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Lecture 21

Bipolar Transistors (Briefly)

A) Motivation and Diode Carriers
B) Bipolar Transistor Structure and Carrier Flow
C) Bipolar Transistor I vs. V
D) Bipolar Transistor Circuits

Reading: Schwarz and Oldham, pp. 499-509, 594-596

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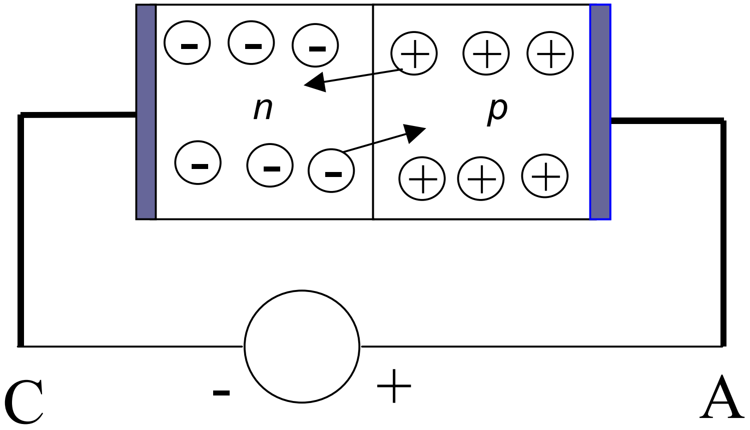
pn Junction Carrier Flow

Forward bias 0.7 V (positive on the p-side):

$N_D = 10^{20}/cm^3$ $N_A = 10^{18}/cm^3$



This is the direction of easy current flow. + charges flow to meet up with – charges. Essentially unlimited conduction.

Carriers types flowing are proportional to doping so see many more electrons than holes crossing the junction.

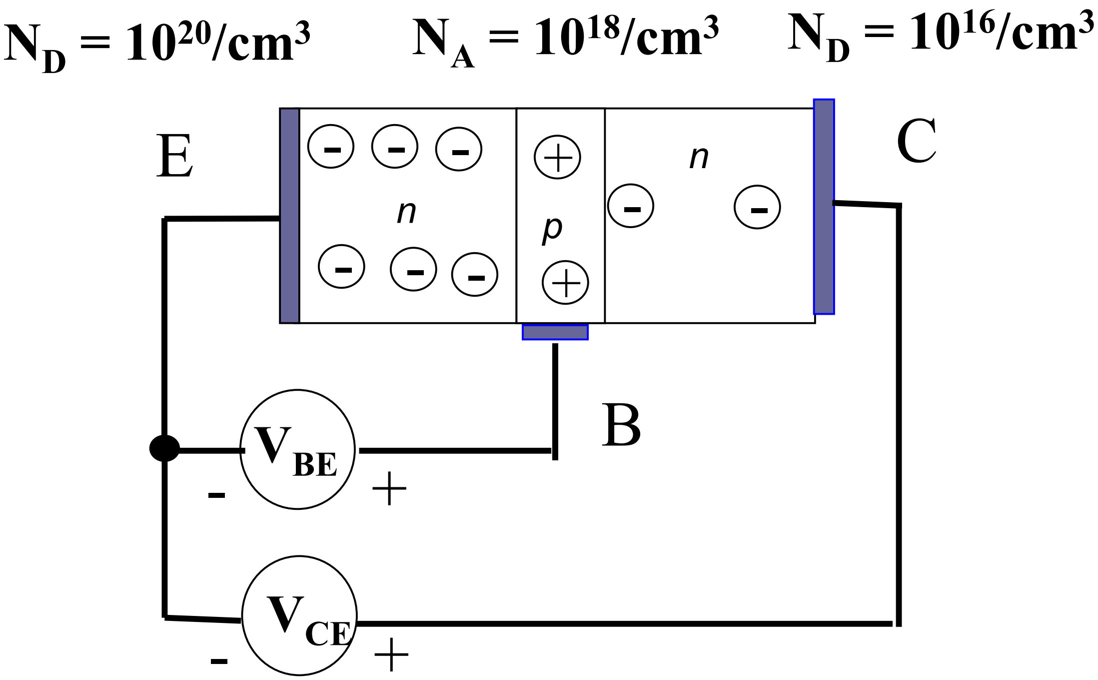
100 electrons => Forward direction

1 hole <= Reverse direction

After the carriers reach the other side of the junction they circle around a carrier of the opposite type and eventually recombine.

npn Bipolar Transistor Structure

$N_D = 10^{20}/cm^3$ $N_A = 10^{18}/cm^3$ $N_D = 10^{16}/cm^3$



Create a npn structure with decreasing doping levels.

Be sure that the base thinner than the electron diffusion length.

Raise collector voltage with respect to emitter so it is electrically asymmetrical and electrons will prefer collector over emitter.

