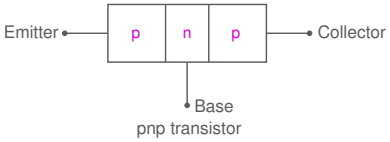
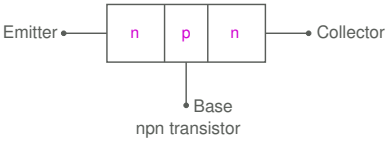
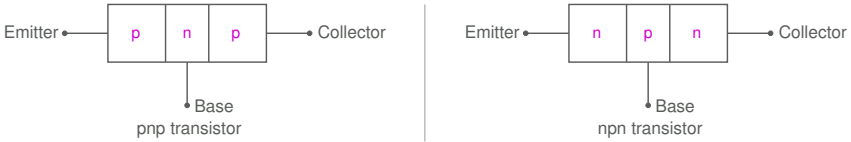


pnp transistor



npn transistor



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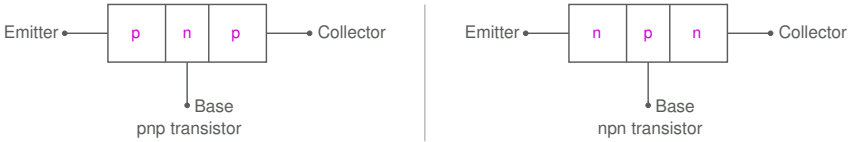

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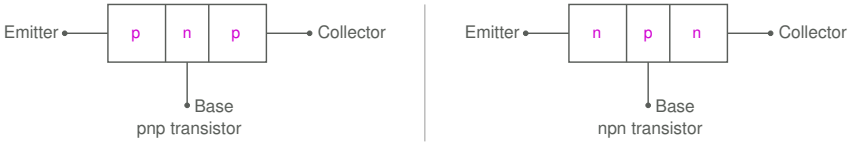

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  WRONG! Let us see why.

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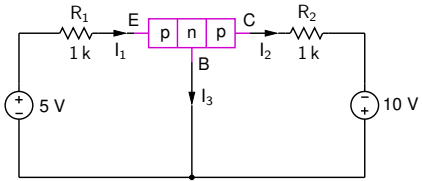

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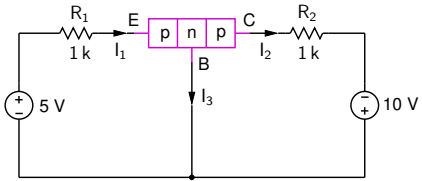

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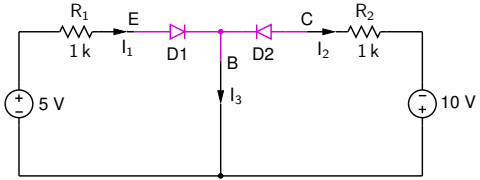

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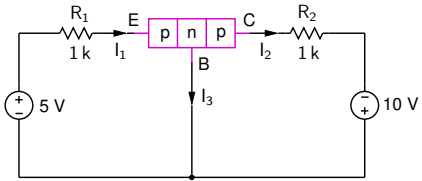

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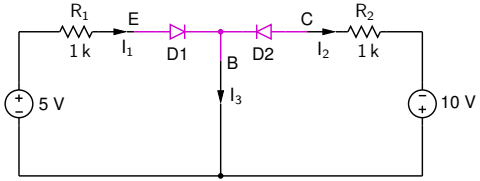
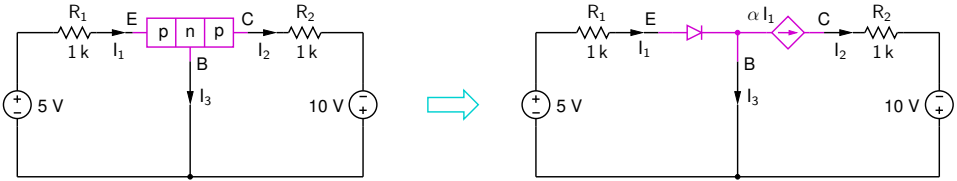


Assuming $V_{on} = 0.7\ V$ for D1, we get

$$I_1 = \frac{5\ V - 0.7\ V}{R_1} = 4.3\ mA,$$

$I_2 = 0$ (since D2 is reverse biased), and $I_3 \approx I_1 = 4.3\ mA$.

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



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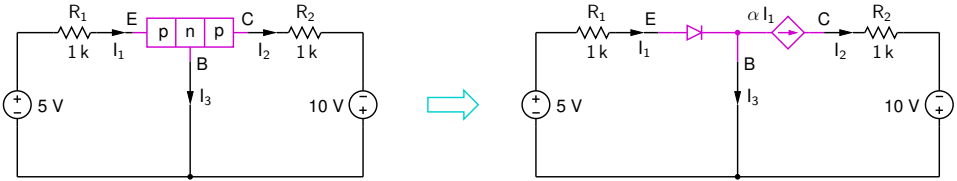

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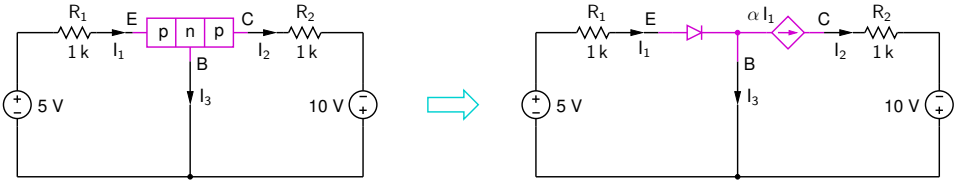

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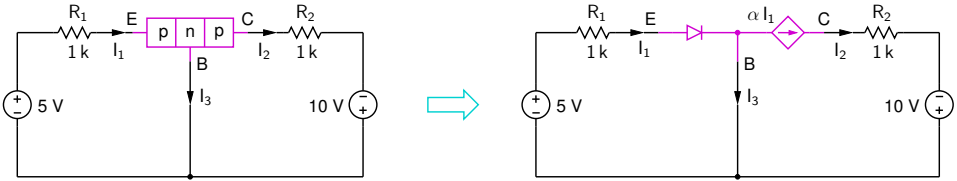

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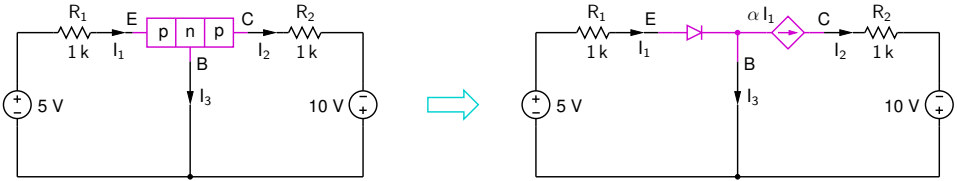

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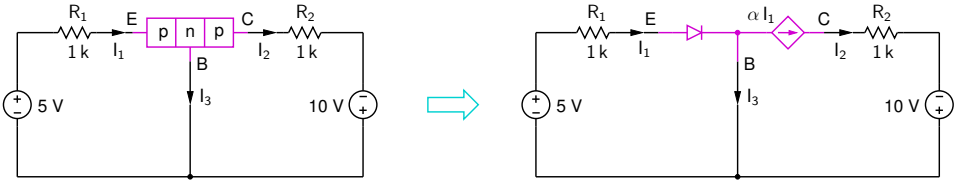

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Conclusion: A BJT is NOT the same as two diodes connected back-to-back
(although it does have two *p-n* junctions).

