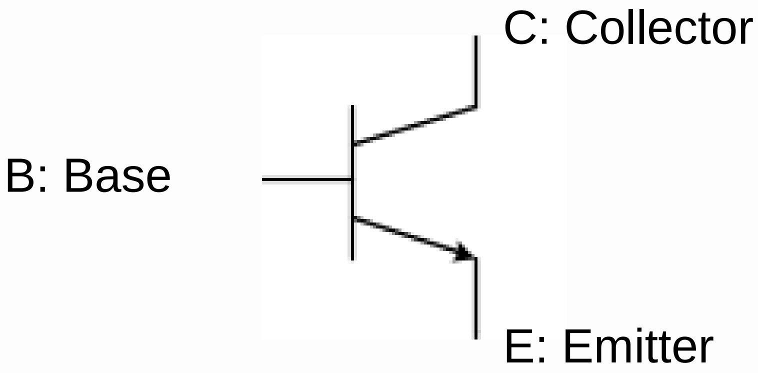
L19: The Bipolar Junction Transistor (BJT)

- BJT is a controlled current source…
  - current amplifier
- The three operating regimes of a BJT
- Controlling a resistive load with a BJT
- Solving for saturation condition



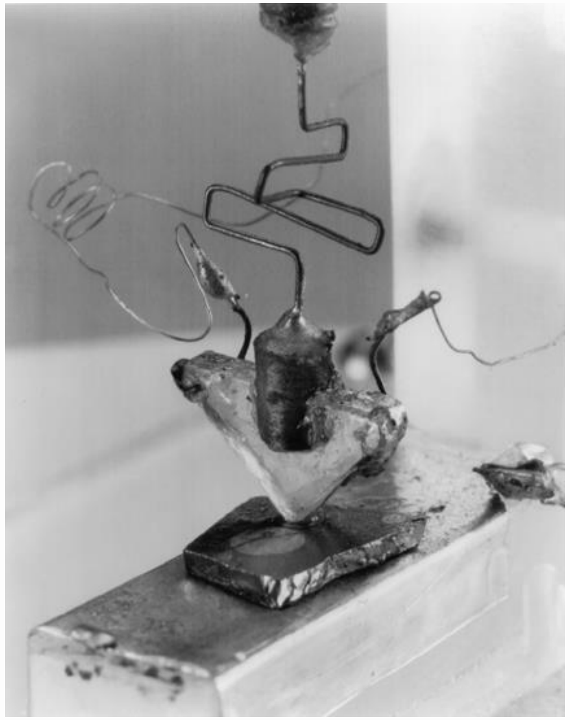
ECE Spotlight…

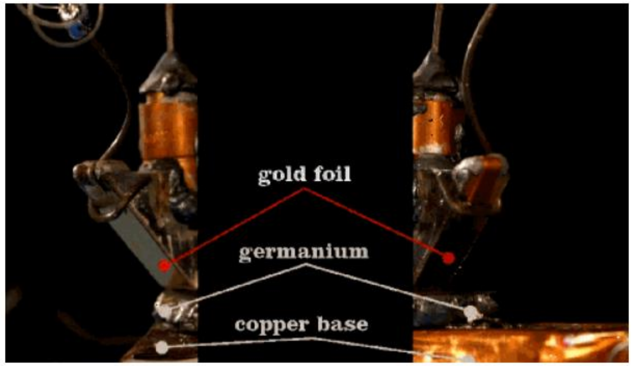
John Bardeen, the co-inventer of the transistor, was also the Ph.D. advisor at the University of Illinois for Nick Holonyak, Jr. of LED fame.

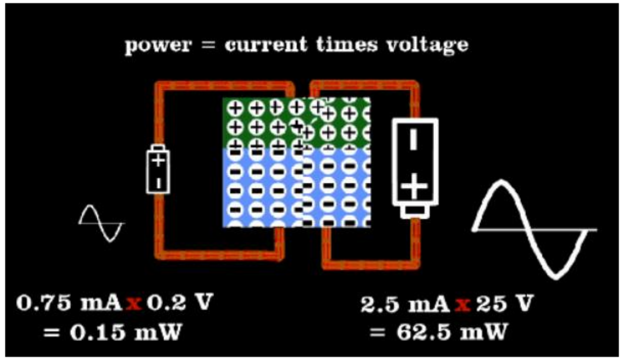
EXPLORE MORE - Inside the bipolar transistor

Bardeen & Brattain – Point contact

In 1947, invention of the point-contact transistor







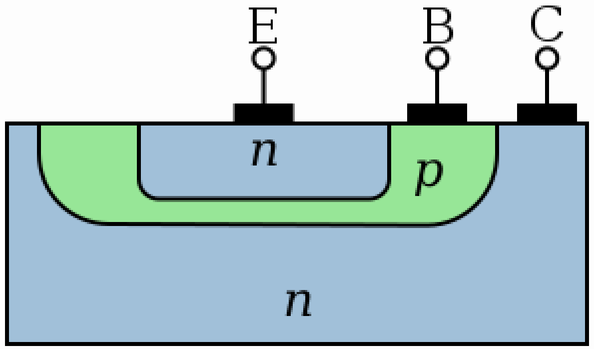
https://www.computerhistory.org/siliconengine/invention-of-the-point-contact-transistor/

http://www.engineerguy.com/videos.htm#more-videos

Shockley – p-n junction

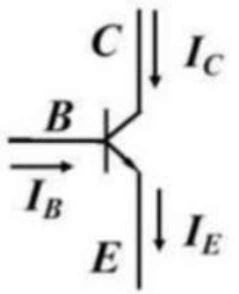
In 1956

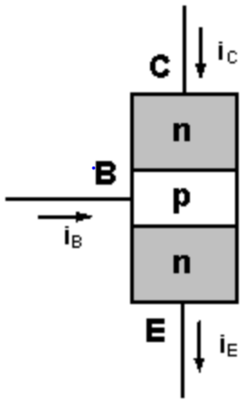
PLANAR TECHNOLOGY



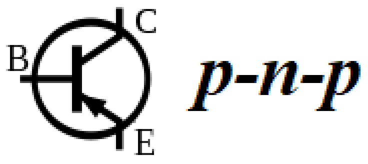
Two types of BJT

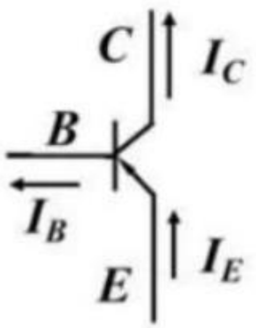
NPN

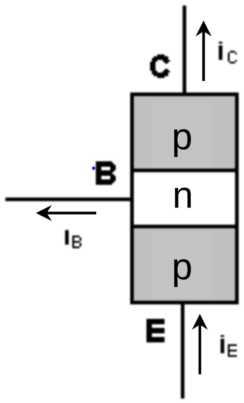




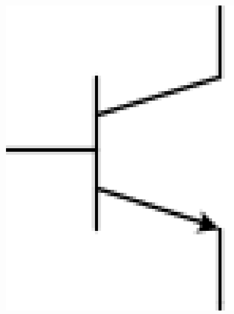
PNP







Transistor Trivia: The symbol



A. was a doodle made by John Bardeen's daughter

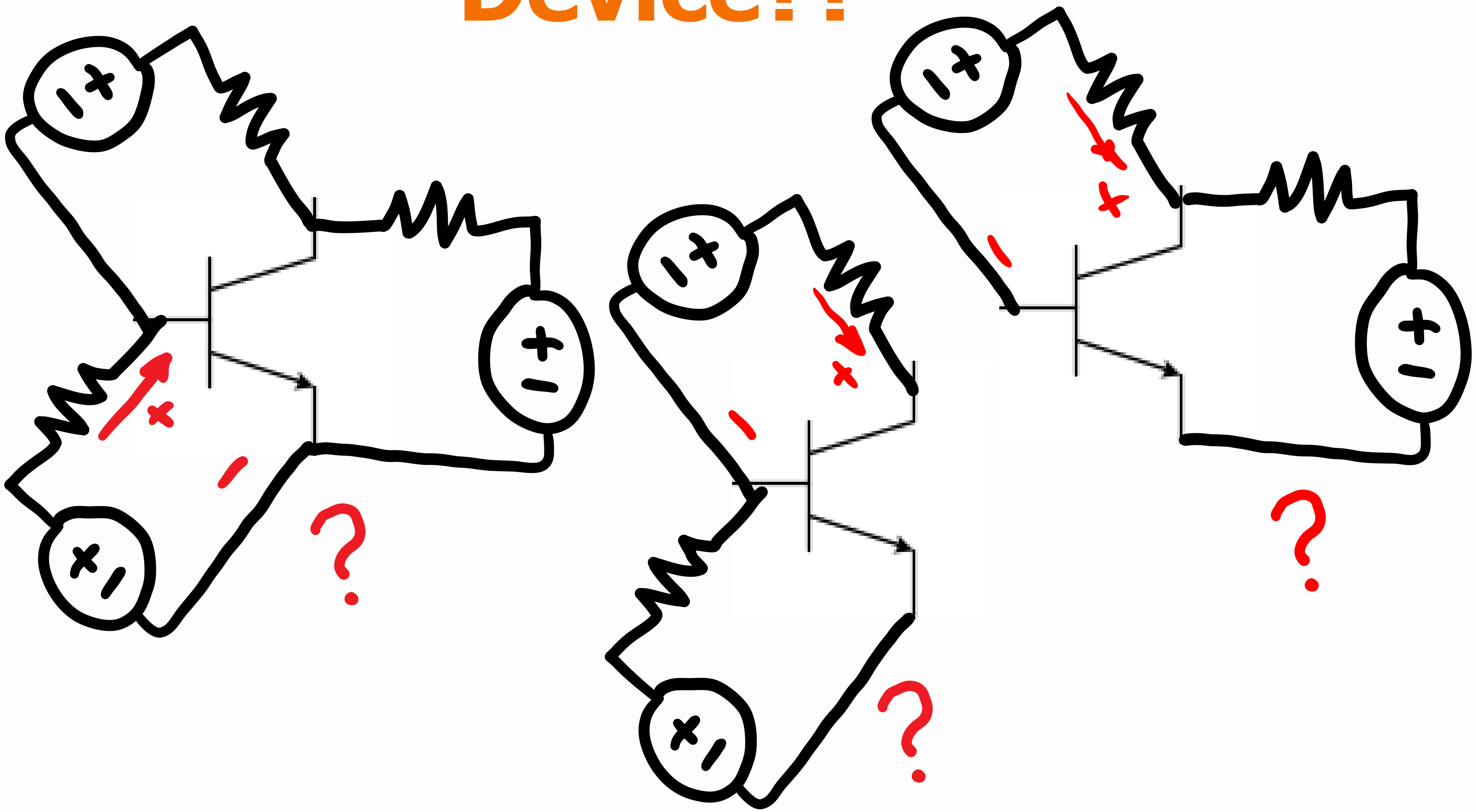
B. ~~represents faithfully the electrical connections of the transistor which need to be resolved exactly with circuit equations~~

NEVER THIS ONE, PLEASE!!!

