

# EE 330

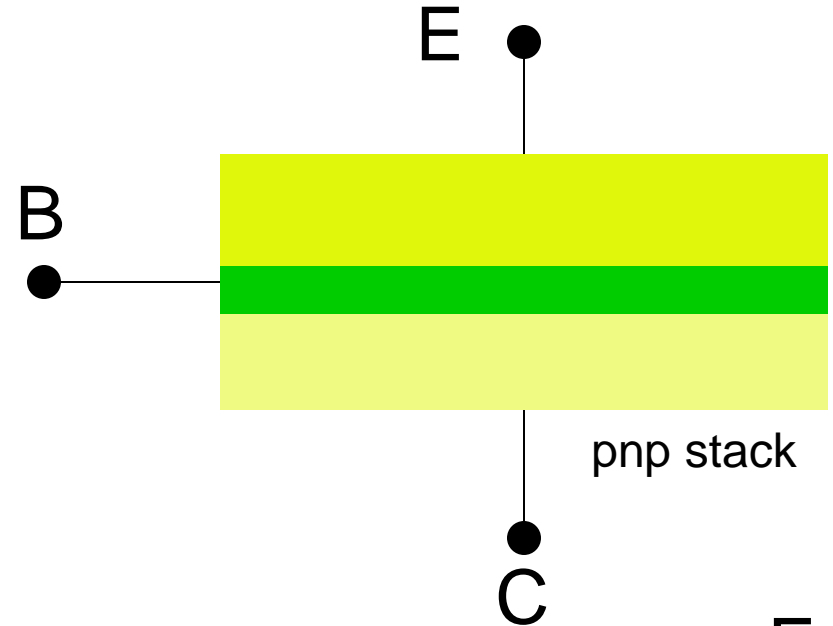
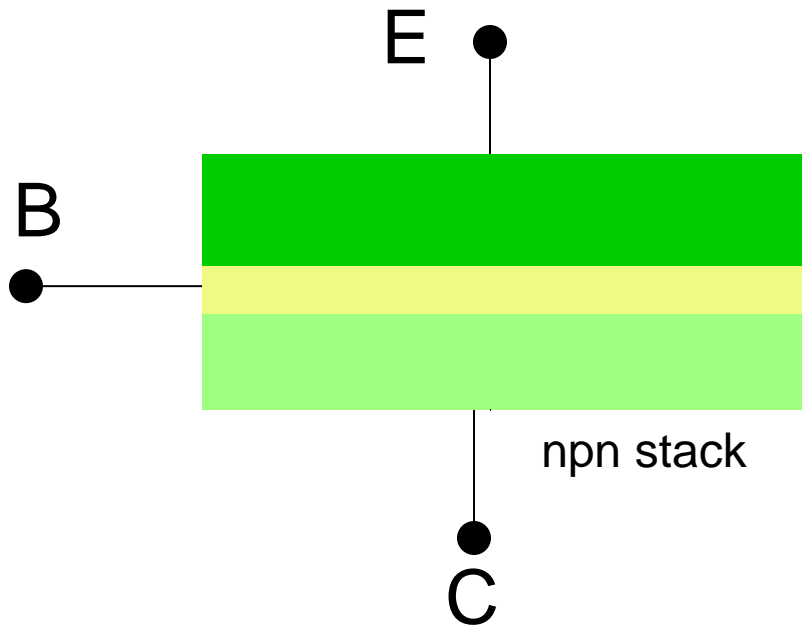
## Lecture 20

Bipolar Device Modeling

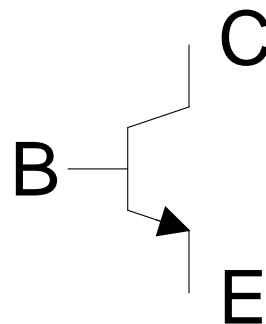
# Fall 2025 Exam Schedule

Exam 1	Friday	Sept 26
Exam 2	Friday	October 24
Exam 3	Friday	Nov 21
Final Exam	Monday	Dec 15 12:00 - 2:00 PM

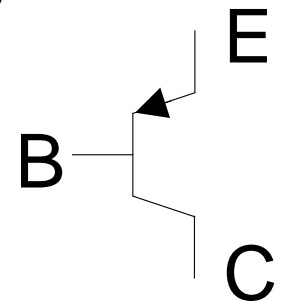
# Bipolar Transistors



- Bipolar Devices Show Basic Symmetry
- Electrical Properties not Symmetric
- Designation of C and E critical



