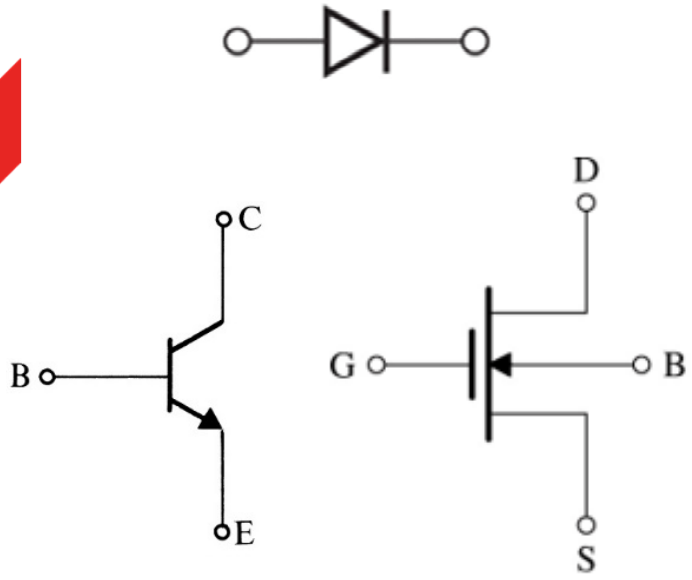
MACQUARIE University

ELEC2005
Electrical and Electronic Systems

BIPOLAR JUNCTION TRANSISTORS – PART 1

DAVID PAYNE



In Today's Lecture

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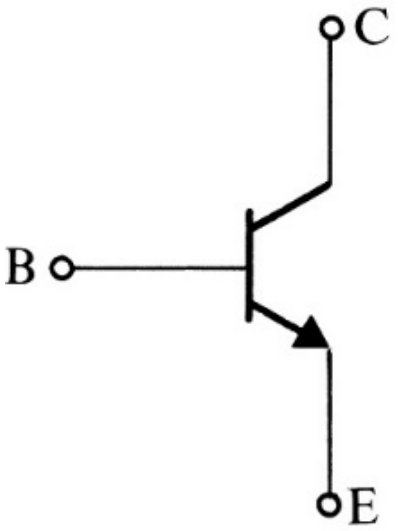
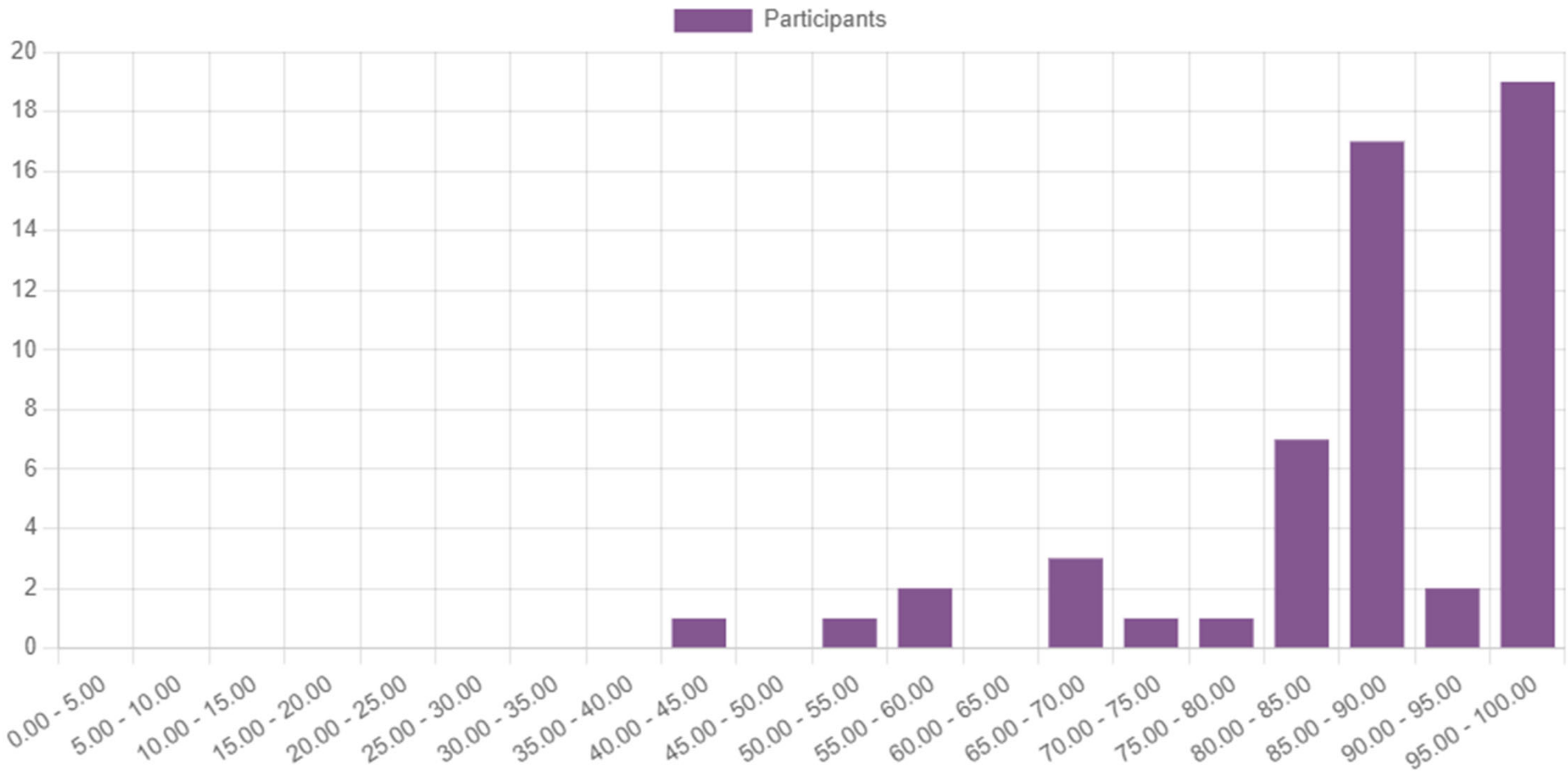
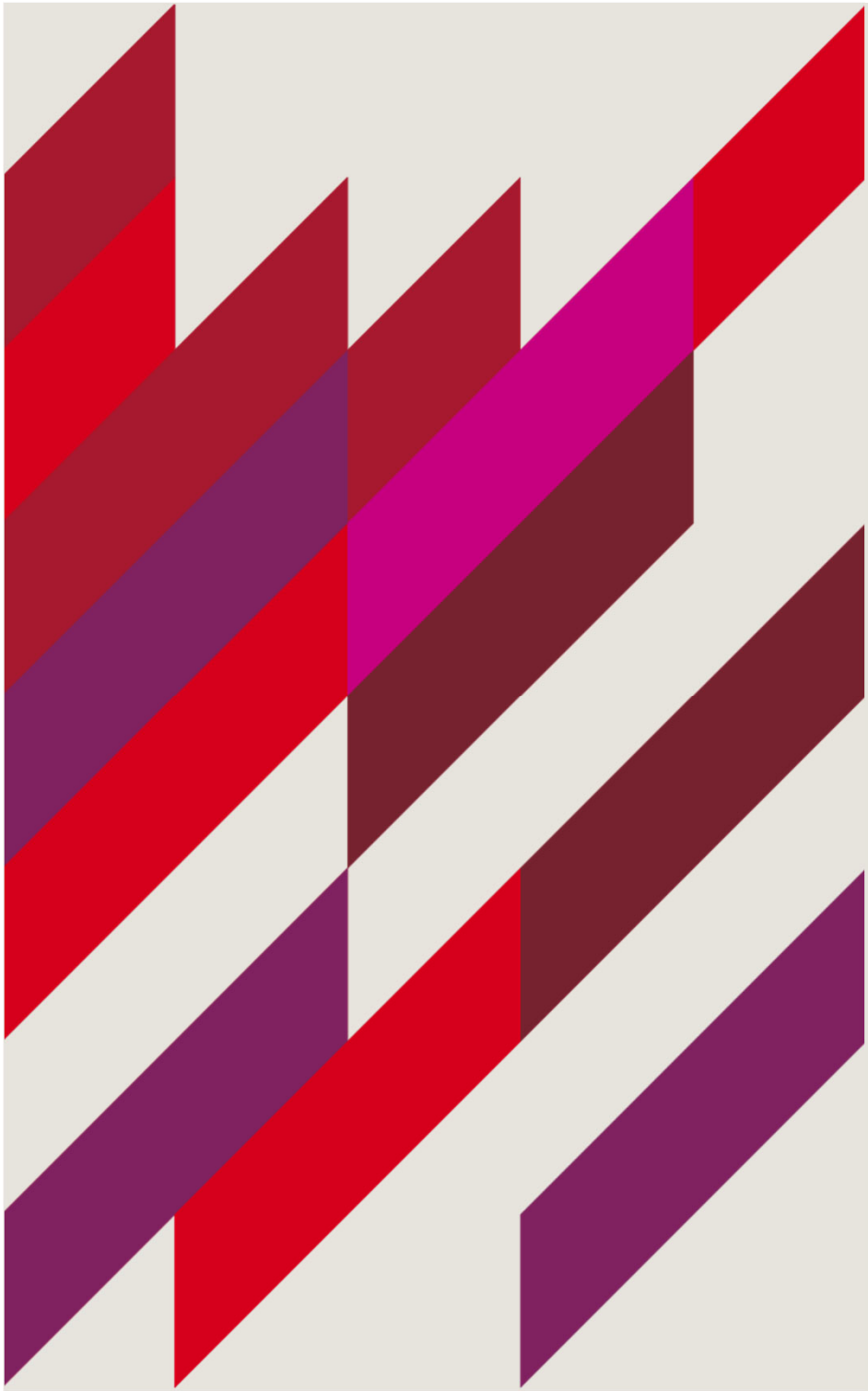
- Introduction to bipolar junction transistors (BJTS)
- BJTs in circuits
  - ❖ Device structure and circuit symbol
  - ❖ Modes of operation
  - ❖ Circuit models



Mini Quiz Review





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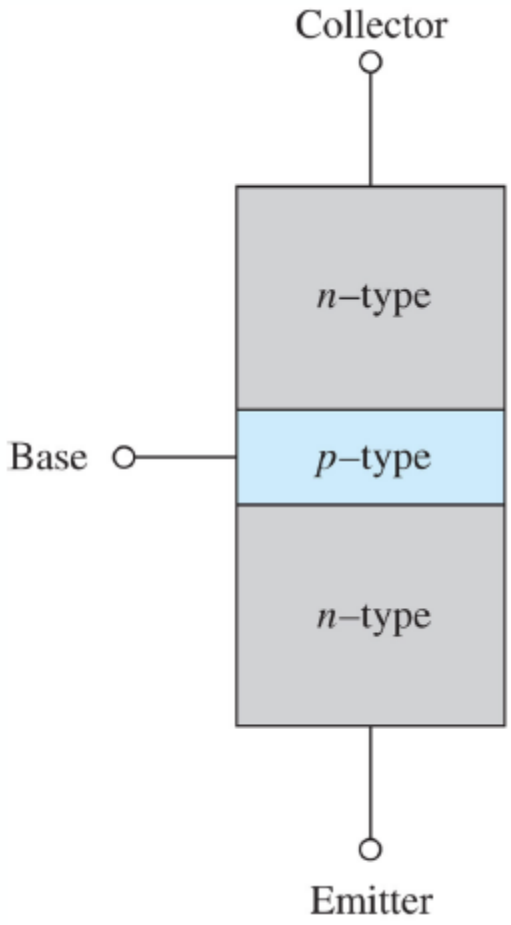
Lecture 3

1. **BJT Device Structure**
2. BJT Modes of Operation
3. BJT Models

The Bipolar Junction Transistor

DIAGRAMS AND CIRCUIT SYMBOLS



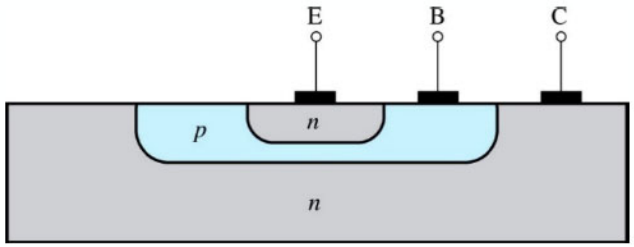
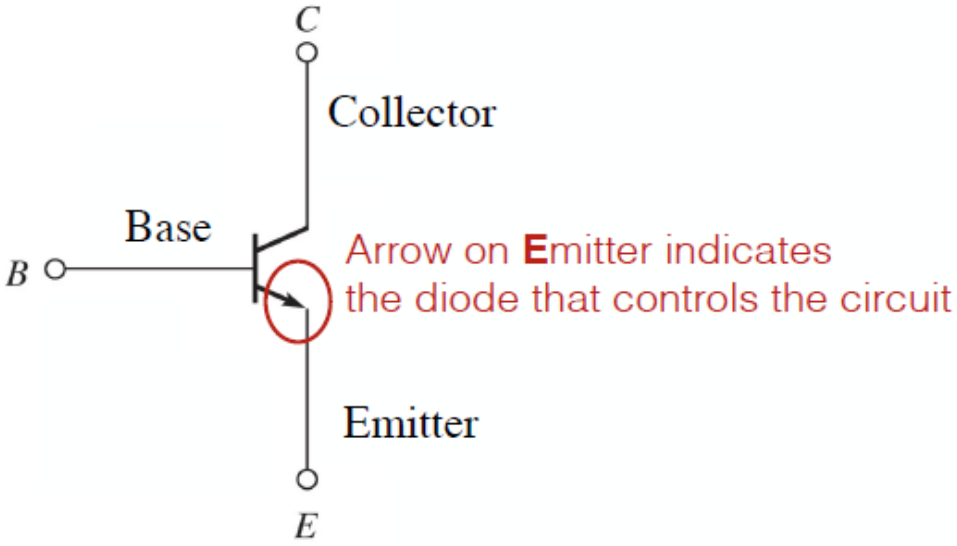


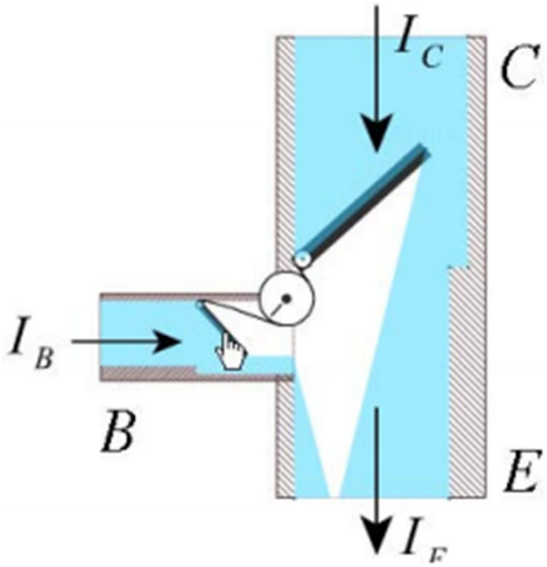
Diagram of physical npn BJT on wafer

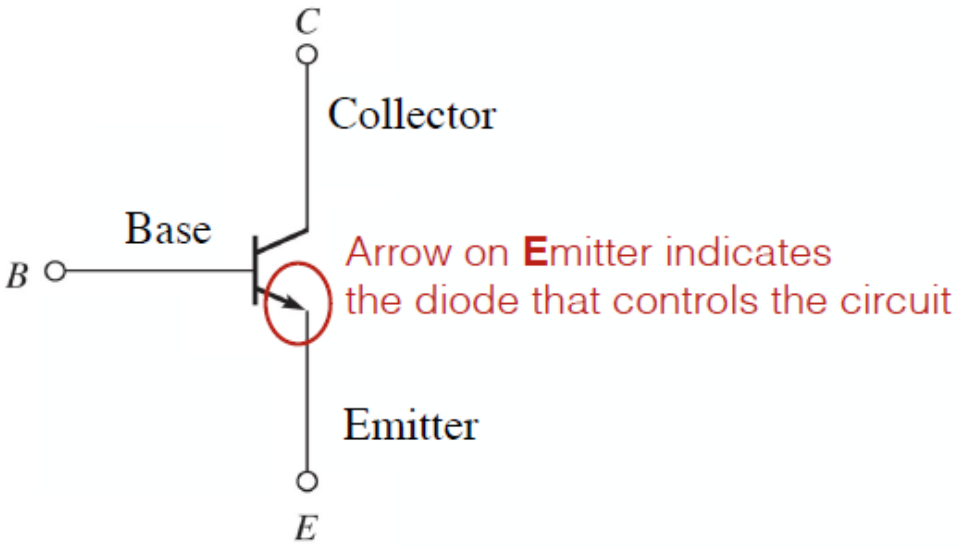


The Bipolar Junction Transistor

THE PIPE ANALOGY

- In the pipe analogy (AKA hydraulic analogy):
- Electric potential is equivalent to pressure. i.e. voltage is equivalent to the difference in pressure between two points
- A BJT is essentially a controlled valve, with the flow of water at the base pipe acting as the control. (not quite as straightforward as the ideal diode!)

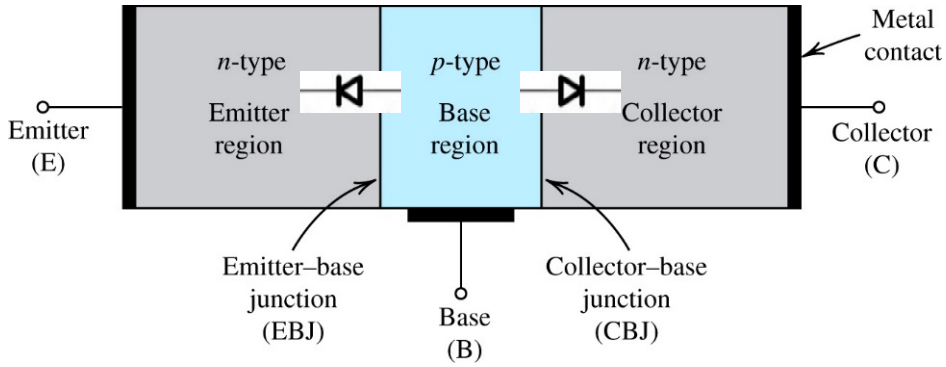




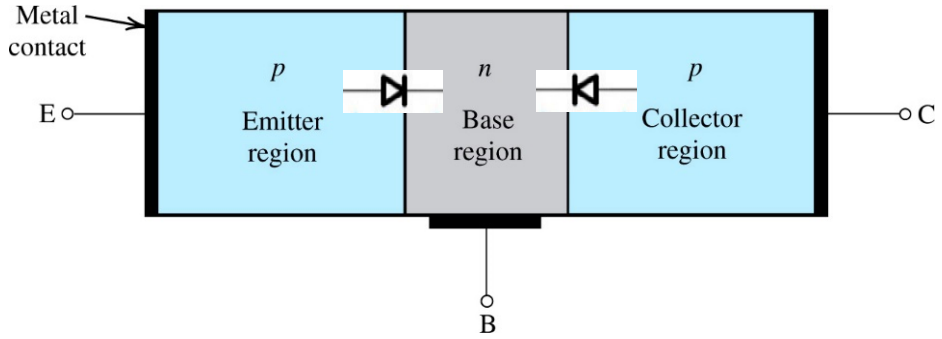
The Bipolar Junction Transistor

DIAGRAMS AND CIRCUIT SYMBOLS: NPN / PNP

- There are naturally two possible arrangements n-p-n or p-n-p

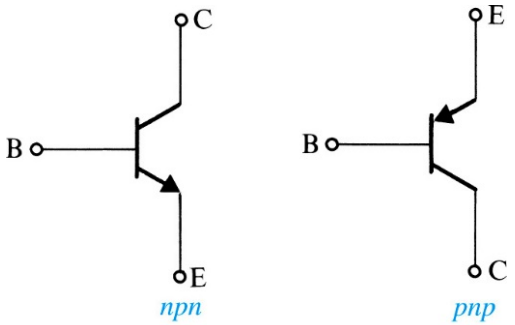


A simplified structure of the npn transistor.



A simplified structure of the pnp transistor.

