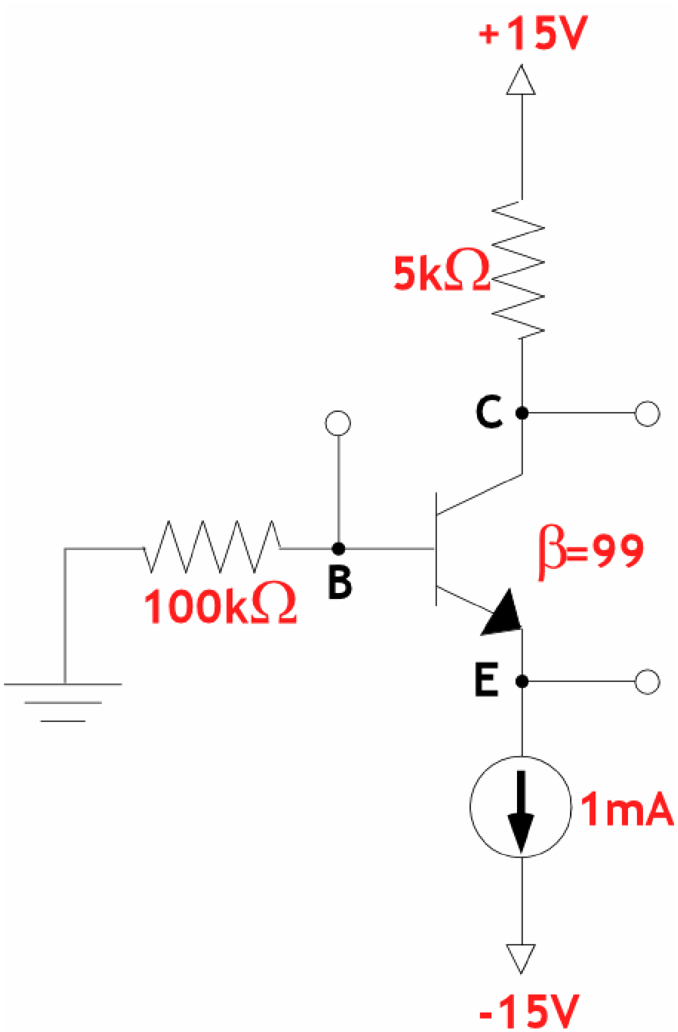
Outline of Chapter 5

- 1- Introduction to The Bipolar Junction Transistor
- 2- Active Mode Operation of BJT
- 3- DC Analysis of Active Mode BJT Circuits
- 4- BJT as an Amplifier
- 5- BJT Small Signal Models
- 6- CEA, CEA with R_E, CBA, & CCA
- 7- Integrated Circuit Amplifiers

DC Analysis – Requires Assumptions



Find voltages & currents

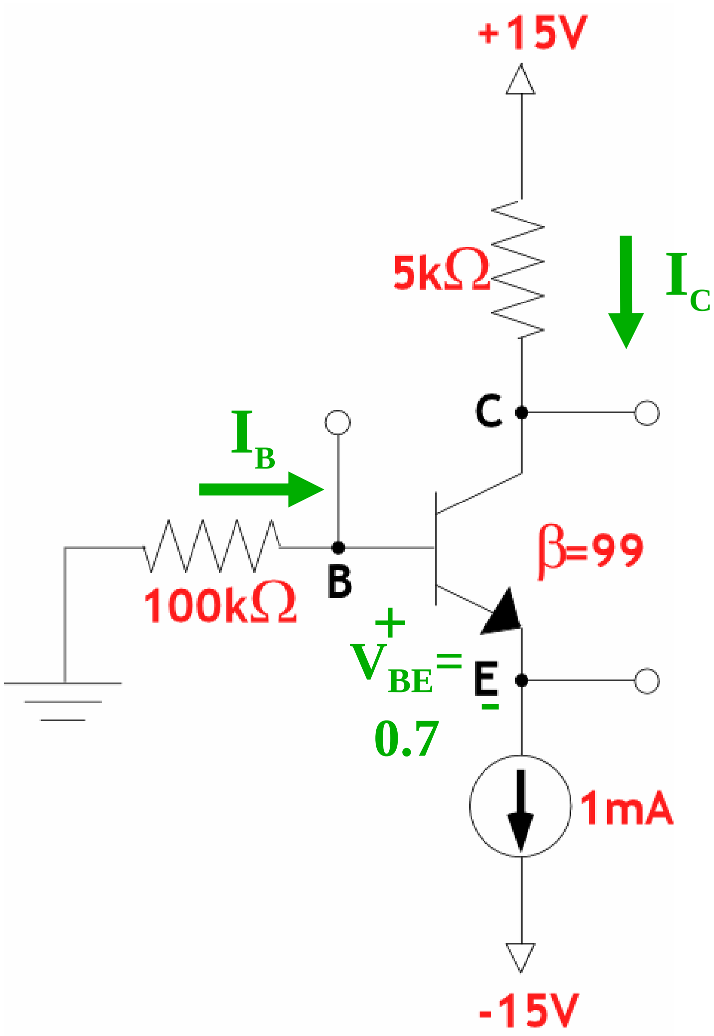
Process:

a) Assume *active* mode operation; $V_{BE} = 0.7V$

b) Based on assumption, calculate branch voltages and currents

c) Verify *active* mode by checking $V_{CB} > 0V$

Perform Analysis



$$I_B = \frac{I_E}{\beta+1} = \frac{1mA}{99+1} = \underline{10\mu A}$$

$$I_C = \alpha I_E = \frac{\beta}{\beta+1} I_E = \frac{99}{99+1} 1mA = \underline{0.99mA}$$

$$V_C = 15 - I_C R_C = 15 - (0.99m)(5k) = \underline{10.05V}$$

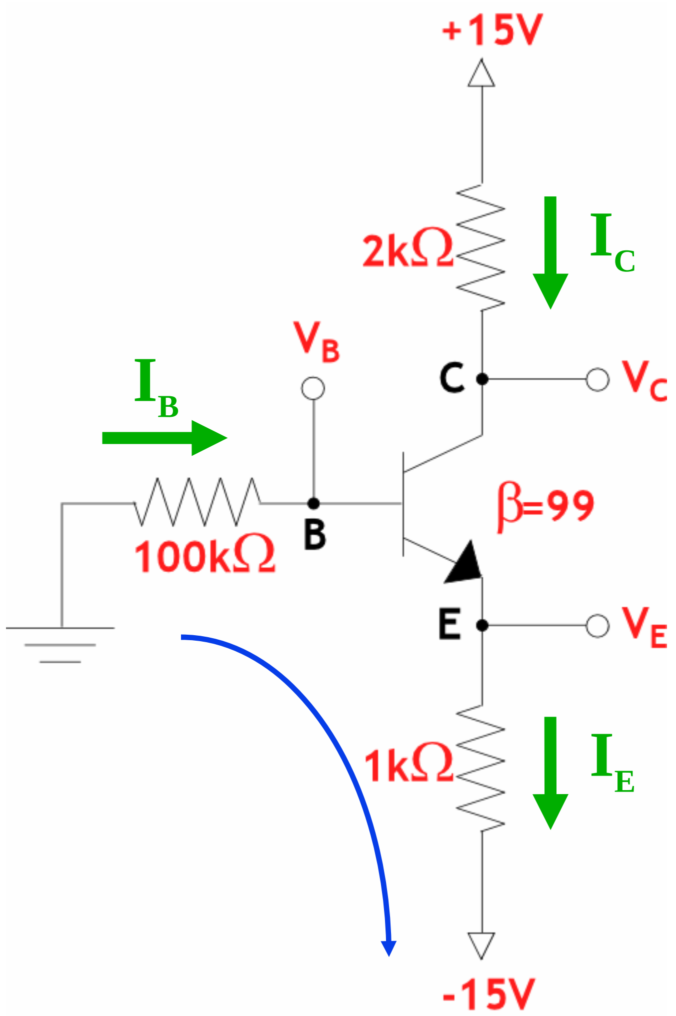
$$V_B = 0 - I_B R_B = -(10\mu A)(100k) = \underline{-1V}$$