**npn transistor**



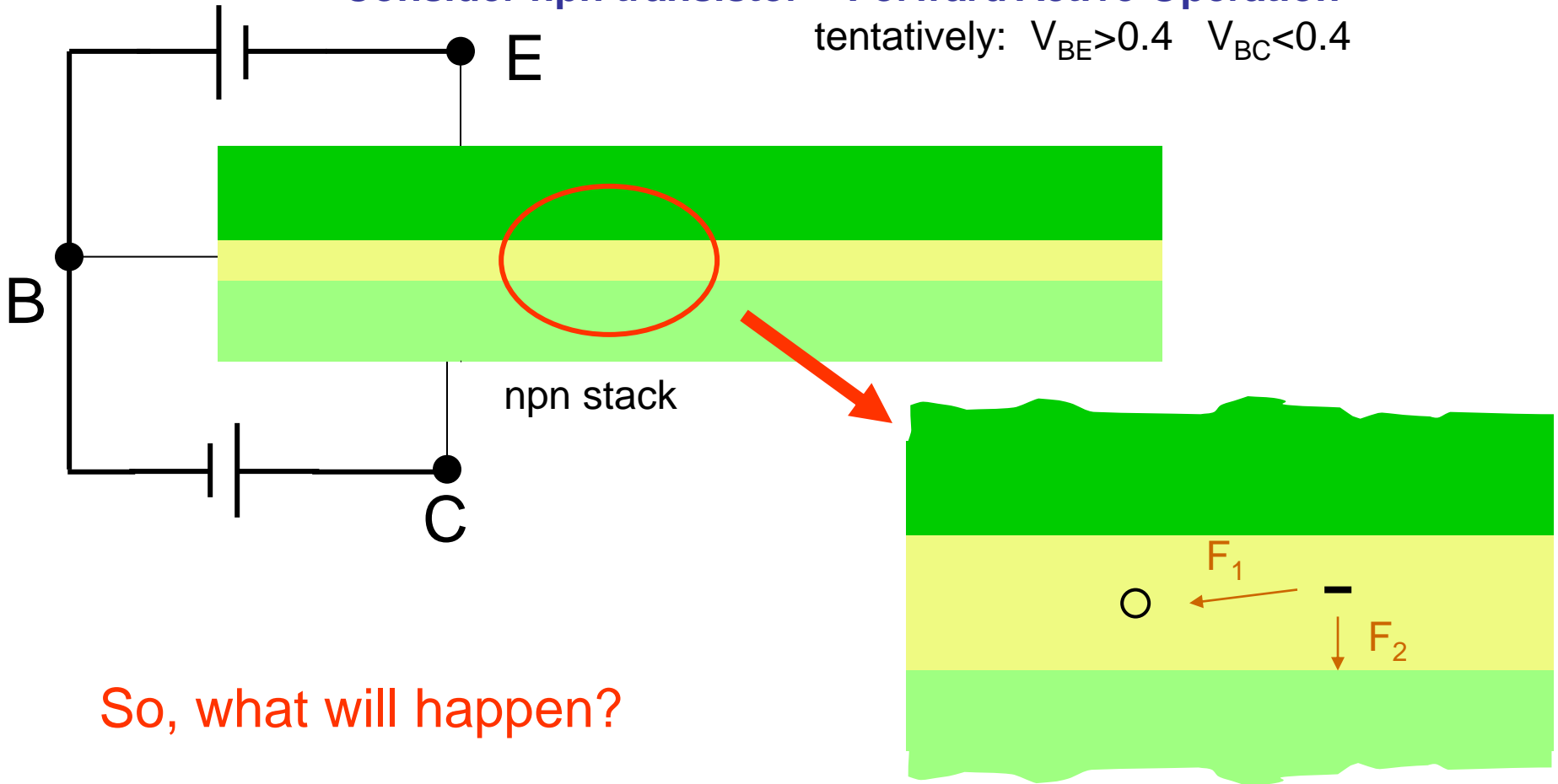
**pnp transistor**

With proper doping and device sizing these form Bipolar Transistors

# Bipolar Operation

Consider npn transistor – Forward Active Operation

tentatively:  $V_{BE} > 0.4$   $V_{BC} < 0.4$



So, what will happen?