BJT symbols



Arrows show the current of controlling pn-junction

The Bipolar Junction Transistor

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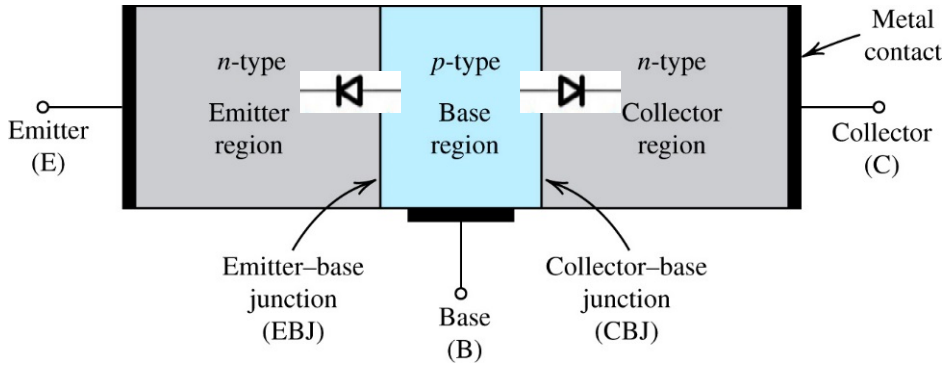

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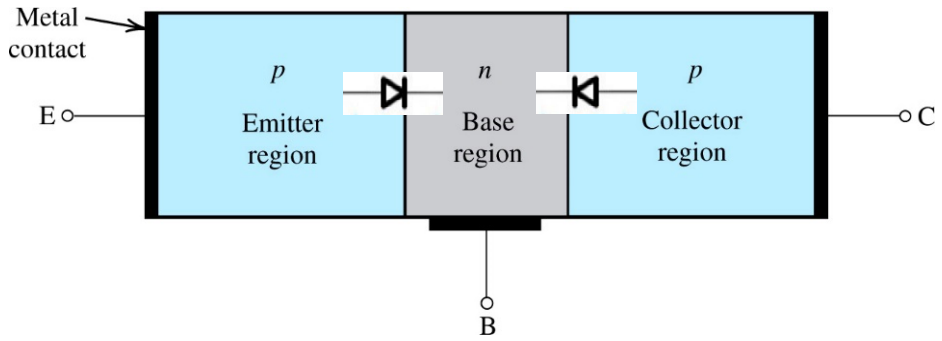

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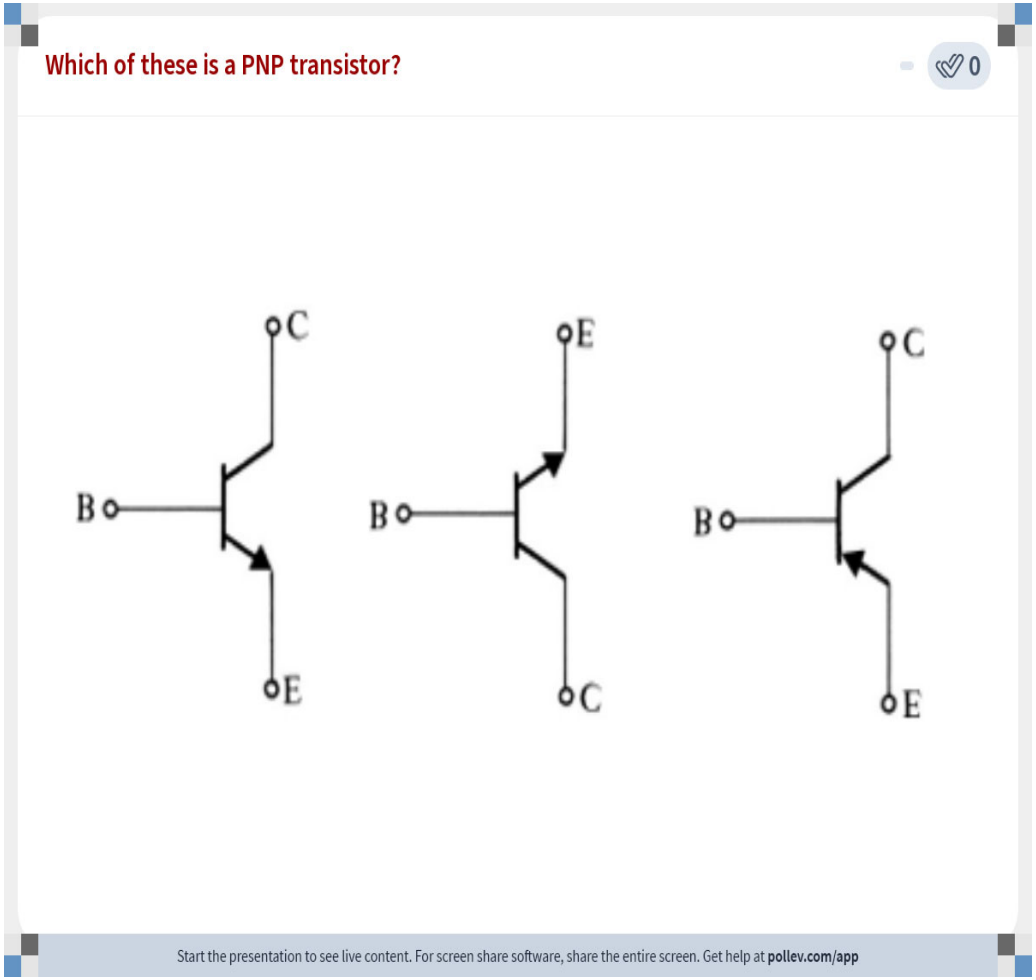

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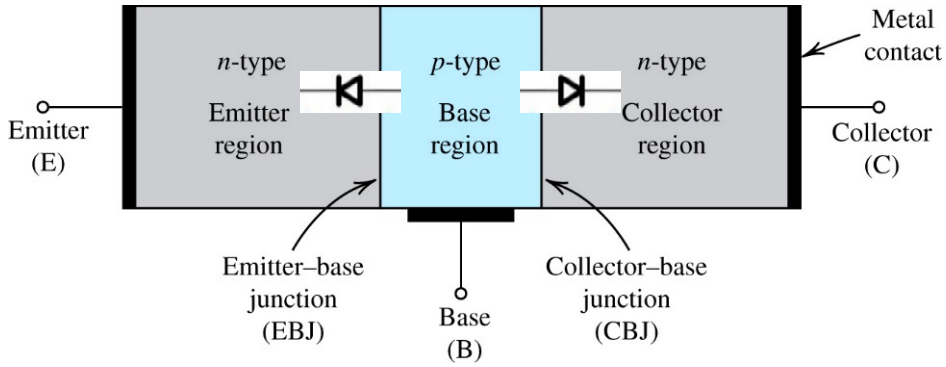

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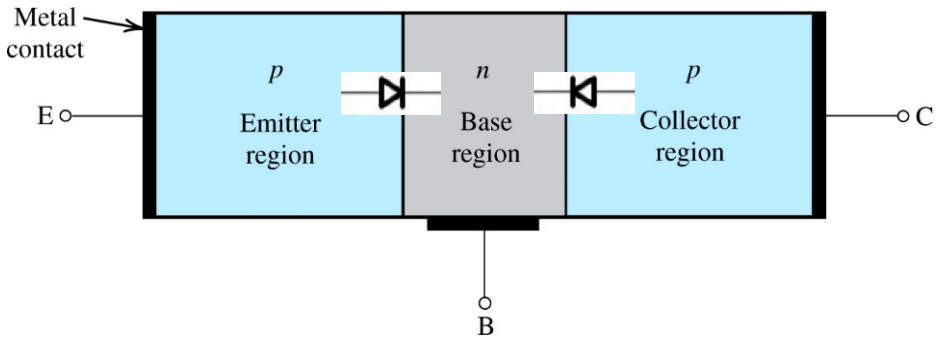

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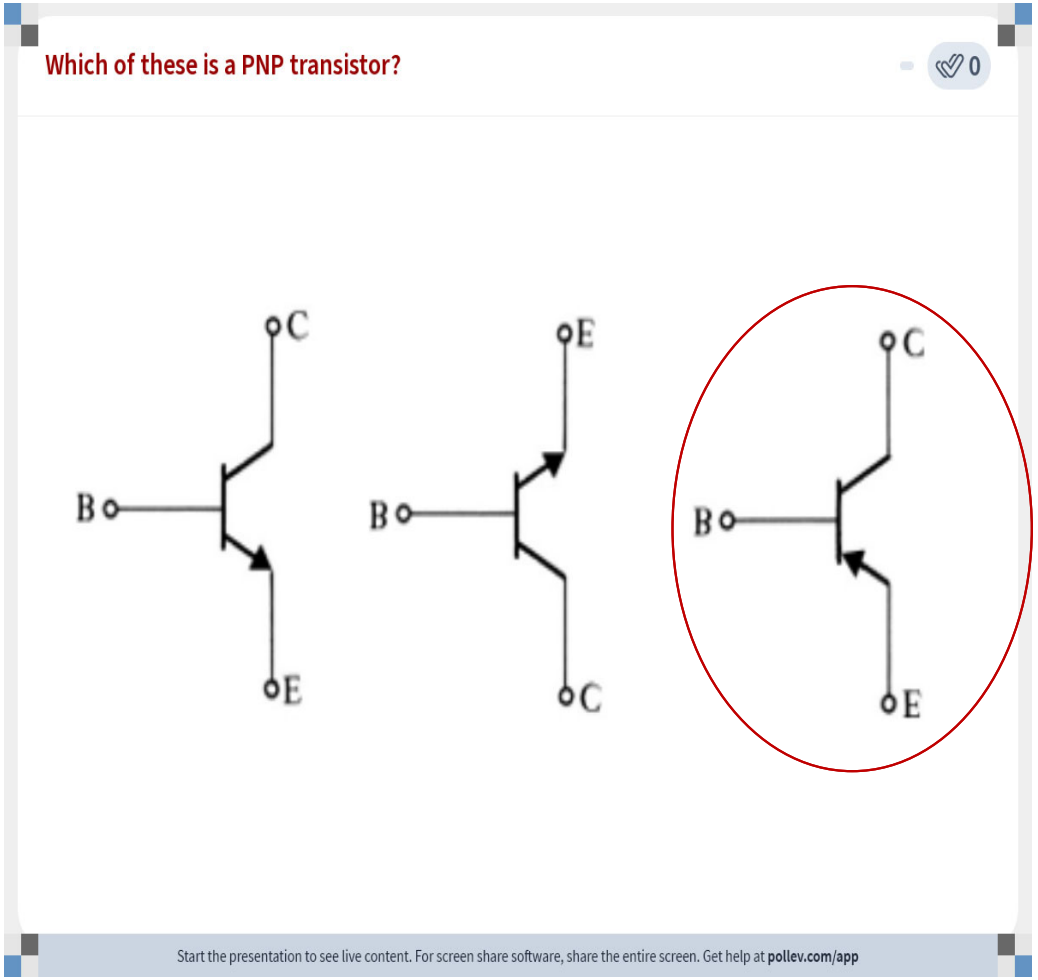

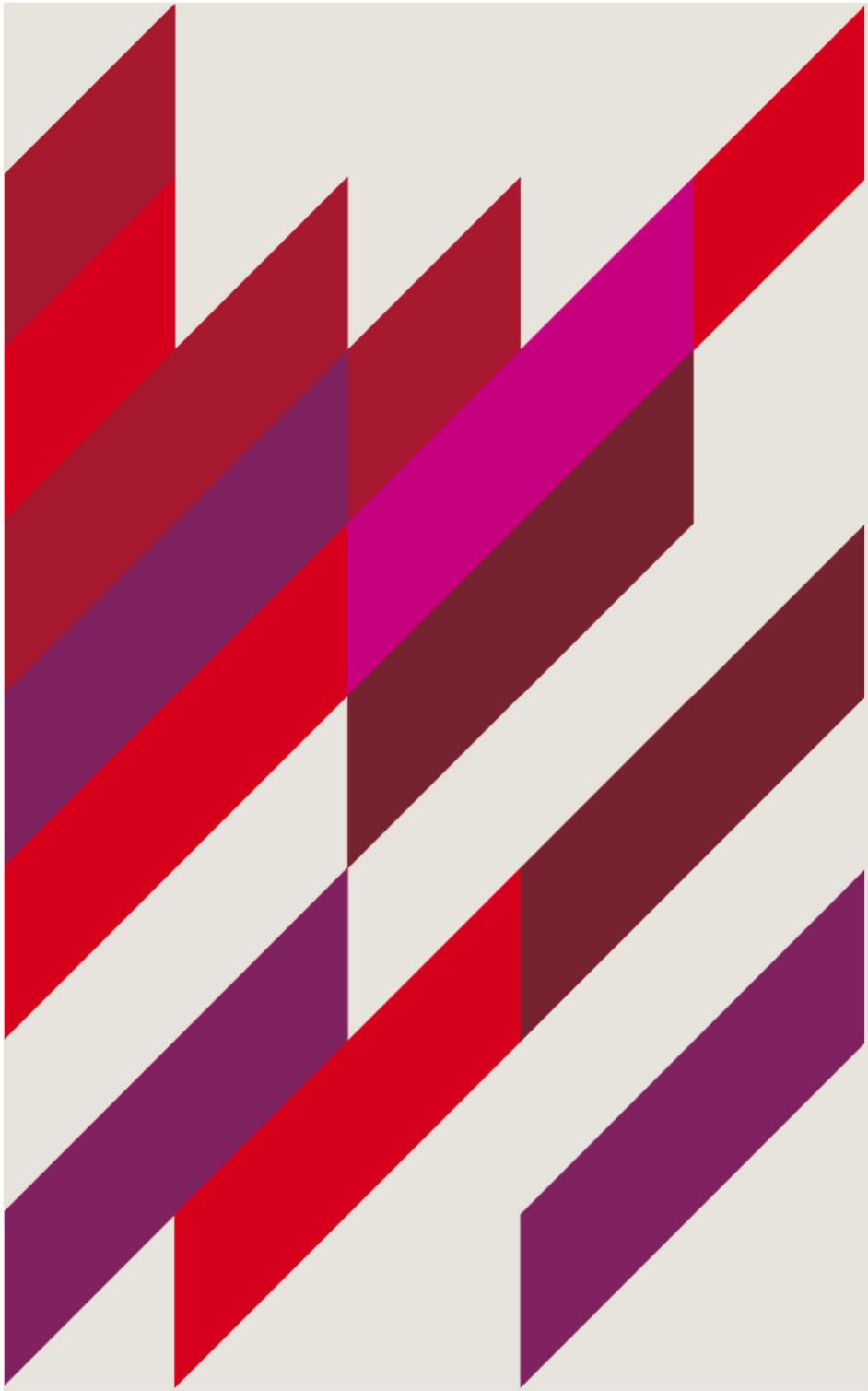

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Lecture 3

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The Bipolar Junction Transistor

MODES OF OPERATION

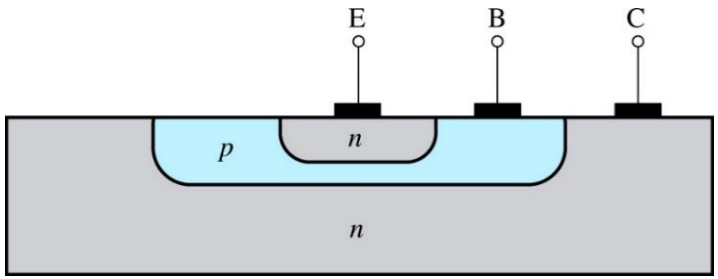
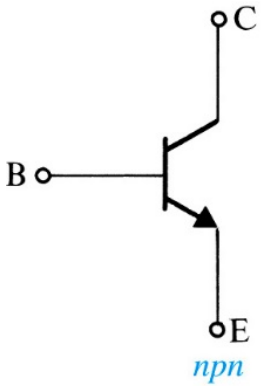
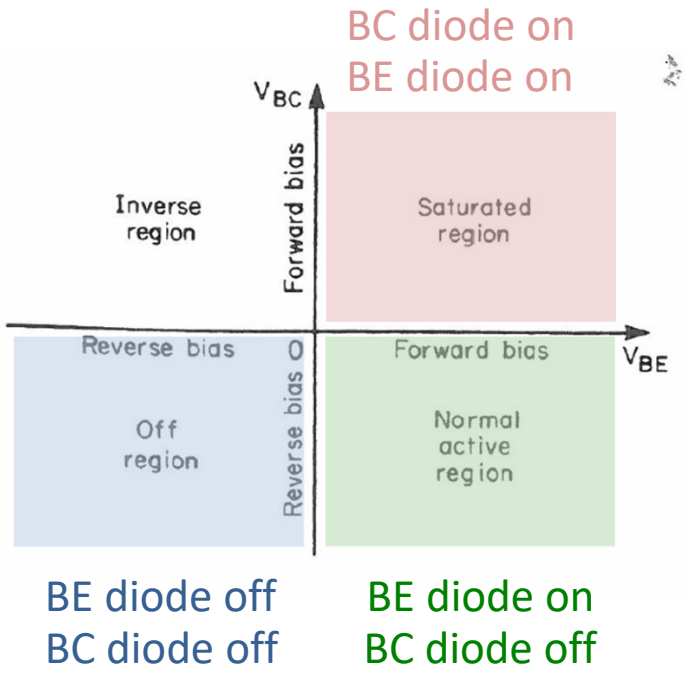


Diagram of physical npn BJT on wafer





Operating mode depends on dc biasing or large signal voltages and currents:

- active mode – used for ac amplification
- cutoff and saturation modes – used for switching.
- BJT is not symmetrical – inverse region is not normally used

The Bipolar Junction Transistor

ACTIVE REGION

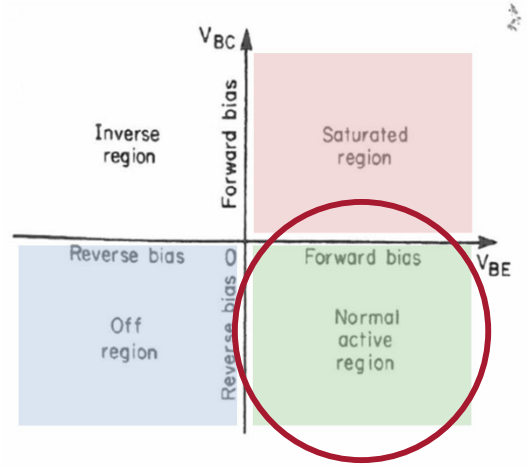
In Active region, BE = Forward biased, BC = Reverse biased

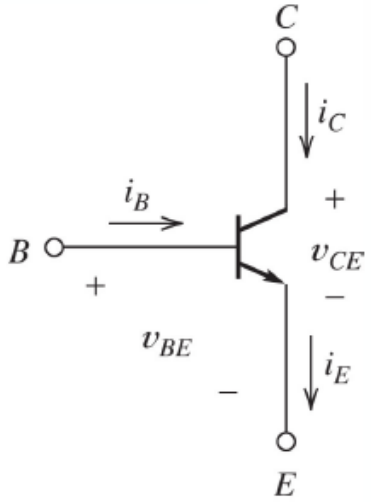
From Kirchoff: $i_E = i_C + i_B$

Base current is much smaller than collector current

We define: $\boxed{i_C = \beta i_B}$ $\quad i_C = \alpha i_E \quad \alpha = \dfrac{\beta}{\beta+1}$

Typical value: $\beta = 100 \quad \alpha = 0.9 - 0.99$





$$i_E = \left(\frac{I_S}{\alpha}\right)\left(e^{v_{BE}/V_T} - 1\right) \approx \left(\frac{I_S}{\alpha}\right) e^{v_{BE}/V_T}$$

$$i_B \approx \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T}$$

$$i_C \approx I_S e^{v_{BE}/V_T}$$

Base-emitter voltage controls the collector current!

Emitter current is the total current.

$$i_E = i_B + i_C = \frac{i_C}{\alpha}$$

The Bipolar Junction Transistor

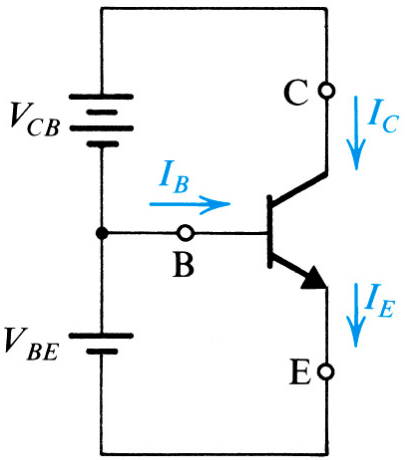
ACTIVE REGION

From Kirchhoff: $i_E = i_C + i_B$

From the diode equation: $i_C = I_s e^{v_{BE}/V_T}$

Constant (Saturation current)

Constant (Thermal voltage)



Base current is much smaller than collector current

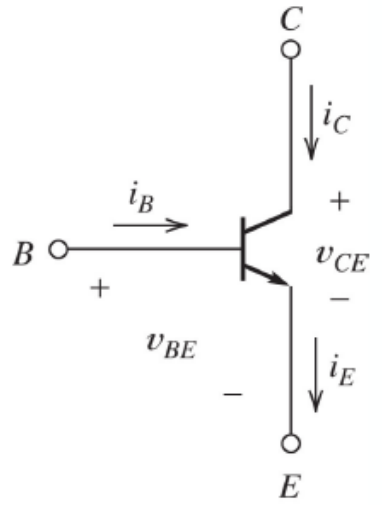
$$i_B = \frac{i_C}{\beta} = \frac{I_s}{\beta} e^{v_{BE}/V_T}$$

common-emitter current gain

Emitter current is the total current.

$$i_E = i_B + i_C = \frac{i_C}{\alpha}$$

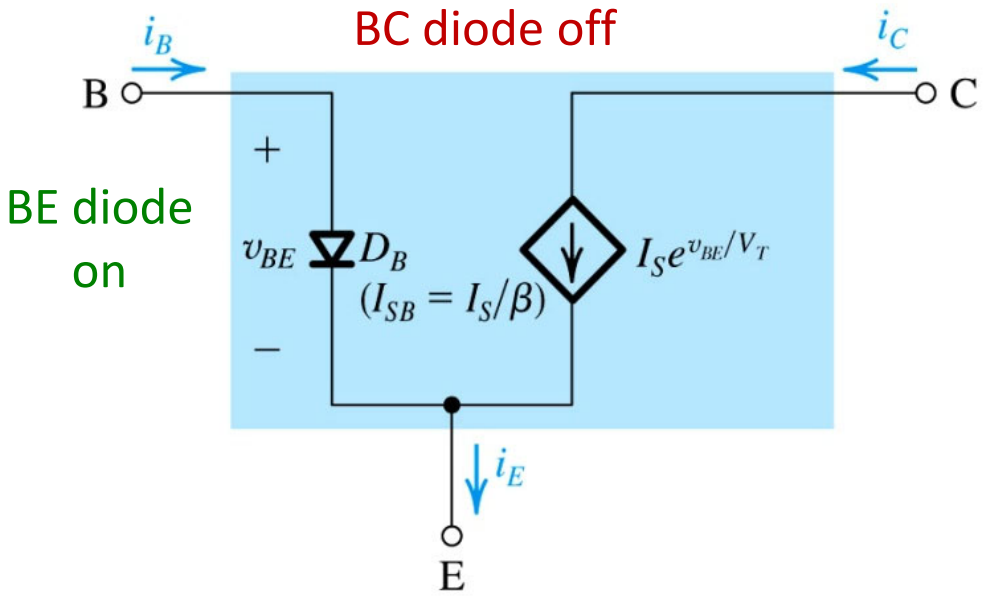
emitter injection efficiency

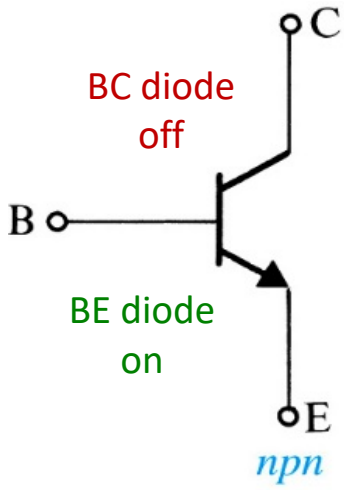


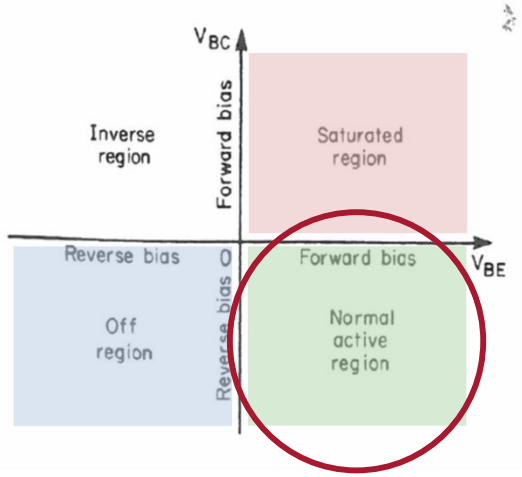
The Bipolar Junction Transistor

ACTIVE MODE – EQUIVALENT CIRCUIT

Large-signal equivalent-circuit model of the *npn* BJT operating **in the forward active mode.**







