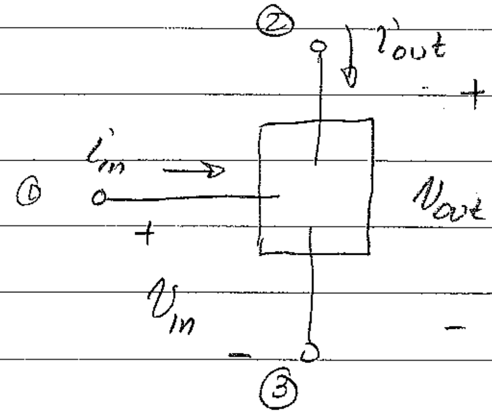
BIPOLAR JUNCTION TRANSISTORS

The BJT is a 3-terminal device, which is useful for two very important applications.



SWITCHING: We can arrange this device so that if we apply the correct input (i_{in} or v_{in}) we get a desireable output (i_{out} or v_{out}). Thus we have a switch ⇒ we can have digital logic and memory circuits

AMPLIFICATION: We can arrange it so that a small change in the input (i_{in} or v_{in}) causes a large change in the output (i_{out} or v_{out}). That is, we can have

$$\frac{\Delta i_{out}}{\Delta i_{in}} \gg 1 \quad \text{or} \quad \frac{\Delta v_{out}}{\Delta v_{in}} \gg 1.$$

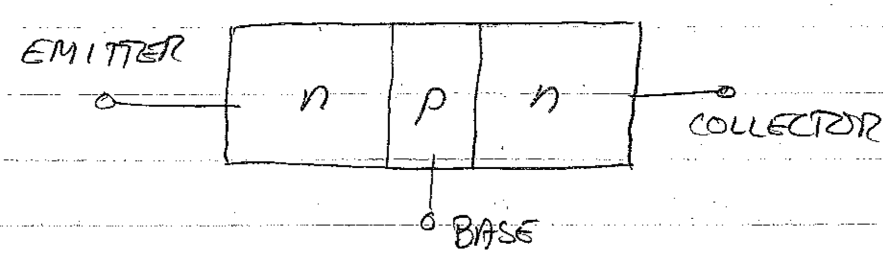
There are two major classes of 3-terminal devices:

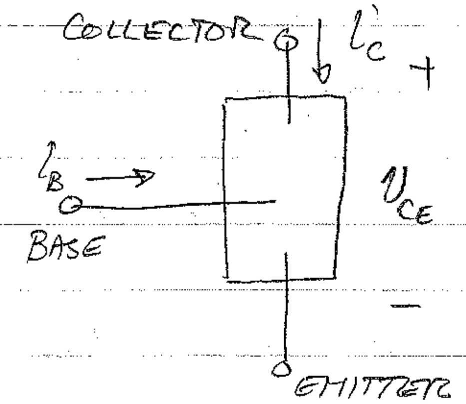
FIELD EFFECT TRANSISTORS (FET)

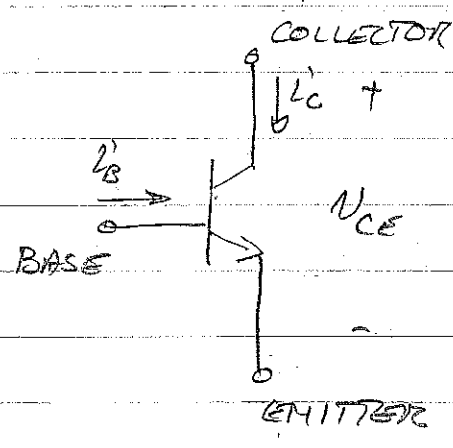
- Metal-Oxide-Semiconductor FET (MOSFET)
- Junction FET (JFET)