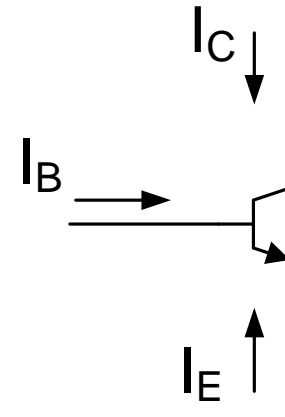
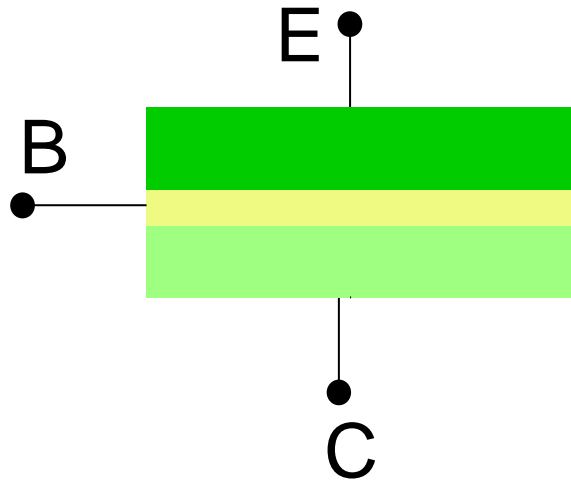
Some will recombine with holes and contribute to base current and some will be attracted across BC junction and contribute to collector

Size and thickness of base region and relative doping levels will play key role in percent of minority carriers injected into base contributing to collector current

# Bipolar Operation

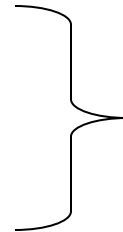
Consider npn transistor – Forward Active Operation

tentatively:  $V_{BE} > 0.4$   $V_{BC} < 0.4$



$$I_C + I_B = -I_E$$

$$I_C = -\alpha I_E$$



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

$$\beta \stackrel{\text{defn}}{=} \frac{\alpha}{1-\alpha}$$

$$I_C = \beta I_B$$

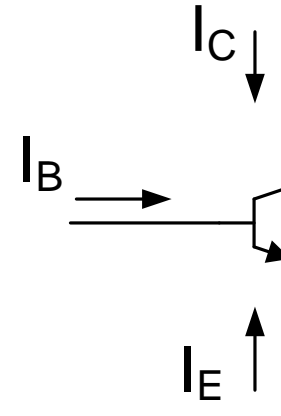
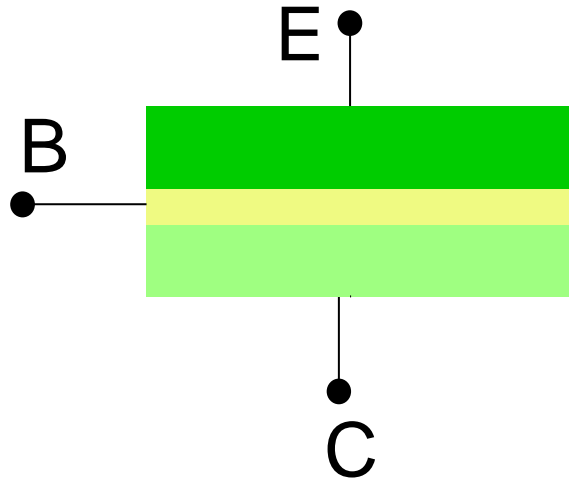
$\beta$  is typically very large

often  $50 < \beta < 999$

# Bipolar Operation

Consider npn transistor – Forward Active Operation

tentatively:  $V_{BE} > 0.4$   $V_{BC} < 0.4$



$$I_C = \beta I_B$$

$\beta$  is typically very large

Bipolar transistor can be thought of as current amplifier with a large current gain

