I_S}\right) - I_{C,Q}\left(1 + \frac{1}{\beta}\right) R_L = 0$$

Non-linear!

Simplify? $V_{BE,Q} = 0.7\text{V}$

$$I_{C,Q} = \frac{V_{IN} - 0.7\text{V}}{\left(1 + \frac{1}{\beta}\right) R_L} \approx \frac{V_{IN} - 0.7\text{V}}{R_L}$$

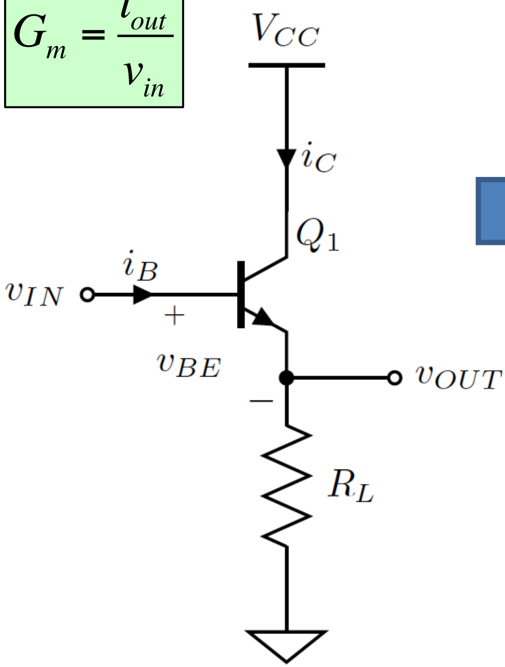
$$V_{OUT} = I_{E,Q} R_L \approx I_{C,Q} R_L = V_{IN} - 0.7\text{V}$$

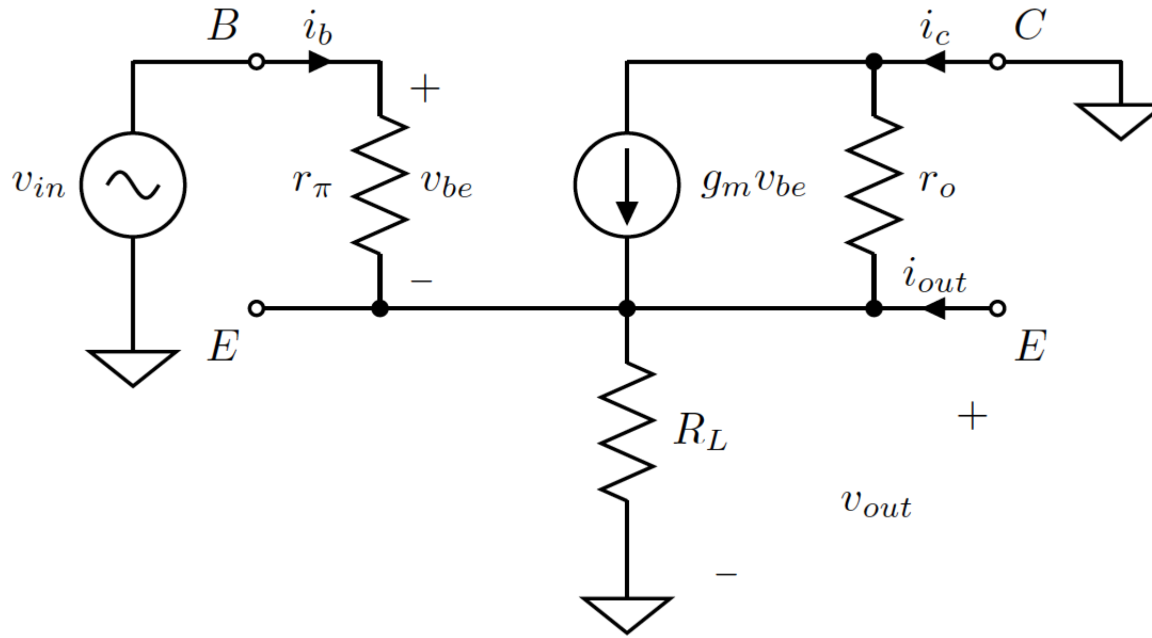
Emitter follower

Forward-active region check: $V_{CE} = V_{CC} - V_{OUT} > V_{CE,sat}$

Common-Collector Small Signal Analysis (1)

$$G_m = \frac{i_{out}}{v_{in}}$$



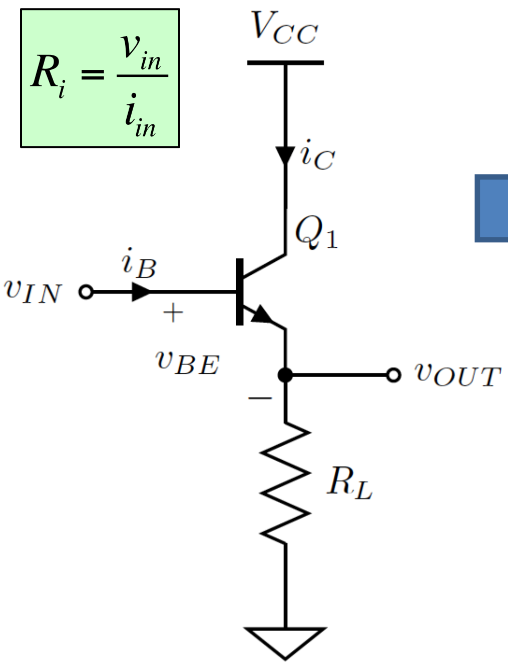


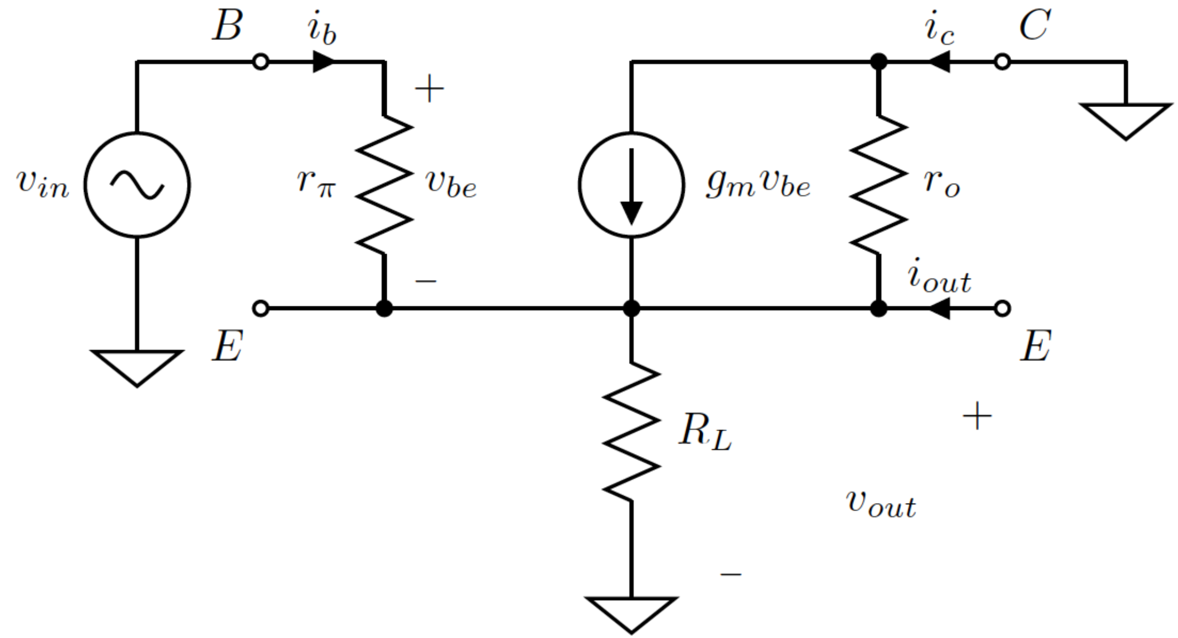
Short the output to ground: $i_{out} = -g_m v_{in} - \dfrac{v_{in}}{r_\pi}$

$$G_m = \frac{i_{out}}{v_{in}} = -g_m - \frac{1}{r_\pi} \approx -g_m$$

Common-Collector Small Signal Analysis (2)

