Lecture 17

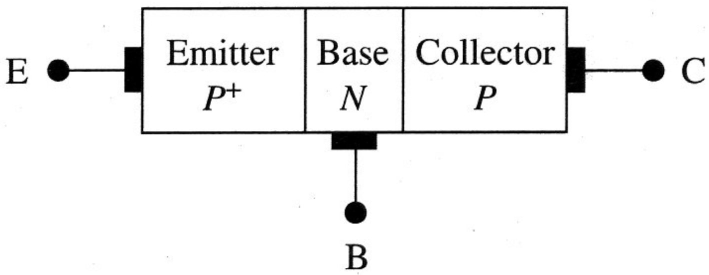
Bipolar Junction Transistors (BJT): Part 1

Qualitative Understanding - How do they work?

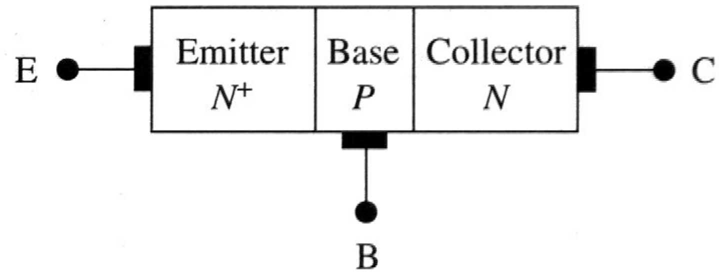
Reading:

Pierret 10.1-10.6, 11.1

Bipolar Junction Transistor Fundamentals

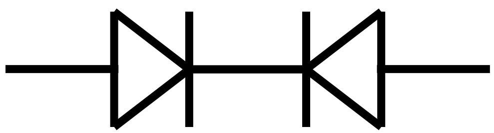


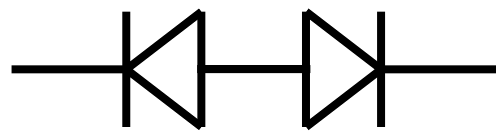
pnp

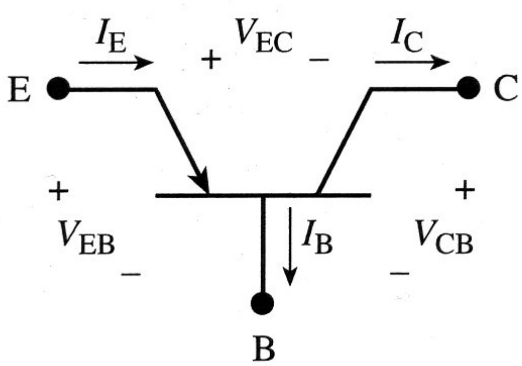


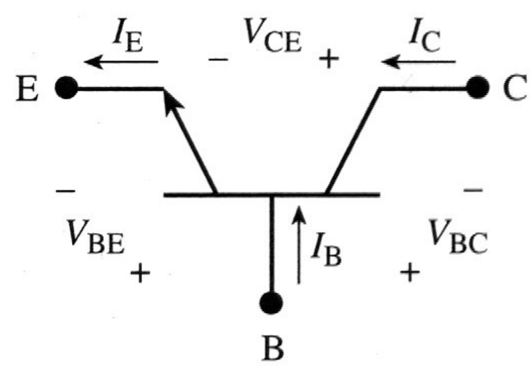
npn

Looks sort of like two diodes back to back









pnp mnemonic:
“Pouring ‘N’ Pot”

npn mnemonic:
“Not Pouring ‘N’ ”

Voltage Nomenclature Standard V_{+-}

Bipolar Junction Transistor Fundamentals

Emitter "emits" holes

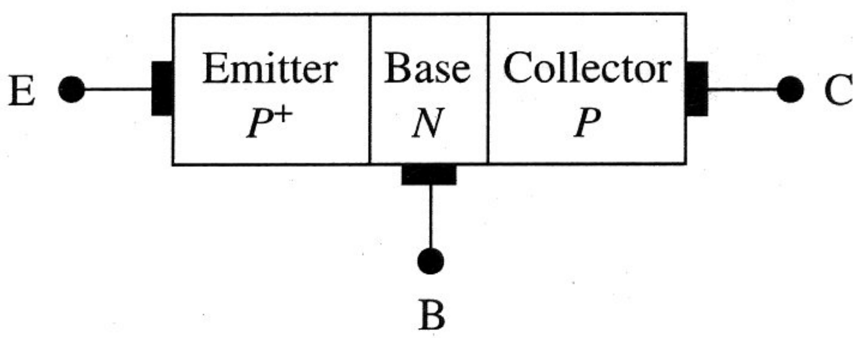
Narrow Base controls number of holes emitted

Collector "collects" holes emitted by the emitter

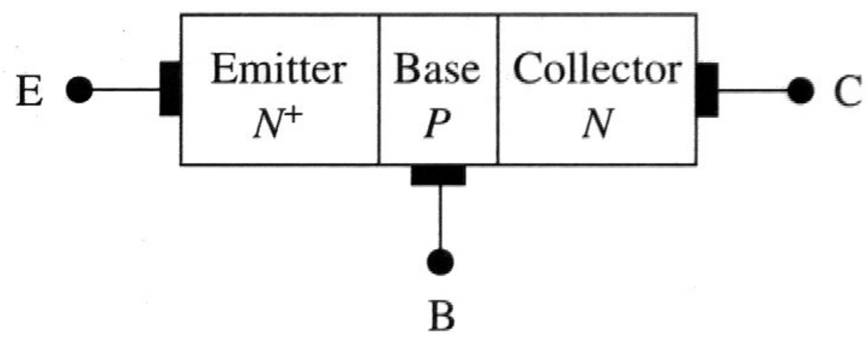
Emitter "emits" electrons

Narrow Base controls number of electrons emitted

Collector "collects" electrons emitted by the emitter

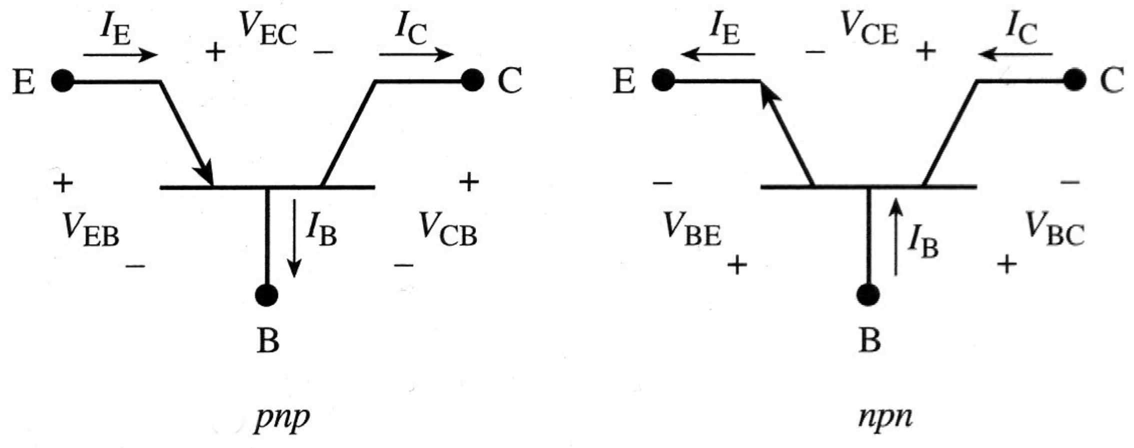


pnp



npn

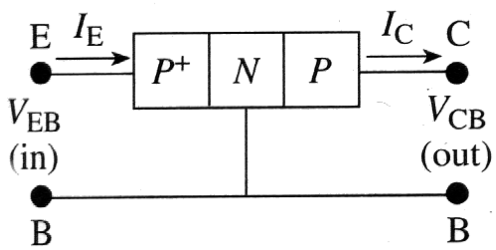
Bipolar Junction Transistor Fundamentals



