Transistors

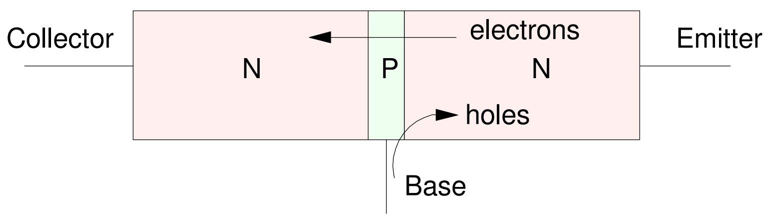
NPN Transistor Theory

Transistors are similar to diodes in that they are made up on n-type and p-type silicon. They differ in that

- Transistors are 3-terminal devices (NPN or PNP),
- Transistors can operate in three states: off, active, and saturated,
- Transistors can be used as a switch to turn a device on and off electrically, and
- Transistors can be used as an amplifier (a current controlled current amplifier).

An NPN is a three-terminal device: collector, base, and emitter. Between the emitter and the collector is a reverse biased PN junction. This prevents current flow from the collector to the emitter (electrons, being negatively charged, flow the opposite direction). The switch is open.

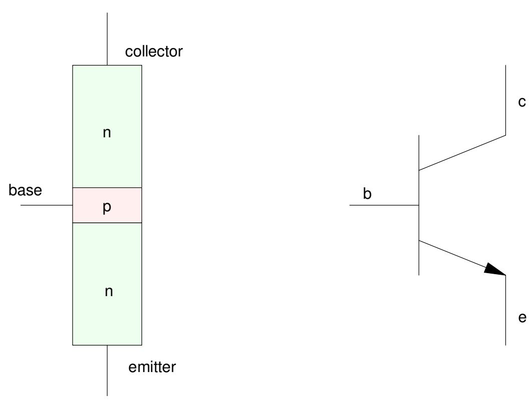
If you apply current to the base to the emitter, however (which is a forward biased PN junction), holes flow from the P-type base and electrons flow from the N-type emitter.



An NPN device makes a transistor

If the base is very thin, most of the electrons pass through the base and appear at the collector, creating current flow from the emitter to the collector. (The switch is closed). If the doping on the emitter side is β times higher than the doping in the P-type base, you get β times more electrons than holes. This creates current amplification.

The symbol for a transistor is as follows. Note that the arrow represents the diode from base to emitter. It reminds you which way current flows.



Symbol for an NPN transistor: the arrow indicated the diode from base to emitter

Transistor VI Characteristics:

The VI characteristic for a 3904 NPN transistor is shown in the following figure. Three regions of operation are defined:

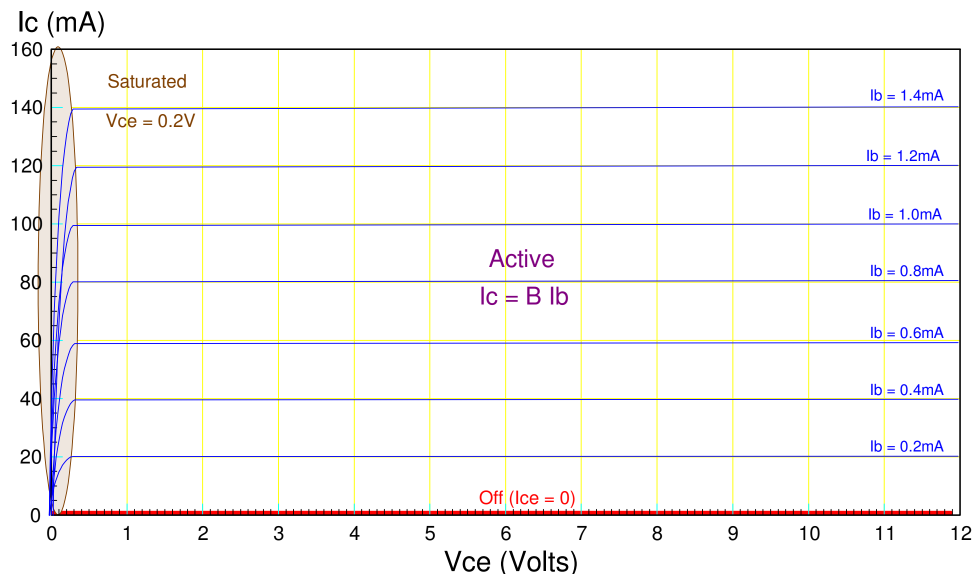
Off: If there is no current in the base (Ibe = 0), there is no current from collector to emitter. This is the "off" state of the transistor.