$$R_i = \frac{v_{in}}{i_{in}}$$

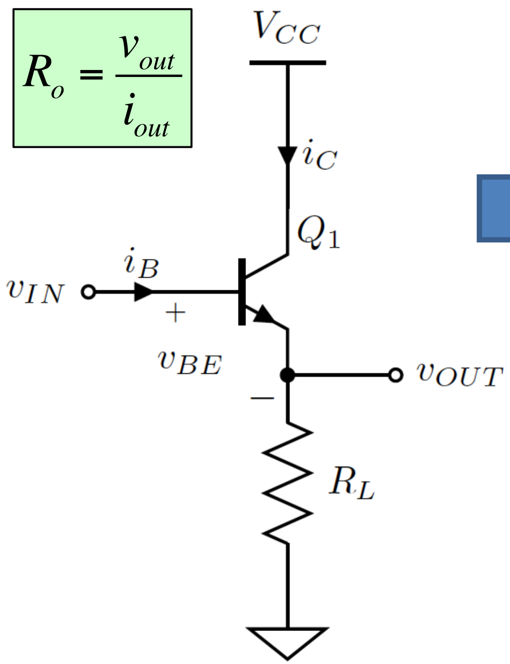


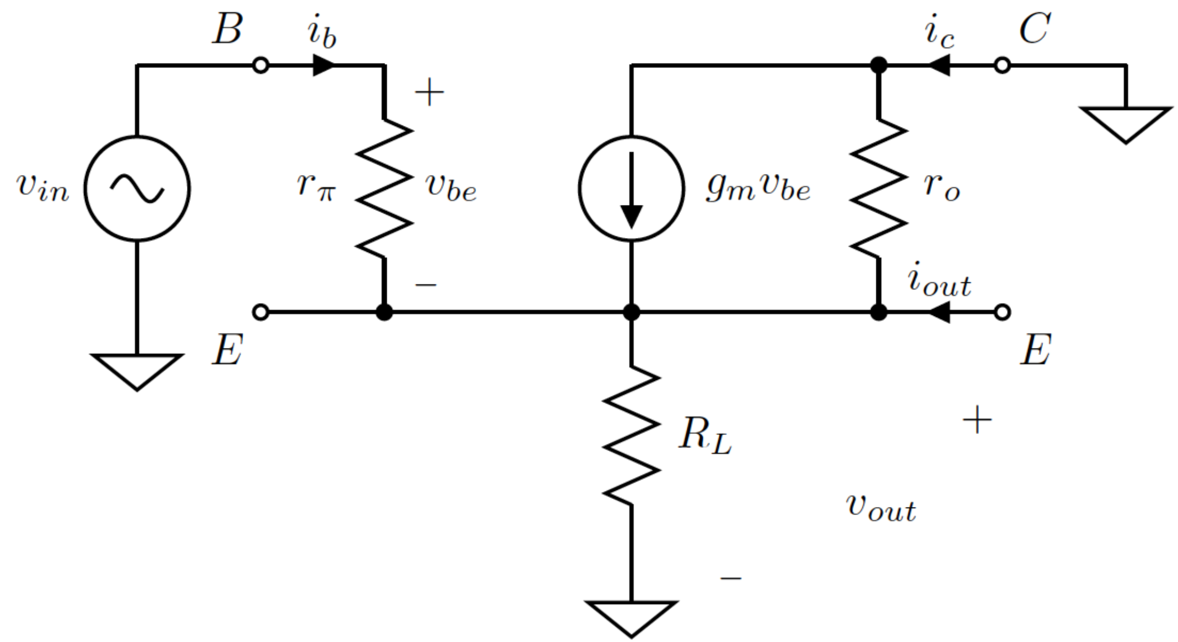


Short the output to ground: $\boxed{R_i = r_\pi}$

Common-Collector Small Signal Analysis (3)

$$R_o = \frac{v_{out}}{i_{out}}$$

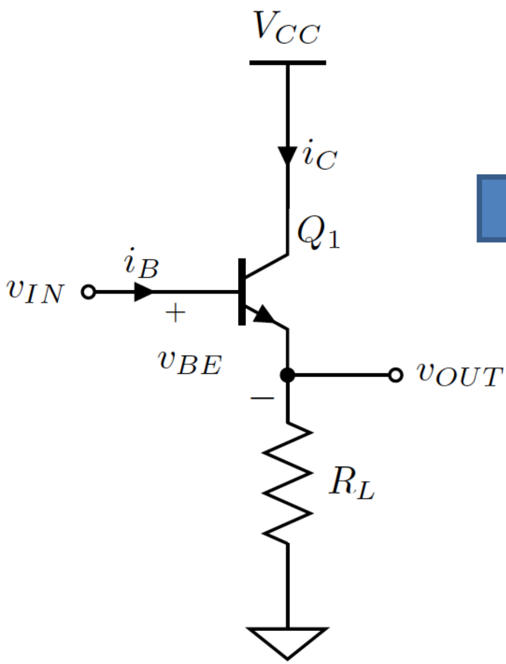


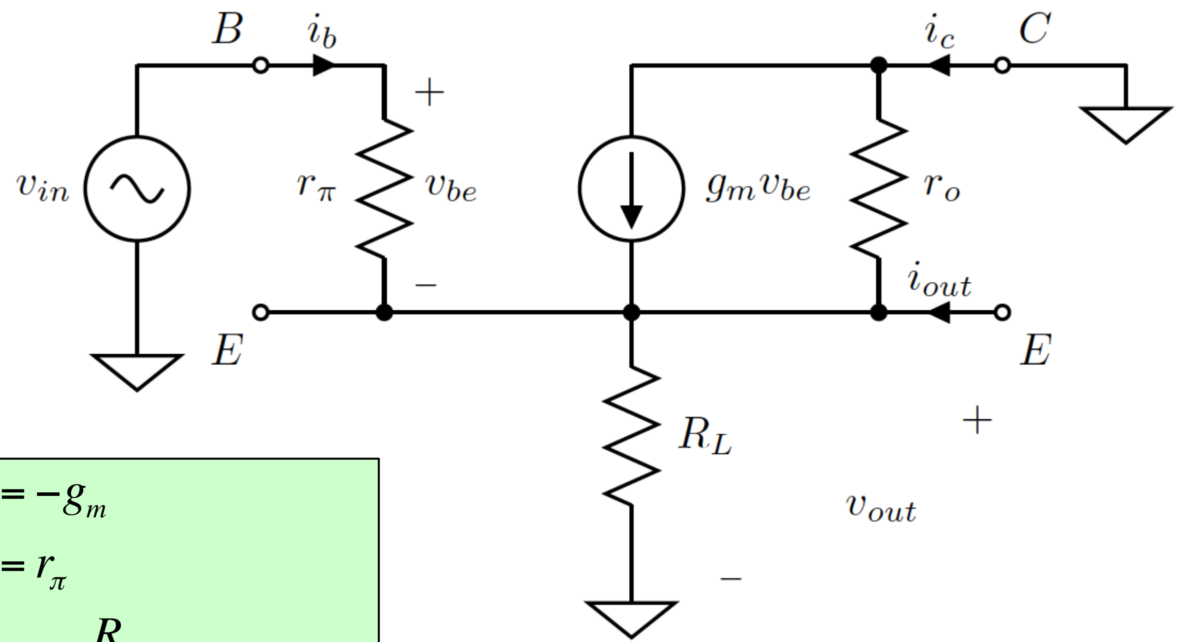


Zero out the input:

$$R_o = \frac{v_{out}}{i_{out}} = r_\pi \parallel r_o \parallel \frac{1}{g_m} \parallel R_L \approx \frac{1}{g_m} \parallel R_L = \frac{R_L}{1 + g_m R_L}$$

