EE204FZ: Analogue Electronics 1

Introduction to Bipolar Junction Transistors (BJTs)

What is a transistor?

The field-effect transistor (FET) uses electric fields, and operates as

A voltage controlled variable "resistor" or "current source" depending on the configuration.

The bipolar-junction transistor (BJT) is also about the movement of charge carriers and will operate as

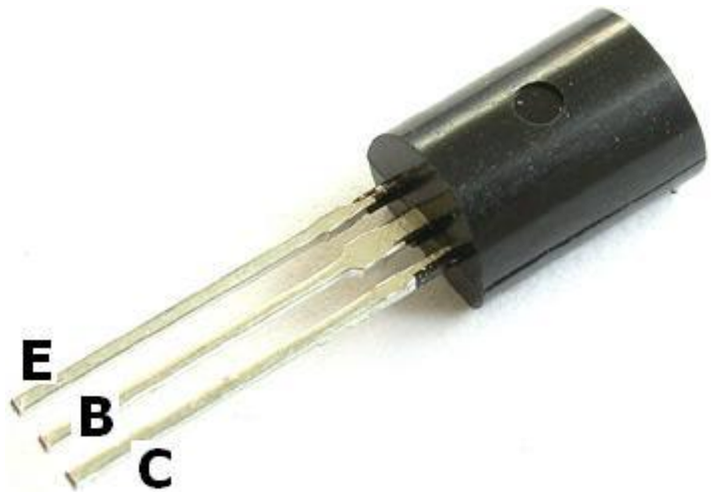
A current controlled "current source".

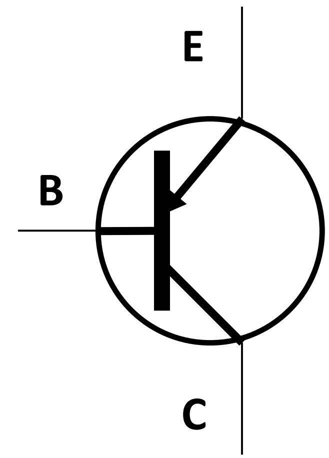
What type of transistor is best??

FETs	BJTs
Most modern designs use them	First type of transistor, so older designs use them
A bit noise	Best for low noise performance
Run slower, but now good up to about 10 Ghz	Run the fastest, up to 50 GHz or higher, material depending
Scales very well with new fab technology, can pack these transistors in very tightly	Do not use the modern very small nanoscale very well
FET circuits can be very power efficient	Not power efficient
Voltage controlled	Current controlled

As usual, take your pick, but mostly we use FETs

What is a ***Bipolar Junction*** Transistor?