$$I_E = I_B + I_C$$

$$V_{EB} + V_{BC} + V_{CE} = 0$$

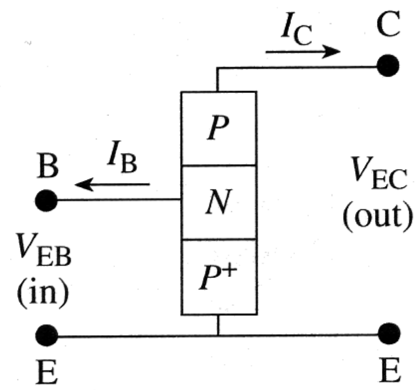
Bipolar Junction Transistor Fundamentals: Wiring the BJT as a 2 Port Network (in and out)



Common base

Both the input and output share the base "in common".

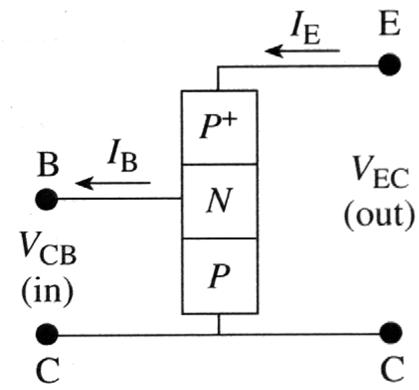
Rarely used. Exceptions include Cascode circuits and voltage protection.



Common emitter

Both the input and output share the emitter "in common".

Widely Used. For example gain stages in amplifiers.



Common collector

Both the input and output share the Collector "in common".

Widely Used. For example impedance transformation or buffer stages in amplifiers.

Bipolar Junction Transistor Fundamentals

Biasing Mode	*Biasing Polarity E–B Junction*	*Biasing Polarity C–B Junction*
Saturation	Forward	Forward
Active	**Forward**	**Reverse**
Inverted	Reverse	Forward
Cutoff	Reverse	Reverse

•Active: Is useful for amplifiers. Most of our work will use this mode. A new model is needed for this…

- α_{DC} and β_{DC} (defined later) are defined and valid

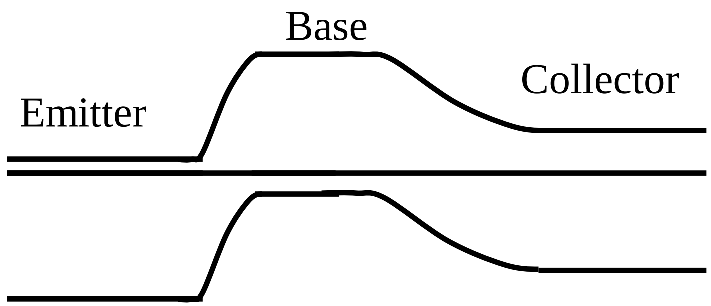
•Saturation: Equivalent to an on state when transistor is used as a switch. Boring Analysis that replaces the transistor with a pair of batteries representing the two junction turn on voltages (CVD model).

•Cutoff : Equivalent to an off state when transistor is used as a switch. Boring analysis that removes the transistor from the circuit leaving an open circuit.

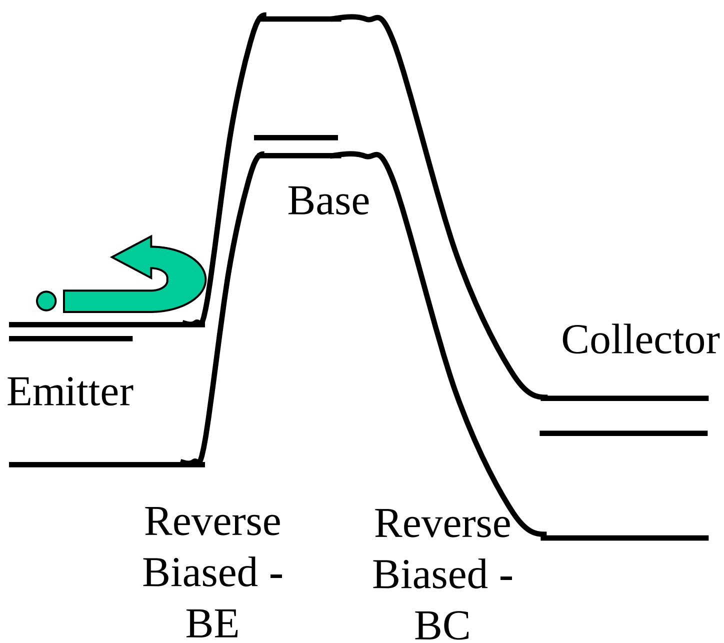
•Inverted: Rarely if ever used.