Common-Collector Small Signal Analysis (4)





$$G_m = -g_m$$

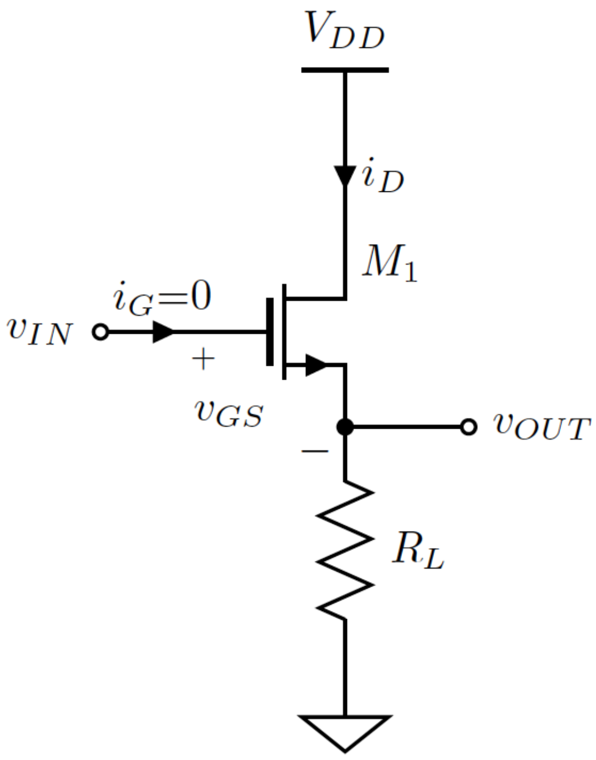
$$R_i = r_\pi$$

$$R_o = \frac{R_L}{1 + g_m R_L}$$

$$A_v = -G_m R_o = \frac{g_m R_L}{1 + g_m R_L}$$

The Common-Drain Amplifier

- DC Analysis:



$$V_{IN} - V_{GS,Q} - I_{S,Q}R_L = 0$$

$$V_{IN} - \left(V_{TH} + \sqrt{\frac{I_{D,Q}}{k}}\right) - I_{D,Q}R_L = 0$$

Quadratic

$$V_{OUT} = I_{D,Q}R_L = V_{IN} - V_{GS}$$

$$= V_{IN} - \left(V_{TH} + \sqrt{\frac{I_{D,Q}}{k}}\right)$$

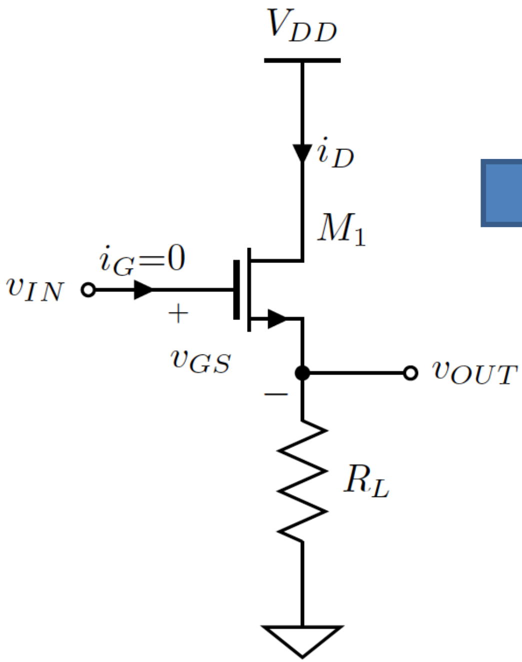
Source follower

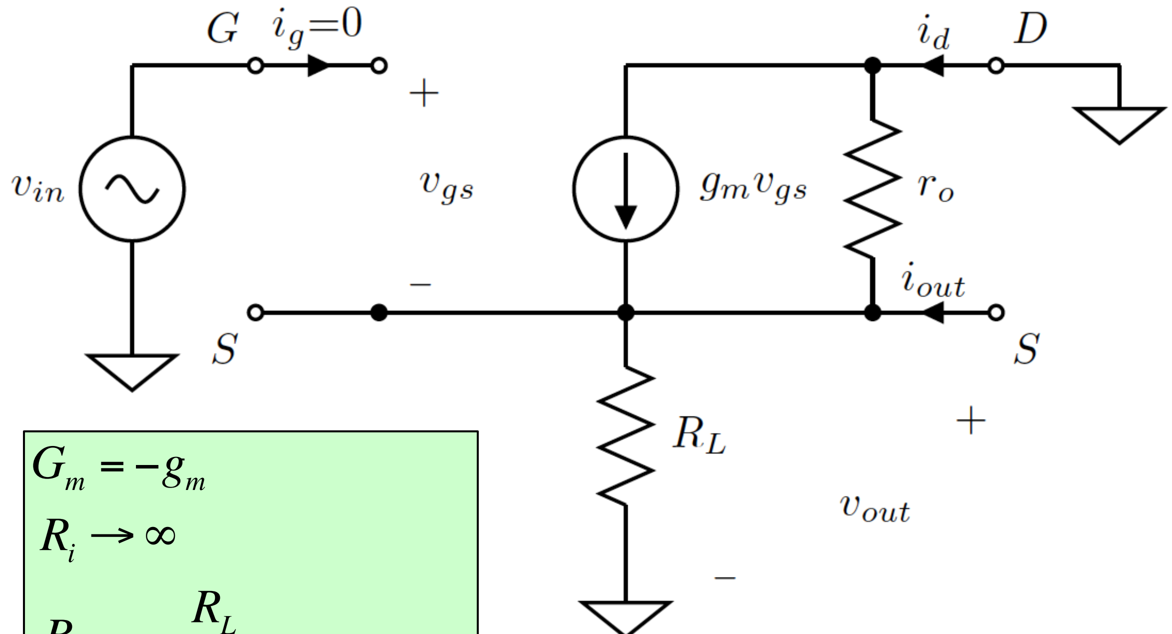
Saturation region check:

$$V_{DS} = V_{DD} - V_{OUT} > V_{GS} - V_{TH} = V_{IN} - V_{OUT} - V_{TH}$$

$$V_{DD} > V_{IN} - V_{TH}$$

Common-Drain Small Signal Model





$$G_m = -g_m$$

$$R_i \to \infty$$

$$R_o = \frac{R_L}{1 + g_m R_L}$$

$$A_v = -G_m R_o = \frac{g_m R_L}{1 + g_m R_L}$$

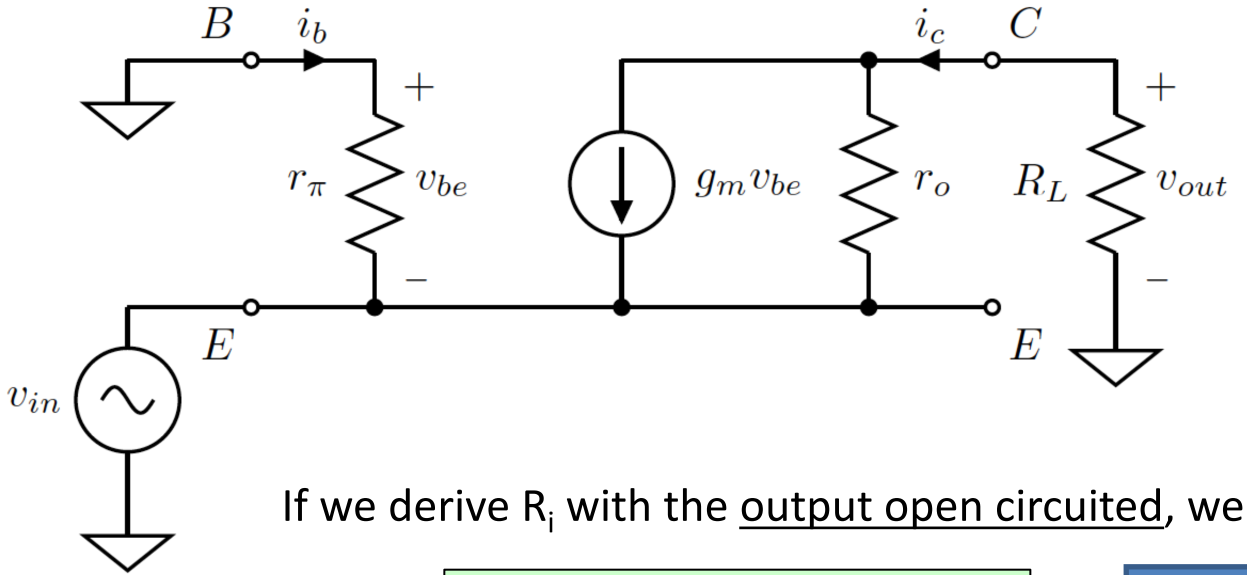
Single-Stage Amplifiers

	CE/CS	CB/CG	CC/CD
G_m	g_m	$-g_m$	$-g_m$
R_o	$r_o \parallel R_L$	$r_o \parallel R_L$	$\frac{R_L}{1+g_m R_L}$
R_i	r_π	$\frac{1}{g_m}$	r_π
A_v	$-g_m\left(r_o \parallel R_L\right)$	$g_m\left(r_o \parallel R_L\right)$	$\frac{g_m R_L}{1+g_m R_L}$

Can we use this diverse set of characteristics to create better amplifiers?