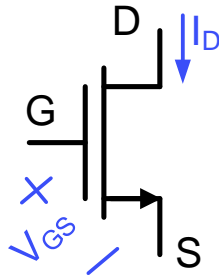
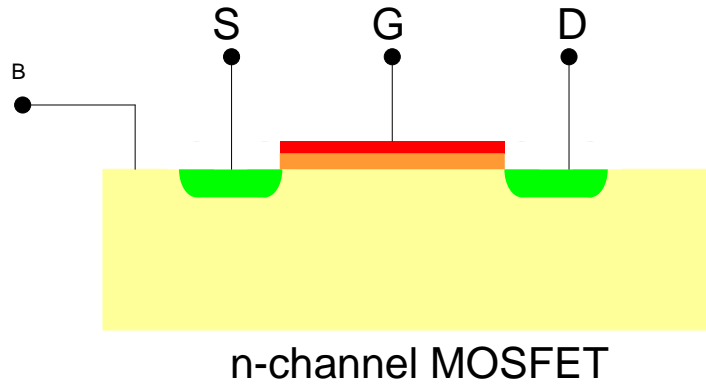
In contrast, MOS transistor is inherently a transconductance amplifier

Current flow in base is governed by the diode equation  $I_B = \tilde{I}_s e^{\frac{V_{BE}}{V_t}}$

Collector current thus varies exponentially with  $V_{BE}$   $I_C = \beta \tilde{I}_s e^{\frac{V_{BE}}{V_t}}$

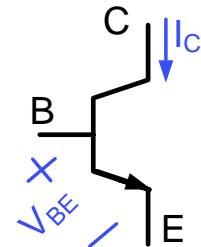
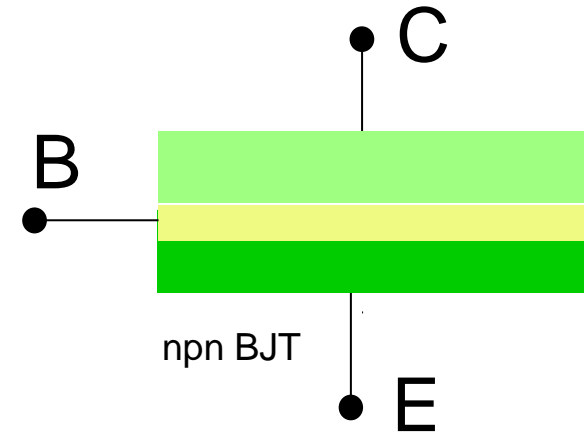
# Preliminary Comparison of MOSFET and BJT

(Saturation vs Forward Active)



$$I_D = \frac{\mu C_{OX} W}{2L} (V_{GS} - V_{TH})^2$$

$I_D$  independent of  $V_{DS}$



$$I_C = \beta \tilde{I}_s e^{\frac{V_{BE}}{V_t}}$$

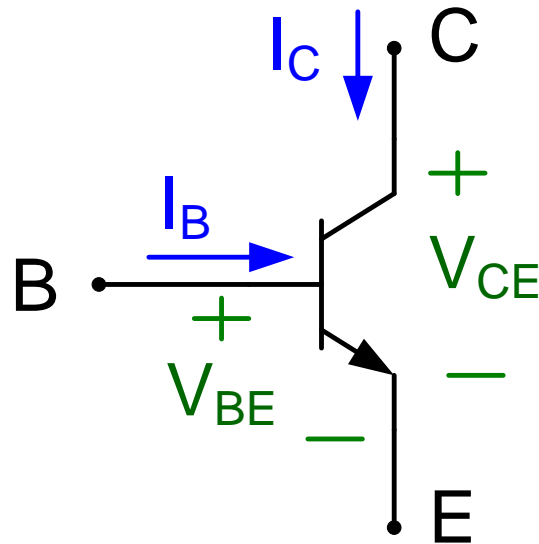
$I_C$  independent of  $V_{CE}$



- The BJT I/O relationship is exponential in contrast to square-law for MOSFET
- Provides a very large “gain” for the BJT (assuming input is voltage and output is current)
- This property is very useful for many applications

# Bipolar Models

## Simple dc Model



Following convention, pick  $I_C$  and  $I_B$  as dependent variables and  $V_{BE}$  and  $V_{CE}$  as independent variables



# Simple dc model

## npn transistor – Forward Active Operation

$$\left. \begin{aligned} I_B &= \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \\ I_C &= J_S A_E e^{\frac{V_{BE}}{V_t}} \end{aligned} \right\}$$
$$V_t = \frac{kT}{q}$$

As with the diode, the parameter  $J_S$  is highly temperature dependent

$$J_S = J_{SX} \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right]$$

Typical values for parameters:  $J_{SX}=20\text{mA}/\mu^2$ ,  $V_{G0}=1.17\text{V}$ ,  $m=2.3$