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

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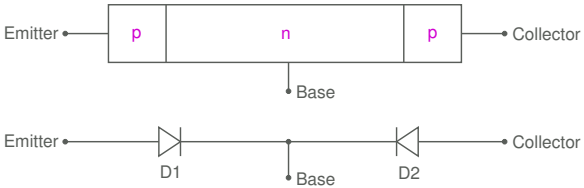

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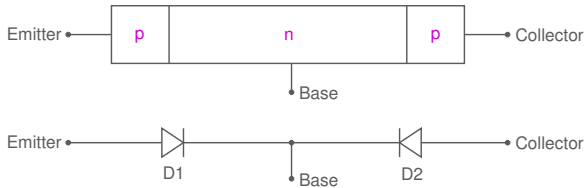

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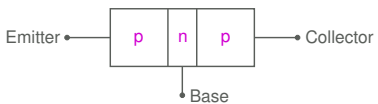

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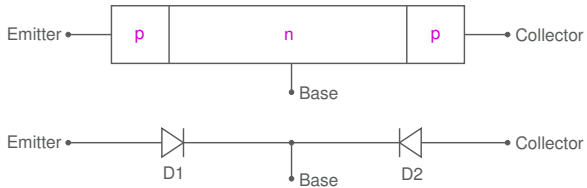

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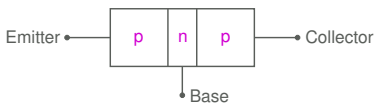
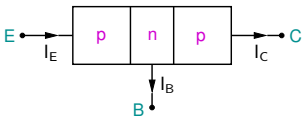
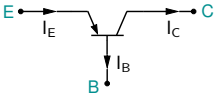
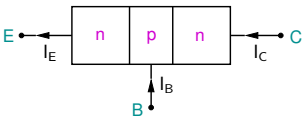


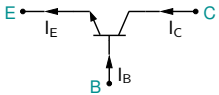
* Later, we will look at the "Ebers-Moll model" of a BJT, which is a fairly accurate representation of the transistor action.

BJT in active mode









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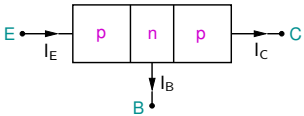
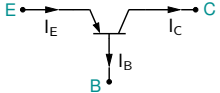
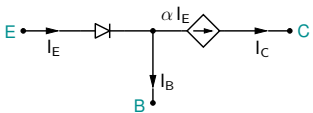
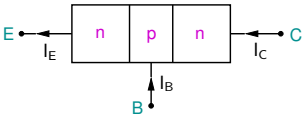
* Analog circuits, including amplifiers, are generally designed to ensure that the BJTs are operating in the active mode.

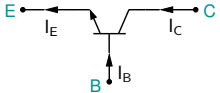
BJT in active mode

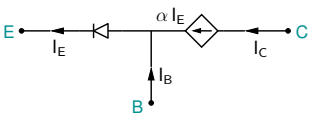












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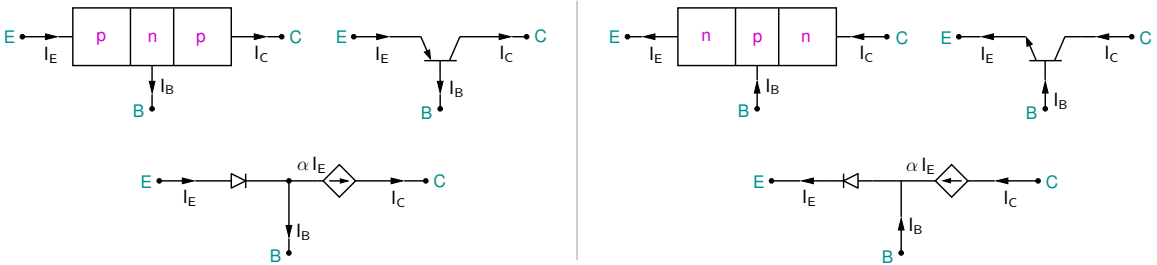

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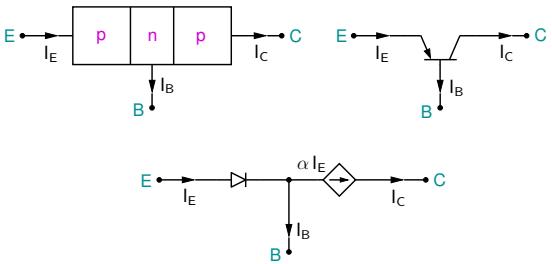

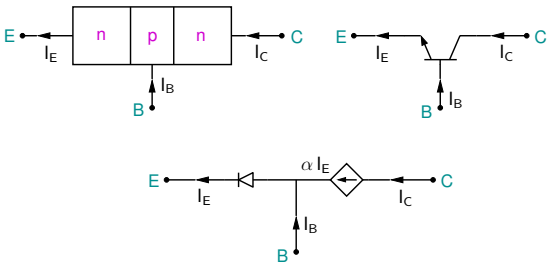

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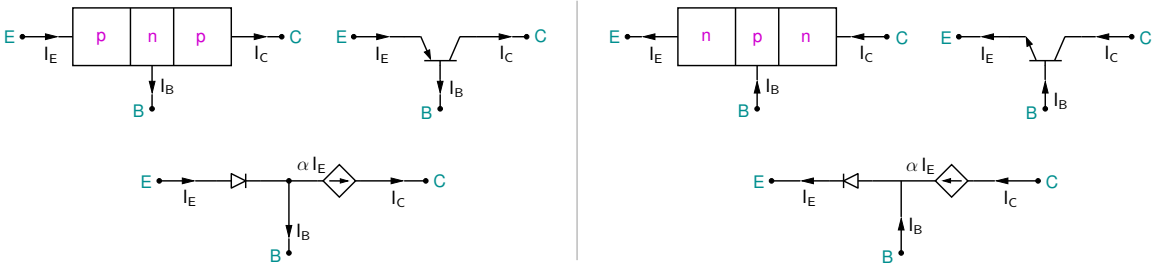

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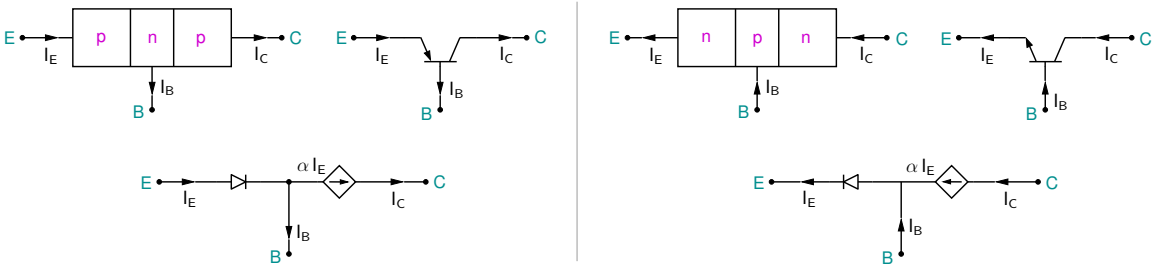
* The ratio I_C / I_B is defined as the current gain β of the transistor.

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

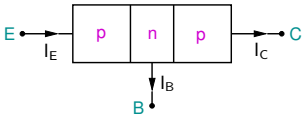
BJT in active mode

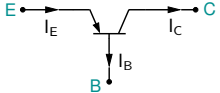


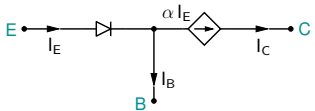
- In the active mode, $I_C = \alpha I_E$, $\alpha \approx 1$ (slightly less than 1).
- $I_B = I_E - I_C = I_E(1 - \alpha)$.
- The ratio I_C/I_B is defined as the current gain β of the transistor.

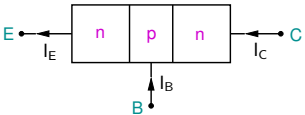
  $$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1 - \alpha}.$$
- β is a function of I_C and temperature. However, we will generally treat it as a constant, a useful approximation to simplify things and still get a good insight.

