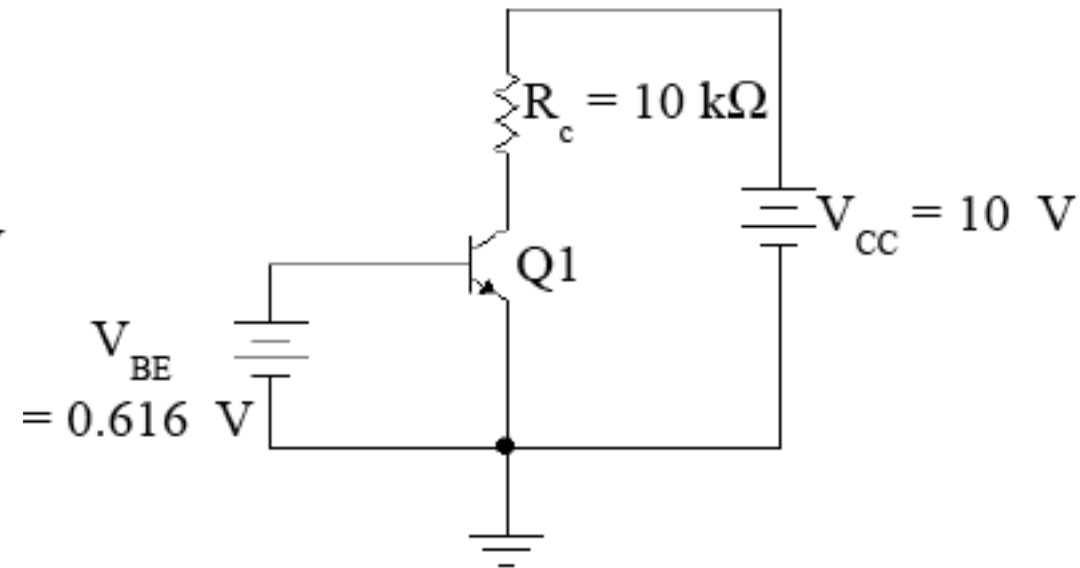
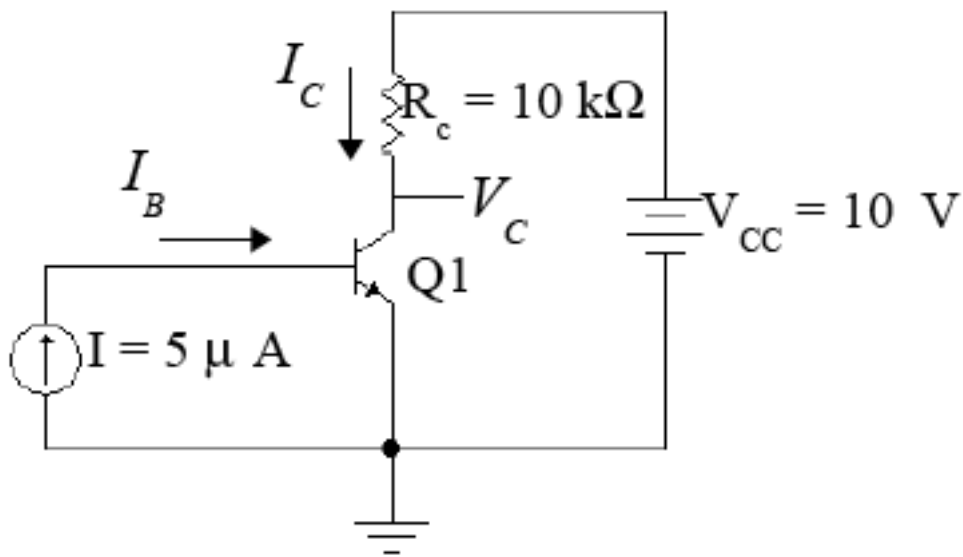


BJT Biasing Cont.

- Biasing for DC Operating Point Stability
- BJT Bias Using Emitter Negative Feedback
- Single Supply BJT Bias Scheme
- Constant Current BJT Bias Scheme
- “Rule of Thumb” BJT Bias Design

Previous Simple Base Biasing Schemes



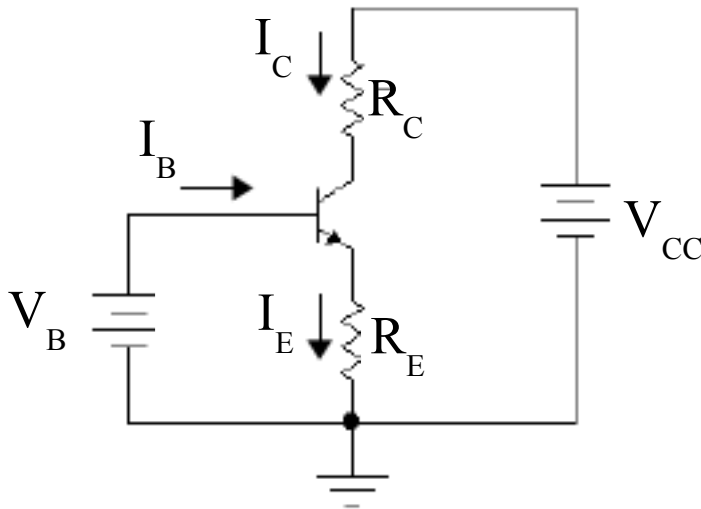
What's wrong with these schemes?

Biasing for Operating Point Stability

A practical biasing scheme must be insensitive to changes in transistor β and operating temperature!

Negative feedback is one solution.

Consider the circuit:



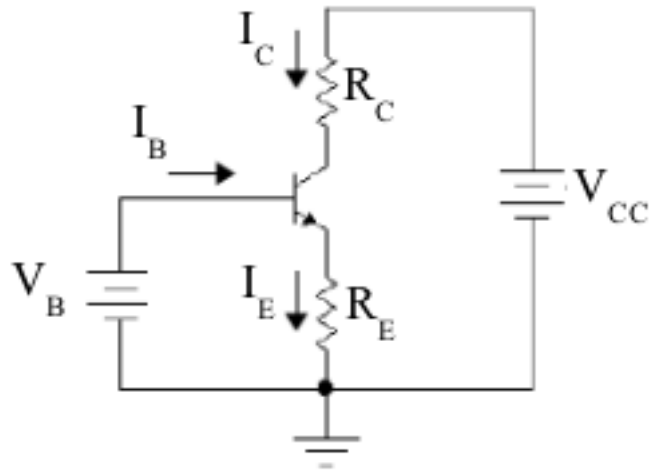
And make the following observations. Assume active mode operation:

$$V_{CE} > 0.2 V.$$

Then:

$$I_C = I_S e^{\frac{V_{BE}}{V_T}}$$

$$V_{BE} = V_B - R_E I_E$$



Basic relationships:

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

$$I_E = \frac{(\beta + 1)}{\beta} I_C = \frac{1}{\alpha} I_C$$

Given the (DC bias) equations:

$$I_C \approx I_S e^{\frac{V_{BE}}{V_T}}$$

$$V_{BE} = V_B - R_E I_E = V_B - R_E \frac{I_C}{\alpha}$$

Assume: $V_{BE} = 0.7 V$, Let: V_B, V_{CC}

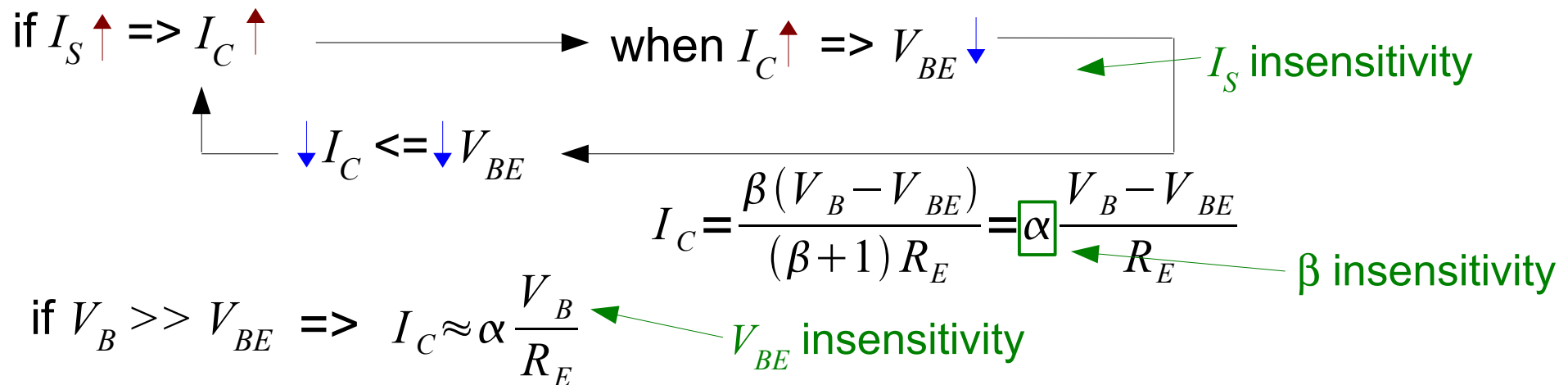
be given and I_C be specified. Then compute R_E to obtain the specified collector current I_C :

$$R_E = \alpha \frac{V_B - 0.7}{I_C}$$

Negative Feedback via R_E

- Negative feedback makes the collector current insensitive to V_{BE} , I_S , and β .
- If I_C increases – due to an increase in I_S then V_{BE} will decrease; thus, limiting the magnitude of the change in I_C .
- The equations that must be satisfied simultaneously are:

$$I_C = I_S e^{\frac{V_{BE}}{V_T}} \quad \text{and} \quad V_{BE} = V_B - R_E \frac{I_C}{\alpha} = V_B - \frac{\beta+1}{\beta} R_E I_C$$



Scilab Analysis of I_C Insensitivity to I_S

Simultaneous equations:

$$I_C = I_S e^{\frac{V_{BE}}{V_T}}$$

or:

$$I_C = \alpha \frac{V_B - V_{BE}}{R_E} = I_S e^{\frac{V_{BE}}{V_T}}$$

Let $R_E = 4\text{k}\Omega$ and $V_B = 4.7\text{V}$ (want $V_B \gg V_{BE}$)

If we plot the exponential function and the straight line function, the solution values of I_C and V_{BE} for the circuit occur at their intersection.

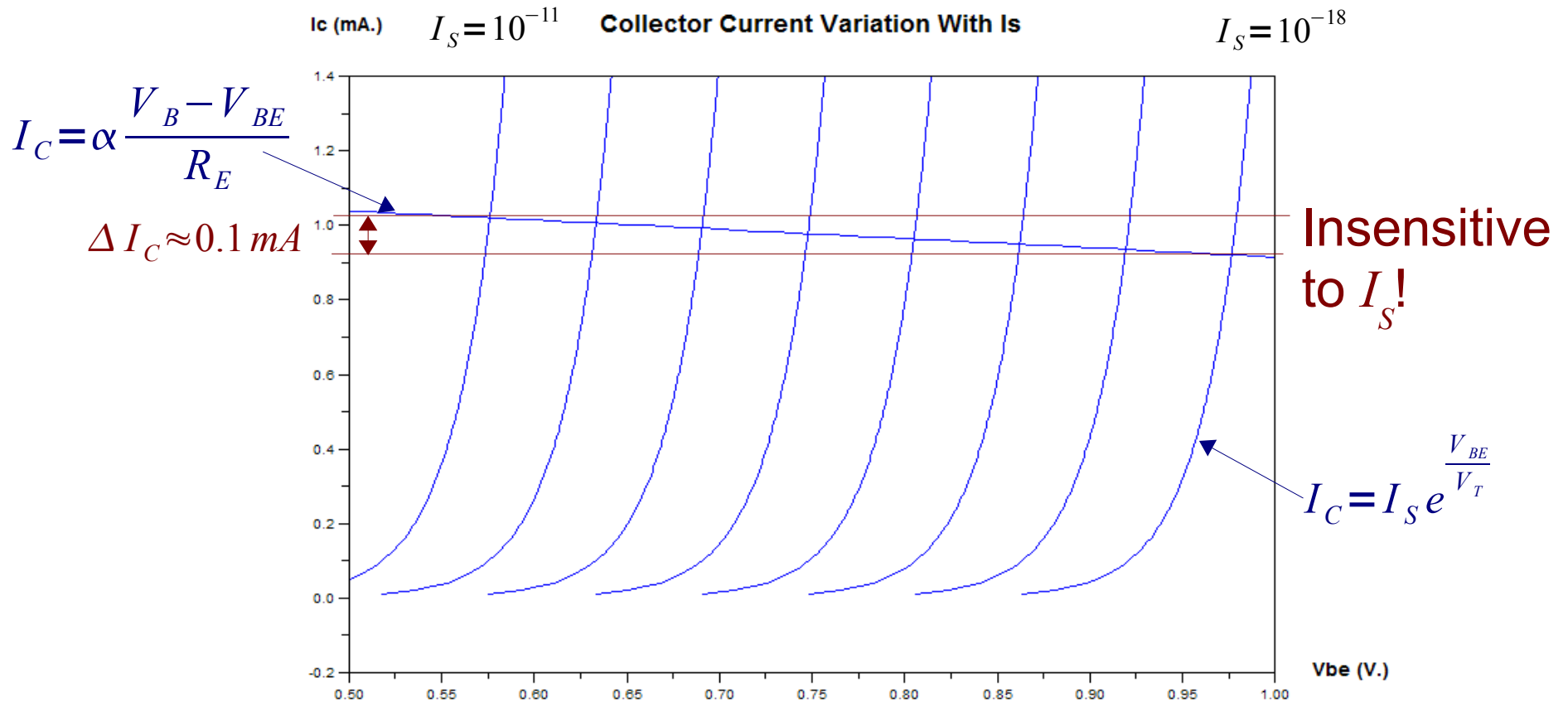
Scilab Program

```
//Calculate and plot npn BJT bias characteristic
beta=100;
alpha=beta/(beta+1);
VsubT=0.025;
VTinv=1/VsubT;
VBB=4.7;
Re=4;
vBE=0.0:0.01:1;
iCline=alpha*(VBB-vBE)/Re;//mA.
plot(vBE,iCline);
iC=0.01:0.01:2; //mA.!
IsubS =1E-16; //mA.
for k= 1:1:8
    IsubS=10*IsubS;
    vBE2=VsubT*log(iC/IsubS);
    plot(vBE2,iC); //Current in mA.
end
```

$$I_C = \alpha \frac{V_B - V_{BE}}{R_E}$$

$$V_{BE} = V_T \ln \frac{I_C}{I_S}$$

I_C vs I_S Results Plot



Inensitivity to Beta

$$R_E = \alpha \frac{V_B - 0.7}{I_C}$$

Example: $\beta = 100$

$$V_B = 4.7 \text{ V}$$

$$I_C = 1 \text{ mA}$$

$$\alpha = \frac{100}{101} \approx 0.99$$

$$R_E = 0.99 \cdot \frac{4.7 - 0.7}{10^{-3}}$$

$$R_E \approx 4000 \ \Omega$$

Writing I_C as a function of β :

