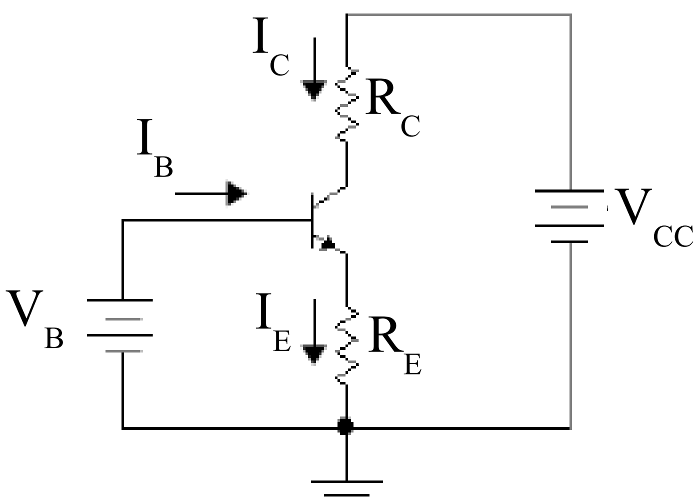
BJT Biasing Cont.

- 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

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:



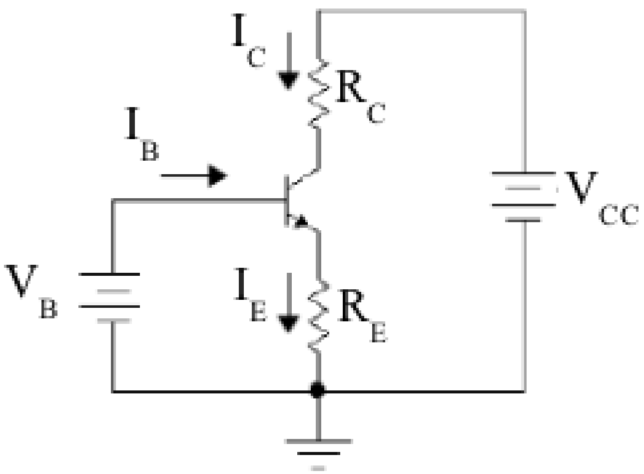
And make the following observations. Assume active mode operation:

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

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: $V_{BE} = 0.7\,V.$

and V_B and V_{CC} are given. Then compute R_E to obtain the desired 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:

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

if $I_S \uparrow$ => $I_C \uparrow$ → when $I_C \uparrow$ => $V_{BE} \downarrow$

$\downarrow I_C$ <= $\downarrow V_{BE}$

I_S insensitivity

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

β insensitivity

if $V_B >> V_{BE}$ => $I_C \approx \alpha \frac{V_B}{R_E}$

V_{BE} insensitivity

Scilab Analysis of I_C Insensitivity to I_S

Simultaneous equations:

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

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

or:

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

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

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.