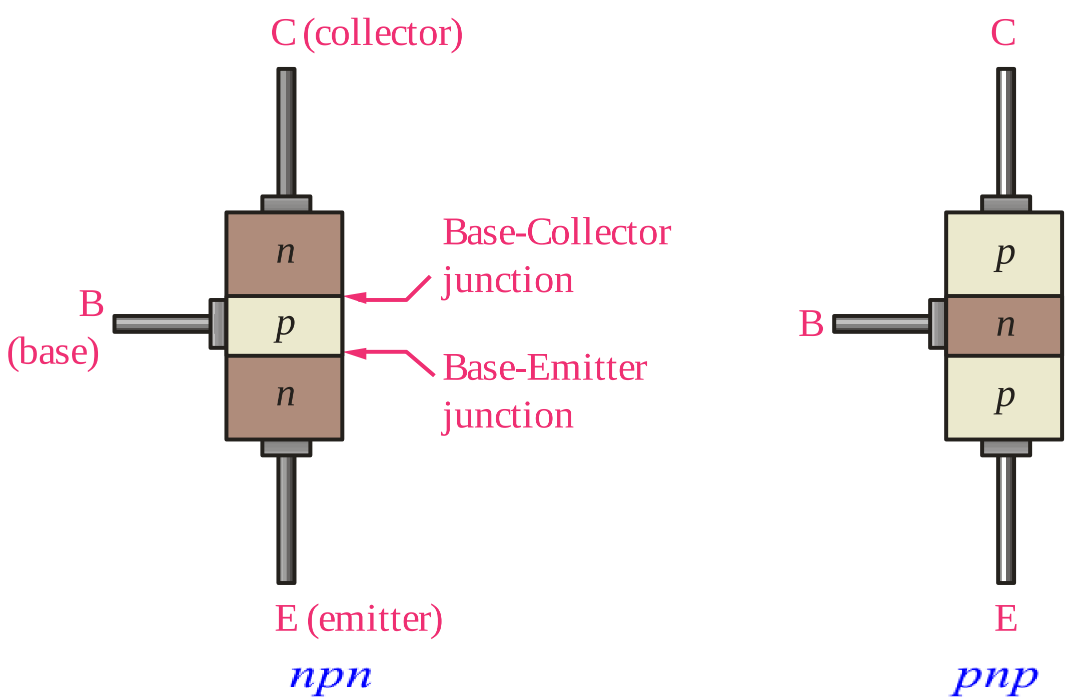
arrow points to N

The current that flows from the collector to the emitter is dependent on the current that flows through the base. There are two types of BJT, PNP and NPN which depends on the base semiconductor type.

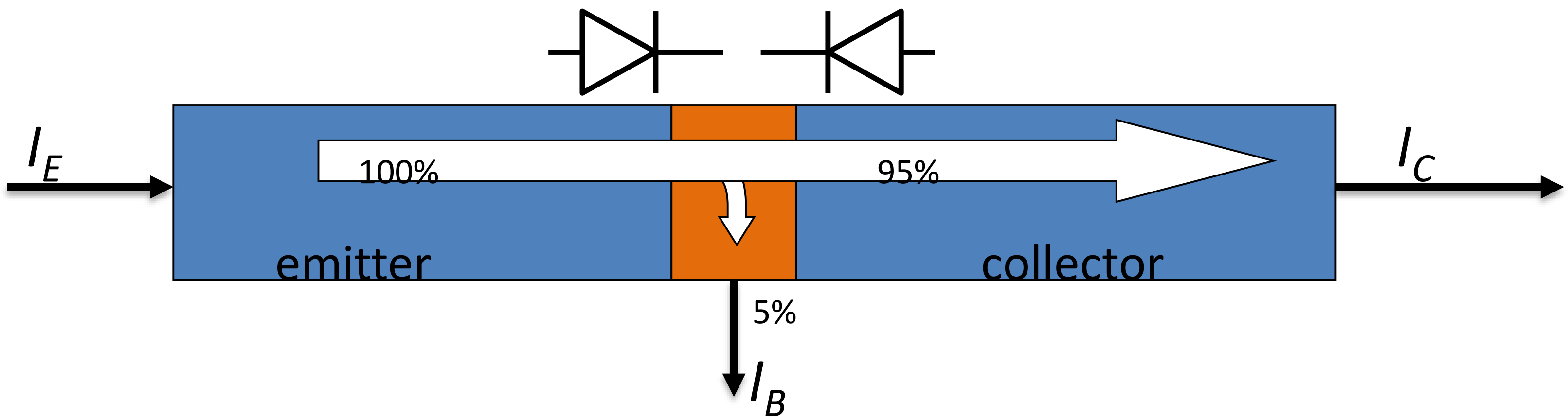
BJT Structure

The BJT has three regions called the emitter, base, and collector. Between the regions are junctions as indicated.

The base is a thin lightly doped region compared to the heavily doped emitter and moderately doped collector regions.