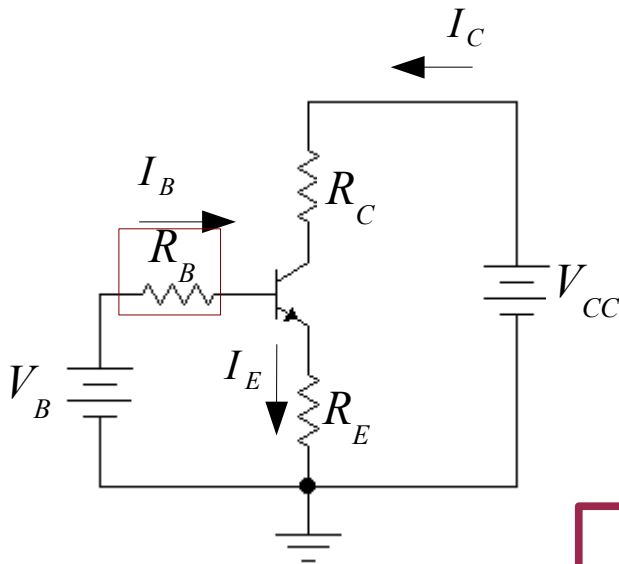
$$I_C = \alpha \frac{V_B - 0.7}{R_E} = \frac{\beta}{\beta + 1} \cdot 10^{-3} \text{ A}$$

Assume: $100 < \beta < 200$

$$\frac{100}{101} \cdot 10^{-3} = 0.990 \text{ mA} < I_C < \frac{200}{201} \cdot 10^{-3} = 0.995 \text{ mA}$$

So I_C is insensitive to changes in β !

Voltage Source With Internal Resistance



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

$$V_B = I_B R_B + V_{BE} + (\beta + 1) I_B R_E$$

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

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

If $R_B \ll (\beta + 1) R_E$

$$I_C = \beta I_B \approx \frac{\beta}{\beta + 1} \frac{(V_B - V_{BE})}{R_E} = \alpha \frac{(V_B - V_{BE})}{R_E}$$

If $R_B \gg (\beta + 1) R_E$

$$I_C = \beta I_B \approx \frac{\beta}{R_B} (V_B - V_{BE}) \text{ no feedback!}$$

Biassing for Operating Point Stability – Quick Review

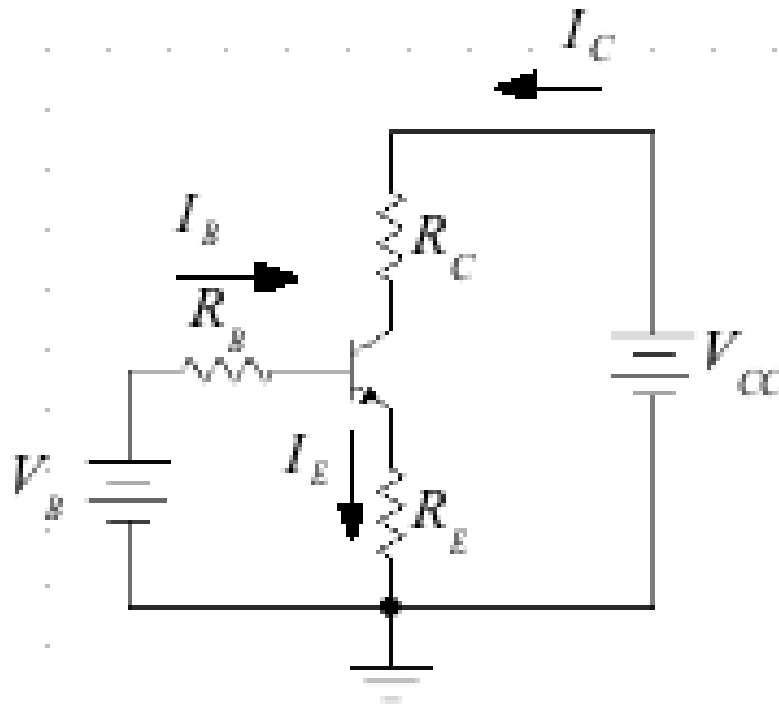
What is the purpose R_E ?

What does R_B represent?

What is the condition on the value of V_B ?

What is the condition on the value of R_E ?

What is our rule of thumb for achieving $x \gg y$?



Observations

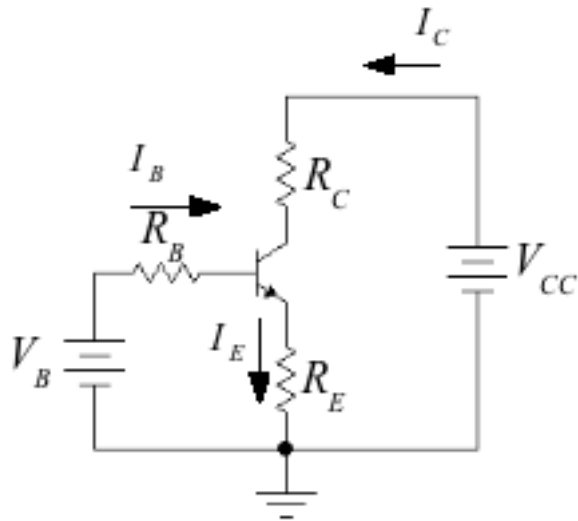
- Emitter feedback stabilizes base voltage source bias.
- To reduce the sensitivity of I_C to V_{BE} , choose $V_B \gg V_{BE}$.
- $R_B = 0$ is not possible, but can be approximated quite well if the voltage source resistance is “not too large,” i.e.

$$R_B \ll (\beta + 1) R_E$$

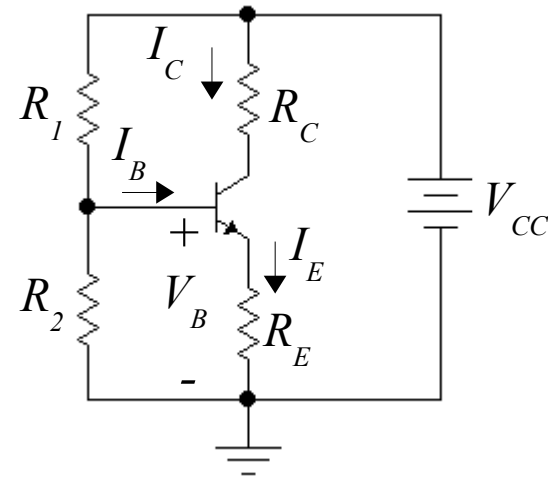
Ideal rule of thumb (if possible):