Active: If you have enough voltage Vce, the collector current Ic is related to the base current as

$$I_c = \beta I_b$$

For the 3904 transistor, note that when Ib = 1mA, Ic = 100mA. The current gain, β, is 100.

Saturated: If for some reason you try to drive Vce < 0, Vce clips at about 0.2V. This is a physical limit for a transistor: negative voltage for Vce means the transistor is producing energy. That can't happen.



VI Characteristics for a 3904 NPN transistor

These three regions result in three models for a transistor - one for each region.

Off State:

If the diode from the base to emitter is off, Ib = 0. If Ib = 0, then Ice = 0 and the transistor is off.

Off Condition:

- $I_{be} = 0$

Off Model:

- $I_{be} = 0$
- $I_{ce} = 0$

Active State

If the diode from base to emitter is on, Ib >0. The transistor then amplifies this current as

$$I_c = \beta I_b .$$

The condition for being in the active region is

- $I_b > 0$
- $V_{ce} > 0.2$

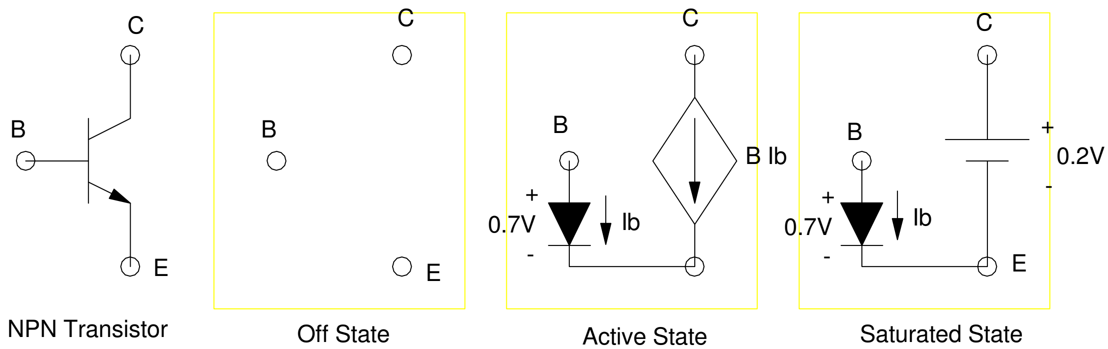
Saturated State

If you try to make Vce go negative, it clips at 0.2V.

$$V_{ce} = 0.2V$$

When saturated, the current Ic is clipped

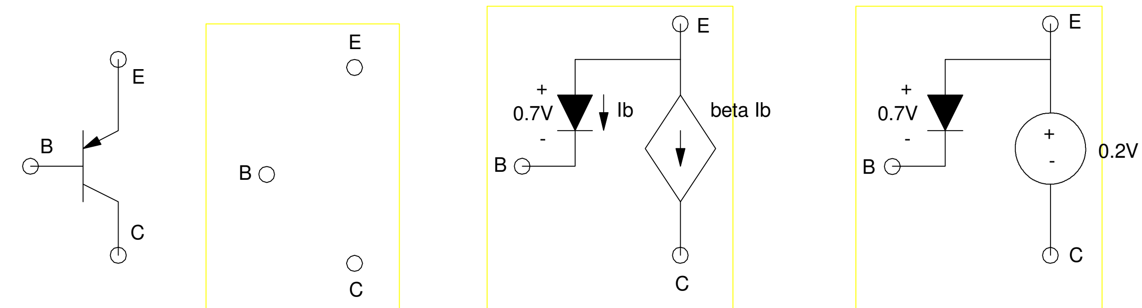
$$I_c < \beta I_b$$



Three models for an NPN transistor. Note that the arrow signifies the direction of the diode from the base.

PNP Transistors:

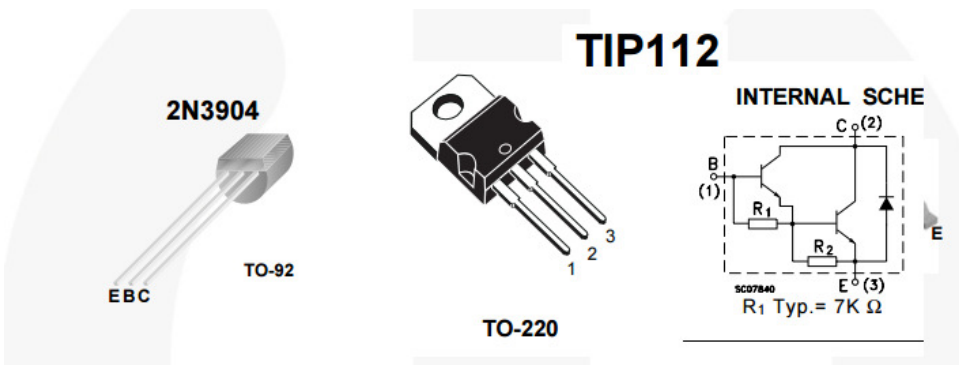
PNP transistors have a PN junction from the collector to the base. This changes the model as follows:



PNP Transistor | Off State | Active State | Saturated State

Again, note that the arrow indicated the direction of the diode relative to the base: current flows to the base from the emitter.

Transistor Specs

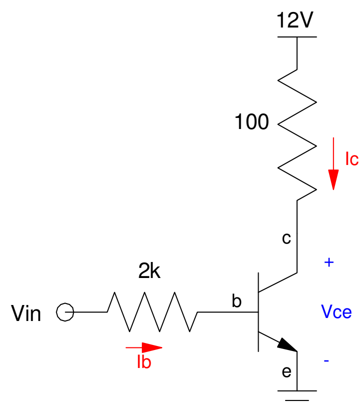


	3904 NPN	TIP112 NPN
hfe (beta)	100 - 300	1,000
Ic (max)	200mA	4A
Vce (max)	40V	40V
Vce (sat)	0.2V	0.9V
cost (ea)	$0.03	$0.59

Transistor Circuit Analysis:

Determine the Q-point (Vce, Ice) and the operating mode of the transistor for

- a) Vin = 0.5V
- b) Vin = 2.0V, amd
- c) Vin = 3.5V

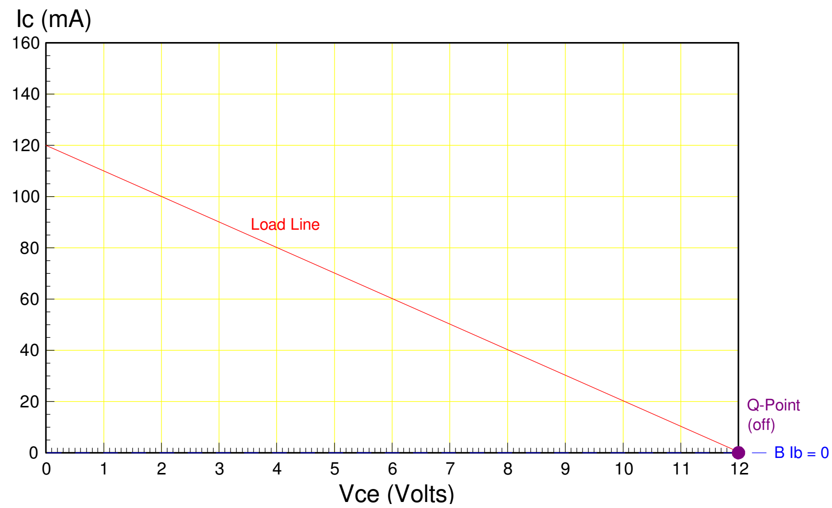


Sample Circuit: Assume a transistor with β=100

a) Vin = 0.5V (Off State): To turn on the diode from base to emitter, you need 0.7V. Vin isn't large enough to turn on this diode, so

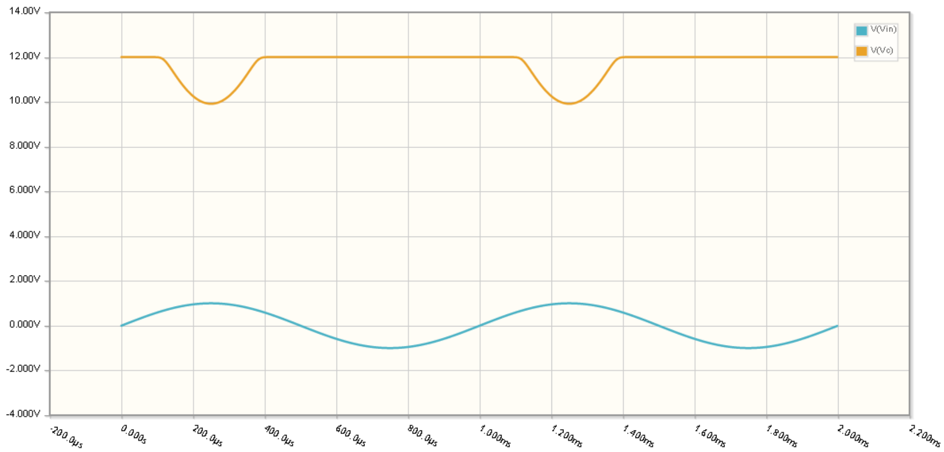
- Ib = 0
- Ic = 0
- Vce = 12V

The transistor is off. This is seen on the load-line as follows:



When Vin = 0.5V, the transistor is off (Ic = 0)

The off state shows up in the following graph. Here, Vin is a 1Vp sine wave with a 0V DC offset. The output (Vc) tries to follow this sinusoid (inverted) but current can't go negative. This results in Vc clipping at +12V (where the transistor turns off)



Vin (blue) and Vc (orange) for a 1Vp sine wave centered at 0V.
When Vc = 12V the transistor turns off.

b) Vin = 2.0V (Active Region). This is enough to turn on the diode from base to emitter. This results in

Vb = 0.7V (diode is on)

The base current, Ib, is then

$$I_b = \left(\frac{2V - 0.7V}{2k\Omega}\right) = 650\mu A$$

Assuming active mode

$$I_c = \beta I_b = 65mA$$

Check: To be in the active region, 0.2V < Vce < 12V:

$$V_{ce} = 12 - 100 I_c = 5.5V$$

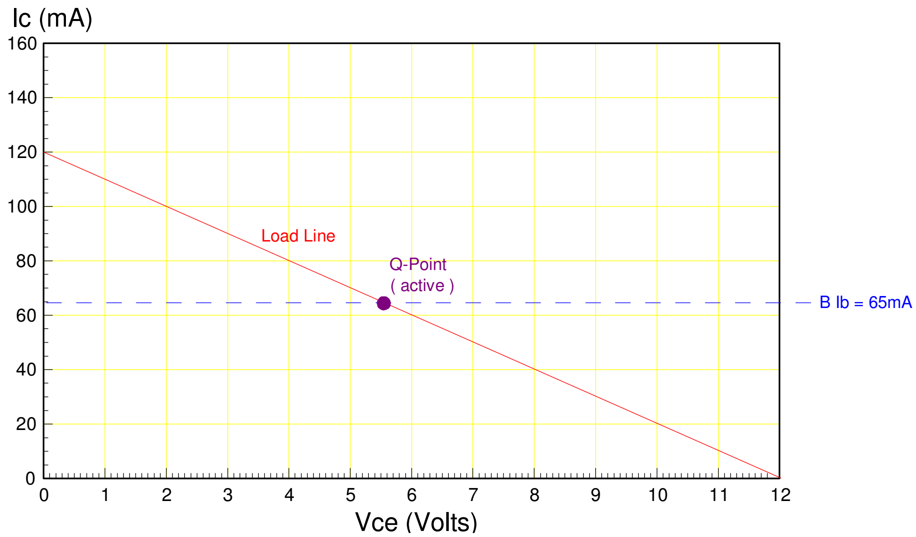
Another way to check this is to see if Ic is less than its maximum value (when saturated)

$$\max(Ic) = \left(\frac{12V - 0.2V}{100\Omega}\right) = 118mA$$

65mA < 118mA, meaning this circuit is capable of driving 65mA. The Q-point is thus

(Vce = 5.5V, Ice = 65mA)

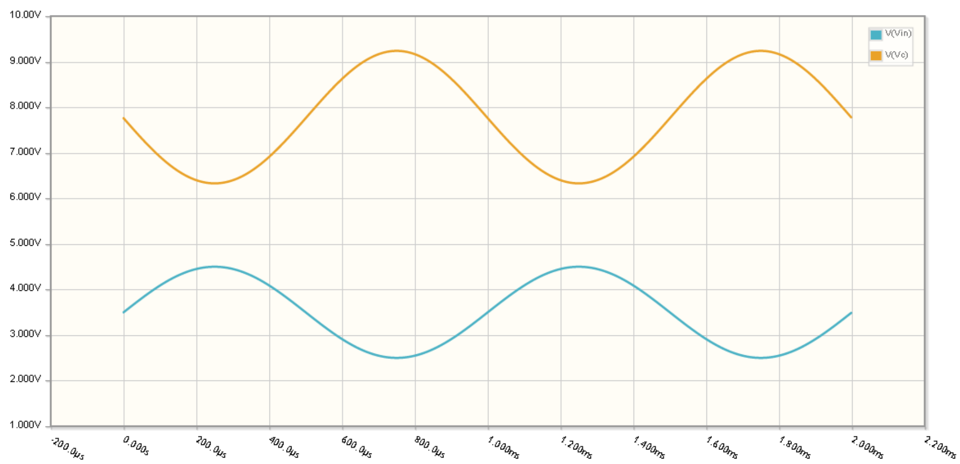
and the transistor is in the active region.



When Vin = 2.0V, the transistor is in the active region

In CircuitLab, the voltage Vc looks like the following:

- Vin is offset. That places the transistor in the active region.
- Vout remains between 0V and 12V, resulting in no clipping of the output. The transistor remains in the active region.



CircuitLab Simulation. By increasing the offset of Vin (blue), the current Ic increases, decreasing the voltage at Vc (orange)
Vc never exceeds +12V or drops below 0.2V, meaning the transistor remains in the active region

c) Vin = 3.5V (Saturated Region). This is again enough to turn on the diode from base to emitter. The base current is then

$$I_b = \left(\frac{3.5V - 0.7V}{2k\Omega}\right) = 1.4mA$$

Assuming the transistor is in the active state

$$I_c = \beta I_b = 140mA$$

This results in

$$V_{ce} = 12 - 100 I_c = -2.0V$$

You can't have a negative voltage - instead Vce clips at 0.2V.