Check V_{BE} (0.7V) and V_{CB} (reverse):

$$V_E = V_B - V_{BE} = (-1) - 0.7 = -1.7V$$

$$V_{CB} = V_C - V_B = 10.05 - (-1) = 11.05V$$

DC Analysis

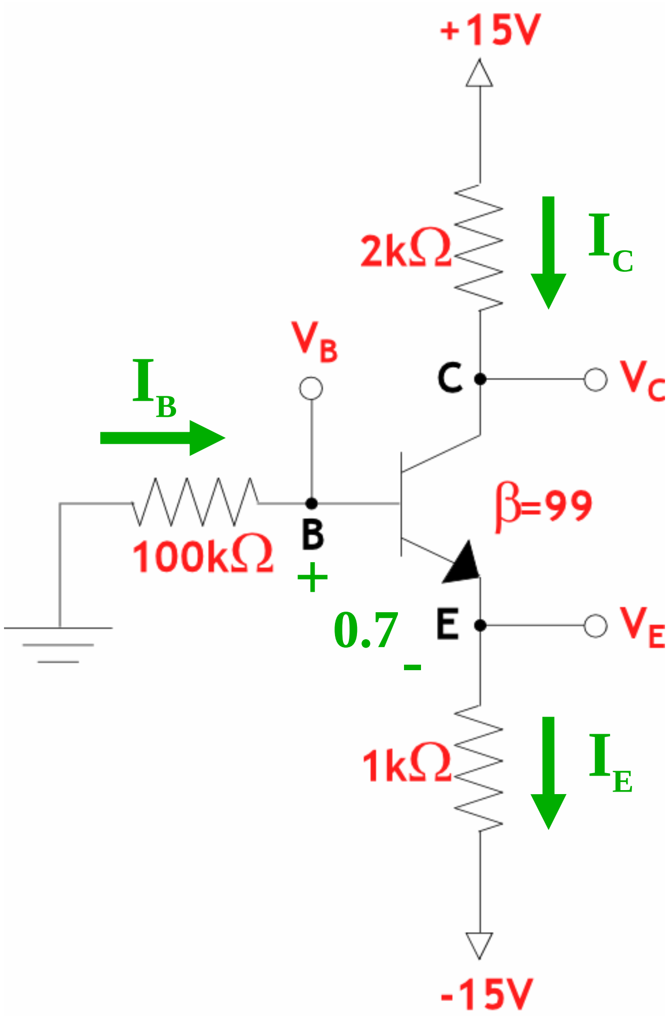


Find voltages & currents

Process:

a) Assume ACTIVE mode operation; $V_{BE} = 0.7V$
b) Based on assumption, calculate branch voltages and currents
c) Verify ACTIVE mode by checking V_{CB}

DC Analysis



$$I_E = \frac{V_E + 15}{1k} \qquad I_B = \frac{0 - V_B}{100k}$$

$$I_E = (\beta + 1) I_B \longrightarrow \frac{V_E + 15}{1k} = (\beta + 1)\frac{0 - V_B}{100k}$$

$$\boxed{V_B = V_E + 0.7} \longrightarrow \frac{V_E + 15}{1k} = (100)\frac{-V_E - 0.7}{100k}$$

Get:

$$V_E = \underline{-7.85V} \qquad I_E = \underline{7.15mA}$$

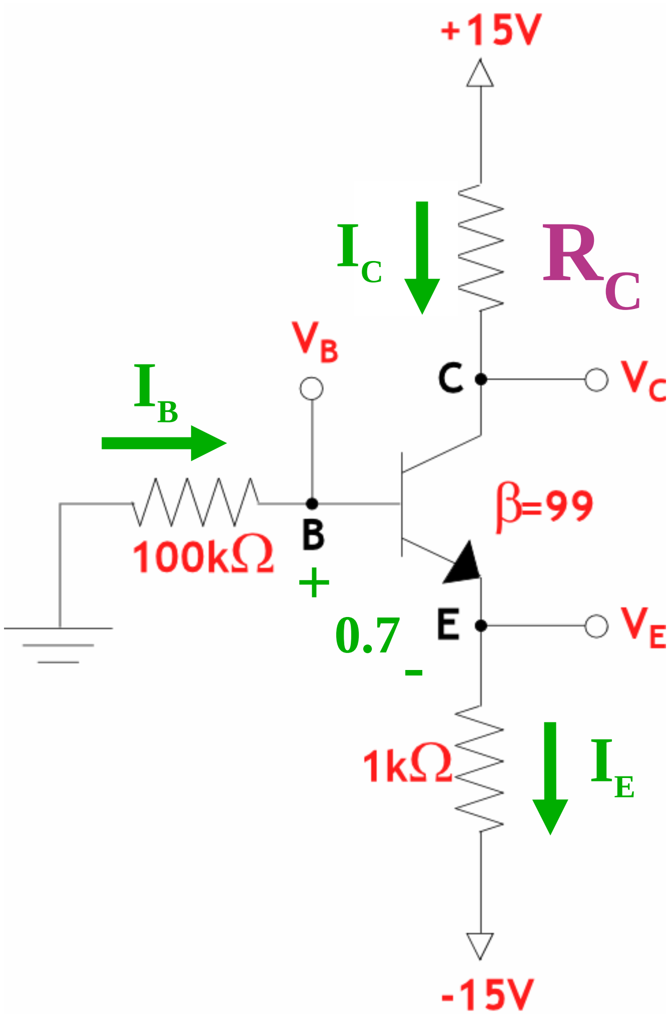
$$V_B = \underline{-7.15V} \qquad I_B = \underline{71.5\mu A}$$

$$I_C = \alpha I_E = \frac{\beta}{\beta + 1} I_E = \frac{99}{100}(7.15m) = \underline{7.08mA}$$

$$V_C = 15 - I_C R_C = 15 - (7.08m)(2k) = \underline{0.84V}$$

Check: V_{CB} = 7.99V (reverse biased) – OK

Edge of Active Mode

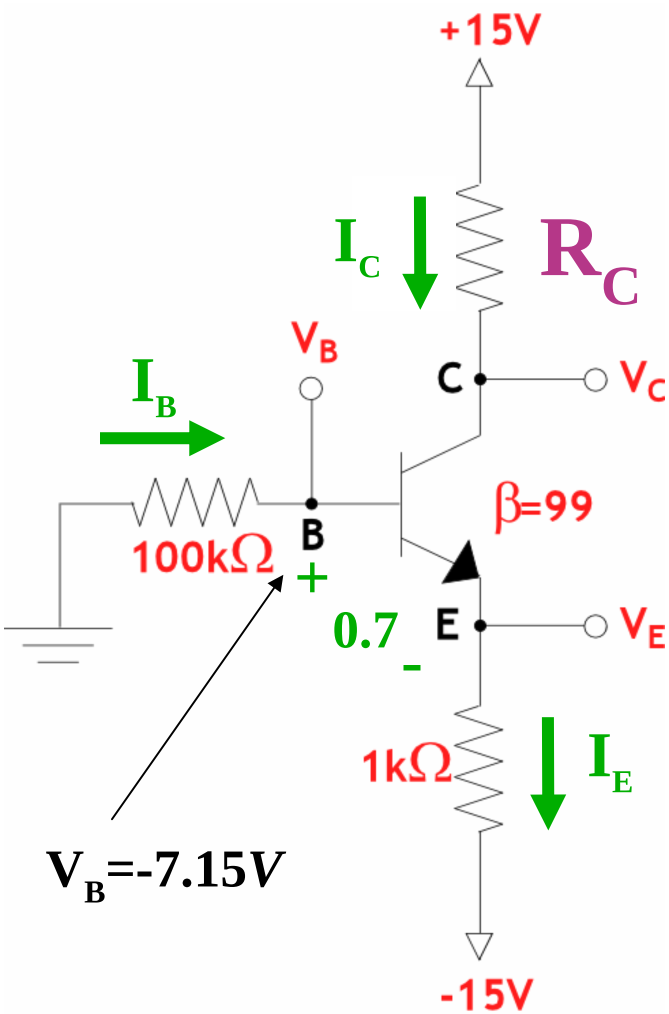


- From previous slide, found:

$$V_C = 15 - I_C R_C = 15 - (7.08m)R_C$$

- In general, *increasing* R_C will not change I_C significantly
- More significant consequence of *increasing* R_C is a *decrease* of V_C
- If R_C is too large, *decrease* of V_C will cause BJT to leave *active* mode and transition to *saturation* mode
- Recall, *active/saturation boundary* occurs for $V_C > V_B$; $V_{CB} > 0V$

Calculate Transition Point



-Use relationship for V_C & I_C:

$$V_C = 15 - I_C R_C = 15 - (7.08mA) R_C$$

-Use previous result for V_B = -7.15V, and write expression for R_C as a function of V_C; solve for maximum R_C in order to stay in *active* mode:

$$V_C = V_B ; 15 - (7.08mA) R_C = -7.15V$$

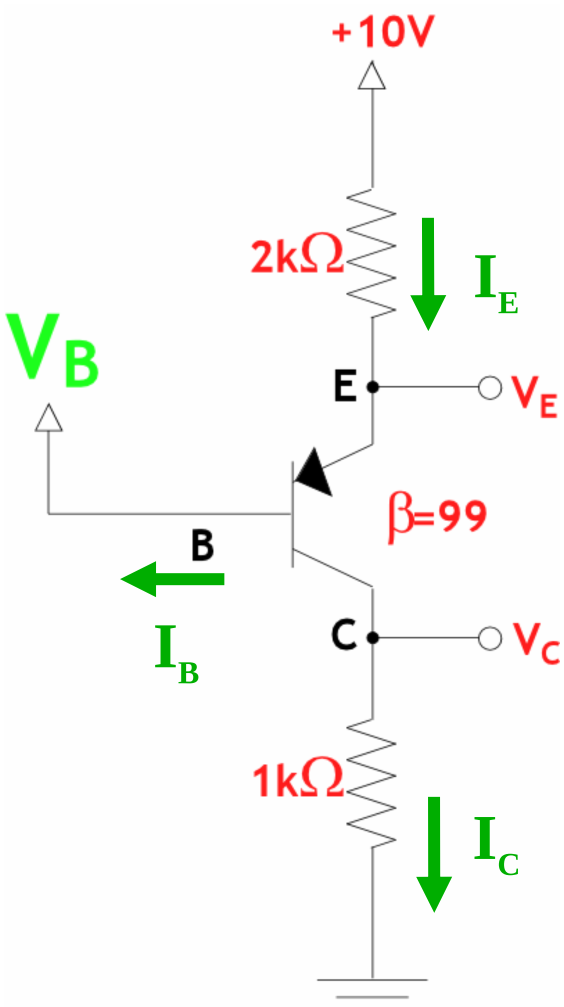
-For active mode operation:

$$\boxed{R_C \le 3.13k\Omega}$$

DC Analysis Comments

- Do not know a priori that BJT is in active mode
- Use approach similar to diode CVDM analysis
  - Assume active mode operation (V_{BE} = 0.7V)
  - Solve circuit
  - Verify active mode operation (check V_{CB})
- Generally never use exponential model for I_C in basic DC analysis
- Generally neglect Early Voltage effect in DC analysis

pnp Transistor Biasing



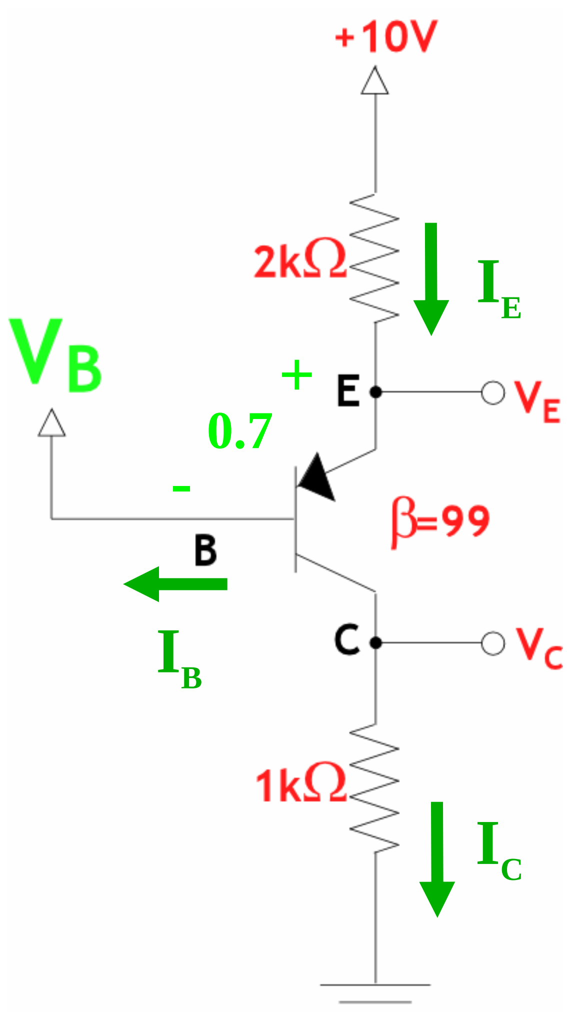
Process:

a) Assume *active* mode operation; $V_{EB} = 0.7V$

b) Based on assumption, calculate branch voltages and currents

c) Verify *active* mode by checking $V_{BC} \geq 0V$

Example: Find V_B That Keeps BJT Active



- As V_B decreases, I_E & I_C increase, V_C increases
- Minimum V_B condition exists while maintaining $V_{EB} = 0.7V$
- In active mode: $V_E - V_B = 0.7V$

$$I_E = \frac{10 - V_E}{2k}$$

$$I_C = \frac{V_C}{1k} = \alpha\, I_E = 0.99 \cdot \frac{10 - (V_B + 0.7)}{2k}$$

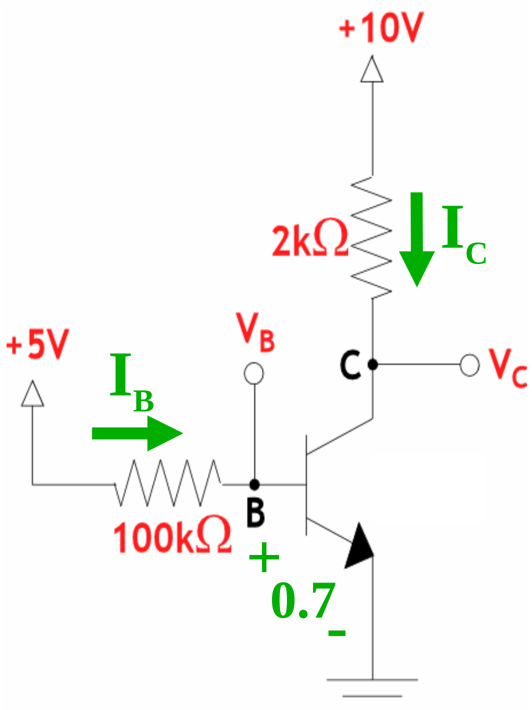
$$V_C = 4.6 - 0.495 V_B$$

At *active/saturation* boundary, $V_C = V_B$:

$$\boxed{V_B \geq 3.08V}$$

Transistor Sensitivity to I_B

β is 107



$R_B = 100k\Omega$

$$V_B = 0.7V$$

$$I_B = \frac{5-0.7}{100k} = 43\mu A$$

$$I_C = \beta I_B = (107)(43\mu A) = 4.601mA$$

$$V_C = 10-(4.601mA)(2k\Omega) = 0.798$$

$R_B = 200k\Omega$

$$V_B = 0.7V$$

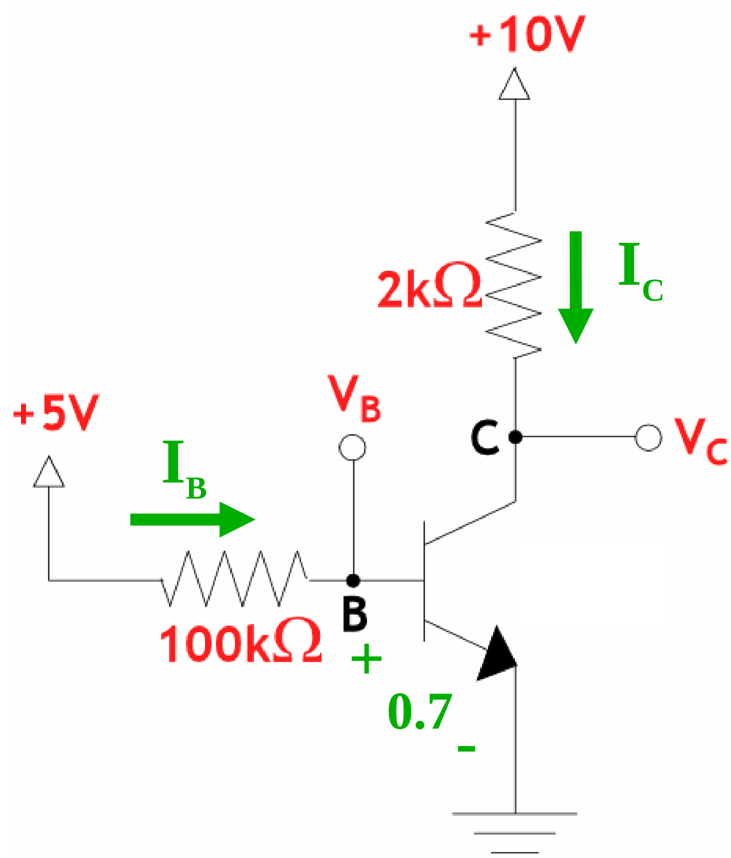
$$I_B = \frac{5-0.7}{200k} = 21.5\mu A$$

$$I_C = \beta I_B = (107)(21.5\mu A) = 2.4075mA$$

$$V_C = 10-(2.4075mA)(2k\Omega) = 5.185$$

- Small changes in base current result in large current changes in the collector: $I_C = \beta I_B$.
- Doubling the base current, causes the collector voltage to decrease more than 6.5 times.

Transistor Sensitivity to β



Find β condition to keep BJT active

$$V_B = 0.7V \qquad I_B = \frac{5-0.7}{100k} = 43\mu A$$

$$I_C = \beta I_B = \beta \cdot 43\mu A$$

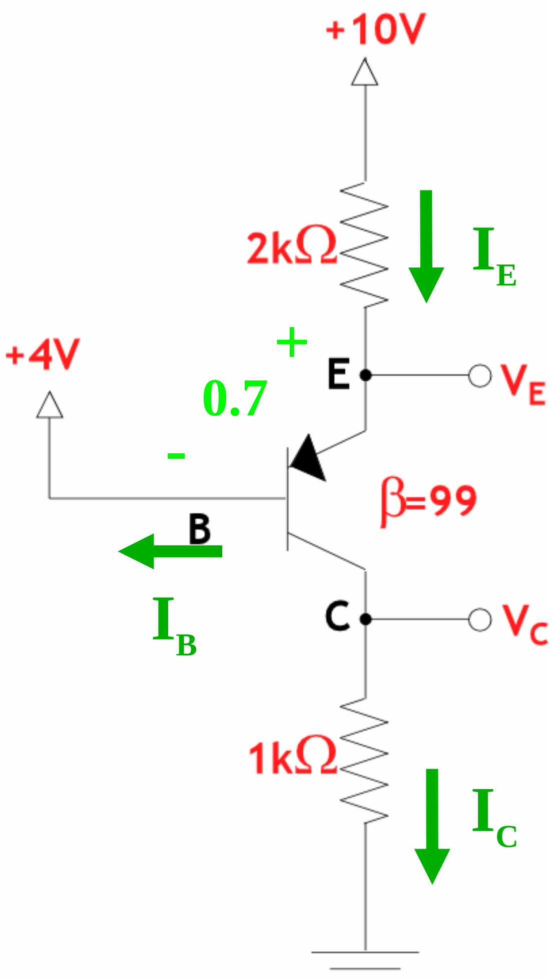
$$V_C = 10 - I_C(2k) = 10 - 0.086\beta$$

