ECE 3274 BJT amplifier design CE, CE with Ref, and CC.

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Section 1: CE amp Re completely bypassed (open Loop)
Section 2: CE amp Re partially bypassed (gain controlled).
Section 3: CC amp (open loop)

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

BJT Part 1: Measure the device parameters
For the design of the amplifier, the 3 parameter values required are $r_o$ and $g_m$. 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. Use Vout 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 very much with small changes in Q-point.

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

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

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

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

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

Where $V_T \approx kT/q$ at room temperature is $V_T \approx 26mV$.

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.

BJT Part 2: Determine the Q-point.

Start with your BJT and selecting 4 resistors.

Step BJT2.1: Choose $V_E$

Because $V_{BE}$ will decrease $\approx 2.5mV / ^\circ C$ 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 BJT2.2: Calculate the midpoint $V_C$ with $Re$ complete bypassed $Re = Reb$, and $Ref = 0$

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.

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

Step BJT2.3: Calculate $R_C$.

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: $V_{out} = i_c \left( R_C || r_o || R_L \right)$ output voltage $V_{outpeak}$

Rewrite: $V_{out} = i_c R_C (r_o || R_L) / (R_c + (r_o || R_L))$ Parallel resistance equation

Substituting in $V_{RC} = i_c R_C$

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

$$R_c = \frac{V_{CC} - V_C}{V_{out} + 20\%V_{out}} (r_o \parallel R_L) - (r_o \parallel R_L)$$

**Step BJT2.4: Calculate $I_c$, $I_e$, and $R_e$.**

$I_c = \frac{(V_{CC} - V_C)}{R_c}$  The Q-point collector current.

$I_b = I_c / \beta$  The base current.

$I_e = I_c (\beta + 1) / \beta$  emitter current.

$R_e = \frac{V_E}{I_e}$  Total emitter resistance.

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

**CE Figure 3: Common Emitter Small Signal Equivalent Circuit**

**CE Part 1: Determine bias resistors.**

**Step CE1.1: Calculate $R_e$. Design for the sum $R_{ef}$ and $R_{eb}$**

Later we will design for a desired $Av$ (voltage gain) by using ($R_{ef}$) and ($R_{eb}$) to control the $Av$.

$R_e = R_{ef} + R_{eb}$

$I_e = I_c (\beta + 1) / \beta$

$$R_e = \frac{V_E}{I_e}$$

**Step CE1.2: Calculate $R_{b1}$, $R_{b2}$.**
\[ V_B = V_E + V_{BE} \quad V_{BE} \text{ is normally between 0.6V and 0.7V} \]
\[ I_b = \frac{I_c}{\beta} \]

Current thru \( R_b1 \) is set to \( 10 \times I_b \)
Current thru \( R_b2 \) is set to \( 9 \times I_b \)
\[ R_b1 = \frac{(V_{cc} - V_B)}{(10 \times I_b)} \]
\[ R_b2 = \frac{V_B}{(9 \times I_b)} \]

Or

**Require Rin set to a given value.** Need \( V_{cc}, V_b, r_{\pi} \) and \( I_b \).
Given Rin calculate Rin2.

\[ \text{Rin2} = \text{Rin} - \text{Ri} \]

Solve Rin2 needed to Rin requirements.

Solve for \( R_b \) from Rin2 and Rbase.
\[ \text{Rbase} = r_{\pi} \quad \text{Re completely bypassed.} \]
\[ R_b = \frac{1}{((1 / \text{Rin2}) - (1 / \text{Rbase}))} \]

Solve for \( R_b \) needed to Rin requirements.

Find \( R_b1 \) first then \( R_b2 \)
\[ R_b1 = \frac{V_{cc}}{(\frac{V_b}{R_b} + I_b)} \]

Solve for \( R_b1 \).
\[ R_b2 = \frac{V_b}{((\frac{V_{cc} - V_b}{R_b1}) - I_b)} \]

Solve \( R_b2 \) from \( V_b \) and current thru \( R_b2 \): \( I_{r_b2} = I_{r_{b1}} - I_b \)

**Check Rin meets requirements**
\[ \text{Rbase} = r_{\pi} \quad \text{Re completely bypassed.} \]
\[ R_b = R_b1 \parallel R_b2. \]
\[ \text{Rin2} = R_b \parallel \text{Rbase} \]
\[ \text{Rin} = \text{Ri} + \text{Rin2} \]