Input Resistance Revisited (1)

- Common-Base/Common-Gate Amplifier



$$R_i = r_\pi \,||\, r_o \,||\, \frac{1}{g_m} \approx \frac{1}{g_m}$$

Derived assuming <u>no-load conditions</u>

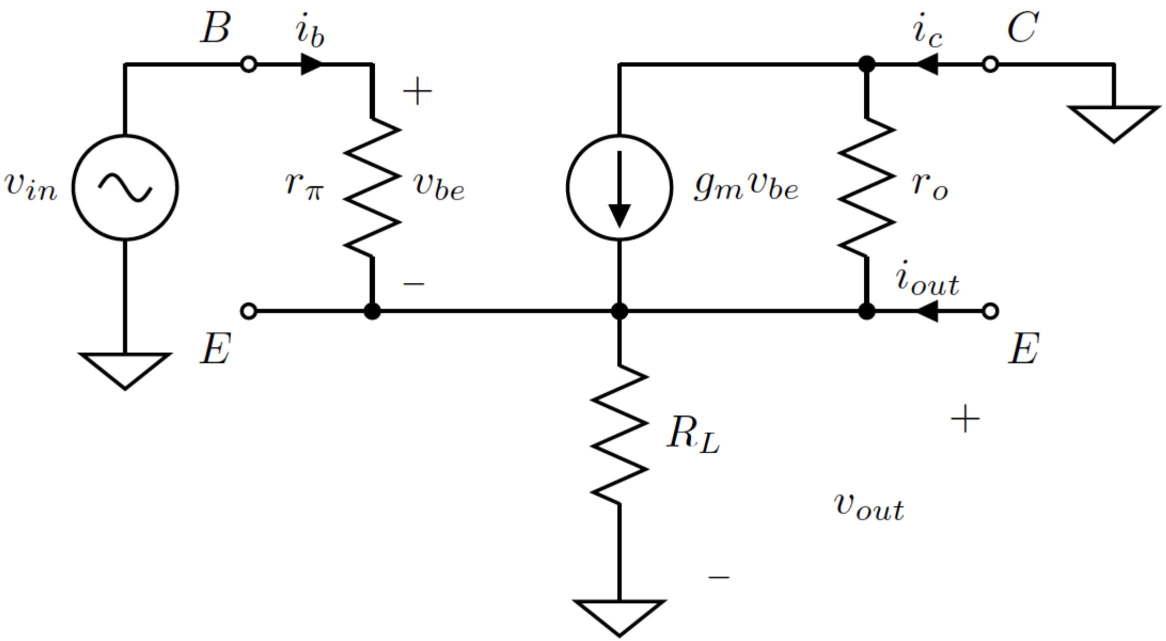
If we derive R_i with the <u>output open circuited</u>, we get:

$$R_i = r_\pi \,||\, \frac{1}{g_m} + \frac{R_L}{g_m r_o} \approx \frac{1}{g_m} + \frac{R_L}{g_m r_o}$$

Dependent on R_L!

Input Resistance Revisited (1)

- Common-Collector/Common-Drain Amplifier



$R_i = r_\pi$

Derived assuming <u>no-load conditions</u>

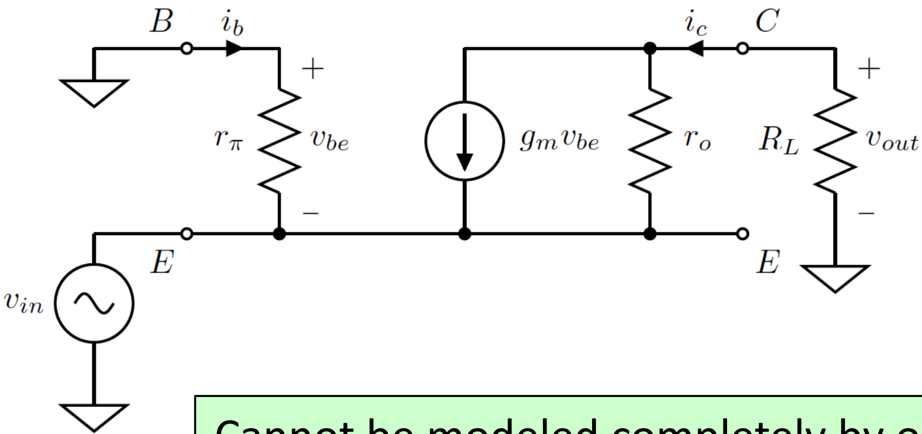
If we derive R_i with the <u>output open circuited</u>, we get:

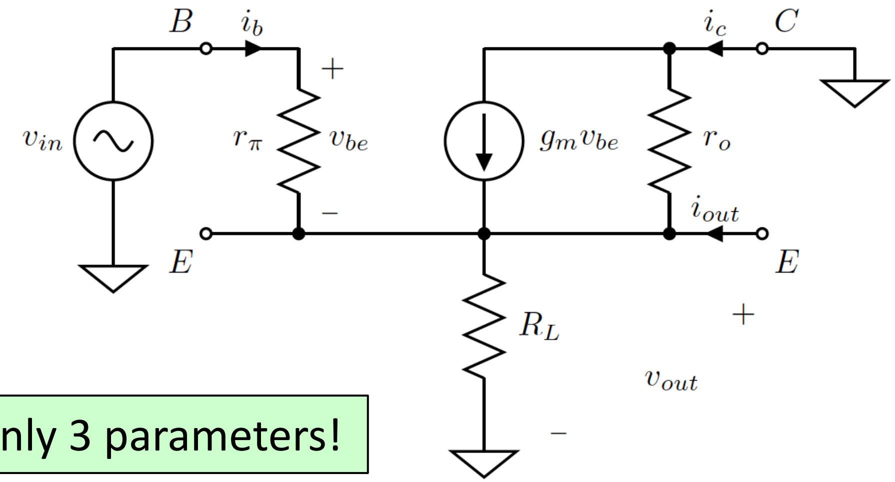
$R_i \approx r_\pi\left(1 + g_m R_L\right)$

Dependent on R_L!

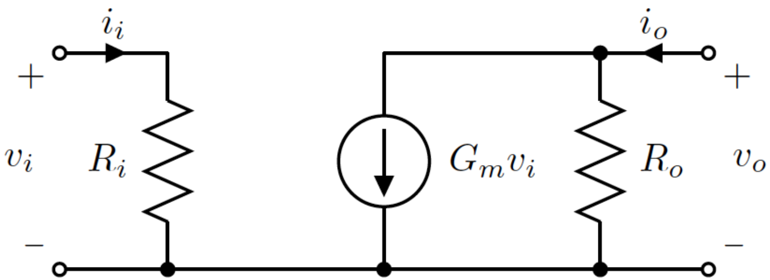
Bilateral Behavior

- CB/CG and CC/CD





Cannot be modeled completely by only 3 parameters!