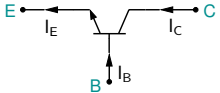
BJT in active mode

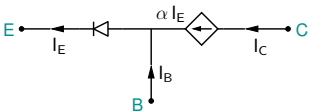












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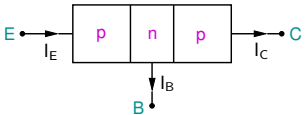
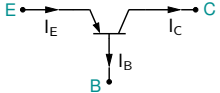
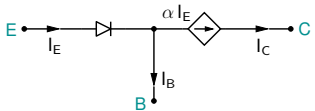
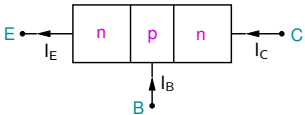
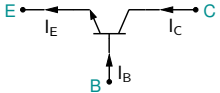
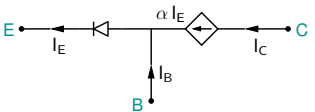








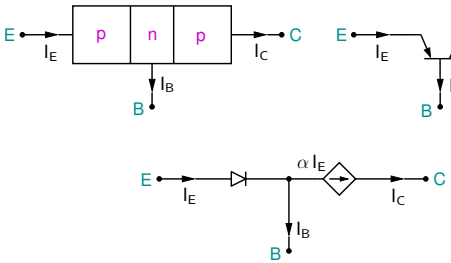


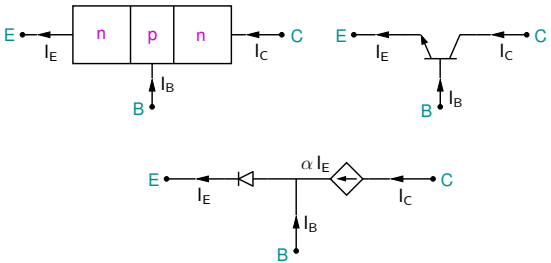


$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

α	β
0.9	9
0.95	19
0.99	99
0.995	199

BJT in active mode





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

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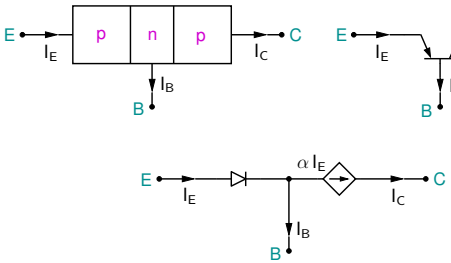

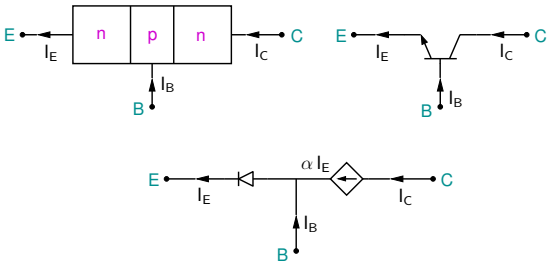

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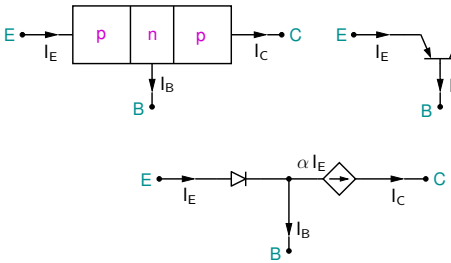

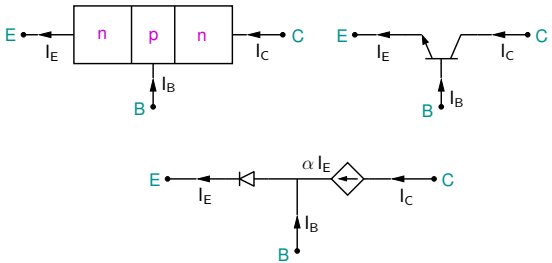

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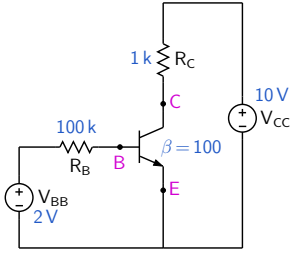
- β increases substantially as $\alpha \to 1$.
- Transistors are generally designed to get a high value of β (typically 100 to 250, but can be as high as 2000 for "super-β" transistors).
- A large $\beta \Rightarrow I_B \ll I_C$ or I_E when the transistor is in the active mode.

A simple BJT circuit



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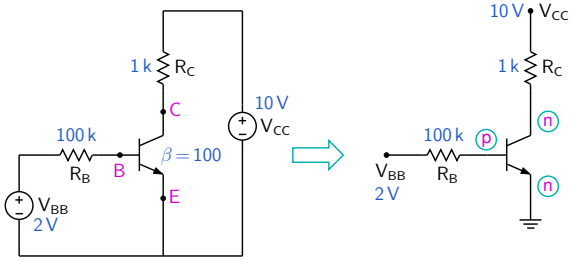

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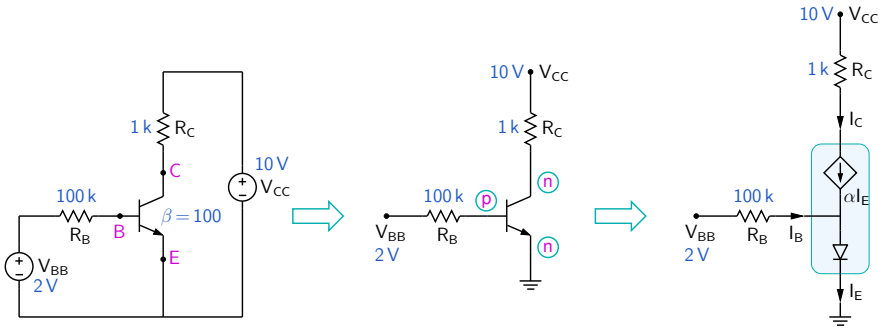

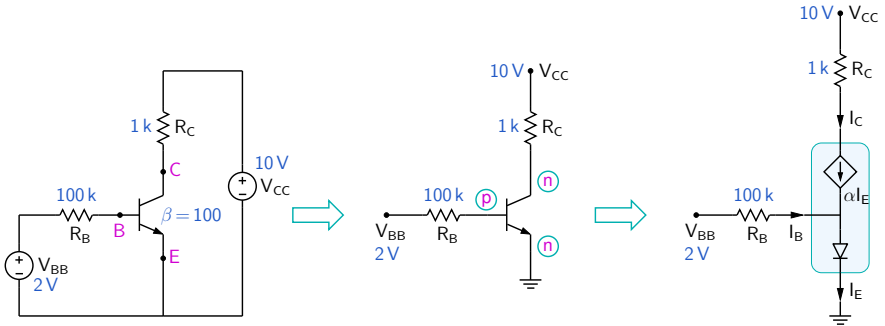

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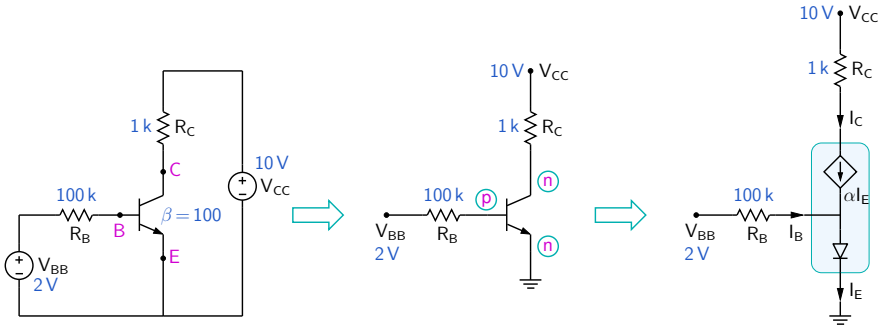