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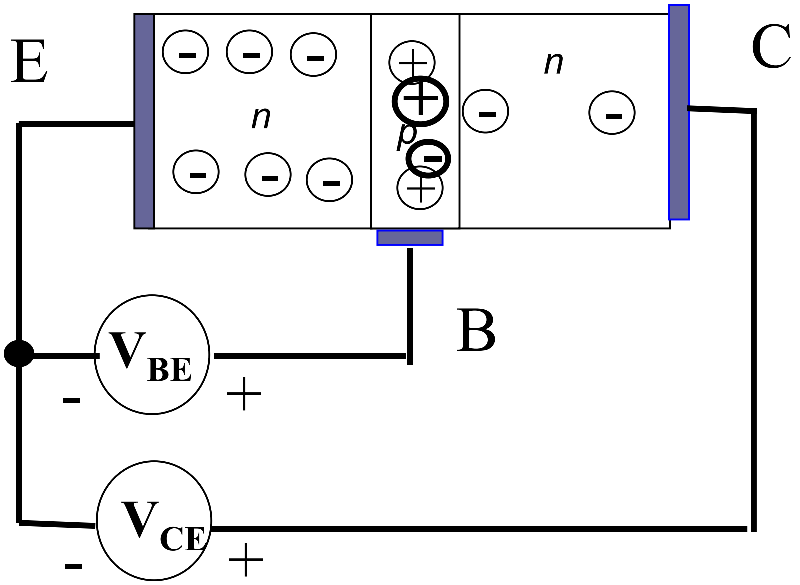
npn Bipolar Transistor Carrier Process



In a good npn transistor 149 electrons go into the collector for every one that recombines with a hole in the base. To accomplish this the base must be much narrower than the electron diffusion length.

Add an extra hole in base (by positive charge flowing into base lead).

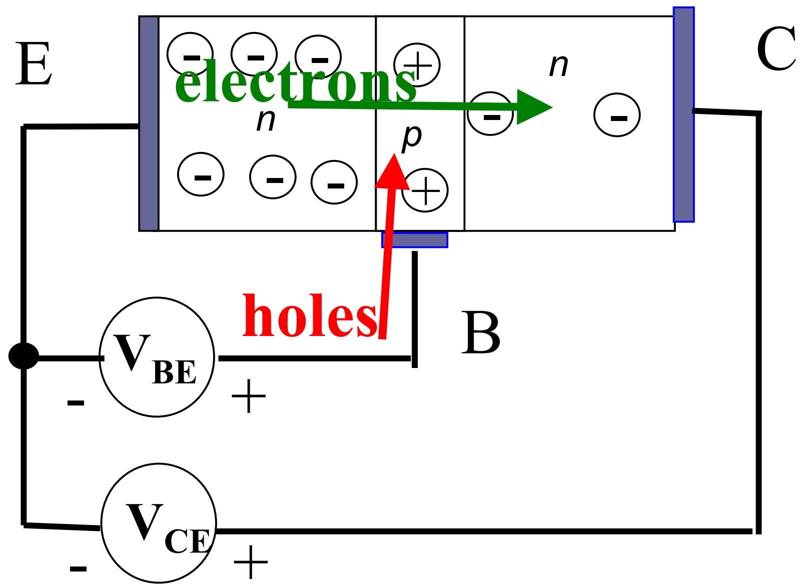
This attracts an electron from the emitter (emitter current).

The electron and hole circle about each other.

But if the electron gets too close to the collector the additional voltage on the collector sweeps it into the collector (current).

npn Bipolar Transistor Carrier Flow

$N_D = 10^{20}/cm^3$ $N_A = 10^{18}/cm^3$ $N_D = 10^{16}/cm^3$

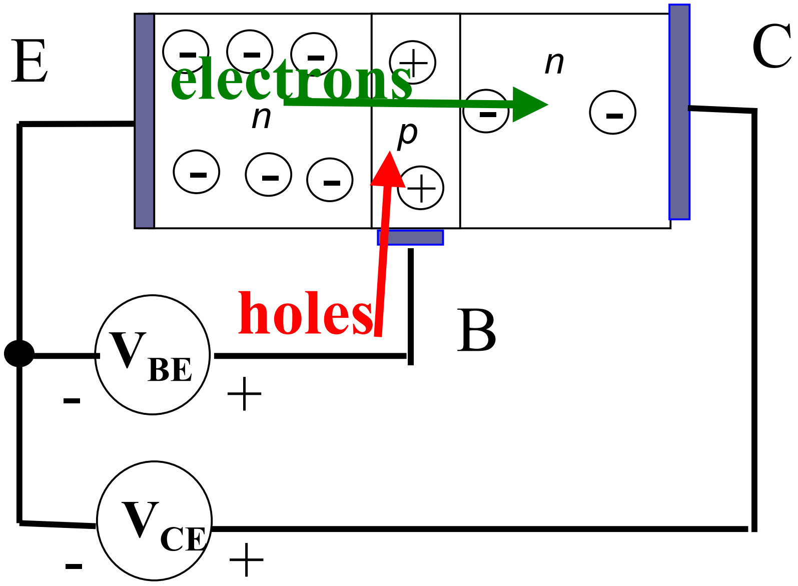


Gain mechanism: A hole in base attracts 150 electrons of which 149 go to collector and one recombines with the hole.

Extra loss mechanism: Like in a diode there is a small reverse flow (injection) of holes from the base into the emitter such as 10 out of every 100 holes.

npn Bipolar Transistor Gain

$N_D = 10^{20}/\text{cm}^3$ $N_A = 10^{18}/\text{cm}^3$ $N_D = 10^{16}/\text{cm}^3$



100 holes into base.

10 lost to emitter leaving 90 to attract electrons.

