BJT transistors

Recommended readings

- https://www.electronics-tutorials.ws/transistor/tran_2.html
- https://www.electronics-tutorials.ws/transistor/tran_4.html
- https://www.electronics-tutorials.ws/logic/logic_4.html
- https://www.electronics-tutorials.ws/logic/logic_2.html
- https://www.electronics-tutorials.ws/logic/logic_3.html

1. Transistors

Resistors, capacitors or diodes are examples of two-terminal devices: for a give voltage, we always obtain the same current (characteristic curve $I = f(V)$).Transistors are **three-terminal devices**, in which one of terminals is going to control the characteristic curve of the other two terminals.

- Depending on the transistor, the **control is made by a current** (e.g. BJT) **or a voltage** (e.g. MOSFET).
- A transistor is an **active** component.
- Why transistor? the term comes from TRANsfer-reSISTOR

Types

- Bipolar transistors: BJT (Bipolar Junction transistor)
- Unipolar transistors: FET (Field effect transistors)
  - JFET (Junction Field Effect Transistor)
  - MOSFET (Metal Oxide Semiconductor Field Effect Transistor)

1.1 Brief history

- 1904 - 1947 vacuum tubes
- The basic principle of the field-effect transistor (FET) was first proposed by Austro-Hungarian physicist Julius Edgar Lilienfeld in 1926, when he filed the first patent for an insulated-gate field-effect transistor (IGFET).
- 1947 : Bardeen y Brattain manufacture the first bipolar transistor at Bell laboratories
- Shockley theory in 1949 (Nobel prize in 1956)
- BJT Quickly substitute vacuum tubes: smaller, less electric consumption, no need to warm-up, reliability

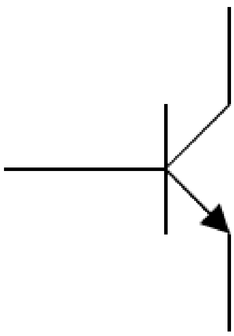
- MOSFET invented by Mohamed M. Atalla and Dawon Kahng at Bell Labs in 1959. It is the basic building block of modern electronics, and the most frequently manufactured device in history.
- In the 80's BJTs is substituted by CMOS technology.

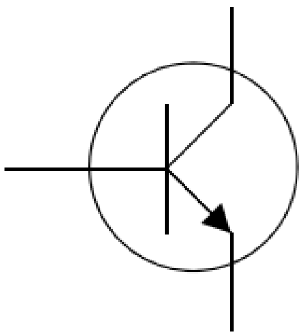
First transistor: December 24th 1947. **Shockley, Bardeen and Brattain** (Nobel prize in 1956)

2. Bipolar junction transistor (BJT)

What is a bipolar junction transistor? Loosely speaking, two inverted diodes connected in series (but not really...).

- Why bipolar? electric current is due to both e^- and h^+
- Utility:
  - A **switch** that regulates the flow of an electric current thanks to low-current control signal.
  - An **amplifier** of electric signals (main application nowadays)

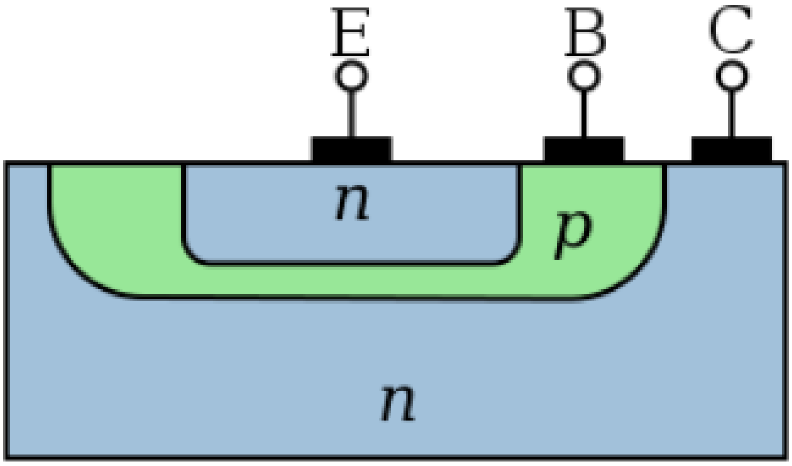




2.1 Structure

It consists of three regions of doped semiconductors each connected to a different terminal, so it's a three-terminal device: emitter (E), base (B) and collector (C)

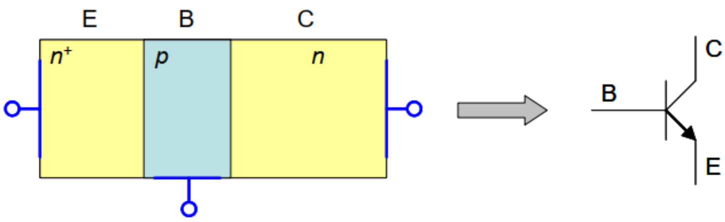
- **Emitter** (E): heavily doped (indicated by +). It behaves as an emitter of charges.
- **Base** (B): a narrow intermediate region. It regulates the current that flows through the transistor.
- **Collector** (C): same doping as E, but lighter.



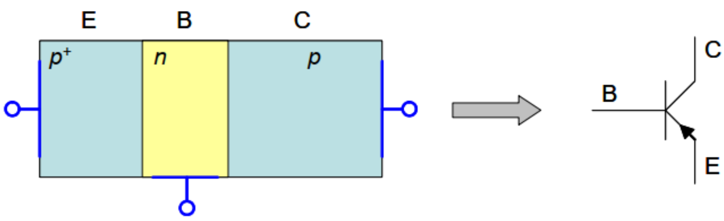
2.2 Types of BJT

Two types

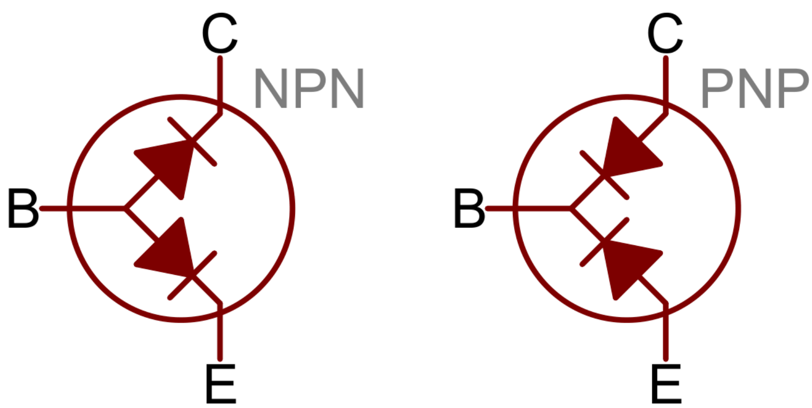
- NPN



- PNP



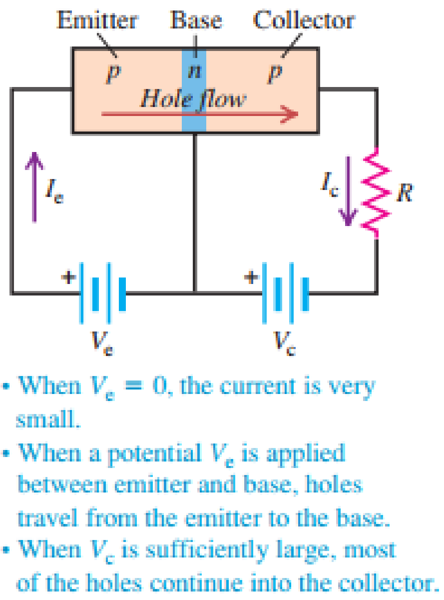
- The arrow is always in emitter. The sense of the arrow is from P to N (like in a diode)
- NPN is more common than the PNP due to the greater mobility of e^- compared to h^+



A key factor is the base width (W), which determines whether we are dealing with a transistor or 2 opposite diodes instead. In a transistor, there is no recombination in the base.