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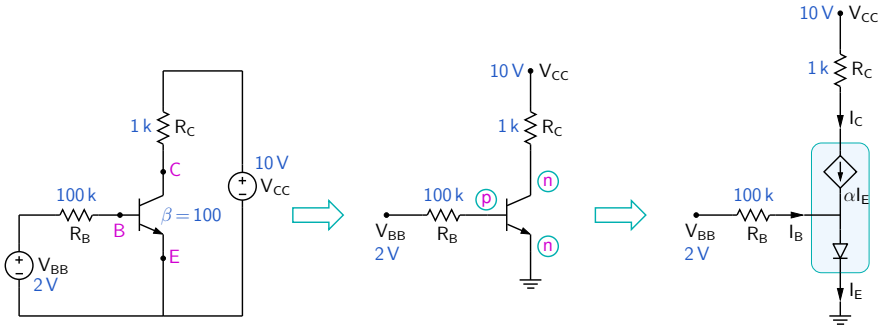

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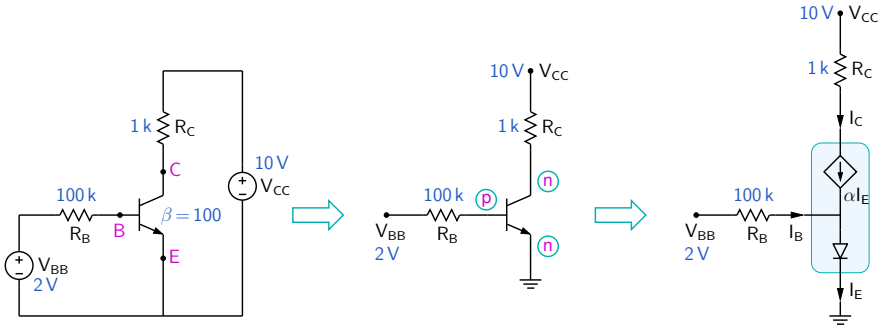

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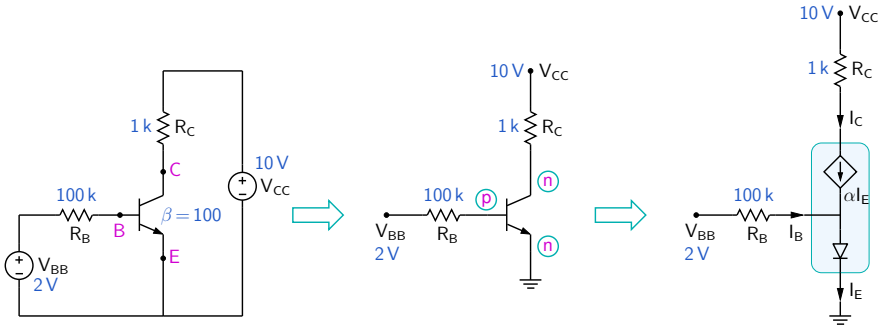

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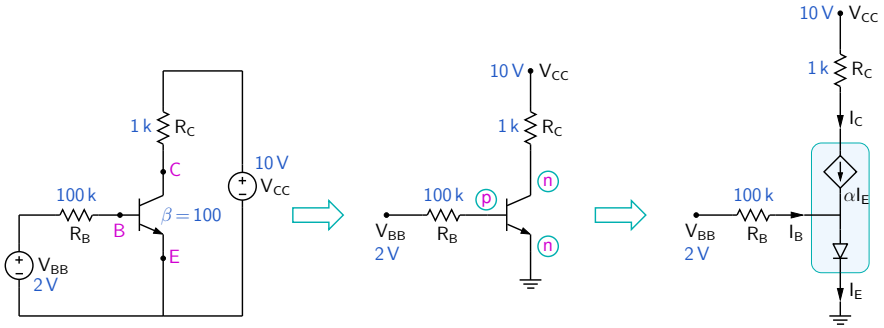

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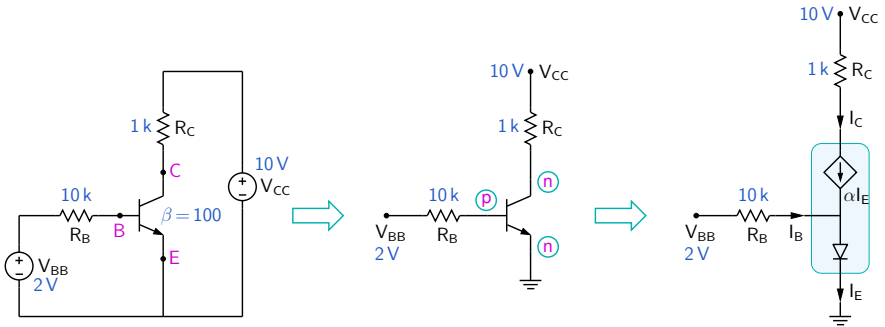
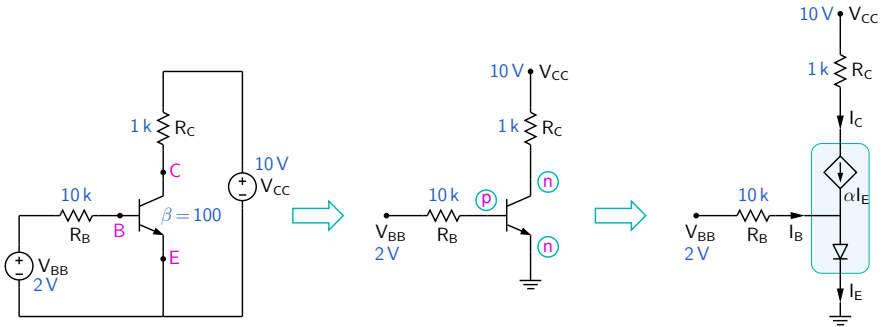
$$V_{BC} = V_B - V_C = 0.7\,V - 8.7\,V = -8.0\,V\,,$$

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



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



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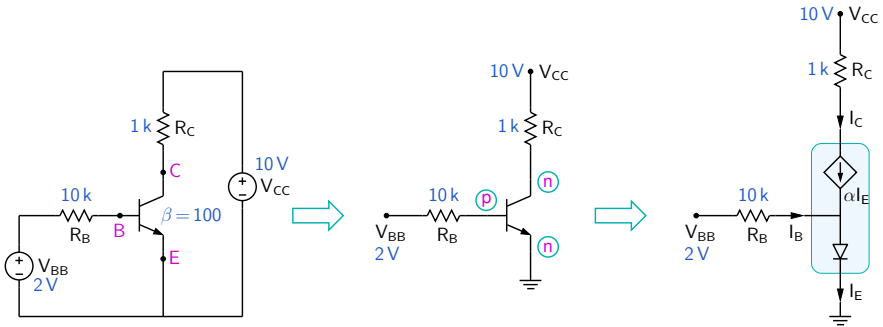

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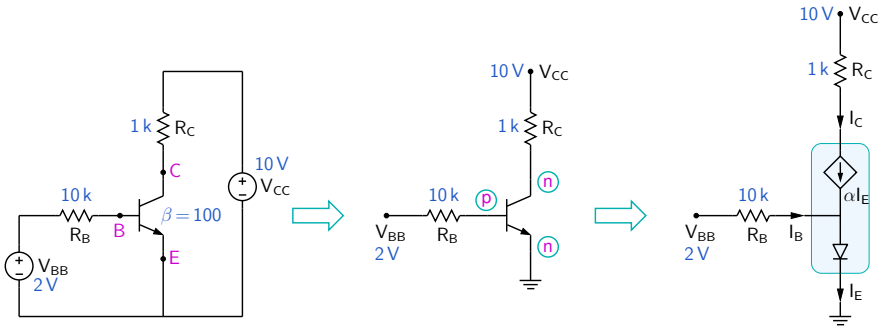

