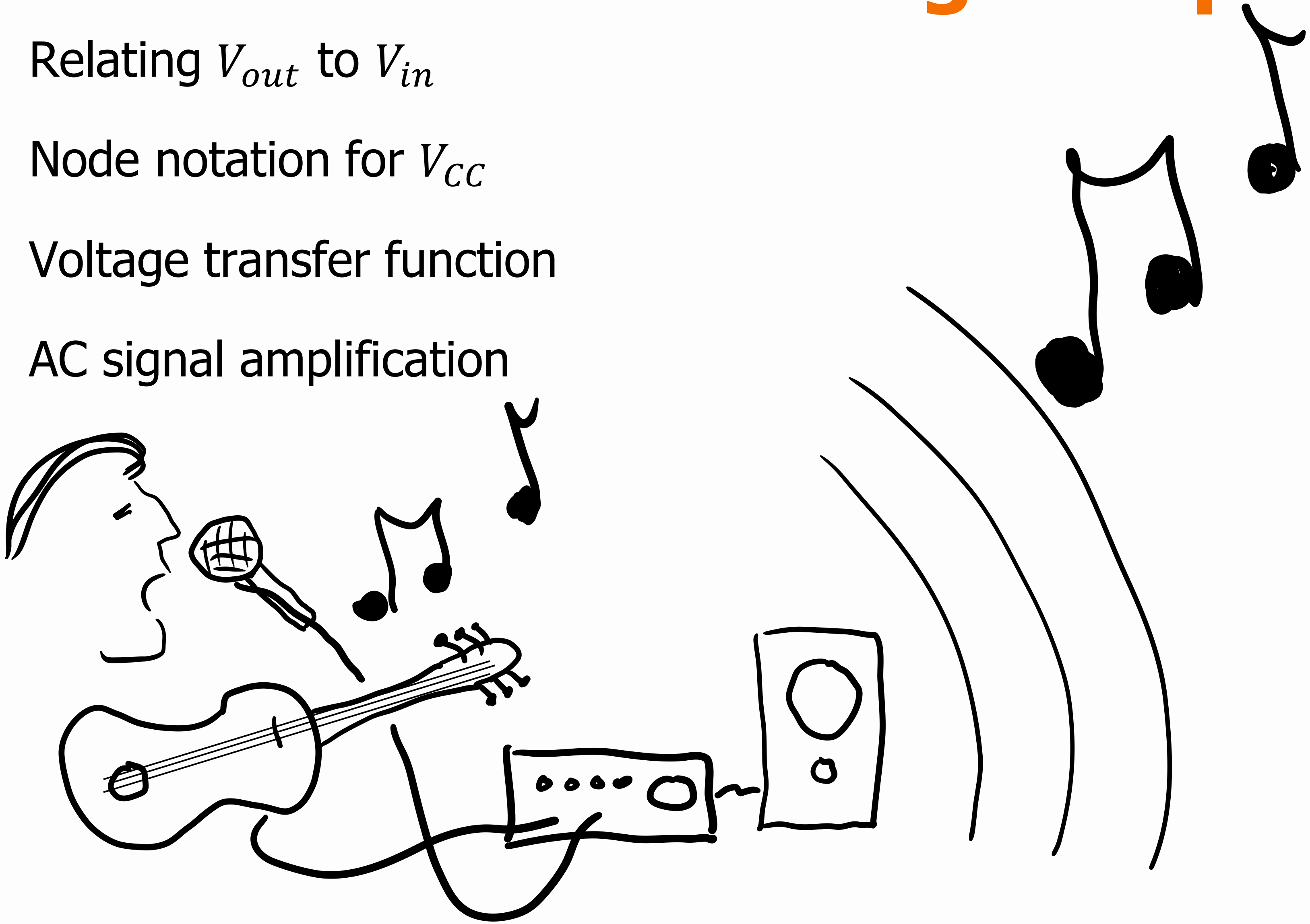
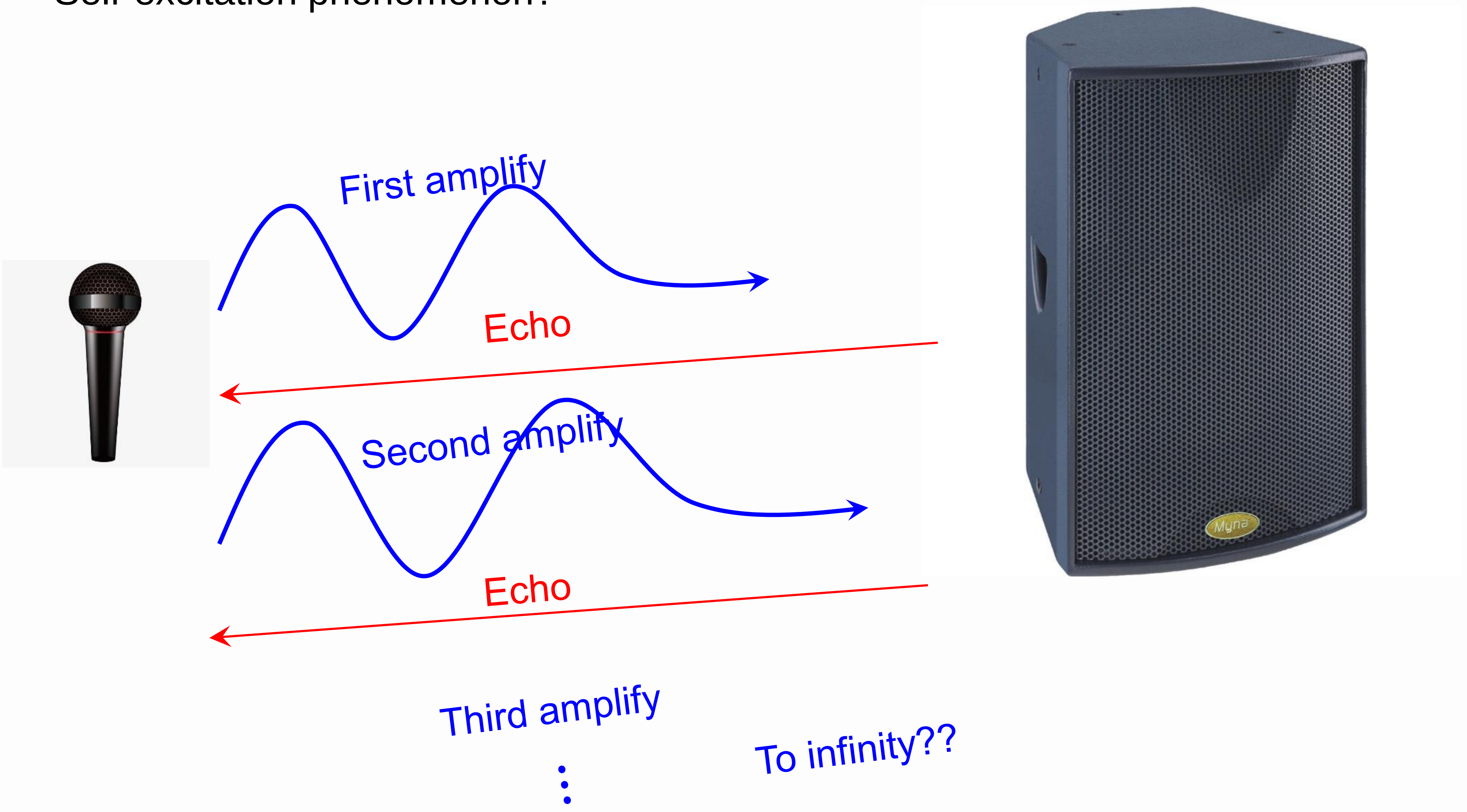
Lecture 21: The BJT Voltage Amplifier

- Relating V_{out} to V_{in}
- Node notation for V_{CC}
- Voltage transfer function
- AC signal amplification

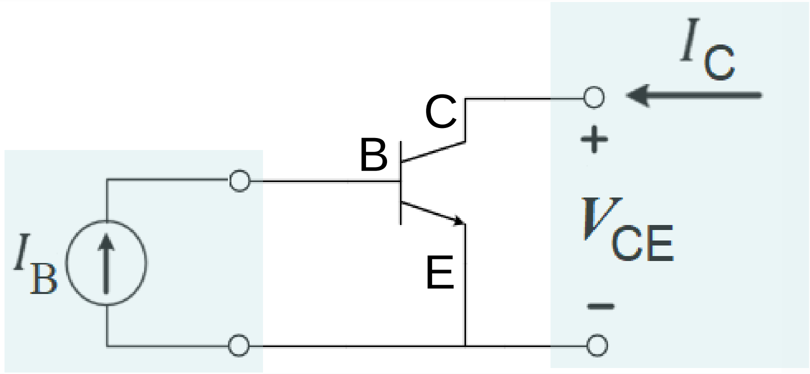


An interesting question

Self-excitation phenomenon?



Notice



1. Cut-off regime

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

2. Active regime

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

$V_{CE} > V_{CE,sat}$

3. Saturation regime

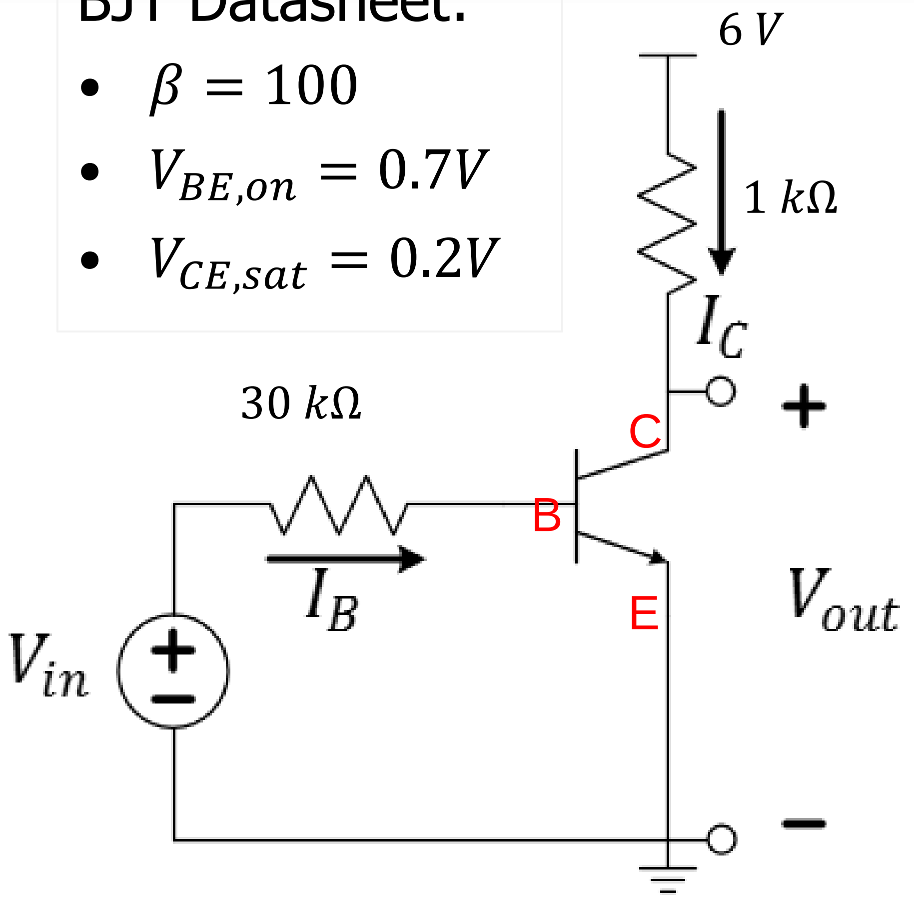
When $V_{BE} \geq V_{on}$, and $V_{CE} = V_{CE,sat}$

$I_c = I_{C,sat}$

Calculating V_{out} from V_{in} (revisited)

BJT Datasheet:

- $\beta = 100$
- $V_{BE,on} = 0.7V$
- $V_{CE,sat} = 0.2V$

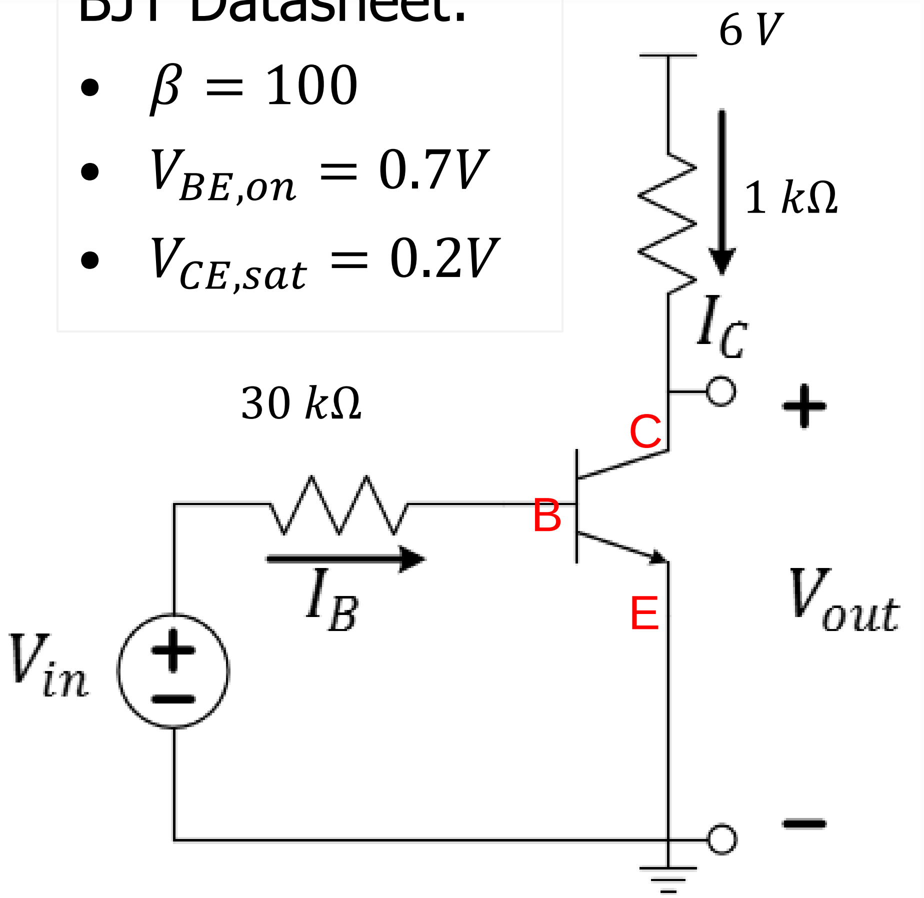


L21Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5 \text{ Volts}$?

