EE2013

NON-LINEAR CIRCUIT ANALYSIS

LECTURE 15: BJT APPLICATIONS

Instructors: Alex Jaeger, Anthony Wall
Coordinator: Prof. Pádraig Cantillon-Murphy

LECTURE SCHEDULE

Thursdays 11am-1pm
(with short break)

Monday 9am-10am slot not used!

LECTURE NOTES

https://www.jaeger.ie/ee2013/lec15

Uploaded after lecture takes place

QUESTIONS?

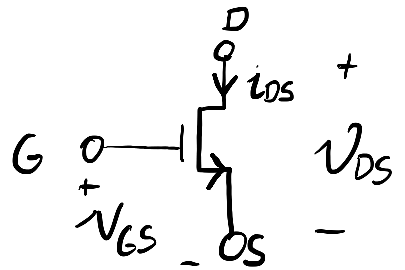
Just ask whenever it comes to you!

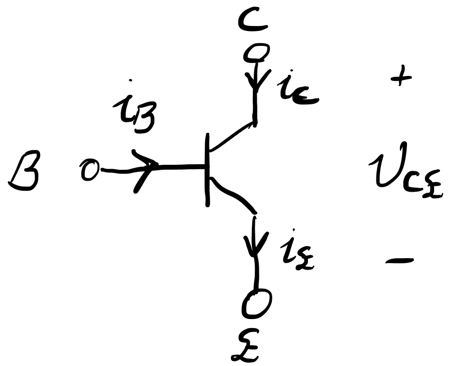
OR:

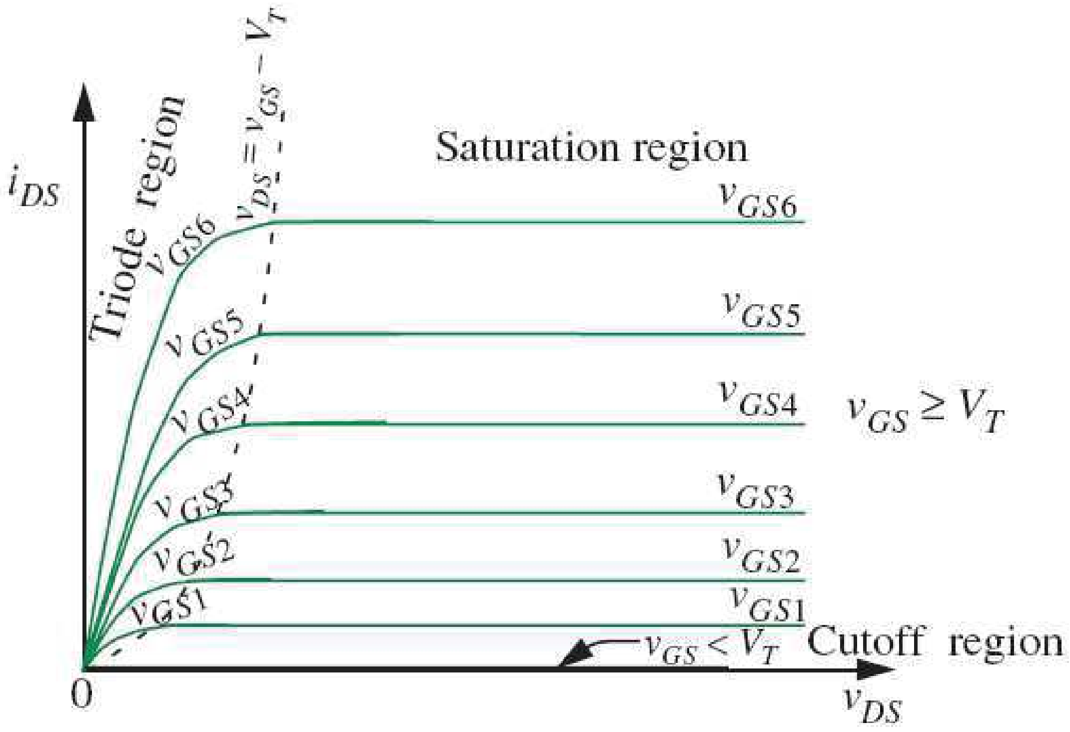
anthony.wall@mcci.ie on Email, Teams or Canvas