C. is simply a conventional representation of a three-terminal bipolar transistor inside a "black box" without specific circuit significance

D. was the shape of the golden clip, used to tie the red ribbon around the Nobel prize certificate, which Walter Shockley thought could make a good symbol for the device

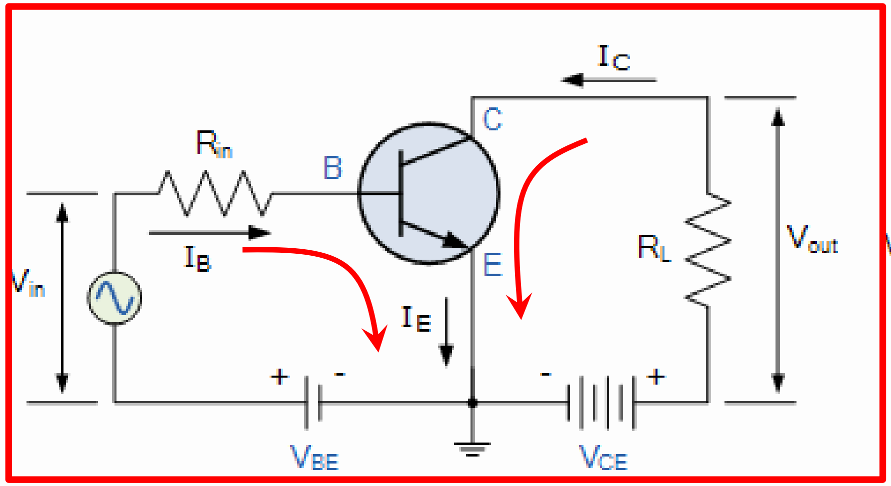
IV Characteristic of a 3-terminal Device??

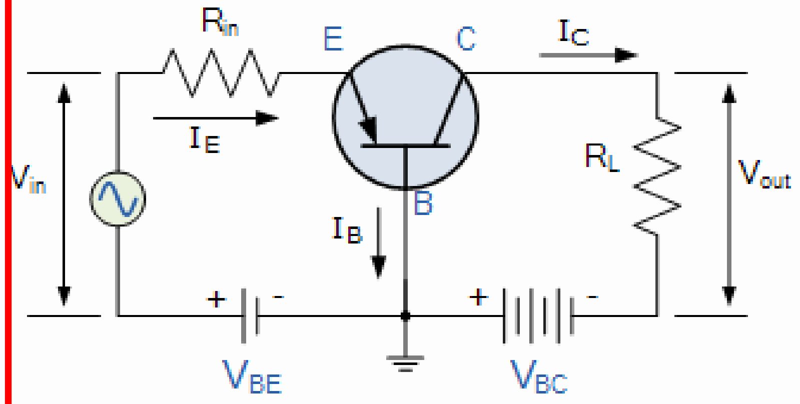


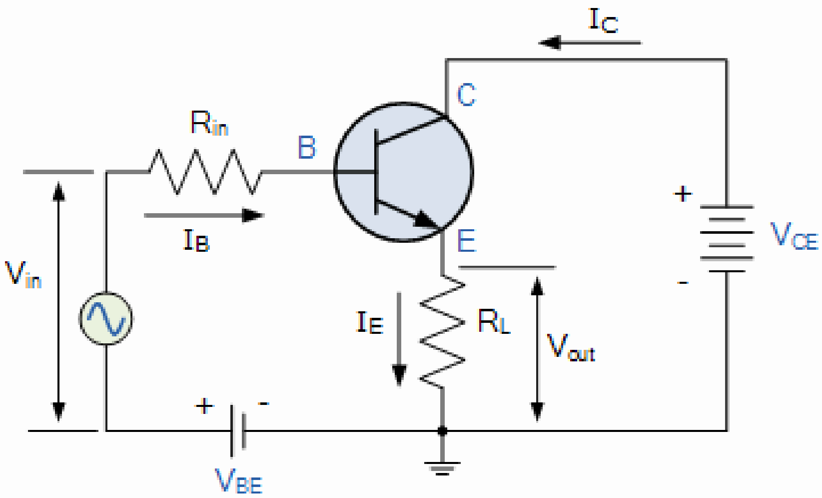
No single way to connect three-terminal device to a linear circuit.

EXPLORE MORE

Transistor circuit configurations





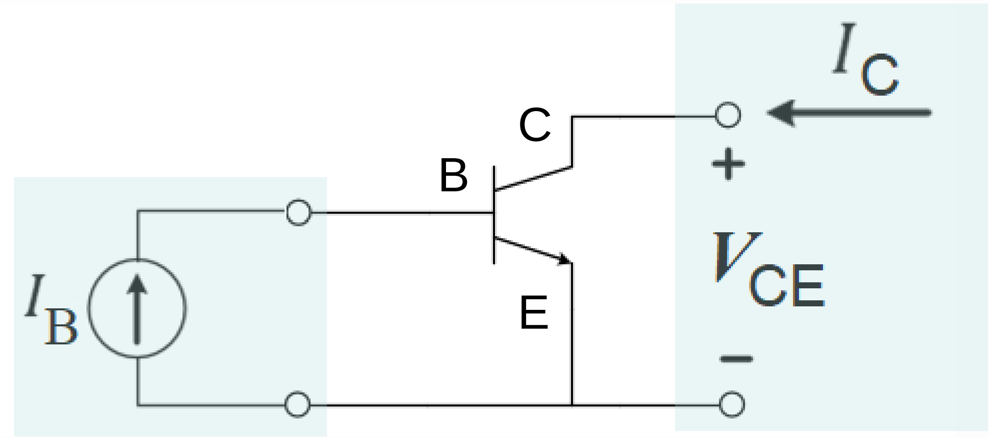


Common Emitter
- **Current gain**
- **Voltage gain**

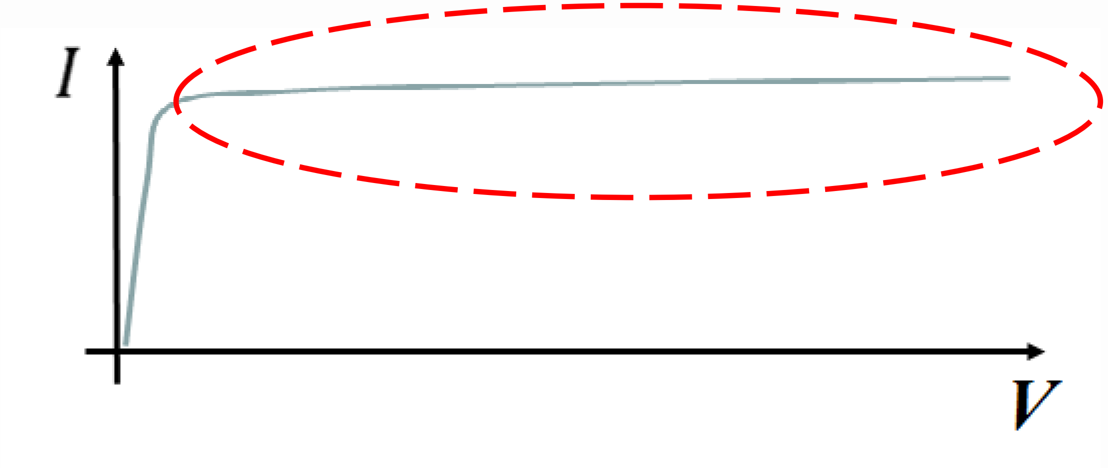
Common Base
- Voltage gain

Common Collector
- Current gain

ECE110 considers only the "common-emitter" configuration

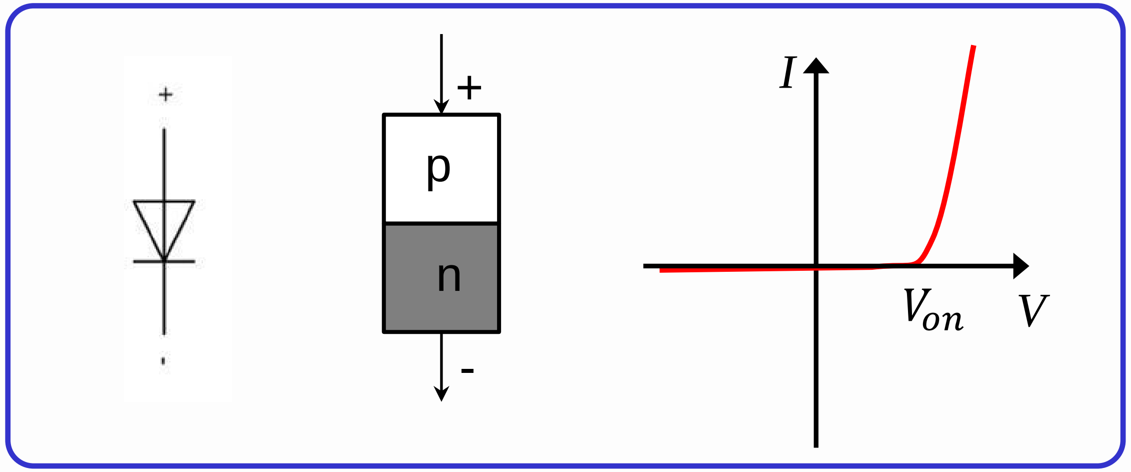


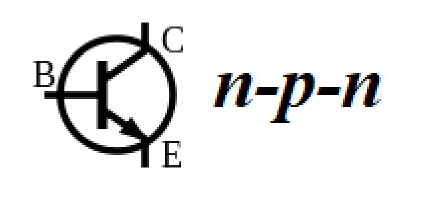
If we fix I_B, we can measure the resulting I and V at the other side.

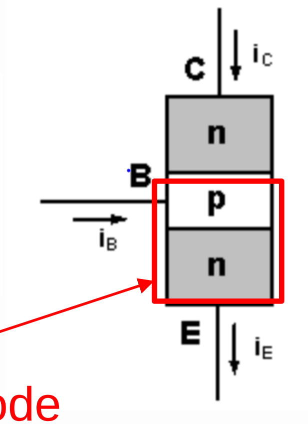


Flat – like current source

Diode & PN junction

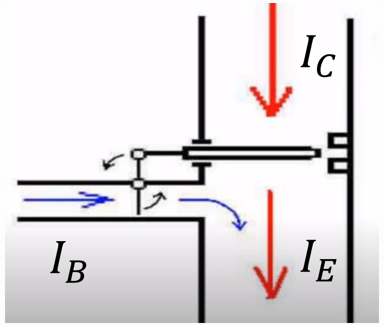


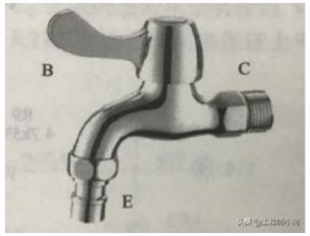




Like a diode

$I_E = I_B + I_c$





Three operating regimes of BJT

1. Cut-off regime

When $V_{BE} < V_{on}$, $I_B = 0, I_C = 0$

In reality, I_C is not exactly zero, due to leakage current. $I_B \approx 0, I_C \approx 0$

