PH-315 Winter 2009 **A. La Rosa**

EXPERIMENT 3

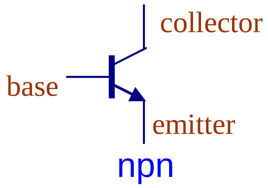
TRANSISTORS AMPLIFIERS

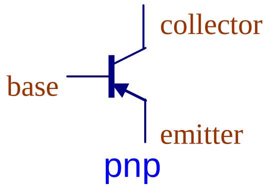
I. PURPOSE

To familiarize with the characteristics of transistors, how to properly implement its DC bias, and illustrate its application as small signal amplifiers.

II. THEORETICAL CONSIDERATIONS

First transistor model: current amplifier

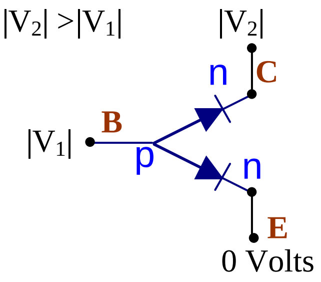


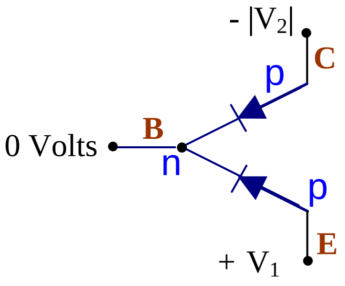


Transistor is a 3-terminal device: emitter, base, collector.

They are available in two flavors: npn and pnp

Diode model: An initial understanding of the transistor can be obtained considering the base-emitter and the base-collector as diodes.





In that context, let's analyze in more detail the **npn transistor**.

- Consider first the **emitter-base diode**.

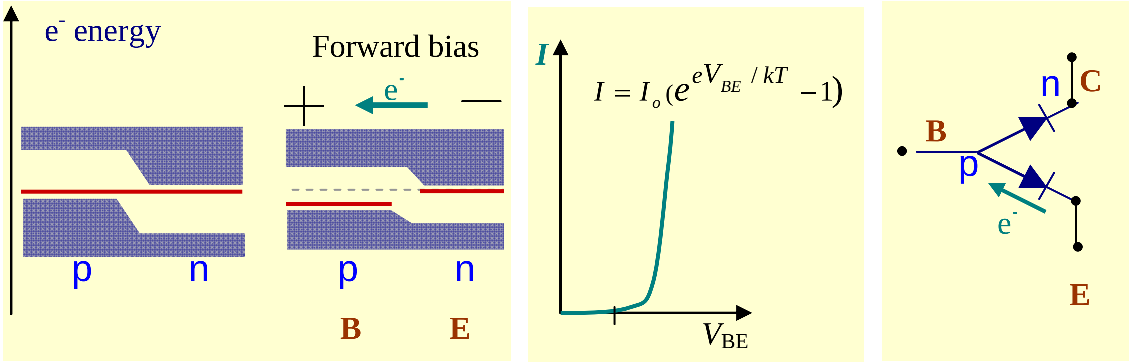


Fig. 1 Left: Energy band diagram of the (base-emitter) pn junction under equilibrium (a barrier exist for the electrons to cross from the n-region to the p-region) and under forward bias (the barrier is lowered and a bias current is established.) **Center:** The forward bias current depends critically on the base-emitter voltage. **Right:** When the base is lightly doped base the net bias current is mainly constituted by electrons (majority carriers) from the n-doped emitter.

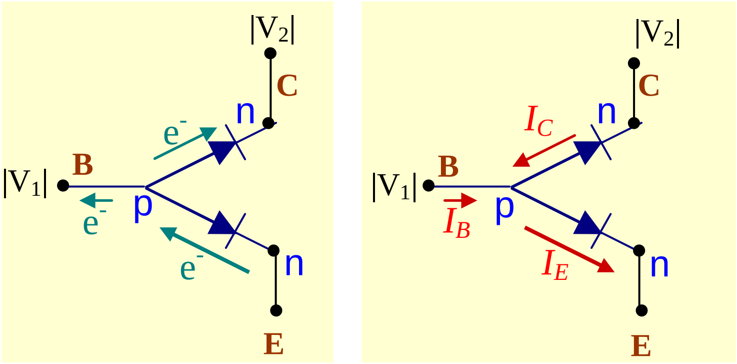


Fig. 2 Left: Injection of majority carriers from the emitter. A relatively small numbers reaches the base but most are swept towards the collector. **Right:** Equivalent picture of the left diagram, but in terms of the more formal currents.