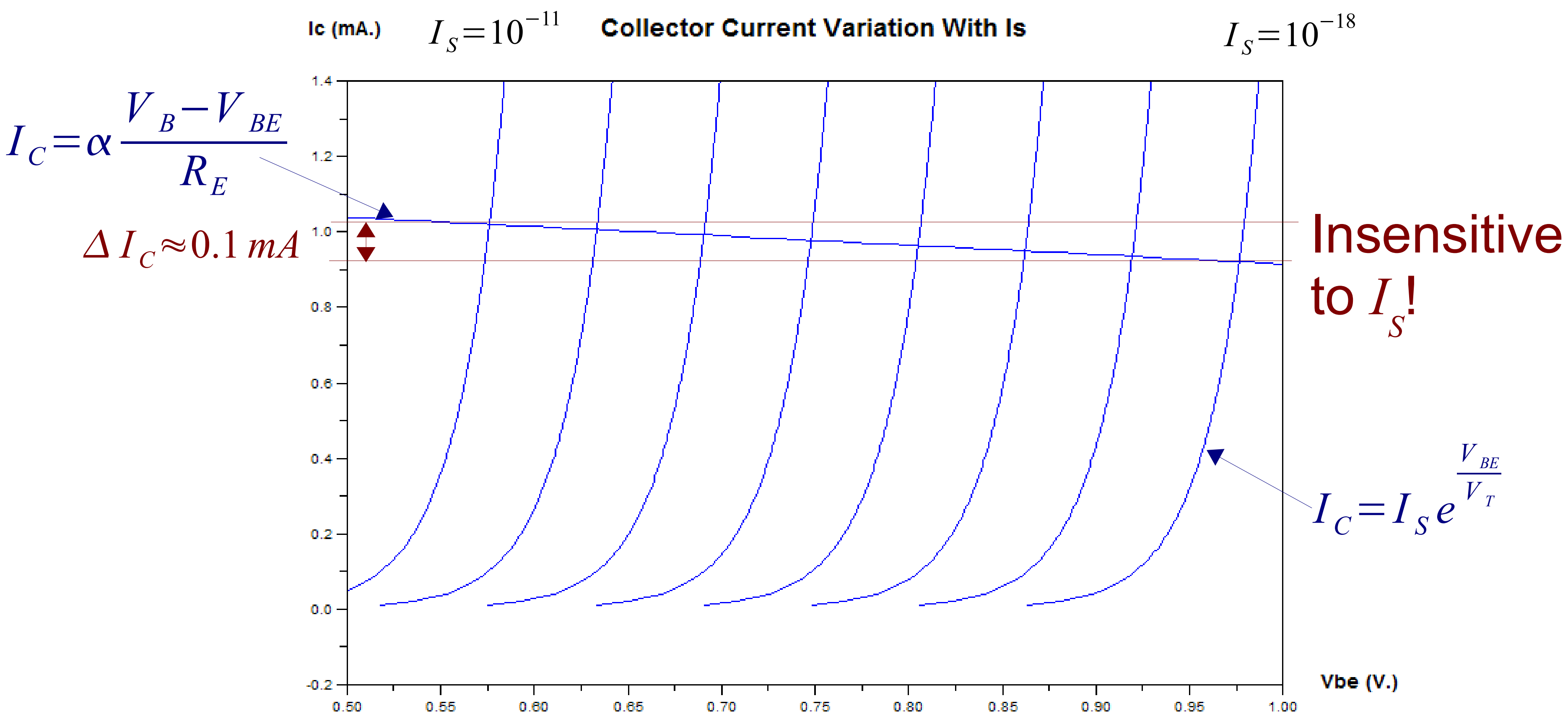
Scilab Program

```
//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



Insensitivity to Beta

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

Example: $\beta = 100$

$$V_B = 4.7\,V$$

$$I_C = 1\,mA$$

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

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

$$R_E \approx 4000\,\Omega$$

Writing I_C as a function of β:

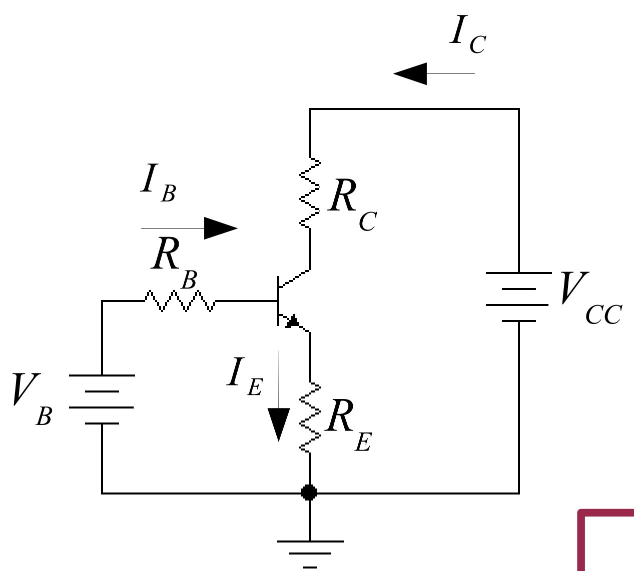
$$I_C = \alpha \frac{V_B - 0.7}{R_E} = \frac{\beta}{\beta + 1} \cdot 10^{-3}\,A$$

Assume: $50 < \beta < 200$

$$\frac{50}{51} \cdot 10^{-3} = 0.980\,mA < I_C < \frac{200}{201} \cdot 10^{-3} = 0.995\,mA$$

So I_C is insensitive to changes in β!

Voltage Source With Internal Resistance



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

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

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

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

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

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

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

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