2. Active regime

When $V_{BE} \geq V_{on}$, $V_c > V_B$

$I_C = \beta I_B$, β is magnification factor, a constant

3. Saturation regime

$V_{BE} \geq V_{on}$

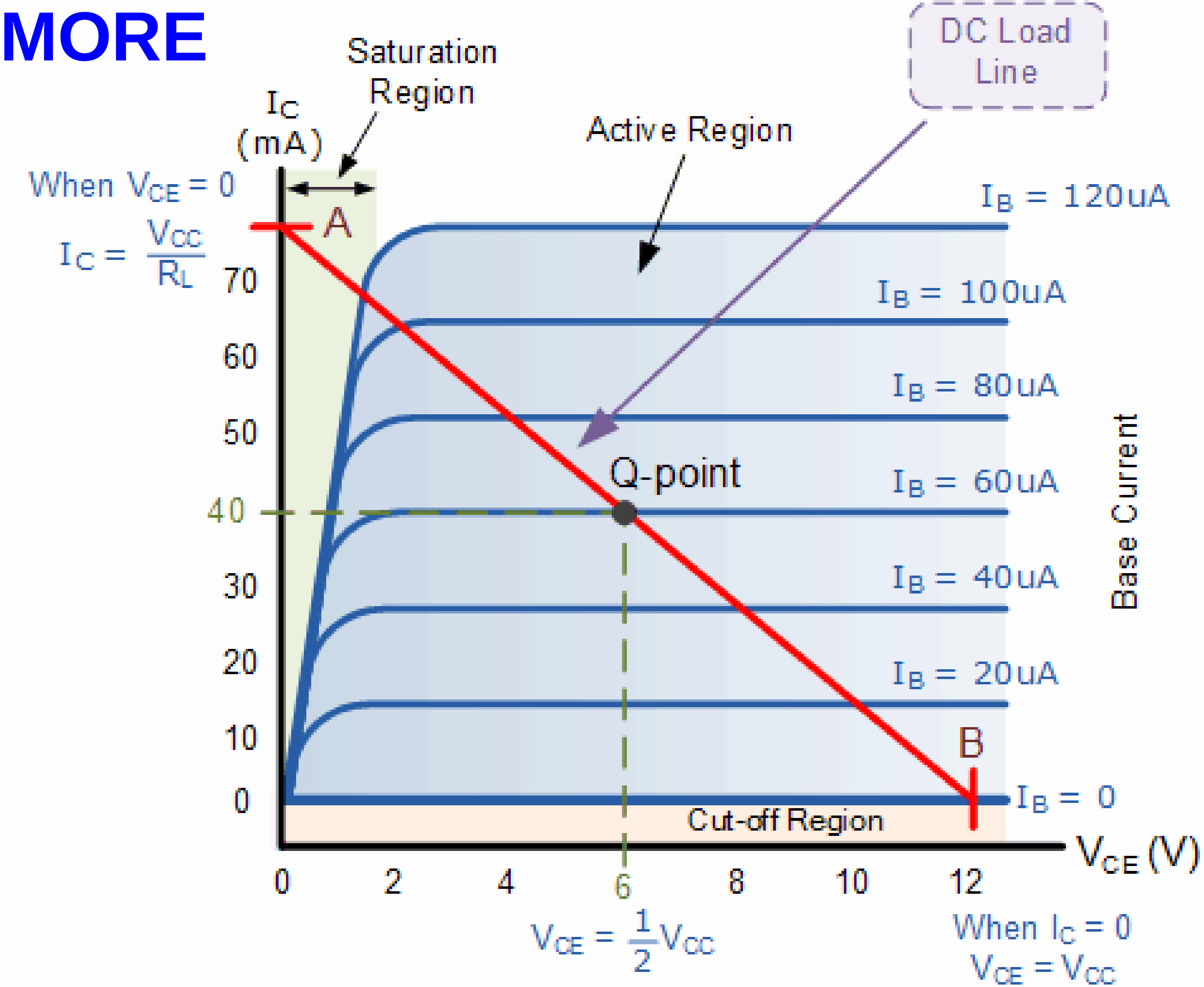
$V_c < V_B$

I_c will not increase with I_B

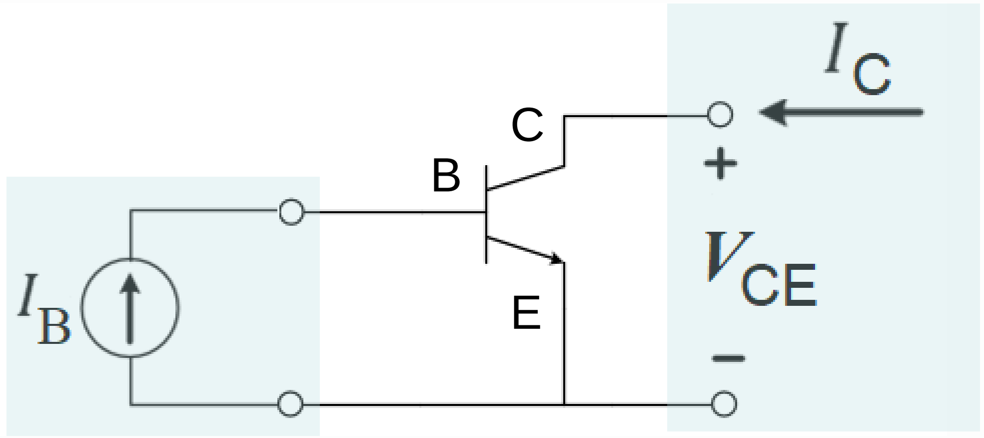
$\beta I_B > I_c$

EXPLORE MORE

BJT Characteristics



One curve for each value of I_B



1. Cut-off regime

   When $V_{BE} < V_{on}$, thus $I_c \approx 0$

2. Active regime

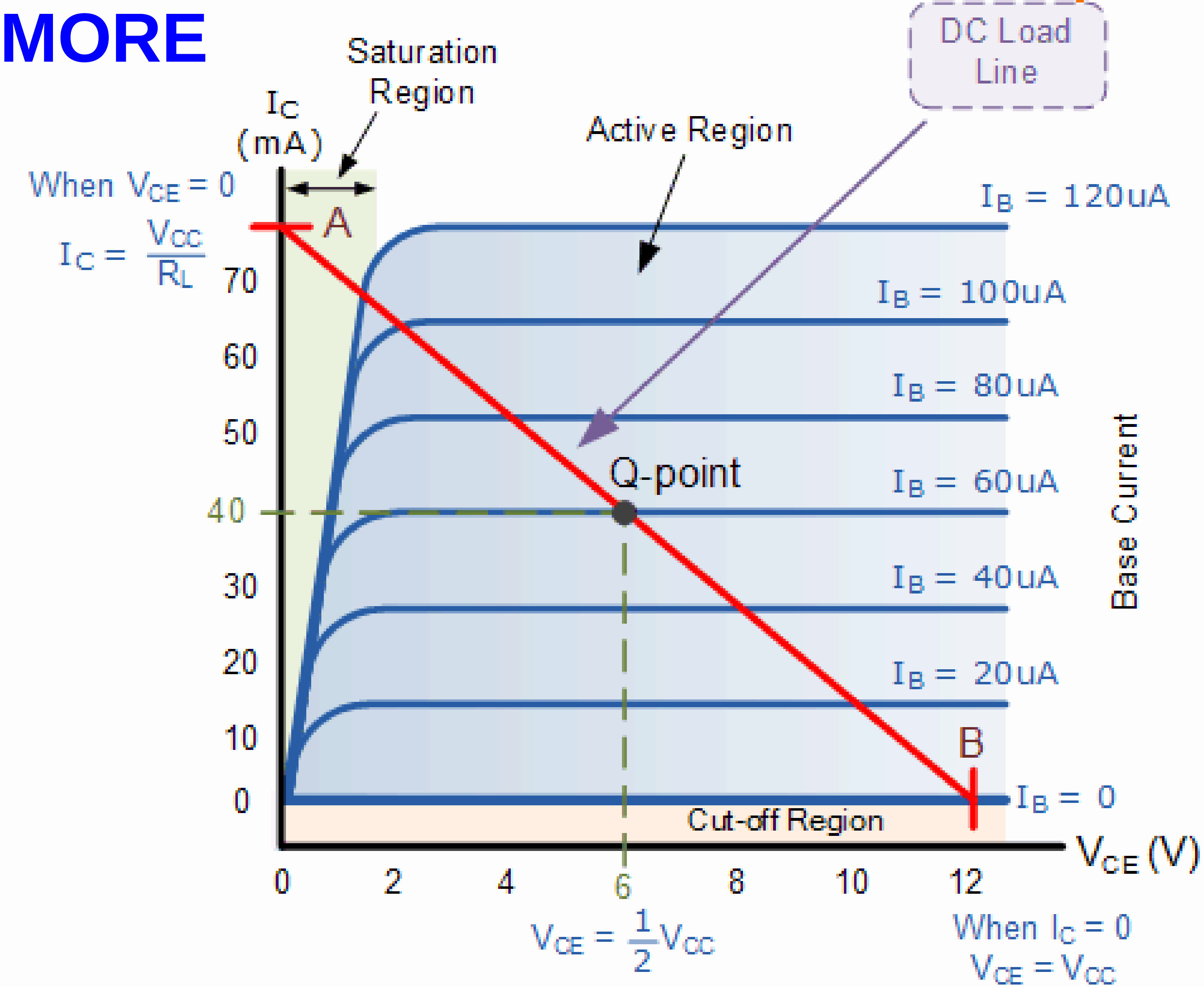
   When $V_{BE} \geq V_{on}$, thus $I_c = \beta I_B$

3. Saturation regime

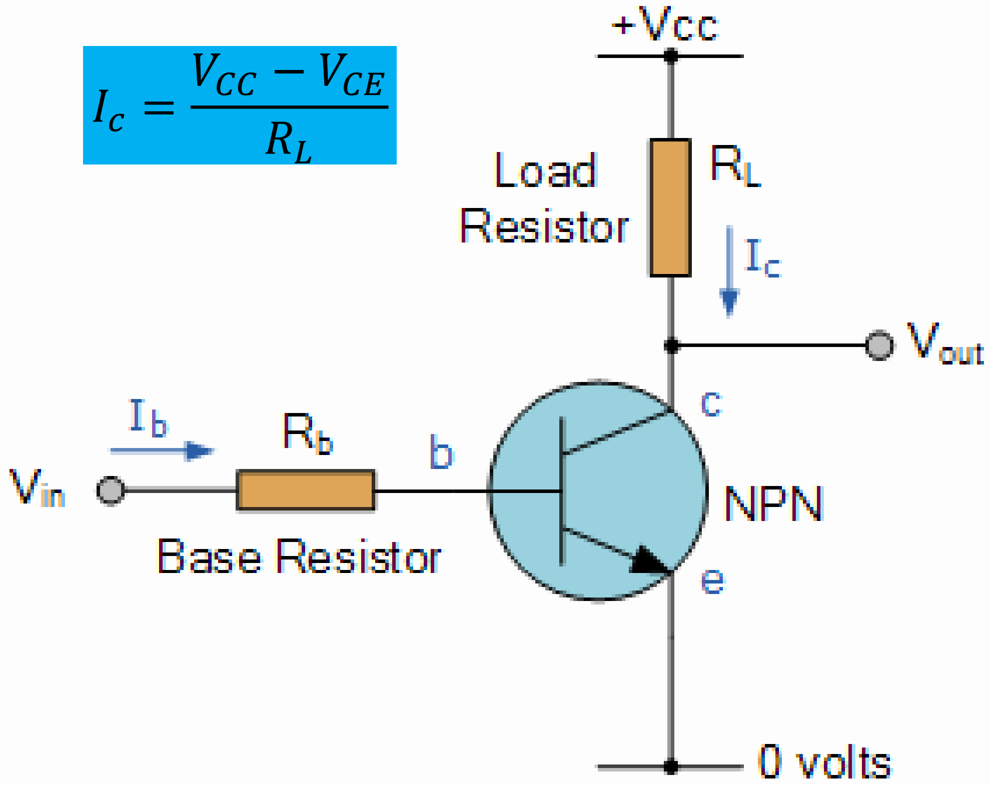
   When $V_{BE} \geq V_{on}$, and $V_c < V_B$