The p region is made lightly doped, thus the forward current is constituted mainly by electrons (majority carriers) from the n-doped emitter.

The p region is also made very thin (~ 0.5 μm) so that few arriving electrons are lost by recombination with the host holes at the base.

The arriving electrons implicitly become **minority carriers** in the host p-region; subsequently they move to the collector by diffusion. (The finite time taken by the minority carriers to cross the base limits the high-frequency response of the transistor.)

- The **base-collector diode**.

  Since |V$_2$ | > |V$_1$ |, the latter being of the order of 0.7 V, this diode is **reversed biased**. Thus, the role of the V$_{BC}$ voltage is just to sweep the charges that, after arriving from the emitter to the base, diffuse to the collector.

  For this reason, it is found that the collector current varies very little with the collector voltage.

When the transistor is properly electrically biased, the net result is:

I_C is roughly proportional to I_B

$$I_C = \beta I_B \qquad (1)$$

The so called current gain β is typically about 100.

(β is not a good transistor parameter; its value can vary from 50 to 250. It also depends on the collector current, collector-to-emitter voltage, and temperature.)

This represents the usefulness of the transistor. A small current into the base controls a much larger current flowing into the collector. That is, the transistor is a current amplifier.

III. EXPERIMENTAL CONSIDERATIONS

III.1 Transistor's characteristic curves. Current gain α and the β value
III.2 DC bias circuit and the operating point
III.3 Small signal amplifier

III.1 Transistor's characteristic curves. Current gain α and the β value

We will use general purpose transistors: 2N 2222, 2N 3906, or the npn 2N **3904**.

Use a npn transistor and setup the circuit indicated in the figure below. Select R$_B$ and R$_C$ such that I_C fall in the range of mA, and I_B in the order of 5 μA to 200 μA. The suggested use of variable resistors is for you to be able to do the proper changes as to keep the I_B constant while obtaining the trace of one of the current collector curves.

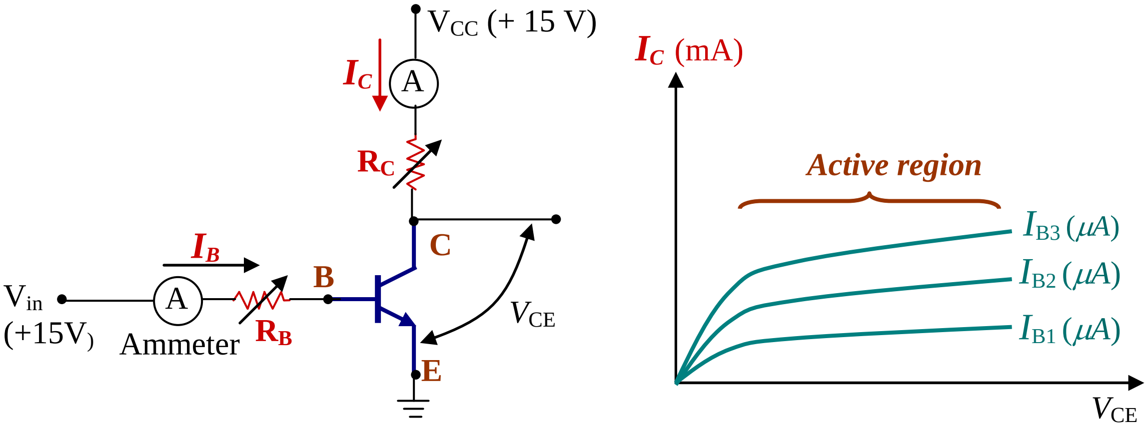


Fig. 3 Grounded-emitter setup for obtaining the collector current characteristics. I_B is approximately constant across the active region.