**CE Part 2: 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 CE2.1: Input Impedance:** AC characteristics
\[ R_b = R_b1 \parallel R_b2 \quad \text{the two base bias resistors.} \]
If Re completely bypassed with \( C_E \) then
\[ \text{Rbase} = r_{\pi} \]
Rin2 = Rb || Rbase
Rin = Ri + Rin2

**Step CE2.2: Output Impedance**

If Re completely bypassed with CE then

Rout = Rc || r0. With Ref = 0

**Step CE2.3: Voltage Gain**

AC voltage Vout = -β Ib (Rout || Rload || ro) Note: use the correct Rout depending on Ref
AC voltage Vin = (Rin/Rin2) Vin2 Input signal from the function generator.
AC voltage Vin2 = vb Input signal on the base

Av2 = Vout / Vin2 = -β (Rc || ro || Rload) / rπ voltage gain at base

Av = Vout / Vin = -β (Rc || ro || Rload) / ((Rin2+Ri) / Rin2) ( rπ )

Rearrange Av = -β (Rin2 / (Rin2 + Ri)) * (Rd || ro || Rload) / rπ

Vgen = ((Rin + Rgen) / Tin) * (Vout/ Av) the open circuit voltage of the function generator.

**Step CE2.4: Current Gain**

\[ Ai = \frac{Iload}{Iin} = \frac{Av}{Rload} \]

**Step CE2.5: Power gain**

\[ G = \frac{Pout}{Pin} = \frac{Vout \cdot Iload}{Vin \cdot Iin} = Av \cdot Ai \]

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

**CE Part 3: 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 Cin, Cout and CE 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.

\[ \text{BWshrinkage} = \sqrt{\frac{1}{2^n} - 1} \]
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 \( n = 3 \).

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

Where \( C \) is the capacitor that sets the breakpoint \( f_C \).

\( \text{RemitterBase} \) is the impedance looking in the BJT emitter to base.

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

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

\[
R_{CE} = R_e \parallel (ro + R_C \parallel R_{Load}) \parallel \text{RemitterBase}
\]

The following table enlists the particular expressions.

<table>
<thead>
<tr>
<th>Rsig</th>
<th>Rgen+Ri</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{in} )</td>
<td>Rsig + Rin2</td>
</tr>
<tr>
<td>( C_{out} )</td>
<td>RLoad + Rout</td>
</tr>
<tr>
<td>( C_E )</td>
<td>Re \parallel (ro + R_C \parallel R_{Load}) \parallel \text{RemitterBase}</td>
</tr>
<tr>
<td>( C_{hi} )</td>
<td>Rsig \parallel Rin2</td>
</tr>
<tr>
<td>( C_{hi2} )</td>
<td>Rout \parallel Rload</td>
</tr>
</tbody>
</table>

CE Table 1: Resistance Seen By Capacitors

In this case because \( \text{Chi, and Ch2} \) 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 \( F_h \) / \( \text{bandshrinkage} = f_{\text{chi}} = f_{\text{ch2}} \) to set the high frequency cutoff.

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

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

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

\[
R_{\text{in2}} = R_b \parallel R_{\text{base}}
\]

\( R \) seen by \( \text{Chi} \) \quad \( R_{\text{Chi}} = (R_{\text{gen}} + R_i) \parallel R_{\text{in2}} \)
\[ C_{hi} = \frac{1}{2 \pi f_{Chi} \left(R \text{ seen by } C_{hi}\right)} \]

\[ R \text{ seen by } C_{hi2} = \frac{R_{out}}{|| R_{load}} \quad \text{Note: use the correct } R_{out} \text{ depending on Ref} \]
\[ C_{hi2} = \frac{1}{2 \pi f_{Chi2} \left(R \text{ seen by } C_{hi2}\right)} \]

Section 2:

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

\[ R_E = R_{ref} + R_{reb} \] 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.

**BJT 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. Use Vout peak to find \( I_{load \text{ peak}} \): \( I_{load} = Vout / R_{load} \).

For an approximate \( I_C \) Q-point use \( I_C \approx 2.2 * I_{load \text{ peak}} \) 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 \( \approx 0.2 \text{ Vdc} \).