$$R_B \leq \frac{1}{10} (\beta + 1) R_E \approx \frac{100}{10} R_E = 10 R_E$$

Emitter-Feedback Bias Design

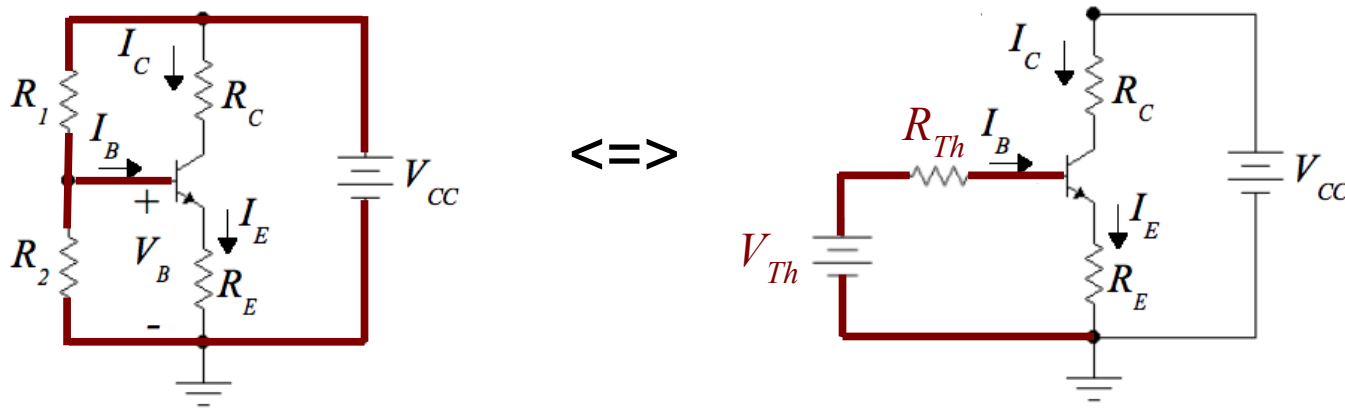


Voltage bias circuit



Single power supply version

Thevenin Equivalent

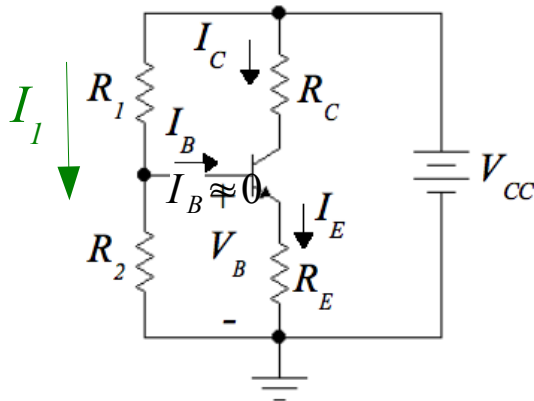


$$R_{Th} = R_B = R_1 \parallel R_2$$

$$V_{Th} = V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

Thevenin Equivalent

Use Thevenin's theorem to simplify base circuit:



$$V_{Th} = V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

Let: $\rho = \frac{R_1}{R_2}$

Since we will specify V_{CC} , V_B and R_B , the inverse is needed for design:

$$\frac{1}{1 + \rho} = \frac{V_B}{V_{CC}}$$

$$V_B = \frac{1}{\rho + 1} V_{CC} \quad \text{determine } \rho$$

$$R_{Th} = R_B = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2} = \frac{R_1}{\rho + 1} \quad \text{determine } R_1$$

$$\frac{R_1 R_2}{R_1 + R_2} = \frac{R_1}{\rho + 1} \Rightarrow R_2 = \frac{R_1}{\rho} \quad \text{determine } R_2$$

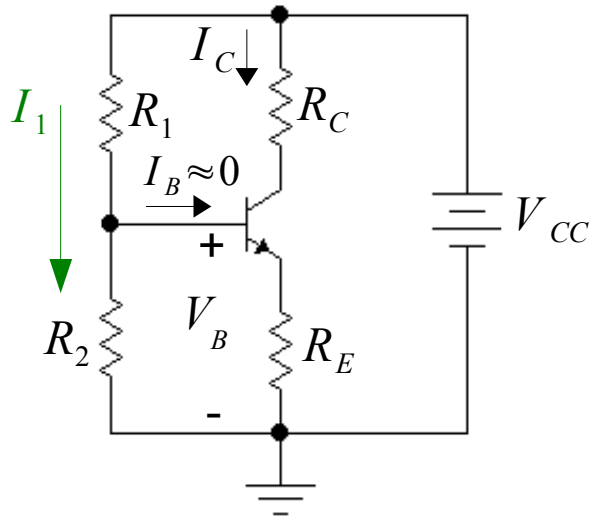
$$\rho = \frac{V_{CC}}{V_B} - 1$$

$$R_1 = (1 + \rho) R_B$$

$$R_2 = \frac{R_1}{\rho}$$

Design
Eqs.

A “Rule of Thumb” for Single Supply Biasing



1. Choose $R_T = R_1 + R_2$ so that $I_1 \ll I_C$, i.e. I_1 is about $1/10$ of the desired collector (or emitter) current (ignoring I_B):

$$I_1 = \frac{V_{CC}}{R_T} = \frac{I_C}{10} \quad R_T = R_1 + R_2 = 10 \frac{V_{CC}}{I_C}$$

2. Use a voltage divider to give the desired base voltage V_B and solve for R_2 :

$$R_2 = R_T \frac{V_B}{V_{CC}}$$

3. Solve for R_1 :

$$R_1 = R_T - R_2 = R_T \left(1 - \frac{V_B}{V_{CC}}\right)$$

4. Calculate R_B : $R_B = R_1 \parallel R_2$

$$I_1 = \frac{V_{CC}}{(R_1 + R_2)} = \frac{V_{CC}}{R_T}$$

$$V_B = V_{CC} \frac{R_2}{R_T}$$

An Unavoidable Design Tradeoff

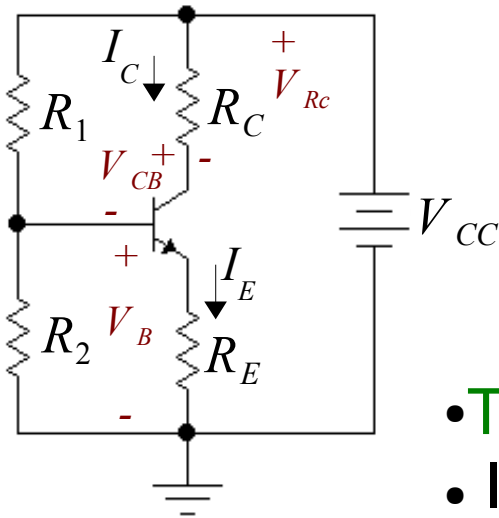
Three design goals so far

$$R_B \ll (\beta + 1) R_E$$

$$V_B \gg V_{BE}$$

$$I_1 \ll I_C \quad \text{also} \quad I_1 \gg I_B$$

$$\text{Constraint: } V_{CC} = V_{Rc} + V_{CB} + V_B$$



- **TRADEOFF**

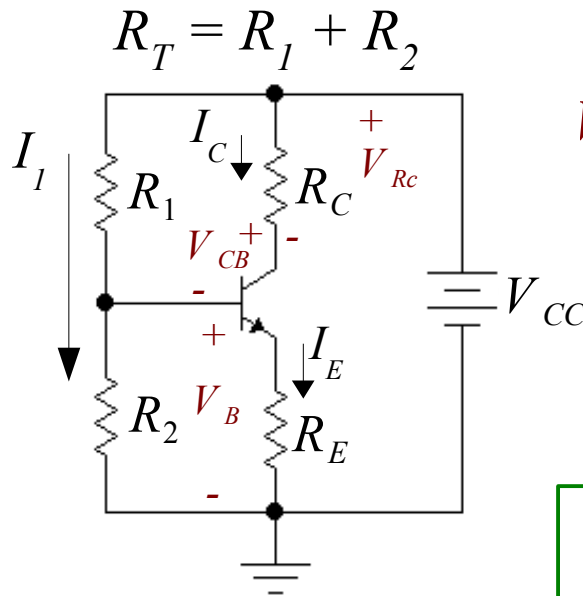
- Increase $V_B \Rightarrow$ Reduce $V_{Rc} + V_{CB}$

- V_{Rc} too large \Rightarrow potential for saturation to reduce operating range (i.e. $v_C < v_B$).

- V_{Rc} too small \Rightarrow potential for cutoff to reduce operating range (i.e. $i_C \rightarrow$ small or zero).

