Bipolar Junction Transistors: Part 1

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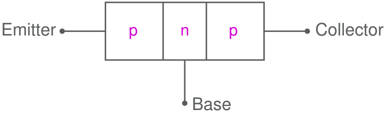
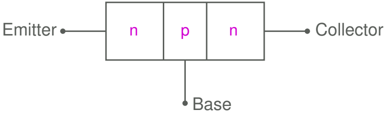
Bipolar Junction Transistors



pnp transistor



npn transistor

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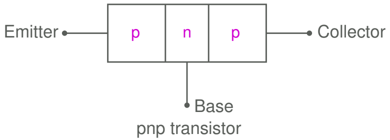

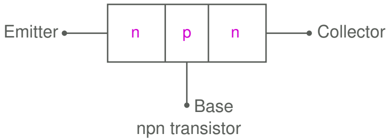

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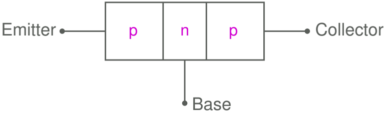

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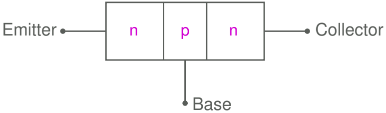

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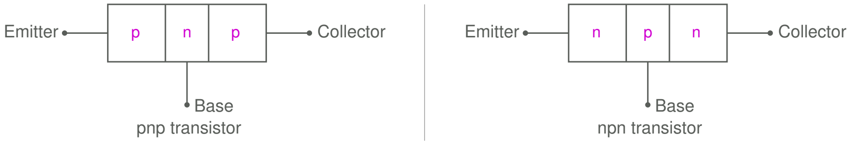

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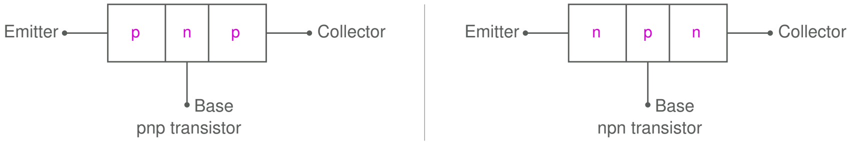

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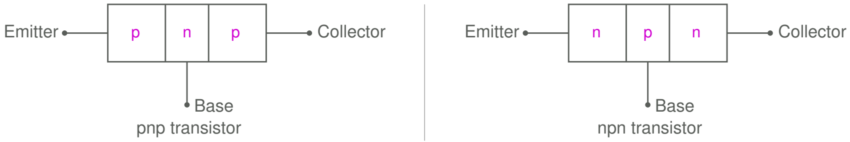

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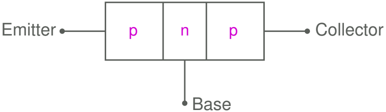

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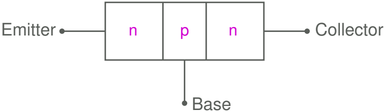

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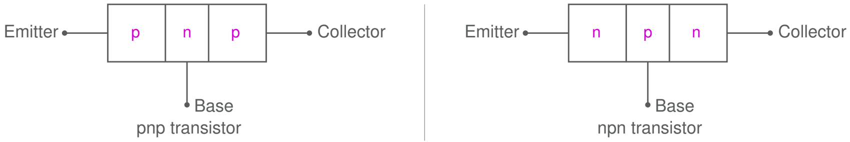

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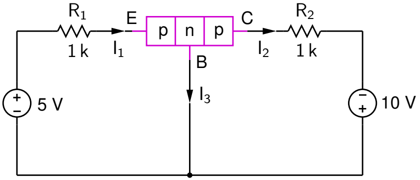
  WRONG! Let us see why.

Consider a *pnp* BJT in the following circuit:



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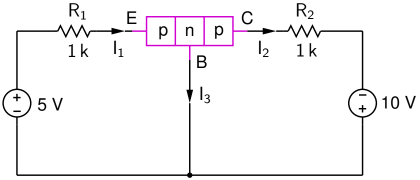

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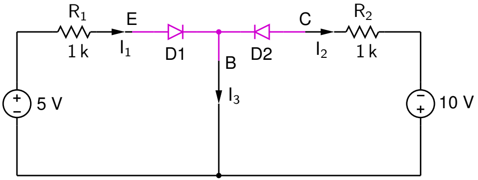

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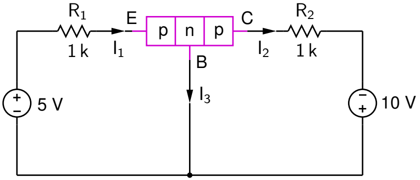

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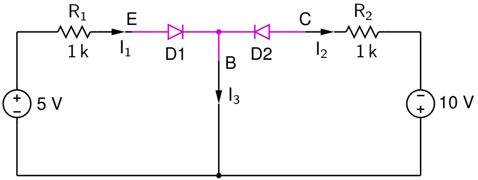
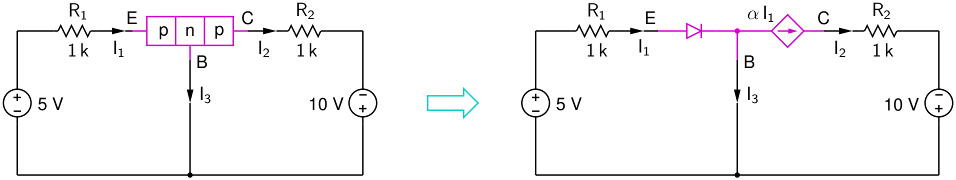


Assuming $V_{\text{on}} = 0.7\ V$ for D1, we get

$I_1 = \dfrac{5\ V - 0.7\ V}{R_1} = 4.3\ \text{m}A$,

$I_2 = 0$ (since D2 is reverse biased), and $I_3 \approx I_1 = 4.3\ \text{m}A$.

Using a more realistic equivalent circuit for the BJT, we obtain,



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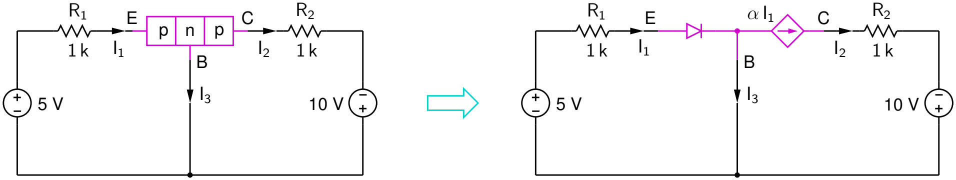

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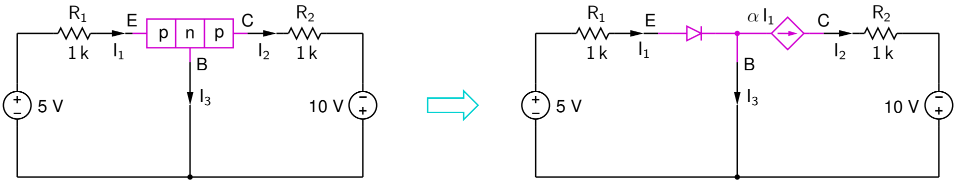

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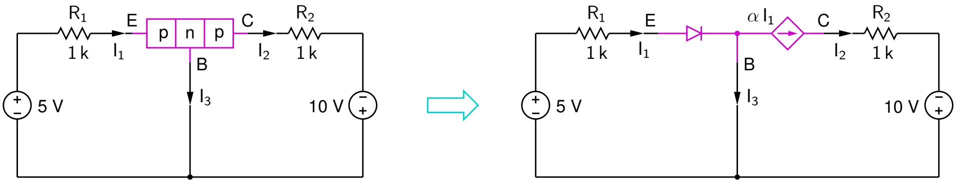

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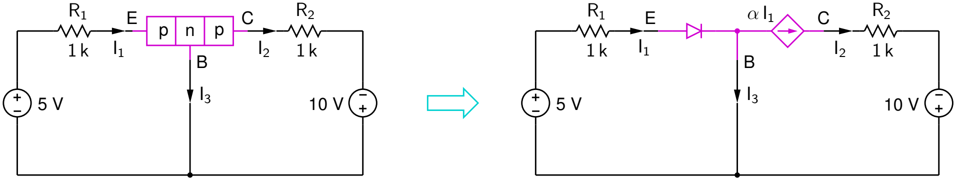

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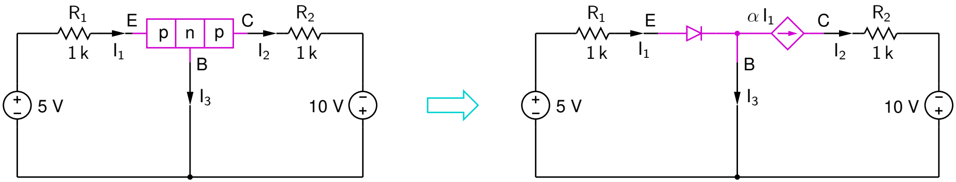

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Conclusion: A BJT is NOT the same as two diodes connected back-to-back (although it does have two *p*-*n* junctions).