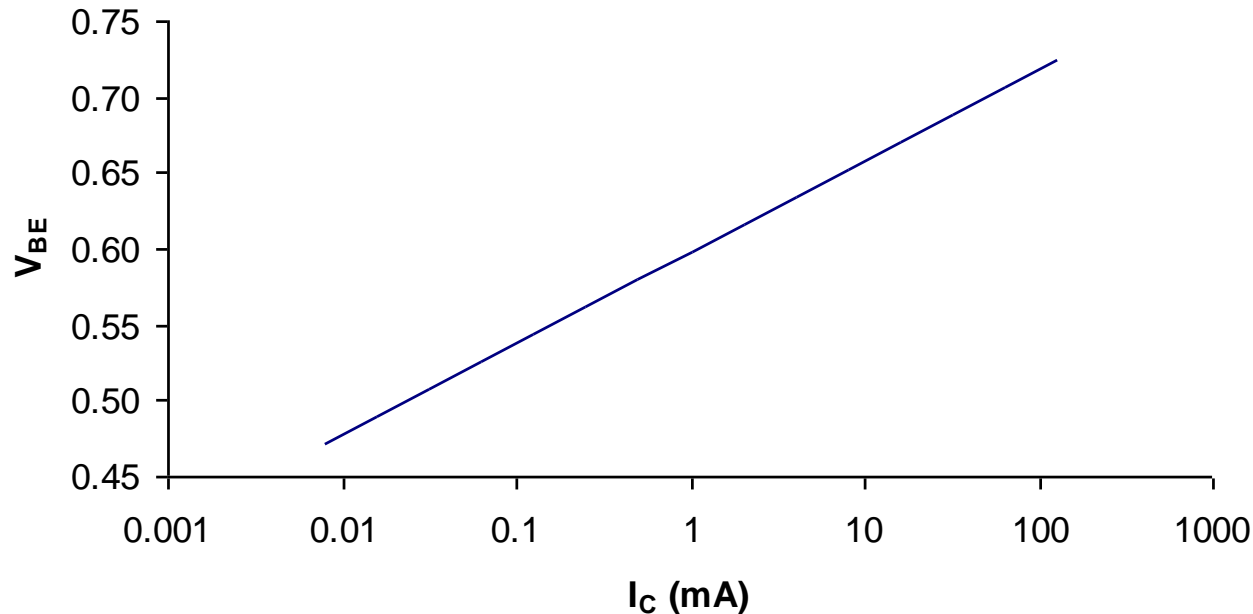
The parameter  $\beta$  is also somewhat temperature dependent but much weaker temperature dependence than  $J_{SX}$ .