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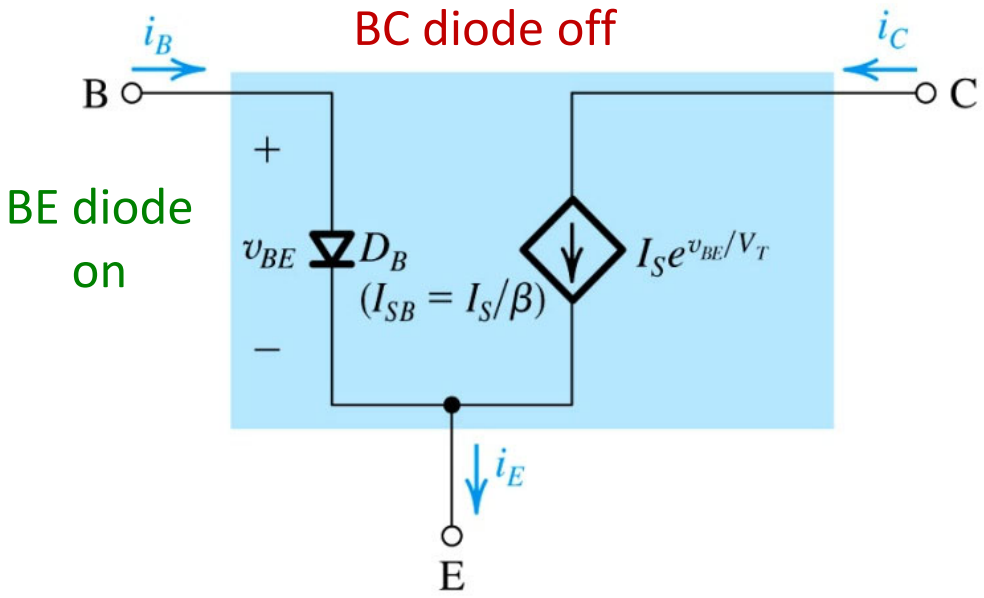
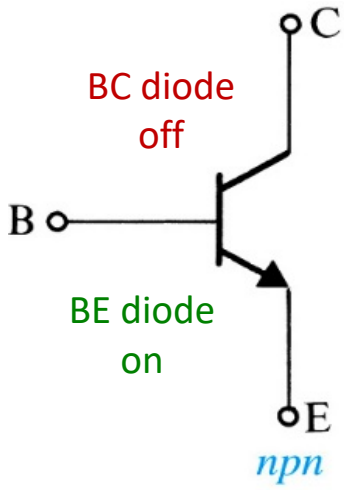
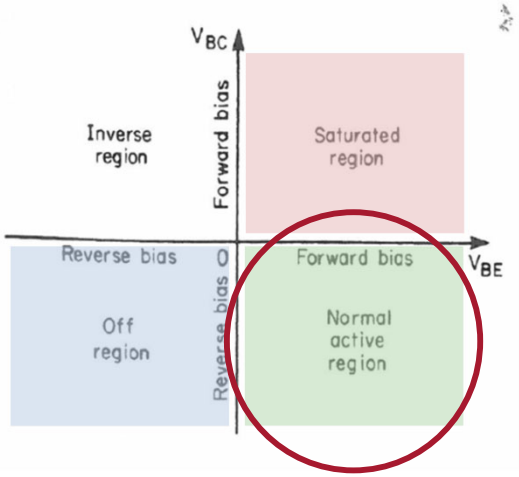






$$\alpha = \frac{\beta}{\beta + 1}$$

Collector current is controlled by the base-emitter voltage:

$$i_C = I_s e^{v_{BE}/V_T}$$

Base current is much smaller than the collector current:

$$i_B = \frac{i_C}{\beta}$$

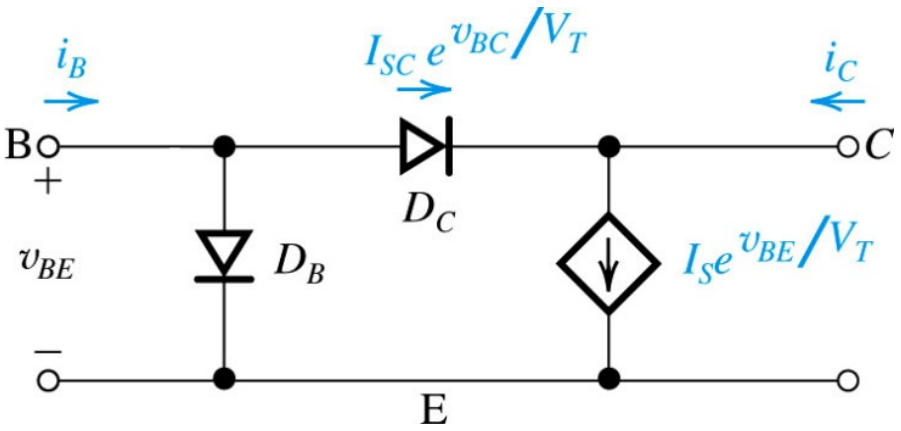
Emitter current is total current:

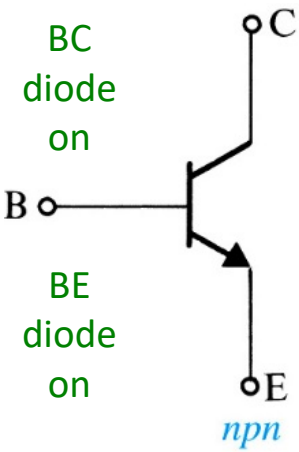
$$i_E = i_B + i_C = \frac{i_C}{\alpha}$$

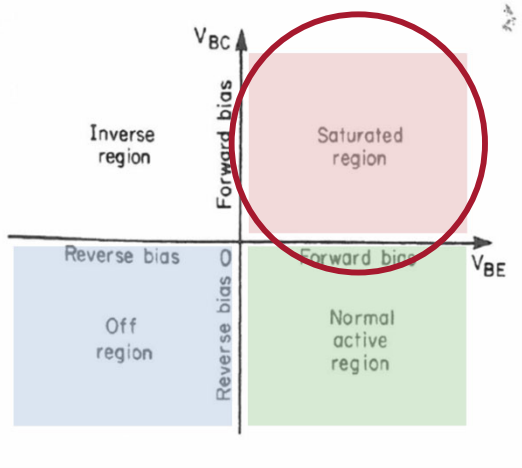
The Bipolar Junction Transistor

SATURATION REGION

npn BJT **in saturation:**







The Bipolar Junction Transistor

SATURATION REGION

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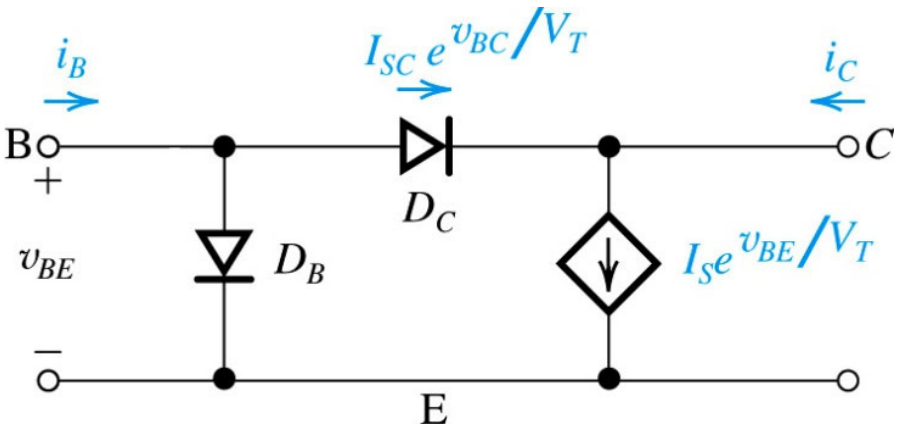
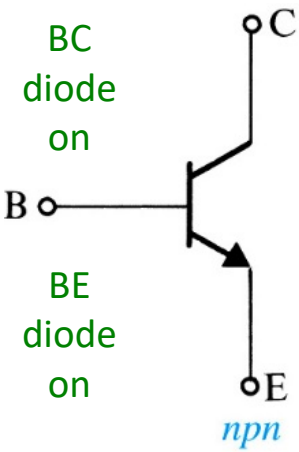
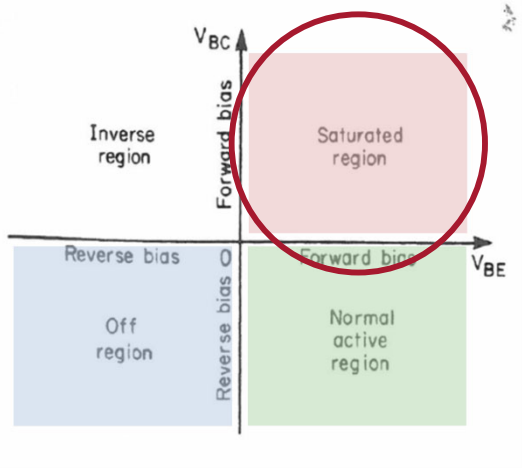






$$i_C = I_s e^{v_{BE}/V_T} - I_{sc} e^{v_{BC}/V_T}$$

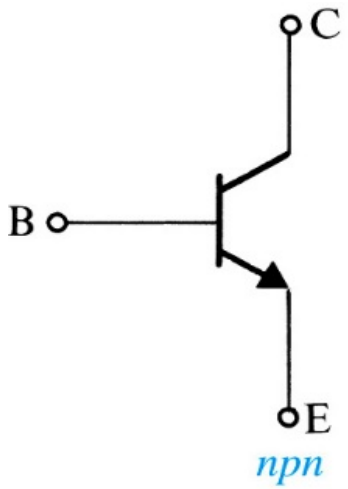
$$i_B = \frac{I_s}{\beta} e^{v_{BE}/V_T} + I_{sc} e^{v_{BC}/V_T}$$

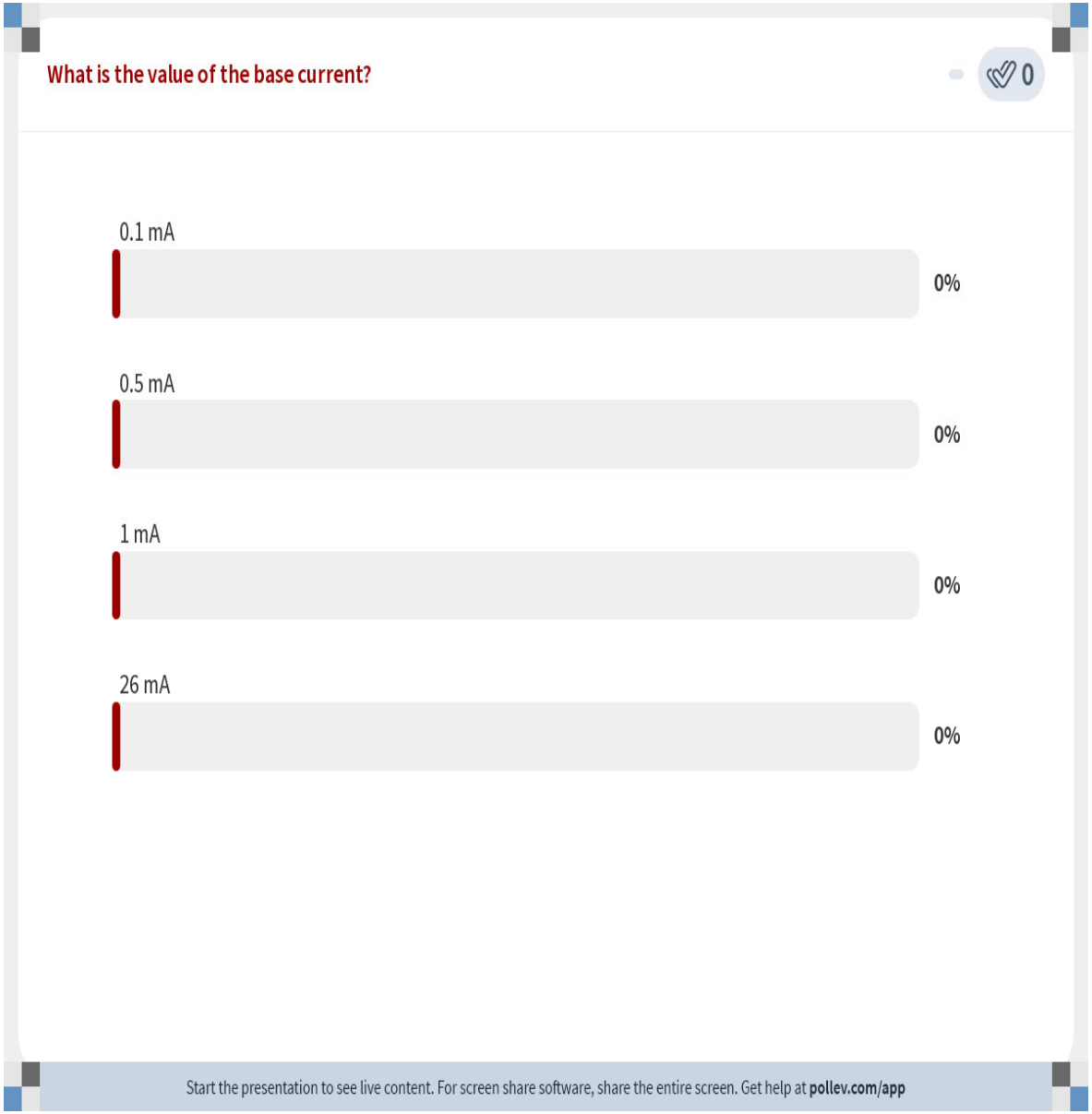
$$\beta_{forced} = \frac{i_C}{i_B}\,(at\ saturation) \leq \beta$$

Class Exercise

Find i_B

For an npn BJT in the active mode, saturation current $I_s = 1pA,\ v_{BE} = 0.6V, \beta = 260$ at room temperature.
Find the base current, i_B





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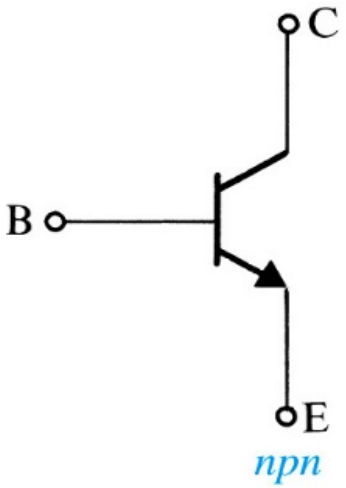
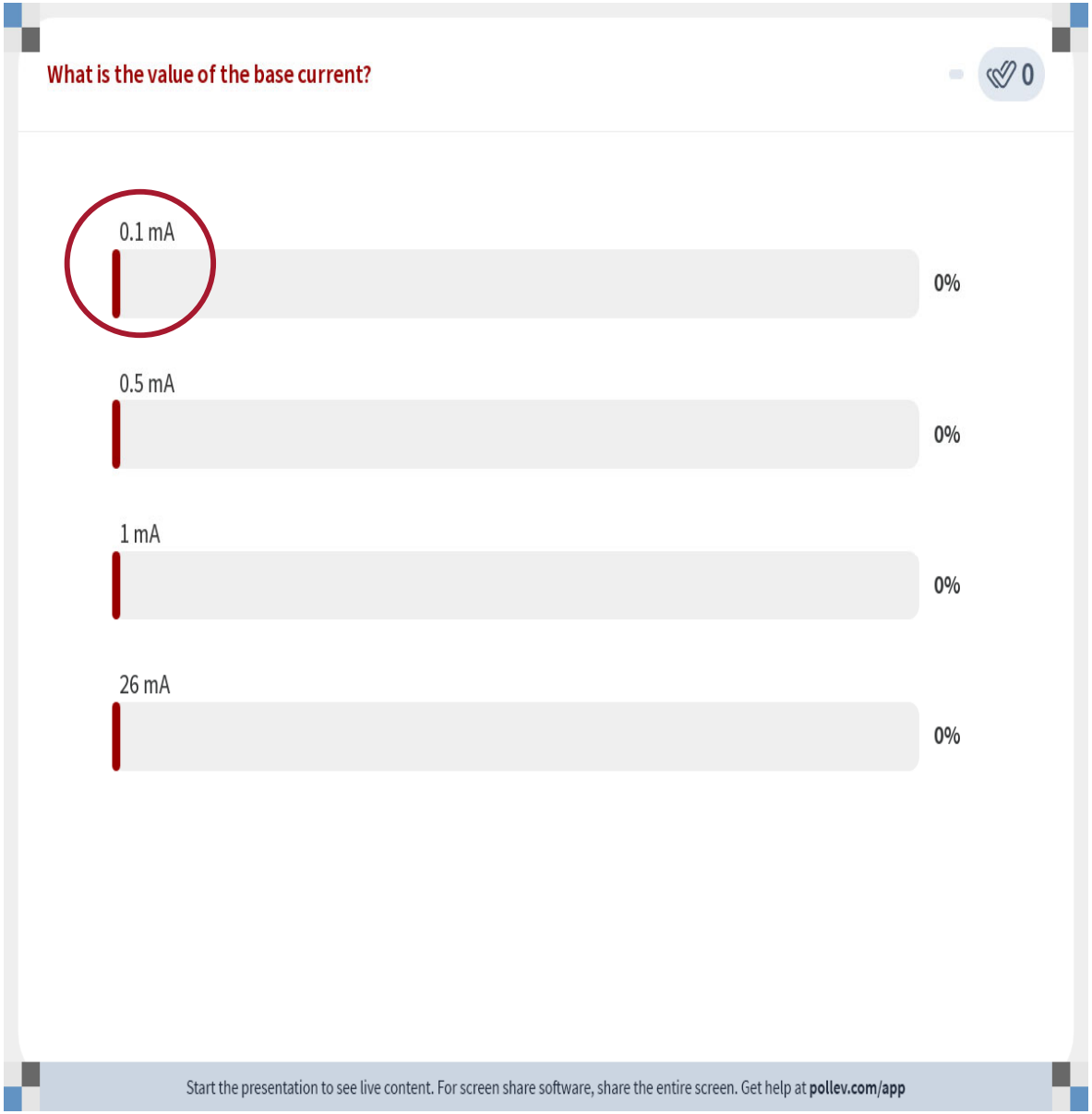
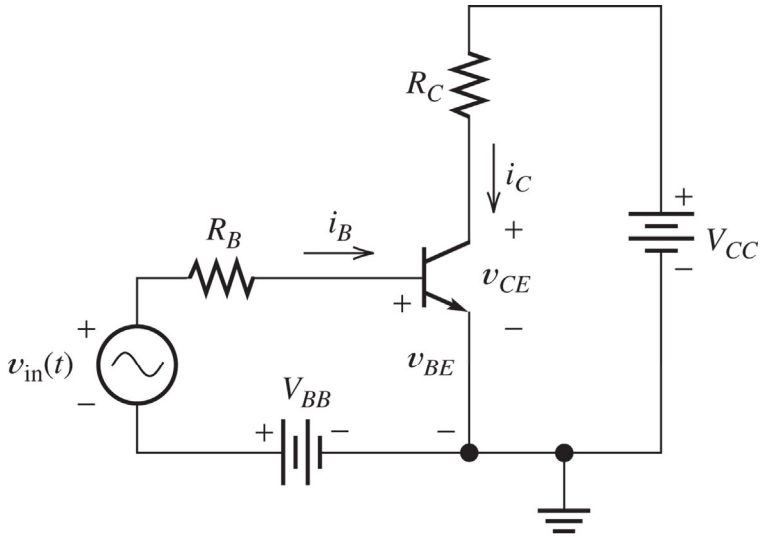