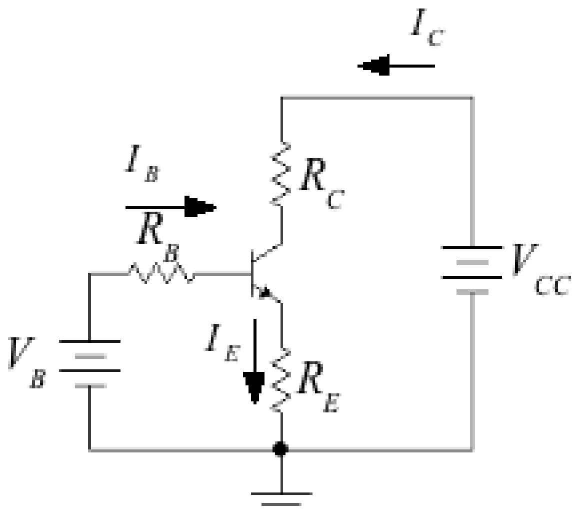
Observations

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

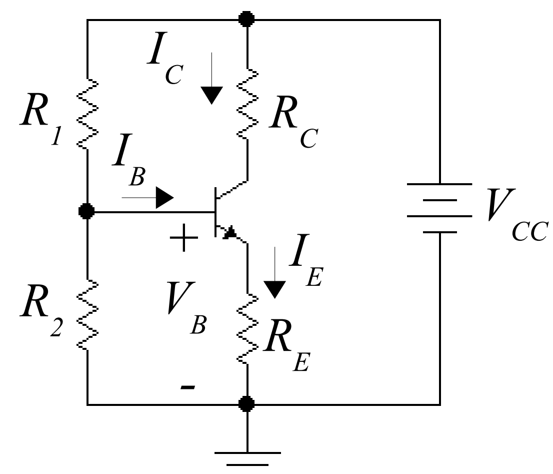
Ideal rule of thumb (if possible):

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

Emitter-Feedback Bias Design

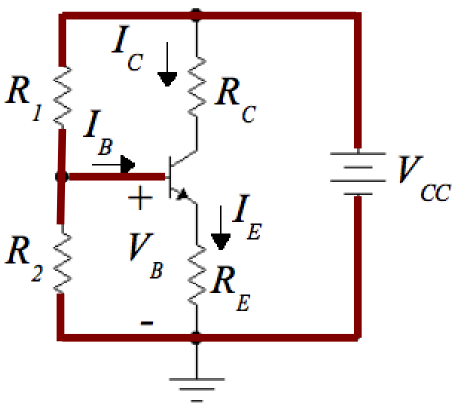


Voltage bias circuit



Single power supply version

Thevenin Equivalent



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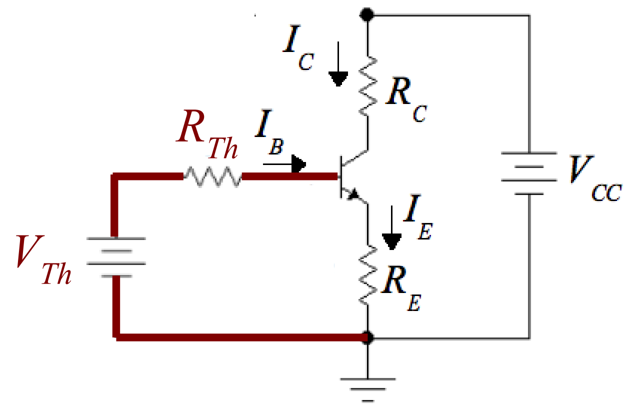
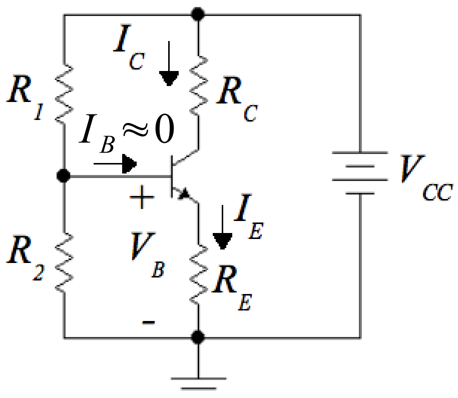


$$R_{Th} = R_B = R_1 \| R_2$$

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

Thevenin Equivalent

Use Thevenin's theorem to simplify base circuit:



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

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

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

$$R_{Th}=R_B=R_1||R_2=\frac{R_1R_2}{R_1+R_2}=\frac{R_1}{\rho+1}$$

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

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

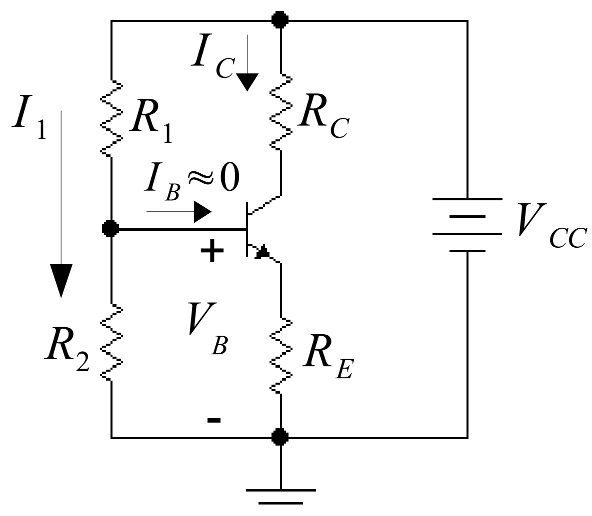
$$\rho=\frac{V_{CC}}{V_B}-1$$

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

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

Design Eqs.