What is wrong with the two-diode model of a BJT?

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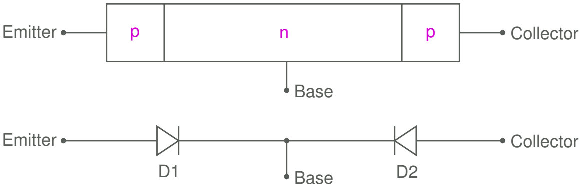

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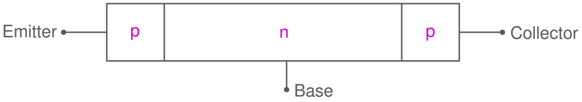
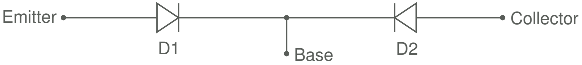
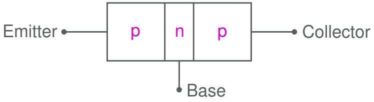




* However, in a BJT, exactly the opposite is true. For a higher performance, the base region is made as short as possible, and the two diodes cannot be treated as independent devices.



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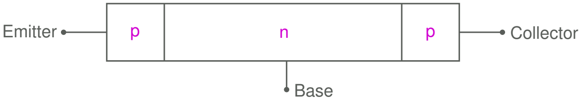

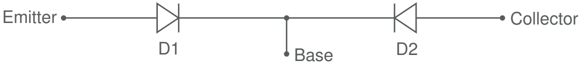

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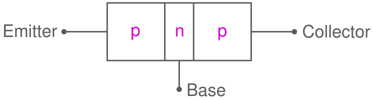
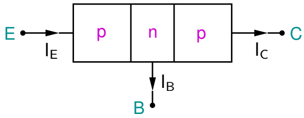
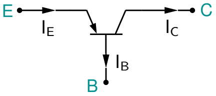
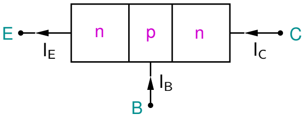


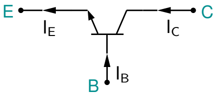
* Later, we will look at the "Ebers-Moll model" of a BJT, which is a fairly accurate representation of the transistor action.

BJT in active mode









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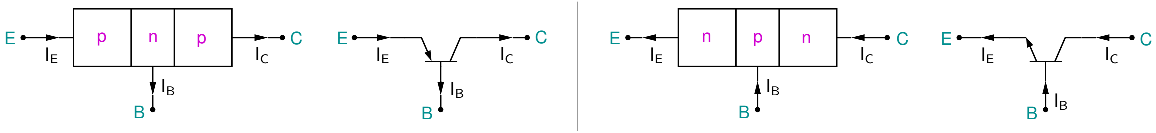

* In the active mode of a BJT, the B-E junction is under forward bias, and the B-C junction is under reverse bias.
  - For a *pnp* transistor, $V_{EB} > 0\ V$, and $V_{CB} < 0\ V$.
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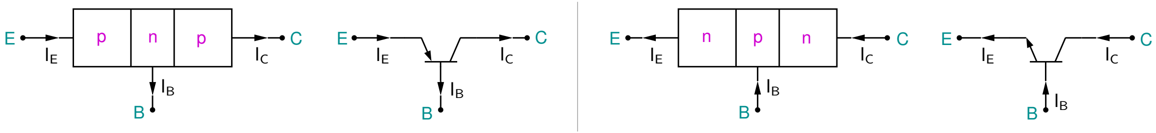

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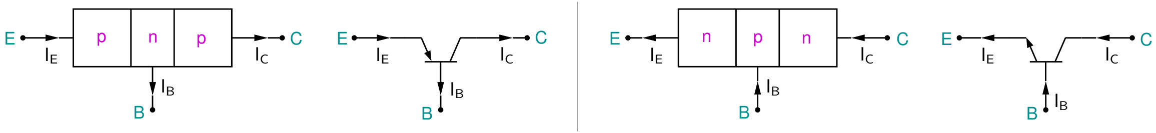

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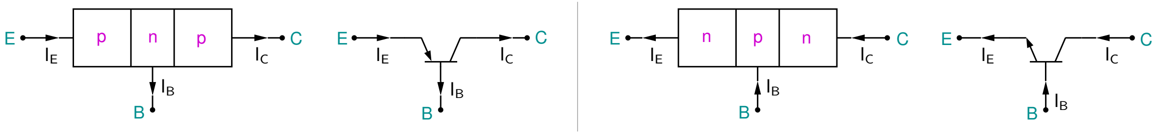

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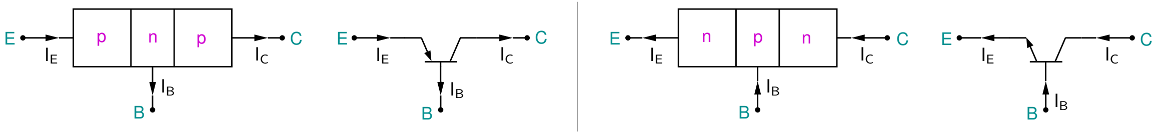

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* Analog circuits, including amplifiers, are generally designed to ensure that the BJTs are operating in the active mode.

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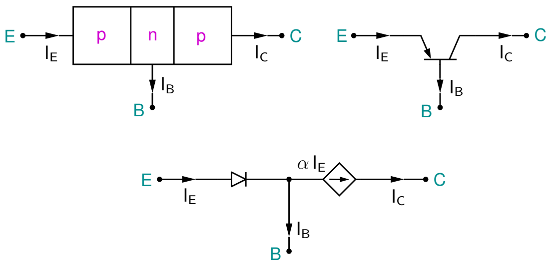

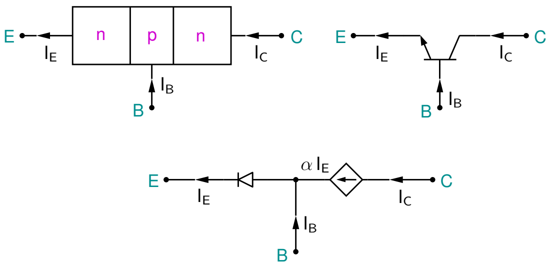

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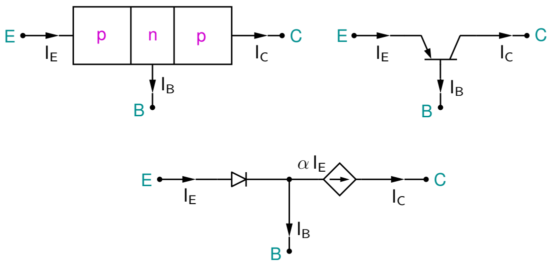

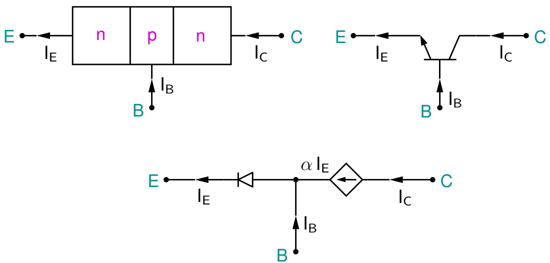

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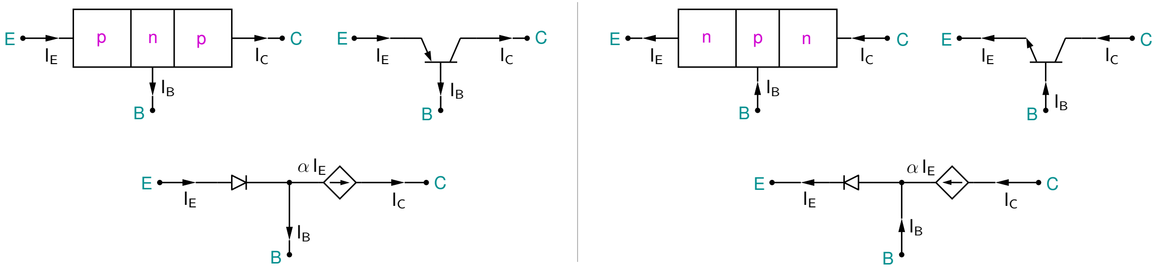