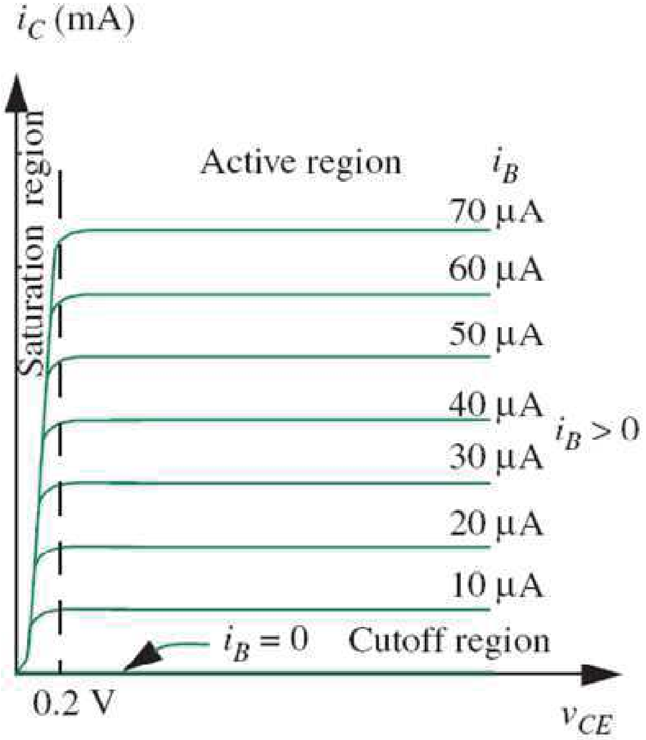
1 Review from Last Time

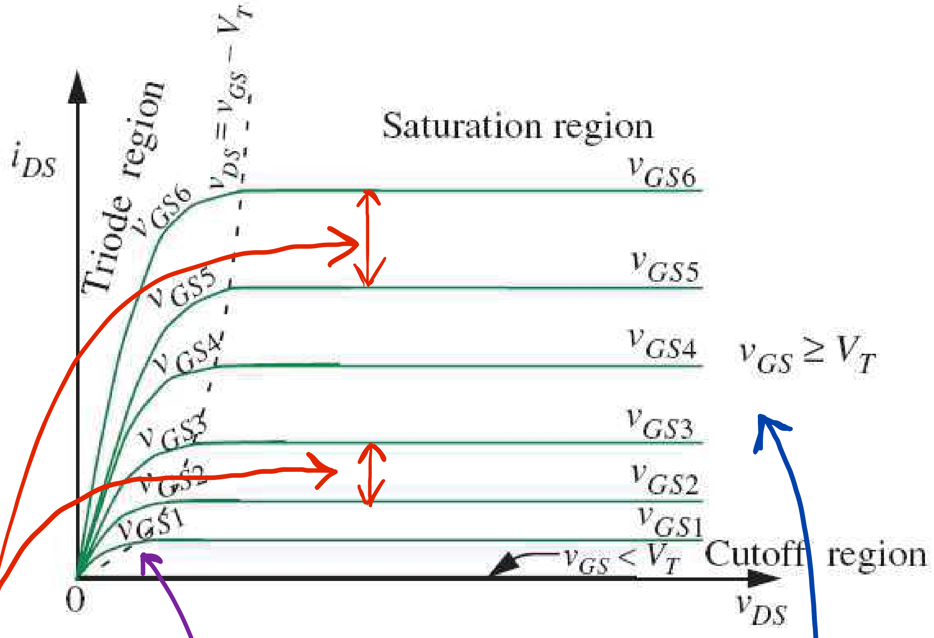
1.1 Comparing the MOSFET and BJT

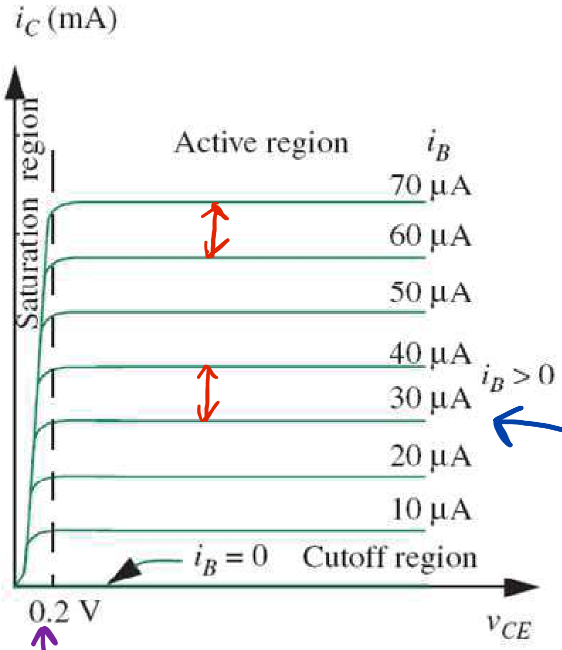






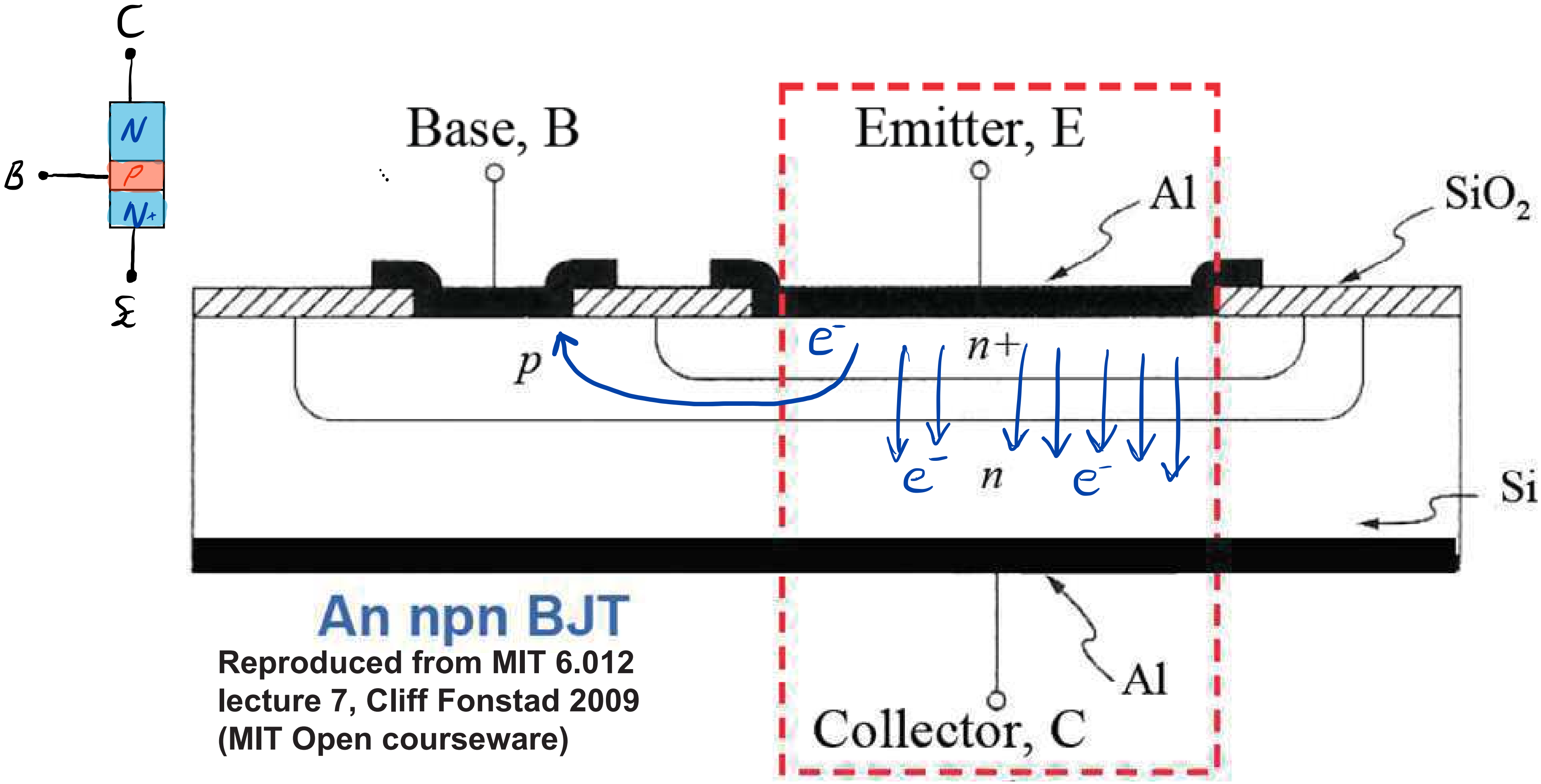






MOSFET	BJT
Saturation for $v_{DS} > v_{GS} - V_T$	Forward active for $v_{CE} > 0.2$ V
$i_{DS(sat)} = \frac{K}{2}(v_{GS} - V_T)^2$	$i_C = \beta i_B$
Voltage controlled current source	Current controlled current source
Non-linear device in saturation	Linear device in forward active