TASK: Estimate the experimental value of the transistor current gain

$$\alpha \equiv \frac{i_C}{i_E}. \tag{2}$$

Keep in mind that usually the current gain is described in terms of the β value of the transistor, the latter being defined as,

$$\beta \equiv \frac{i_C}{i_B} = \frac{i_C}{i_E - i_C} = \frac{\alpha}{1-\alpha} \tag{3}$$

III. 2 DC bias circuit and the operating point

Given the transistor curves characteristics, our objective is to bias the transistor properly as to make it function around a given operating point inside the active region (point P in the diagram below, for example.) The procedure will help us understand **how the output voltage depends on the input voltage**.

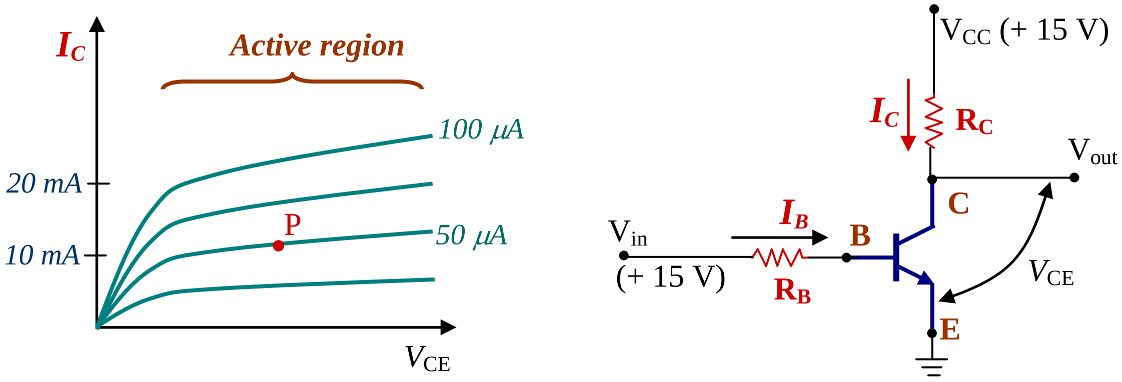


Fig. 4 Given the collector current characteristics. R_C and R_B should be selected to have the transistor operating around the point P in the active region.

How to choose R_C? (Load line analysis)

Even though we do not know I_C neither V_{CE} a relationship between them can be obtained through the Kirchhoff's law applied to the right side branch of the circuit above (and reproduced below for convenience.); $15V - I_C\ R_C - V_{CE} = 0$, which leads to,

$$I_C = \frac{15V}{R_C} - \frac{1}{R_C} V_{CE} \qquad (I_C \text{ decreases linearly with } V_{CE}.)$$

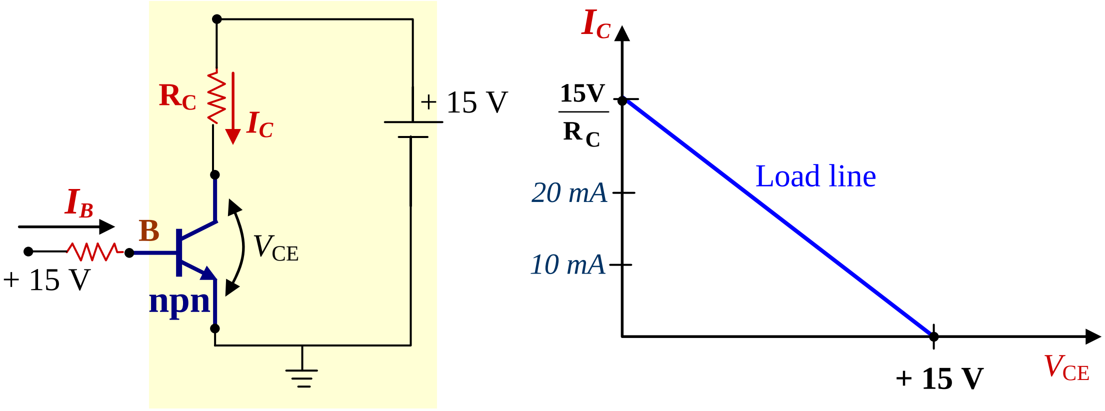


Fig. 5 Application of the Kirchhoff law to the right-side branch of the circuit gives a relationships to be satisfied by I_C and V_{CE}.