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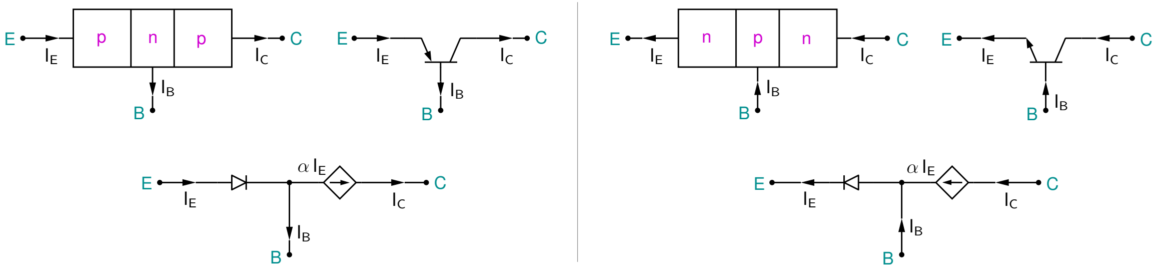

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$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}\,.$$

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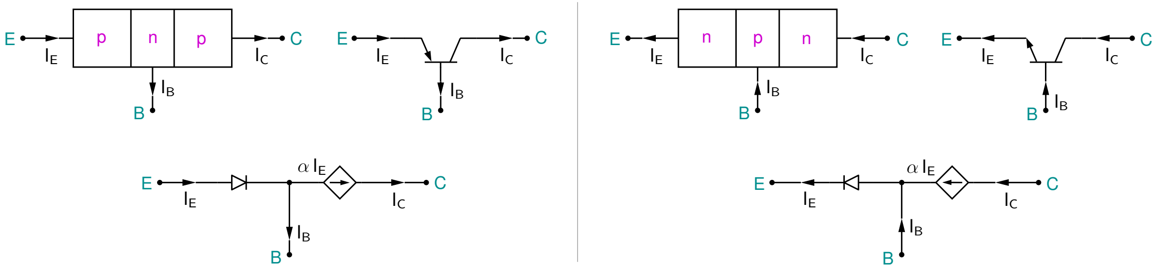

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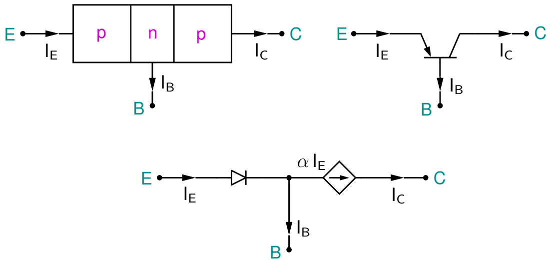
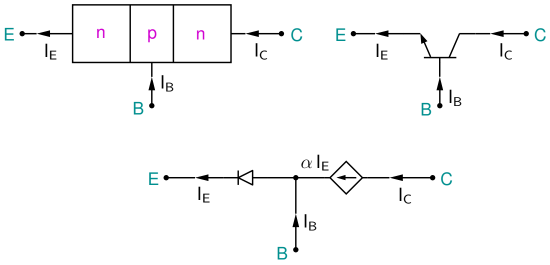
  $$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}\,.$$
* β is a function of I_C and temperature. However, we will generally treat it as a constant, a useful approximation to simplify things and still get a good insight.

BJT in active mode





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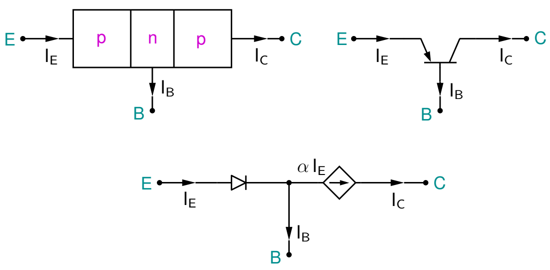

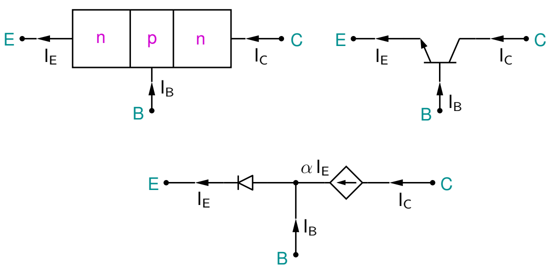

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

α	β
0.9	9
0.95	19
0.99	99
0.995	199

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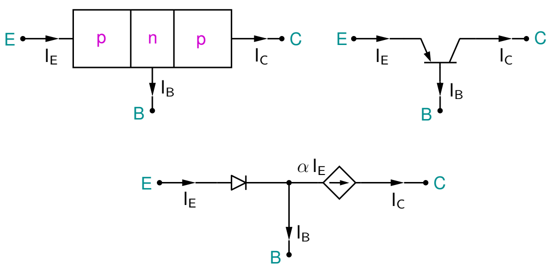

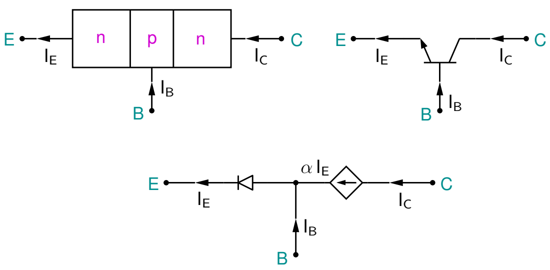

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* β increases substantially as $\alpha \rightarrow 1$.

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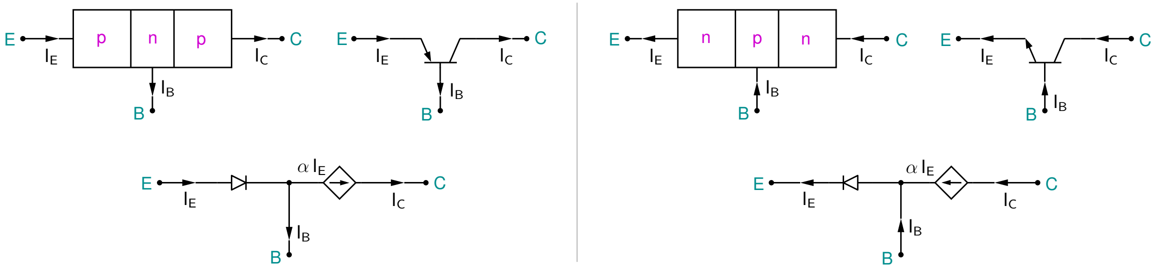

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* Transistors are generally designed to get a high value of β (typically 100 to 250, but can be as high as 2000 for "super-β" transistors).

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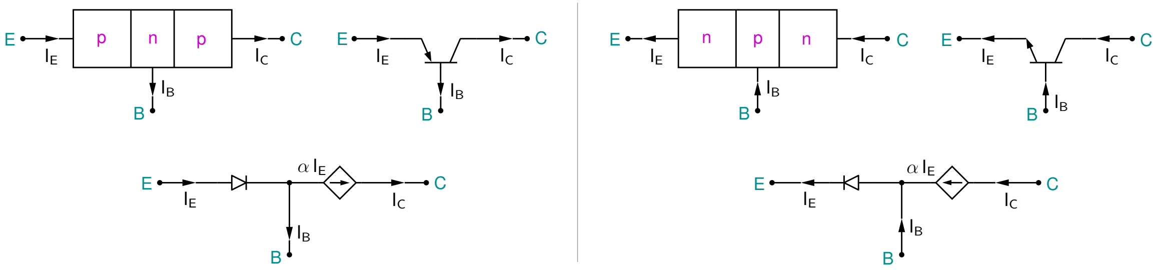

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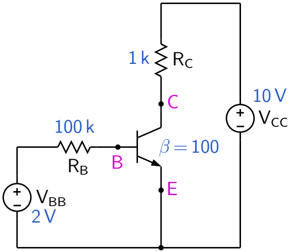
* β increases substantially as $\alpha \rightarrow 1$.
* Transistors are generally designed to get a high value of β (typically 100 to 250, but can be as high as 2000 for "super-β" transistors).
* A large $\beta \Rightarrow I_B \ll I_C$ or I_E when the transistor is in the active mode.