CHECK THE $I_{C,sat}$ FIRST

BJT Datasheet:

- $\beta = 100$
- $V_{BE,on} = 0.7V$
- $V_{CE,sat} = 0.2V$



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

$$= \frac{6 - 0.2}{1k} = 5.8mA$$

$$I_{B,sat} = \frac{I_{C,sat}}{\beta} = 58\mu A$$

I_B at onset of saturation

L21Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5 \text{ Volts?}$

Calculating V_{out} from V_{in} (revisited)

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- $\beta = 100$
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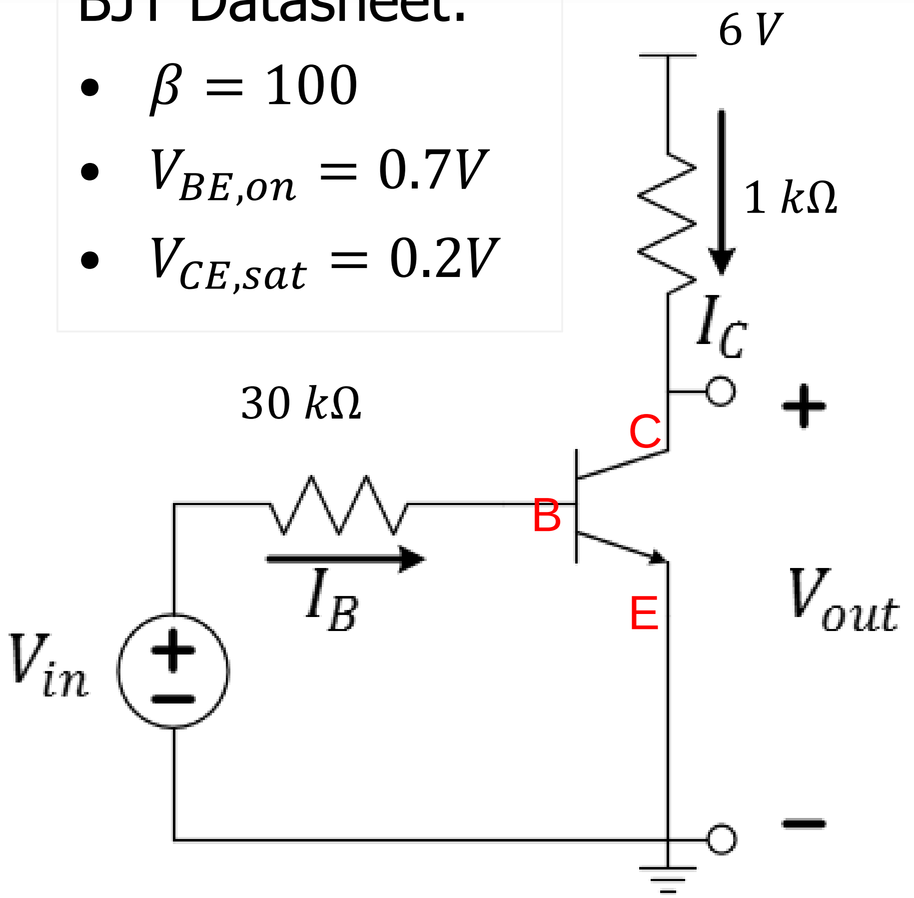


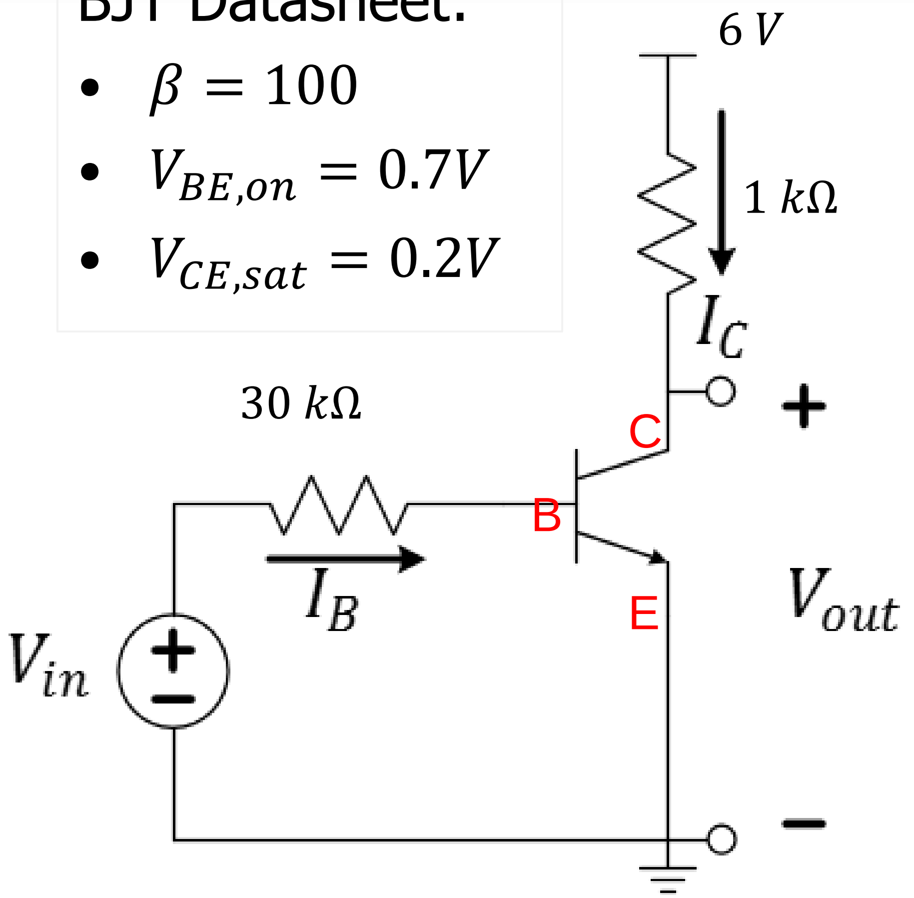
$$V_{in} = 0.3V$$
$$I_B = 0A$$
$$I_C = 0A$$
$$V_{out} = 6V$$

L21Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5$ Volts?

Calculating V_{out} from V_{in} (revisited)

BJT Datasheet:

- $\beta = 100$
- $V_{BE,on} = 0.7V$
- $V_{CE,sat} = 0.2V$



$$V_{in} = 1V$$

$$I_B = \frac{1 - 0.7}{30k} = 10\mu A$$

$$I_C = \beta I_B = 1mA \quad \boxed{I_C < I_{C,sat}}$$

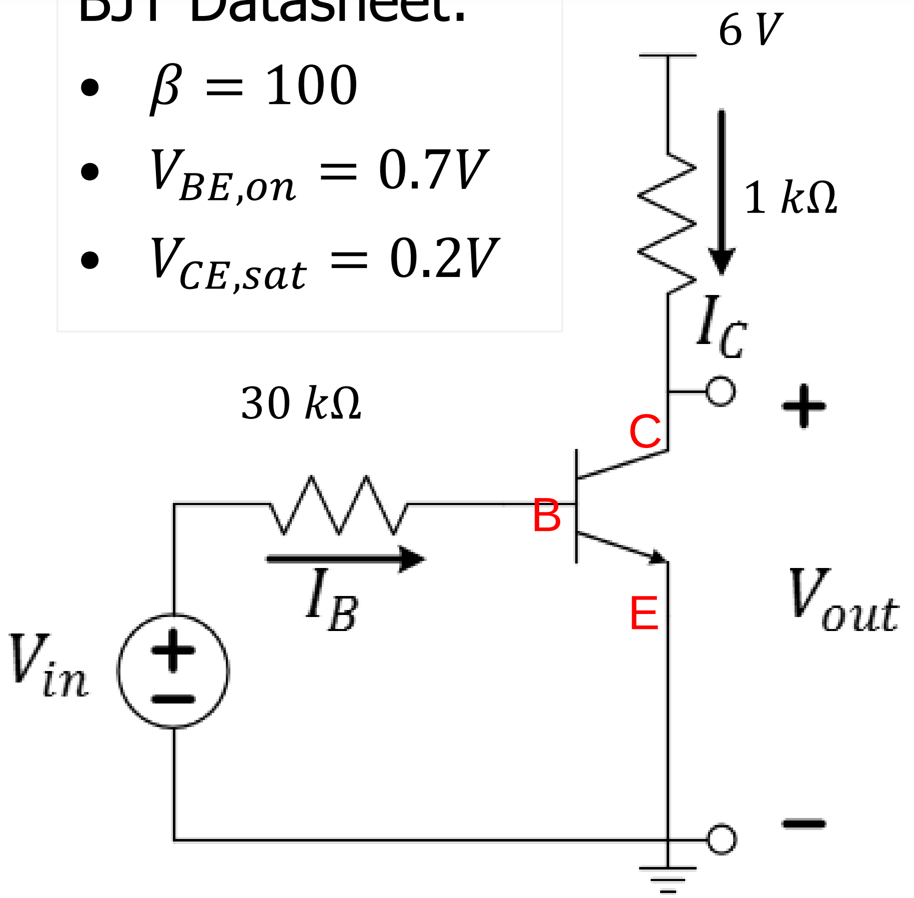
$$V_{out} = 6 - (1k)(1m) = 5V$$

L21Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5$ Volts?

Calculating V_{out} from V_{in} (revisited)

BJT Datasheet:

- $\beta = 100$
- $V_{BE,on} = 0.7V$
- $V_{CE,sat} = 0.2V$



$$V_{in} = 2.5V$$

$$I_B = \frac{2.5 - 0.7}{30k} = 60\mu A$$

$$I_C = \beta I_B = 6mA > I_{C,sat}$$

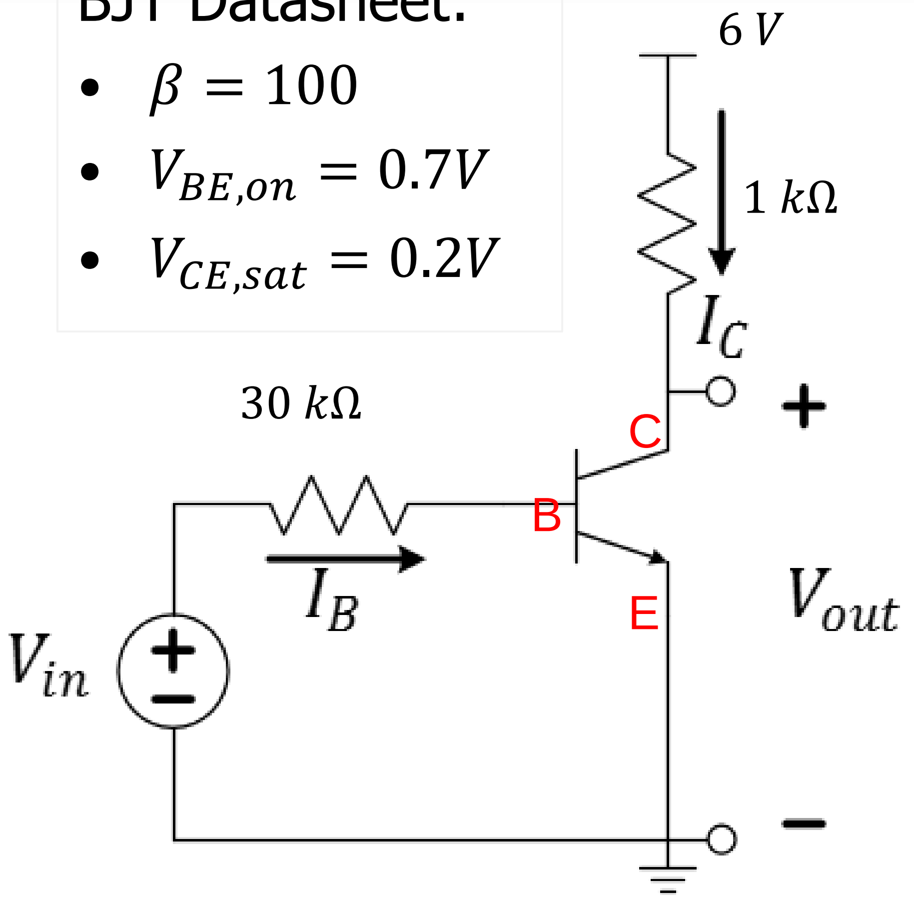
$$V_{out} = V_{C,sat} = 0.2V$$

L21Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5$ Volts?

Calculating V_{out} from V_{in} (revisited)

BJT Datasheet:

- $\beta = 100$
- $V_{BE,on} = 0.7V$
- $V_{CE,sat} = 0.2V$



$$V_{in} = 3.5V$$

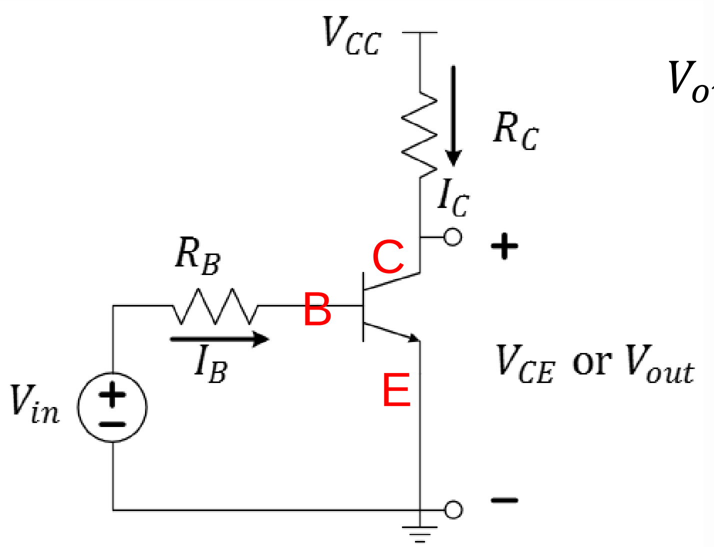
$$I_B = \frac{3.5 - 0.7}{30k} = 93\mu A$$

$$I_C = \beta I_B = 9.3mA > I_{C,sat}$$

$$V_{out} = V_{C,sat} = 0.2V$$

L21Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5 \text{ Volts?}$

Review of BJT operating regimes



A. $V_{in} = \frac{V_{CC} - V_{CE,sat}}{R_C}$

B. $V_{in} = V_{CC} + V_{BEon}$

C. $V_{in} = V_{CE,sat} + I_B R_B$

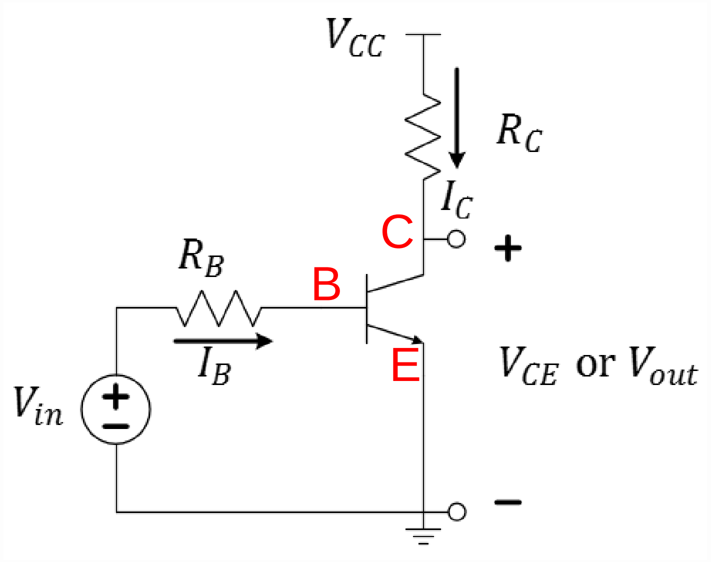
D. $V_{in} = V_{CC} - I_C R_C + I_B R_B$

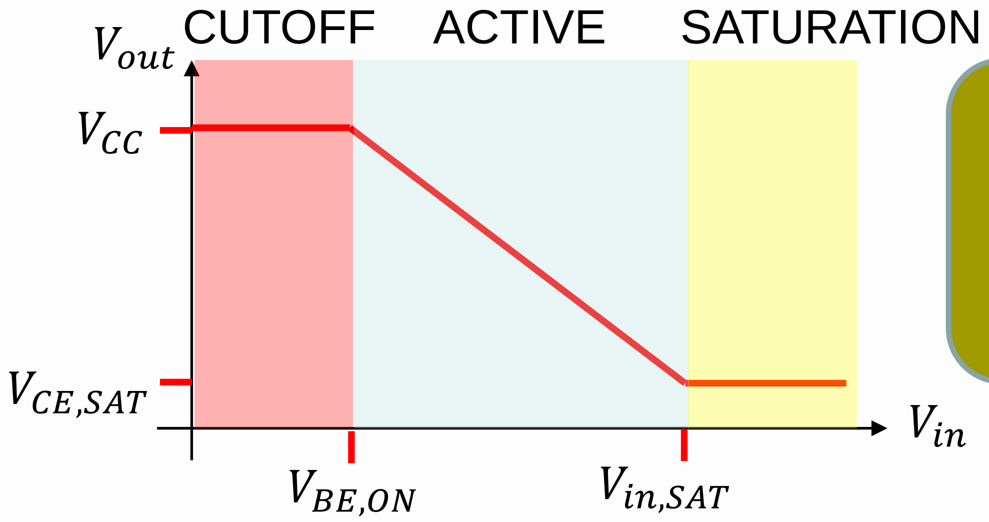
E. $V_{in} = V_{BEon} + \frac{R_B}{\beta R_C}(V_{CC} - V_{CE,sat})$

Regime	Vin	IB	IC	VC

L21Q2: What is the formula for minimum V_{IN} which causes saturation?