# Transfer Characteristics

## npn transistor – Forward Active Operation

$$J_S = .25 \text{ fA}/\mu^2$$

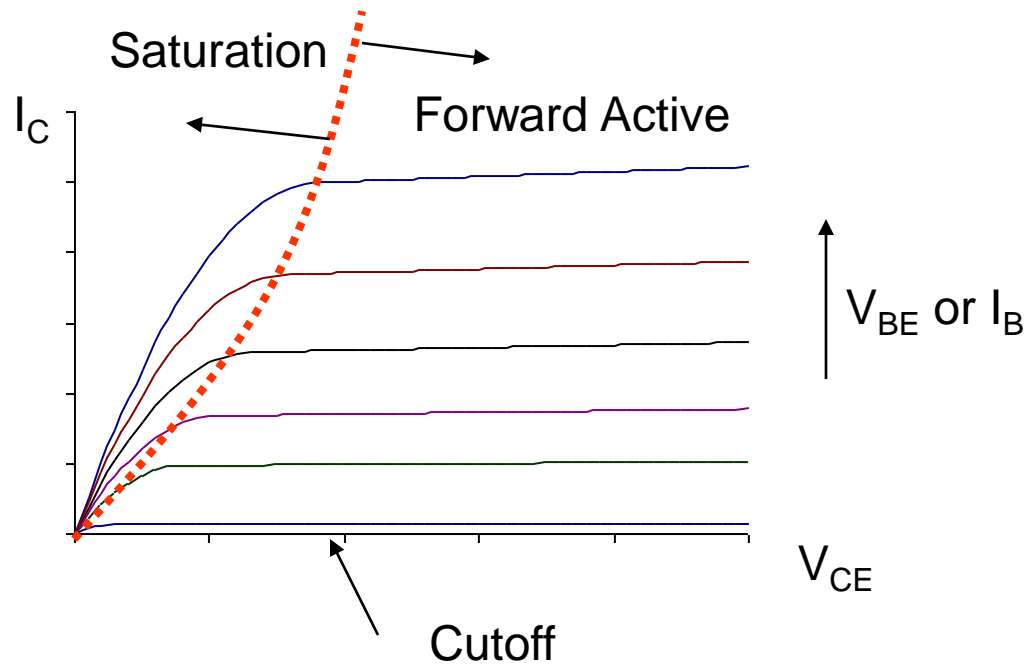
$$A_E = 400 \mu^2$$



$V_{BE}$  close to 0.6V for a four decade change in  $I_C$  around 1mA

# Simple dc model

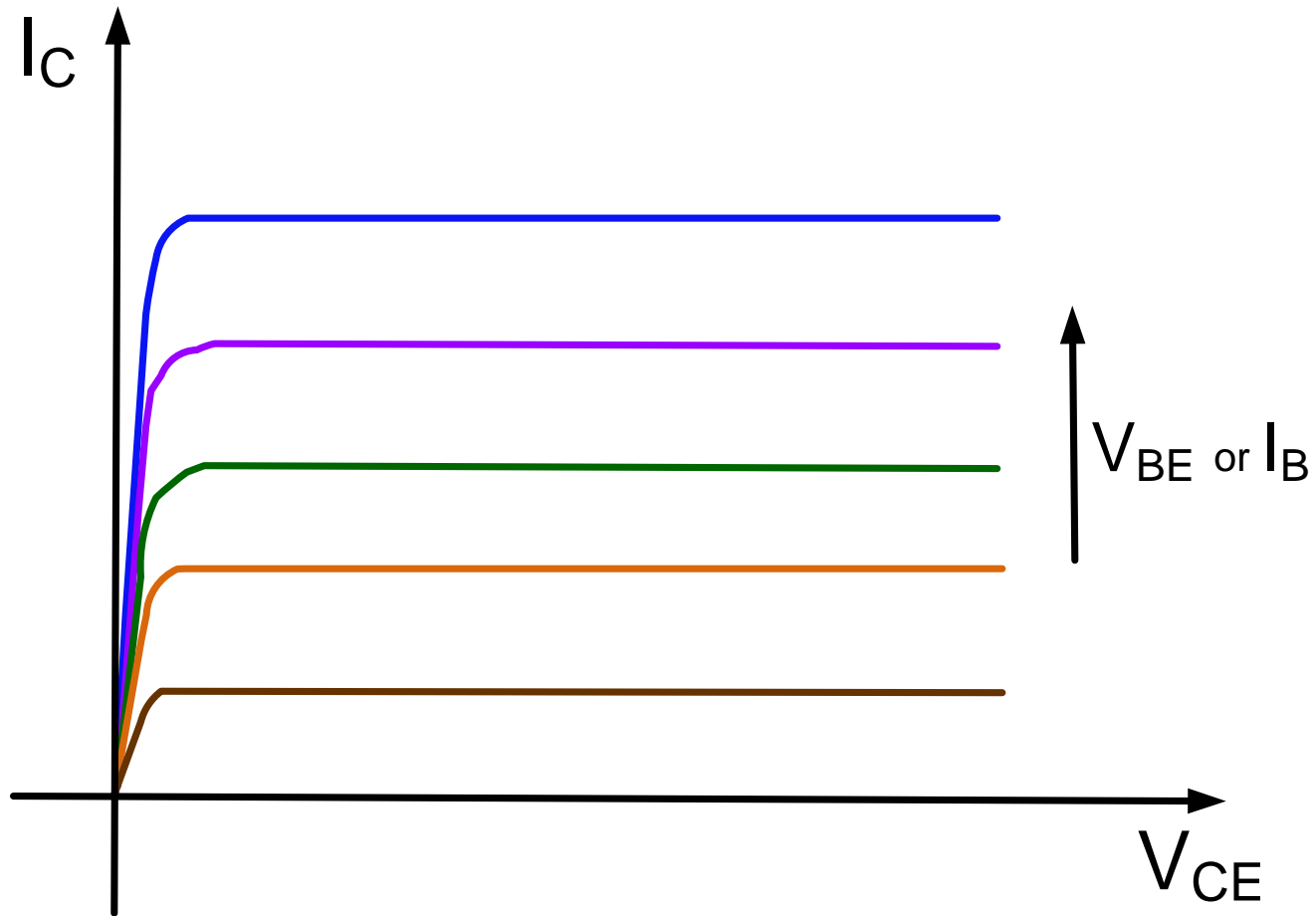
Typical Output Characteristics



Forward Active region of BJT is analogous to Saturation region of MOSFET

Saturation region of BJT is analogous to Triode region of MOSFET

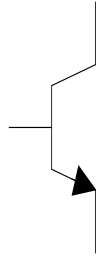
# Better Model of Output Characteristics