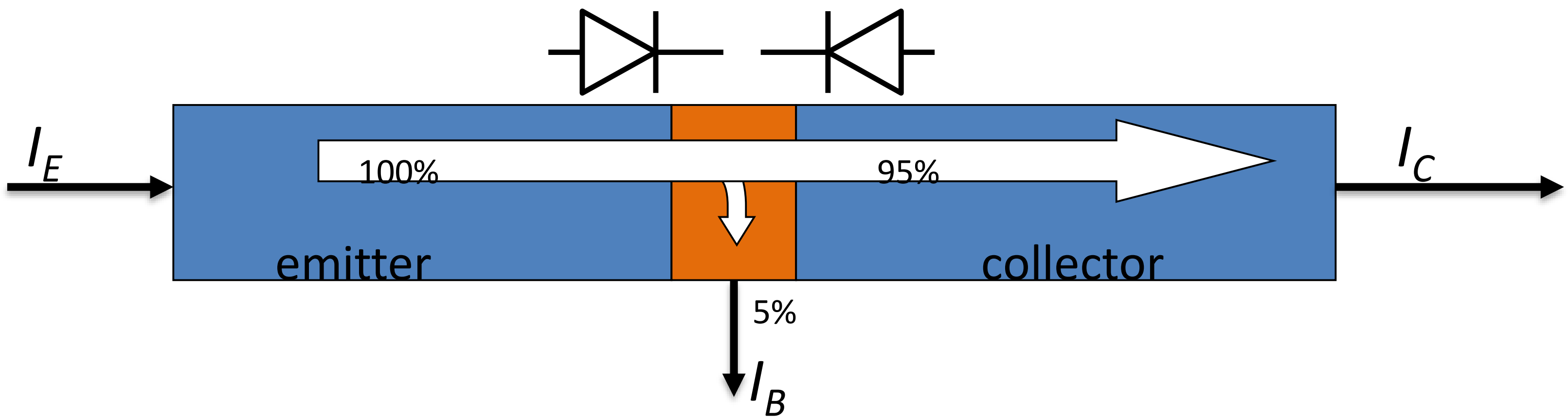


BJT Operation - Qualitative



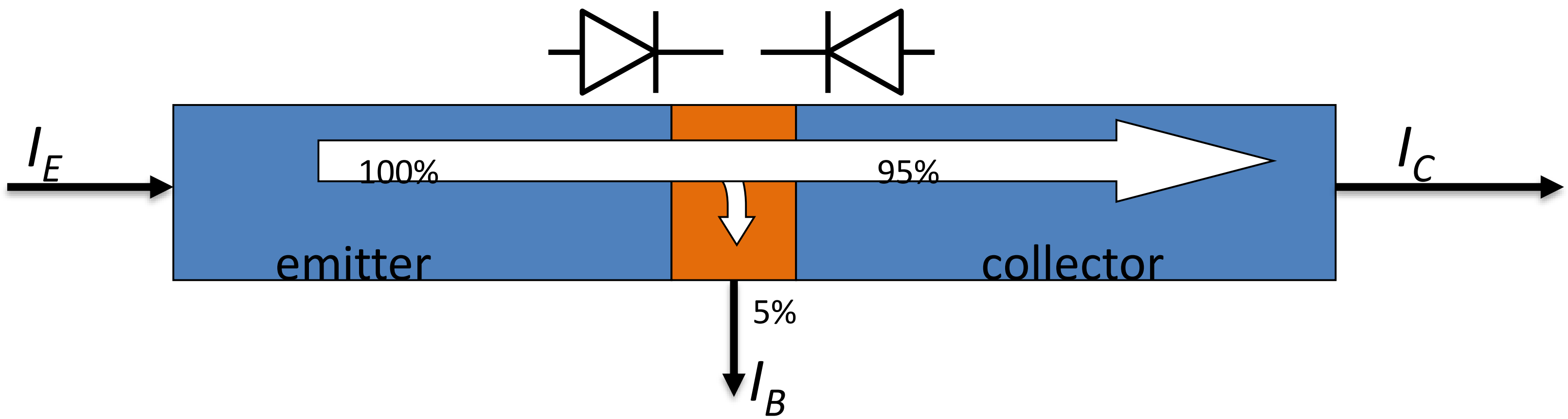
- The left hand (EB) junction is forward biased, the other (BC) is reverse biased.
- A current I_B is pulled from base which forces majority carriers from emitter into the base where they are **minority carriers**.
- Minority carriers near a **reverse biased junction** get swept across the junction.
- When the **base is narrow**, most carriers get caught by the reverse biased junction without recombining. The small percentage that gets drawn out of the base forms I_B.

BJT Operation - Qualitative



- A certain percentage of carriers **(assume holes)** will recombine, holes with electrons in the n base. They never make it across .
- The electrons used up in the base by recombination with travelling holes, are supplied by the base current.
- If we don't, a charge imbalance will build up which will stop the emitter-collector current. So no base current, no full current.
- There is a fixed ratio between base and collector current. The main limit on the large current is how fast we can pump in replacement electrons, the faster we do it the better.
- The more base current, the bigger the electron current.