Review of BJT operating regimes





In active regime

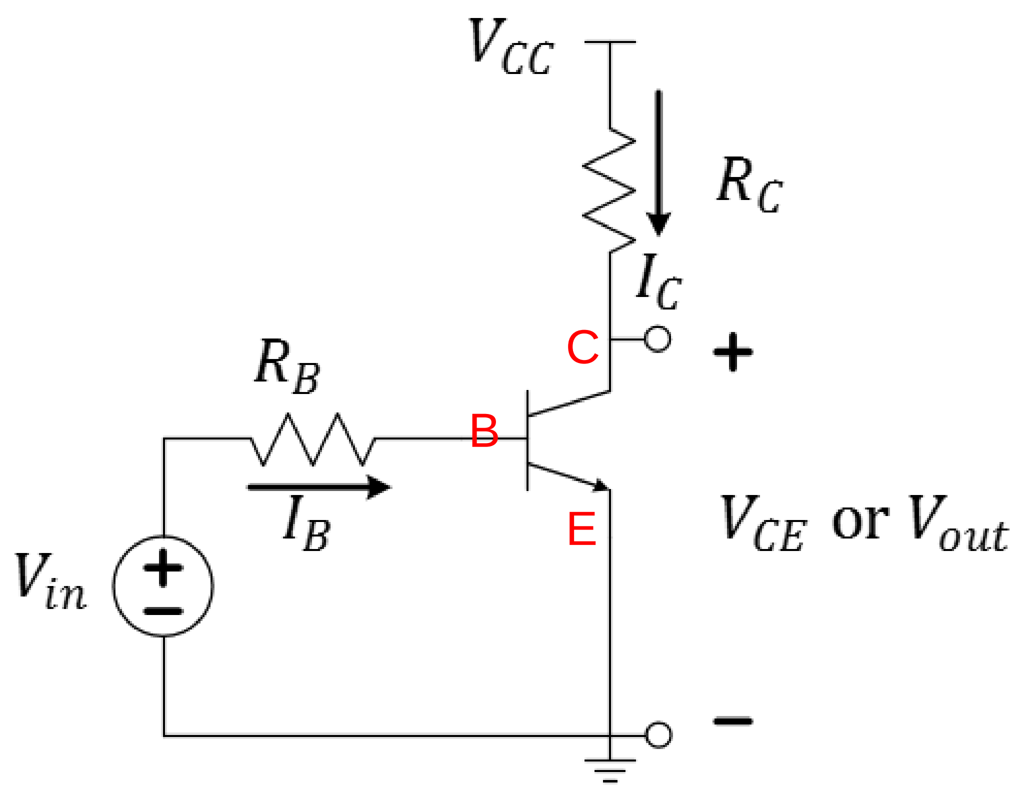
$V_{in} \uparrow \;\Rightarrow I_B \uparrow$

$\Rightarrow I_C \uparrow \Rightarrow V_{out} \downarrow$

Regime	Vin	I_B	Ic	VCE
CUTOFF	$V_{in} < V_{BE,ON}$	0	0	V_{CC}
ACTIVE	$V_{BE,ON} \le V_{in} \le V_{in,SAT}$	$(V_{in} - V_{BE,ON})/R_B$	$I_C = \beta I_B$	$V_{CC} - R_C I_C$
SATURATION	$V_{in} > V_{in,SAT}$	$(V_{in} - V_{BE,ON})/R_B$	$I_{CE,SAT}$	$V_{CE,SAT}$

What's the value of $V_{in,sat}$?

L21Q2: What is the formula for minimum V_{IN} which causes saturation?



A. $V_{in} = \frac{V_{CC} - V_{CE,sat}}{R_C}$

B. $V_{in} = V_{CC} + V_{BEon}$

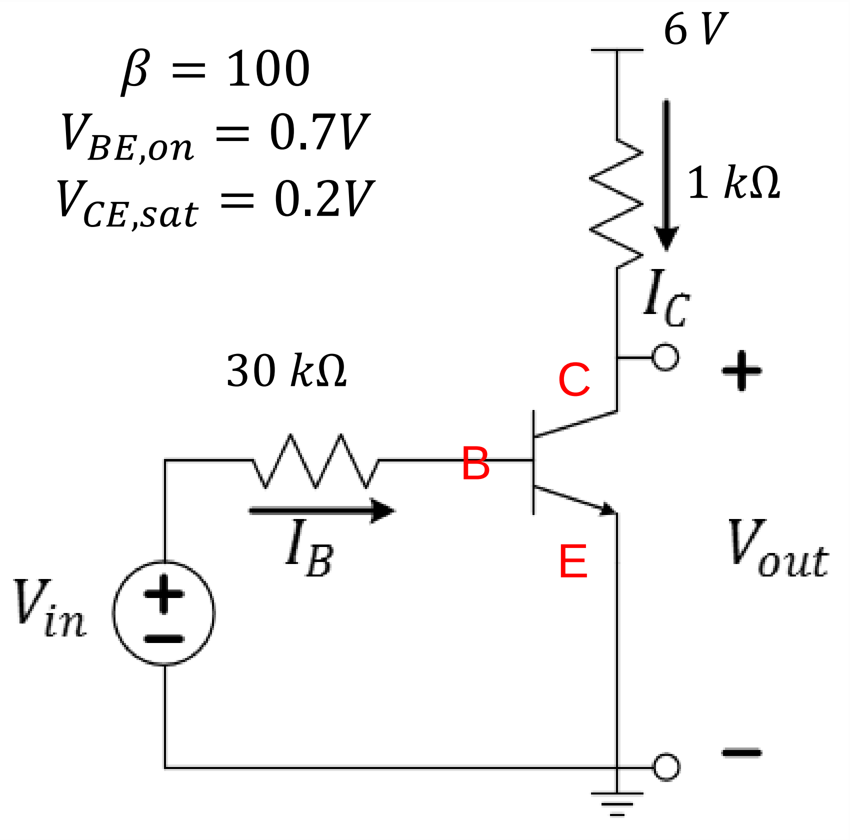
C. $V_{in} = V_{CE,sat} + I_B R_B$

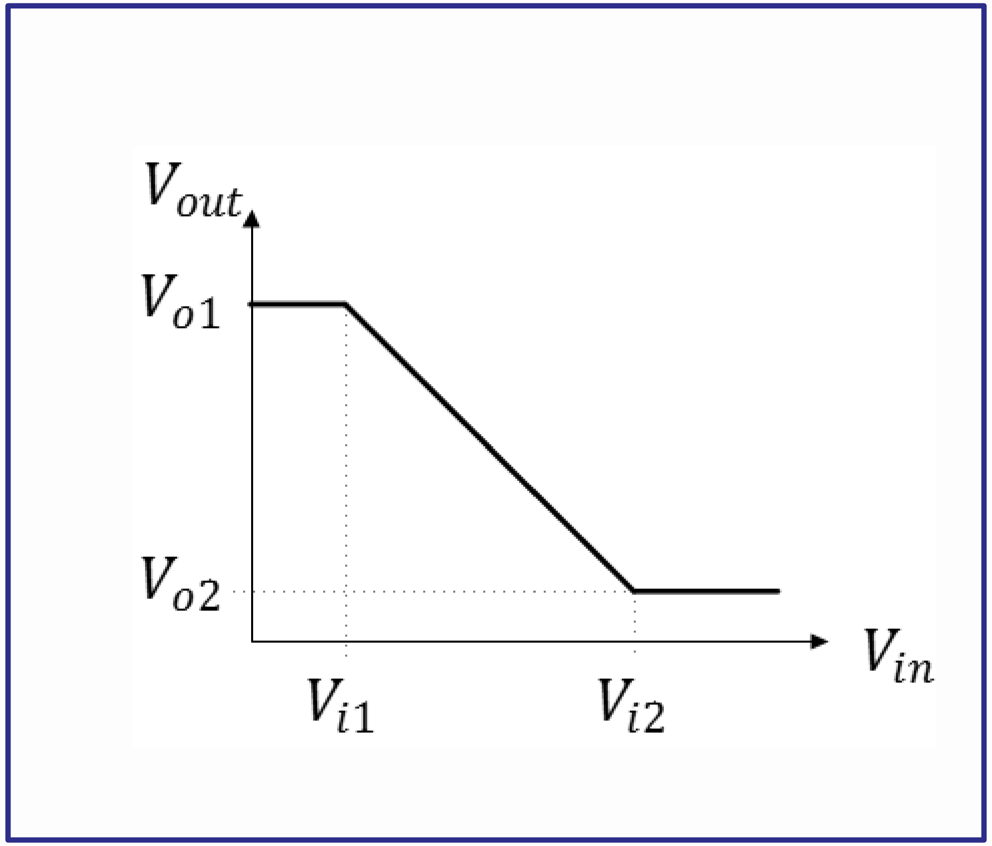
D. $V_{in} = V_{CC} - I_C R_C + I_B R_B$

E. $V_{in} = V_{BEon} + \frac{R_B}{\beta R_C}(V_{CC} - V_{CE,sat})$

$$V_{in,sat} = V_{BEon} + R_B \times \frac{I_C}{\beta} = V_{BEon} + R_B \times \frac{1}{\beta} \times \frac{V_{CC} - V_{CE,sat}}{R_C} = V_{BEon} + R_B \times \frac{I_{C,sat}}{\beta} = V_{BEon} + R_B \times I_{B,sat}$$

Voltage transfer characteristics

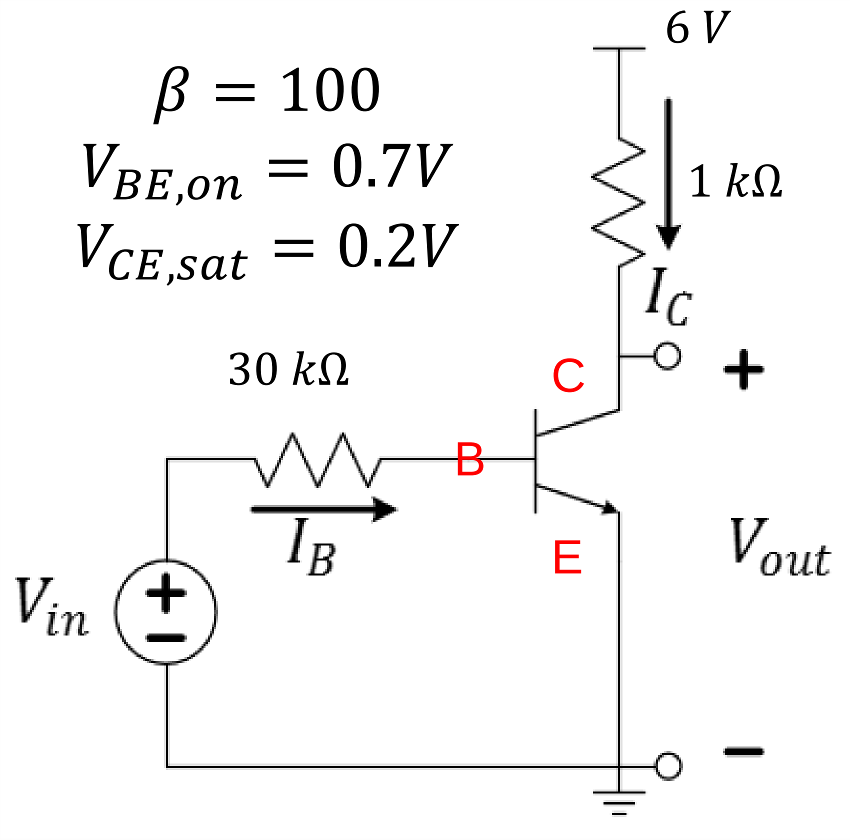




L21Q3: What are the four values $V_{o1}, V_{o2}, V_{i1}, V_{i2}$?

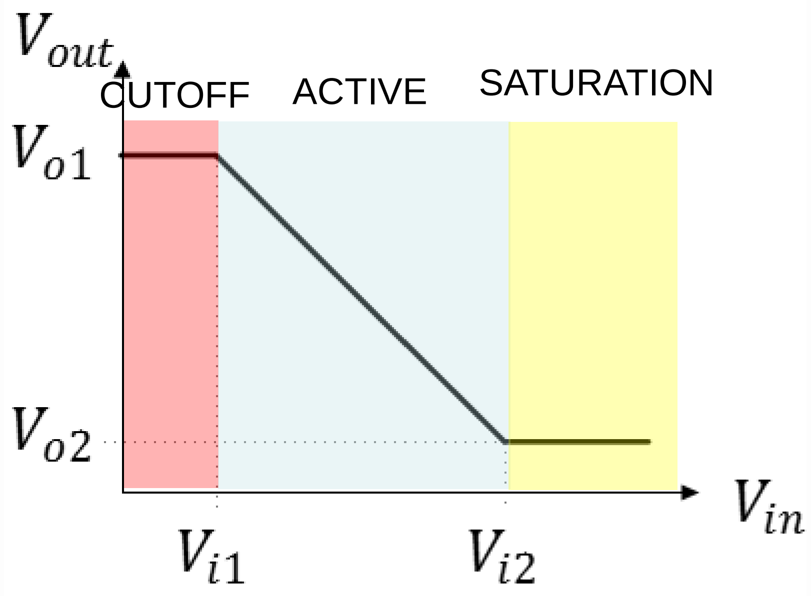
L21Q4: What is the $\frac{\Delta V_{out}}{\Delta V_{in}}$ slope in the active region?

L21Q3: What are the four values $V_{o1}, V_{o2}, V_{i1}, V_{i2}$?



$$V_{o1} = V_{CC} = 6V$$

$$V_{o2} = V_{CE,sat} = 0.2V$$

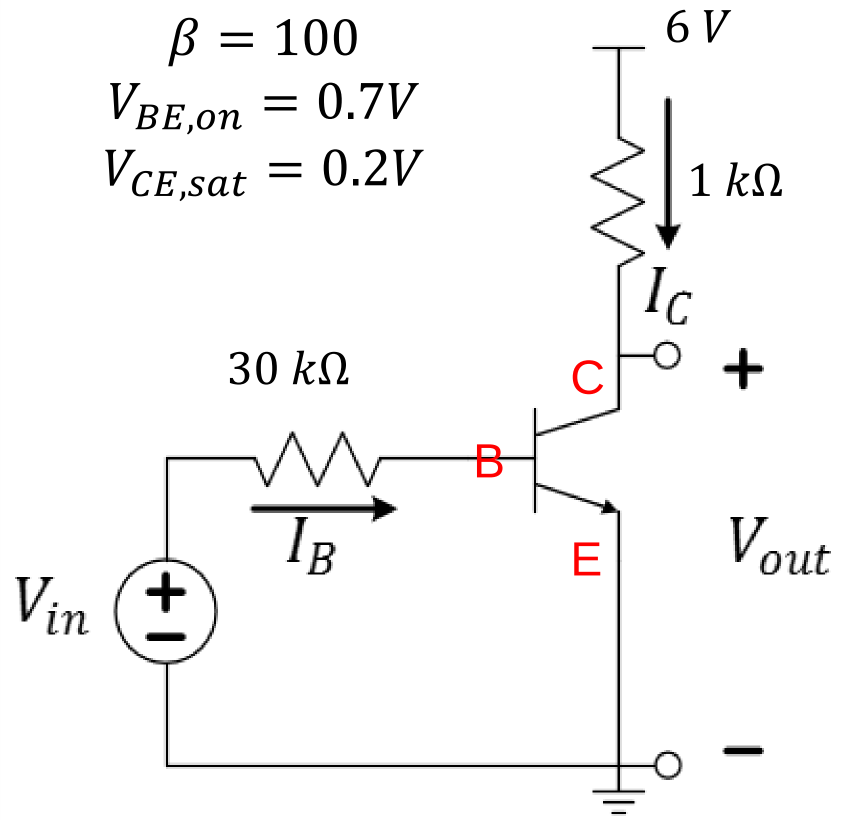


$$V_{i1} = V_{BE,on} = 0.7V$$

$$V_{i,2} = V_{BEon} + \frac{R_B}{\beta R_C}\left(V_{CC} - V_{CE,sat}\right) = 0.7 + \frac{30k}{(100)(1k)}(6 - 0.2)$$

$$= 2.44V$$

L21Q4: What is the $\frac{\Delta V_{out}}{\Delta V_{in}}$ slope in the active region?