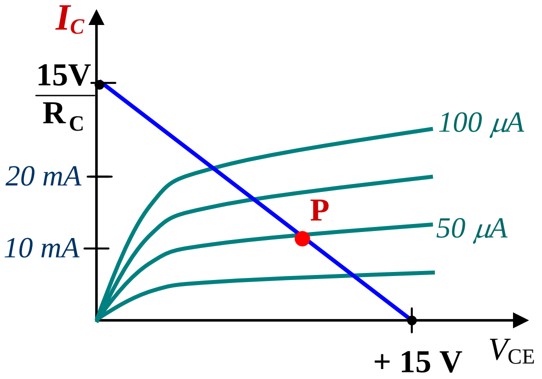


Fig. 6 Load line superimposed with the transistor characteristic curves.

If we want to work with, for example, a current base of 50 μA, many values of Rc are possible. Still, there is a restriction to be satisfied, which is not to exceed the transistor's heat dissipation tolerance. For example, the data sheet may specify,

$$V_{CE;\,max}\ I_{CE;\,max} < 350 \text{ mWatts}$$

Applying this condition to our case, one obtains

$$(15\text{ V})\ (\ 15\text{ V}/R_C\ ) < 350 \text{ mWatts}$$

Thus, in this case, a resistor $R_C > 1$ KΩ would be good enough

How to choose R_B?

Since we want to operate the transistor at the point P, that is a current base of 50 μA, all we have to do is to choose an R_B that allows delivering a current of that magnitude

$$R_B \sim \frac{15V - 0.7V}{50\ \mu A}$$

which takes into account that, when operating in the active region, the base voltage is about 0.7 V (for silicon transistors.)

The operating point **P** results then from the intersection of the load line and the transistor curve corresponding to 50 µA.

How the output voltage depends on the input voltage

Instead of using a fixed V_{in} voltage, vary its value a bit as to produce slightly different base currents. The diagram below helps illustrate the expected variation of the V_{CE} voltage.

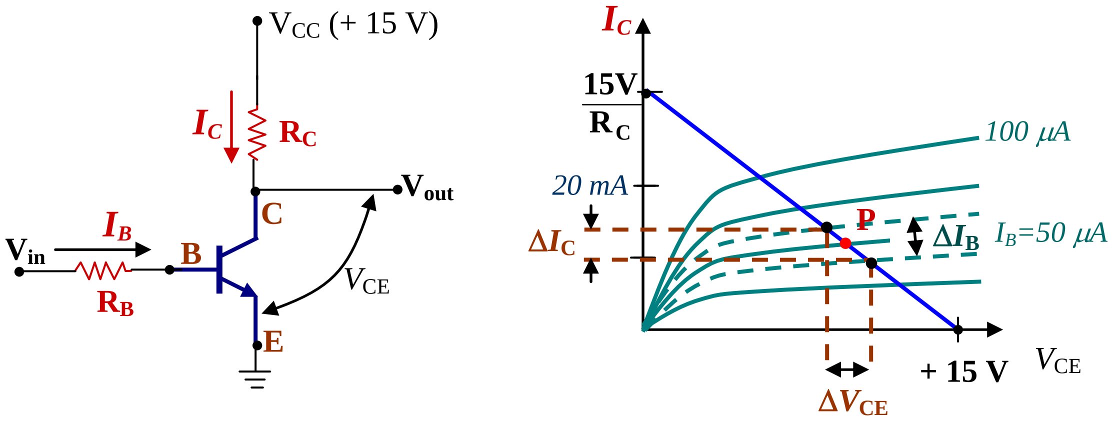


Fig. 6 Small variations of I_B moves the operating point **P** along the load line, causing a variation of V_{CE} (and, correspondingly, a variation in I_C.)

TASKS:
Make a plot of V_{out} vs V_{in}
(Notice, in this case, $V_{out} = V_{CE}$)

Verify that the plot looks like the graph shown in the figure at the right.
From this experimentally obtained graph, evaluate the voltage gain: $\Delta V_{out} / \Delta V_{in}$

NOTE: Notice from figures 6 and 7, that the greater V_{in}, the greater I_B, the greater I_C and greater drop of voltage across R_C, the lower V_{CE} (output voltage.) Thus, small variations of the input voltage around a given value, will be 180° out of phase with the output voltage.

