IDC102:Hands-on Electronics
Lecture - 8

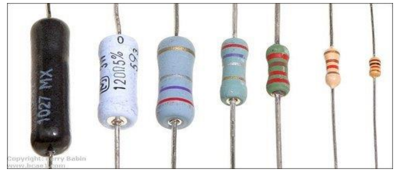
Transistors

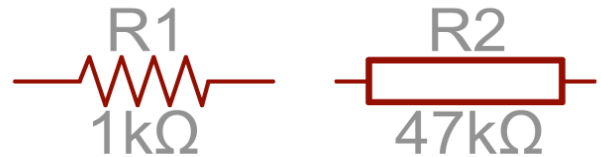
IISER

Satyajit Jena, 11/07/2022

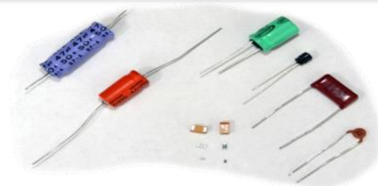
Components

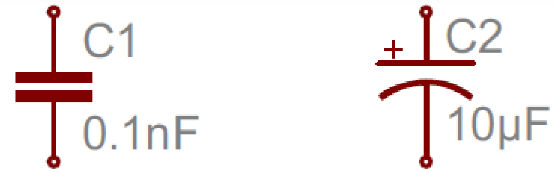
Resistor



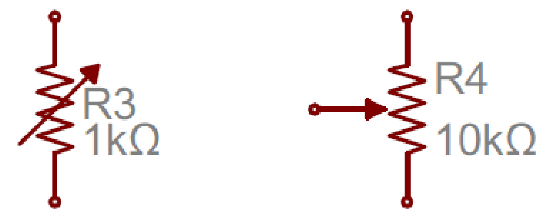


Capacitors



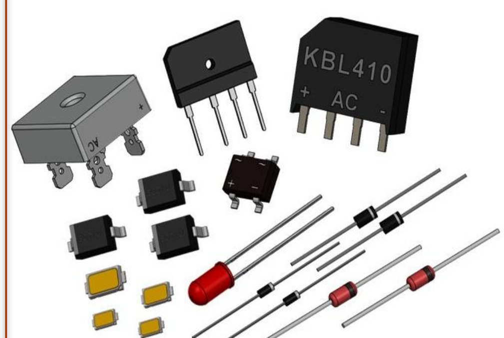


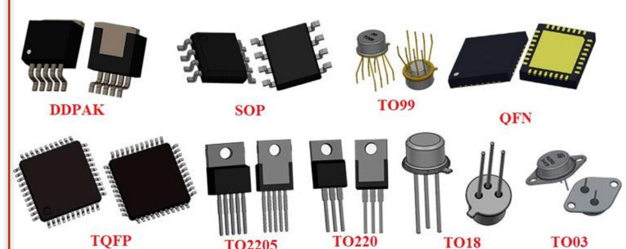
Variable Resistor



Inductors

Diodes





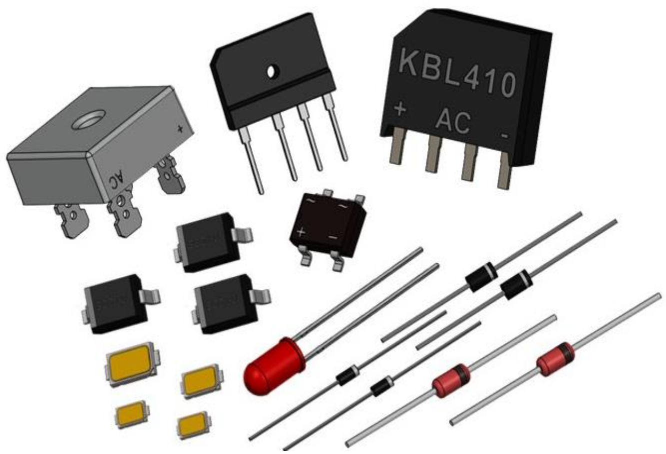
Transistor and IC

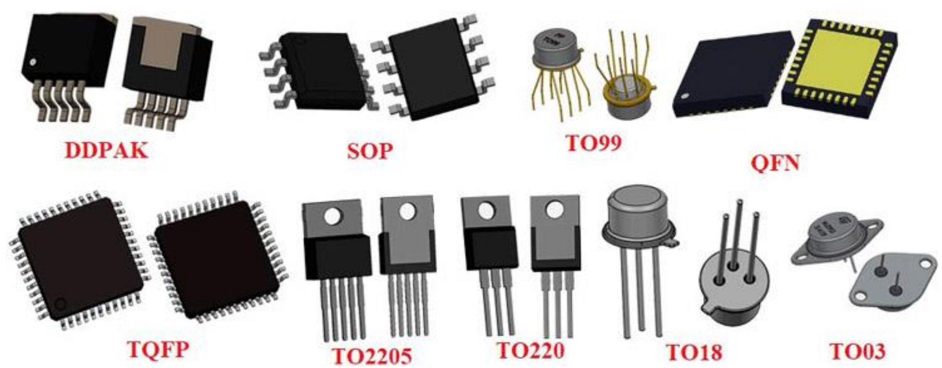
Active Components

Active Components:

Active components are devices that are capable of controlling voltages or currents and can create a switching action in the circuit. They can amplify or interpret a signal. They include diodes, transistors and integrated circuits. They are usually semiconductor devices.

Transistor and IC



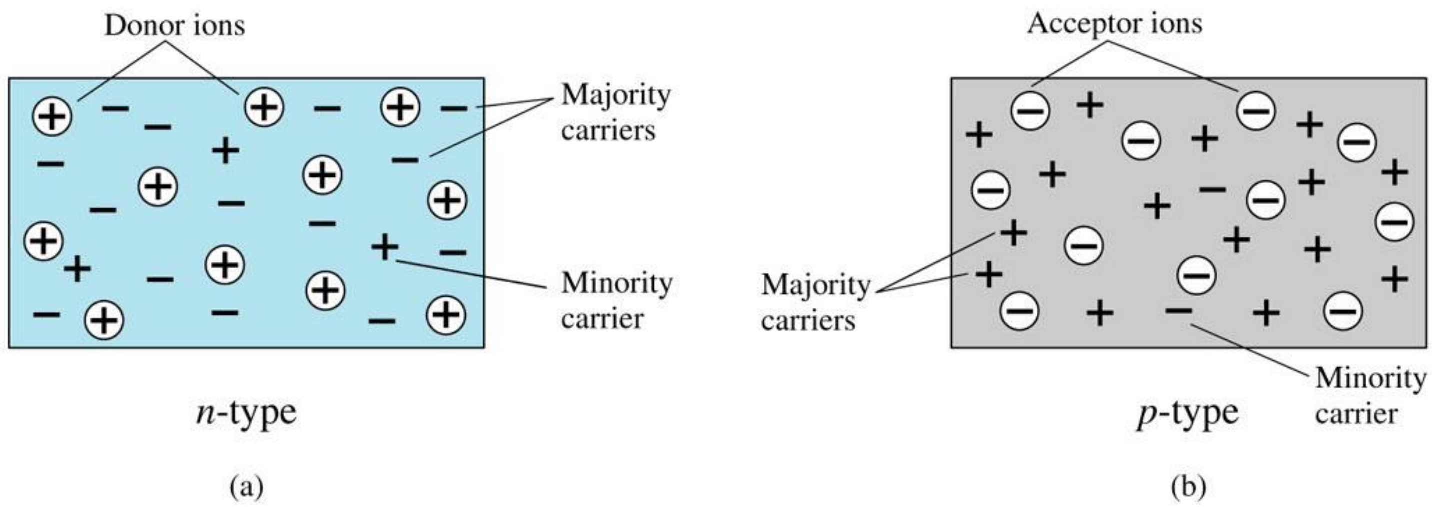


Diodes

To understand them we should know about the material properties

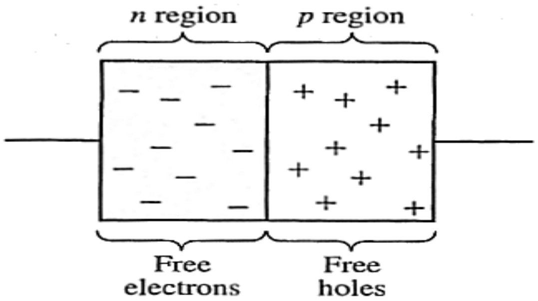
n-type versus p-type

- In n-type - the electrons are the majority carriers and holes are the minority carriers.
- In p-type - the holes are called the majority carriers and electrons are the minority carriers.

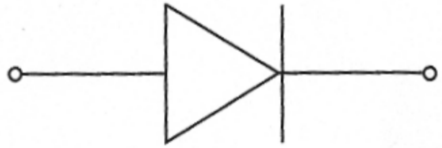


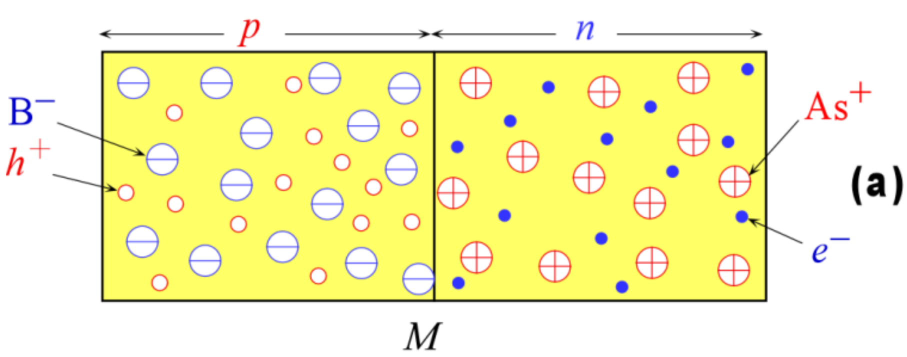
A device using p and n type

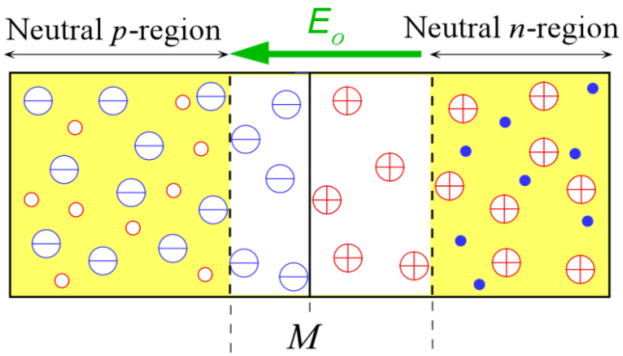
Electronic devices created by bringing together a *p*-type and *n*-type region within the same semiconductor lattice. Used for rectifiers, LED etc



It is represented by the following symbol, where the arrow indicates the direction of positive current flow.

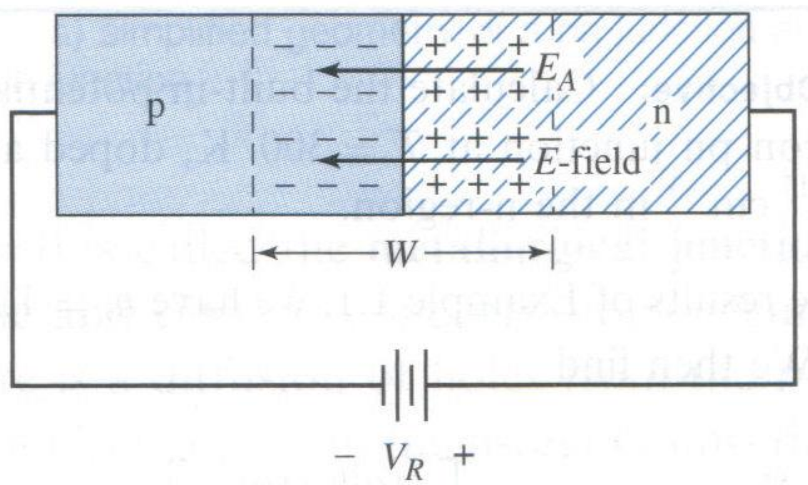






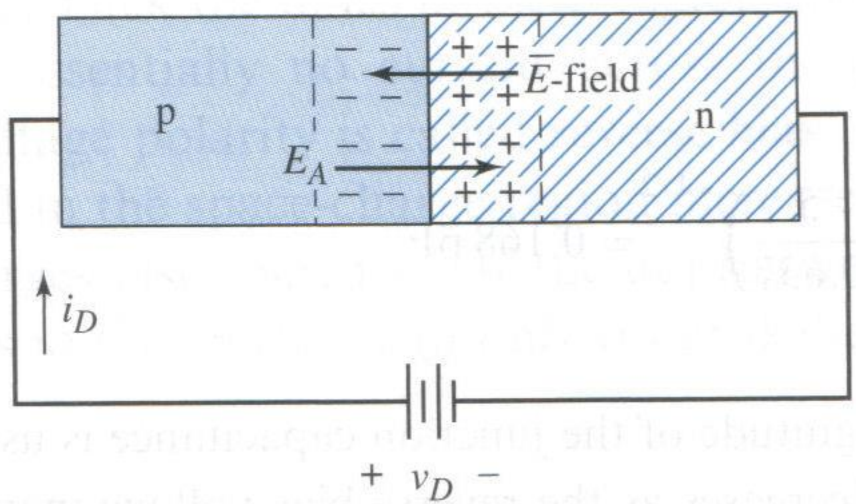
Reverse-Biased pn Junction

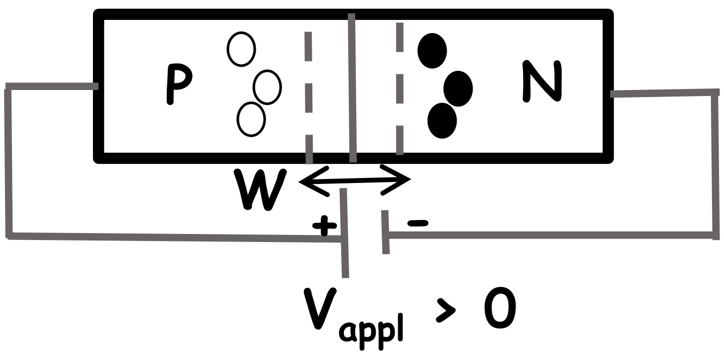
- +ve terminal is applied to the n-region of the pn junction and vice versa.
- Applied voltage V_R will induce an applied electric field E_A.
- Direction of the E_A is the same as that of the E-field in the space-charge region.
- Magnitude of the electric field in the space-charge region increases above the thermal equilibrium value. Total $E_T = E + E_A$
- Increased electric field holds back the holes in the p-region and the electrons in the n-region.

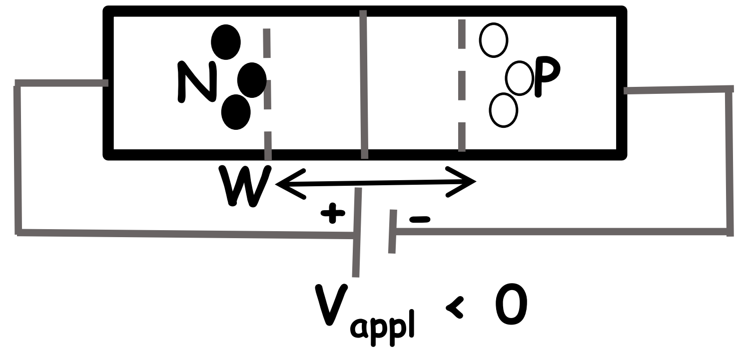


Forward-Biased pn Junction

- +ve terminal is applied to the p-region of the pn junction and vice versa.
- Direction of the applied electric field E_A is the opposite as that of the E-field in the space-charge region.
- The net result is that the electric field in the space-charge region lower than the thermal equilibrium value causing diffusion of charges to begin again.
- The diffusion process continues as long as V_D is applied.





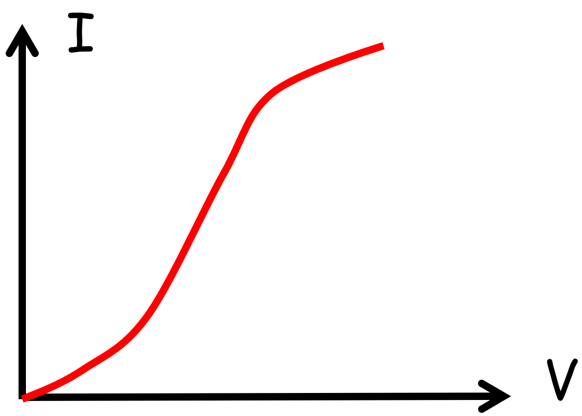


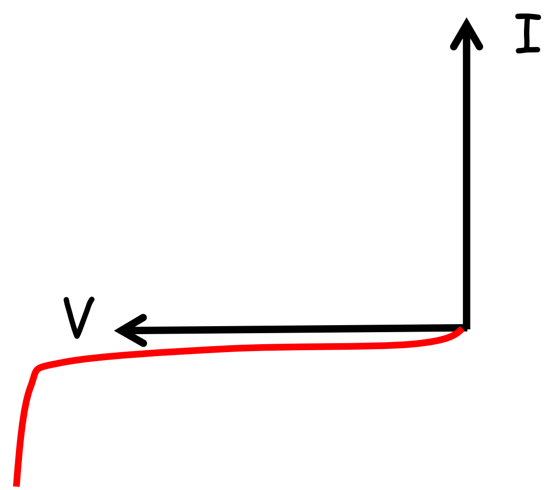
Forward bias, + on P, - on N (Shrink W, V_{bi})

Reverse bias, + on N, - on P (Expand W, V_{bi})

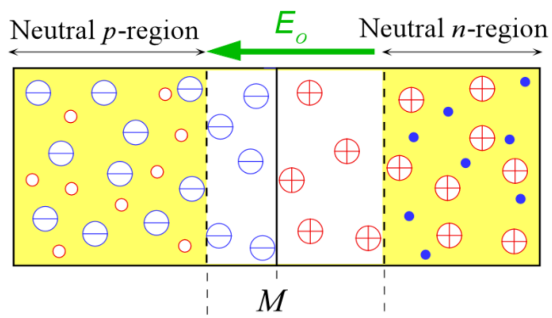
Allow holes to jump over barrier into N region as minority carriers

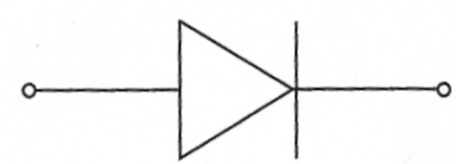
Remove holes and electrons away from depletion region



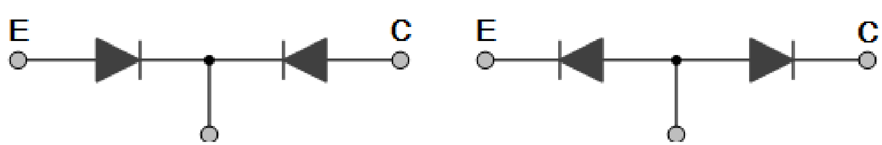


In the diode we saw that simple diodes are made up from two pieces of semiconductor material to form a simple p-n junction and we also learnt about their properties and characteristics.



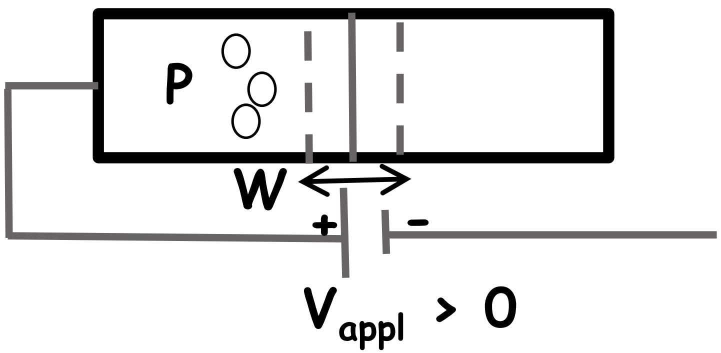


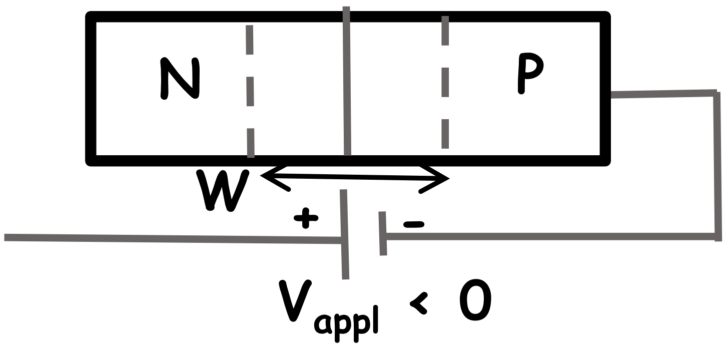
If we now join together two individual signal diodes back-to-back: there are two possibilities. (a) Joining both in n-sides (b) Joining both in p-sides



Eventually we create two type of connections

So if we combine these by fusing their terminals…





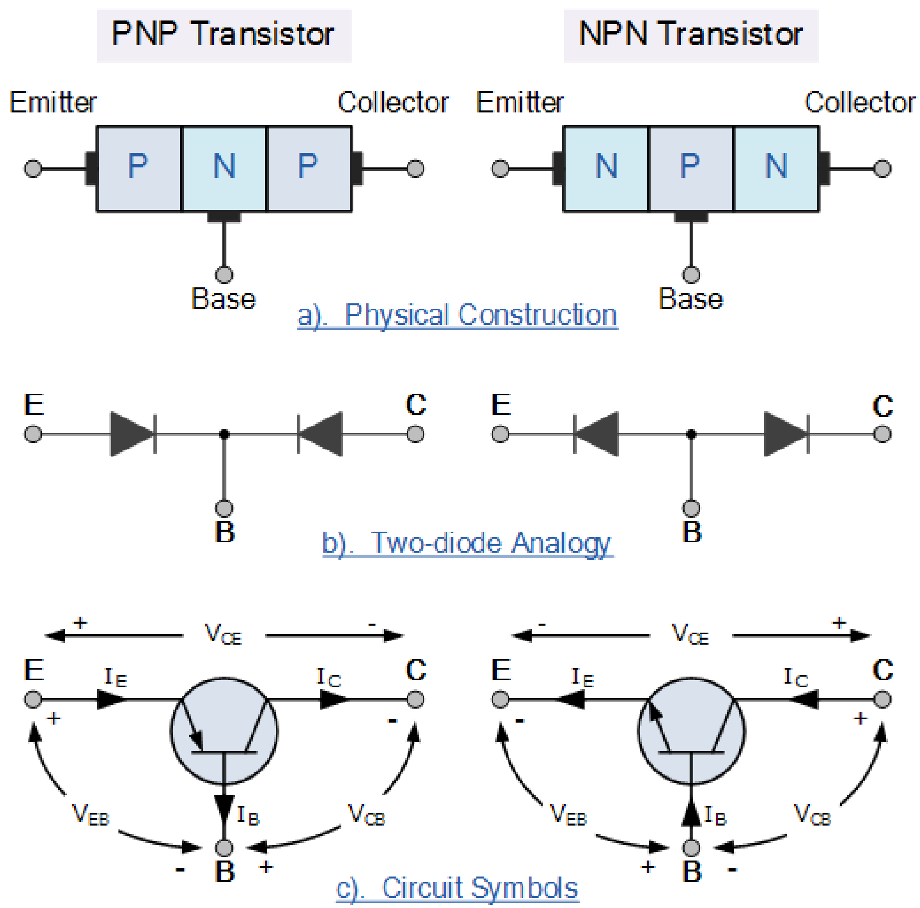
Holes from P region ("Emitter") of 1st PN junction driven by FB of 1st PN junction into central N region ("Base")

Driven by RB of 2nd PN junction from Base into P region of 2nd junction ("Collector")

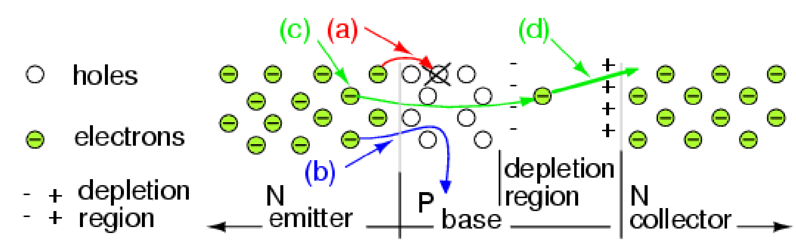
- 1st region FB, 2nd RB
- If we want to worry about holes alone, need P+ on 1st region
- For holes to be removed by collector, base region must be thin

Transistor

The fusion of these two diodes produces a three layer, two junction, three terminal device forming the basis of a **Bipolar Junction Transistor**, or **BJT** for short.