Bipolar Junction Transistor Fundamentals

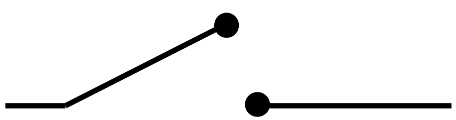
Equilibrium



Cutoff

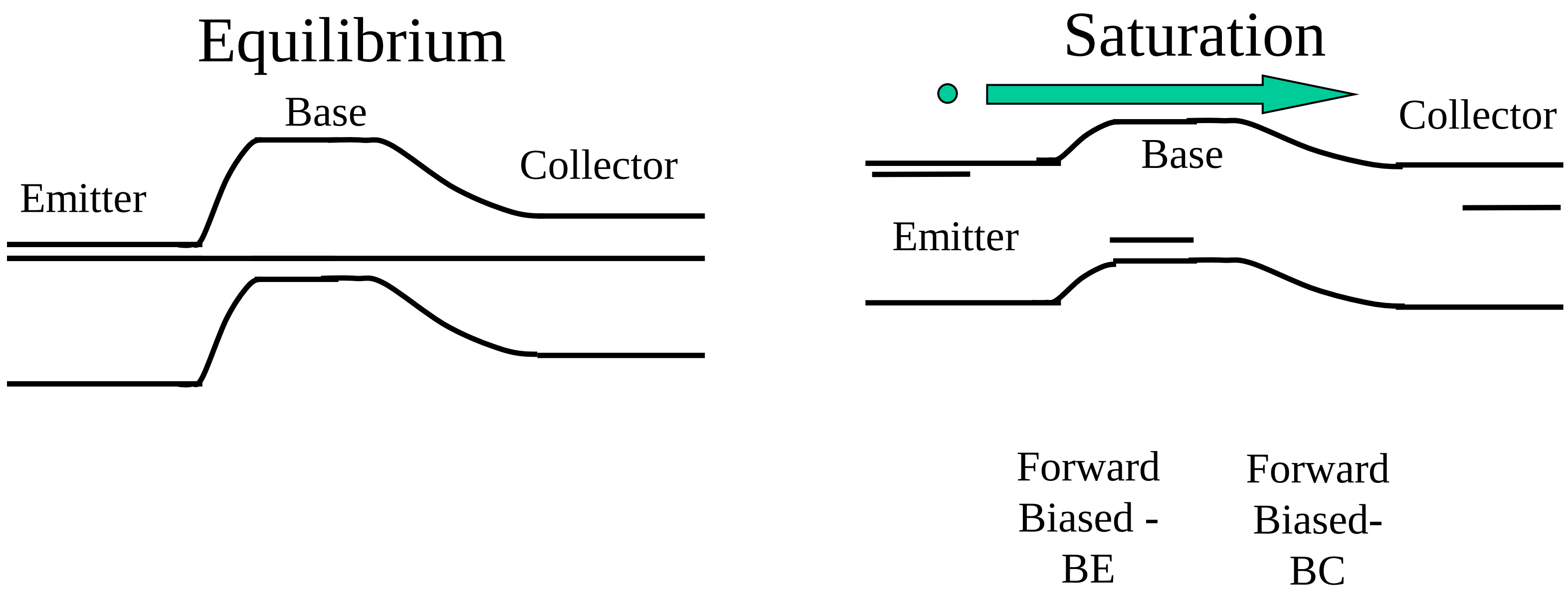


By reverse biasing both junctions, the barriers to diffusion current flow are increased resulting in only a small leakage current flowing. This looks like an open switch (large voltage drops, small current).

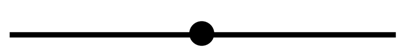


Note: Green arrows indicate directions and magnitude of electron motion not current direction

Bipolar Junction Transistor Fundamentals

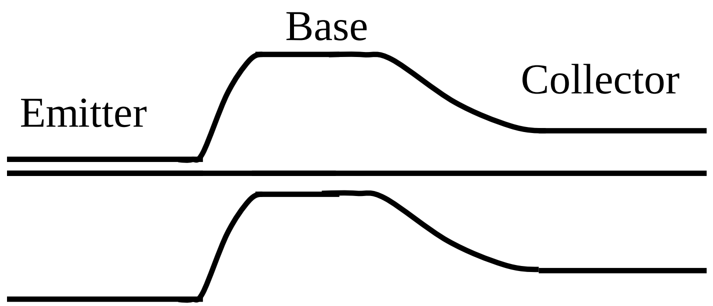


By forward biasing both junctions, the barriers to diffusion current flow are lowered allowing huge currents to flow with small voltage drops (forward biased junctions). This looks like a closed switch (large current, small voltage drops).



Bipolar Junction Transistor Fundamentals

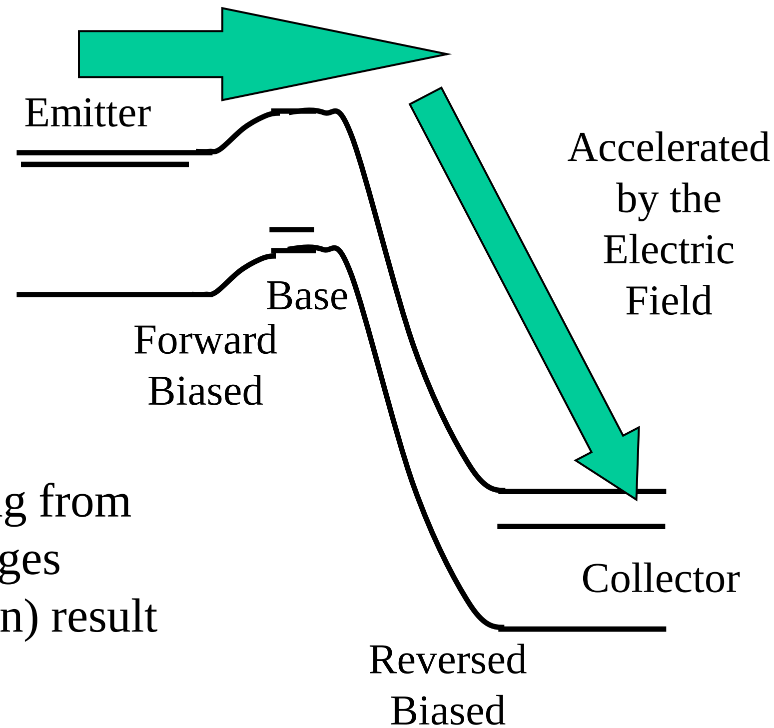
Equilibrium



1) By forward biasing the EB junction, the barrier to diffusion current flow is lowered allowing huge concentrations of carriers to flow from the emitter into the base with small voltage drops (forward biased junction) where it diffuses (and partially recombines) on its way toward the collector.

2) By reverse biasing the BC junction, large voltages are supported and since this reverse bias scavenges the emitter current surviving the diffusion in the base, the collector current almost matches the emitter current (in the case of a thin base).

Active (or Forward Active)



3) The combination of large currents (originating from the forward biased BE junction) and large voltages (supported across the reverse biased BC junction) result in large power (amplification is possible).

Note: Green arrows indicate directions and magnitude of electron motion not current direction

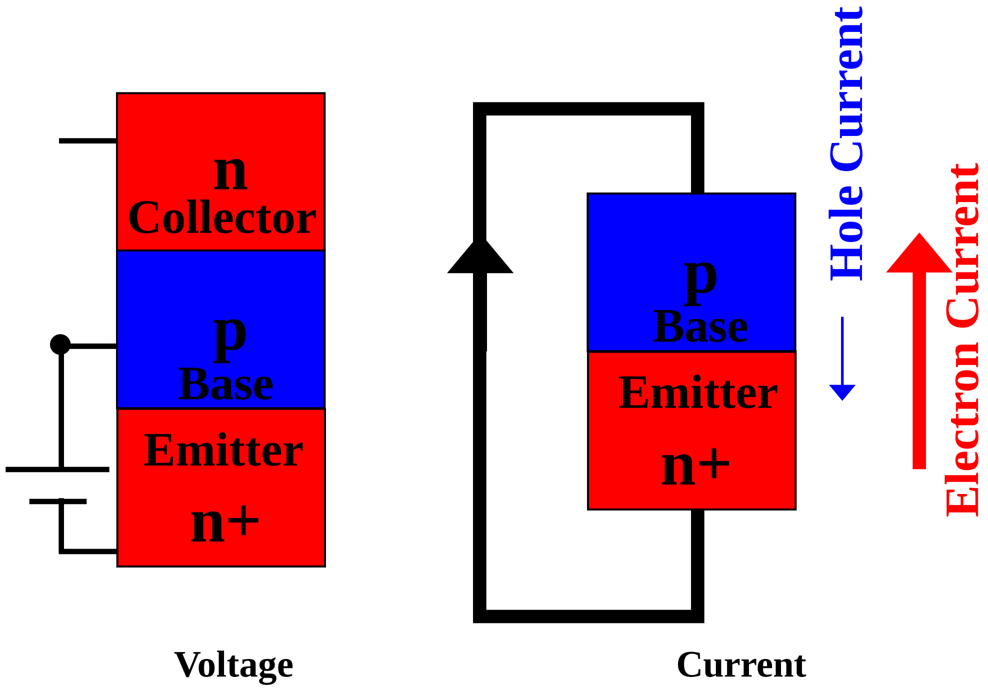
Understanding a BJT Circuit

Adding an extra layer (collector) to a diode: The base current is much smaller than the emitter and collector currents in forward active mode

If the collector of an npn BJT transistor was open circuited, it would look like a diode.