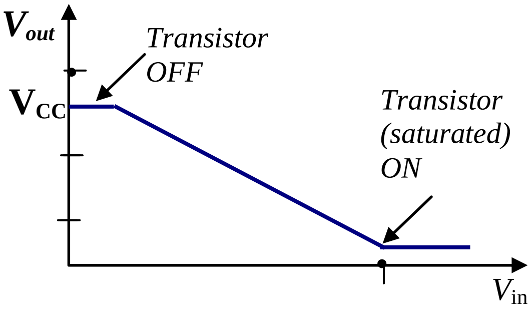


Fig. 7 The greater V_{in}, the greater I_B, the greater I_C and greater drop of voltage across R_C, the lower V_{CE} voltage.

III.3 Small signal amplifier

Very frequently the signal amplitudes applied to a transistor amplifier are small compared with the full range of voltages covered by the transistor curve characteristics.
A small-signal amplifiers must have:
- a dc bias circuit for placing the transistor in its amplifying region
- a mean for introducing the input signal
- a mean for supplying its output signal to the next stage.

The circuits used in the previous section deal with the first two aspects. But, as it turns out, such circuits are very sensitive to temperature variation. For that reason, they will be modified a bit, but their equivalence with our older circuit will become transparent in the course of the discussion.

III.3.A Modified DC-bias Circuit

The simple bias circuit in Fig. 6 above is generally not satisfactory because the operating point shifts drastically with temperature.)

A more satisfactory transistor bias is obtained when using a voltage divider, as shown in Fig. 8.

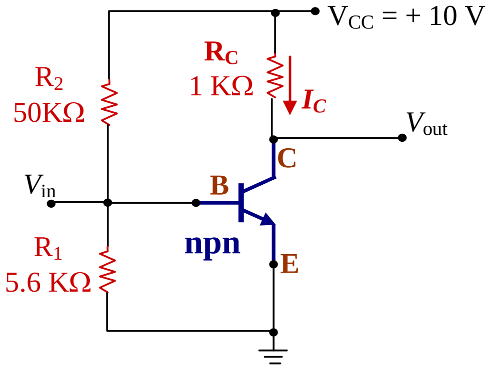


Fig. 8 DC bias circuit.

TASK: Construct the circuit shown in Fig. 8.

Thevenin equivalent circuit

We can use the Thevening's theorem to show the equivalence between the circuits in Fig. 6 and Fig. 8. This is made more evident by re-drawing Fig. 8 as shown in Fig. 9 below.

The Thevenin voltage V_{BB} is the open circuit voltage (across XY in the circuit) $V_{BB} = \dfrac{V_{CC}}{R_1 + R_2} R_1$.

R_{B} designates the Thevenin equivalent series resistance

The short circuit currents are V_{CC}/R_2 and $V_{\mathrm{BB}}/R_{\mathrm{B}}$ respectively. Hence, $R_B = \dfrac{R_2}{V_{CC}} V_{BB}$, or

$$R_B = \frac{R_2 R_1}{R_1 + R_2}$$

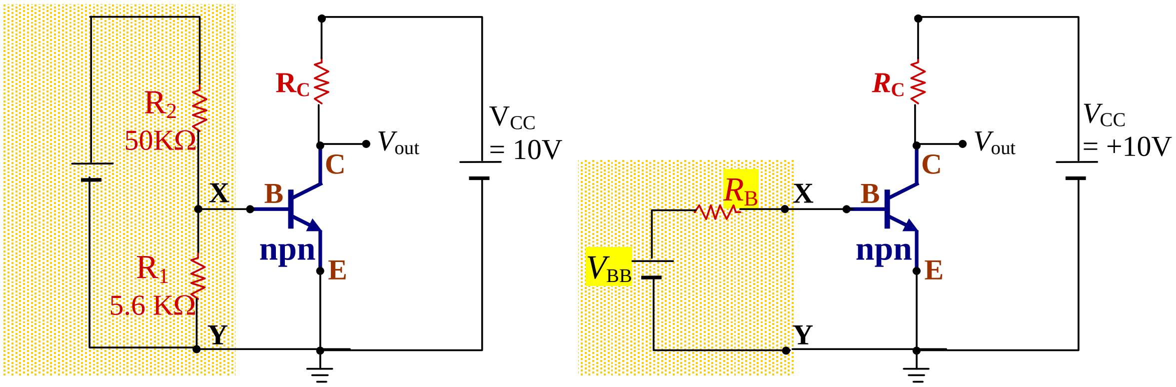


Fig. 9 DC bias circuit and its Thevenin equivalent. The latter helps to calculate the different parameters associated to the intended operating point of the transistor (using the analysis described I the previous section) based on the values of R_1 and R_2.