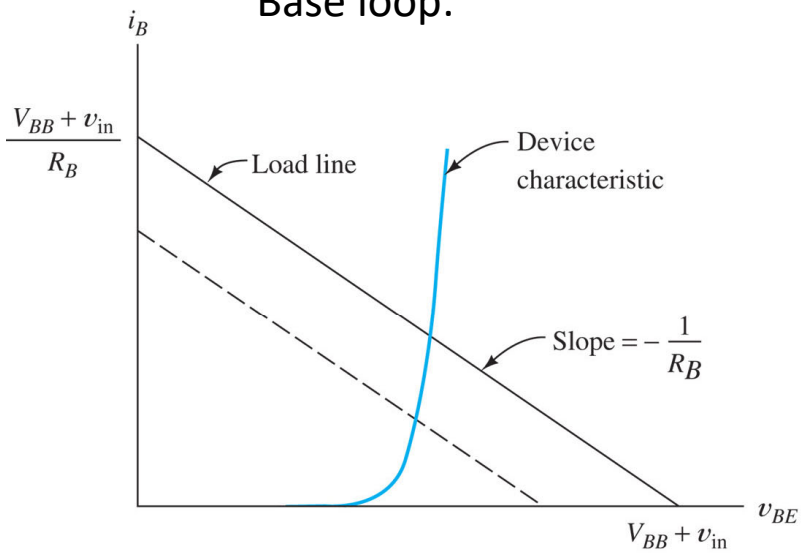


The Bipolar Junction Transistor

LOAD LINE ANALYSIS

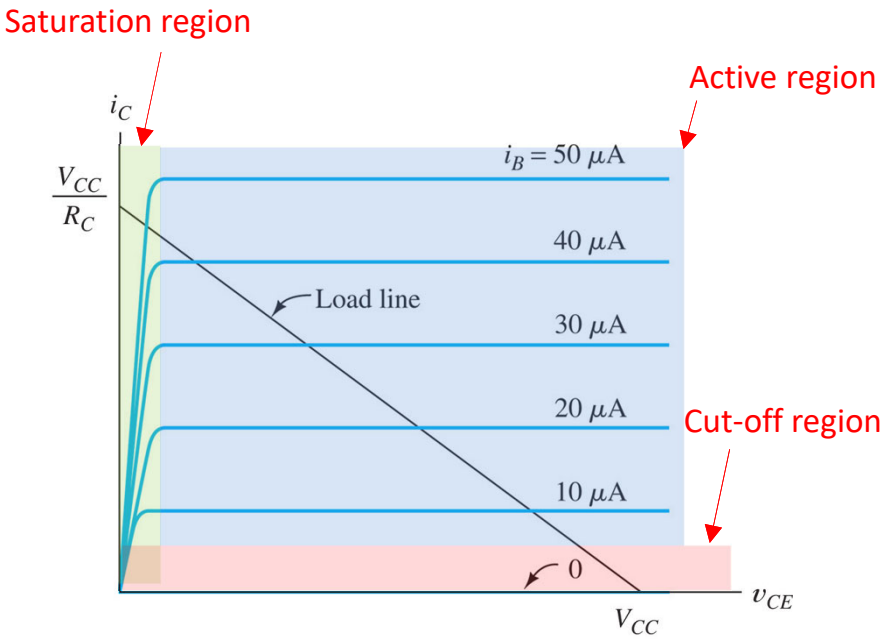


Base loop:



(a) Input load line (shifts to dashed line for a smaller value of v_{in})

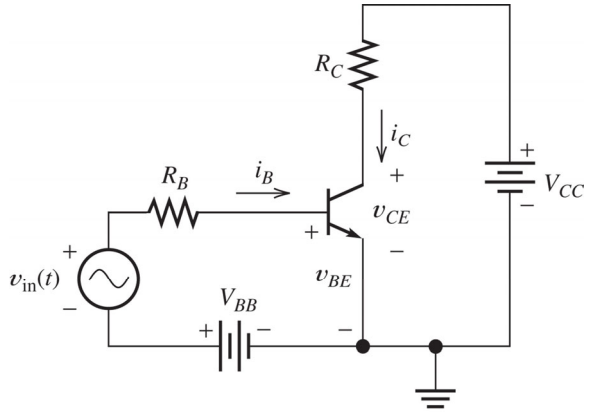
Collector loop:



(b) Output

The Bipolar Junction Transistor

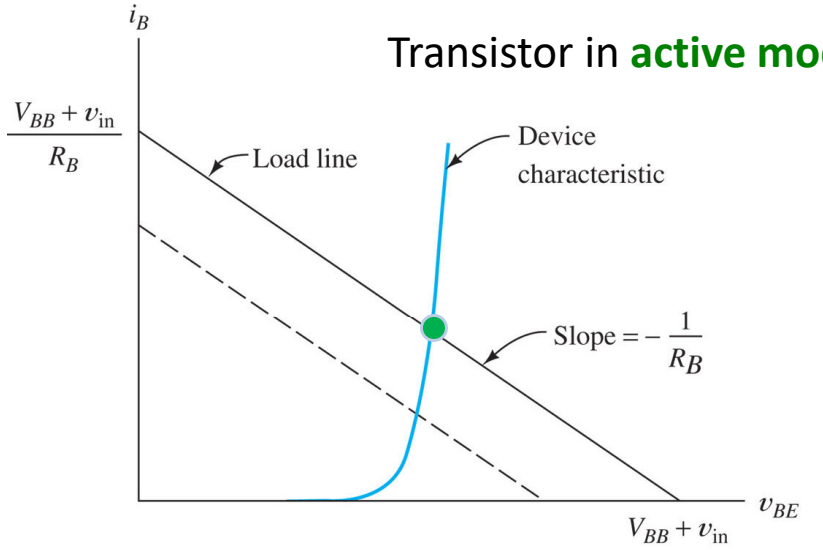
LOAD LINE ANALYSIS



Base loop:

Transistor in **active mode**

Collector loop:



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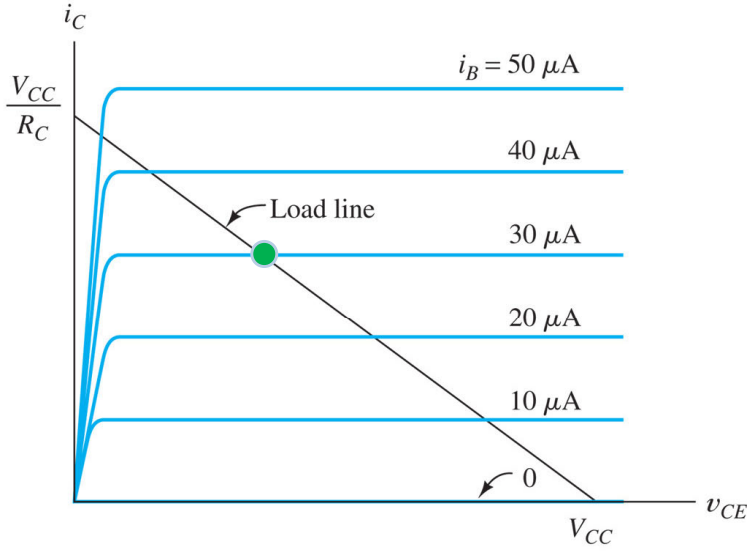
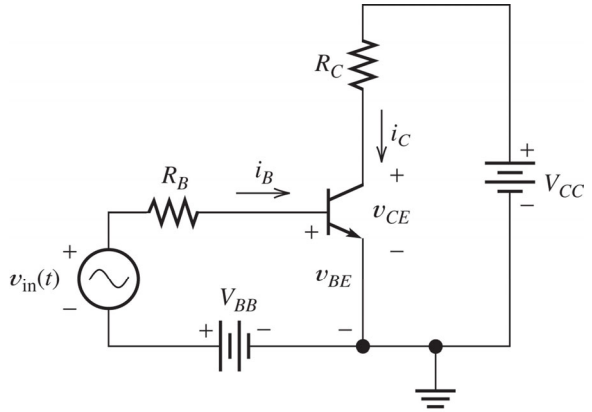


(b) Output

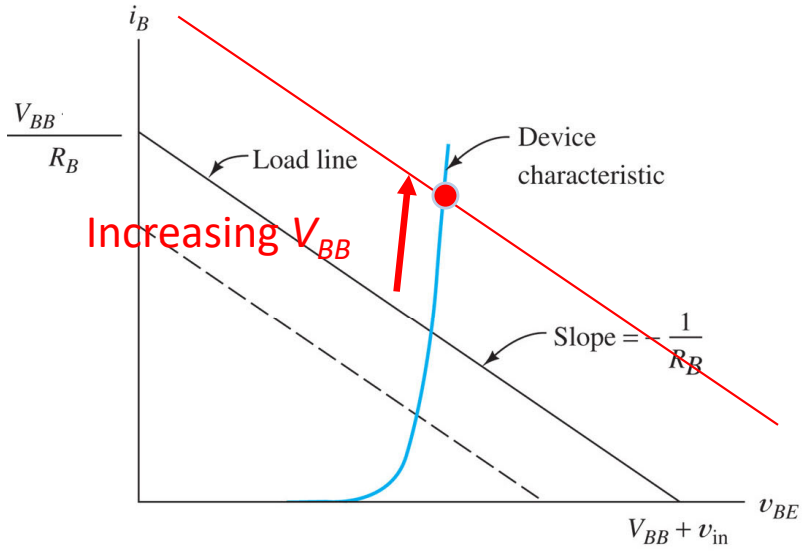
The Bipolar Junction Transistor

LOAD LINE ANALYSIS

If the base current is too high we reach saturation

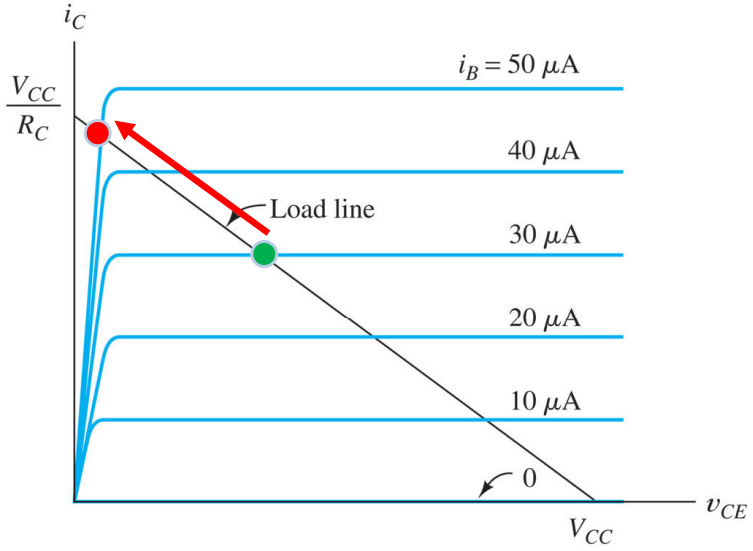


Base loop:



(a) Input load line (shifts to dashed line for a smaller value of v_{in})

Collector loop:

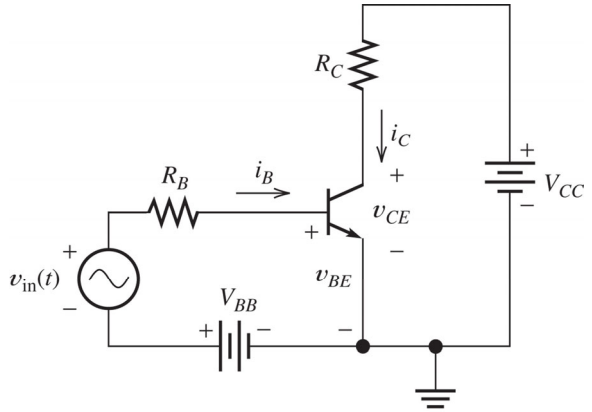


(b) Output

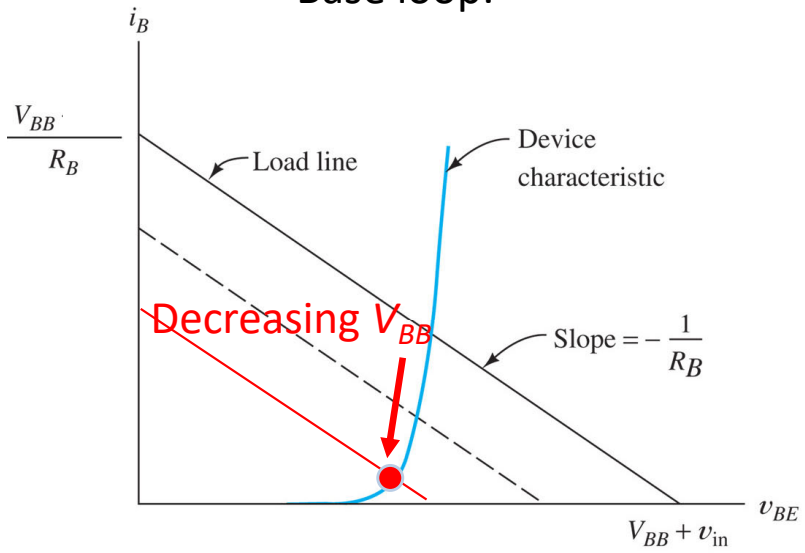
The Bipolar Junction Transistor

LOAD LINE ANALYSIS

If the base current is too low we reach cut-off

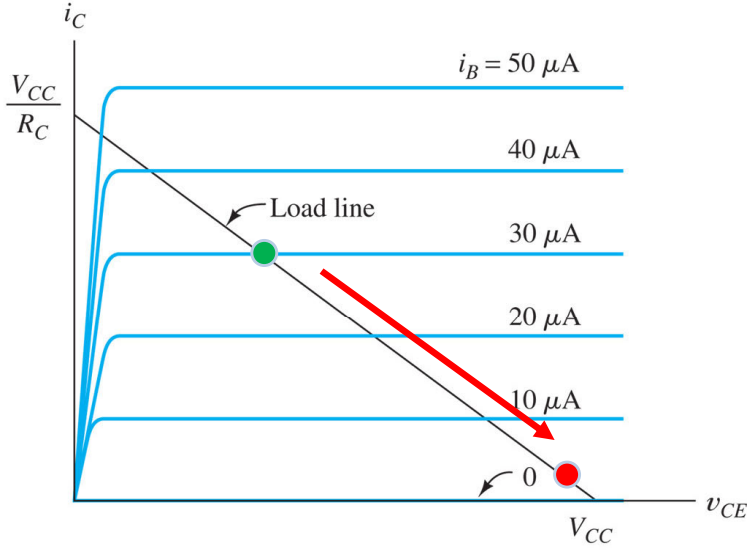


Base loop:



(a) Input load line (shifts to dashed line for a smaller value of v_{in})

Collector loop:



(b) Output

The Bipolar Junction Transistor

LARGE SIGNALS CURRENT SUMMARY

$V_{CE} > 0 \qquad V_A = \infty \qquad V_T = \frac{kT}{q} \cong 25\ \text{mV at room temperature}$

On the formula sheet!

V_{BE}	V_{BC}	$V_{CE}\,(>0)$	Mode	$I_C(V_{BE}, V_{CE})$
< 0.5	< 0.4	> 0	cut-off	$I_C \cong 0$
~ 0.7	> 0.4	< 0.3	saturation	$V_{CE} \cong 0.2$ or $I_C = I_S e^{V_{BE}/V_T} - I_{SC} e^{V_{CE}/V_T}$
~ 0.7	~ 0.4	~ 0.3	edge of saturation and active	$I_C = I_S e^{V_{BE}/V_T}$
~ 0.7	< 0.4	> 0.3	active	$I_C = I_S e^{V_{BE}/V_T}$

For pnp BJT use the same current equations but with reversed voltage polarities

MACQUARIE University

Lecture 3

1. BJT Device Structure
2. BJT Modes of Operation
3. **BJT Models**

The Bipolar Junction Transistor

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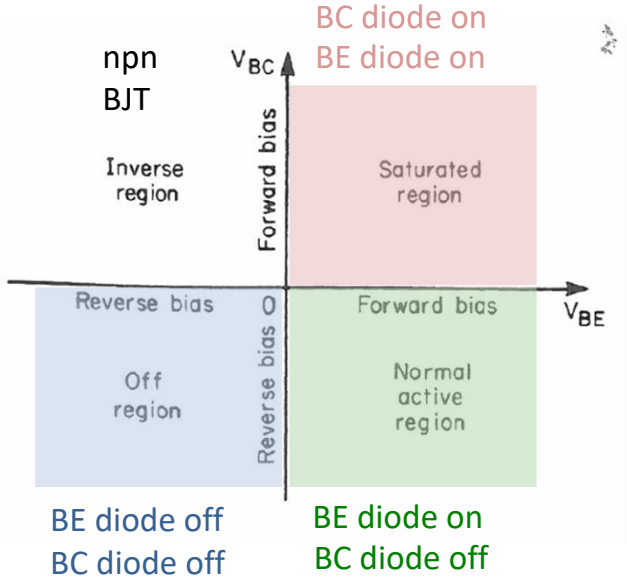
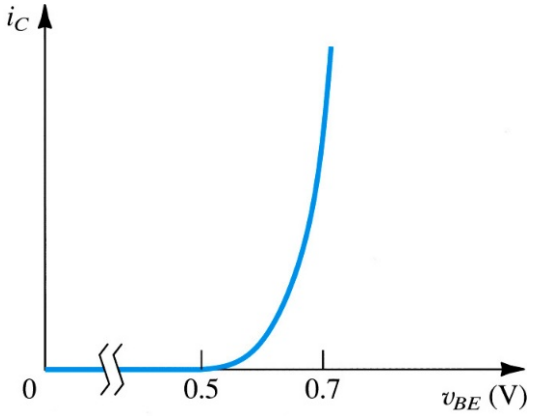
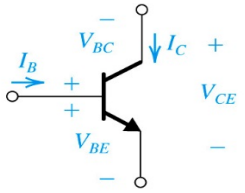
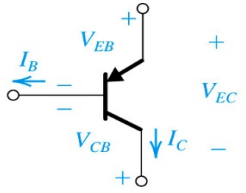
SUMMARY OF SIMPLE BJT MODELS

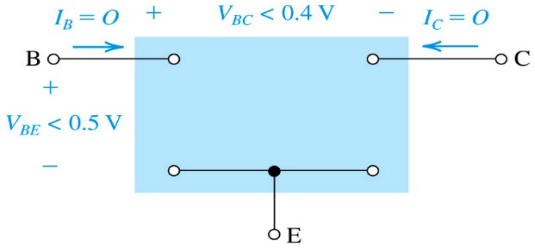


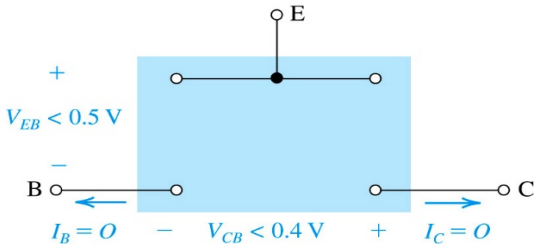




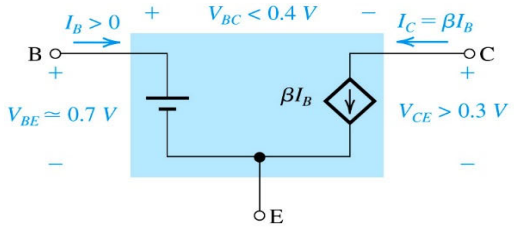


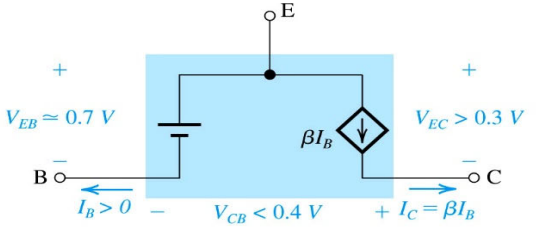
Cut-off



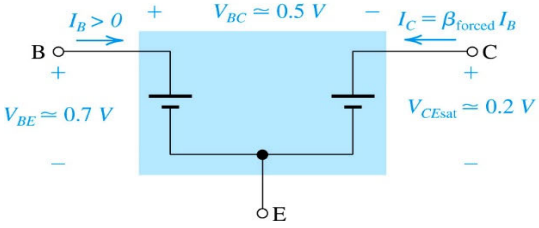


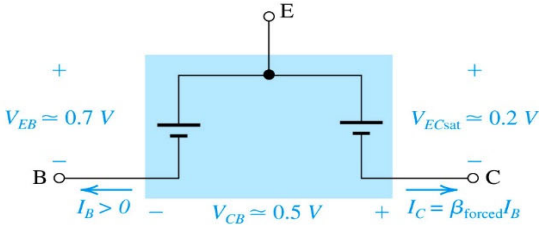
Active





Saturation



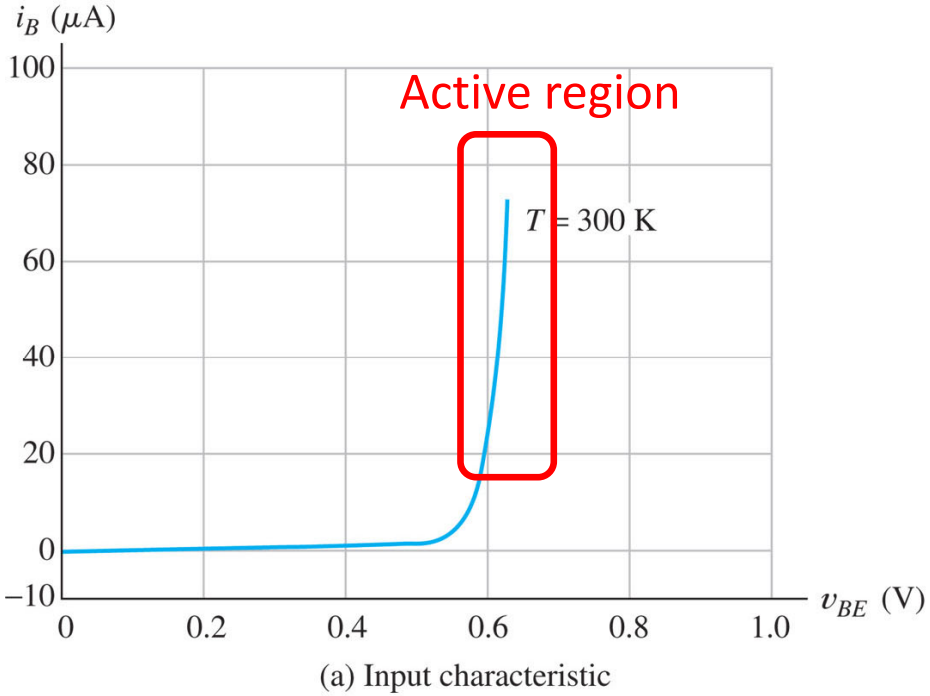


Remember these models are only approximate!

