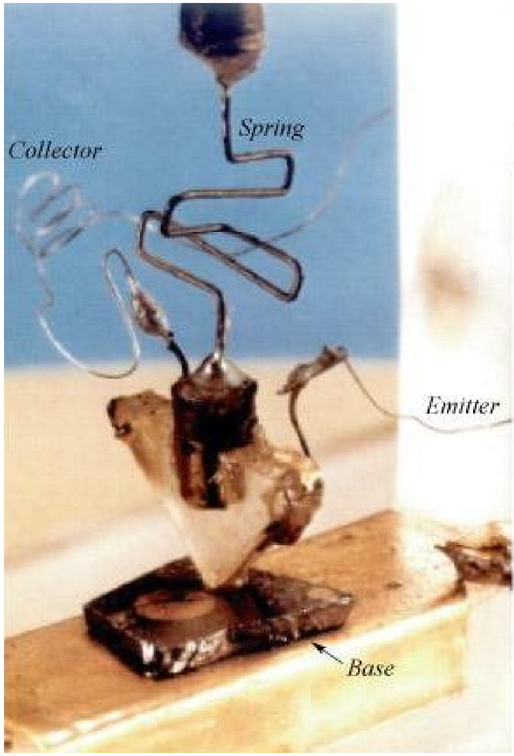
Bipolar Junction Transistor (BJT)

Objectives

- To understand the structure of BJT.
- To explain and analyze the basic transistor circuits.
- To use transistors as an amplifier and electronic switch.
- To design the simple circuits using transistors.
- To study transistor parameters from datasheet.

What is Transistor?

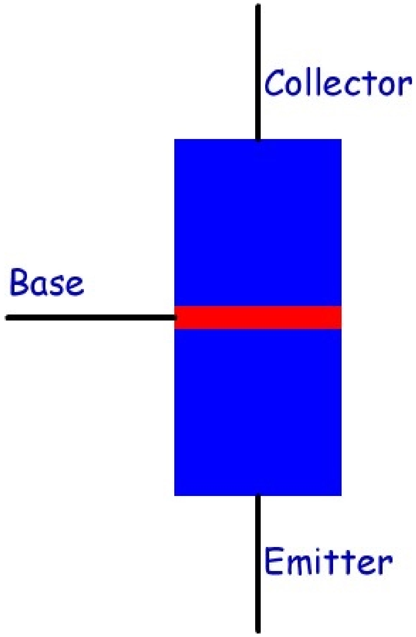
- Invented in 1947 by John Bardeen, Walter Brattain and William Shockley
- Hugh revolution in field of electronics
- First solid-state device able to amplify electric signal
- Universally used is Bipolar Junction Transistor(BJT)



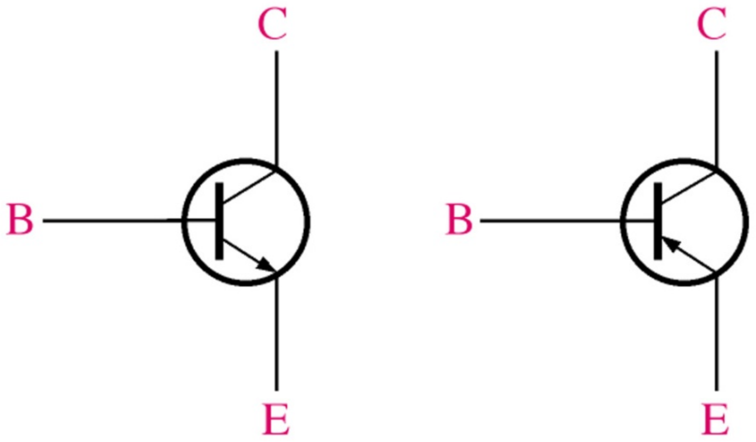
Transistor in 1947

Basic Functions

- Signal Amplifier
- Electronic Switch



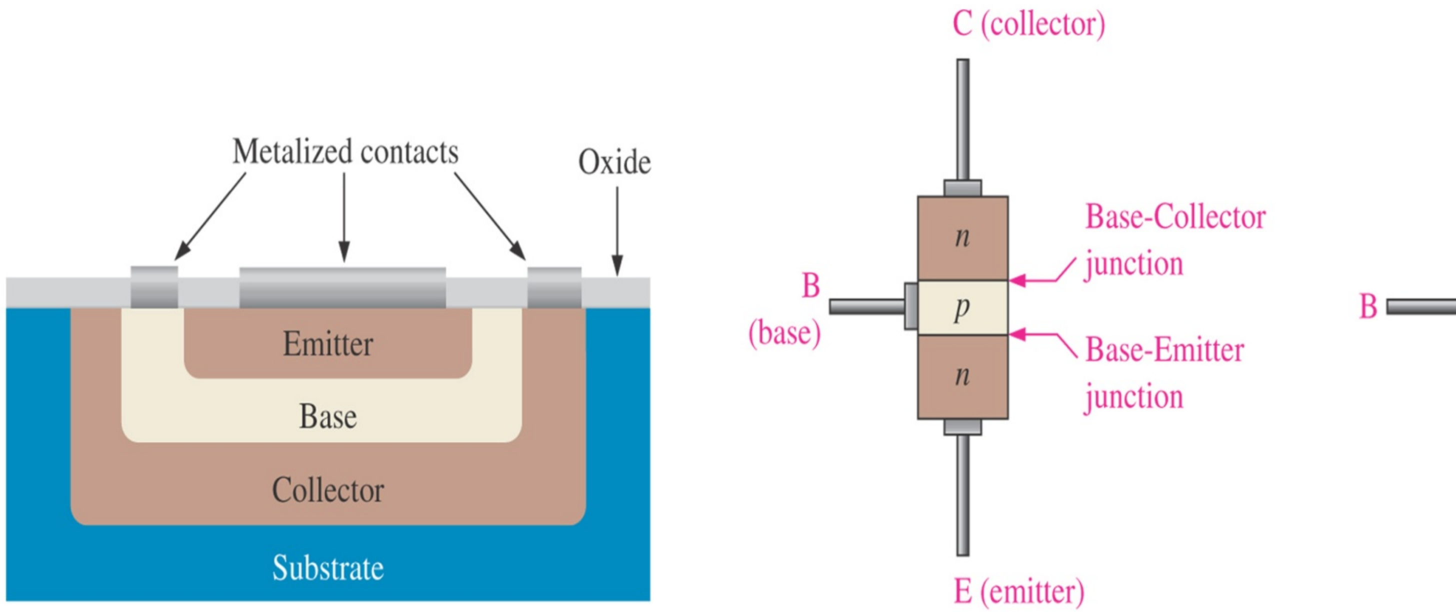
2 Types



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

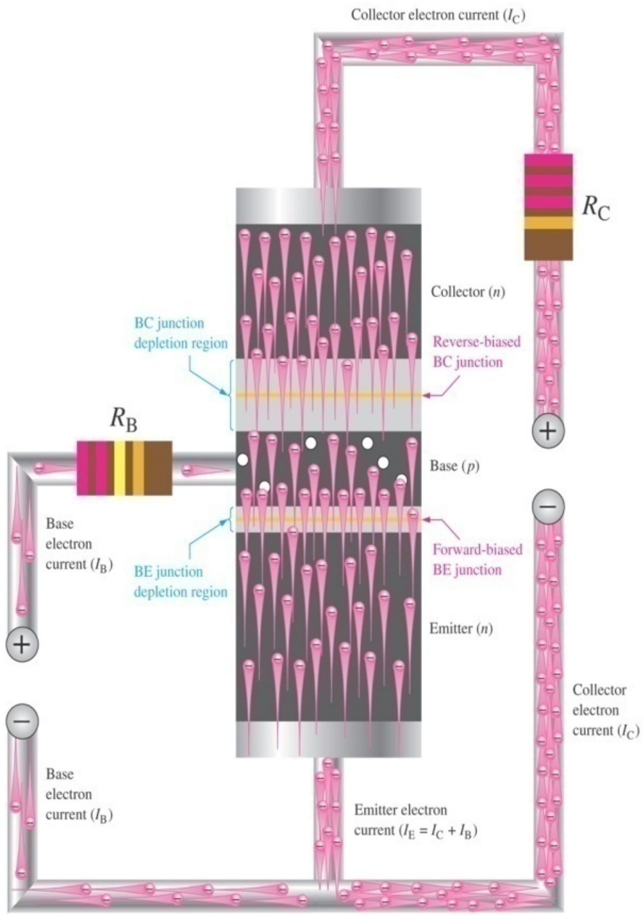
Transistor Structure

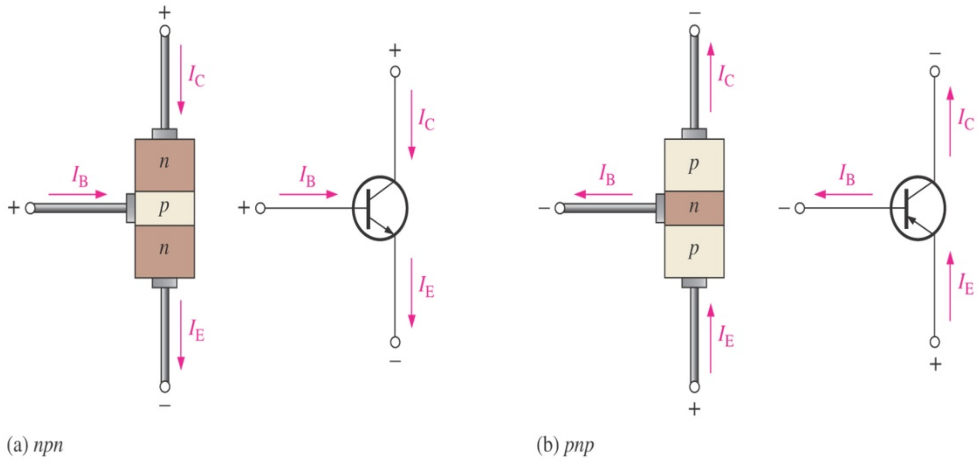
With diodes there is one p-n junction. With **bipolar junction transistors (BJT)**, there are three layers and *two p-n junctions.*.



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

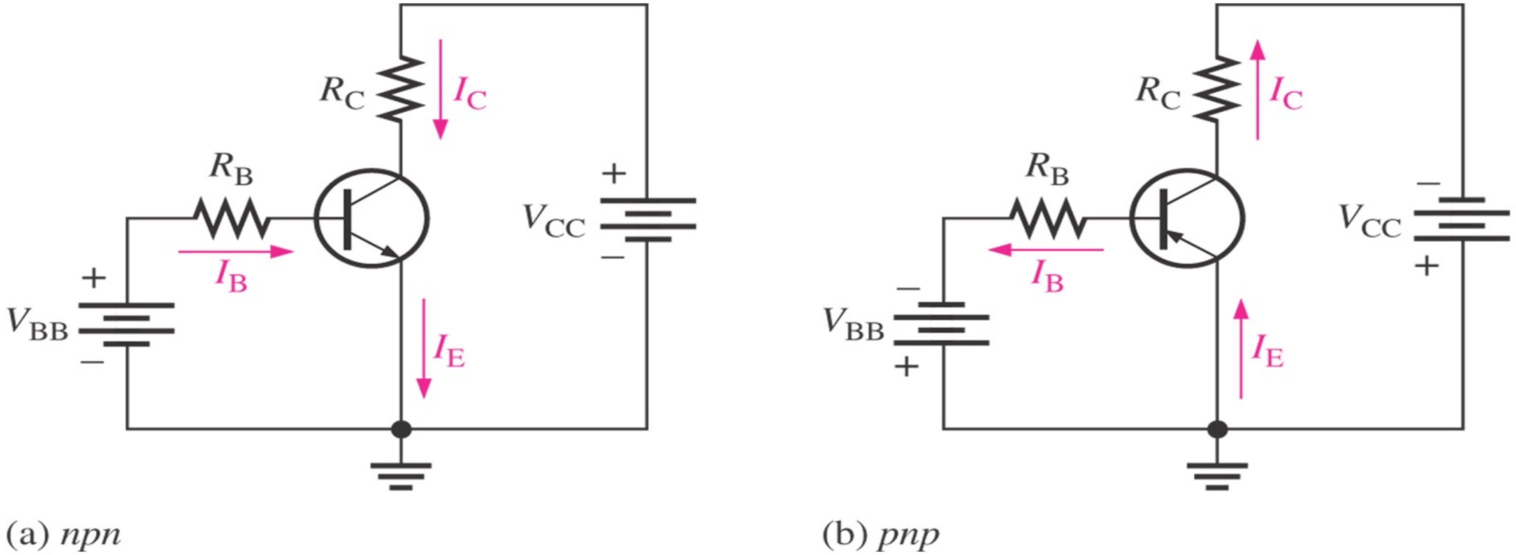
Conducting Current Direction



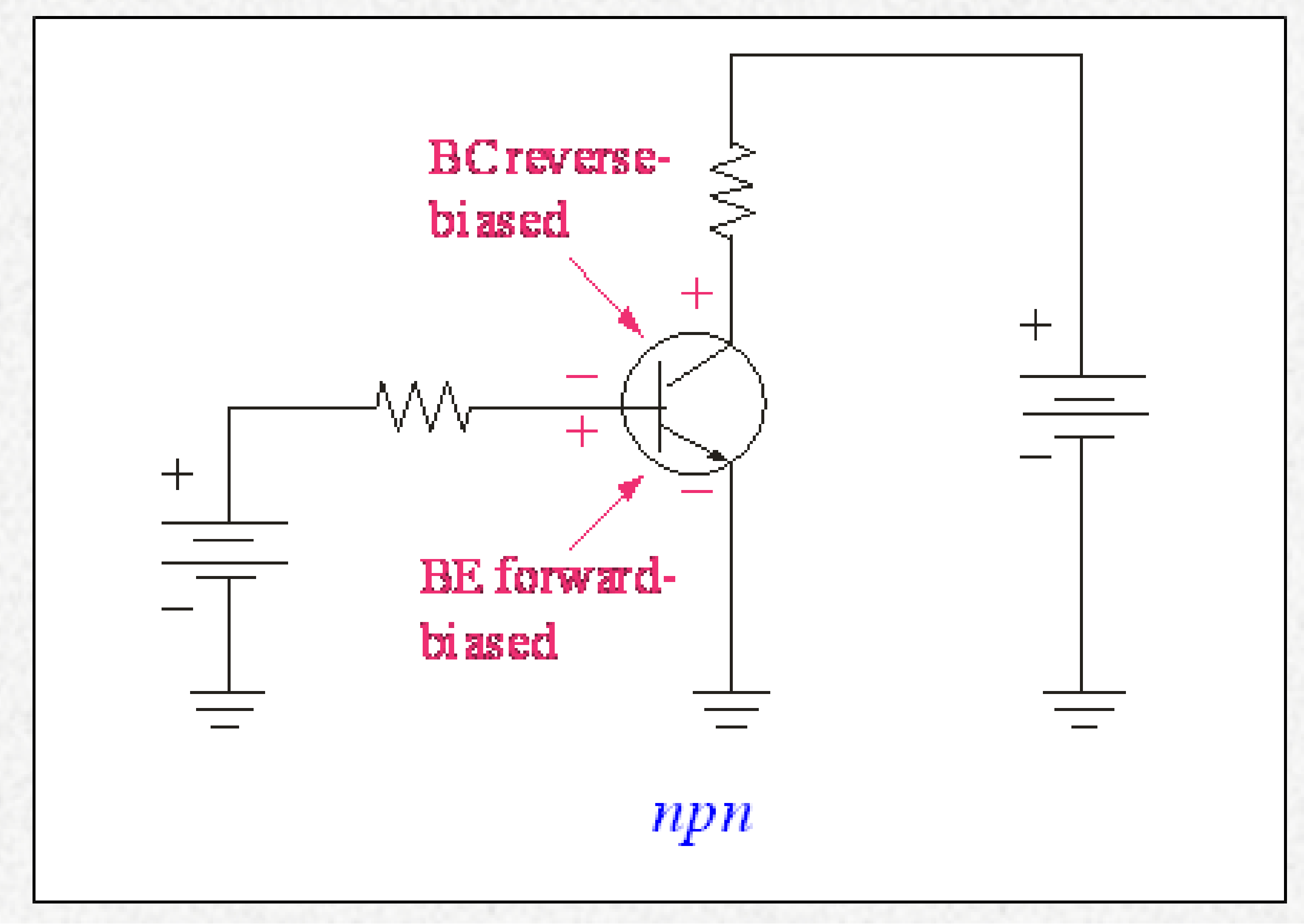


Basic Operation

Look at this one circuit as two separate circuits, the base-emitter(left side) circuit and the collector-emitter(right side) circuit. Note that the emitter leg serves as a conductor for both circuits. The amount of current flow in the base-emitter circuit controls the amount of current that flows in the collector circuit. Small changes in base-emitter current yields a large change in collector-current.



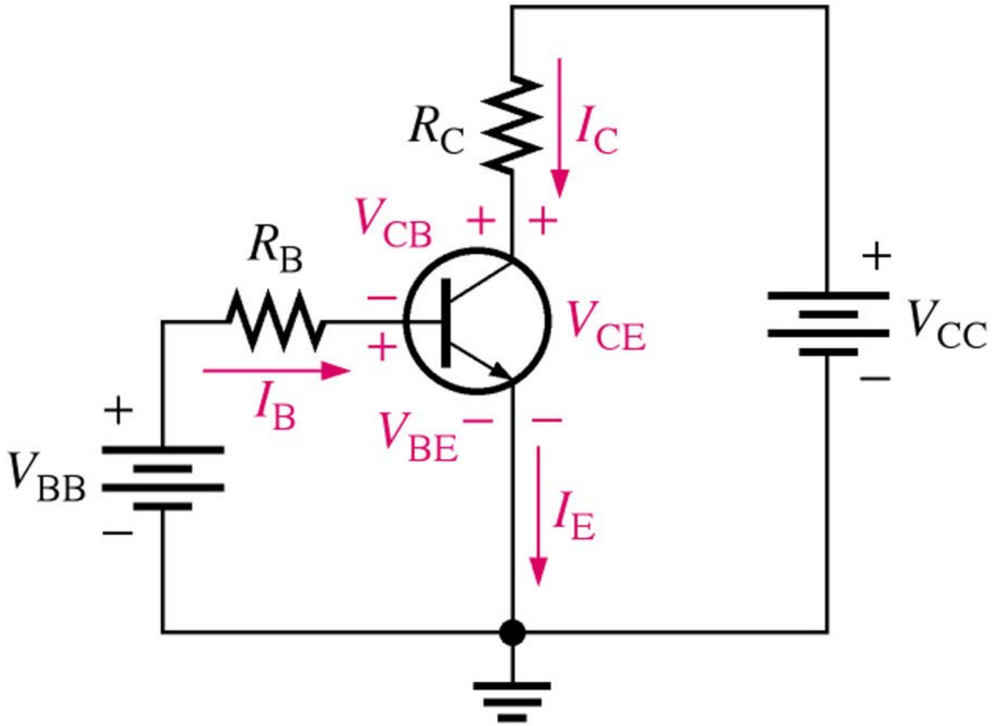
BJT Operation



Transistor Characteristics and Parameters

As previously discussed, base-emitter current changes yield large changes in collector-emitter current. The factor of this change is called ***beta*(β)**.

$$\beta = I_C / I_B$$



Common Emitter Configuration

The beta for a transistor is not always constant. Temperature and collector current both affect beta, not to mention the normal inconsistencies during the manufacture of the transistor.

There are also maximum power ratings to consider.

The data sheet provides information on these characteristics.

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**

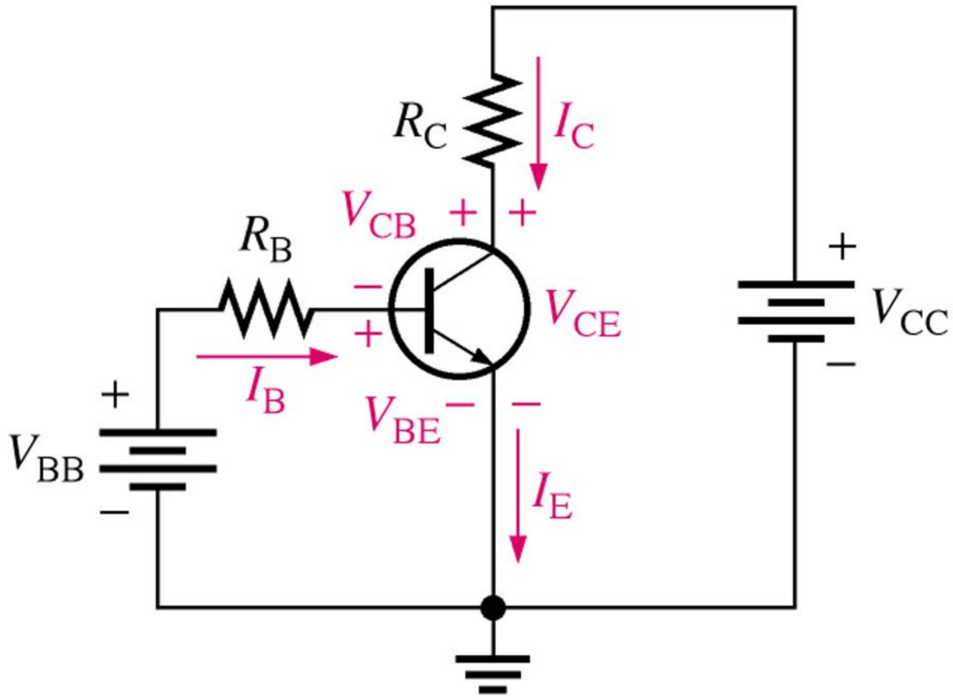
***I_E*: dc emitter current**

***I_C*: dc collector current**

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

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

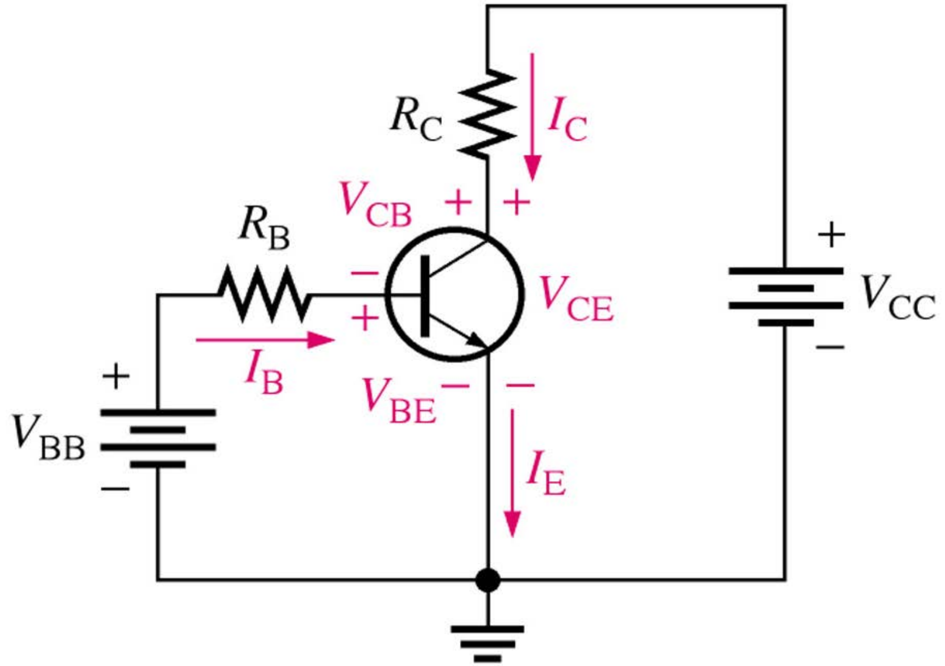
***V_{CE}*: dc voltage from collector to emitter**



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

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

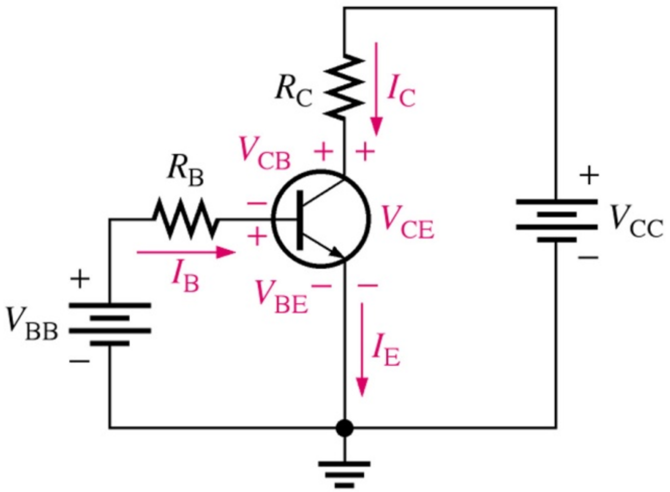
Remember that current flow through the base-emitter junction will help establish the path for current flow from the collector to emitter.



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

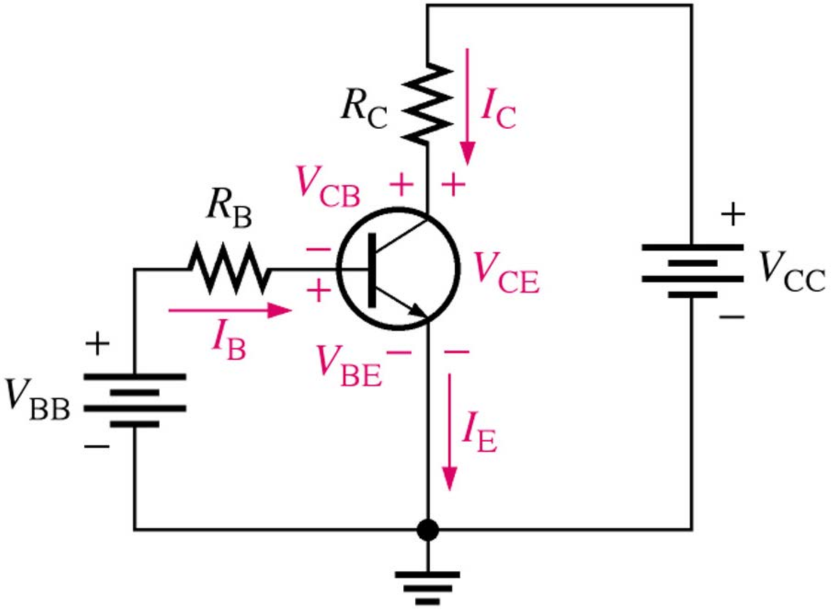
Application of these laws begins with the base circuit to determine the amount of base current. Using Kirchhoff's voltage law, subtract the .7 V_{BE} and the remaining voltage is dropped across R_B. Determining the current for the base with this information is a matter of applying of Ohm's law. $\mathbf{V_{RB}/R_B = I_B}$

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

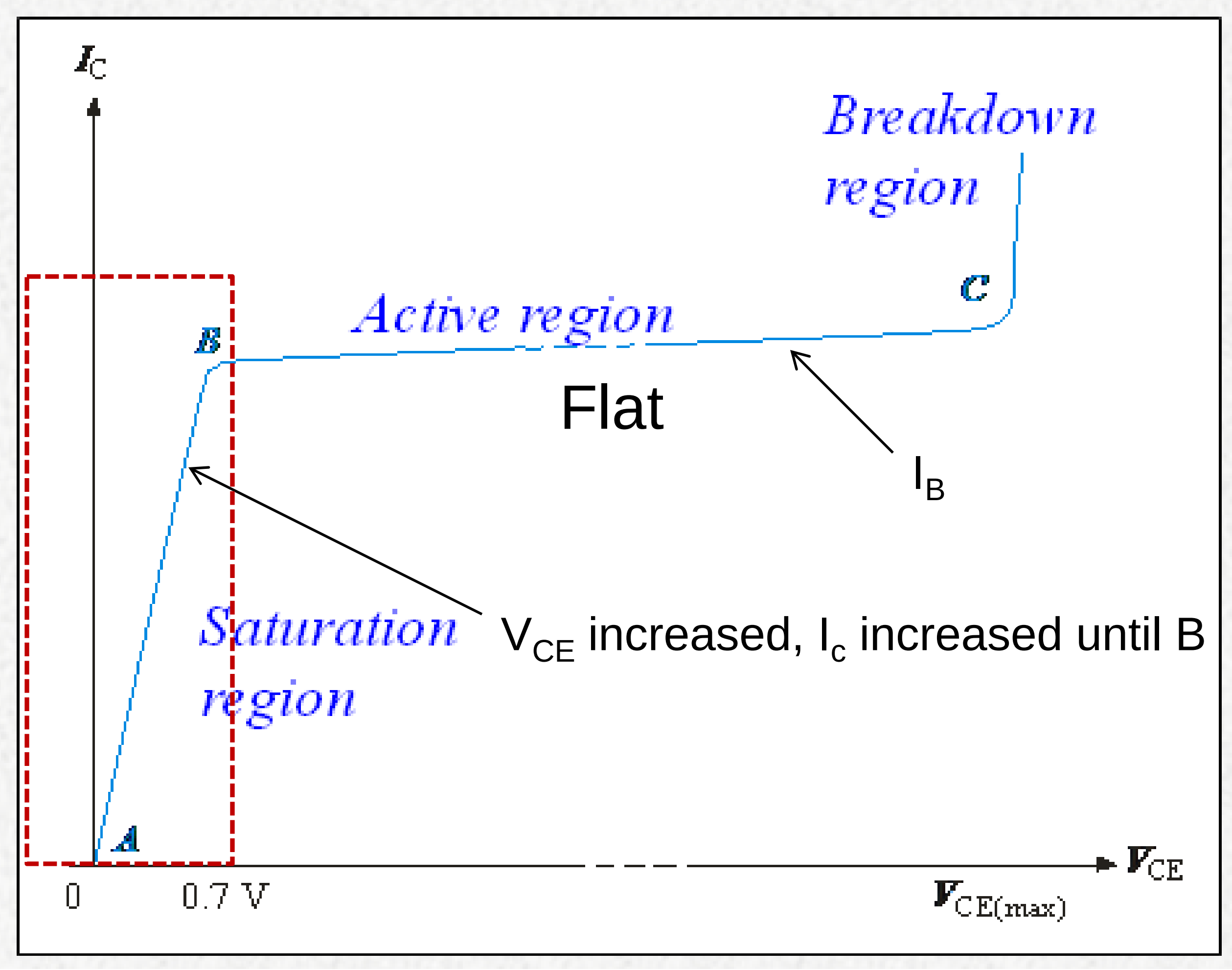


Note. V_{BE} = 0.7 will be used in most analysis examples.

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}).

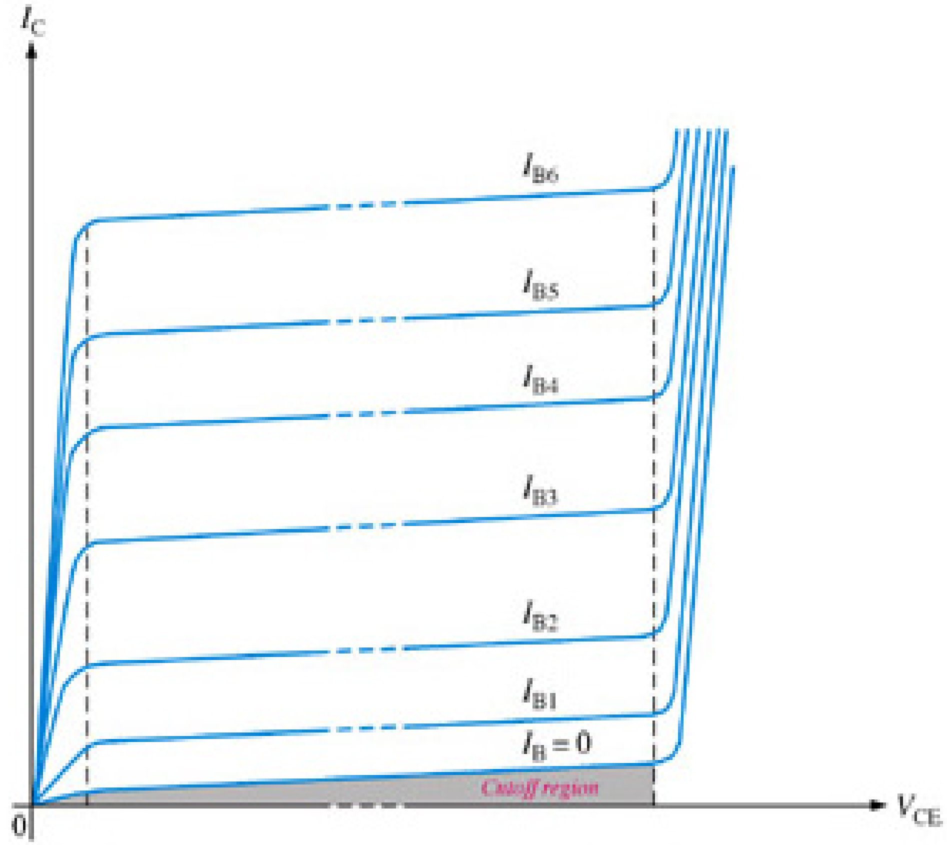


Three-transistor currents

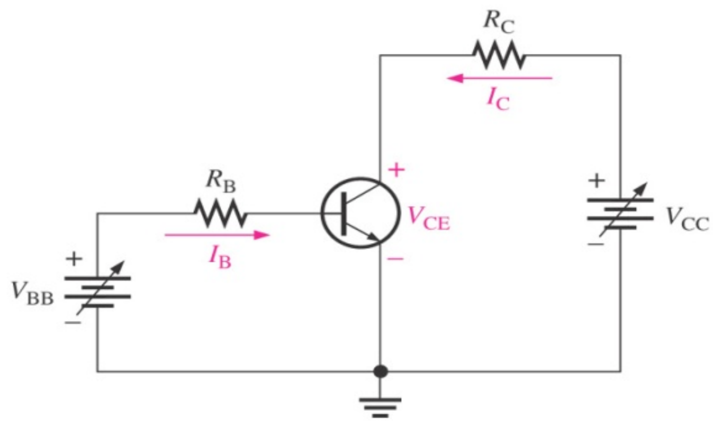


Curve shown for one fixed base current

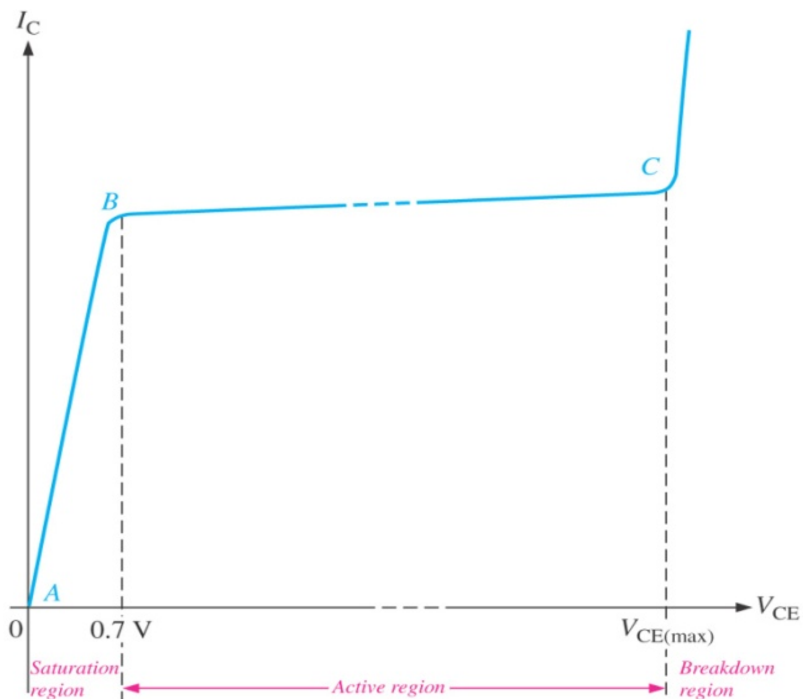
Collector characteristic curves give a graphical illustration of the relationship of collector current and V_{CE} with specified amounts of base current. With greater increases of V_{CC} , V_{CE} continues to increase until it reaches breakdown, but the current remains about the same in the **linear** region from .7V to the breakdown voltage.



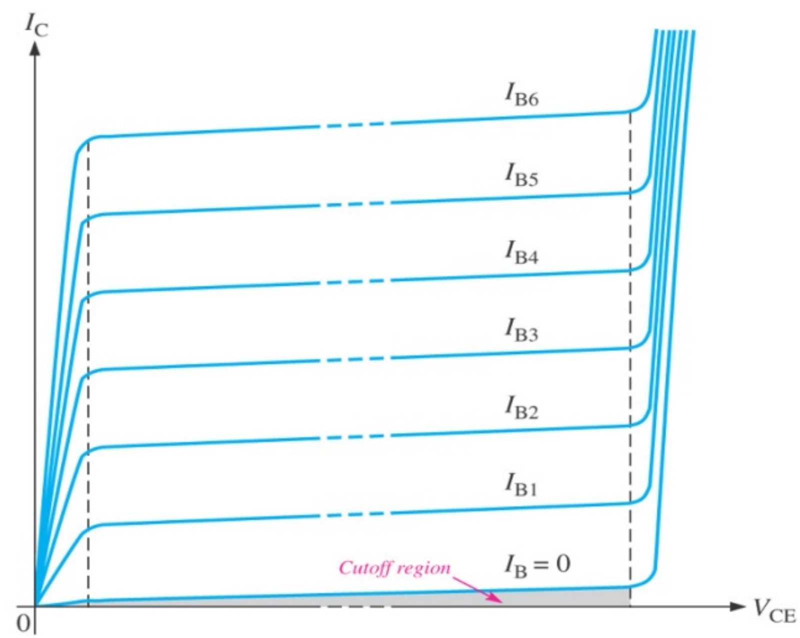
(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)



(a) Circuit



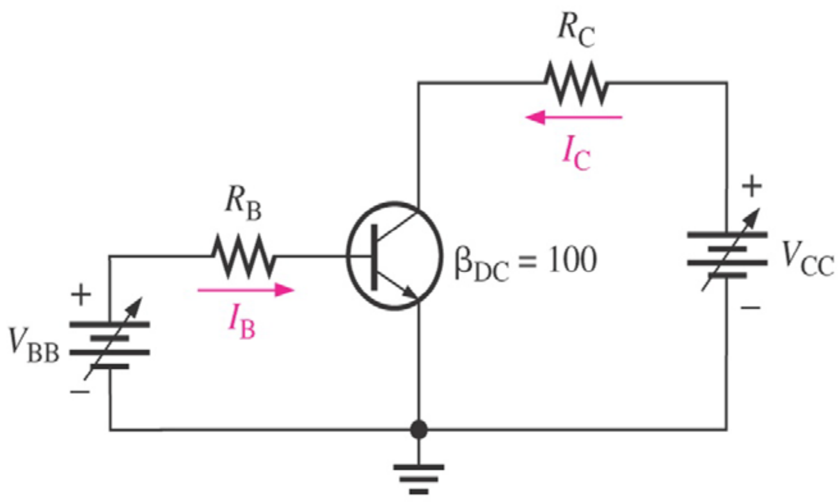
(b) I_C versus V_{CE} curve for one value of I_B

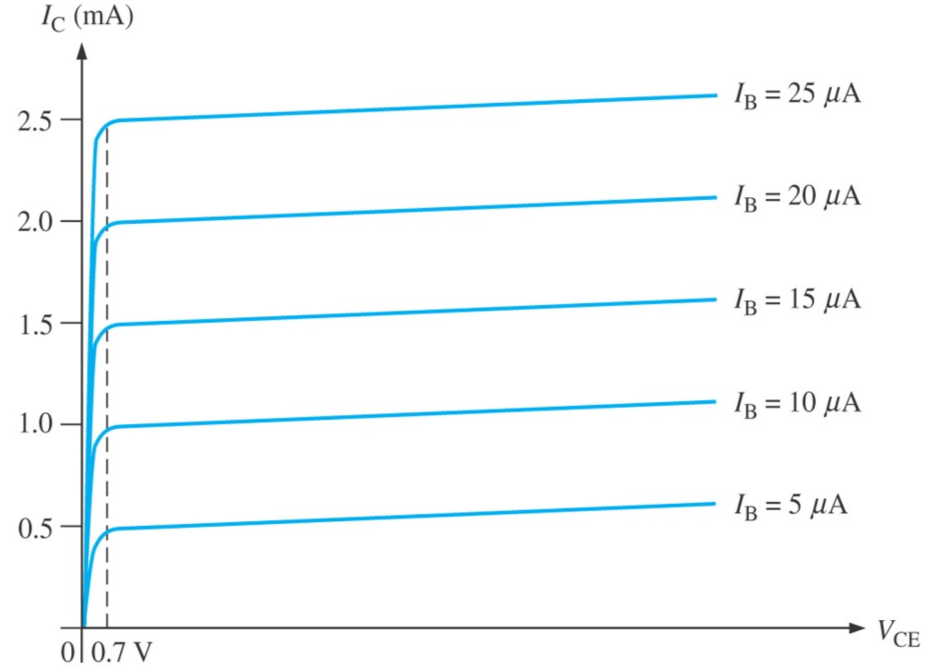


(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)

Example

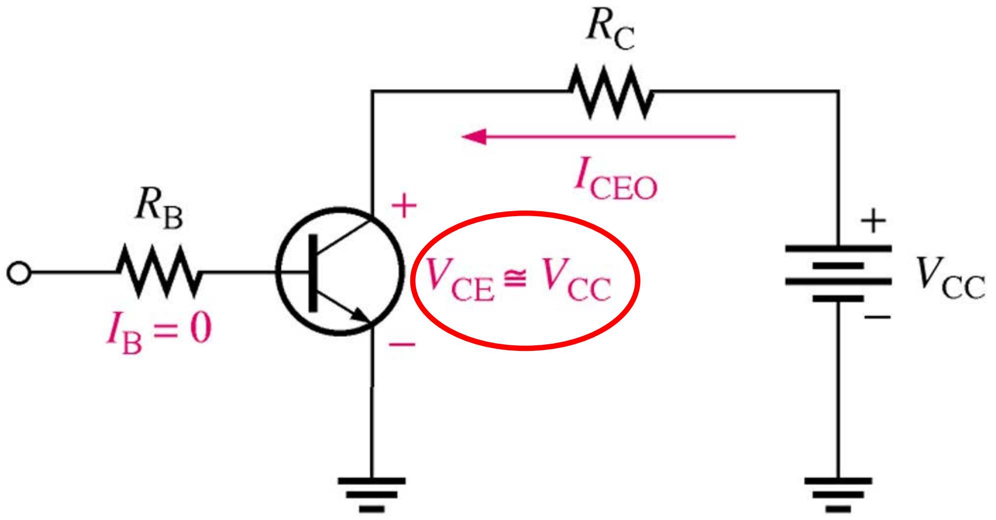
Sketch the transistor characteristic curve for I_B=5uA to 25 uA with 5uA increment Assume V_{CE} does not exceed breakdown.





Cut-off Mode

With no I_B the transistor is in the **cutoff** region and just as the name implies there is practically no current flow in the collector part of the circuit. This results in only an extremely small leakage current(I_{CEO}) in the collector circuit. With the transistor in a cutoff state the full V_{CC} can be measured across the collector and emitter(V_{CE}).



Saturation Mode

Current flow in the collector part of the circuit is, as stated previously, 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, $I_{C(sat)} = (V_{CC} - V_{CE})/R_C$ **.** For Ideal case, the measured voltage across the now "**shorted**" collector and emitter(**V_{CE}**) is 0V. The practical value is around 0.2V

In saturation, an increase of base current has no effect on collector circuit and the relationship $I_C = \beta . I_B$ is no longer valid.

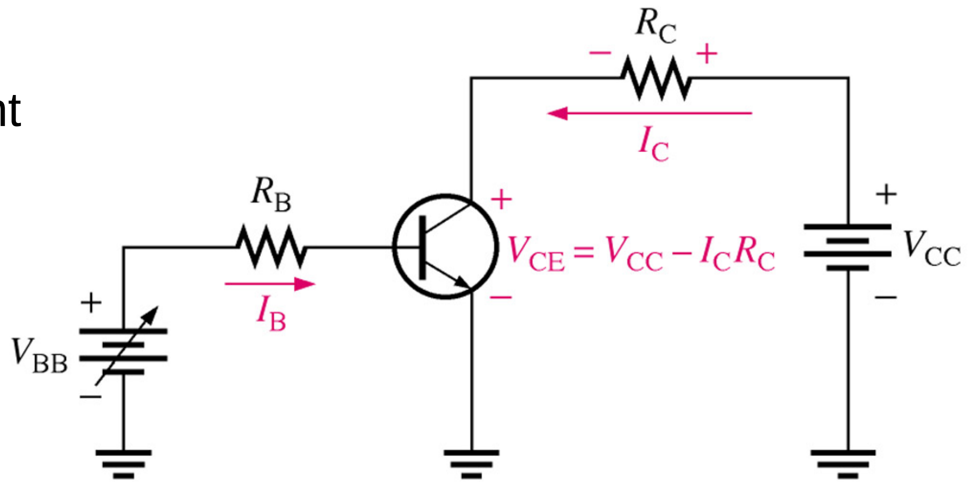
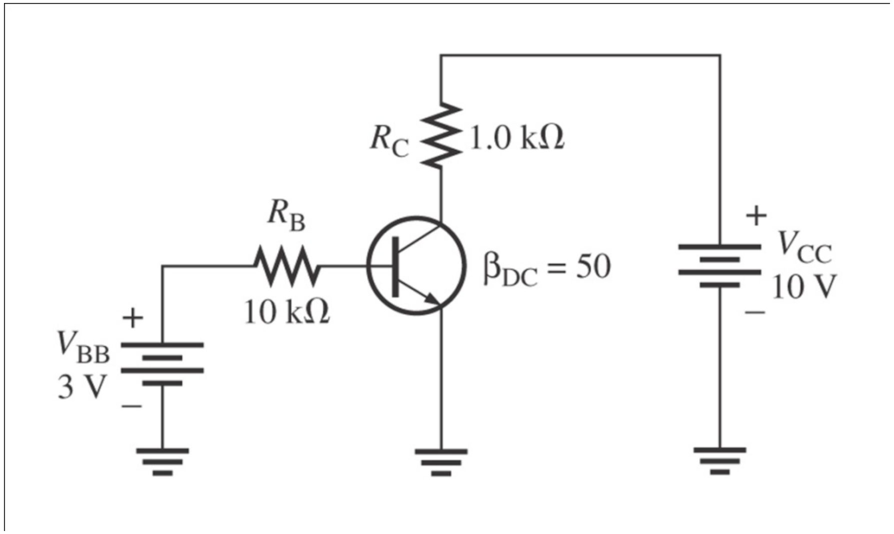


Figure. Saturation: As I_B increases due to increasing V_{BB}, I_C also increases and V_{CE} decreases due to the increased voltage drop across R_C. When the transistor reaches saturation, I_C can increase no further regardless of further increase in I_B.

Example

- Determine whether or not the transistor is in saturation. Assume $V_{CE(sat)}$=0.2V.



DC load line

The **dc load line** graphically illustrates $I_{C(sat)}$ and cutoff for a transistor. Basically, dc load line represents the circuit which is external to transistor

KVL(Collector-Emitter)

$$V_{CE}=V_{CC}-I_CR_C$$

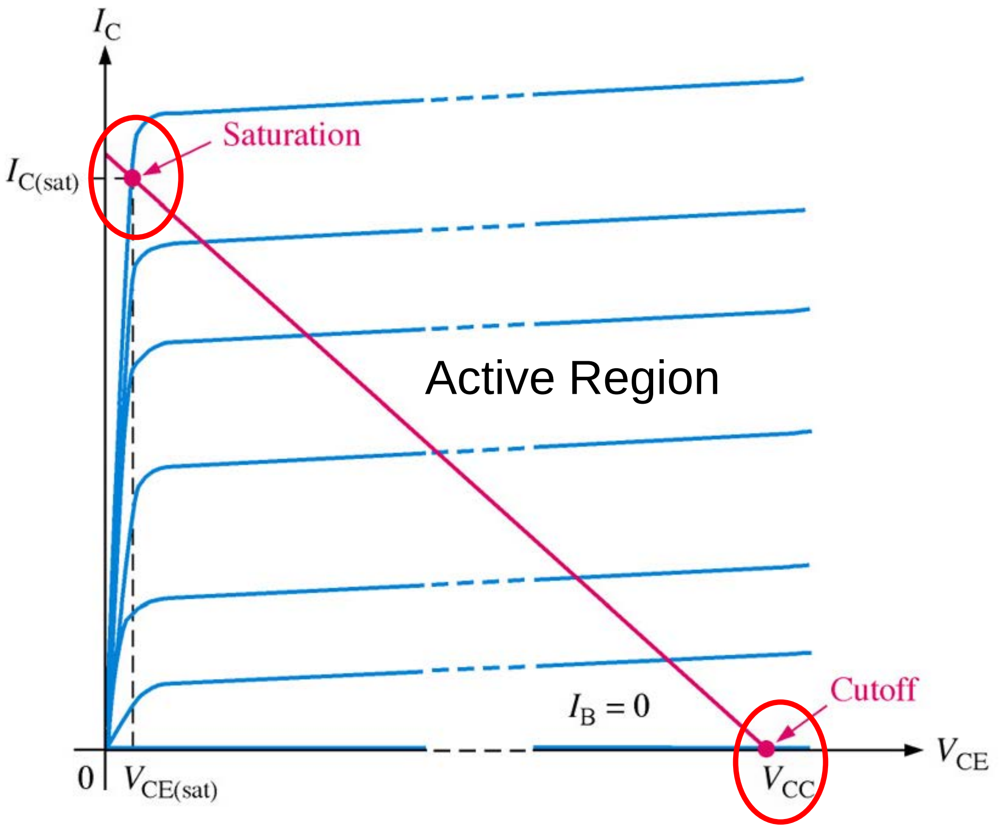
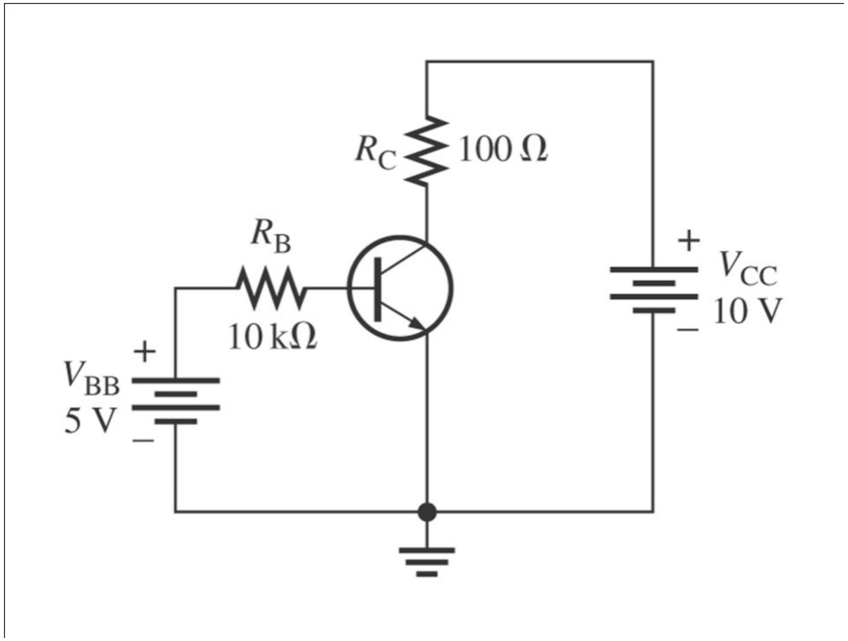


Figure. DC load line on a family of collector characteristic curves illustrating the cutoff and saturation conditions.

Example

- From a given circuit, determine I_B,I_C,I_E,V_{BE},V_{CE} and V_{CB}. The transistor has a β_{DC} =150. Assume $V_{CE(ON)}$=0.7V.

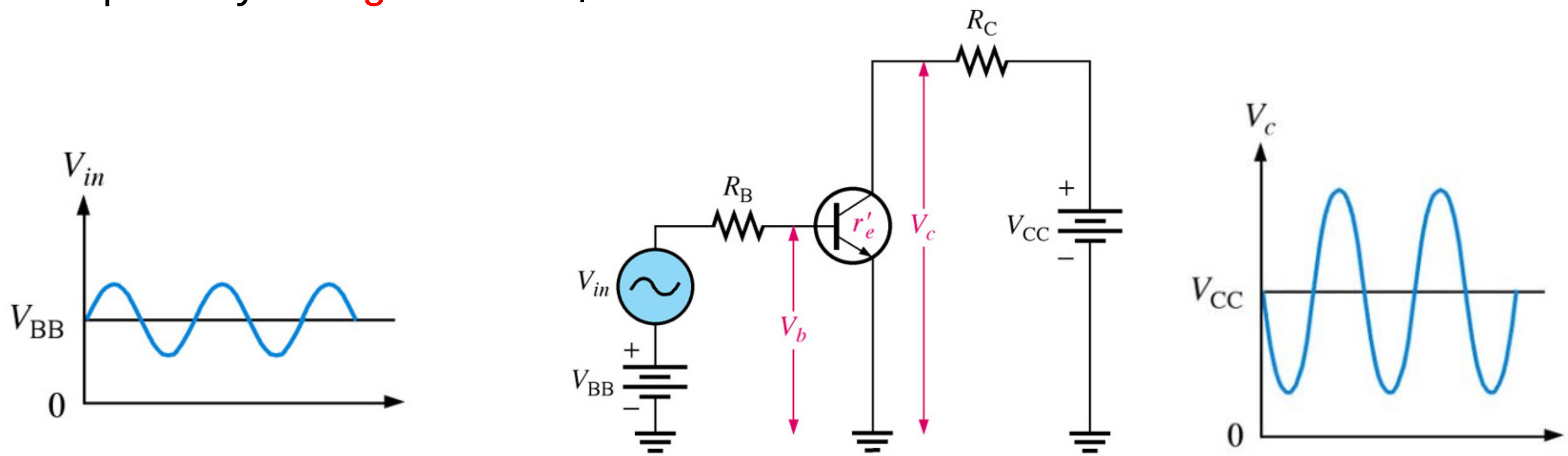


Transistor as Amplifier

Amplification of a relatively small ac voltage can be had by placing the ac signal source in the base circuit.

Recall that small changes in the base current circuit causes large changes in collector current circuit.

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.

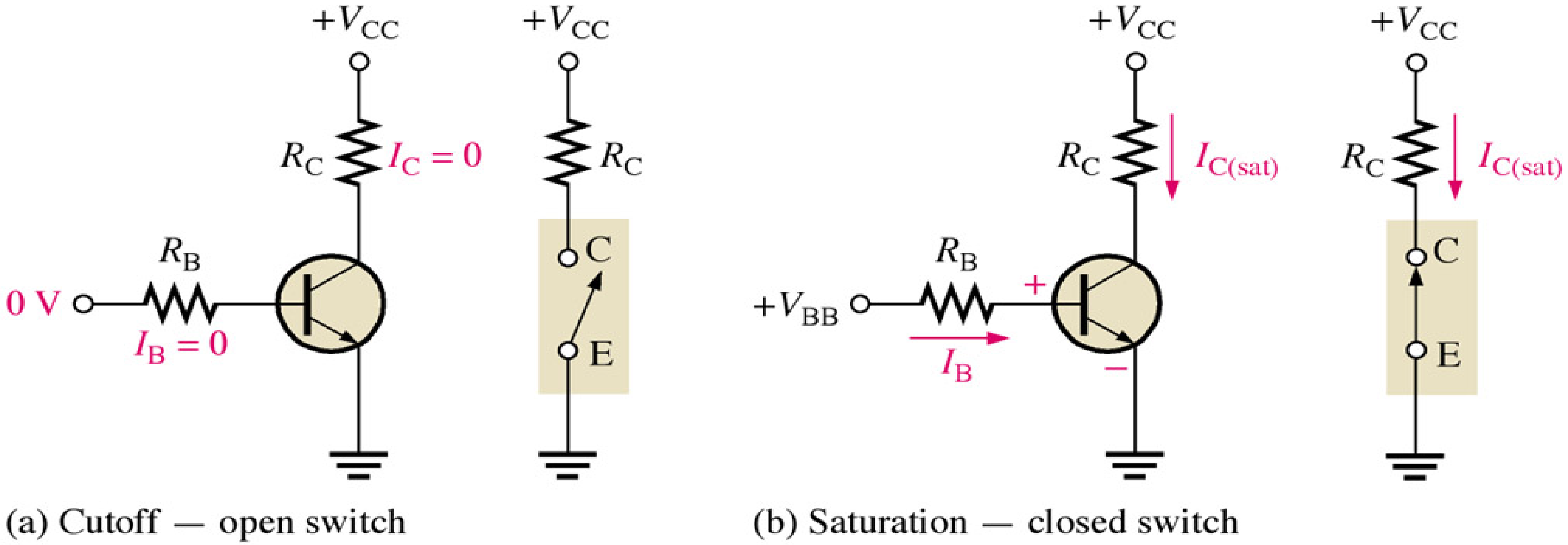


(a) Circuit with ac input voltage V_{in} and dc bias voltage superimposed

(b) Waveforms

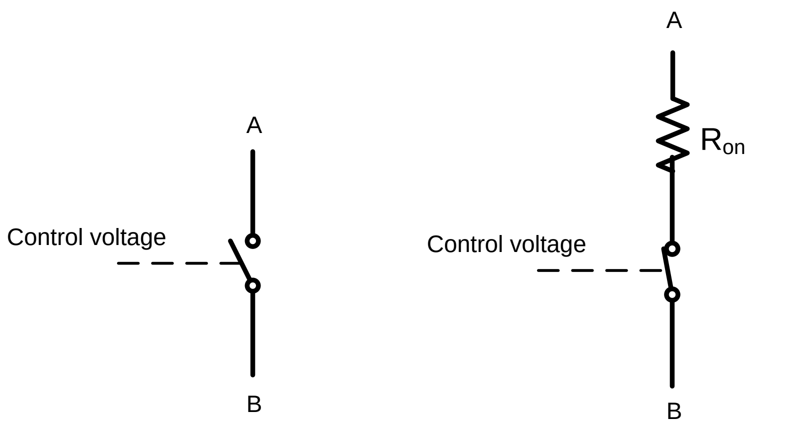
Transistor as (Electronic)Switch

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.



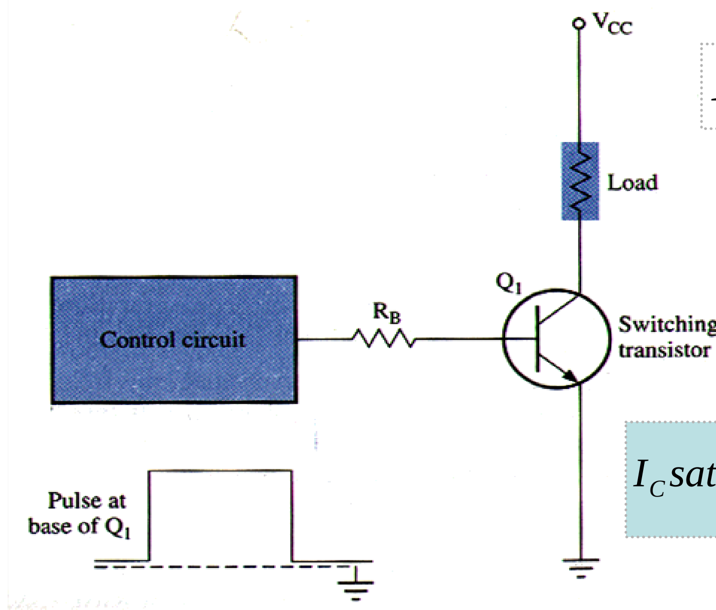
Electronic Switch

- Electronic switch uses electrical control signal for operation.
- The electronic switch does not contain mechanical contacts but semiconductor devices such as bipolar junction transistors or field-effect transistors.
- For the design, input voltage should be selected such that the output is either completely off, or completely on i.e transistor works in **saturation mode**.



Switch is open

Switch is closed

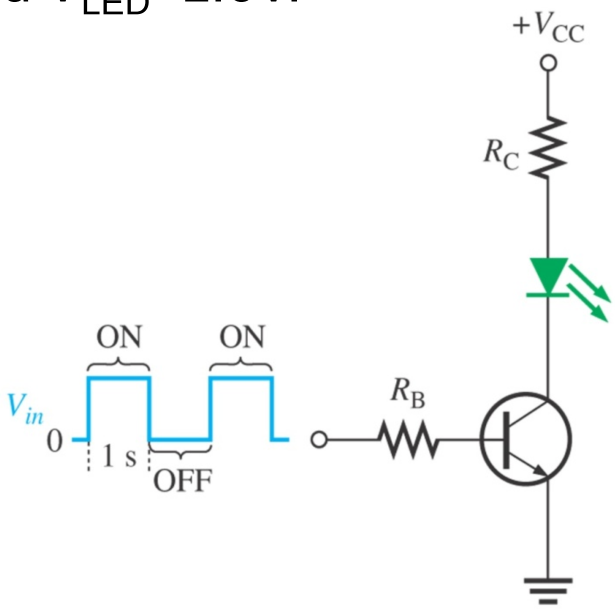


$$I_C = I_B \times \beta_{dc}$$

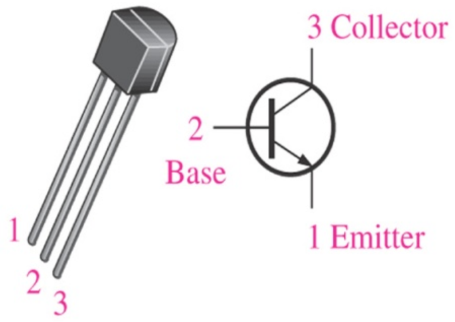
$$I_C sat = \frac{[V_{CC} - V_{CE} sat]}{R_L}$$

Simple Application

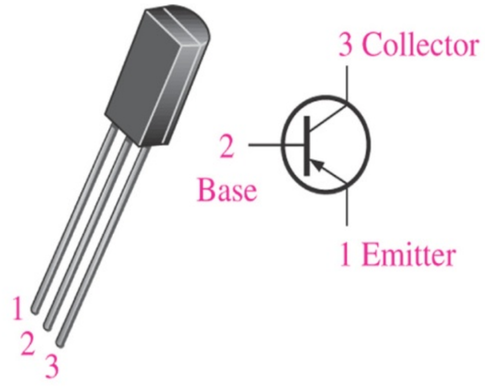
The LED in a given circuit requires 30mA to emit a sufficient light. Determine the amplitude of square wave necessary to make sure the LED emit sufficient Light. Use double the minimum value of base current as a safety margin to ensure saturation. V_{CC}=9V,$V_{CE(SAT)}$=0.3V, R_C=220Ω , R_B=3.3kΩ, $\boldsymbol{\beta_{DC}}$ = 50, and V_{LED}=1.6V.



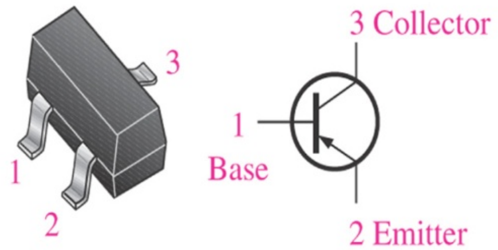
Plastic cases
for general-purpose/small-signal transistors.



(a) TO-92 or TO-226AA

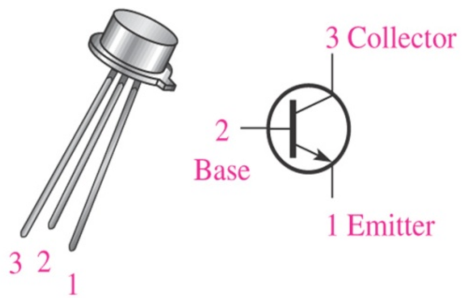


(b) TO-92 or TO-226AE

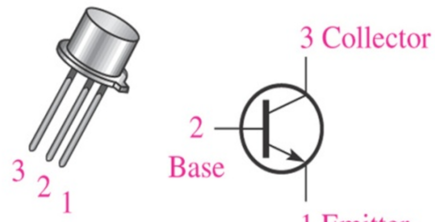


(c) SOT-23 or TO-236AB

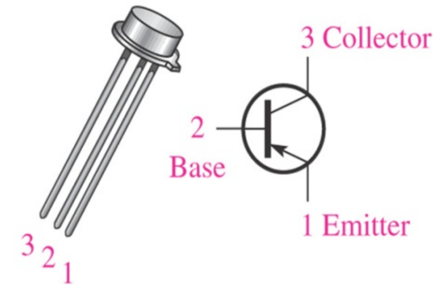
Metal cases
for general-purpose/small-signal transistors



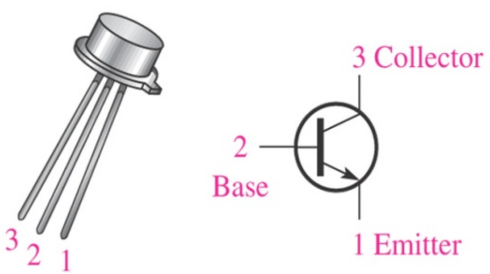
(a) TO-18 or TO-206AA



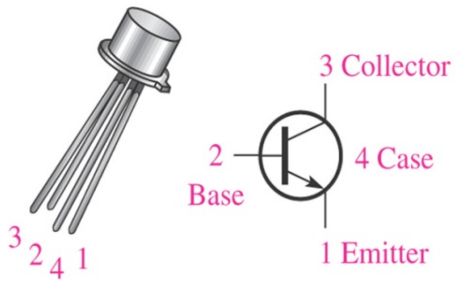
(b) TO-39 or TO-205AD



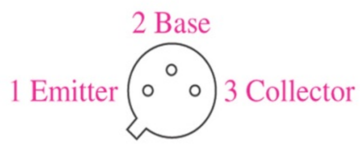
(c) TO-46 or TO-206AB



(d) TO-52 or TO-206AC

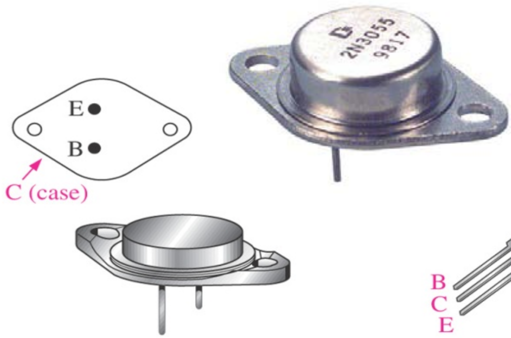


(e) TO-72 or TO-206AF

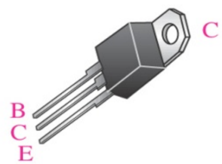


(f) Pin configuration (bottom view).
Emitter is closest to tab.

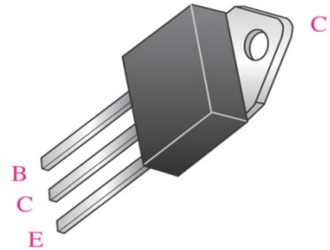
Power Transistors



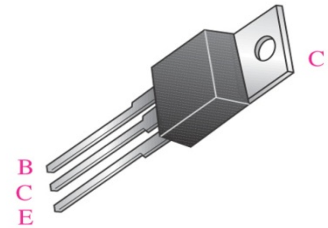
(a) TO-3 or TO-204AE



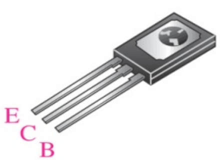
(b) TO-218



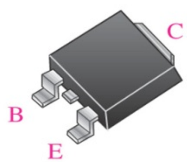
(c) TO-218AC



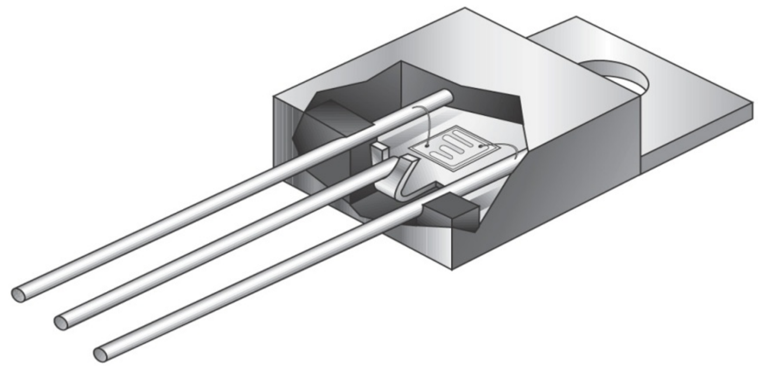
(d) TO-220AB



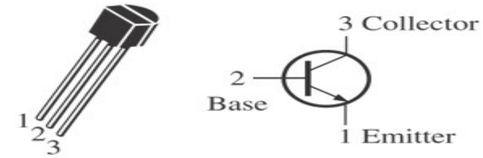
(e) TO-225AA



(f) Surface-mount technology


(g) Greatly enlarged cutaway view of tiny transistor chip mounted in the encapsulated package

2N3903
2N3904



General-Purpose Transistors

NPN Silicon

Maximum Ratings

Rating	Symbol	Value	Unit
Collector-Emitter voltage	V_{CEO}	40	V dc
Collector-Base voltage	V_{CBO}	60	V dc
Emitter-Base voltage	V_{EBO}	6.0	V dc
Collector current — continuous	I_C	200	mA dc
Total device dissipation @ $T_A = 25°C$ Derate above 25°C	P_D	625 5.0	mW mW/°C
Total device dissipation @ $T_C = 25°C$ Derate above 25°C	P_D	1.5 12	Watts mW/°C
Operating and storage junction Temperature range	T_J, T_{stg}	–55 to +150	°C

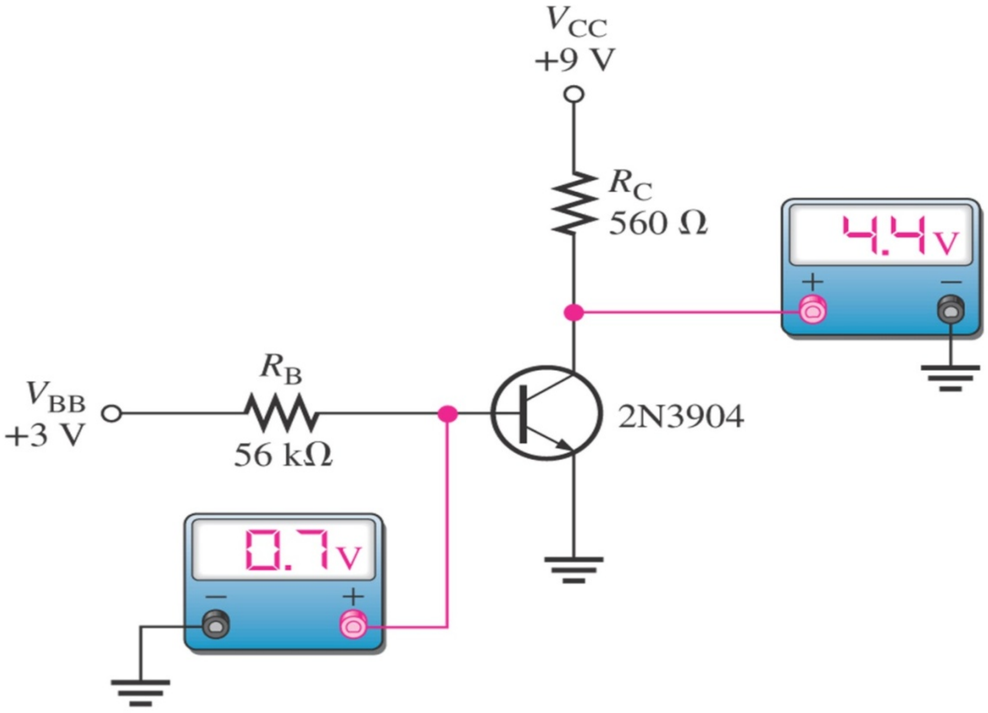
Thermal Characteristics

Characteristic	Symbol	Max	Unit
Thermal resistance, junction to case	$R_{\theta JC}$	83.3	°C/W
Thermal resistance, junction to ambient	$R_{\theta JA}$	200	°C/W

Electrical Characteristics ($T_A = 25°C$ unless otherwise noted.)

Characteristic		Symbol	Min	Max	Unit
OFF Characteristics					
Collector-Emitter breakdown voltage ($I_C = 1.0$ mA dc, $I_B = 0$)		$V_{(BR)CEO}$	40	–	V dc
Collector-Base breakdown voltage ($I_C = 10\ \mu$A dc, $I_E = 0$)		$V_{(BR)CBO}$	60	–	V dc
Emitter-Base breakdown voltage ($I_E = 10\ \mu$A dc, $I_C = 0$)		$V_{(BR)EBO}$	6.0	–	V dc
Base cutoff current ($V_{CE} = 30$ V dc, $V_{EB} = 3.0$ V dc)		I_{BL}	–	50	nA dc
Collector cutoff current ($V_{CE} = 30$ V dc, $V_{EB} = 3.0$ V dc)		I_{CEX}	–	50	nA dc
ON Characteristics					
DC current gain		h_{FE}			–
($I_C = 0.1$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		20 40	– –	
($I_C = 1.0$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		35 70	– –	
($I_C = 10$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		50 100	150 300	
($I_C = 50$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		30 60	– –	
($I_C = 100$ mA dc, $V_{CE} = 1.0$ V dc)	2N3903 2N3904		15 30	– –	
Collector-Emitter saturation voltage ($I_C = 10$ mA dc, $I_B = 1.0$ mA dc) ($I_C = 50$ mA dc, $I_B = 5.0$ mA dc)		$V_{CE(sat)}$	– –	0.2 0.3	V dc
Base-Emitter saturation voltage ($I_C = 10$ mA dc, $I_B = 1.0$ mA dc) ($I_C = 50$ mA dc, $I_B = 5.0$ mA dc)		$V_{BE(sat)}$	0.65 –	0.85 0.95	V dc

Example

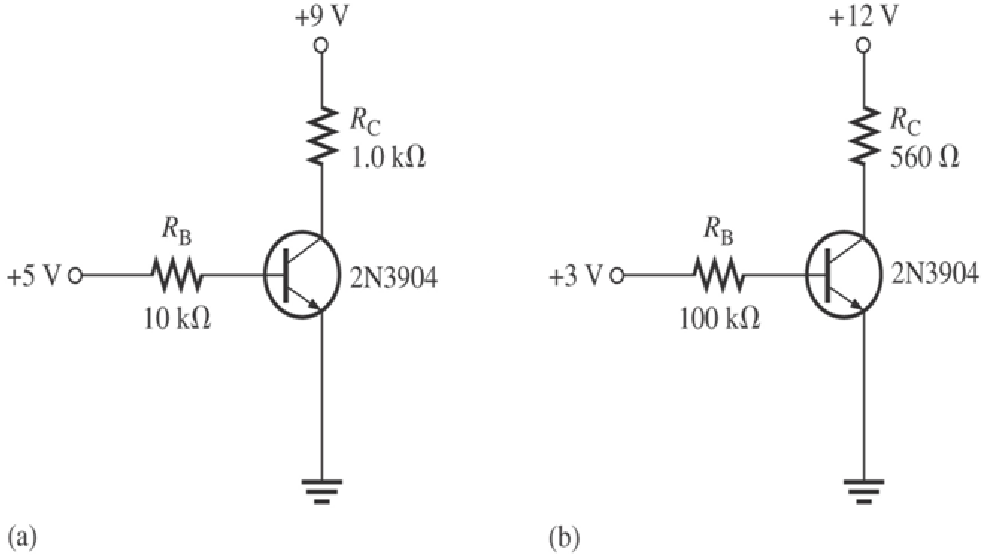


Find beta or h_{FE} or dc current gain

= __________

Example

Refer to the datasheet. Determine whether or not the transistor is saturated in each circuit based on the maximum specific value of h_{FE} .



BC547 NPN TRANSISTOR

ELECTRICAL CHARACTERISTICS

	Symbol	Min.	Typ.	Max.	Unit
DC Current Gain					
at V_{CE} = 5 V, I_C = 10μA					
Current Gain Group A	h_{FE}	–	90	–	–
B	h_{FE}	–	150	–	–
C	h_{FE}	–	270	–	–
at V_{CE} = 5 V, I_C = 2 mA					
Current Gain Group A	h_{FE}	110	180	220	–
B	h_{FE}	200	290	450	–
C	h_{FE}	420	500	800	–
at V_{CE} = 5 V, I_C = 100 mA					
Current Gain Group A	h_{FE}	–	120	–	–
B	h_{FE}	–	200	–	–
C	h_{FE}	–	400	–	–
Thermal Resistance Junction to Ambient Air	R_{thJA}	–	–	250[1)]	K/W
Collector Saturation Voltage					
at I_C = 10 mA, I_B = 0.5 mA	V_{CEsat}	–	80	200	mV
at I_C = 100 mA, I_B = 5 mA	V_{CEsat}	–	200	600	mV
Base Saturation Voltage					
at I_C = 10 mA, I_B = 0.5 mA	V_{BEsat}	–	700	–	mV
at I_C = 100 mA, I_B = 5 mA	V_{BEsat}	–	900	–	mV
Base-Emitter Voltage					
at V_{CE} = 5 V, I_C = 2 mA	V_{BE}	580	660	700	mV
at V_{CE} = 5 V, I_C = 10 mA	V_{BE}	–	–	720	mV
Collector-Emitter Cutoff Current					
at V_{CE} = 80 V **BC546**	I_{CES}	–	0.2	15	nA
at V_{CE} = 50 V **BC547**	I_{CES}	–	0.2	15	nA
at V_{CE} = 30 V **BC548, BC549**	I_{CES}	–	0.2	15	nA
at V_{CE} = 80 V, T_j = 125 °C **BC546**	I_{CES}	–	–	4	μA
at V_{CE} = 50 V, T_j = 125 °C **BC547**	I_{CES}	–	–	4	μA

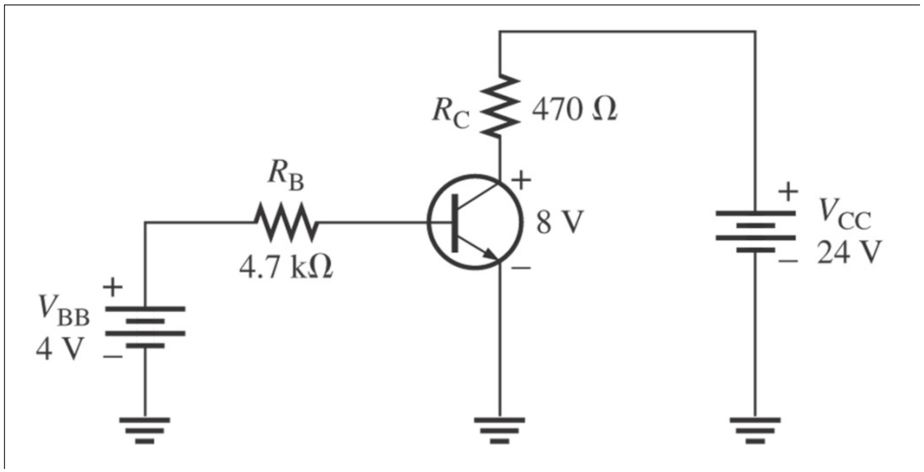
Hint for h_{FE} Selection

The datasheet shows that the h_{FE} can not be specified precisely by the manufacturer, because it varies very much between transistors and with electrical and thermal conditions. However, it is possible to get an approximated value.

Students can start with the roughly calculation of I_c. For example, if I_c =20mA, we can take an intermediate value between the h_{FE} for I_c =2mA (500) and the h_{FE} for I_c =100mA (400), so let's take h_{FE} =450.

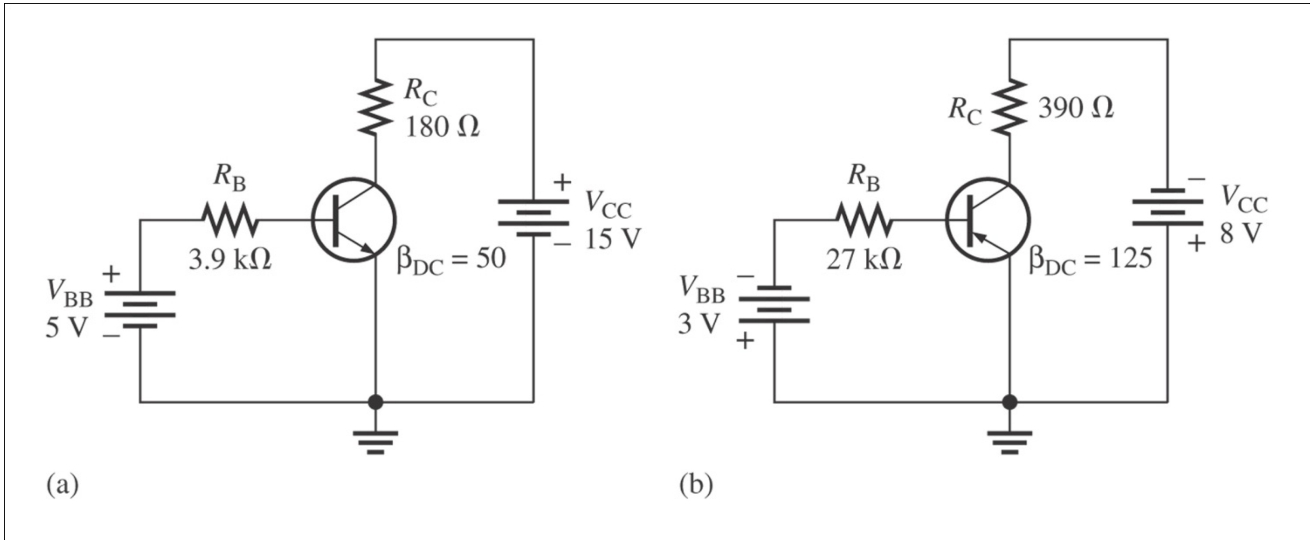
Example

- Determine I_B,I_C,I_E and β_{DC} .



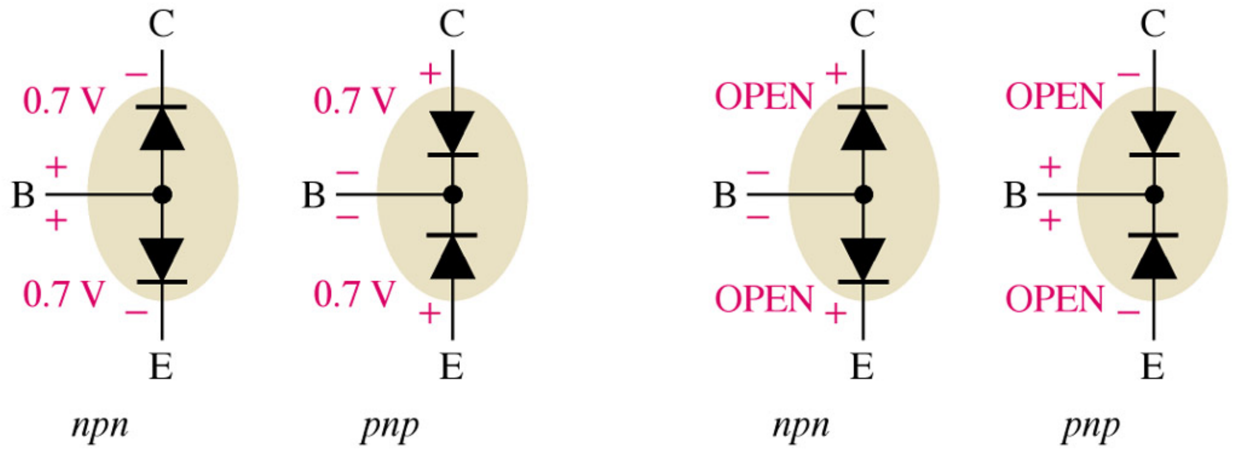
Example

- Find V_{CE},V_{BE},V_{CB} in both circuits.



Testing Transistors

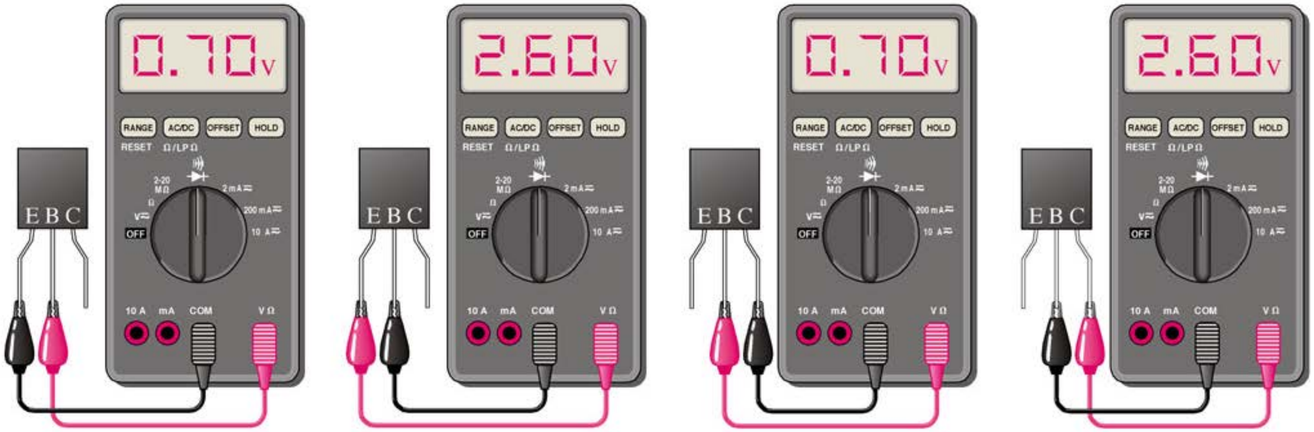
Testing a transistor can be viewed more simply if you view it as testing two diode junctions. Forward bias having low resistance and reverse bias having infinite resistance.



(a) Both junctions should read 0.7 V ± 0.2 V when forward-biased.

(b) Both junctions should ideally read OPEN when reverse-biased.

The diode test function of a multimeter is more reliable than using an ohmmeter. Make sure to note whether it is an npn or pnp and polarize the test leads accordingly.



(a) Forward-bias test of BE junction (b) Reverse-bias test of BE junction (c) Forward-bias test of BC junction (d) Reverse-bias test of BC junction

In addition to the traditional DMMs there are also transistor testers. Some of these have the ability to test other parameters of the transistor, such as leakage and gain. Curve tracers give us even more detailed information about a transistors characteristics.

Conclusions

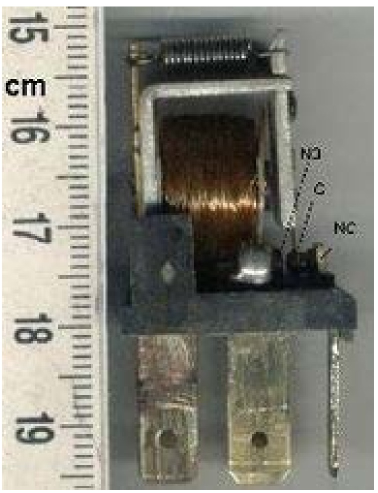
- The bipolar junction transistor (BJT) is constructed of three regions: base, collector, and emitter.
- The BJT has two pn junctions, the base-emitter junction and the base-collector junction.
- The two types of transistors are pnp and npn.
- For the BJT to operate as an amplifier, the base-emitter junction is forward-biased and the collector-base junction is reverse-biased.
- Of the three currents I_B is very small in comparison to I_E and I_C.
- Beta is the current gain of a transistor. This the ratio of I_C/I_B.

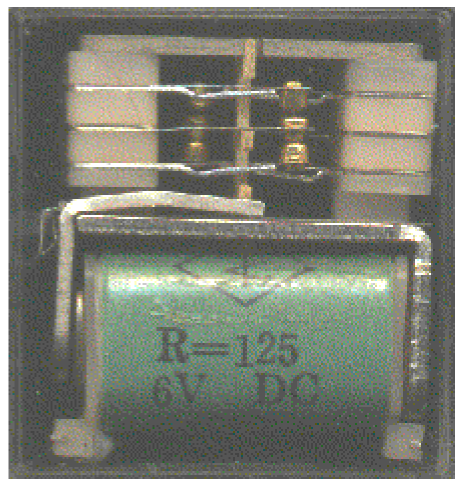
- A transistor can be operated as an electronics switch.
- When the transistor is off it is in cutoff condition (no current).
- When the transistor is on, it is in saturation condition (maximum current).
- Beta can vary with temperature and also varies from transistor to transistor.

Supplement

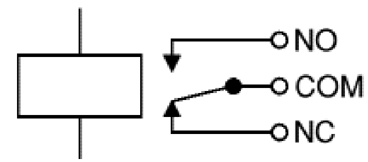
Relays

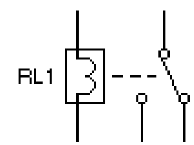
- A relay is an **electrically operated switch**. Current flowing through the coil of the relay creates a magnetic field which attracts a lever and changes the switch contacts. The coil current can be on or off so relays have two switch positions and they are **double throw** (**changeover**) switches.



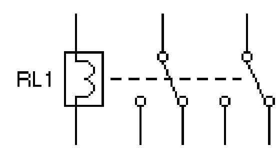


Symbol

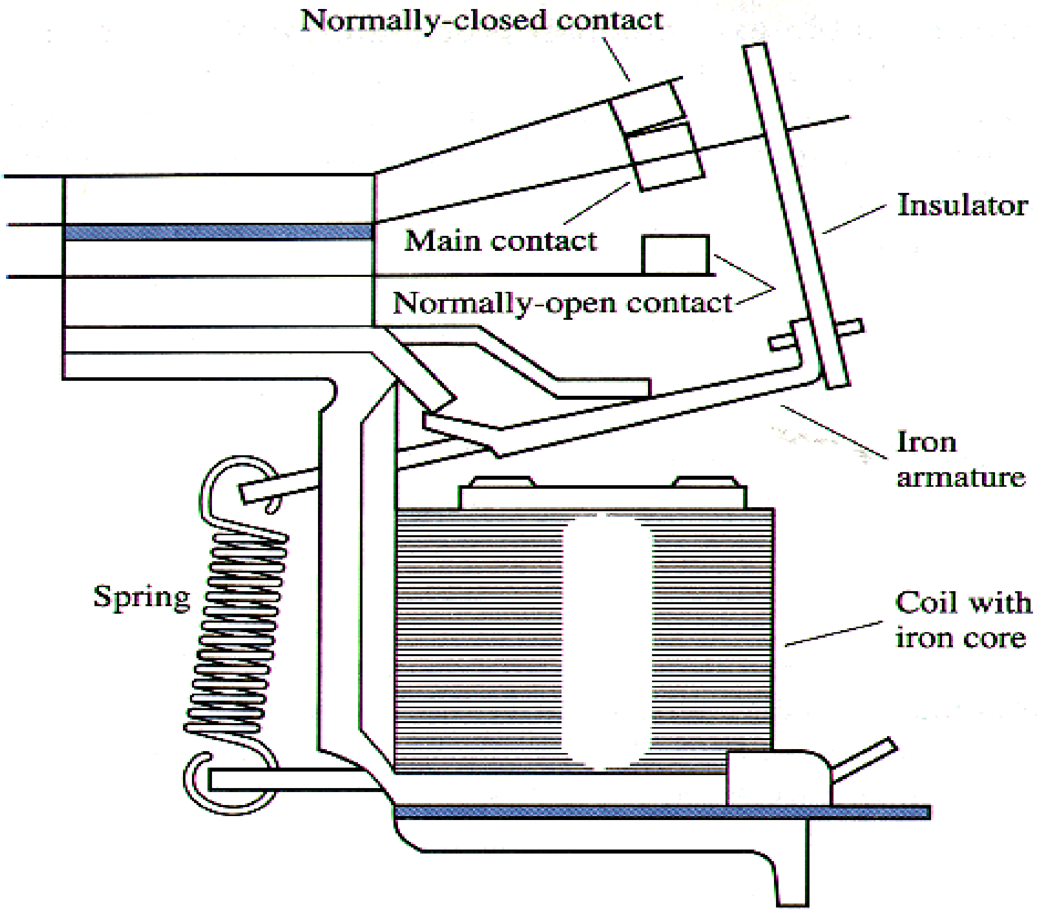




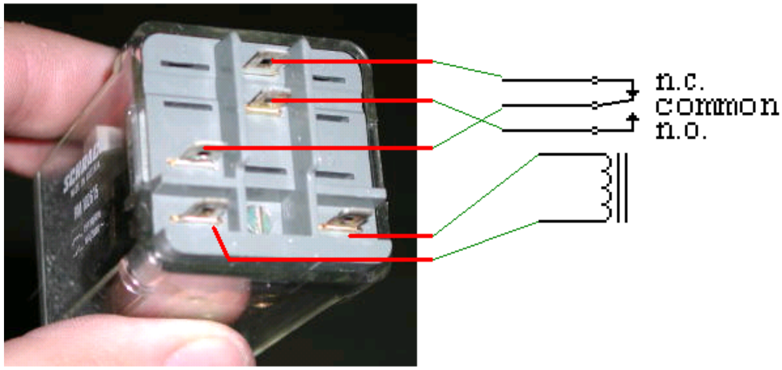
SPDT Relays

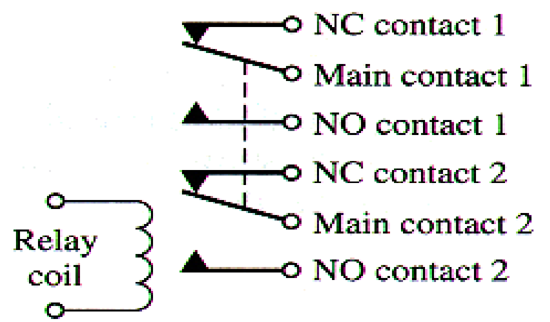


DPDT Relays



(a) Physical structure of the electromechanical relay





(b) Schematic representation of a relay with DPDT contacts