Section 1: Common Emitter CE Amplifier Design

Designing procedure of common emitter BJT amplifier has three areas. First, we have to set the Q-point, which is the DC operating point. Since, no specification regarding the Q-point is mentioned in the design requirements; it leaves the designer enough freedom to choose the operating point as necessary for the application. However, remember that the specifications given in terms of input and output impedance, gain, frequency response characteristics and peak output voltages ultimately restricts the Q-point in a narrow window. It is difficult derive the Q-point without some intelligent guess and the following steps would work out for the given conditions. We will start to choose a Q-point to allow maximum output voltage swing.

In this configuration, $R_e$ is completely bypassed. The circuit diagram with necessary variables is provided in CE Figure 1.
CE Figure 1: BJT Common Emitter

BJT Figure 2: BJT characteristics. The example not your Q-point

Step CE 1.1: Measure the device parameters
For the design of the amplifier, the 3 parameter values required are $r_o$ and $\beta$. Derived from the transistor characteristics curve shown in CE Figure 2, one can set an approximate Q-point ($V_{CE}$ and $I_C$) in the active region and measure $r_o$ and $\beta$. We will solve for $V_{ce}$ and estimate $I_C$.

Solve for $V_{CE}$ see below Step CE2.2. Use $V_{out}$ peak to find $I_{load}$ peak: $I_{load} = V_{out} / R_{load}$.

For an approximate $I_C$ Q-point use $I_C \approx 2.2 \times I_{load}$ peak this is not the solution to your design Q-point. We can use an approximate $I_C$ because $r_o$ and $\beta$ will not vary much with small changes in Q-point.

The $V_{ce\text{SAT}}$ ($V_{ce}$ saturation voltage) is found from the BJT characteristics curve where the curve begins to flatten out $\approx 0.2 \text{ Vdc}$.

$r_o = \Delta V_{CE} / \Delta I_C$ the slope of a line thru Q-point

$\beta_{AC} = \Delta I_C / \Delta I_B$ measured around Q-point

$V_{ce\text{SAT}} = V_{ce}$ begins to flatten

$\beta = (\beta V_T) / I_C$ $r_n$ is base to emitter resistance Hybrid Pie model.

Where $V_T = kT / q$ at room temperature is $V_T \approx 26\text{ mV}$.

Plot the estimated Q-point ($V_{CE}, I_C$) on the BJT characteristics curve.

Plot the estimated Q-point ($V_{CE}, I_C$) on the BJT characteristics curve.

**CE Part 2: Determine the Q-point.**

Start with your BJT and selecting 4 resistors.

**Step CE2.1: Choose $V_E$**

Because $V_{BE}$ will decrease $\approx 2.5\text{ mV} / \degree C$ rise we set $V_E = \text{between 2V to 3V}$. $V_E$ and $R_E$ will provide negative feedback to stabilize $\beta$ and $V_{BE}$.

**Step CE2.2: Calculate the midpoint $V_C$ with $R_E$ complete bypassed $R_E = R_{eb}$, and $R_{ref} = 0$**

Midpoint selection will allow for maximum output voltage swing.

We will add 20% to $V_{out}$ so the design is not on the edge of the solution.

$$V_{C(\text{max})} = V_{CC} - (V_{out} + 20\%V_{out})$$
$$V_{C(\text{min})} = V_E + V_{CE \text{ sat}} + (V_{out} + 20\%V_{out})$$
$$V_C = \left( V_{C(\text{max})} + V_{C(\text{min})} \right) / 2 \quad \text{Midpoint $V_C$ Q-point}$$
$$V_{CE} = V_C - V_E \quad \text{This is the Q-point $V_{CE}$}$$

**Step CE2.3: Calculate $R_C$**

The DC equation: $V_{CC} - V_C = V_{RC} = R_C I_C$ voltage across $R_C$ derived from $V_{cc}$ and Q-point $V_C$.

The AC equation: $V_{out} = i_c \left( R_C \parallel r_o \parallel R_L \right)$ output voltage $V_{out \text{ peak}}$

Rewrite: $V_{out} = i_c R_C \left( r_o \parallel R_L \right) / \left( R_C + \left( r_o \parallel R_L \right) \right)$ Parallel resistance equation

Substituting in $v_{RC} = i_c R_C$

Combined equation: $V_{out} = V_{RC} \left( r_o \parallel R_L \right) / \left( R_C + \left( r_o \parallel R_L \right) \right)$
Solve for $R_c$; Add 20%$V_{out}$ so the collector current is not set to an edge.

$$R_C = \frac{V_{CC} - V_C}{V_{out} + 20\%V_{out}} \left( r_o \ || \ R_L \right) - \left( r_o \ || \ R_L \right)$$

**Step CE2.4: Calculate $I_C$, $I_E$, and $R_e$.**

$I_C = (V_{CC} - V_C) / R_C$  \( \text{The Q-point collector current.} \)

$I_B = I_C / \beta$  \( \text{The base current.} \)

$I_E = I_C (\beta + 1) / \beta$  \( \text{Emitter current.} \)

$R_e = V_E / I_E$  \( \text{Total emitter resistance.} \)

Thus, Q-point is $(V_{CE}, I_C)$.

**CE Part 3: Determine bias resistors.**

**Step CE3.1: Calculate $R_E$. Design for the sum $Ref$ and $Reb$**

Later we will design for a desired Av (voltage gain) by using $(Ref)$ and $(Reb)$ to control the Av.