BIPOLAR JUNCTION TRANSISTORS (BJT)

npn BJT



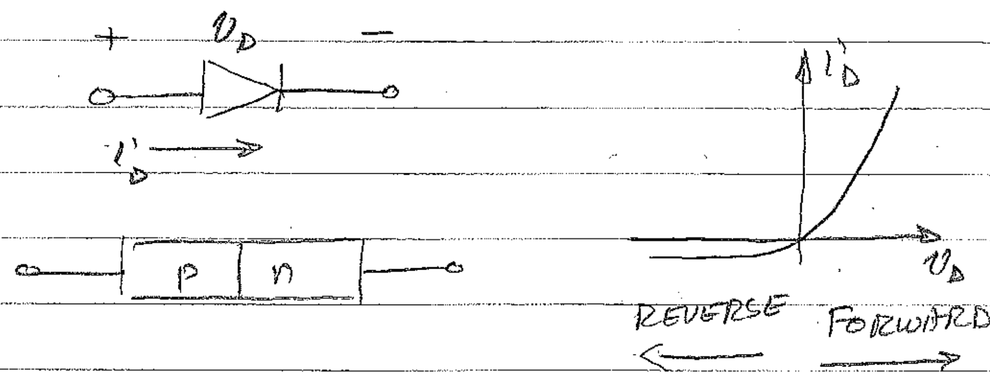




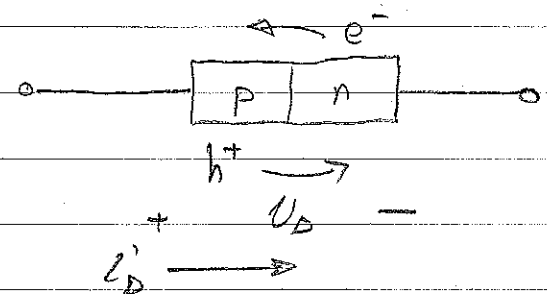
We may also make a pnp BJT.

DIODE BIASING

In thinking about BJT operation, it will be useful to recall diode biasing:

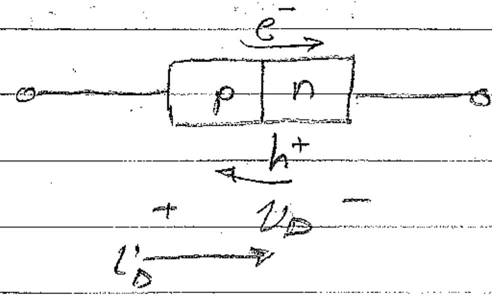


FORWARD BIAS



- $v_D > 0$, $i_D > 0$
- electrons flow $n \to p$, holes flow $p \to n$
- p-side is positive with respect to n-side