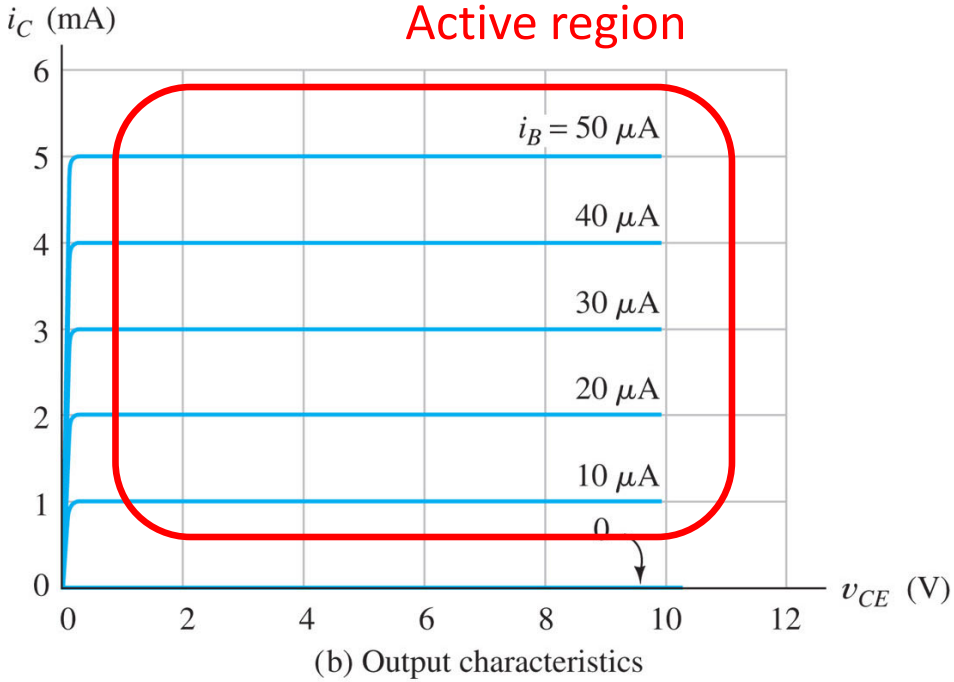
The Bipolar Junction Transistor

CONSTANT VOLTAGE DROP APPROXIMATION

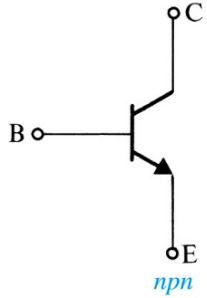
In the active region we can use a constant voltage (base side) and constant current (collector side) approximation:



(a) Input characteristic



(b) Output characteristics



$\upsilon_{BE} = \upsilon_B - \upsilon_E = 0.7\ \text{V}$

$\upsilon_{CE} = \upsilon_C - \upsilon_E > 0.2\ \text{V}$

$$i_B = \frac{i_C}{\beta} \qquad i_C = I_s e^{v_{BE}/V_T}$$

$$i_E = i_B + i_C = \frac{i_C}{\alpha}$$

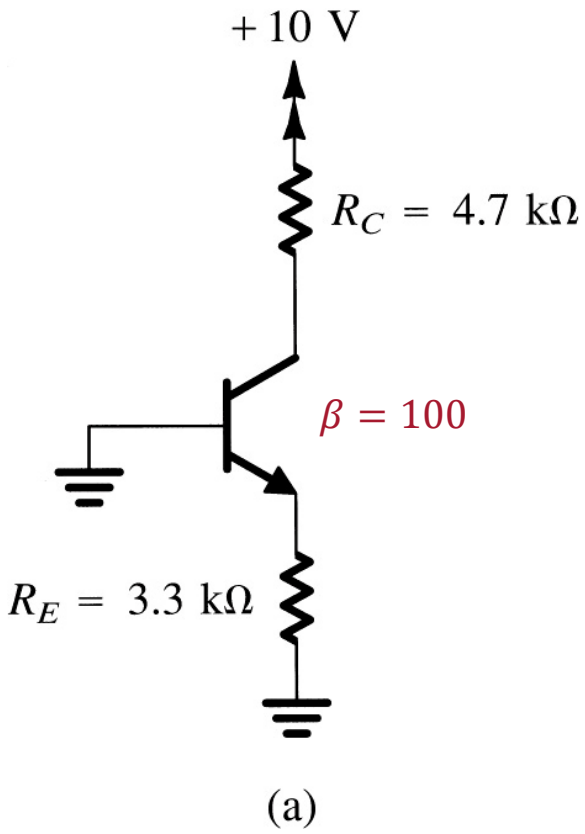
The Bipolar Junction Transistor

EXAMPLE-1

Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on.

Is BE diode ON in this circuit?



(a)

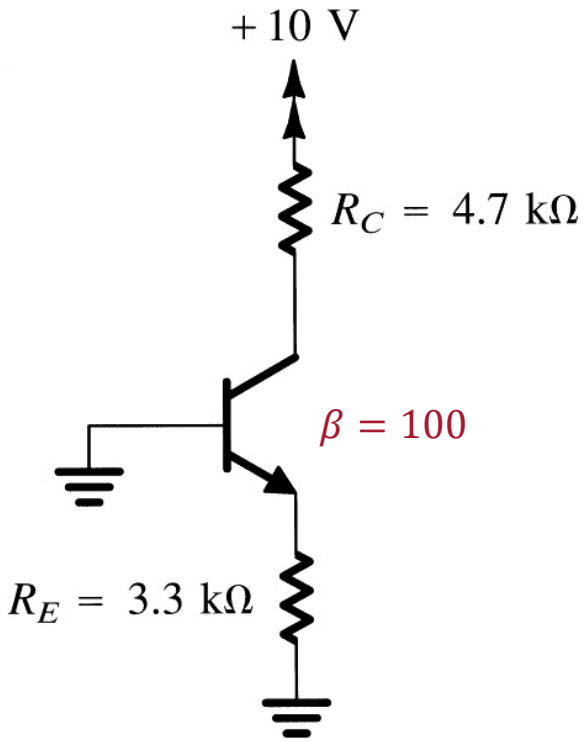
The Bipolar Junction Transistor

EXAMPLE-1

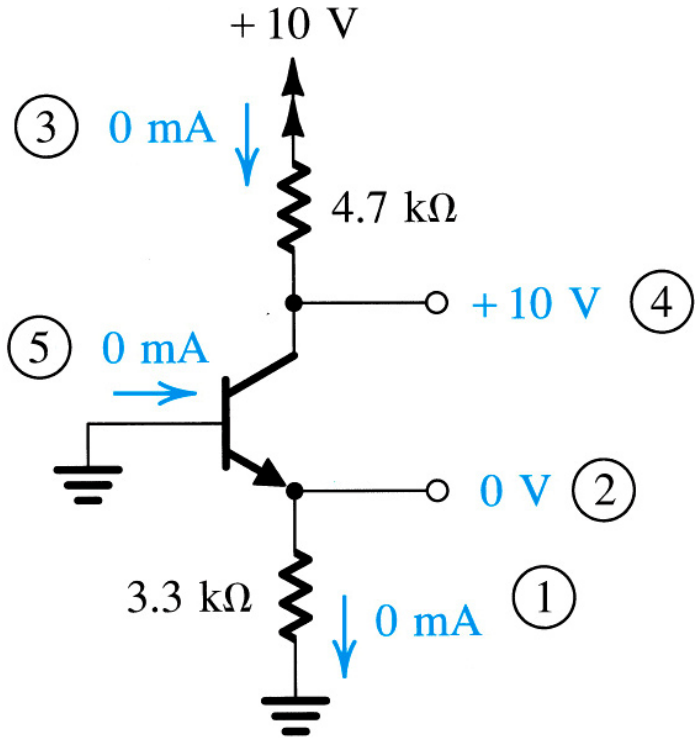
Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on

Is BE diode ON in this circuit?



(a)



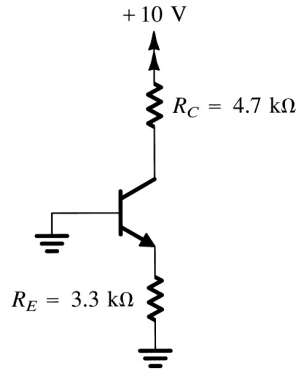
(b)

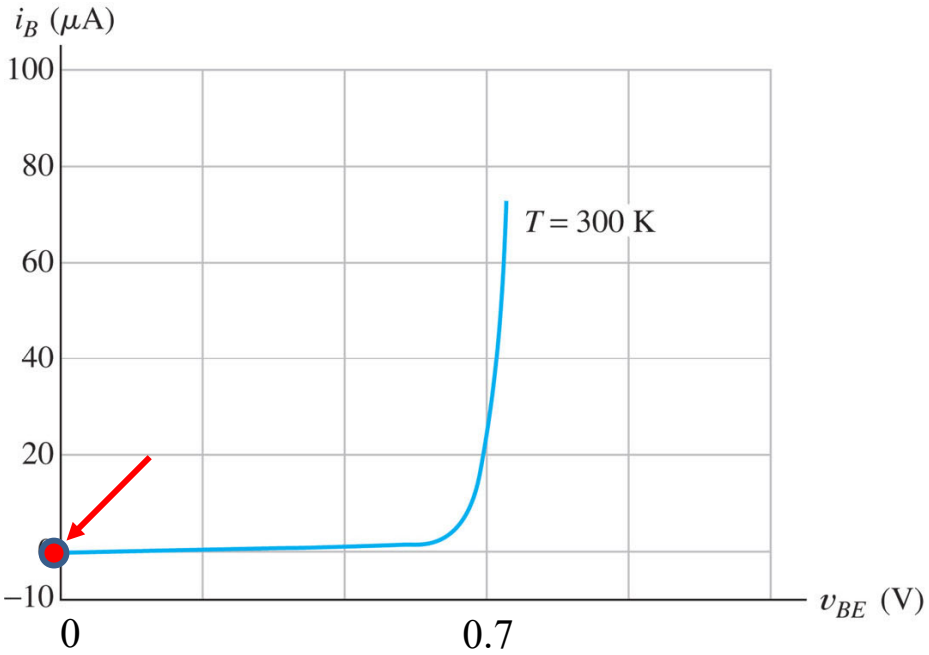
The Bipolar Junction Transistor

EXAMPLE-1 – CUT-OFF

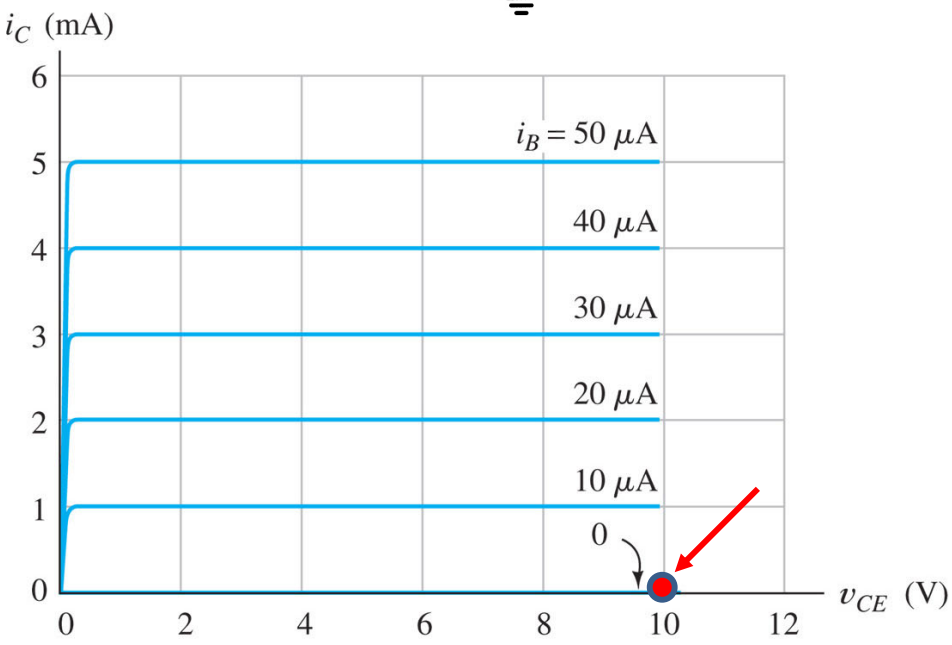
That was an example of cut-off

Operating in this region:





(a) Input characteristic



(b) Output characteristics

The Bipolar Junction Transistor

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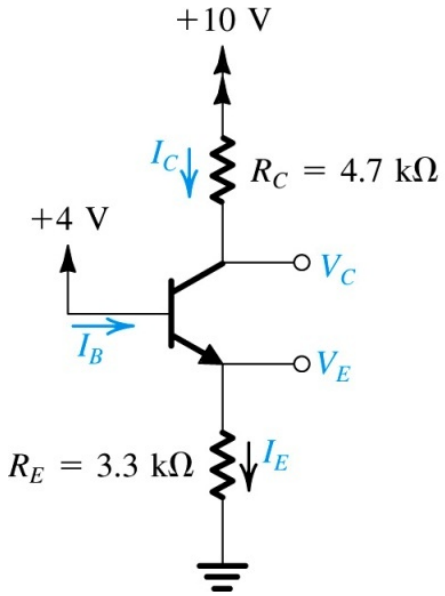
EXAMPLE-2

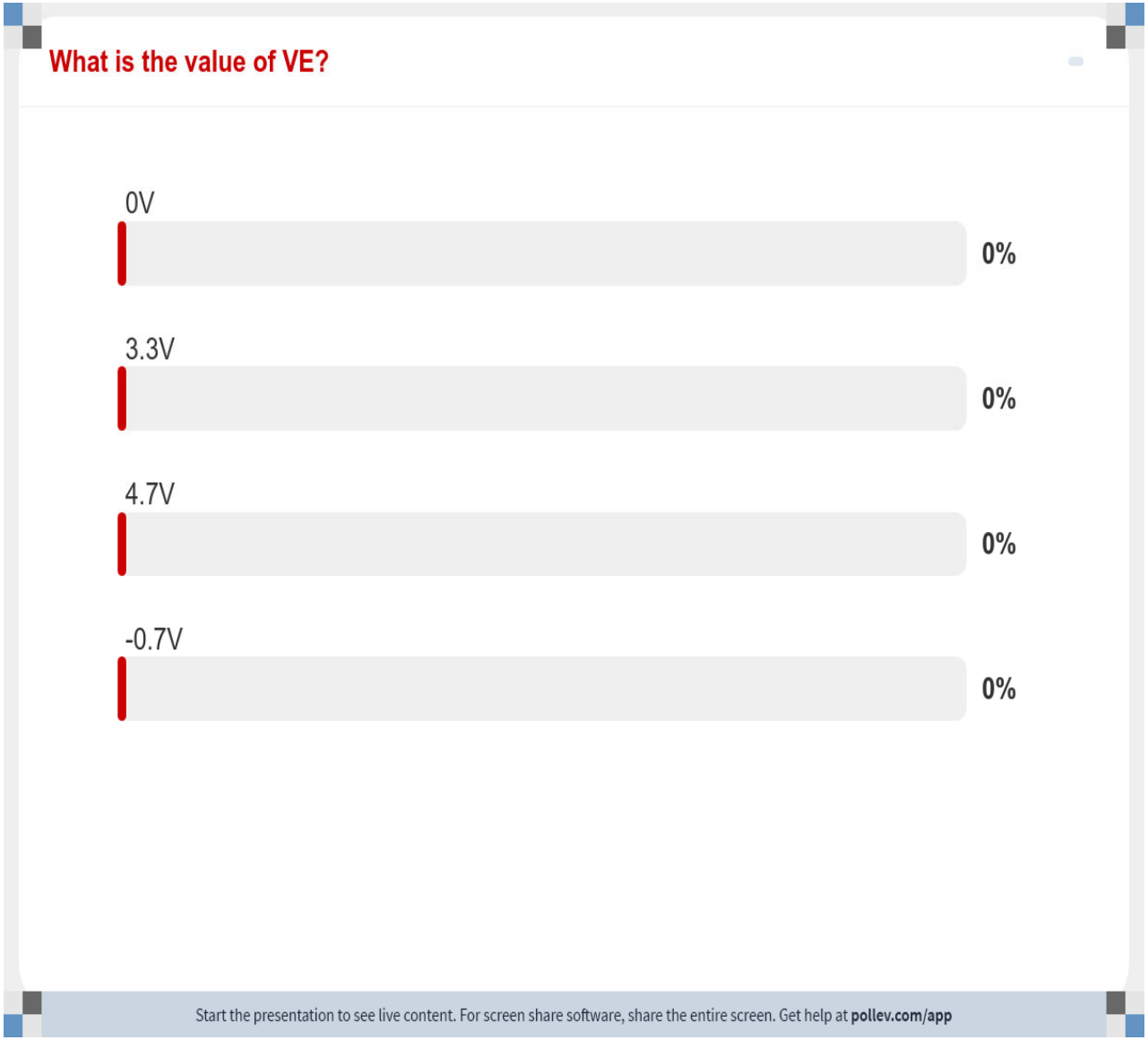
Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on

$\beta = 100$



Same as the previous circuit but V_B is higher



The Bipolar Junction Transistor

EXAMPLE-2

Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on

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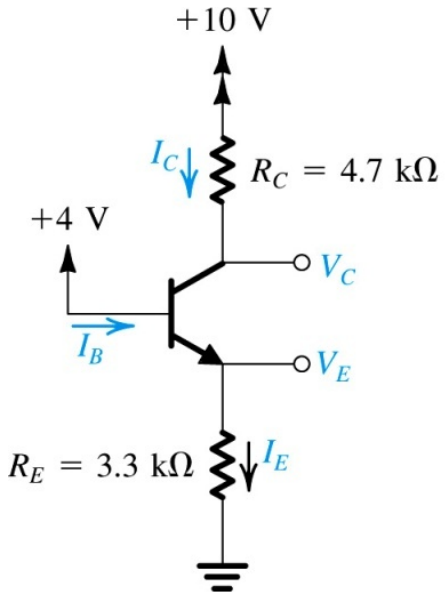
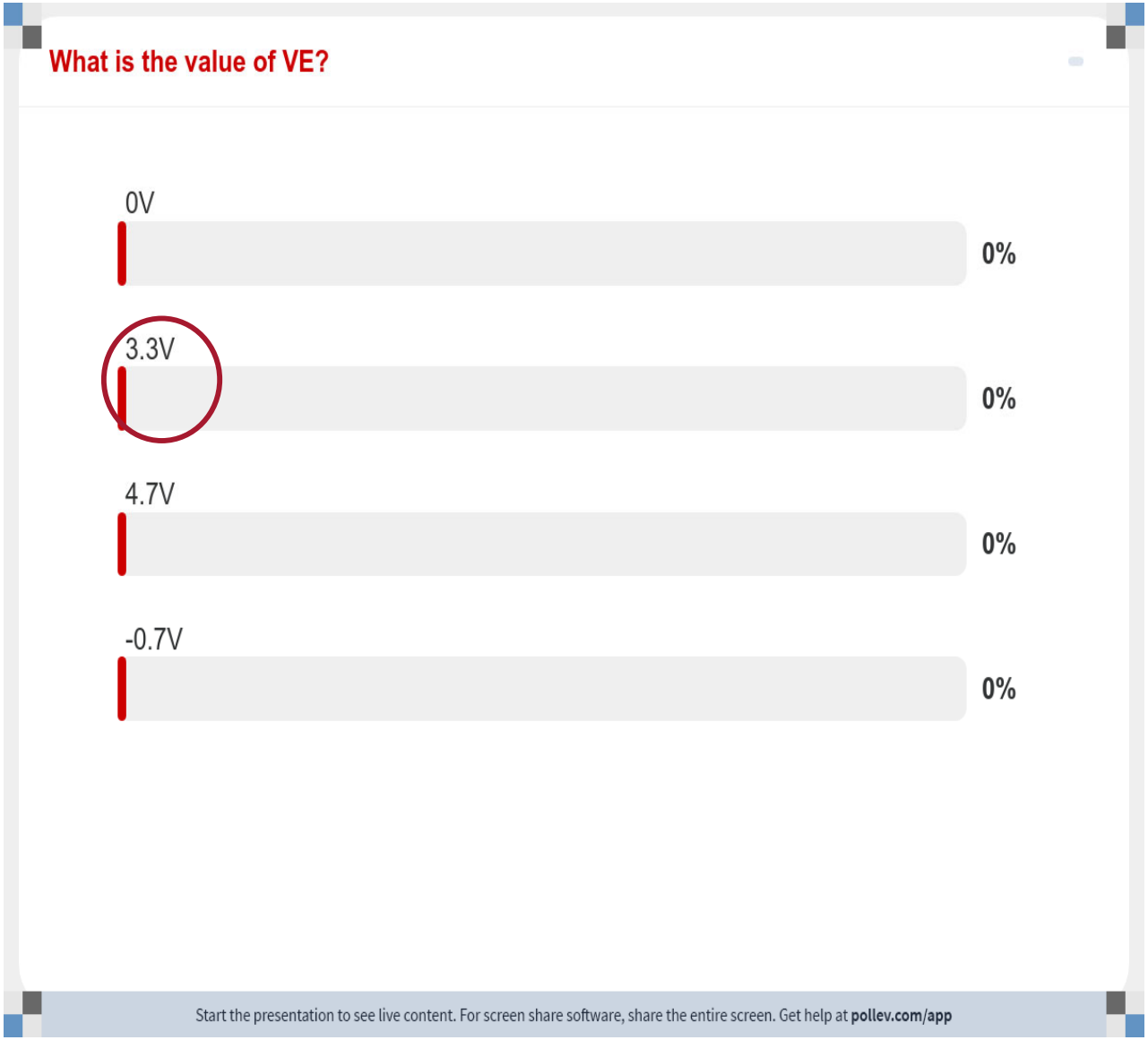