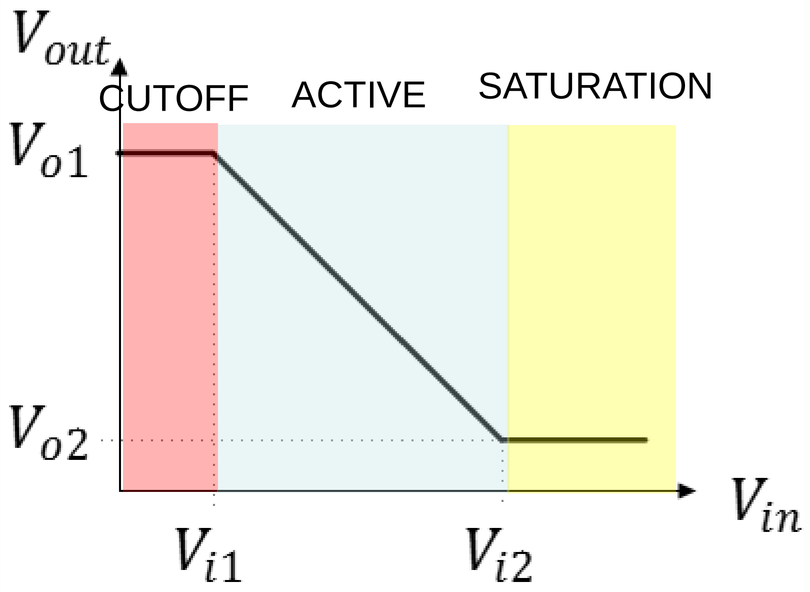


$$V_{o1} = 6V$$

$$V_{o2} = 0.2V$$

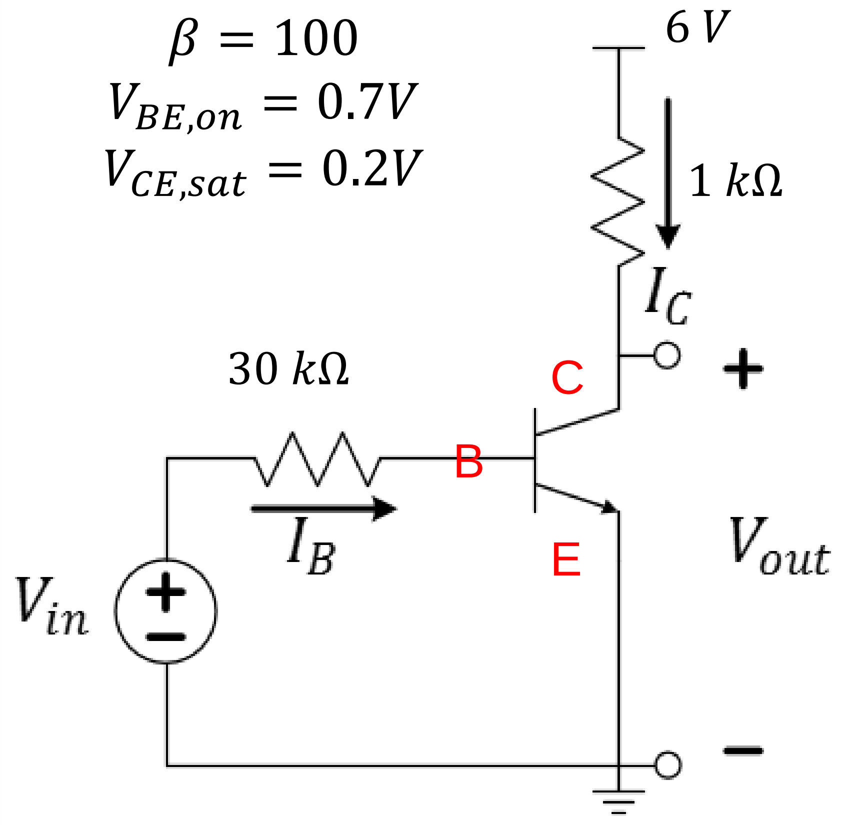
$$V_{i1} = 0.7V$$

$$V_{i2} = 2.44V$$



$$\frac{\Delta V_{out}}{\Delta V_{in}} = \frac{V_{o2} - V_{o1}}{V_{i2} - V_{i1}} = \frac{0.2 - 6}{2.44 - 0.7} = -3.\overline{3}$$

MORE on incremental Voltage Gain



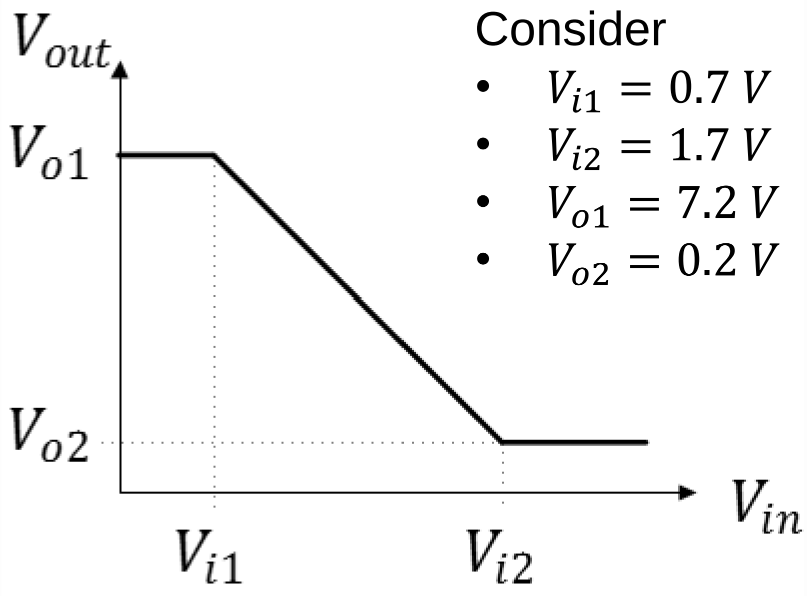
$$G_V = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{-\Delta I_C R_C}{\Delta I_B R_B} = -\beta \frac{R_C}{R_B}$$

$$\boldsymbol{G_V = -\beta \frac{R_C}{R_B} = -100 \frac{1k}{30k} = -3.\overline{3}}$$

Same as previous result

$$\frac{\Delta V_{out}}{\Delta V_{in}} = \frac{V_{o2} - V_{o1}}{V_{i2} - V_{i1}} = -3.\overline{3}$$

Active regime for signal amplification



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

Q7:

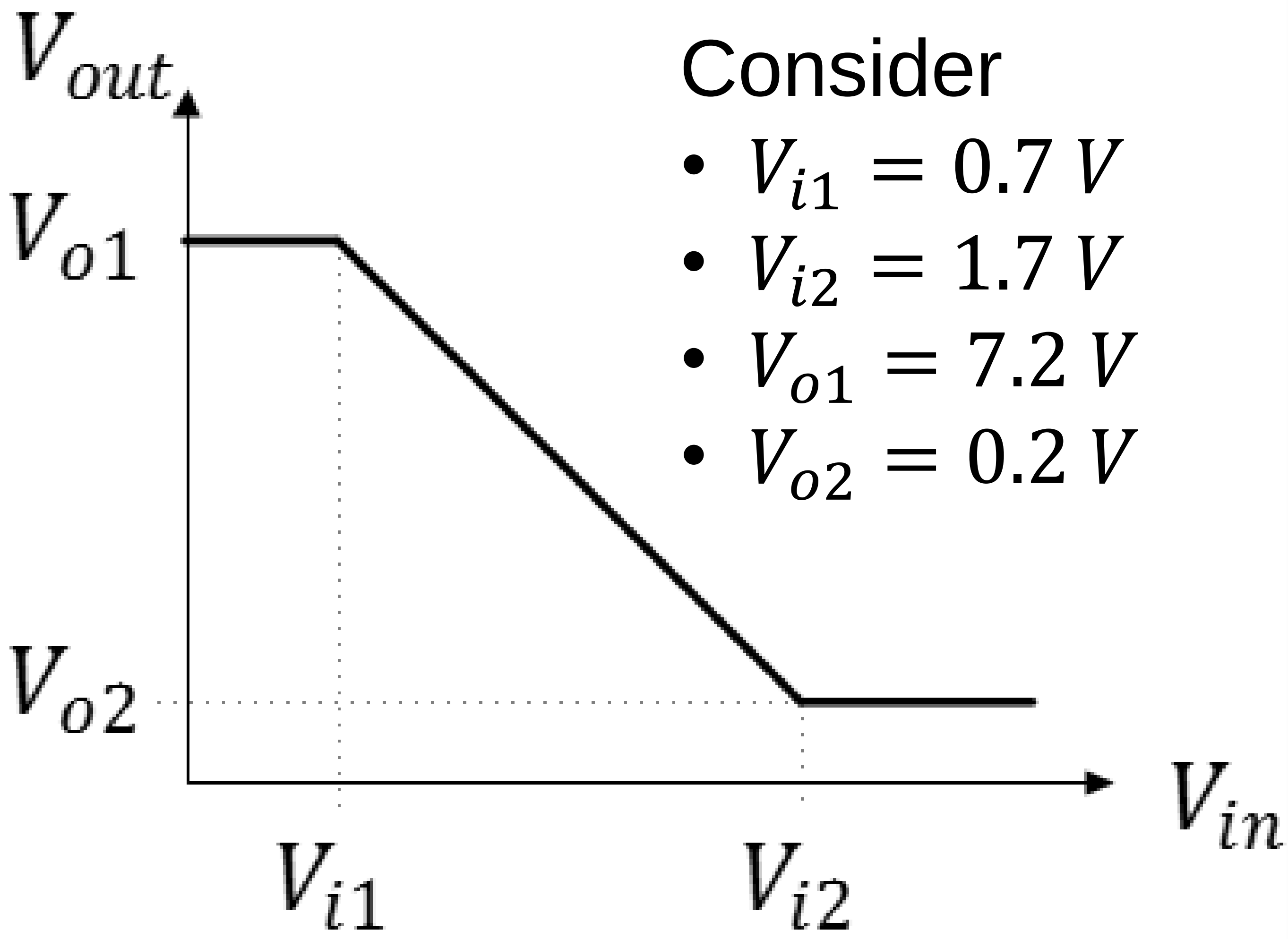
A. Active only
B. Cutoff and active
C. Active and saturation
D. Saturation only
E. Cutoff, active, and saturation

L21Q5: If $V_{IN} = 1.2 + 0.2\cos(2\pi 100t)$ what is the equation for V_{out}?

L21Q6: What is different if $V_{in} = 1.2 + 0.6\cos(2\pi 100t)$?

L21Q7: What transistor regimes are entered if $V_{in} = 1.1 + 0.3\cos(\omega t)$?

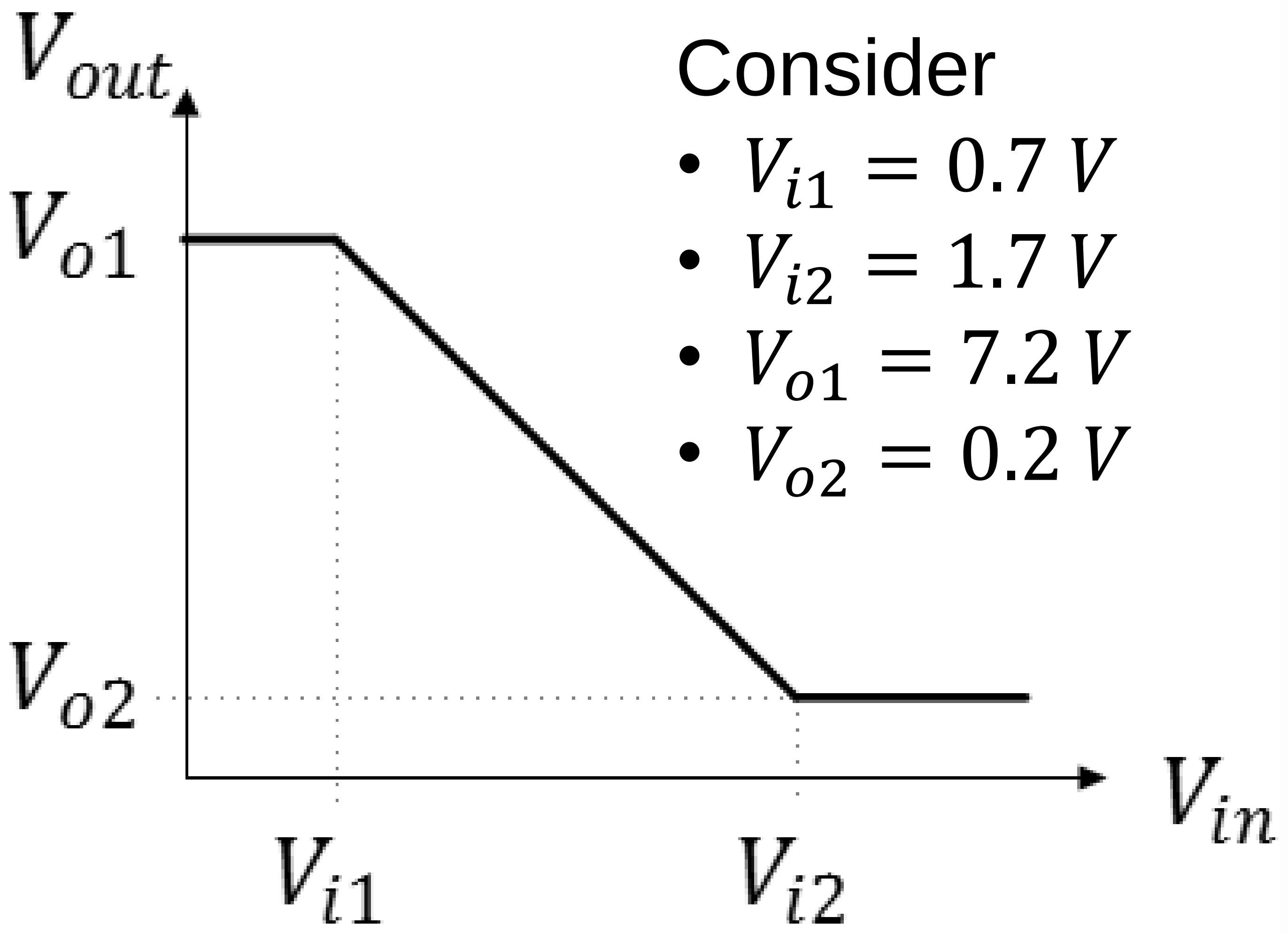
What is the Voltage Gain?



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

What is the Voltage Gain?



Consider
- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

Voltage gain is not β

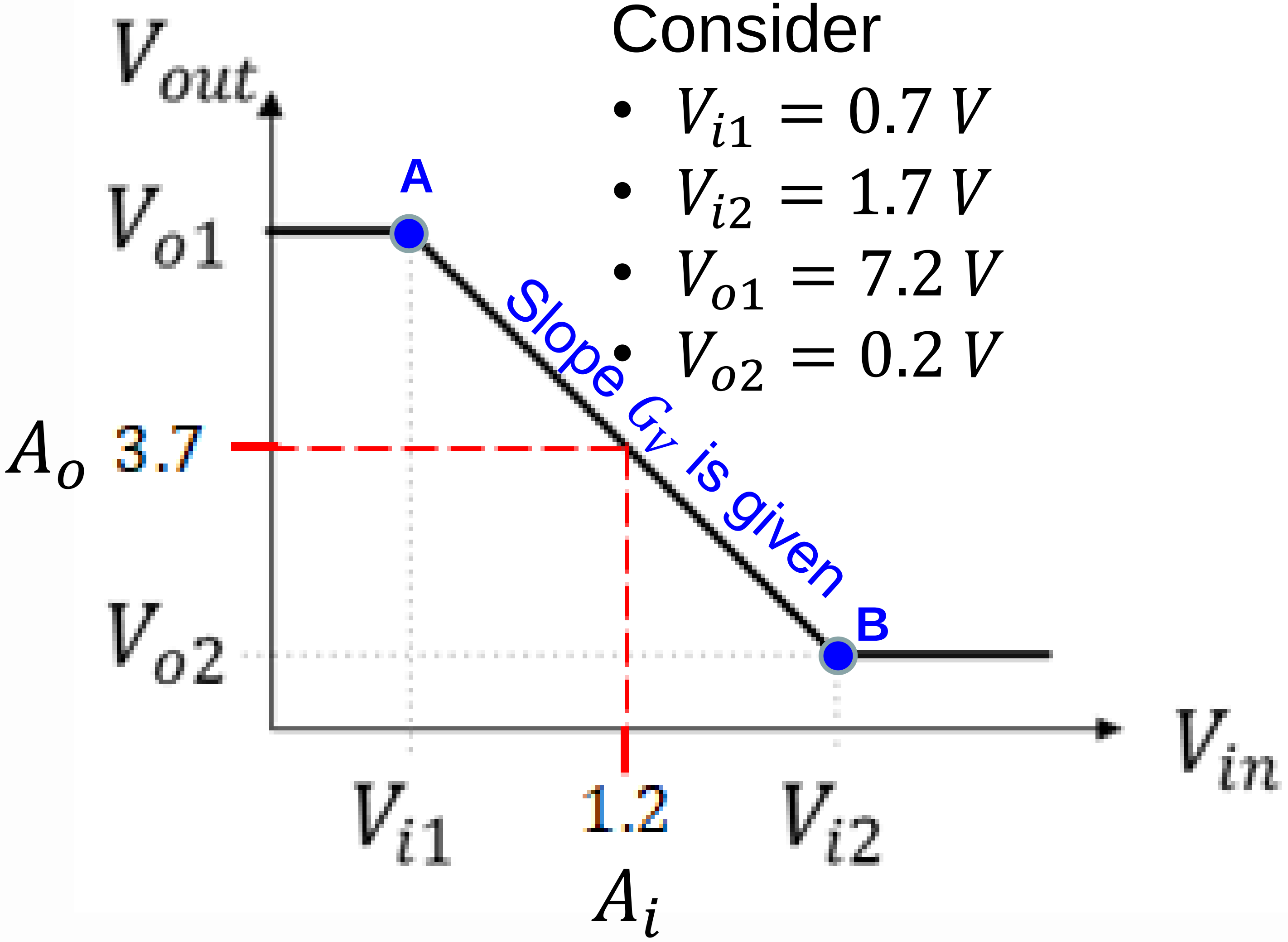
$$G_V = \frac{V_{o2} - V_{o1}}{V_{i2} - V_{i1}}$$