The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two.



Electron Flow

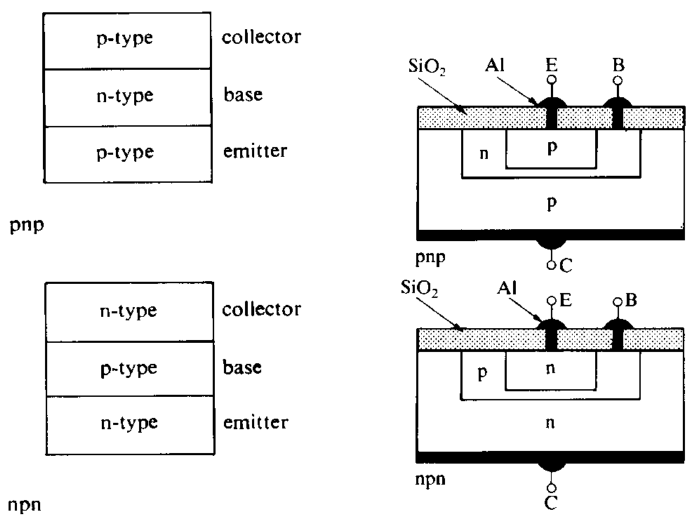
These three terminals are known and labeled as the Emitter (E), the Base (B) and the Collector (C) respectively

Transistors

Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage. The transistor's ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics). Then bipolar transistors have the ability to operate within three different regions:

The word Transistor is a combination of the two words Transfer Variator which describes their mode of operation way back in their early days of electronics development. There are two basic types of bipolar transistor construction, PNP and NPN, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

- A transistor is a device with three separate layers of semiconductor material stacked together
  - The layers are made of *n*–type or *p*–type material in the order *pnp* or *npn*
  - The layers change abruptly to form the *pn* or *np* junctions
  - A terminal is attached to each layer



(a) *schematic construction* (b) *practical construction*

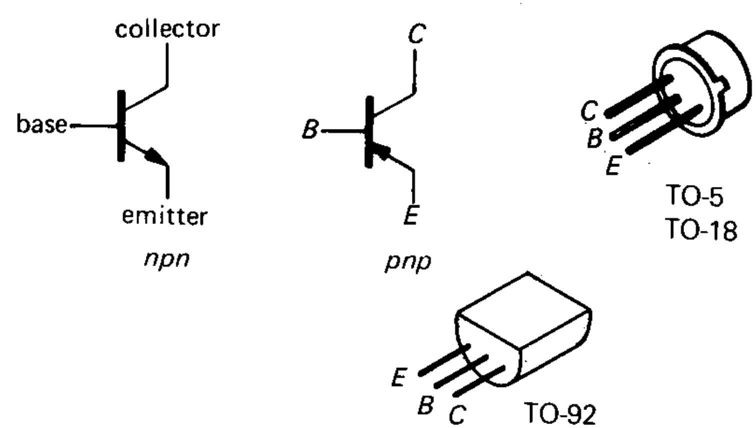
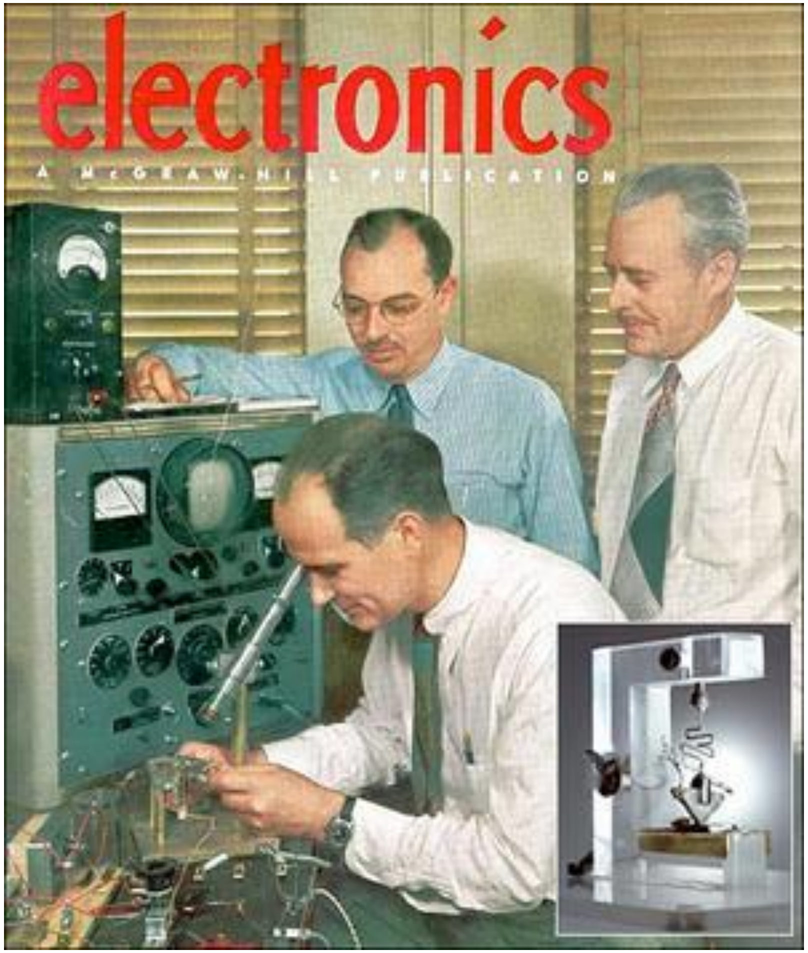


Figure 2.1. Transistor symbols, and small transistor packages.

Transistors

Electronic Materials

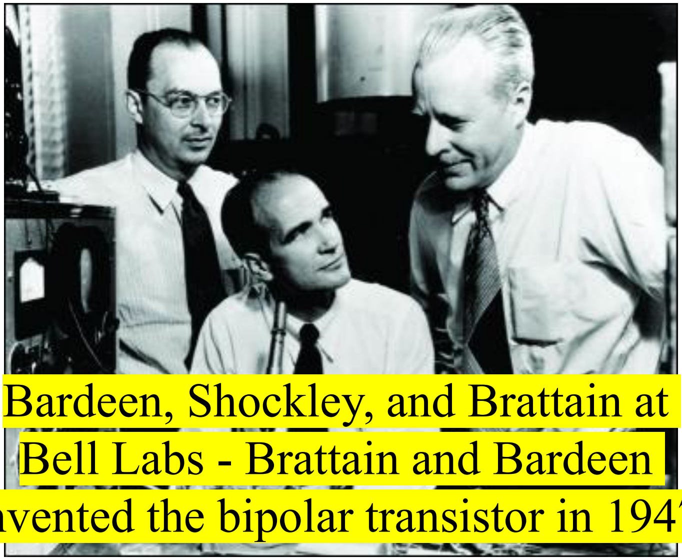


“IN DECEMBER 1947, Bells Labs scientists John Bardeen and Walter Brattain first revealed what would come to be known as the transistor. Soon after Bardeen and Brattain made their breakthrough, William Shockley, also at Bell Labs, invented the first semiconductor transistor. All three were awarded the 1956 Nobel prize for their efforts.

Justin Rattner, chief technology officer of Intel, calls the transistor "the fundamental building block of the information age.”

http://www.smh.com.au/news/technology/the-transistor-at-60/2007/11/26/1196036813732.html

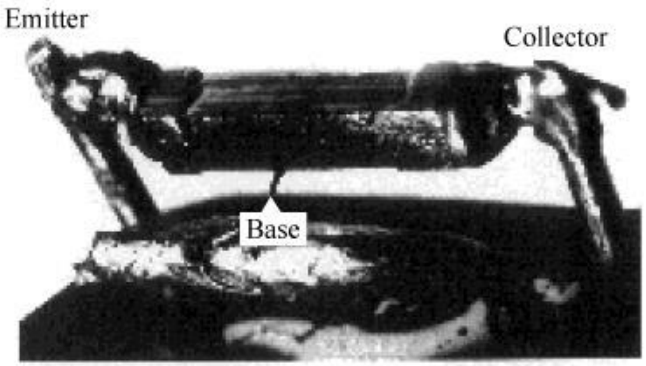
History: 1947 First Transistor

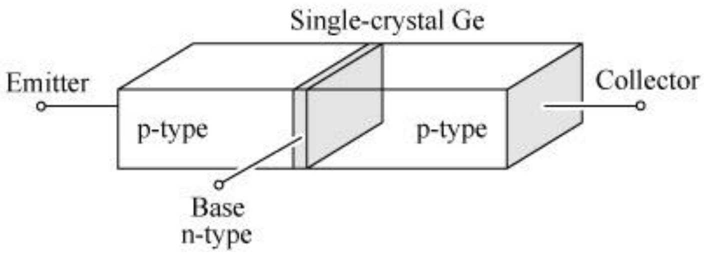


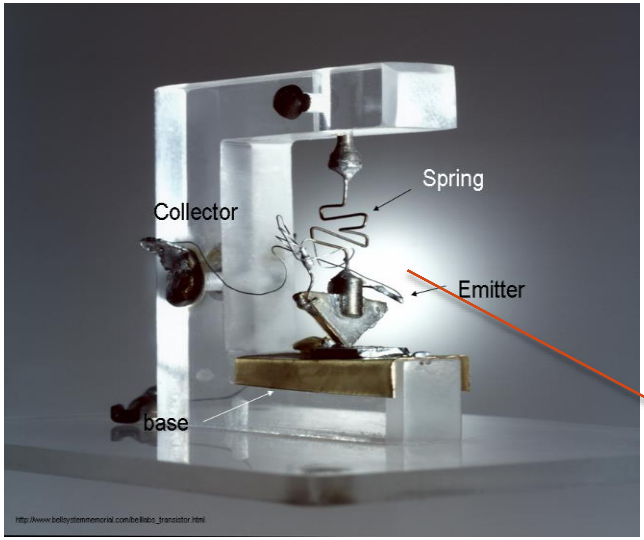
Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the bipolar transistor in 1947.

The First Junction Transistor

First transistor with diffused pn junctions by *William Shockley*
Bell Laboratories, Murray Hill, New Jersey (1949)







The first germanium bipolar transistor. Roughly 50 years later, electronics account for 10% (4 trillion dollars) of the world GDP.

Electronics Milestones

1874 Braun invents the solid-state rectifier.

1906 DeForest invents triode vacuum tube.

1907-1927

First radio circuits developed from diodes and triodes.

1925 Lilienfeld field-effect device patent filed.

1947 Bardeen and Brattain at Bell Laboratories invent bipolar transistors.

1952 Commercial bipolar transistor production at Texas Instruments.

1956 Bardeen, Brattain, and Shockley receive Nobel prize.

1958 Integrated circuits developed by Kilby and Noyce

1961 First commercial IC from Fairchild Semiconductor

1963 IEEE formed from merger of IRE and AIEE

1968 First commercial IC opamp

1970 One transistor DRAM cell invented by Dennard at IBM.

1971 4004 Intel microprocessor introduced.

1978 First commercial 1-kilobit memory.

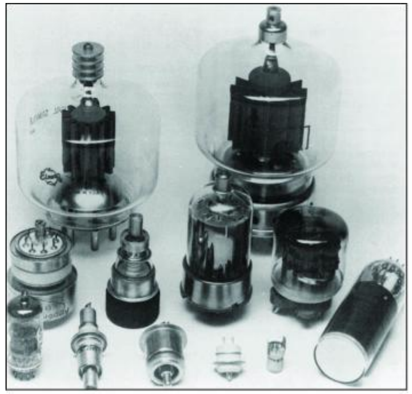
1974 8080 microprocessor introduced.

1984 Megabit memory chip introduced.

2000 Alferov, Kilby, and Kromer share Nobel prize

Evolution of Electronic Devices

Vacuum Tubes



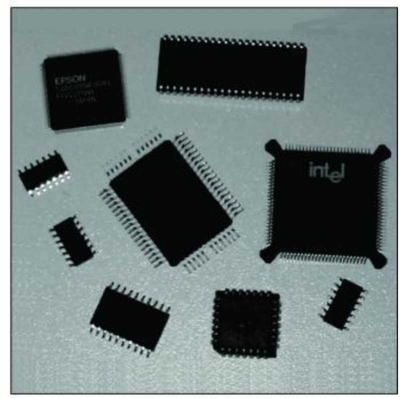
(a)

(b)

Discrete Transistors

SSI and MSI Integrated Circuits

(c)



(d)

VLSI Surface-Mount Circuits

Foundation of Shockley Semiconductor 1955

- Foundation of Shockley Semiconductor, sowing the seeds of silicon valley

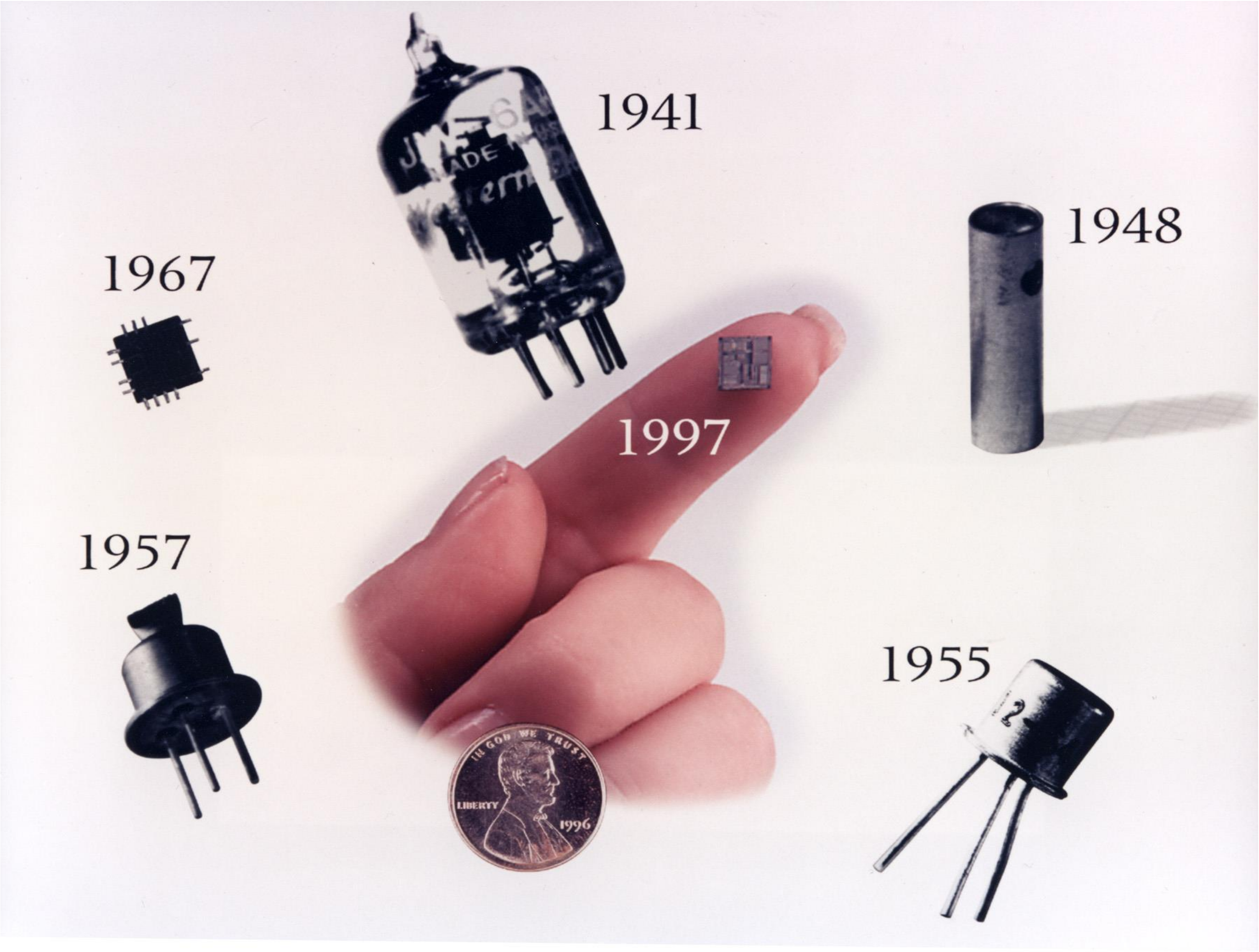
1957 and 1968

The traitorous eight abandoned Shockley founding Fairchild Semiconductor.

Bob Noyce and Gordon Moore, two of the traitorous eight together with Andy Grove, form Intel Corporation

http://www.granneman.com/techinfo/background/history/

History

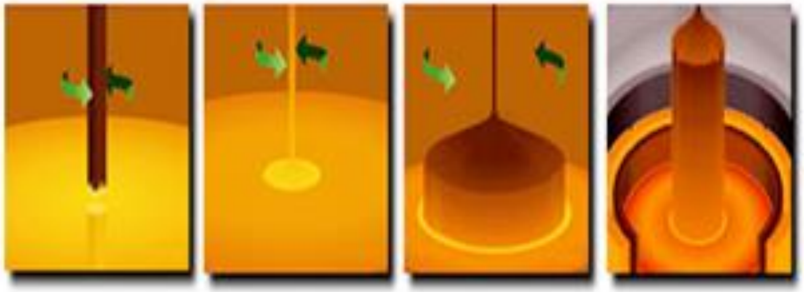


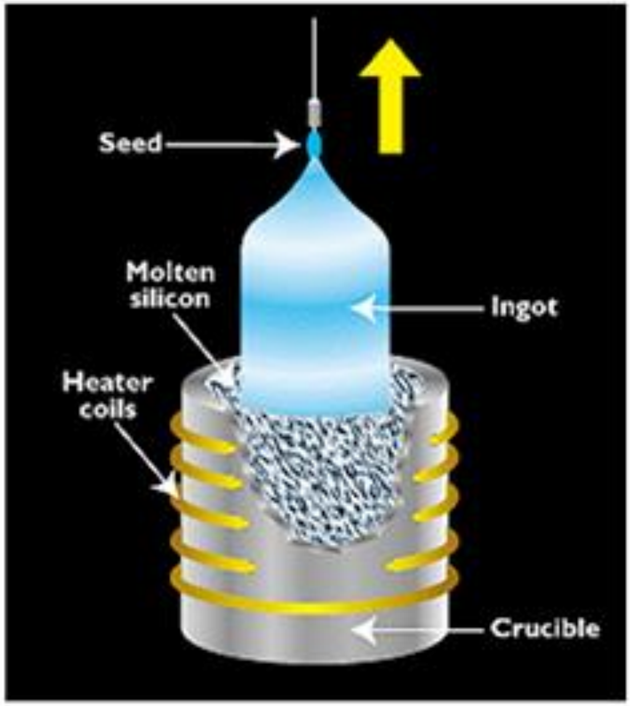
Microelectronics Proliferation

- The integrated circuit was invented in 1958.
- 1965 10devices/chip but by 1969 1000 devices/chip
- Doubles every 1 1/2-2 years: Moores Law is born
- 1971 put multiple functions on a single chip birth of the microprocessor
- World transistor production has more than doubled every year for the past twenty years.
- Every year, more transistors are produced than in all previous years combined.
- Approximately 10^{18} transistors were produced in a recent year.
- Roughly 50 transistors for every ant in the world.

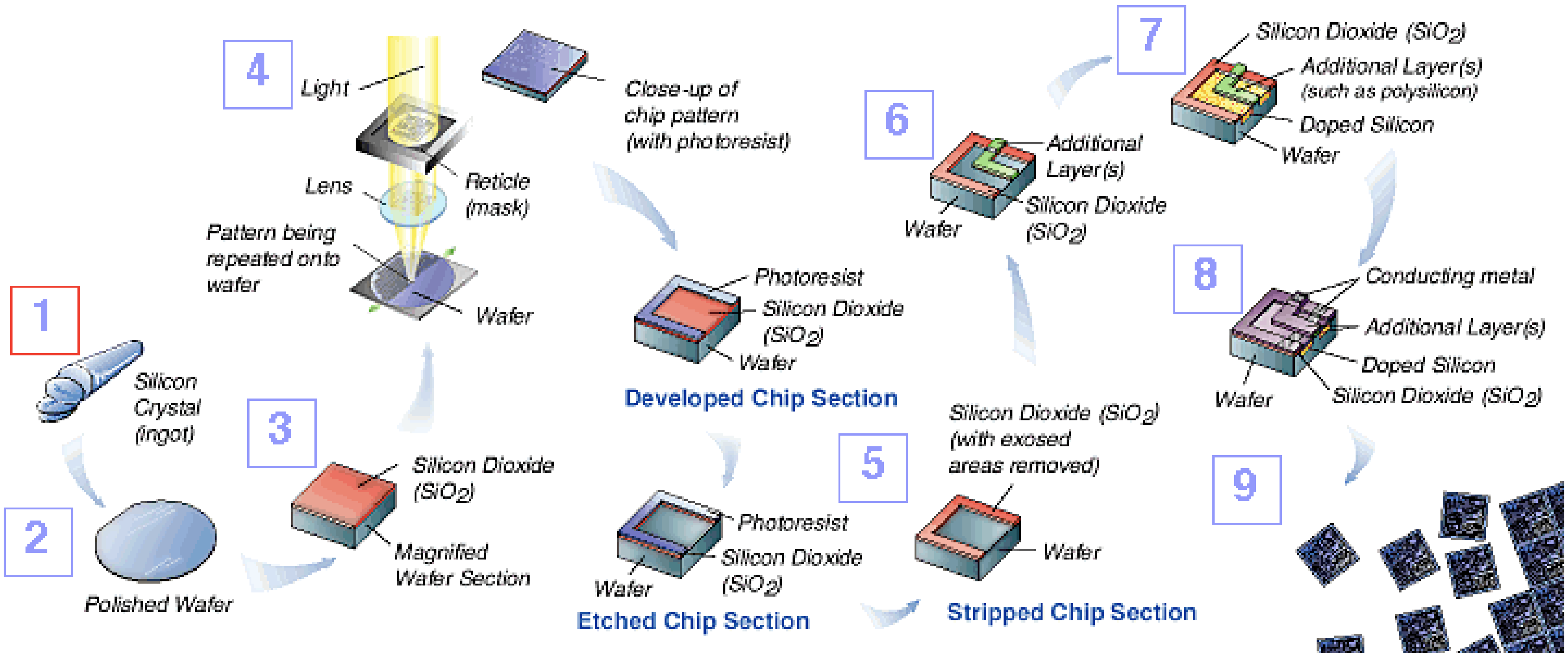
*Source: Gordon Moore's Plenary address at the 2003 International Solid State Circuits Conference.