Let $V_C = V_B = 0.7$

$V_C \geq V_B \Rightarrow \quad \beta \leq 108$

- β can vary; want designs with DC conditions that are insensitive to β

Avoiding β Sensitivity



Find β condition to keep BJT active

$$V_E = 4.7V \quad I_E = \frac{10-4.7}{2k} = 2.65mA$$

$$I_C = \alpha I_E = \frac{\beta}{\beta+1} 2.65mA$$

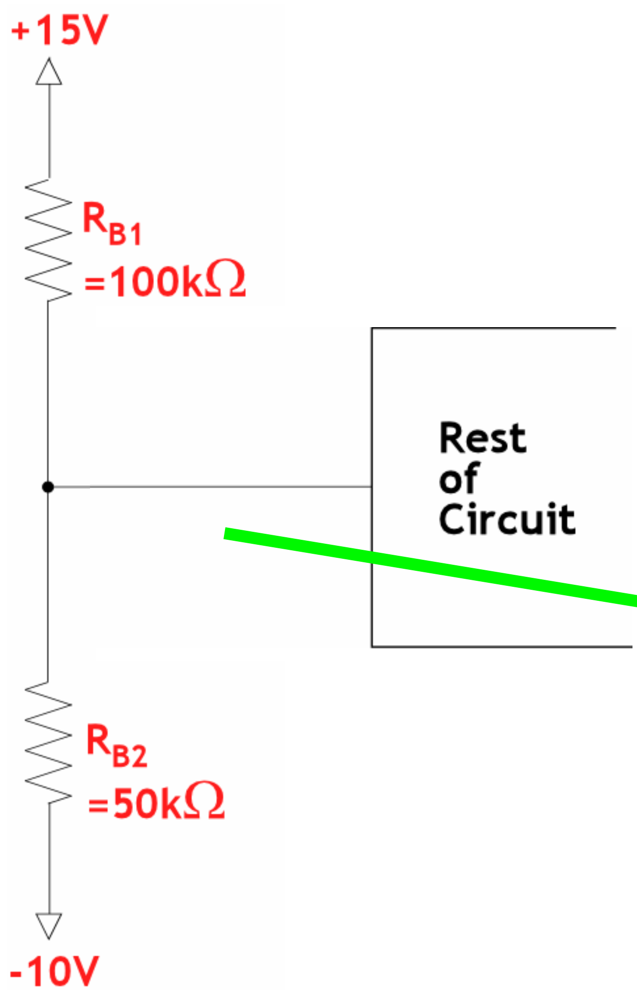
$$V_C = I_C(1k\Omega) = (2.65)\frac{\beta}{\beta+1}$$

Let $V_C = V_B = 4V$

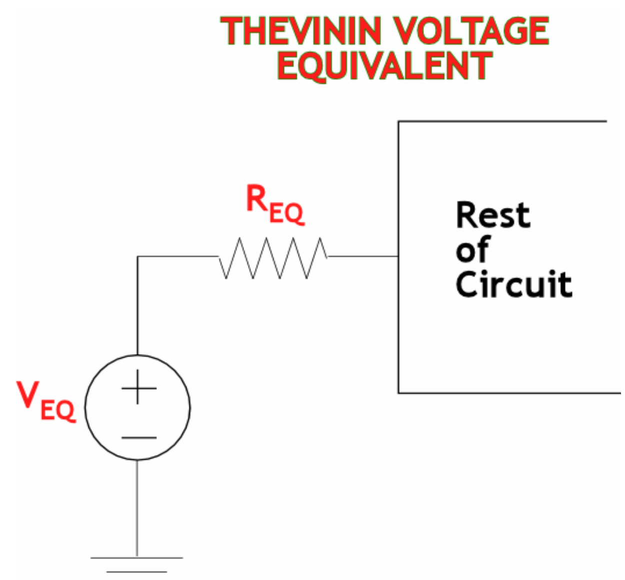
$V_C \leq V_B \Rightarrow \quad \beta \geq -2.96$ OK for any β

- Putting resistance in the emitter generally stabilizes DC biasing

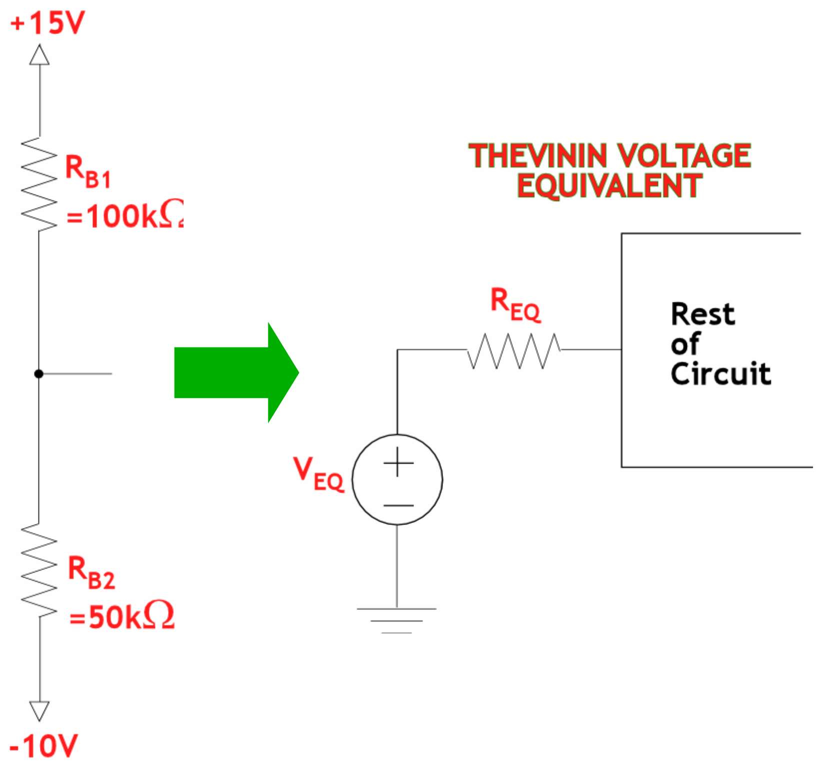
Transistor Biasing



- Typical resistor arrangement for base-biasing of the BJT amplifier configurations.
- Start by simplifying base network R_{B1} & R_{B2}



Thevenin Circuit for Transistor Biasing



– V_{EQ}: use superposition

$$V_{EQ}\Big|_{+15V\text{ source}} = \frac{R_{B2}}{R_{B1}+R_{B2}}15 = 5V$$

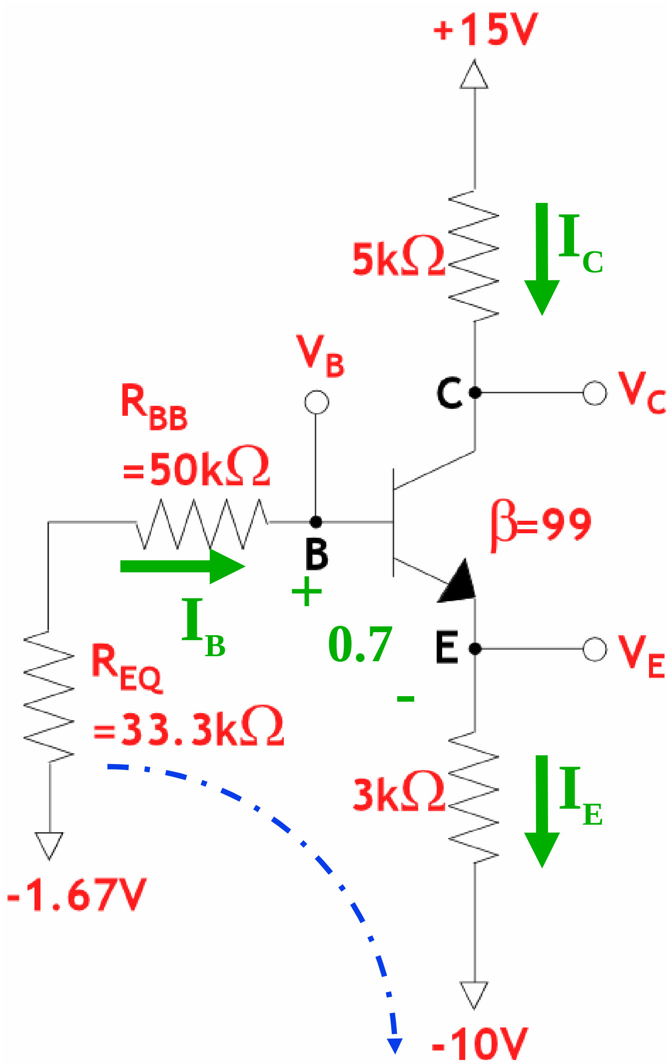
$$V_{EQ}\Big|_{-10V\text{ source}} = \frac{R_{B1}}{R_{B1}+R_{B2}}(-10) = -6.67V$$

$$\therefore V_{EQ} = -1.67V$$

– R: by inspection

$$R_{EQ} = R_{B1} \| R_{B2} = 33.3k\Omega$$

Example



$$I_E = \frac{V_E + 10}{3k} \qquad I_B = \frac{-1.67 - V_B}{83.3k}$$

$$I_E = (\beta + 1) I_B \longrightarrow \frac{V_E + 10}{3k} = (\beta + 1)\frac{-1.67 - V_B}{83.3k}$$

$$V_B = V_E + 0.7 \longrightarrow \frac{V_E + 10}{3k} = (100)\frac{-V_E - 2.37}{83.3k}$$