Same as the previous circuit but V_B is higher



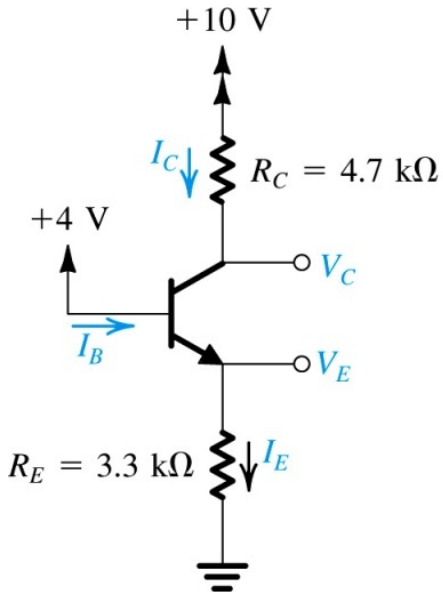
The Bipolar Junction Transistor

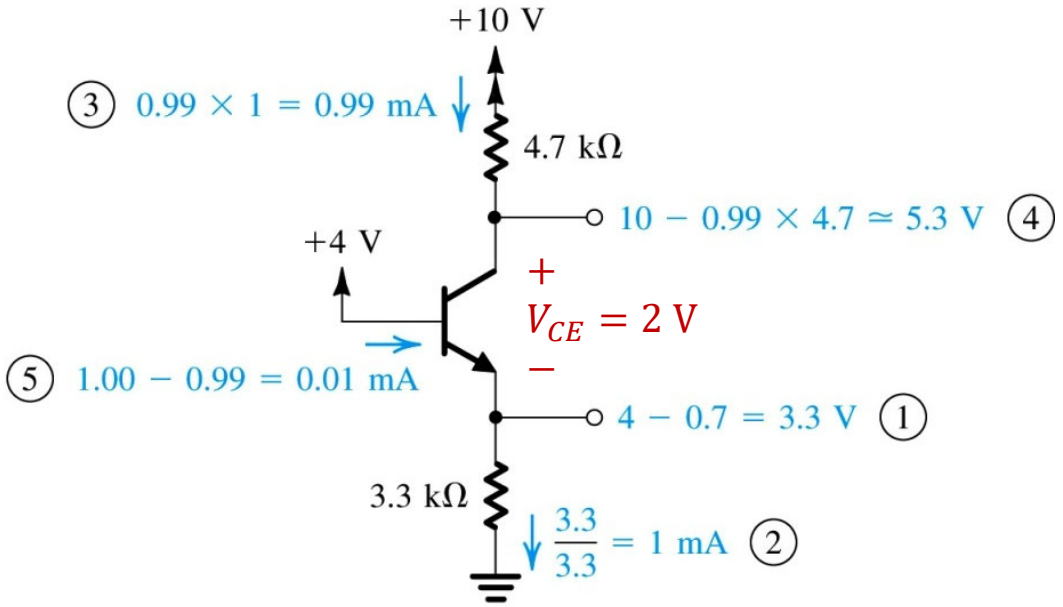
EXAMPLE-2

Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\beta = 100$

Same circuit but V_B is higher

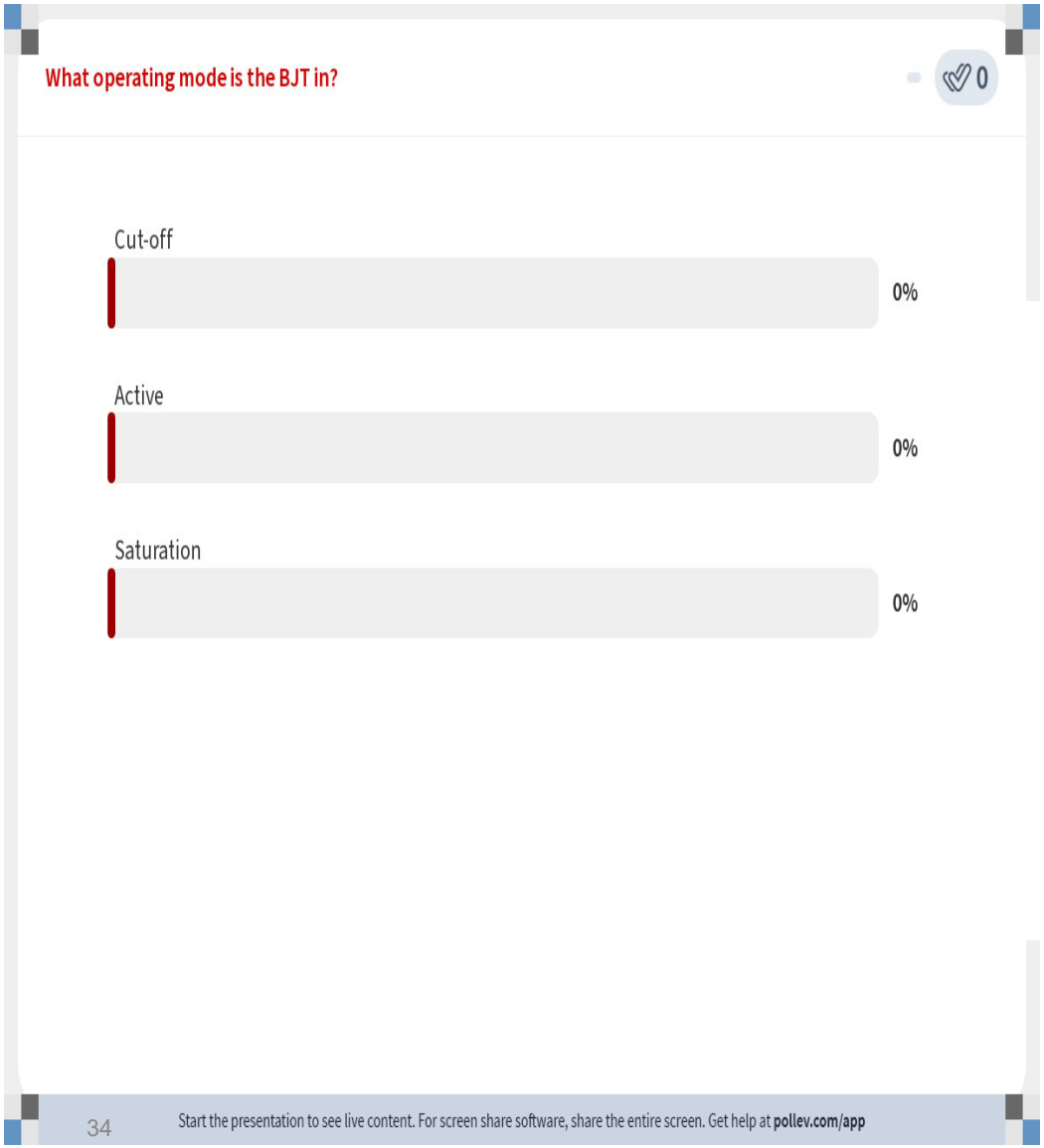




Find all the currents and voltages in the circuit

The Bipolar Junction Transistor

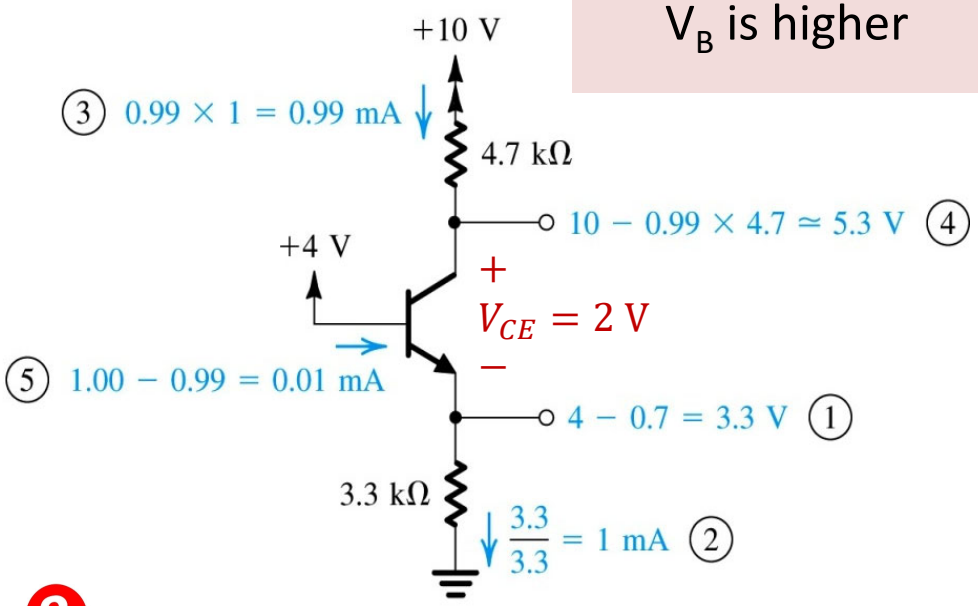
EXAMPLE-2



Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\quad \beta = 100$

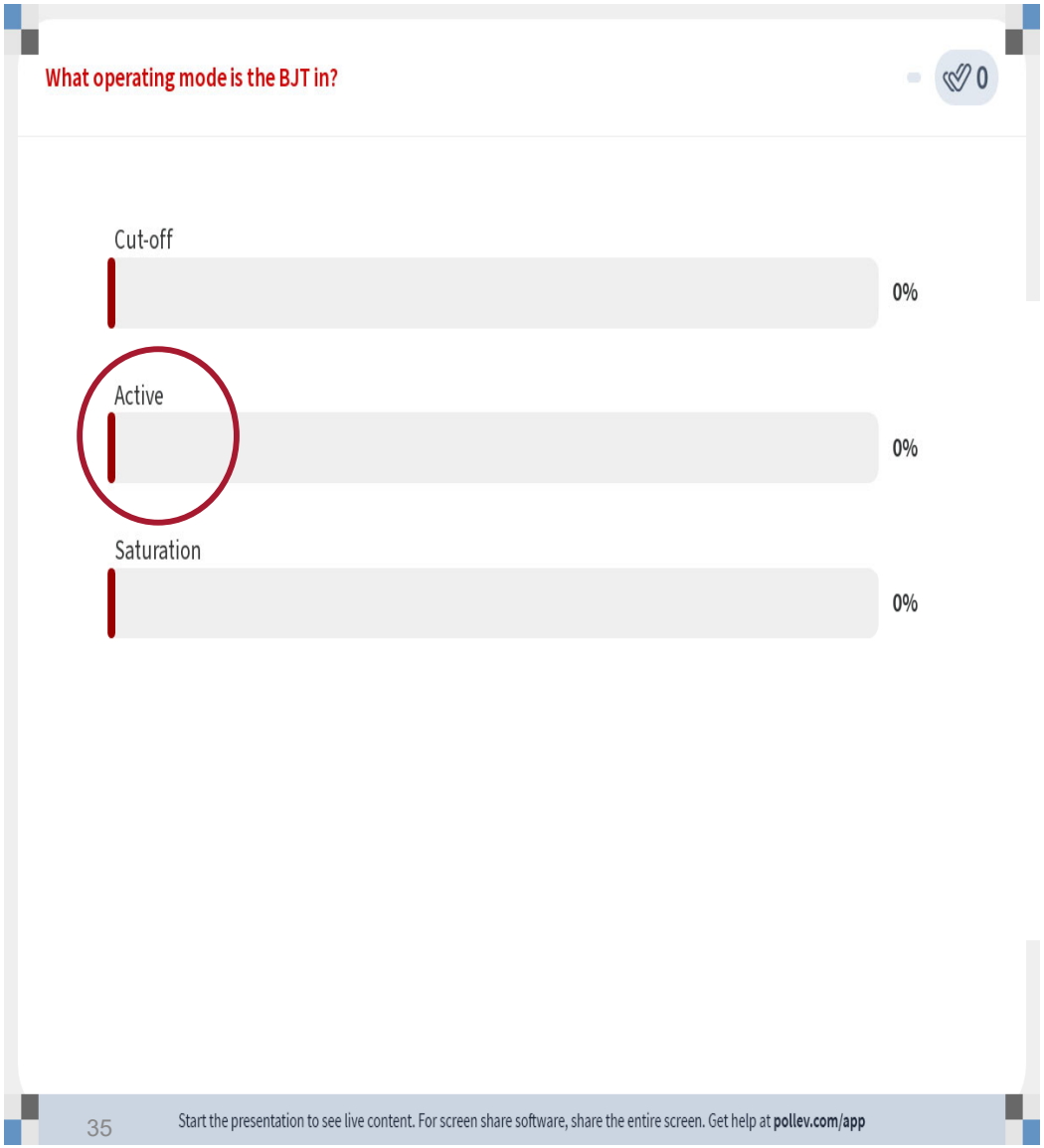
Same circuit but V_B is higher



In what operating mode is this BJT?

The Bipolar Junction Transistor

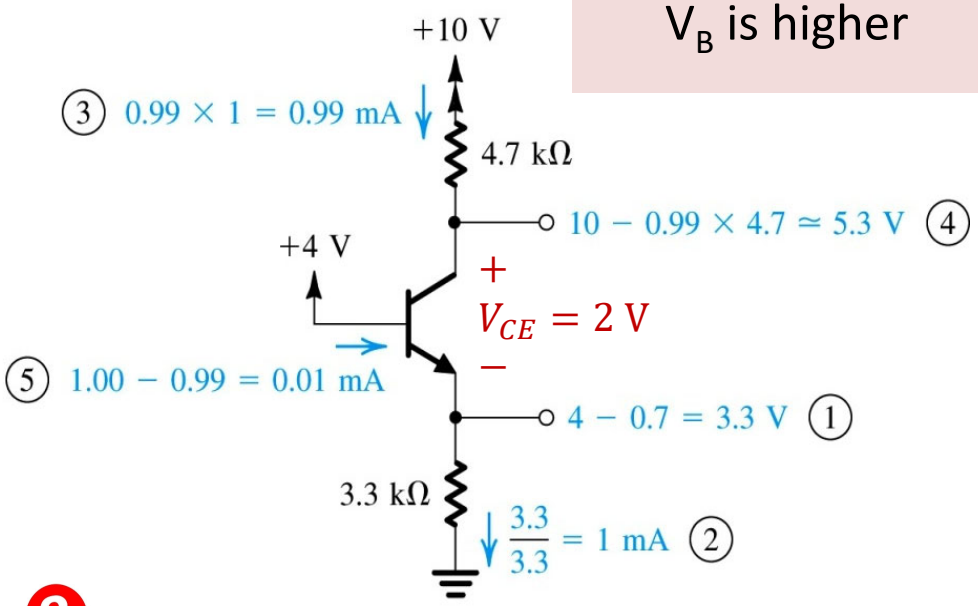
EXAMPLE-2



Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\quad \beta = 100$

Same circuit but V_B is higher



In what operating mode is this BJT?

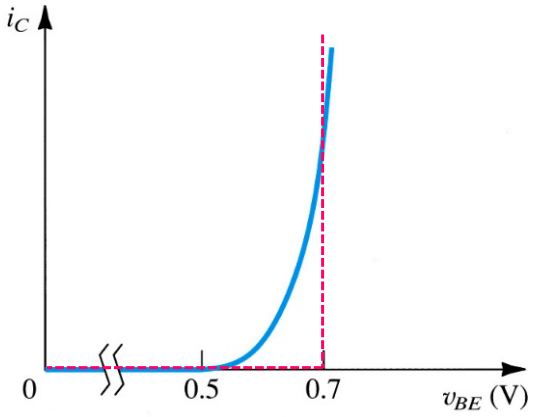
The Bipolar Junction Transistor

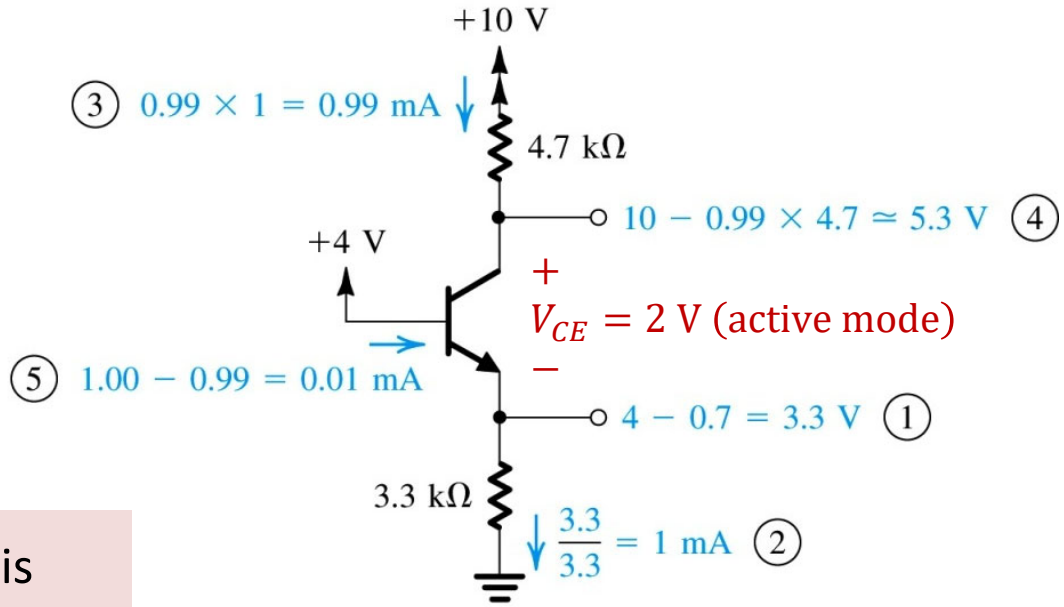
EXAMPLE-2

Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\qquad \beta = 100$

Same circuit but V_B is higher





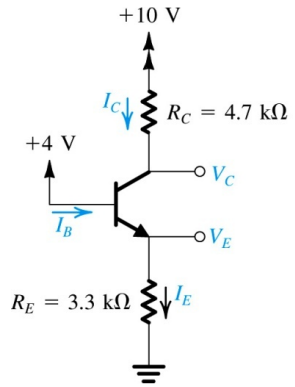
Remember, the model is approximate, so the solution will also be only approximate!

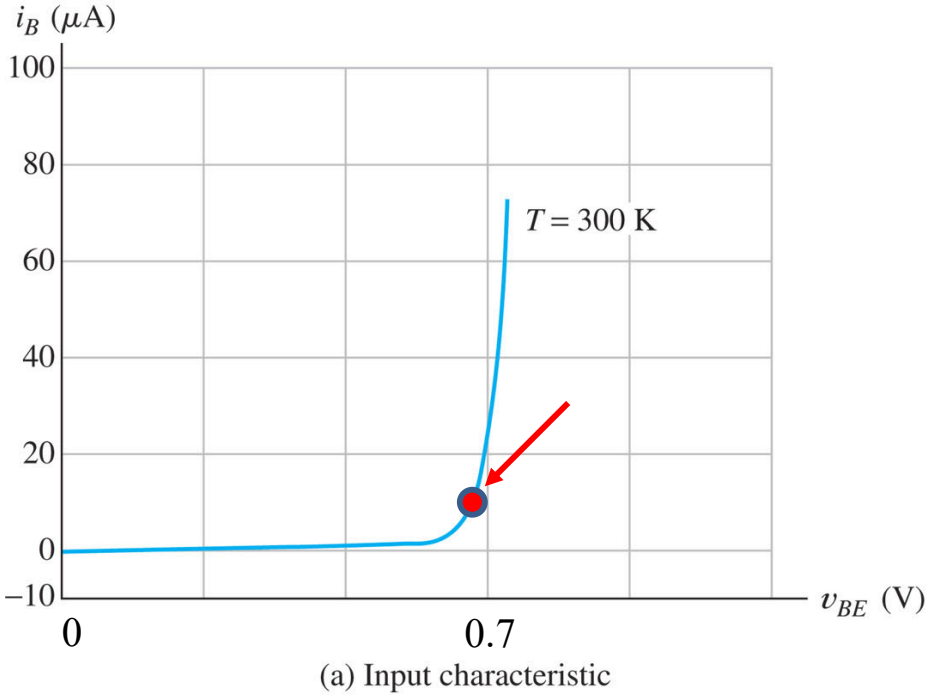
The Bipolar Junction Transistor

EXAMPLE-2 – ACTIVE

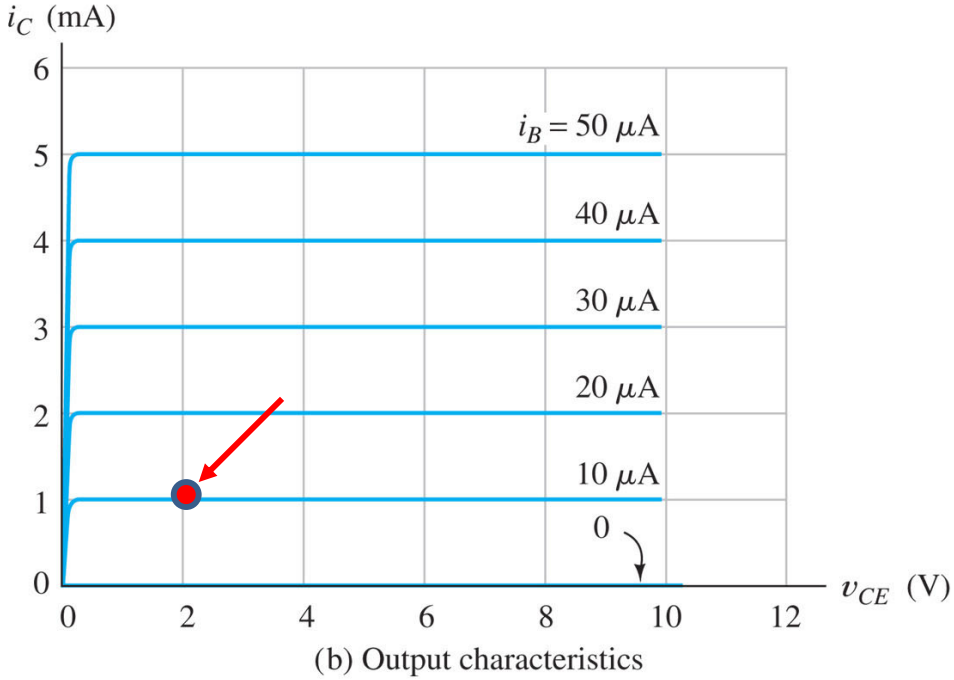
This was an example of active mode

Operating in this region:





(a) Input characteristic



(b) Output characteristics

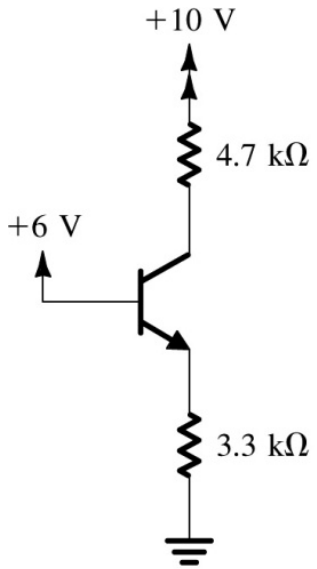
The Bipolar Junction Transistor

EXAMPLE-3

Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\quad \beta = 100$

Same circuit but V_B is even higher



Find all the currents and voltages in the circuit

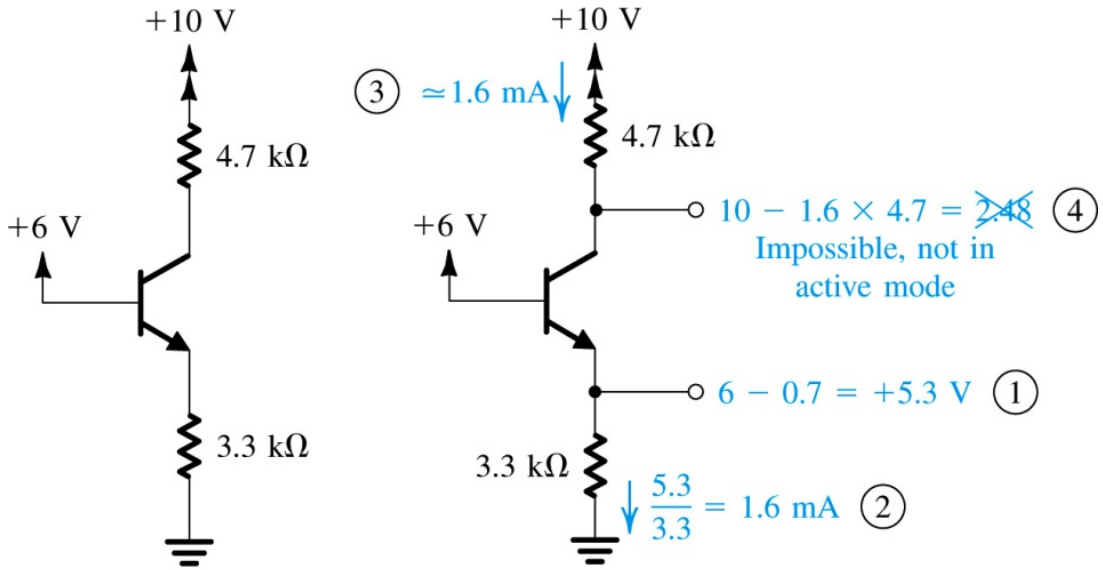
The Bipolar Junction Transistor

EXAMPLE-3

Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\quad \beta = 100$

Same circuit but V_B is even higher



Find all the currents and voltages in the circuit

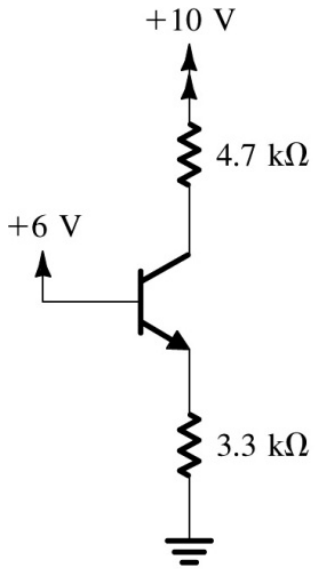
The Bipolar Junction Transistor

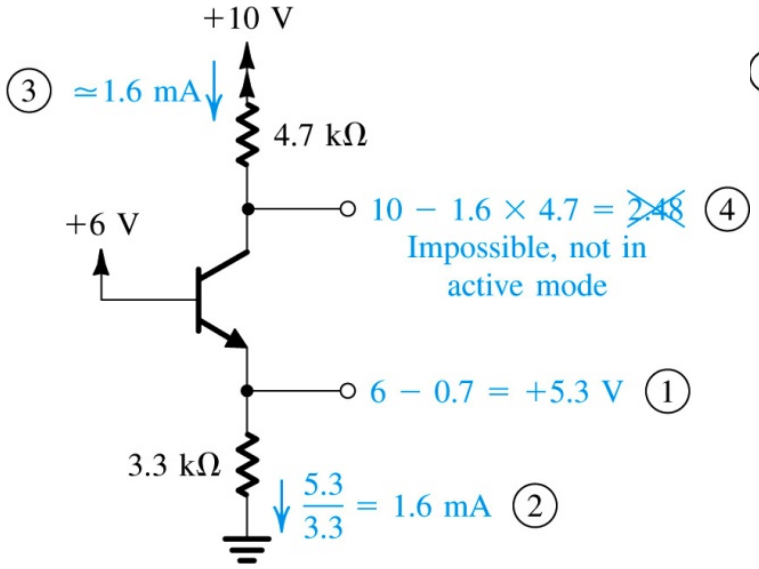
EXAMPLE-3

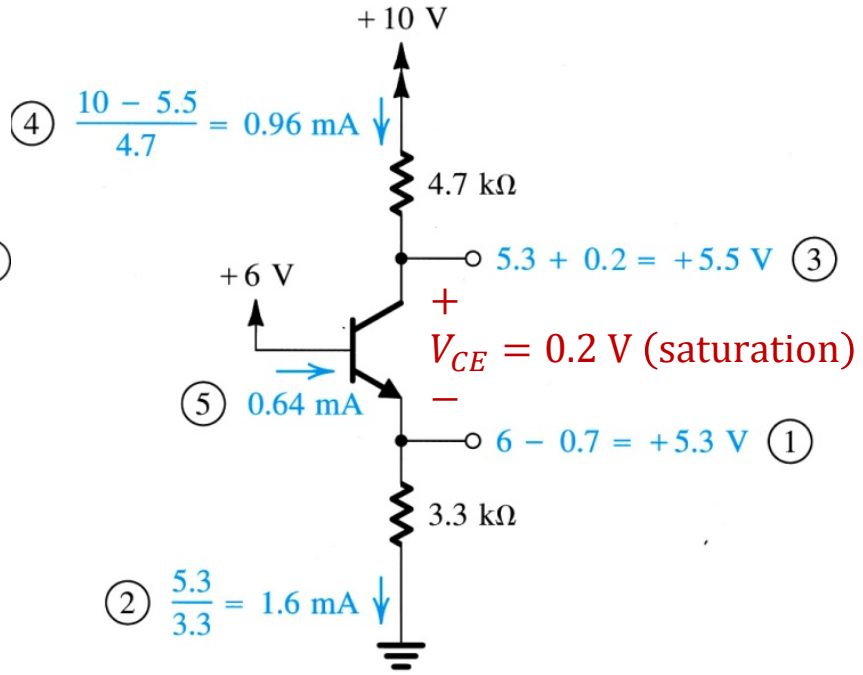
Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\quad \beta = 100$

Same circuit but V_B is even higher





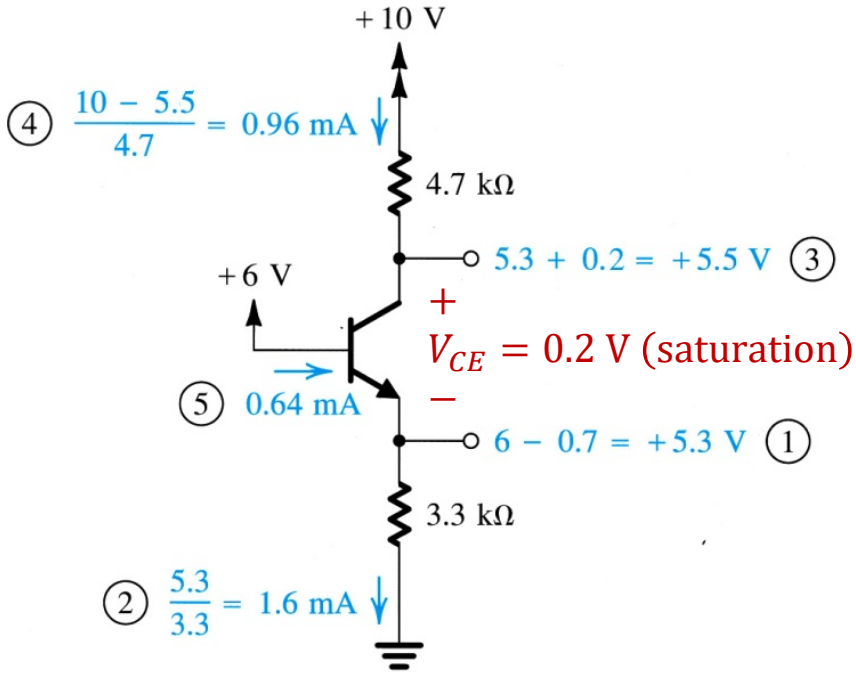


The Bipolar Junction Transistor

EXAMPLE-3

Use the constant voltage drop model:

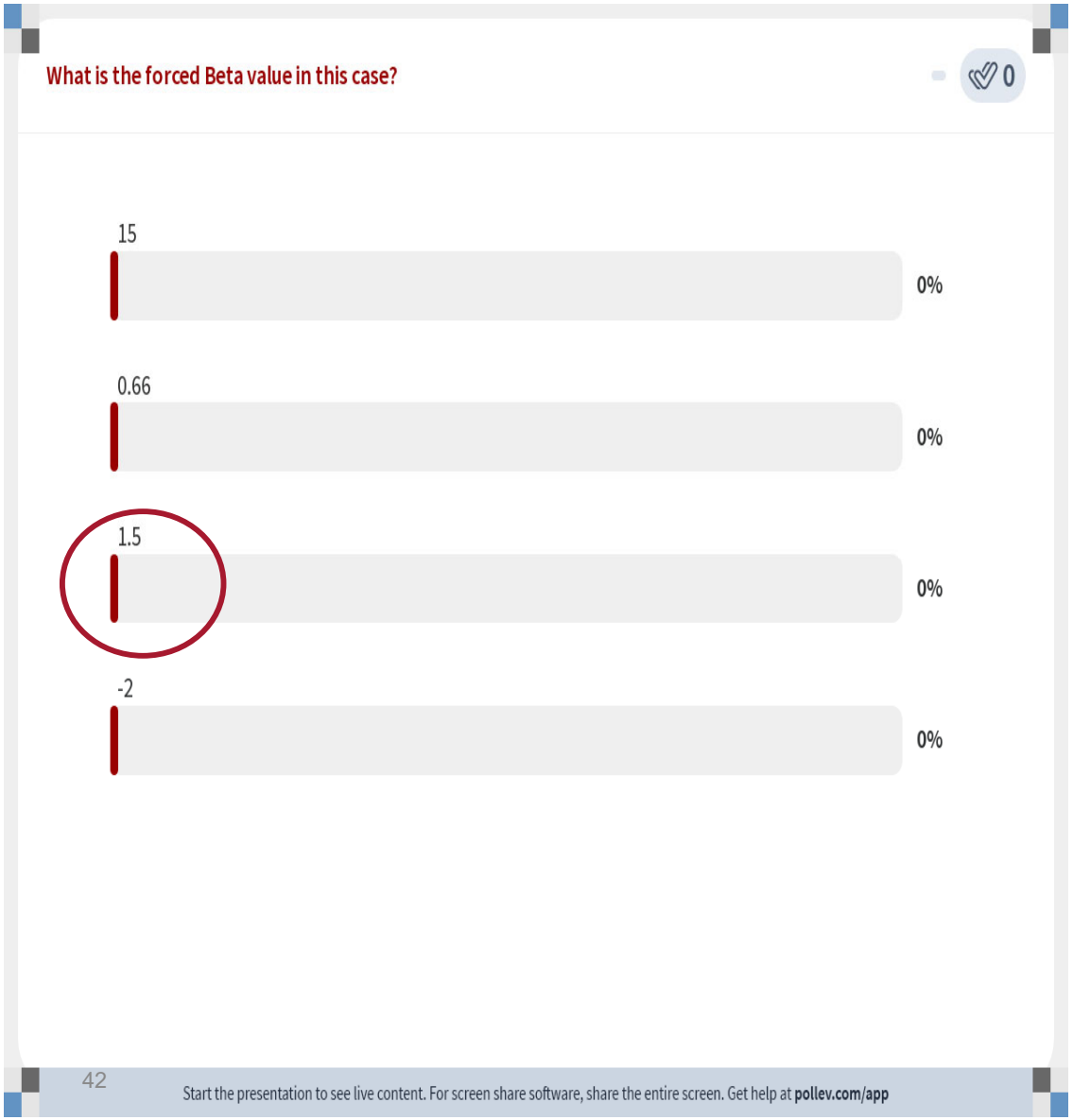
$V_{BE} = 0.7$ V when BE diode is on $\qquad \beta = 100$



Same circuit but V_B is even higher

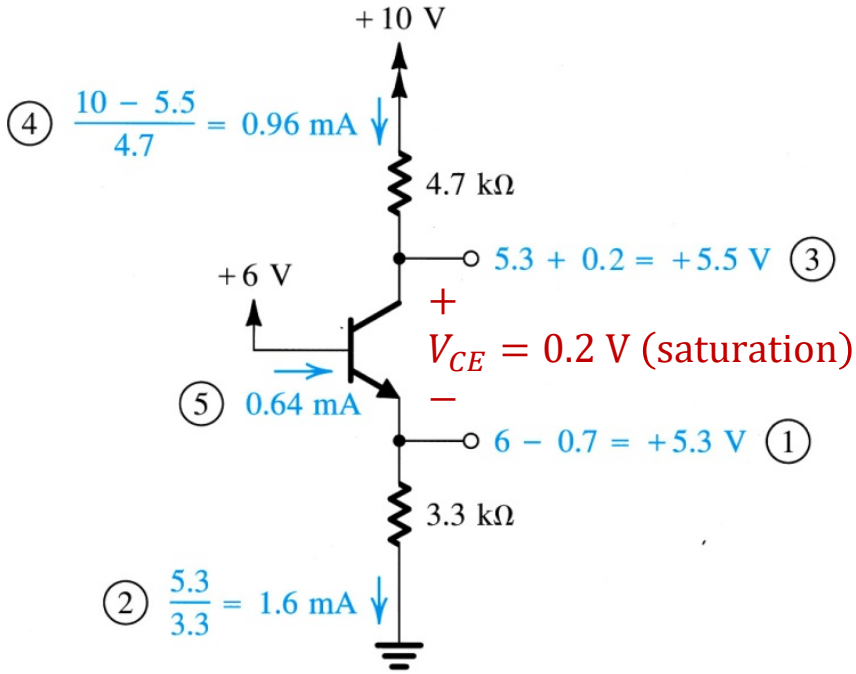
The Bipolar Junction Transistor

EXAMPLE-3



Use the constant voltage drop model:

$V_{BE} = 0.7$ V when BE diode is on $\qquad \beta = 100$



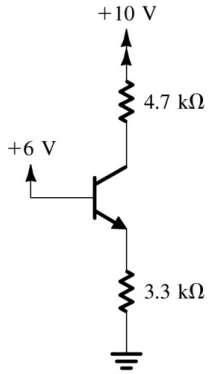
Same circuit but V_B is even higher

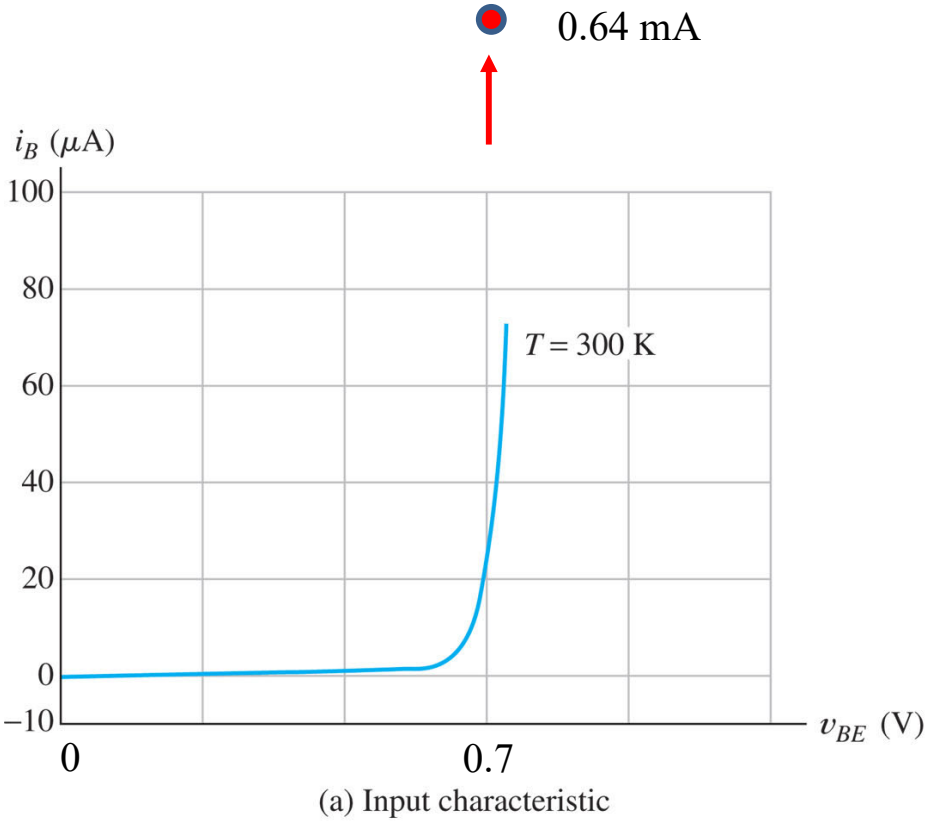
The Bipolar Junction Transistor

EXAMPLE-3 – SATURATION

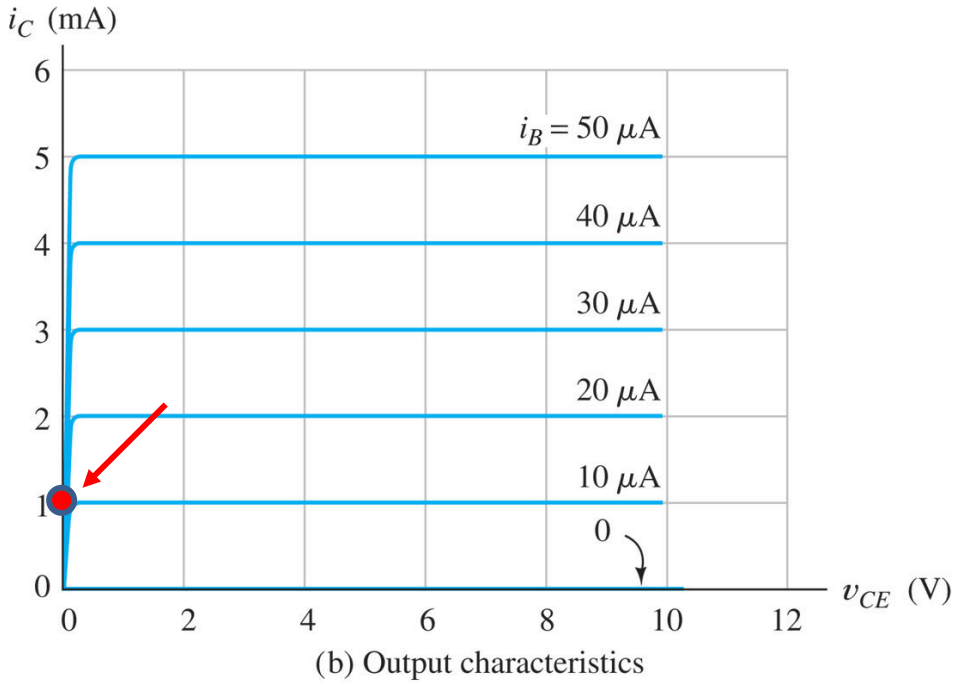
This was an example of saturation

Operating in this region:





(a) Input characteristic



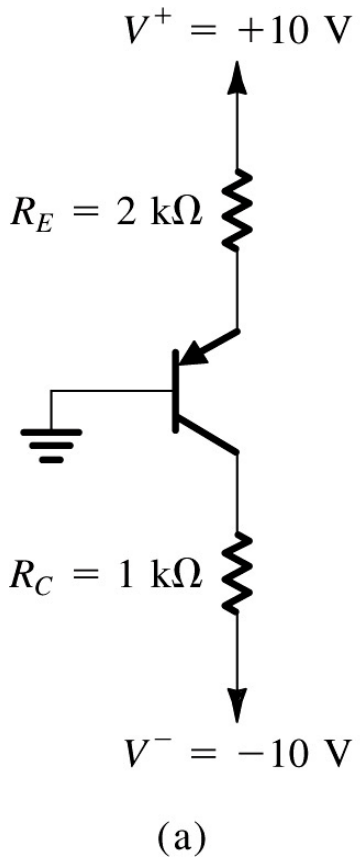
(b) Output characteristics

The Bipolar Junction Transistor

EXAMPLE-4 – PNP

What about for a PNP BJT?