Processing of Silicon

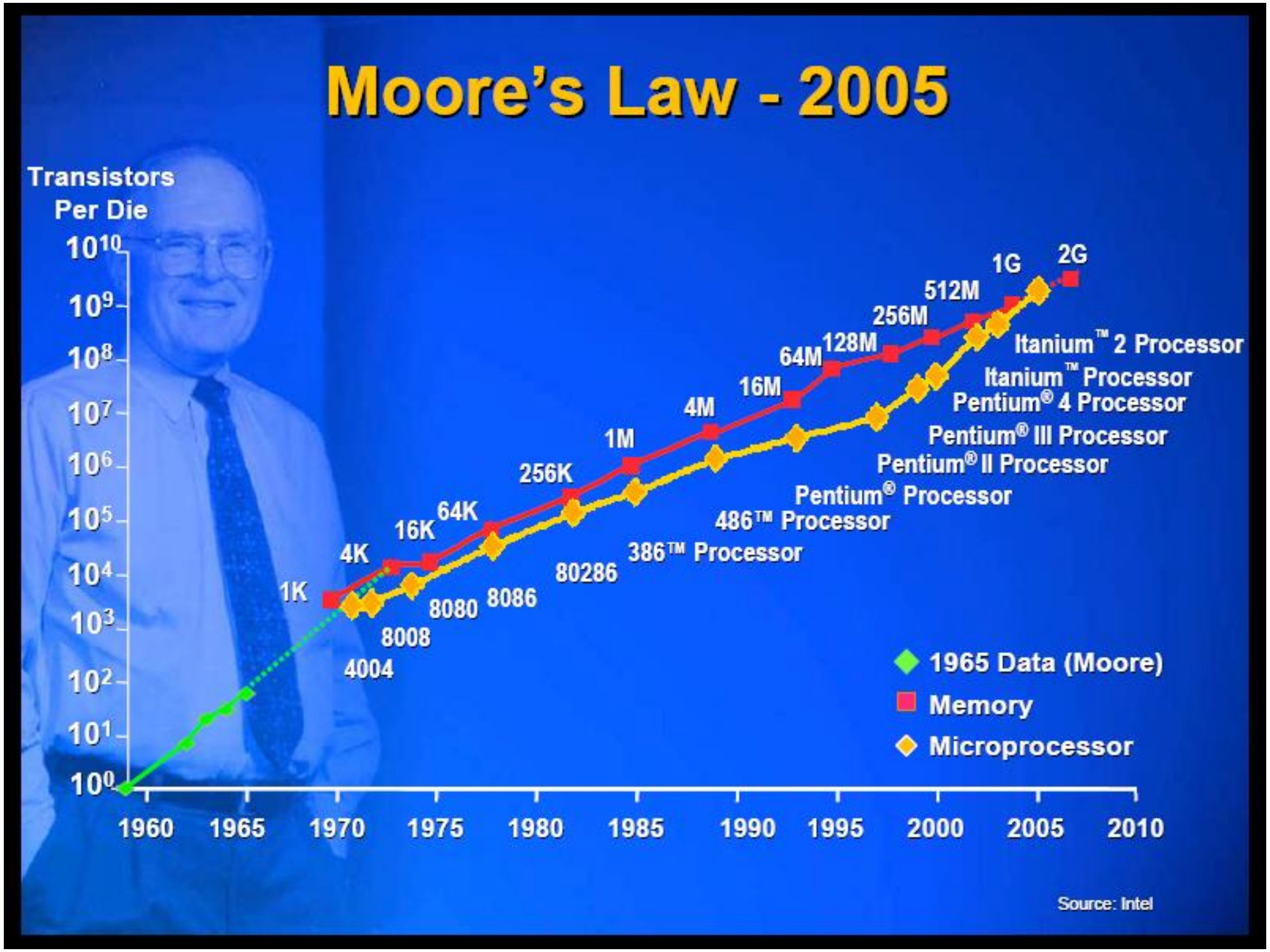




Microelectronics Processing

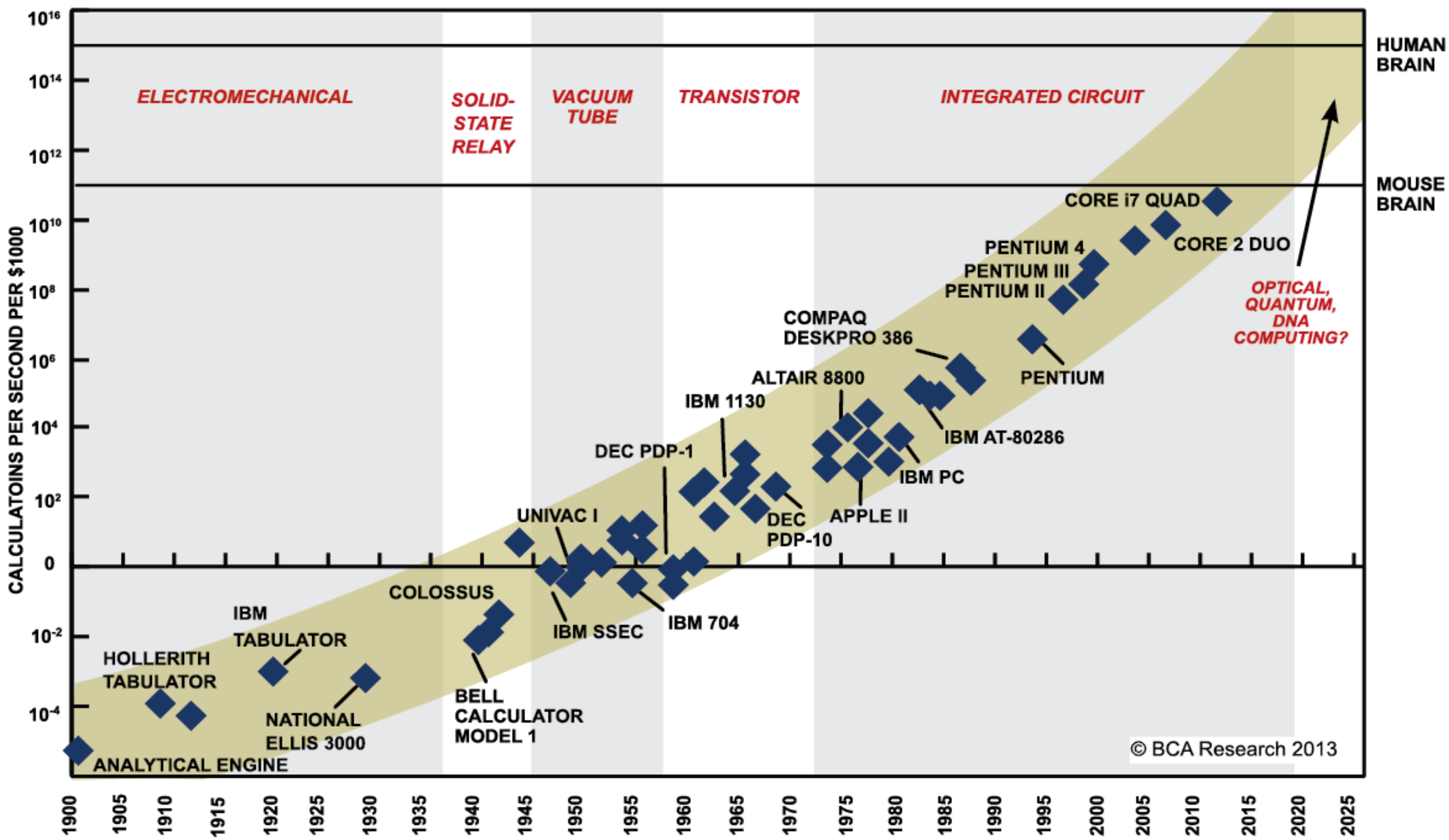


Moore’s Law



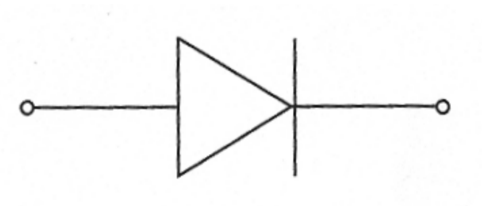
The transistor count in an IC would double every 18 months

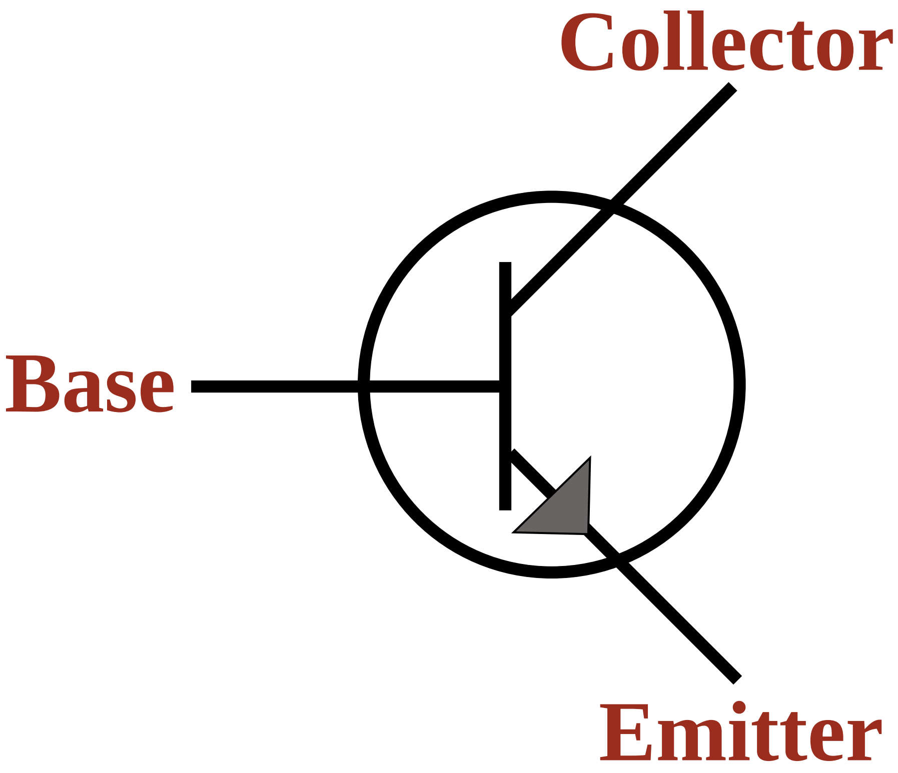
Another way to look at Moores law



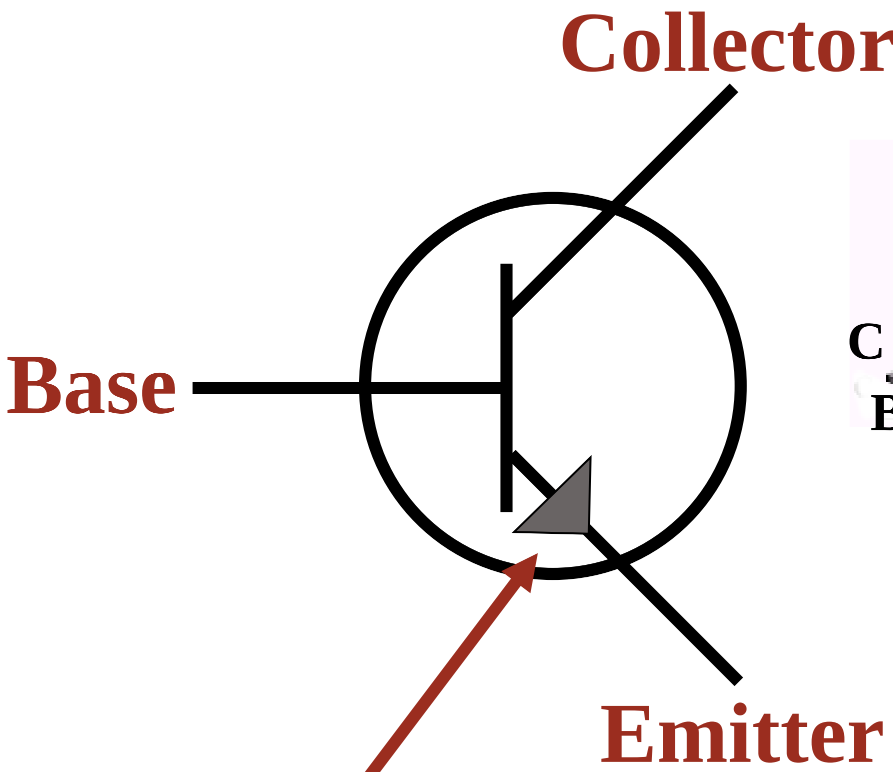
SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

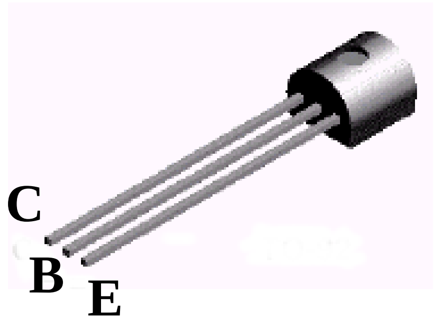
Transistor Symbol





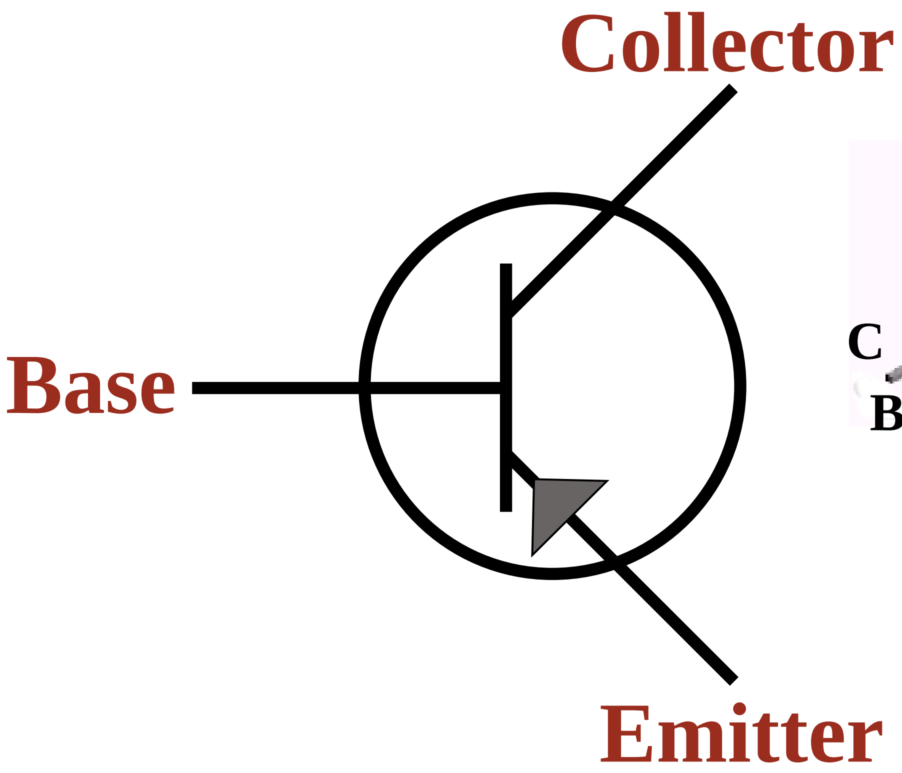
NPN Schematic Symbol

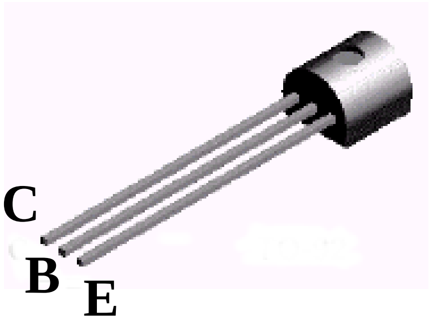




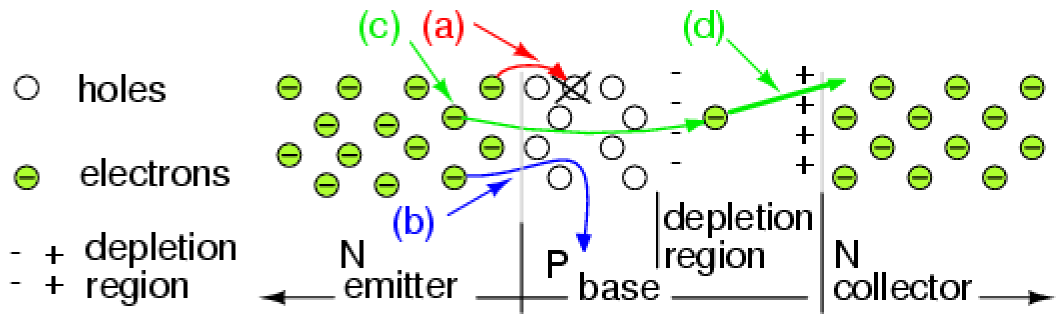
Memory aid: NPN means Not Pointing iN.

PNP Schematic Symbol

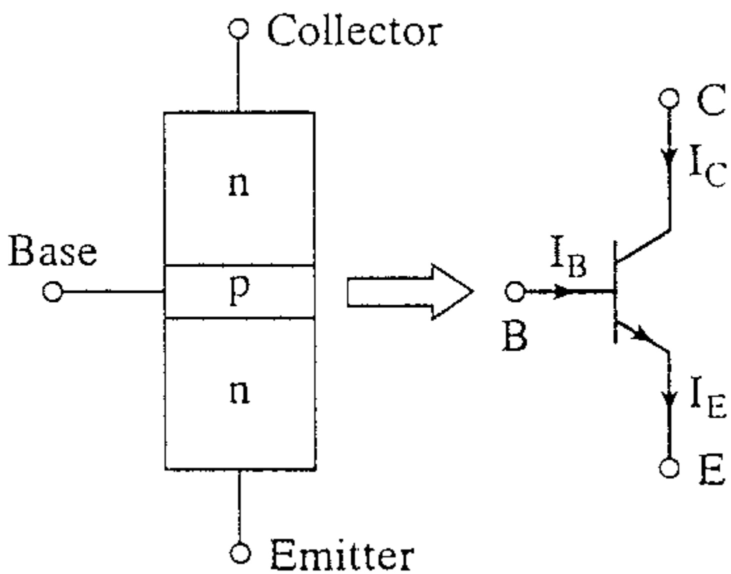




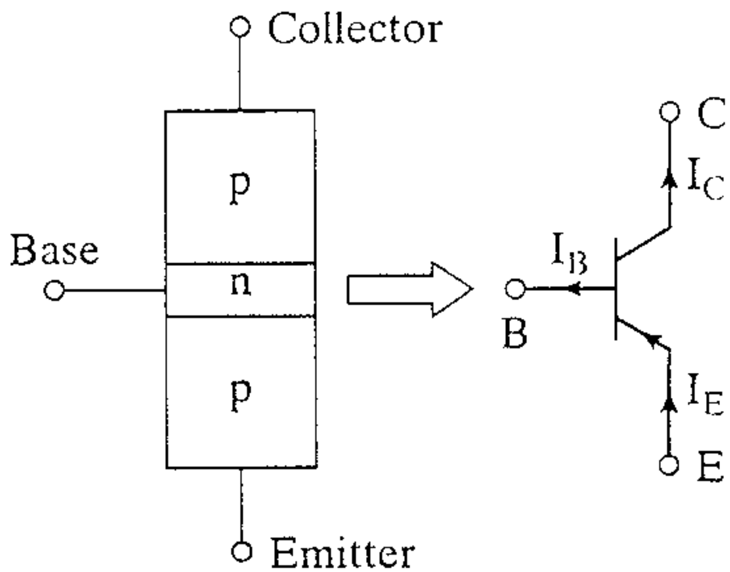
Transistors



Electron Flow



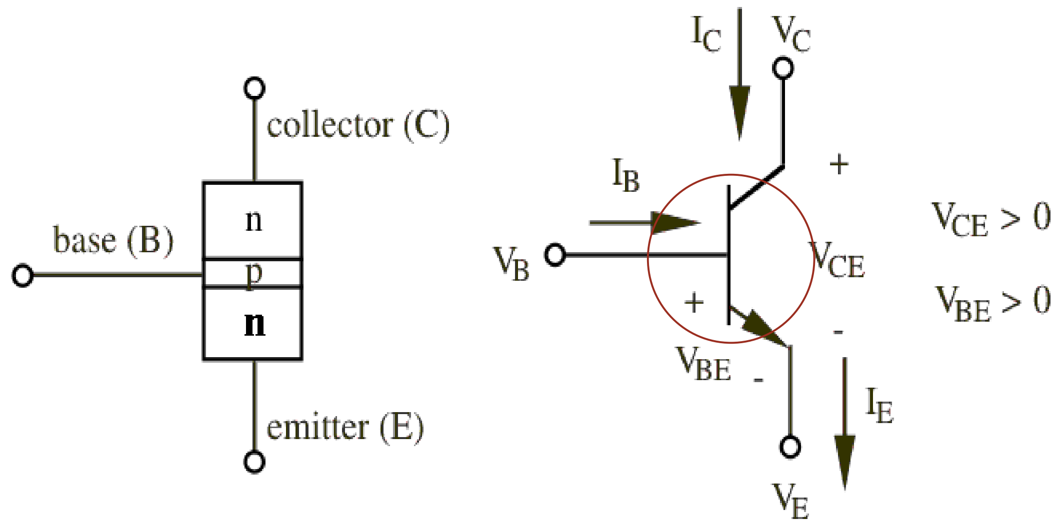
NPN



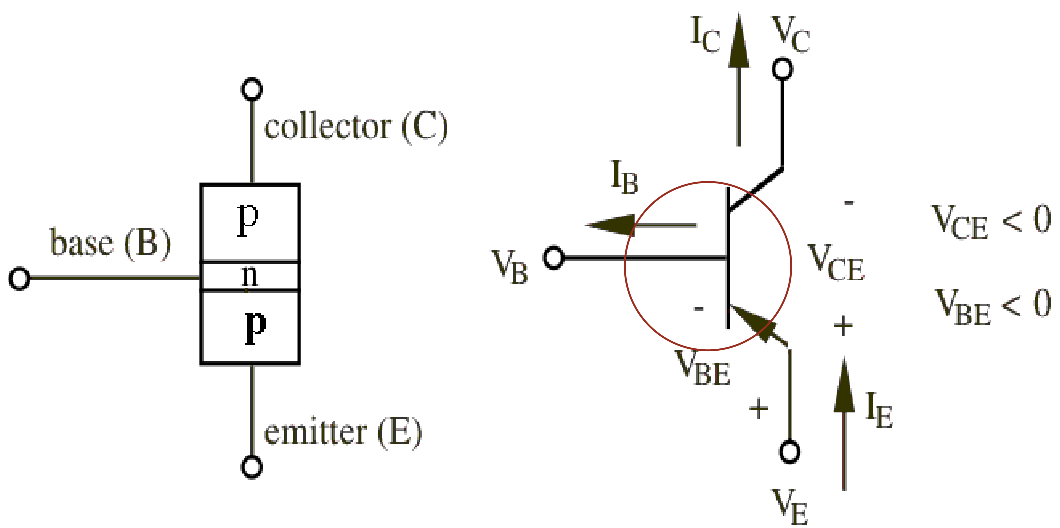
PNP

BJT Schematic

- Bipolar Junction Transistors (BJT) consists of three "sandwiched" semiconductor layers
- The three layers are connected to collector (C), emitter (E), and base (B) pins
- Current supplied to the base controls the amount of current that flows through the collector and emitter

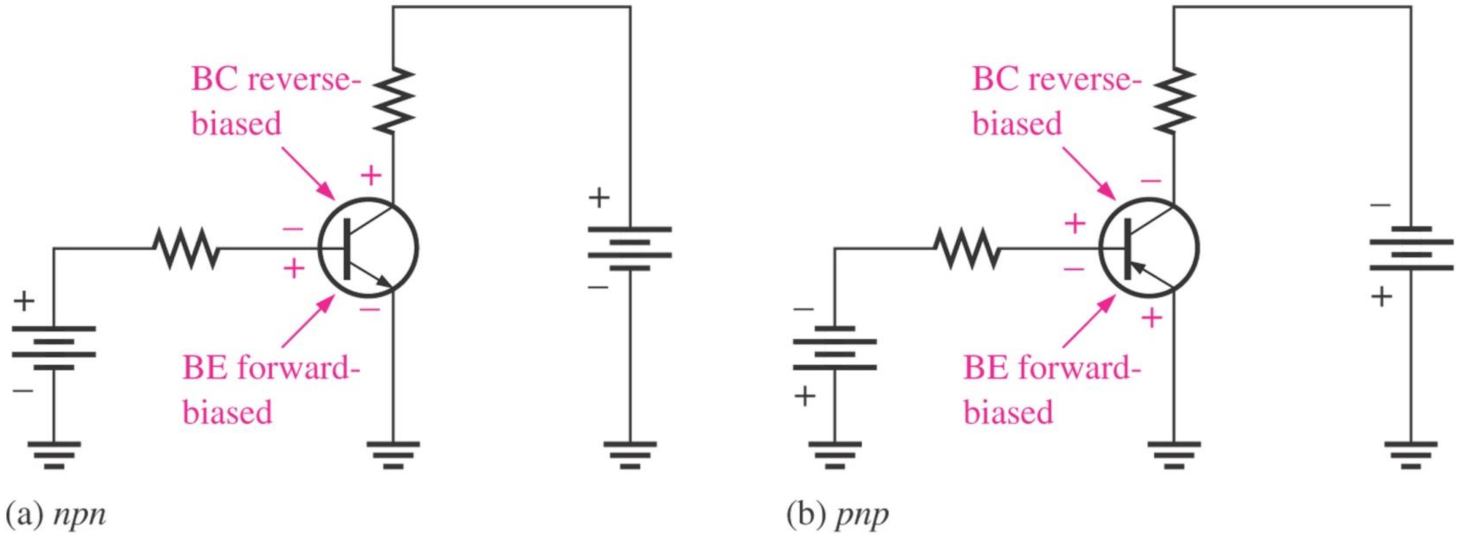


- NPN
  - BE forward bias
  - BC reverse bias
- PNP
  - BE reverse bias
  - BC forward bias



BJT Operation: Biasing

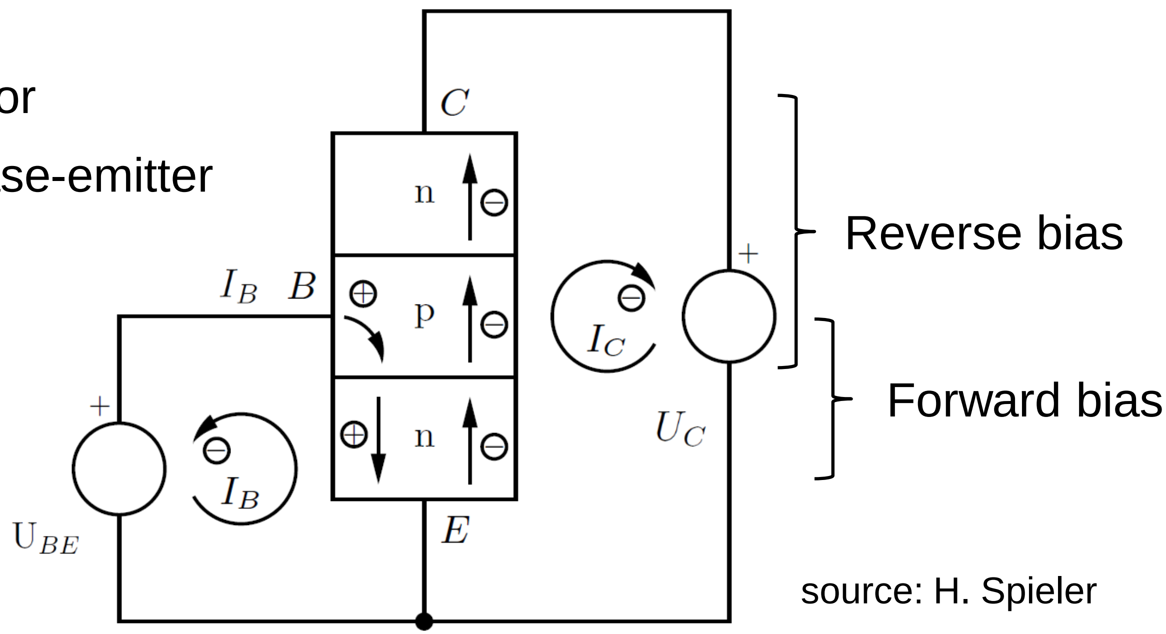
- two pn junction must be correctly biased with external dc voltages to operate the transistor properly.
- The figure shown the proper bias arrangement for both *npn* and *pnp* transistor for active operation as an amplifier.