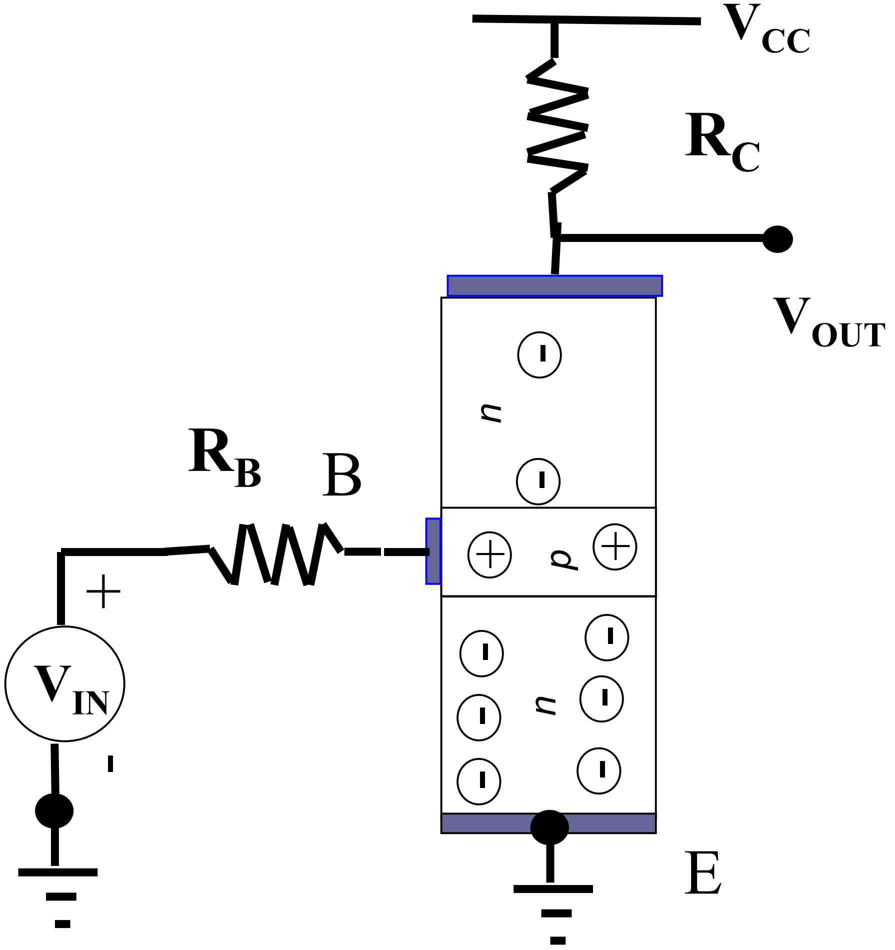
Each of the 90 attracts 149 or 13,410 electrons that reach collector.

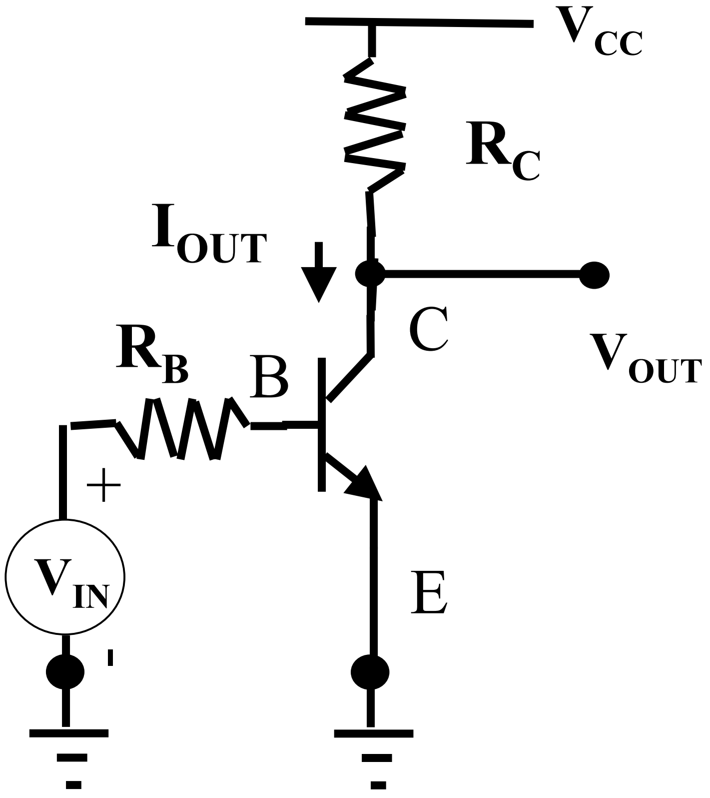
$$\beta = (I_C/I_B) = (13{,}410)/(10+90) = 134$$

$$\alpha = (I_C/I_E) = (13{,}410)/(13{,}4010+10+90) = 0.9926$$

Note that since $I_E = I_C + I_B$, α and β are related by $\beta = \alpha/(1-\alpha)$

npn Bipolar Transistor Circuit





We need a model for the base and model for I_{OUT} versus V_{OUT} collector side of the bipolar transistor.