REVERSE BIAS

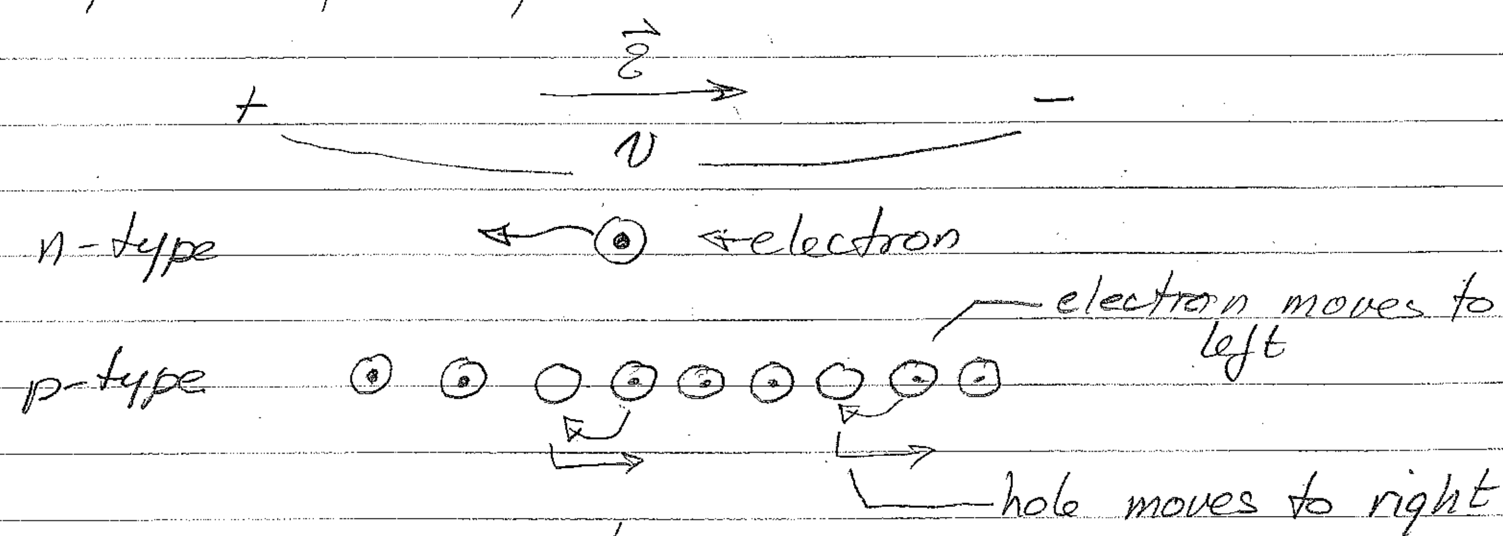


- $v_D < 0$, $i_D < 0$
- electrons "pulled back" to n-side, holes "pulled back" to p-side
- p-side negative with respect to n-side.

Holes ?? Electrons, too ??

In "n-type" semiconductors (such as Si), electrons are responsible for current flow. A semiconductor is made n-type by adding chemical impurities (n-type "dopants") to it. These impurities provide large numbers of electrons

It is also possible to make "p-type" semiconductors (by adding p-type impurities). In these materials it is convenient to think of current as being carried by holes, which are missing electrons (and thus positively charged).



v ≡ applied voltage

$\vec{\mathcal{E}}$ ≡ electric field

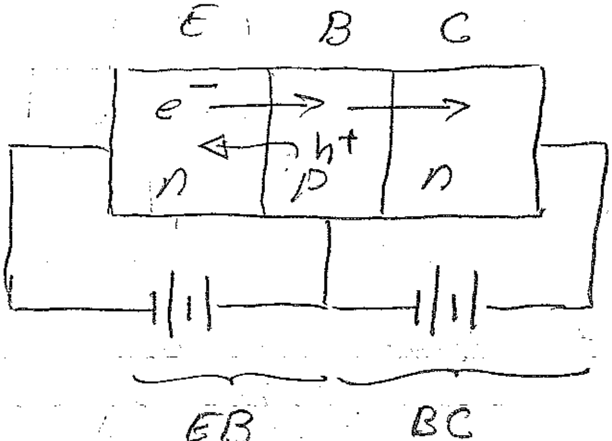
⊙ ≡ electron

○ ≡ hole

BJT: This device can be thought of as two pn junction diodes:

We have "npn" and "pnp" BJTs. Each type has an EMITTER (E), BASE (B), and COLLECTOR (C).

Since there are two pn junctions, each of which can be forward or reverse-biased, there are four possible "states". Consider the npn...

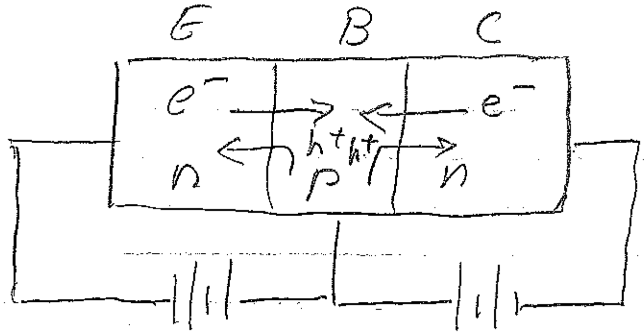


EB diode is FORWARD biased

BC diode is REVERSE biased

This is the LINEAR REGION or ACTIVE REGION. It is the biasing arrangement we require for AMPLIFICATION.

Electrons are emitted into the base and flow into the collector.

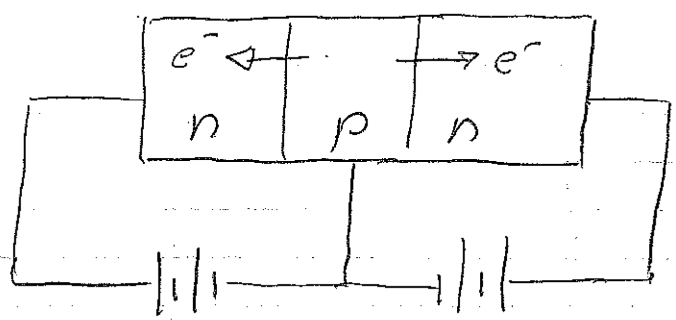


EB: FORWARD

BC: FORWARD

This is the SATURATION REGION. Electrons are emitted from the emitter, and from the collector, into the base because both junctions are forward biased.