BJT Operation – Key Equations



From using KCL for the currents in the base, we get

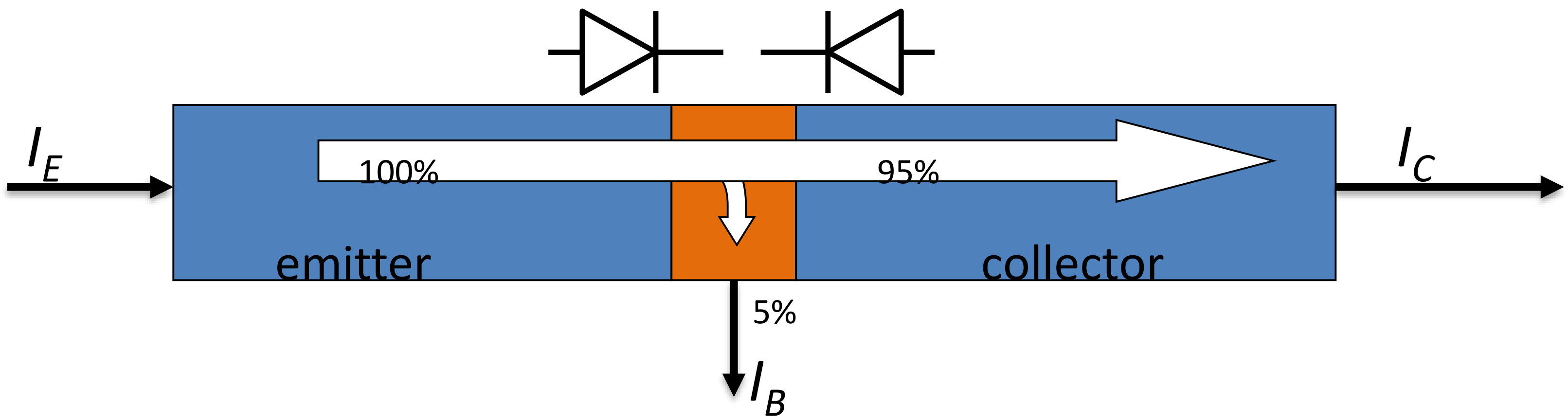
$$I_E = I_C + I_B$$

$$I_C = \alpha I_E$$

where α is always less than 1.0. It is called the common base current gain or **forward current transfer function**.

Hand-waving: Not all the emitter current gets to the collector, some always is lost in the base, has to be. But the closer to 1.0 the better.

BJT Operation – Key Equations



Reworking the equations a little, we get

$$I_C = \beta I_B$$

where β is typically large, > 50, called the **common-emitter, current gain**. When people mention BJT transistor current gain, they normally mean β.

Hand-waving: This tells us how powerful the base current is in modifying the main current, how big a change in the main current occurs for a little change in the base current. The higher the better.

More technically… the diode equation

Lets manipulate our equations a bit more.