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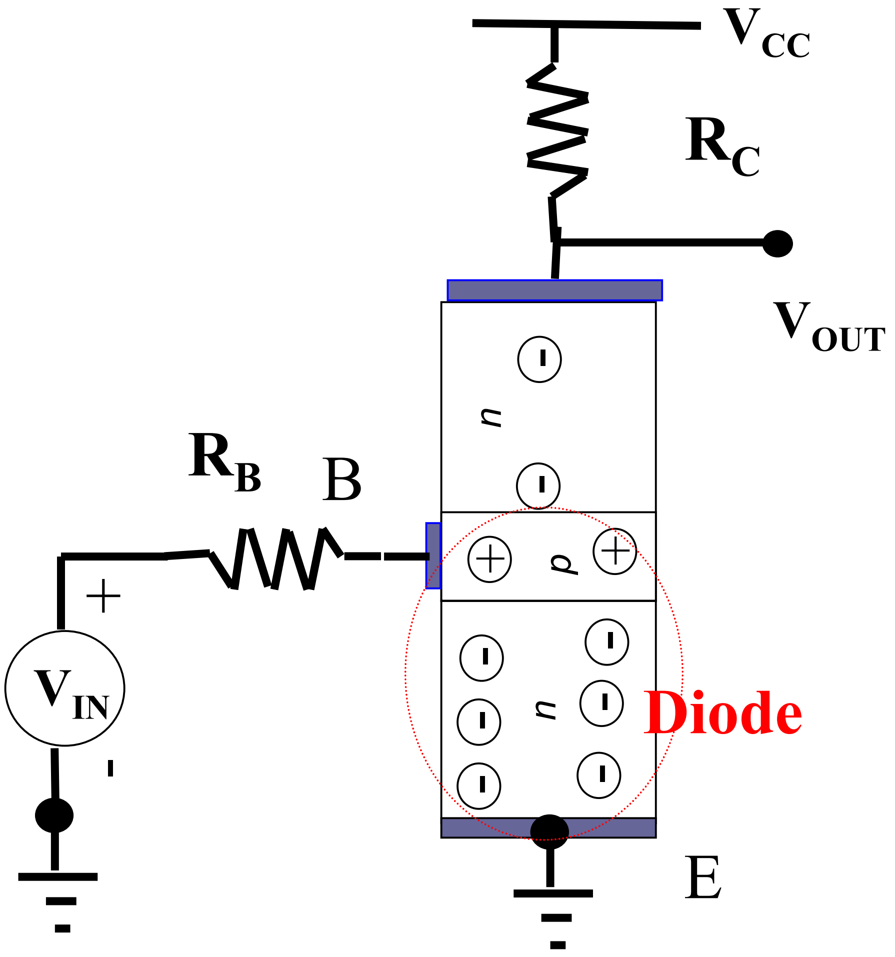
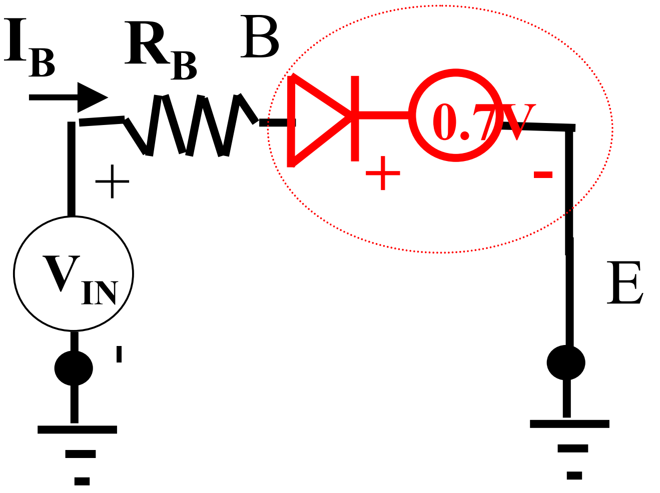
npn Bipolar Transistor: Base Circuit Model

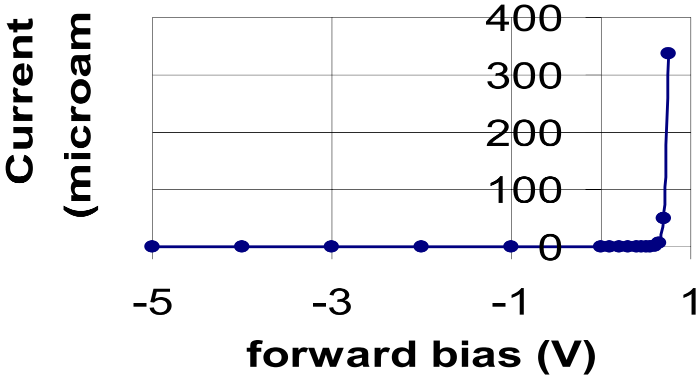


Large Signal Diode Model

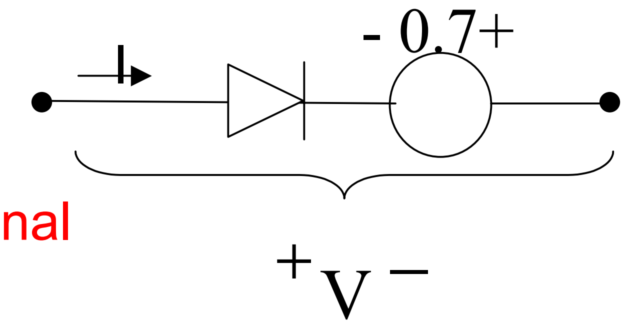


The base-emitter is modeled as a large signal diode.