Get:

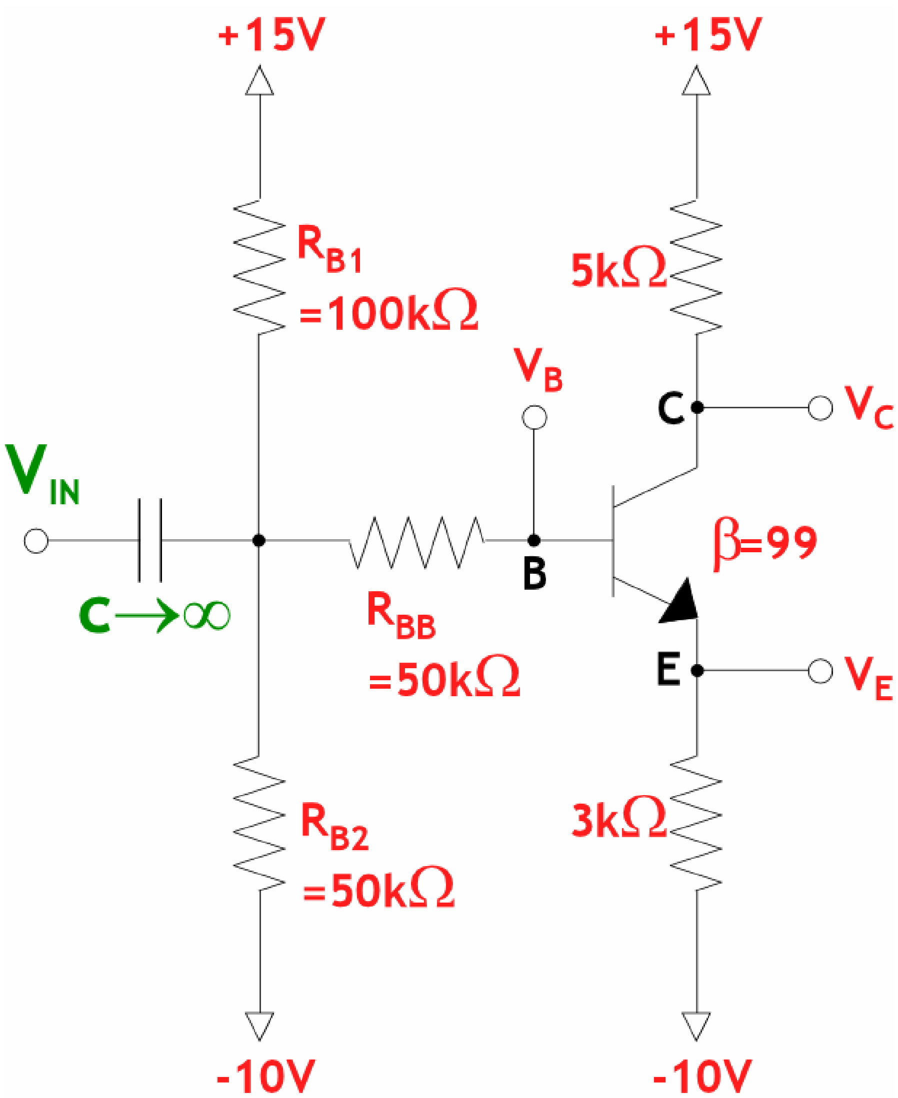
$V_E = \underline{-4.03V}$	$I_E = \underline{1.99mA}$
$V_B = \underline{-3.33V}$	$I_B = \underline{19.9\mu A}$

$$I_C = \alpha I_E = \frac{\beta}{\beta + 1} I_E = \frac{99}{100}(1.99m) = \underline{1.97mA}$$

$$V_C = 15 - I_C R_C = 15 - (1.97m)(2k) = \underline{5.15V}$$

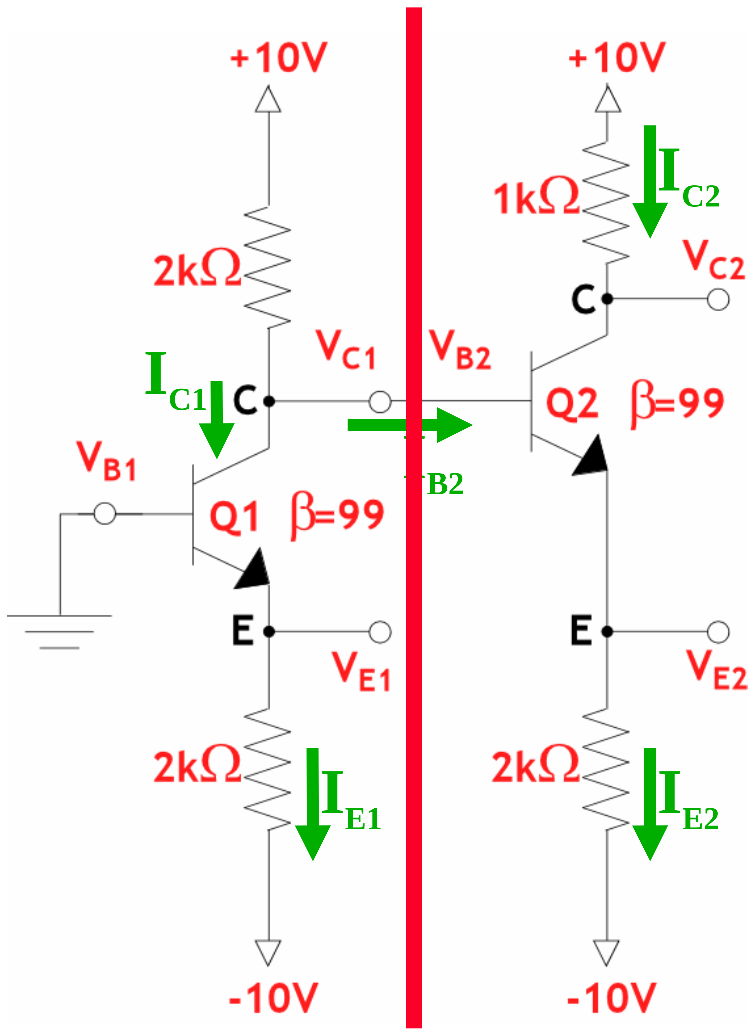
Check: V_{CB} = 8.48V (reverse biased) – OK

AC-Signal Coupling



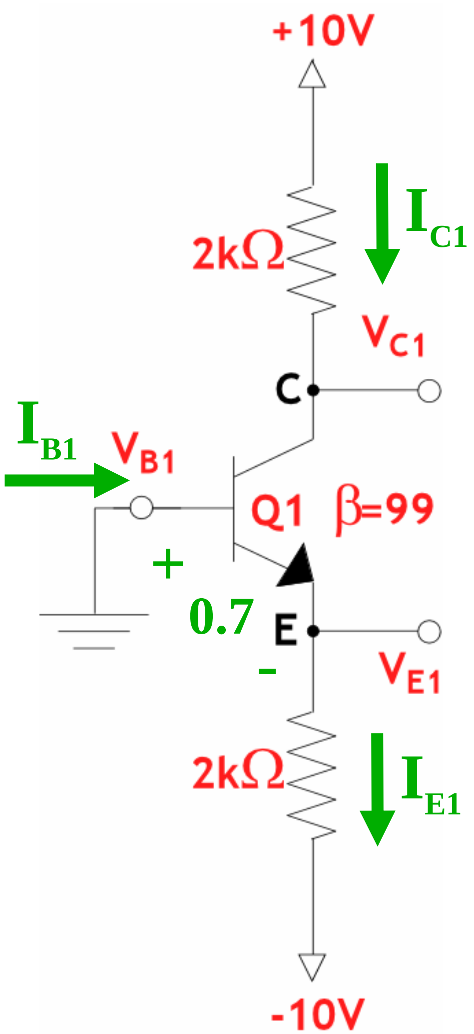
- Couple an input signal via a coupling capacitor:
  - $C \rightarrow \infty$ is open circuit at DC, short circuit for AC signals.
  - If R_{B1} & R_{B2} not present, BJT would not be DC biased
  - C prevents signal source from having to provide DC current
  - Completely decouples DC biasing from signal source

Two-Stage BJT DC Circuits Analysis



- Analysis approach: perform DC analysis on individual transistors.
- In this example, decouple at V_{C1} - V_{B2} circuit connection
- Assume that $I_{B2} = 0$ and calculate V_{B2}
- Analyze each BJT separately
- Compare results for I_{B2} and I_{C1}
- Through iteration/simulation, can verify approximation