$$G_V = \frac{0.2 - 7.2}{1.7 - 0.7} = -7$$

$V_{out} = G_V(V_{in} - V_{i1}) + V_{o1}$

$V_{out} = G_V(V_{in} - V_{i2}) + V_{o2}$

Find the formula for V_{out}



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

$$V_{IN}(t) = A_i + B_i \cos(\omega t)$$

$$V_{out}(t) = A_o + B_o \cos(\omega t)$$

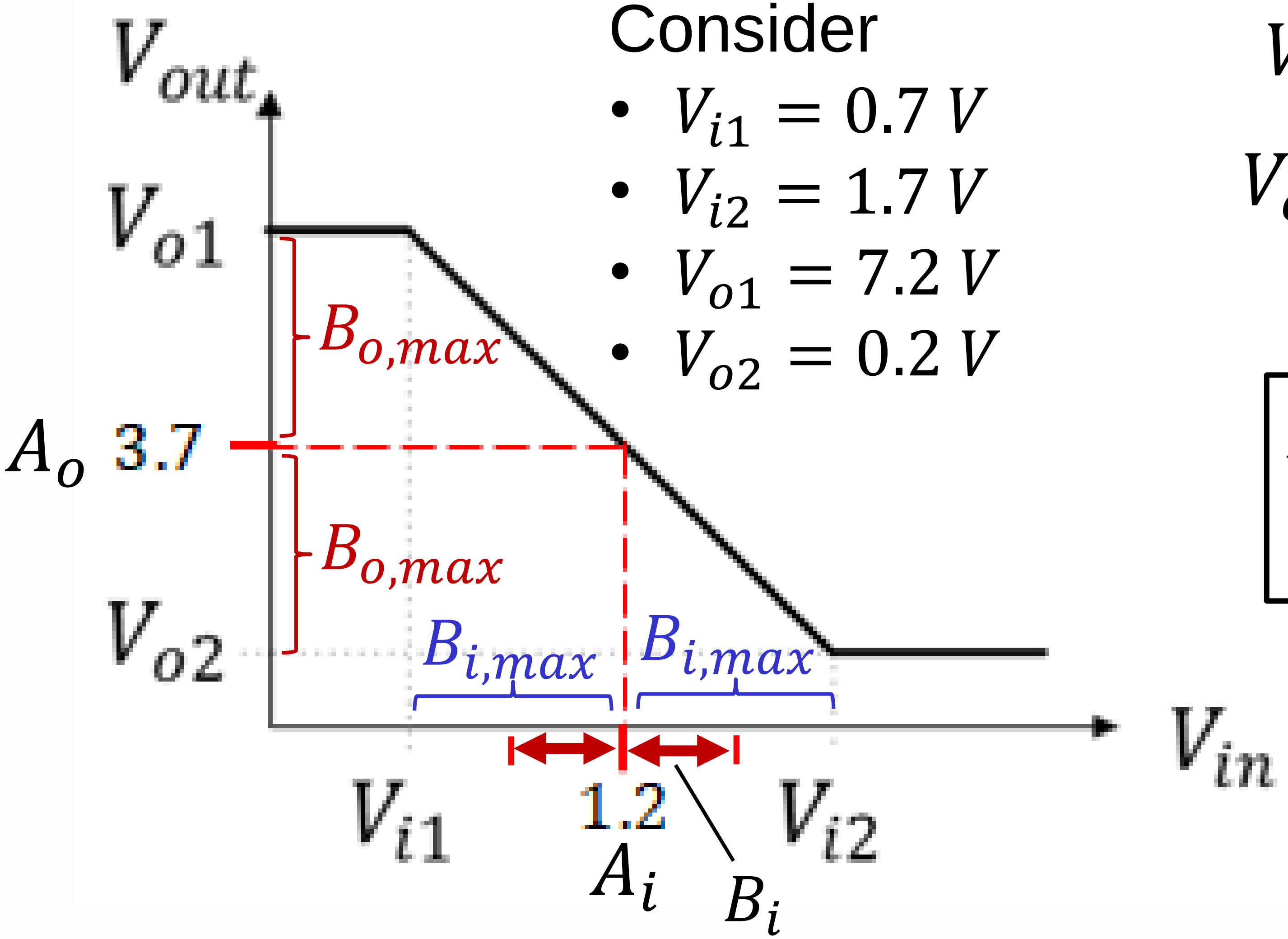
$$A_o = \cancel{V_{o2} + G_V(V_{i1} - A_i)}$$

$$A_o = V_{o2} + G_V(A_i - V_{i2})$$

For this specific problem

$$A_o = 0.2 - 7(0.7 - 1.2)$$
$$= 3.7V$$

Find the formula for V_{out}



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

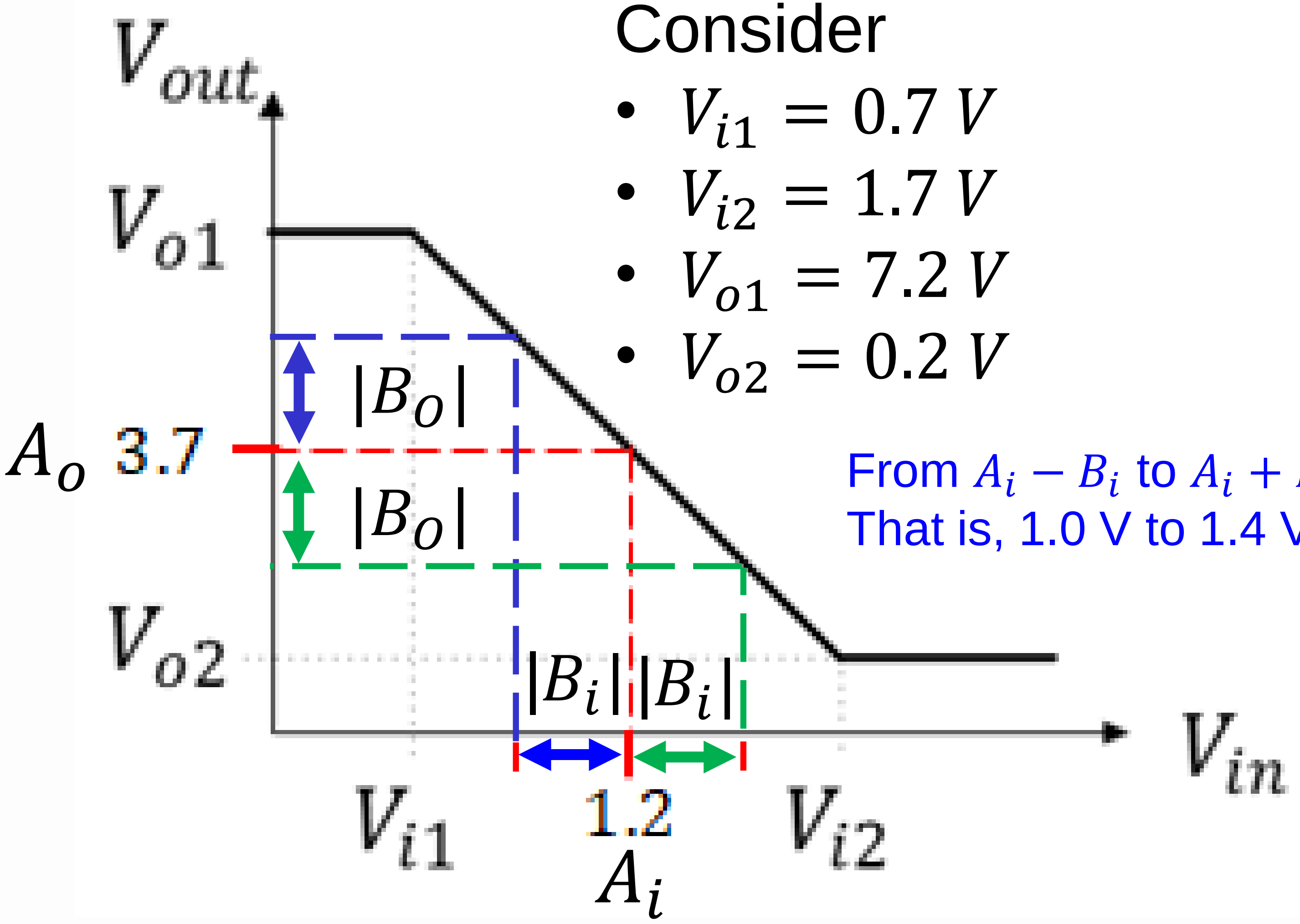
$$V_{IN}(t) = A_i + B_i\cos(\omega t)$$

$$V_{out}(t) = A_o + B_o\cos(\omega t)$$

$B_{i,max}$ & $B_{o,max}$

Limits for Active Region

Find the formula for V_{out}



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

From $A_i - B_i$ to $A_i + B_i$
That is, 1.0 V to 1.4 V

$$V_{IN}(t) = A_i + B_i \cos(\omega t)$$

$$V_{out}(t) = A_o + B_o \cos(\omega t)$$

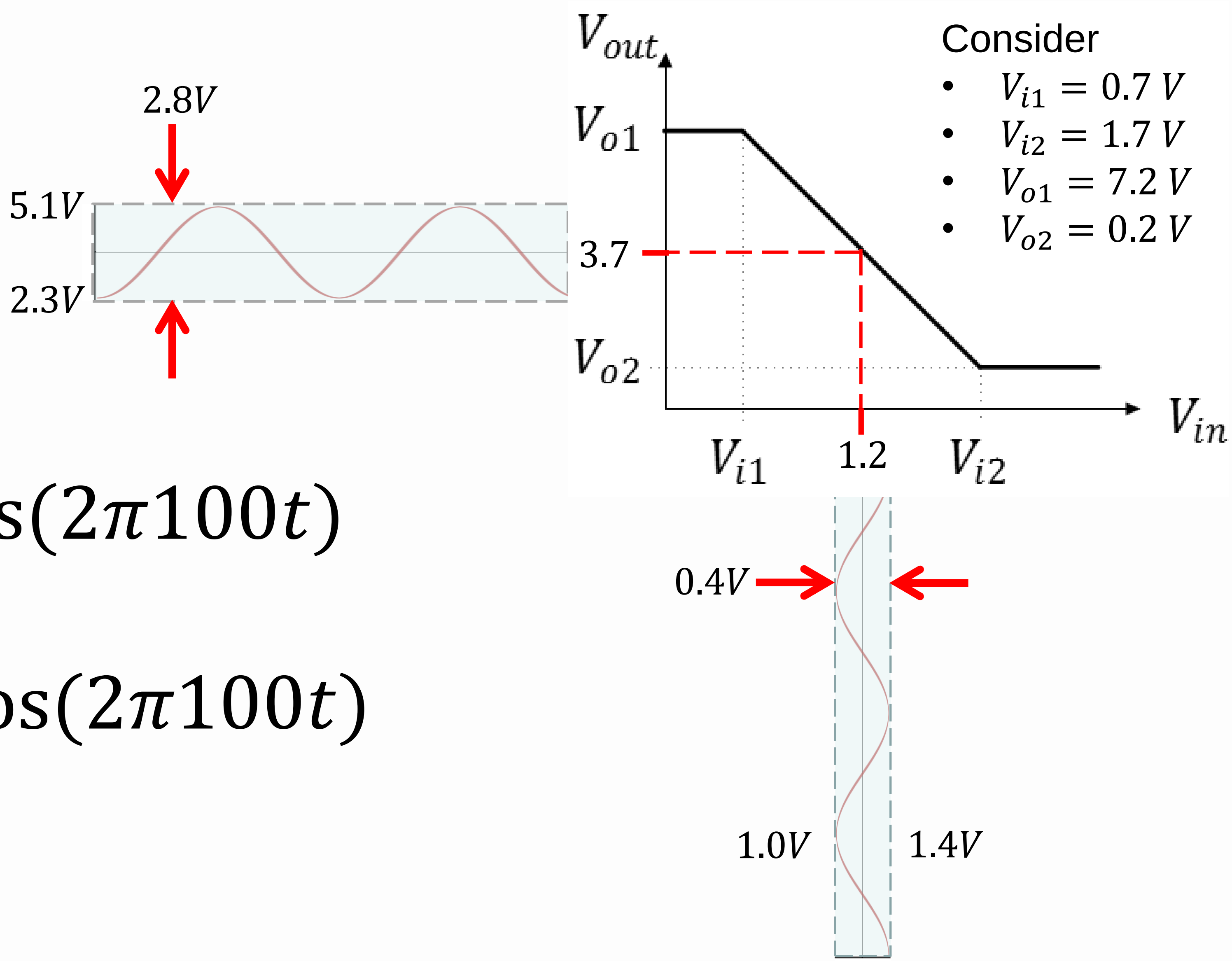
$$B_o = G_V B_i$$

For this specific problem

$$B_i = 0.2$$

$$B_o = -7B_i = -1.4$$

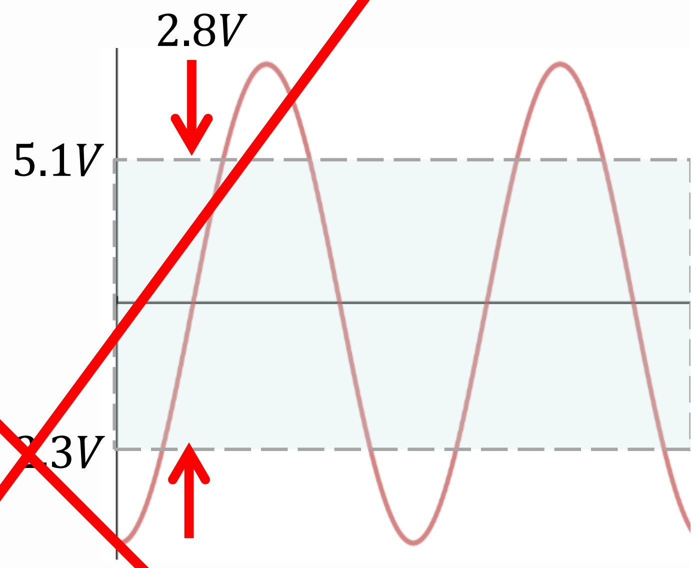
L21Q5: If $V_{IN} = 1.2 + 0.2\cos(2\pi 100t)$ what is the equation for V_{out}?

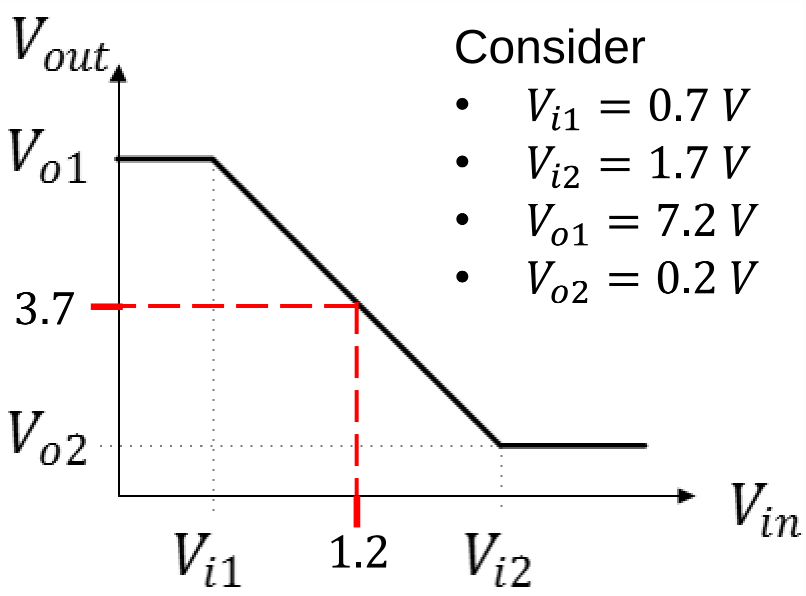


$$V_{IN} = 1.2 + 0.2\cos(2\pi 100t)$$

$$V_{OUT} = 3.7 - 1.4\cos(2\pi 100t)$$

L21Q6: If $V_{IN} = 1.2 + 0.6\cos(2\pi 100t)$ what is the equation for V_{out}?