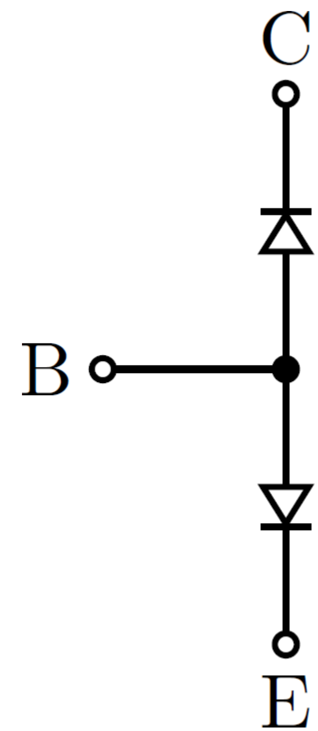
BJT Operation: Biasing NPN

npn transistor

Collector-base-emitter



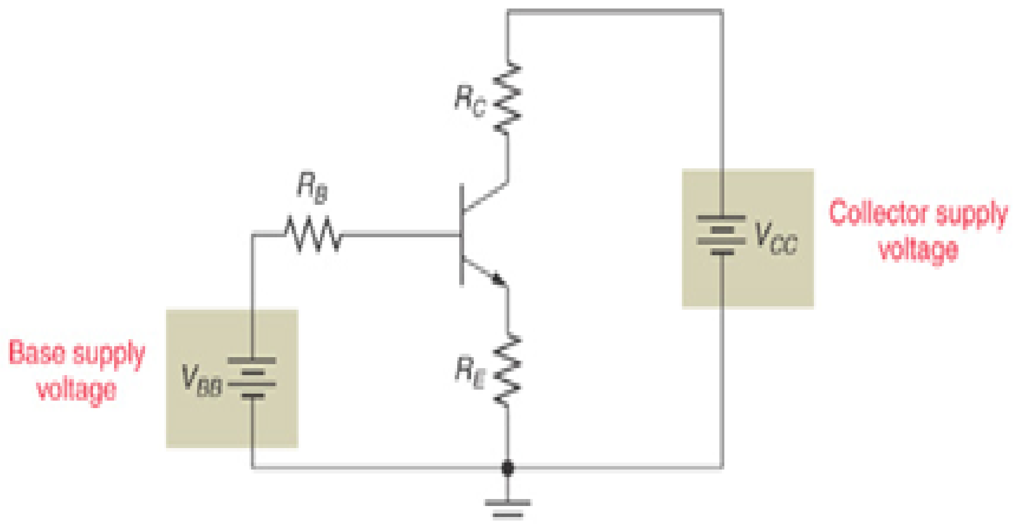
source: H. Spieler



Base current (voltage) drives collector current.

Transistor Voltages:

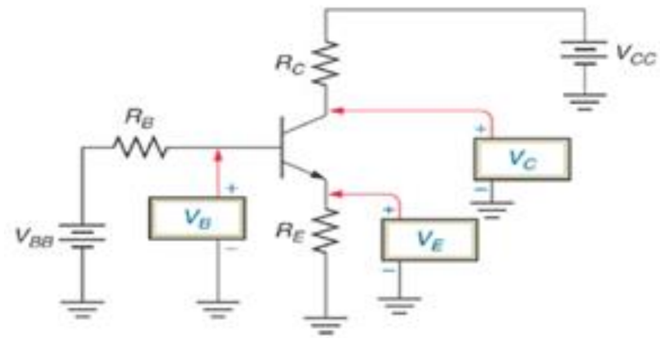
- V_{CC} – collector supply voltage. This is a power supply voltage applied directly to collector of transistor.
- V_{BB} – base supply voltage. this is dc voltage used to bias base of transistor.
- V_{EE} – emitter supply voltage. dc biasing voltage and in many cases, VEE is simply a ground connection.



(a) Transistor supply voltages

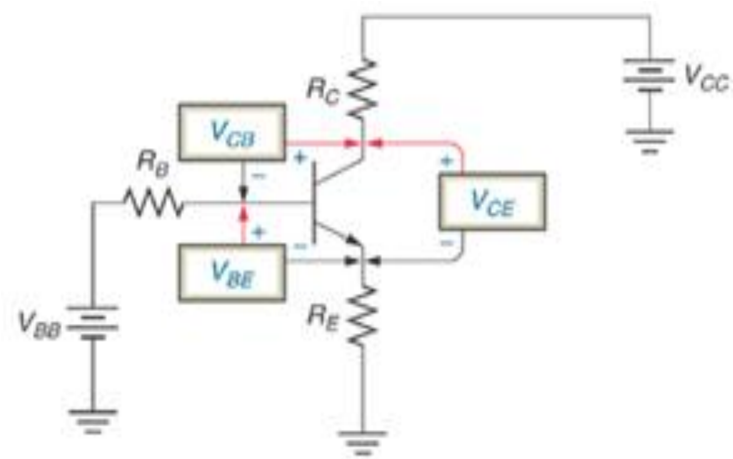
Transistor Voltages:

- V_C – dc voltage measured from collector terminal of component to ground
- V_B – dc voltage measured from base terminal to ground.
- V_E – dc voltage measured from emitter terminal to ground.



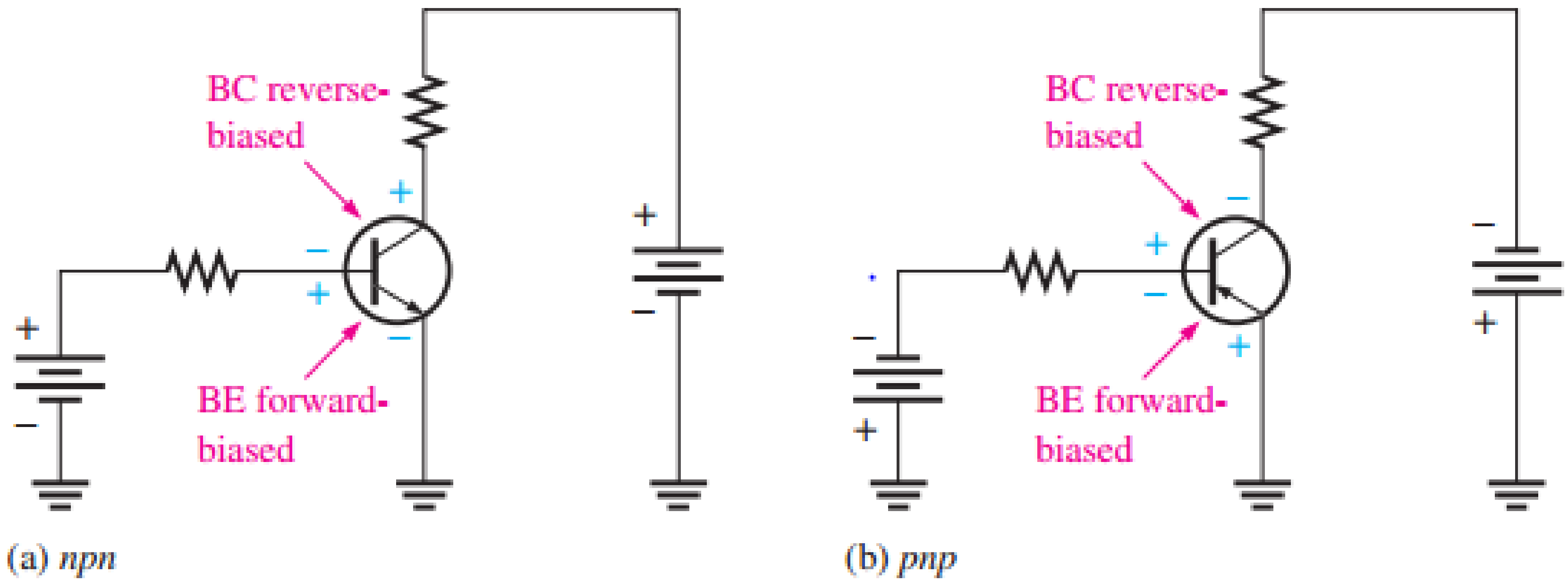
(b) Transistor terminal voltages to ground

- V_{CE} – dc voltage measured from collector to emitter terminal of transistor.
- V_{BE} – dc voltage measured from base to emitter terminal of transistor.
- V_{CB} – dc voltage measured from collector to base terminal of transistor.



(c) The voltages measured across the transistor junctions

Basic circuits of BJT



- NPN
  - BE forward bias
  - BC reverse bias
- PNP
  - BE reverse bias
  - BC forward bias

➢ Applying Kirchhoff's current law to the transistor,

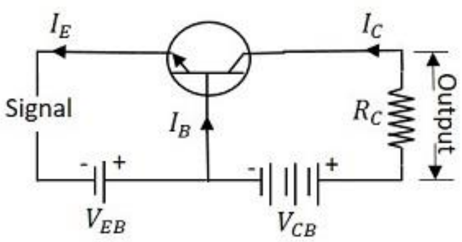
$$I_E = I_C + I_B$$

➢ Three types of transistor configuration:

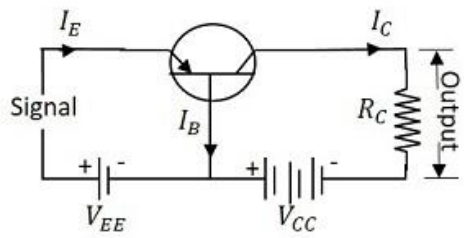
1. Common Base configuration (CB)
2. Common Emitter configuration (CE)
3. Common Collector configuration (CC)

Basic circuits of BJT

Common Base Connection

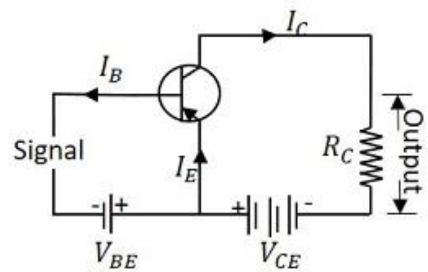


Using NPN transistor

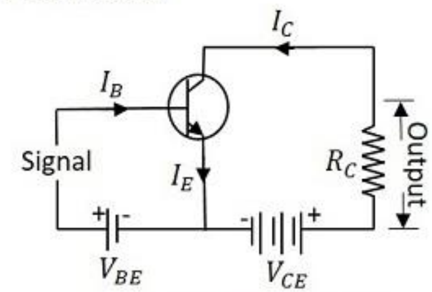


Using PNP transistor

Common Emitter Connection

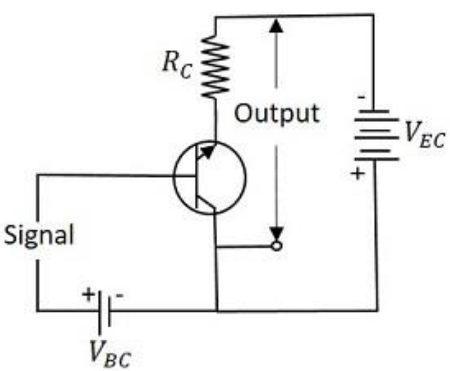


Using NPN transistor

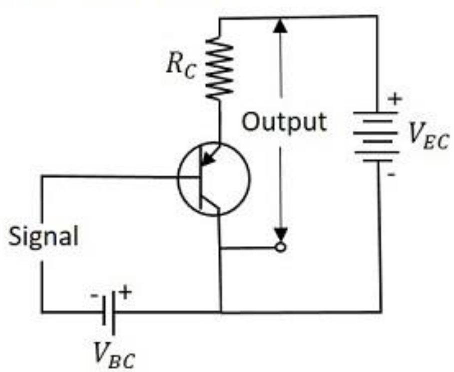


Using PNP transistor

Common Collector Connection

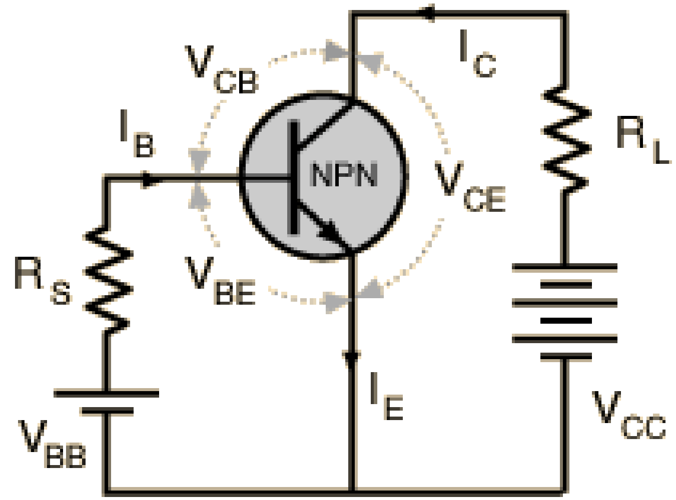


Using NPN transistor



Using PNP transistor

Basic circuits of BJT



- Transistor Currents: $I_E = I_C + I_B$
- **alpha** (α_{DC}): $I_C = \alpha_{DC} I_E$
- **beta** (β_{DC}) $I_C = \beta_{DC} I_B$
  - β_{DC} typically has a value between 20 and 200

- DC voltages for the biased transistor:
- Collector voltage $V_C = V_{CC} - I_C R_C$
- Base voltage: $V_B = V_E + V_{BE}$
  - for silicon transistors, $V_{BE} = 0.7$ V
  - for germanium transistors, $V_{BE} = 0.3$ V

DC Beta and Alpha

The dc current **gain** of a transistor is the ratio of the dc collector current (I_C) to the dc base current (I_B) and is designated dc **beta** (β_{DC}).

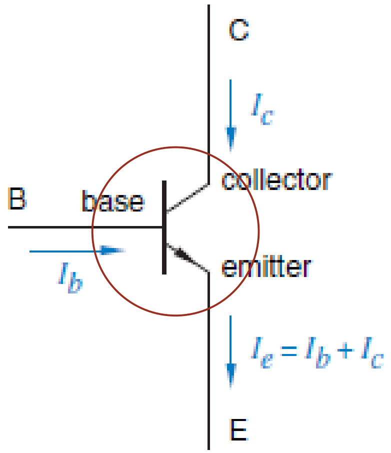
$$\beta_{DC} = \frac{I_C}{I_B}$$

Typical values of β_{DC} range from less than 20 to 200 or higher.

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc **alpha** α_{DC}.

$$\alpha_{DC} = \frac{I_C}{I_E}$$

The alpha is a less-used parameter than beta in transistor circuits. Typically, values of α_{DC} range from 0.95 to 0.99 or greater, but α_{DC} is always less than 1.



DC Beta and Alpha

A relationship can be developed between β and α using the basic relationships introduced thus far. Using $\beta = I_C/I_B$ we have $I_B = I_C/\beta$, and from $\alpha = I_C/I_E$ we have $I_E = I_C/\alpha$. Substituting into

$$I_E = I_C + I_B$$

we have
$$\frac{I_C}{\alpha} = I_C + \frac{I_C}{\beta}$$

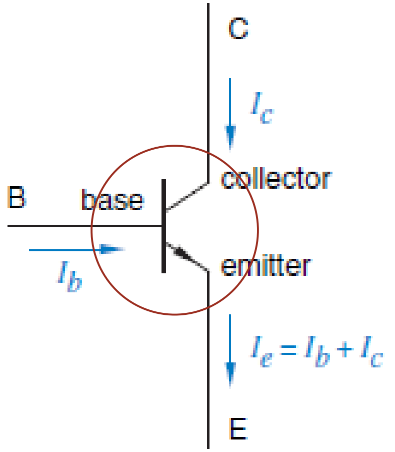
and dividing both sides of the equation by I_C will result in

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

or
$$\beta = \alpha\beta + \alpha = (\beta + 1)\alpha$$

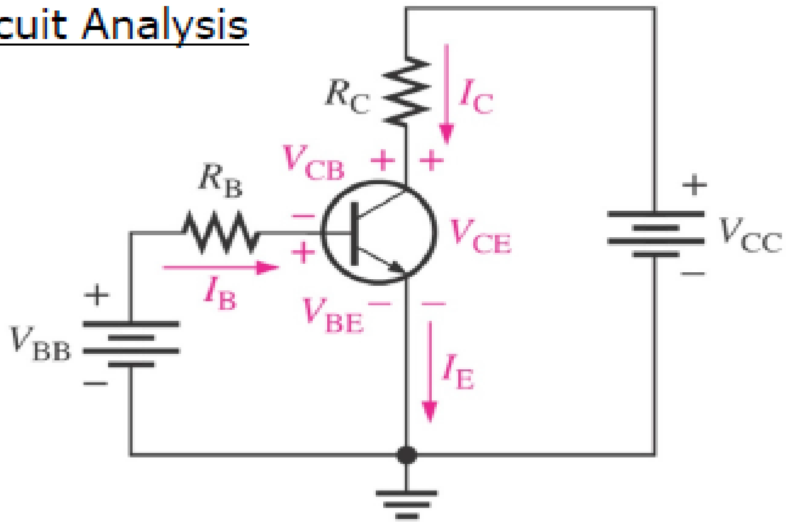
so that
$$\boxed{\alpha = \frac{\beta}{\beta + 1}}$$

or
$$\boxed{\beta = \frac{\alpha}{1-\alpha}}$$



BJT Circuit

BJT Circuit Analysis



➤ KVL at B-E loop

$$-V_{BB} + V_{R_B} + V_{BE} = 0$$

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

$$\boxed{I_B = \frac{V_{BB} - V_{BE}}{R_B}}$$

Note : $V_{BE}=0.7V$ For silicon

➤ KVL at C-E loop

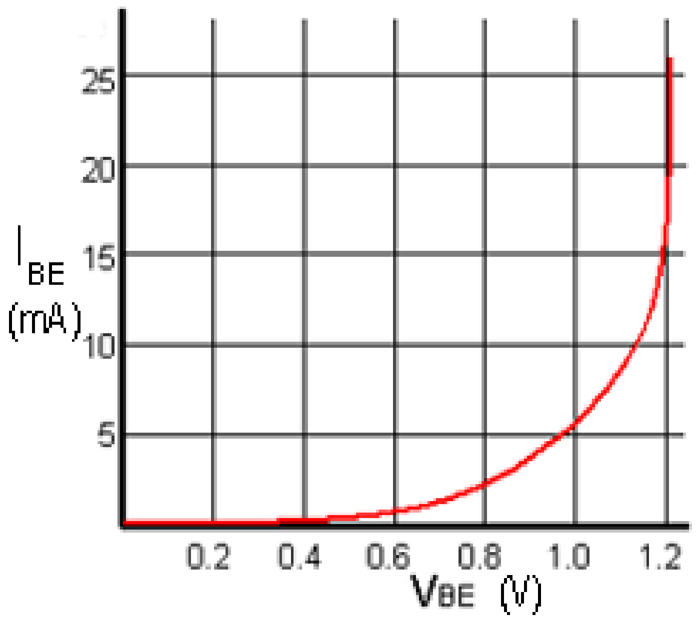
$$-V_{CC} + V_{R_C} + V_{CE} = 0$$

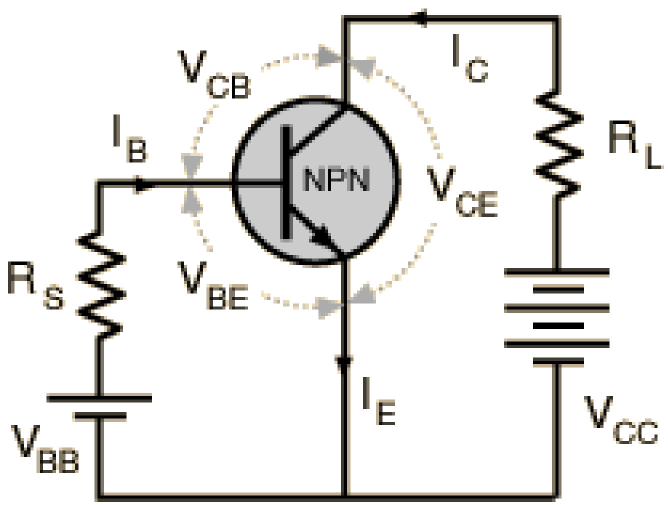
$$V_{CE} = V_{CC} - V_{R_C}$$

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

BJT: Input Characteristic

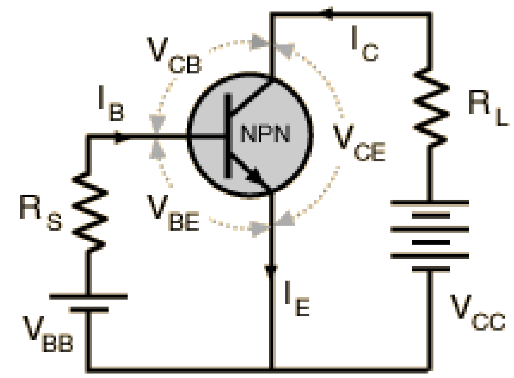
- The **Input Characteristic** is the base emitter current I_{BE} against base emitter voltage V_{BE}
- I_{BE}/V_{BE} shows the input **Conductance** of the transistor.
- The increase in slope of when the V_{BE} is above 1 volt shows that the input conductance is rising
- There is a large increase in current for a very small increase in V_{BE}.