2 Physical BJT Operation

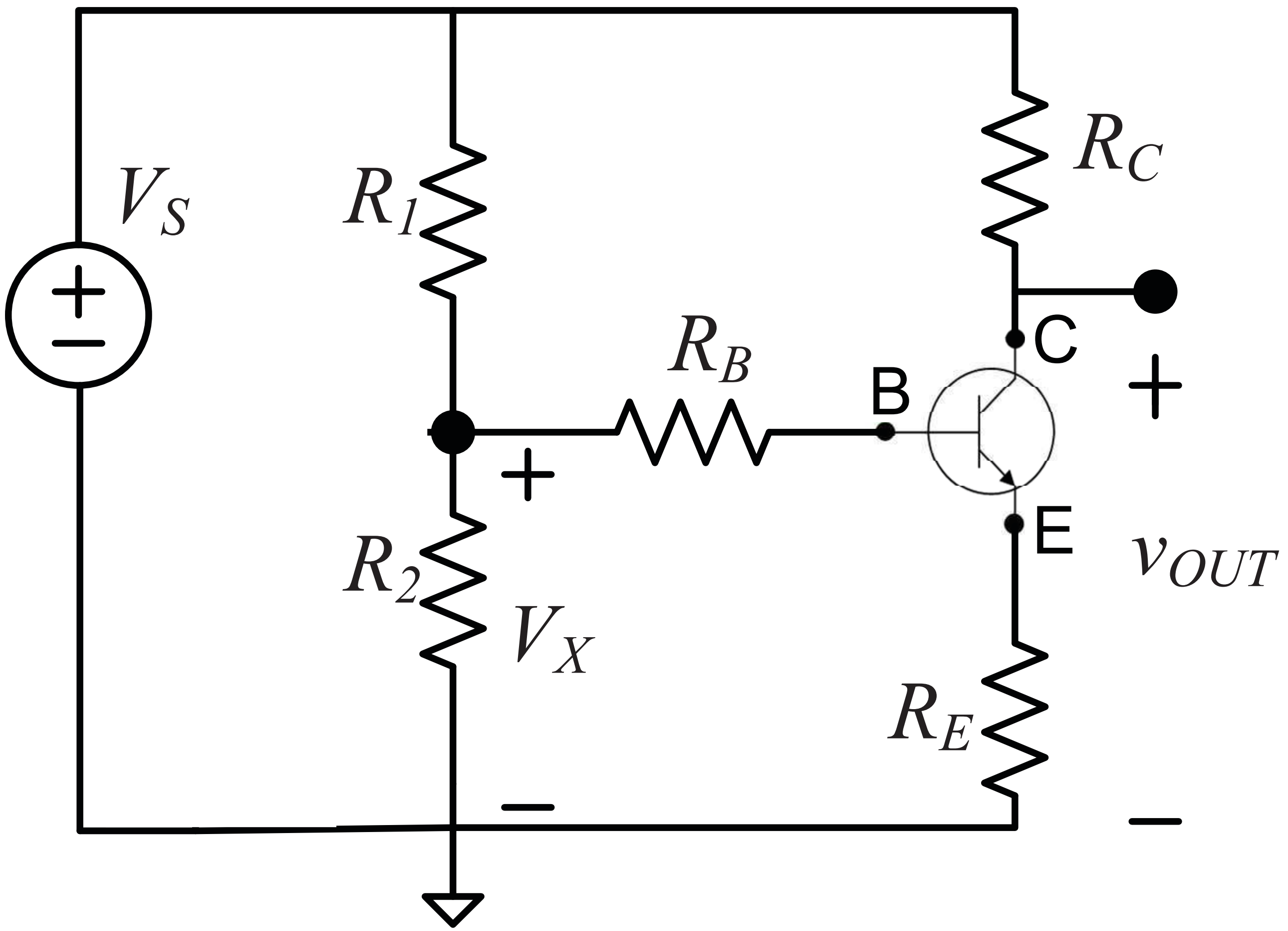


Reproduced from MIT 6.012 lecture 7, Cliff Fonstad 2009 (MIT Open courseware)

A typical NPN transistor comprises two semiconductor p-n junctions that share a thin p-doped 'sandwich.' In typical operation, the base-emitter junction is forward biased ($v_{BE} \approx 0.6$ V) so that thermally excited electrons are injected from the emitter into the base region. These electrons diffuse through the base from the region of high concentration near the emitter towards the region of low concentration near the collector. The collector-base junction is reverse-biased ($v_{CB} < 0.4$ V), and so little electron injection occurs from the collector to the base, but electrons that diffuse through the base towards the collector are swept into the collector by the electric field in the depletion region of the collector-base junction. It is this phenonomen that results in the large current gain, characterised by β, when the device operates in the *forward active region.*

3 DC bias and the Common Emitter Amplifier

It is usual to ensure that the BJT operates in its forward active region by adding some *biasing* resistors at the input to ensure $i_B > 0$. Consider the circuit shown below with the biasing resistors, R_1 and R_2.