When forward biased, the current in the base-emitter junction would consist of holes injected into the emitter from the base and electrons injected into the base from the emitter.

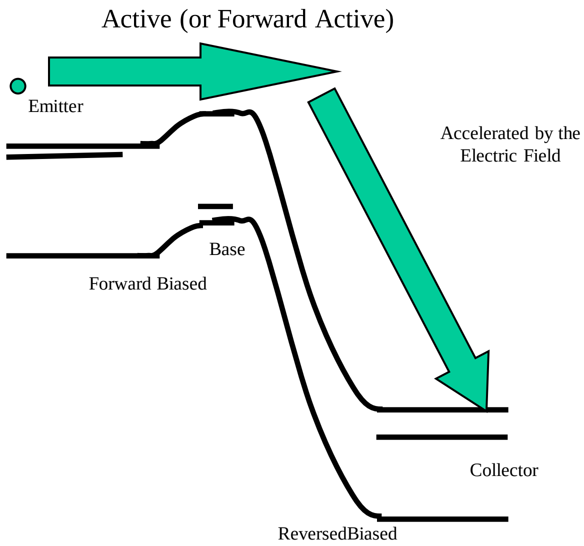
But since there are MANY more electrons in the n+ emitter than holes in the p base, the vast majority of the current will be due to electrons.



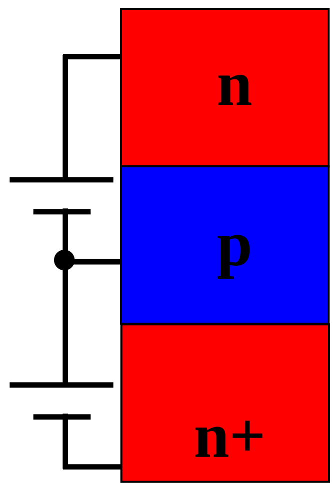
What if we added a junction to suck out the electrons injected from the emitter. That layer is said to “collect” the electrons

When the reverse biased collector-base junction is added, it “sucks” the electrons out of the base. Thus, the base-emitter current is due predominantly to hole current (the smaller current component) while the collector-emitter current is due to electrons (larger current component due to more electrons from the n+ emitter doping).

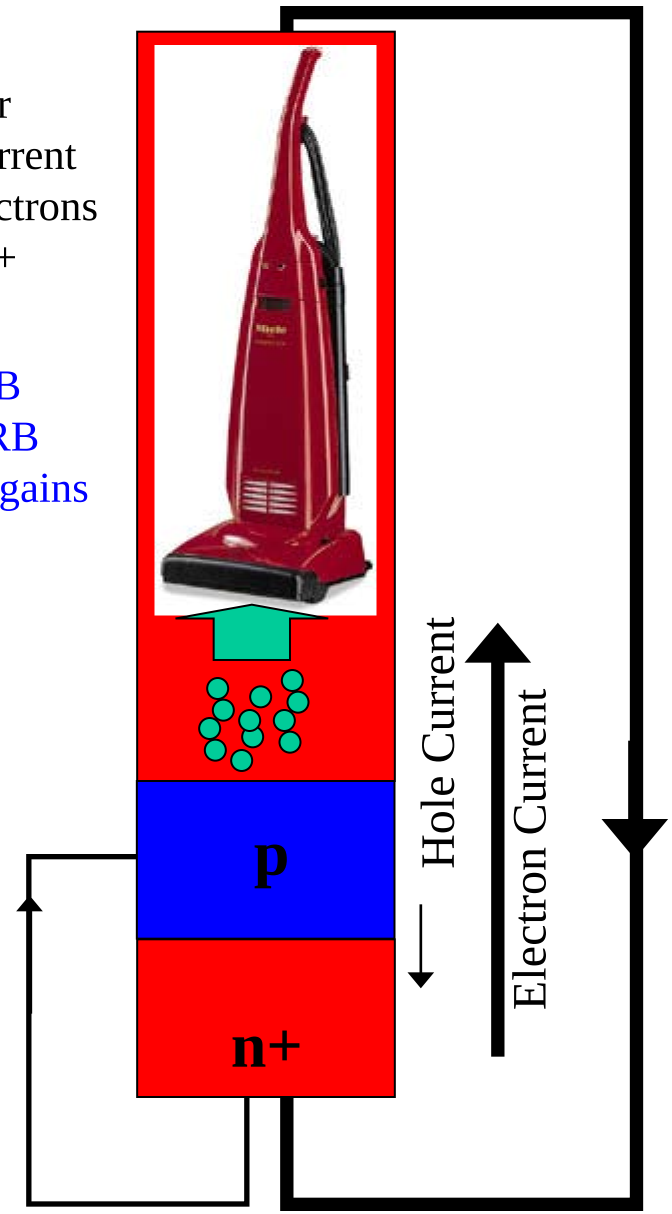
Since the device has a large current flow (originating in a FB emitter base junction) and a large voltage (originating in a RB collector base junction), the device can deliver large power gains (current x voltage).



Energy Band Diagram



Voltage



Current

Note: Green arrows indicate directions and magnitude of electron motion not current direction