$$I_C = I_E - I_B$$
$$I_C = \alpha I_E = \beta I_B$$

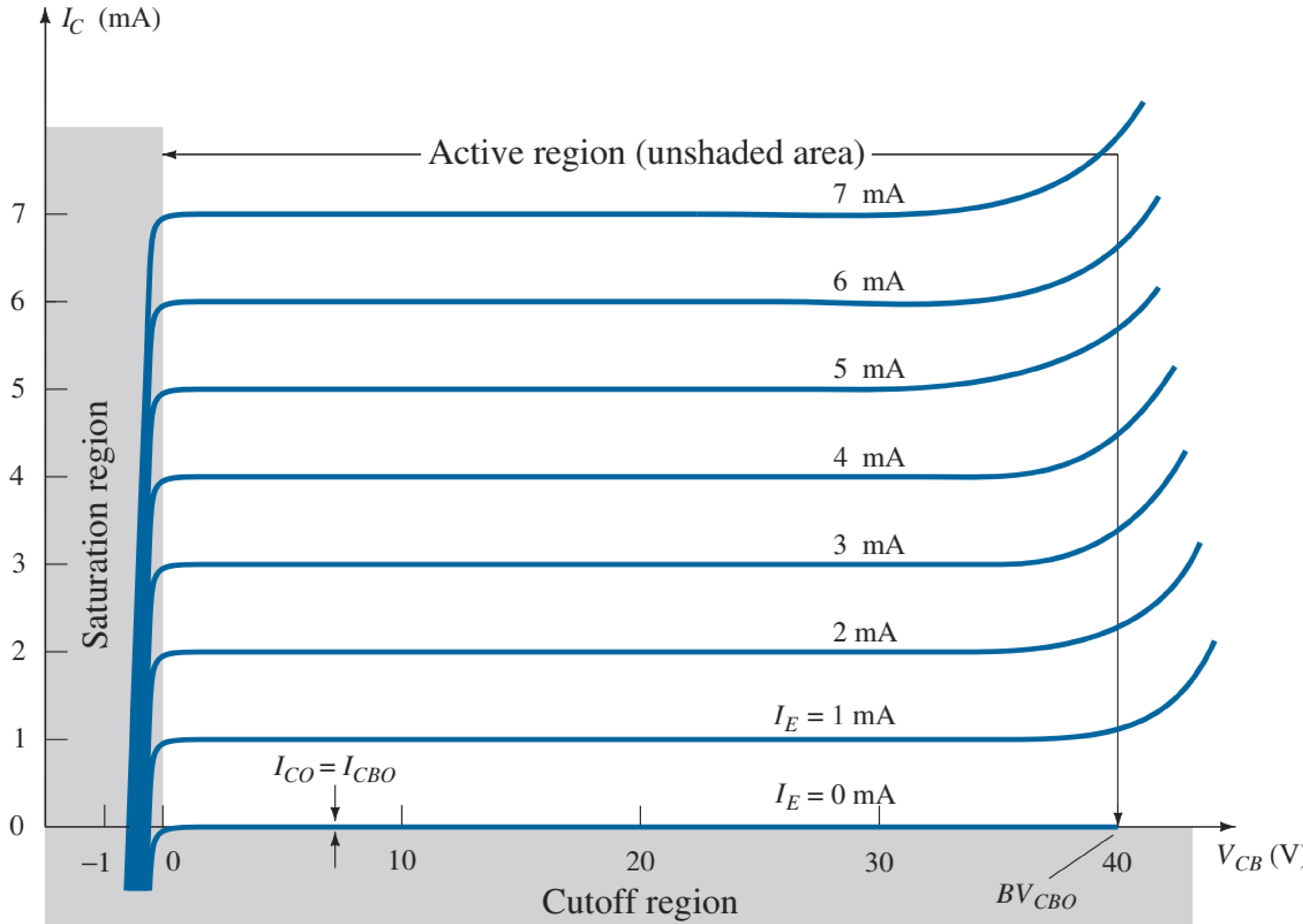
So

$$\alpha\left(I_C + I_B\right) = \beta I_B$$
$$\alpha\left(\beta I_B + I_B\right) = \beta I_B$$
$$\alpha\left(\beta + 1\right) I_B = \beta I_B$$
$$\alpha\left(\beta + 1\right) = \beta$$

Finally

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

BJT Operation – Plotting



BJT Operation – Key Equations

$$I_E = I_S\left(e^{(qV_{BE}/KT)} - 1\right) \quad *$$

$$I_C = \beta I_B \quad *$$

$$I_E = IC + I_B \quad *$$

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

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

$$V_{\mathrm{CE}} > V_{\mathrm{CE(SAT)}}$$

$$V_{\mathrm{BE}} > V_{\mathrm{BE(SAT)}}$$

$V_{CE(SAT)}$ and $V_{BE(SAT)}$ are the **effective boundaries** of the active region of the BJT transistor and in the active region, we basically do not have the exponential, and just $I_C=\beta I_B$.

$V_{BE(SAT)}$ or $V_{BE(ON)}$ is the voltage required to make the forward biased diode work. If V_{BE} isn't bigger than this, no current flows.

$V_{CE(SAT)}$ is the minimum voltage required to make the transistor operate in the flat-region of the current, not the exponential area.