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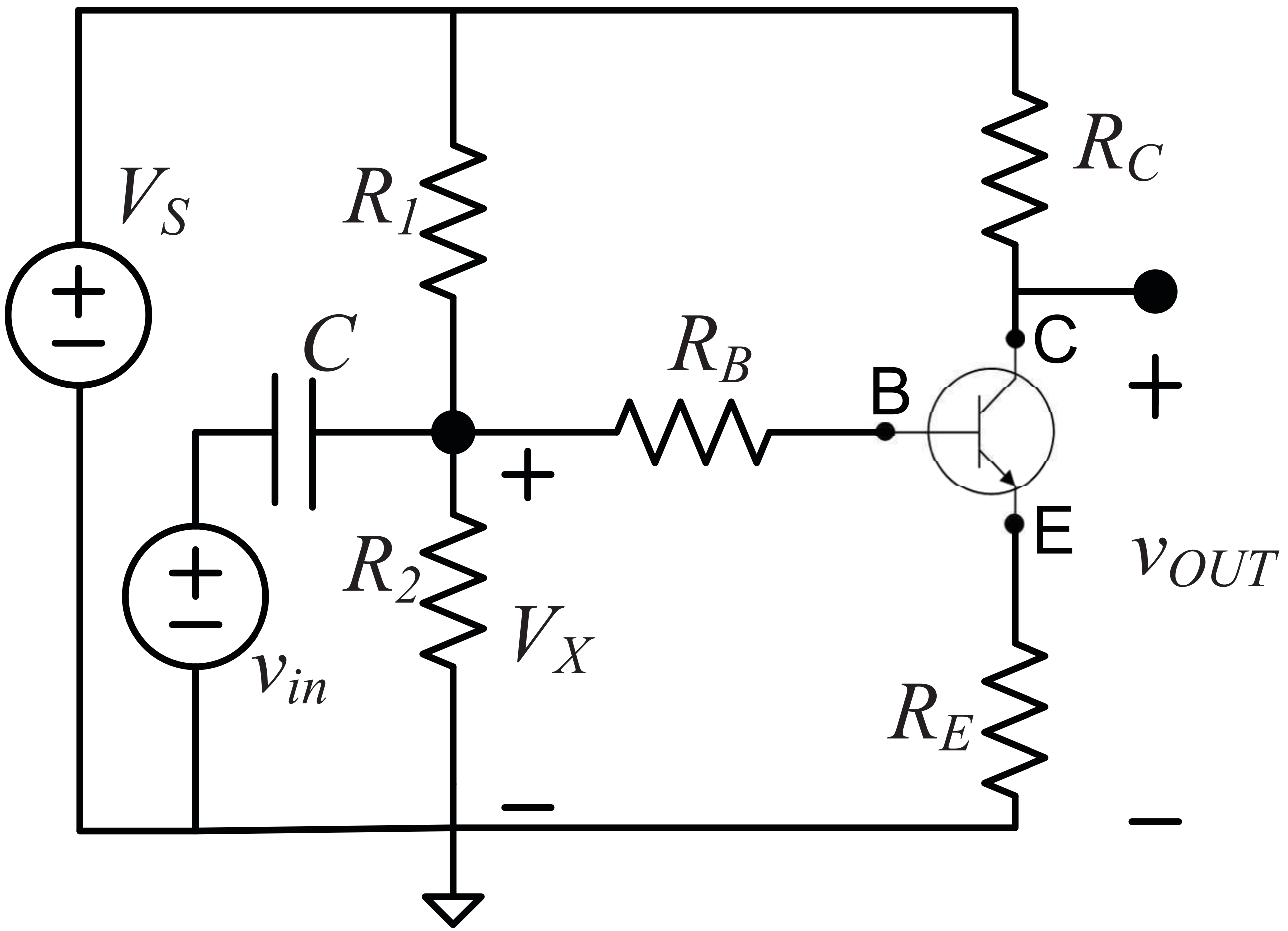

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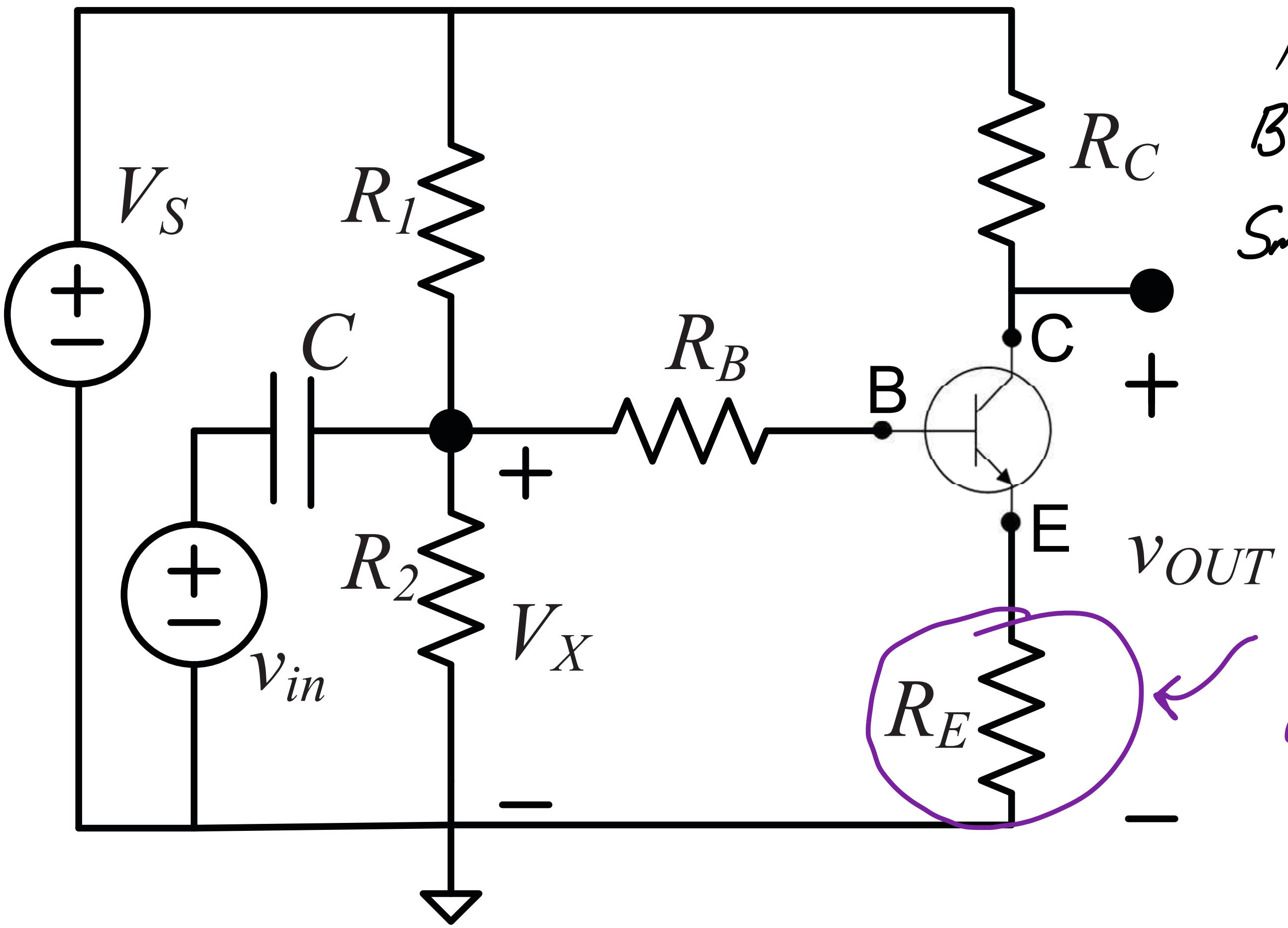


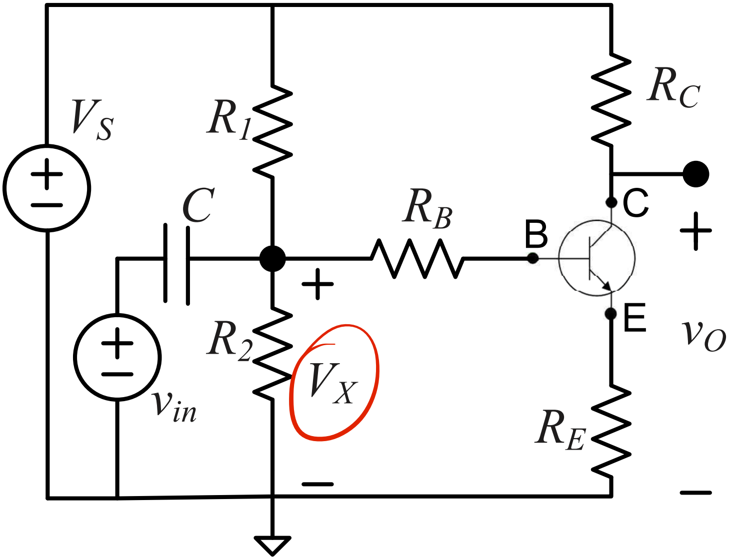
β varies between otherwise identical BJTs.