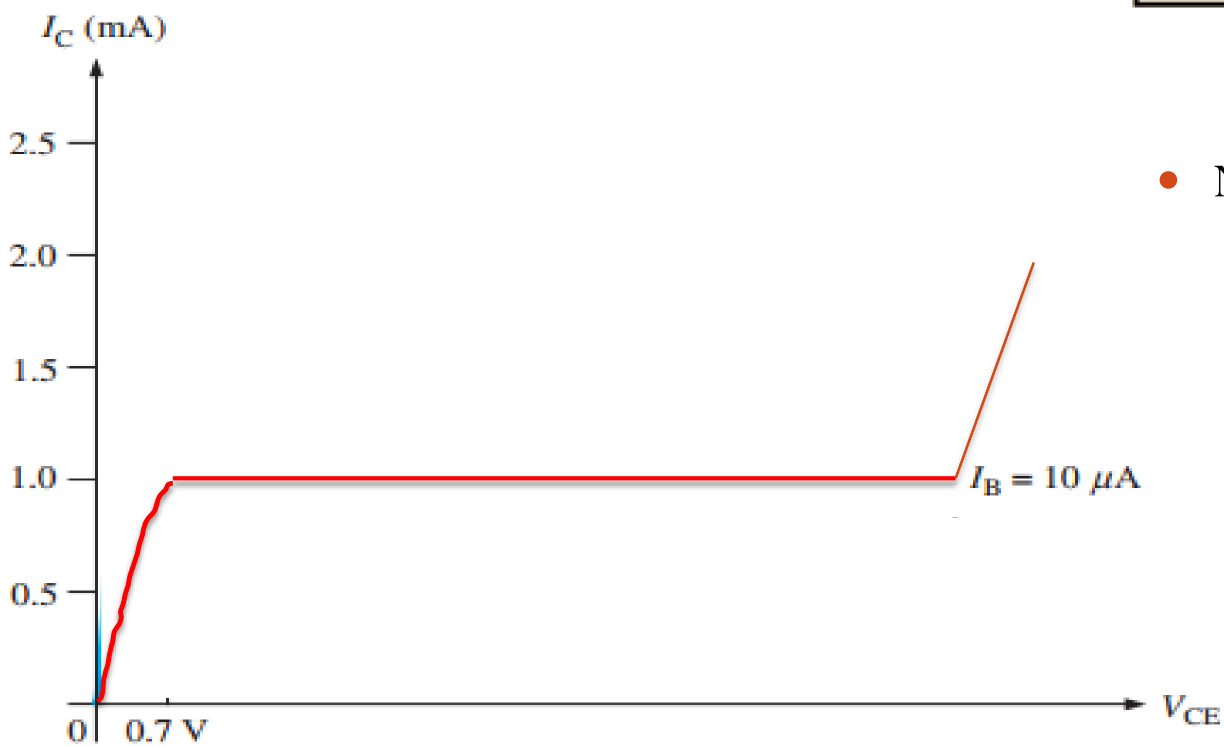




BJT: Output Characteristic

- collector current (I_C) is nearly independent of the collector-emitter voltage (V_{CE}), and instead depends on the base current (I_B)





- NPN
  - BE forward bias
  - BC reverse bias

Collector Characteristics Curve

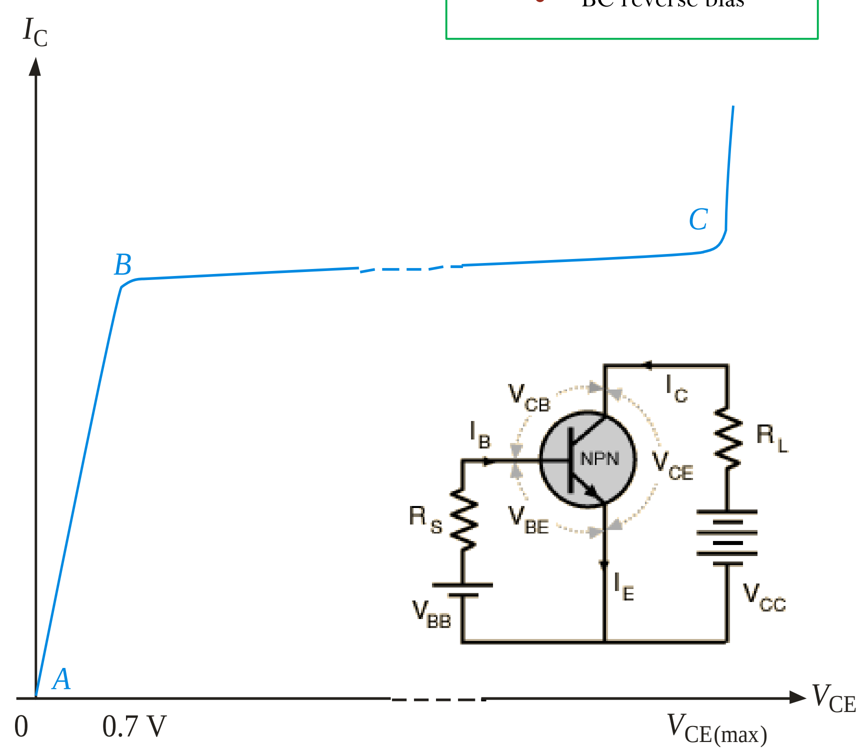
The collector characteristic curves shows three mode of operations of transistor with the variation of collector current I_C w.r.t V_{CE} for a specified value of base current I_B.

- NPN
  - BE forward bias
  - BC reverse bias

V_{BB} is set to produce a certain value of I_B and V_{CC} is zero and V_{CE} is zero.

As V_{CE} is increased, I_C increases until B.

Both BE and BC junctions are forward biased and the transistor is in Saturation region.



Output Characteristic

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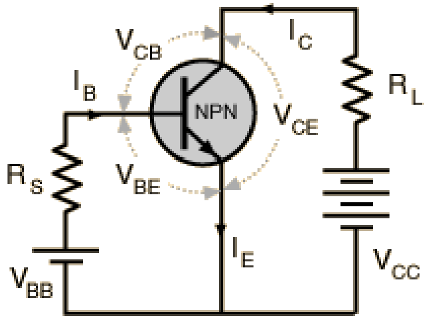
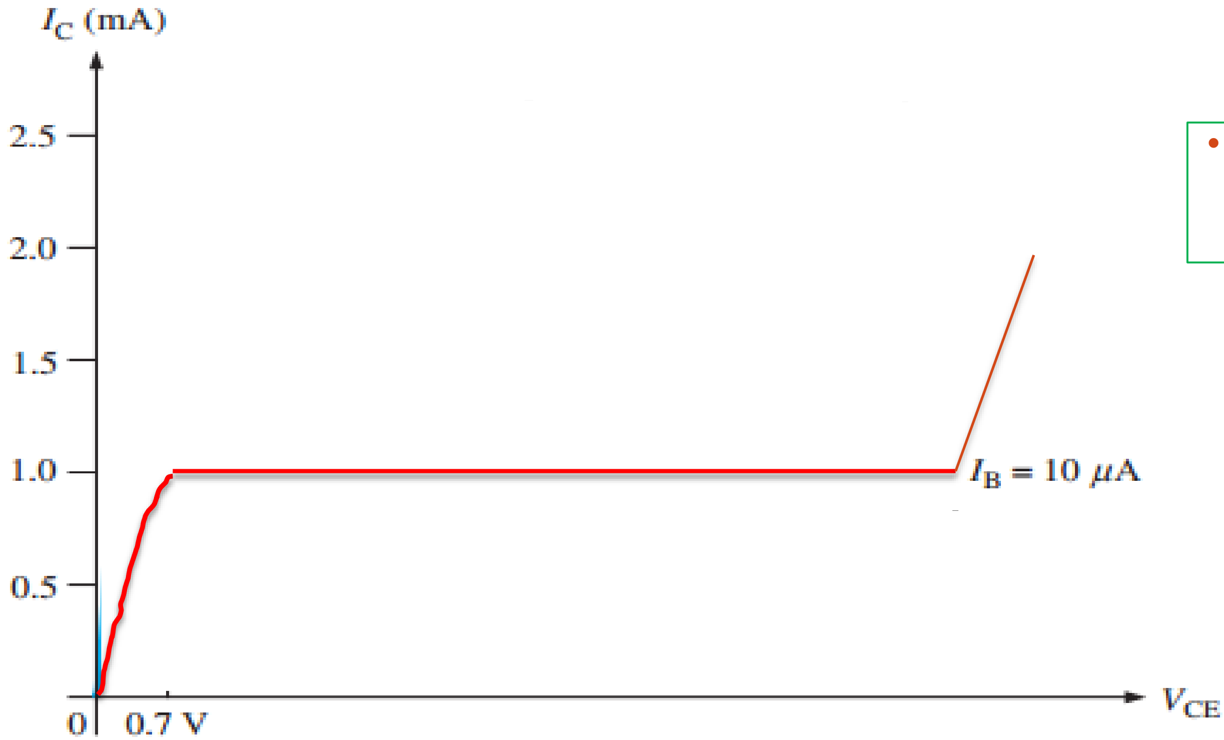




- NPN
  - BE forward bias
  - BC reverse bias

Currents and voltages in BJT

I_B : dc base current
I_E: dc emitter current
I_C: dc source current

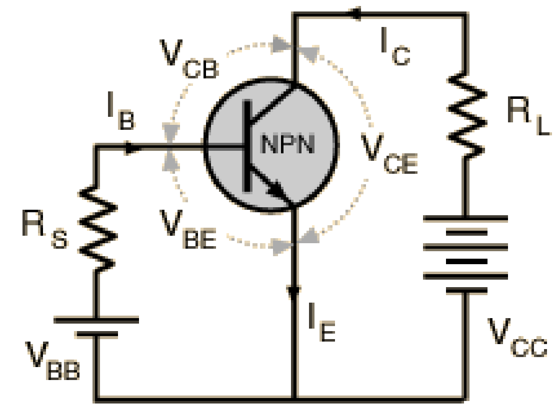
V_{BE}: dc voltage at base wrt. emitter
V_{CE}: dc voltage at collector wrt. emitter.
V_{CB}: dc voltage at collector wrt. Base.

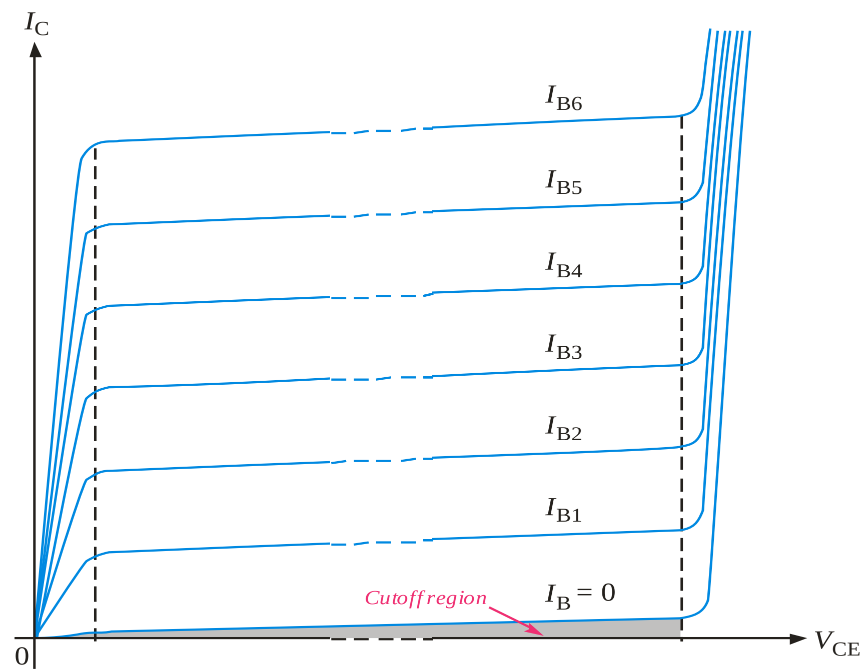
$$V_{BE} = 0.7\text{V}$$

$$V_{CE} = V_{CC} - \text{I}_C \text{ R}_C$$

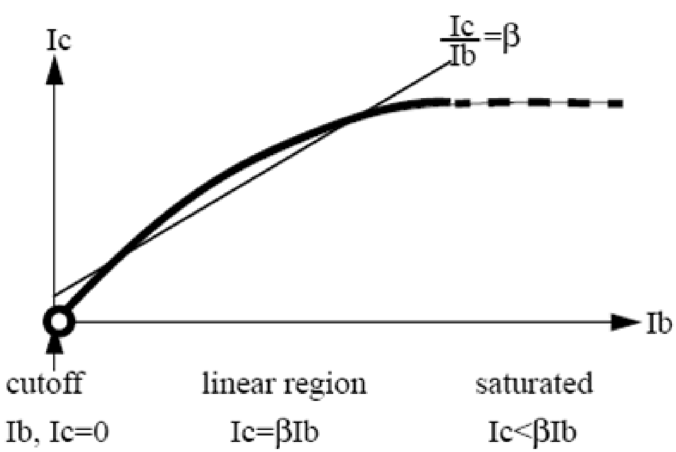
$$I_B = (V_{BB} - V_{BE}) / \text{R}_B$$

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

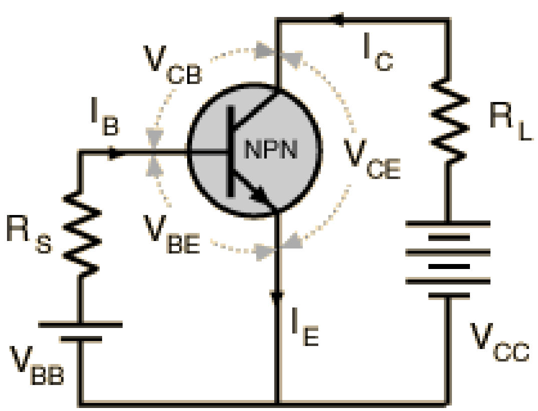




BJT Operating Regions



Operating Region	Parameters	Mode
Cut Off	$V_{BE} < V_{cut\text{-}in}$ $V_{CE} > V_{supply}$ $I_B = I_C = 0$	Switch OFF
Linear	$V_{BE} = V_{cut\text{-}in}$ $V_{sat} < V_{CE} < V_{supply}$ $I_C = \beta * I_B$	Amplification
Saturated	$V_{BE} = V_{cut\text{-}in},$ $V_{CE} < V_{sat}$ $I_B > I_{C,max}, \; I_{C,max} > 0$	Switch ON



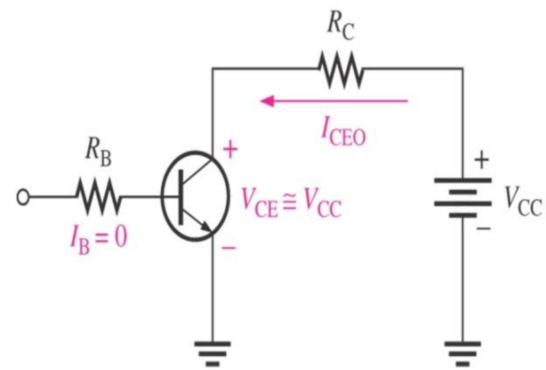
- BJT will operates in one of following four region
  - Cutoff region (for digital circuit)
  - Saturation region (for digital circuit)
  - Linear (active) region (to be an amplifier)
  - Breakdown region (always be a disaster)

BJT Characteristics and Parameters

Transistor Operating Regions:

1.Cutoff region:

- Both transistor junctions are reverse biased
- All terminal current are approximately equal to zero. Since I_{CEO} neglected, $\mathbf{V_{CE} = V_{CC}}$

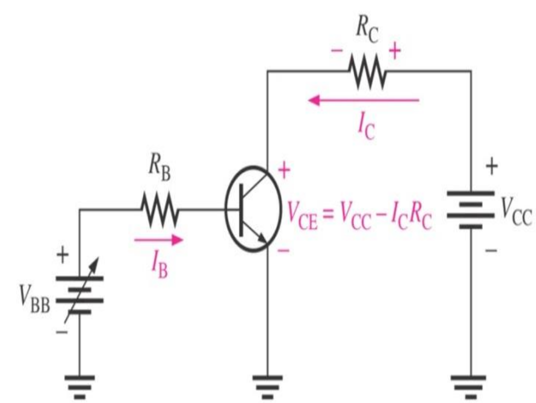


2.Active region:

- The *BE* junction is forward biased and the *BC* junction is reverse biased
- All terminal currents have some measurable value
- The magnitude of *IC* depends on the values of and *IB*
- VCE is approximately near to 0.7V and VCE falls in ranges VBE<VCE<VCC

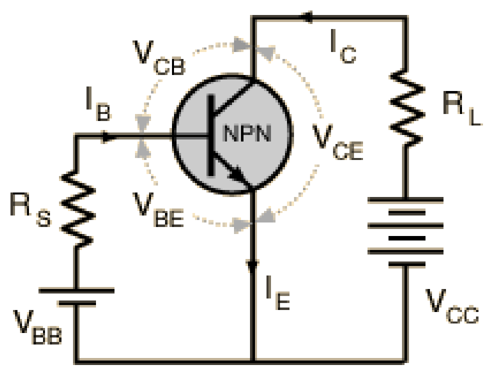
3.Saturation:

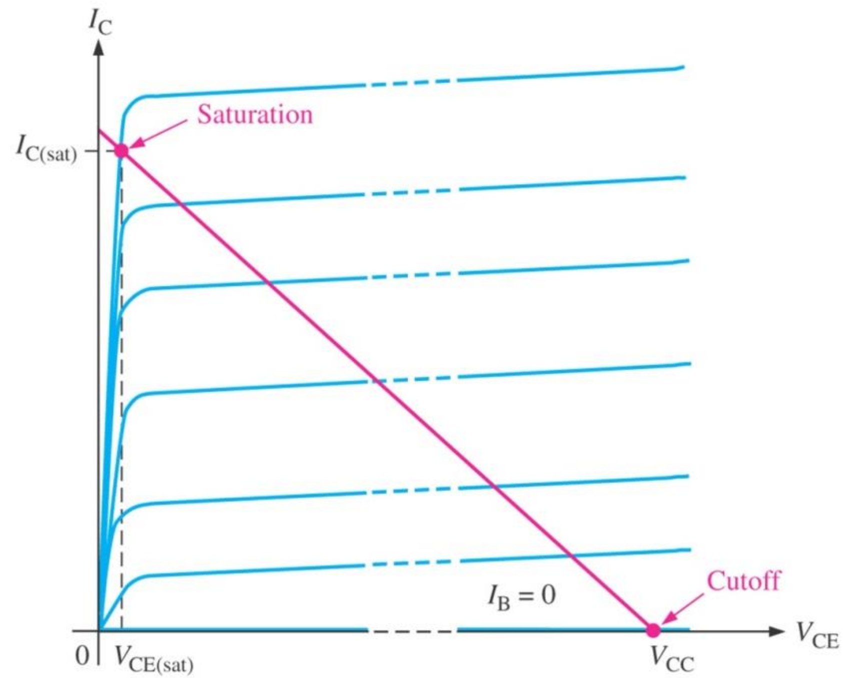
- Both transistor junctions are forward biased
- *IC* reaches its maximum values- determine by the component in the CE circuit, and independent of the values of and *IB*
- VBE is approximately 0.7V and VCE < VBE



DC Load Line:

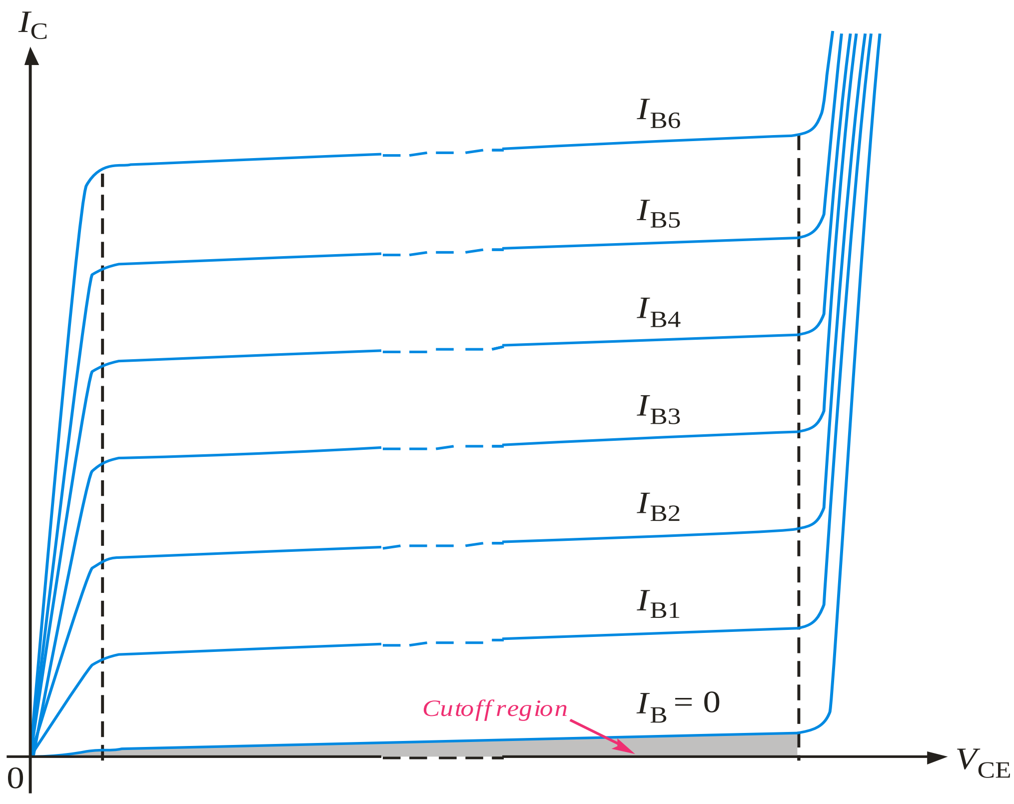
- **Cutoff** and **saturation** can be illustrated in **relation to the collector characteristic curves** by the use of a **load line**.
- **DC load line** drawn on the connecting **cutoff** and **saturation** point.
- The **bottom of load line** is ideal **cutoff** where **$I_C=0$ & $V_{CE}=V_{CC}$**.
- The **top of load line** is **saturation** where **$I_C=I_{C(sat)}$ & $V_{CE}=V_{CE(sat)}$**
- In **between cutoff and saturation** is the **active region** of transistor's operation.

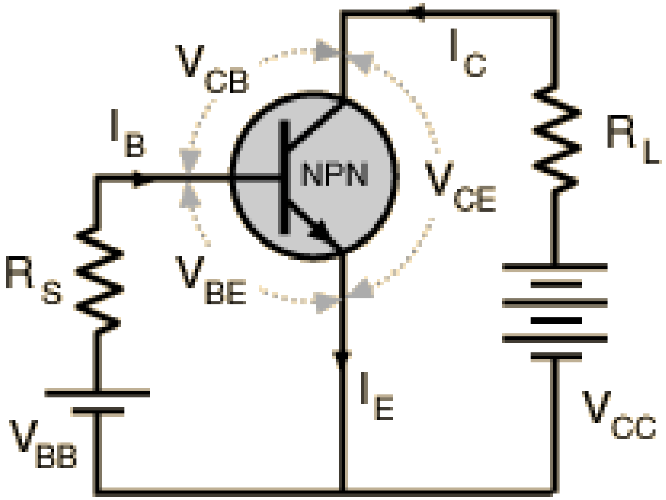




What we learned about the output Characteristic

- collector current (I_C) is nearly independent of the collector-emitter voltage (V_{CE}), and instead depends on the base current (I_B)



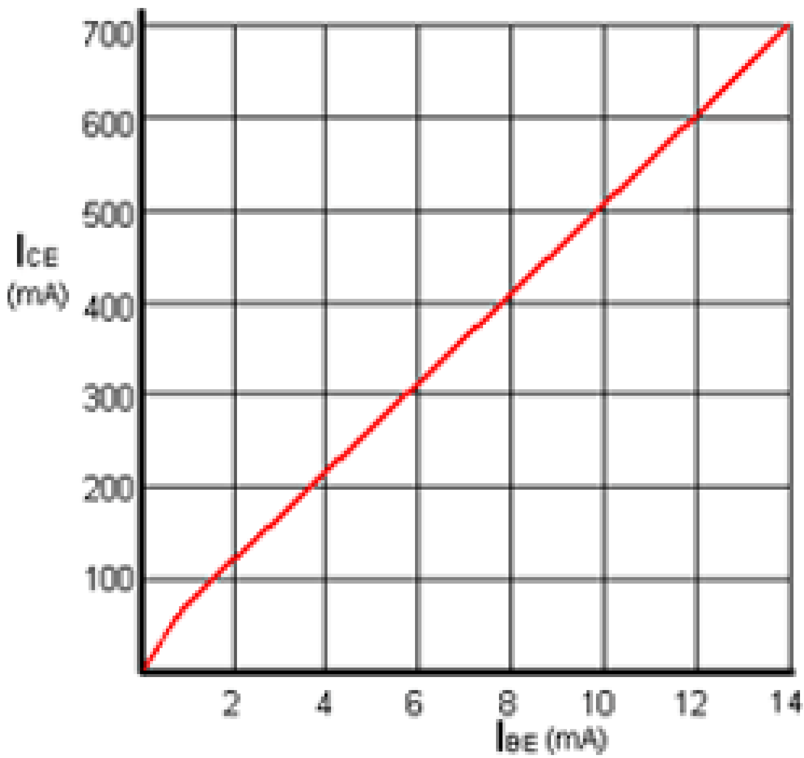


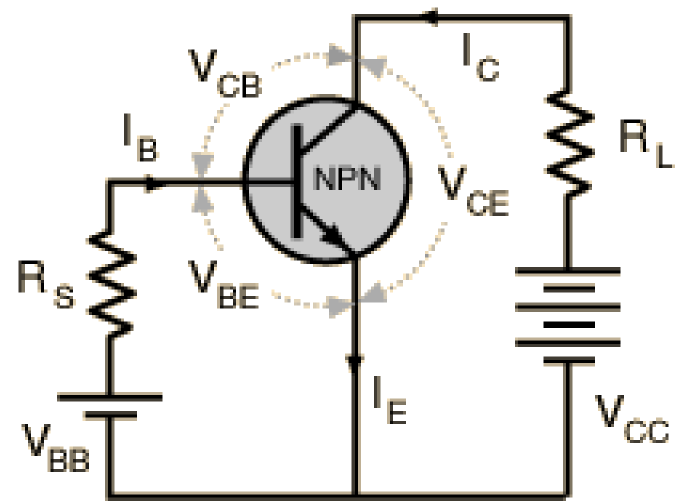
BJT: Transfer Characteristic

- Characteristic curves can be drawn to show other useful parameters of the transistor
- The slope of I_{CE} / I_{BE} is called the Transfer Characteristic (β)

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

β > 1

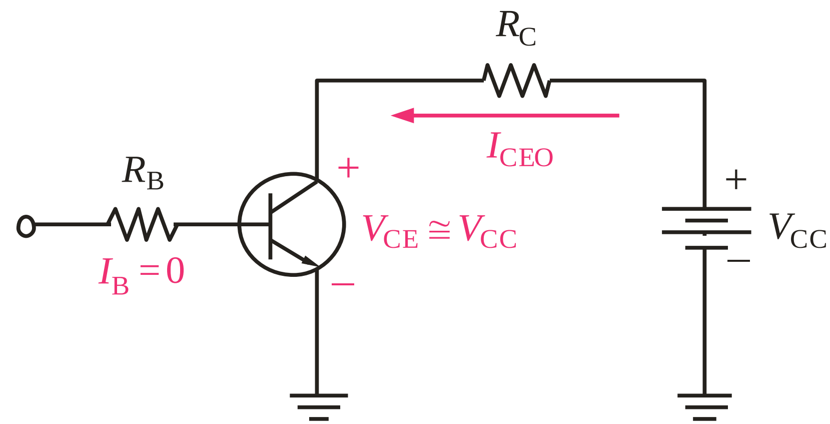




Collector Characteristics Curve - Cutoff

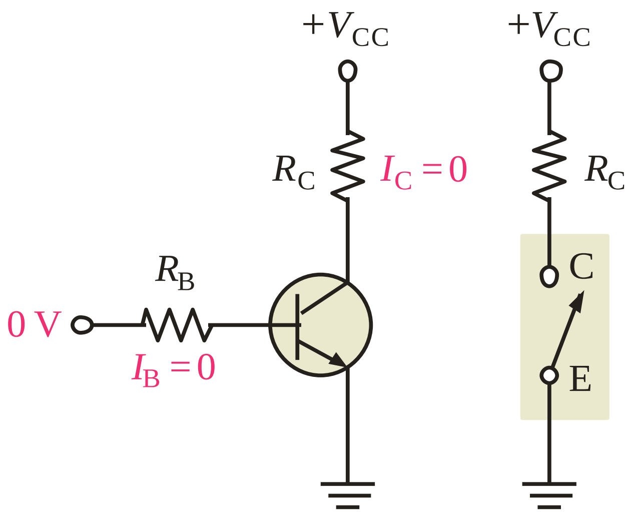
In a BJT, **cutoff** is the condition in which there is no base current, which results in only an extremely small leakage current (I_{CEO}) in the collector circuit. For practical work, this current is assumed to be zero.