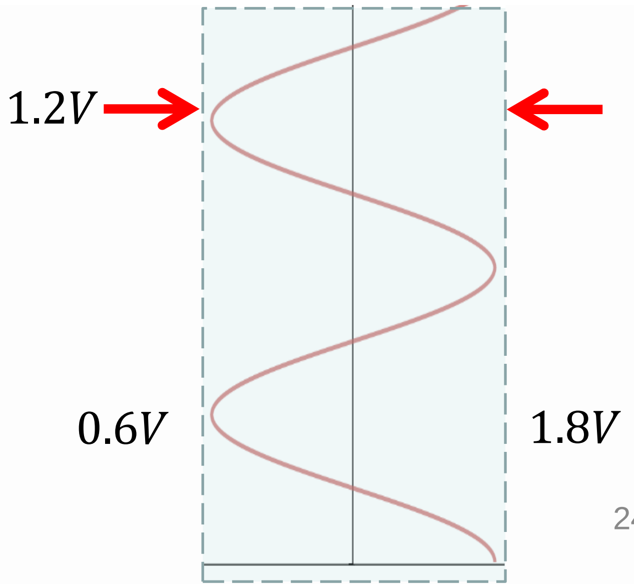


$$V_{IN} = 1.2 + 0.6\cos(2\pi 100t)$$

$$V_{OUT} = 2.3 \qquad \{V_{in} \le 0.7V\}$$

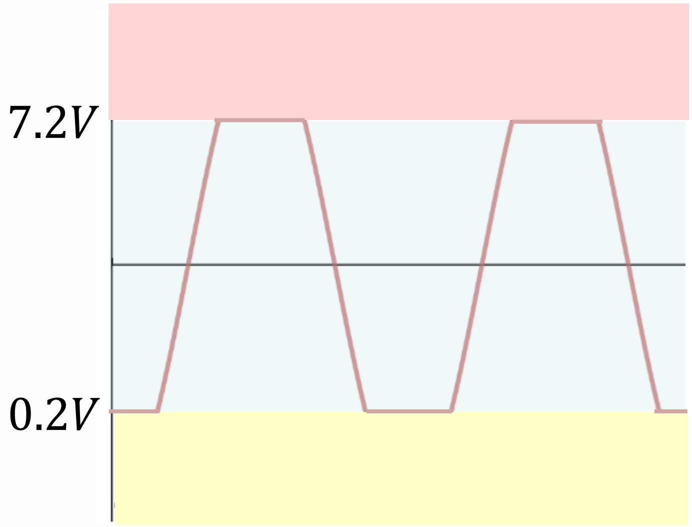
$$V_{OUT} = 3.7 - 4.2\cos(2\pi 100t) \qquad \{2.3 \ge V_{out} \le 5.1V\}$$

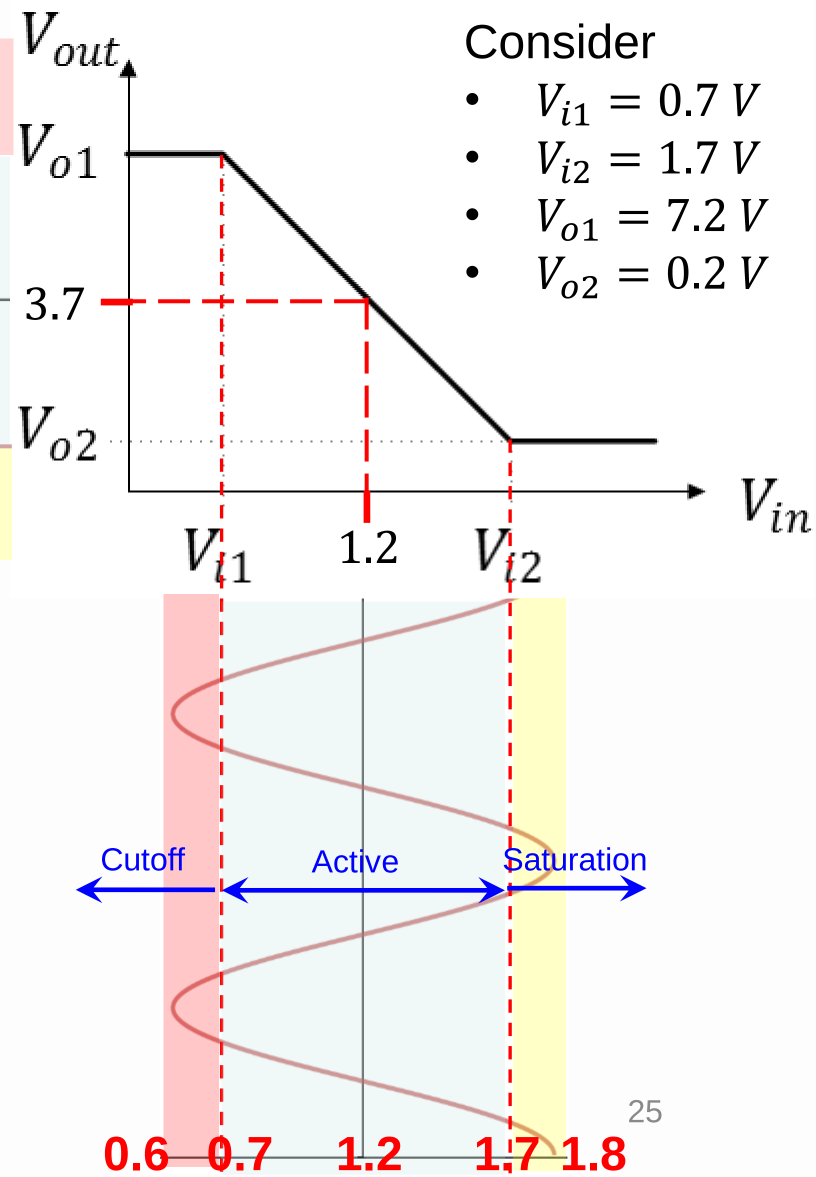
$$V_{OUT} = 5.1V \qquad \{V_{in} \ge 1.7V\}$$



L21Q6: If $V_{IN} = 1.2 + 0.6\cos(2\pi 100t)$ what is the equation for V_{out}?

$G_V = -7$





Consider
- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

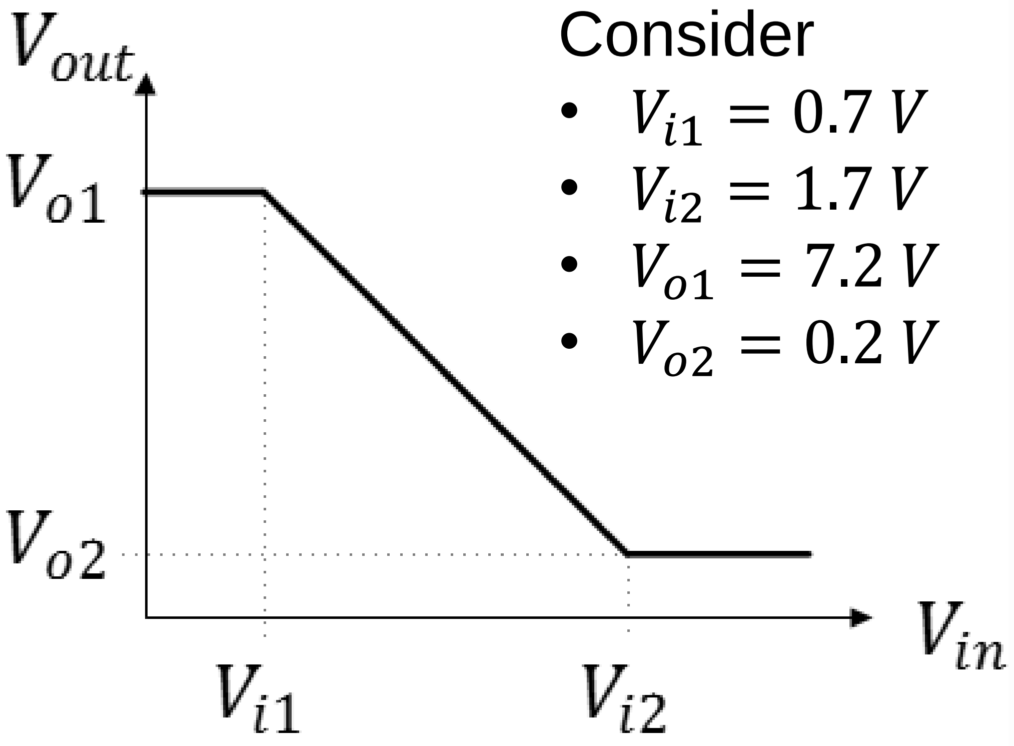
$$V_{IN} = 1.2 + 0.6\cos(2\pi 100t)$$

$$V_{OUT} = 7.2V \qquad \{V_{in} \leq 0.7V\}$$

$$V_{OUT} = 3.7 - 4.2\cos(2\pi 100t) \qquad \{0.7 \leq V_{in} \leq 1.7V\}$$

$$V_{OUT} = 0.2V \qquad \{V_{in} \geq 1.7V\}$$

L21Q7: What transistor regimes are entered if $V_{in} = 1.1 + 0.3\cos(\omega t)$?



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

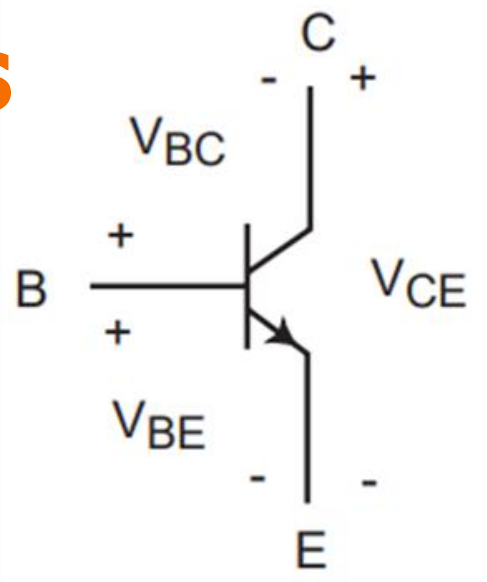
Q7:

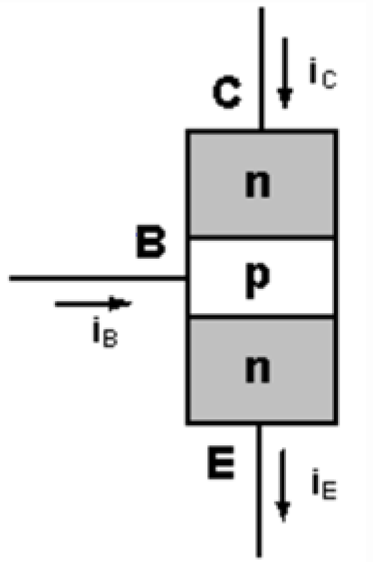
A. Active only
B. Cutoff and active
C. Active and saturation
D. Saturation only
E. Cutoff, active, and saturation

$$\boldsymbol{V_{in,min} = 1.1 - 0.3 = 0.8V > V_{i1}}$$

$$\boldsymbol{V_{in,max} = 1.1 + 0.3 = 1.4V < V_{i2}}$$

MORE About current in BJTs





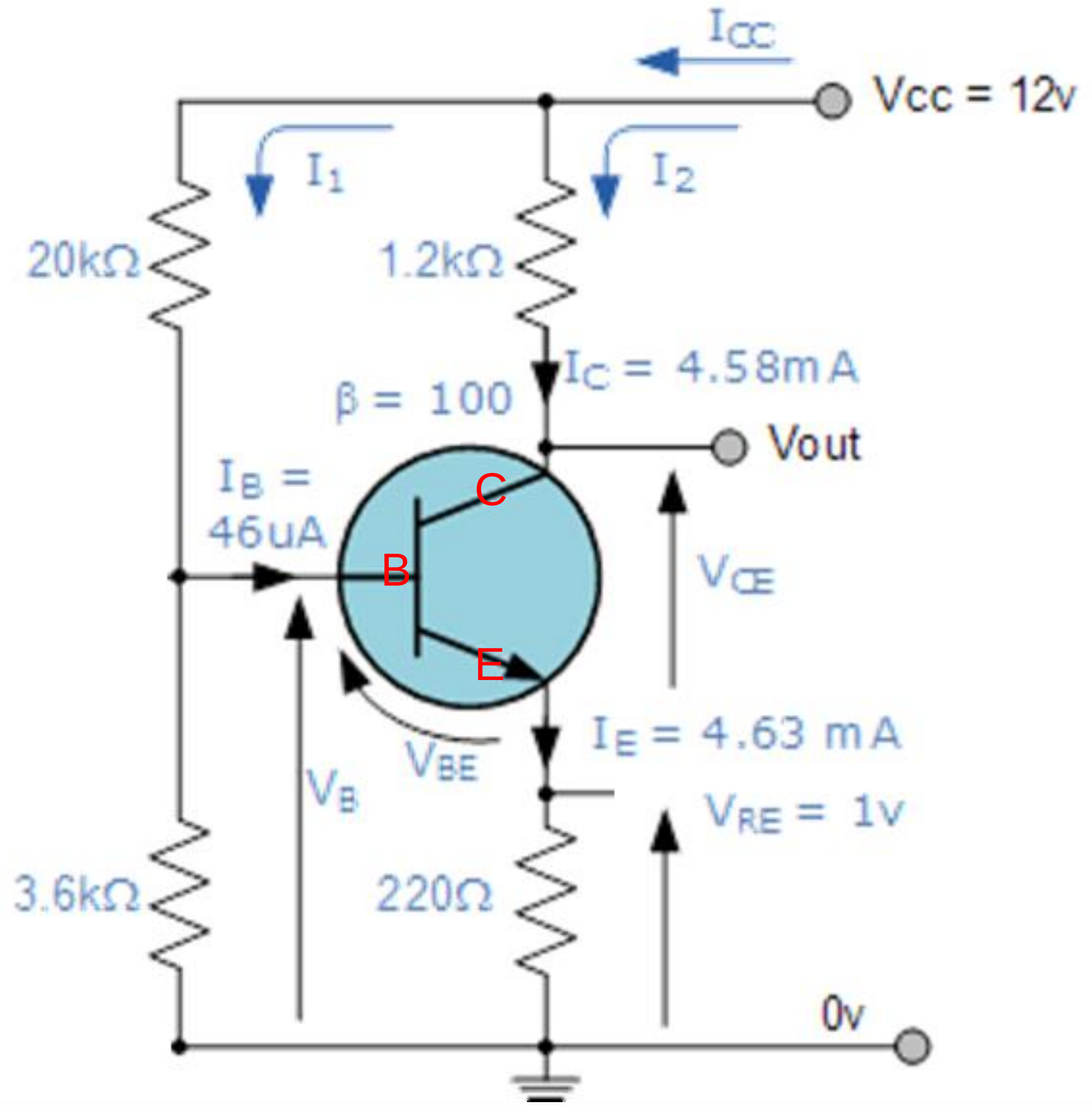
- In the Active Region $I_C = \beta I_B$
- The KVL for a BJT $I_C + I_B - I_E = 0$
- Combine the two expressions to obtain

$$I_E = (1+\beta)I_B$$

$$I_C = \frac{\beta}{1+\beta} I_E \quad \text{where} \quad \alpha = \frac{\beta}{1+\beta} \quad \Rightarrow \quad I_C = \alpha\, I_E$$

- α quantifies the % of electrons originating from the emitter which are able to reach the collector