Bipolar Junction Transistor Fundamentals: Electrostatics in Equilibrium

Emitter Doping >Base Doping>Collector Doping

Emitter is heavily doped

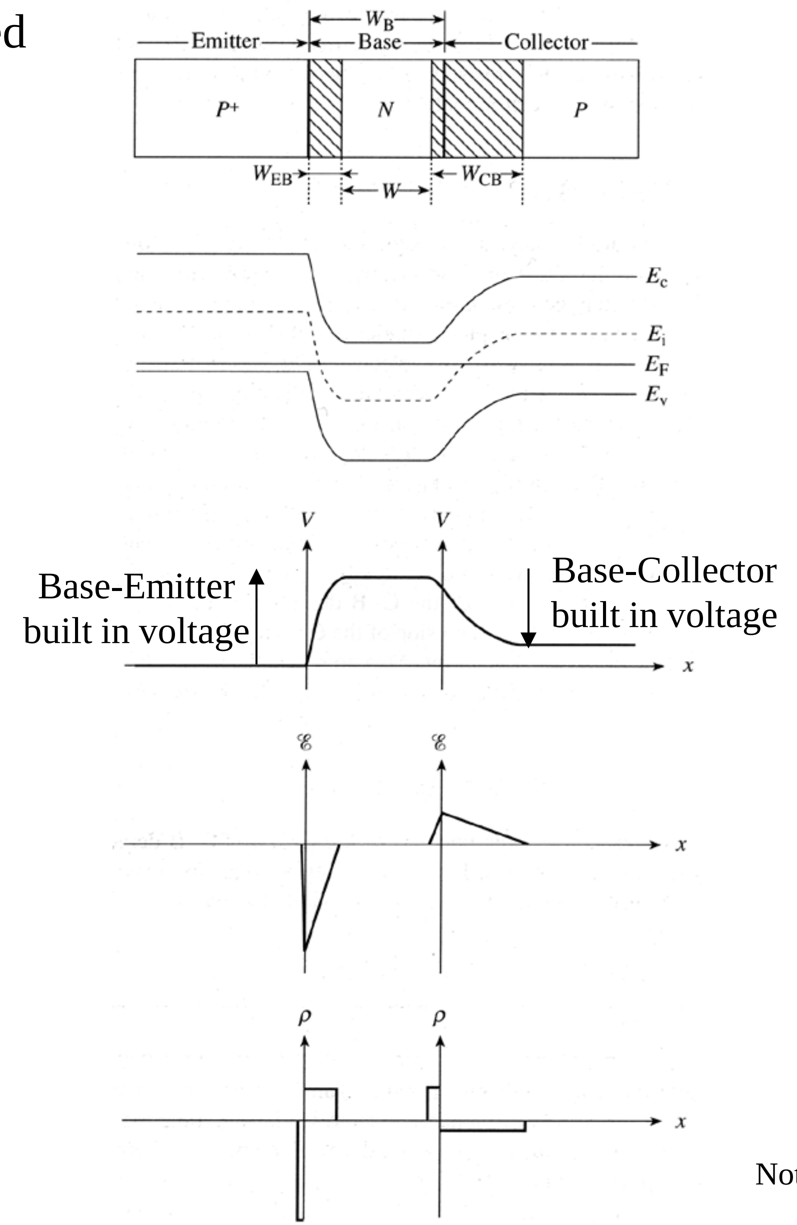
W=width of the base quasi-neutral region