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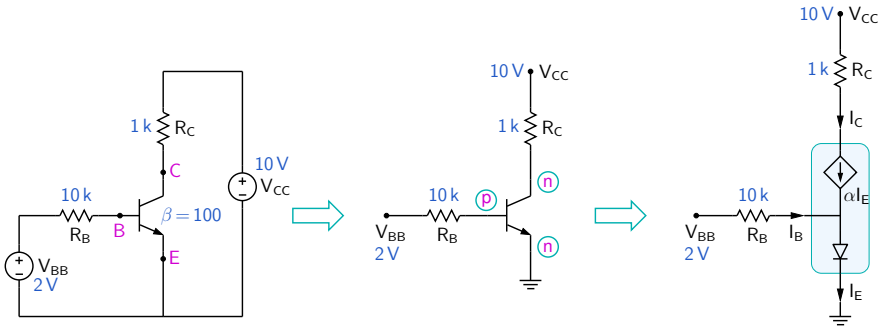

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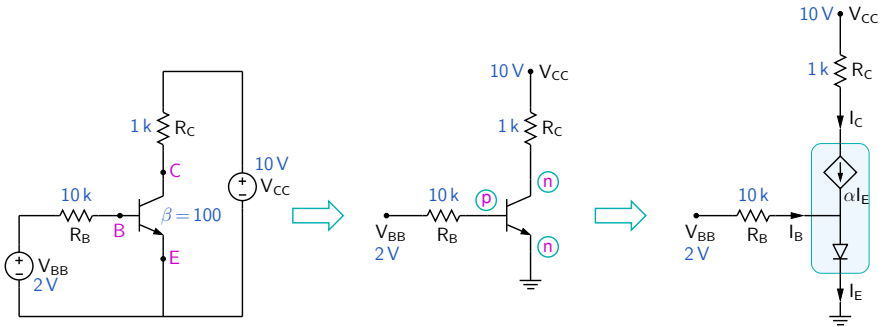

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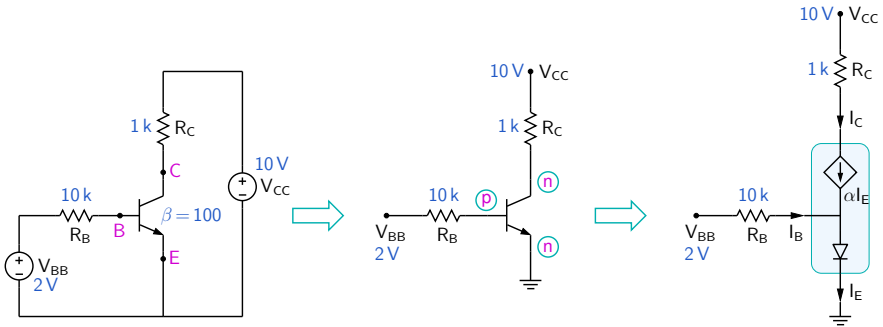

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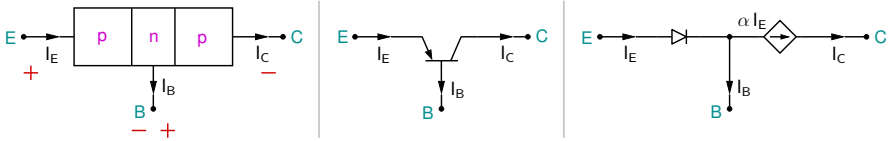
V_{BC} is not only positive, it is *huge*!

$\rightarrow$ 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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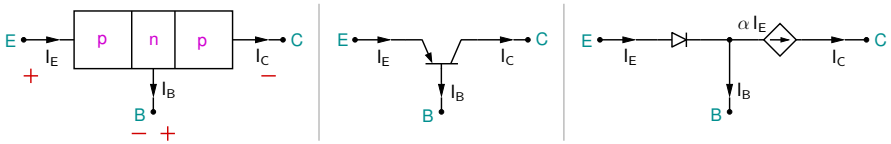

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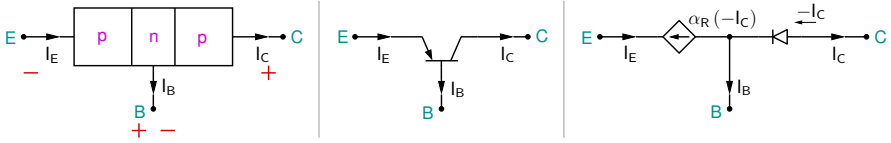

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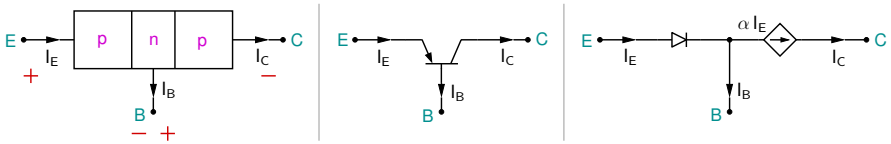

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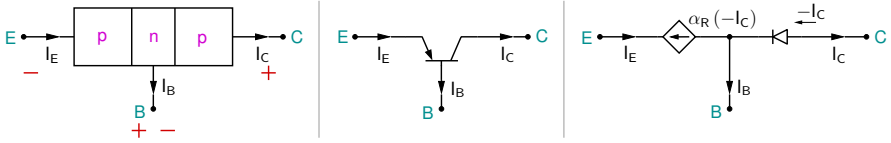
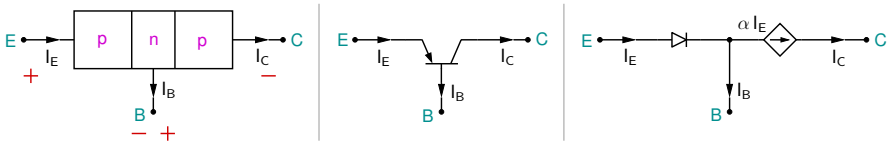


In the reverse active mode, emitter $\leftrightarrow$ collector. (However, we continue to refer to the terminals with their original names.)

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



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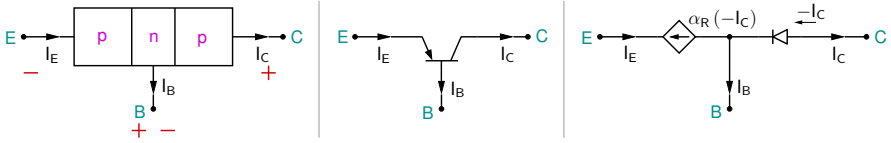

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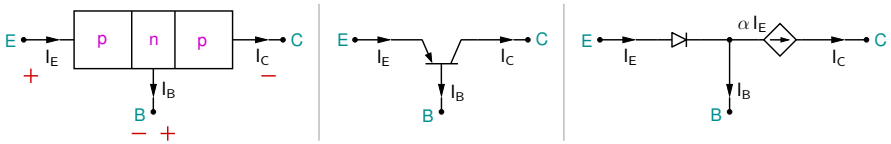

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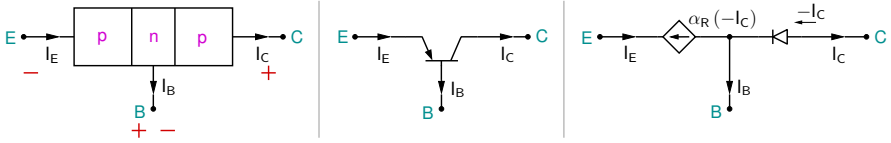