Using BJT's

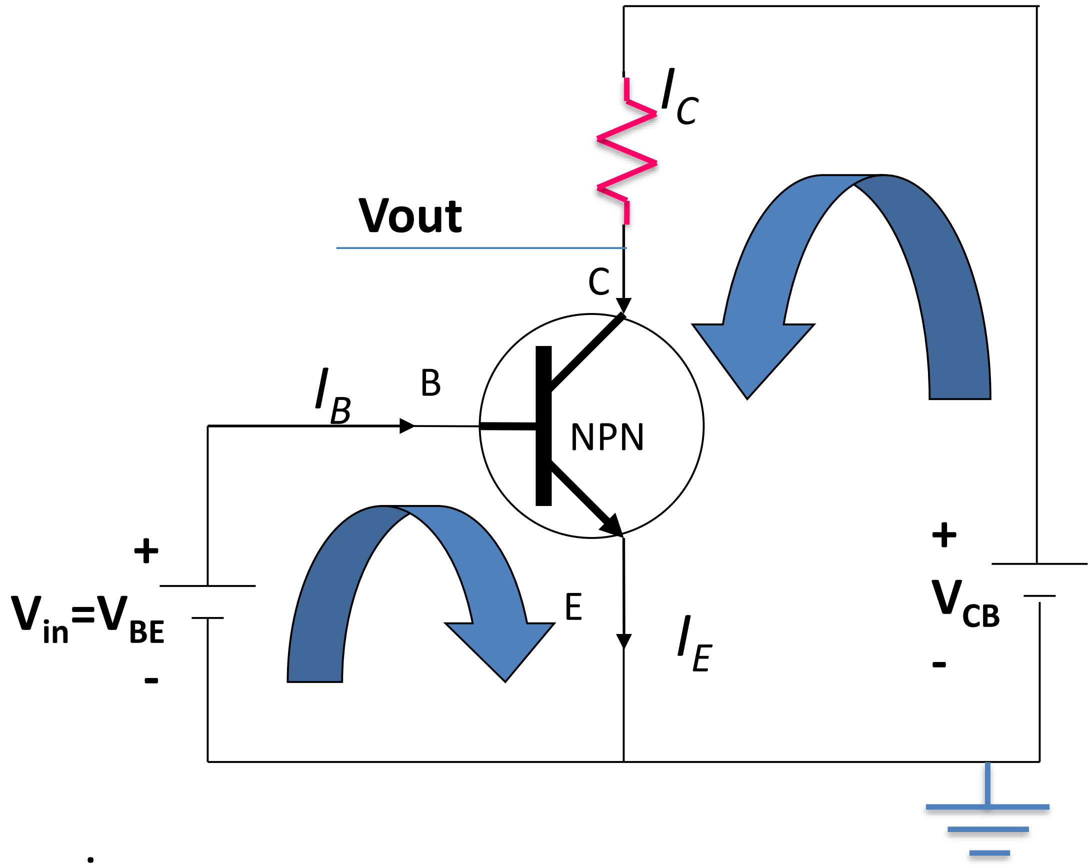
Like FETs there are two aspects to a circuit using BJT's:

- Large signal or dc operation – which we call **biasing**
- Small signal operation – or amplification

There are three modes of operation for a bipolar junction transistor:

- **Common base** – an input buffer and as an amplifier
- **Common collector** – an output buffer
- **Common emitter** – an amplifier

BJT – Common Emitter



Phase inversion

current gain > 1 (10 to 200)

voltage gain > 1

Common-Base Configuration

Input impedance is higher than CB (GOOD for weak input signals)

Output impedance is lower than CB (GOOD for driving high-freq)

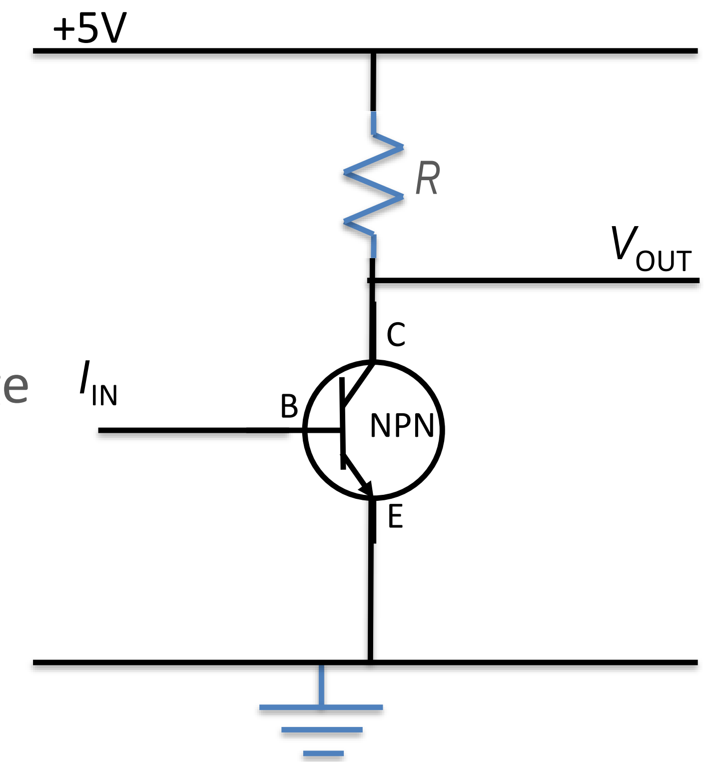
power gain > 1

BJT Biasing – BIG DIFFERENCE

Current flows through the base of a BJT transistor

A Biasing example

I have a small voltage signal that I am going to add on top of a DC average value. I will want some small-signal gain and a maximum output voltage swing of +/- 1.5 volts. Pick values of R, I_C and I_B for my design.