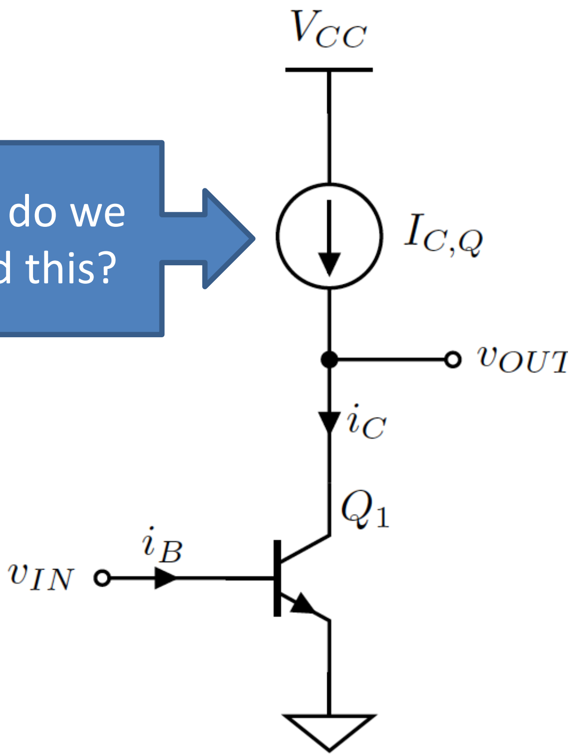


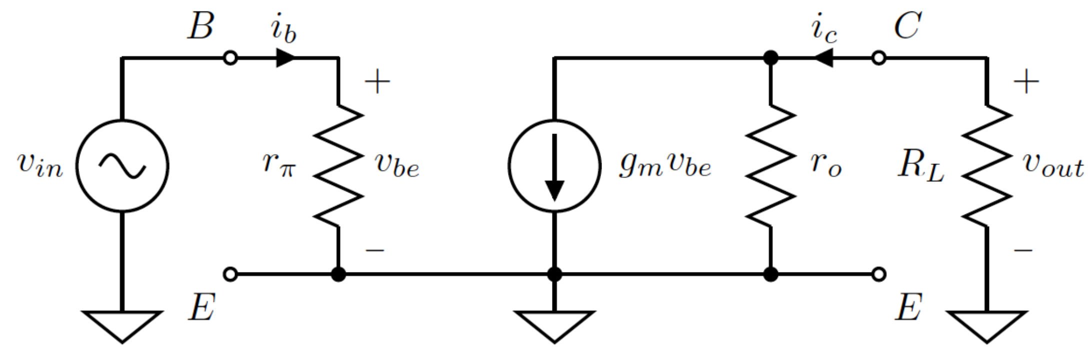
Model results in <u>output condition dependent</u> R_i

Current Sources

- Recall: When can we achieve a gain close to a_o?

How do we build this?



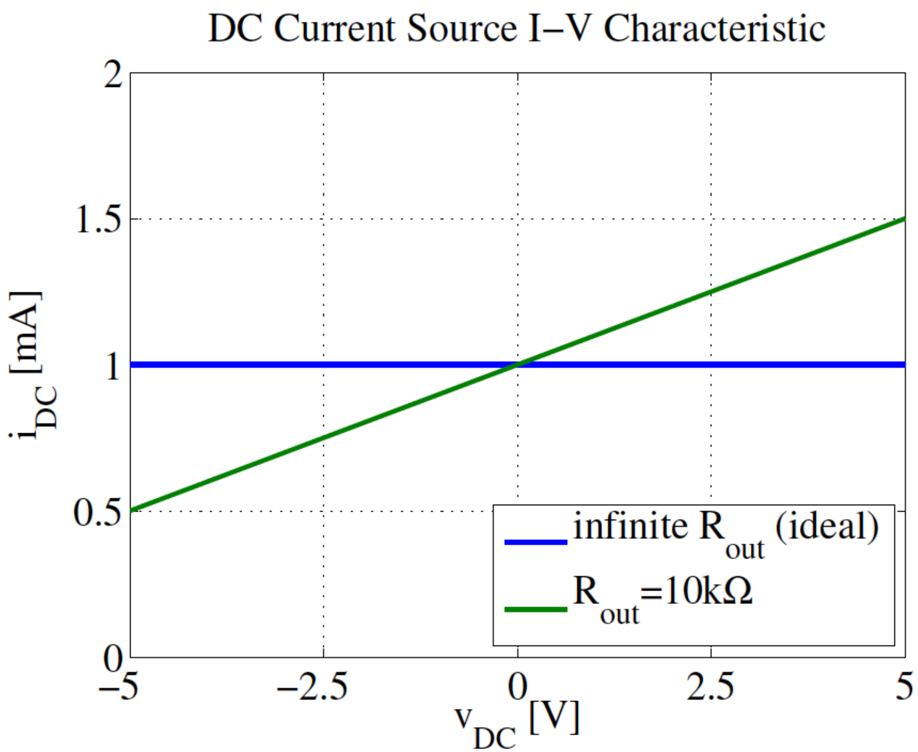


$R_L \to \infty$

$$\boxed{a_o = -g_m r_o}$$

What Are Current Sources?

- Practical Current Sources



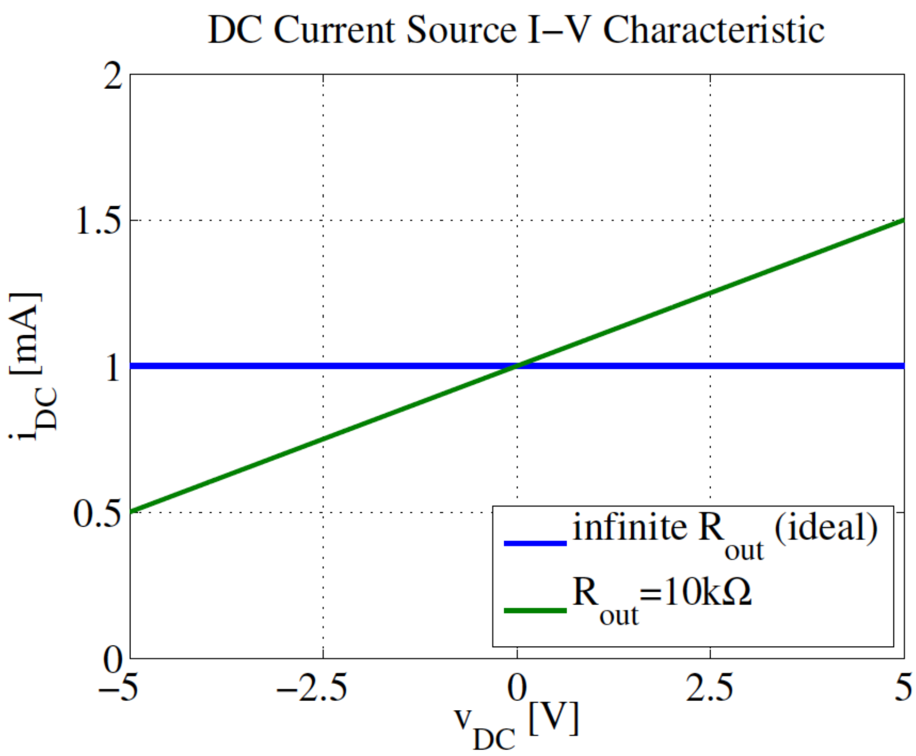
We can't really make a perfect current source (yet)…

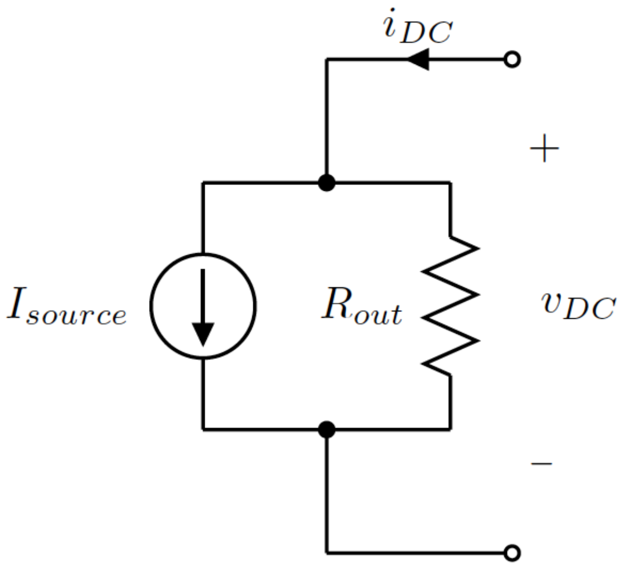
But we can get <u>very</u> close

Current source metrics?