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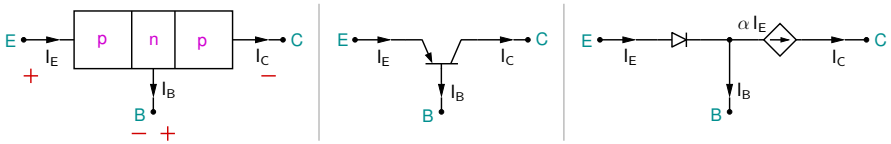

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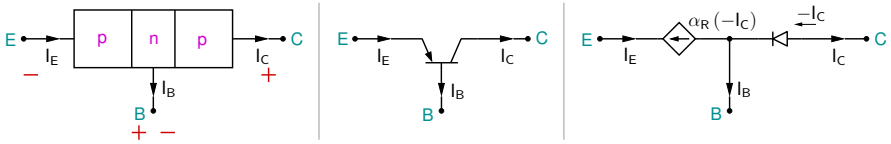

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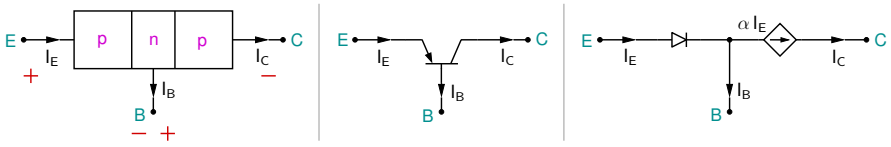

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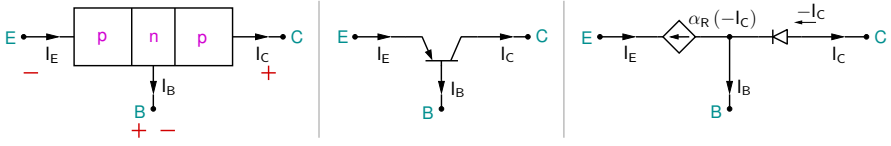

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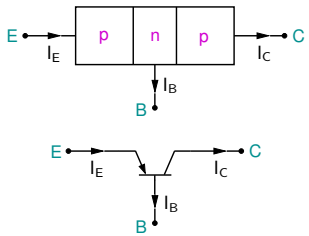
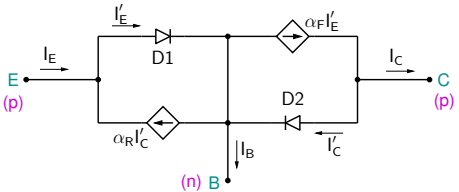
In amplifiers, the BJT is biased in the forward active mode (simply called the "active mode") in order to make use of the higher value of β in that mode.

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





Ebers-Moll model for a *pnp* transistor

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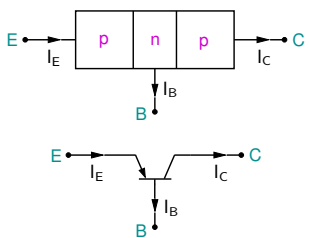

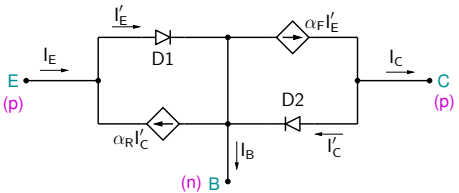

The currents I'_E and I'_C are given by the Shockley diode equation:

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

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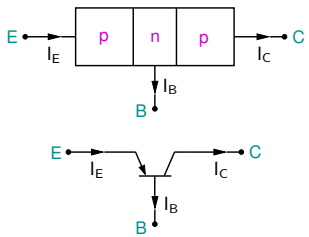

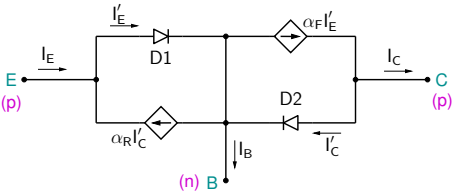

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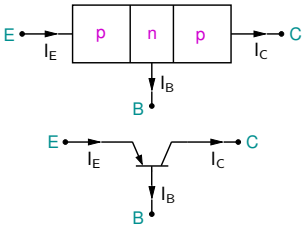
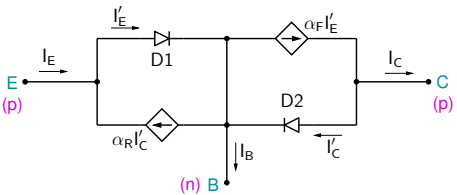
Mode	B-E	B-C	
Forward active	forward	reverse	$I'_E \gg I'_C$
Reverse active	reverse	forward	$I'_C \gg I'_E$
Saturation	forward	forward	I'_E and I'_C are comparable.
Cut-off	reverse	reverse	I'_E and I'_C are negliglbe.



pnp transistor



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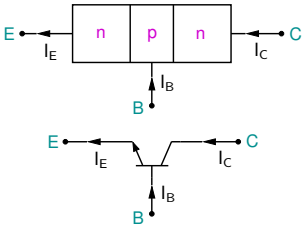
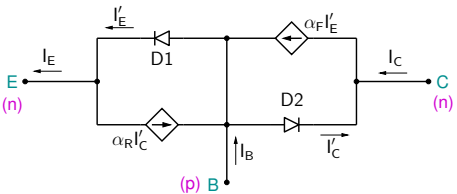


npn transistor



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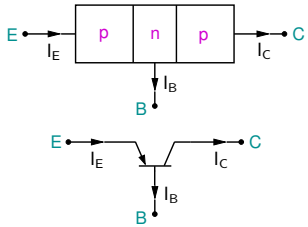

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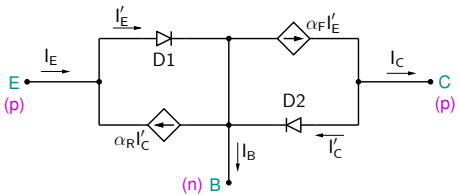

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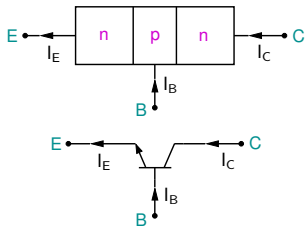

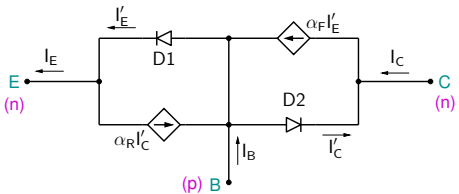

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Ebers-Moll model in active mode

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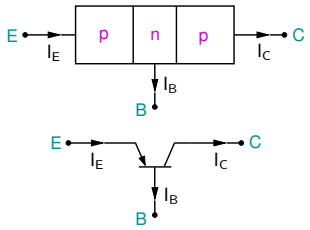

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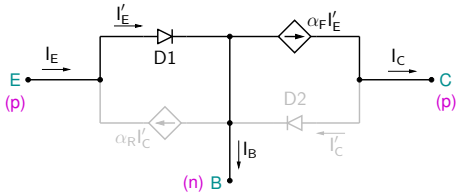

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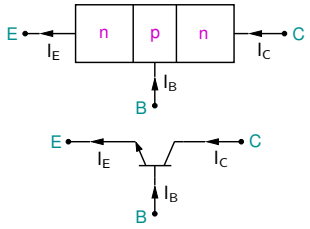
$$I_C = \alpha_F\, I_E = \beta_F\, I_B$$



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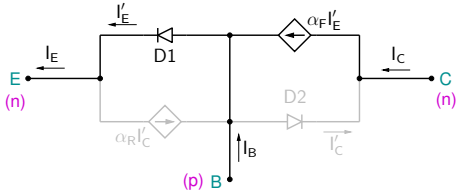

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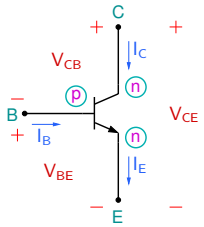
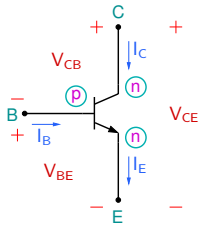
BJT *I-V* characteristics