In cutoff, neither the base-emitter junction, nor the base-collector junction are forward-biased.

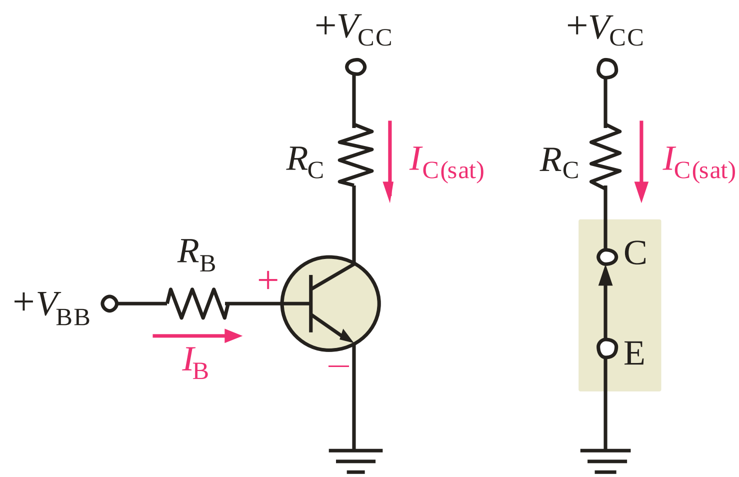


Cutoff Switch

A BJT can be used as a switching device in logic circuits to turn on or off current to a load. As a switch, the transistor is normally in either cutoff (load is OFF) or saturation (load is ON).



In cutoff, the transistor looks like an open switch.

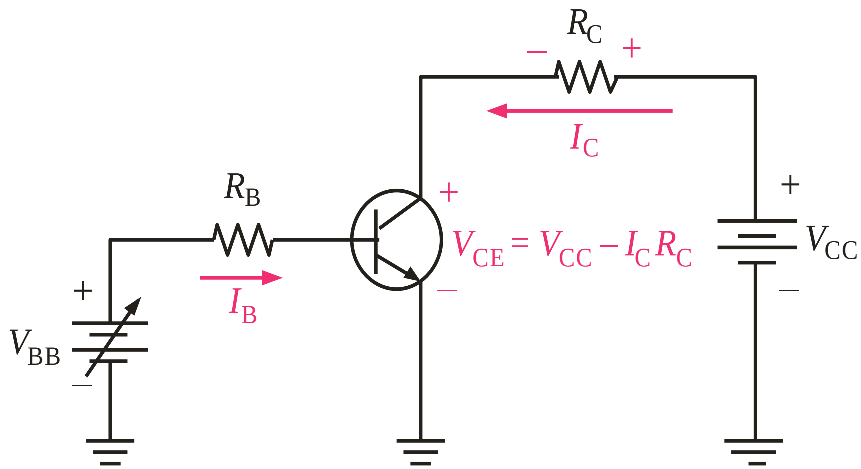


In saturation, the transistor looks like a closed switch.

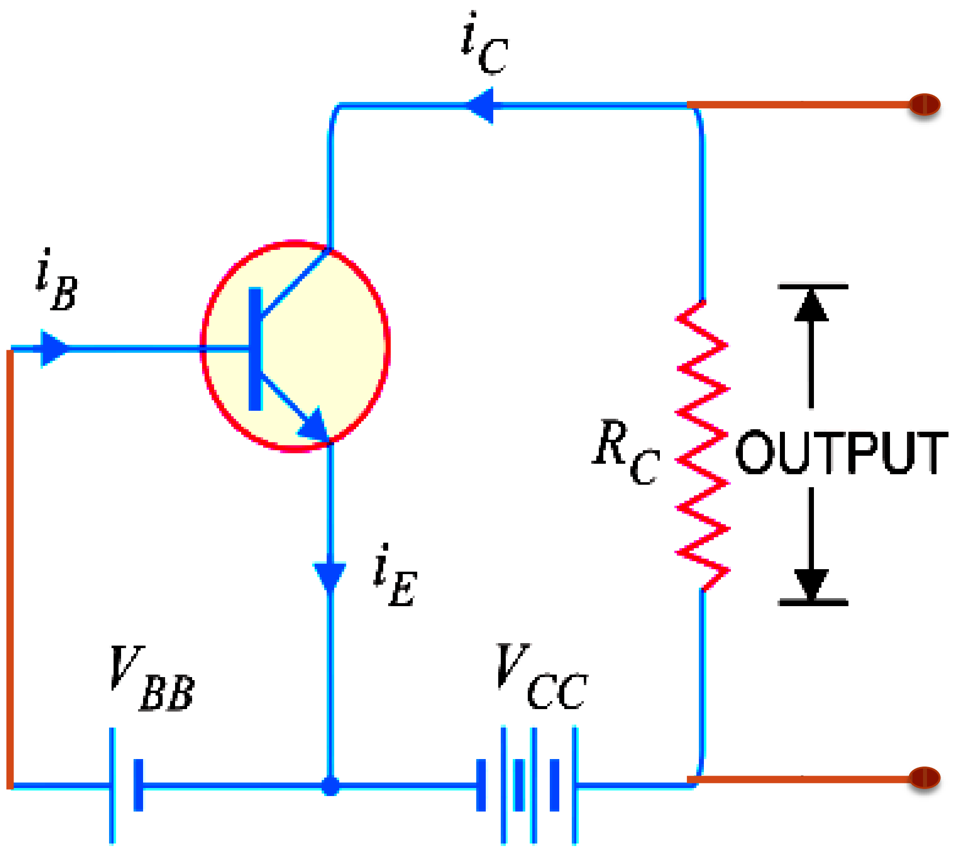
In saturation, an increase of base current has no effect on the collector circuit and the relation $I_C = \beta_{DC} I_B$ is no longer valid.

$$I_{C(SAT)} = V_{CC} - V_{CE(SAT)} / R_C$$

At this point, the transistor current is maximum and voltage across collector is minimum, for a given load.



How it respond to AC

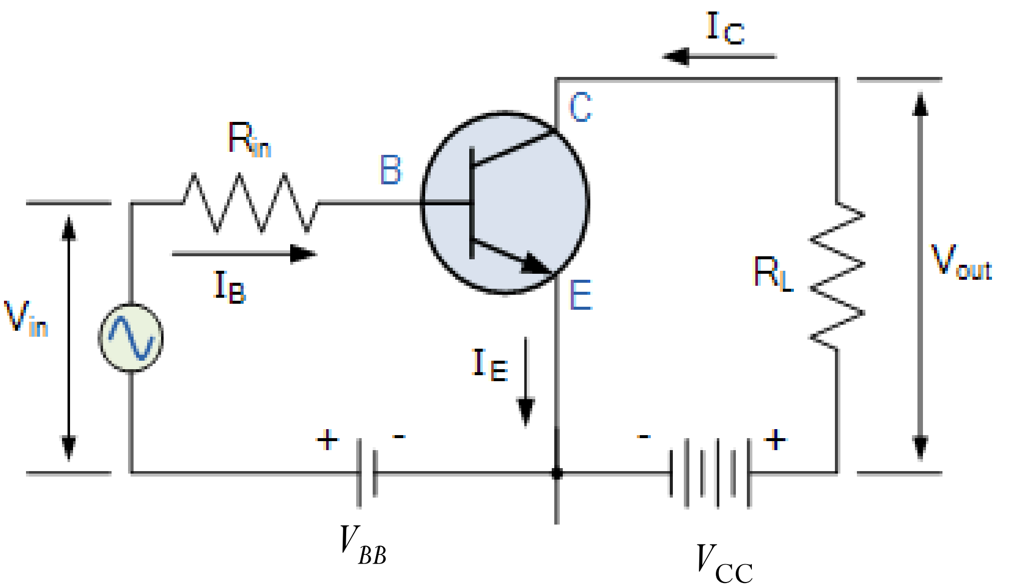


How it respond to AC

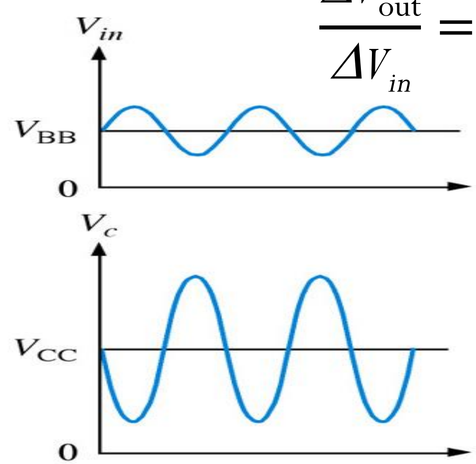
$$V_{BE} = 0.7V \text{ Cutoff}$$

$$I_E = I_B + I_C$$

$$V_{BE} = V_{BB} + V_{in} - I_B R_B$$
$$\Delta V_{BE} = \Delta V_{BB} + \Delta V_{in} - \Delta I_B R_B$$
$$\Delta V_{BE} = \Delta V_{in} - \Delta I_B R_B$$
$$\Delta V_{in} = \Delta I_B R_B$$



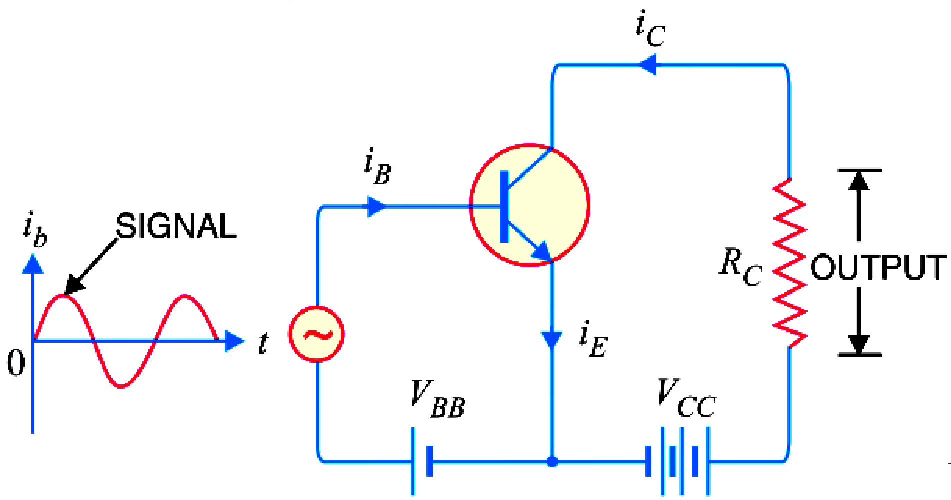
$$\frac{\Delta V_{out}}{\Delta V_{in}} = \frac{-\Delta I_C RL}{\Delta I_B RB}$$

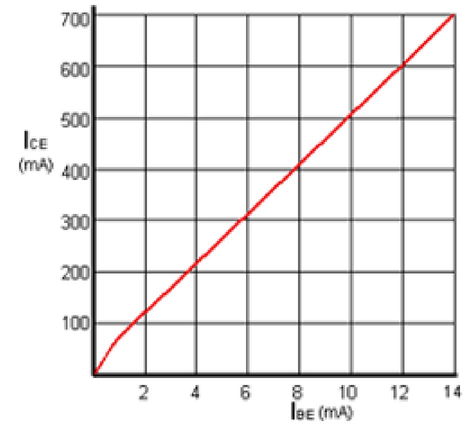


(b) Waveforms

$$V_{CE} = V_{out} = V_{CC} - I_C R_L$$

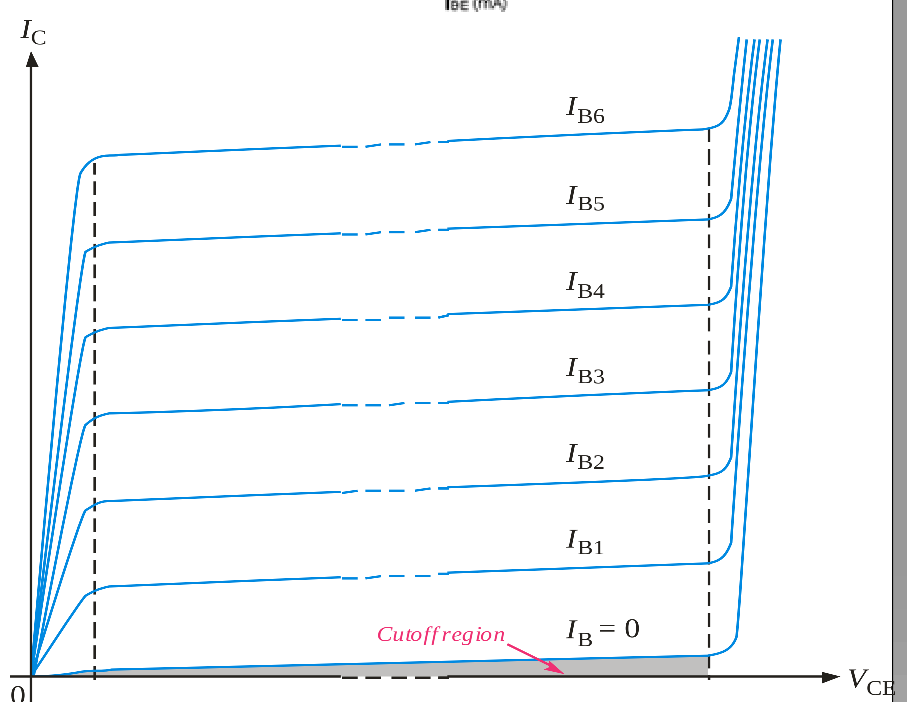
$$\Delta V_{CE} = (V_{CC} - V_{CC}) - \Delta I_C R_L = -\Delta I_C R_L$$
$$\Delta V_{out} = (V_{CC} - V_{CC}) - \Delta I_C R_L = -\Delta I_C R_L$$





$\beta > 1$

- Transistor amplify current because $I_C = \beta_{DC} I_B$
- $\mathbf{I_B}$ is very small, so $\mathbf{I_C \approx I_E}$.
- $\mathbf{V_{in}}$ is **superimposed** on the DC bias voltage $\mathbf{V_{BB}}$ by connecting them in **series with base resistor $\mathbf{R_B}$**.
- **Small changes** in the **base current circuit** causes **large changes** in **collector current circuit**.

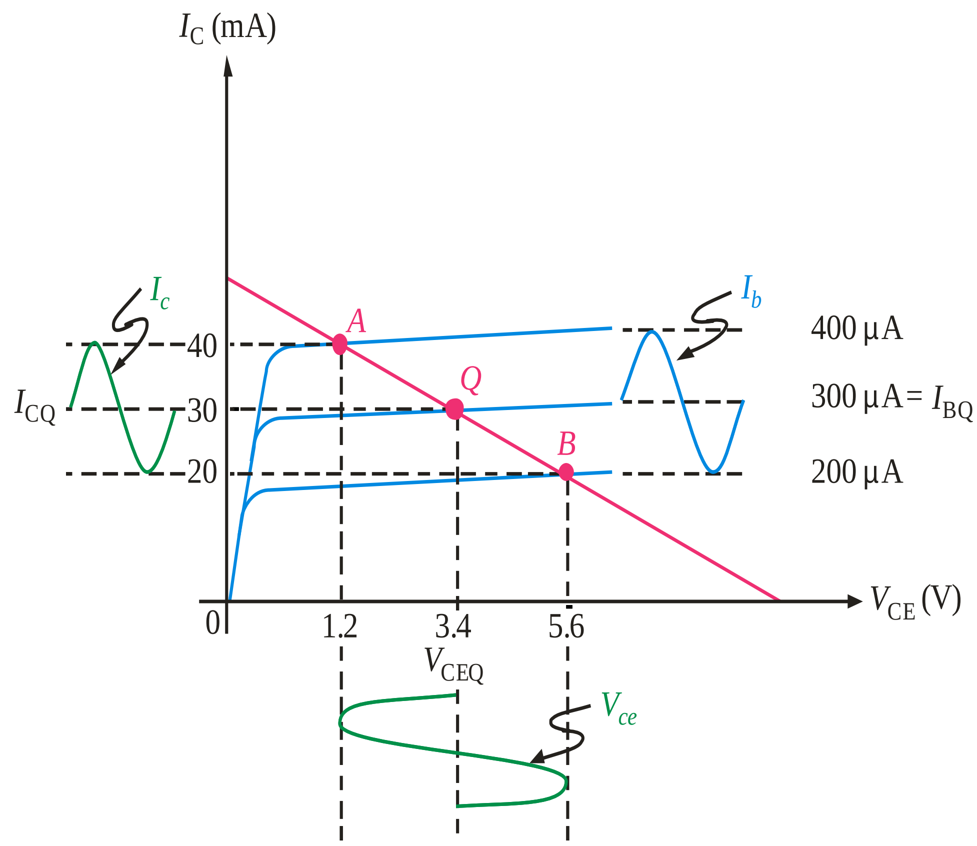


DC Operating Point

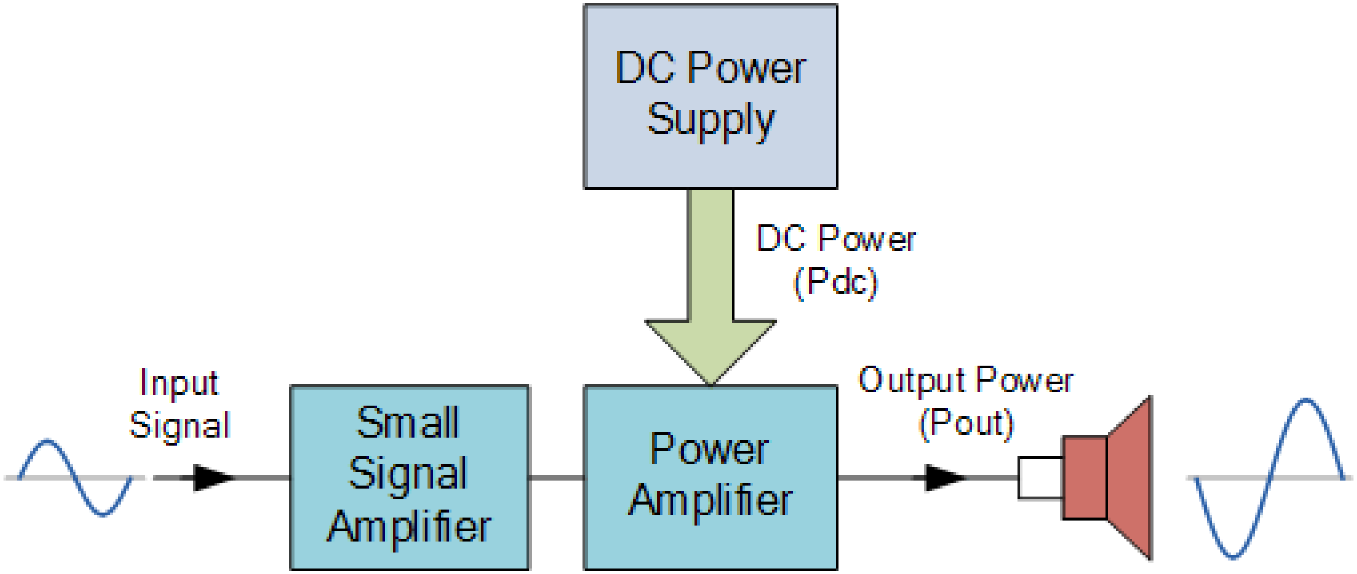
The point at which the load line intersects a characteristic curve represents the Q-point for that particular value of IB.

Point A,Q,B represents the Q-point for I_B 400μA. 300 μA and 200 μA respectively.

Assume a sinusoidal Ib is superimposed on VBB varying between 200uA to 400uA. It makes the collector current varies between 20 mA and 40 mA.



BJT as an amplifier

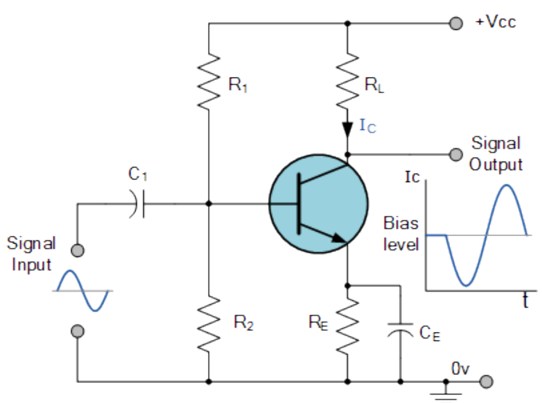


- Class A Amplifiers
- Class B Amplifiers
- Class AB amplifier

- Class A: – The amplifiers single output transistor conducts for the full 360° of the cycle of the input waveform.
- Class B: – The amplifiers two output transistors only conduct for one-half, that is, 180° of the input waveform.
- Class AB: – The amplifiers two output transistors conduct somewhere between 180° and 360° of the input waveform.

