SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

7. Bipolar Junction Transistors

- DT009, Year 1, Semester 2
- Module Title: Electronic Systems 1.1
- Module Code: ELEC1109
- ECTS Credits : 5

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Syllabus - Analogue Electronics

1. Introduction to semiconductor solid state physics.
2. The characteristics of a pn junction.
3. Characteristics of both npn and pnp BJTs.
4. Characteristics of n and p channel FETs.
5. The design of simple circuits using diodes and transistors.

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Objectives

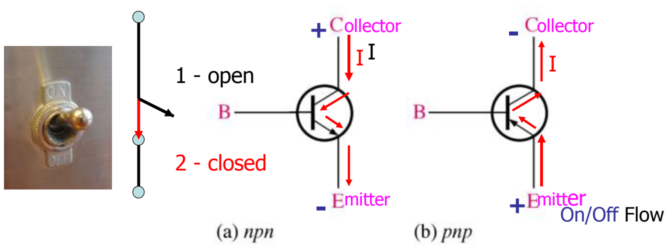
- Describe the basic structure of the bipolar junction transistor (BJT)
- Explain and analyze basic transistor bias and operation
- Discuss the parameters and characteristics of a transistor and how they apply to transistor circuits
- Discuss how a transistor can be used as an amplifier or a switch

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Introduction

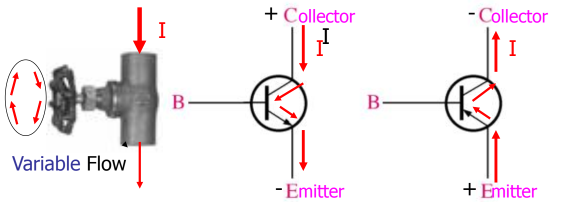
A transistor is a device that can be used to either switch flow on/off or "control flow" device.

Let's first consider its operation in a simpler view as a flow switching device.



Introduction

Let's first consider its operation in a simpler view as a current controlling device.

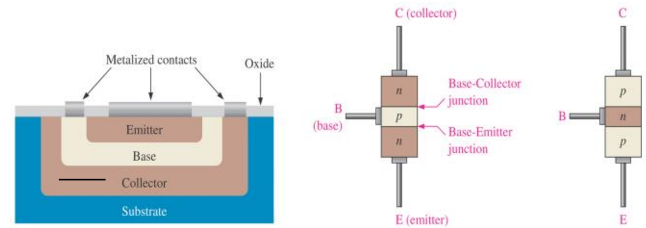


(a) *npn* (b) *pnp*

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

BJT Construction

1. Physical construction of a BJT is deposited layers of "doped " N and P semiconductor materials (Fig.a).
2. With diodes there is one p-n junction. With **bipolar junction transistors (BJT)**, there are three layers forming two p-n junctions. Transistors can be either **npn** (Fig.b) or **pnp** (Fig.c) type.

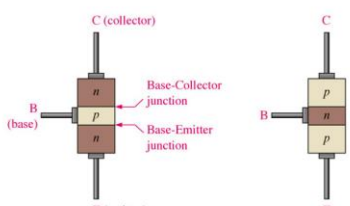


(a) Basic epitaxial planar structure (b) *npn* (c) *pnp*

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Structure

With diodes there is one p-n junction. With **bipolar junction transistors (BJT)**, there are three layers forming two p-n junctions. Transistors can be either **pnp** or **npn** type.

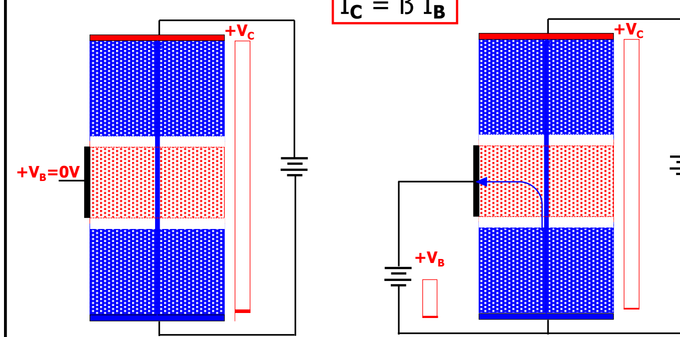


(b) *npn* (c) *pnp*

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Operation Principle

$$\boxed{I_C = \beta I_B}$$

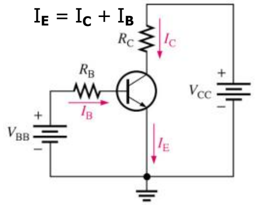


Basic Transistor Operation

Look at this one circuit as two separate circuits:

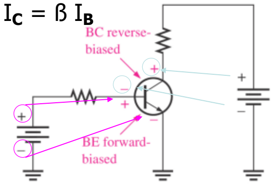
- The base-emitter (left side) circuit and collector-emitter (right side) circuit. The amount of current flow in the base-emitter circuit controls the amount of current that flows in the collector circuit.
- Small changes in the transistor base-emitter current yields a large change in collector-current.
- Note that base-emitter junction is *forward-biased*, while the base-collector junction is *reverse-biased* (known as forward-reverse bias).

$I_E = I_C + I_B$



(a) *npn*

$I_C = \beta I_B$



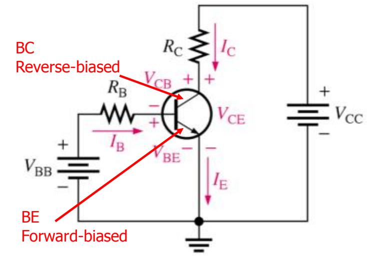
Transistors Characteristics and Parameters

For proper operation, the base-emitter junction is forward-biased by V_{BB} and conducts just like a diode. I_B is set.

The collector-base junction is reverse biased by V_{CC} and blocks current flow through it's junction just like a diode.

Current flow through the base-emitter junction will help establish the path for current flow from the collector to emitter.

$I_C + I_B$ results in I_E



Transistors Characteristics and Parameters

Analysis of transistor circuit to predict the dc voltages and currents requires use of Ohm's law, Kirchhoff's voltage law and the β for the transistor.

Determine the base BIAS current.

Using Kirchhoff's voltage law, subtract the 0.7 (V_{BE}) from V_{BB} and the remaining voltage is dropped across R_B. Determining the current for the base with this information is a matter of applying of Ohm's law.

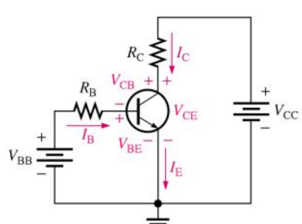
$V_{R_B}/R_B = I_B$ (ohm's law)

The collector DC current is determined by multiplying the base current by beta.

$I_{C_{dc}} = \beta I_{B_{dc}}$

or $\beta_{DC} = I_C/I_B$

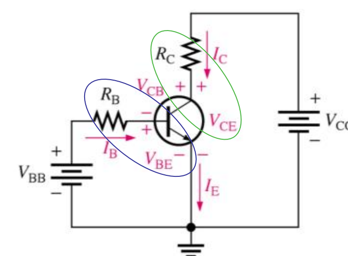
Note:
0.7 V_{BE} will be used in most analysis examples.



Transistor Characteristics and Parameters

What we ultimately determine by use of Kirchhoff's voltage law for series circuits is that; In the base circuit, V_{BB} is distributed across the base-emitter junction and R_B in the base circuit.

In the collector circuit we determine that V_{CC} is distributed proportionally across R_C and the transistor (V_{CE}).



SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Characteristics and Parameters

- Small $\Delta I_{DC\,base\text{-}emitter}$ yields Large $\Delta I_{DC\,collector\text{-}emitter}$
- This relationship of current change (collector to base) ($\Delta I_{DC\,collector\text{-}base}$) is called ***beta.*** **(β)**

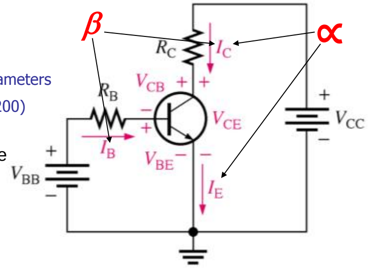
$\beta_{DC} = I_C / I_B$ (Current Gain)

Data sheets will refer to hybrid (h) parameters
$h_{FE} = \beta_{DC}$ (typical h_{FE} values 20 – 200)

- The relationship of current change (collector to emitter) ($\Delta I_{DC\,collector\text{-}emitter}$) is called alpha. **($\propto$)**

$\propto_{DC} = I_C / I_E$ is always >1.

(Typical $\propto$ values 0.95 – 0.99+)



SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Characteristics and Parameters

There are three key dc voltages and three key dc currents to be considered. Note that these measurements are important for troubleshooting.

***I_B*: dc base current**

***I_E*: dc emitter current**

***I_C*: dc collector current**

***V_{BE}*: dc voltage across base-emitter junction**

***V_{CB}*: dc voltage across collector-base junction**

***V_{CE}*: dc voltage from collector to emitter**

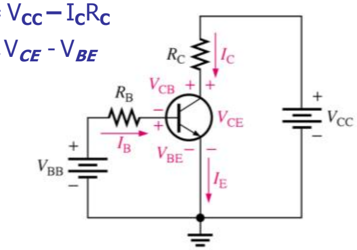
Relationships of Key Parameters:

$V_{BE} = 0.7$ V.

$I_B = (V_{BB} - V_{BE})/R_B = (V_{BB} - 0.7V)/R_B$

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

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

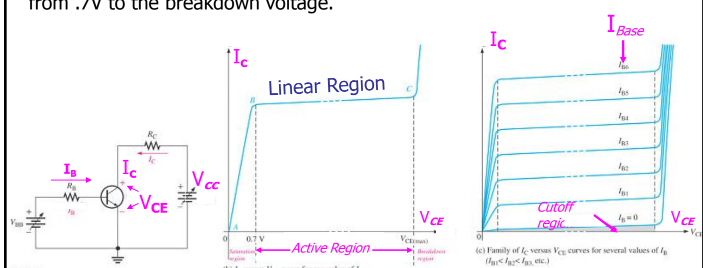


SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Collector Characteristic Curves

Collector characteristic curves give a graphical illustration of the relationship of: Ic (collector current), and V_{CE} (Voltage-Collector to Emitter) with specified amounts of I_B (base current).

With greater increases of V_{CC} , V_{CE} continues to increase until it reaches breakdown, but the current remains about the same in the **linear** region from .7V to the breakdown voltage.

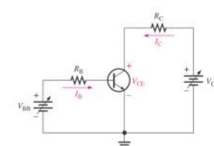


(a) Circuit
(b) I_C versus V_{CE} curve for one value of I_B
(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)

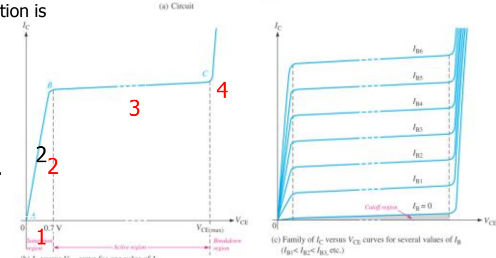
SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Characteristics Curves - Review

1. Vcc = 0
   I_B is thru the base & emitter.
   Transistor is in Saturation
2. V_{CC}↑, V_{CE}↑ and Ic ↑ with increase Vcc
3. V_{CE} exceeds 0.7V
   Base/Collector junction is reverse-biased
   Transistor operates in Linear region
4. "breakdown" or Avalanche region.
   .... Bad!!



(a) Circuit



(b) I_C versus V_{CE} curve for one value of I_B
(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)

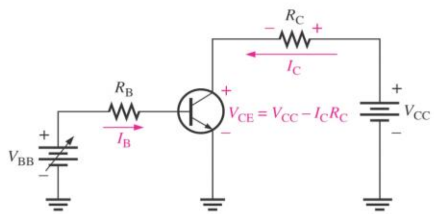
SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Characteristics and Parameters

Current flow in the collector part of the circuit is, determined by I_B multiplied by β.
However, there is a limit to how much current can flow in the collector circuit regardless of additional increases in I_B.
Once this maximum is reached, the transistor is said to be in **saturation**.
Note that saturation can be determined by application of Ohm's law.

$$I_{C(sat)} = V_{CC}/R_C$$

The measured voltage across the now "shorted" collector and emitter is $V_{CE} = 0V$.



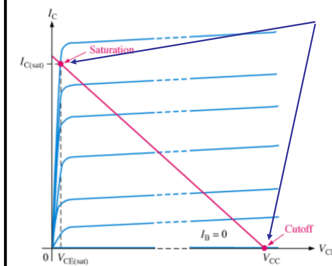
SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Characteristics and Parameters

The **dc load line** graphically illustrates $I_{C(sat)}$ and cutoff for transistor.

Practically the operation (quiescent) point of transistor (V_{CEQ}, I_{CQ}) has coordinates (V_{CC}-$V_{CE(sat)}/2$, $I_{C(sat)}/2$).

In case of $V_{CC} >> V_{CE(sat)}$ the quiescent point is even simpler: $I_{CQ}=V_{CC}/2R_C$ and $V_{CEQ}=V_{CC}/2$



NOTE:

This will be the area of operation for all out transistor applications.

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

BJT (Transistor) Amplifier

Amplification is the process of linearly increasing the amplitude of an electrical signal.

Some designation standards and conventions:

DC Currents: I_C I_E I_B

DC Voltages: V_{BE} V_{CB} V_{CE} V_B V_C V_E

External DC Resistance: R_E R_C R_B

AC Currents: I_c I_e I_b

AC Voltages: V_{be} V_{cb} V_{ce} V_b V_c V_e

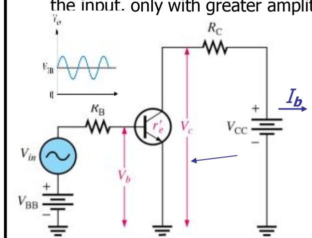
External AC Resistances: R_e R_c R_b

Internal Transistor Resistances: r' r'_e

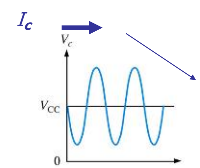
SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

BJT (Transistor) Amplifier

1. Amplification of a relatively small ac voltage can be had by placing the ac signal source in the base circuit.
2. Recall that small changes in the base current circuit causes large changes in the collector current circuit.
3. The small ac voltage causes the base current to increase and decrease accordingly and with this small change in current the collector current will mimic the input, only with greater amplitude.



(a) Circuit with ac input voltage V_{in} and dc bias voltage superimposed



(b) Waveforms

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

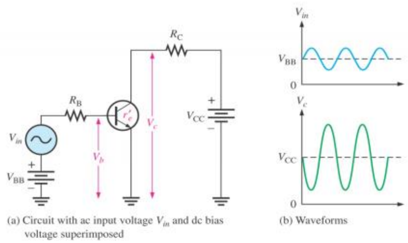
Transistor Voltage Amplification

A transistor amplifier requires DC biasing voltages to "enable" the base-emitter junction to pass DC current, I_{BE}, from base to emitter. I_{BE} is "multiplied" by β in the collector-emitter circuit, enabling I_{CE} to flow collector to emitter.

Follow the signal thru this transistor amplifier:

1. A small AC *voltage*, (*Vs*), is applied to the base-emitter circuit.
2. The signal, Vs, is superimposed on the $I_{B\,DC}$ thru a "coupling capacitor".
3. The combined Vs/$I_{B\,DC}$ ac signal, V_b is applied to the base.
4. $V_b = I_e r'_e$
5. I_b x β = Ic
6. *Ic* passes thru Rc, creating an output voltage *Vc*.
7. *Vc* is β times larger than Vs.

We have successfully amplified Vs to Vc,



(a) Circuit with ac input voltage V_{in} and dc bias voltage superimposed

(b) Waveforms

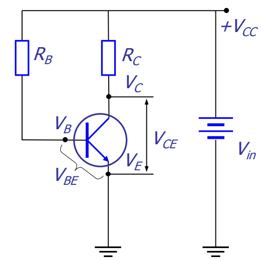
SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Biasing

The previous circuit needs a separate DC voltage source V_{BB} to arrange a proper transistor biasing.

Practically R_B can be connected directly to V_{CC}.

Calculate the bias condition ($I_{CQ}=V_{CC}/2R_C$ and $V_{CEQ}=V_{CC}/2$) using the following formulas:



$$I_{CQ} = \frac{V_{CC}}{R_C} \qquad V_{BEQ} \approx 0.7\ \text{V}$$

$$I_{CQ} = \frac{V_{CC}}{2R_C}$$

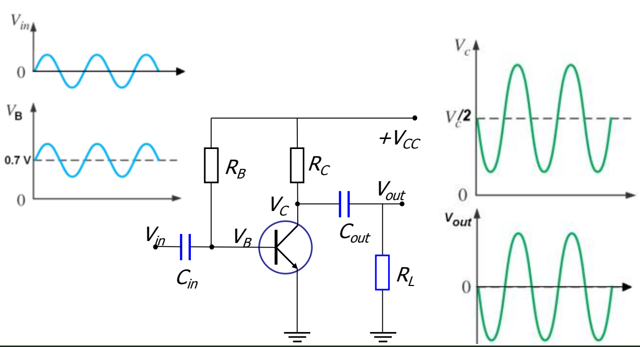
$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{V_{CC}}{2\beta R_C}$$

$$R_B = \frac{V_{CC}-V_{BE}}{I_{BQ}} = \frac{2R_C(V_{CC}-0.7V)\beta}{V_{CC}} \approx 2R_C\beta$$

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Amplifier

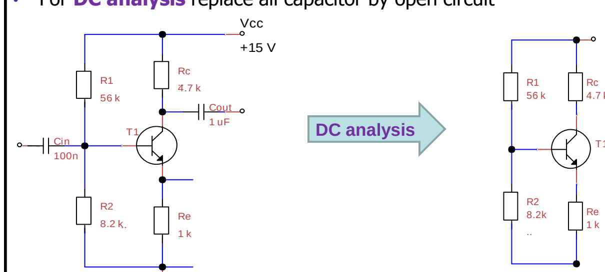
In order to amplify ac signal the ac signal Source and Load must be connected to the circuit via capacitors (C_{in}, C_{out}) to avoid disturbance of dc biasing.



SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

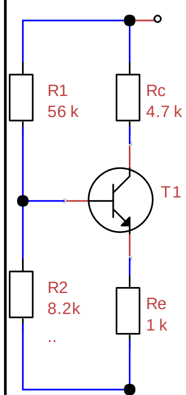
Practical Transistor Amplifier

- In previous circuit *Ic=Ib* x *β*, therefore it depends on *β*, which can very with large tolerance, e.g. from 100 to 300.
- More practical circuit is BJT amplifier with base *Voltage Divider* and feedback resistor R_E.
- Capacitors are used to separated pure ac Vin and Vout from dc biased Transistor pins
- For **DC analysis** replace all capacitor by open circuit



SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

CE Amplifier (DC Analysis)



1. Begin with V_B determined by Voltage divider

$$V_B = V_{CC}\left(\frac{R_2}{R_1+R_2}\right) = 15\text{V}\cdot\left(\frac{8.2\text{ k}}{56\text{ k}+8.2\text{ k}}\right) \approx 1.92\text{V}$$

2. The Base-Emitter p-n junction is forward biased, therefore $\boxed{V_{BE} \approx 0.7\text{ V}}$ and V_E is:

$$V_E = V_B - V_{BE} = 1.92\text{ V} - 0.7\text{ V} = 1.22\text{ V}$$

3. Applying Ohm's law for R_E and assuming

$$I_C \approx I_E = \frac{V_E}{R_E} = \frac{1.22\text{ V}}{1\text{ k}\Omega} = 1.22\text{ mA}$$

4. Finally, the collector voltage V_C is :

$$V_{CE} = V_{CC} - I_C R_C = 15\text{ V} - 1.22\text{ mA}\cdot 4.7\text{ k}\Omega \approx 9.28\text{ V}$$

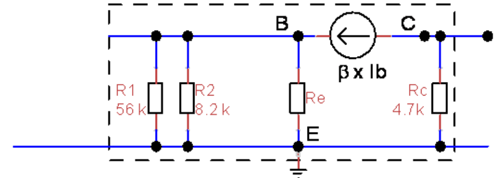
5. And base current is

$$I_B = I_C/\beta = 1.22\text{ mA}/200 \approx 0.0061\text{ mA} = 6.1\,\mu\text{A}$$

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

CE Amplifier (Impedance)

1. To calculate input and output impedance we have
   - to replace DC Voltage source by short circuit (just ground it) and
   - Replace the transistor by its t-equivalent ac model



2. In case $R2 << \beta \cdot R_E$ the input impedance is

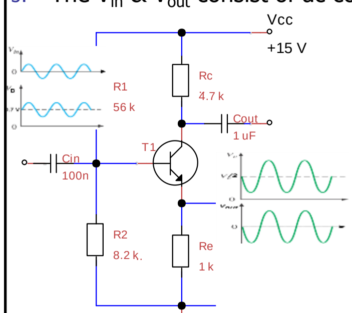
$$Z_{in} = R1 \,\|\, R2 = \frac{R1 \times R2}{R1 + R2} = \frac{56 \times 8.2}{56 + 8.2} = 7.15\text{ k}\Omega$$

3. The output impedance is just a $Z_{out} = R_C = 4.7\text{ k}\Omega$.

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

CE Amplifier (Voltage gain)

1. The voltage gain is a ratio output and input Voltages: V_{out}/V_{in}.
2. The voltages on Transistor pins are the sums of DC bias and ac voltages: $V_B = V_{BQ} + v_b;\ V_E = V_{EQ} - 0.7\text{ V} + v_e;\ V_C = V_{CQ} + v_c$
3. The V_{in} & V_{out} consist of ac components due to capacitors

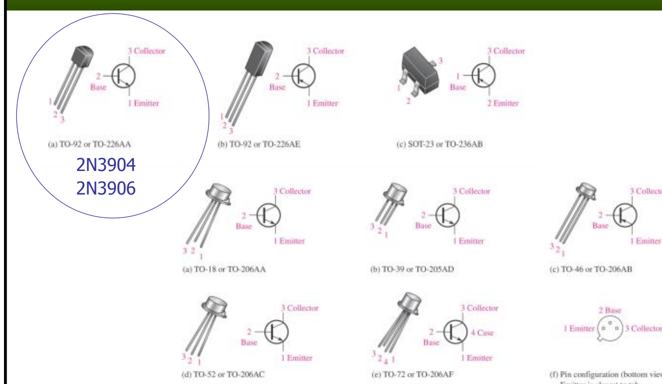


1. Therefore $v_{in} = v_b$ and $v_{out} = v_c$
2. AC voltage and currents are $v_c = i_c \cdot R_C;$ and $i_c \approx i_e = v_e/R_E = v_b/R_E$
3. Therefore $v_c = R_C \cdot v_b / R_E$ and

$$Av = \frac{v_{out}}{v_{in}} = \frac{v_c}{v_b} = \frac{R_C v_b / R_E}{v_b} = \frac{R_C}{R_E} = \frac{4.7\text{ k}\Omega}{1\text{ k}\Omega} = 4.7$$

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Types & Packaging



Same transistor type in metal packaging

Summary

1. The bipolar junction transistor (BJT) is constructed of three regions: base, collector, and emitter.
2. The BJT has two pn junctions, the base-emitter junction and the base-collector junction.
3. The two types of transistors are pnp and npn.
4. For the BJT to operate as an amplifier, the base-emitter junction is forward-biased and the collector-base junction is reverse-biased.
5. The base current, I_B is very small in comparison to I_E and I_C.
6. The ratio of $\beta=I_C/I_B$ is the current gain of a transistor.

Summary

1. A transistor can be operated as an electronics switch.
2. When the transistor is off it is in cutoff condition (no current).
3. When the transistor is on, it is in saturation condition (maximum current).
4. Beta can vary with temperature and also varies from transistor to transistor.

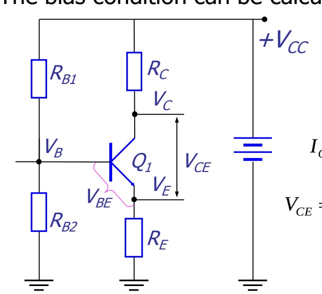
Bipolar Junction Transistors (OPTIONAL)

Practical Transistor Amplifier

In previous circuit *Ic=Ib* x *β*, therefore it depends on *β*, which can very with large tolerance, e.g. from 100 to 300.

More practical circuit is BJT amplifier with base voltage divider and feed back resistor R_E.

The bias condition can be calculate using the following formulas



$$V_B = V_{CC}\left(\frac{R_{B2}}{R_{B1}+R_{B2}}\right)$$

$$V_E = V_B - V_{BE} \qquad V_{BE} \approx 0.7\text{ V}$$

$$I_C \approx I_E = \frac{V_E}{R_E} = \frac{V_B - V_{BE}}{R_E} = \frac{V_B - 0.7V}{R_E}$$

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E \approx V_{CC} - I_C(R_C + R_E)$$

$$\text{Bias condition: } V_{CE} = (V_{CC} - 1)/2$$

$$I_C(R_E + R_C) = (V_{CC} - 1)/2$$

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Practical Transistor Amplifier - Biasing

Example Given: G=4, V_{CC}=15V

Set R_E=1k, R_C=R_E x G=4k

Bias condition : $V_{CE} = (V_{CC} - 1)/2$

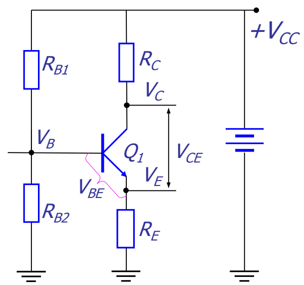
$I_C = (V_{CC} - 1)/2(R_E + R_C) = 1.4mA$

$V_{BE} \approx 0.7\,\text{V}$

$V_B = V_E + V_{BE} = 1.4V + 0.7V = 2.1V$

$V_B R_{B1} = (V_{CC} - V_B) R_{B2}$

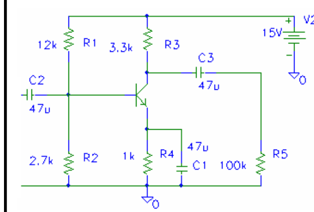
$R_{B1} = R_{B2} \cdot (V_{CC} - V_B)/V_B = 10k \cdot 12.9V / 2.1V \approx 61.5k$



SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Practical Transistor Amplifier

1. On the circuit diagram show the following Voltages: V_{CC}, V_B, V_E, V_C, V_{BE}, V_{CE}, and Currents I_B, I_C, I_E,
2. Calculate the bias condition using the following formulas:
3. Is this amplifier properly biased.
4. What is the gain of this amplifier



$$V_B = V_{CC}\left(\frac{R_{B2}}{R_{B1} + R_{B2}}\right) = 15\frac{2.7}{14.7} = 2.75V$$

$$I_C \approx \frac{V_B - 0.7V}{R_E} = \frac{2.05V}{1k} = 2.05mA$$

$$V_{CE} = V_{CC} - I_C(R_C + R_E) =$$
$$= 15 - 2.05 \cdot 4.3 \approx 5.5V$$

Bias condition : $V_{CE} = (V_{CC} - 1)/2$

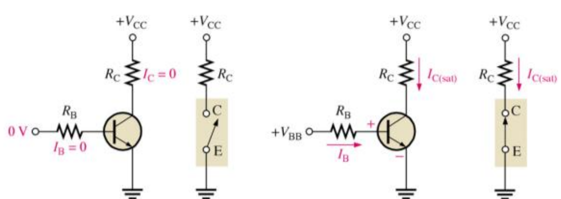
$(V_{CC} - 1)/2 = 7V$

$V_{CE} = 5.5V$

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Switch

A transistor when used as a switch is simply being biased so that it is in cutoff (switched off) or saturation (switched on). Remember that the V_{CE} in cutoff is V_{CC} and 0 V in saturation.



(a) Cutoff — open switch

(b) Saturation — closed switch

$V_{CE(cutoff)} = V_{CC}$

$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{\beta_{DC}}$

$I_{B(min)} = \frac{I_{C\,(sat)}}{\beta_{DC}}$

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

Transistor Switch

Application: Transistor Switch

Base of transistor is "pulsed" with a "squarewave".

"Off" periods provide no base biasing….transistor remains OFF.

"On" periods provide DC bias, switching the transistor "ON"

I_B is max. Ic is max.

LED lights!!