W_B=Total Base width

W_{EB}=Base-Emitter depletion width

W_{CB}=Base-Collector depletion width

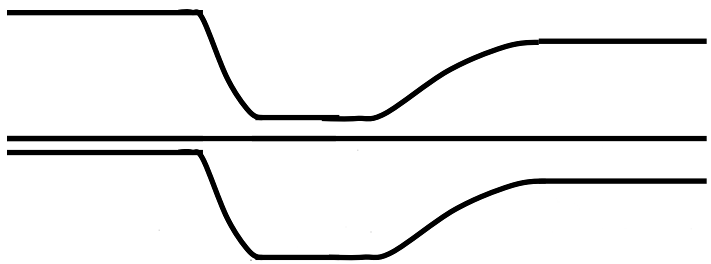
$W_{EB} < W_{CB}$

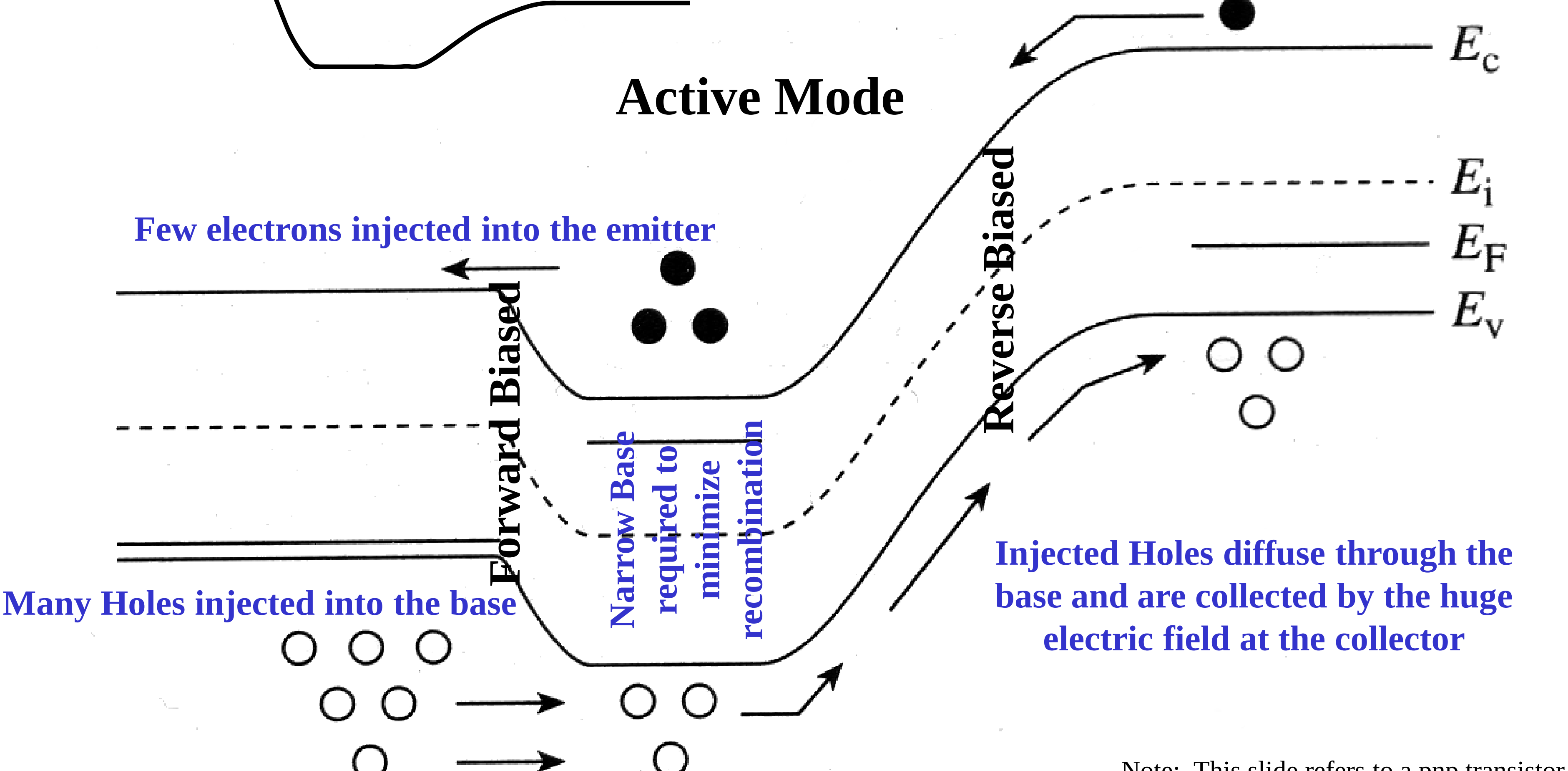


Note: This slide refers to a pnp transistor

Bipolar Junction Transistor Fundamentals

Equilibrium

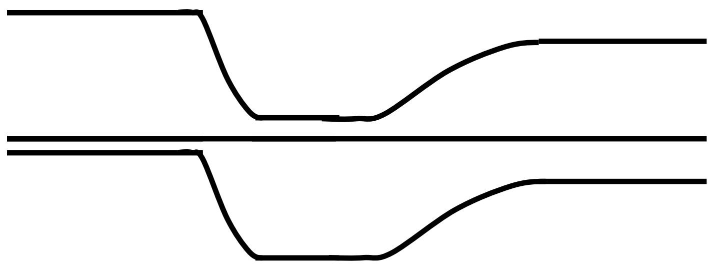




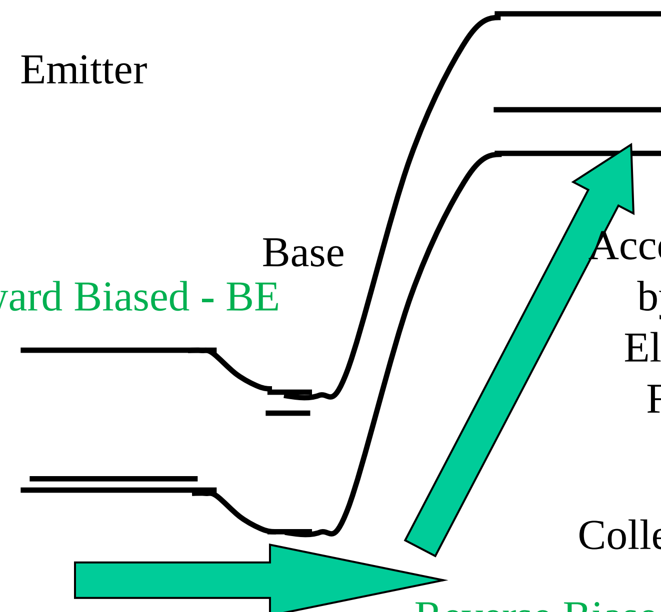
Note: This slide refers to a pnp transistor

PNP Bipolar Junction Transistor

Equilibrium



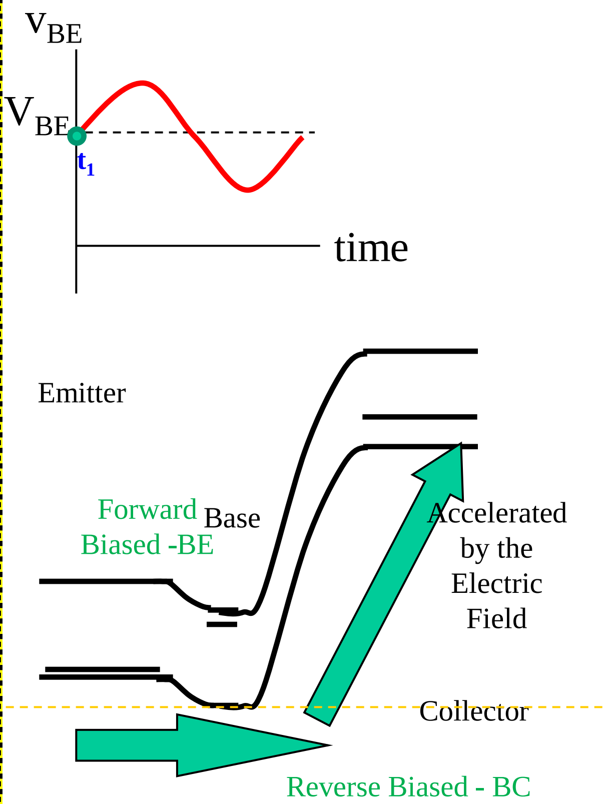
Active (or Forward Active)

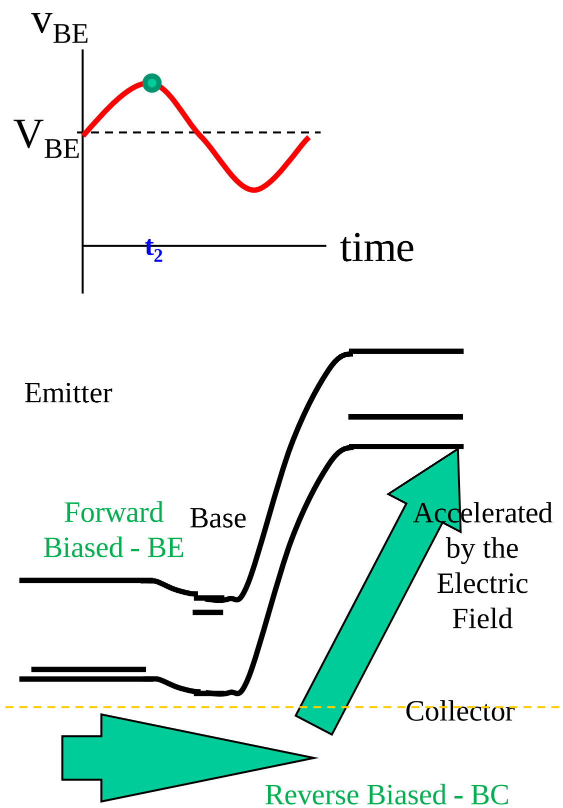


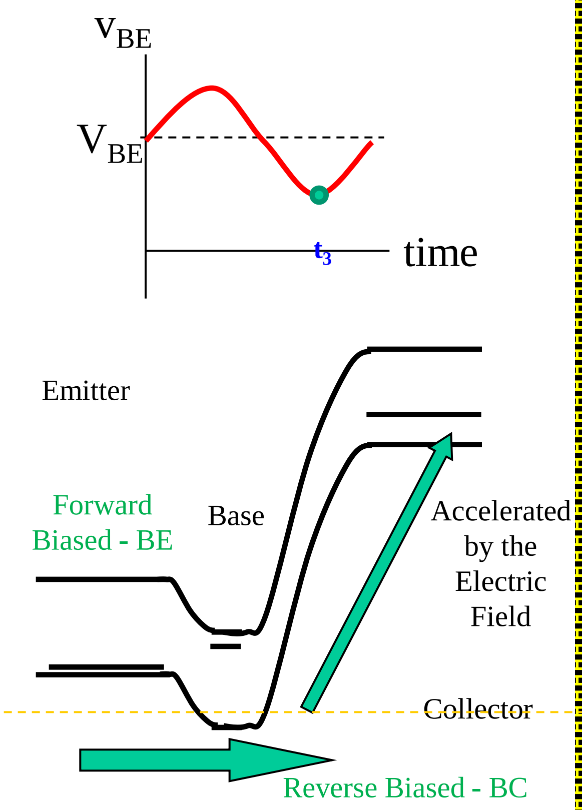
Note: This slide refers to a pnp transistor

Note: Green arrows indicate directions and magnitude of hole motion.