EXPLORE MORE

BJT as an amplifier or as a switch



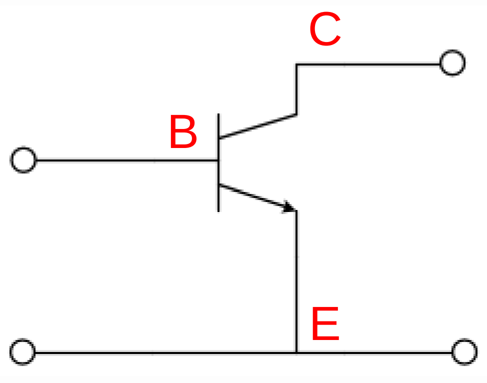
$$I_c = \frac{V_{CC} - V_{CE}}{R_L}$$

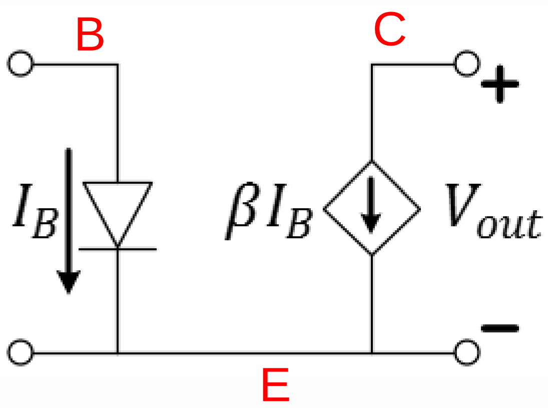


Q bias point – Amplifier

A and B points – Logic Inverter

The BJT's "common-emitter NPN" model





Equivalent model

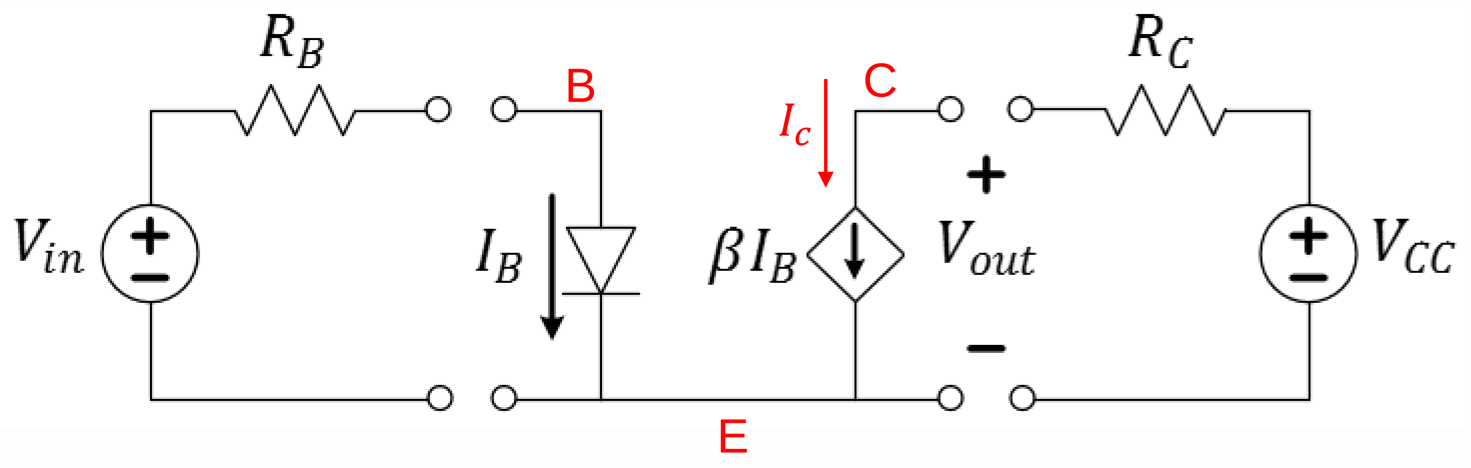
Constraints:

- Limited current range: $\beta I_B \geq 0$
- Limited voltage range: $V_{out} > 0$

L19Q1: Given these constraints, can this "dependent" current source deliver power?

A. Yes, all current sources can supply power
B. No, this current source cannot supply power
C. Neither A or B is correct.

Two Loops Coupled by Current Equation



DC bias circuit determines operating point of the transistor

Also called $I_{c,sat}$

$V_{min} = V_{CE,sat}$

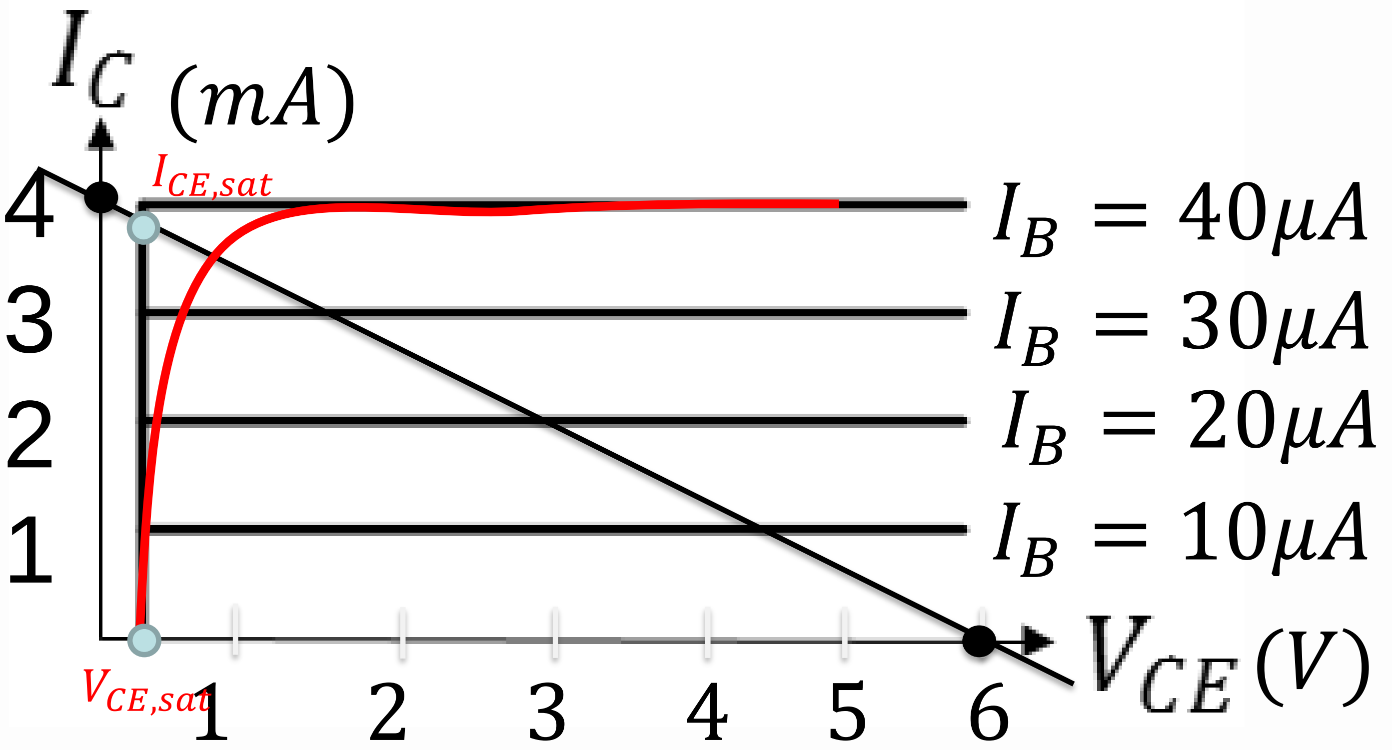
Constraints:

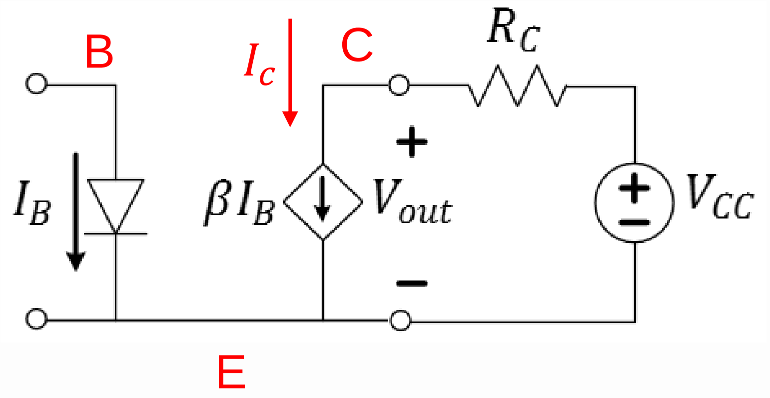
- Limited current range: $0 \le \beta I_B \le I_{max}$ (implied by V_{min})
- Limited voltage range: $V_{out} \ge V_{min} \approx 0$

