BJT Transistors

First Transistor: Bell Labs 1947

Transistor Analogy 1: Rules
- Rules: (Which Always Apply!)
  - $I_B$ is the sense or control current
  - $I_B$ can only flow in one direction
  - $I_E = I_C + I_B$
- Results in 3 operating modes:

What Is It & Why (and Where) Would I Use One?
- Active Components (as opposed to passive components)
- Current Source / Amplifier
- Change Input / Output impedances
  - "Transform "resistances" => TRANS-(res)ITOR"

Transistor Analogy 1: Three Operating Modes
1. (Cut) Off: (Application: Switch)
   - $I_B = 0$, so $I_C = 0$ and $I_E = 0$
2. Active: (Application: Amplifier)
   - $I_C = \beta I_B$
     - $\beta$ is the (current) gain
     - $\beta$ is sometimes also called $h_{fe}$
     - $\beta$ is typically between 100 to 200
     - $I_E = I_C + I_B = I_C + I_C/\beta \equiv I_C$

Transistor Analogy 1: Operating Modes (continued)
3. Saturated: (Application: Switch)
   - $I_C \neq \beta I_B$
     - The transistor has reached its limits in regulating $I_C$: therefore, the relations ship $I_C = \beta I_B$ is NO LONGER VALID!
     - In this case, $I_B \ll I_C$ is NO LONGER VALID!
     - $I_E = I_C + I_B$ (still holds!)

Water Transistor Analogy
BJT* Transistor Symbols

*BJT = Bipolar Junction Transistor (as opposed to a “Field Effect” Transistor, i.e., “FET”)

“npn” mnemonic: “never points in”
Two pn-diodes do not make a transistor!

Transistor Circuit Solving: DC Analysis

DC Analysis
- Replace all capacitors with open circuits
- Short all (independent) AC voltage sources
- Replace the transistor with its appropriate DC equivalent circuit model
- Solve (hm...)

Transistor Circuit Solving Approach: 5 Steps

Note: It’s an iterative approach!

Step 1:
- Pick a Transistor Operating Mode (Cutoff, Active, Saturated)

Steps 2, 3 & 4:
- DC & AC Analysis and then Superposition

Step 5:
- Check your results; if wrong, choose a different model and start at step 1 again.

Transistor Circuit Solving: DC, AC Analysis and Superposition

Superposition:
- Solve the transistor circuit with only DC bias applied, i.e., find the quiescent voltages and currents
- Solve the transistor circuit with only AC signals applied.
- Finally combine the results:
  \[ V_{\text{Total}} = V_{\text{DC}} + V_{\text{AC}} \]

DC Equivalent Transistor Circuit Model

For Active and Cutoff Mode Only
- \[ V_{BC} = V_B - V_E = 0.6 \text{ V in active (forward biased) mode} \]

DC Equivalent Transistor Circuit Model

For Saturated Mode Only
- \[ V_{\text{Sat}} = 0.1 \text{ to } 0.3 \text{ V typically} \]
- \[ V_{BE} = 0.6 \text{ V in forward biased mode} \]
Transistor Circuit Solving: AC Analysis

- AC Analysis
  - Again replace the transistor with its appropriate AC equivalent circuit model.
  - Also replace all capacitors with short circuits.
  - Short all (independent) DC voltage sources.
  - Trick: for now short circuit \( r_\pi \).
  - Only active AC model is provided since for cutoff or saturation AC signal no longer propagates.
  - Solve (hm...)

AC Equivalent Transistor Circuit Model For ACTIVE Mode ONLY!

\[
r_\pi = \beta \frac{V_{TH}}{I_C} = \beta / (40 I_C)
\]

Example:
\[\beta = 100; \quad I_C = 1\text{mA}; \quad r_\pi \approx 1\text{k}\Omega\]

For the rest ignore \((\text{short})\) \( r_\pi \), i.e., \( r_\pi \approx 0! \)

Example 1: Common Collector Emitter Follower Analysis:

Find all voltages and currents
\[v_0 < 1.0\text{V}\]
\[\beta = 100\]

Step 1: Assume circuit is in active mode!

Example 1 Analysis: Step 2: DC Analysis

Use appropriate DC equivalent model; short all AC sources; open all capacitors.

\[
\begin{align*}
V_B &= \\
V_E &= \\
V_C &= \\
V_{OUT} &= \\
I_E &= \\
I_C &= \\
I_B &= 
\end{align*}
\]

Example 1 Analysis: Step 3: AC Analysis

Use AC equivalent model & short all DC sources and all capacitors. For simplicity, assume \( r_\pi = 0 \).