\( r_o = \Delta V_{ce} / \Delta I_C \) the slope of a line thru Q-point

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

\( V_{ce\text{SAT}} = V_{ce} \text{ begins to flatten} \)

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

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

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

Start with your BJT and selecting 4 resistors.

**Step BJT2.1: Choose $V_E$**

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

**Step BJT2.2: Calculate the midpoint $V_C$ with Re partially bypassed $Re = Reb + Ref$**

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. This will also help with the additional loading because of high frequency capacitors as the frequency approaches the high frequency break points.

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

**Step BJT2.3: Calculate $R_C$**

The AC equation: $V_{out} = i_c (R_C || r_o || R_L)$ output voltage $V_{out peak}$

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

Substituting in $v_{RC} = i_c R_C$

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

Solve for $R_C$; Add 20%$V_{out}$ so the collector current is not set to an edge.

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

**Step BJT2.4: Calculate $I_C$, $I_E$, and $Re$.**

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

- $I_E = I_C (\beta + 1) / \beta$ emitter current.
- $Re = V_E / I_E$ 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 $Re = I_e (Ref + Reb)$ the total emitter resistance.
We now have, $V_e$, $V_c$, $R_c$, $R_e$, $I_c$, $I_e$, $V_{ce}$, $V_{ce\text{SAT}}$

CEwRef Figure 1: Amplifier with emitter partially bypassed.
CEwRef Figure 2: Small signal model with partial bypass of Re

**Step CEwRef3.1: Output Impedance with Ref**

If Re partially bypassed with $C_E$ bypassing Ref.

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

RemitterBase = $(r_π + R_b || (R_i + R_{gen})) / (β + 1)$ Small value, because divided by $β +1$.

RemitterBase = $(r_π + R_b || (150 + 50 )) / (β + 1) = (r_π + 200 ) / 151$ Small value $≈ 10\,Ω$

$R_{out} = R_c || (r_0 + Ref || RemitterBase) = R_c || 40kΩ ≈ R_c$

The complete equation below for $R_{out}$, but we do not have Ref yet or Rb

$R_{out} = R_c || ( r_0 + Ref || (r_π + R_b || (R_i + R_{gen})) / (β +1))$

Because $r_0$ is greater than 40kΩ we approximate $R_{out} = R_c || “large” = R_c$

**CEwRef Part 4: Calculating impedance and Gain with Ref**

We use the same Q-point and bias resistors $R_b1$, $R_b2$, $R_c$, and $R_e = Ref + Reb$.

**Step CEwRef4.1: find Ref based on Voltage Gain requested**

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

AC voltage $V_{out} = -β i_b (R_{out} || R_{load} || r_0)$. Note: use the approximant $R_{out}$ because Ref is not known yet.

AC voltage $V_{in} = (R_{in}/R_{in2}) V_{in2}$ Input signal from the function generator.

AC voltage $V_{in2} = i_b(r_π + (β + 1) Ref)$ Input signal on the base

$Av2 = V_{out} / V_{in2} = -β (R_c || r_0 || R_{load}) / (r_π + (β + 1) Ref)$ Voltage gain at base, we do not need to find $i_b$ since $i_b$ cancels.

$Av = V_{out} / V_{in} = -β (R_c || r_0 || R_{load}) / (R_{in}/R_{in2}) (r_π + (β + 1) Ref)$ Voltage gain at input

$Av = - β (R_{in2}/R_{in}) (R_c || r_0 || R_{load}) / (r_π + (β + 1) Ref)$

Rearrange $Av$ to solve for Ref from requested $Av$

$Ref = -( β (R_{in2}/R_{in}) (R_c|| r_0 || R_{load}) / Av) - r_π) / (β + 1)$

$Reb = Re − Ref$ remember that Re is the total emitter residence

**Find $R_b1$ and $R_b2$ based on requested $R_{in}$**
**Require Rin set to a given value.** Need Vcc, Vb, $r_\pi$ and $I_\beta$ (DC bias base current). Given Rin calculate Rin2.

$$Rin2 = Rin - Ri$$  
Solve Rin2 needed to meet the Rin requirements.