A simple BJT circuit



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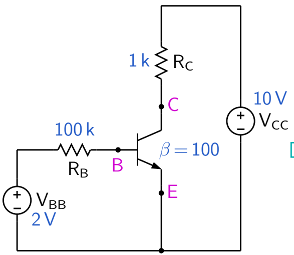

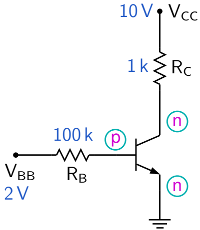

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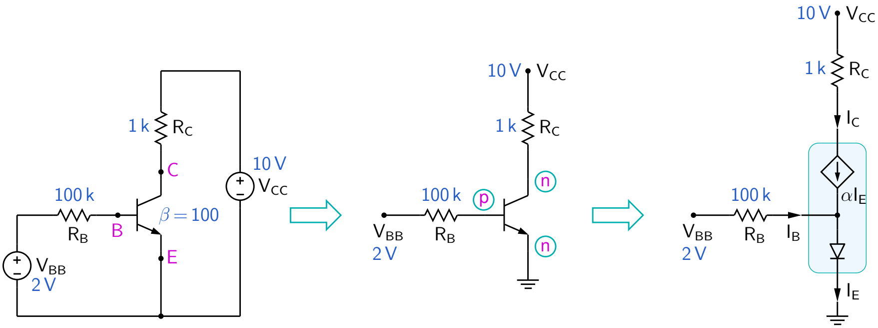

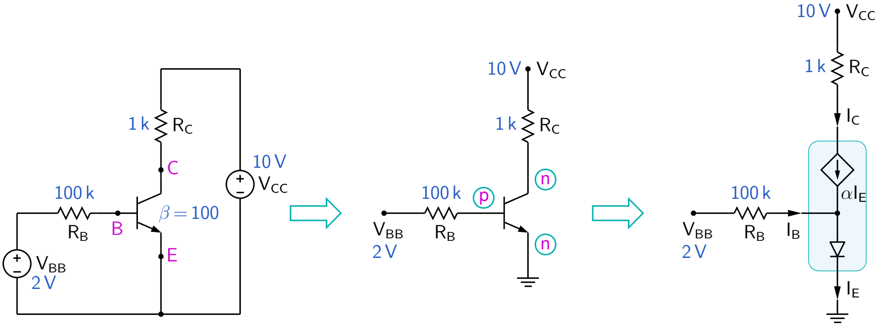

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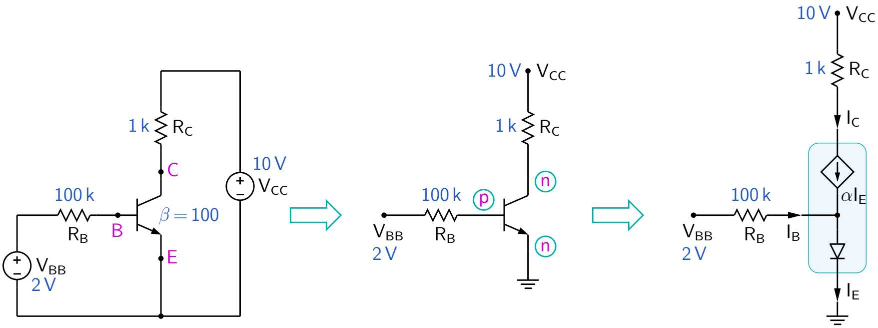

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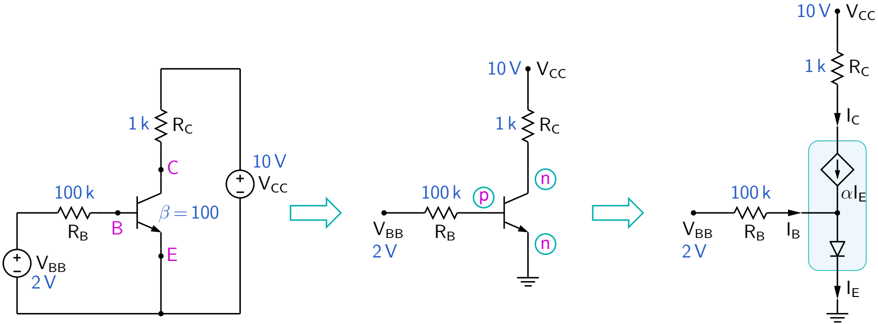

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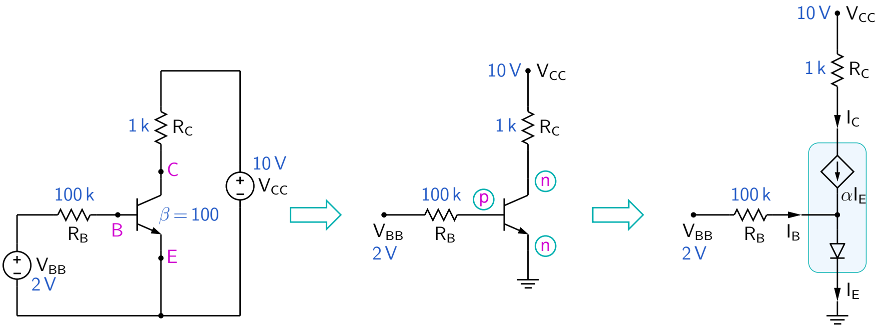

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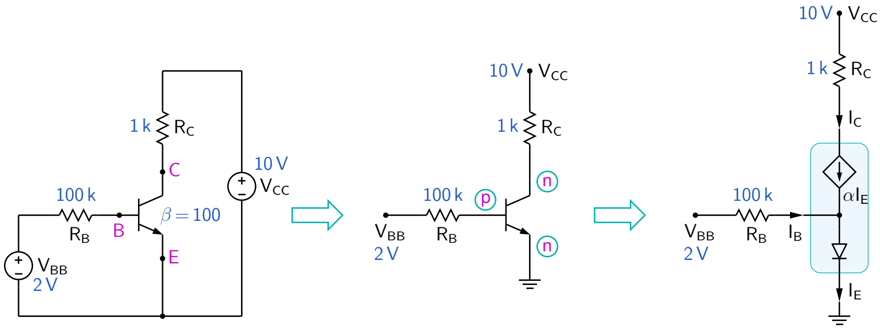

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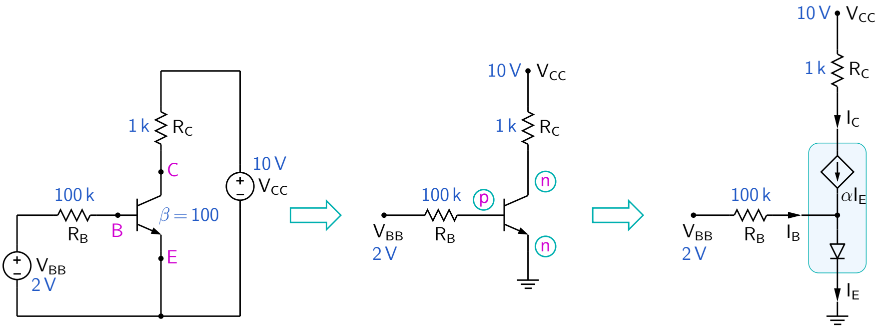
Let us check whether our assumption of active mode is correct. We need to check whether the B-C junction is under reverse bias.

A simple BJT circuit



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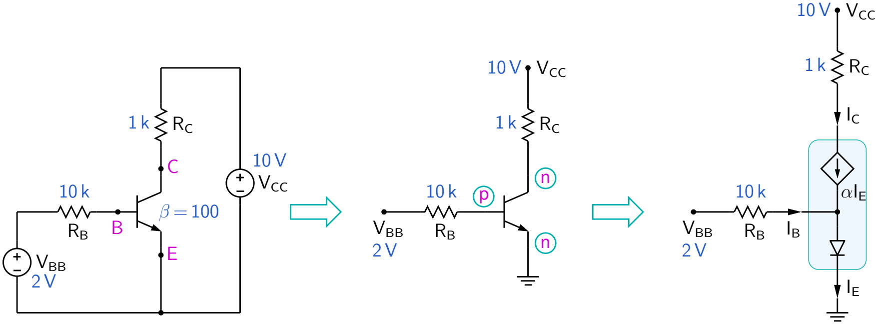
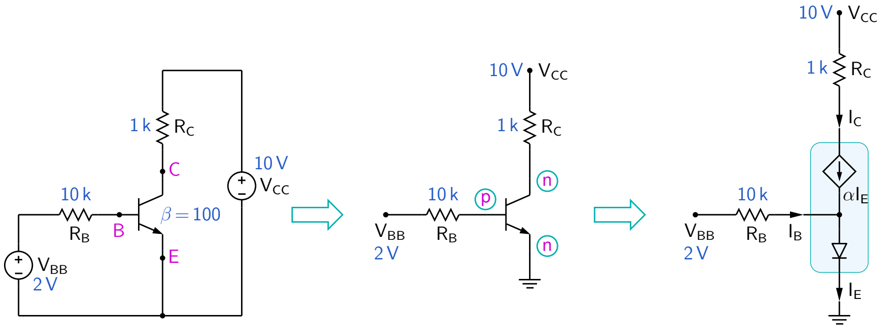
$V_{BC} = V_B - V_C = 0.7\ V - 8.7\ V = -8.0\ V$,

i.e., the B-C junction is indeed under reverse bias.