BJT Class A Amplifiers

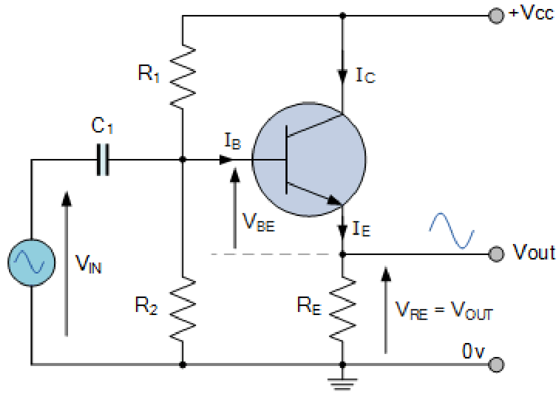
- In a class A amplifier, the transistor conducts for the full cycle of the input signal (360°)
  - used in low-power applications
- The transistor is operated in the active region, between saturation and cutoff
  - saturation is when both junctions are forward biased
  - the transistor is in cutoff when $I_B = 0$
- The *load line* is drawn on the collector curves between saturation and cutoff



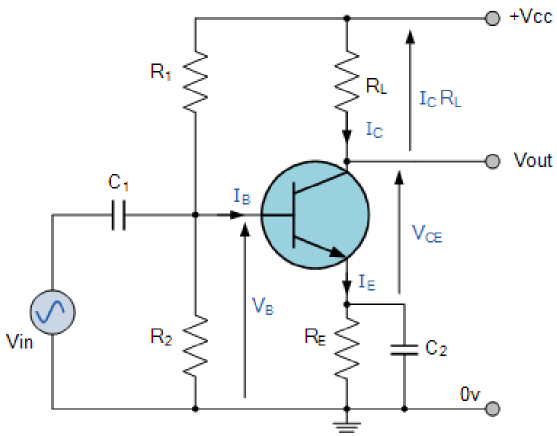
Ingle Stage Amplifier

- Three biasing mode for class A amplifiers
  - **common-emitter** (CE) amplifier
  - **common-collector** (CC) amplifier
  - **common-base** (CB) amplifier

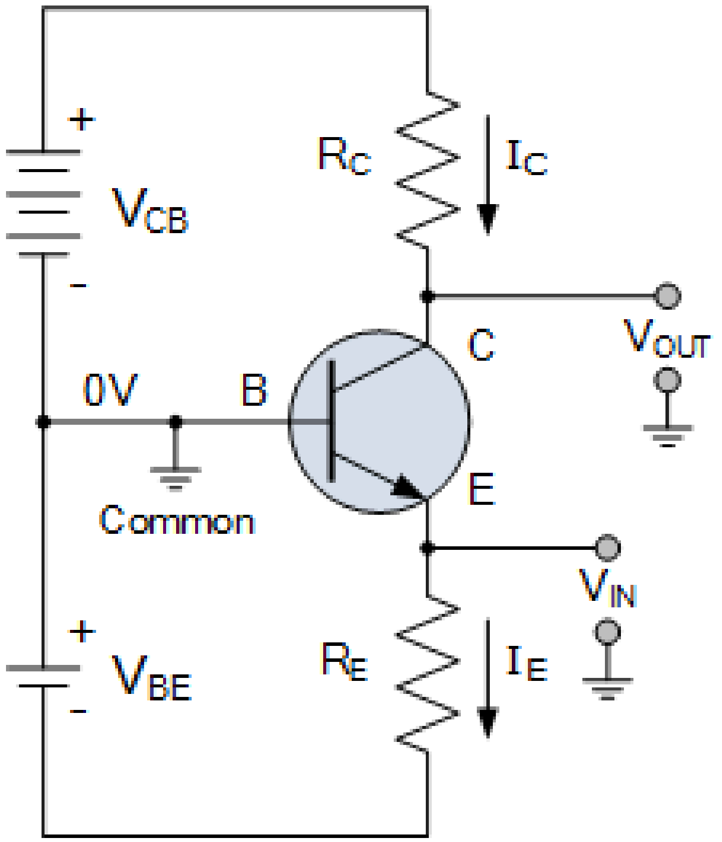
BJT Class A Amplifiers



Common Collector Amplifier

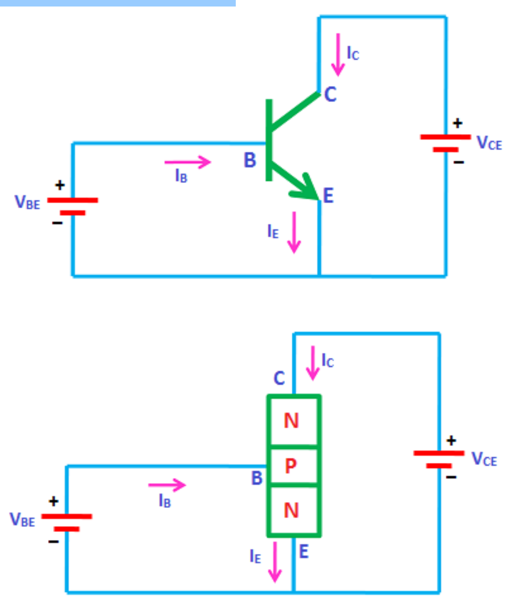


Common Emitter Amplifier

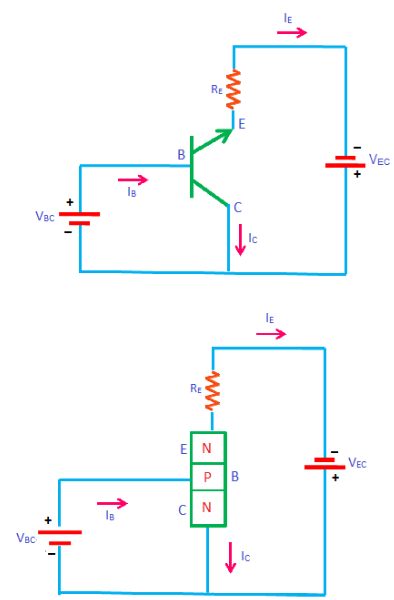


Common Base Amplifier

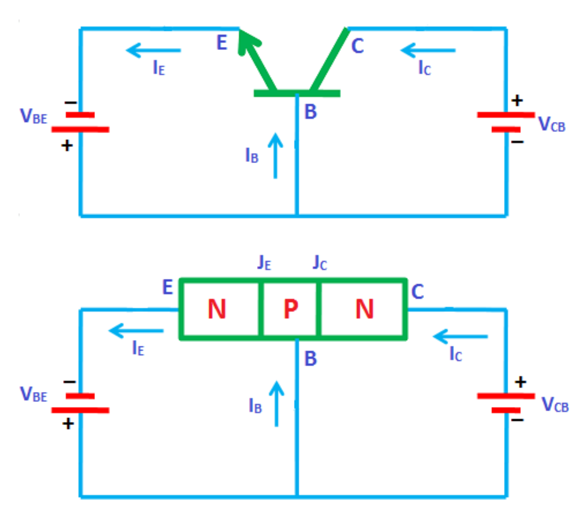
Parameter	Common Emitter	Common Collector	Common Base
Voltage gain Av	High (about 100)	Unity (1)	Medium (10-50)
Current Gain	High (50 - 800)	High (50 -800)	Less than unity (<1)
Input Impedance	Medium (about 3 to 5k)	High (several k)	Low (about 50R)
Output Impedance	Medium, Approx = Load resistor value	Low (a few ohms)	High (about 1M)



Common emitter configuration



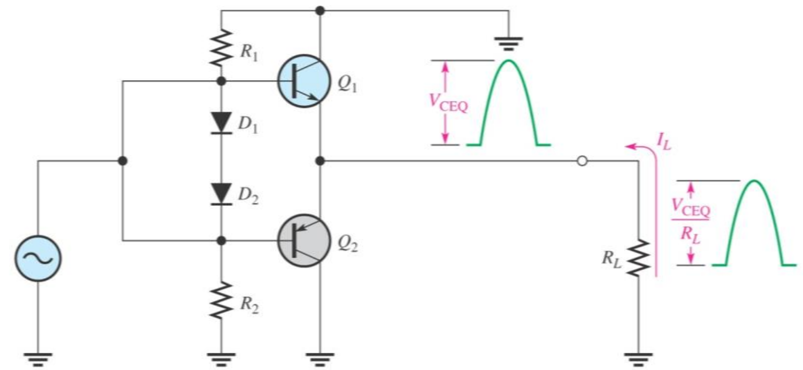
Common collector configuration



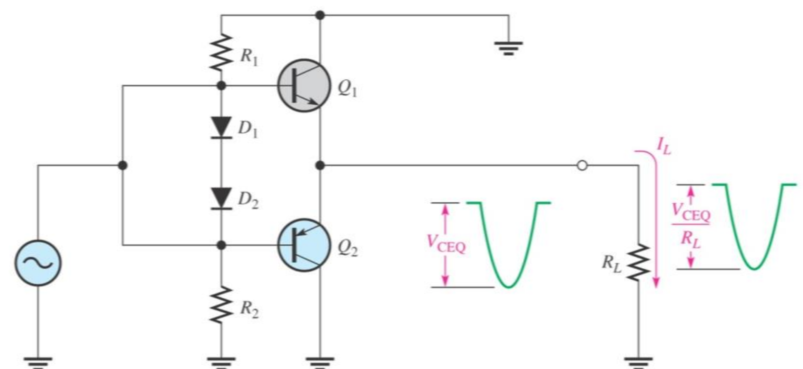
Common base configuration

BJT Class B Amplifiers

- When an amplifier is biased such that it operates in the linear region for 180° of the input cycle and is in cutoff for 180°, it is a class B amplifier
  - A class B amplifier is more efficient than a class A
- In order to get a linear reproduction of the input waveform, the class B amplifier is configured in a push-pull arrangement
  - The transistors in a class B amplifier must be biased above cutoff to eliminate crossover distortion

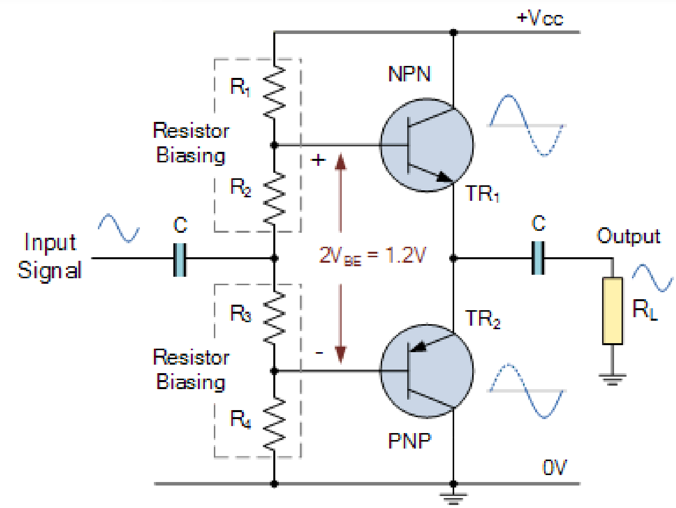


(a) Q_1 conducting with maximum signal output

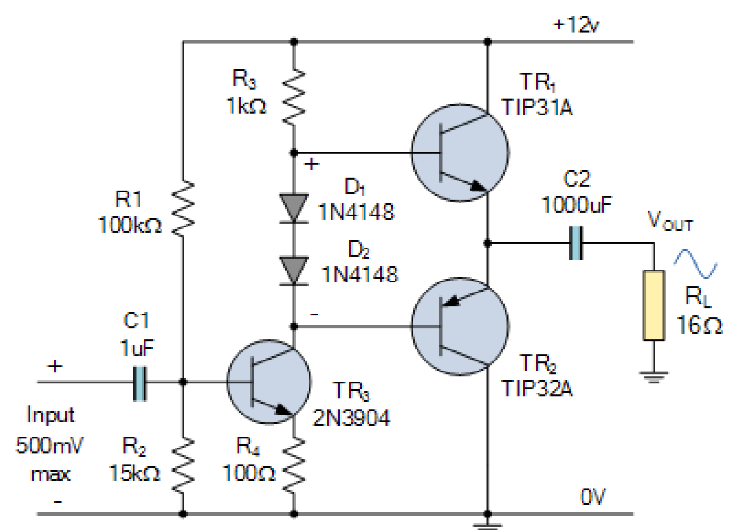


(b) Q_2 conducting with maximum signal output

- As the Class B amplifier is biased so that the output current flows through each transistor for only half of the input cycle, the output waveform is therefore not an exact replica of the input waveform since the output signal is distorted.
- This distortion occurs at every zero-crossing called cross-over distortion
- By biasing the transistor slightly above its cut-off point but much below the centre Q-point of the class A amplifier, we can create a Class AB amplifier circuit. Then the basic purpose of a Class AB amplifier is to preserve the basic Class B configuration while at the same time improving its linearity by biasing each switching transistor slightly above threshold.



Class AB Amplifier Resistor Biasing

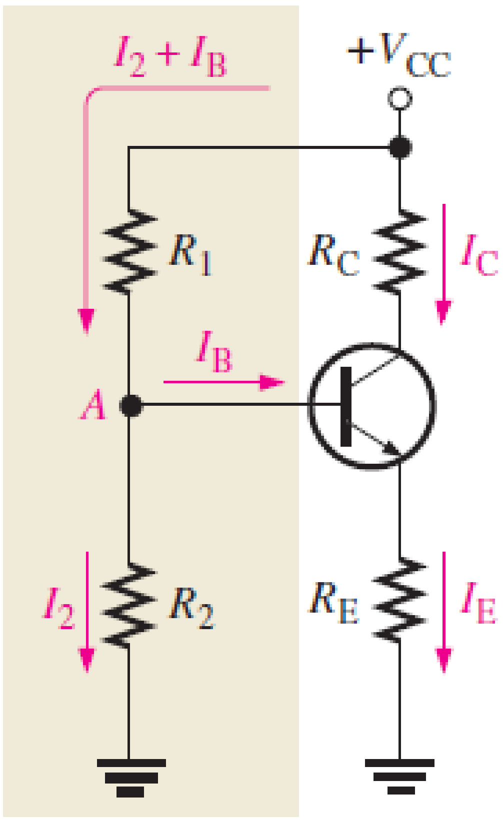


Class AB Amplifier Driver Stage

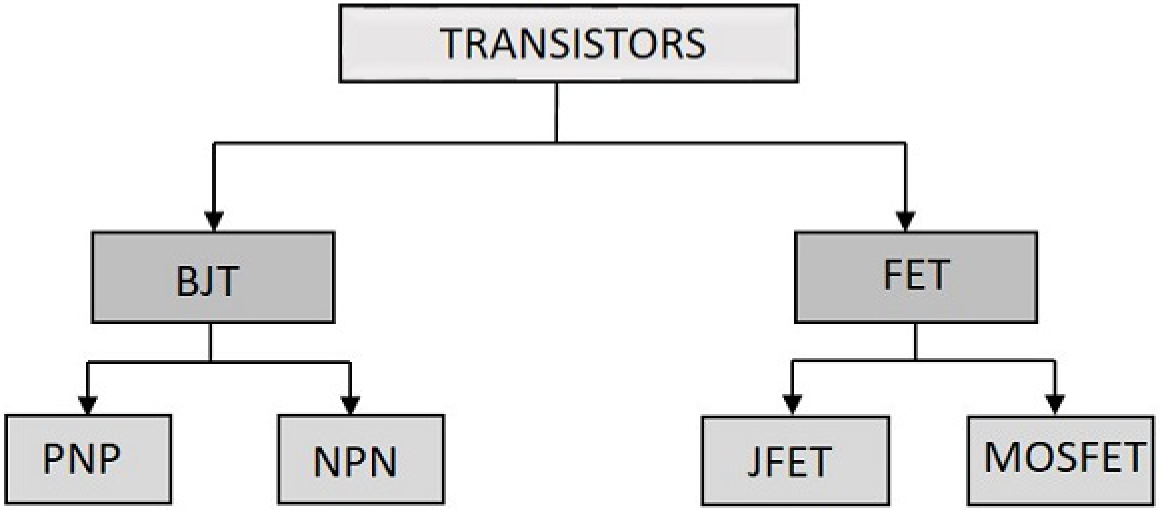
Voltage-Divider

A practical biasing technique that utilize single biasing sources instead of separate V_{CC} and $V_{BB.}$

A dc bias voltage at the base of the transistor can be developed by a resistive voltage divider that consists of $R1$ and $R2$



Other type of transistor



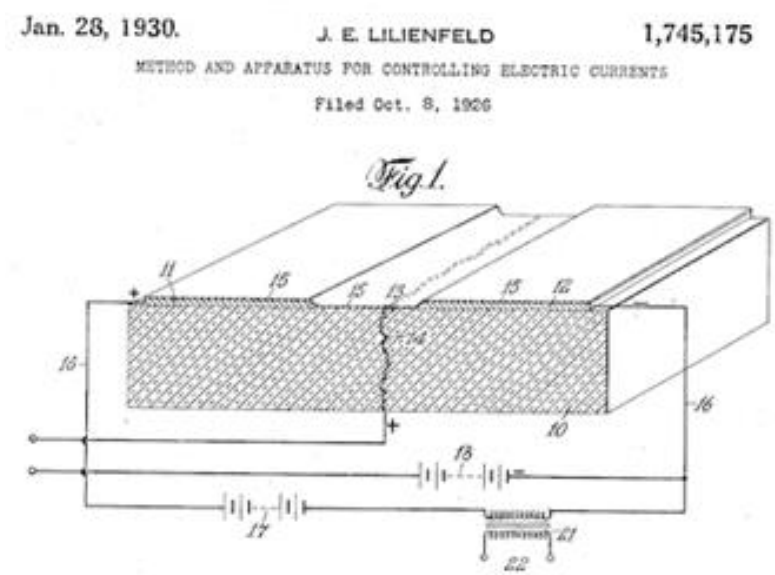
Field Effect Transistor

- The field-effect transistor (FET) is a generic term for a device that controls current through a circuit via an applied voltage, i.e. it behaves like a voltage-controlled resistor.
- A FET has three terminals:
  - gate: as in the "gate" keeper of the current
  - source: the source of the current
  - drain: the destination of the current
- The FET operation is as follows:
  - apply a voltage to the gate
  - this voltage sets up an electric field in the "body" of the device
  - electric field inhibits/supports the flow of charge from source to drain
- There are two main varieties of FETs:
  - junction FETs (JFETs)
  - metal-oxide FETs (MOSFETs)
- FETs can be made in NPN or PNP variety.
- FETs are "Unipolar" (conduct either electrons or holes, not both)

Field Effect Transistor

The idea for a field-effect transistor (FET) was first proposed by Julius Lilienthal, a physicist and inventor. In 1930 he was granted a U.S. patent for the device.

His ideas were later refined and developed into the FET. Materials were not available at the time to build his device. A practical FET was not constructed until the 1950's. Today FETs are the most widely used components in integrated circuits.

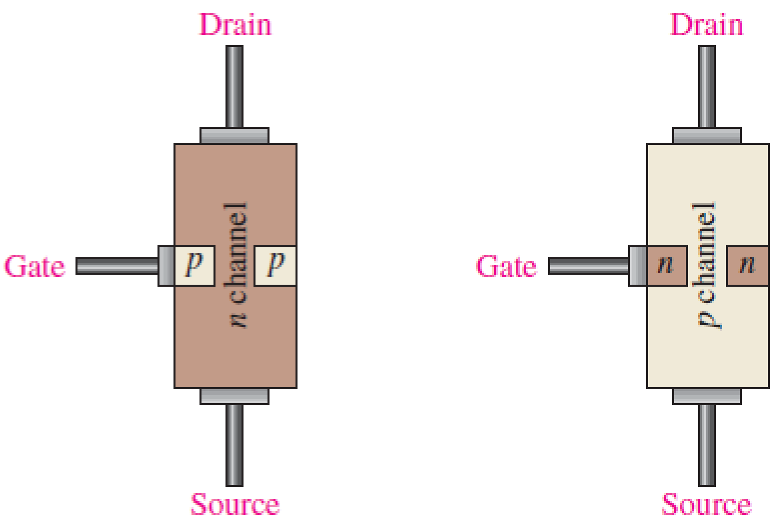


JFET

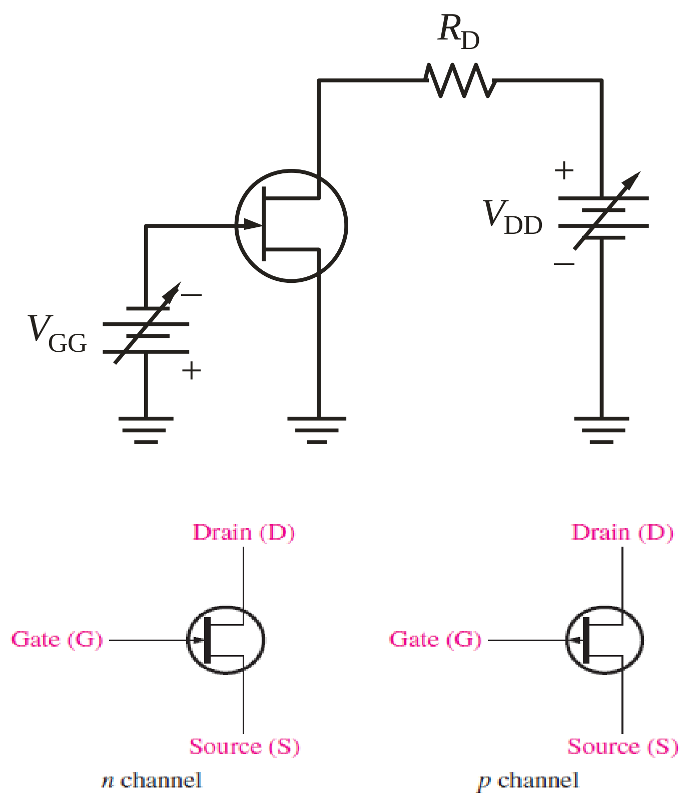
The JFET (or Junction Field Effect Transistor) is a normally ON device.

The n-channel is connected with two leads i.e. Drain and Source

Two p-type regions are diffused in n-type material and both connected to gate.

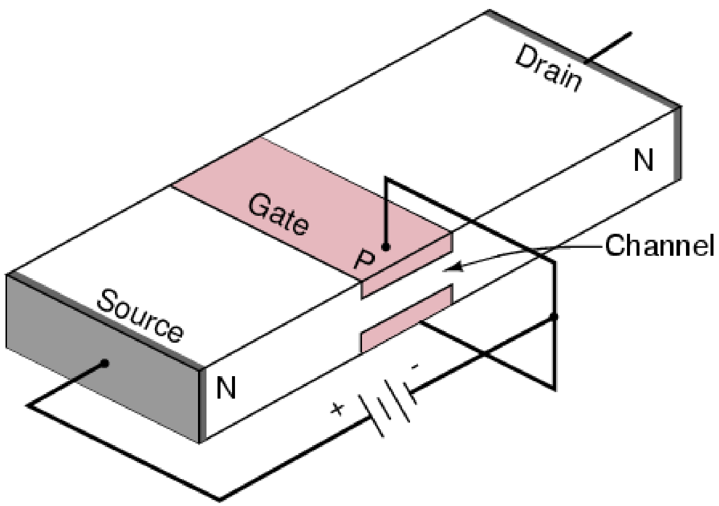


(a) *n* channel (b) *p* channel



Junction Field-Effect Transistor (JFET)

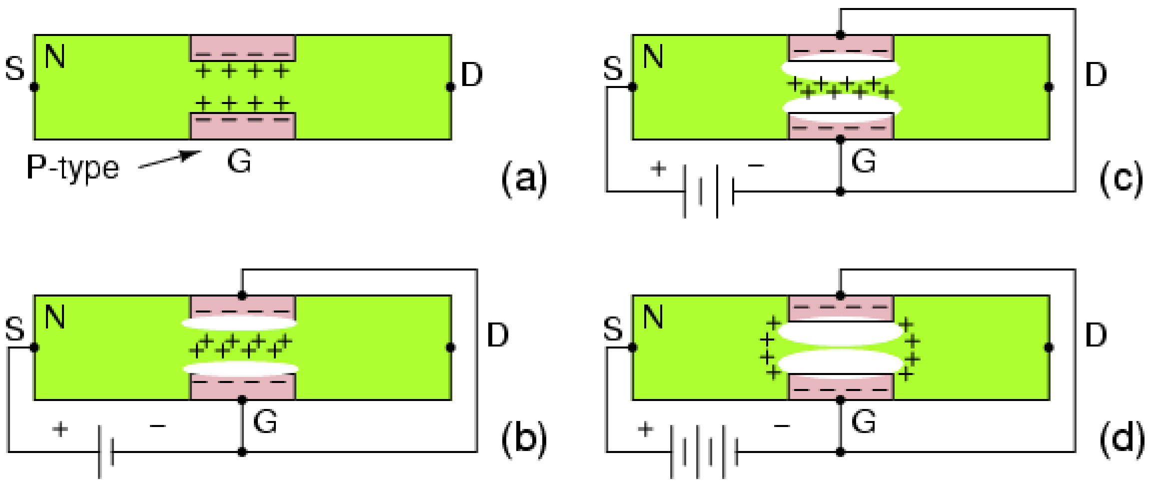
- An n channel JFET is composed of:
  - n-type body
  - p-type
- Gate is generally reverse biased to control current flow.
- Channel conducts regardless of polarity between source and drain.