A "Rule of Thumb" for Single Supply Biasing



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

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

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

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

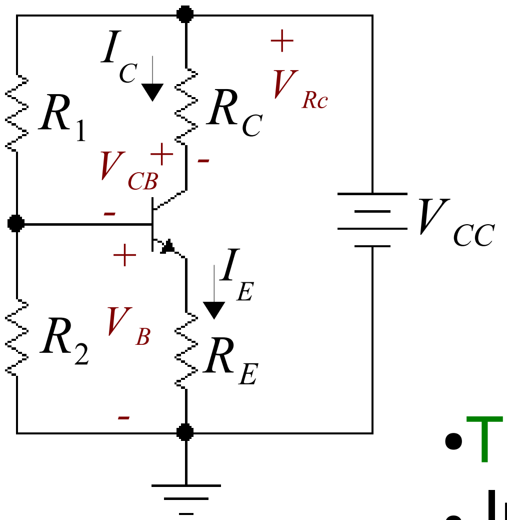
2. Use a voltage divider to give the desired base voltage:

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

Solve for R_1

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

An Unavoidable Design Tradeoff



Two design goals so far

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

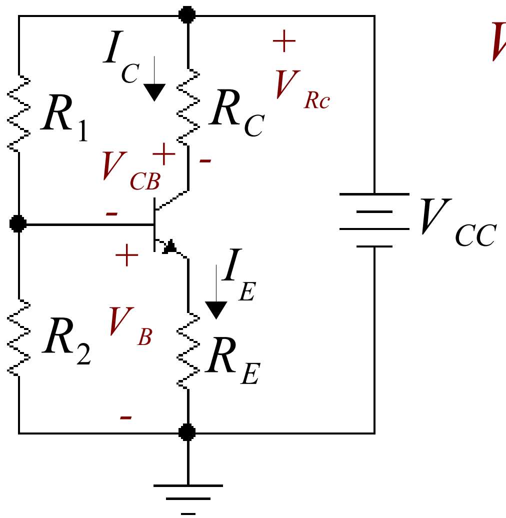
$$V_B \gg V_{BE}$$

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

- TRADEOFF
- Increase V_B => Reduce $V_{Rc} + V_{CB}$
- V_{Rc} large => large signal swing & large voltage gain (before cutoff).
- V_{CB} (or V_{CE}) large => large voltage swing (before saturation).
- NEED A COMPROMISE!

Another Useful "Rule of Thumb"
"1/3, 1/3, 1/3 Rule"

$$R_T = R_1 + R_2$$



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

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

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

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