SATURATION ⇒ the base region is saturated with electrons.

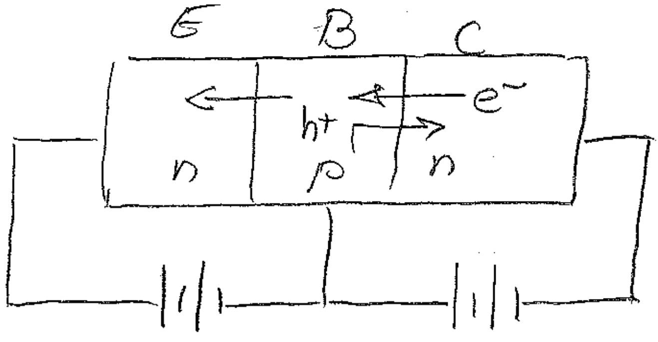


EB: REVERSE

BC: REVERSE

In CUTOFF, both junctions are reverse-biased. There is a very small reverse-bias current flowing in both junctions. To a good approximation, all currents are zero.

In DIGITAL LOGIC or SWITCHING applications, BJTs are either in saturation ("ON") or CUTOFF ("OFF").



EB: REVERSE

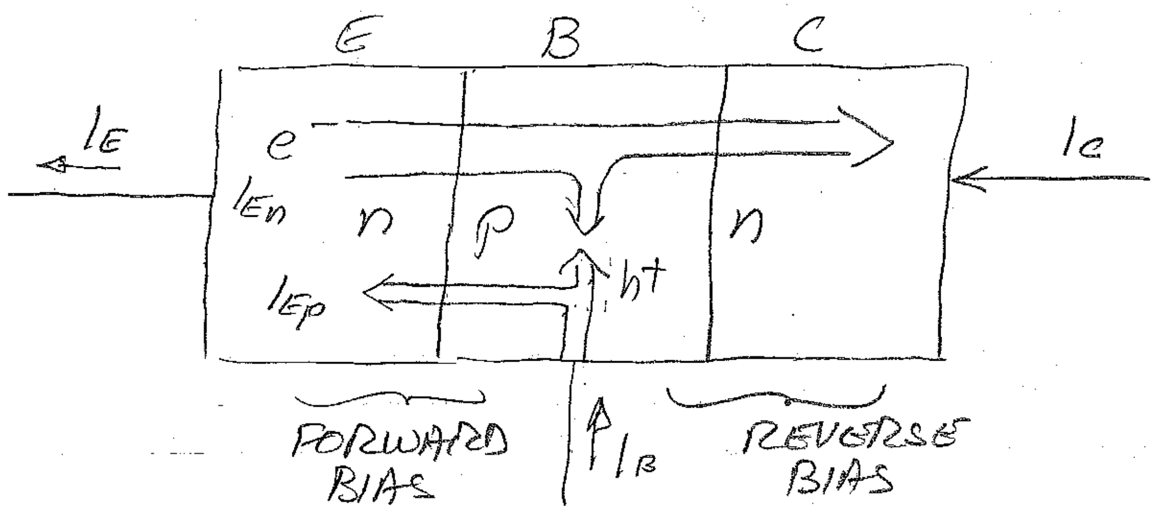
BC: FORWARD

This is REVERSE-ACTIVE region. Electrons now come from the collector, and flow through the base to the emitter.

Although this is simply the reverse of the active region, it is not useful for amplification because the gain here is very small. This is because the BJT is not symmetric: it is designed for high current gain in the active region, which gives it low current gain in reverse-active.

We will not use the reverse-active mode very often.

We look at the LINEAR region for an npn BJT in more detail. An analysis of current flow will allow us to see that current gain is possible.



EMITTER: The emitter current has two components: electron flow into the base, and hole flow from the base:

$$I_E = I_{En} + I_{Ep}$$

BASE: Some of the electrons flowing through the base get lost due to "recombination" of an electron and a hole:

The electron and the hole are both lost in the recombination process. The holes must be replaced by current flow at the base contact.