A simple BJT circuit: continued



What happens if R_B is changed from 100 k to 10 k?



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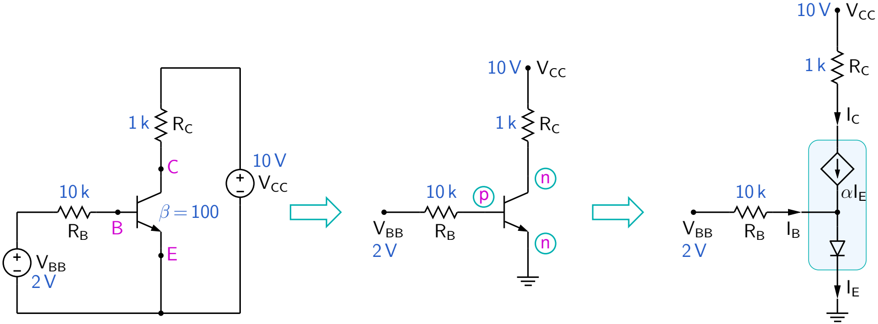

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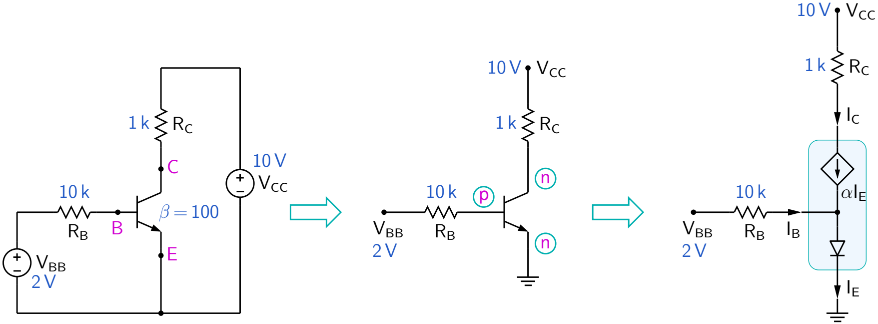

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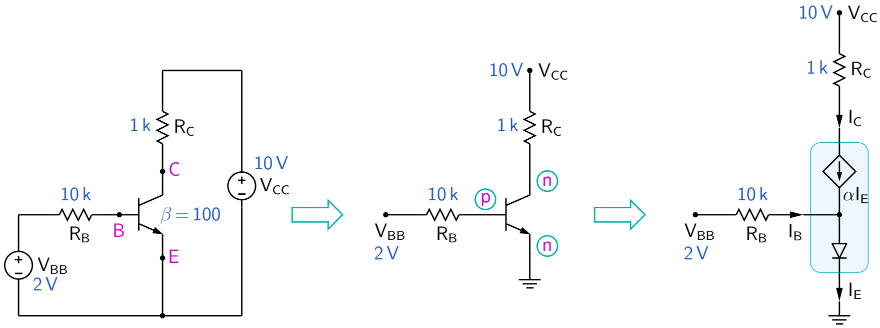

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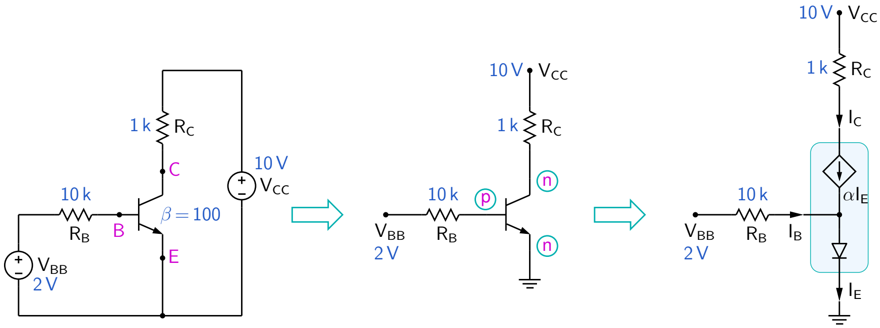

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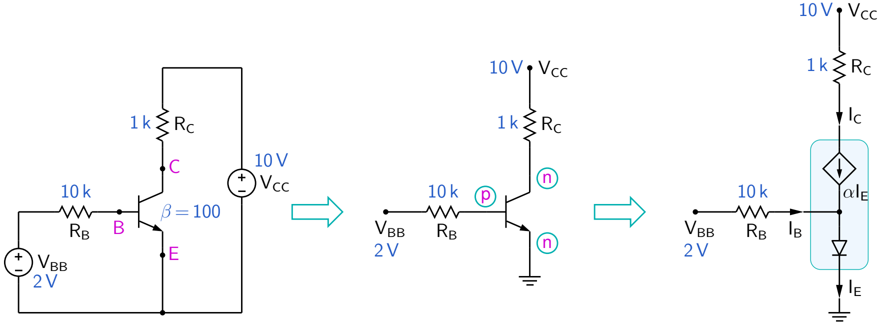

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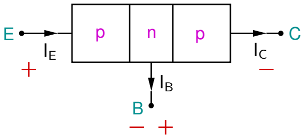
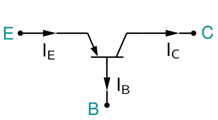
V_{BC} is not only positive, it is *huge*!

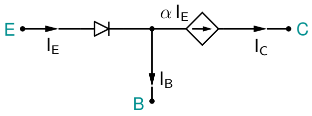
$\rightarrow$ The BJT cannot be in the active mode, and we need to take another look at the circuit.

Ebers-Moll model for a *pnp* transistor

Active mode ("forward" active mode): B-E in f.b. B-C in r.b.







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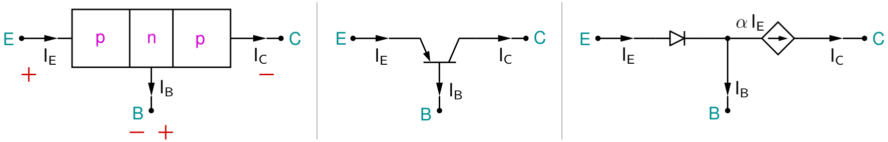

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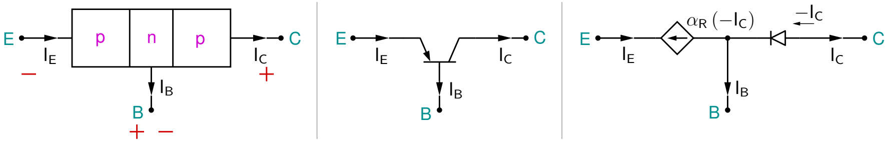

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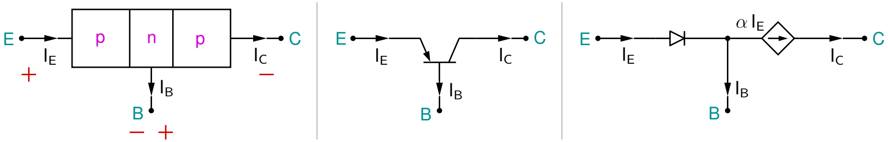

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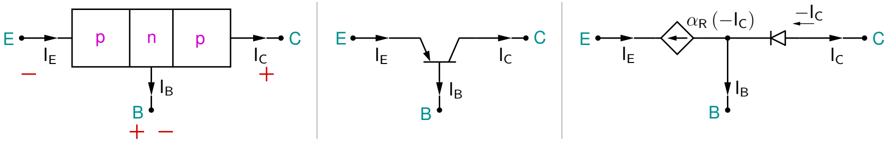

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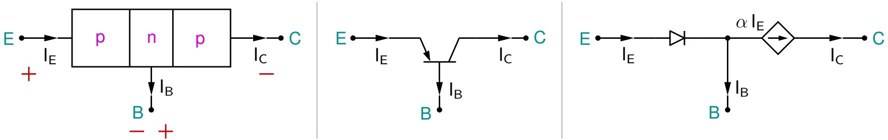

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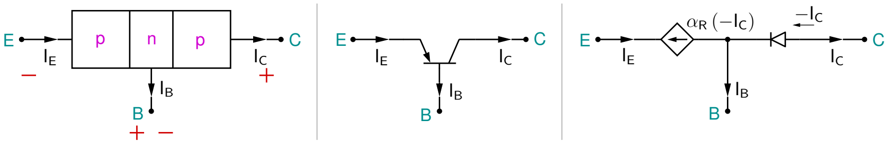

