

EEE118: Electronic Devices and Circuits

Lecture XV

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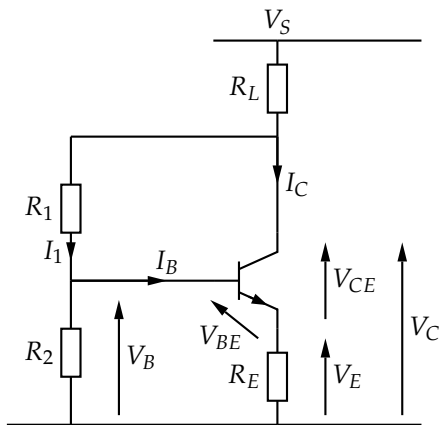
Review

- Introduced some terminology (gain, bias, input, output impedance).
- Introduced three ideal amplifiers in terms of their gain and input and output impedance.
- Considered what happens to signals when applied to an un-biased transistor
- Shown that biasing allows linear operation of an amplifier.
- Derived the voltage gain of a simple transistor amplifier with bias.
- Noted that the biasing terms and signal terms can be separated
- Introduced one of two biasing circuits, which operate using negative feedback, to control collector current nearly independently of device parameters and temperature.

Outline

- 1 Review
- 2 A Tale of Two Circuits... Continued
- 3 Design of Bias Circuits
 - Compromises in Design
- 4 Getting Signals in to the and out of the Amplifier
 - Circuit One
 - Circuit Two
- 5 Small Signal Model of a Transistor Operating as an Amplifier
- 6 Review
- 7 Bear

Circuit Two



Circuit 2.

In this circuit R_E provides negative feedback as in circuit one, but negative feedback is also provided from V_C via R_1 and R_2 . If the transistor attempts to increase I_C slightly, V_C will be reduced. As a consequence V_B will be reduced as well and the transistor collector current will fall slightly. This circuit will operate without R_E because there is still negative feedback through $R_1 + R_2$. Circuit one will not operate properly without R_E . This circuit is often used at higher frequencies with $R_E = 0$.

Working Out the Biasing Conditions

Assume, I_B is negligible, $V_{BE} = 0.7 \text{ V}$, $h_{FE} \gg 1 \therefore I_C \approx I_E$ Using KVL,

$$I_1 R_2 + I_1 R_1 + (I_1 + I_C) R_L = V_S \quad (1)$$

or,

$$V_S = I_C R_L + I_1 (R_L + R_1 + R_2) \quad (2)$$

Also by KVL,

$$I_1 R_2 = V_E + V_{BE} = V_E + 0.7 \quad (3)$$

or,

$$I_1 R_2 = I_C R_E + 0.7 \quad (4)$$

Either I_1 or I_C should be eliminated from (2) using (4). For example, eliminating I_1 gives,

$$V_S = I_C R_L + \frac{I_C R_E + 0.7}{R_2} (R_L + R_1 + R_2) \quad (5)$$

or

$$I_C = \frac{V_S - \frac{0.7(R_L + R_1 + R_2)}{R_2}}{R_L \frac{R_E(R_L + R_1 + R_2)}{R_2}} \quad (6)$$

This result for I_C can be used in (4) to find I_1 . V_C is found using,

$$V_C = V_S - (I_C + I_1) R_L \quad (7)$$

It is not the result that is important. Learning the circuit's skills to get to the result is what counts. No two circuits have the same equations!

Only the transistor V_{BE} can be relied upon. V_{CE} and V_{CB} should *not* appear in your equations.

The assumption that I_B is negligible really means that the existence of I_B does not disturb the voltage on the base significantly.

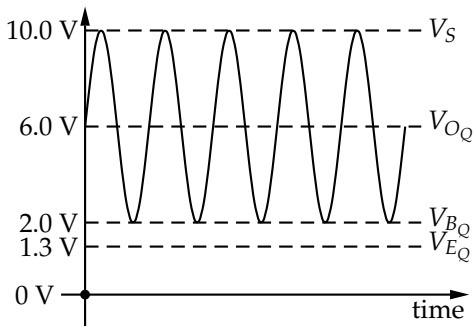
Designing Bias Circuits

- One of the two circuits must be selected.
- This choice depends on the frequency of operation. At low frequencies circuit one is often selected but at higher frequencies circuit two with $R_E = 0$ is more common.
- The “ I_B is negligible” approximation must be considered. It is the smallest value of h_{FE} that yields the largest value of I_B .
- The objective is to control I_C , $I_B (max) = \frac{I_C}{h_{FE} (min)}$. If $I_B (max) \leq 10 \times I_1$ then I_B is considered negligible.
- The collector current, collector voltage and base voltage have some (indirect) effect on the signal conditions in the circuit so choosing them is often a compromise.