$$V_{BE} = 0.7\,V$$

$$V_{Re} = I_E R_E$$

$$V_B >> V_{BE}$$

Design Equations

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

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

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

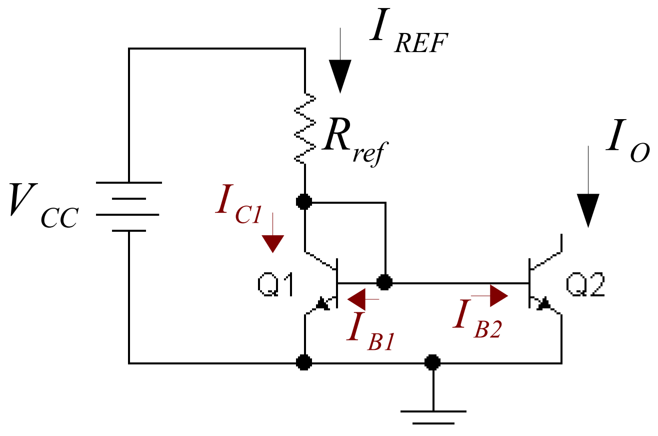
$$I_1 = \frac{V_{CC}}{R_T} = \frac{I_C}{10}$$

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

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

Constant Emitter Current Bias

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



$V_{CE1}=V_{BE1}$ $V_{BE2}=V_{BE1}$

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.

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

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

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

$$R_{ref}\approx\frac{V_{CC}-0.7}{I_{E1}}\approx\frac{V_{CC}-0.7}{I_{C1}}$$

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

Constant Emitter Current

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

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

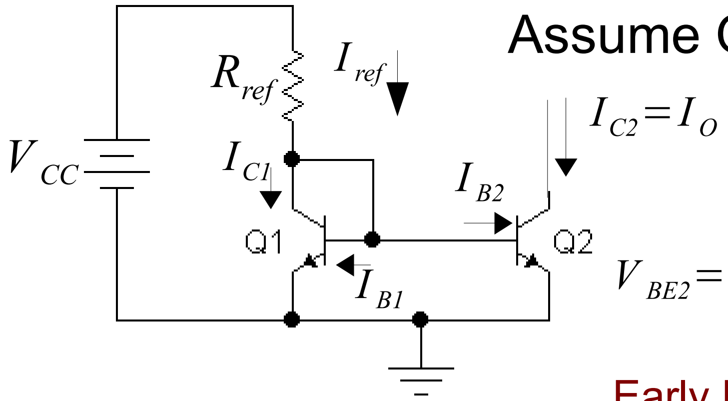
And the transistors are at the same temperature: $T_1 = T_2$

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