Small signal gain:

$$\frac{v_o}{v_i} = -\beta\left(\frac{R_C}{R_B}\right)$$

Adding R_E removes gain dependance on R_E

In order to ensure that the bias resistor divider voltage (V_X) is not shorted to ground for large-signals (when $v_{in} \to 0$), we need to add a *blocking* capacitor, C, which can be treated as an open circuit for DC signals and a short for *small-signal* analysis. The circuit also differs from that last lecture, due to the addition of the emitter resistance, R_E. We assume the DC voltage drop between the base and emitter is 0.6 V when the device operates in forward active mode.



3.1 Large Signal (DC) Analysis

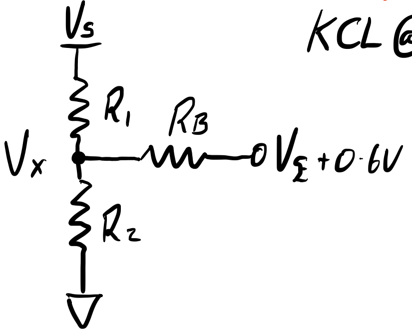
Consider the DC component of the output voltage, V_{OUT}:

$$V_{OUT} = V_S - I_C R_C = V_S - \beta I_B R_C$$

$$I_B = \frac{V_X - V_B}{R_B} = \frac{V_X - (V_E + 0.6)}{R_B} = \frac{V_X - [(\beta+1) I_B R_E + 0.6]}{R_B}$$

In terms of I_B: $I_B = \dfrac{V_X - 0.6}{R_B + (\beta + 1) R_E}$

What is V_X?

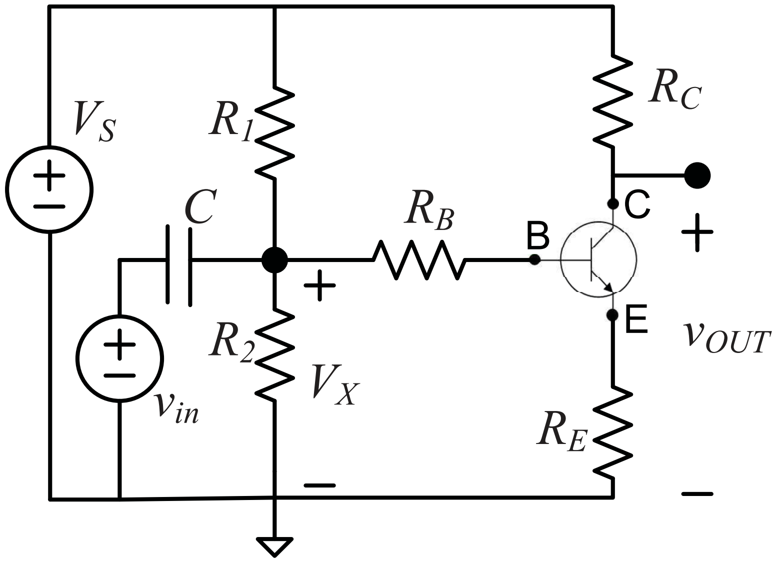


KCL @ V_X: $\dfrac{V_S - V_X}{R_1} - \dfrac{V_X}{R_2} - \dfrac{V_X - (V_E + 0.6)}{R_B} = 0$

$$V_X = \frac{(V_E + 0.6)\frac{R_1}{R_B} + V_S}{1 + R_1\left(\frac{R_B R_2}{R_B + R_2}\right)}$$

$$V_X \simeq \frac{V_S R_2}{R_1 + R_2}$$

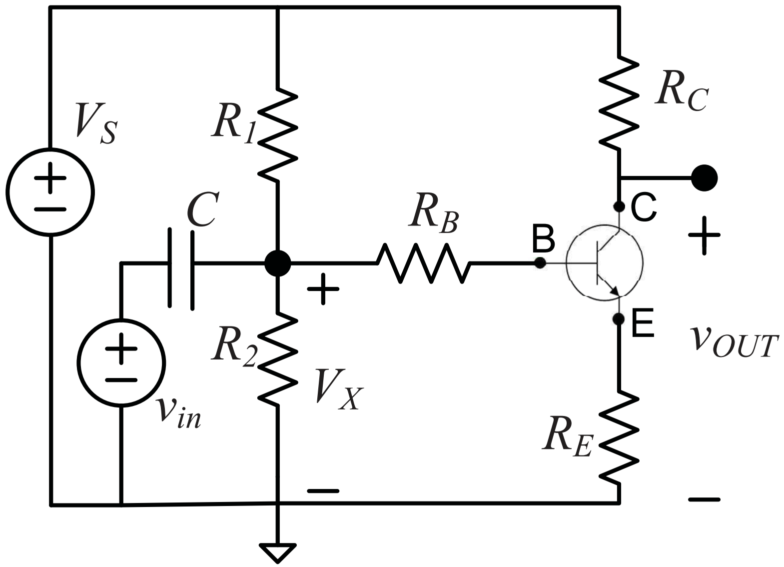
When $R_B >> R_1, R_2$ ONLY



Consider the numerical quantities given here: ~~$R_B = 1\text{k}\Omega$~~, $R_C = 10\text{k}\Omega$, $\beta = 100$, and $V_S = 10$ V. Also, assume ~~$R_1 = 6\text{M}\Omega$~~, ~~$R_2 = 4\text{M}\Omega$~~, and $R_E = 10\text{k}\Omega$. $R_B = 100\text{k}\Omega$, $R_1 = 50\text{k}\Omega$, $R_2 = 50\text{k}\Omega$