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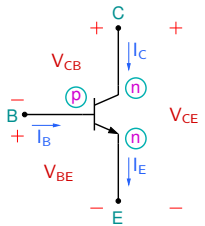

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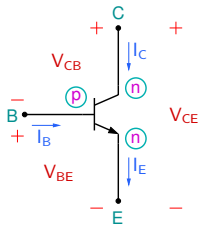

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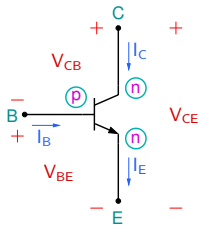

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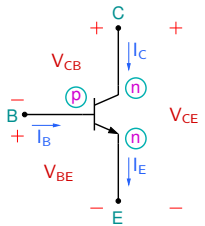
  - I_C versus V_{CE} for different values of I_B



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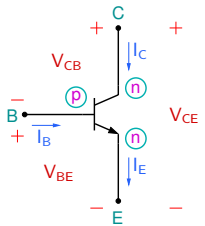

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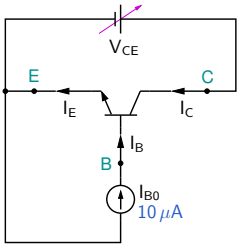
* The I_C-V_{CE} characteristics for different I_B values are useful in understanding amplifier biasing.



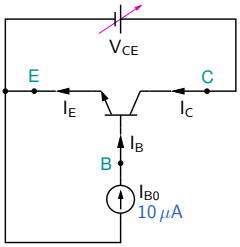
$\alpha_F = 0.99 \rightarrow \beta_F = \dfrac{\alpha_F}{1-\alpha_F} = 99$

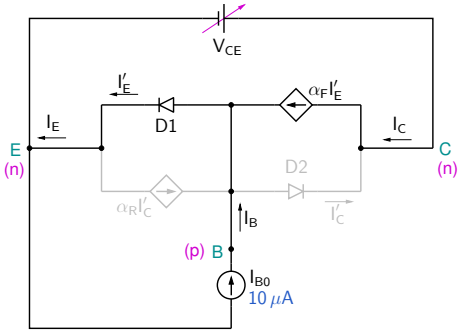
$\alpha_R = 0.5 \rightarrow \beta_R = \dfrac{\alpha_R}{1-\alpha_R} = 1$

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

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

BJT I-V characteristics





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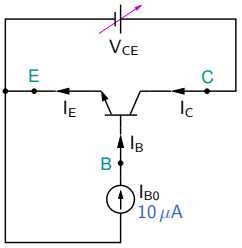
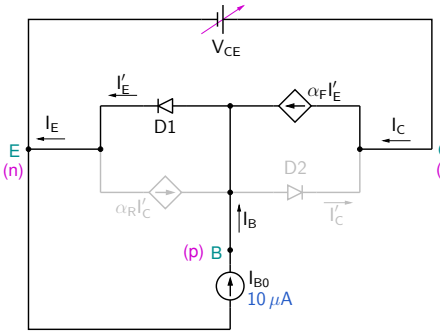
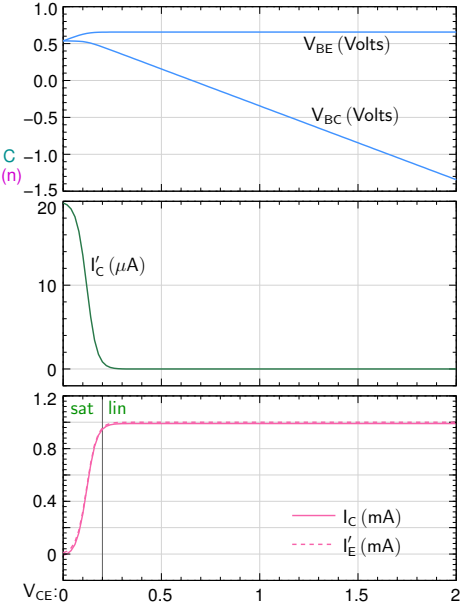
$I'_C = I_{CS}\,[\exp(V_{BC}/V_T) - 1]$

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

BJT I-V characteristics







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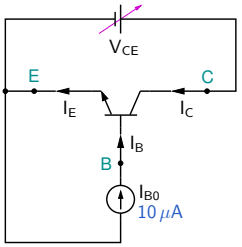
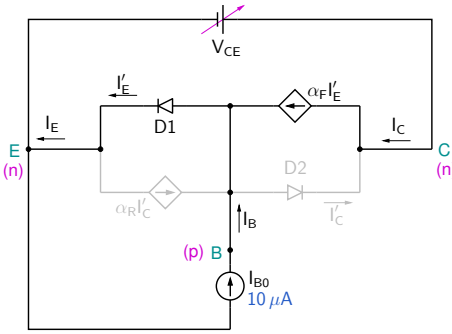
$I_C = \alpha_F\, I_E = \beta_F\, I_B$ in active mode





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

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

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

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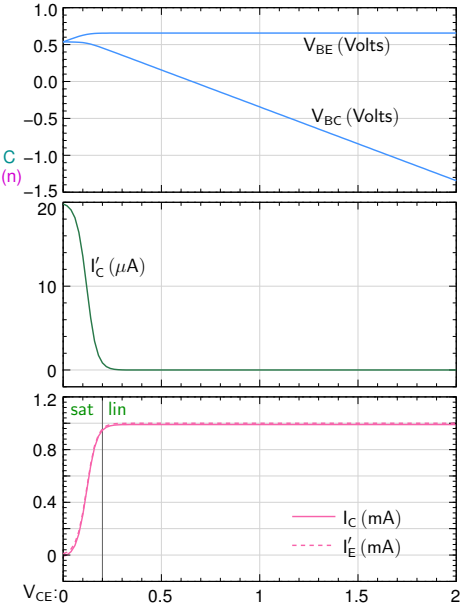
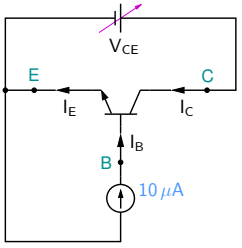
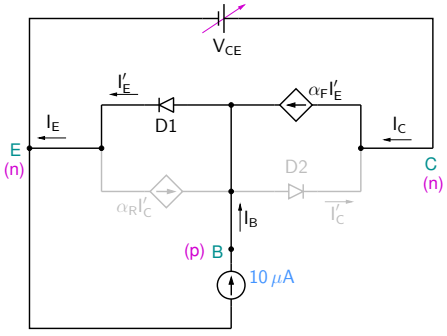
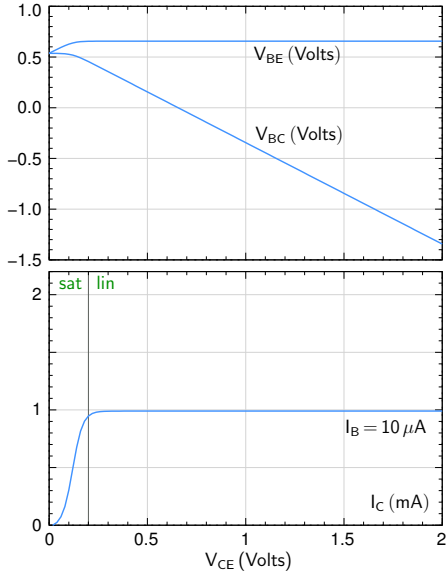


* linear region: B-E under forward bias, B-C under reverse bias, $I_C = \beta_F I_B$
* saturation region: B-E under forward bias, B-C under forward bias, $I_C < \beta_F I_B$