- **NEED A COMPROMISE!**

Another Useful “Rule of Thumb” “1/3, 1/3, 1/3 Rule”



$$V_B = \frac{V_{CC}}{3} \quad V_{Rc} = I_C R_C = \frac{V_{CC}}{3} \quad V_{CB} = V_{CC} - V_{Rc} - V_B = \frac{V_{CC}}{3}$$

or $V_{CE} = V_{Rc} - V_{Re} \approx \frac{V_{CC}}{3}$

where $V_{CC} = V_{Rc} + V_{CB} + V_B$

Design Equations

$$V_B = V_{BE} + I_E R_E \approx I_1 R_2$$

$$V_{BE} = 0.7V$$

$$V_{Re} = I_E R_E$$

$$V_B \gg V_{BE}$$

$$R_C = \frac{V_{Rc}}{I_C} = \frac{V_{CC}}{3I_C}$$

$$R_E = \frac{(V_B - V_{BE})}{I_E} = \frac{(\frac{V_{CC}}{3} - 0.7V)}{I_E}$$

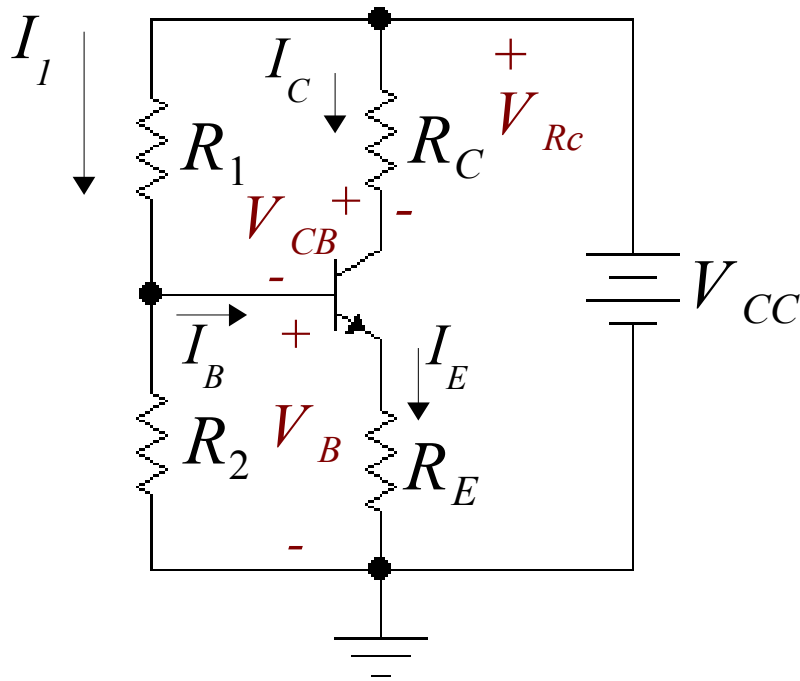
$$V_{CC} \frac{R_2}{R_1 + R_2} = V_B = \frac{V_{CC}}{3}$$

$$I_1 = \frac{V_{CC}}{R_T} = \frac{I_C}{10}$$

$$R_2 = R_T \frac{V_B}{V_{CC}} = \frac{1}{3} R_T$$

$$R_1 = R_T \left(1 - \frac{V_B}{V_{CC}}\right) = \frac{2}{3} R_T$$

Biasing for Operating Point Stability – Quick Review



What is the condition on the value of V_B ?

What is the condition on the value of R_E ?

What is the purpose for R_1 & R_2 ?

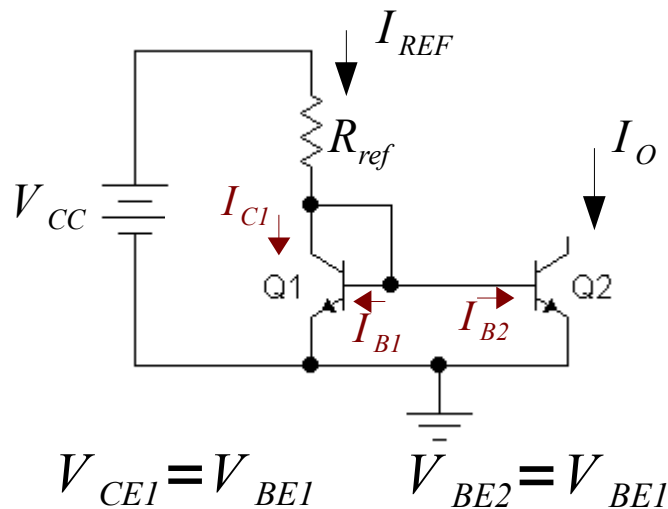
What happened to R_B ?

What is the constraint on the value of I_1 ?

What is the “1/3, 1/3, 1/3 Rule”?

Constant Emitter Current Bias

The *current mirror* is used to create a current source:



1. A BJT collector is the current source:

$$I_C = I_S e^{\frac{V_{BE}}{V_T}}$$

2. A diode-connected transistor sets the current.

$$I_{REF} = \frac{V_{CC} - V_{BE1}}{R_{ref}}$$

$$I_{REF} = I_{C1} + I_{B1} + I_{B2} \approx I_{C1} \approx I_{E1}$$

$$I_O = I_{C2}$$

3. Choose R_{ref} for the desired current:

$$R_{ref} = \frac{V_{CC} - 0.7}{I_{REF}} \approx \frac{V_{CC} - 0.7}{I_{C1}}$$

4. If $Q1 = Q2$ then $I_{C2} = I_{C1} \Rightarrow I_O \approx I_{ref}$
matched

Constant Emitter Current

Now: $V_{BE1} = V_{BE2}$

If Q_1 and Q_2 have the same saturation current: $I_{S1} = I_{S2}$

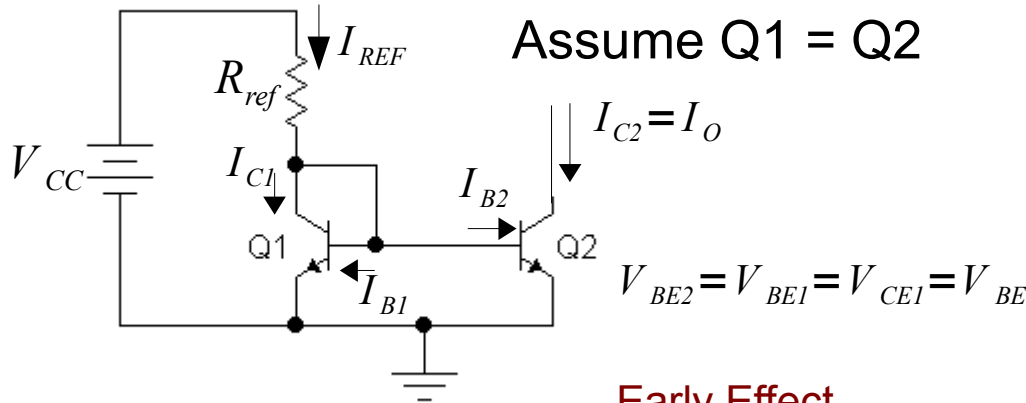
And the transistors are at the same temperature: $T_1 = T_2$

The two collector currents – set primarily by R_{ref} – are equal, *as long as Q2 is not saturated.*

$$I_O = I_{C2} = I_{REF} \approx \frac{V_{CC} - 0.7}{R_{ref}}$$

$V_{CE1} \neq V_{CE2}$, the Early Effect needs to be included in simulations.

Constant Emitter Current – Early Voltage



For Q2:

$$I_O = I_{C2} = I_S e^{V_{BE}/V_T} \left(1 + \frac{V_{CE2}}{V_A}\right) \quad (1)$$

Since I_B is not effected by V_A , i.e.

$$I_{B2} = \frac{I_S}{\beta} e^{V_{BE}/V_T} = \frac{I_{C2}}{\beta_F} \quad \text{where } \beta_F = \beta \left(1 + \frac{V_{CE2}}{V_A}\right)$$

For Q1: $I_{B1} = I_{B2}$

$$I_{REF} = I_{C1} + I_{B1} + I_{B2} = I_{C1} + 2 I_B$$

$$\begin{aligned} I_{REF} &= I_S e^{V_{BE}/V_T} \left(1 + \frac{V_{CE1}}{V_A}\right) + 2 \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_T}} \\ &= I_S e^{V_{BE}/V_T} \left(1 + \frac{V_{BE}}{V_A}\right) + 2 \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_T}} \end{aligned}$$

Solving for $I_S e^{V_{BE}/V_T}$

$$I_S e^{V_{BE}/V_T} = \frac{I_{REF}}{1 + \frac{V_{BE}}{V_A} + \frac{2}{\beta}} \quad (2)$$

Sub (2) into (1)

$$I_O = I_{C2} = I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{V_{BE}}{V_A} + \frac{2}{\beta}}$$

Constant Emitter Current – Early Voltage Cont.