Solve for Rb from Rin2 and Rbase.

$$Rbase = r_\pi + (\beta + 1) (Ref || (ro + Rc || Rload))$$  
Looking into the Base of the BJT. We will ignore the branch looking thru $r_o$ because $r_o$ is large.

$$Rbase = (r_\pi + (\beta + 1) Ref)$$  
Ref is the portion of Re not bypassed.

$$Rb = 1/((1/Rin2) - (1/Rbase))$$  
Solve for Rb needed to meet Rin requirements.

Find Rb1 first then Rb2

$$I_\beta = I_C / \beta$$ DC bias base current.

$$Rb1 = Vcc / ((Vb / Rb) + Ib)$$ Solve for Rb1.

$$Rb2 = Vb / (((Vcc - Vb)/Rb1) - Ib)$$ Solve Rb2 from Vb and current thru Rb2: $Irb2 = Ir_{b1} - Ib$

**Check Rin meets requirements**

$$Rbase = r_\pi + (\beta + 1) Ref$$ looking into base

$$Rb = Rb1 || Rb2.$$  

$$Rin2 = Rb || Rbase$$

$$Rin = Ri + Rin2$$

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

$$Rb = Rb1 || Rb2$$

Where Ref is the part of $R_E$ that is not bypassed by $C_E$.

$$Rbase = r_\pi + (\beta + 1) (Ref || (ro + Rc || RlOAD))$$  
Looking into the Base of the BJT.

$$Rin2 = Rb || Rbase$$

$$Rin = Ri + Rin2$$

**Step CEwRef4.4: Current Gain**

$$Ai = \frac{R_{load}}{R_{in}} = AV \frac{R_{in}}{R_{load}}$$
Step CEwRef4.5: Power gain

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

In decibels \[ G_{\text{dB}} = 10 \log (A_v \cdot A_i) \]

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.

First we will select \( C_{\text{in}}, C_{\text{out}} \) and \( C_{\text{E}} \) 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.

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

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

\[ f_L = \frac{f_{C_{\text{in}}} + f_{C_{\text{out}}} + f_{C_{\text{E}}}}{3\sqrt{2^{3/4} - 1}} \]

Setting 3 frequencies equal, we get,

\[ f_{C_{\text{in}}} = f_{C_{\text{out}}} = f_{C_{\text{E}}} = f_L \sqrt{2^{1/3} - 1} \]

Find the \( C \) for each breakpoint \( f_{C_{\text{in}}}, f_{C_{\text{out}}}, \) and \( f_{C_{\text{E}}} \) where \( n = 3 \).

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

Where \( C \) is the capacitor that sets the breakpoint \( f_C \)

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

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

\[ \text{RemitterBase} = (r_n + R_b \| (R_i + R_{\text{gen}})) / (\beta + 1) \quad \text{Small value} \]

\[ R_{C_{\text{E}}} = R_{\text{eb}} \| (R_{\text{f}} + (R_o + R_{C} \| R_{\text{Load}}) \| \text{RemitterBase}) \]

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

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

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\[ \begin{array}{|c|c|} 
\hline 
\text{Cout} & \text{RLoad + Rout} \\
\hline 
\text{CE} & \text{Reb} \parallel (\text{Ref} \parallel (\text{ro} + \text{RC} \parallel \text{RLoad}) \parallel \text{RemitterBase}) \\
\hline 
\text{Chi} & \text{Rsig} \parallel \text{Rin2} \\
\hline 
\text{Chi2} & \text{Rout} \parallel \text{Rload} \\
\hline 
\end{array} \]

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

\( C_{hi} \) Sets the higher cut-off frequency \( f_h \) which is to be set from the specified range.

In this case because \( \text{Chi} \), and \( \text{Ch2} \) 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 \( F_h / \text{bandshrinage} = f_{chi} = f_{ch2} \) to set the high frequency cutoff.

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

\( R_b = R_b1 \parallel R_b2 \) Base bias resistors

\( R_{\text{base}} = r_{\pi} + (\beta + 1) \) (Ref || (ro + Rc || Rload)) Looking into the Base of the BJT.