TASK: For the final values that you use for R_1 and R_2 calculate V_{BB} and R_{B}.

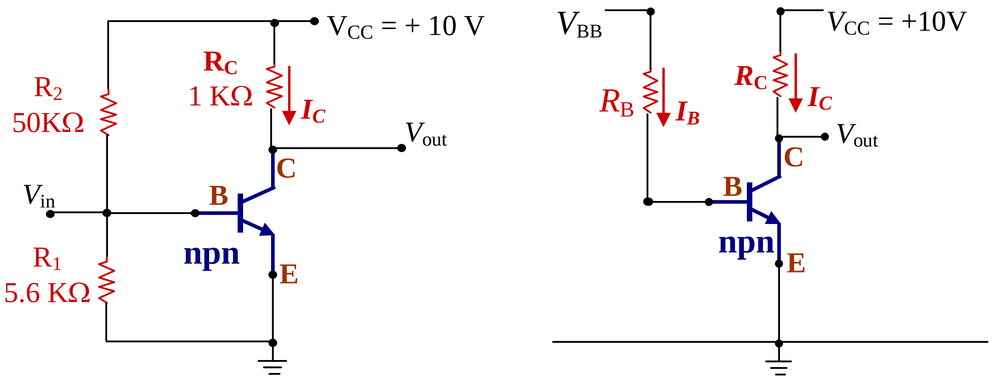


Fig. 10 Equivalent representation of the circuits in Fig. 9.

III.3.B Connecting to an oscillator

If the oscillator is connected directly across V_{in}, it may change the bias level and/or draw some current away from I_b. It is normally better to put a capacitor (1μf should be sufficient) in series with the oscillator to block the flow of DC current -- as long as the frequency is not too low the capacitive reactance should be small with respect to the resistances involved.

TASK: Couple a small sinusoidal signal into the circuit shown in Fig. 11 (Left diagram).

Monitor the input and output signals in the oscilloscope.

Measure the voltage amplification, as well as the relative phase between the input and output voltage.

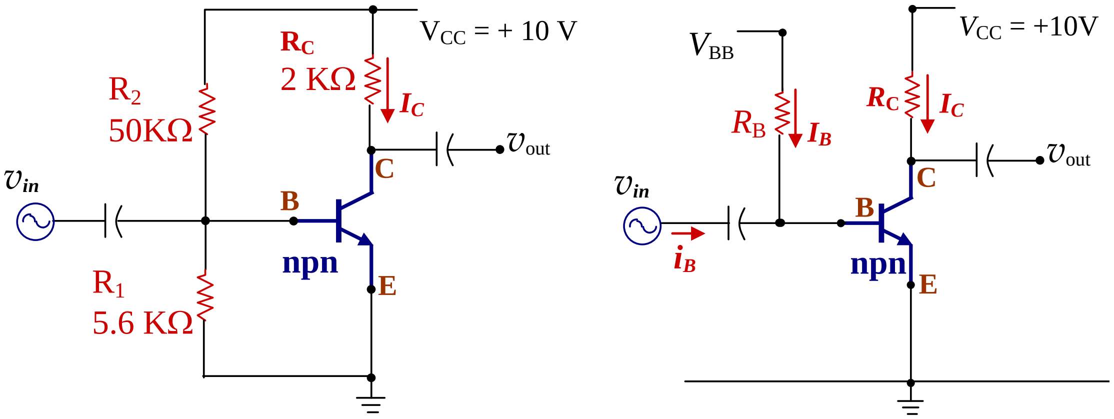


Fig. 11 Left: Small signal amplifier circuit. **Right:** Equivalent circuit, which helps to differentiate the additional (AC) base current injected by the signal generator from the DC base current established by the bias circuit.