Since it isn't off and isn't active, the transistor must be saturated

Vce = 0.2V

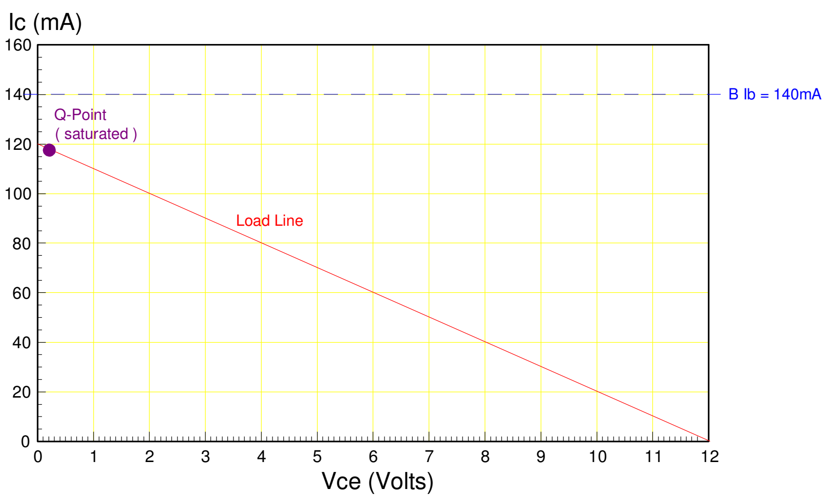
Ic is then clipped at its maximum value:

$$I_c = \max(I_c) = \left(\frac{12V - 0.2V}{100}\right) = 118mA$$

The Q-point is thus

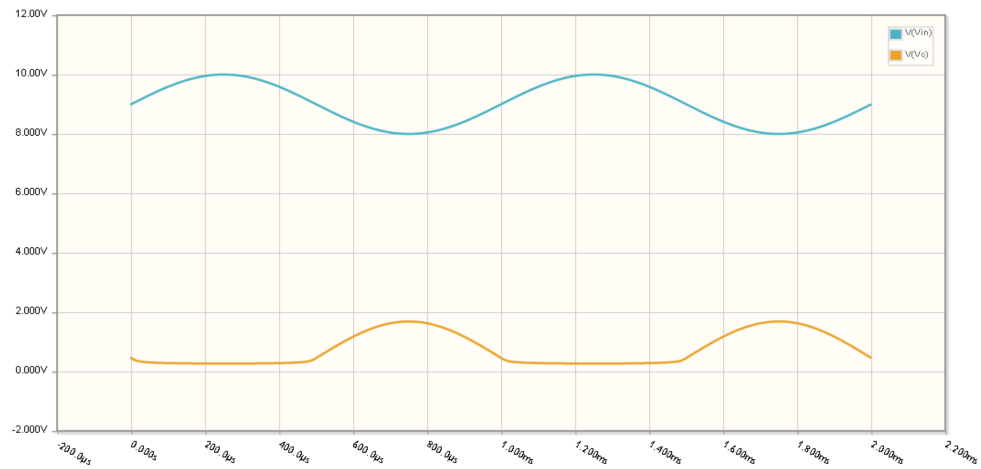
(Vce = 0.2V, Ice = 118mA)

and the transistor is saturated.



Load Line for Vin = 3.5V. In this case, βI_b is more than the maximum possible, so Ic clips at its maximum: 118mA

In CircuitLab, if you add too much offset to Vin, the output will start to clip at 0.2V. This is called saturation.



CircuitLab Simulation. By increasing the offset of Vin (blue), the current Ic increases, decreasing the voltage at Vc (orange)
When Vc tries to go negative, it clips at 0.2v (i.e. it enters the saturated region).

Note: When working with a circuit which has N diodes, there are 2^N possible circuits to analyze. It helps if you can guess which diodes are on and which ones are off so that you don't have to analyze all 2^N possible circuits.

When working with a circuit with N transistors, there are 3^N possible circuits to analyze. It really helps to guess the right circuit in this case. To do this, it helps to know what the circuit is supposed to do:

- If the transistor is being used as a switch (ECE 320), the transistor is probably operating in the off and saturated (on) regions.
- If the transistor is being used as an amplifier (ECE 321), it's probably operating in the active region.

That is, assuming the designer knew what he/she was doing.