Let \( v_c(\omega t) = \delta v_n = v_n \)

\[
\begin{align*}
v_B &= \\
v_E &= \\
v_C &= \\
i_E &= \\
i_C &= \\
i_B &= \\
v_{gain} &= \frac{v_{out}}{v_n} =
\end{align*}
\]

Example 1 Analysis: Step 4: Superposition

Combine results from step 2 and 3. Again, \( v_c(\omega t) = \delta v_n \).

\[
\begin{align*}
V_B &= \\
V_E &= \\
V_C &= \\
V_{OUT} &= \\
i_E &= \\
i_C &= \\
i_B &=
\end{align*}
\]
Example 1 Analysis: Step 5: Check Model

Find Limits of DC Model: Adjust DC Bias Voltage
Source $V_{DC}$: Try $V_{DC} = 1V$ and $20V$ and $\delta v_{in} = 1 \text{ VAC}$.

Example 1 Analysis: Step 5: Check Model: Limits

Limits:
- CutOff: $V_B <$
- Saturated: $V_B >$
- Conclusion(s):
  - Transistor Model Used:
  - Purpose of Circuit:

Example 2: C. C. E. Follower

AC Output Impedance

$z_{out} = \frac{V_{out}}{I_{out}}$

Solve use AC small signal model

Conclusion:

Example 2: C. C. E. Follower

AC Output Impedance

Use appropriate AC equivalent model; assume $r_o = 0$ and short all DC sources and short all capacitors.

$z_{out} = \frac{V_{out}}{I_{out}}$

$I_{out} = I_1 - I_e$

$I_1 = \frac{V_{out}}{R_E}$

$I_e = I_b (\beta + 1)$

$I_b = -\frac{V_{out}}{R_B}$

$z_{out} = \frac{R_B}{(\beta + 1) + \frac{R_B}{R_E}}$  

$z_{out} \approx \frac{R_B}{(\beta + 1)}$

Use appropriate AC equivalent model; assume $r_o = 0$ and short all DC sources and short all capacitors.

Common Collector Emitter Follower Conclusions

1. AC Voltage Gain:
2. $z_{in}^*$:
3. $z_{out}^*$:
Biasing the Common Collector Emitter Follower 1
- Requires 2 DC Power Supplies
- $\delta v_{in}$ must be “floating”

Biasing the Common Collector Emitter Follower 2
Circuit 1
Circuit 2

Biasing the Common Collector Emitter Follower 3
1. Determine the Optimal $V_{out}$ Quiescent Point for Max. Symmetrical Output
2. Calculate all other Voltages
3. Find $I_B$
4. Calculate $R_1$ and $R_2$

Biasing the Common Collector Emitter Follower 4
- Optimized Follower (Larger Dynamic Range!)
- Find $z_{in}$ and $z_{out}$
- Determine $C_{in}$ and $C_{out}$ if: $20 \text{ Hz} < f_n < 20 \text{ kHz}$

Biasing Considerations
- Select the Voltages Based on an Optimal $V_{out}$ Quiescent Point Based On:
  - Best Input / Output Range
  - Transistor Operating Mode Range
  - Quiescent $V_{out}$ Power Consumption
- Select the Voltage Divider Resistance Values Based on (Quiescent) Power Consumption
  - Consider $Z_{net}$, i.e., $R_{load}$
  - Factor of 10 Rule for Voltage Dividers

Follower Definition
1. No Voltage Gain
2. Large $Z_{in}$
3. Low $Z_{out}$
- Where and why would I use one?
What's the difference between the follower circuit? "How" does it amplify the input voltage? (Hint: Use small signal model.)

Example: Design a Common Emitter Amplifier Circuit with the following characteristics:
- AC Voltage Gain: -20
- $z_{out} = 20 \, \text{k} \Omega$ (Hint: $z_{out}$ Common Emitter Amplifier is $R_C$.)
- Optimal (Largest) Output Voltage Range

Find all voltages, currents, resistances and $v_{in}$ range.

Circuits so far only amplify an AC voltage signal.
Need a "differential" amplifier to amplify DC
Common Mode Gain vs. Differential Gain; Common Mode Rejection Ratio (CMRR)