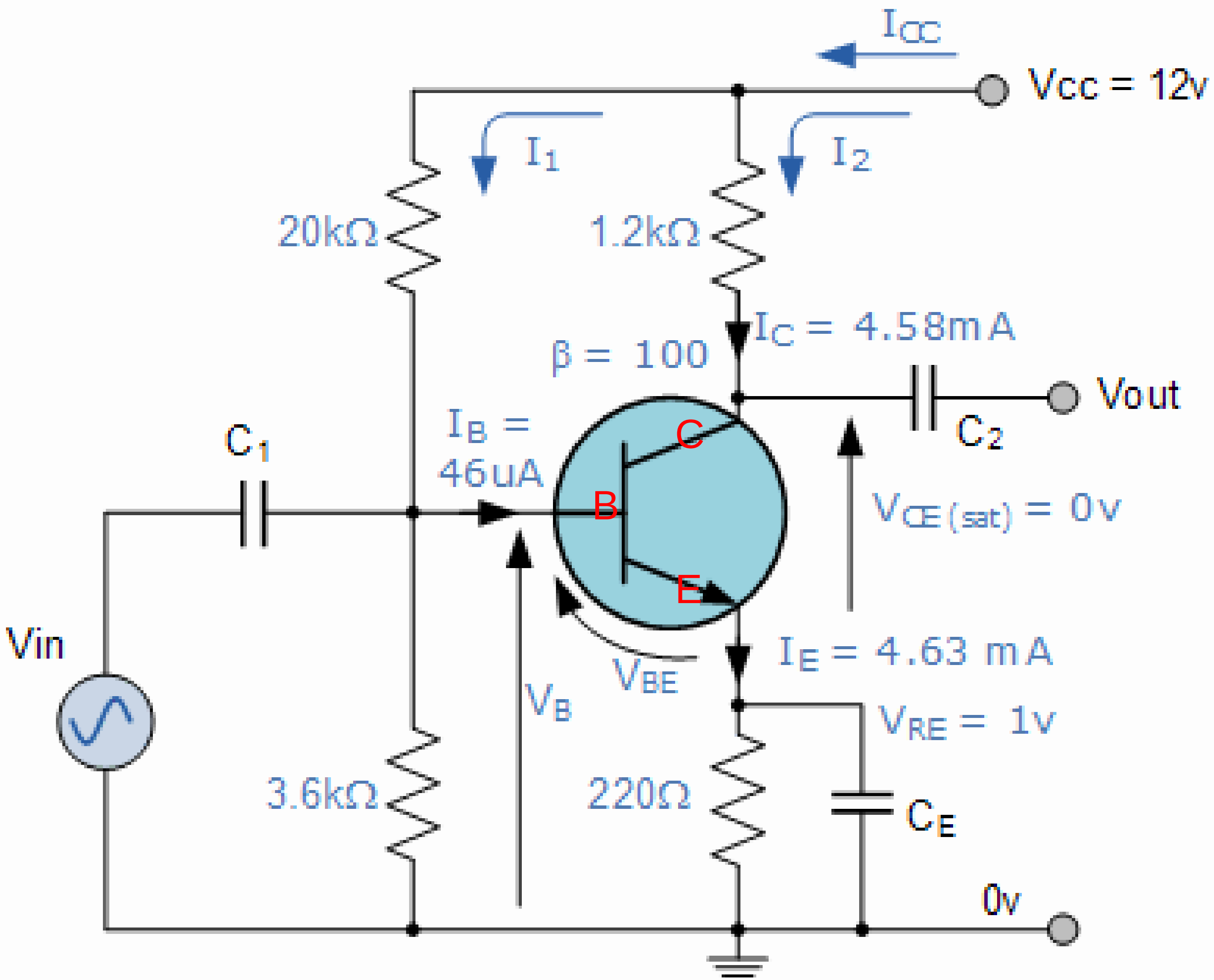
MORE on BJT common emitter amplifiers



PRACTICAL DESIGN

- **Single battery bias**

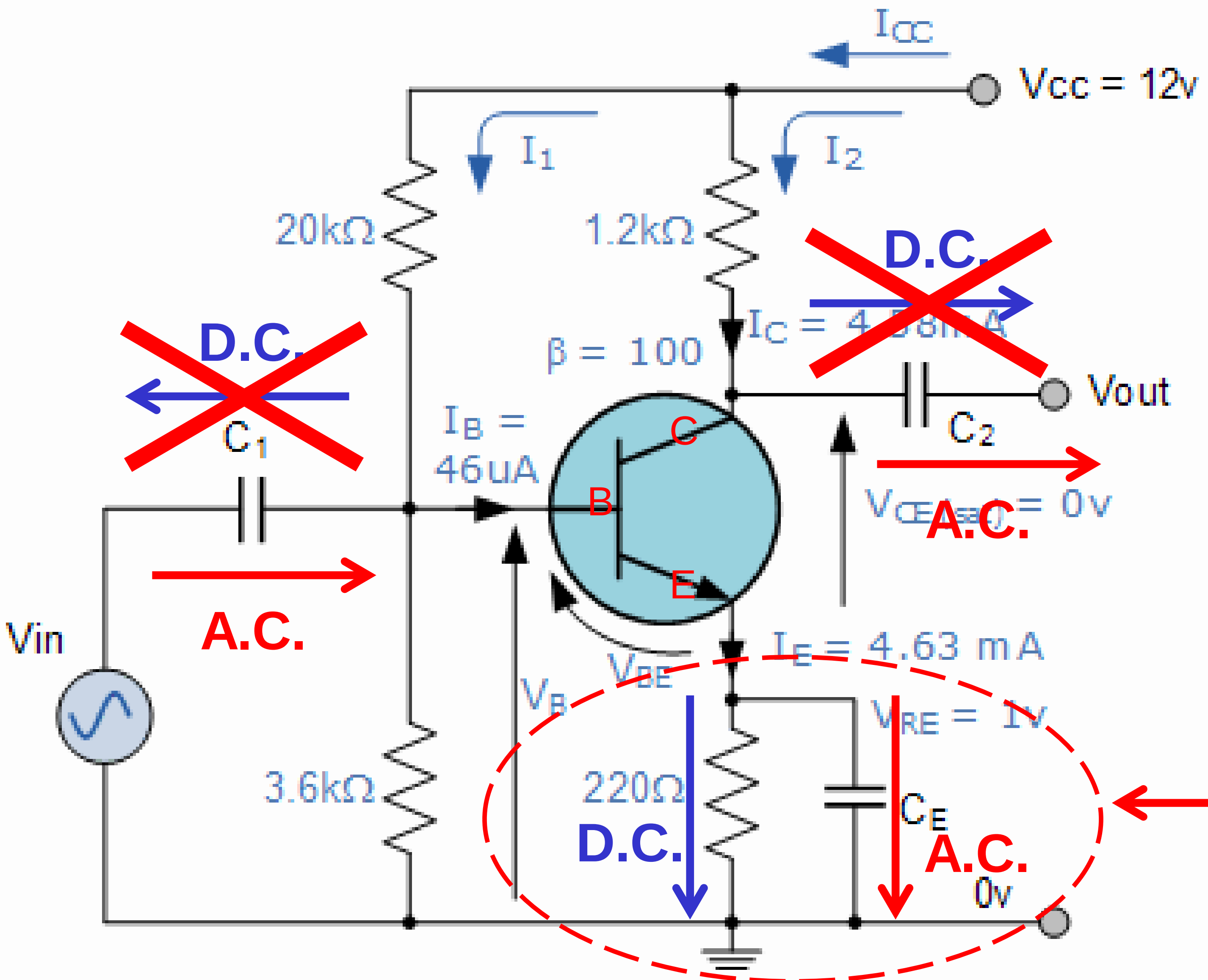
MORE on BJT common emitter amplifiers



PRACTICAL DESIGN

- **Single battery bias**
- **Coupling capacitors for A.C. signal components**

MORE on BJT common emitter amplifiers

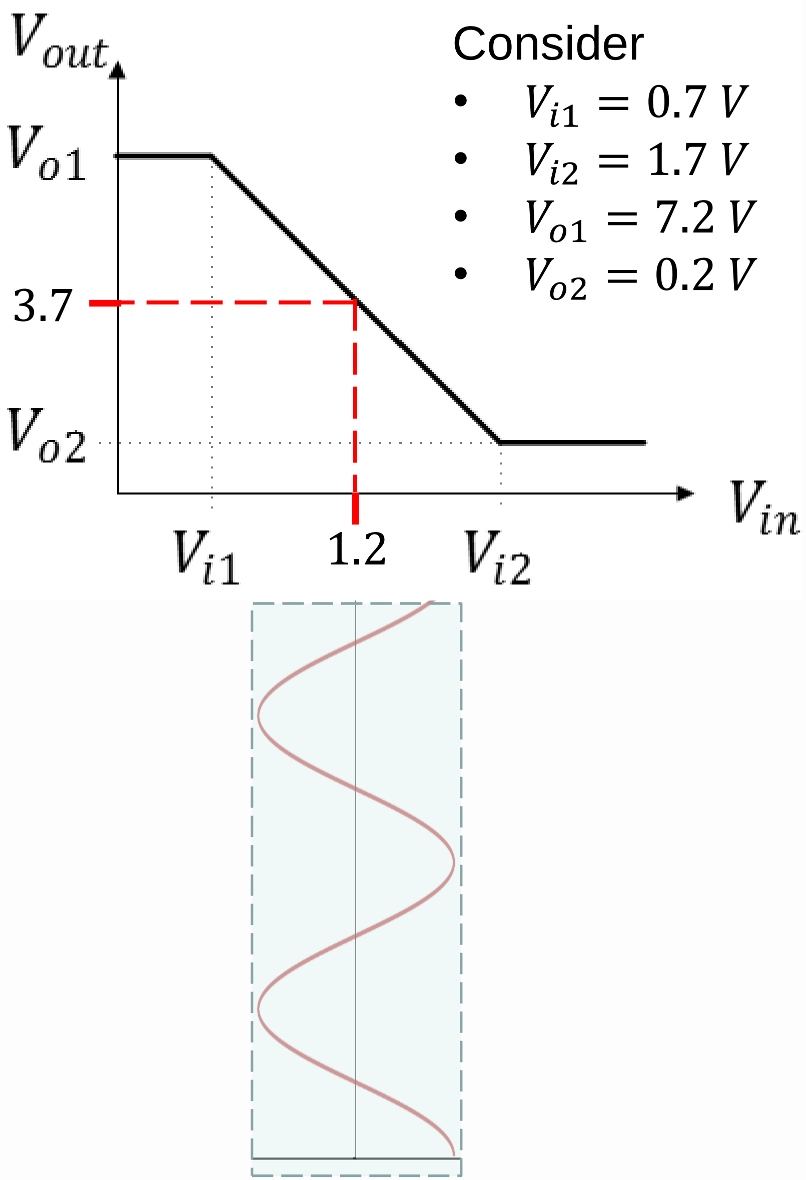


PRACTICAL DESIGN

- Single battery bias
- Coupling capacitors for A.C. signal components

- Resistor conducts for D.C. current
- Capacitor bypasses resistor for A.C. signal so emitter is effectively connected to ground