Assume Q1 = Q2

$$V_{BE2}=V_{BE1}=V_{CE1}=V_{BE}$$

For Q2:

Early Effect

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

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

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

For Q1:

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

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

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

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

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

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.

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

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

If also $\beta = \infty$ => $I_O = I_{ref}$

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

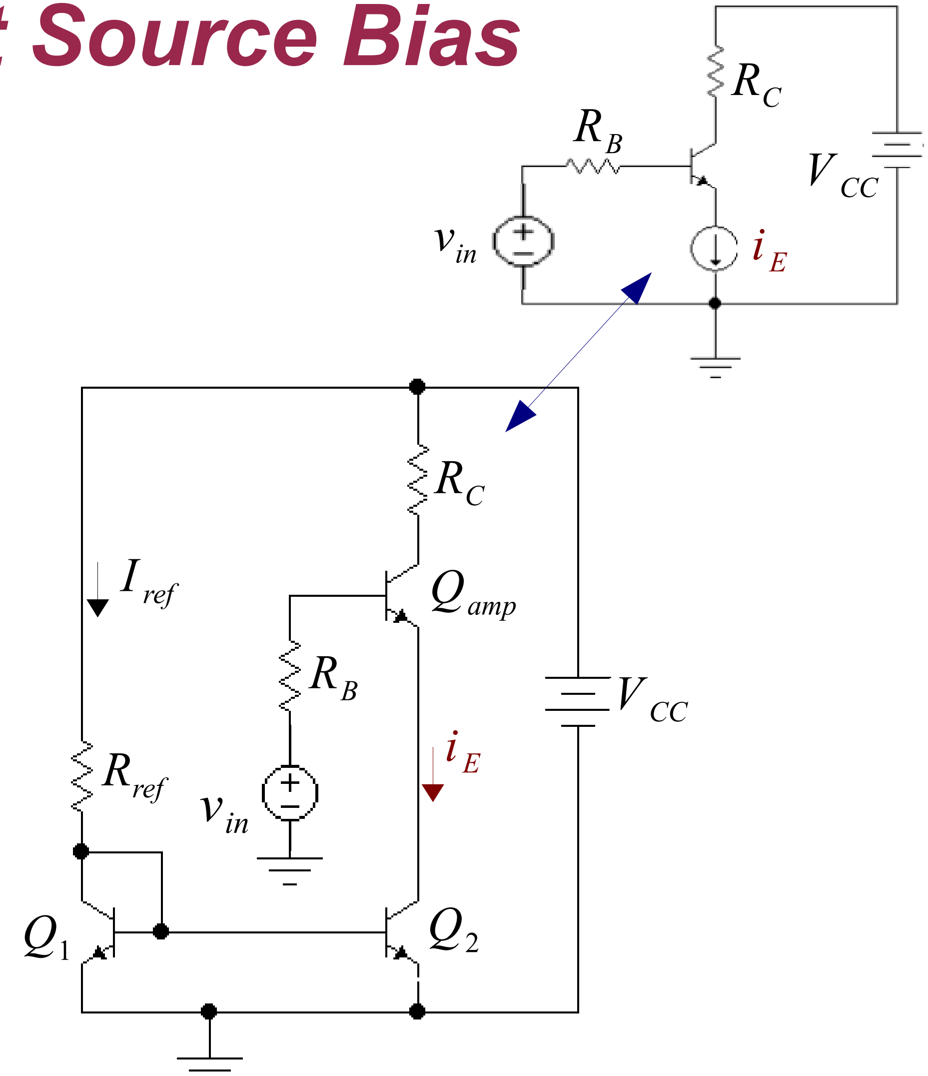
$$\frac{I_O}{I_{ref}} = f(V_{CE2}) = \frac{1 + 0.02\, V_{CE2}}{1.034} = 0.97(1 + 0.02\, V_{CE2})$$

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 voltage source in the base with a feed-back resistance in the emitter circuit.
  - Place a current source directly in the emitter cir-cuit.

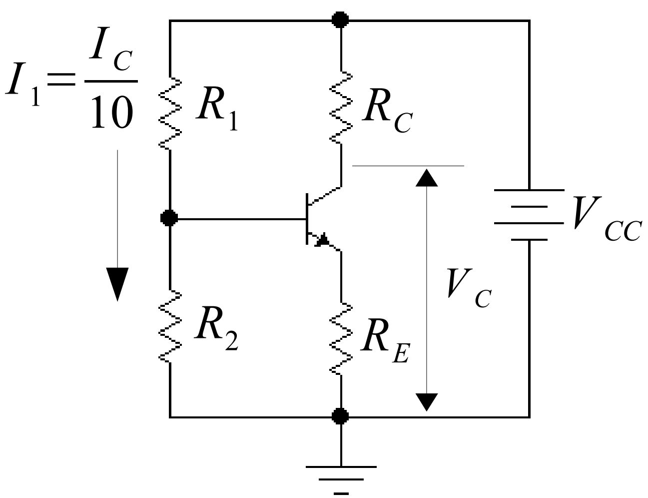
Emitter-Feedback Bias Design