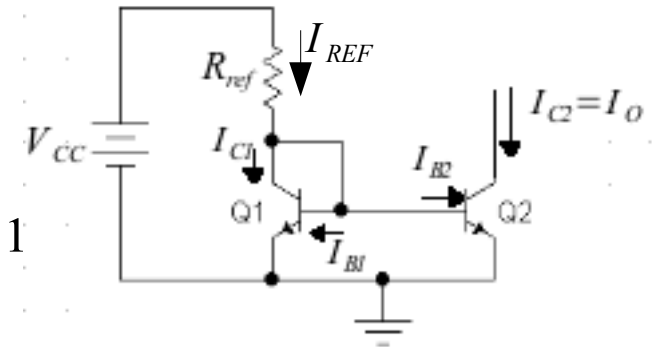
$$I_O = I_{C2} = I_{REF} \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{V_{BE}}{V_A} + \frac{2}{\beta}} \Rightarrow \frac{I_O}{I_{REF}} = \frac{1 + \frac{V_{CE2}}{V_A}}{1 + \frac{V_{BE}}{V_A} + \frac{2}{\beta}}$$

Let $V_A = \infty \Rightarrow$ Early effect is negligible $\frac{I_O}{I_{REF}} = \frac{1}{1 + \frac{2}{\beta}} \approx 1$

If also $\beta = \infty \Rightarrow I_O = I_{REF}$

Let $V_A = \text{finite}$ and $V_A = 50 \text{ V}$, $V_{BE} = 0.7 \text{ V}$, $\beta = 100$

$$\frac{I_O}{I_{REF}} = f(V_{CE2}) = \frac{1 + 0.02 V_{CE2}}{1.034} = 0.97(1 + 0.02 V_{CE2})$$

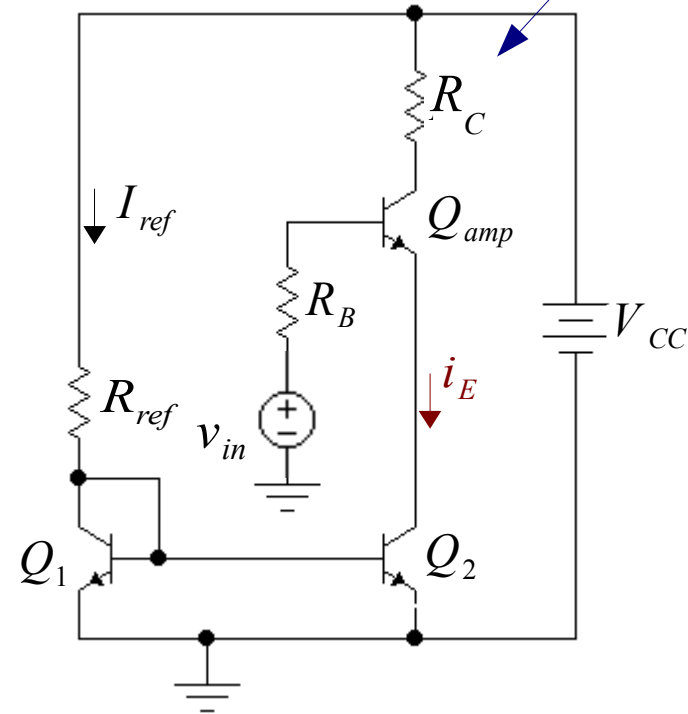
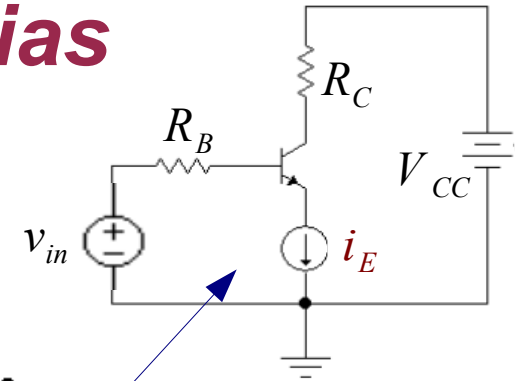


BJT Emitter Current Source Bias

We thus can use a current mirror to provide stable control of transistor collector current. R_{ref} sets the emitter and collector currents and the collector-ground voltage for Q_{amp} .

v_{in} is the ac input voltage source.

R_B can be any “reasonable” value – this is not voltage biasing!



Summary

- Two practical methods for achieving stable bias for a BJT are:
 - Use a dc voltage source in the base with a feedback resistance in the emitter circuit.
 - Place a dc current source directly in the emitter circuit.

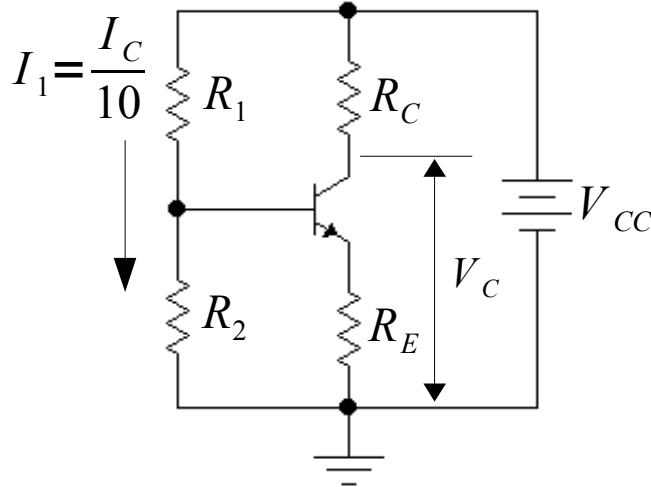
Emitter-Feedback Bias Design

1. Use single supply for base bias and collector sources.
2. Use the $I_C/10$ rule for the current I_I through the base bias network (R_1 and R_2).
- 3-1. Try less negative feedback using a smaller emitter resistor R_E “saving” more of the V_{CC} supply voltage for the R_C voltage drop.

or

- 3-2. Use the “ $1/3, 1/3, 1/3$ Rule”.

Try “3-1 Emitter-Feedback” Bias Design



Complete the bias design given the following design values:

$$V_{CC} = 12\text{ V} \quad I_C = 1\text{ mA} \quad V_C = 6\text{ V} \quad \beta = 100$$

It follows:

$$R_C = \frac{V_{Rc}}{I_C} = \frac{V_{CC} - V_C}{I_C} = 6\text{ k}\Omega \quad V_{Rc} = 6\text{ V}$$

$$I_1 = \frac{I_C}{10} = 0.1\text{ mA} \Rightarrow R_1 + R_2 = \frac{V_{CC}}{I_1} = \frac{12}{10^{-4}} = 120\text{ k}\Omega$$

“3-1 Emitter-Feedback” Bias - Cont.