MORE

Simplified I-V curves

$$I_c = \frac{V_{CC} - V_{CE}}{R_C}$$



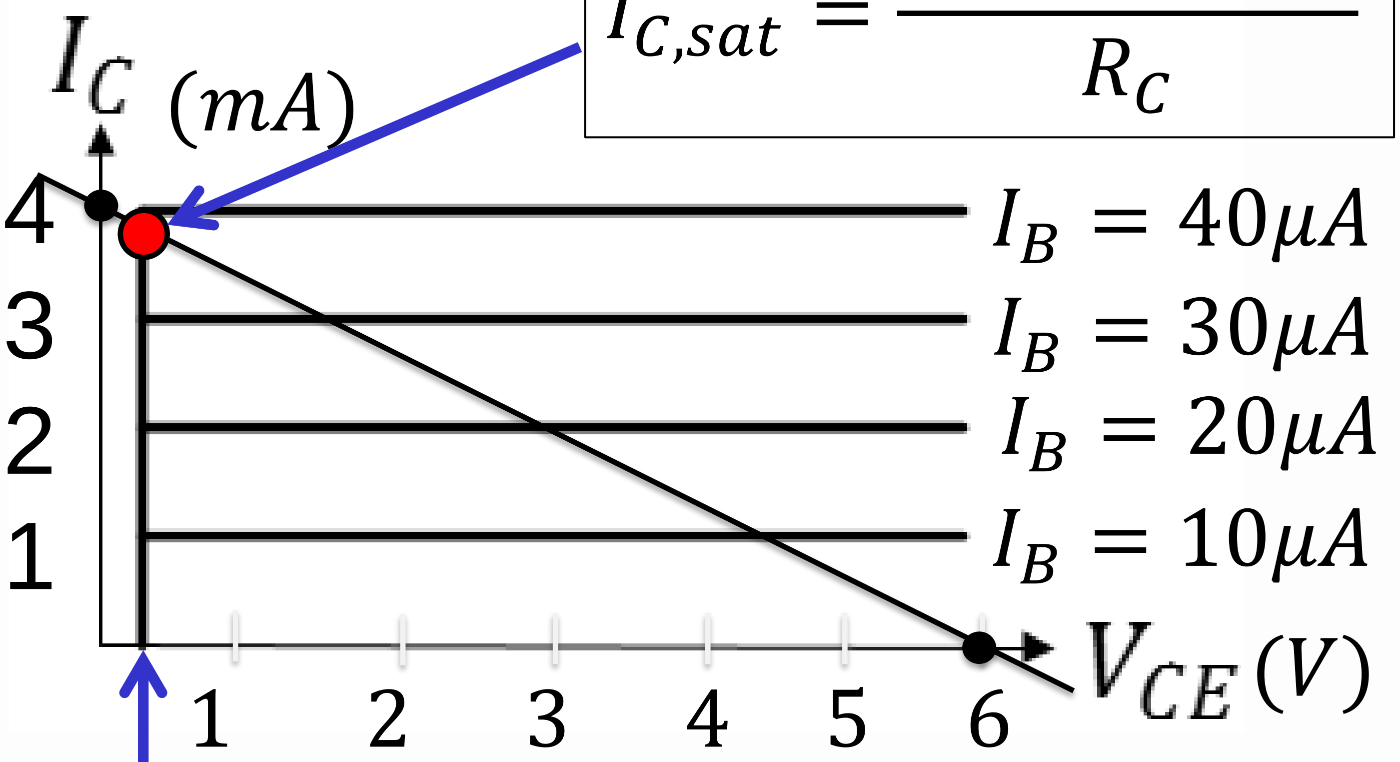


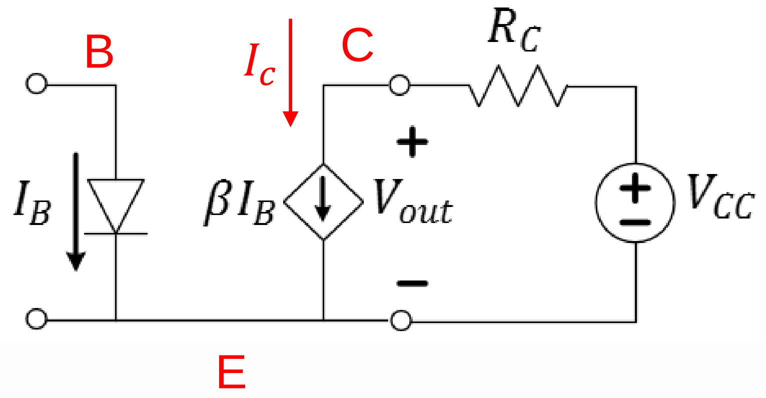
MORE **SUMMARY of technical terminology**

$$I_c = \frac{V_{CC} - V_{CE}}{R_C}$$

$$I_{C,sat} = \frac{V_{CC} - V_{CE,sat}}{R_C}$$

$$I_C = min\{\beta I_B, I_{C,sat}\}$$





$$I_{max} = I_{C,sat}$$
$$V_{min} = V_{CE,sat}$$

$V_{CE,sat} \approx$ typically $0.2V$ to $0.3V$

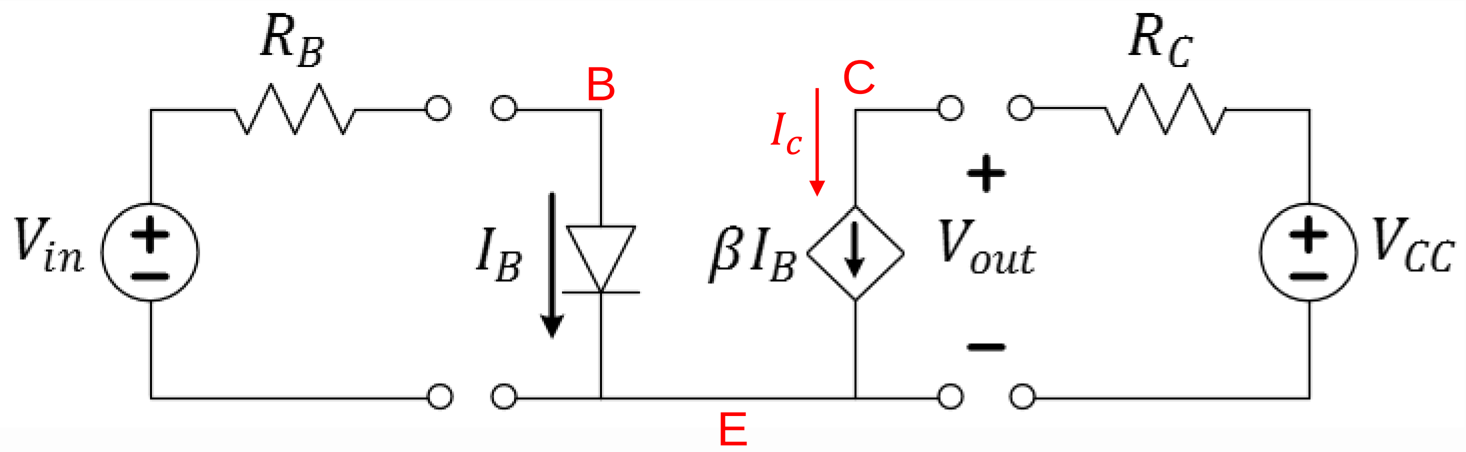
MORE SUMMARY of technical terminology

- In saturation the collector current cannot grow any longer if the base current is increased. Therefore:

$$\boxed{I_C = I_{C,sat} < \beta I_B}$$

- At the same time, the voltage between collector and emitter($\boldsymbol{V_{CE}}$)reaches its lowest possible level ($\boldsymbol{V_{CE,sat}}$)

Two Loops Coupled by Current Equation



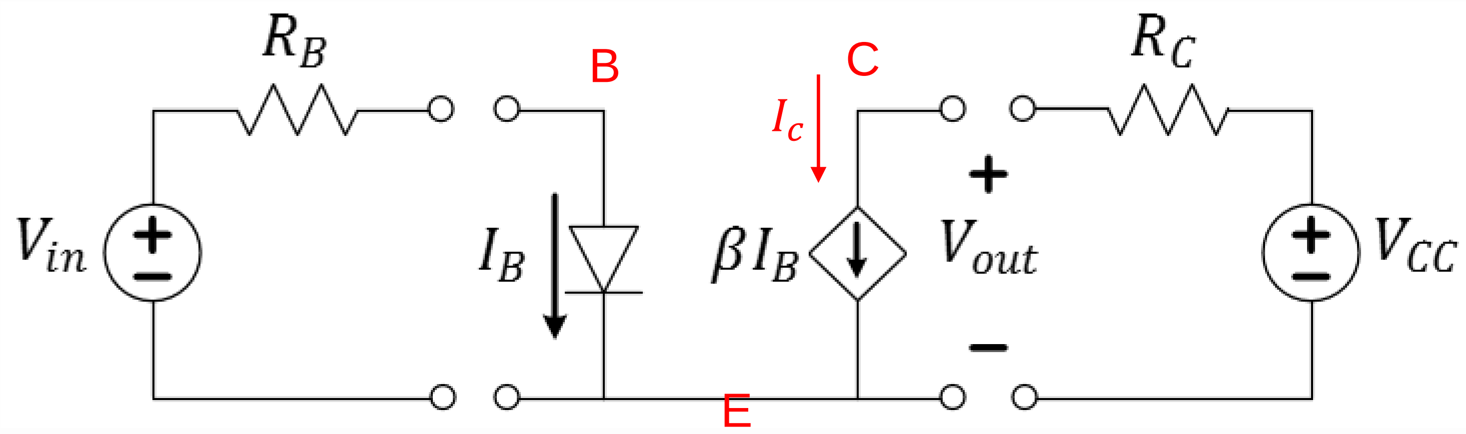
L19Q2: Right-side KVL: Find an equation relating I_{max} to V_{min}.

L19Q3: Left-side KVL: Find the smallest V_{in} such that $I_B > 0$ (if $\mathrm{V_{on}} = 0.7\ V$)?

L19Q4: What is I_B if $V_{in} = 3\ V$ and $R_B = 4.6\ k\Omega$?

L19Q5: Let $V_{CC} = 6\ V, R_C = 580\ \Omega, V_{min} = 0.2\ V, \beta = 100$. What is I_C under the same input settings as the previous question?

L19Q2: Right-side KVL: Find an equation relating I_{max} to V_{min}.



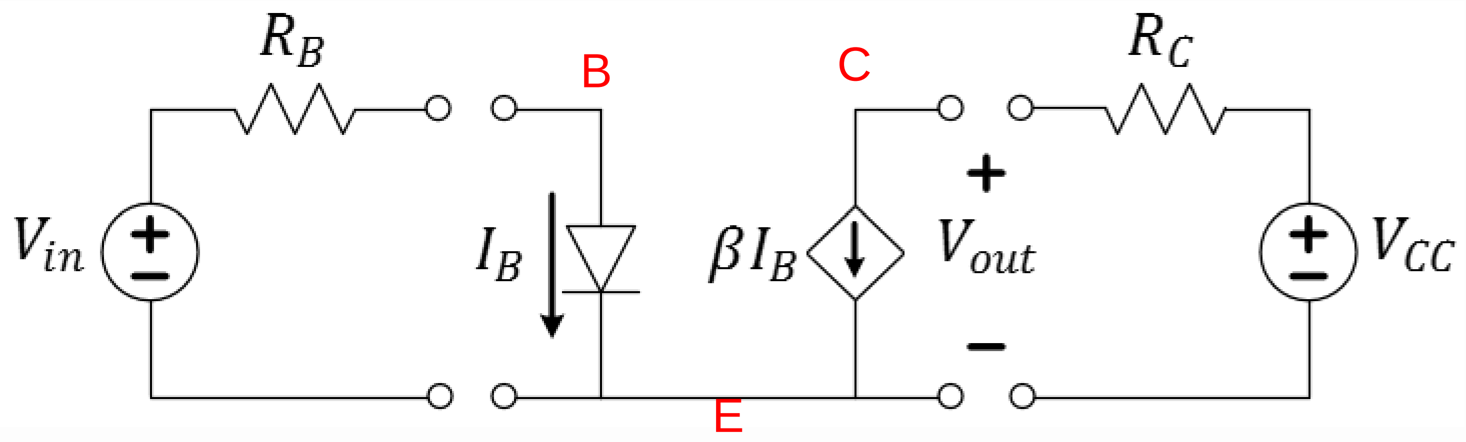
$$I_{max} = I_{C,sat}$$
$$V_{min} = V_{CE,sat}$$

$$I_{max} = I_{C,sat} = \frac{V_{CC} - V_{min}}{R_C} = \frac{V_{CC} - V_{CE,sat}}{R_C}$$

L19Q3: Left-side KVL: Find the smallest V_{in} such that $I_B > 0$ (if $\mathrm{V_{on}} = 0.7\,V$)?

$$V_{in} > V_{on} = 0.7V \quad \Rightarrow \quad I_B > 0$$

L19Q4 -What is I_B if $V_{in} = 3\ V$ and $R_B = 4.6\ k\Omega$?