1. Use single supply for base bias and collector sources.
2. Use the $I_C/10$ rule for the current 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.

"Emitter-Feedback 3-1" Bias Design



Complete the bias design given the following design values:

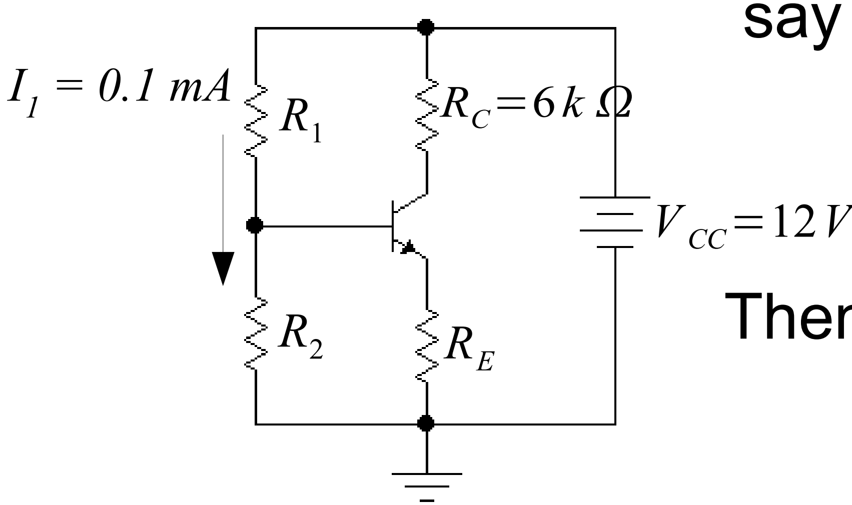
$$V_{CC} = 12\,V \quad I_C = 1\,mA \quad V_C = 6\,V \quad \beta = 100$$

It follows:

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

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

"Emitter-Feedback 3-1" Bias Design - Continued



$I_C = 1\,mA \quad \beta = 100$

$R_1 + R_2 = 120\,k\,\Omega$

Let's choose a small feedback voltage, say *1 V*. Ignoring the base current:

$$R_E = \frac{1\,V}{I_C} = 1\,k\,\Omega$$

Then the voltage across R_2 is $1.7\ V$

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

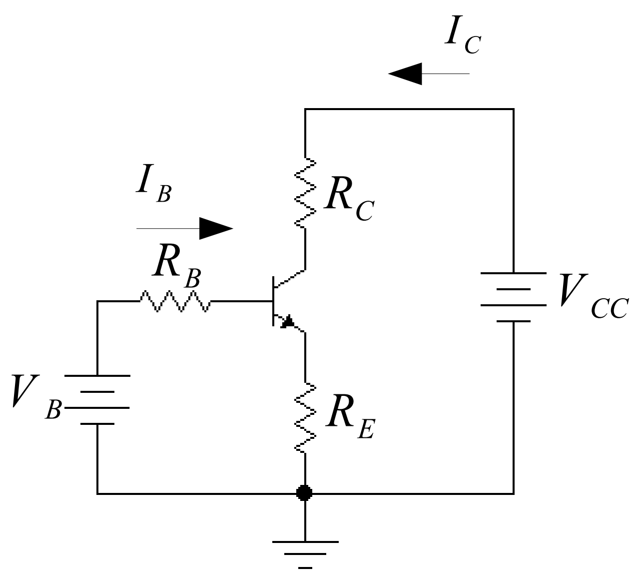
$$R_1 = 120\text{k} - 17\text{k} = 103\,k\,\Omega$$

$V_B = 1.7\,V$

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

$$R_B = R_1 \| R_2 = \frac{103}{120} \cdot 17 \approx 14.5\,k\,\Omega > \frac{1}{10}(\beta+1) R_E \approx 10\,k\,\Omega$$

RECALL: Voltage Source With Internal Resistance



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