Note that there are two principal base current components: the recombination current and the flow of holes into the emitter. To find base current we use Kirchhoff's current law:

$$I_B = I_E - I_C$$

<u>COLLECTOR</u>: Not all of the electrons make it through the base (some are lost to recombination). So we write

$$I_C = \alpha I_{En}$$

$\alpha \equiv$ BASE TRANSPORT FACTOR. If most of the electrons make it to the collector, $\alpha \lesssim 1$.

Define EMITTER INJECTION EFFICIENCY

$$\gamma = \frac{I_{En}}{I_{En} + I_{Ep}}$$

GAIN: If our input is the base current and our output is the collector current, then current gain is

$$\beta \equiv \frac{I_C}{I_B}$$

So...

$$\beta = \frac{I_C}{I_B} = \frac{\alpha I_{En}}{(I_{En}+I_{Ep}) - \alpha I_{En}}$$

$$= \frac{\alpha \gamma}{1 - \alpha \gamma}$$

Now if $\alpha \approx 1$ and $\gamma \approx 1$, β is very large, so we can have large current gain! But how do we get $\alpha \approx 1$ and $\gamma \approx 1$?

α: If we reduce the width of the base as much as possible, recombination current will be small (electrons won't have time to get lost!)

γ: If we reduce I_{Ep}, $\gamma \to 1$. This is done by increasing the number of n-type impurities in the emitter!

(Basic semiconductor device physics tells us that

$$I_{Ep} \propto \frac{1}{N_E}$$

where N_E is the number of n-type impurities in the emitter.)

[The fact that N_E is large and N_C (# of impurities in the collector) is not is what makes the BJT assymmetric. We make N_C small to increase the breakdown voltage of the BC junction.]

NOTE: Many electronics texts (including SEDRA/SMITH) assume that $\underline{\gamma \equiv 1}$. Then

$$\beta = \frac{\alpha}{1-\alpha}$$

$$\Longrightarrow \qquad \alpha = \frac{\beta}{\beta+1}$$

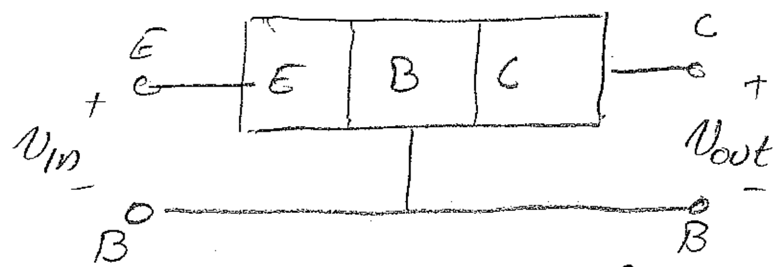
We could have done the same sort of analysis for pnp...

AMPLIFIER CONFIGURATIONS

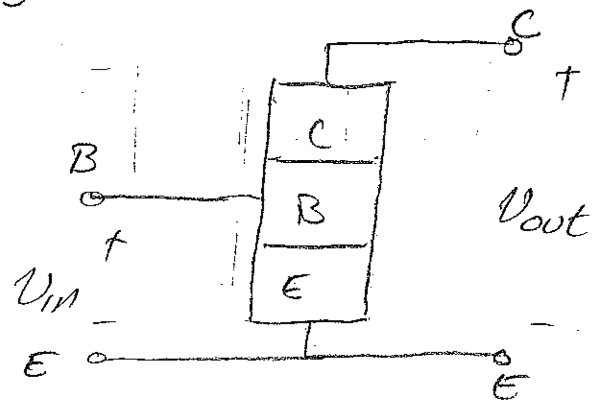
Since the BJT has three terminals, and since two each are required for input and output, there are three possible configurations:

FIGS, 10-3, 10-4 PIERRET ‡

COMMON BASE:

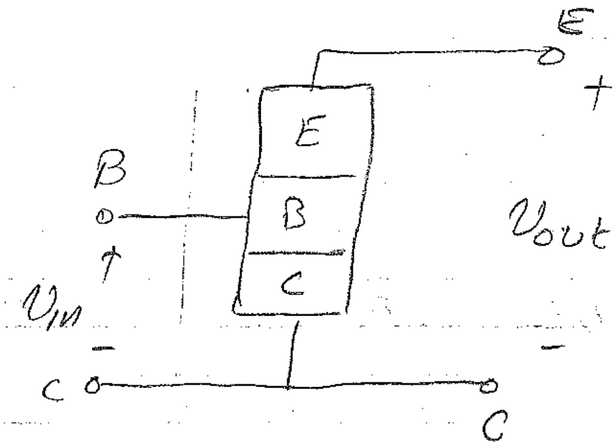


COMMON EMITTER



‡ R. Pierret, "Semiconductor Device Fundamentals", Prentice Hall, 1996

COMMON COLLECTOR:



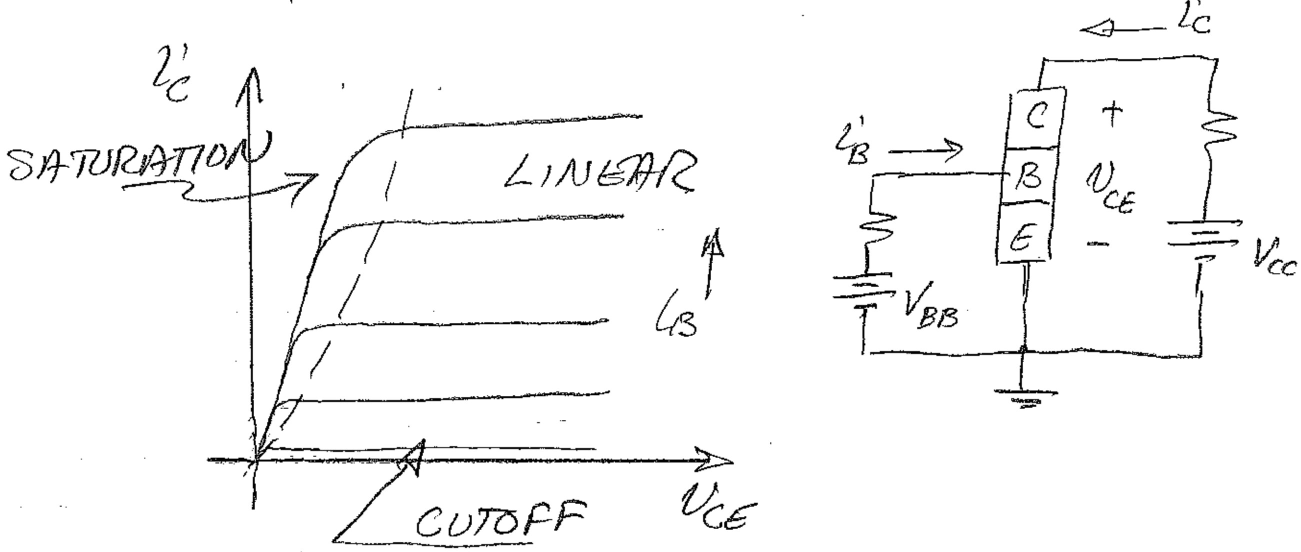
As amplifiers, each of these configurations has different properties: Z_{in}, Z_{out}, A_V, A_I.

We will look at these configurations a bit more later.

BJT CHARACTERISTIC CURVES AND OPERATING REGIONS

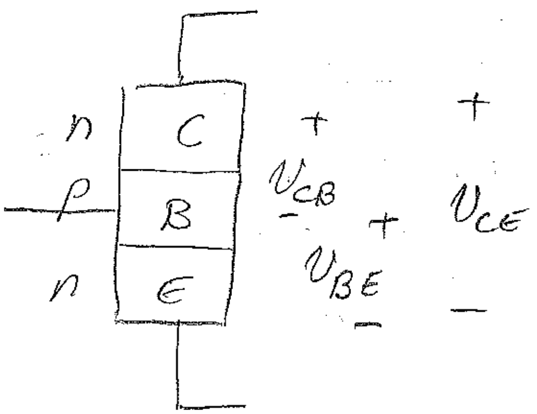
In discussing operating regions it will be convenient to look at the common emitter configuration. In particular we examine the $i_C - v_{CE}$ curves:

FIG 10-5 PIERRET



The figure shows a "family" of $i_C - v_{CE}$ curves. Each curve corresponds to a different value of i_B. We can think of i_B as an input, which determines the particular $i_C - v_{CE}$ curve.