Q1 Analysis



2 assumptions: a) *active* mode, and b) *no current flowing* into Q2 via V_{C1} node: $I_{B2}=0$

$$V_E = -0.7V \quad I_E = \frac{-0.7+10}{2k} = 4.65mA$$

$$I_C = \alpha I_E = \frac{\beta}{\beta+1} 4.65mA = 4.604mA$$

$$V_C = 10 - I_C(2k\Omega)$$

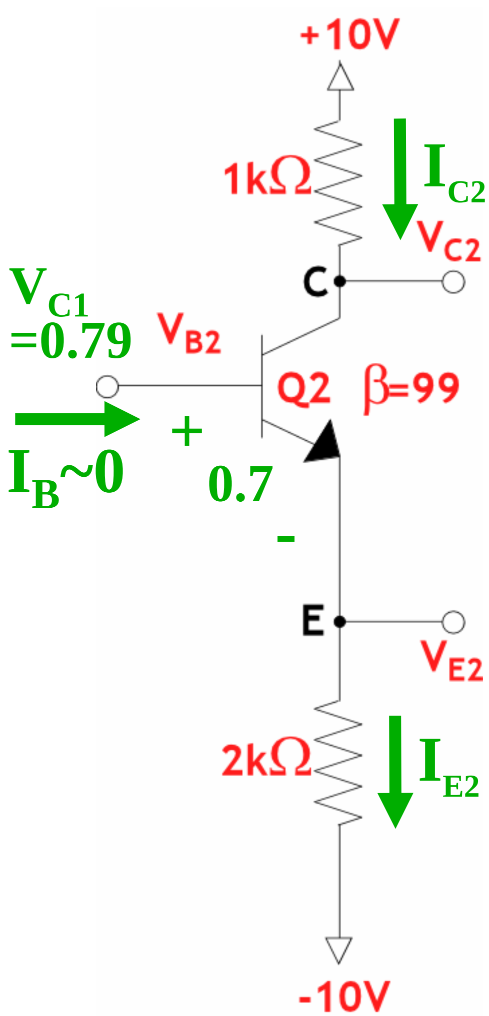
$$= 10 - (4.605mA)(2k\Omega) = 0.79V$$

$$V_{E1} = \underline{-0.7V} \quad I_{E1} = \underline{4.65mA}$$

$$I_{B1} = \underline{46.5\mu A}$$

$$V_{C1} = \underline{0.79V} \quad I_{C1} = \underline{4.60mA}$$

Q2 Analysis – Same Assumptions



2 assumptions: a) *active* mode, and b) *no current flowing* into Q2 via V_{C1} node: $I_{B2}=0$

$$V_E = 0.79 - 0.7 = 0.09V$$

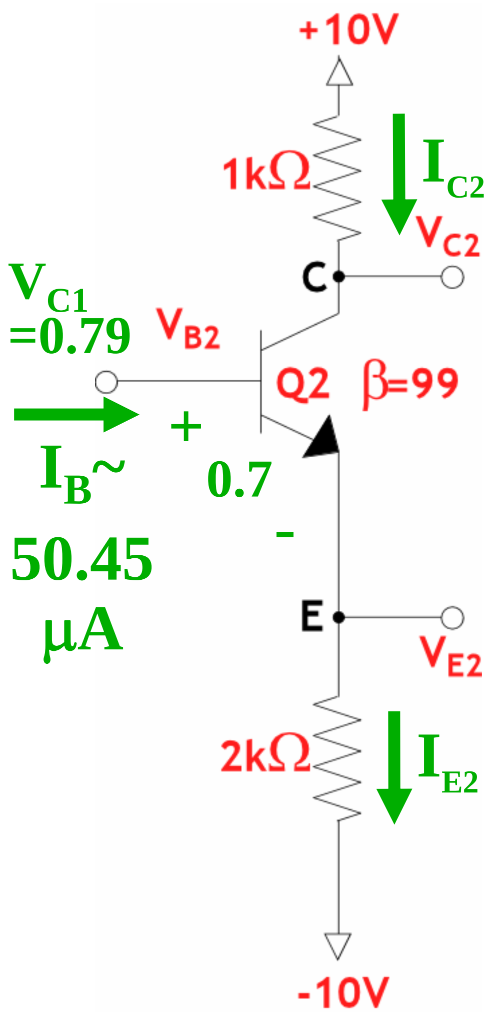
$$I_E = \frac{0.09+10}{2k} = 5.045mA$$

$$I_C = \alpha\, I_E = \frac{\beta}{\beta+1} 5.045mA = 4.995mA$$

$$V_C = 10 - I_C(1k\Omega)$$
$$= 10 - (4.995mA)(1k\Omega) = 4.995V$$

$$V_{E2} = \underline{0.09V} \quad I_{E2} = \underline{5.05mA}$$
$$V_{C2} = \underline{4.995V} \quad I_{C2} = \underline{4.995mA}$$

Compute Q2 Base Current

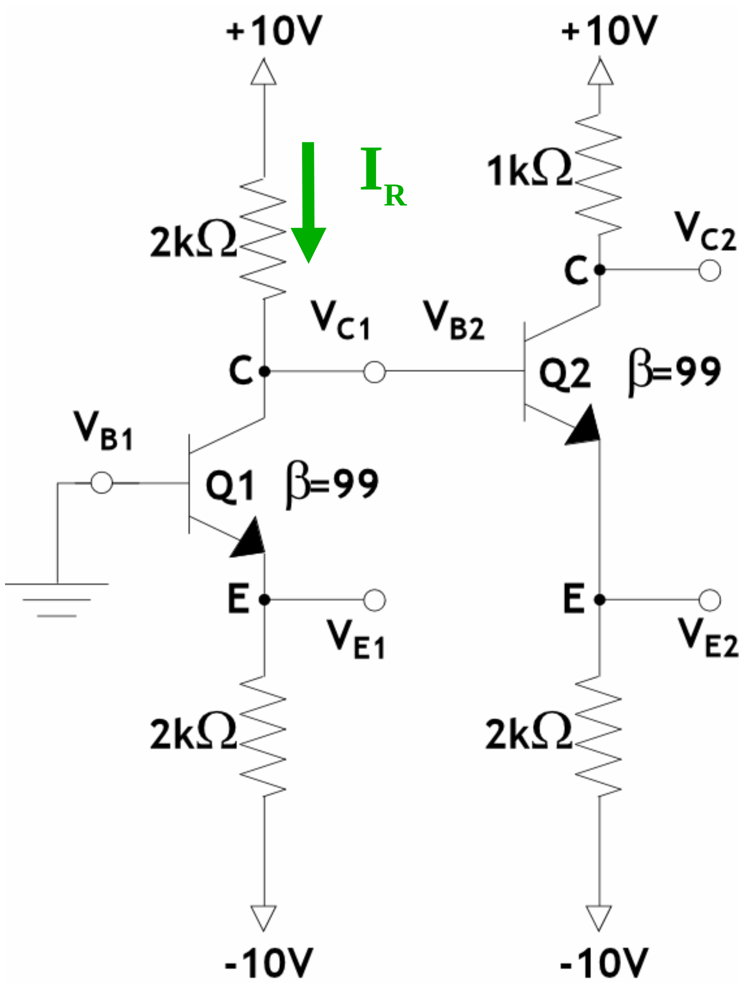


From previous:

$$I_C = \alpha\, I_E = \frac{\beta}{\beta+1} 5.045mA = 4.995mA$$

$$I_B = \frac{I_C}{\beta} = \frac{4.995mA}{99} = 50.45\mu A$$

Iterate to Get Exact Solution; Verify On Own



Add I_{B2} to I_{C1} current flowing in 2kΩ

$$I_R = I_{C1} + I_{B2} = 4.604 + 0.0505 = 4.6545 mA$$

$$V_{C1} = 10 - I_R(2k\Omega)$$

$$= 10 - (4.6545 mA)(2k\Omega) = 0.691$$

Re-DO the calculations for Q2:

$$V_{E2} = 0.691 - 0.7 = -0.01V$$

$$I_{E2} = \frac{-0.01 + 10}{2k} = 4.995 mA$$

$$I_{C2} = \alpha\, I_{E2} = \frac{\beta}{\beta + 1} 4.995 mA = 4.945 mA$$

$$V_{C2} = 10 - I_{C2}(1k\Omega)$$

$$= 10 - (4.945 mA)(1k\Omega) = 4.945V$$

$$I_{B2} = \frac{I_{C2}}{\beta} = \frac{4.945 mA}{99} = 49.95 \mu A$$

DC Analysis of Active Mode BJT Circuits – Summary

- General approach to active mode DC analysis
- Collector resistance and its effect on active mode operation
- Sensitivity of BJT DC bias to variations in β, and how to avoid it
- Practical biasing arrangement for coupling AC signals
- Analysis approach to DC analysis of circuits involving multiple BJTs