\( \text{Rin2} = R_b \parallel R_{\text{base}} \)

\[ R \text{ seen by } C_{hi} \quad R_{\text{Chi}} = (\text{Rgen} + \text{Ri}) \parallel \text{Rin2} \]

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

\[ R \text{ seen by } C_{hi2} \quad R_{\text{Chi2}} = \text{Rout} \parallel \text{Rload} \quad \text{Note: use the correct Rout depending on Ref} \]

\[ C_{hi2} = \frac{1}{2\pi f_{chi2} (R \text{ seen by } C_{hi2})} \]
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 Rb1, Rb2 and Re with few minor changes. Note that Rc is absent in this case

Figure 1: BJT Common Collector CC configuration
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. Use Vout peak to find $I_{load}$ peak: $I_{load} = Vout / Rload$.

For an estimated $I_C$ Q-point use $I_{Cq} \approx 2.6 \times I_{load}$ 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.

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

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

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

---

CC Figure 2: CC BJT curve.
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).

$V_{CESat} = 0.2V$

$V_E(max) = Vcc - V_{CESat} - (Vout + 20\%Vout)$

$V_E(min) = Vout + 20\%Vout$

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

$V_{CE} = Vcc - V_E$  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:  $Vout = i_e (R_E || r_o || R_{Load})$  Parallel resistance equation

Rewrite:  $Vout = i_e R_E (r_o || R_L) / (R_E + (r_o || R_L))$  Parallel resistance equation

Substituting in $V_E = i_e R_E$

Combined equation:  $Vout = V_E (r_o || R_{Load}) / (R_E + (r_o || R_{Load}))$

Solve for $R_E$: Add 20\%Vout so the collector current is not set to an edge.

$R_E = \frac{V_E}{V_{out} + 20\%Vout} (r_o || R_L) - (r_o || R_L)$  Rearrange combined equation

Calculate $I_E$

$I_E = V_E / R_E$

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

CC Part 3: Find Rb1, and Rb2

Step CC3.1: Calculate Rb1, Rb1.

We will set the current in the base bias resisters Rb1, and Rb2 lower then 10*Ib from CE keep the Rin to a higher value.

$I_{rb1} = 3*I_B$ and $I_{rb2} = 2*I_B$  Current thru the base bias resisters

$V_B = V_E + V_{BE}$  Q-point values

$Rb1 = (Vcc - Vb) / 3 I_B$

$Rb2 = Vb / 3 I_B$

$Rb = Rb1 || Rb2$  Base bias resisters.

Or

Require Rin set to a given value. Need Vcc, Vb, $r_n$, $r_o$, $\beta$, $R_e$, Rload, and Ib.

Given Rin calculate Rin2.

$Rin2 = Rin - Ri$  Solve Rin2 needed to Rin requirements.

Solve for Rb from Rin2 and Rbase.
Rbase = \( r_\pi + (\beta + 1) \left( \frac{1}{R_E} \parallel \frac{1}{Rload} \right) \) Impedance looking into BJT base at midband.

\[ Rb = \frac{1}{\left( \left( \frac{1}{Rin2} \right) - \left( \frac{1}{Rbase} \right) \right)} \] Solve for \( Rb \) from \( Rin2 \), and \( Rbase \) to meet \( Rin \) requirements.

Find \( Rb1 \) first then \( Rb2 \)

\[ Rb1 = \frac{Vcc}{\left( \frac{Vb}{Rb} \right) + Ib} \] Solve for \( Rb1 \).

\[ Rb2 = \frac{Vb}{\left( \frac{Vcc - Vb}{Rb1} \right) - Ib} \] Solve \( Rb2 \) from \( Vb \) and current thru \( Rb2 \): \( I_{rb2} = I_{rb1} - Ib \)

**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:**

\[ Rb = Rb1 || Rb2 \]

\[ Rbase = \left( r_\pi + (\beta + 1) \left( \frac{1}{R_E} \parallel \frac{1}{Rload} \right) \right) \] Impedance looking into BJT base.

\[ Rin2 = Rb || Rbase \]

\[ Rin = Rin2 + Ri \] 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.

\[ RemitterBase = \left( \frac{1}{R_\pi + Rb} \parallel \frac{1}{Ri + Rgen} \right) / (\beta + 1) \]

\[ Rout = \frac{R_E}{ro} \parallel RemitterBase \]

**Step CC4.3: Calculation of Av Voltage Gain**
Referring to CC Fig.3, let us find \[\frac{V_{out}}{V_{in}}\] which would be a key step in calculating \(Av\).

\[R_{\text{base}} = r_\pi + (\beta + 1) ((r_0 || R_E || R_{\text{load}}))\] Impedance looking into BJT base.