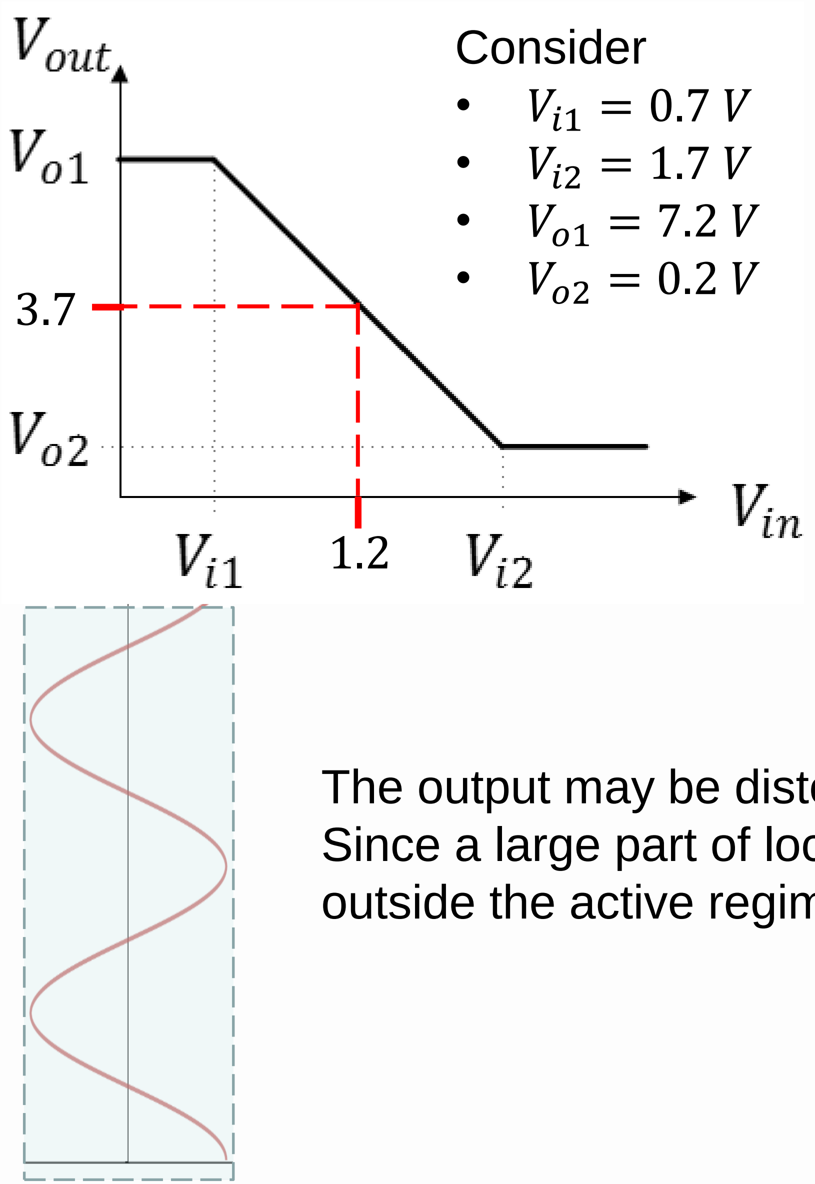
With DC bias



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

Without DC bias

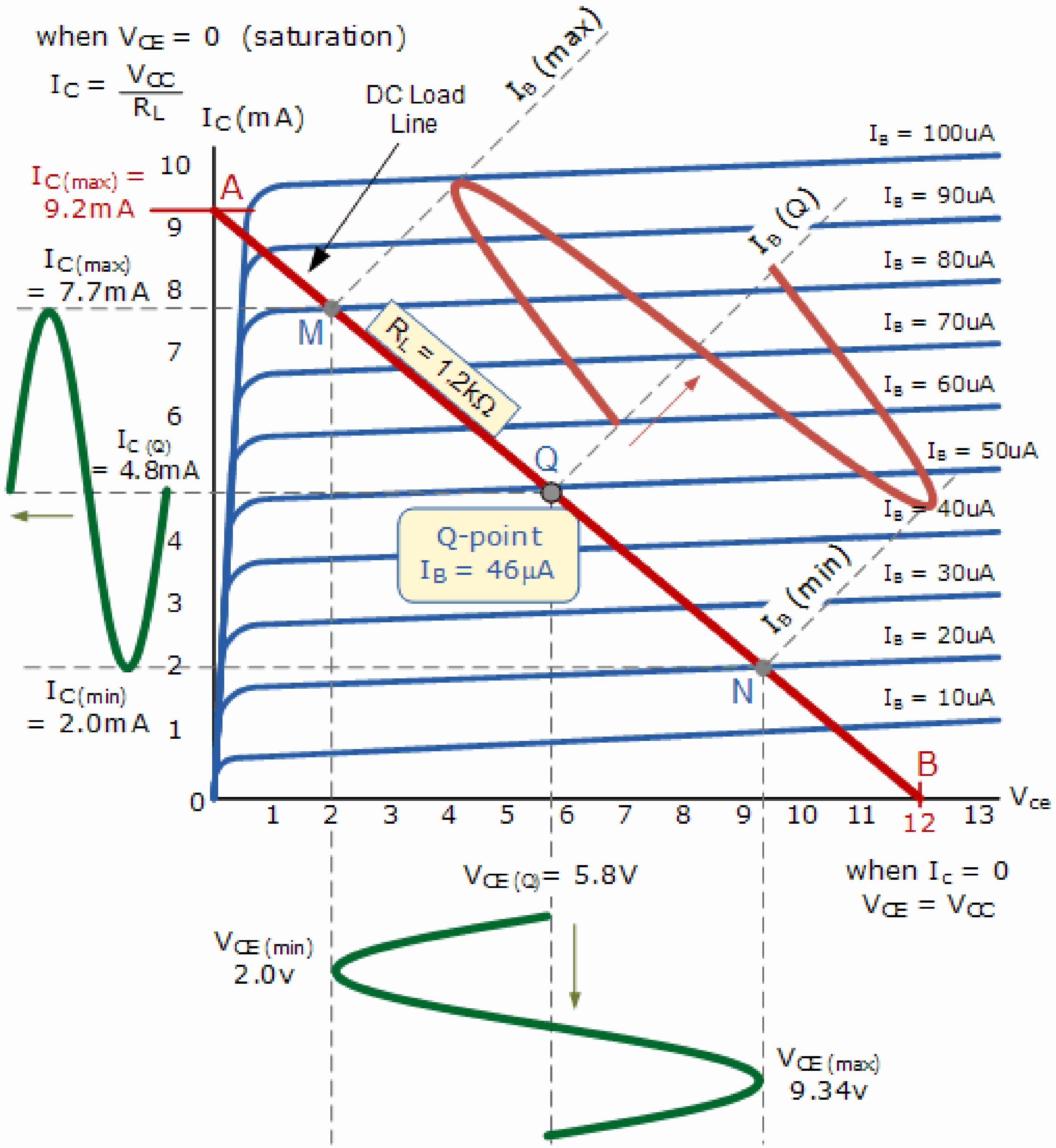


Consider

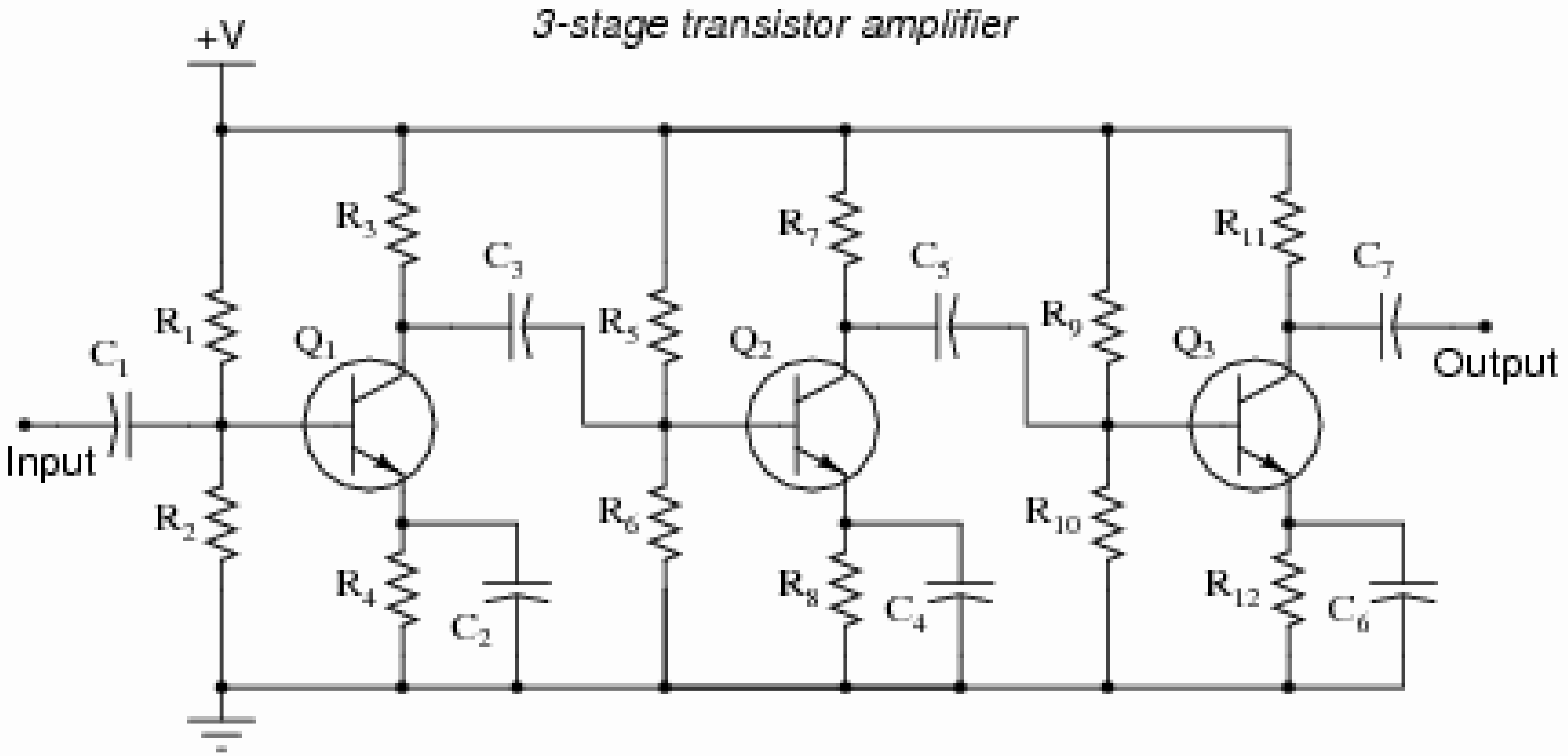
- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

The output may be distorted
Since a large part of locates
outside the active regime.

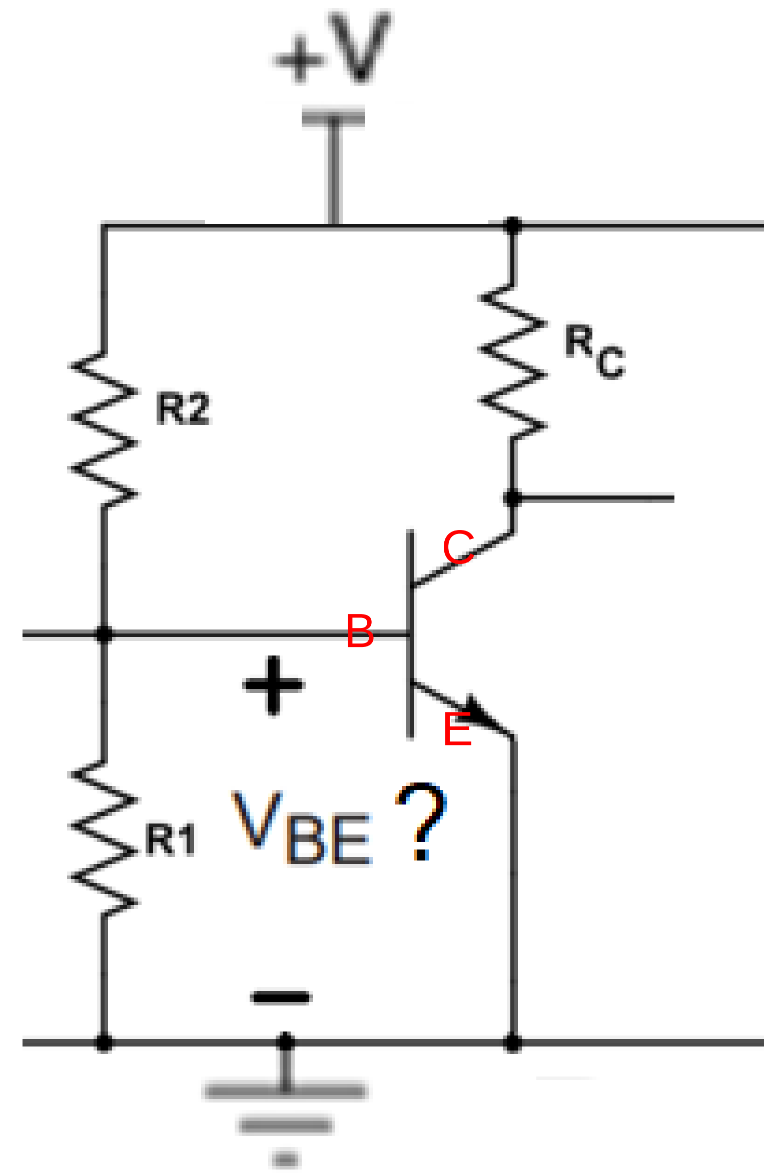
MORE


when VCE = 0 (saturation)
IC = VCC / RL
IC (mA)
DC Load Line
IB (max)
IC(max) = 9.2mA
IC(max) = 7.7mA
IC (Q) = 4.8mA
IC(min) = 2.0mA
A
M
Q
N
B
RL = 1.2kΩ
IB (Q)
IB (min)
Q-point
IB = 46µA
IB = 100uA
IB = 90uA
IB = 80uA
IB = 70uA
IB = 60uA
IB = 50uA
IB = 40uA
IB = 30uA
IB = 20uA
IB = 10uA
Vce
0 1 2 3 4 5 6 7 8 9 10 11 12 13
1 2 3 4 5 6 7 8 9 10
VCE (Q) = 5.8V
when Ic = 0
VCE = VCC
VCE (min) 2.0v
VCE (max) 9.34v

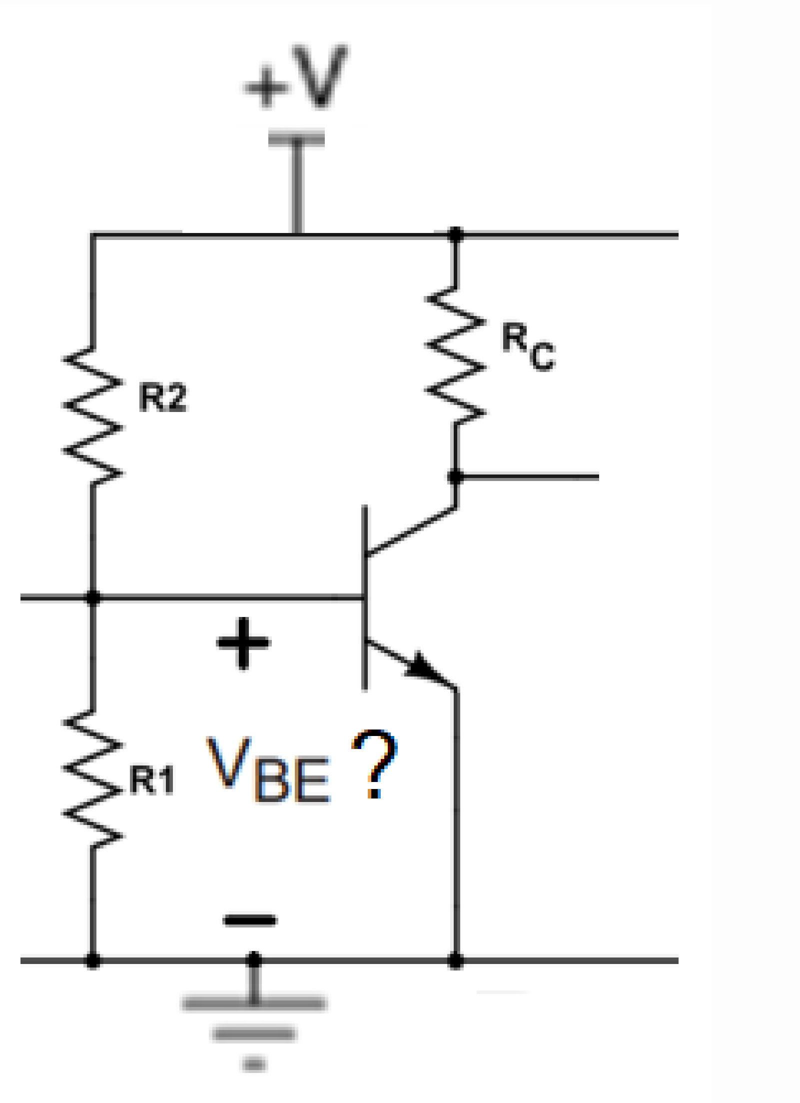
MORE

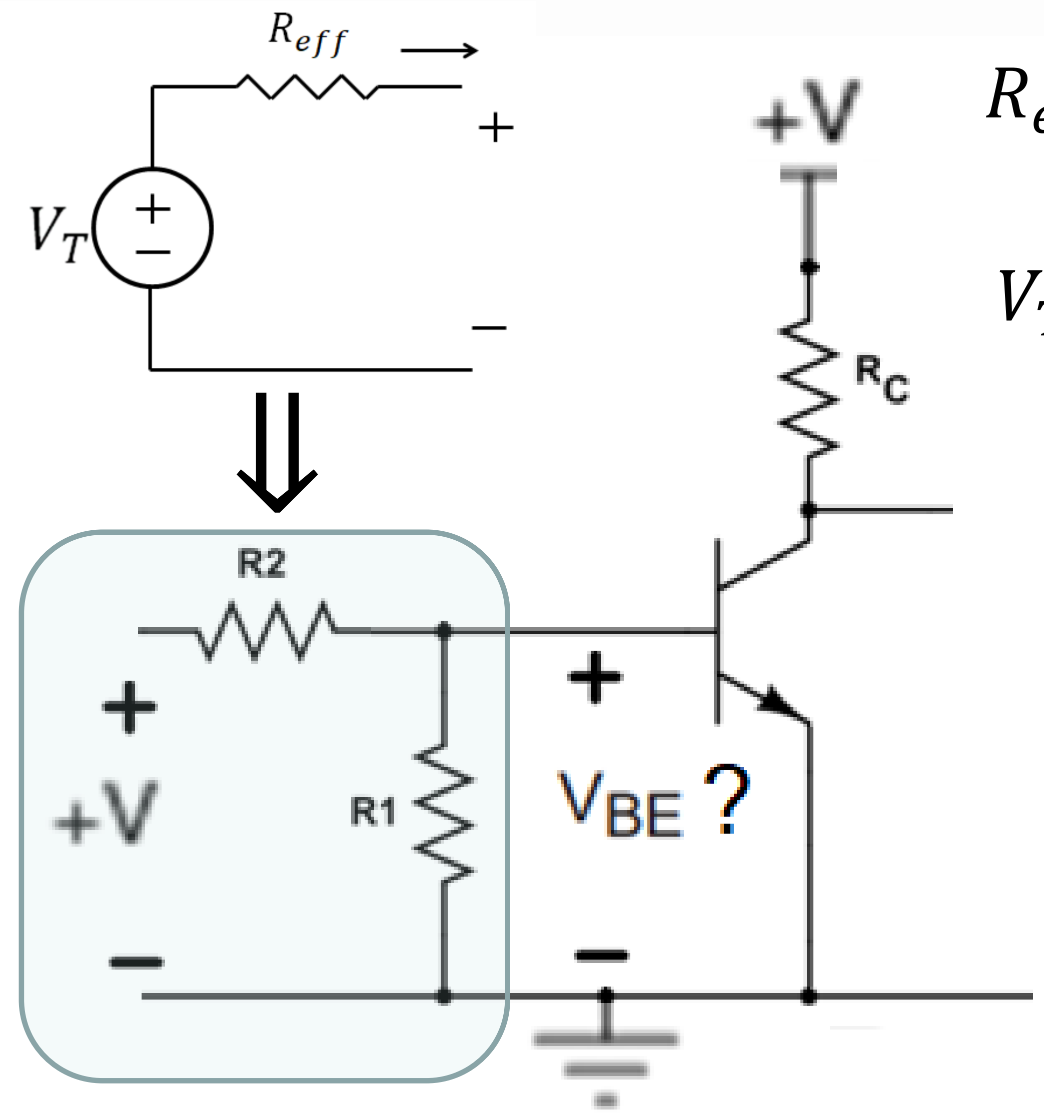

3-stage transistor amplifier
+V
R3
R1
C1
Input
R2
Q1
R4
C2
C3
R5
R6
Q2
R7
R8
C4
C5
R9
R10
Q3
R11
R12
C6
C7
Output

MORE



MORE FIND THEVENIN EQUIVALENT





$$R_{eff} = R_1 // R_2$$

$$V_T = V \frac{R_1}{R_2 + R_2}$$

L21 Learning Objectives

a. Explain the voltage transfer curve (V_{out} vs. V_{in})
b. Find the transition points on the voltage transfer curve
c. Find the slope of the active region in the transfer curve
d. Determine the operating regions for an AC+DC input
e. Evaluate and AC+DC output for linear amplification

Lecture 22: Exercises

- We will use this lecture to catch up, if needed
- We will also do multiple exercises
- Slides may be distributed in lecture