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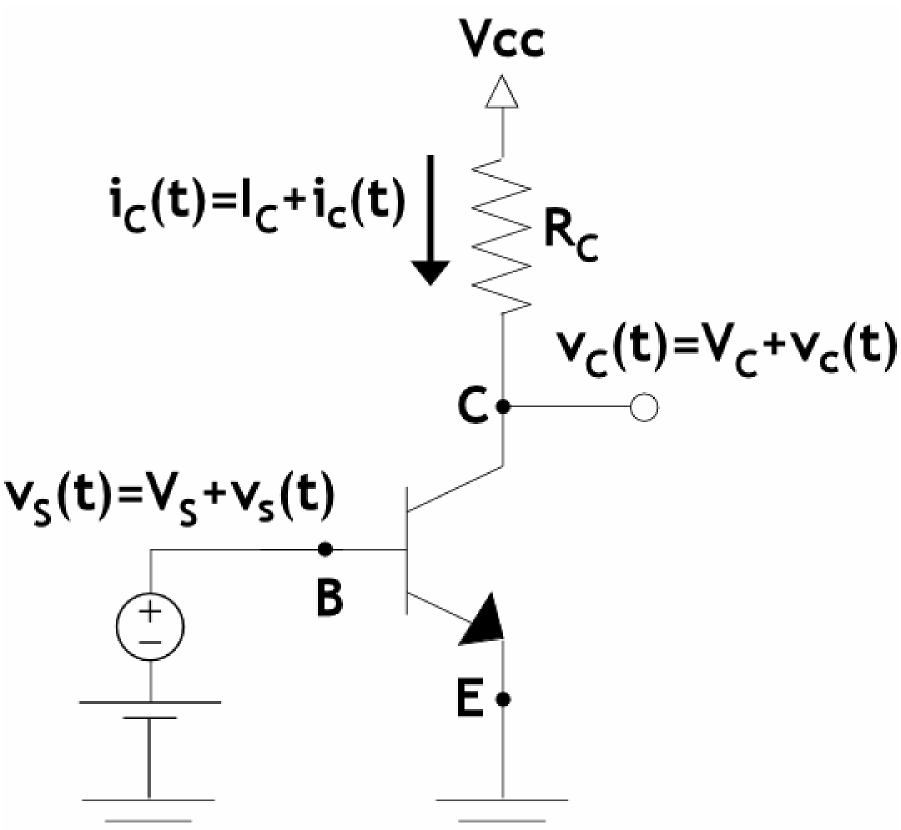
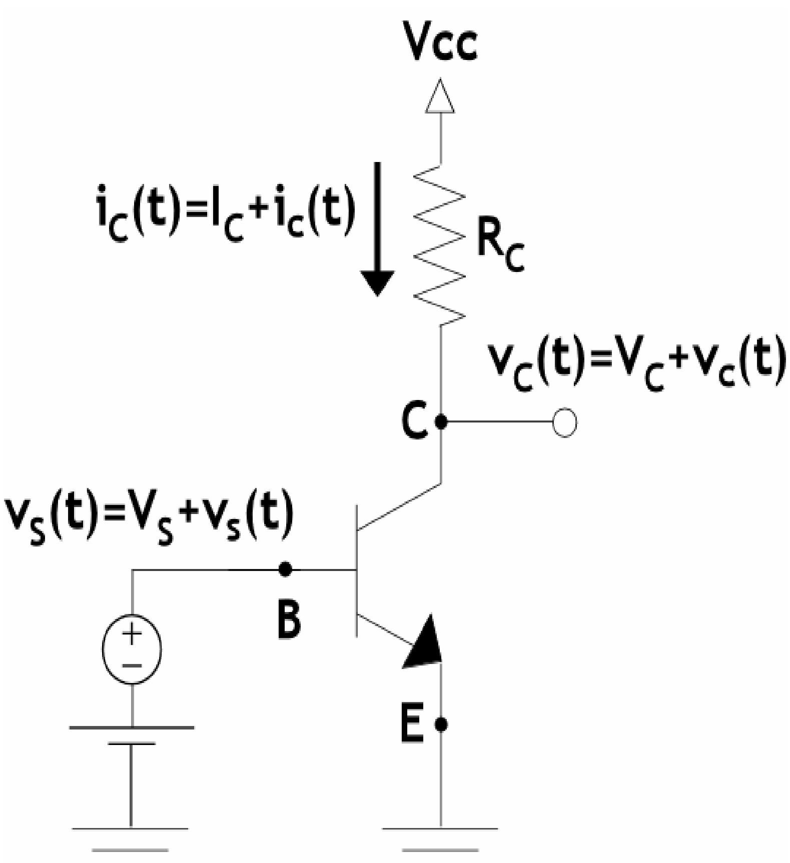
BJT Signal Analysis

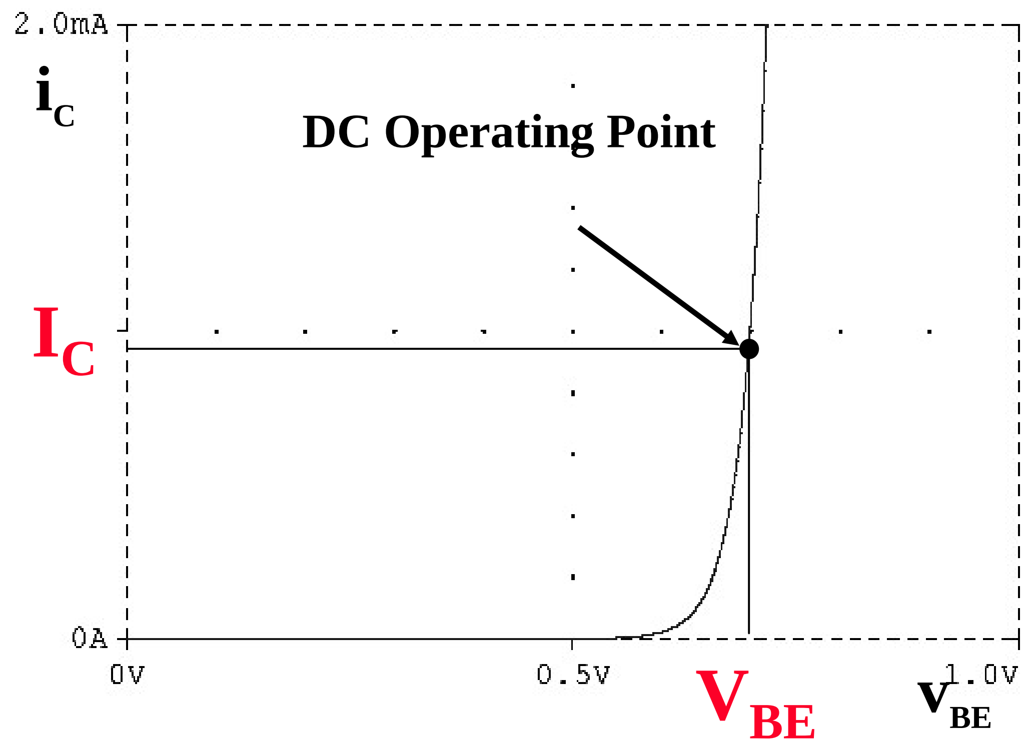


- Input has DC and AC components
- Output has DC and AC components
- Because the two are linearly super-imposed, can separate DC and AC analysis as did with diode

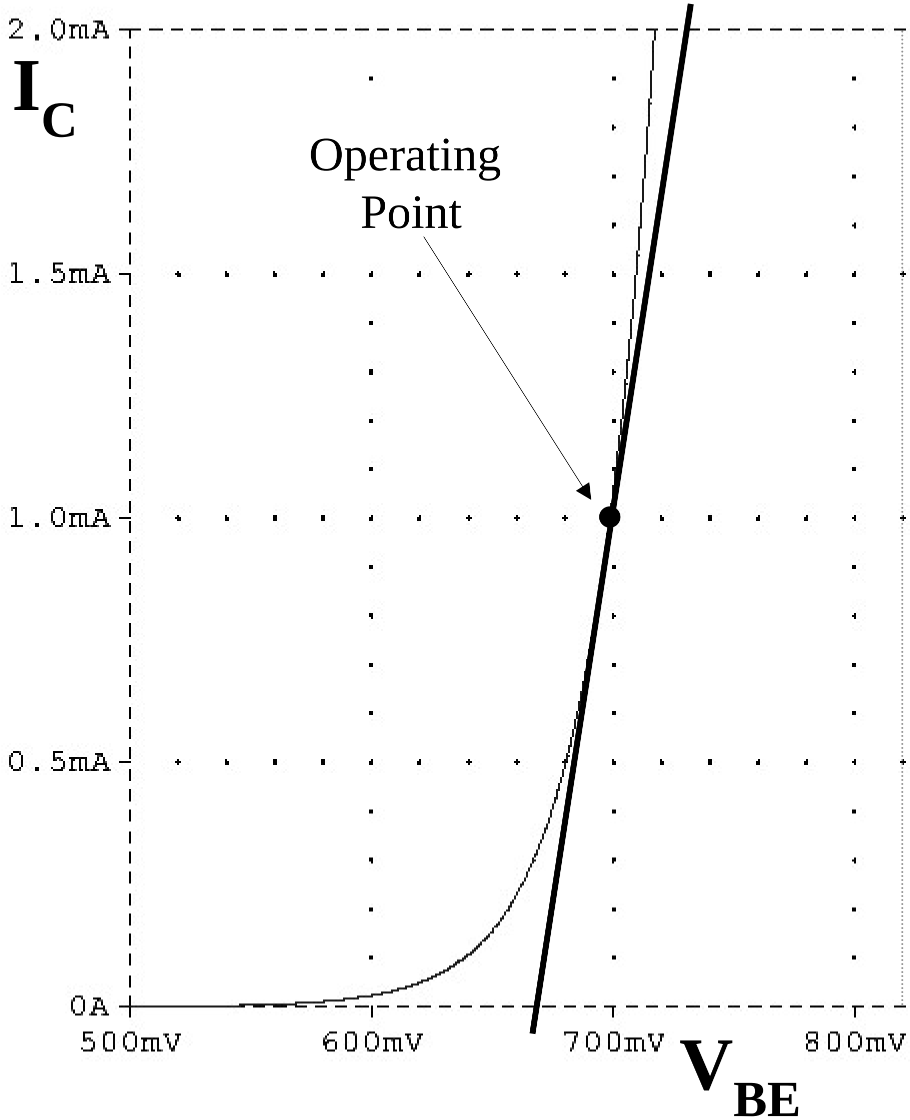
DC Analysis – Operating Point, I_C vs V_{BE}