1. Output resistance
2. Minimum output voltage

Current Source Output Resistance, R_{out}

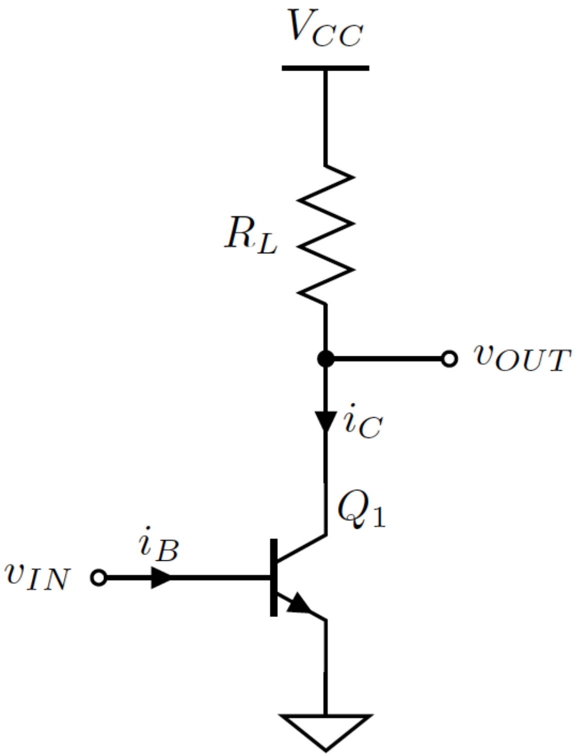




$$i_{DC} = I_{source} + \frac{v_{DC}}{R_{out}}$$

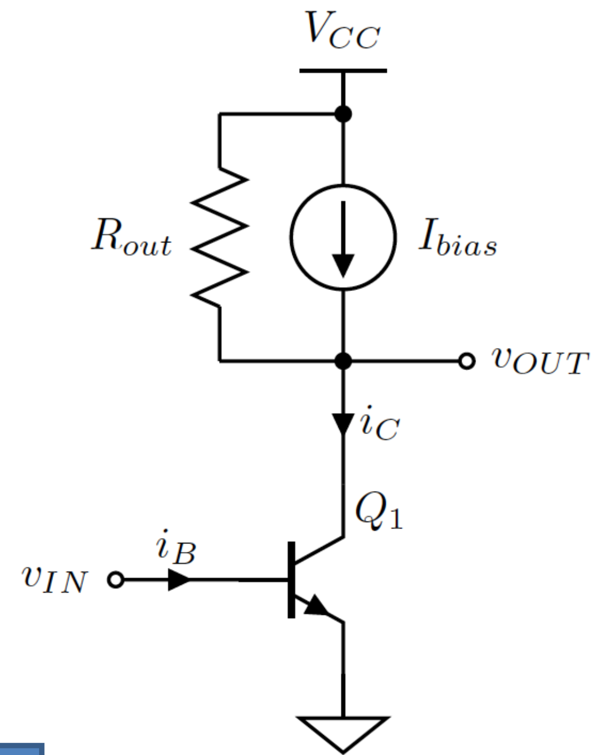
Voltage dependent!

Implications of Using Current Source for Biasing



Spot the difference?

vs.

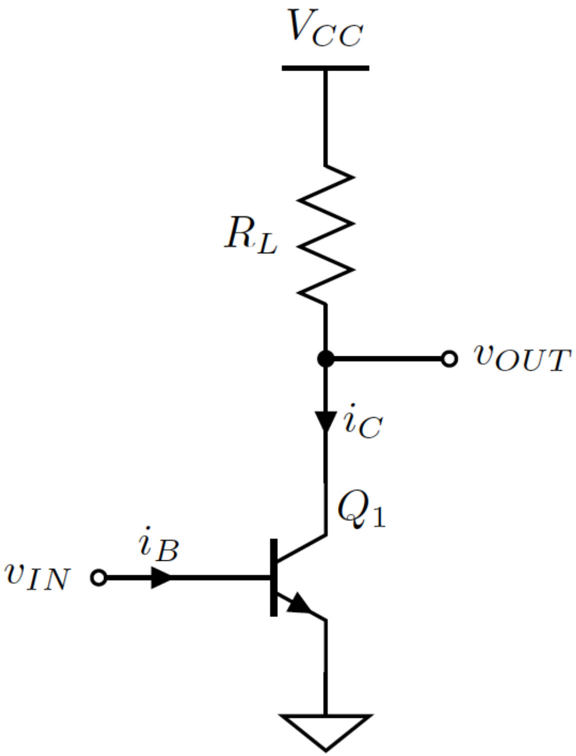


$$A_v = -g_m \left(r_o \parallel R_L \right)$$

To increase A_v, increase R_L and R_{out}

$$A_v = -g_m \left(r_o \parallel R_{out} \right)$$

Can We Increase R_L Arbitrarily?



$$A_v = -g_m \left(r_o \parallel R_L \right)$$

What happens to the output DC voltage?

$$V_{OUT} = V_{CC} - I_{C,Q} R_L$$

For the same current, increasing R_L reduces V_{OUT}

To remain in the forward-active region:

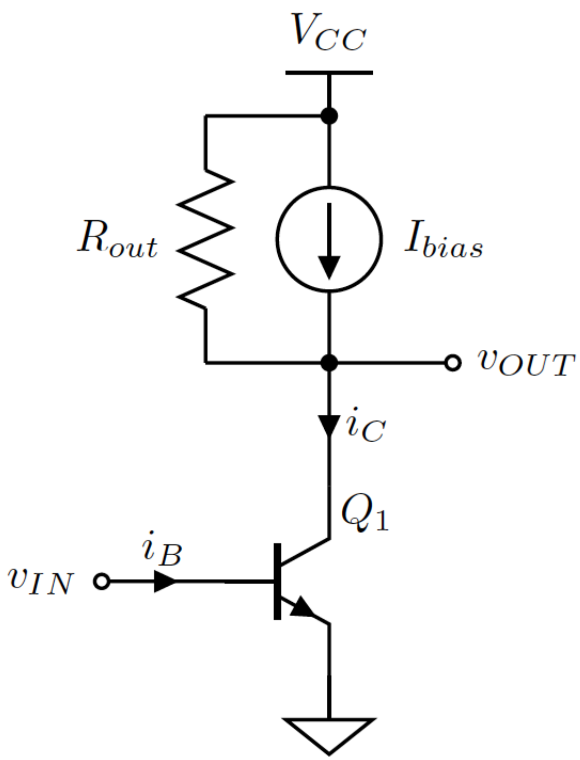
$$V_{OUT} = V_{CE,Q} > V_{CE,sat} \Rightarrow R_L < \frac{V_{CC} - V_{CE,sat}}{I_{C,Q}}$$

To increase R_L, we can increase V_{CC}

→ Is this a good idea?

→ **Tradeoff between A_v and V_{CC}!**

Biasing The BJT Using A Current Source



$$A_v = -g_m \left(r_o \parallel R_{out} \right)$$

Output DC voltage?

