

**PHYSICS 3500/8800**  
**SUPPLEMENTARY MATERIAL:**  
**DESIGN OF TRANSISTOR AMPLIFIERS**

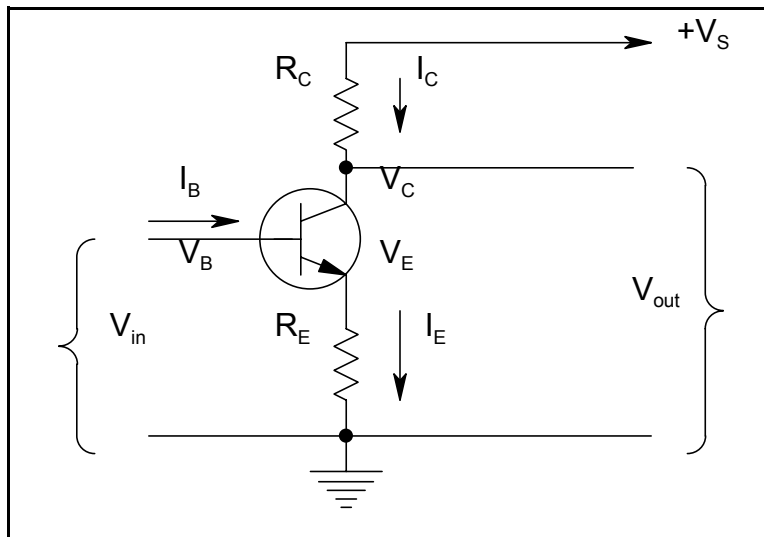
**Main Characteristic:** The primary characteristic of transistors is that the collector current ( $I_c$ ) is controlled by the base current ( $I_b$ ). To a first approximation, their ratio is constant, and is called "current gain", "forward current transfer ratio", or something synonymous. On most data sheets now the symbol  $h_{FE}$  is used to indicate the "DC current gain", and represents the ratio:

$$h_{FE} = I_c / I_b.$$

The similar symbol  $h_{fe}$  is used to represent the AC "small-signal current gain" which is the ratio of the *change* in collector current ( $\Delta I_c$ ) to the *change* in base current ( $\Delta I_b$ ):

$$h_{fe} = \Delta I_c / \Delta I_b.$$

For an "average" silicon transistor, both are approximately 100. (See the attached data sheets for the type 2222a transistors which you are using in lab.)



**Figure 1: "Basic Amplifying" section.**

**Transistors as Voltage Amplifiers:** To use transistors as voltage amplifiers it is necessary to use resistors to convert the "natural" current amplification into voltage amplification. The "basic amplifying unit" is sketched above, and consists of two resistors in addition to the transistor:

Analysis of the AC voltage amplification factor is as follows:

$$(1) \quad I_c = h_{FE} I_b$$

$$(2) \quad V_{in} = V_b = V_e + V_{be} \quad (V_{be} = 0.7V \text{ for Si})$$

$$(3) \quad V_e = I_e R_e$$

$$(4) \quad I_e = I_c + I_b = (h_{FE} + 1) I_b \approx h_{fe} I_b$$

$$(5) \quad V_{out} = V_c = V_s - I_c R_c = V_s - h_{FE} I_b R_c$$

For AC signals, the amplification is the **change** in the output ( $\Delta V_{out}$ ) resulting from a **change** in the input ( $\Delta V_{in}$ ):

$$(6) \quad A = \Delta V_{out} / \Delta V_{in}$$

In the expressions above, the supply voltage (V) and the base-emitter voltage ( $V_{be}$ ) are constants and do not change. Thus the **changes** are given by:

$$(7) \quad \Delta V_{out} = -\Delta I_b h_{FE} R_c$$

$$(8) \quad \Delta V_{in} \approx \Delta I_b h_{FE} R_e$$

Taking the ratio of these gives the AC voltage amplification as:

$$(9) \quad A \approx -R_c / R_e$$

The minus is the result of the way chosen for obtaining the output voltage in combination with the fact that **increasing** the input voltage **increases** the base current, and consequently **increases** the collector current. The result of increasing input is an increase in the voltage across the collector resistor; however, the output is taken as the **difference** between the supply voltage and this voltage. Thus, for this choice of output connections, **increasing** the input **decreases** the output, and *vice versa*. The advantage of this choice of connections is that the power supply common (or "ground") is also one connection for both input and output signals.

**Base "Bias" Resistors:** In order for the transistor to behave as described above, it is necessary for base and collector current to exist, **even when no signal is present**. The idea is that the effect of the AC signal is to cause a change in the base current, and a corresponding change in the collector current. In order to establish the no-signal (or "quiescent") currents, it is necessary that the base-emitter junction be forward biased. To do so, additional resistors (bias resistors) are used as sketched below. The result is that the "standard" transistor (common-emitter) amplifier circuit consists of the transistor and four resistors.