We restrict our attention here to CUTOFF, LINEAR, and SATURATION regions. We assume an npn BJT



$$v_{CE} = v_{CB} + v_{BE}$$

LINEAR REGION

Biasing: BE forward biased

$\Rightarrow v_{BE} \approx 0.6$ V

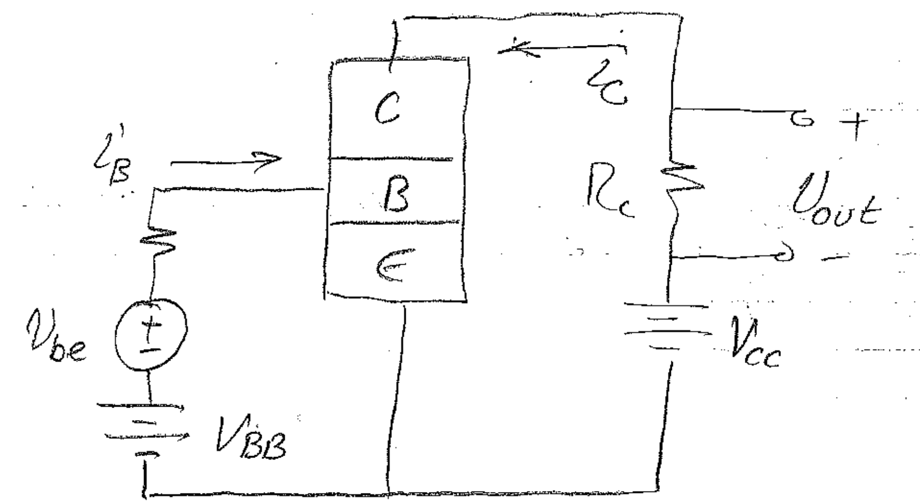
BC reverse biased

$\Rightarrow v_{CB} >> 0$

In this region v_{CE} is relatively large and positive.

The linear region is used for amplification. The signal can be applied as a base current, as shown below.

Changing v_{be} causes a change in i_b – this is the input signal. A change in i_b causes a larger change in i_c – this is the output signal, and $\beta \equiv i_c/i_b >> 1$.



$$i_B = i_b + I_B \qquad\qquad i_C = i_c + I_C$$

I_B, I_C are the dc biasing current established by V_{BB} and V_{CC}. The ac signal input is i_b and the ac signal output is i_c.

We can also take v_{out} as our output. Depending on the configuration, we can have

$$A_v \equiv v_{out}/v_{be} >> 1$$

that is, we can have a voltage gain.

CUTOFF

If we reduce i_B to ~ 0, BE will no longer be forward biased. With both junctions reverse biased, all currents become 0.

SATURATION

Suppose we have a fixed i_B but begin to reduce v_{CE} to something small, say $v_{CE} \simeq 0.2$ V. As long as BE remains forward biased, we have

$$v_{CE} = 0.2 = v_{BE} + v_{CB}$$

$$= 0.6 + v_{CB}$$

$$\Longrightarrow v_{CB} = -0.4 \text{ V}$$

But this value of v_{CB} will forward bias the BC junction. With both junctions forward biased, we are in saturation.

Note that with $v_{BE} = 0.6$V and $v_{CB} = -0.4$V, the BE junction will be more forward biased than CB, so the net collector current is still positive.

When biased in the LINEAR region, the following equations apply. (See our earlier analysis of the current components.)

$$\gamma \equiv 1 \qquad \text{(assumed)}$$

- $$\beta = \frac{\alpha}{1-\alpha} \Rightarrow \alpha = \frac{\beta}{1+\beta}$$

- $$i_C' = \alpha i_E' \qquad (i_E' \equiv i_{En}' \text{ since } \gamma = 1 \Rightarrow i_{Ep}' = 0)$$

$$\beta = \frac{i_C'}{i_B'}$$

- $$\Rightarrow i_B' = \frac{i_C'}{\beta} = \frac{\alpha}{\beta} i_E'$$

- $$\underline{\underline{i_B'}} = \frac{\alpha i_E'}{\beta} = \frac{\alpha}{\alpha/(1-\alpha)} i_E' = \underline{\underline{(1-\alpha) i_E'}}$$

- $$\underline{\underline{i_E'}} = \frac{\beta}{\alpha} i_B' = \frac{\beta}{\beta/(1+\beta)} i_B' = \underline{\underline{(1+\beta) i_B'}}$$

BE CAREFUL: These relations DO NOT HOLD in CUTOFF or SATURATION.