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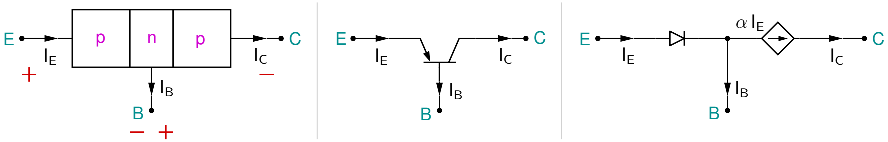

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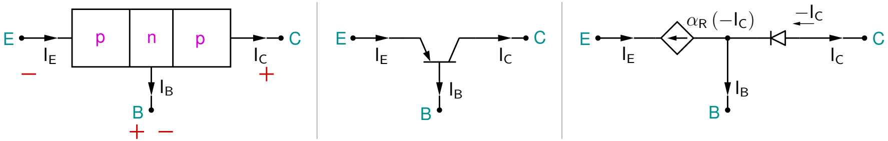

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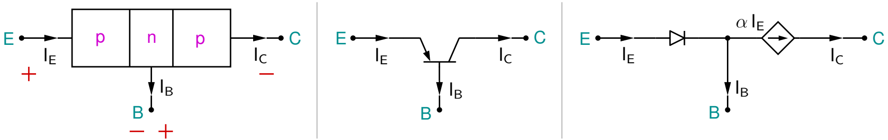

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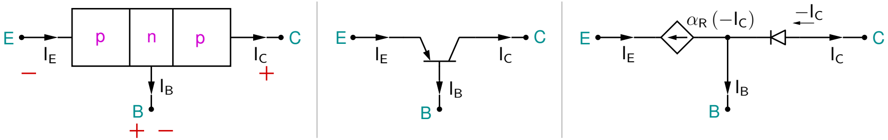

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M. B. Patil, IIT Bombay

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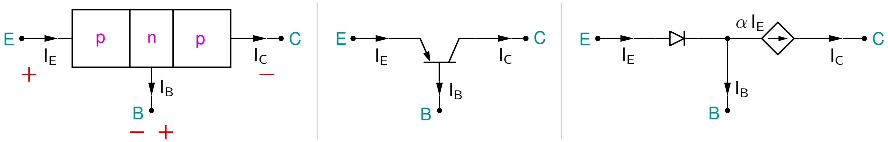

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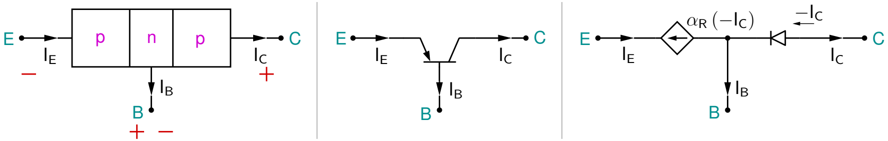

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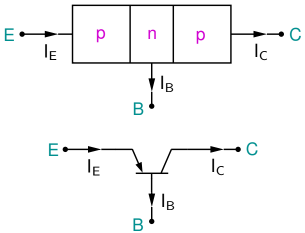
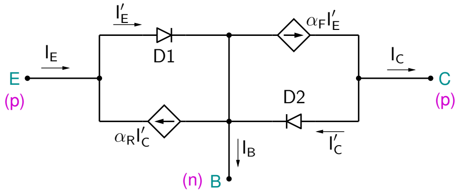
In amplifiers, the BJT is biased in the forward active mode (simply called the "active mode") in order to make use of the higher value of β in that mode.

The Ebers-Moll model combines the forward and reverse operations of a BJT in a single comprehensive model.





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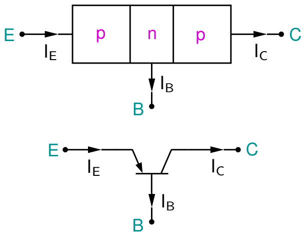
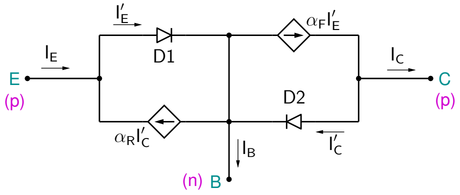


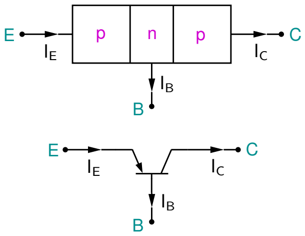


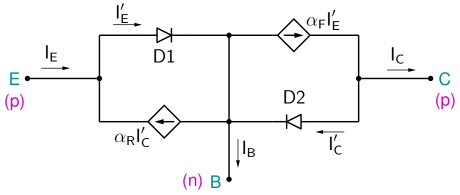
The currents I'_E and I'_C are given by the Shockley diode equation:

$$I'_E = I_{ES} \left[\exp\left(\frac{V_{EB}}{V_T}\right) - 1 \right], \quad I'_C = I_{CS} \left[\exp\left(\frac{V_{CB}}{V_T}\right) - 1 \right].$$

Ebers-Moll model for a *pnp* transistor

The Ebers-Moll model combines the forward and reverse operations of a BJT in a single comprehensive model.





The currents I'_E and I'_C are given by the Shockley diode equation:

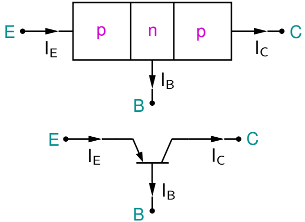
$$I'_E = I_{ES}\left[\exp\left(\frac{V_{EB}}{V_T}\right) - 1\right], \quad I'_C = I_{CS}\left[\exp\left(\frac{V_{CB}}{V_T}\right) - 1\right].$$

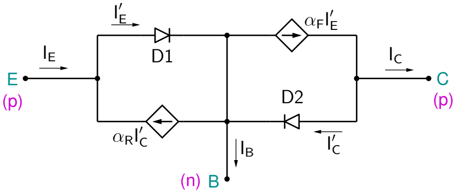
Mode	B-E	B-C	
Forward active	forward	reverse	$I'_E \gg I'_C$
Reverse active	reverse	forward	$I'_C \gg I'_E$
Saturation	forward	forward	I'_E and I'_C are comparable.
Cut-off	reverse	reverse	I'_E and I'_C are negliglbe.

M. B. Patil, IIT Bombay

Ebers-Moll model

pnp transistor





$$I'_E = I_{ES}\,[\exp(V_{EB}/V_T) - 1]$$

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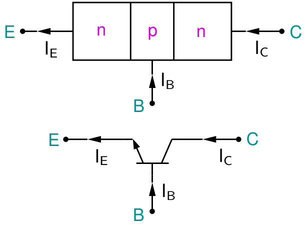
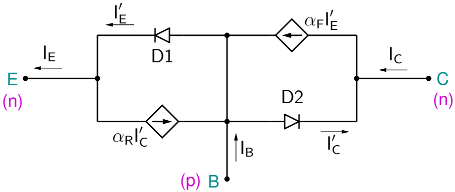
npn transistor





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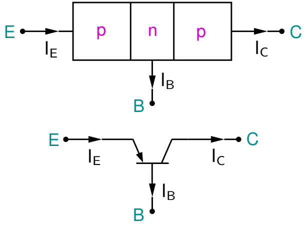
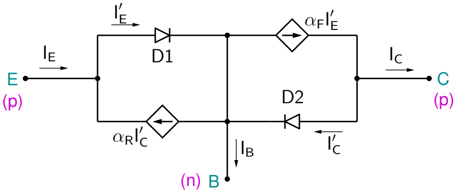
Ebers-Moll model

pnp transistor





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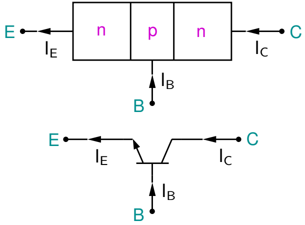
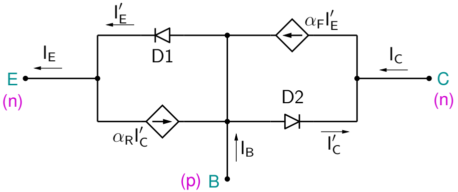
npn transistor





$$I'_E = I_{ES}\,[\exp(V_{BE}/V_T) - 1]$$

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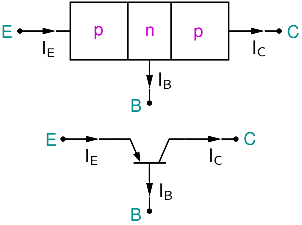
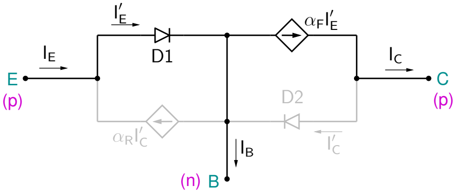
Ebers-Moll model in active mode