$R_E = Ref + Reb$

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

$I_B = I_C / \beta$

$\therefore R_E = \frac{V_E}{I_E}$
Step CE3.2: Calculate $R_{b1}$, $R_{b2}$. Method 1.
(Do not use Method 1 for your design.) Use step CE 3.3

$$V_B = V_E + V_{BE} \quad V_{BE} \text{ is normally between } 0.6V \text{ and } 0.7V$$

$$I_b = I_c / \beta$$

Current thru Rb1 is set to $10 \times I_b$
Current thru Rb2 is set to $9 \times I_b$

$$R_{b1} = \frac{V_{cc} - V_B}{10 \times I_b}$$

$$R_{b2} = \frac{V_B}{9 \times I_b}$$

Step CE3.3: Calculate $R_{b1}$, $R_{b2}$. Method 2.
(Use this Method)

Require Rin set to a given value. Need Vcc, Vb, $r_\pi$ and Ib.

Given Rin calculate Rin2.

$$R_{in2} = Rin - Ri$$

Solve Rin2 needed to Rin requirements.

Solve for Rb from Rin2 and Rbase.

$$R_{base} = r_\pi \quad \text{Re completely bypassed.}$$

$$R_b = \frac{1}{((1 / Rin2) - (1 / R_{base}))} \quad \text{Solve for Rb needed to Rin requirements.}$$

Find Rb1 first then Rb2

$$R_{b1} = \frac{V_{cc}}{((V_b / R_b) + I_b)} \quad \text{Solve for Rb1.}$$

$$R_{b2} = \frac{V_b}{(((V_{cc} - V_b) / R_{b1}) - I_b)} \quad \text{Solve Rb2 from Vb and current thru Rb2: } I_{rb2} = I_{rb1} - I_b$$

Check Rin meets requirements

$$R_{base} = r_\pi \quad \text{Re completely bypassed.}$$

$$R_b = R_{b1} || R_{b2}.$$  

$$R_{in2} = R_b || R_{base}$$

$$R_{in} = R_i + R_{in2}$$

CE Part 4: Calculating impedance and Gain

Refer to the small signal equivalent of the circuit you have just built in CE Fig. 3. We can calculate the following:
Step CE4.1: Input Impedance: AC characteristics

\[ R_{b} = R_{b1} \parallel R_{b2} \] the two base bias resistors.

If \( R_e \) completely bypassed with \( C_E \) then

\[ R_{\text{base}} = r_{\pi} \]

\[ R_{\text{in}2} = R_b \parallel R_{\text{base}} \]

\[ R_{\text{in}} = R_i + R_{\text{in}2} \]

Step CE4.2: Output Impedance

If \( R_e \) completely bypassed with \( C_E \) then

\[ R_{\text{out}} = R_C \parallel r_0. \text{ With } R_{\text{ref}} = 0 \]

Step CE4.3: Voltage Gain

AC voltage \( V_{\text{out}} = -\beta I_b (R_{\text{out}} \parallel R_{\text{load}} \parallel r_\pi) \) Note: use the correct \( R_{\text{out}} \) depending on \( R_{\text{ref}} \)

AC voltage \( V_{\text{in}} = (R_{\text{in}}/R_{\text{in}2}) V_{\text{in}2} \) Input signal from the function generator.

AC voltage \( V_{\text{in}2} = v_{\text{in}} \) Input signal on the base

\[ A_{\text{v2}} = V_{\text{out}} / V_{\text{in}2} = -\beta (R_C \parallel r_0 \parallel R_{\text{load}}) / r_{\pi} \] voltage gain at base

\[ A_v = V_{\text{out}} / V_{\text{in}} = -\beta (R_C \parallel r_0 \parallel R_{\text{load}}) / ((R_{\text{in}2}+R_i) / R_{\text{in}2}) (r_{\pi}) \]

Rearrange \( A_v = -\beta (R_{\text{in}2} / (R_{\text{in}2} + R_i)) \ast (R_{\text{load}} \parallel r_0 \parallel R_{\text{load}}) / r_{\pi} \)

\[ V_{\text{gen}} = ((R_{\text{in}} + R_{\text{gen}}) / R_{\text{in}}) \ast (V_{\text{out}} / A_v) \] the open circuit voltage of the function generator.

Step CE4.4: Current Gain

\[ A_i = \frac{I_{\text{load}}}{I_{\text{in}}} = \frac{V_{\text{out}} / R_{\text{load}}}{V_{\text{in}} / R_{\text{in}}} = A_v \frac{R_{\text{in}}}{R_{\text{load}}} \]

Step CE4.5: Power gain

\[ G = P_{\text{out}} / P_{\text{in}} = V_{\text{out}} \ast I_{\text{load}} / V_{\text{in}} \ast I_{\text{in}} = A_v \ast A_i \]

In decibels \( G_{\text{dB}} = 10\log (A_v \ast A_i) \)

Step CE4.6: Vin and Voc of Vgen

Input signal level need to produce the required output voltage.

\[ V_{\text{in}} = V_{\text{out}} / A_v \]

The open circuit voltage of the generator to produce the required output voltage.

Because of Voltage divider because the output impedance of the \( R_{\text{gen}} = 50\Omega \)
Vgen = Vin (Rgen + Rin) / Rin

Use this value in LTspice and the laboratory Function generator

**CE Part 5: Frequency response**

With the Q-point being set after the sequence of steps, we can go for the selection of capacitors and finally connect the signal generator at input and measure the output amplified waveform.