$V_{CE(SAT)} = 0.3$ V $V_{BE(ON)} = 0.7$ V $\beta = 50$

To get a ± 1.5 volts swing, pick a mid-point on the range, and a little bit on the high side to get the BJT some extra voltage. For me, I'll pick

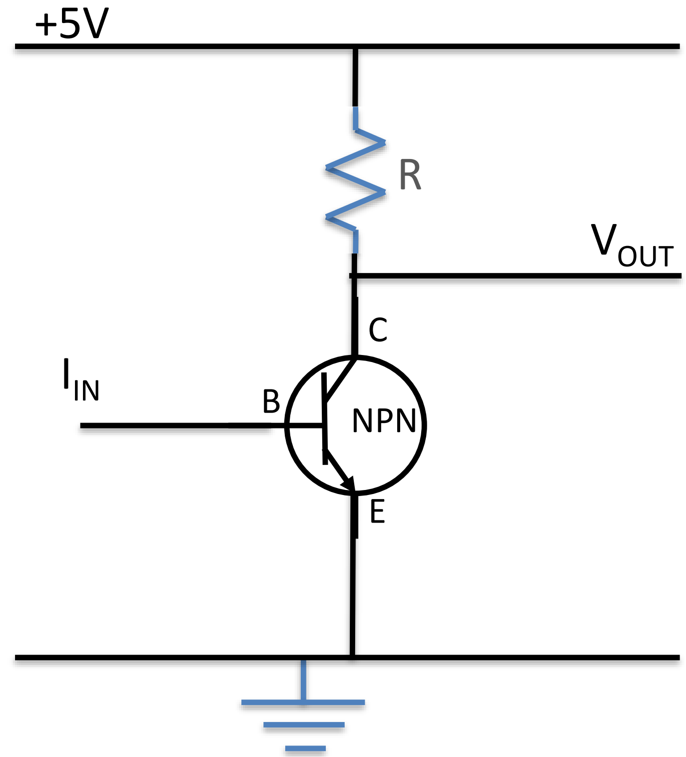
V_{OUT} to be 3 volts

$I_C \times R = 2$ volts

$V_{CE} = 3$ volts $\gg V_{CE(SAT)}$

A Biasing example

V_{OUT} to be 3 volts
$I_C \times R = 2$ volts
$V_{CE} = 3$ volts >> $V_{CE(SAT)}$

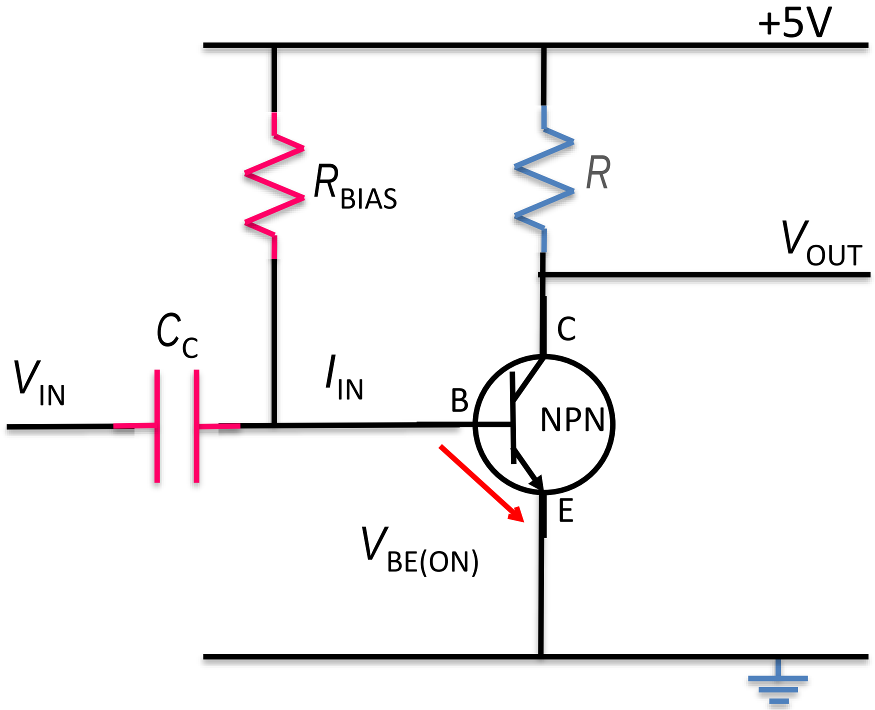


Normally you would need to look up a datasheet to find a value for I_C that gives you a good value of β.

Let's cheat, and say that $I_C = 1$ mA gives me a β of 50.