$$V_{OUT} = V_{CC} - \left(I_{C,Q} - I_{bias} \right) R_L$$

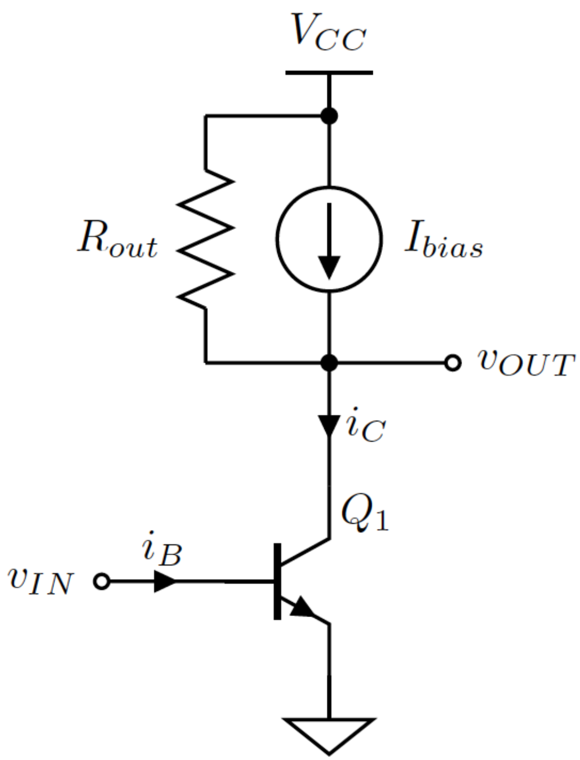
But…

$R_L \to \infty$ ⇒ $I_{bias} \to I_{C,Q}$

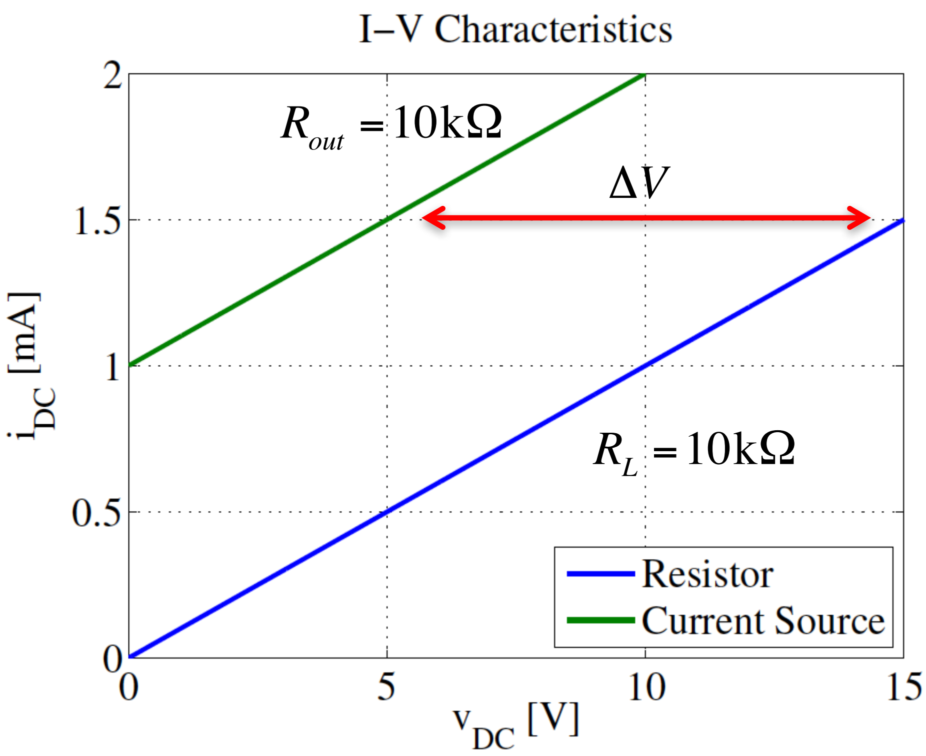
Can increase R_L indefinitely without having to increase V_{CC}!

In practice, this usually means we can get away with <u>lower supply voltages</u> if we use current sources!

Resistor vs. Current Source Biasing



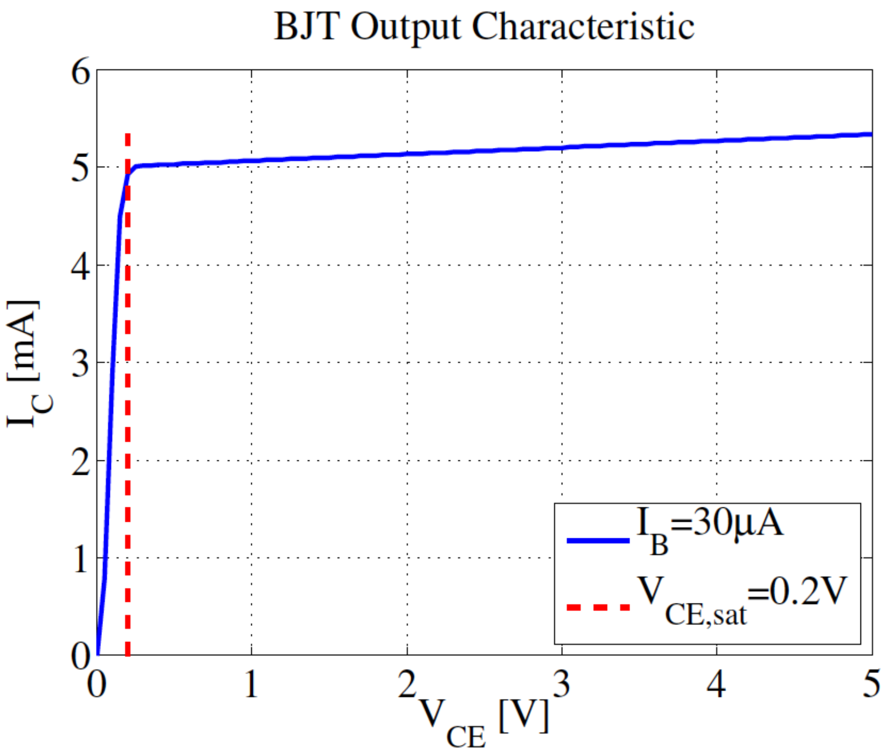
$$A_v = -g_m \left(r_o \parallel R_{out} \right)$$

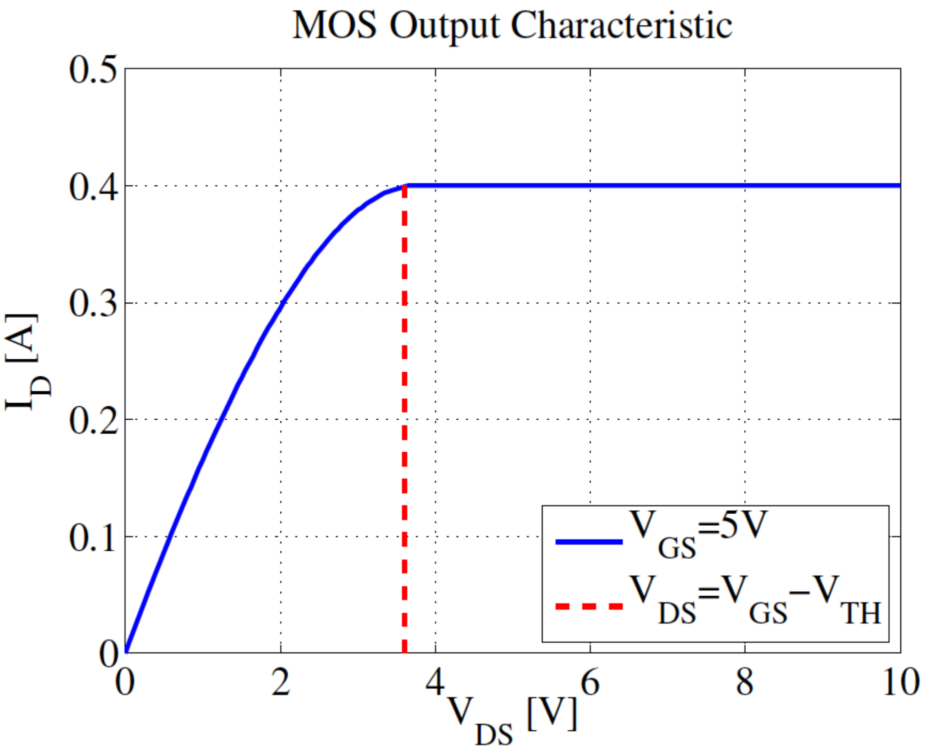


Linear vs. Non-linear

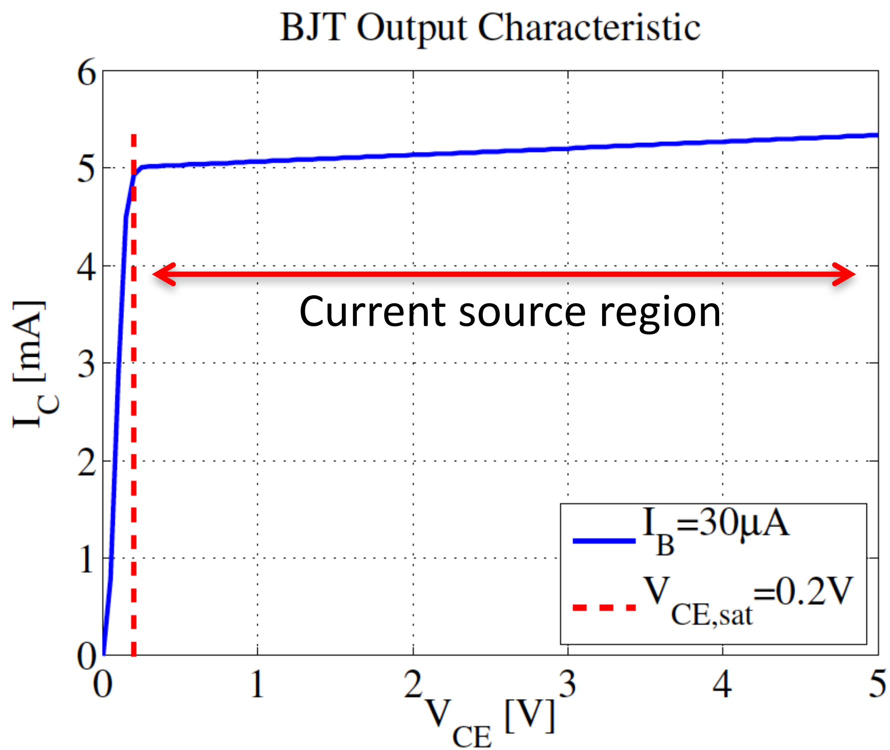
How Do We Build Current Sources?