First we will select $C_{in}$, $C_{out}$ and $C_E$ which jointly would set the roll-off beyond the lower cut-off frequency. Set any frequency within the range as your lower cut-off frequency and let us call it $f_L$. Three capacitors will introduce 3 zeros in the transfer function of the system. Because we will set 3 zeros at the same frequency we must use the Band Width Shrinkage factor.

$$BW_{shrinkage} = \sqrt{\frac{1}{2^n} - 1}$$

Where $n$ is the number of zeros for low frequency breakpoints at same frequency.

$$f_L = \frac{f_{C_{in}} + f_{C_{out}} + f_{C_E}}{3\sqrt{2^{\frac{1}{3}} - 1}}$$

Setting 3 frequencies equal, we get,

$$f_{C_{in}} = f_{C_{out}} = f_{C_E} = f_L \sqrt{2^{\frac{1}{3}} - 1}$$

Find the $C$ for each breakpoint $f_{C_{in}}$, $f_{C_{out}}$, and $f_{C_E}$ where $n = 3$.

$$C = \frac{1}{2\pi f_C (R \text{ seen by } C)}$$

Where $C$ is the capacitor that sets the breakpoint $f_C$.

RemitterBase is the impedance looking in the BJT emitter to base.

$$\text{RemitterBase} = (r_\pi + R_b || (R_i + R_{gen})) / (\beta + 1) \quad \text{Small value}$$

$R$ is the Thevenin equivalent resistance seen by the capacitor.

$$R_{CE} = R_{e} || (r_0 + R_C || R_{Load}) || \text{RemitterBase}$$

The following table enlists the particular expressions.
<table>
<thead>
<tr>
<th>Rsig</th>
<th>Rgen + Ri</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_re</td>
<td>Rsig + Rin2</td>
</tr>
<tr>
<td>Cout</td>
<td>RLoad + Rout</td>
</tr>
<tr>
<td>C_E</td>
<td>Re</td>
</tr>
<tr>
<td>Ch_i</td>
<td>Rsig</td>
</tr>
<tr>
<td>Ch_i2</td>
<td>Rout</td>
</tr>
</tbody>
</table>

**Table 1: Resistance Seen By Capacitors**

In this case because Chi, and Ch2 are to the same break point. We must use the band shrinkage factor with n = 2. We need only to find a two poles at \( F_n / \text{bandshrinkage} = f_{chi} = f_{ch2} \) to set the high frequency cutoff.

Set \( F_{chi} = F_{chi2} = \frac{F_h}{\sqrt{2^{1/2}} - 1} \)

\( R_b = R_b1 || R_b2 \)

\( R_{base} = r_\pi \)

\( R_{in2} = R_b || R_{base} \)

R seen by \( C_{hi} \quad R_{Chi} = (R_{gen} + R_i) || Rin2 \)

\[
C_{hi} = \frac{1}{2\pi f_{chi} (\text{R seen by } C_{hi})}
\]

R seen by \( C_{hi2} \quad R_{Chi2} = Rout || R_{load} \quad \text{Note: use the correct Rout depending on Ref} \)

\[
C_{hi2} = \frac{1}{2\pi f_{chi2} (\text{R seen by } C_{hi2})}
\]
Section 2:

CEwRef Common Emitter with Re that partially is bypassed by Ce.

\[ R_E = \text{Ref} + \text{Reb} \] the total \( R_E \) for the DC bias design.

Ref is the portion of Re that is not bypassed by Ce.

Reb is the portion of Re that is bypassed by Ce.

CEwRef Part 1: Measure the device parameters

For the design of the amplifier, the 3 parameter values required are \( V_{ce\text{SAT}} \), \( r_o \) and \( \beta \). Derived from the transistor characteristics curve shown in BJT Figure 2 above, one can set an approximate Q-point (\( V_{CE} \) and \( I_C \)) in the active region and measure \( r_o \) and \( \beta \). We will solve for \( V_{ce} \) and estimate \( I_C \).

Solve for \( V_{CE} \) see below Step CEwRef 2.2. Use Vout peak to find \( I_{load \text{ peak}} \): \( I_{load} = \frac{V_{out}}{R_{load}} \).

For an approximate \( I_C \) Q-point use \( I_C \approx 2.2 \times I_{load \text{ peak}} \) this is not the solution to your design Q-point. We can use an approximate \( I_C \) because \( r_o \) and \( \beta \) will not very much with small changes in Q-point.

The \( V_{ce\text{SAT}} \) (Vce saturation voltage) is found from the BJT characteristics curve where the curve begins to flatten out \( \approx 0.2 \) Vdc.

\[ r_o = \frac{\Delta V_{CE}}{\Delta I_C} \] the slope of a line thru Q-point

\[ \beta_{AC} = \frac{\Delta I_C}{\Delta I_B} \] measured around Q-point

\[ V_{ce\text{SAT}} = V_{ce} \text{ begins to flatten} \]

\[ r_n = \left( \frac{\beta}{V_T} \right) / I_C \] \( r_n \) is base to emitter resistance Hybrid Pie model.

Where \( V_T = kT/q \) at room temperature is \( V_T \approx 26mV \).

Plot the estimated Q-point (\( V_{CE},I_C \)) on the BJT characteristics curve.

CEwRef Part 2: Determine the Q-point.
Start with your BJT and selecting 4 resistors.

**Step CEwRef 2.1: Choose \( V_E \)**

Because \( V_{BE} \) will decrease \( \approx 2.5 \text{mV} / \degree \text{C rise} \) we set \( V_E = \) between 2V to 3V. \( V_E \) and \( R_E \) will provide negative feedback to stabilize \( \beta \) and \( V_{BE} \).

**Step CEwRef 2.2: Calculate the midpoint \( V_C \) with \( R_E \) partially bypassed \( R_E = Reb + Ref \)**

Midpoint selection will allow for maximum output voltage swing.