The DC base voltage, V_B is then calculated from I_B:

$$V_B = V_X - I_B R_B =$$



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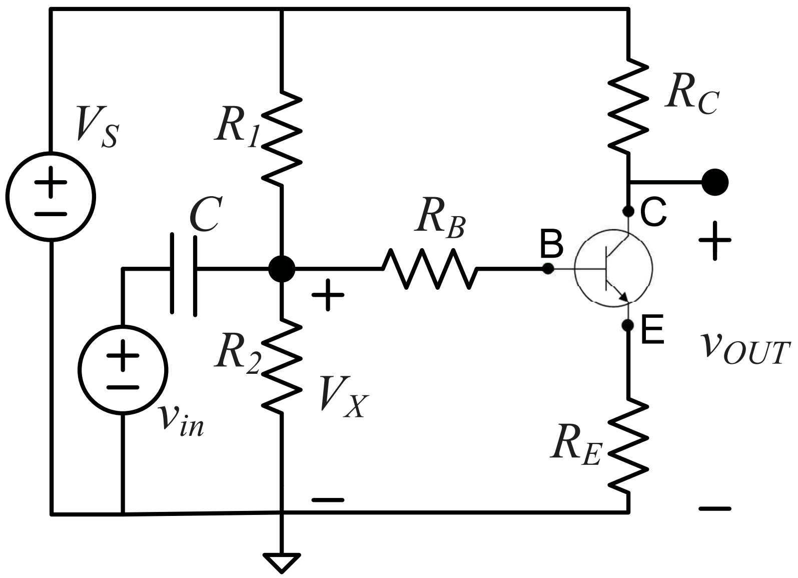
$$V_X \simeq \frac{(10)(50k)}{50k + 50k} = 5\,V \qquad I_B = \frac{5 - 0.6}{(100k) + (100+1)(10k)} = 3.4\,\mu A$$

The DC base voltage, V_B is then calculated from I_B:

$$V_B = V_X - I_B R_B = 5 - (3.4\mu)(100k) = 4.66\,V$$



The DC base and emitter voltages only differ by the internal diode drop in forward active operation:

$$V_E = V_B - 0.6 = 4.06\,V$$

Therefore, V_{CE} is given by:

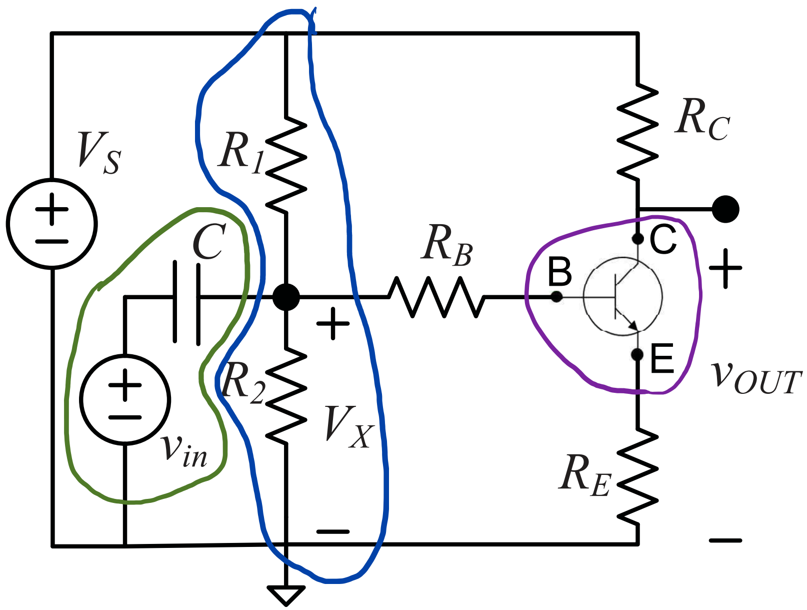
$$V_{CE} = V_{OUT} - V_E = [V_S - (\beta I_B)R_C] - V_E$$

$$= 10 - 100(3.4\mu)(10k) - 4.06$$

$$= 2.54\,V$$

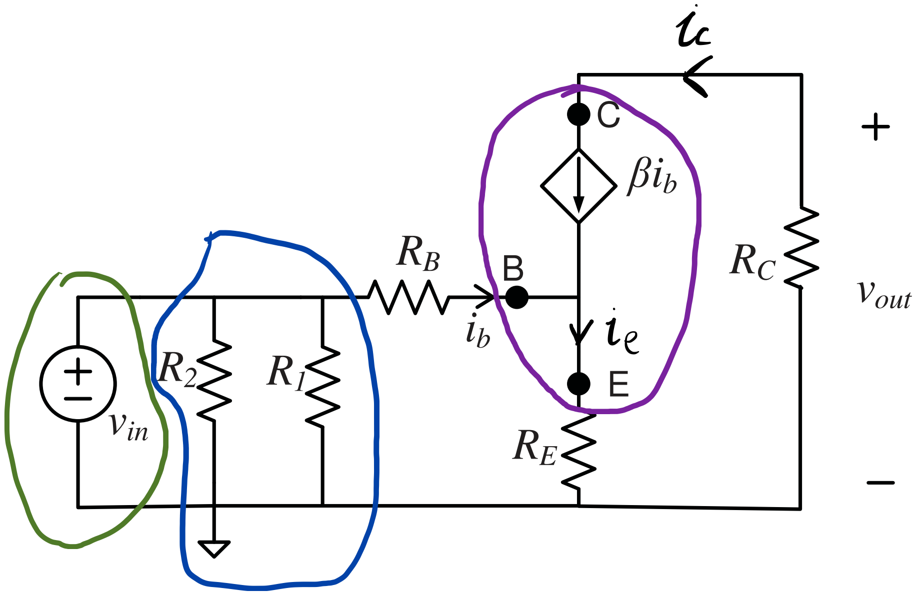
✓ forward Active Region

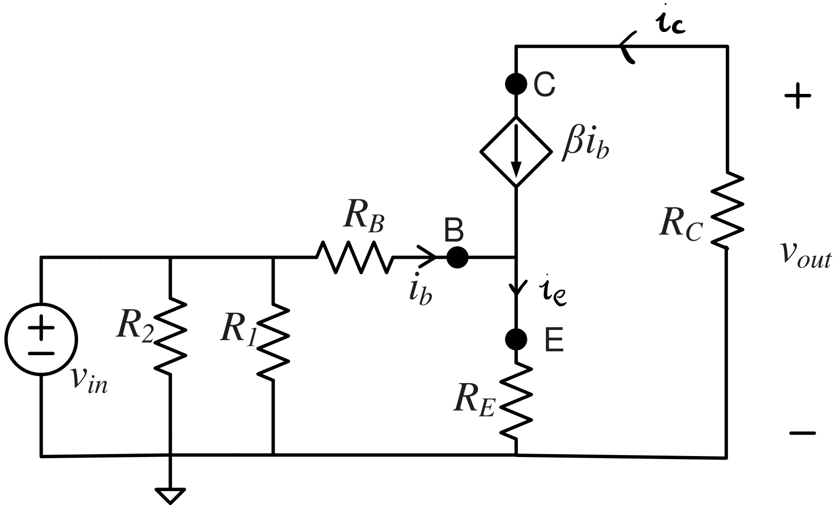
Clearly the condition for the device to operate in its forward active region ($V_{CE} > 0.2$ V) is satisfied.