DIODE I-V CHARACTERISTICS AND MODELS

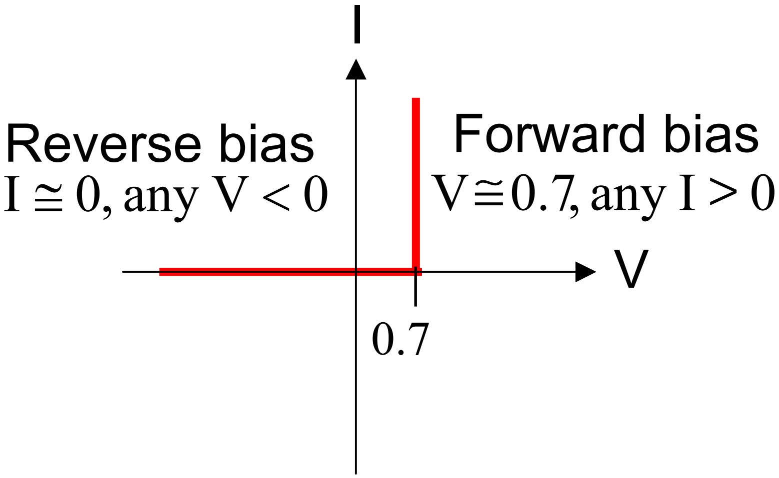


The Large-Signal Diode Model



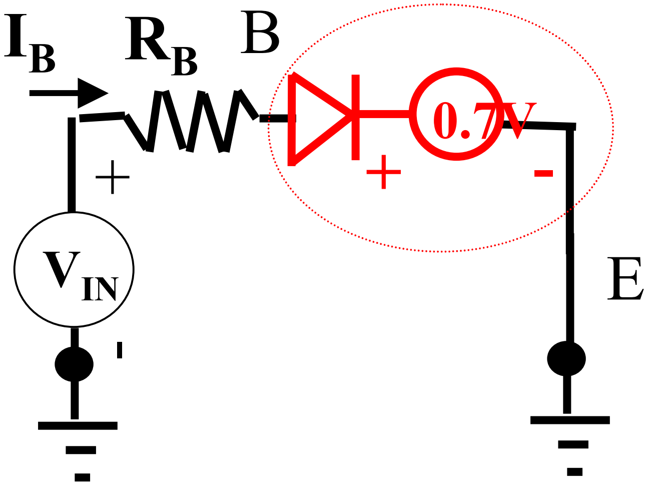
Improved “Large-Signal Diode” Model:

If we choose not to ignore the small forward-bias voltage drop of a diode, it is a very good approximation to regard the voltage drop in forward bias as a constant, about 0.7V. the “Large signal model” results.