We will add 20% to Vout so the design is not on the edge of the solution. This will also help with the additional loading because of high frequency capacitors as the frequency approaches the high frequency break points.

\[
\begin{align*}
V_{C(max)} &= V_{CC} - (Vout + 20\% Vout) \\
V_{C(min)} &= V_E + V_{CE sat} + (Vout + 20\% Vout) \\
V_C &= (V_{C(max)} + V_{C(min)}) / 2 & \text{Midpoint } V_C \text{ Q-point} \\
V_{CE} &= V_C - V_E & \text{This is the Q-point } V_{CE}
\end{align*}
\]

**Step CEwRef 2.3: Calculate \( R_C \).**

**Looking into the collector we see** \( r_o + \| \) \( (r_{\pi} + Rb1\| Rb2 \| (Ri +Rgen)) / (\beta +1) \approx r_o \) so we will use just \( r_o \).

The DC equation: \( V_{CC} - V_C = V_{RC} = R_C I_C \) voltage across Rc derived from Vcc and Q-point Vc.

The AC equation: \( Vout = i_c ( R_C \| r_o \| R_L ) \) output voltage Voutpeak

Rewrite AC: \( Vout = i_c R_C (r_o \| R_L ) / (Rc + (r_o \| R_L)) \) Parallel resistance equation

Substituting in \( v_{RC} = i_c R_C \)

Combined equation: \( Vout = V_{RC} (r_o \| R_L ) / (Rc + (r_o \| R_L)) \)

Solve for \( R_C \); Add 20\%Vout so the collector current is not set to an edge.

\[
R_C = \frac{V_{CC} - V_C}{Vout + 20\% Vout} (r_o \| R_L) - (r_o \| R_L)
\]

**Step CEwRef 2.4: Calculate \( I_C, I_E, \) and \( R_E \).**

\( I_C = (V_{CC} - V_C) / R_C \) The Q-point collector current.

\( I_B = I_C / \beta \) The base current.

\( I_E = I_C (\beta + 1) / \beta \) emitter current.

\( R_E = V_E / I_E \) Total emitter resistance.

Thus, Q-point is \( (V_{CE}, I_C) \).

We have already choose \( V_E \) to be between 2V to 3V to provide negative feedback in the DC bias circuit. We will use \( V_E \) and \( I_C \) where \( I_E = ((\beta +1) / \beta) I_c \). Now calculate \( R_E = I_e (Ref + Reb) \) the total emitter resistance.

We now have, \( V_E, V_c, R_c, R_e, I_c, I_e, V_{cesat} \)
CEwRef Figure 1: Amplifier with emitter partially bypassed.

CEwRef Figure 2: Small signal model with partial bypass of Re
CEwRef Part 3 Calculating impedance and Gain with Ref

We use the same Q-point and bias resistors Rb1, Rb2, Rc, and Re = Ref + Reb.

Step CEwRef3.1: find Ref based on Voltage Gain requested

Note: i_b is the AC base current that results from Vin.

Looking into the collector we see ro + Ref || [ (rπ + Rb1|| Rb2 || (Ri +Rgen) ] / (β +1) ≈ ro so we will use just ro.

AC voltage Vout = - β i_b (Rc || Rload || ro)  Note: use the approximant ro because Ref is not known yet.

AC voltage Vin = (Rin/Rin2) Vin2 Input signal from the function generator.

AC voltage Vin2 = i_b(rπ + (β + 1) Ref) Input signal on the base

Given Rin calculate Rin2.

Rin2 = Rin –Ri Solve Rin2 needed to meet the Rin requirements.

Av2 = Av * Rin / Rin2 Av2 at base needed to meet Av requested.

Av2 = Vout / Vin2 = -β (Rc || ro || Rload) / (rπ + (β + 1) Ref) voltage gain at base, we do not need to find i_b since i_b cancels.

Step CEwRef3.2: Solve for Ref by using gain at base Av2.

Ref = = [ ( -β (Rc || ro || Rload) / Av2 ) - rπ ] / ( β +1) from Av2 or use equation below

Step CEwRef3.3: Solve for Ref by using overall gain Av.

Av = Av2 * Rin2 / Rin

Av = Vout / Vin = - β (Rc || ro || Rload) / (Rin/Rin2) (rπ + (β + 1) Ref) voltage gain at input

We can see that voltage gain Av can be controlled by the value of Ref

Av = - β (Rin2/Rin) (Rc || ro || Rload) / (rπ + (β + 1) Ref)

Rearrange Av to solve for Ref from requested Av

Ref = -( β (Rin2/Rin) (Rc|| ro || Rload) / Av) - rπ) / (β +1) from Av overall gain

Step CEwRef3.4: Solve for Reb from Re and Ref

Remember that Re is the total emitter residence from step CEwRef 2.4.

Reb = Re – Ref
**Step CEwRef4.1: Rb1 and Rb2 based on requested Rin**

**Require Rin set to a given value.** Need Vcc, Vb, $r_{\pi}$ and $I_B$ (DC bias base current).
Given Rin calculate Rin2.

\[ \text{Rin2 = Rin} - Ri \]  
Solve Rin2 needed to meet the Rin requirements.

Solve for Rb from Rin2 and Rbase.

\[ \text{Rbase} = r_{\pi} + (\beta + 1) \left( \frac{1}{\text{Rin2}} \right) - \left( \frac{1}{R_{\text{base}}} \right) \]  
Looking into the Base of the BJT.

\[ \text{R} = \frac{1}{\left( \frac{1}{\text{Rin2}} \right) - \left( \frac{1}{R_{\text{base}}} \right)} \]  
Solve for Rb needed to Rin requirements.