- Kill AC sources
- Operating point determined by V_{BE}



BJT Signal Analysis – i_C vs v_{BE}



Consider superposition of an AC signal at the DC operating point

- Slope of i_C-v_{BE} curve at operating defined as BJT transconductance, g_m

$$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)$$

g_m Operating Point Dependence

- Since g_m represents slope at a fixed *operating point*, can derive an expression for g_m, at this operating point

$$g_m \equiv \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C}$$

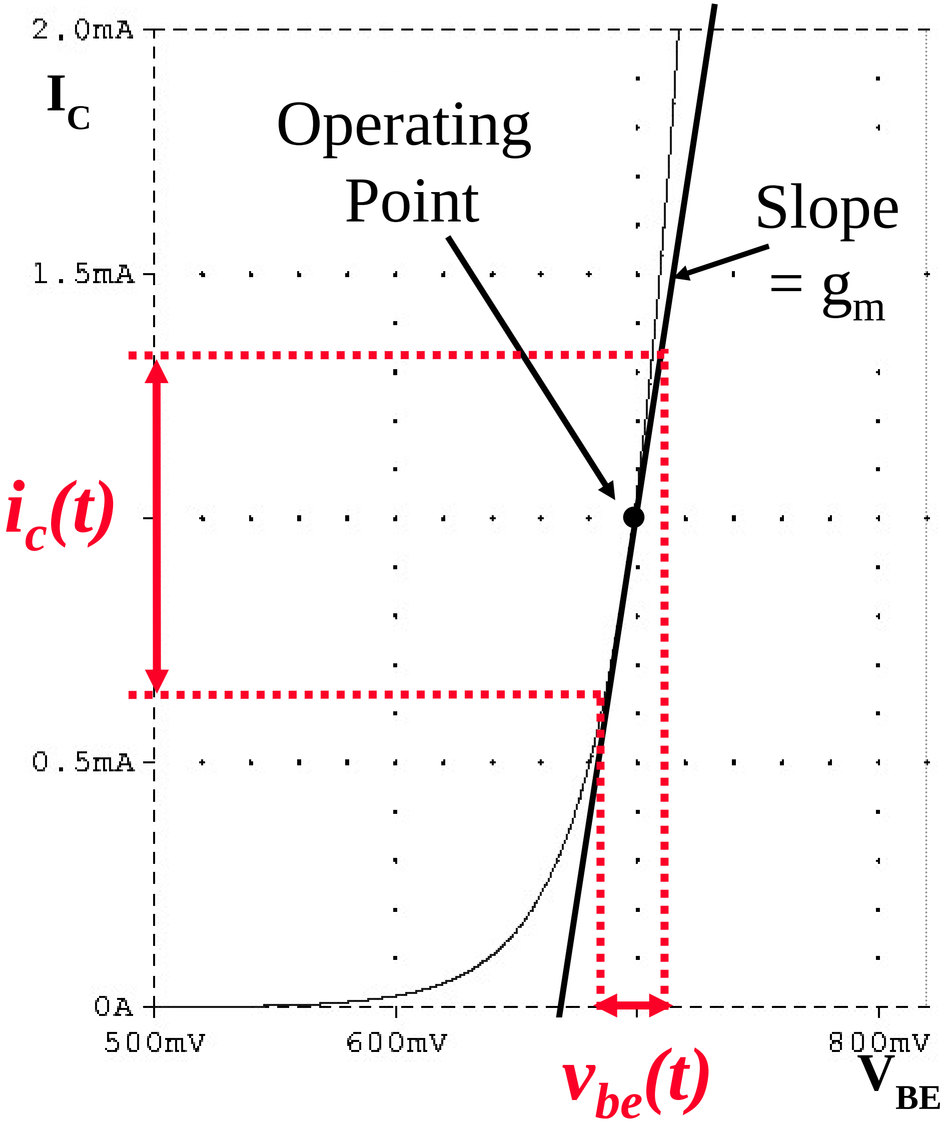
$$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)$$

- Take derivative and simplify
- Final expression for g_m indicates BJT operating point dependence based on I_C, the DC collector current.

$$\left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C} = \underbrace{I_S \exp\left(\frac{V_{BE}}{V_T}\right)}_{I_C} \cdot \frac{1}{V_T}$$

$$\boxed{g_m = \frac{I_C}{V_T}}$$

BJT Small Signal – i_C vs v_{BE}



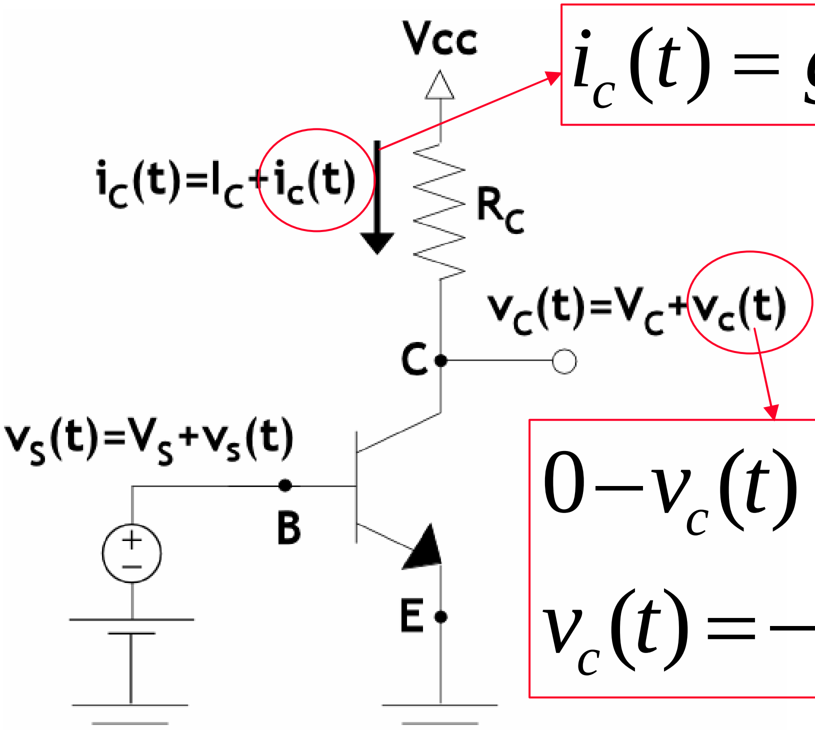
Define transconductance as slope of the i_C-v_{BE} curve at an operating point:

In the *small signal* limit, can write expression for gm as follow:

$$g_m = \frac{i_c(t)}{v_{be}(t)}$$

g_m determines the BJT gain

Common Emitter BJT Amplifier



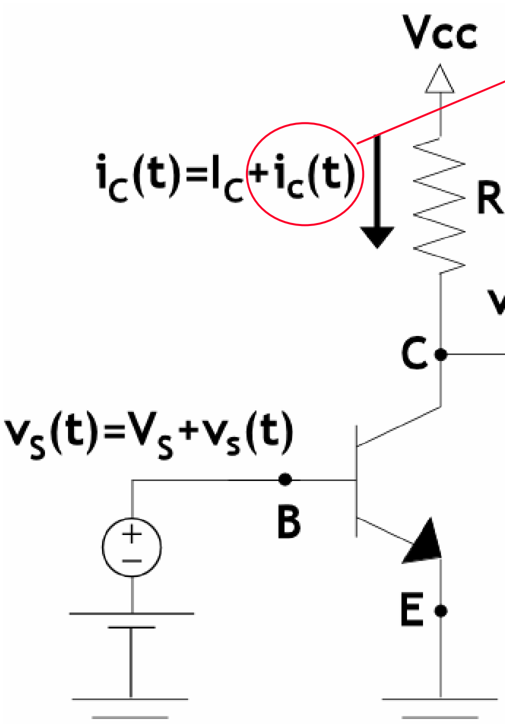
$$i_c(t) = g_m v_{be}(t)$$

$$0 - v_c(t) = i_c R_C$$

$$v_c(t) = -g_m v_{be}(t) R_C$$

- Apply small signal at base: $v_s(t)=v_{be}(t)$
- Results in signal current, $i_c(t)$, at collector
- Signal current through R_C produces output voltage at BJT collector terminal

Common Emitter BJT Voltage Gain



$$i_c(t) = g_m v_{be}(t)$$

$$0 - v_c(t) = i_c R_C$$

$$v_c(t) = -g_m v_{be}(t) R_C$$

- Define voltage gain:

$$A_V = \frac{v_c(t)}{v_{be}(t)} = -g_m R_C$$

Common Emitter BJT Voltage Gain

- From SPICE: