Transistors

The BJT is a three terminal device whose output current, voltage and power are controlled by its input ***current.***

In communication systems, the transistor is used as the primary component in an ***amplifier***, a circuit that is used to increase the strength of an ac signal.

There are two basic types of transistors that we will be studying.

- The Bipolar Junction Transistor (BJT)
- The Field Effect Transistor (FET)

The term "transistor" usually refers to the BJT. Field Effect Transistors are generally referred to as a FET.

The BJT (Bipolar Junction Transistor)

The BJT is a three terminal device , the terminals called , ***the emitter***, ***the base*** and ***the collector***.

The collector and emitter are made up of the same type of semiconductor material (*p* or *n* type) while the base is made up of the other type.

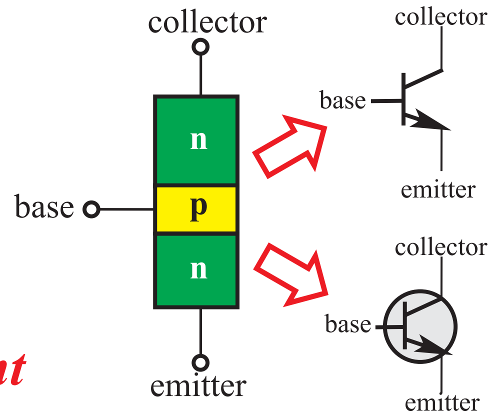
There are two types of BJTs

- pnp - ***p type*** collector --- ***n type*** base --- ***p type*** emitter
- npn - ***n type*** collector --- ***p type*** base --- ***n type*** emitter

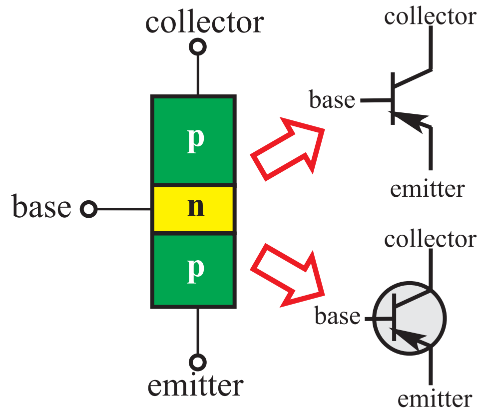
The Bipolar Junction Transistor

Schematic Symbols

The arrow is always on the emitter and points in ***the direction of conventional current flow.***



npn type transistor
Schematic Symbols



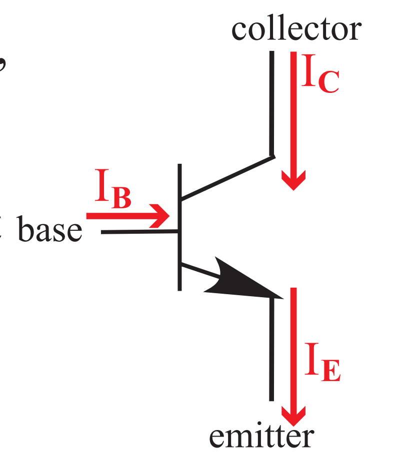
pnp type transistor
Schematic Symbols

Transistor Currents

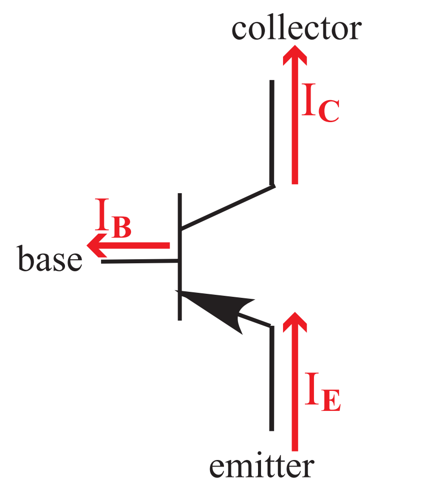
The currents are named I_B, I_C and I_E respectively.

I_B is normally the smallest current.

Normally , I_C the second largest current and joins with I_B to become I_E , the largest current.



npn Transistor



pnp Transistor

Note that the currents are opposite in a pnp transistor.

The transistor is a ***current controlled device***. This means that the ***current in the collector and emitter are controlled by the current in the base.***

The base current is generally very small but it controls a much larger current in the collector and emitter.

An increase or decrease in the value of I_B causes a larger but similar change in I_C and I_E.

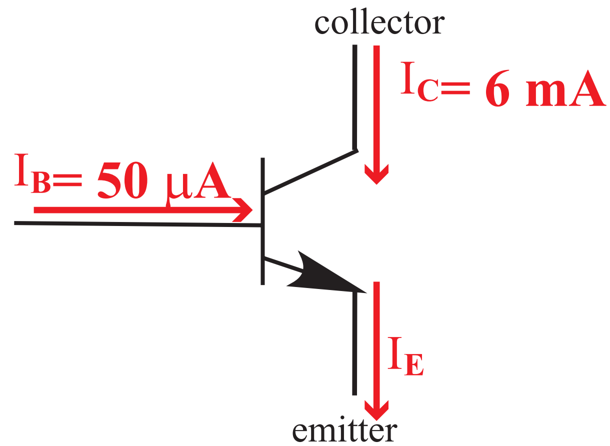
DC Current Gain (β)

The value of I_C is generally some multiple of I_B. This factor by which the current increases from base to collector is called the forward dc current gain of the device (β beta) also called h_{FE}.

Example

If I_B is 50 μA and β is 120 then :

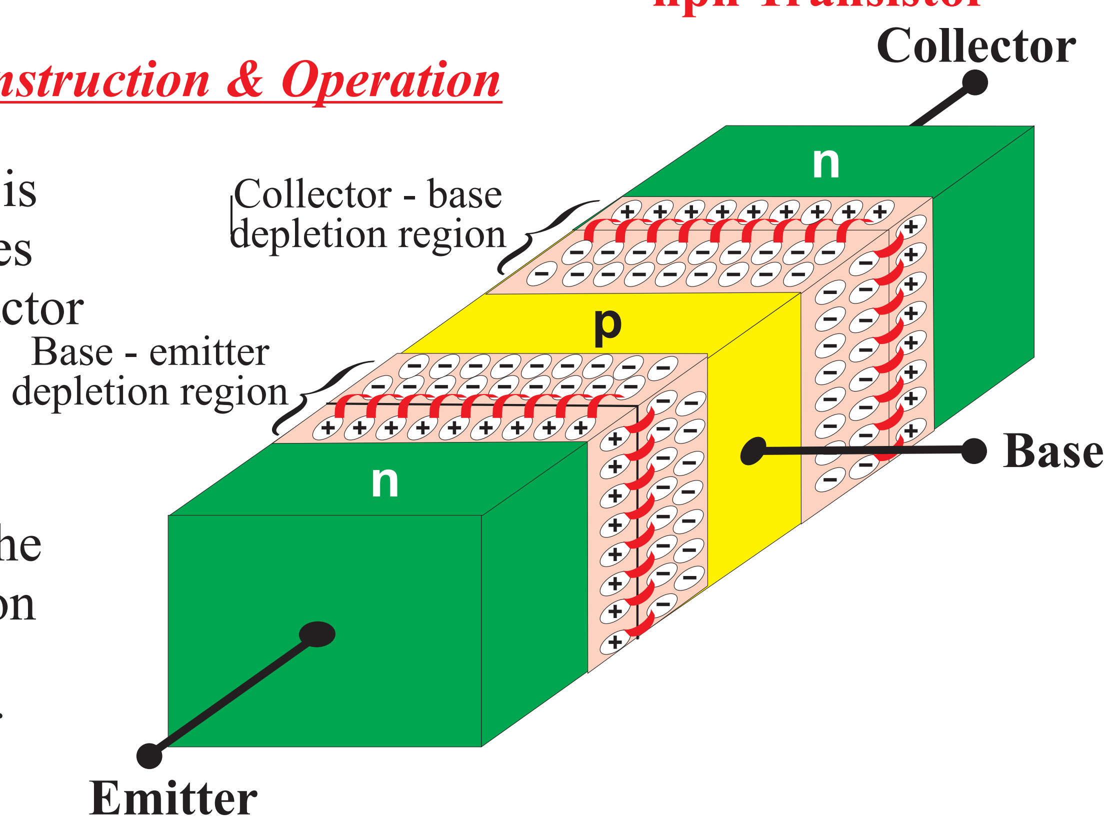
$$I_C = \beta I_B$$
$$= (120)(50\ \mu A)$$
$$= 6\ mA$$