Find Rb1 first then Rb2

\[ \text{I}_B = \frac{I_C}{\beta} \]  
DC bias base current.
\[ \text{Rb1 = Vcc} / ((Vb / Rb) + Ib) \]  
Solve for Rb1.
\[ \text{Rb2 = Vb} / (((Vcc - Vb) / Rb1) - Ib) \]  
Solve Rb2 from Vb and current thru Rb2: $I_{rb2} = I_{rb1} - Ib$

**Check Rin meets requirements**

\[ \text{Rbase} = r_{\pi} + (\beta + 1) \left( \frac{1}{\text{Rin2}} \right) - \left( \frac{1}{R_{\text{base}}} \right) \]

\[ \text{R} = \text{Rb1} \parallel \text{Rb2}. \]
\[ \text{Rin2 = Rb} \parallel \text{Rbase} \]
\[ \text{Rin = Ri} + \text{Rin2} \]

**Step CEwRef4.2: Input Impedance: AC characteristics**

\[ \text{R} = \text{Rb1} \parallel \text{Rb2} \]

Where Ref is the part of $R_E$ that is not bypassed by $C_E$.
\[ \text{Rbase} = r_{\pi} + (\beta + 1) \left( \frac{1}{\text{Rin2}} \right) - \left( \frac{1}{R_{\text{base}}} \right) \]  
Looking into the Base of the BJT.

\[ \text{Rin2 = Rb} \parallel \text{Rbase} \]
\[ \text{Rin = Ri} + \text{Rin2} \]
**Step CEwRef4.3: Output Impedance with Ref**

If Re partially bypassed with $C_E$ bypassing Ref.

$$R_b = R_b1 || R_b2.$$ 

RemitterBase is the impedance looking in the BJT emitter toward the base.

$$\text{RemitterBase} = \left( r_n + R_b \right) || \left( R_i + R_{gen} \right) / (\beta + 1) \quad \text{Small value, because divided by } \beta +1.$$

The complete equation below for $R_{out}$,

$$R_{out} = R_C || \left( r_o + \text{Ref} || \left[ r_n + R_b \right] \left( R_i + R_{gen} \right) \right) / \left( \beta +1 \right)$$

Because $r_o$ is greater than 30k$\Omega$ we approximate $R_{out} = R_c || \text{“large”} = R_c$

**Step CEwRef4.4: Current Gain**

The current gain $A_i$ can be obtained $i_{load}$ and $i_{in}$ or calculated from $Av$ $R_{in}$ and $R_{load}$.

$$A_i = \frac{i_{load}}{i_{in}} = \frac{V_{out}}{V_{in}} = Av \frac{R_{in}}{R_{load}}$$

**Step CEwRef4.5: Power gain**

$$G = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{load}}{V_{in} \cdot I_{in}} = Av \cdot A_i$$

In decibels $G_{db} = 10 \log \left( Av \cdot A_i \right)$

**Step CEwRef4.6: Vin and Voc of Vgen**

Input signal level need to produce the required output voltage.

$$V_{in} = \frac{V_{out}}{Av}$$

The open circuit voltage of the generator to produce the required output voltage. Because of Voltage divider because the output impedance of the $R_{gen} = 50\Omega$

$$V_{gen} = \frac{V_{in} \left( R_{gen} + R_{in} \right)}{R_{in}}$$

Use this value in LTspice and the laboratory Function generator.
CEwRef Part 5: Frequency response with Ref

With the Q-point being set after the sequence of steps, we can go for the selection of capacitors and finally connect the signal generator at input and measure the output waveform.

Step CEwRef 5.1: Low frequency cut off. $F_L$

First we will select $C_{in}$, $C_{out}$ and $C_E$ which jointly would set the roll-off beyond the lower cut-off frequency. Set any frequency within the range as your lower cut-off frequency and let us call it $f_L$. Three capacitors will introduce 3 zeros in the transfer function of the system. Because we will set 3 zeros at the same frequency we must use the Band Width Shrinkage factor.

$$BW_{shrinkage} = \sqrt{\frac{1}{2^{n/2}} - 1}$$

Where $n$ is the number of zeros for low frequency breakpoints at same frequency. The low frequency cutoff average of the individual time constants with shrinkage faction applied be we have set all the time constants the same.

$$f_L = \frac{f_{Cin} + f_{Cout} + f_{CE}}{3\sqrt{2^{\frac{3}{2}} - 1}}$$

Setting 3 frequencies equal, we get,

$$f_{Cin} = f_{Cout} = f_{CE} = f_L \sqrt{2^{\frac{3}{2}} - 1}$$

Find the $C$ for each breakpoint $f_{Cin}$, $f_{Cout}$, and $f_{CE}$ where $n = 3$.

$$C = \frac{1}{2\pi f_{C} (R \text{ seen by } C)}$$

Where $C$ is the capacitor that sets the breakpoint $f_C$

$R$ is the Thevenin equivalent resistance seen by the capacitor.

RemitterBase is the impedance looking in the BJT emitter to base.

$$\text{RemitterBase} = \frac{(r_n + R_b) \parallel (R_i + R_{gen})}{(\beta + 1)} \quad \text{Small value}$$

$$R_{CE} = R_{eb} \parallel (Rf + (r_o + R_C) \parallel R_{Load}) \parallel \text{RemitterBase}$$
**Step CEwRef 5.2**: High frequency cut off. $F_H$

$C_{hi}$ Sets the higher cut-off frequency $f_{hi}$ which is to be set from the specified range.

In this case because Chi, and Ch2 are to the same break point. We must use the band shrinkage factor with $n = 2$. We need only to find a two poles at $F_h / \text{bandshrinkage} = f_{chi} = f_{ch2}$ to set the high frequency cutoff.

Set $F_{chi} = F_{chi2} = F_h / \sqrt{2^{1/2} - 1}$

$R_b = R_{b1} || R_{b2}$ Base bias resistors

$R_{base} = r_n + (\beta + 1) (Ref || (ro + Rc || R_{load}))$ Looking into the Base of the BJT.

