SECTION 3: BJT AMPLIFIERS

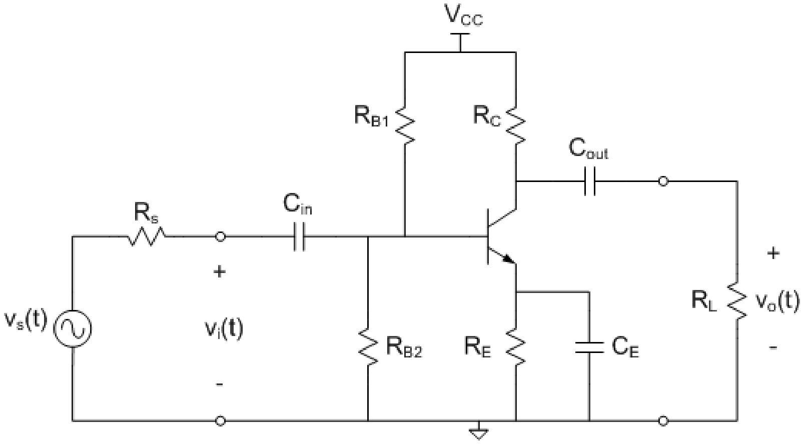
ECE 322 – Electronics I

BJT Amplifier Circuits

Transistor Amplifier Circuits – Preview

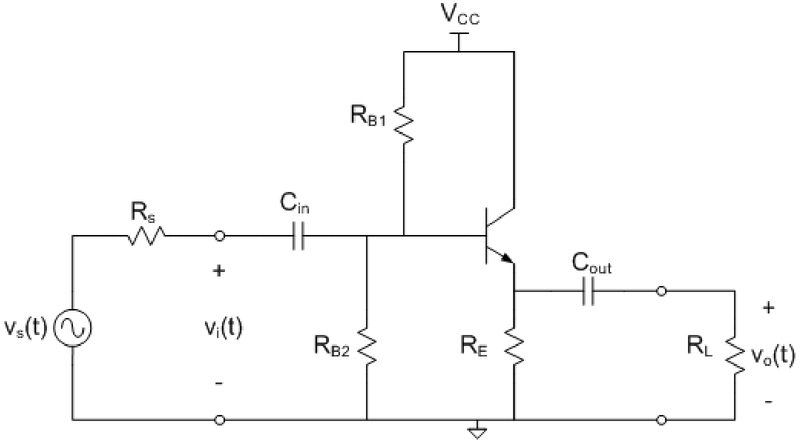
- In this section of the course, we will look at three BJT amplifiers, with a focus on the following two circuits:

Common-Emitter Amplifier:



- High voltage gain
- An amplifier

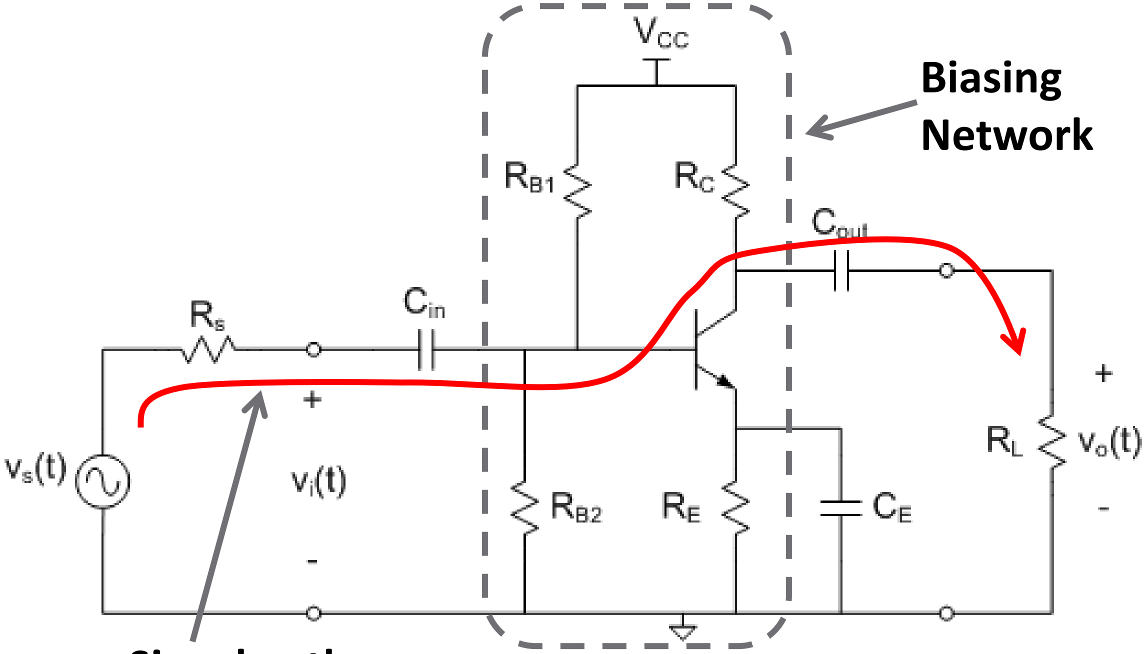
Emitter-Follower Amplifier:



- Near unity gain
- A buffer

BJT Amplifier Circuits

- Recall the two functional pieces of a BJT amplifier:
  - ***Bias network***
    - Sets the DC operating point of the transistor
    - Ensures the BJT remains in the forward-active region
  - ***Signal path***
    - Sets the gain of the amplifier circuit
- Significant overlap between the two parts



Biasing Network

Signal path

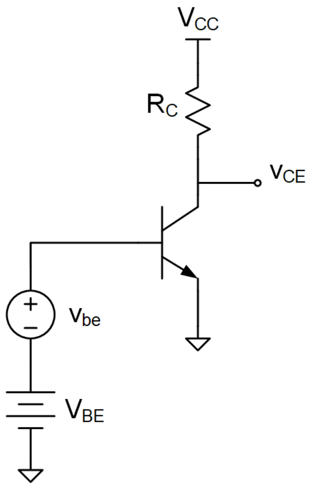
BJT Amplifier Biasing

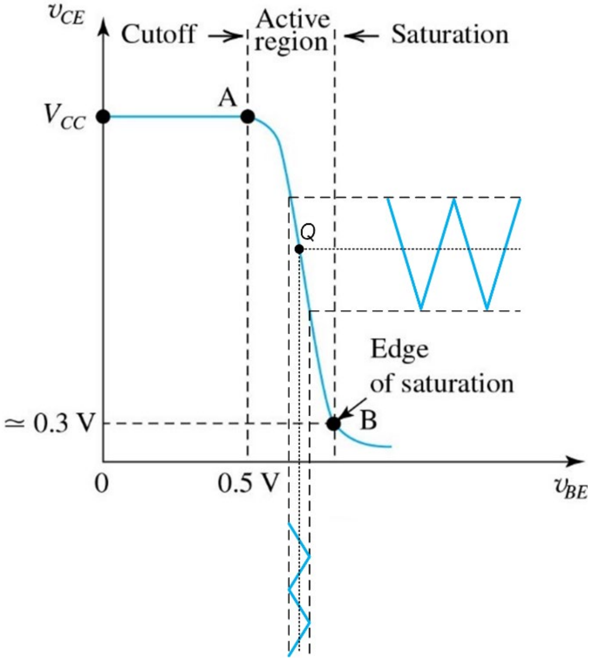
BJT Amplifier Biasing

- To function as an amplifier, a transistor must be biased in the ***forward-active region***
- DC operating point set by the ***bias network***
  - Resistors and power supply voltages
  - Sets the transistor's ***DC terminal voltages and currents*** – its DC bias
- How a transistor is ***biased*** determines:
  - Small-signal characteristics
  - Small-signal model parameters
  - How it will behave as an amplifier

Voltage Transfer Characteristic

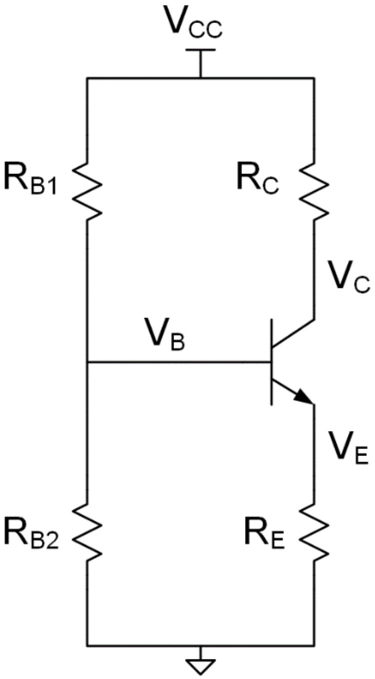
- BJT amplifier biased in the middle of its linear region
- Slope of the large-signal transfer characteristic gives the amplifier gain
  - Negative slope – gain is inverting
  - Small input signals yield larger output signals
  - Slope is nearly linear in this region





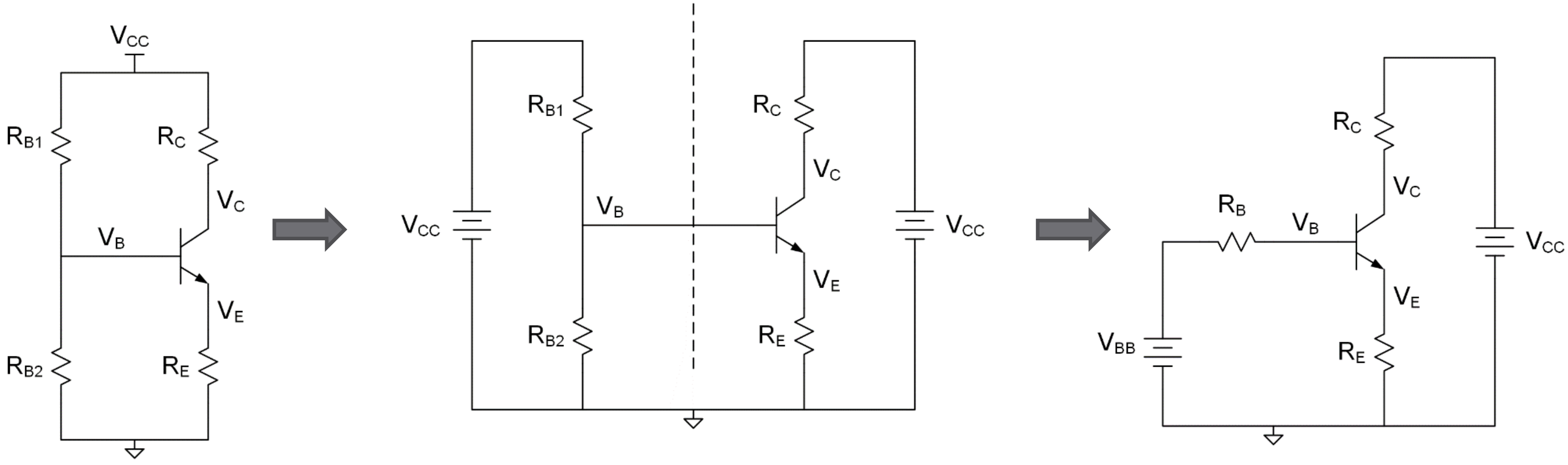
BJT Biasing – Four-Resistor Bias Circuit

- ***Four-resistor bias circuit:***
  - Commonly-used for both ***common-emitter*** amplifiers and ***emitter-followers***
  - Single power supply or bipolar supply
- Provides ***nearly-β-independent biasing***
  - β is often unknown and may be variable
  - DC operating point stays nearly constant as β changes
- Analyze the bias circuit by replacing the transistor with its large-signal model



Analysis of the Four-Resistor Bias Circuit

- To analyze the bias circuit, replace the transistor with its large-signal model
- First, simplify by replacing the base network with its Thevenin equivalent



$$V_{BB} = V_{CC}\frac{R_{B2}}{R_{B1}+R_{B2}}, \qquad R_B = \frac{R_{B1}R_{B2}}{R_{B1}+R_{B2}}$$

Analysis of the Four-Resistor Bias Circuit

- Replace the transistor with its large-signal model
- Apply KVL around the B-E loop:

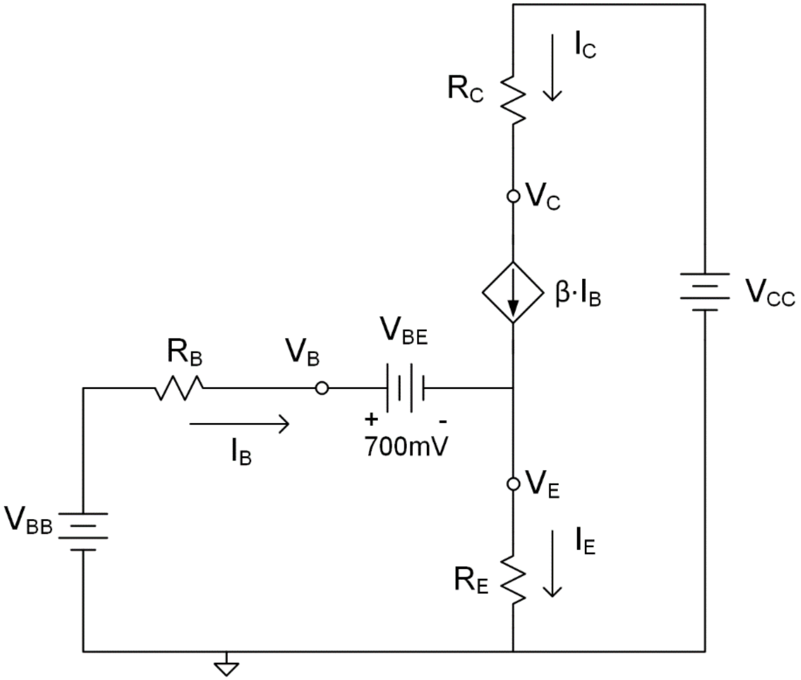
$$V_{BB} - I_B R_B - V_{BE} - I_E R_E = 0$$

- Express I_E in terms of I_B, then solve for I_B:

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

$$V_{BB} - I_B R_B - V_{BE} - (\beta + 1) I_B R_E = 0$$

$$\boxed{I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1) R_E}}$$



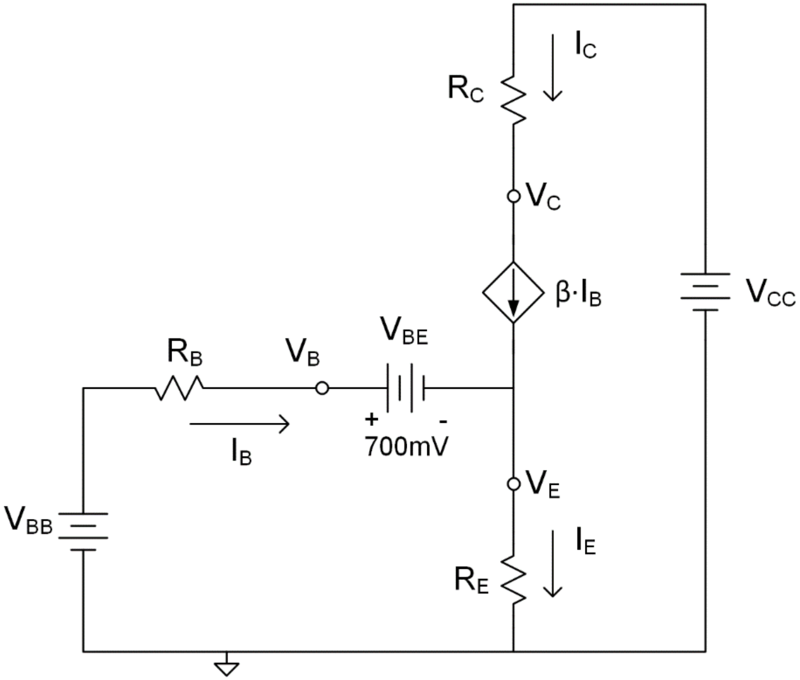
Analysis of the Four-Resistor Bias Circuit

- Get I_C and I_E from I_B

$$\boxed{\begin{aligned} I_C &= \beta I_B \\ I_E &= (\beta+1) I_B \end{aligned}}$$

- Use currents to calculate terminal voltages:

$$\boxed{\begin{aligned} V_C &= V_{CC} - I_C R_C \\ V_E &= I_E R_E = V_B - V_{BE} \\ V_B &= V_{BB} - I_B R_B = V_E + V_{BE} \end{aligned}}$$



- Verify that the transistor is biased in the forward active region:
  - $V_{BE} > 0$
  - $V_{BC} < 0$
- Next, we'll use the DC operating point to determine small-signal model parameters and a small-signal equivalent circuit

Design of the Four-Resistor Bias Network

- Design the bias network for bias current that is ***independent of β and temperature variation***
- ***β independence***
  - Changes in base current do not affect bias current
  - Current in the base bias resistors (R_{B1} and R_{B2}) must be much larger than the base current

$$I_{R_{B1,2}} \gg I_B$$

  - Set resistive divider current in same order of magnitude as bias current

$$0.1 I_E \le I_{R_{B1,2}} \le I_E$$

- ***Temperature independence***
  - Changes in B-E voltage with temperature do not affect bias current
  - Set base voltage much larger than B-E voltage

$$V_B \gg V_{BE}$$

Design of the Four-Resistor Bias Circuit

- ***Rule of thumb for designing a bias network***:
  - Select R_{B1} and R_{B2} to conduct approximately 1/10 of the desired bias current

$$\frac{V_{CC}}{R_{B1}+R_{B2}} \approx 0.1 I_E$$

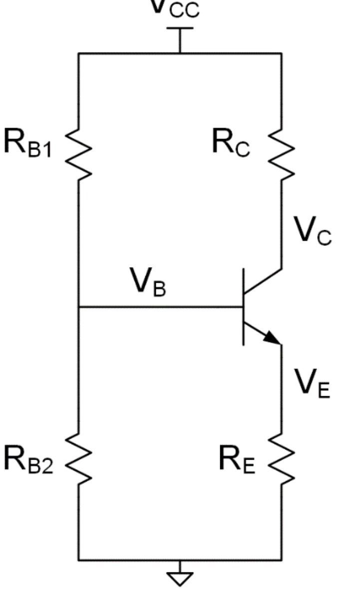
  - Set V_{BB} to approximately 1/3 of the supply voltage

$$V_{BB} \approx \frac{V_{CC}}{3}$$

$$\frac{R_{B2}}{R_{B1}+R_{B2}} \approx \frac{1}{3}$$

  - Select R_C to drop approximately 1/3 of the supply voltage

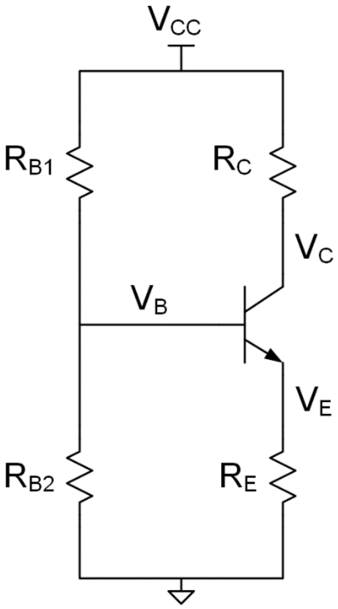
$$R_C \approx \frac{V_{CC}/3}{I_C}$$



Design of the Four-Resistor Bias Circuit

- ***Rule of thumb for designing a bias network*** (continued):
  - Determine R_E to provide the desired bias current

$$R_E = \frac{V_{BB} - V_{BE}}{I_E} - \frac{R_B}{\beta + 1}$$



- This configuration provides approximately:
  - $V_{CC}/3$ across R_C
  - $V_{CC}/3$ across the C-B junction
  - $V_{CC}/3$ at the base (or, roughly, across R_E)
- v_o can swing approximately:
  - $V_{CC}/3$ in the positive direction, before cutoff
  - $V_{CC}/3$ in the negative direction, before saturation

Bias Circuit Design - Example

- Design the bias network to provide $I_E = 1\ mA$
- Set R_{B1} and R_{B2} to conduct approximately $0.1I_E$

$$\frac{V_{CC}}{R_{B1} + R_{B2}} = 0.1I_E = 100\ \mu A$$

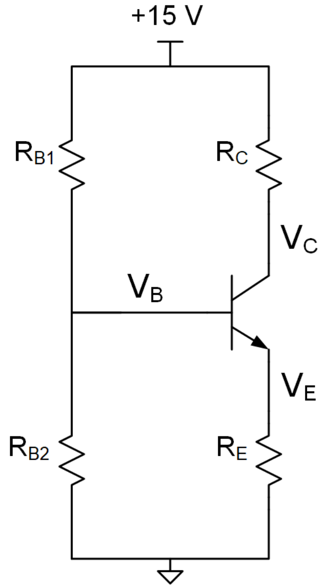
$$R_{B1} + R_{B2} = \frac{15\ V}{100\ \mu A} = 150\ k\Omega$$

- Determine R_{B1} and R_{B2} to set $V_{BB} \approx V_{CC}/3$

$$\frac{R_{B2}}{R_{B1} + R_{B2}} = 1/3$$

$$R_{B1} = 2R_{B2}$$

$$\boxed{\begin{aligned} R_{B1} &= 100\ k\Omega \\ R_{B2} &= 50\ k\Omega \end{aligned}}$$



$\beta = 100$

Bias Circuit Design - Example

- Select R_C to drop approximately 1/3 of the supply voltage

$$R_C = \frac{\frac{V_{CC}}{3}}{I_E} = \frac{5\ V}{1\ mA}$$

$$\boxed{R_C = 5\ k\Omega}$$

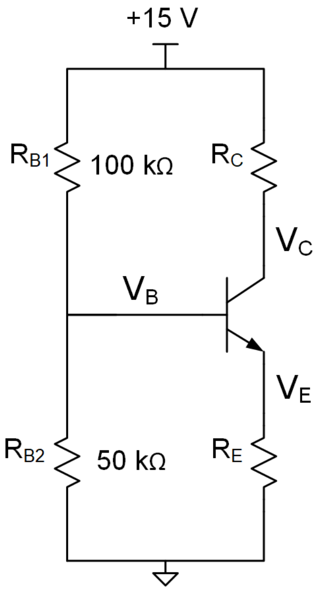
- Finally, determine R_E to provide the desired bias current

$$R_E = \frac{V_{BB} - V_{BE}}{I_E} - \frac{R_B}{\beta + 1}$$

$$R_E = \frac{(5\ V - 700\ mV)}{1\ mA} - \frac{(100\ k\Omega || 50\ k\Omega)}{101}$$