PNP Bipolar Junction Transistor Under DC Active Bias Mode with Added AC Modulation







t_1:Forawrd biased v_{BE} results in large i_E which diffusies through the base and is swept out of the collector making $i_C \sim i_E$ (large) and a large v_{CE} resulting in power.

t_2:Larger instantaneous v_{BE} than t_1 results in larger i_E and i_C but almost the same v_{CE}

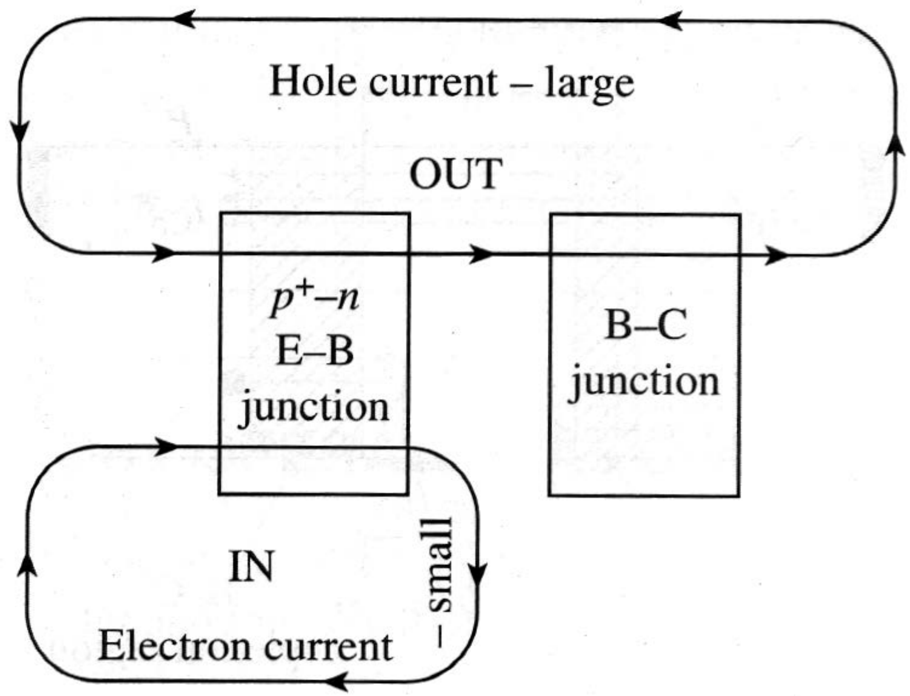
t_3:Smaller instantaneous v_{BE} than t_1 results in smaller i_E and i_C but almost the same v_{CE}

Small changes in v_{be} make very large changes in i_c with a large v_{CE} and thus, AMPLIFICATION!

Note: This slide refers to a pnp transistor

Note: Green arrows indicate directions and magnitude of hole motion.

Bipolar Junction Transistor Fundamentals



Consider a pnp Transistor: A small electron base current (flowing into the emitter from the base) controls a larger hole current flowing from emitter to collector. Effectively, we can have the collector-emitter current controlled by the base-emitter current, a current controlled current source.

Alternatively it can be viewed as a voltage controlled current source if we say the B-E voltage (which determines the base to emitter electron current) controls the E-C current..

Note: This slide refers to a pnp transistor

Bipolar Junction Transistor Fundamentals:
Performance Parameters

Optional

$$(1)\quad \gamma = \frac{I_{Ep}}{I_E} = \frac{I_{Ep}}{I_{Ep} + I_{En}}$$

Emitter Efficiency: Characterizes how effective the large hole current is controlled by the small electron current. Unity is best, zero is worst.

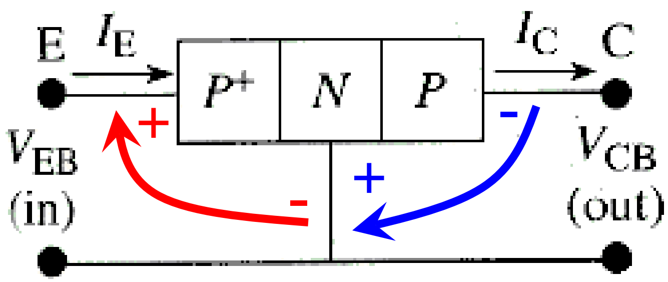
$$(2)\quad \alpha_T = \frac{I_{Cp}}{I_{Ep}}$$

Base Transport Factor: Characterizes how much of the injected hole current is lost to recombination in the base. Unity is best, zero is worst.

Note: This slide refers to a pnp transistor

Bipolar Junction Transistor Fundamentals:
Performance Parameters

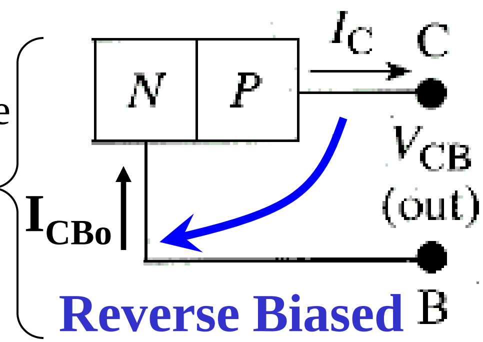
Active Mode, Common Base Characteristics



Forward Biased - EB

Reverse Biased - BC

I_{CBo} is defined as the collector current when the emitter is open circuited. It is the Collector-base junction saturation current.



Reverse Biased

I_C=fraction of emitter current making it across the base + leakage current always present even when there is no V_{EB}

$$(3) \quad I_C = \alpha_{dc} I_E + I_{CBo}$$ where α_{dc} is the common base DC current gain

Optional

Combining (1) and (2),

$$I_{Cp} = \alpha_T I_{Ep} = \gamma \alpha_T I_E$$

$$I_C = I_{Cp} + I_{Cn} = \alpha_T I_{Ep} + I_{Cn} = \gamma \alpha_T I_E + I_{Cn}$$

Thus comparing this to (3),

$$\alpha_{dc} = \gamma \alpha_T \quad and \quad I_{CBo} = I_{Cn}$$

Note: This slide refers to a pnp transistor

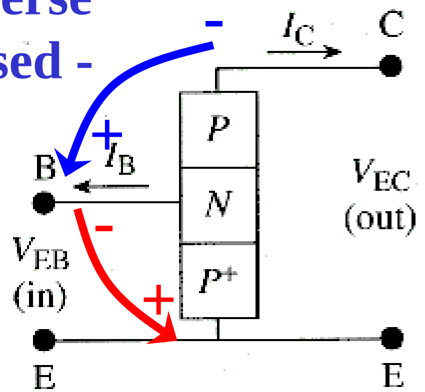
Bipolar Junction Transistor Fundamentals:

Performance Parameters

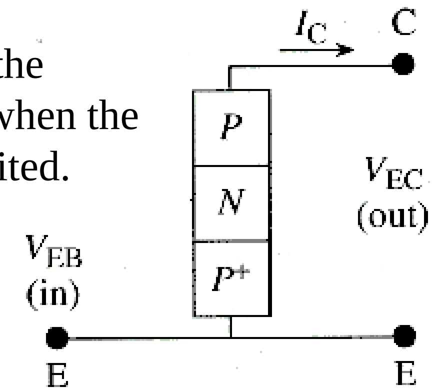
Active Mode, Common Emitter Characteristics

Reverse Biased - BC

Forward Biased - EB



I_{CEo} is defined as the collector current when the base is open circuited.