The purpose of the bias resistors is to provide the base current, and the necessary base voltage. As is seen in the sketch, the resistors act as a "voltage divider". From the currents indicated, it is obvious that  $I_{R_{b1}}$  must equal or exceed the necessary base current. Although  $R_{b2}$  does not appear to be necessary, it is desirable in order to stabilize the currents. Finally, one piece of information other than the necessary  $I_b$  and  $V_b$  values is necessary for obtaining specific values for the bias resistors.

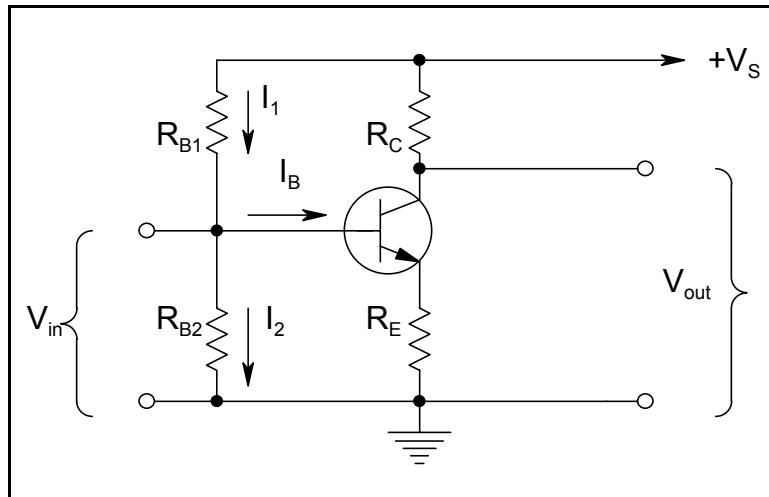


Figure 2: The “standard” transistor amplifier

**Choosing “Suitable” Resistor Values:** The overall design problem consists of making appropriate calculations for selecting “appropriate” values for the four resistors. In order to select specific values for the resistors, several *considerations* must be made, as listed below.

1. **Amplification factor:** This determines  $R_c/R_e$ , but does not give specific values for either. To obtain specific values two approaches may be used:
  - a. **Choose** a specific  $R_c$ . This is the approach necessary when the output resistance of the circuit is a design target.
  - b. **Choose** a specific  $I_c$ . From this,  $R_c$  can be calculated as:

$$R_c = (V_s - V_c) / I_c = V_s / 2I_c$$

2. **Maximum symmetrical voltage swing:** The AC output is the *change* in  $V_c$ . However, the greatest  $V_c$  can be is the supply voltage  $V_s$ , and the least it can be in 0. Therefore, in order that the output be able to both up and down the greatest amount, **it is wise** to choose the no-signal conditions so that  $V_c$  is one-half the supply voltage when no signal is applied. This consideration leads to a “target” value for  $V_c$ . In addition, the target for  $V_c$  in combination with a chosen value for  $R_c$  yields the necessary  $I_c$  mentioned above in **1b**.
3. **Forward bias:** In order for  $I_b$  and  $I_c$  to exist,  $V_{be}$  must be the appropriate value (0.7v for Si).  $V_e$  is determined by the collector current and  $R_e$  as follows:

$$(a) \quad V_e \approx I_c R_e,$$

$$(b) \quad I_c = (V_s - V_c) / R_c, \text{ but by (2)}$$

$$(c) \quad (V_s - V_c) = V_s/2, \text{ thus}$$

$$(d) \quad I_c = V_s/2R_c, \text{ and}$$

$$(e) \quad V_e \approx VR_e / 2R_c = V_s / 2A$$

Therefore, the bias resistors  $R_{b1}$  and  $R_{b2}$  must be chosen so that

$$(f) \quad V_b = V_{be} + V_s / 2A$$

4. **Bias Resistors:** Several possible approaches may be taken to calculating specific values for the bias resistors:

a. **Select  $R_b$ 's so that  $R_{b1} // R_{b2}$  meets a specified value.** This approach is one way to meet the requirement of the input resistance being a specified value. From the // equivalent specification, and from the  $V_b$  needed, it is possible to calculate the R's. However, it is necessary to check for suitable currents. For example,  $I_{Rb1}$  must equal or exceed the necessary  $I_b$ . This is one approach to obtaining a specified input resistance. This will be illustrated in the example below. (This method is the one to use when there is a "target" value of  $R_{in}$  to meet.)