$R_{in2} = R_b || R_{base}$

$R$ seen by $C_{hi}$ $R_{chi} = (R_{gen} + R_i) || R_{in2}$

$C_{hi} = \frac{1}{2\pi f_{chi} (R \text{ seen by } C_{hi})}$

$R$ seen by $C_{hi2}$ $R_{chi2} = Rout || R_{load}$ Note: use the correct $Rout$ depending on Ref

$C_{hi2} = \frac{1}{2\pi f_{chi2} (R \text{ seen by } C_{hi2})}$

The following table list the equivalent resistance expressions seen by the capacitors.

<table>
<thead>
<tr>
<th>Rsig</th>
<th>Rgen + R_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>RemitterBase</td>
<td>$(r_n + R_b</td>
</tr>
<tr>
<td>$C_{in}$</td>
<td>Rsig + $R_{in2}$</td>
</tr>
<tr>
<td>$C_{out}$</td>
<td>$R_{load} + Rout$</td>
</tr>
<tr>
<td>$C_E$</td>
<td>Reb</td>
</tr>
<tr>
<td>$C_{hi}$</td>
<td>Rsig</td>
</tr>
<tr>
<td>$C_{hi2}$</td>
<td>$Rout</td>
</tr>
</tbody>
</table>

CEwRef Table 1: Resistance Seen By Capacitors
Section 3: Common Collector CC Amplifier Design

Designing procedure of common collector BJT amplifier has three areas. First, we have to set the Q-point, which is the DC operating point. Since, there is no specification regarding the Q-point in the design requirements; it leaves the designer enough freedom to choose the operating point as necessary for the application. However, remember that the specifications are in terms of input and output impedance, gain, frequency response characteristics and peak output voltages ultimately restricts the Q-point in a narrow window. It is difficult to derive this point without some intelligent guess and the following steps would work out for the given conditions. We will start to choose a Q-point to allow maximum output voltage swing.

For the Common Collector configuration, the circuit diagram shown in CC Figure 1. The small signal equivalent model in CC Figure 3.

For this configuration, same steps are involved for the calculation of $R_{b1}$, $R_{b2}$ and $R_E$ with few minor changes. Note that $R_C$ is absent in this case.

![Figure 1: BJT Common Collector CC configuration](image-url)
CC Part 1: Measure the device parameters

Step CC1.1: We need to estimate a Q-point to find an estimate for $r_o$ and $\beta$.

For the design of the amplifier, the 2 parameter values required are $r_o$ and $\beta$. Derived from the transistor characteristics curve shown in CC Fig. 2, one can set an approximate Q-point ($V_{CE}$ and $I_C$) in the active region and measure $r_o$ and $\beta$. We will solve for $V_{CE}$ and estimate $I_C$.

Solve for $V_{CE}$ see below Step CC2.1. Use Vout peak to find $I_{load}$ peak: $I_{load} = \frac{Vout}{R_{load}}$.

For an estimated $I_C$ Q-point use $I_C \approx 2.6 \times I_{load}$ peak this is not the solution to your design Q-point. We can use an estimated $I_C$ because $r_o$ and $\beta$ will not very much with small changes in Q-point.

$$ro = \frac{\Delta V_{CE}}{\Delta I_C} \text{ the slope of a line thru the estimated Q-point}$$

$$\beta = \frac{\Delta I_C}{\Delta I_B} \text{ measured around the estimated Q-point}$$

Plot the estimated Q-point ($V_{CE}$, $I_C$) on the BJT characteristics curve. From the curves CC Fig. 2 estimate $V_{CE}_{sat}$ the point where the curve begins to flattens out $\approx 0.2 V_{dc}$.
CC Part 2: Find the Q-point

Step CC2.1: Derive $V_E$ and $V_{CE}$ Q-point

We will start with $V_E$(max) and $V_E$(min).

$V_{CESat} = 0.2V$

$V_{outEmitter} = V_{out} + I_{Load} \times R_{iso}$ The AC output voltage at the emitter.

$V_E$(max) = $V_{CC} - V_{CESat} - (V_{outEmitter} + 20\%V_{outEmitter})$

$V_E$(min) = $V_{outEmitter} + 20\%V_{outEmitter}$

$V_E = (V_E$(max) + $V_E$(min)) / 2 Midpoint $V_E$ Q-point

$V_{CE} = V_{CC} - V_E$ The $V_{CE}$ Q-point

Step CC2.2: Now find the value of $R_E$ and $I_E$

The DC equation: $V_E = R_E I_E$

The AC equation: $V_{outEmitter} = i_e (R_E \parallel r_0 \parallel (R_{Load} + R_{iso}) )$

Rewrite: $V_{outEmitter} = i_e R_E (r_0 \parallel (R_L + R_{iso}) )/ (R_E + (r_0 \parallel (R_L + R_{iso}))$ Parallel resistance equation

Substituting in $V_E = i_e R_E$

Combined equation: $V_{outEmitter} = V_E (r_0 \parallel (R_{Load} + R_{iso})) / (R_E + (r_0 \parallel (R_{Load} + R_{iso})))$

Solve for $R_E$; Add 20% VoutEmitter t so the collector current is not set to an edge.

$$R_E = \frac{V_E}{V_{outEmitter} + 20\%V_{outEmitter}} (r_0 \parallel R_L + R_{iso}) - (r_0 \parallel R_L + R_{iso})$$ Rearranged combined equation

Calculate $I_E$, $I_C$, and $r_\pi$

$I_E = V_E / R_E$

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

$r_\pi = (\beta \cdot vt) / I_C$ $r_\pi$ is base to emitter resistance Hybrid Pie model. Where $vt = kT/q$ at room temperature is $vt \approx 26mV.$

CC Part 3: Find $Rb1$, and $Rb2$. (2 Methods)

Method 1.