pnp transistor





$$I'_E = I_{ES}\,[\exp(V_{EB}/V_T) - 1]$$

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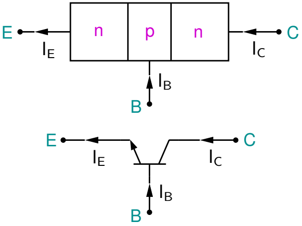
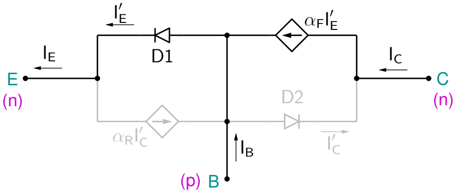
$$I_C = \alpha_F\, I_E = \beta_F\, I_B$$

npn transistor





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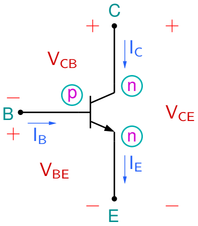
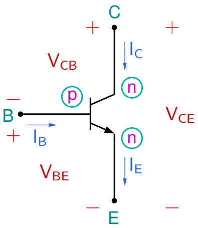
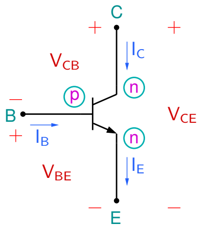
BJT I-V characteristics



BJT I-V characteristics



* Since BJT is a three-terminal device, its behaviour can be described in many different ways, e.g.,



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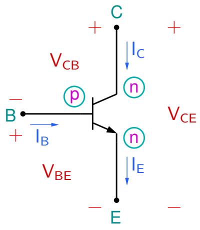
  - I_C versus V_{CB} for different values of I_E



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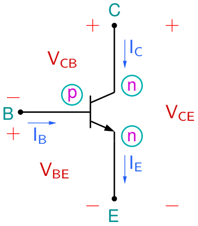

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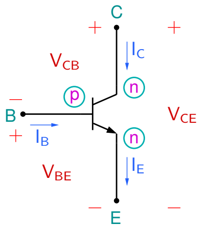

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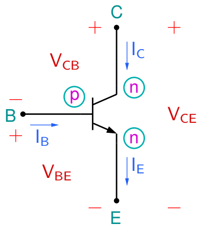
* The I-V relationship for a BJT is not a single curve but a "family" of curves or "characteristics."

BJT I-V characteristics



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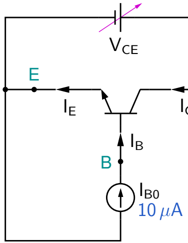
  - I_C versus V_{CE} for different values of I_B
* The I-V relationship for a BJT is not a single curve but a "family" of curves or "characteristics."
* The I_C-V_{CE} characteristics for different I_B values are useful in understanding amplifier biasing.

BJT I-V characteristics



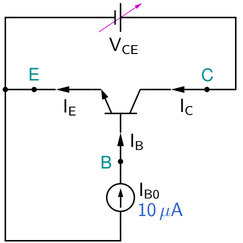
$\alpha_F = 0.99 \rightarrow \beta_F = \dfrac{\alpha_F}{1 - \alpha_F} = 99$

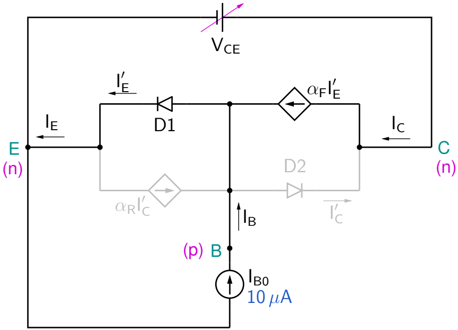
$\alpha_R = 0.5 \rightarrow \beta_R = \dfrac{\alpha_R}{1 - \alpha_R} = 1$

$I_{ES} = 1 \times 10^{-14}\,$A

$I_{CS} = 2 \times 10^{-14}\,$A

BJT I-V characteristics





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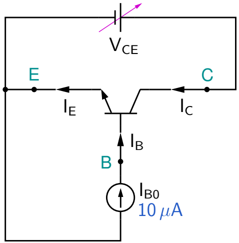
$I_C = \alpha_F\, I_E = \beta_F\, I_B$ in active mode

BJT I-V characteristics



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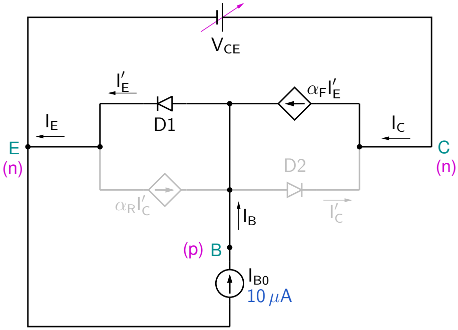

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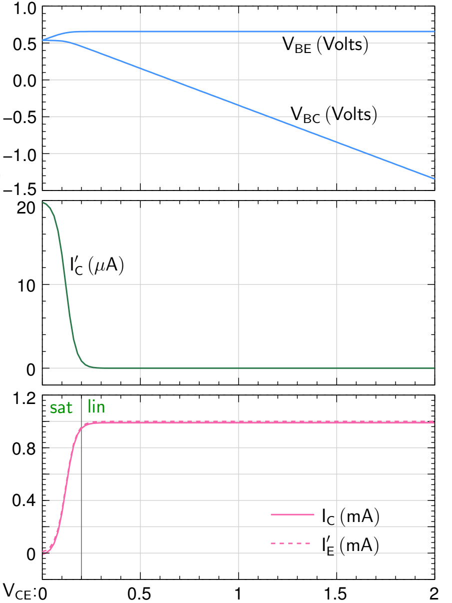

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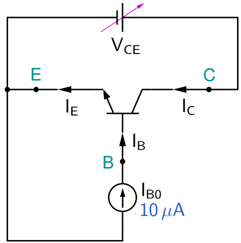

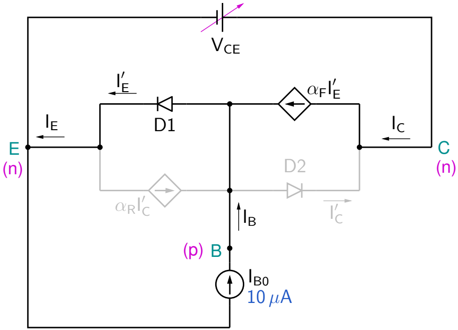

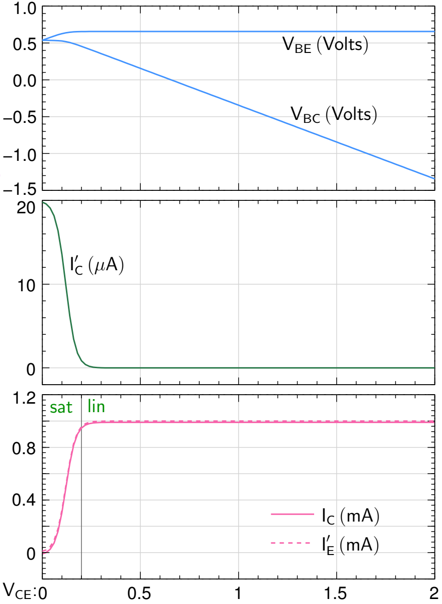

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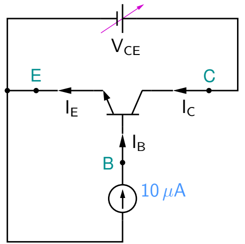
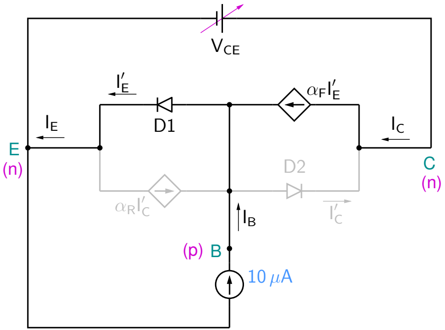
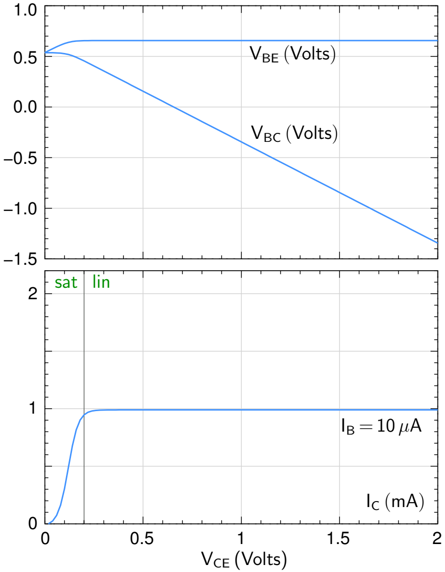
BJT I-V characteristics