npn Transistor

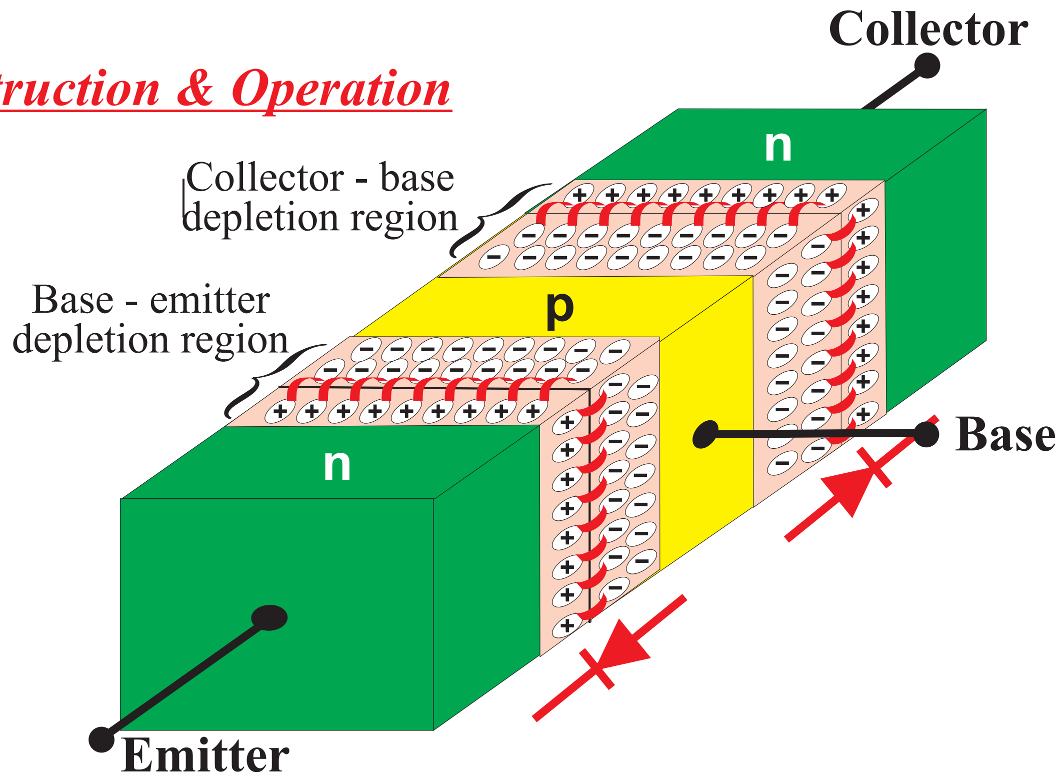
Transistor Construction & Operation

The transistor is made of 3 types of semi-conductor materials that form two ***pn*** junctions as shown. Note the wire connection to each of the base, collector and emitter.



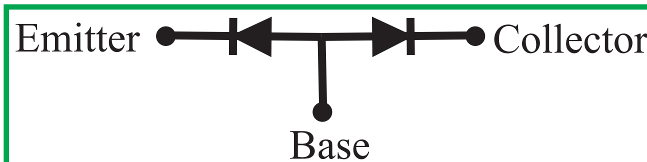
Transistor Construction & Operation

Note that the depletion layers extend well into the base region and less into the collector and emitter region. This is due to the light doping of the base region.



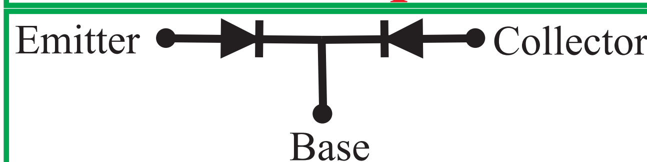
In its unbiased form (zero bias), the transistor will form two pn junction diodes as shown above. These junctions form a barrier potential, similar to the diode that we have studied.

These diodes can be checked with an ohmmeter in the same way as we have checked diodes in the past.



*The unbiased **npn** BJT*

Note that for the pnp transistor, the diodes are reversed.



*The unbiased **pnp** BJT*

Regions of Operation

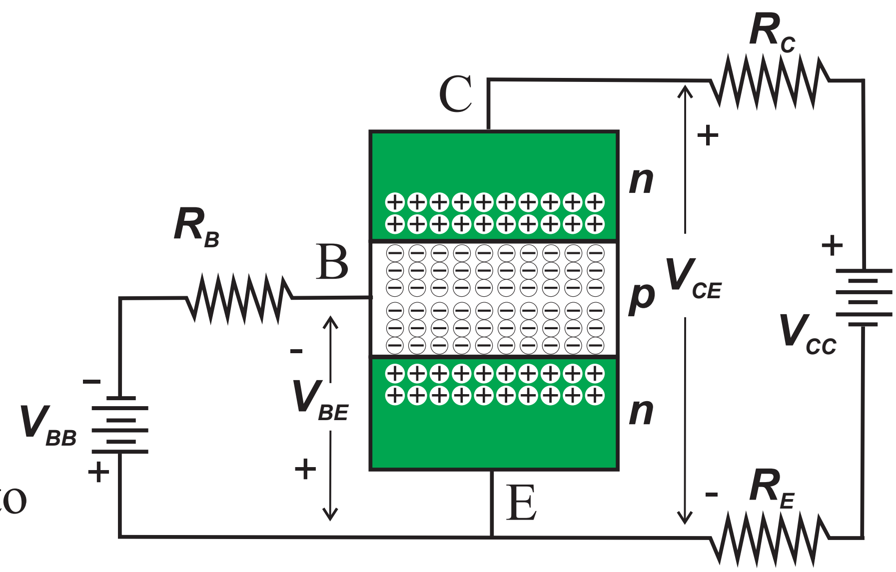
The two junctions are normally operated in one of three biasing combinations as shown below.

Base - Emitter Junction	*Collector-Base Junction*	*Operating Region*
Reverse Biased	Reverse Biased	Cutoff
Forward Biased	Reverse Biased	Active
Forward Biased	Forward Biased	Saturation

The Cutoff Region

Base - Emitter Junction	Collector-Base Junction	Operating Region
Reverse Biased	Reverse Biased	Cutoff

Here, both junctions are ***reverse biased.***



Transister Biased to Cutoff

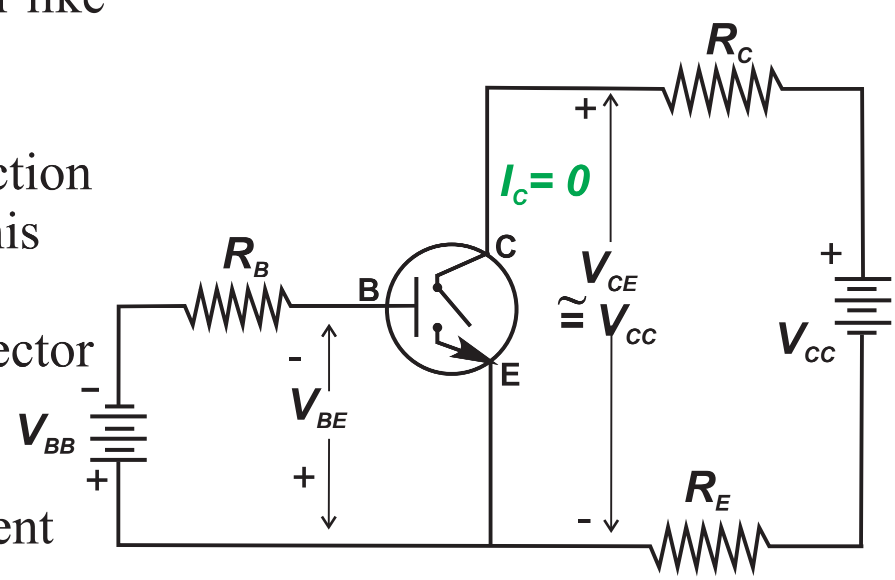
Very little current flows from the collector to the emitter.

The depletion zones are wide and extend well into the base region.

When the transistor is in cutoff, the collector to emitter terminals appear like an open switch.

The base to emitter junction is reverse biased, and this causes the open switch action between the collector and emitter.