npn Bipolar Transistor: Base Circuit Analysis

Large Signal
Diode Model



Cutoff

$V_{BE} < 0.7V \Rightarrow I_B = 0$

On

$V_{BE} = 0.7V$

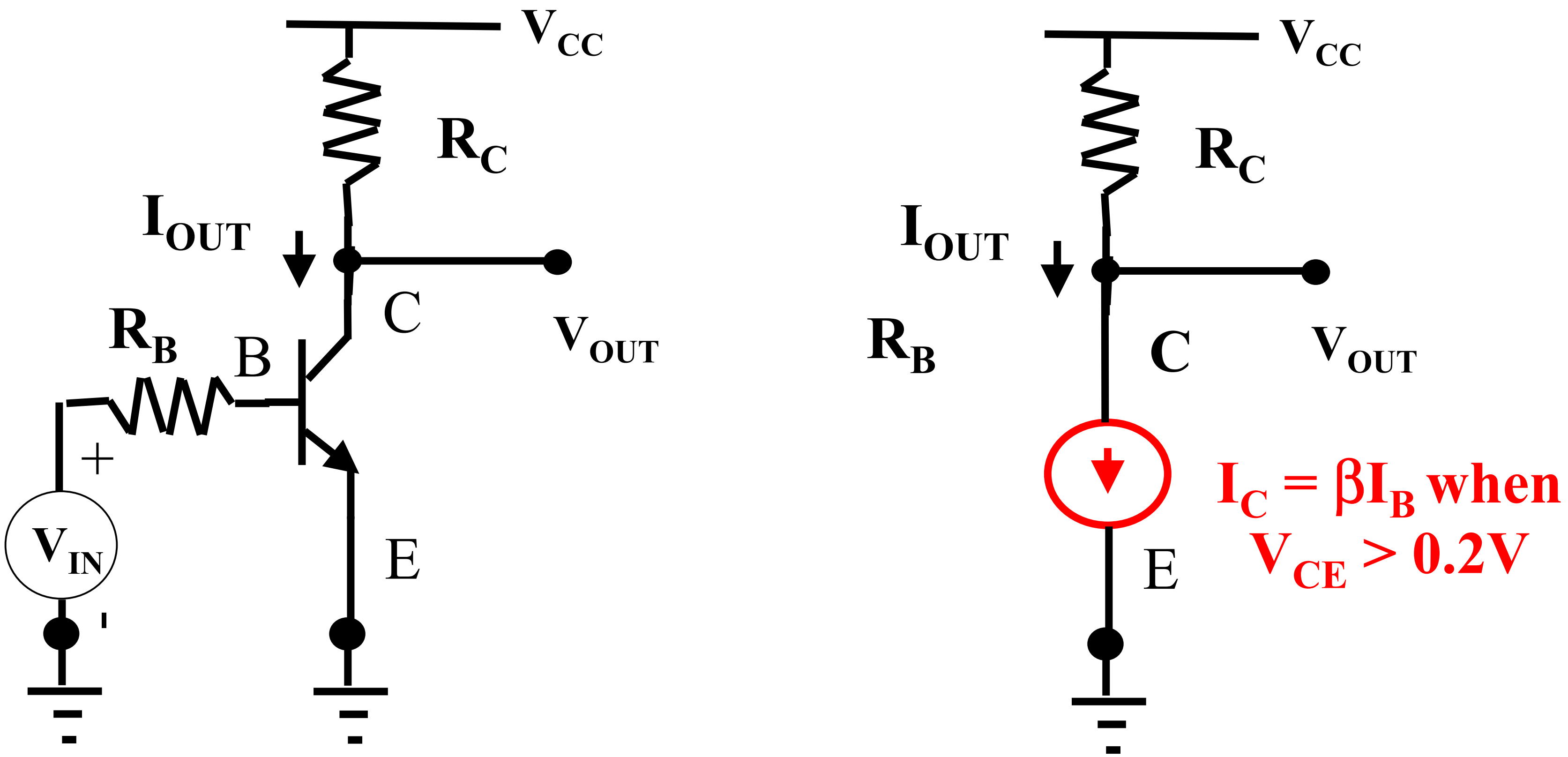
$I_B = (V_{IN} - 0.7V)/R_B$

Example: $V_{IN} = 2.5V$, $R_B = 10k\Omega$

$I_B = (2.5V - 0.7V)/10k\Omega = 180\ \mu A$

The base circuit analysis is the same as that for a diode.

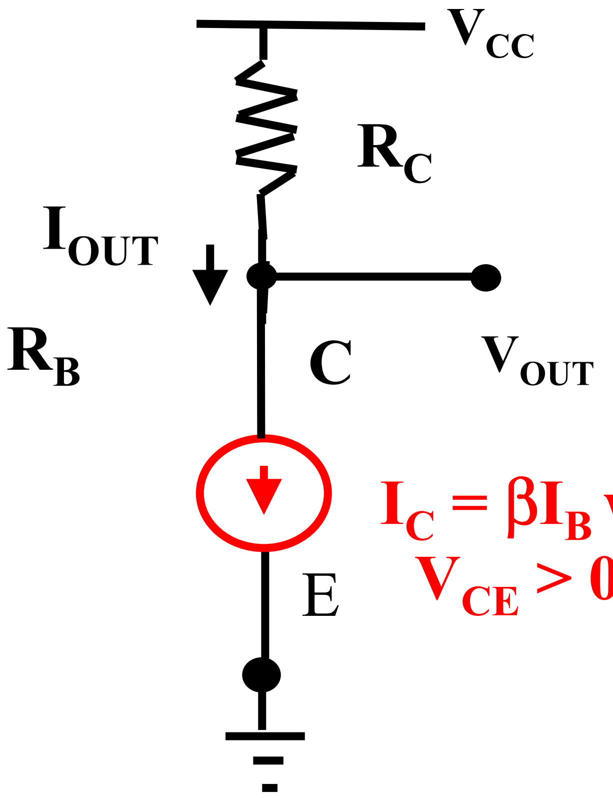
npn Bipolar Transistor: Collector Circuit Model



$I_C = \beta I_B$ when $V_{CE} > 0.2V$

The collector current is programmed by the base current to be β times the base current. However, the current stops growing larger whenever the collector base voltage drops to 0.2V.