3.2 Small-signal Voltage Gain

To calculate the small-signal voltage gain, A_v, we set all DC voltage sources to zero (including the internal 0.6 V voltage drop from the base-emitter diode) and replace the capacitor with a short circuit. The BJT is replaced with its small-signal model in forward active operation.





$$v_{out} = -i_c R_c = -\beta i_b R_c$$

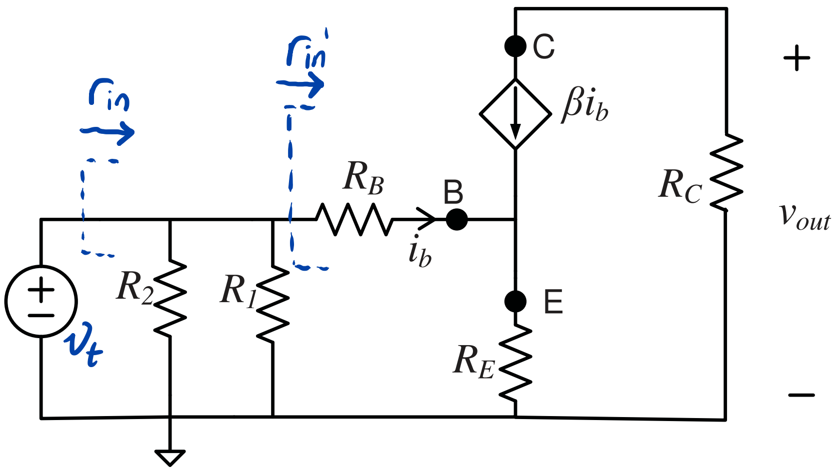
$$i_b = \frac{v_{in} - v_e}{R_B} = \frac{v_{in}}{R_B} - \frac{(\beta+1)\, i_b R_E}{R_B}$$

Simplifying this expression in terms of i_b: $i_b = \dfrac{v_{in}}{R_B + (\beta + 1)R_E}$

$$\frac{v_{out}}{v_{in}} = \frac{-\beta R_c}{R_B + (\beta+1)R_E} \approx \frac{-\beta R_c}{(\beta+1)R_E} \approx \frac{-R_c}{R_E}$$

3.3 Small-signal Input Resistance

To calculate the small-signal input resistance, we turn off v_{in} and apply a test source to the input.



To simplify this process, let's look beyond R_1 and R_2, and consider the 'input resistance' looking into the base resistance, R_B. This new 'internal resistance,' r'_{in} appears in parallel with R_1 and R_2.

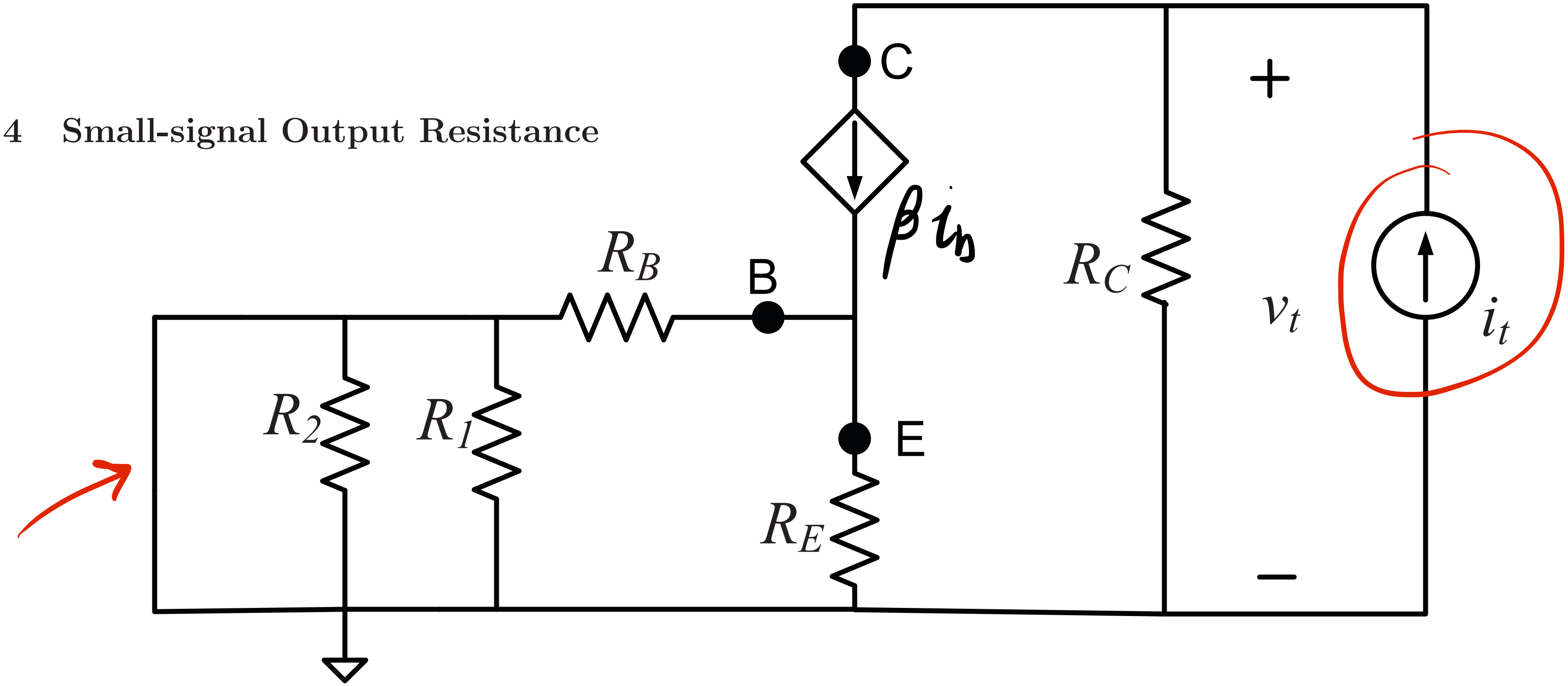
$$r'_{in} = \frac{v_t}{i_b} = R_B + (\beta+1)R_E$$