- By Ohm’s Law (Nodal method)

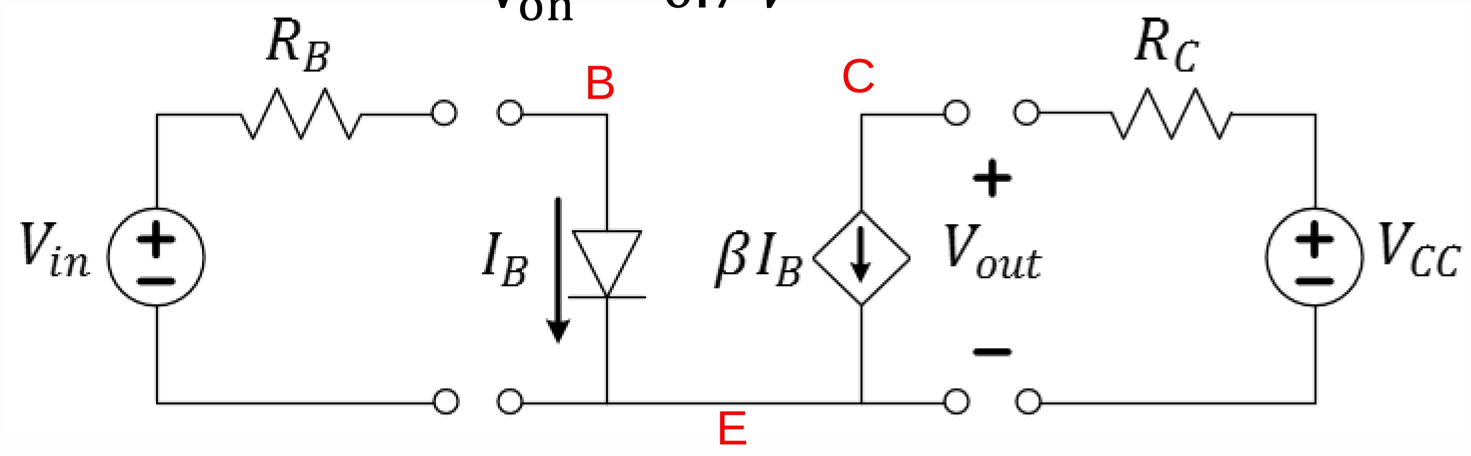
$$I_B = \frac{3-0.7}{4.6k} = 0.5\ mA$$

$$I_B = \frac{V_{in} - V_{on}}{R_B}$$

L19Q5 - Let $V_{CC} = 6\ V, R_C = 580\ \Omega, V_{min} = 0.2\ V, \beta = 100$. What is I_C with the previous input settings ($V_{in} = 3\ V$ and $R_B = 4.6\ k\Omega$)

$\mathrm{V_{on}} = 0.7\ V$

From Q4: $I_B = 0.5\ mA$



$$I_C = 100 I_B = 50\ mA.$$

We need to verify that $I_C < I_{C,sat}$

Working in active regime

Since: $I_{C,sat} = \frac{V_{CC}-V_{min}}{R_C} = \frac{5.8}{580} = 100\ mA > 50\ mA$

$\Rightarrow$ 50 mA looks OK

BJT Datasheet Parameters
2N5192G

$\approx \beta$

$V_{CE,sat}$

$V_{BE,on} \leq$

ELECTRICAL CHARACTERISTICS* (T_C = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
ON CHARACTERISTICS (Note 1)				
DC Current Gain	h_{FE}			–
(I_C = 1.5 Adc, V_{CE} = 2.0 Vdc)				
2N5190G/2N5191G		25	100	
2N5192G		20	80	
(I_C = 4.0 Adc, V_{CE} = 2.0 Vdc)				
2N5190G/2N5191G		10	–	
2N5192G		7.0	–	
Collector−Emitter Saturation Voltage	$V_{CE(sat)}$			Vdc
(I_C = 1.5 Adc, I_B = 0.15 Adc)		–	0.6	
(I_C = 4.0 Adc, I_B = 1.0 Adc)		–	1.4	
Base−Emitter On Voltage	$V_{BE(on)}$			Vdc
(I_C = 1.5 Adc, V_{CE} = 2.0 Vdc)		–	1.2	

L19Q6: Approximate the values of β, V_{BEon}, and $V_{CE,sat}$ from the datasheet.

BJT Datasheet Parameters 2N5192G

h_{FE} = small signal gain
β = d.c. gain (a.k.a. H_{FE})
$\beta \approx h_{FE}$

ELECTRICAL CHARACTERISTICS* (T_C = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
ON CHARACTERISTICS (Note 1)				
DC Current Gain	h_{FE}			–
(I_C = 1.5 Adc, V_{CE} = 2.0 Vdc)				
2N5190G/2N5191G		25	100	
2N5192G		20	80	
(I_C = 4.0 Adc, V_{CE} = 2.0 Vdc)				
2N5190G/2N5191G		10	–	
2N5192G		7.0	–	
Collector–Emitter Saturation Voltage	$V_{CE(sat)}$			Vdc
(I_C = 1.5 Adc, I_B = 0.15 Adc)		–	0.6	
(I_C = 4.0 Adc, I_B = 1.0 Adc)		–	1.4	
Base–Emitter On Voltage	$V_{BE(on)}$			Vdc
(I_C = 1.5 Adc, V_{CE} = 2.0 Vdc)		–	1.2	

$\approx \beta$

$V_{CE,sat}$

$V_{BE,on} \leq$

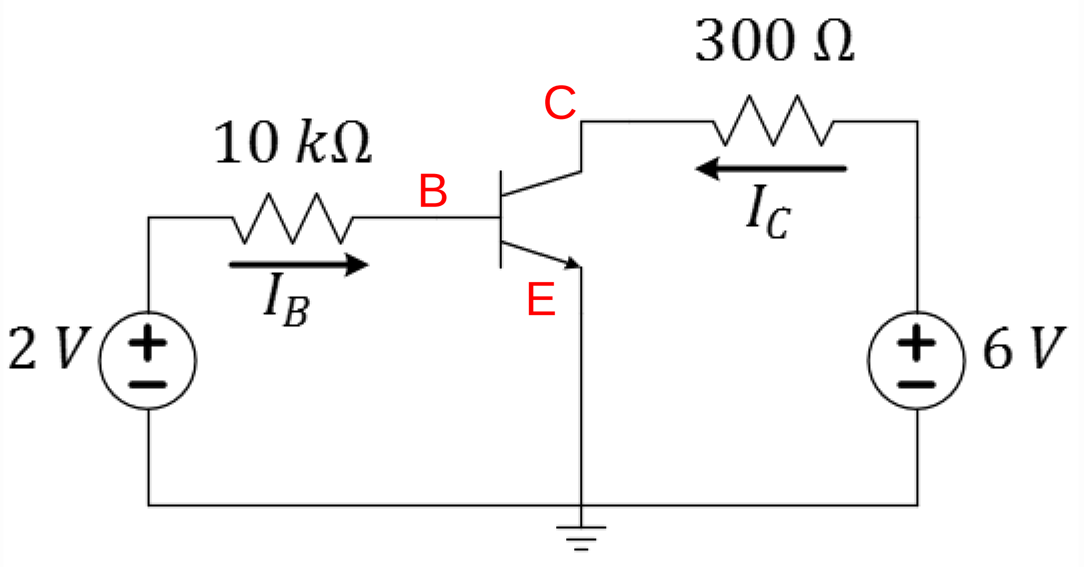
L19Q6: Approximate the values of $\beta, V_{BEon},$ and $V_{CE,sat}$ from the datasheet.

$\boldsymbol{\beta \approx 20\ to\ 50,} \qquad \boldsymbol{V_{BEon} \approx 0.6\ to\ 1\ V,} \qquad \boldsymbol{V_{CEsat} \approx 0.6\ to\ 1.2V}$

BJT in Active Region

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



Q7:

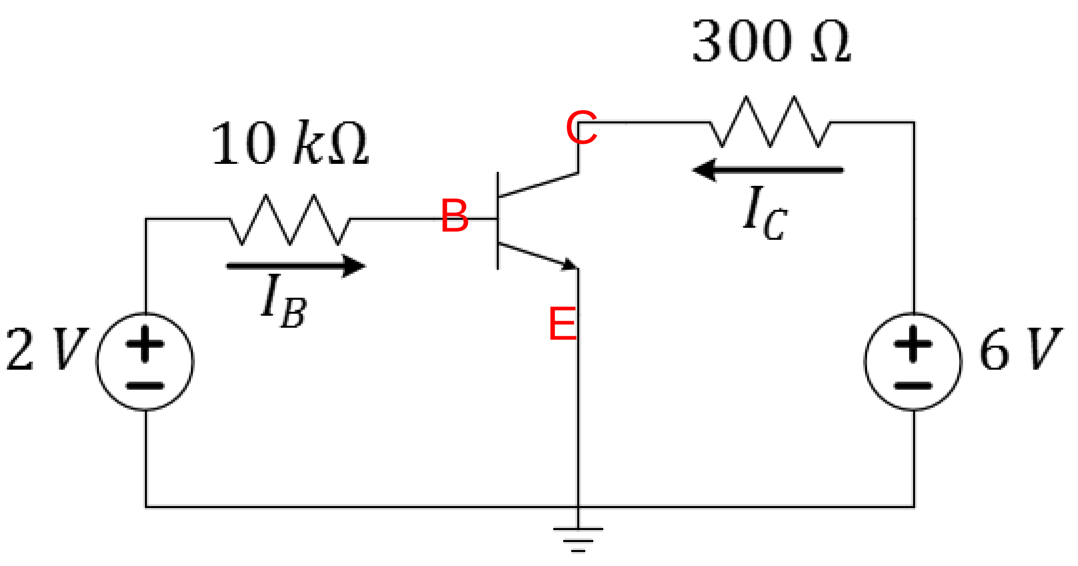
A. $I_B = 0\ \mu A$
B. $I_B = 1\ \mu A$
C. $I_B = 2\ \mu A$
D. $I_B = 10\ \mu A$
E. $I_B = 100\ \mu A$

L19Q7: Find I_B.
L19Q8: Find I_C.

BJT in Active Region – L19Q7: Find I_B

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



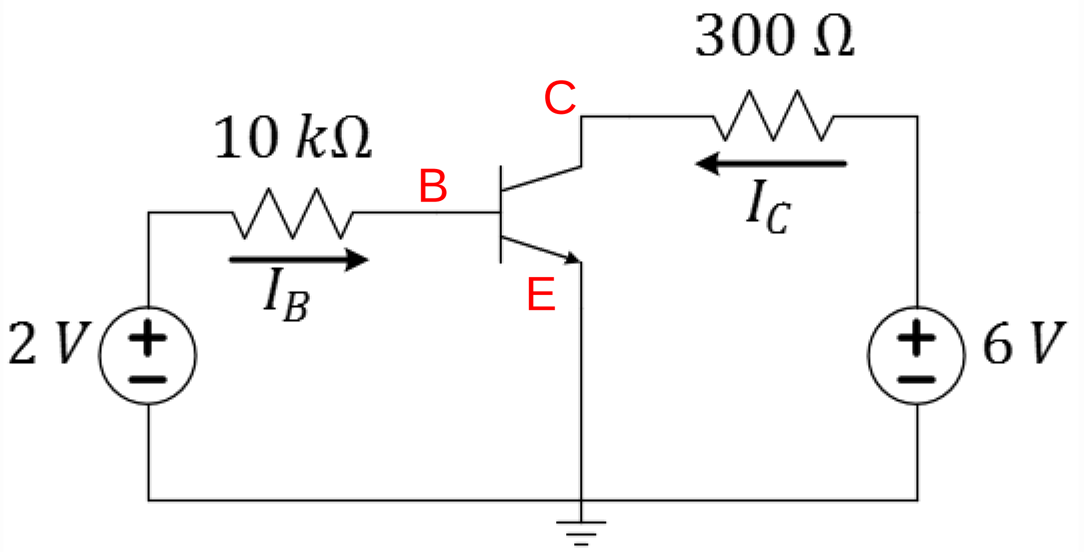
Q7:
A. $I_B = 0\ \mu A$
B. $I_B = 1\ \mu A$
C. $I_B = 2\ \mu A$
D. $I_B = 10\ \mu A$
E. $\boxed{I_B = 100\ \mu A}$