- Transistor Output Characteristics (hmmm...)

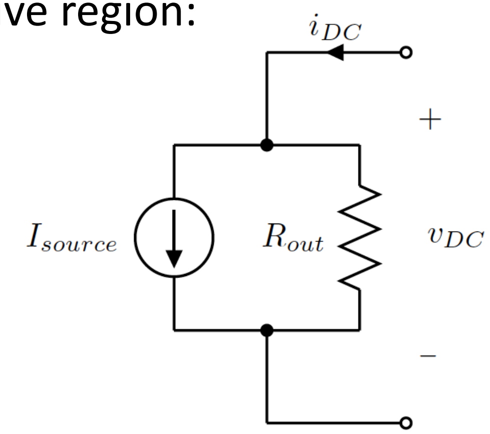




A BJT Current Source



In the forward-active region:



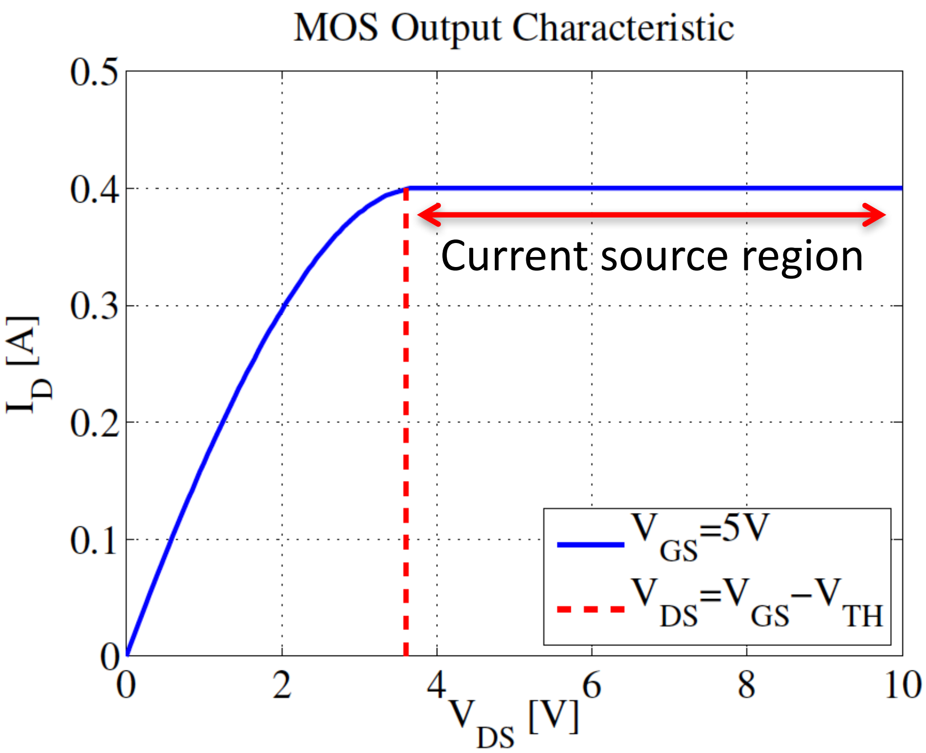
$$I_{source} \approx 5\text{mA}$$

$$R_{out} = \left(\frac{\partial I_C}{\partial V_{CE}}\right)^{-1} = r_o$$

Additional metric: $\mathbf{V_{min}}$

$$\boxed{V_{\min} = V_{CE,sat}}$$

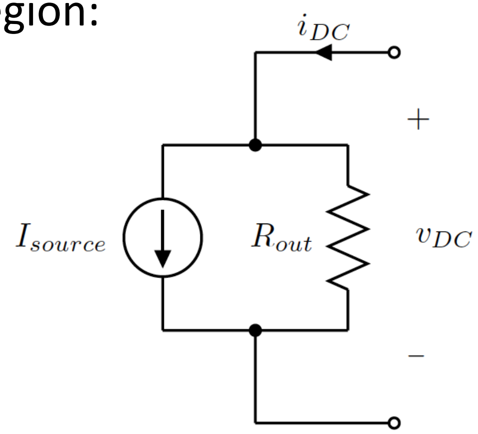
A MOSFET Current Source



In the saturation region:

$$I_{source} \approx 0.4\text{A}$$

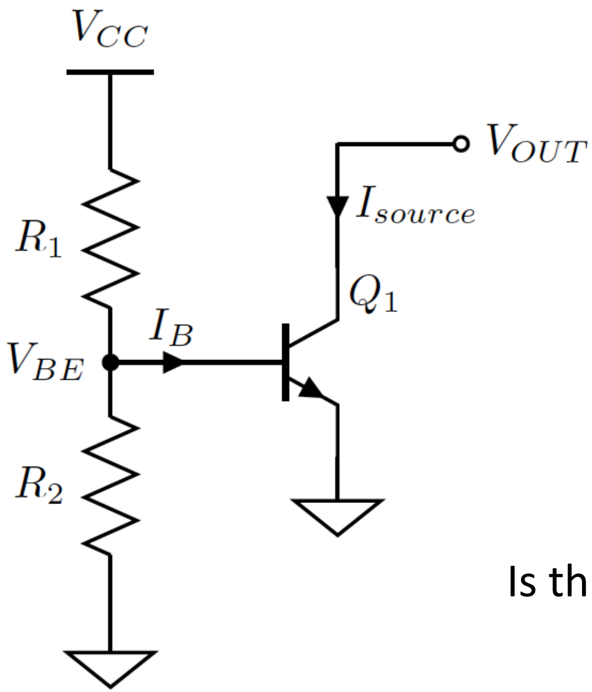
$$R_{out} = \left(\frac{\partial I_D}{\partial V_{DS}}\right)^{-1} = r_o$$



Additional metric: $\mathbf{V_{min}}$

$$\boxed{V_{\min} = V_{GS} - V_{TH}}$$

- Provide V_{BE} using a voltage divider



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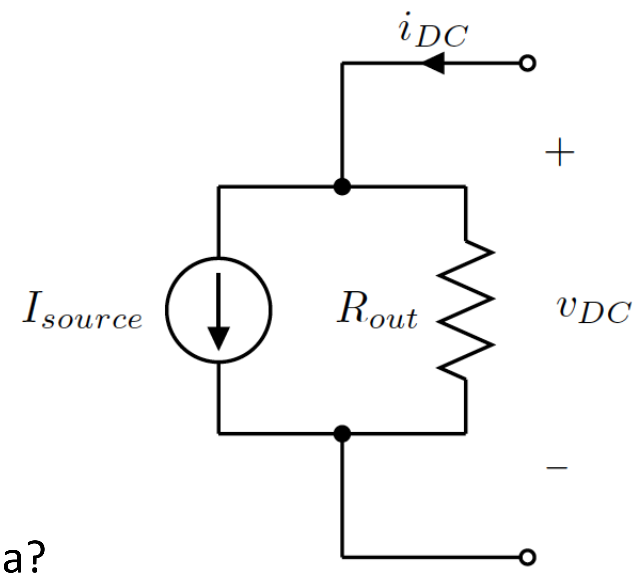

Is this a good idea?

Next Meeting

- Current Mirrors
- Differential Circuits