npn Bipolar Transistor: Collector Circuit Analysis



$I_C = \beta I_B$ when $V_{CE} > 0.2V$

Cutoff: $V_{BE} < 0.7V$

$I_B = I_C = 0$

Forward Active: $V_{BE} = 0.7V$ and $V_{CE} > V_{CE\text{-}SAT} = 0.2V$

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

$I_C = \beta I_B$

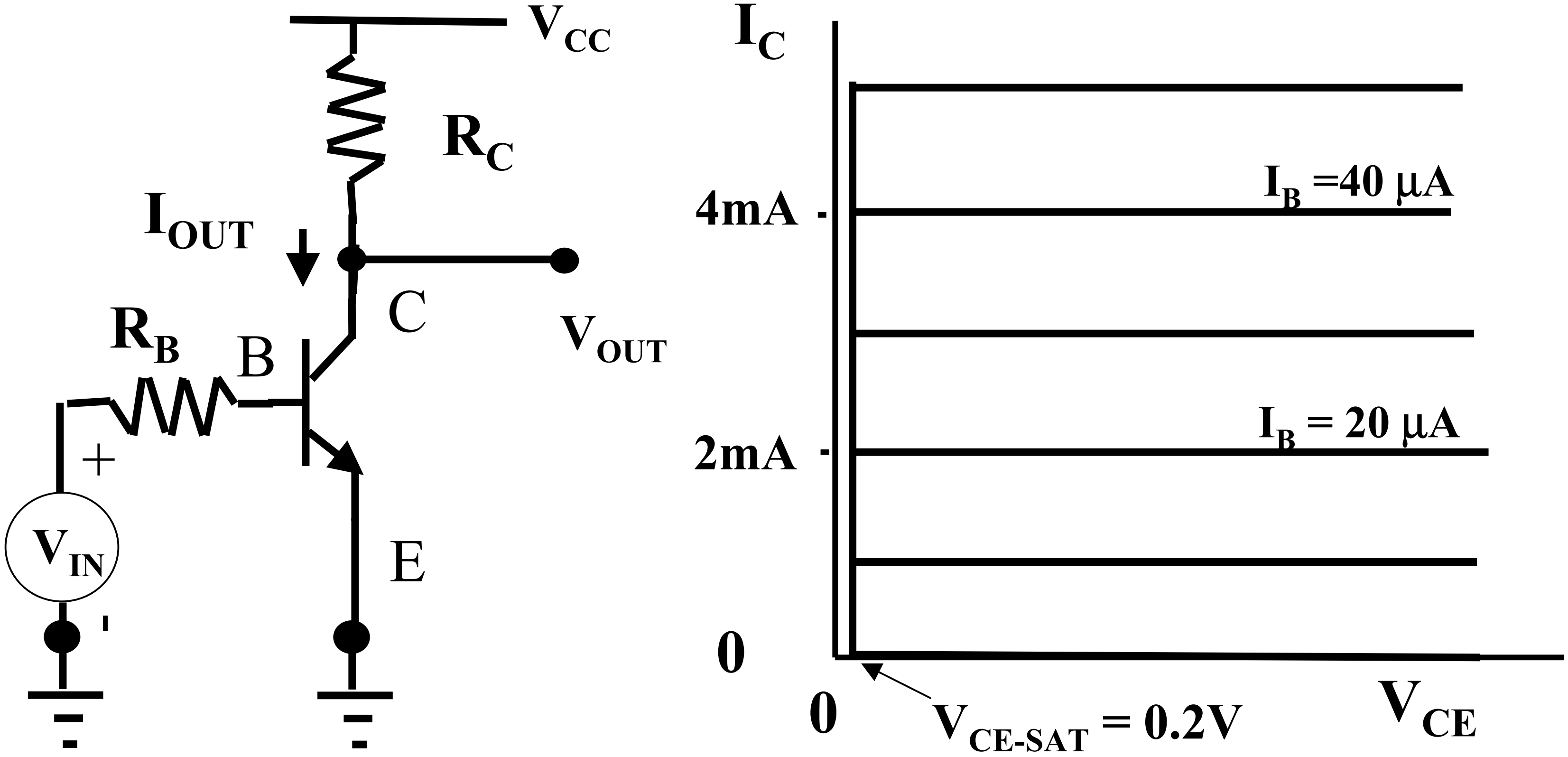
Saturated: $V_{BE} = 0.7V$ and $V_{CE} = V_{CE\text{-}SAT} = 0.2V$

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

$I_{C\text{-}SAT} = (V_{CC} - 0.2V)/R_C$

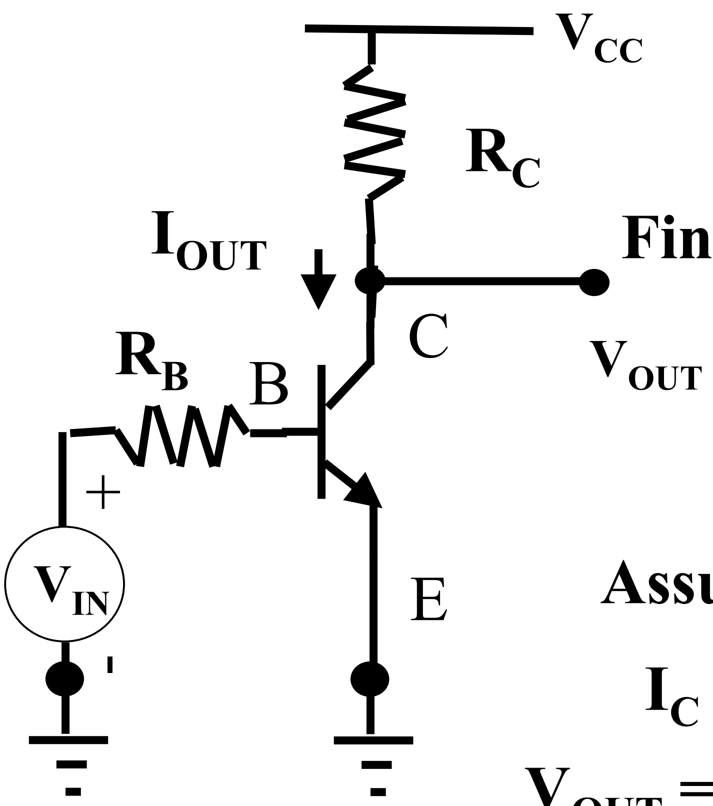
The collector current is programmed by the base current to be β times the base current. However, the current stops growing larger whenever the collector base voltage drops to 0.2V.

npn Bipolar Transistor: I_C vs. V_{CE} Graph



The I_C versus V_{CE} graph for the first order model is a set of horizontal lines with heights β times I_B. Loadline techniques can easily be applied.

npn Bipolar Transistor: Example Circuit



$\beta = 100$ $R_B = 10k\Omega$

$R_C = 1k\Omega$ $V_{CC} = 5V$

Find V_{OUT} when V_{IN} =1.0V using equations.