$\beta = 100$



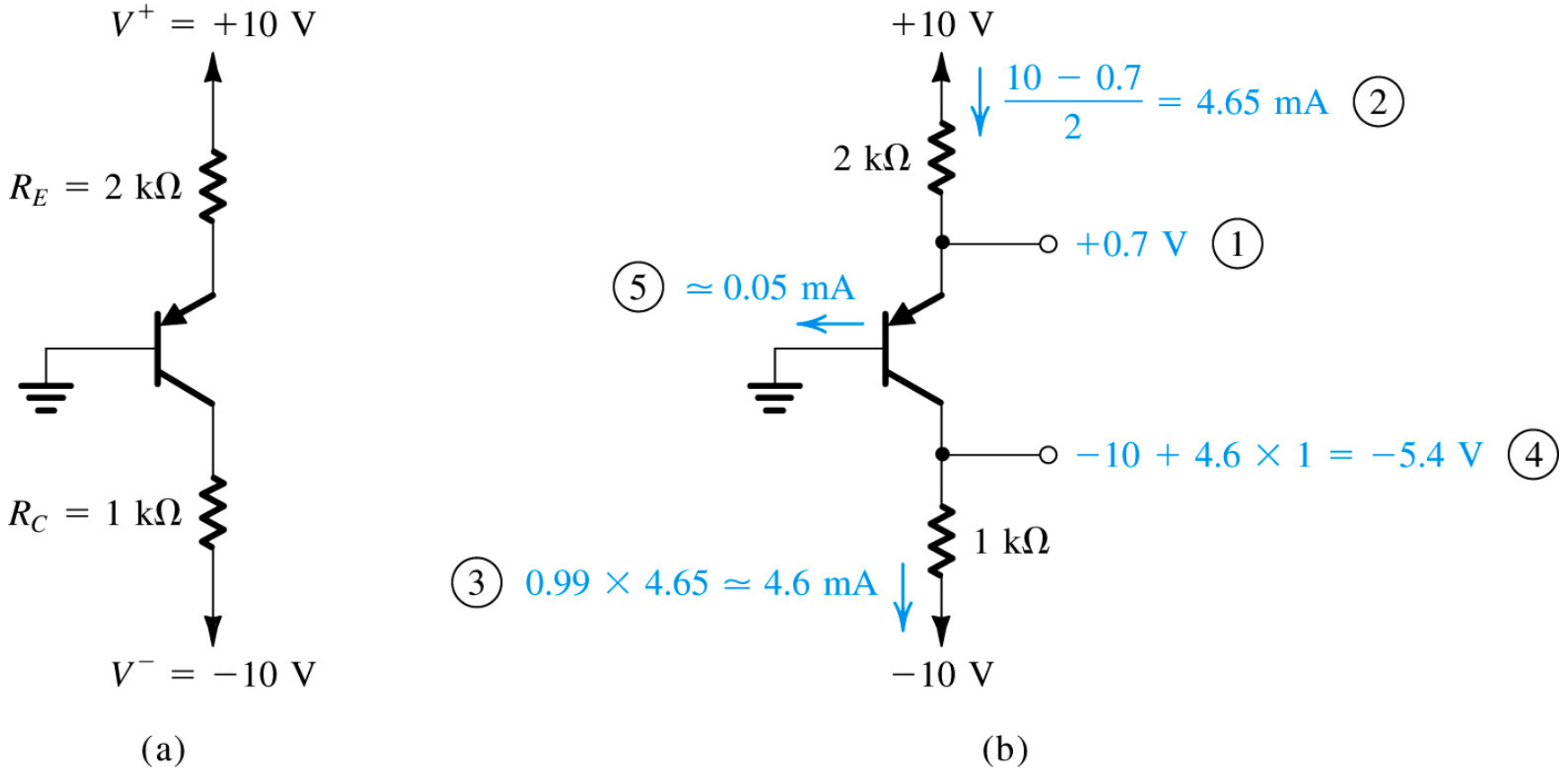
(a)

The Bipolar Junction Transistor

EXAMPLE-4 – PNP

What about for a PNP BJT?

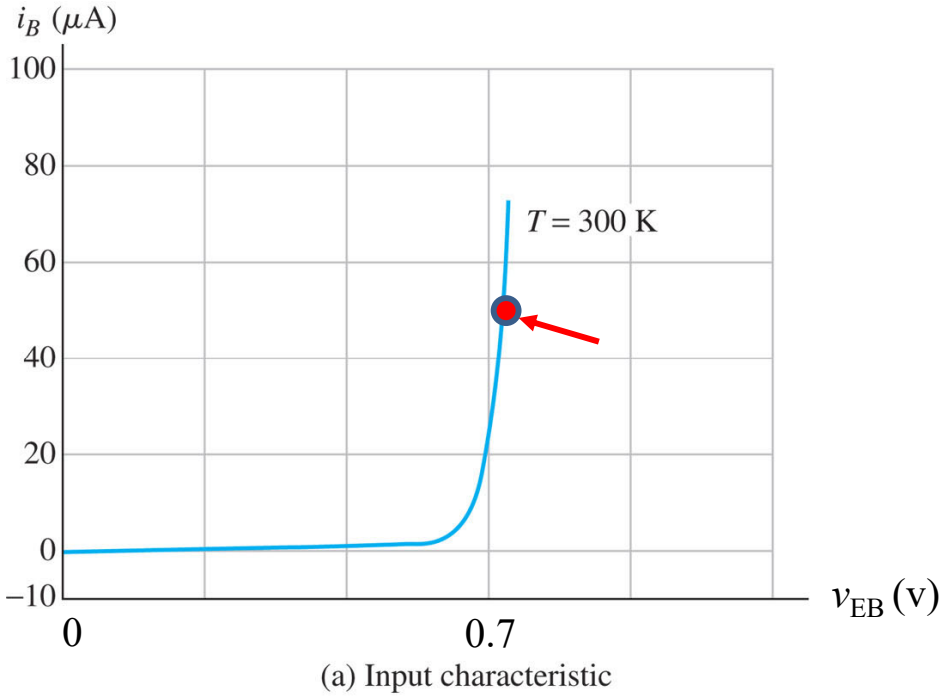
$\beta = 100$



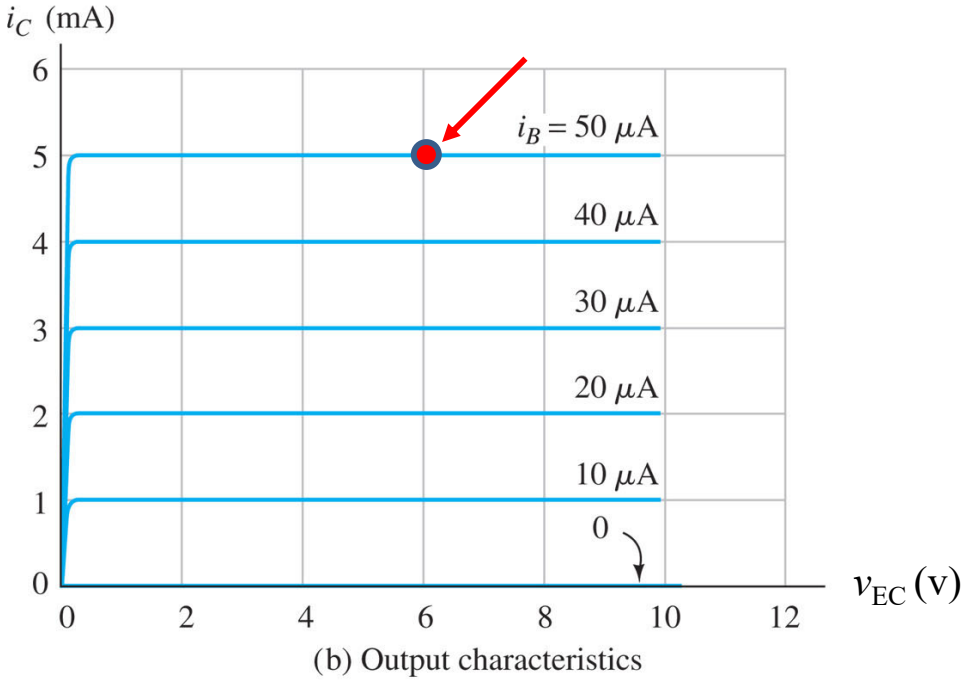
The Bipolar Junction Transistor

EXAMPLE-4 – PNP

Here we are in active mode:



(a) Input characteristic



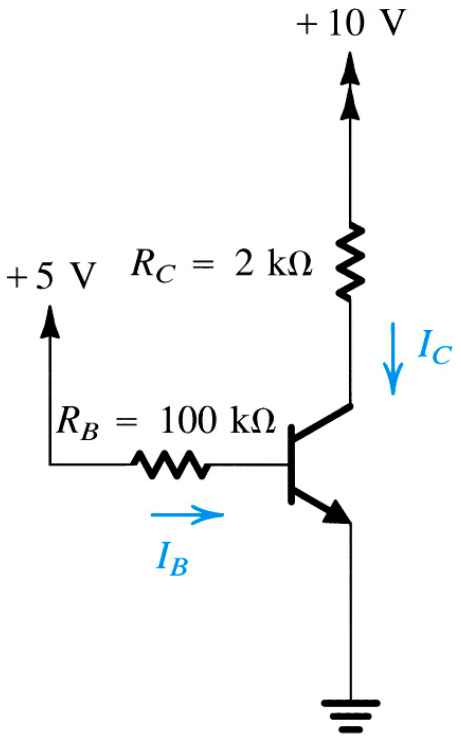
(b) Output characteristics

The Bipolar Junction Transistor

EXAMPLE-5

Now, with a base resistor.

$\beta = 100$

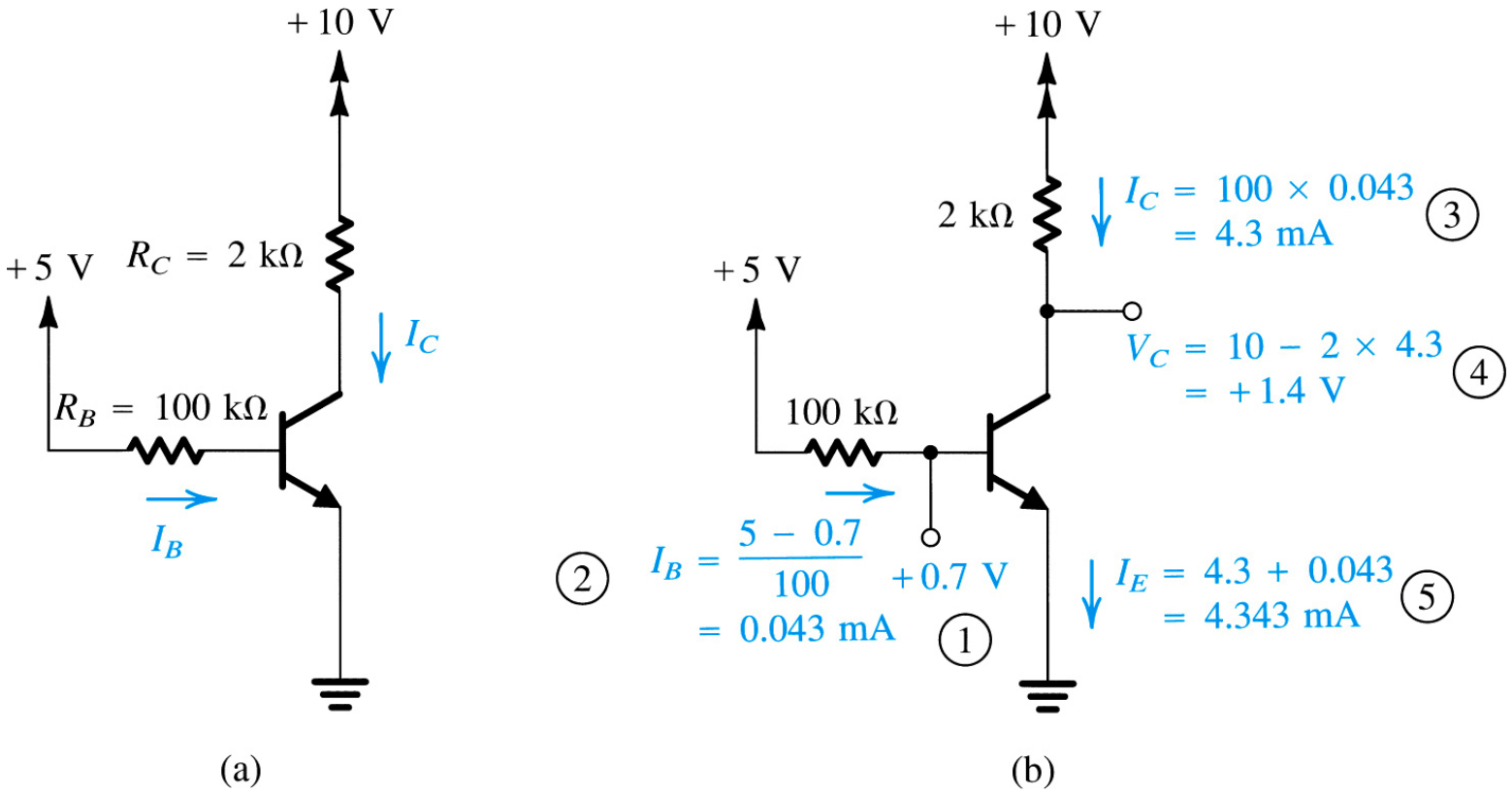


(a)

The Bipolar Junction Transistor

EXAMPLE-5

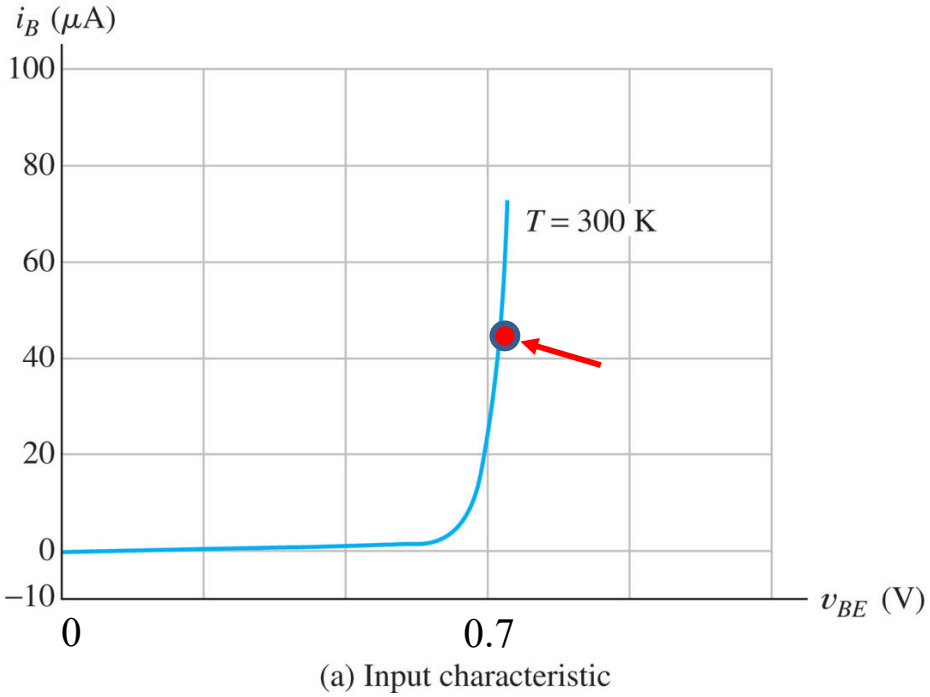
$\beta = 100$



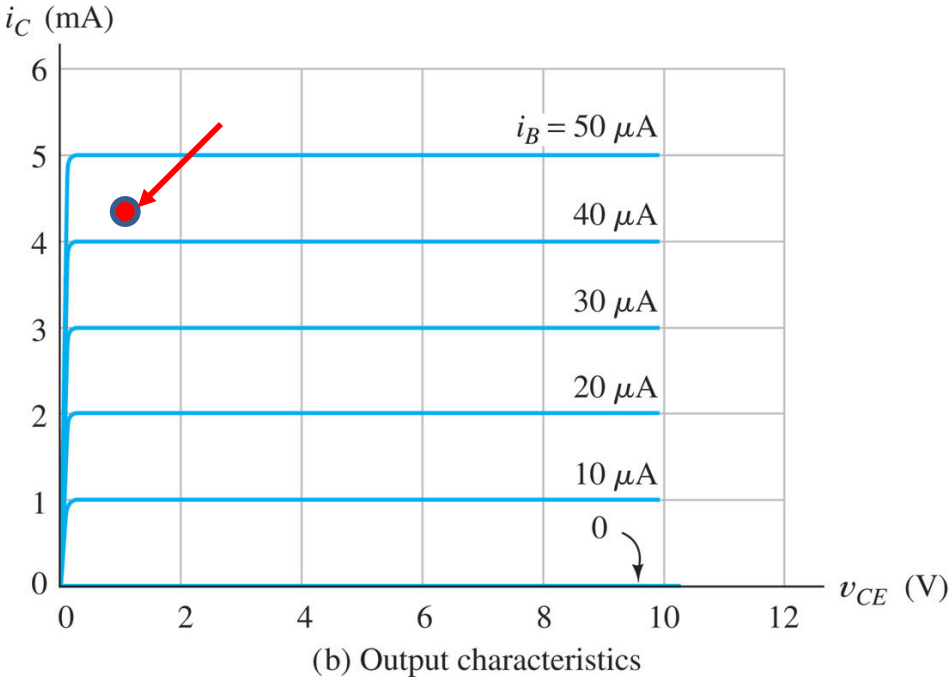
The Bipolar Junction Transistor

EXAMPLE-5

Here we are in active mode:



(a) Input characteristic

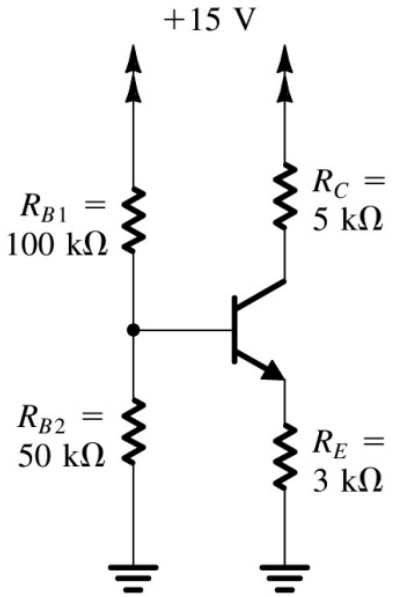


(b) Output characteristics

The Bipolar Junction Transistor

EXAMPLE-6 – NPN

$\beta = 100$

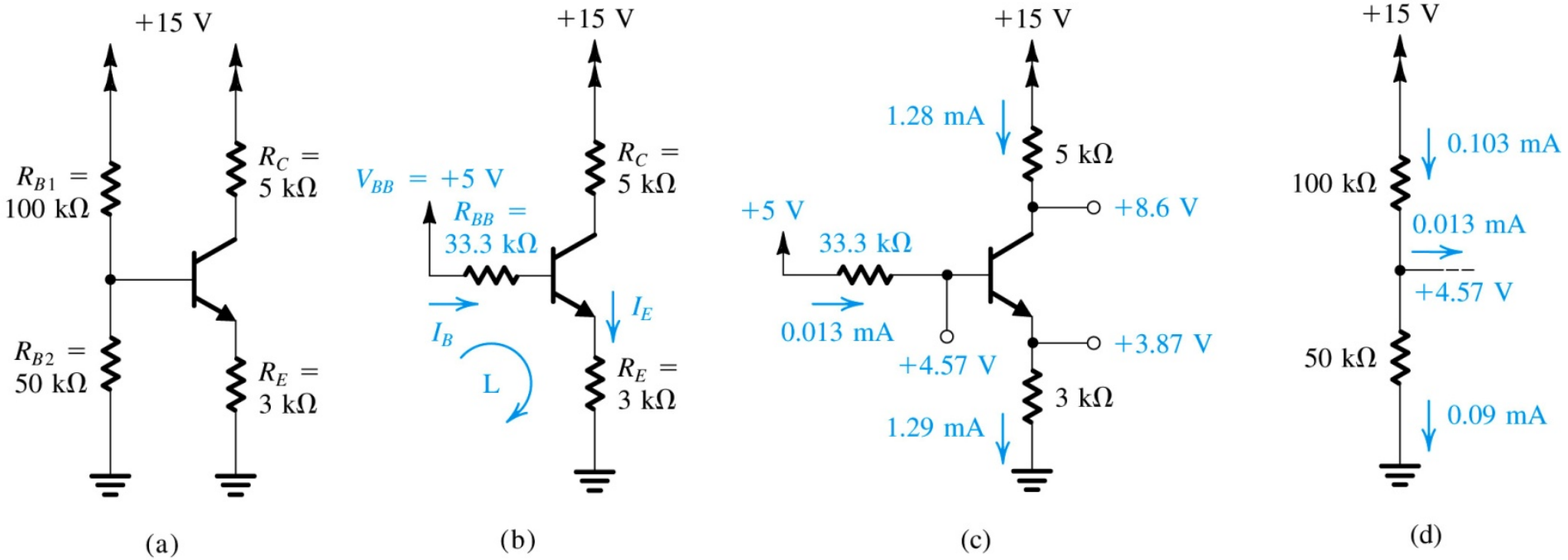


(a)

The Bipolar Junction Transistor

EXAMPLE-6 – NPN

$\beta = 100$



This week

DIODE CIRCUITS LAB + FIRST ASSIGNMENT

Preparation before the lab:

- The worksheet and submission quiz is available on iLearn
- Do at least the pre-lab section before coming to the timetabled support session
- Record your worksheet answers in a digital logbook and upload individual answers to the iLearn submission before 11:55pm on the day of the timetabled lab session

First Assignment!

- Your first assignment will be posted this week
- This will be an iLearn quiz on the topics of diodes and BJTs
- You will have at least 10 days to complete it (Submission due in week 5)