$$R_E = 4.3\ k\Omega - 330\ \Omega$$

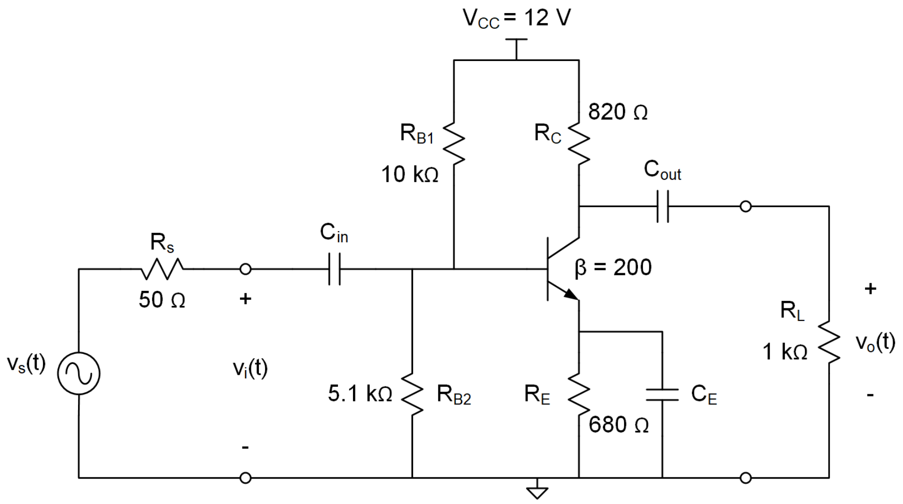
$$\boxed{R_E = 3.97\ k\Omega}$$



$$\beta = 100$$

Common-Emitter Amplifier

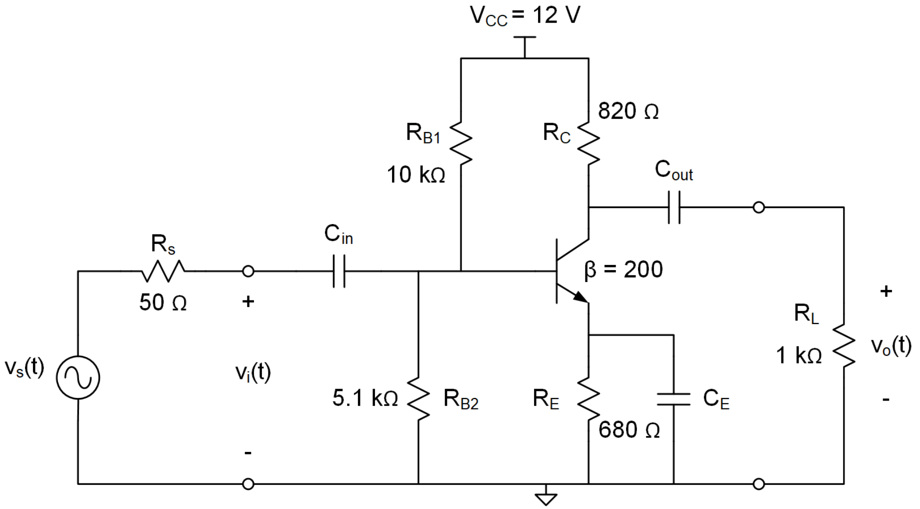
Common-Emitter Amplifier

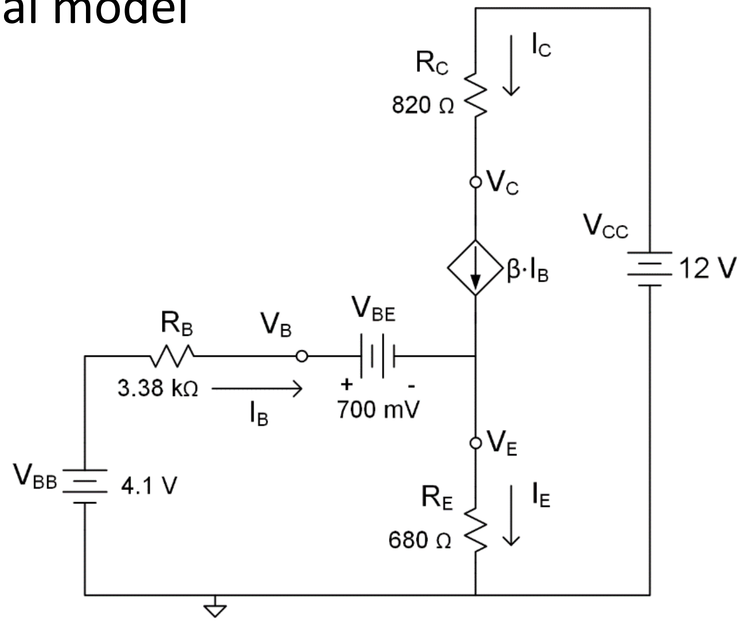


- Common-emitter amplifier
- All capacitors are ***AC-coupling/DC blocking capacitors***
  - Open at DC
  - Shorts at signal frequencies
  - Isolate transistor bias from source/load
- Called *common*-emitter, because emitter is connected to common – i.e., ground or a power supply
  - C_E is a small-signal short to ground
  - Emitter is at small-signal ground

Common-Emitter Amplifier

- Analyze the amplifier to find:
  - DC operating point
  - Small-signal voltage gain
- ***Large-signal (DC) equivalent circuit:***
  - Replace all capacitors with open circuits
  - Simplify the base bias network
  - Replace the transistor with its large-signal model





C-E Amplifier – Large-Signal Analysis

- As we have seen, base current is given by

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{4.1\ V - 700\ mV}{3.38\ k\Omega + 201 \cdot 680\ \Omega} = 24.3\ \mu A$$

- Use I_B to get I_C and I_E

$$I_C = \beta I_B = 200 \cdot 24.3\ \mu A = 4.9\ mA$$

$$I_E = (\beta + 1)I_B = 201 \cdot 24.3\ \mu A = 4.9\ mA$$

- Next, use currents to determine terminal voltages

$$V_B = V_{BB} - I_B R_B = 4.1\ V - 24.3\ \mu A \cdot 3.38\ k\Omega = 4.02\ V$$

$$V_C = V_{CC} - I_C R_C = 12\ V - 4.9\ mA \cdot 820\ \Omega = 7.98\ V$$

$$V_E = I_E R_E = 4.9\ mA \cdot 680\ \Omega = 3.33\ V$$

C-E Amplifier – Large-Signal Analysis

- The complete DC operating point:

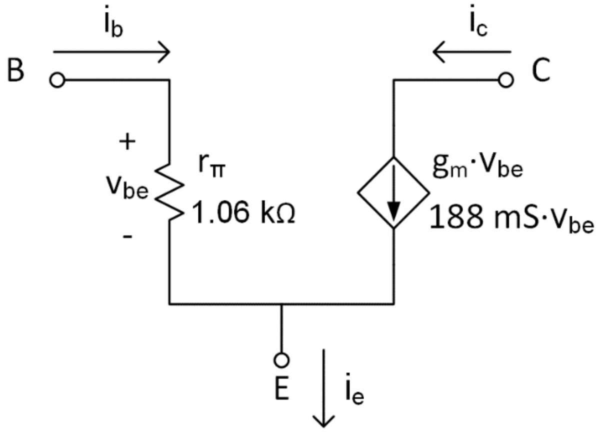
$$\boxed{\begin{array}{ll} I_B = 24.3\ \mu A & V_B = 4.02\ V \\ I_C = 4.9\ mA & V_C = 7.98\ V \\ I_E = 4.9\ mA & V_E = 3.33\ V \end{array}}$$

- Use the operating point to determine small-signal model parameters

$$g_m = \frac{I_C}{V_{th}} = \frac{4.9\ mA}{26\ mV} = 188\ mS$$

$$r_\pi = \frac{\beta}{g_m} = 200 \cdot \frac{V_{th}}{I_C} = 1.06\ k\Omega$$

$$r_e = \frac{r_\pi}{\beta + 1} = 5.28\ \Omega$$



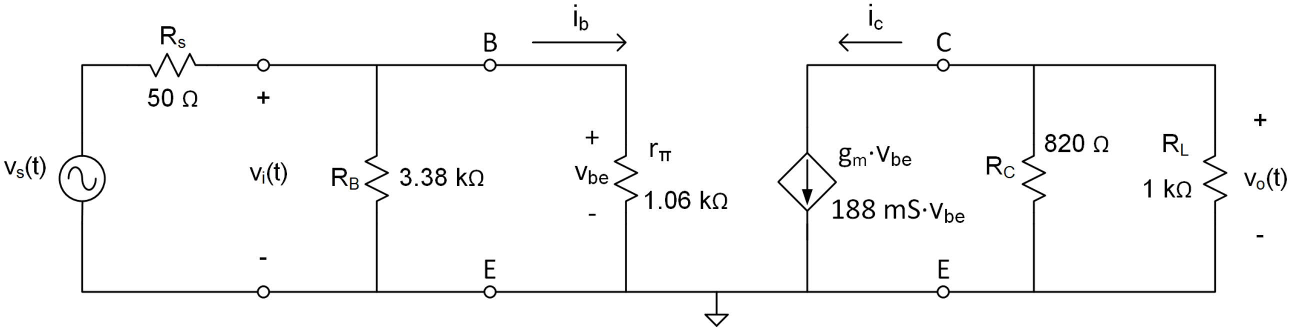
C-E Amplifier – Small-Signal Analysis

- The DC operating point allowed us to determine the small-signal model for the transistor
- Next, create the ***small-signal equivalent circuit*** for the amplifier and perform a ***small-signal analysis***

- ***Small signal analysis:***
  1. Replace all AC coupling capacitors with shorts
     - Large enough to look like shorts at signal frequencies
  2. Connect all DC supply voltages to ground
     - From a small-signal perspective these are all constant voltages
     - Small-signal ground
  3. Replace the transistor with its small-signal model

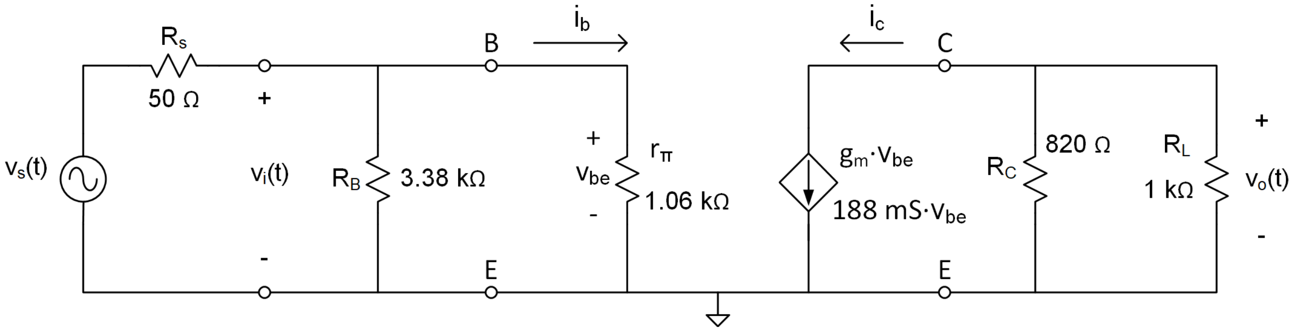
C-E Amplifier – Small-Signal Analysis

- Small-signal equivalent circuit
  - Use to determine small-signal voltage gain



- Emitter connected to ground
  - Emitter capacitor, C_E, is a small-signal short
- R_B is in parallel with r_π, and both connect to ground
- R_C is in parallel with R_L, and both connect to ground
- Input voltage, $v_i(t)$, appears across r_π and is the same as v_{be}
- The transistor is a ***transconductance*** device
  - Input voltage, v_{be}, creates output current, i_c

C-E Amplifier – Small-Signal Analysis



- ☐ Determine the small-signal voltage gain:

$$A_v = \frac{v_o}{v_i} \tag{1}$$

- ☐ The input is applied across the B-E junction, so

$$v_{be} = v_i \tag{2}$$

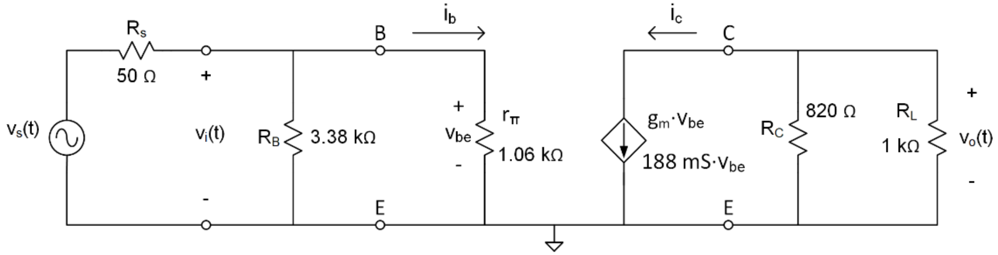
- ☐ The output is the collector current applied across the output resistance

$$v_o = -i_c R_o = -g_m v_{be} R_o \tag{3}$$

where R_o is the total resistance seen by the collector:

$$R_o = R_C || R_L = \frac{R_C R_L}{R_C + R_L} \tag{4}$$

C-E Amplifier – Small-Signal Analysis



- Substituting (4) and (2) into (3), we have

$$v_o = -g_m v_i R_o = -v_i \cdot g_m(R_C||R_L) \qquad (5)$$

- The amplifier gain:

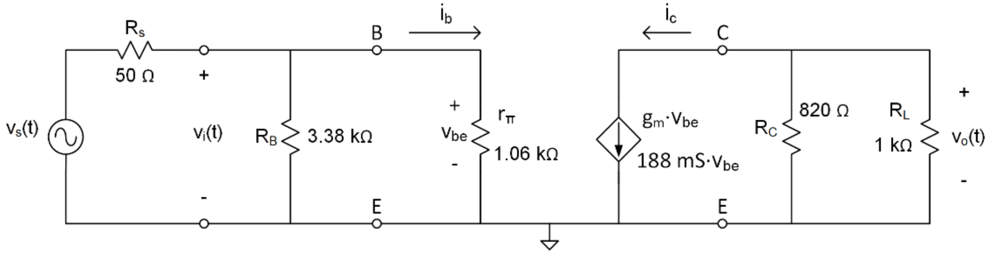
$$A_v = \frac{v_o}{v_i} = -g_m(R_C||R_L) = -g_m R_o \qquad (6)$$