There is almost no current flow in the collector to emitter circuit and VCE is approximately equal to VCC

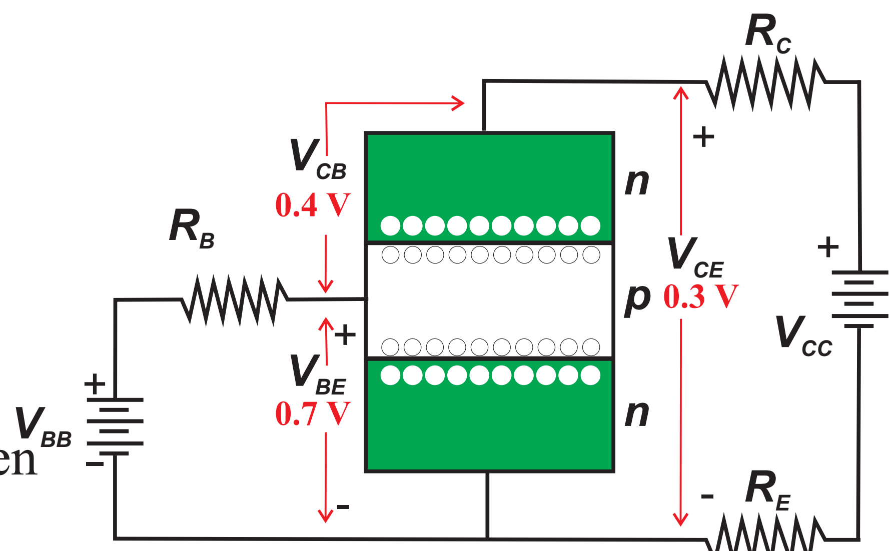


Transister Biased to Cutoff
Collector to Emitter is like an open switch

The Saturation Region

Base - Emitter Junction	*Collector-Base Junction*	*Operating Region*
Forward Biased	Forward Biased	Saturation

This is the opposite of cutoff. ***Saturation*** is the condition where ***further increases in I_B will not cause increases in I_C.***

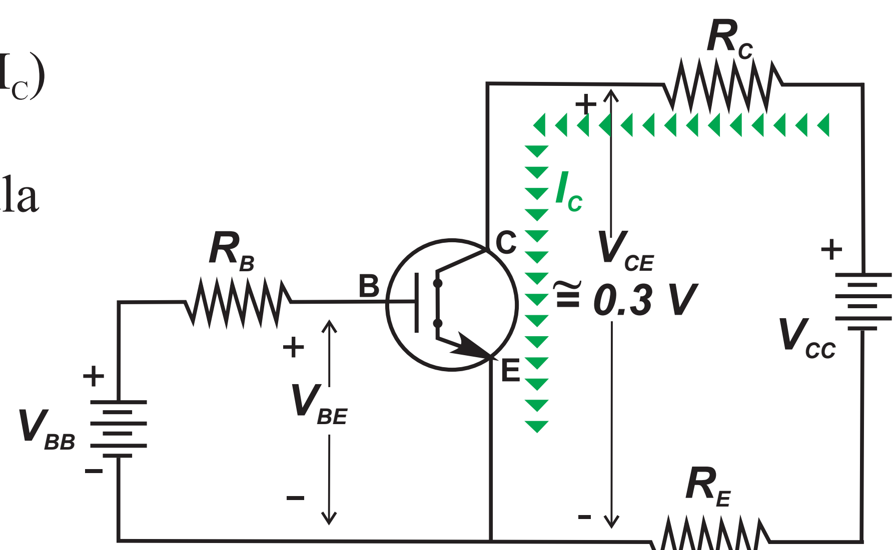


Transistor Biased to Saturation

The maximum current in the circuit is reached when the collector to emitter terminals appear like a closed switch.

The maximum current (I_C) in the circuit is now determined by the formula

$$I_C = \frac{V_{CC}}{R_C + R_E}$$



Transistor Biased to Saturation
Collector to Emitter is like closed switch

Now $I_C = \beta I_B$ no longer holds true since increasing I_B does not increase I_C. Further increasing I_B forward biases both junctions of the transistor.

The Active Region

Base - Emitter Junction	Collector-Base Junction	Operating Region
Forward Biased	Reverse Biased	Active

The transistor is said to be operating in the active region when the base-emitter junction is forward biased and the collector-base junction is reverse biased.

Generally, the transistor is operating in the active region when it is between cutoff and saturation.

To understand the theory, consider ***electron flow.***.

In Figure 1, SW_1 is open and no base current is flowing. Therefore no collector current is flowing either.

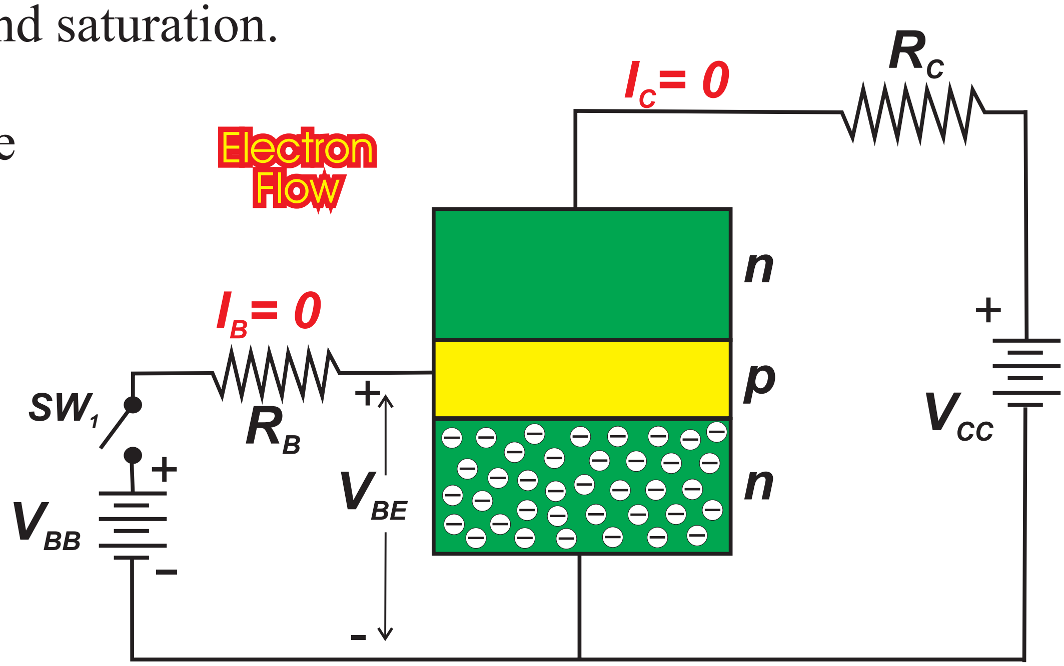


Figure 1

☑ **Electron Flow**

The emitter is heavily doped and contains many free electrons. Its job is to emit or inject electrons into the base. Until the base - emitter junction is forward biased by V_{BB}, this cannot happen.

The base area is lightly doped and is very thin. It will pass most of the emitter ejected electrons on to the collector.

☑ **Electron Flow**

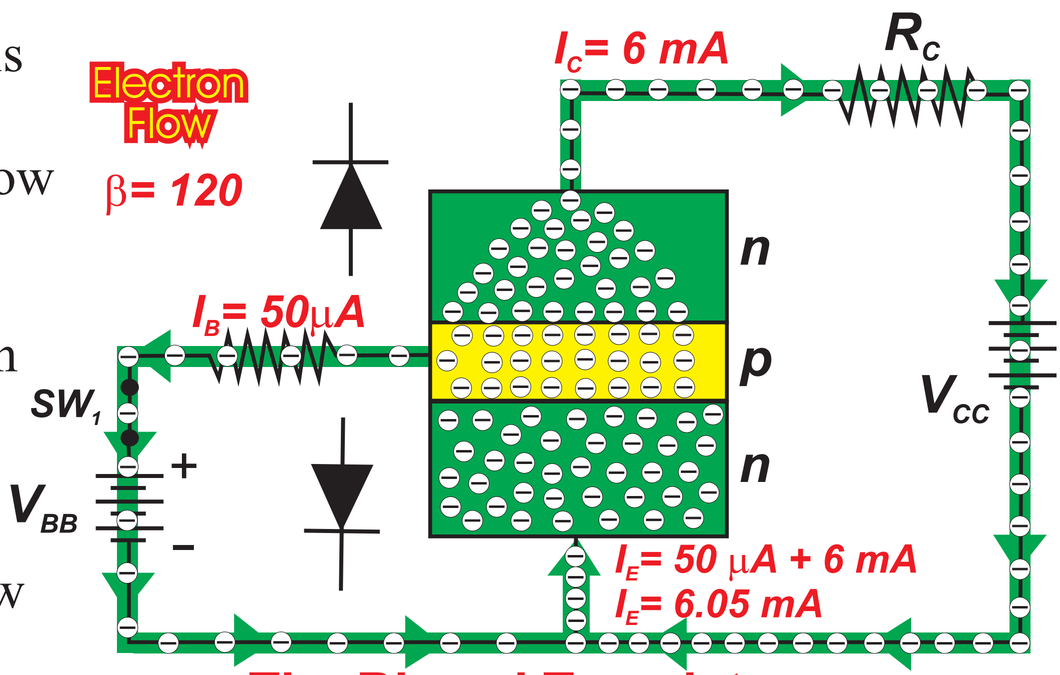
The collector is so named because it ***gathers*** or ***collects*** electrons from the base. Its doping level is between the heavy doping level of the emitter and the light doping level of the base.

Emitter Electrons

☑ **Electron Flow**

At the moment before SW_1 is closed, electrons from the emitter have not entered the base region.

In Figure 2, SW_1 is closed and the emitter diode is now forward biased. Electrons flood across the junction and into the base region.



The Biased Transistor
Figure 2

Now they can flow in either of two directions. They can flow to the left and out the base, or they can flow into the collector. Most will flow to the collector.

☑ **Electron Flow**

The reasons are:

- The base is lightly doped. Because of this electrons have a long lifetime in the base. This gives then the time needed to reach the collector.
- The base area is very thin. This gives the electrons a better chance of reaching the collector.

Base Electrons

☑ **Electron Flow**

To flow out of the base, electrons must recombine with holes in the base. Then as valence electrons, they can flow out of the base and leave via the external wire.

Since the base is lightly doped and very thin, very few electrons manage to re-combine and leave via the base lead.

Collector Electrons

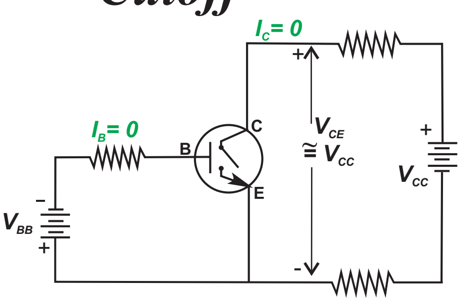
☑ **Electron Flow**

Almost all the free electrons go to the collector. Here they feel the attraction of V_{CC} and leave via the collector lead. They flow through R_C and return to the positive terminal of V_{CC}

In most transistors, *more than 95% of the emitter electrons flow to the collector: less than 5% leave via the base*

Summary *(Using Conventional Current Flow)*

Cutoff



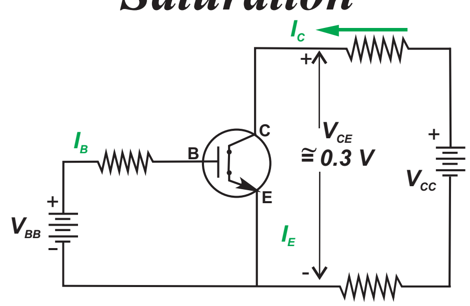
Collector to Emitter is like an open switch

B-E Junction **Reverse**

C-B Junction **Reverse**

Collector Current (I_C)
Approximately equal to zero

Saturation



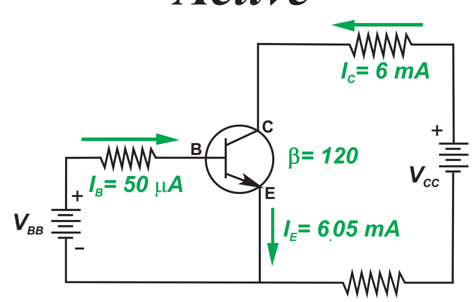
Collector to Emitter is like a closed switch

B-E Junction **Forward**

C-B Junction **Forward**

Collector Current (I_C)
Maximum, limited only by external components in the collector-emitter circuit.

Active



Collector Current is beta times Base Current

B-E Junction **Forward**

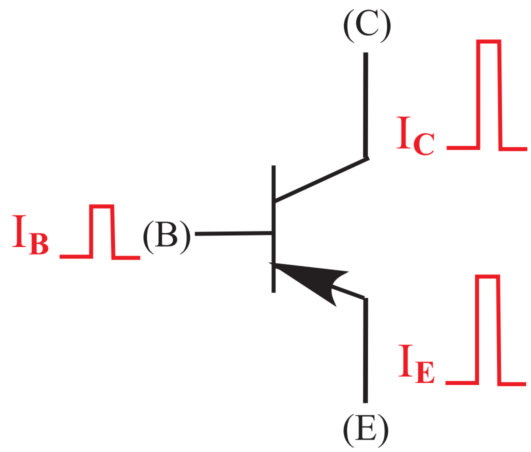
C-B Junction **Reverse**

Collector Current (I_C)
Determined by the values of β and I_B ($I_C = \beta\, I_B$)

Transistor Currents

We know that a transistor is a current controlled device. This means that ***a small change in base current produces a large change in both the emitter and collector currents***.

The magnitude of the change is determined by the current gain (β).



Pnp Transistor Current Relationships

Example 6.1 illustrates this point (p 208)

Relationships Between I_E, I_C, & I_B

We already know the formula

$$I_E = I_B + I_C$$

and since I_B is usually much less than I_C : then the collector and emitter currents are approximately equal.

$$I_C \cong I_E$$

DC Beta (β)

The ***dc Beta*** rating of a transistor is the ***ratio of dc collector current to dc base current***.

Remember that Beta is a ratio of current values and has ***no units of measure.***

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

This is an extremely important rating because most of the common transistor circuits have ***the input signal applied to the base*** and the ***output signal taken from the collector***

Other terminal currents can be found as:

$$I_C = \beta I_B \qquad I_E = I_B(1 + \beta)$$

Examples 6.2 , 6.3 , & 6.4 show how to use beta and any one terminal current to find the other two terminal currents.

DC Alpha

The dc Alpha rating of a transistor is the ratio of collector current to emitter current

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

Since I_E is always $I_C + I_B$, it will always be slightly larger than I_C. This fact makes α ***always slightly less than 1.***

DC alpha is also referred to ***collector current efficiency***.

DC Alpha will usually be 0.9 or higher. Note that it is a ratio and

Other useful formulas are:

$$I_C = \alpha I_E \qquad I_E = \frac{I_C}{\alpha} \qquad I_B = I_E(1 - \alpha)$$

You can determine the value of alpha from the value of beta with this formula.

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

Maximum Current Ratings

Most transistor specification sheets list the maximum collector current rating for both saturation and cutoff. When a transistor is saturated , the collector current can go as high as several hundred milliamperes. High power transistors can have current ratings as high as several amperes.

If we know the maximum collector current , we can find the maximum base current using this formula.

$$I_{B(max)} = \frac{I_{C(max)}}{\beta_{(max)}}$$

The beta rating is generally given as a range of values on the spec. sheet. We will be looking at this aspect later.

Example 6.6 demonstrates the use of this formula

Maximum Cutoff Current Ratings

Transistors also have a maximum cutoff current ratings. These ratings are usually in the low nano-ampere range are specified for exact values of V_{CE} and reverse V_{BE}

Transistor Voltages

We have seen that there a number of different voltage measurements involved when using transistors. the table below lists them and the diagram shows their location.

V_{CC} — ***Collector Supply Voltage.*** This is a power supply voltage applied directly or indirectly to the collector.

V_{BB} — ***Base Supply Voltage.*** The dc voltage used to bias the base of the transistor. It may come directly from a dc voltage supply or it may be applied indirectly to the base by a resistive circuit.

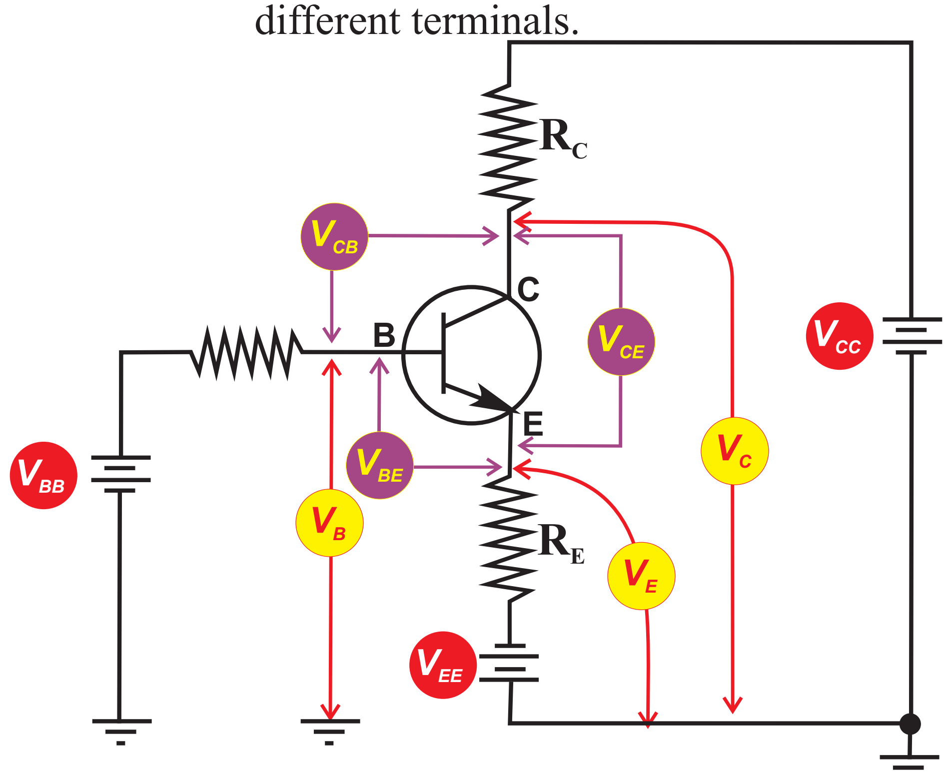
V_{EE} — ***Emitter Supply Voltage***. This is a supply voltage applied to the emitter. In many cases V_{EE} is simply a ground connection.

V_C — The dc voltage measured from ***collector to ground.***
V_B — The dc voltage measured from ***base to ground.***
V_E — The dc voltage measured from ***emitter to ground.***

V_{CE} — The dc voltage measured ***between the collector and the emitter.***
V_{CB} — The dc voltage measured ***between the collector and the base.***
V_{BE} — The voltage measured ***between the base and the emitter.***

Remember — ***Double subscripts*** refer to supply voltages
Single subscripts are voltages taken from a point to ground.
Two different subscripts are voltages measured between two different terminals.

Transistor Voltages

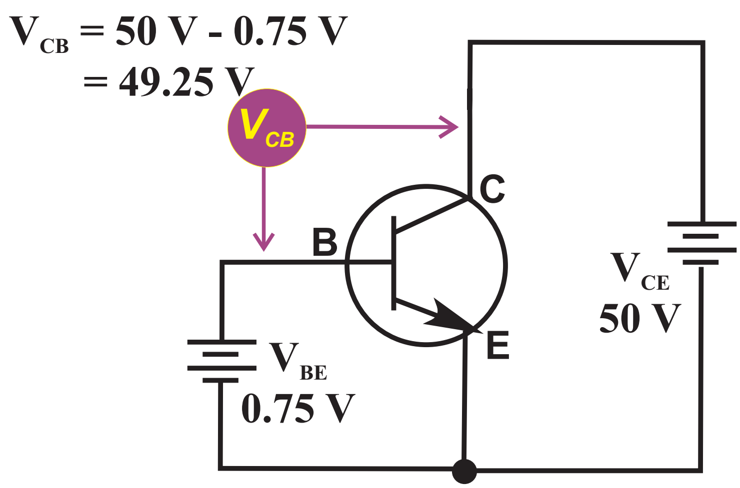


Transistor Voltage Ratings

There are several voltage ratings that we must concern ourselves with when working with transistors.

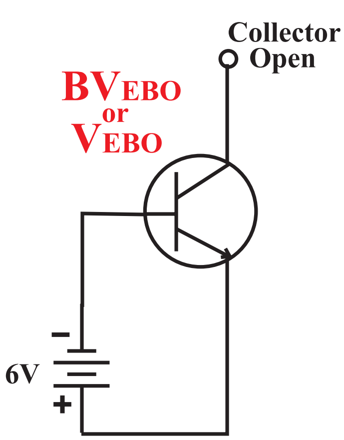
V_{CB} Most spec sheets give a maximum value for this voltage from collector to base. It refers to the maximum amount of reverse bias that can be applied to the collector- base junction without damaging the transistor. This rating is important since this junction is reverse biased for operation in the active region.

For the circuit shown V_{CE} is 50 V and V_{BE} is 0.75 V. V_{CB} is the difference between these or 49.25 V If this voltage is greater than the maximum rating for V_{CB} that is specified in the spec sheet, then the transistor will likely be destroyed.

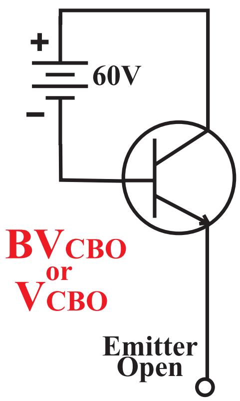


Transistor Breakdown Ratings

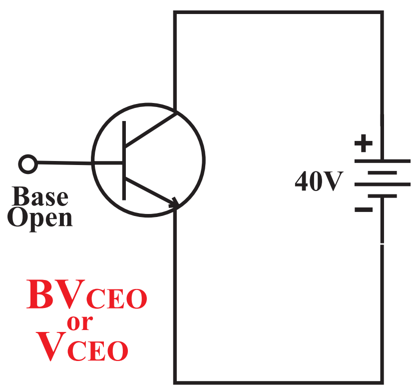
Transistors have three breakdown ratings. These indicate the maximum reverse voltages that the transistor can withstand. If any of these voltage maximums are exceeded, the transistor will likely be destroyed.



BV_{EBO} or V_{EBO} This is the maximum allowable reverse voltage that the transistor can withstand from emitter to base. The "O" indicates that the collector terminal is open when the rating is measured. This ensures that the BJT is in Cutoff when the parameter is measured.



BV_{CBO} or V_{CBO} This is the maximum allowable reverse voltage that the transistor can withstand from collector to base. The “O” indicates that the emitter terminal is open. when the rating is



BV_{CEO} or V_{CEO} This is the maximum allowable reverse voltage that the transistor can withstand from collector to emitter.. The base terminal is open. when the rating is measured.

Transistor Characteristic Curves

There are three characteristic curves that describe the operation of a transistor. These are the ***collector***, ***base***, and ***beta*** curves.

The Collector Curves

The characteristic collector curves relate to the values of I_C, I_B, and V_{CE}.

- Each collector curve is derived for a specific value of I_B.
- Each collector curve is divided into 3 parts

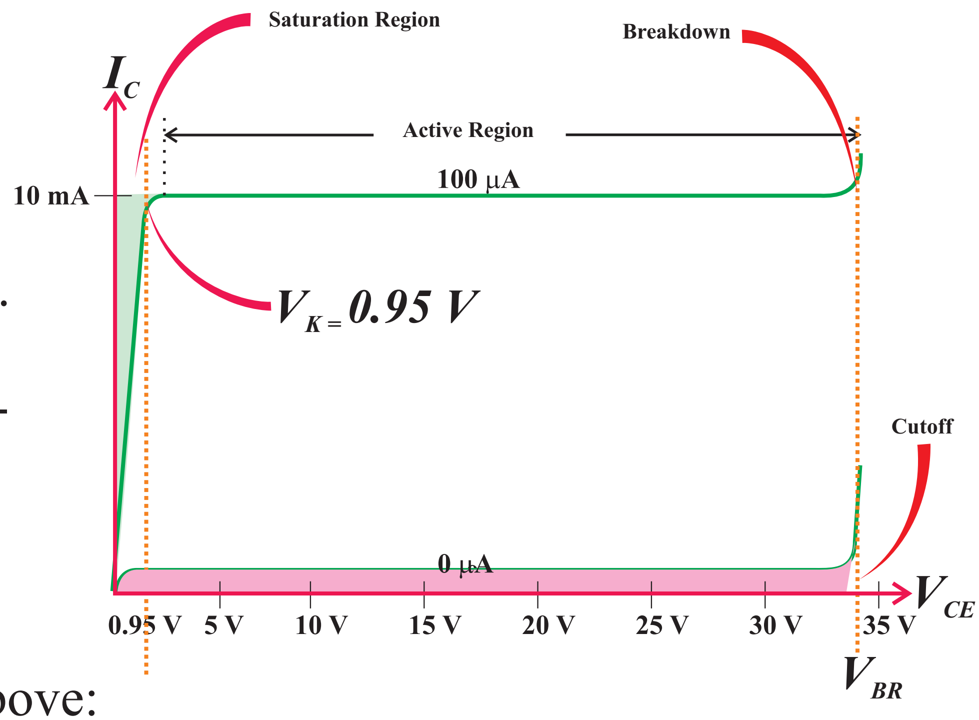
The Collector Curves (cont)

Saturation Region - where V_{CE} is less than V_K

Active Region - the flat area of the curve.

Breakdown Region - the area beyond the breakdown voltage V_{BR}.

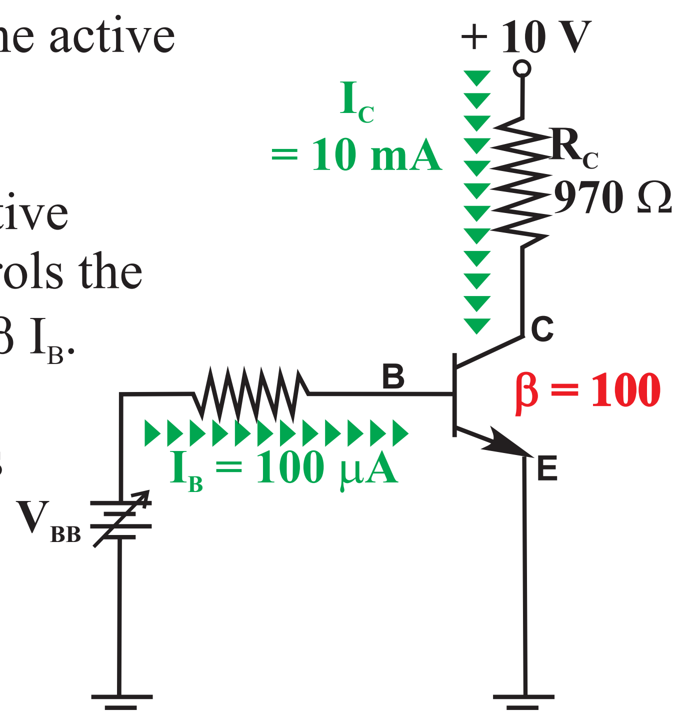
A Single Collector Curves



Note for the curve above:

- The base current I_B is 100 μA.
- The collector current is 10 mA when the transistor is operating in the active region.
- When operating in the active region, the transistor controls the collector current and $I_C = \beta I_B$.
- The dc current gain of this transistor is then:

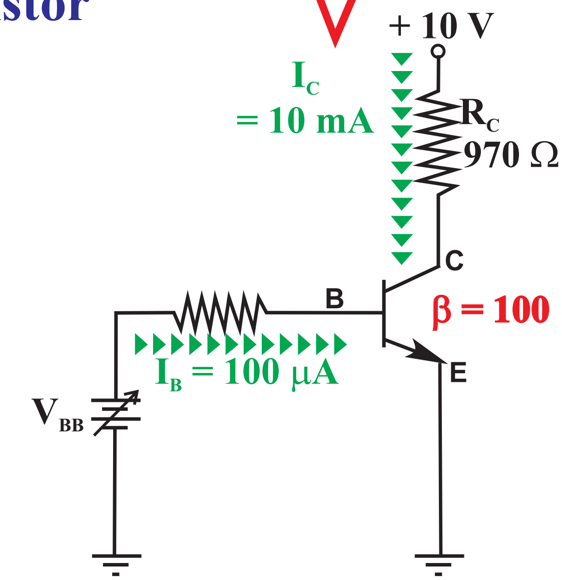
$$\beta = \frac{I_C}{I_B} = \frac{10\ \text{mA}}{100\ \mu\text{A}} = 100$$



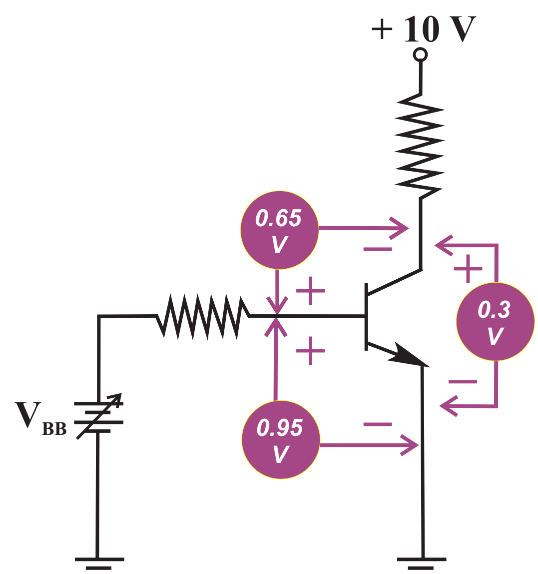
The Bipolar Junction Transistor

For the same transistor circuit as shown on the previous page, if I_C is 10 mA, then what is the voltage across the collector -emitter terminals.

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



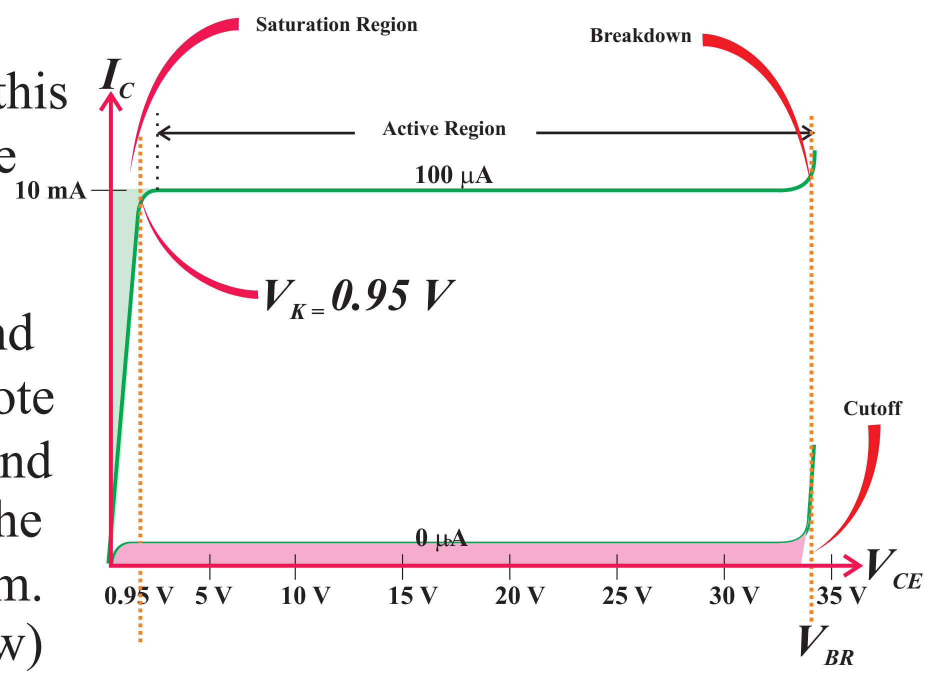
This means that when I_C is 10 mA, the transistor is in saturation.



We know from before that this transistor will have a V_{CE} of approximately 0.3 V when it is saturated and in the fully "on" condition.

The figure opposite shows the terminal voltages around the transistor at saturation.

V_{CE} is less than V_K and this puts the transistor in the saturation region.



V_{BE} is around 0.95 V and V_{CE} is approx. 0.3 V. Note the polarities of these and we can see that V_{CB} is the difference between them. (Kirchoff's Voltage Law)

This difference voltage of 0.65 V is enough to forward bias the C-B junction. This means both junctions are forward biased and the transistor is in saturation.

The Active Region

In the active region (where the curve is flat) the transistor acts like a constant current source. In this area, the transistor controls the collector current (I_C).

We know that the transistor is at saturation when R_C is at 970 Ω. If we reduce the value of R_C to 400 Ω, then :

$$I_C = \beta I_B$$
$$= (100)(100\ \mu A)$$
$$= 10\ mA$$

and

$$V_{CE} = V_{CC} - I_C R_C$$
$$= 10V - 10mA * 400\Omega$$
$$= 10V - 4V$$
$$= 6V$$

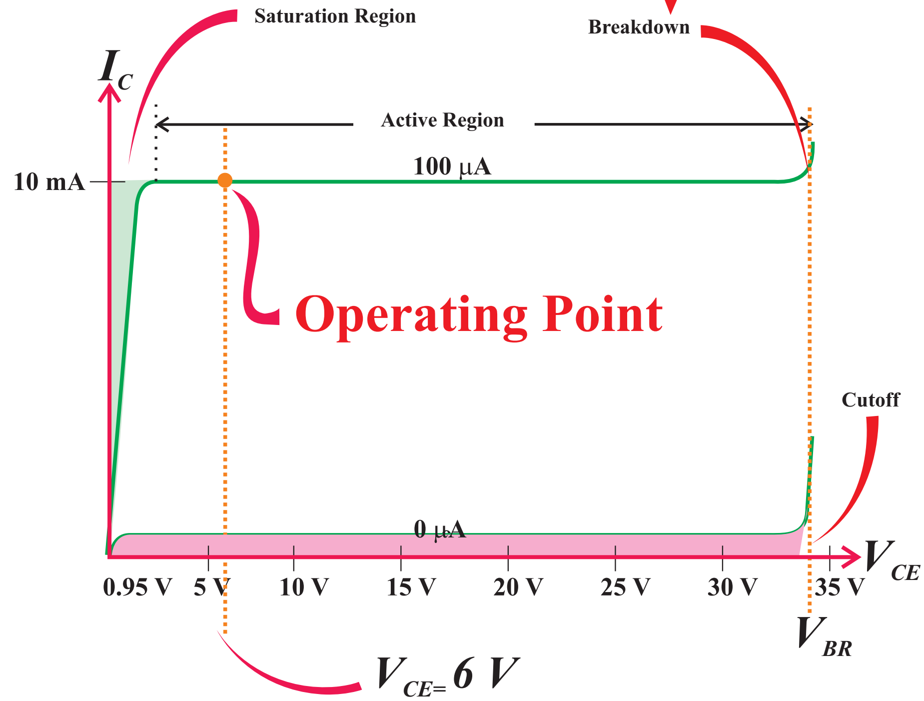
I_C has not changed but V_{CE} has gone from 0.3 V to 6V in order to maintain an I_C of 10 mA. The transistor is now well within the active region. Remember that in this region the transistor will adjust to maintain I_C at constant current.

As you can see, changing the value of R_C does little to effect the value of I_C. This is because the transistor's dc current gain controls the current here in the active region. The transistor adjusts to keep the current at a value determines by $I_C = \beta I_B$.

When the transistor is operating in the active region --

I_C remains almost constant for changes in V_{CE} from V_K to V_{BR}.

To change I_C, the value of I_B or beta must change.



With Rc = 400 Ω, the transistor is now operating in the active region

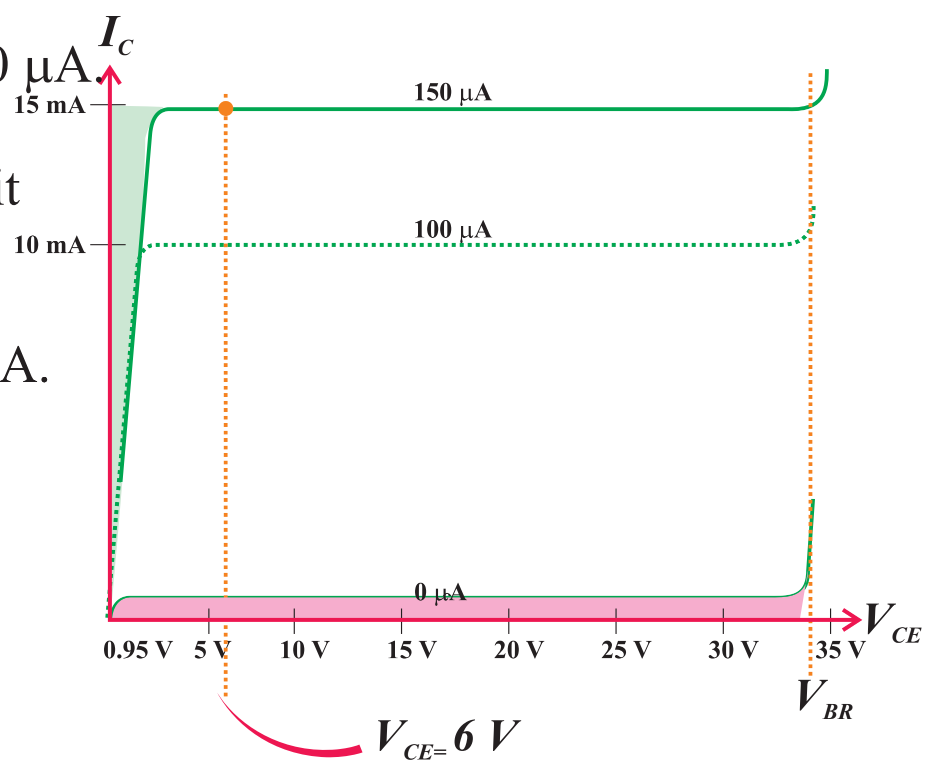
What happens if we increase I_B?

We have raised I_B to 150 µA. Beta has not changed nor has any of the circuit values.

I_C has increased to 15 mA.

By formula:

$$I_C = 100\,(150\ \mu A) = 15\ mA$$



I_C is dependant only on beta and I_B.

Ib increases from 100 µA to 150 µA
Ic increases from 10 mA to 15 mA
The gain is still 100

The Breakdown Region

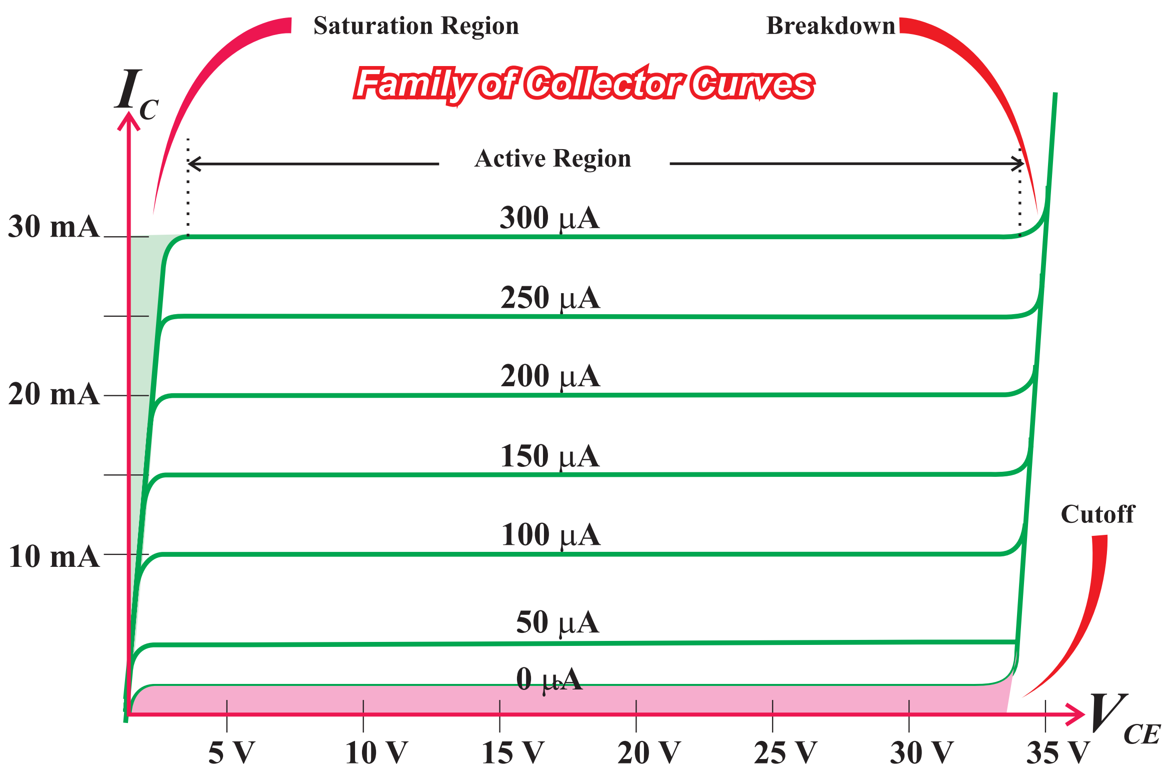
The breakdown region is the area beyond V_{BR}. If V_{CE} increases into this area, then I_C increases dramatically and the transistor will be destroyed by the excessive heat.

The Family of Characteristic Curves

When several I_B versus I_C curves are plotted, a composite graph is created.

This is the same example that we have been using.

Note that $\beta = 100$ for each of the curves.



Examples

For the 150 µA curve	*For the 200 µA curve*	*For the 300 µA curve*
$I_C = \beta I_B$	$I_C = \beta I_B$	$I_C = \beta I_B$
=	=	=
=	=	=

The Base Curves

The Base curve is a plot of I_B versus V_{BE}.

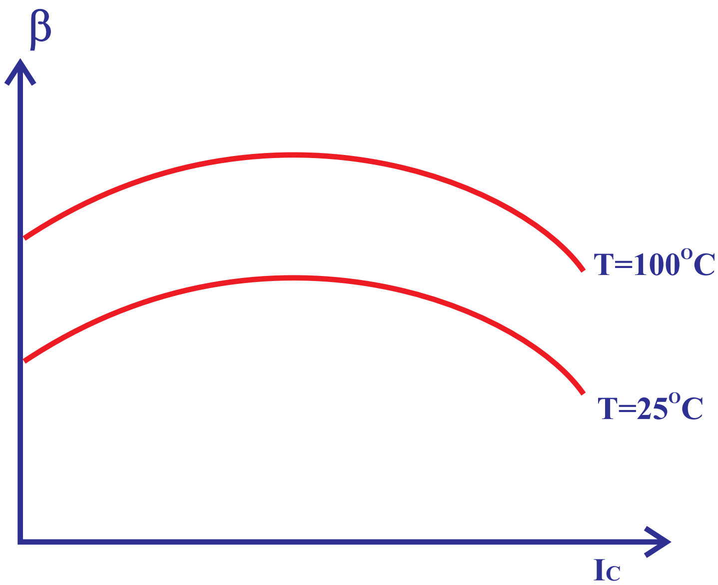
Note that it resembles the forward operating curve of the typical ***pn - junction*** diode.

A Base Characteristic Curve

The Beta Curves

The beta curves show the relationship between beta and temperature and/or collector current.

- beta increases with temperature
- beta increases (up to a point) for increases in I_C
- When I_C increases beyond a certain value, beta starts to decrease.