b. **Choose the  $R_b$ 's so that  $I_{Rb2} \approx I_b$ .** The procedure is the same as (a), except that the current values are now:

$$i. \quad I_{Rb1} = 2I_b$$

$$ii. \quad I_{Rb2} = I_b$$

The advantage of this approach is that the  $R_b$ 's are larger than in (a), which is useful when the **input resistance** of the circuit must be maximum. However, it is more sensitive to **device variations** than (a).

c. **Choose the  $R_b$ 's so that  $I_b \ll I_{Rb1}$  ( $I_{Rb1} \approx 10I_b$  is probably enough).** In this case  $I_b$  can be ignored, as can the difference in the two  $I_{Rb}$ 's, and the  $R_b$ 's calculated as follows:

$$i. \quad I_b = I_c/h_{FE}$$

$$ii. \quad I_{Rb1} \approx I_{Rb2} = 10 I_b$$

$$iii. \quad R_{b1} = (V_s - V_b) / I_{Rb1}$$

$$\text{iv. } R_{b2} = V_b / I_{Rb2}$$

The advantage of this approach is that the actual value of  $I_b$  needed is dependent on the value of  $h_{FE}$ . By choosing the  $R_b$ 's so that the actual  $I_b$  is negligible, the circuit is less dependent on variations from one transistor (of the same type) to another. The disadvantage is that the effective input resistance of the amplifier ( $R_{in}$ ) will be lower than that obtained with the other procedures above.

**EXAMPLE of Procedure 4a:**

Design an amplifier circuit with the following specifications:

$$A \geq 10 \quad \text{Assume: NPN; Si; } h_{FE} \approx 100; V_s = 20V$$

$$R_c \leq 2k$$

$$R_{b1} // R_{b2} \geq 12k$$

1.  $A \rightarrow R_c = 10R_e$
2.  $R_c \leq 2k \rightarrow R_c = 2k; \rightarrow R_e = .2k = 200\Omega$
3.  $V_s = 20V \rightarrow V_e = 1V \rightarrow V_b = 1.7V$
4.  $V_{Rb2} = V_b = 1.7V; V_{Rb1} = 18.3V$

$$(I_{Rb1} = I_{Rb2} + I_b; I_b \approx I_c / h_{FE})$$

**Trial and Error Procedure:** Choose  $R_{b2} = 20k$ ; from the // requirement ,  $R_{b1} \geq 30k$ ; from the  $V_b$  requirement  $I_{Rb2} = 1.7V/20k = 85\mu A$ ; from  $V_c$  and  $R_c$ ,  $I_c = 5mA \rightarrow I_b \approx .05 mA = 50\mu A$ ; Thus,  $I_{Rb1} = I_b + I_{Rb2} \approx 135\mu A$ ;  $R_{b2} = V_{Rb2} / I_{Rb2} = 18.3 / .135mA \approx 136k$ . All values are consistent with the required // R's, the necessary I's, and the amplification.

**RESULT:**  $R_e = .2k = 200\Omega$   $R_{b1} = 136k$

$$R_c = 2k \quad R_{b2} = 20k$$

**Exact Procedure:** By Kirchoff's laws, the following relations apply:

$$1. \quad V_b = V_s - I_{Rb1} \times R_{b1}$$

$$2. \quad V_b = I_{R_{b2}} \times R_{b2}$$

$$3. \quad I_{R_{b1}} = I_{R_{b2}} + I_b,$$

and the requirement on the biasing resistors is:

$$4. \quad R_{b1} // R_{b2} = R_{b1} \times R_{b2} / (R_{b1} + R_{b2}) = R$$

The known values are  $V_b$ ,  $V_s$ ,  $I_b$ , and  $R$ ; the unknowns are  $I_{R_{b1}}$ ,  $I_{R_{b2}}$ ,  $R_{b1}$ , and  $R_{b2}$ . The algebraic solutions for  $R_{b1}$  and  $R_{b2}$  are:

$$R_{b1} = R \times V_s / (V_b + R \times I_b)$$

$$R_{b2} = R \times R_{b1} / (R_{b1} - R)$$

Thus, for the numbers above ( $R = 12k$ ;  $V_b = 1.7V$ ;  $V_s = 20V$ ;  $I_b = 50 \mu a.$ ):

$$R_{b1} = 104.35k$$

$$R_{b2} = 13.56k.$$

**N.B.:** Before getting too excited about this as an “exact” procedure, remember that the  $I_b$  value is necessary, and it is highly approximate owing to its non-linearity and the wide variation in  $h_{fe}$  values for different transistors of the same type. Thus, the term “exact” is quite misleading! *In summary*, the “trial and error” procedure is at least as sensible as the “exact” approach in terms of the amount of computation and the “exactness” of results.