- This is the gain for *any* common-emitter amplifier

$$\boxed{A_v = -g_m R_o}$$

- The negative sign indicates that the amplifier has ***inverting*** gain

C-E Amplifier – Small-Signal Analysis



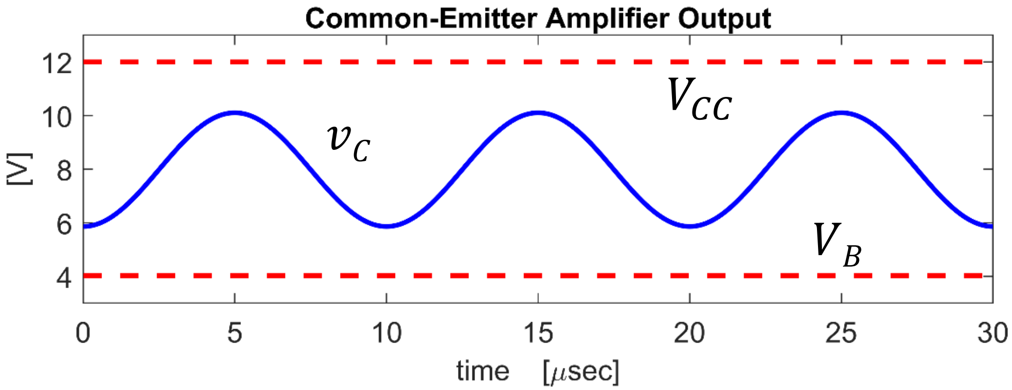
- For this circuit, the output resistance is

$$R_o = R_C||R_L = 820\ \Omega||1\ \text{k}\Omega = 451\ \Omega$$

- The gain is

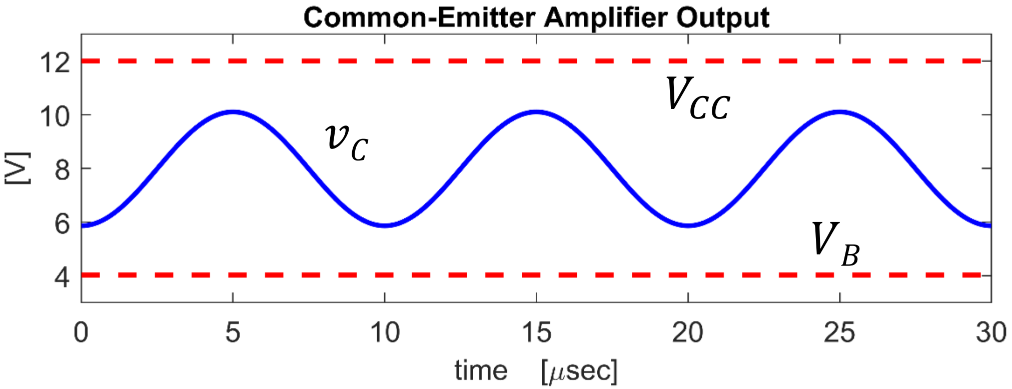
$$A_v = -188\ mS \cdot 451\ \Omega = -84.7$$

- The output for a 50 mV_{pp}, 100 kHz input:



C-E Amplifier – Dynamic Range

- ***Dynamic range***
  - Range of input or output signal for which the transistor remains in the ***forward-active region***
  - The amplifier's ***linear range***



- For forward-active bias:
  - B-C junction must remain reverse biased

$$v_{BC} < 0$$

  - Total collector voltage must remain above the base voltage

$$v_C > v_B$$

  - Collector cannot enter the cutoff region

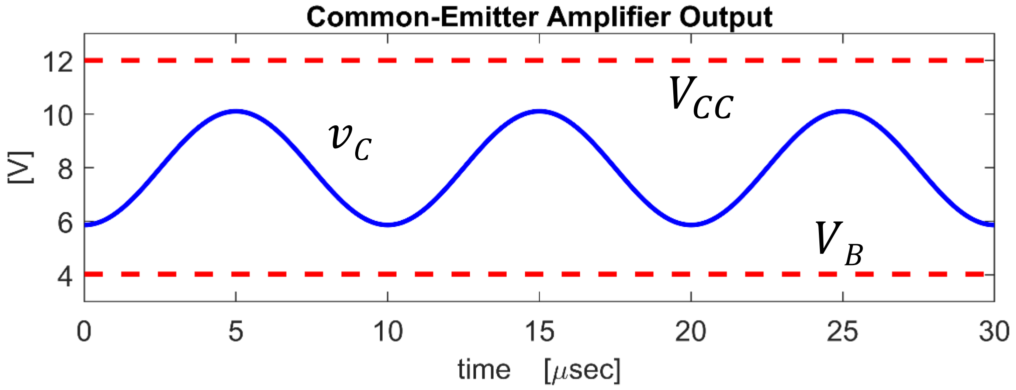
$$I_C > 0,\ v_C < V_{CC}$$

C-E Amplifier – Dynamic Range

- Optimal collector bias
  - DC collector voltage halfway between the base voltage and supply

$$V_C = \frac{(V_{CC} + V_B)}{2}$$

  - Output can swing positive and negative equal amounts



- Then, the output dynamic range is

$$v_{o_{pp}} < (V_{CC} - V_B)$$

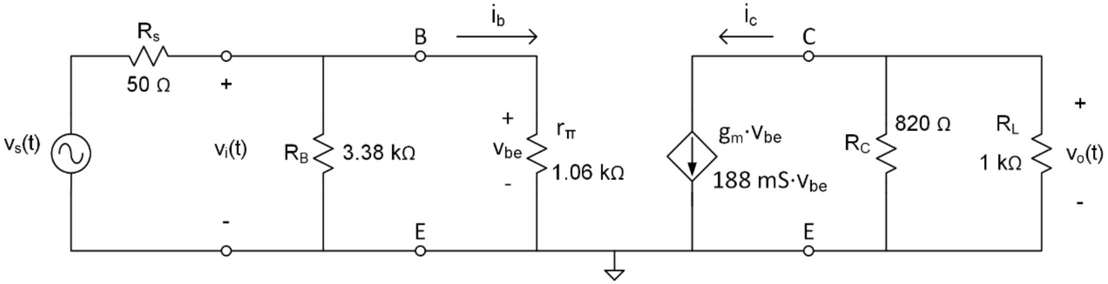
- The input is smaller than the output by the gain factor, so

$$v_{i_{pp}} < \frac{(V_{CC} - V_B)}{A_v}$$

- Here,

$$v_{o_{pp}} < 8\,V \quad \text{and} \quad v_{i_{pp}} < 94.5\,mV$$

C-E Amplifier – Gain from $v_s(t)$



- If, instead, we want gain from other side of source resistance, v_s to v_o, we must account for source loading
  - Cascade of gain from v_s to v_i with gain from v_i to v_o

$$A_v = \frac{v_o}{v_s} = \frac{v_i}{v_s} \cdot \frac{v_o}{v_i}$$

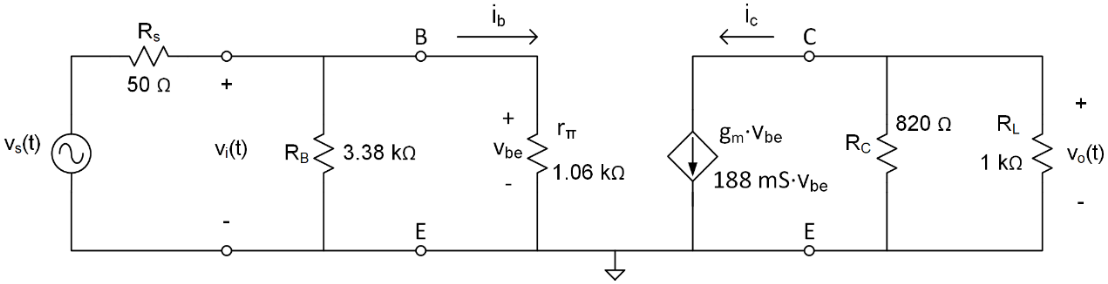
- Voltage division from v_s to v_i

$$\frac{v_i}{v_s} = \frac{R_B||r_\pi}{R_s + R_B||r_\pi} = \frac{R_i}{R_s + R_i}$$

- Overall gain is now

$$A_v = -\frac{R_i}{R_s + R_i} g_m R_o$$

C-E Amplifier – Input Resistance



- **Input resistance** is an important property of any amplifier
- For the C-E amplifier,

$$R_i = R_B || r_\pi$$

$$R_i = R_B || \frac{\beta}{g_m}$$

$$R_i = R_B || \frac{\beta V_{th}}{I_C}$$

  - Dependent on β and I_C

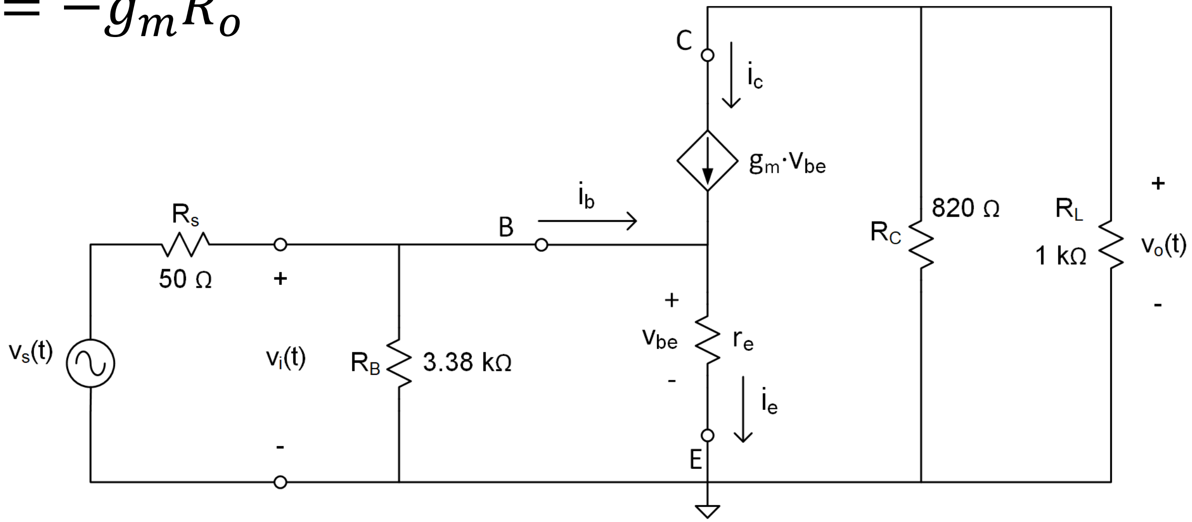
C-E Amplifier – Analysis with T-Model

- We used the hybrid-π model for small-signal analysis
  - Could also use the T-model
- Result is the same:

$$v_o = -i_c R_o = -g_m v_{be} R_o$$

$$v_o = -g_m R_o \cdot v_i$$

$$A_v = \frac{v_o}{v_i} = -g_m R_o$$



C-E Amplifier – Gain

$$A_v = -g_m R_o$$

- C-E gain is ***determined by g_m and R_o***
  - Select R_o (R_C) for desired gain
  - Transconductance is proportional to bias current