The Relationship among Beta, IC & Temperature

The spec. sheet for the 2N3904 lists the following minimum beta values.

Minimum Beta	*Condition*
40	$I_C = 0.1\ mA_{DC}$
70	$I_C = 1.0\ mA_{DC}$
100	$I_C = 10\ mA_{DC}$
60	$I_C = 50\ mA_{DC}$
30	$I_C = 100\ mA_{DC}$

Note that as I_C increases above 10 mA, the value of beta deceases.

Transistor Specification Sheets

The transistor spec sheet gives us a wide variety of dc and ac operating characteristics. We will look at some of them.

Refer to the spec sheet on page 219 on the 2N3904

Maximum Ratings

The V_{CEO} , V_{CBO} , and V_{EBO} ratings are the maximum reverse ratings that we studied earlier.

The device dissipation (P_D) rating shows the 2N3904 has a P_D rating of 625 mW when the ambient (room) temperature is 25^{O}C.

If the case temperature (T_C) is held at 25^{O}C, the device P_D rating increases to 1.5 Watts.

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector-Emitter Voltage	V_{CEO}	40	Vdc
Collector-Base Voltge	V_{CBO}	60	Vdc
Emitter-Base Voltage	V_{EBO}	6.0	Vdc
Collector Current — Continuous	I_C	200	mAdc
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

The case temperature can be held at 25^{O}C with use of a fan or a heat sink.

Both ratings must be derated as temperature increases.

Thermal Characteristics

The thermal ratings of the transistor are primarily used in development applications.

*THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Ambient	$R_{\theta JA}$	200	°C/W
Thermal Resistance, Junction to Case	$R_{\theta JC}$	83.3	°C/W

*Indicates Data in addition to JEDEC Requirements.

Off Characteristics

These describe the operation of the transistor when it is operated in cutoff.

The first 3 ratings are familiar. These are the maximum reverse voltage ratings that we have seen earlier. They are repeated here for convenience.

The ***collector cutoff current*** (I_{CEX}) rating, indicates the ***maximum value of I_C when the device is in cutoff.***

The base ***cutoff current*** (I_{BL}) rating, indicates the ***maximum value of base current present when the emitter-base junction is in cutoff.***

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted.)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector-Emitter Breakdown Voltage(1) (I_C = 1.0 mAdc, I_B = 0)	$V_{(BR)CEO}$	40	—	Vdc
Collector-Base Breakdown Voltage (I_C = 10 μAdc, I_E = 0)	$V_{(BR)CBO}$	60	—	Vdc
Emitter-Base Breakdown Voltage (I_E = 10 μAdc, I_C = 0)	$V_{(BR)EBO}$	6.0	—	Vdc
Base Cutoff Current (V_{CE} = 30 Vdc, V_{EB} = 3.0 Vdc)	I_{BL}	—	50	nAdc
Collector Cutoff Current (V_{CE} = 30 Vdc, V_{EB} = 3.0 Vdc)	I_{CEX}	—	50	nAdc

As the I_{CEX} and I_{BL} ratings indicate, the terminal currents of the cutoff transistor are very low. In the case of the 2N3904, I_B and I_C will not be greater than 50 nA. This means that the value of I_E will be no greater than the sum of the two, or 100 nA

On Characteristics

ON CHARACTERISTICS

Characteristic	Device	Symbol	Min	Max	Unit
DC Current Gain(1)		h_{FE}			—
(I_C = 0.1 mAdc, V_{CE} = 1.0 Vdc)	2N3903		20	—	
	2N3904		40	—	
(I_C = 1.0 mAdc, V_{CE} = 1.0 Vdc)	2N3903		35	—	
	2N3904		70	—	
(I_C = 10 mAdc, V_{CE} = 1.0 Vdc)	2N3903		50	150	
	2N3904		100	300	
(I_C = 50 mAdc, V_{CE} = 1.0 Vdc)	2N3903		30	—	
	2N3904		60	—	
(I_C = 100 mAdc, V_{CE} = 1.0 Vdc)	2N3903		15	—	
	2N3904		30	—	
Collector-Emitter Saturation Voltage(1)		$V_{CE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)			—	0.2	
(I_C = 50 mAdc, I_B = 5.0 mAdc)			—	0.3	
Base-Emitter Saturation Voltage(1)		$V_{BE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)			0.65	0.85	
(I_C = 50 mAdc, I_B = 5.0 mAdc)			—	0.95	

These describe the dc operating characteristics for the active and the saturation regions of operation

The dc current gain (h_{FE}) rating of a transistor is the value of dc beta.

Note that the values of h_{FE} are measured at different values of I_C. This is because h_{FE} varies with both temperature and collector current. We covered this fact earlier.

The ***collector-emitter saturation voltage*** $V_{CE(sat)}$ rating indicates the maximum value of V_{BE} when the device is in saturation. For the 2N3904, the value of $V_{CE(sat)}$ is

$$0.2 \text{ V when } I_C = 10 \text{ mA}_{dc}.$$

$$0.3 \text{ V when } I_C = 50 \text{ mA}_{dc}.$$

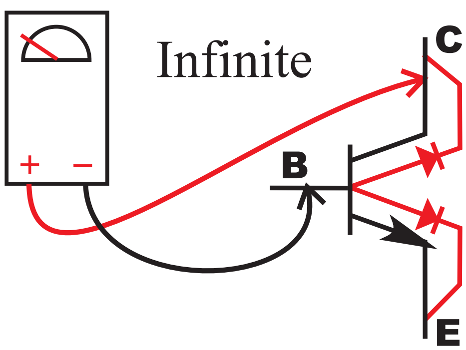
At the rated values of I_C, V_{CE} will be no greater than 0.2 or 0.3 V.

The ***base-emitter saturation voltage*** $\boldsymbol{V_{BE(sat)}}$ rating the maximum value of V_{BE} when the device is in saturation. For the 2N3904, this can be 0.85 V or 0.95 V depending on the rated value of I_B.

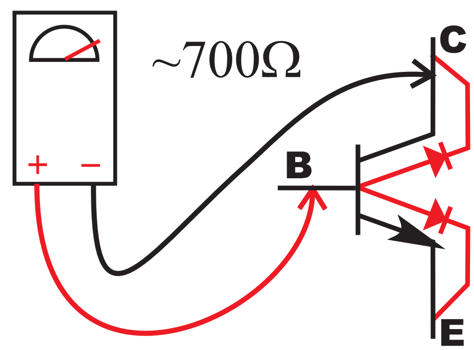
Transistor Testing

Transistors, like diodes, can be checked with an ohmmeter. This involves checking the forward and reverse resistance of the base-emitter diode and the collector-base diode. It is done in exactly the same way we have done in the past with regular diodes.

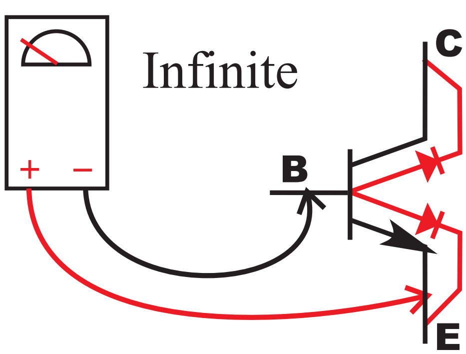
Other checks are required to determine if the transistor will operate correctly, however this is a fast, first-line check to determine the condition of the transistor. The transistor is bad if any of the diode checks fail.



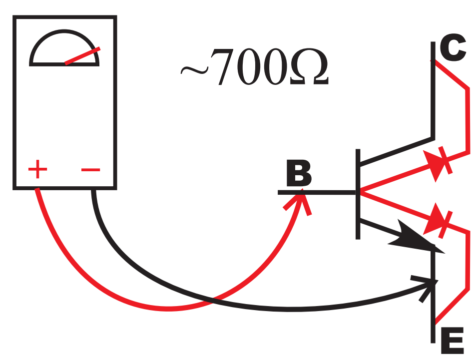
Checking the collector-base diode
Reverse Bias



Checking the collector-base diode
Forward Bias



Checking the base-emitter diode
Reverse Bias



Checking the base-emitter diode
Forward Bias

Transistor Testing

Transistors can also be tested using a DMM with h_{FE} capabilities. Using a meter, the transistor is placed in the 3pin grooves, the meter is placed in h_{FE} mode and the reading will be the B or h_{FE} measurement of the transistor. For a NPN 2N3904, a good transistor will read between 160 to 260.

This verifies the transistor is functional.
Note: The image shown is a
Mastercraft 25$ meter.

Further readings: Chapter 6.7
- -pnp vs. npn
- -High Voltage Transistors
- -High Current Transistors
- -High Power Transistors

Example Practical Cct: (LED switching, npn transistor used in saturation)

2N3904