$$I_B = \frac{V_{in} - V_{BE,on}}{10k} = \frac{2-1}{10k} = 0.1mA = 100\mu A$$

BJT in Active Region – L19Q8: Find I_C

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



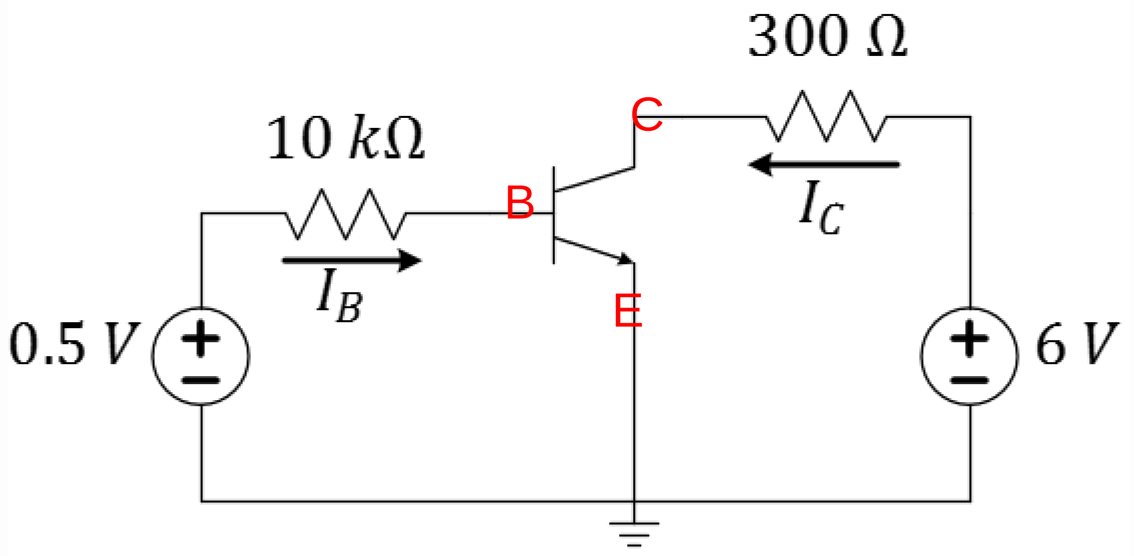
$$I_C = \beta I_B = 10mA$$

$$I_{C,sat} = \frac{V_{CC} - V_{CE,sat}}{300} = \frac{6 - 0.2}{300} = 19.3mA$$

BJT in Cutoff

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



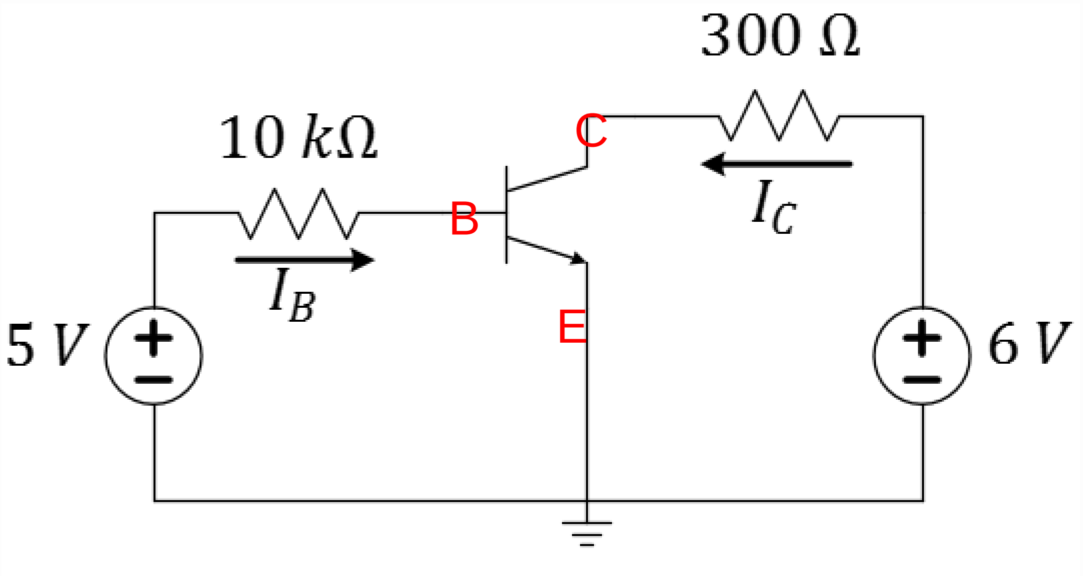
L19Q9: Find I_B.
L19Q10: Find I_C.

$$V_{in} = 0.5\text{V} < \ V_{BE,on}$$
$$I_B \approx 0 \quad \& \quad I_C \approx 0$$

BJT in Saturation

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$

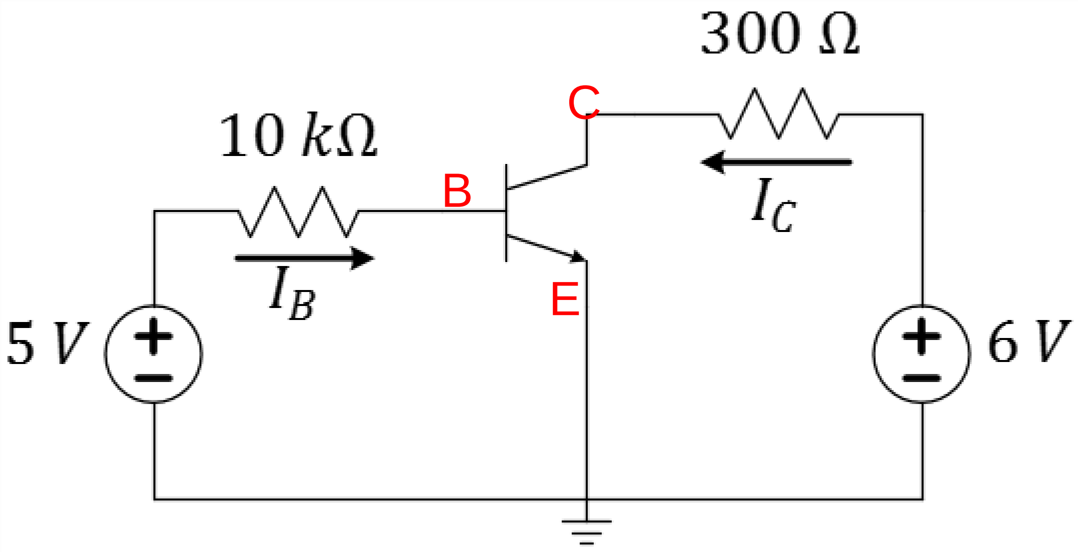


L19Q11: Find I_B.
L19Q12: Find I_C.

BJT in Saturation

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



$$I_B = \frac{V_{in} - V_{BE,on}}{10k} = \frac{5-1}{10k} = 0.4mA = 400\mu A$$

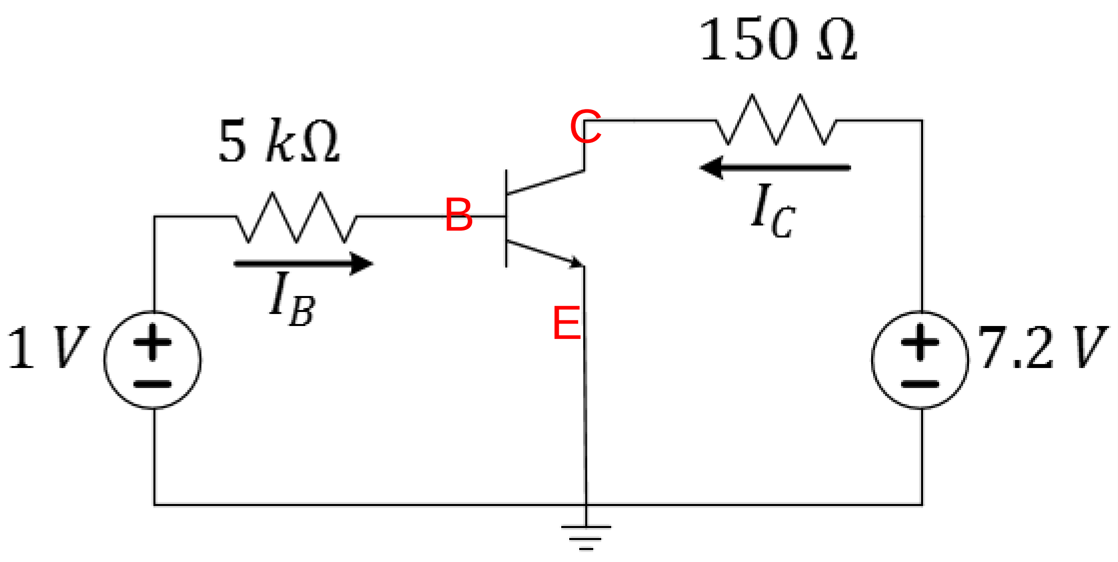
$I_C = \beta I_B = 40mA\ > I_{C,sat} = 19.3mA$ (cannot be supplied)

$$I_C = I_{C,sat} = 19.3\ mA$$

BJT Exercise

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



L19Q13: Find I_C and identify in which regime the transistor is operating.

L19Q13: Find I_C and identify in which regime the transistor is operating.

BJT datasheet parameters:

- $\beta = 100$
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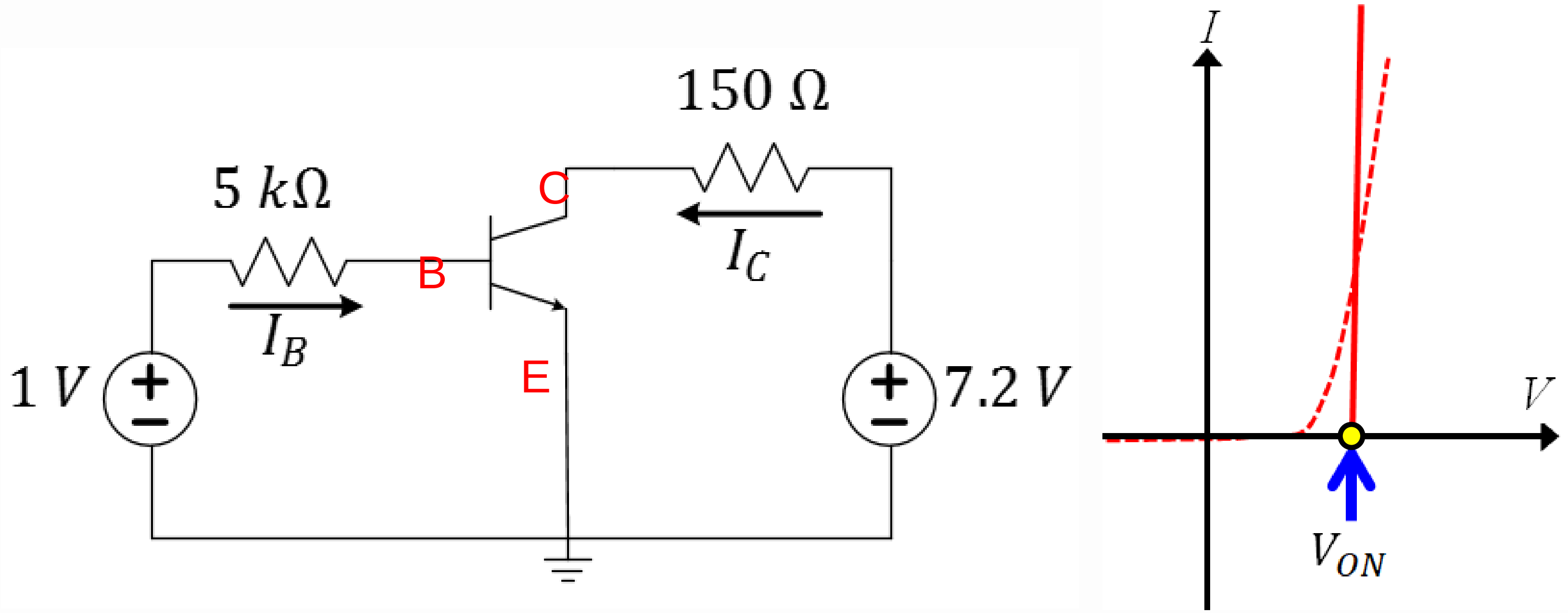