I_C=multiple of the base current making it across the base + leakage current

$$(4) \quad I_C = \beta_{dc} I_B + I_{CEo}$$ where β_{dc} is the common emitter DC current gain

Optional

But using $I_E=I_C+I_B$ in (2),

$$(5) \quad I_C = \alpha_{dc}(I_C + I_B) + I_{CBo}$$

and solving for I_C

$$(6) \quad I_C = \frac{\alpha_{dc}}{1-\alpha_{dc}} I_B + \frac{I_{CBo}}{1-\alpha_{dc}}$$

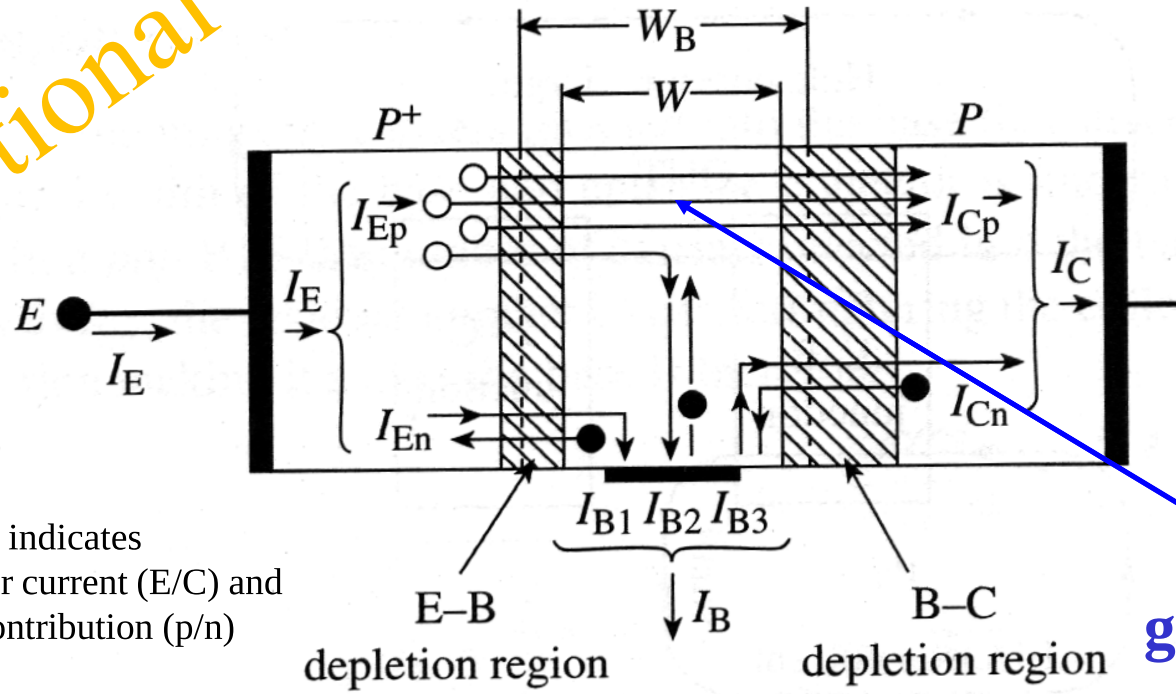
comparing (4) *and* (6)

$$\beta_{dc} = \frac{\alpha_{dc}}{1-\alpha_{dc}} \quad and \quad I_{CEo} = \frac{I_{CBo}}{1-\alpha_{dc}} \quad and \quad \beta_{dc} \cong \frac{I_C}{I_B}$$

Note: This slide refers to a pnp transistor

Bipolar Junction Transistor Fundamentals

Optional



Note: Subscript indicates emitter/collector current (E/C) and hole/electron contribution (p/n)

Neglecting recombination-generation means I_{Cp}~=I_{Ep}

$$I_E = I_{Ep} + I_{En}$$

$$I_C = I_{Cp} + I_{Cn}$$

Since emitter is more heavily doped than the base, $I_{En} << I_{Ep}$

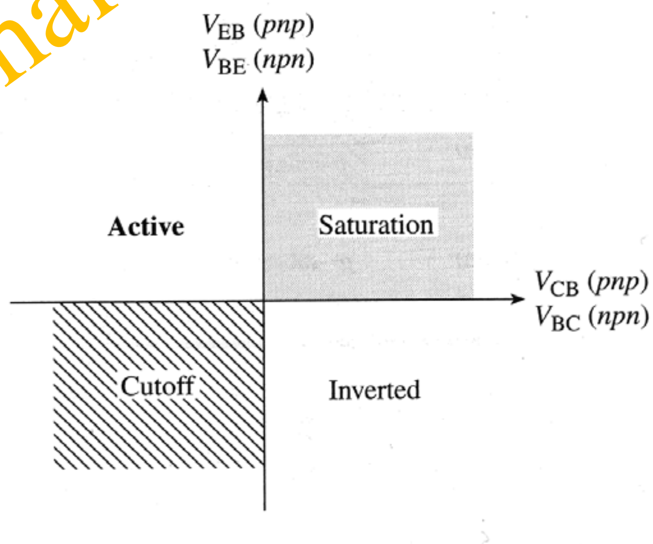
Since the base-collector junction is reverse biased, $I_{Cn} << I_{cp}$

I_C ~= I_E and ($I_B = I_E - I_C$) is small compared to I_C and I_E

Note: This slide refers to a pnp transistor

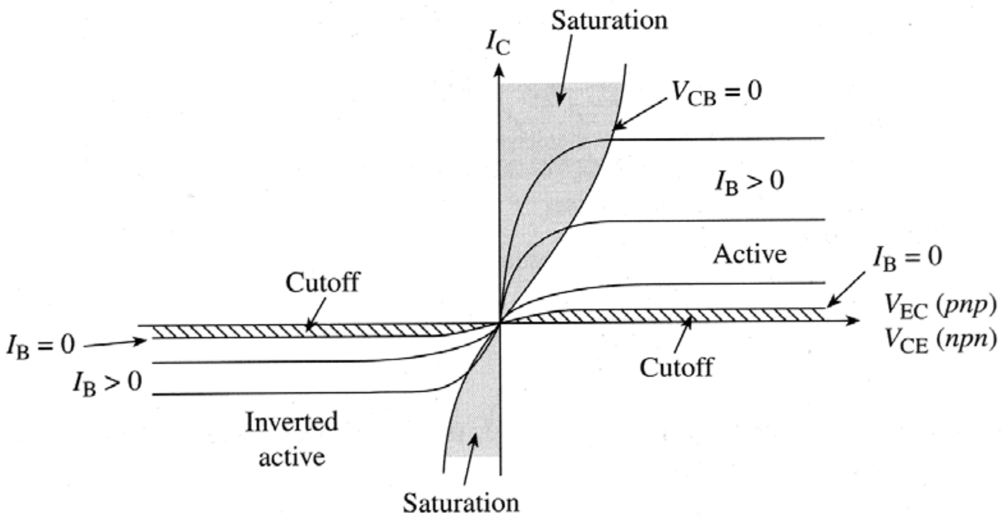
Bipolar Junction Transistor Fundamentals

Optional



(a)

- •Operational modes can be defined based on base-emitter voltages and base-collector voltages



(b)

- •When there is no base current, almost no collector current flows
- •When base current flows, a collector current can flow
- •The device is then a current controlled current device