Let's choose a small feedback voltage, say $V_{Re} = 1\text{ V}$. Ignoring the base current:

$$R_E = \frac{V_{Re}}{I_E} \approx \frac{1\text{ V}}{I_C} = 1\text{ k}\Omega$$

Then the voltage across R_2 is 1.7 V

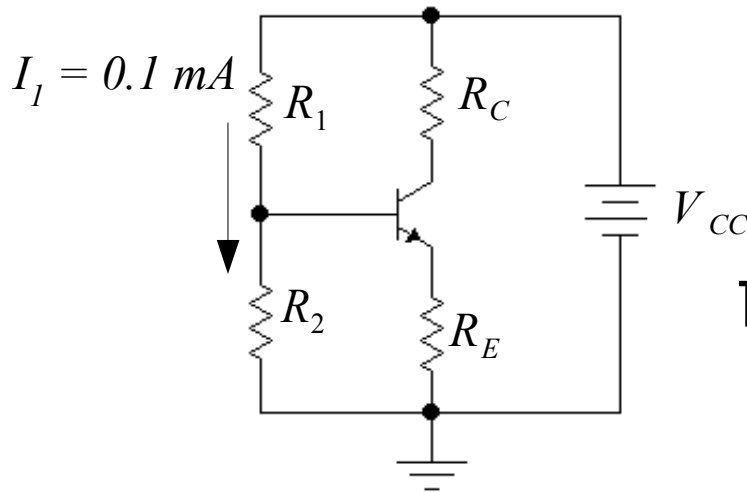
$$R_2 = \frac{1.7\text{ V}}{10^{-4}\text{ A}} = 17\text{ k}\Omega$$

$$R_1 = 120\text{ k}\Omega - 17\text{ k}\Omega = 103\text{ k}\Omega$$

$$V_B = 1.7\text{ V}$$

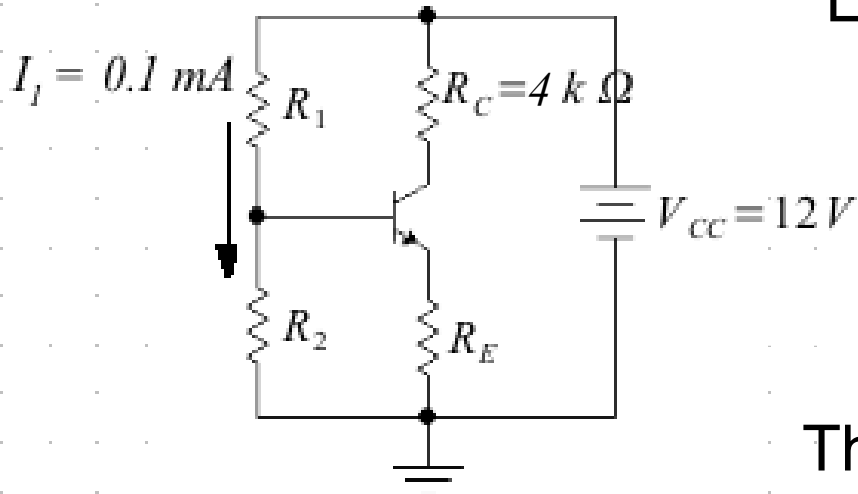
Recall: $R_B \leq \frac{1}{10}(\beta + 1)R_E$

$$R_B = R_1 \parallel R_2 \approx 14.5\text{ k}\Omega > \frac{1}{10}(\beta + 1)R_E \approx 10\text{ k}\Omega$$



Previous slide $I_C = 1\text{ mA}$ $R_C = 6\text{ k}\Omega$
 $R_1 + R_2 = 120\text{ k}\Omega$

3-2 Emitter-Feedback “1/3, 1/3, 1/3 Rule” Bias



$$I_C = 1 \text{ mA} \quad \beta = 100$$

$$R_1 + R_2 = 120 \text{ k}\Omega$$

Recall: $R_B \leq \frac{1}{10} (\beta + 1) R_E$

$$R_B = R_1 \parallel R_2 \approx 26.7 \text{ k}\Omega < \frac{1}{10} (\beta + 1) R_E \approx 33 \text{ k}\Omega$$

Let's choose $V_{Rc} = V_B = \frac{V_{CC}}{3} = 4 \text{ V}$

$$R_C = \frac{V_{Rc}}{I_C} = \frac{4 \text{ V}}{10^{-3} \text{ A}} = 4 \text{ k}\Omega$$

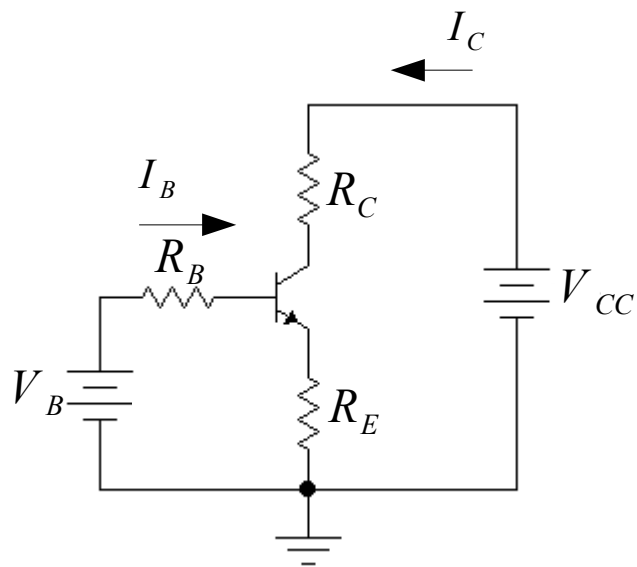
$$R_E = \frac{4 \text{ V} - 0.7 \text{ V}}{I_C} = 3.3 \text{ k}\Omega$$

Then the voltage across R_2 is $V_B = 4 \text{ V}$

$$R_2 = \frac{4 \text{ V}}{10^{-4} \text{ A}} = 40 \text{ k}\Omega$$

$$R_1 = 120 \text{ k} - 40 \text{ k} = 80 \text{ k}\Omega$$

RECALL: Bias Stability Condition Argument



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

$$V_B = I_B R_B + V_{BE} + (\beta + 1) R_E I_B$$

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

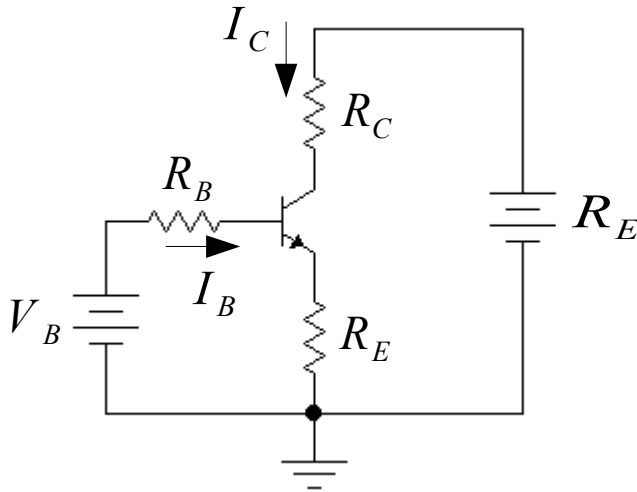
$$I_C = \beta I_B = \frac{\beta}{R_B + (\beta + 1) R_E} (V_B - V_{BE})$$

if $R_B \ll (\beta + 1) R_E$

$$I_C = \beta I_B \approx \frac{\beta}{\beta + 1} \frac{(V_B - V_{BE})}{R_E} = \alpha \frac{(V_B - V_{BE})}{R_E}$$



“3-1 Emitter-Feedback” β Sensitivity



$V_{CC} = 12V$
 $V_B = 1.7V$
 $V_{BE} = 0.7V$
 $I_C = 1mA$
 $\beta = 100$
 $R_C = 6k\Omega$
 $R_E = 1k\Omega$
 $R_B = 14.5k\Omega$

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

$\beta = 100;$	$I_C = 0.873 mA$
$\beta = 200;$	$I_C = 0.932 mA$
$\beta = \infty;$	$I_C = 1 mA$
$\beta = 100 \ \& \ R_B = 0 \ \Omega;$	$I_C = 0.99 mA$



“3-1 Emitter-Feedback” I_S Sensitivity

//3-1 Bias Scheme with Re=1 K

Beta=100;

VsubT=0.025;

VB=1.7;

Rb=14.5;

Re=1;

BetaPlusRe=101;

vBE=0.0:0.01:1;

iCline=Beta*(VB-vBE)/(Rb+BetaPlusRe); //mA.

plot(vBE,iCline);

iC=0.01:0.01:2; //mA.!

lsubS =1E-16; //mA.

for k= 1:1:8

lsubS=10*lsubS;

vBE2=VsubT*log(iC/lsubS);

plot(vBE2,iC); //Current in mA.