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

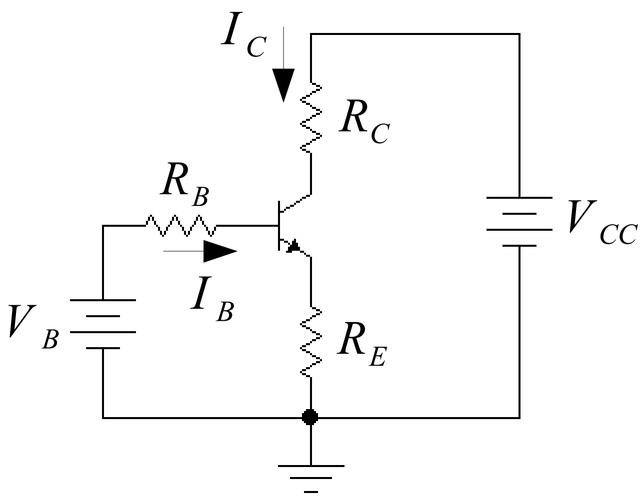
$$I_B=\frac{V_B-V_{BE}}{R_B+(\beta+1)R_E}$$

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

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

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

"Emitter-Feedback 3-1" β Sensitivity



$V_{CC} = 12V$

$V_B = 1.7\ V$

$V_{BE} = 0.7\ V$

$I_C = 1\ mA$

$\beta = 100$

$R_C = 6k\Omega$

$R_E = 1\ k\Omega$

$R_B = 14.5\ k\Omega$

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

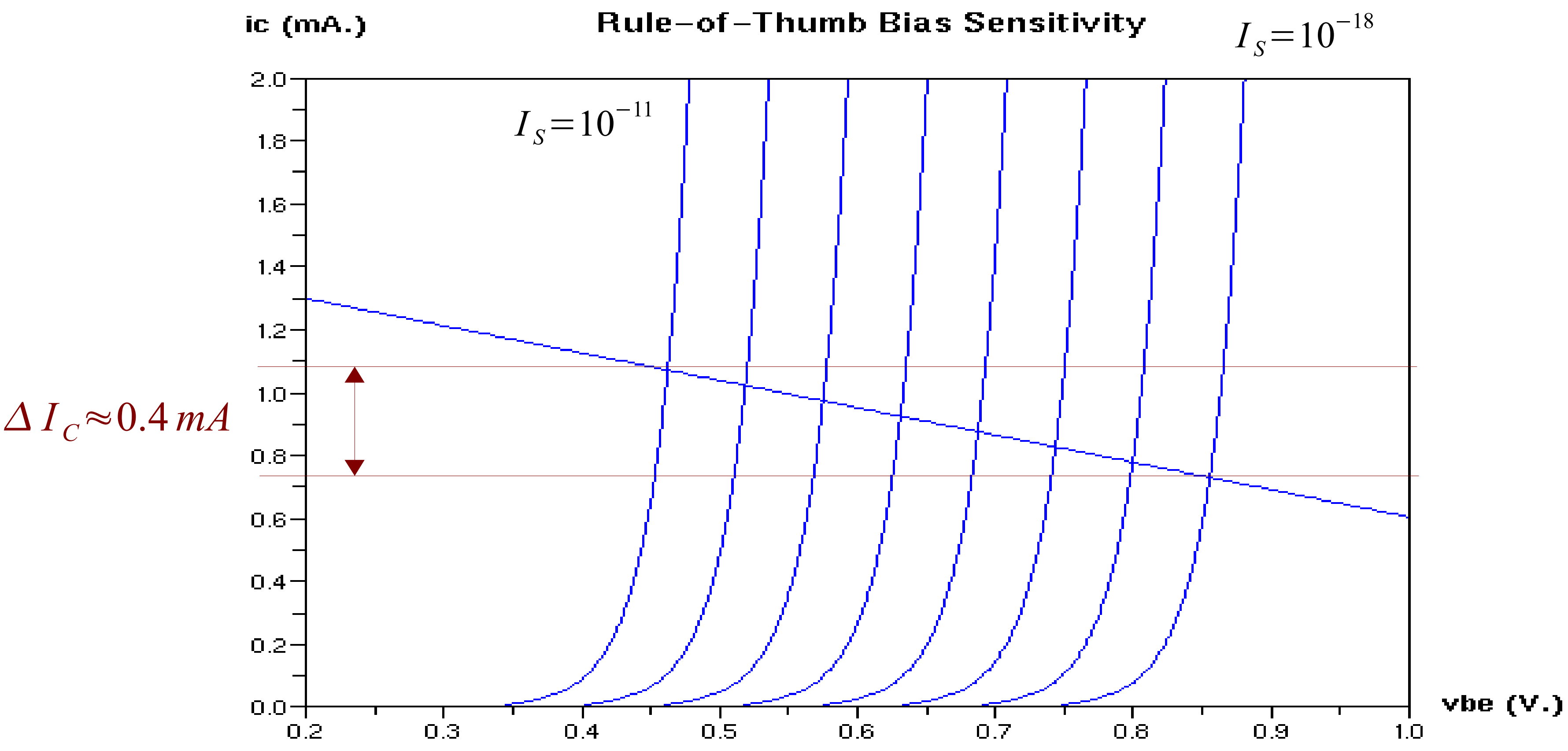
$\beta = 50;$	$I_C = 0.775\ mA$
$\beta = 100;$	$I_C = 0.873\ mA$
$\beta = 200;$	$I_C = 0.932\ mA$
$\beta = \infty;$	$I_C = 1\ mA$
$\beta = 100\ \&\ R_B = 0\ \Omega;$	$I_C = 0.99\ mA$

"Emitter-Feedback 3-1" Bias Scilab Simulation

```
//Rule of thumb BJT bias sensitivity
Beta=100;
VsubT=0.025;
VB=1.7;
Rb=14.5;
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.!
IsubS =1E-16; //mA.
for k= 1:1:8
  IsubS=10*IsubS;
  vBE2=VsubT*log(iC/IsubS);
  plot(vBE2,iC);    //Current in mA.
end
```

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

Scilab Plot (Zoomed)



Compare with Ideal I_C vs I_S Results Plot

$\Delta I_C \approx 0.1\, mA$

$R_B = 0$