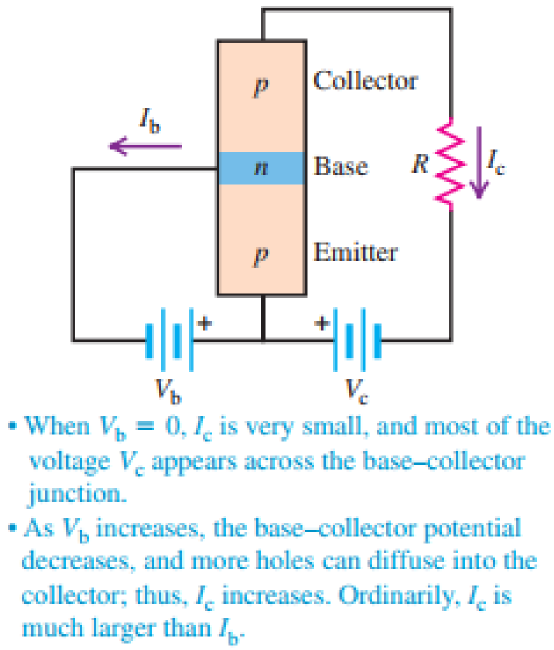
3. Qualitative functioning

Common Base



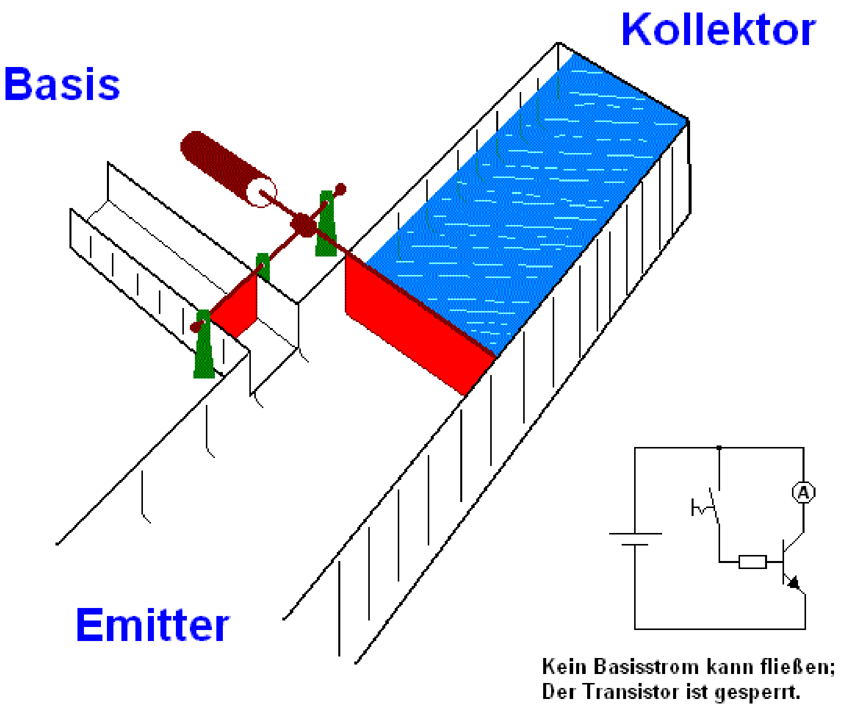
When there is no current in the left loop of the circuit, base-collector is a reversed diode, so there is no current flowing through the resistor. The transistor is switched-off. But when there is some current, the holes traveling from emitter to base now jump through the base to the collector, increasing the current through the resistor. The transistor is on. The current in the collector circuit is **controlled** by the current in the emitter circuit.

Common Emitter



When there is no current in the left loop of the circuit, base-collector is a reversed diode, so there is no current flowing through the resistor. The transistor is switched-off. But when there is some current, the holes traveling from emitter to base now jump through the base to the collector, increasing the current through the resistor. The current in the collector side of the circuit is much larger than that in the base side, resuling in **current amplification**. The current in the collector circuit is **controlled** by the current in the base circuit.

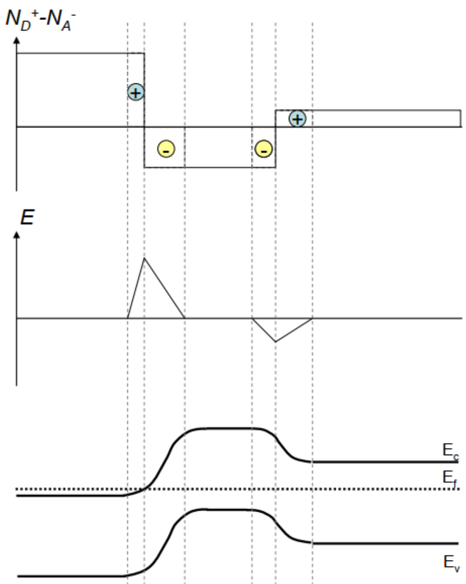
NPN analogy



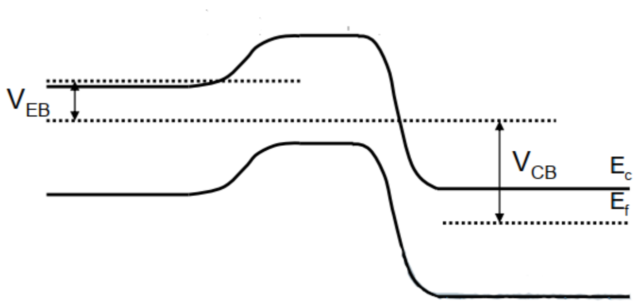
3.1 Doping profile and energy bands

For the N^+PN, when a **forward bias is applied to the E-B junction** and a **reverse bias to the B-C junction** (active mode), the energy band is modified as follows.

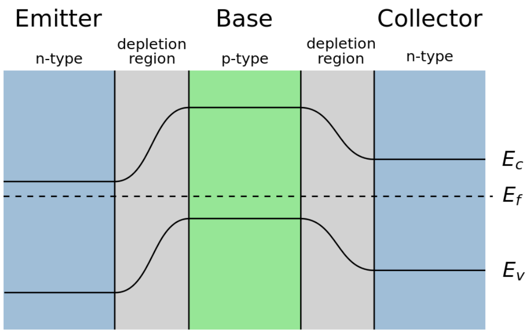
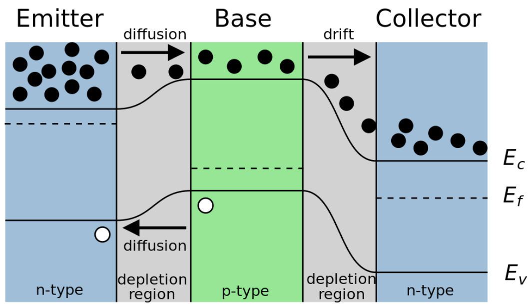
EQUILIBRIUM



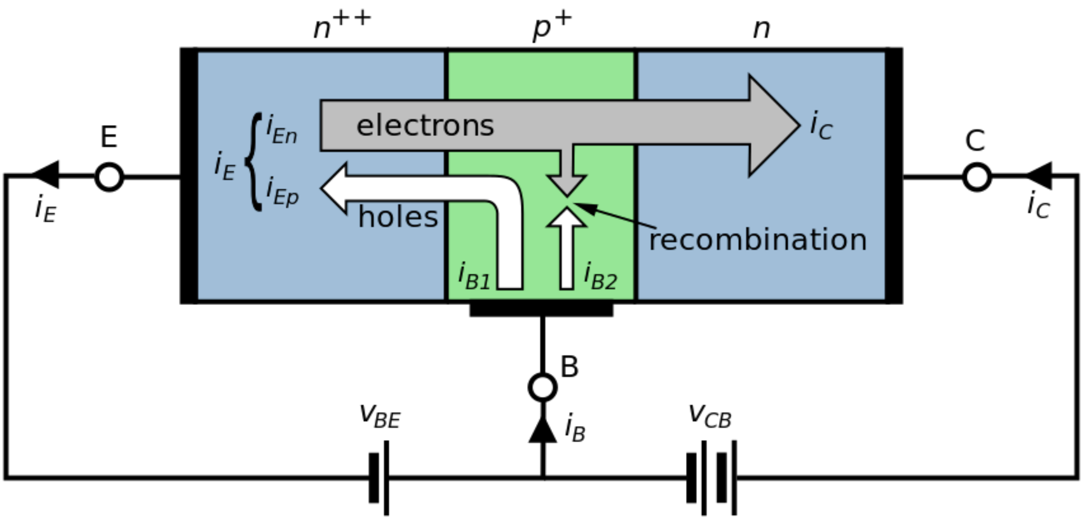
ACTIVE



The charge carriers in the emitter E can get through the potential barrier E-B by diffusion and arrive to the base B (being a N^+P junction, the e^- is the majority of carriers.) In turn, all the carriers that arrive to the base are now drifted by the electric field between B-C.Base width must be small to avoid recombination before arriving to the B-C junction.

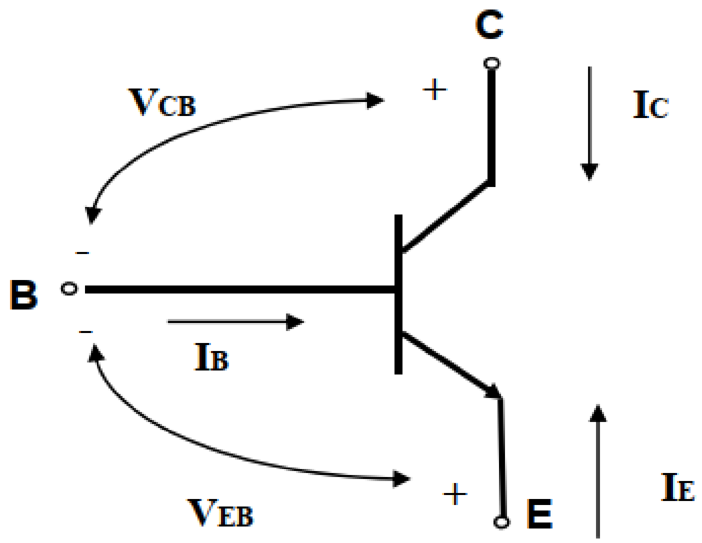
EQUILIBRIUM	ACTIVE
	

3.2 Currents



4. Polarization of a BJT transistor

Polarization of a transistor: to establish a certain operating point characterized by its three voltages V_{CE}, V_{CB}, V_{EB} (and consequently the currents I_C, I_B, I_E).

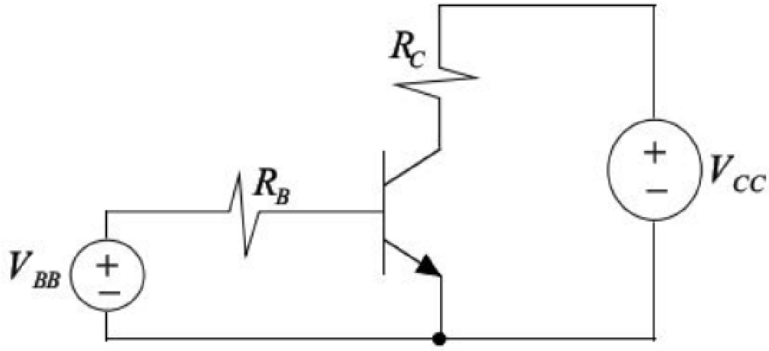


There exist four possible ways to polarize the transistor depending on the signs of V_{CB}, V_{EB}, which give rise to **four possible modes**. As normally $V_{EB} < V_{CB}$ only three of them are used in practice.

Mode	Polarization	PNP	NPN	Application
Active	EB forward; BC reverse	$V_{EB} > 0$ $V_{CB} < 0$	$V_{EB} < 0$ $V_{CB} > 0$	Amplification
Reverse	EB reverse; BC forward	$V_{EB} < 0$ $V_{CB} > 0$	$V_{EB} > 0$ $V_{CB} < 0$	Not used
Saturation	EB forward; BC forward	$V_{EB} > 0$ $V_{CB} > 0$	$V_{EB} < 0$ $V_{CB} < 0$	logic
Cut-off	EB reverse; BC reverse	$V_{EB} < 0$ $V_{CB} < 0$	$V_{EB} > 0$ $V_{CB} < 0$	logic

4.1 Operating point

We previously required two magnitudes to characterize a two-terminal device (one characteristic equation), now we require 6 equations to define an operating point: $Q(I_B, I_E, I_C, V_{BE}, V_{CE}, V_{BC}) = 0$.



Using KCL and KVL on the transistor we always have

$$I_B + I_C = I_E$$

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

KCL left mesh

$$V_{BB} = R_B I_B + V_{BE}$$

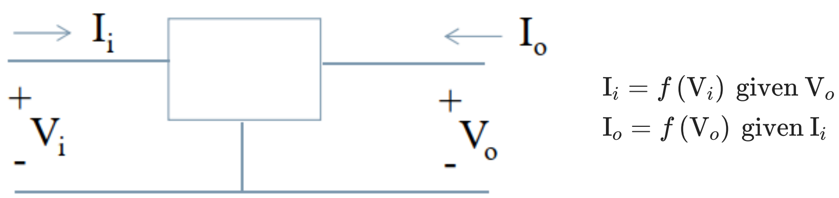
KCL right mesh

$$V_{CC} = R_C I_C + V_{CE}$$

6 unkwons-4 equations $\implies$ we need 2 characteristic equations.

4.2 Configurations

One of the terminals is common between input and output.

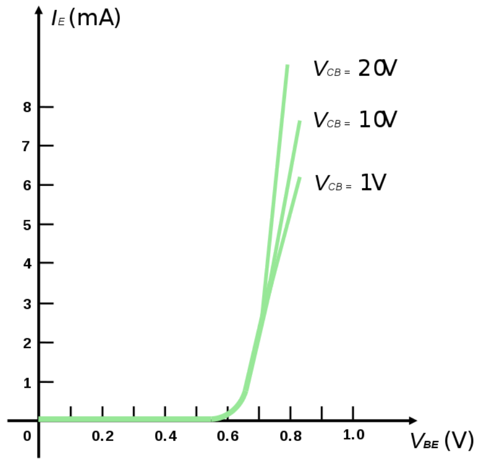


4.3 Characteristic curves

Let us experimentally characterize the BJT measuring both families of characteristic curves.

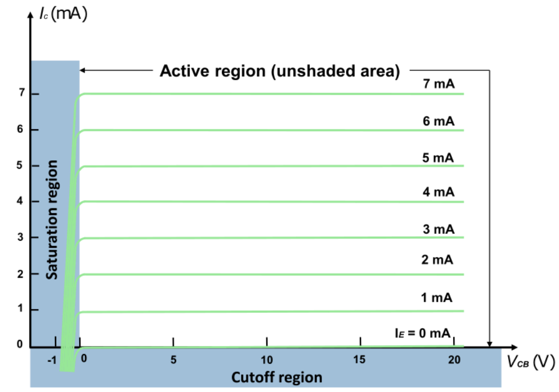
4.3.1 Common Base

$$I_E = f\left(V_{BE}, V_{CB} = \text{ cte }\right)$$



Characteristic curve of a diode. It barely depends on the output voltage.

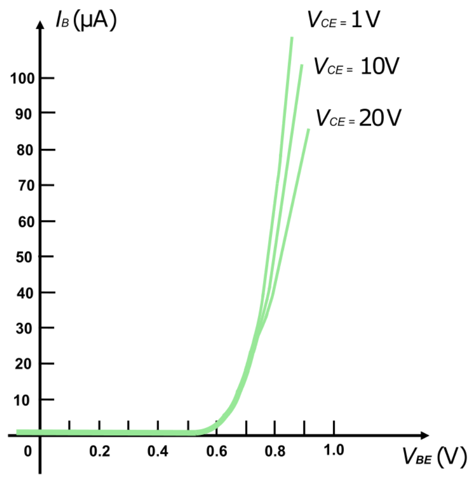
$$I_C = f\left(V_{CB}, I_E = \text{ cte }\right)$$



Current is essentially constant with no amplification.

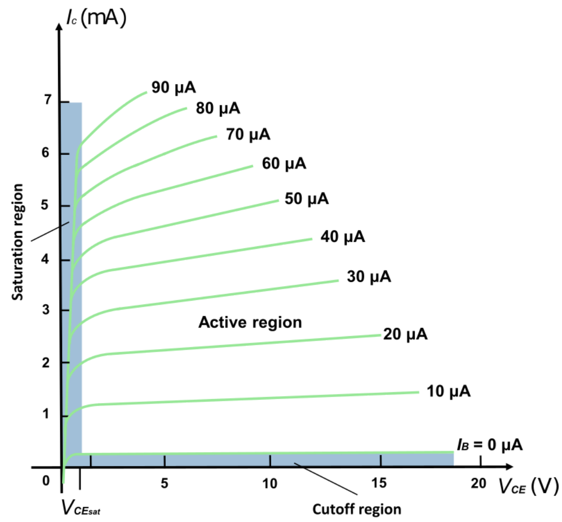
4.3.2 Common Emitter

$$I_B = f\left(V_{BE}, V_{CE} = \text{ cte }\right)$$



Essentially the characteristic curve of a diode. For high enough voltage V_{CE} saturates and $V_{BE} \approx 0.7V(Si)$

$$I_C = f\left(V_{CE}, I_B = \text{ cte }\right)$$



For $V_{CE} > 0.2V$ $I_B > 0$, the output current is mostly constant, and there is current gain $I_C = \beta I_B$.

Remarks:

- In active mode, the collector behaves as a **current source**: the current I_C does not change (almost) even though the voltage V_{CE} does. Such current source is **controlled** by the base current I_B.
- When a transistor operates in active region its input resistance is high while its output resistance is low. TRANSfer-resISTOR indicates such capacity to transfer its resistance from high to low.
- In saturation, V_{CE} reaches a minimum and stays there, and we could think of the transistor as a shorted circuit between collector and emitter. (Fully ON).

4.4 Modes

- **Cut-off**: both B-E and B-C are *reverse-biased*. Therefore, $V_{BE} \leq 0.7V$, $V_{BC} \leq 0.7V$, and there is no current $I_C = I_B = I_E = 0$.
- **Active**: B-E is *forward-biased* so there is some current flowing into the base. We have seen that $V_{CE} \geq 0.2V$ (so $V_{BC} = -V_{CE} + V_{BE} = 0.7V - V_{CE} \leq 0.5V$ and B-C is *reverse-biased*). Also, $I_C \propto I_B$, and much higher than I_B (and then $I_E \approx I_C \gg I_B$)
- **Saturation**: both B-E and B-C are *forward-biased* so there is current flowing into the base. In this case the current in the base will be higher than the current in the emitter $I_B > I_E$.

4.5 Transistor parameters

4.5.1 Current gain in common emitter (β)

Also appearing as h_{FE} on datasheets.

$$\beta = h_{FE} = \frac{I_C}{I_B}$$

The higher, the better amplifier

4.5.2 Current gain in common base (α)

$$\alpha = \frac{I_C}{I_E} \approx 1$$

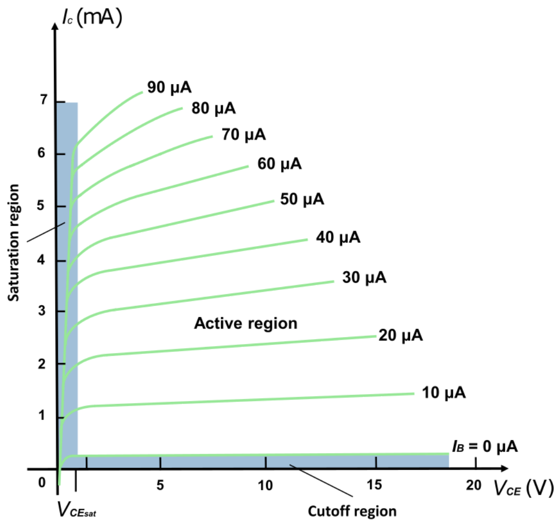
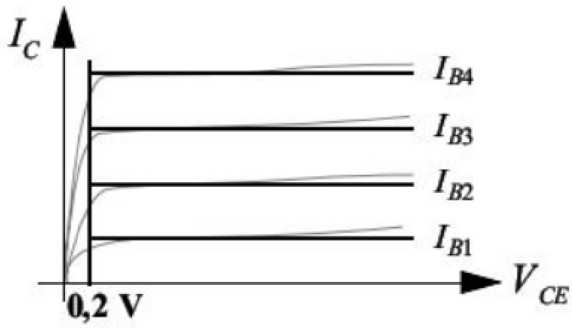
$$\beta = \frac{\alpha}{(1-\alpha)}$$

$\alpha \approx 1 \implies$ Short circuit

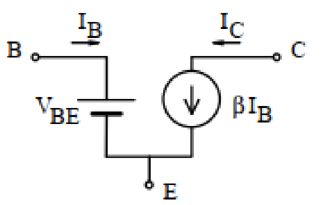
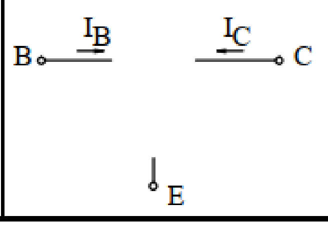
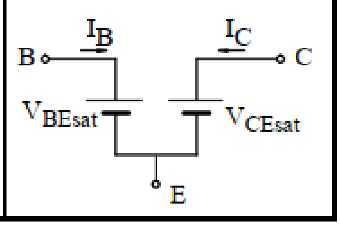
5. Modeling the transistor

5.1 Piecewise-linear model

A transistor is a non-linear component. However, one can approximate the global non-linear behavior by local linear behavior where the transistor is effectively replaced by linear components.

EXPERIMENT	MODEL
	

Mode		Equations	Conditions
Active	NPN	$V_{BE}=0.7V$ $I_C=\beta_F I_B$	$I_B>0$ $V_{CE}>0.2V$
	PNP	$V_{BE}=-0.7V$ $I_C=\beta_F I_B$	$I_B<0$ $V_{CE}<-0.2V$
Saturation	NPN	$V_{BE}=0.7V$ $V_{CE}=0.2V$	$I_B>0$ $I_C/I_B<\beta_F$
	PNP	$V_{BE}=-0.7V$ $V_{CE}=-0.2V$	$I_B<0$ $I_C/I_B<\beta_F$
Cut-off	NPN	$I_B=0$ $I_C=0$	$V_{BE}<0.7V$ $V_{BC}<0.7V$
	PNP	$I_B=0$ $I_C=0$	$V_{EB}<0.7V$ $V_{CB}<0.7V$

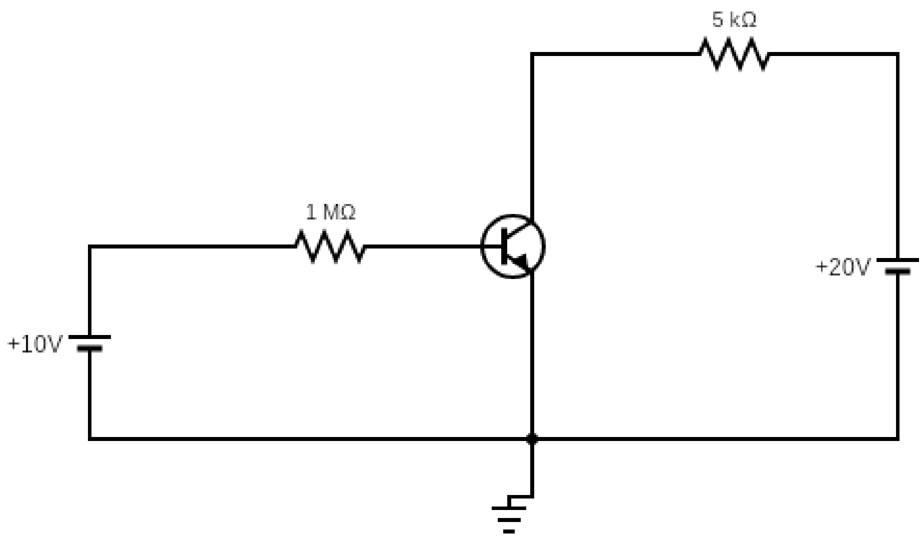
Mode	Active	Cut off	Saturation
Circuit Model			

6. Circuit analysis of transistors

1. Assume direction of currents in B,C,E
2. Assume a mode for the transistor and write down the corresponding equations.
3. Write down Kirchhoff equations for the circuit.
4. In general we'll have to solve a non-linear system of equations, by means of:
   - Graphically using the I-V curves of the transistor
   - Circuit simulations
   - **Linear approximation**
   - Other models (like Ebbers-Moll model described in the Appendix)

5. In case we get a contradiction with the conditions of the transistor mode, we start all over again assuming the different mode.