end

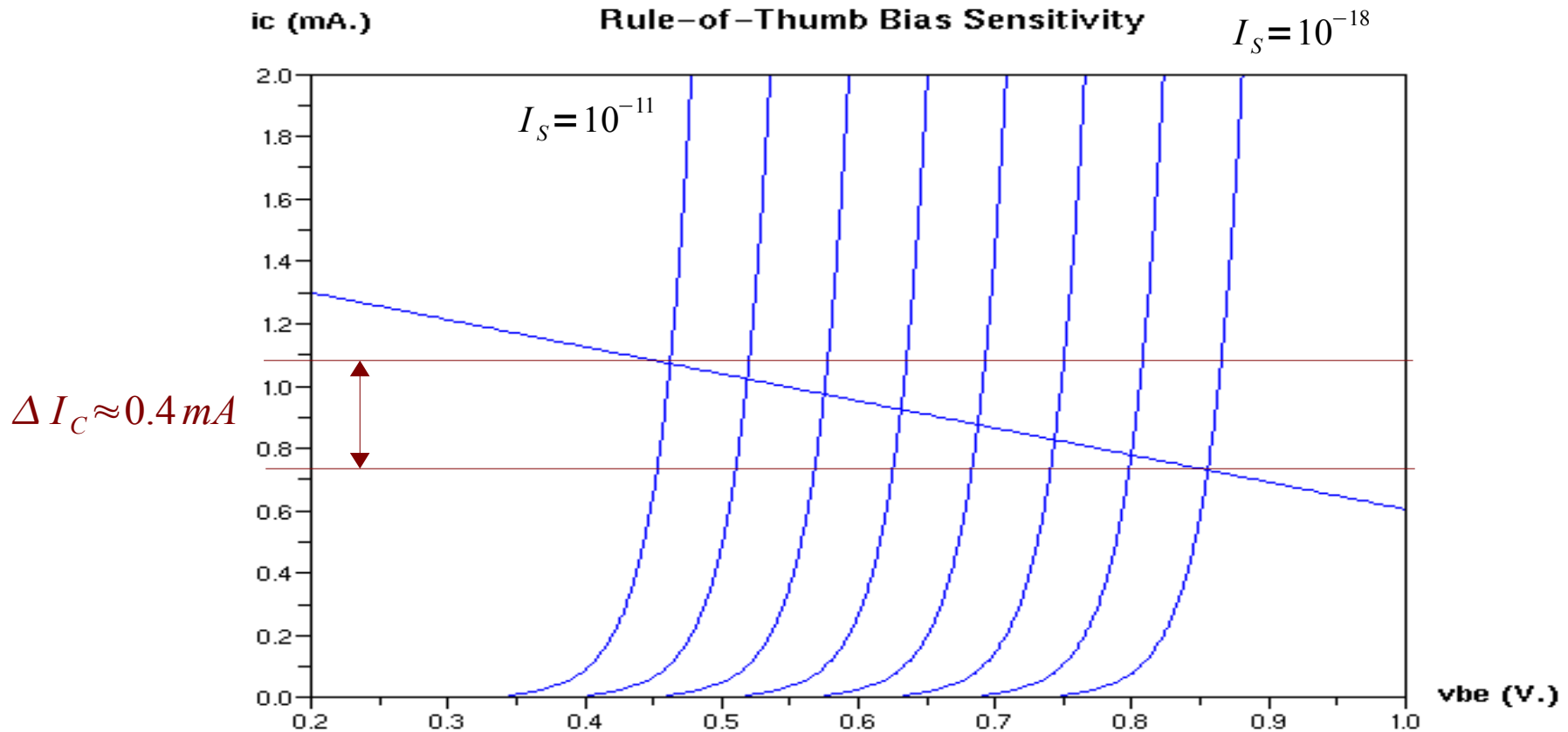
Sensitivity to I_S

$$I_C = \frac{\beta}{R_B + (\beta + 1)R_E} (V_B - V_{BE})$$

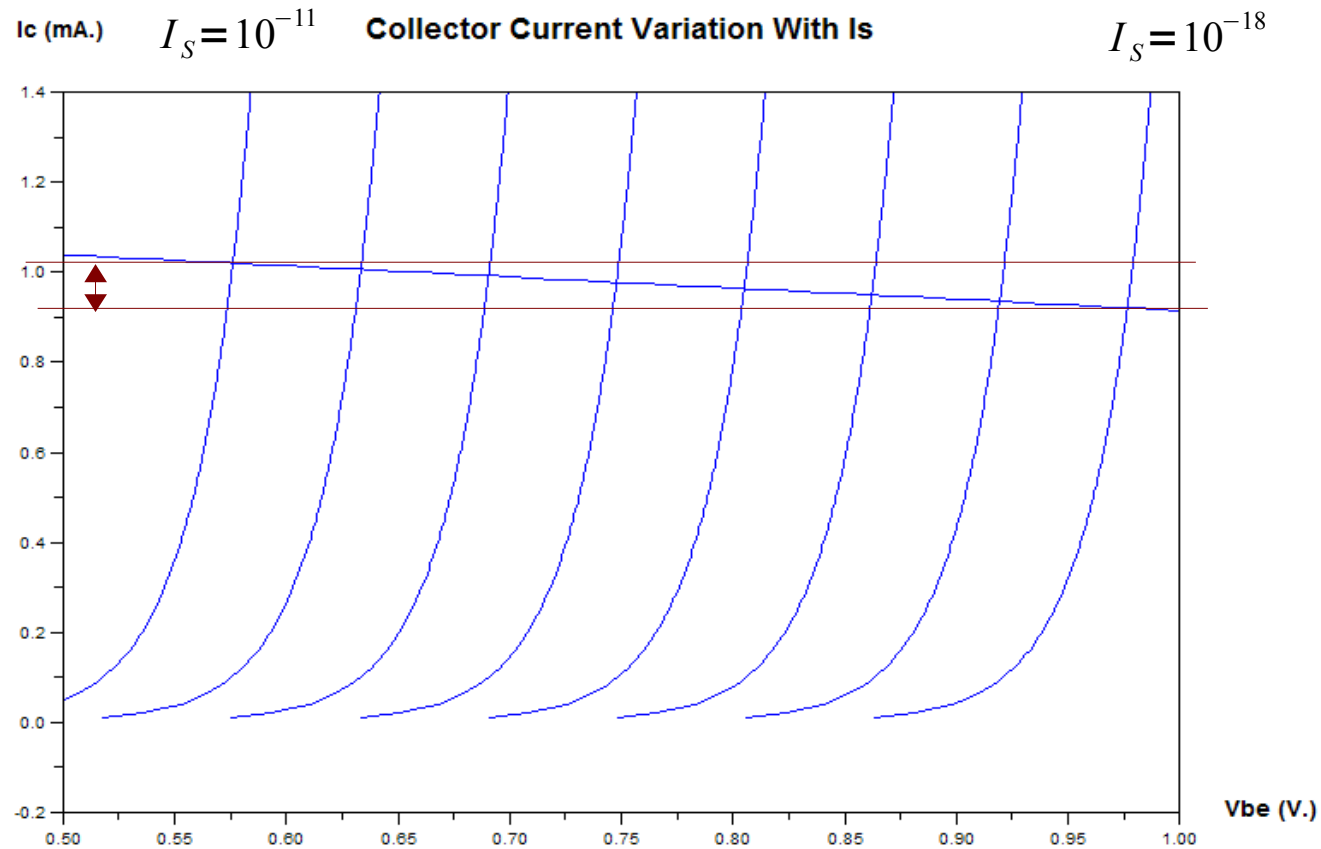




3-1 Scilab Plot (Zoomed)



Compare to I_C vs I_S Results Plot with Ideal Emitter Feedback (1/3,1/3,1/3 Rule)



$$\Delta I_C \approx 0.1 \text{ mA}$$

$$R_B \approx 0$$

or

$$R_B \ll (\beta + 1) R_E$$

Conclusion

“1/3, 1/3, 1/3 Rule” Provides a Good Compromise Base Voltage Bias Scheme