$$I_B = \frac{V_{in} - V_{BE,on}}{10k} = \frac{1-1}{10k} = 0\ A$$

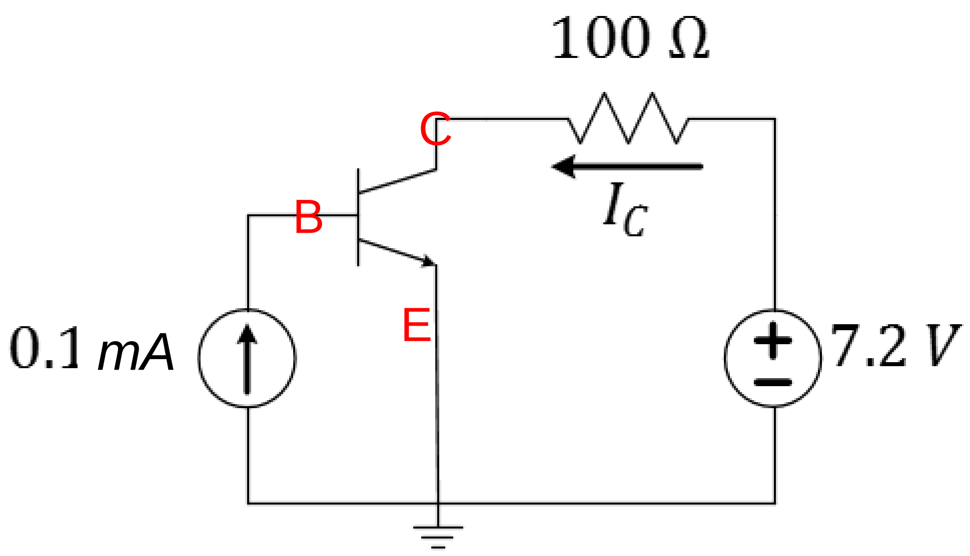
$$I_C = 0$$

Right at the boundary between "<u>cutoff</u>" and "<u>active</u>" regime (corner point)

BJT Exercise

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$

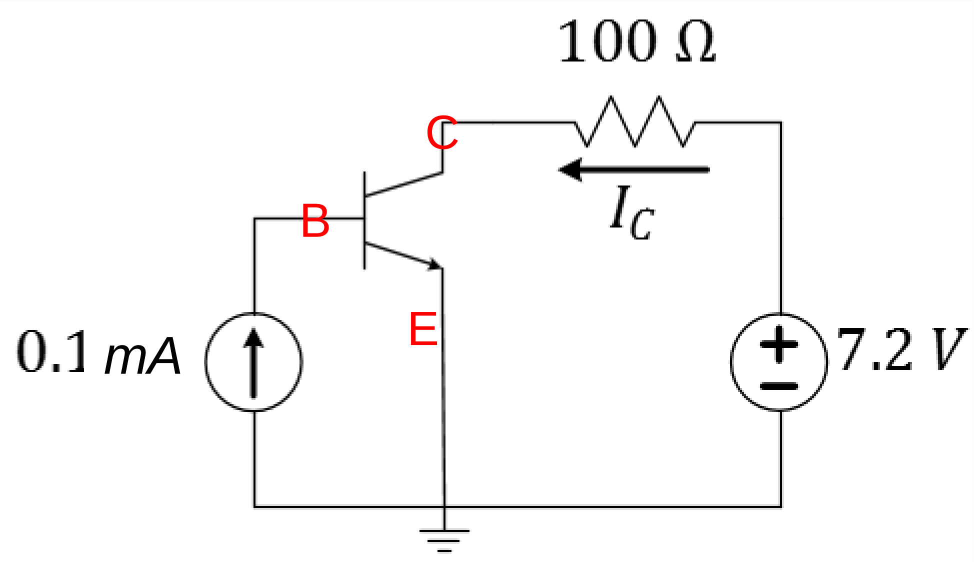


L19Q14: Find I_C and identify in which regime the transistor is operating.
L19Q15: Determine the power consumed by the transistor.

L19Q14: Find I_C and identify in which regime the transistor is operating
L19Q15: Determine the power consumed by the transistor

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



$\boldsymbol{I_C < I_{C,sat}}$

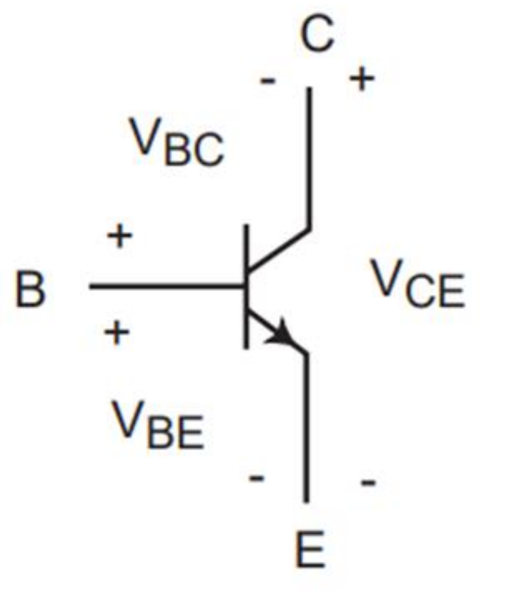
Active regime

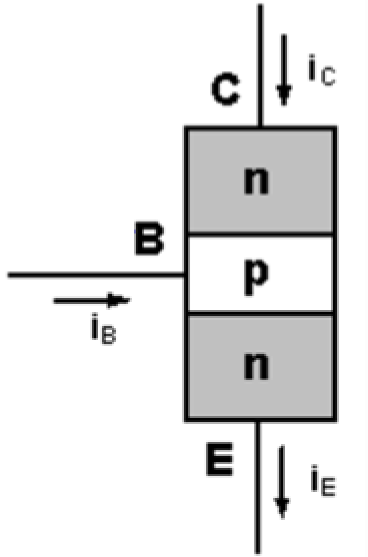
$$I_C = \beta I_B = 10mA \quad \left(I_{C,sat} = \frac{7.2-0.2}{100} = 70mA \right)$$

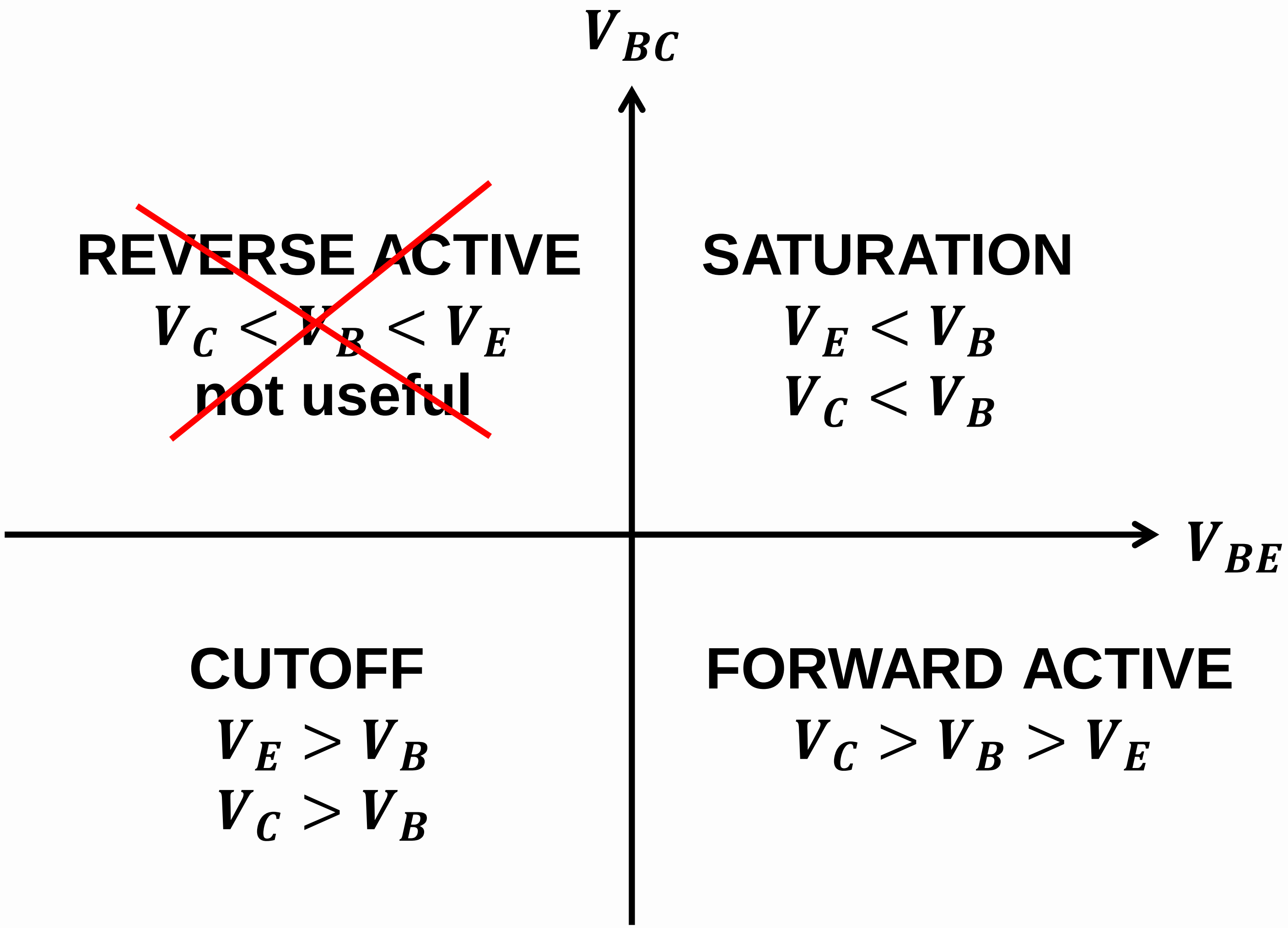
$$P = V_{BE,on} I_B + V_{CE} I_C = 1 \times 0.1m + (7.2 - 100 \times 10m) \times 10m$$
$$= 0.1mW + 62mW = 62.1mW$$

MORE

Summary n-p-n BJT regimes







L19 Learning Objectives

a. Identify B, E, C terminals on an npn-BJT symbol
b. Explain BJT's three regimes of operation
c. Calculate active-regime I_C using V_{BEon} in the BE loop
d. Calculate maximum I_C based on $V_{CE,sat}$ and CE loop
e. Calculate I_C given complete biasing conditions and transistor parameters, no matter which regime
f. Calculate the power dissipated by a transistor