Solve the circuit knowing that $\beta = 100$



Applying KVL

$$10 = 1I_B + V_{BE}$$
$$20 = 5I_C + V_{CE}$$

Assuming cut-off:

$$I_B = I_C = 0$$

Solution:

$$I_B = 0 \text{ mA}, I_C = 0 \text{ mA}, V_{BE} = 10 \text{ V}, V_{CE} = 20 \text{ V}$$

but

$$V_{BE} = 10 \text{ V} > 0.7 \text{ V}$$

Inconsistent!

Assuming active mode:

$$V_{BE} = 0.7V$$
$$I_C = 100I_B$$

Solution:

$$I_B = 9.3\mu\text{A}, I_C = 0.93\text{mA}, V_{BE} = 0.7 \text{ V}, V_{CE} = 15.35\text{V}$$

$$V_{CE} = 15.35 \text{ V} > 0.2V$$

7. Digital circuits

Electronic circuits that process digital signals, in particular binary signals that only take two values. Typically these values are encoded in two voltages, HIGH=5V and LOW=0V

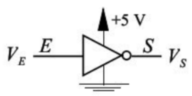
The simples digital circuit is a **logic gate**, a elementary logic operation. Any complex operation can be decomposed in terms of simpler logic gates.

Digital circuits are represented by a **truth table**.

7.1 Logic gates

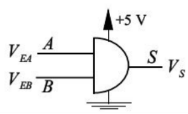
NOT

V_E	V_S
L	H
H	L



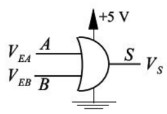
AND

V_{EA}	V_{EB}	V_S
L	L	L
L	H	L
H	L	L
H	H	H



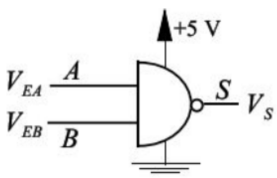
OR

V_{EA}	V_{EB}	V_S
L	L	L
L	H	H
H	L	H
H	H	H



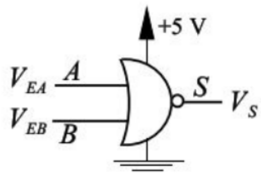
NAND

V_{EA}	V_{EB}	V_S
L	L	H
L	H	H
H	L	H
H	H	L



NOR

V_{EA}	V_{EB}	V_S
L	L	H
L	H	L
H	L	L
H	H	L



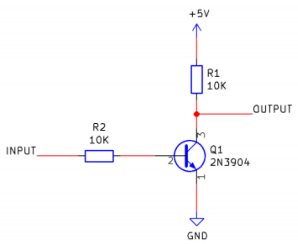
7.2 Logic families

- Diode logic (DL)
- Diode-Transistor logic (DTL)
- Resistor-Transistor logic (RTL)
- Transistor-Transistor logic (TTL)
- NMOS logic
- CMOS logic

7.3 RTL logic

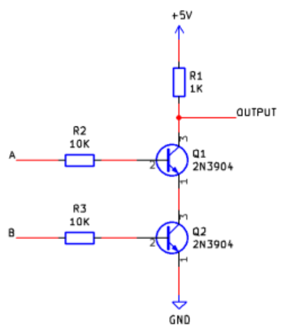
Logic gates combine resistors and BJTs. Used in Apollo missions. The disadvantage of RTL is its high power dissipation when the transistor is switched on.

NOT



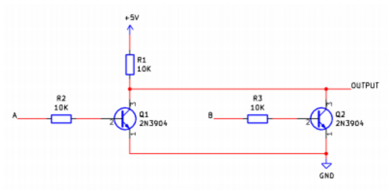
NOT Gate

NAND



NAND Gate

NOR



NOR Gate

RTL inverter: When the input is off (Input = 0V) the transistor is switched off (CUT-OFF) and there is no current. This means that the output is connected to 5V via the 10K resistor and therefore the output is on (5V). When the input is on (Input = V_{input}) the transistor turns on (SATURATION) and therefore connects the output to ground through the transistor. Therefore, the output switches to $0.2V \approx 0V$.

This configuration can be used to switch on high currents (used to power a DC motor) with a small control current in the base.