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

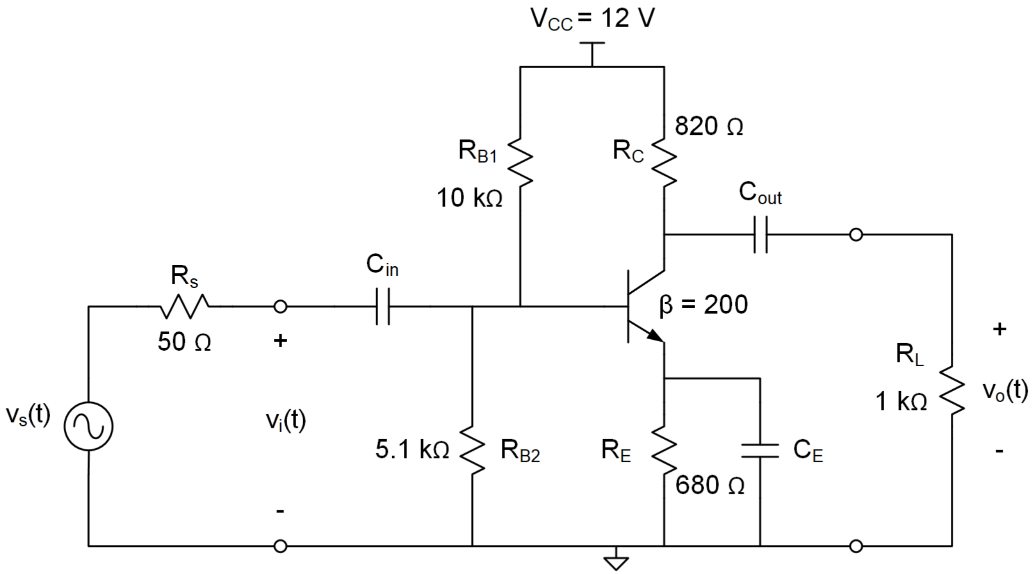
    - Therefore, ***gain is proportional to bias current***
  - Transconductance is inversely proportional to temperature

$$g_m = \frac{I_C q}{kT}$$

    - Therefore, ***gain is inversely proportional to temperature***

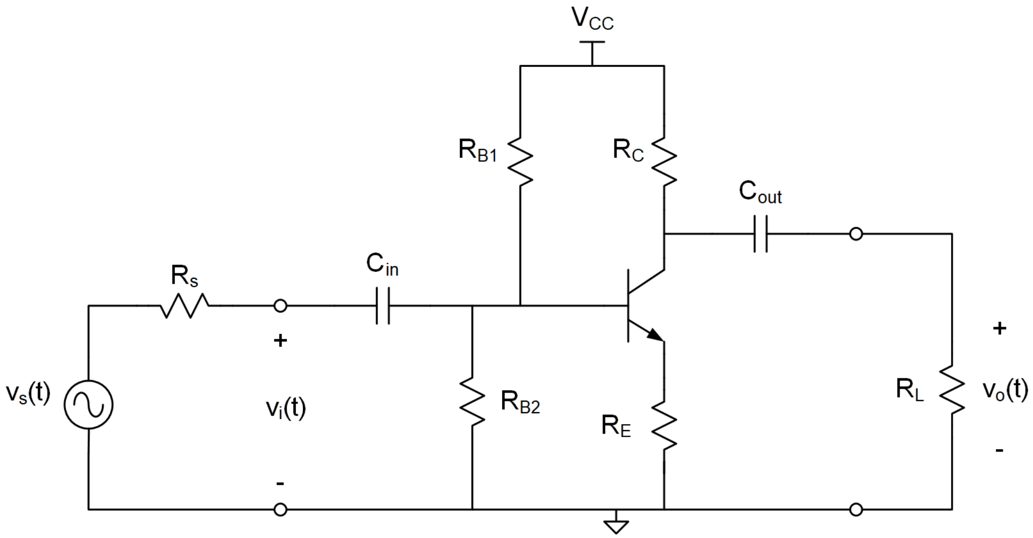
Emitter Degeneration

C-E Amplifier – Emitter Degeneration



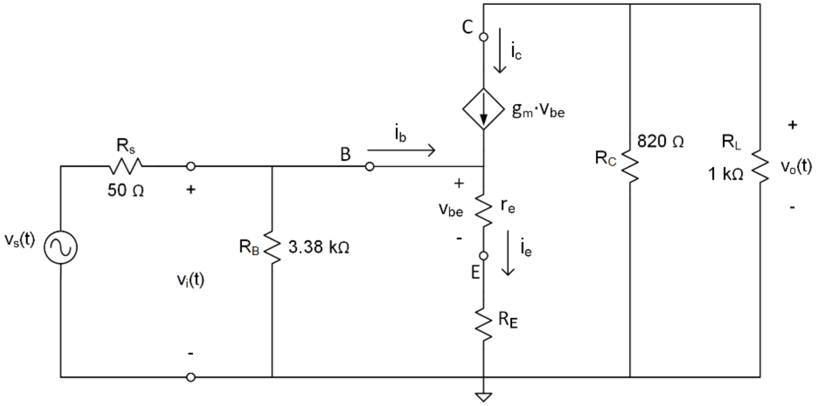
- The C-E amplifier we have looked at so far had its emitter grounded (small-signal ground)
  - Due to bypass capacitor, C_E, around R_E
- What if we remove C_E?
  - Or add another emitter resistor not bypassed by C_E
  - ***Emitter degeneration***

C-E Amplifier – Emitter Degeneration



- Now, R_E is included in the small signal equivalent circuit
  - Emitter is no longer connected to small-signal ground
- Analysis will be simplified if we use the T-model
  - Usually the case whenever we have emitter resistance
  - R_E will be in series with r_e from the model

C-E Amplifier – Emitter Degeneration



- The output is still given by

$$v_o = -i_C R_o = -g_m v_{be} R_o$$

- But, now, v_{be} is the portion of v_i that appears across r_e

$$v_{be} = v_i \frac{r_e}{r_e + R_E}$$

$$v_{be} = v_i \frac{\frac{\alpha}{g_m}}{\frac{\alpha}{g_m} + R_E} = v_i \frac{\alpha}{\alpha + g_m R_E}$$

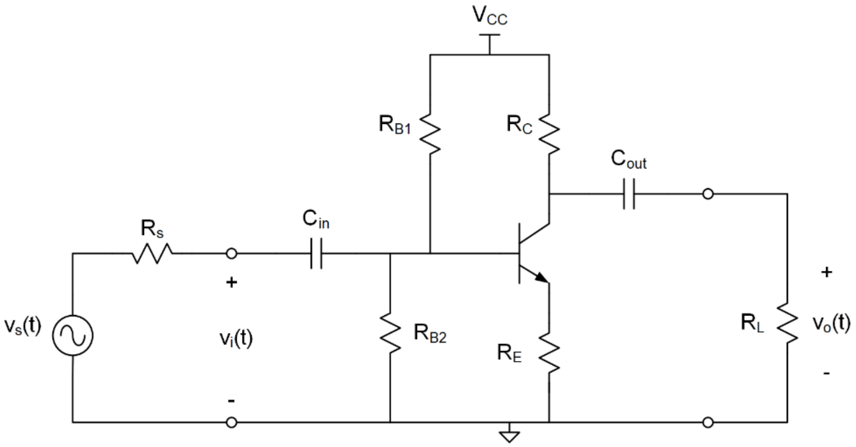
- The output is

$$v_o = v_i \left(-g_m R_o \frac{\alpha}{\alpha + g_m R_E} \right)$$

Emitter Degeneration – Gain

- Rearranging the expression for the output gives the gain

$$A_v = -g_m R_o \frac{\alpha}{\alpha + g_m R_E}$$



- Recognizing that $\alpha \approx 1$, we can simplify

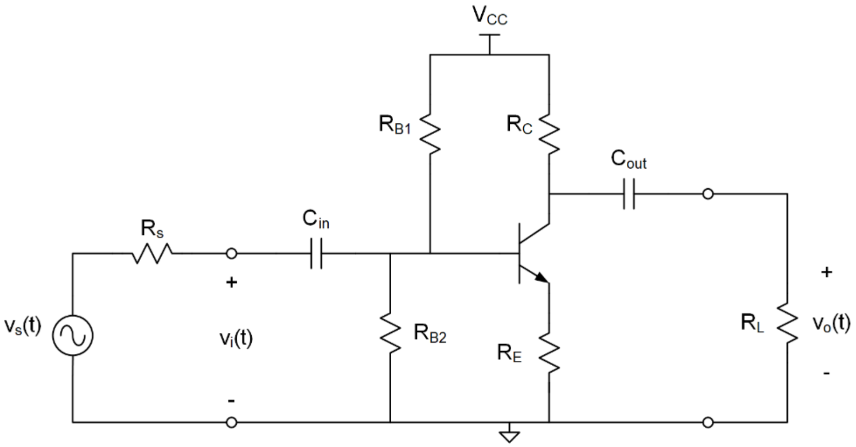
$$\boxed{A_v \approx -\frac{g_m R_o}{1 + g_m R_E}}$$

- ***Emitter degeneration reduces the gain by a factor of*** $(1 + g_m R_E)$
- If $R_E \gg r_e$, then $g_m R_E \gg 1$, and

$$\boxed{A_v \approx -\frac{R_o}{R_E}}$$

Emitter Degeneration – Transconductance

$$A_v \approx -\frac{g_m R_o}{1 + g_m R_E}$$



- We can rewrite the gain as

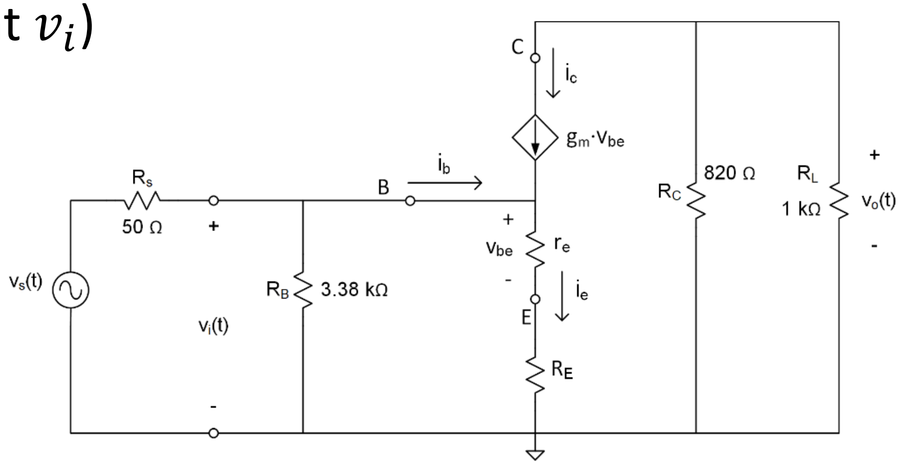
$$\boxed{A_v = -G_m R_o}$$

- G_m is the ***effective transconductance of the amplifier***

$$\boxed{G_m = \frac{g_m}{1 + g_m R_E}}$$

- ***Emitter degeneration reduces the transconductance by a factor of*** $(1 + g_m R_E)$
  - This is why we see a reduction in gain by the same factor

Emitter Degeneration – Input Resistance



- By definition, the input resistance (at v_i) is given by

$$R_i = \frac{v_i}{i_b}$$

- Base current is related to emitter current

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

- Emitter current is

$$i_e = v_i/(r_e + R_E)$$

- Substituting into the previous expressions gives

$$R_i = \frac{v_i}{i_b} = \frac{v_i}{\dfrac{v_i}{(\beta + 1)(r_e + R_E)}}$$

$$R_i = (\beta + 1\,)(r_e + R_E)$$

Resistance Reflection Rule

$$R_i = (\beta + 1)(r_e + R_E)$$

- Resistance reflection rule:

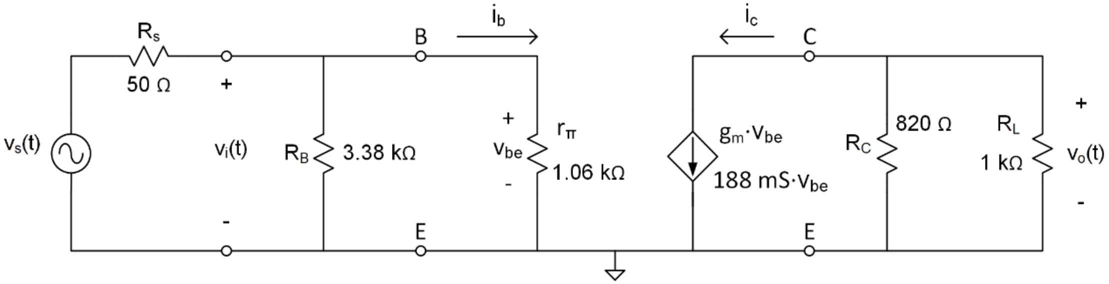
> ***The resistance seen looking into the base is*** $(\beta + 1)$ ***times the total resistance at the emitter***

- Equally applicable when $R_E = 0$:

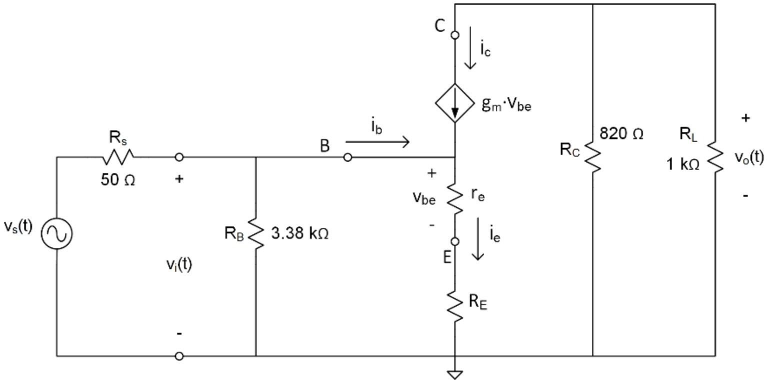
$$R_i = (\beta + 1) r_e = r_\pi$$

- ***Base input resistance,*** r_π***, is the reflected emitter resistance***

$$r_\pi = (\beta + 1) r_e$$



Emitter Degeneration – Negative Feedback



- *Without* emitter degeneration, any increase in v_i appears as v_{be}
- Think through what happens when v_i increases *with* emitter degeneration:
    - v_{be} *does* increase
    - i_c and i_e increase
    - Voltage drop across R_E increases, driving v_e up
    - Increasing v_e reduces the amount of the v_i increase that appears as v_{be}
- This is ***negative feedback***
    - Increasing output, i_c or i_e, subtracted from the input:

$$v_{be} = v_i - i_e R_E$$

- Similar to negative feedback in opamp circuits
    - Feedback reduces gain
    - In the limit, gain is set by a resistor ratio

Emitter Degeneration – Example

- Determine the gain of the C-E amplifier with emitter degeneration
  - DC circuit is the same as before, but now only part of R_E is bypassed
- DC operating point unchanged:

$$I_B = 24.3\ \mu A \qquad V_B = 4.02\ V$$

$$I_C = 4.9\ mA \qquad V_C = 7.98\ V$$

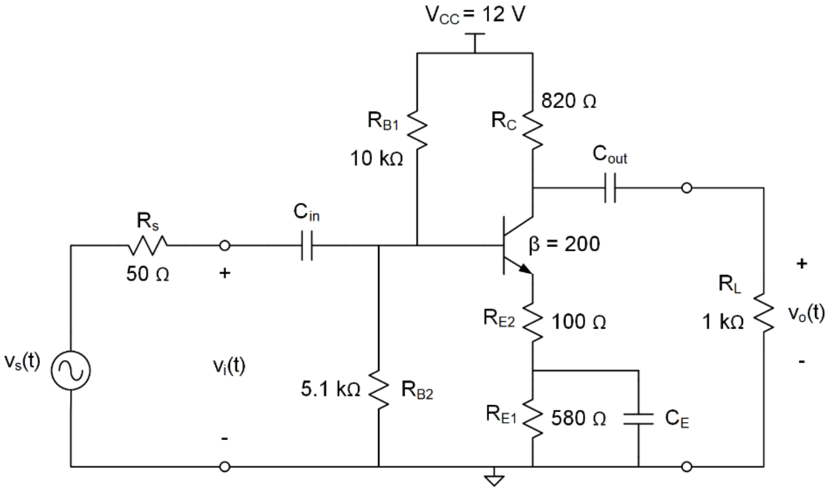
$$I_E = 4.\,mA \qquad V_E = 3.33\ V$$

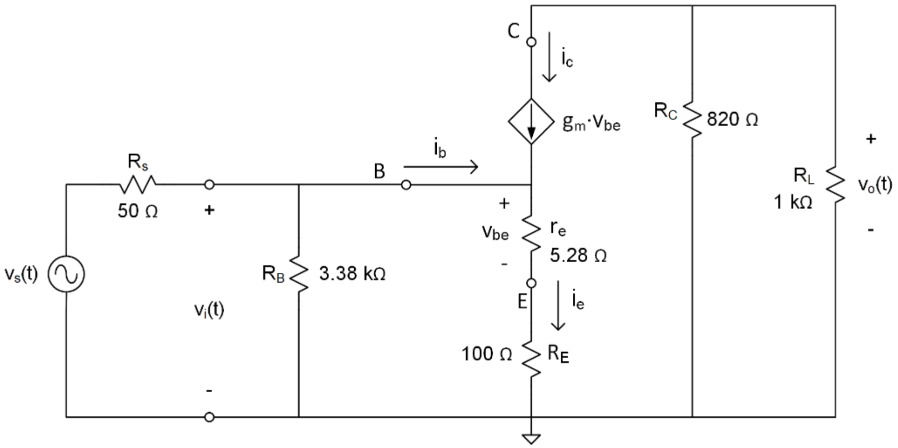
- Small-signal model parameters unchanged:

$$g_m = 188\ mS$$

$$r_\pi = 1.06\ k\Omega$$

$$r_e = 5.28\ \Omega$$





Emitter Degeneration – Example

- Gain is given by

$$A_v = -G_m R_o$$

where

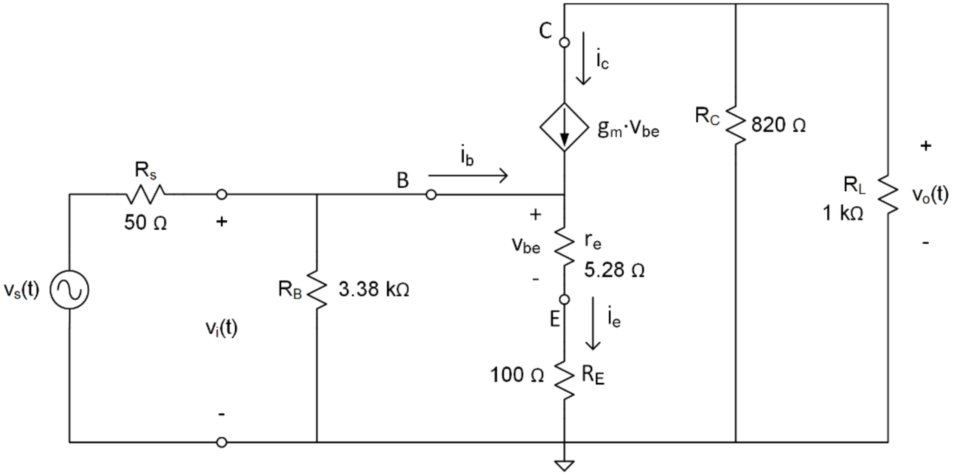
$$G_m = \frac{g_m}{(1 + g_m R_E)} = \frac{188\ mS}{19.8}$$

$$G_m = 9.5\ mS$$

so

$$A_v = -9.5\ mS \cdot 451\ \Omega$$

$$\boxed{A_v = -4.3}$$



- Note the reduction in gain due to the emitter degeneration

$$A_v = -\frac{g_m R_o}{(1 + g_m R_E)} = -\frac{84.7}{19.8} = -4.3$$

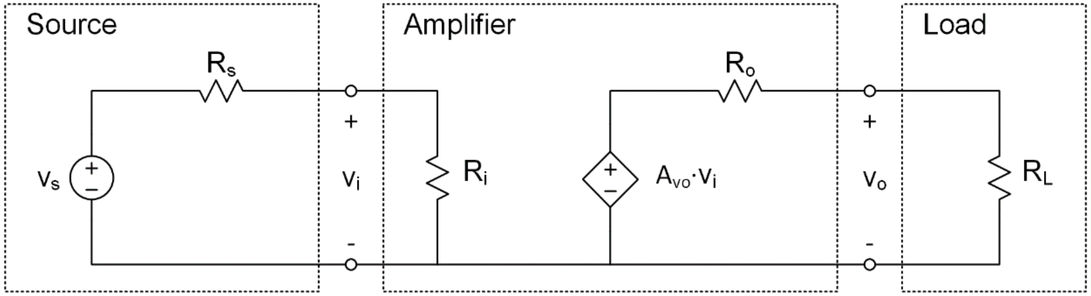
- Also note that we can roughly approximate the gain as

$$A_v \approx -\frac{R_o}{R_E} = -\frac{451\ \Omega}{100\ \Omega} = -4.5$$

Emitter Follower

Buffering

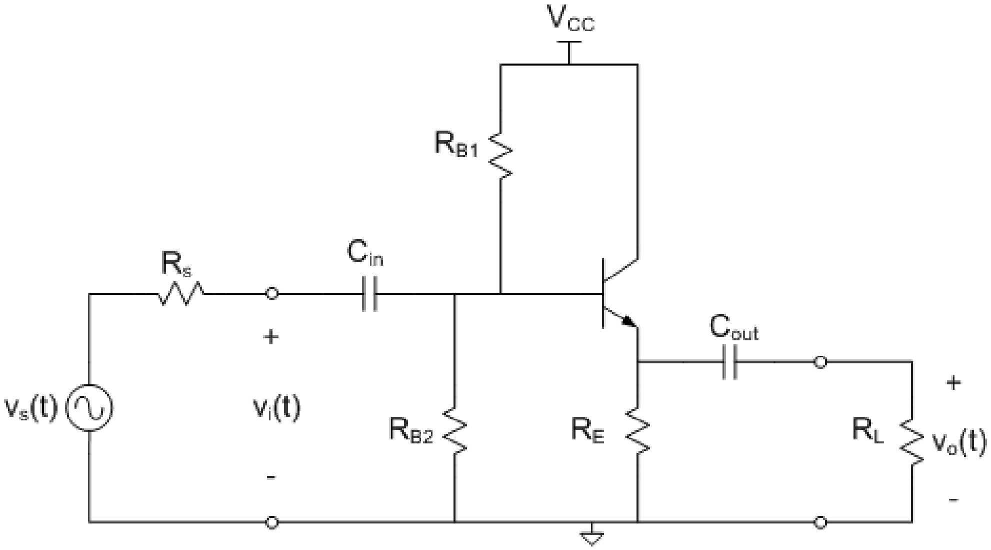
- In previous classes, you have learned about ***loading effects***
  - Signal attenuation between output/input resistances of cascaded stages



$$v_i < v_s \quad \text{and} \quad v_o < A_{vo} \cdot v_i$$

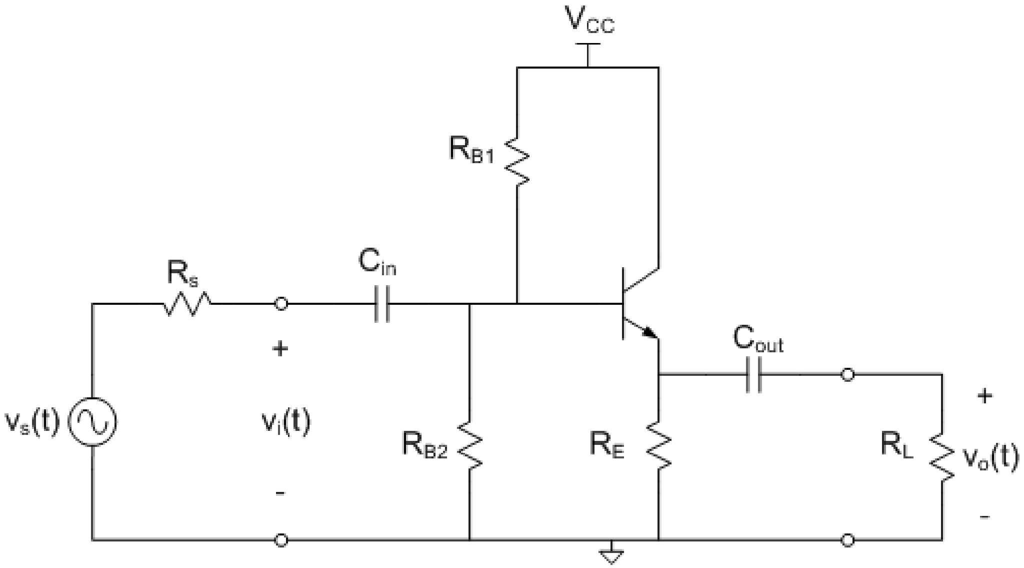
- Inter-stage ***buffers*** can reduce attenuation due to loading
  - High input resistance, low output resistance
  - Unity gain
- We can use BJTs as buffers
  - ***Emitter follower***