(Do not use Method 1 for your design.) Use step CC3.2

Step CC3.1: Calculate $Rb1$, $Rb1$. Based on $I_B$

We will set the current in the base bias resistors $Rb1$, and $Rb2$ lower then $10^*Ib$ from CE keep the Rin to a higher value.
Irb1 = 3*Ib and Irb2 = 2*Ib  Current thru the base bias resistors
V_B = V_E + V_BE  Q - point values
Rb1 = (Vcc – Vb) / 3 Ib
Rb2 = Vb / 2 Ib

Rb = Rb1 || Rb2  Base bias resistors.

Method 2.
(Use this Method)

Step CC3.2: Calculate Rb1, and Rb2 Based on the requested Rin
Require Rin set to a given value. Need Vcc, Vb, rπ, ro, β, Re, Rload, and Ib.
Given Rin calculate Rin2.

Rin2 = Rin – Ri  Solve Rin2 needed to Rin requirements.

Solve for Rb from Rin2 and Rbase.
Rbase = rπ + (β + 1) ((ro || Re || (Riso + Rload)))  Impedance looking into BJT base at midband.

Rb = 1 /((1 / Rin2 ) – (1 / Rbase ))  Solve for Rb from Rin2, and Rbase to meet Rin requirements.

Find Rb1 first then Rb2
Rb1 = Vcc / ( ( Vb / Rb ) + Ib)  Solve for Rb1.
Rb2 = Vb / ((( Vcc – Vb) /Rb1) – Ib )  Solve Rb2 from Vb and current thru Rb2:  Irb2 = Irb1 – Ib

CC Figure 3: Small signal equivalent model for common collector model
CC Part 4: Calculate Rin, Rout, Av, and Ai

Step CC4.1: Input Impedance:

\[ R_b = R_{b1} \parallel R_{b2} \]

\[ R_{\text{base}} = r_n + (\beta + 1) \left( (r_o \parallel R_E) \parallel (R_{\text{iso}} + R_{\text{load}}) \right) \]

Impedance looking into BJT base.

\[ \text{Rin2} = R_b \parallel R_{\text{base}} \]

\[ \text{Rin} = \text{Rin2} + \text{Ri} \quad \text{Note: Ri is the resistor in the input used as a shunt to measure input current.} \]

Step CC4.2: Output Impedance

RemitterBase is the impedance looking in the BJT emitter towards the base.

\[ \text{RemitterBase} = \frac{(r_n + R_b \parallel (R_i + R_{\text{gen}}))}{(\beta + 1)} \]

\[ \text{Rout} = (R_E \parallel r_o \parallel \text{RemitterBase}) + R_{\text{iso}} \]

Step CC4.3: Calculation of Av Voltage Gain

Referring to CC Fig.3, let us find \( Av = \frac{\text{Vout}}{\text{Vin}} \) which would be a key step in calculating Av.

\[ R_{\text{base}} = r_n + (\beta + 1) \left( (r_o \parallel R_E) \parallel (R_{\text{iso}} + R_{\text{load}}) \right) \]

Impedance looking into BJT base.

\[ R_b = R_{b1} \parallel R_{b2} \]

\[ \text{Rin2} = R_b \parallel R_{\text{base}} \]

\[ \text{Rin} = R_i + \text{Rin2} \]

\[ \text{RemitterBase} = \frac{(r_n + R_b \parallel (R_i + R_{\text{gen}}))}{(\beta + 1)} \]

Impedance looking into the BJT emitter towards the Base.

\[ \text{Rout} = (R_E \parallel r_o \parallel \text{RemitterBase}) + R_{\text{iso}} \]

AC Voltage at the emitter.

AC voltage \( \text{VoutEmitter} = (\beta + 1) i_b (R_E \parallel r_o \parallel (R_{\text{iso}} + R_{\text{load}})) \)

Voltage across the load resistor \( \text{Vout} = \text{VoutEmitter} \ast \left( R_{\text{load}} / (R_{\text{load}} + R_{\text{iso}}) \right) \)

AC voltage \( \text{Vout} = (\beta + 1) i_b (R_E \parallel r_o \parallel (R_{\text{iso}} + R_{\text{load}})) \ast \left( R_{\text{load}} / (R_{\text{load}} + R_{\text{iso}}) \right) \)

AC Voltage at the function generator \( \text{Vin} = \text{Vin2} \ast (\text{Rin} / \text{Rin2}) \)
AC Voltage at the base  \( \text{Vin}_2 = V_{BE} + \text{VoutEmitter} \)

\[
\text{Vin}_2 = R\pi i_b + i_b (\beta + 1) (R_E \parallel ro \parallel (R_{load} + R_{iso})) = i_b (R\pi + (\beta+1) (R_E \parallel ro \parallel (R_{load} + R_{iso})))
\]

\[
\text{Av}_2 = \frac{\text{Vout}}{\text{Vin}_2} = (\beta+ 1) i_b (R_E \parallel ro \parallel (R_{load} + R_{iso})) / i_b (R\pi + (\beta+1) (R_E \parallel ro \parallel (R_{load} + R_{iso})))
\]

\[
\text{Vin} = \text{Vin}_2 (\frac{R_{in}}{R_{in2}}) \quad \text{Voltage divider Vin to Vin}_2
\]

\[
\text{Vout} = \text{VoutEmitter} \times \frac{(R_{load} / (R_{load} + R_{iso})) \quad \text{Voltage divider VoutEmitter to Vout}}{i_b (R\pi + (\beta+1) (R_E \parallel ro \parallel (R_{load} + R_{iso})))}
\]

Canceling out \( i_b \) and including the factor for \( \text{Vin}_2 \) to \( \text{Vin} \) gives

This is the final equation for \( \text{Av} = \frac{\text{Vout}}{\text{Vin}} \)

\[
\text{Av} = (\frac{R_{in2}}{R_{in}}) (\frac{\text{Rload} / (\text{Rload} + \text{Riso}) (\beta+ 1) i_b (R_E \parallel ro \parallel (R_{load} + R_{iso})) / i_b (R\pi + (\beta+1) (R_E \parallel ro \parallel (R_{load} + R_{iso})))}{\text{Rload}})
\]

Thus, the voltage gain should be close to 1. Hence, the output follows the input. So, the Common Collector configuration is also known as an Emitter follower.