BJT I-V characteristics







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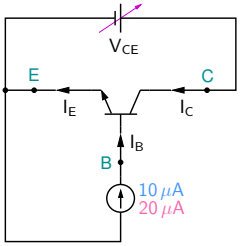

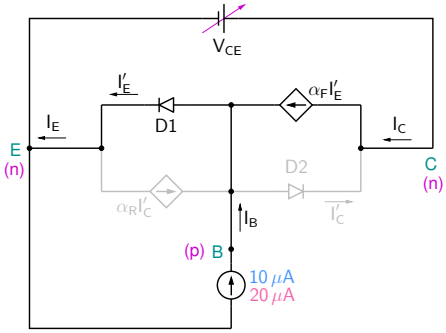

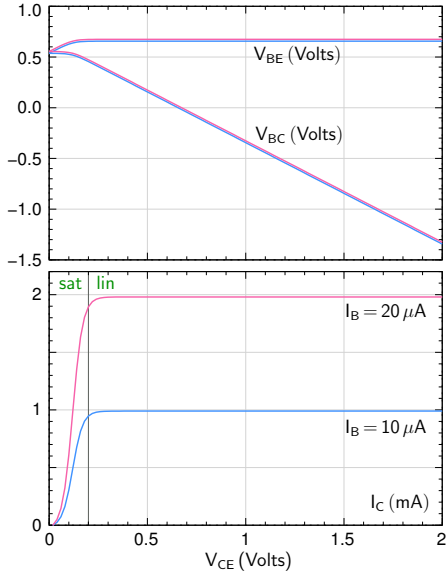

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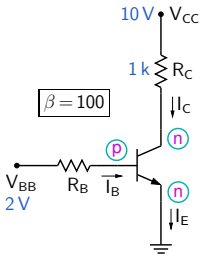
A simple BJT circuit (revisited)



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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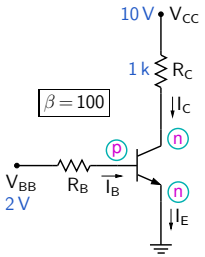

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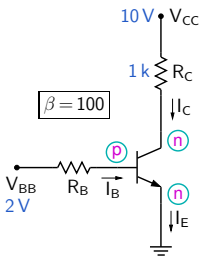

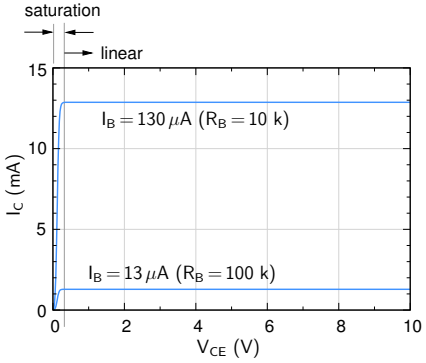

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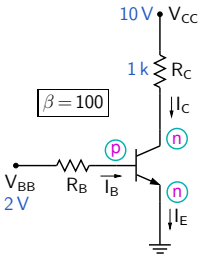

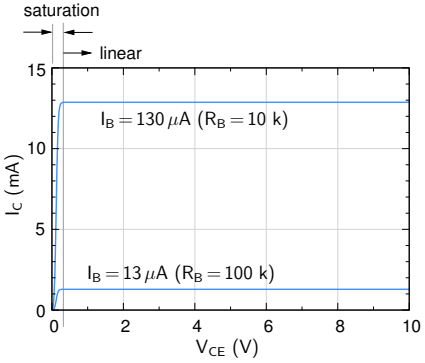

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In addition to the BJT $I_C - V_{CE}$ curve, the circuit variables must also satisfy the constraint, $V_{CC} = V_{CE} + I_C R_C$, a straight line in the $I_C - V_{CE}$ plane.

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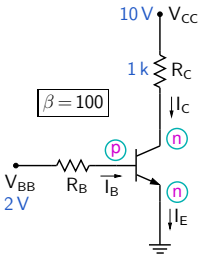

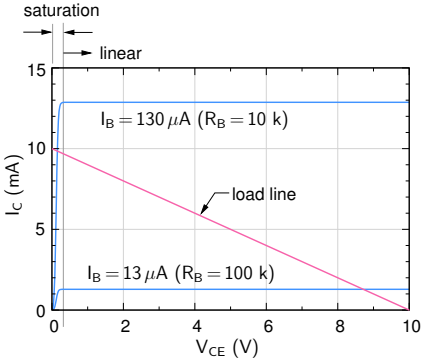

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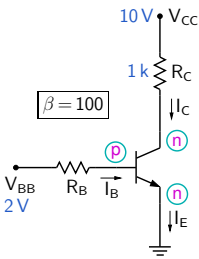

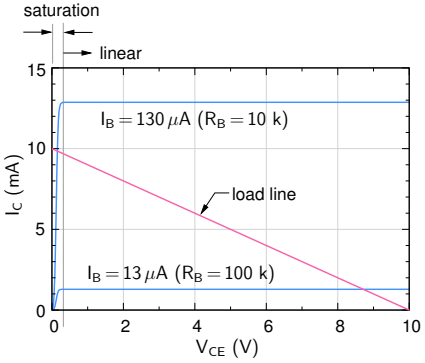

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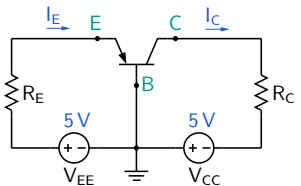
The intersection of the load line and the BJT characteristics gives the solution for the circuit. For $R_B = 10$ k, note that the BJT operates in the saturation region, leading to $V_{CE} \approx 0.2\,V$, and $I_C = 9.8\,mA$.

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 $V_{BC} = 1\,\text{V}$ ($\alpha \approx 1$).



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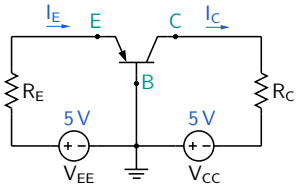

$V_{EB} - V_{EE} + I_E R_E = 0$

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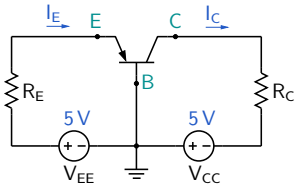

$V_{EB} - V_{EE} + I_E R_E = 0 \quad \rightarrow \quad I_E R_E = 5 - 0.7$

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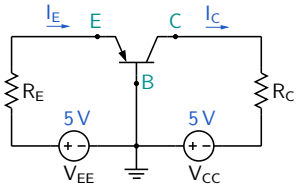

$$V_{EB} - V_{EE} + I_E R_E = 0 \;\rightarrow\; I_E R_E = 5 - 0.7 \;\rightarrow\; R_E = \frac{4.3\,\text{V}}{2\,\text{mA}} = 2.15\,\text{k}.$$

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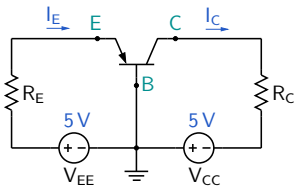

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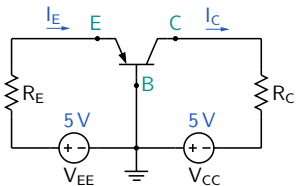

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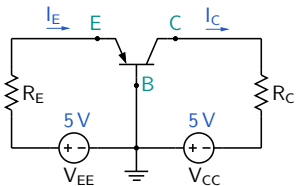

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Since $\alpha \approx 1$, $I_C \approx I_E$

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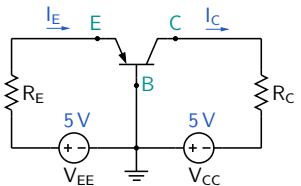

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Since $\alpha \approx 1$, $I_C \approx I_E \;\rightarrow\; I_E R_C \approx 5 - 1 \;\rightarrow\; R_C = \dfrac{4\,\text{V}}{2\,\text{mA}} = 2\,\text{k}.$