$V_{IN} > 0.7\ V \Rightarrow$ ON

$I_B = (1.0V - 0.7V)/10k\Omega = 30\ \mu A$

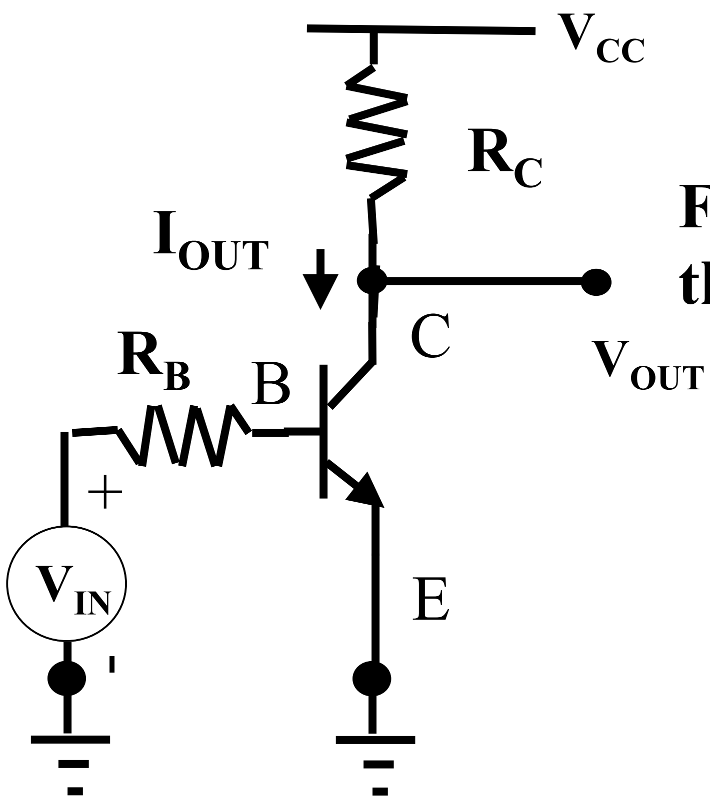
Assume Forward Active

$I_C = (100)(30\ \mu A) = 3\ mA$

$V_{OUT} = V_{CC} - I_C R_C = (5V - 3mA)(1k\Omega) = 2V$

Check Assumption : $V_{CE} = 2.0V - 0V = 2V > 0.2V \Rightarrow$ Forward Active

npn Bipolar Transistor: Maximum Current



$\beta = 100$ $R_B = 10k\Omega$

$R_C = 1k\Omega$ $V_{CC} = 5V$

Find the maximum collector current and the input voltage at which it occurs.

Assume Edge of Saturation where still Forward Active

$$I_C = (V_{CC} - V_{CE\text{-}SAT})/R_C$$
$$= (5V - 0.2V)/1k\Omega = 4.8\text{ mA}$$

$$I_B = I_C/\beta = 4.8\text{mA}/100 = 48\ \mu A$$

$$V_{IN} = I_B R_B + 0.7V = (48\ \mu A)(1k\Omega) + 0.7V = 1.18V$$

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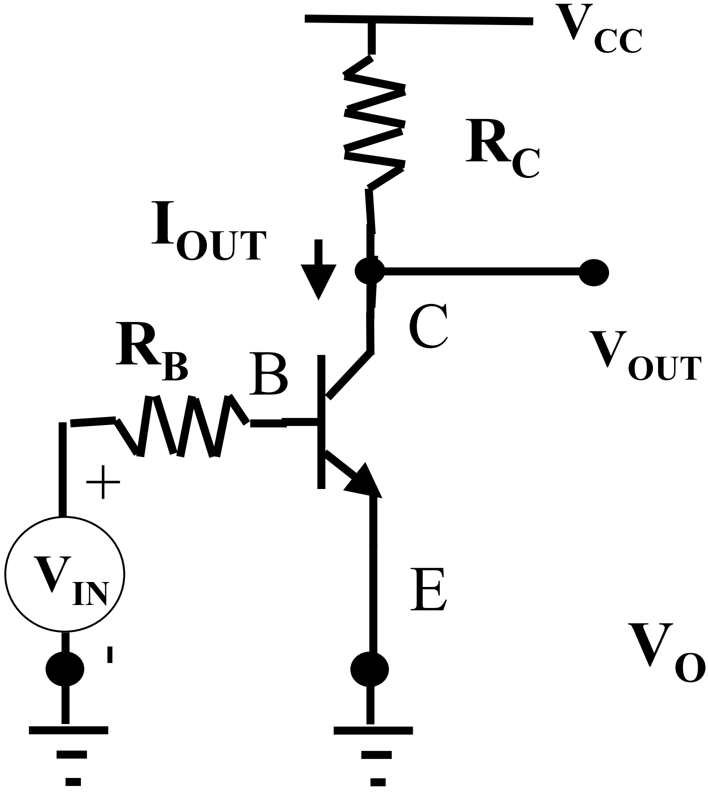
npn Bipolar Transistor: V_{OUT} vs. V_{IN}



$\beta = 100$ $R_B = 10k\Omega$

$R_C = 1k\Omega$ $V_{CC} = 5V$

1) V_{OUT} is V_{CC} till V_{IN} reaches 0.7V

2) V_{OUT} decreases linearly with V_{IN} until V_{OUT} reaches 0.2V at V_{IN} = 1.18V

3) V_{OUT} remains at 0.2 V for all values of V_{IN} above 1.18V