- The collector voltage affects the available output voltage swing. In circuit one V_C can fall between V_S and V_E (although we say V_B for caution's sake).
- To obtain maximum symmetrical swing, $V_C = \frac{V_S + V_E}{2}$.
- Both V_S and V_E affect the max symmetrical swing, which is $V_S - V_E$ (although we say V_B for caution's sake). V_S is often set by external factors, but V_E is often a free choice.
- Larger V_E gives better control over I_C but eats into the available voltage swing. The negative feedback effect of V_E diminishes as V_E approaches V_{BE} . Generally $V_E > 1$ V in the first circuit.
- I_C is chosen by considering the nature of the load, but it also affects the the effective input impedance of the circuit. Generally R_L must be much smaller than the input impedance of whatever is connected to the output of the amplifier.
- $R_1 + R_2$ should be as large as possible (but not violate the $I_1 \sim 10 \times I_B$ rule).

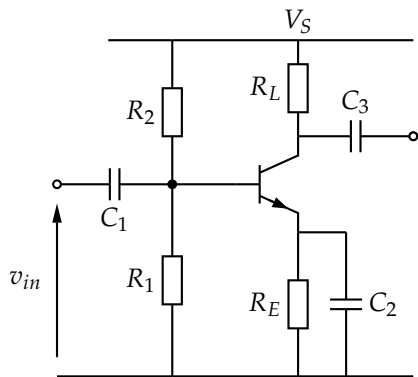
The available voltage in the circuit is shared between the various parts. The transistor must be kept in the forward active region so $V_{BE} = 0.7 \text{ V}$. A diagram is sometimes helpful.

Increasing V_E reduces the range of voltage that can be occupied by V_O . The optimum position of V_O for maximum signal swing is half way between V_B and V_S .



Most amplifiers will work with V_O swinging down to 200 mV above V_{E_Q} . But there are good reasons to keep V_O above V_{B_Q} .

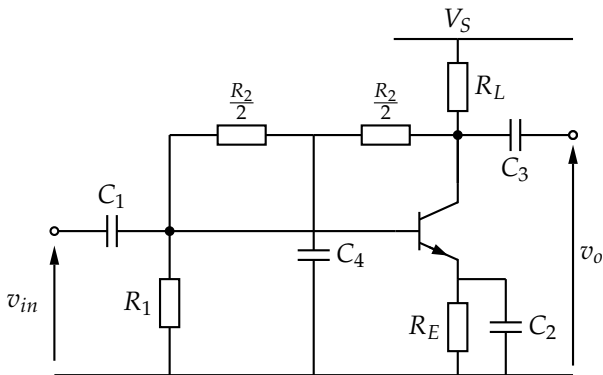
- Passing signals between two points in a circuit is called “coupling”.
- Removing signals from a node (to leave only DC) is called “de-coupling”.
- As was done for the compressor in lecture 10 “coupling” (or “blocking” capacitors can be used to pass AC signals into the amplifier circuit without the signal source DC conditions affecting the amplifier circuit DC conditions.
- Amplifiers can be coupled with transformers too, this is more common at higher frequencies where the load may be resonant, and in thermionic valve circuits for impedance transformation purposes.
- Amplifiers coupled by capacitors are called “R-C coupled”. Amplifiers coupled by transformers are (predictably) “transformer coupled”.



C_1 couples the signal from the source to the transistor base without allowing the source to affect the bias conditions, or allowing the bias conditions to affect the source.

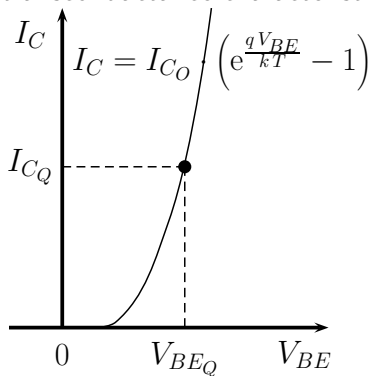
C_2 decouples the emitter node of the transistor. C_2 shorts the emitter node to ground from the signal's point of view. This prevents R_E having the same stabilising effect on the signals as it does on the quiescent conditions. If R_E was not bypassed the voltage gain of the amplifier would be significantly reduced.

C_3 couples the signal from the output to the load without allowing disturbance of the biasing conditions or the imposition of the amplifier's quiescent conditions on the load.



C_4 decouples the mid point of R_2 . Since R_2 is also a negative feedback pathway it will reduce the circuit gain is AC as well as DC voltages can be transmitted via I_B to the base. C_4 shorts the mid point of R_2 to ground as far as signals are concerned, hence eliminating the effect of negative feedback through R_2 on the voltage gain.