SWITCHING APPLICATIONS

When used as a simple switch or for digital logic applications, the BJT switches from SATURATION to CUTOFF and vice-versa.

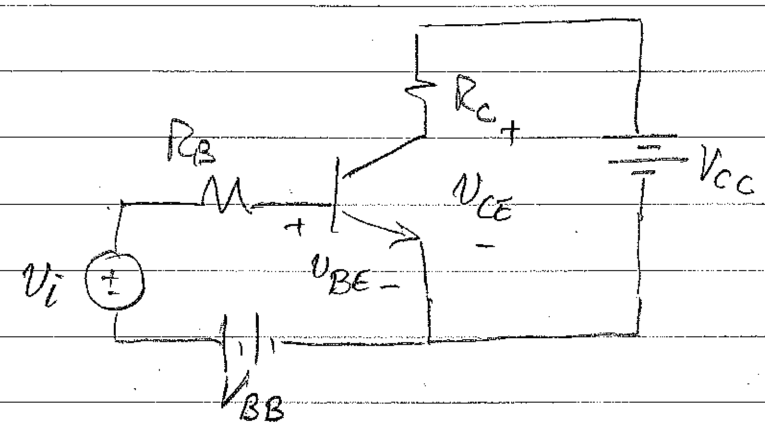
SATURATION $\Rightarrow$ low V_{CE}, high i_C

CUTOFF $\Rightarrow$ high V_{CE}, low i_C

So we have two stable states.

GRAPHICAL ANALYSIS

Recall we used the graphical "load line" technique to analyze the operating point of a diode. We can do the same for the BJT:



KVL at input circuit:

$$V_{BB} + v_i = R_B i_B' + v_{BE}$$

At the Input:

Note: $i_B' = 0 \Rightarrow v_{BE} = V_{BB} + v_i$

$$v_{BE} = 0 \Rightarrow i_B' = \frac{V_{BB} + v_i}{R_B}$$

At the output

$$V_{CC} = R_C i_C + v_{CE}$$

Note: $i_C = 0 \Rightarrow v_{CE} = V_{CC}$

$v_{CE} = 0 \Rightarrow i_C = V_{CC}/R_C$, slope $= -1/R_C$

POINT: The transistor is constrained to operate along the load line, i.e., $i_C - v_{CE}$ values are those that intersect the load line.

DISTORTION OCCURS if the input drives $i_C - v_{CE}$ to saturation or to cut-off.

See Trombetta PowerPoint notes on the BJT, specifically Sedra/Smith figs 5.29 & 5.30 in that presentation, for figures representing these ideas

We will examine biasing circuits to determine which of the operating regions a transistor is in.

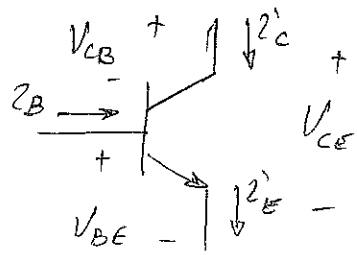
For now we will confine the discussion to LINEAR, SAT., and CUTOFF.

<u>DEFINITIONS</u> <u>and RULES</u>

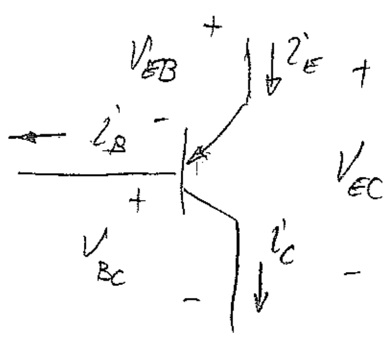
CURRENT POLARITY

Currents are POSITIVE as drawn

npn



pnp



<u>NOTE</u>: We use V_{BE} for npn and V_{EB} for pnp since these give positive values. Same for V_{EC}, V_{CE}.

APPLICATIONS

1. In amplifier circuits, we are generally using the BJT to amplify (make larger) a small ac signal (either current or voltage).

To do this, we need to ensure that the BJT is in the linear region, that is, we need to apply <u>dc bias</u>. For operation in the linear region, we need:

EB junction forward biased

BC junction reverse biased

2. In digital applications, dc voltages are being applied such that the BJT is switching from ON (saturation) to OFF (cut-off).