Emitter-Follower



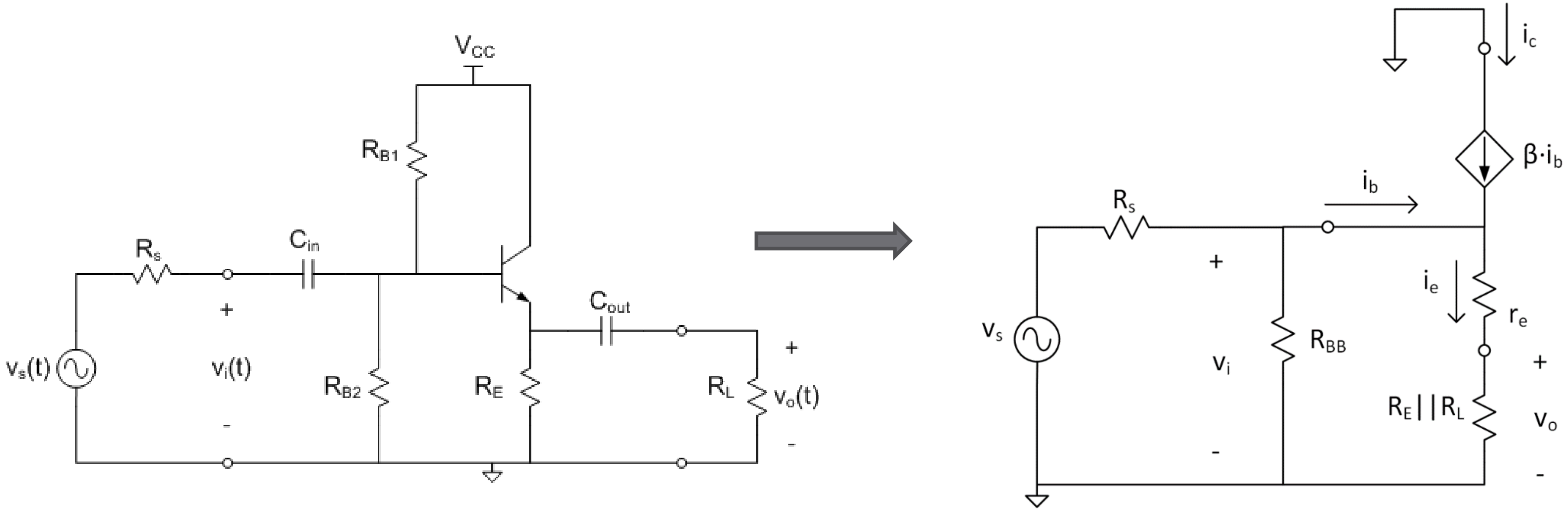
- ***Emitter-follower amplifier***
  - Input applied to the base
  - Output at the emitter
  - Emitter *follows* the base
- Also called a ***common-collector*** amplifier (CC)
  - Collector is connected to small-signal ground

Emitter-Follower



- Similar to opamp unity-gain buffer
  - Near-unity gain
  - High R_i, low R_o
  - Buffers source impedance
  - Reduces attenuation due to loading
- We will now analyze the emitter-follower
  - Large-signal analysis is the same as for the CE amplifier
  - Perform a small-signal analysis to determine voltage gain

Emitter Follower – Small-Signal Analysis



- Replace the BJT with small-signal model
  - Emitter resistance, so use T-model
  - Short coupling caps
  - DC voltages connect to ground
  - Simplify parallel resistances

Emitter Follower – Small-Signal Analysis

- First, determine gain from v_i to v_o

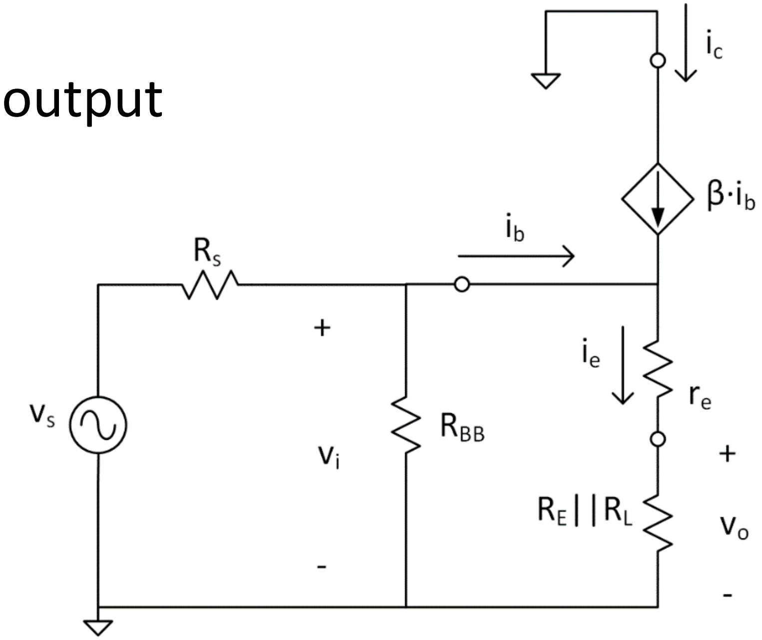
$$A_v = \frac{v_o}{v_i}$$

Applying voltage division gives the output

$$v_o = v_i \frac{R_E||R_L}{(R_E||R_L + r_e)}$$

Rearrange to get the gain

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



  - Clearly, $A_v < 1$
  - But, for $R_E||R_L \gg r_e$, $A_v \approx 1$

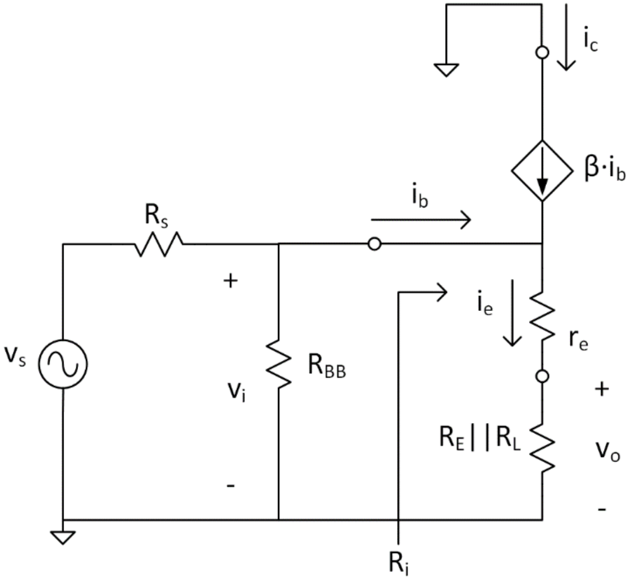
Emitter Follower – Input Resistance

- The emitter follower's input resistance is defined as

$$R_i = \frac{v_i}{i_b}$$

where

$$i_b = \frac{i_e}{\beta + 1} = \frac{v_i}{(\beta + 1)(r_e + R_E||R_L)}$$



- The input resistance is

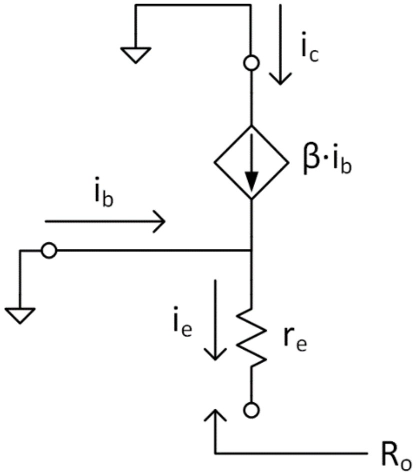
$$\boxed{R_i = (\beta + 1)(r_e + R_E||R_L)}$$

  - $(\beta + 1)$ times larger than the total resistance at the emitter
    - The ***reflected*** emitter resistance
  - Typically a ***very large input resistance***, as we would expect from a circuit used as a buffer

- Note that this is the resistance ***at the base***
  - In parallel with R_{BB}

Emitter Follower – Output Resistance

- To determine output resistance, set the input to zero
    - First, consider the case where the input is applied directly to the base (i.e., $R_s = 0$)
        - Set v_i to zero – ground the base
- For now, ignore R_E
    - In parallel with what we will calculate as R_o
- The output resistance is simply r_e



$$\boxed{R_o = r_e}$$

- Recall the expression for r_e

$$r_e = \frac{V_{th}}{I_E} = \frac{\alpha}{g_m} \approx \frac{1}{g_m}$$

- Typically a ***small resistance***, as expected from a circuit used as a buffer
    - Increasing bias current decreases r_e and R_o

Emitter Follower – Output Resistance

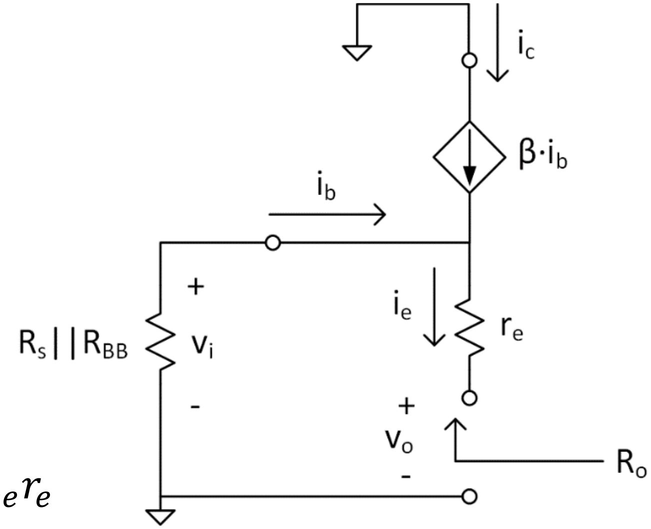
- Next, determine R_o for non-zero source resistance, $R_s \neq 0$
  - Set v_s to zero – ground the source
- By definition

$$R_o = -\frac{v_o}{i_e}$$

  - Emitter current is

$$i_e = (\beta + 1) i_b$$

  - KVL around the B-E loop



$$v_o = -i_b(R_s||R_{BB}) - i_e r_e = -\frac{i_e}{\beta + 1}(R_s||R_{BB}) - i_e r_e$$

$$v_o = -i_e\left(\frac{(R_s||R_{BB})}{\beta + 1} + r_e\right)$$

  - R_o now includes all resistance at the base, ***reflected*** to the emitter:

$$\boxed{R_o = \frac{(R_s||R_{BB})}{\beta + 1} + r_e = \frac{(R_s||R_{BB})}{\beta + 1} + \frac{r_\pi}{\beta + 1}}$$

Resistance Reflection Rule

- The input and output resistance of the emitter follower illustrate two versions of the ***resistance reflection rule***

- Version 1:
  - ***Resistance seen at the base is the total resistance at the emitter increased by a factor of*** $(\beta+1)$

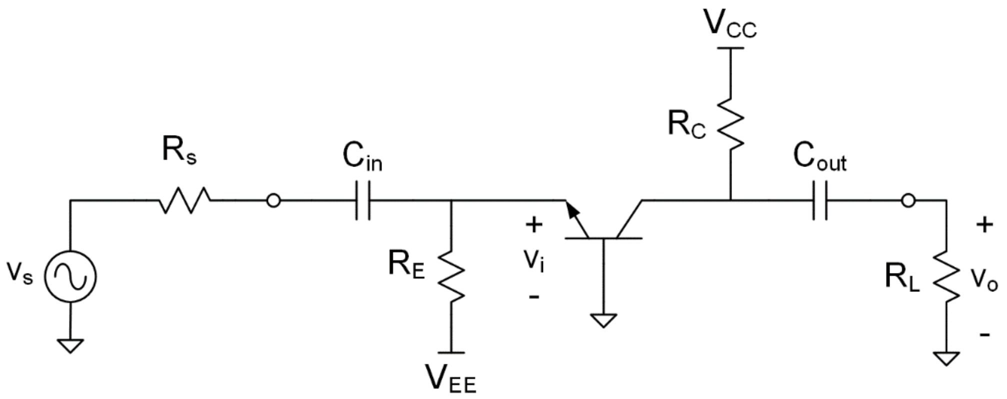
$$R_b = (\beta+1)(r_e + R_E)$$

- Version 2:
  - ***Resistance seen at the emitter is the total resistance at the base reduced by a factor of*** $(\beta+1)$

$$R_e = \frac{(r_\pi + R_B)}{(\beta+1)}$$

Common-Base Amplifier

Common-Base Amplifier



- The third BJT amplifier configuration we will look at is the ***common-base amplifier***
  - Input applied to the emitter
  - Output taken from the collector
  - Base is connected to small-signal ground
  - By far the least common of the three amplifiers