- controlled by the applied gate voltage, they draw very little ate current and hence present a very high input resistance to any signal source
- low noise at low frequency
- the reverse-biased junctions can tolerate a considerable amount of radiation damage without any appreciable change in FET operation.

JFET Architecture

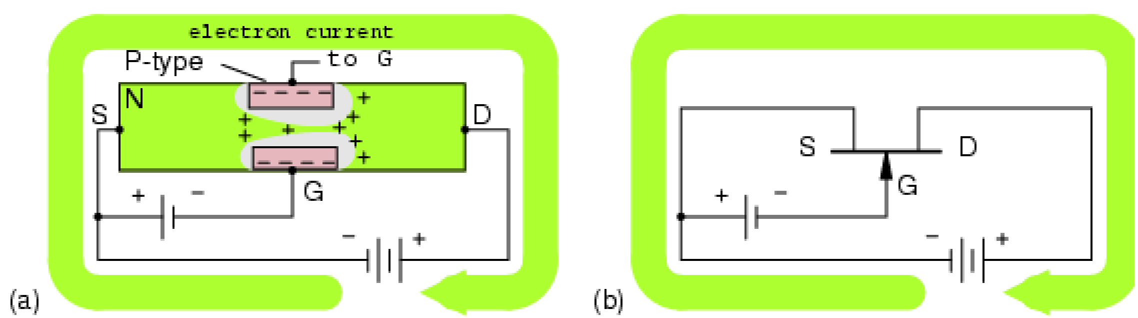
- The gate and channel form depletion regions.
- A stronger reverse bias makes the depletion regions wider and closer to each other.
- Therefore, voltage controls channel resistance.



N-channel JFET: (a) Depletion at gate diode. (b) Reverse biased gate diode increases depletion region. (c) Increasing reverse bias enlarges depletion region. (d) Increasing reverse bias pinches-off the S-D channel.

JFET Architecture

- Source and drain are interchangeable.
- Figure (b) shows the schematic symbol for an N-channel field effect transistor compared to the silicon cross-section at (a). The gate arrow points in the same direction as a junction diode. The"pointing" arrow and "non-pointing" bar correspond to P and N-type semiconductors, respectively.
- N-channel JFET electron current flow from source to drain in (a) cross-section, (b) schematic symbol.



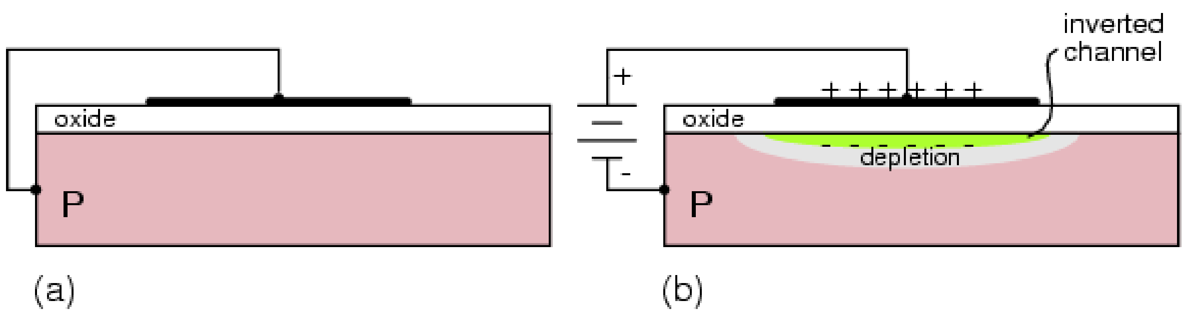
Large electron current flow from (-) battery terminal, to FET source, out the drain, returning to the (+) battery terminal. This current flow may be controlled by varying the gate voltage. A load in series with the battery sees an amplified version of the changing gate voltage.

Metal-Oxide Field-Effect Transistor (MOSFET)

- A MOSFET is a FET with an insulated gate.
- Today, most transistors are MOSFETs in digital integrated circuits.
- While the MOSFET has source, gate, and drain terminals like the FET, its gate lead is not in contact with the silicon.
- The MOSFET has an higher input impedance than the JFET (10 to 100 million megohms). Therefore, the MOSFET is even less of a load on preceding circuits.

Metal-Oxide Field-Effect Transistor (MOSFET)

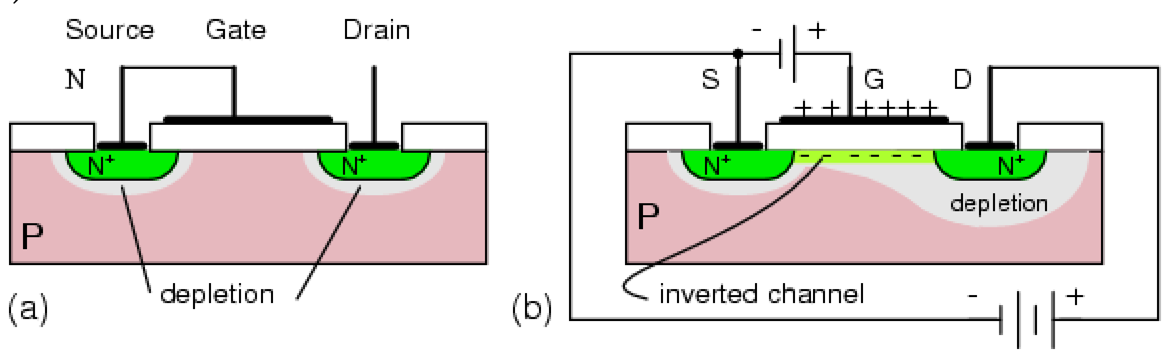
- The MOSFET gate is a metallic or polysilicon layer atop a silicon dioxide insulator. The gate bears a resemblance to a metal oxide semiconductor (MOS) capacitor.
- When charged, the plates of the capacitor take on the charge polarity of the respective battery terminals. The lower plate is P-type silicon from which electrons are repelled by the negative (-) battery terminal toward the oxide, and attracted by the positive (+) top plate.
- This excess of electrons near the oxide creates an inverted (excess of electrons) channel under the oxide. This channel is also accompanied by a depletion region isolating the channel from the bulk silicon substrate.



N-channel MOS capacitor: (a) no charge, (b) charged.

MOSFET Architecture

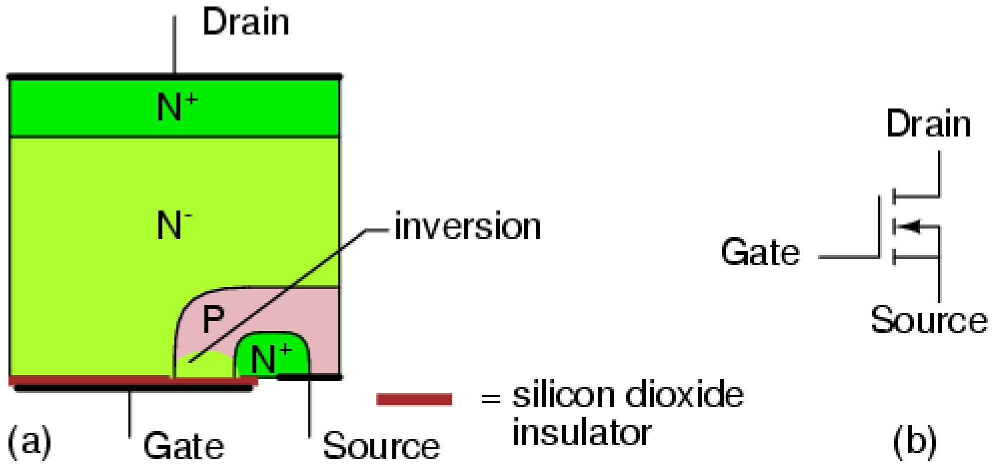
- Consider a MOS capacitor between a pair of N-type diffusions in a P-type substrate. With no charge on the capacitor, no bias on the gate, the N-type diffusions, the source and drain, remain electrically isolated.
- A positive bias charges the capacitor.
- The P-type substrate below the gate takes on a negative charge.
- An inversion region of electrons forms below the gate oxide, connecting source and drain.
- One type of charge carrier is responsible for conduction (unipolar).



N-channel MOSFET (enhancement type): (a) 0V gate bias, (b) positive gate bias.

MOSFET Architecture

- The cross-section of an N-channel discrete MOSFET is shown in the figure:
  - The N+ indicates that the source and drain are heavily N-type doped. This minimizes resistive losses in the high current path from source to drain.
  - The N-indicates light doping.
  - The P-region under the gate, between source and drain can be inverted b

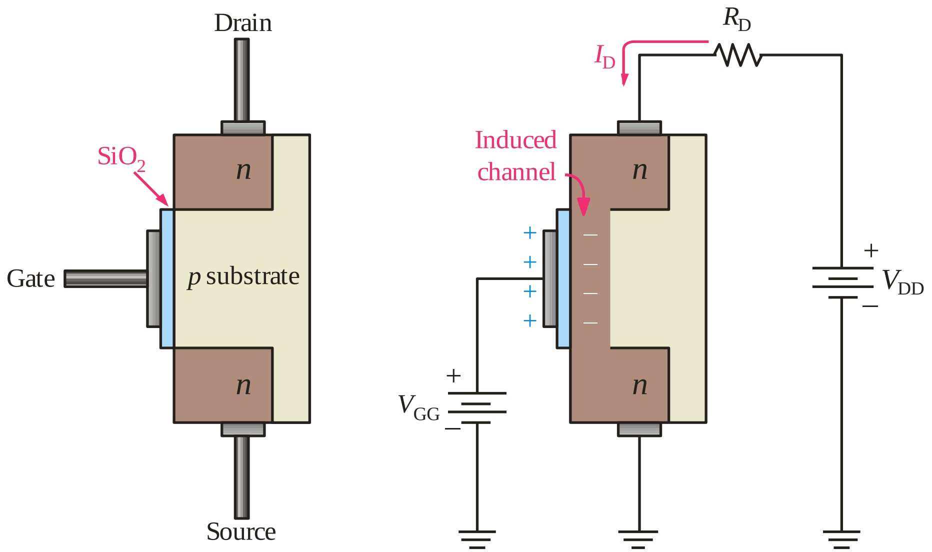


N-channel MOSFET (enhancement type): (a) Cross-section, (b) schematic symbol.

E-MOSFET

The metal oxide semiconductor FET uses an insulated gate to isolate the gate from the channel. Two types are the enhancement mode (E-MOSFET) and the depletion mode (D-MOSFET).

An E-MOSFET has no channel until it is induced by a voltage applied to the gate, so it operates only in enhancement mode. An *n*-channel type is illustrated here; a positive gate voltage induces the channel.

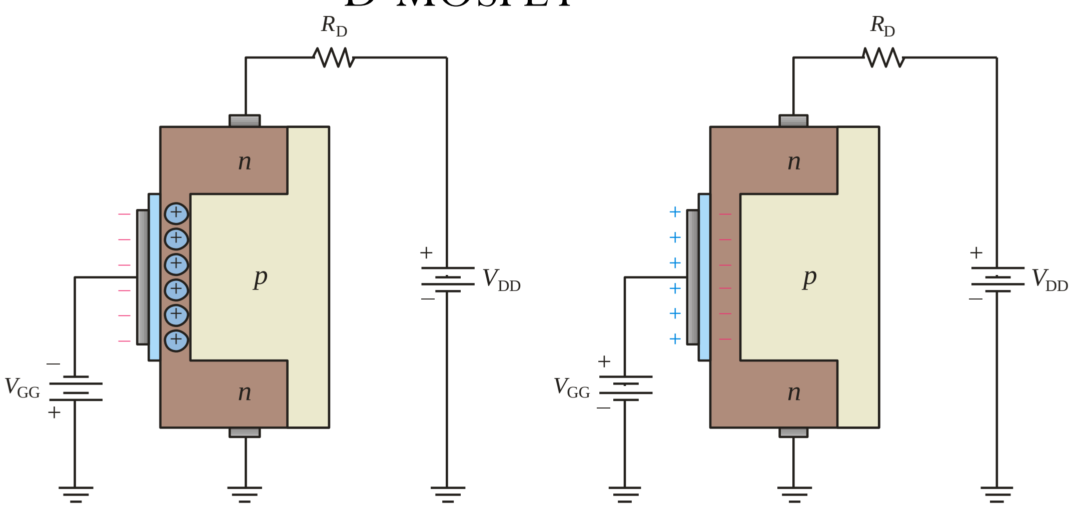


D-MOSFET

The D-MOSFET has a channel that can is controlled by the gate voltage. For an *n*-channel type, a negative voltage depletes the channel; and a positive voltage enhances the channel.

A D-MOSFET can operate in either mode, depending on the gate voltage.

D-MOSFET



operating in D-mode

operating in E-mode

Backup

Several Comments about Transistor

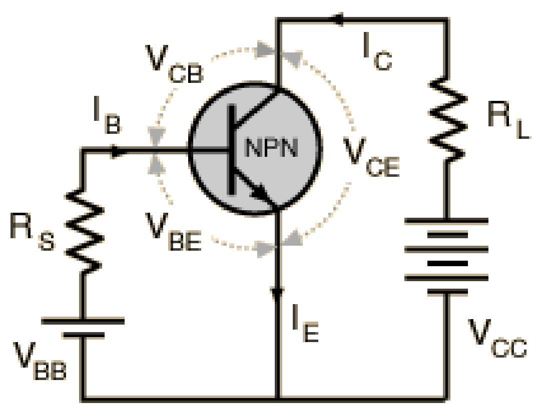
- Bipolar transistor consists of two PN junctions, with two types: NPN and PNP
- BJT is a current control device.
- The ratio of currents leads to one of the most important parameters of a transistor, which is its "current gain", often referred to as its "Beta".

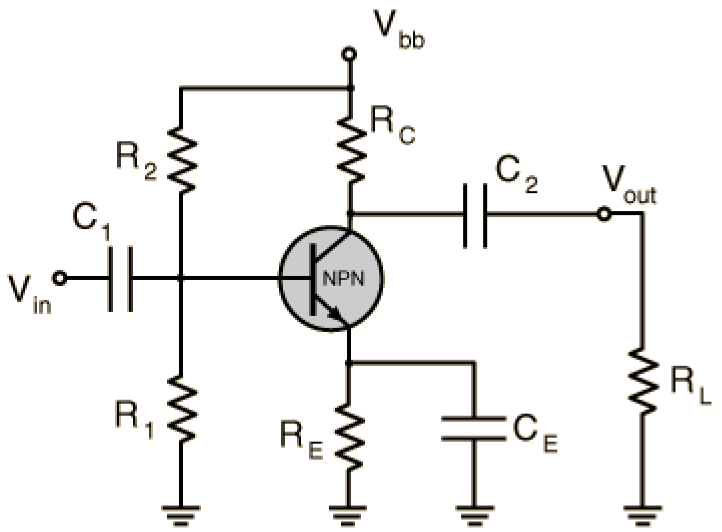
$$\beta = \frac{I_C}{I_B}$$

- BJT itself does not generate extra energy for amplifying, it just uses small current change to control big current change, which comes from the power supply.

The Common Emitter Amplifier

- NPN Transistor
  - Both the signal source and the load share the emitter lead as a common connection point
  - The common emitter configuration lends itself to voltage amplification and is the most common configuration for transistor amplifiers.





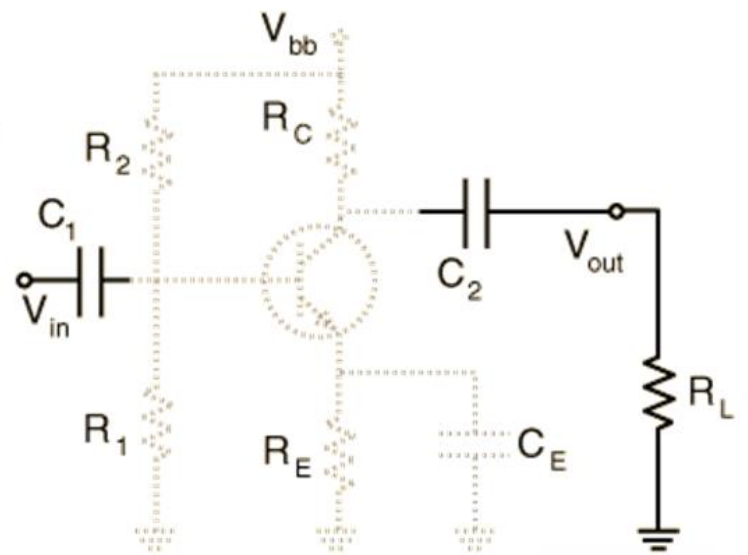
The Common Emitter Amplifier

- The capacitor C1 must be used t0 keep any DC component from disturbing the carefully developed biasing which establishes the operating point
- But C1 also puts a High-Pass Filter on the Input and must be chosen so that it does not filter out the lowest frequency which is to be amplified

$$\frac{1}{R_{II}C} < 2\pi f_{low}; R_{II} = R_1 || R_2$$

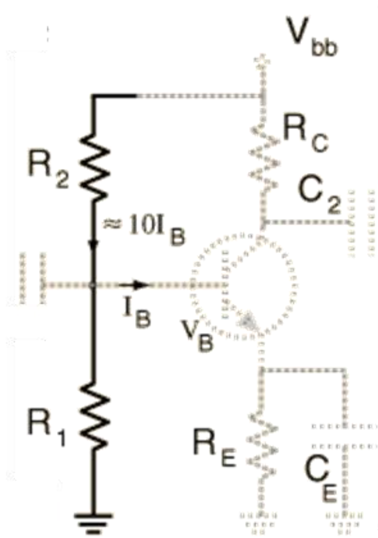
- Likewise, the capacitor C2 provides DC blocking and must be prevented from attenuating the signal

$$\frac{1}{R_L C} < 2\pi f_{low}$$



The Common Emitter Amplifier

- Resistors R1 and R2 are used to properly bias the transistor to keep it working in the active region
- These resistors are used as a voltage divider to provide proper value of base voltage to fit the chosen operating point.
- For reasonable stability, usually make the current through these resistors at least 10 times of the base current.



In the range of active operation of the Transistor

$$V_B = V_E + 0.6$$
$$I_C \cong I_E$$

The base voltage is

$$V_B = I_E R_E + 0.6$$

The voltage divider requirement is

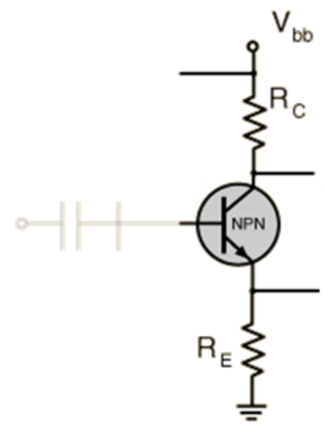
$$\frac{R_1}{R_1 + R_2} = \frac{I_E R_E + 0.6}{V_{bb}}$$

$$R_1 + R_2 = \frac{V_{bb}}{10 I_C/\beta}$$

The Common Emitter Amplifier

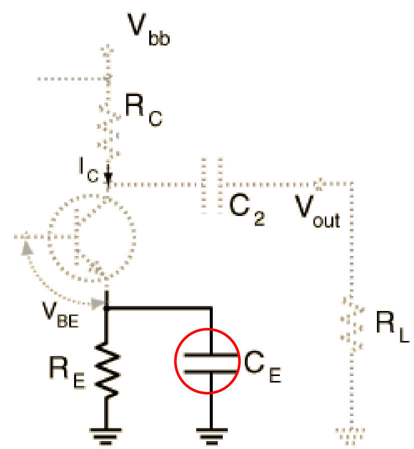
The resistance $R_C + R_E$ determines the maximum collector current

$$R_C + R_E = \frac{V_{bb}}{I_C(Max)}$$



The capacitor C_E bypasses the emitter resistor R_E, making it an AC ground.
The reason is that a rise in signal would increase the current through the resistor and therefore the voltage at the emitter.

$$C_E \,\square\, \frac{1}{2\pi f_{low} R_E}$$



The Common Emitter Amplifier

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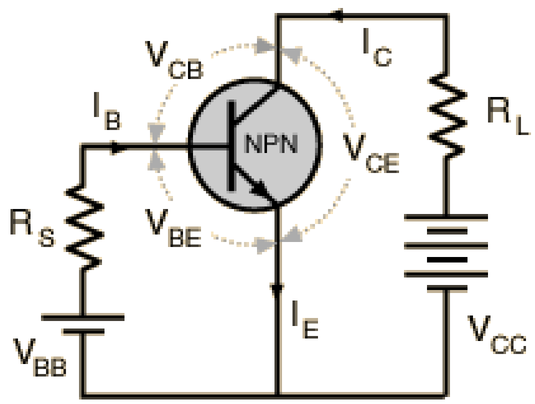
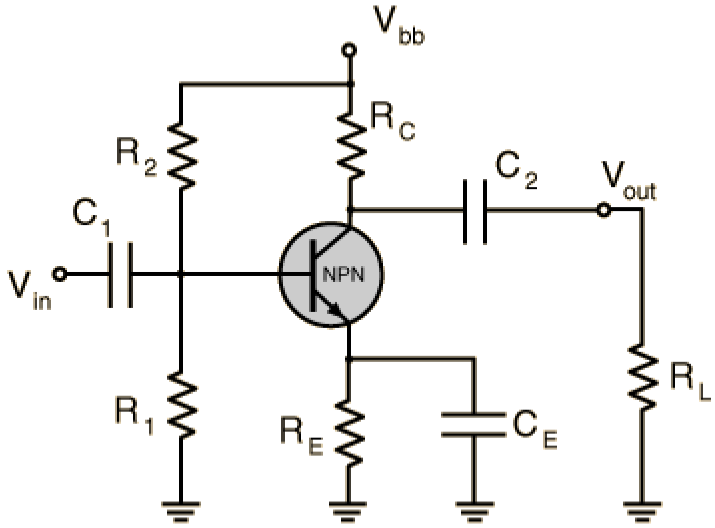
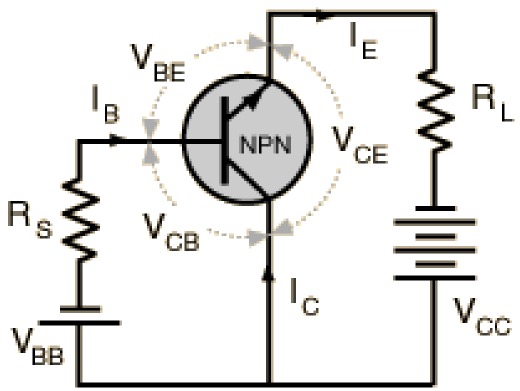




The Common Collector Amplifier

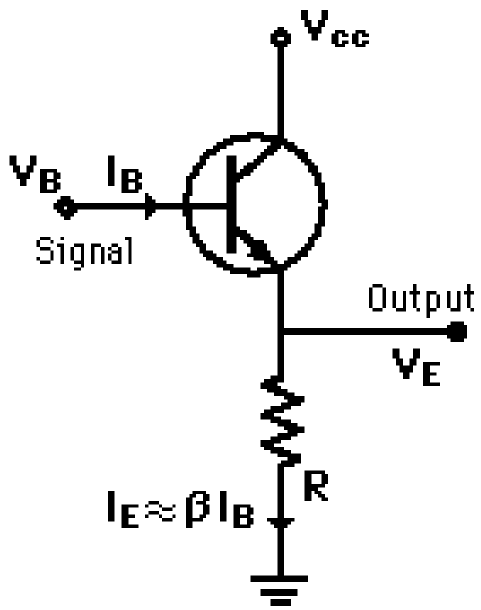
- NPN Transistor

  The common collector amplifier, often called an emitter follower since its output is taken from the emitter resistor, is useful as an impedance matching device since its input impedance is much higher than its output impedance. It is also termed a "buffer" for this reason and is used in digital circuits with basic gates.



- Emitter Follower Discussion

The voltage gain of an emitter follower is just a little less than one since the emitter voltage is constrained at the diode drop of about 0.6 volts below the base . Its function is not voltage gain but current or power gain and impedance matching. It's input impedance is much higher than its output impedance so that a signal source does not have to work so hard. This can be seen from the fact that the base current in on the order of 100 times less that the emitter current. The low output impedance of the emitter follower matches a low impedance load and buffers the signal source from that low impedance



The Common Base Amplifier

- NPN Transistor

This configuration is used for high frequency applications because the base separates the input and output, minimizing oscillations at high frequency. It has a high voltage gain, relatively low input impedance and high output impedance compared to the common collector.