So $I_C = 1$ mA and $I_C \times R = 2$ volts, so $R = 2$ kohm.

If $I_C = 1$ mA, then I_B must be equal to 1 mA/β or 20 μA.

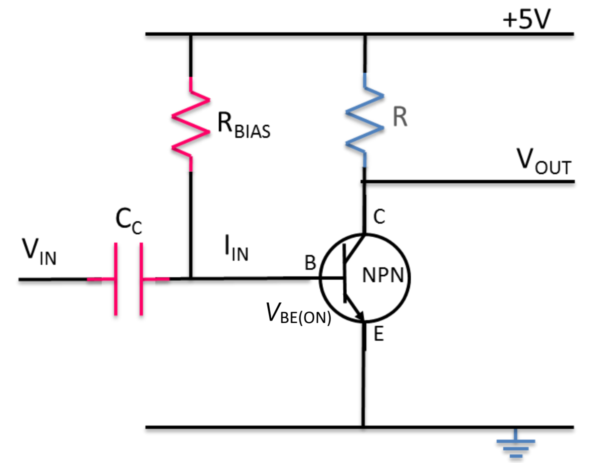


So we add a resistor to the V_{CC} (5 V) supply and let the current flow. Flowing from base to emitter, the current will experience a voltage drop called $V_{BE(ON)}$. We need to make sure it is always bigger than that, even with an input swing, so we add the amplitude of our input signal voltage to it:

$$I_{IN}\left(R_{BIAS}\right)+V_{BE(ON)}=5$$

$$R_{BIAS}=\frac{5-V_{BE(ON)}}{I_B}=\frac{\beta\left(5-V_{BE(ON)}\right)}{I_C}$$

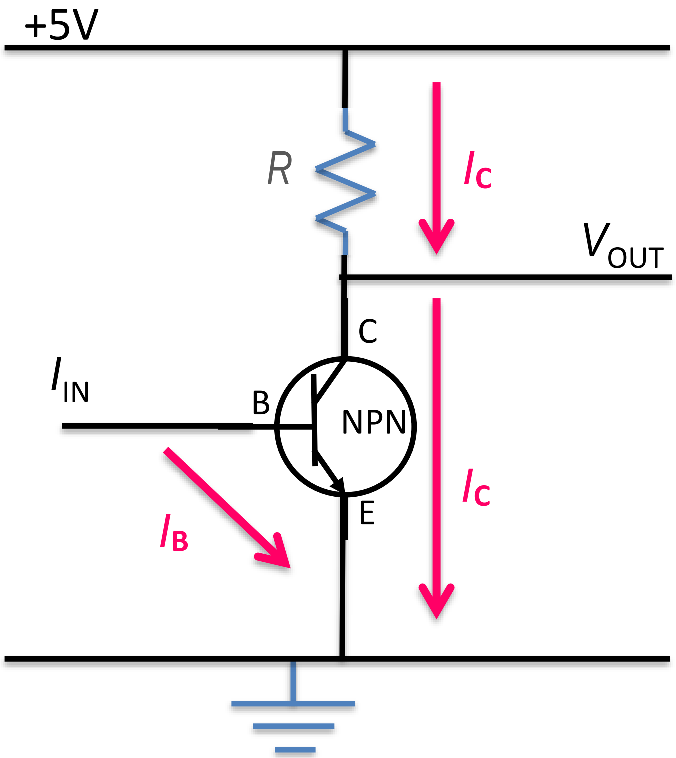
A Biasing example



Plugging in the numbers, and remembering we want V_{BE} to be always a little bigger than $V_{BE(ON)}$ so that our input signal won't turn it off when it goes a little low (say V_{IN} has amplitude 0.2). Altogether we get

$$\begin{aligned} R_{\mathrm{BIAS}} &= \frac{V_{\mathrm{BIAS}}}{I_{\mathrm{B}}} \\ &= \frac{\left(5 - V_{\mathrm{BE(ON)}} - |V_{\mathrm{IN}}|\right)}{I_{\mathrm{C}} / \beta} \\ &= \frac{(5 - 0.7 - 0.2)}{0.001/50} \\ &= \frac{50(4.1)}{0.001} = \frac{205}{0.001} \\ &= 205\,\mathrm{k}\Omega \end{aligned}$$

Amplification



So very similar to the FET:

I_B increases, then $I_C = \beta I_B$ goes up.

I_C goes up, then $I_C \times R$ goes up.

$I_C \times R$ goes up, V_{OUT} goes down.

Thus we get amplification.