$$r_{in} = r'_{in} // R_1 // R_2$$

$$\Rightarrow r_{in} = R_1 // R_2 // (R_B + (\beta+1)R_E)$$

$$= 50k // 50 // (100k + (101)(10k)) = 24.45\,k\Omega$$

3.4 Small-signal Output Resistance



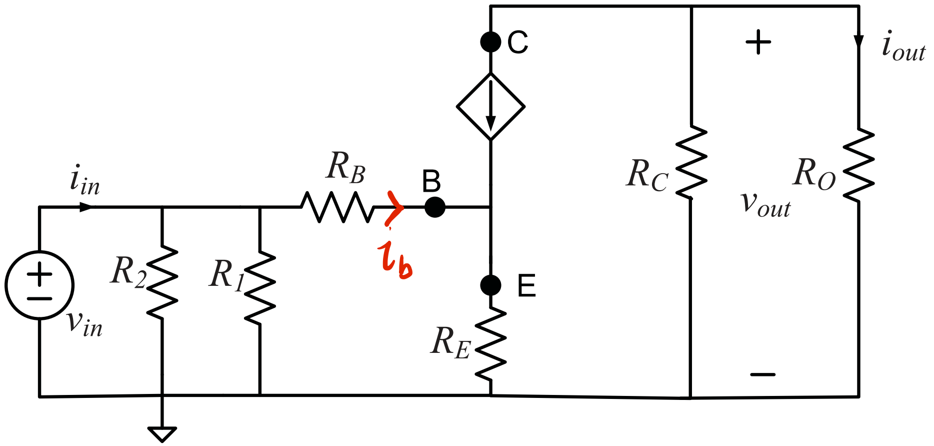
For the small-signal output resistance, we apply a test source at the output with $v_{in} \rightarrow 0$. Note that since the transistor is modeled by a small-signal current source, it is convenient to apply a test current source, i_t.

Since $v_{in}=0$, $i_b=0$, $\beta i_b=0$

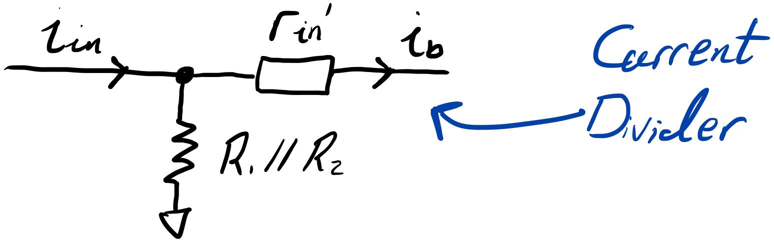
$$r_o = \frac{v_t}{i_t} = R_c = 10\,k\Omega \text{ here}$$

3.5 Small Signal Current Gain, A_i

To calculate the small-signal current gain, $A_i = i_{out}/i_{in}$, it is necessary to add an output resistance, R_O, with a value of 10 kΩ.



How much i_{in} makes it to i_b?



$$\frac{i_b}{i_{in}} = \frac{(R_1 // R_2)}{r_{in}' + (R_1 // R_2)} = \frac{25\,k\Omega}{(1.11\,M\Omega) + 25\,k\Omega}$$

$$= 0.022$$

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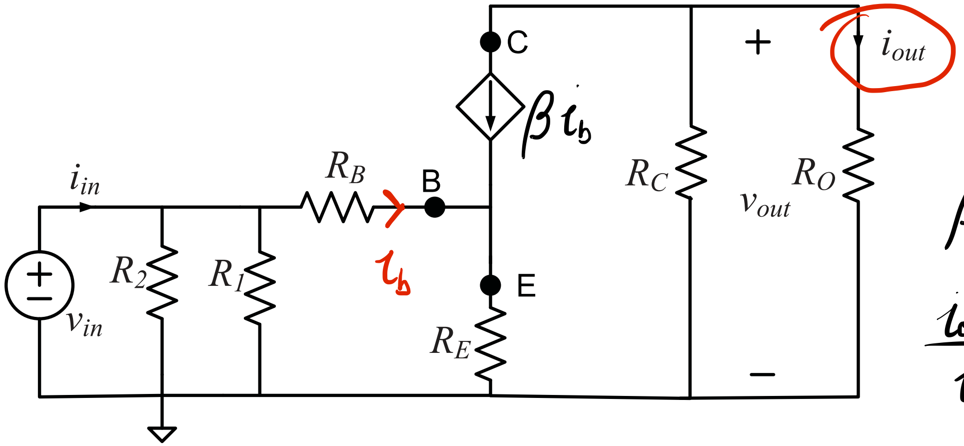

How does i_{out} relate to i_b?

KCL @ v_{out}:

$$\beta i_b + \frac{v_{out}}{R_c} + i_{out} = 0$$

$$\beta i_b + \left(\frac{-\beta i_b (R_c // R_o)}{R_c}\right) + i_{out} = 0$$

$$\frac{i_{out}}{i_b} = \beta \left(\frac{R_o}{R_c + R_o}\right) = 100 \frac{10k}{10k + 10k} = 50$$

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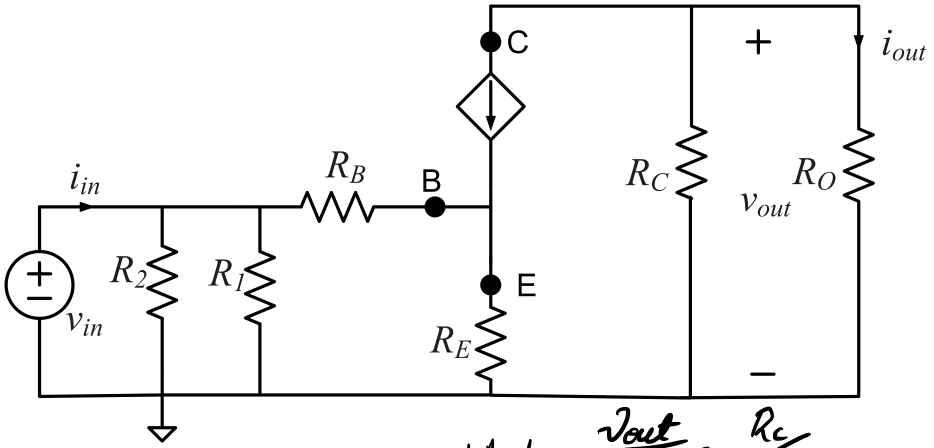

$$|A_v| = \frac{v_{out}}{v_{in}} \approx \frac{R_C}{R_E}$$

What is the Current Gain?

$$A_i = \frac{i_{out}}{i_{in}} = \frac{i_{out}}{i_b} \cdot \frac{i_b}{i_{in}}$$

$$A_i = \beta \left(\frac{R_O}{R_C + R_O}\right) \cdot \frac{(R_1 // R_2)}{r_{in}' + (R_1 // R_2)}$$

$$= (50)(0.022) = 1.1$$

What is the Power Gain?

$$A_p = |A_v||A_i| = (1)(1.1)$$