Common-Base Amplifier – Gain

- There is emitter resistance, so use the T-model for small-signal analysis
- The output is given by

$$v_o = -i_c R_C || R_L$$

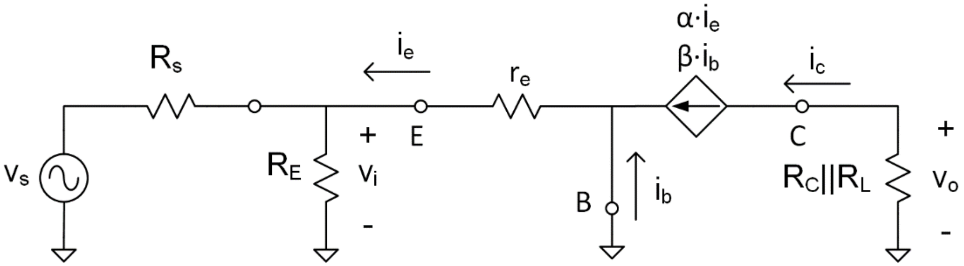
$$v_o = -\alpha i_e R_C || R_L$$

where

$$i_e = -\frac{v_i}{r_e}$$

so

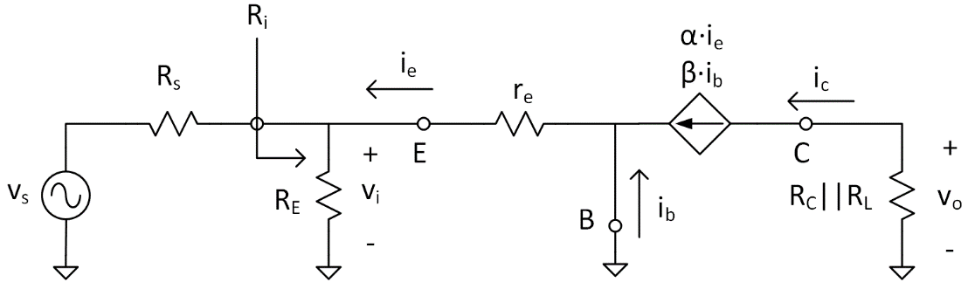
$$v_o = v_i \frac{\alpha}{r_e} R_C || R_L = v_i g_m R_C || R_L$$



- Common-base voltage gain is

$$\boxed{A_v = g_m R_C || R_L}$$

Common-Base – Input Resistance



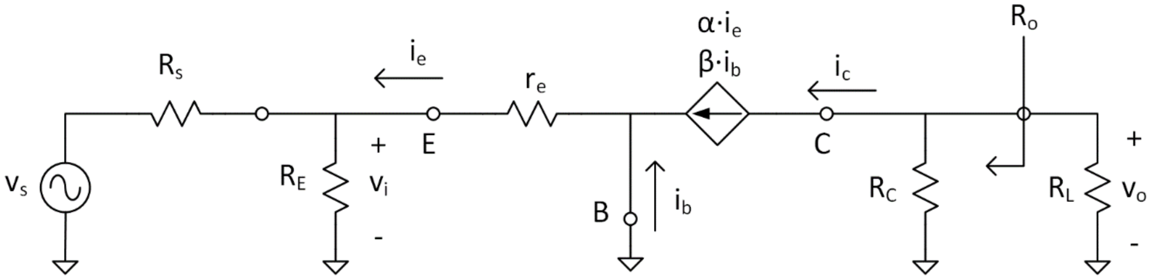
- R_i is the parallel combination of the resistance connected to the emitter and the resistance looking into the emitter

$$\boxed{R_i = R_E || r_e = R_E || \frac{\alpha}{g_m}}$$

- Note that typically, r_e is quite small, so

$$\boxed{R_i \approx r_e \approx \frac{1}{g_m}}$$

Common-Base – Output Resistance



- If we neglect the transistor’s output resistance, r_o, the common-base output resistance is

$$\boxed{R_o = R_C}$$

  - Entirely determined by the collector resistor

Common-Base Amplifier

- Low input resistance

$$R_i = r_e \approx \frac{1}{g_m}$$

  - For $R_s \gg r_e$, there will be significant attenuation from v_s to v_i

$$v_i \ll v_s$$

  - The overall gain from v_s to v_o may be small
- Typically only useful in certain applications:
  - Low source resistance
    - E.g., amplifiers driven by cables
    - R_i matched to Z_0 (e.g. 50 Ω or 75 Ω) to avoid reflections
  - Current buffers
    - E.g., in ***cascode*** amplifiers

Transistors as Switches

Transistors as Switches

- Our focus in this course is the use of transistors for designing ***linear amplifiers***
  - Output is a scaled version of the input
- Transistors can be used also be used as ***nonlinear switches***
  - Either ***on*** or ***off*** (closed or open)
  - Fundamental building block of ***digital integrated circuits***
    - Microprocessors have ***billions*** of transistors (MOSFETS) used as switches
  - Useful for switching large amounts of current, e.g.,
    - Controlling a mechanical device (e.g., pump, heater, motor) with a microcontroller
    - Power inverters

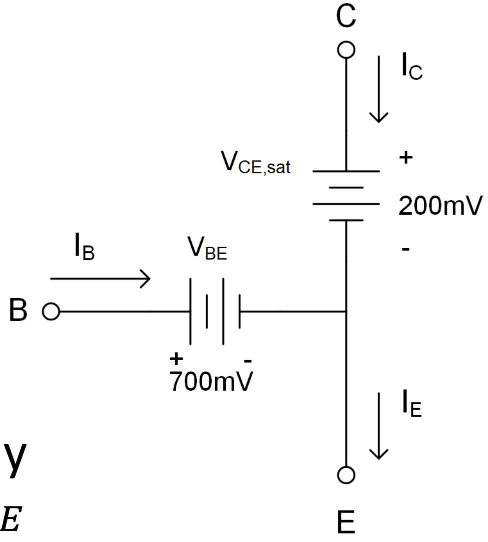
Saturation/Cutoff Region Models

- Transistors used as ***amplifiers*** must stay in the ***forward active*** region
- Transistors used as ***switches*** operate alternately in the ***saturation*** (closed) and ***cutoff*** (open) regions
- Equivalent circuit models:

Saturation Region (on):

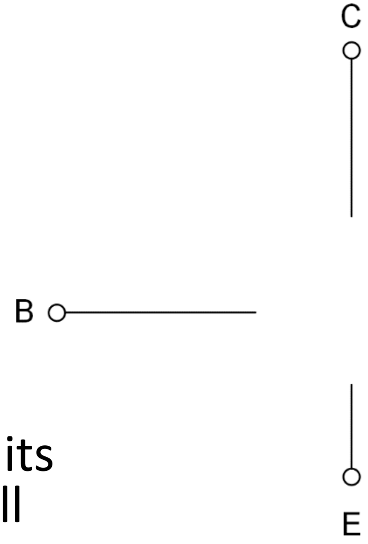
- Both junctions forward biased
- Small, nearly constant V_{CE}

$$V_{CE,sat} \approx 200\ mV$$



Cutoff Region (off):

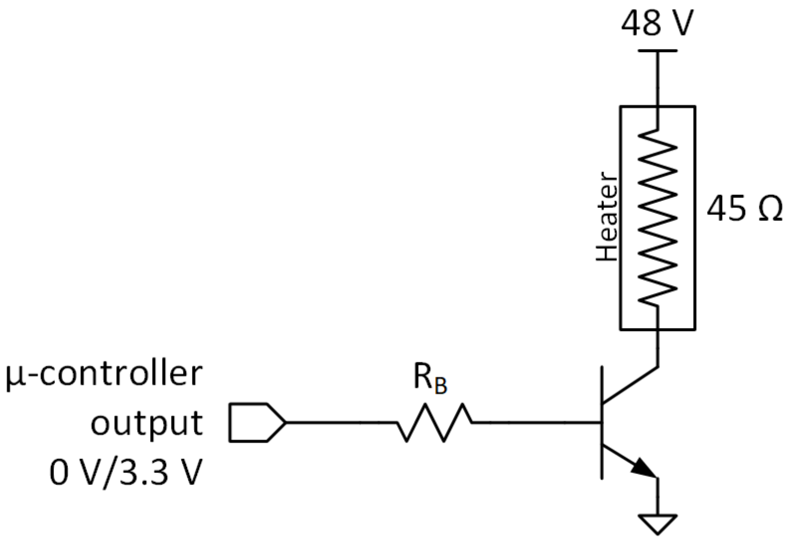
- Both junctions reverse biased
- Open circuits between all terminals



Using a BJT as a Switch - Example

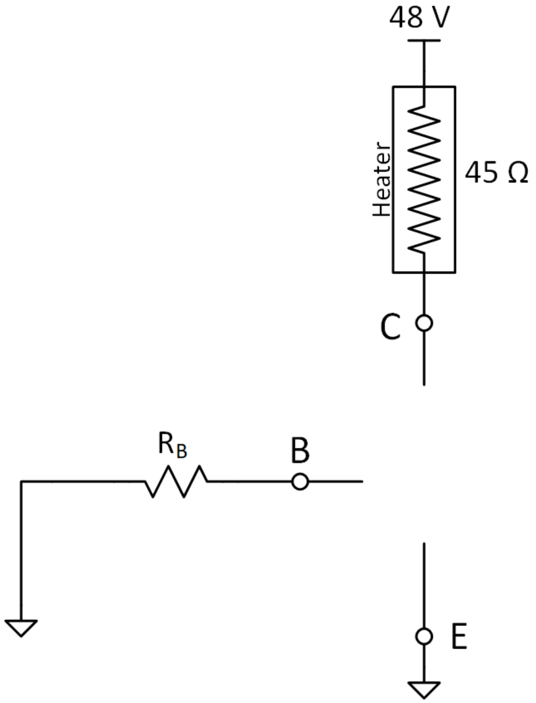
- Let’s say we want to turn resistance heater on and off using a microcontroller
    - Heater may require amperes of current
    - Microcontroller output may be limited to tens of mA

- Control a BJT switch with the microcontroller output
    - Low-current control signal from the microcontroller
        - Base resistor limits output current
    - BJT switches the large current required by the heater



Using a BJT as a Switch - Example

- When the μ-controller's output is low (0 V)
  - $V_{BE} = 0\ V$
  - Transistor is in the cutoff region
  - Switch is off
  - No current flows
  - The heater is off



Using a BJT as a Switch - Example

- When the μ-controller's output is high (3.3 V)
  - $V_{BE} \approx 700\ mV$
  - $V_{CE} = V_{CE,sat} \approx 200\ mV$
  - Transistor is saturated
  - Switch and heater are on
- Collector/heater current:

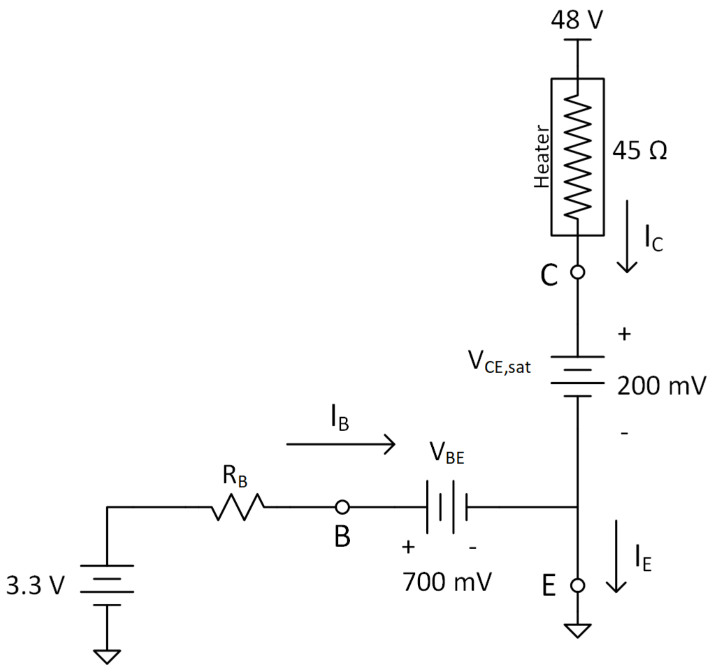
$$I_C = \frac{48\ V - 200\ mV}{45\ \Omega} = 1.1\ A$$

- Heater power:

$$P_h = I_C^2 \cdot R_h$$

$$P_h = (1.1\ A)^2 \cdot 45\ \Omega$$

$$P_h = 50.8\ W$$



Using a BJT as a Switch - Example

- Microcontroller output current (base current) :

$$I_B = \frac{3.3\,V - V_{BE}}{R_B}$$

- Select R_B to limit base current
  - Let’s say $I_{B,max} = 20\,mA$

$$R_B \geq \frac{3.3\,V - 700\,mV}{I_{B,max}} = \frac{2.6\,V}{20\,mA}$$

$$R_B \geq 130\,\Omega$$

- Typically choose R_B to keep I_B well below $I_{B,max}$