Just as large and small signal models were developed for a diode and large signal models were developed for a transistor operated as a switch, a small signal model for a transistor amplifier exists. The fundamental mechanism underpinning “transistor action” is the transconductance - a small change in input voltage elicits a larger change in output current. For small signals it is the slope of the transconductance characteristic that is significant.



$$I_C = I_{C0} \left(\exp\left(\frac{qV_{BE}}{kT}\right) - 1 \right) \quad (8)$$

the slope is,

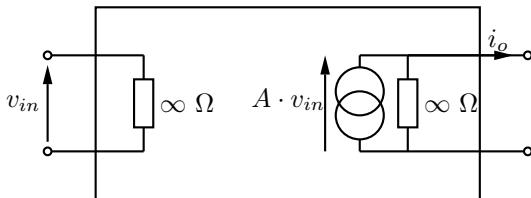
$$\frac{dI_C}{dV_{BE}} = I_{C0} \frac{q}{kT} \exp\left(\frac{qV_{BE}}{kT}\right) \quad (9)$$

For a conducting diode, $\exp\left(\frac{qV_{BE}}{kT}\right) \gg 1$ so,

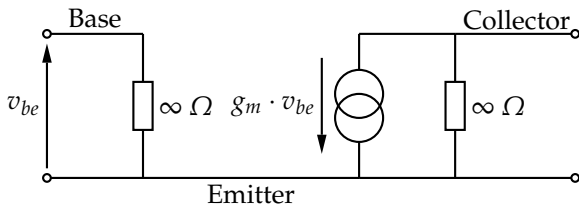
$$I_C = I_{C0} \left(\exp\left(\frac{qV_{BE}}{kT}\right) - 1 \right) \approx I_C = \left[I_{C0} \exp\left(\frac{qV_{BE}}{kT}\right) \right] \quad (10)$$

$$\therefore \frac{dI_C}{dV_{BE}} = \frac{q}{kT} \cdot \left[I_{C0} \exp\left(\frac{qV_{BE}}{kT}\right) \right] = \frac{qI_C}{kT} \quad (11)$$

$g_m = \frac{qI_C}{kT}$ is a fundamental relationship which holds over more than nine orders of magnitude of I_C . Remember it! Looking back at lecture 14, the generalised transconductance amplifier is,



But, the transistor only has three terminals. For the circuits in this course the emitter terminal is common to both the input and output networks. The small signal model of a transistor reduces to,



this is a good low frequency model for JFETs, MOSFETs and Valves. The BJT is special however because there is recombination of carriers in the base region, a base current flows. As a result the resistance looking into the base towards the emitter must be finite (by Ohm's law). The characteristics can be used indirectly to yield the small signal base emitter resistance, r_{be} .

$$r_{be} = \frac{d V_{BE}}{d I_B} = \frac{d I_C}{d I_B} \cdot \frac{d V_{BE}}{d I_C} \quad (12)$$

$$\frac{d I_C}{d I_B} = \beta = \text{small signal current gain (see datasheet)} \quad (13)$$

$$\frac{d V_{BE}}{d I_C} = \frac{1}{g_m} \quad (14)$$

$$\therefore r_{be} = \frac{\beta}{g_m} \quad (15)$$

This is another vital BJT relationship. $d V_{BE}$, $d I_C$ and $d I_B$ are the small changes in the bias conditions and may be represented as small signal quantities, v_{be} , i_b and i_c .

$$r_{be} = \frac{\beta}{g_m} = \frac{d V_{BE}}{d I_B} = \frac{v_{be}}{i_b} \quad (16)$$

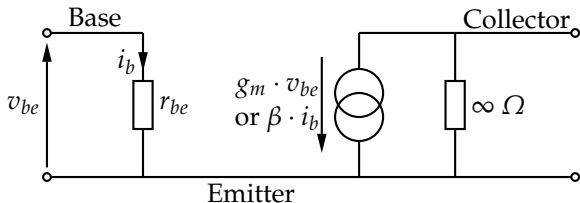
$$r_{be} = \frac{\beta}{g_m} = \frac{v_{be}}{i_b} \quad (17)$$

multiplying through yields,

$$g_m v_{be} = \beta i_b \quad (18)$$

This means that the BJT can be thought of as a device which accepts an input voltage and outputs a current (transconductance amplifier) or a device that accepts an input current and outputs a current (current amplifier). The choice of how one should think about it depends on the situation. Some circuits are easier to solve if the transistor is thought about in terms of a current amplifier and other circuits are solved more simply by considering the transistor a transconductance device. Only BJTs have the option of two avenues of thought. MOSFETs, JFETs and Valves can only be thought about in terms of transconductance.

Including the effect of a finite r_{be} in the small signal model yields,



- Usually $\beta \neq h_{FE}$. β is a small signal parameter and h_{FE} is a large signal parameter.
- β is sometimes called h_{FE} (notice the lower case subscripts). h_{fe} and β can be assumed equal at low frequencies
- Other circuit elements can be added to more accurately reflect real device performance e.g. the infinite resistance in parallel with the $g_m \cdot v_{be}$ generator is finite and is responsible for the gentle slope of the output characteristics in the forward active region.

Review

- Gave an example of calculation of circuit two's DC conditions.
- Discussed the design of biasing circuits
 - Noted that there is (almost) always some compromise required.
- Looked in detail at coupling and decoupling in the two bias circuits.
 - Coupling - signals in to or out of the circuit.
 - Decoupling - signals shorted to ground where they are unwanted.
- Developed a small signal model for the BJT / MOSFET / JFET / Valve.
 - Looked at the transconductance amplifier / current amplifier duality of BJTs.
 - Derived some key small signal relationships for BJT circuit from the transconductance characteristics.