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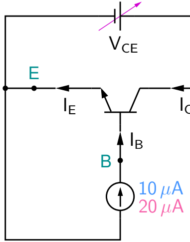

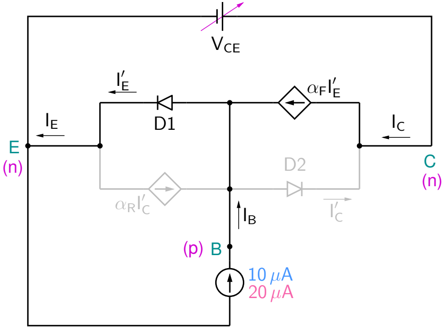

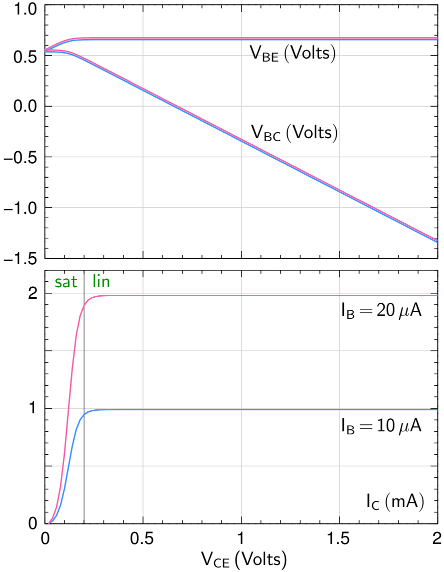

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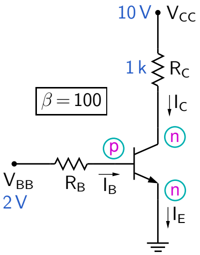
A simple BJT circuit (revisited)



We are now in a position to explain what happens when R_B is decreased from 100 k to 10 k in the above circuit.

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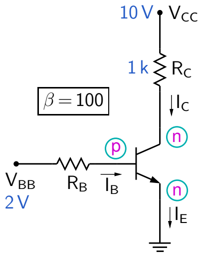

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Let us plot $I_C - V_{CE}$ curves for $I_B \approx \dfrac{V_{BB} - 0.7\ V}{R_B}$ for the two values of R_B.

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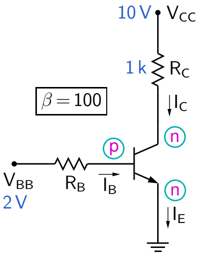

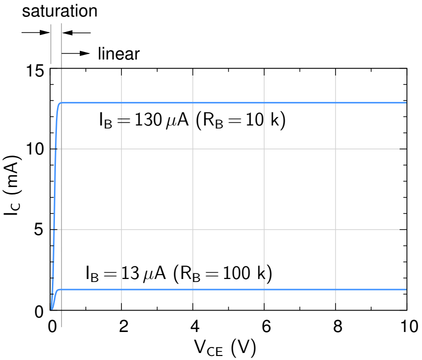

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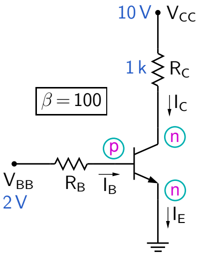

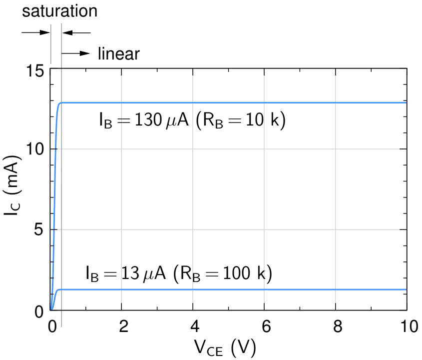

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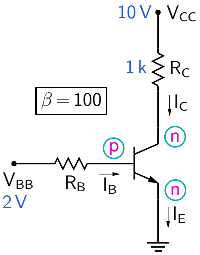
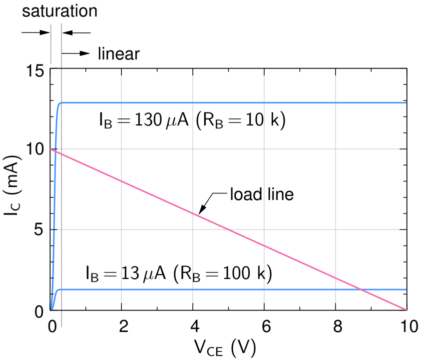
Let us plot $I_C - V_{CE}$ curves for $I_B \approx \dfrac{V_{BB} - 0.7\ V}{R_B}$ for the two values of R_B.

In addition to the BJT $I_C - V_{CE}$ curve, the circuit variables must also satisfy the constraint,
$V_{CC} = V_{CE} + I_C R_C$, a straight line in the $I_C - V_{CE}$ plane.

A simple BJT circuit (revisited)





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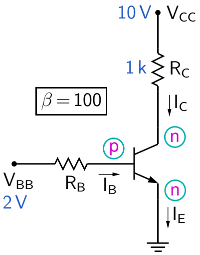
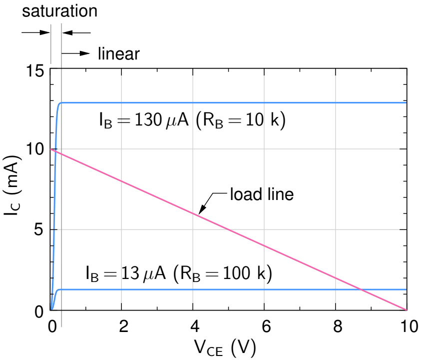
A simple BJT circuit (revisited)





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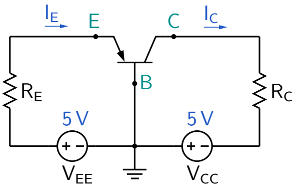
Let us plot $I_C - V_{CE}$ curves for $I_B \approx \dfrac{V_{BB} - 0.7\ V}{R_B}$ for the two values of R_B.

In addition to the BJT $I_C - V_{CE}$ curve, the circuit variables must also satisfy the constraint, $V_{CC} = V_{CE} + I_C R_C$, a straight line in the $I_C - V_{CE}$ plane.

The intersection of the load line and the BJT characteristics gives the solution for the circuit. For $R_B = 10$ k, note that the BJT operates in the saturation region, leading to $V_{CE} \approx 0.2\ V$, and $I_C = 9.8\ mA$.

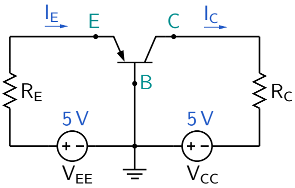
BJT circuit example

Assuming the transistor to be operating in the active region, find R_E and R_C to obtain $I_E = 2\,\text{mA}$, and $V_{BC} = 1\,\text{V}$ ($\alpha \approx 1$).



BJT circuit example

Assuming the transistor to be operating in the active region, find R_E and R_C to obtain $I_E = 2\,\text{mA}$, and $V_{BC} = 1\,\text{V}$ ($\alpha \approx 1$).



$$V_{EB} - V_{EE} + I_E R_E = 0$$

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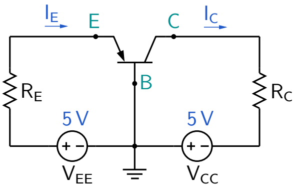

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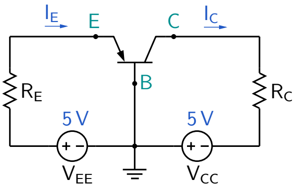

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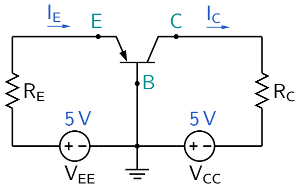

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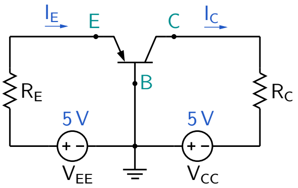

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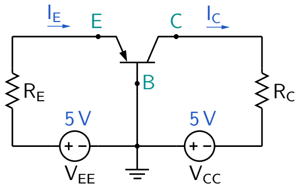

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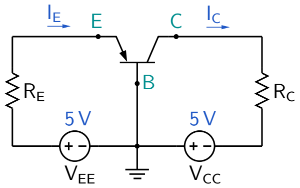

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Since $\alpha \approx 1$, $I_C \approx I_E \;\rightarrow\; I_E R_C \approx 5 - 1 \;\rightarrow\; R_C = \dfrac{4\,\text{V}}{2\,\text{mA}} = 2\,\text{k}.$