**Step CC4.4: Calculation Ai Current Gain**

\[
\text{Ai} = \frac{l_{load}}{l_{in}} = \frac{V_{out}/\text{Rload}}{V_{in}/R_{in}} = \text{Av} \times \frac{R_{in}}{\text{Rload}}
\]

**Step CC4.5: Power gain**

\[
G = \frac{\text{Pout}}{\text{Pin}} = \frac{\text{Vout} \times l_{load}}{\text{Vin} \times l_{in}} = \text{Av} \times \text{Ai}
\]

In decibels \( G_{dB} = 10\log(\text{Av} \times \text{Ai}) \)

**Step CC4.6: Vin and Voc of Vgen**

Input signal level need to produce the required output voltage.

\[
\text{Vin} = \frac{\text{Vout}}{\text{Av}}
\]

The open circuit voltage of the generator to produce the required output voltage. Because of Voltage divider because the output impedance of the \( R_{gen} = 50\Omega \)
Vgen = Vin (Rgen + Rin) / Rin

Use this value in LTspice and the laboratory Function generator.

**CC Part 5: Frequency response.**

The capacitor values can be calculated as before (CE amp), the only difference being \( n = 2 \) for low pass calculations since we are using two capacitors instead of 3.

With the Q-point being set after the sequence of steps, we can go for the selection of capacitors and finally connect the signal generator at input and measure the output amplified waveform.

**Step CC5.1:** Low frequency cut off. \( F_L \)

First we will select \( C_{in} \), and \( C_{out} \) which jointly would set the roll-off beyond the lower cut-off frequency. Set any frequency within the range as your lower cut-off frequency and let us call it \( f_l \). Two capacitors will introduce 2 zeros in the transfer function of the system. Because we will set 2 pole at the same frequency we must use the Band Width Shrinkage factor.

\[
\text{BWshrinkage} = \sqrt{\frac{1}{2^n - 1}} \quad n = 2
\]

Where \( n \) is the number of zeros for low frequency breakpoints at same frequency.

Setting 2 frequencies equal, we will, multiply the \( F_L \) by the Band Width Shrinkage factor

\[
f_{Cin} = f_{Cout} = f_l \sqrt{2^{1/2} - 1}
\]

Find the C for each breakpoint \( f_{Cin} \), and \( f_{Cout} \), where \( n = 2 \).

\[
C = \frac{1}{2\pi f_C (R \text{ seen by } C)}
\]

Where \( C \) is the capacitor that sets the breakpoint \( f_{Cin} \), and \( f_{Cout} \)

\( R \) is the Thevenin equivalent resistance seen by the capacitor.

**Step CC 5.2:** High frequency cut off. \( F_H \)

\( \text{Chi} \), and \( \text{Chi2} \) on the contrary, sets the high cut-off frequency \( f_H \) which is to be set from the specified range. Where \( n = 2 \) the number of high frequency break points at the same frequency.

In this case because \( \text{Chi} \), and \( \text{Chi2} \) are set to the same break point. We must use the band shrinkage factor with \( n = 2 \). We need only to find a two poles at \( F_H / \text{bandshrinage} = f_{\text{chi}} = f_{\text{ch2}} \) to set the high frequency cutoff.

Setting the 2 high frequencies break point equal, we will, divide the \( F_h \) (high frequency cutoff desired) by the Band Width Shrinkage factor
Set \( F_{\text{chi}} = F_{\text{chi}2} = \frac{F_h}{\sqrt{2^{3/2} - 1}} \)

\[ R_{\text{base}} = r_m + ((\beta + 1) \times (r_o || R_E || (R_{\text{load}} + R_{\text{iso}}))) \]

Impedance looking into BJT base.

\[ R_b = R_{b1} || R_{b2} \]

\[ R_{\text{in}2} = R_b || R_{\text{base}} \]

R seen by \( C_{\text{hi}} \):

\[ R_{\text{hi}} = (R_{\text{gen}} + R_i) || R_{\text{in}2} \]

\[ C_{\text{hi}} = \frac{1}{2\pi f_{\text{hi}} (R \text{ seen by } C_{\text{hi}})} \]

R seen by \( C_{\text{hi}2} \):

\[ R_{\text{hi}2} = R_{\text{out}} || R_{\text{load}} \]

\[ C_{\text{hi}2} = \frac{1}{2\pi f_{\text{hi}2} (R \text{ seen by } C_{\text{hi}2})} \]

The following table enlists the particular expressions.

**Thevenin equivalent resistance seen by the capacitor.**

<table>
<thead>
<tr>
<th>( R_{\text{sig}} )</th>
<th>( R_{\text{gen}} + R_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{\text{in}} )</td>
<td>( R_{\text{sig}} + R_{\text{in}2} )</td>
</tr>
<tr>
<td>( C_{\text{out}} )</td>
<td>( R_{\text{load}} + R_{\text{out}} )</td>
</tr>
<tr>
<td>( C_{\text{hi}} )</td>
<td>( R_{\text{sig}}</td>
</tr>
<tr>
<td>( C_{\text{hi}2} )</td>
<td>( R_{\text{out}}</td>
</tr>
</tbody>
</table>

**CC Table 1: Resistance Seen By Capacitors**