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

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

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

\[R_{\text{emitter base}} = (r_\pi + R_b || (R_i + R_{\text{gen}})) / (\beta + 1)\] Impedance looking into the BJT emitter towards the Base.

\[R_{\text{out}} = R_E || r_0 || R_{\text{emitter base}}\]

AC voltage \(V_{\text{out}} = (\beta + 1) i_b (R_E || r_0 || R_{\text{load}})\) Voltage across the load resistor

AC Voltage at the function generator \(V_{\text{in}} = V_{\text{in}2} (R_{\text{in}} / R_{\text{in}2})\)

AC Voltage at the base \(V_{\text{in}2} = V_{BE} + V_{\text{out}}\)

\[V_{\text{in}2} = R_\pi i_b + i_b (\beta + 1) (R_E || r_0 || R_{\text{load}}) = i_b (R_\pi + (\beta + 1) (R_s || r_0 || R_{\text{load}}))\]

\[Av_2 = V_{\text{out}} / V_{\text{in}2} = (\beta + 1) i_b (R_E || r_0 || R_{\text{load}}) / i_b (R_\pi + (\beta + 1) (R_E || r_0 || R_{\text{load}}))\]

\[V_{\text{in}} = V_{\text{in}2} (R_{\text{in}} / R_{\text{in}2})\]

\[Av = V_{\text{out}} / V_{\text{in}} = (R_{\text{in}2} / R_{\text{in}}) (\beta + 1) i_b (R_E || r_0 || R_{\text{load}}) / i_b (R_\pi + (\beta + 1) (R_E || r_0 || R_{\text{load}}))\]

Canceling out \(i_b\) and including the factor for \(V_{\text{in}2}\) to \(V_{\text{in}}\) gives

\[Av = (R_{\text{in}2} / R_{\text{in}}) (\beta + 1) (R_E || r_0 || R_{\text{load}}) / (R_\pi + (\beta + 1) (R_E || r_0 || R_{\text{load}}))\]

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**

\[
Ai = \frac{I_{\text{load}}}{I_{\text{in}}} = Av \frac{R_{\text{in}}}{R_{\text{load}}}
\]
Step CC4.5: Power gain

\[ G = \frac{P_{out}}{P_{in}} = \frac{V_{out}}{V_{in}} \frac{I_{load}}{I_{in}} = Av \times Ai \]

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

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.

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.

\[ BW_{shrinkage} = \sqrt{\frac{1}{2^n - 1}} \quad n = 2 \]

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

\[ f_{Cin} = f_{Cout} = f_L \sqrt{\frac{1}{2^n}} - 1 \]

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.

The following table enlists the particular expressions.

<table>
<thead>
<tr>
<th>( R_{sig} )</th>
<th>( R_{gen+Ri} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{in} )</td>
<td>( R_{sig + Rin2} )</td>
</tr>
<tr>
<td>( Cout )</td>
<td>( R_{Load + Rout} )</td>
</tr>
<tr>
<td>( Chi )</td>
<td>( R_{sig</td>
</tr>
<tr>
<td>( Chi2 )</td>
<td>( Rout</td>
</tr>
</tbody>
</table>

CC Table 1: Resistance Seen By Capacitors
Chi, and 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 Chi, and Ch2 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 $F_h / \text{bandshrinkage} = f_{ch1} = f_{ch2}$ 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 $F_{ch1} = F_{ch2} = \frac{F_h}{\sqrt{2}^{1/2} - 1}$

$R_{\text{base}} = r_\pi + (\beta + 1) ((R_o || R_E || R_{\text{load}}))$ Impedance looking into BJT base.

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

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

$R$ seen by $C_{hi}$ $R_{ch1} = (R_{\text{gen}} + R_i) || R_{in2}$

$C_{hi} = \frac{1}{2\pi f_{ch1} (R \text{ seen by } C_{hi})}$

$R$ seen by $C_{hi2}$ $R_{ch2} = R_{out} || R_{\text{load}}$

$C_{hi2} = \frac{1}{2\pi f_{ch2} (R \text{ seen by } C_{hi2})}$