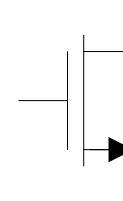
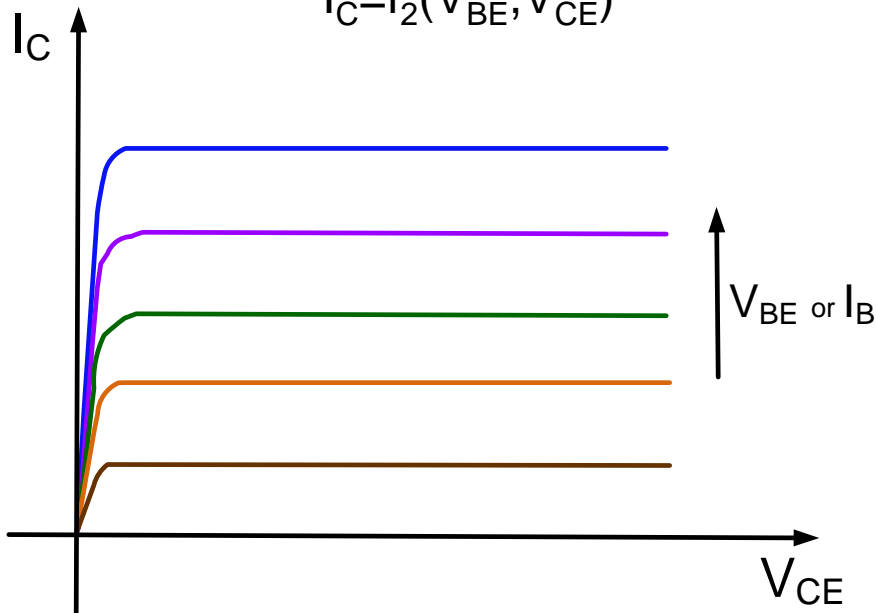
With scaled  $V_{CE}$  axis, transition in saturation very steep

# BJT and MOSFET Comparison

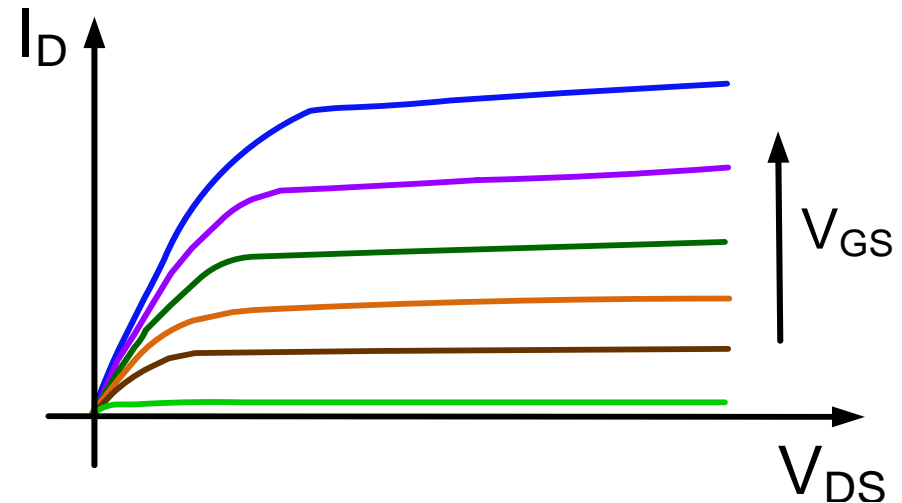
## Output Characteristics



$$I_C = f_2(V_{BE}, V_{CE})$$

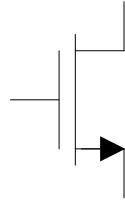


$$I_D = f_{2M}(V_{GS}, V_{DS})$$

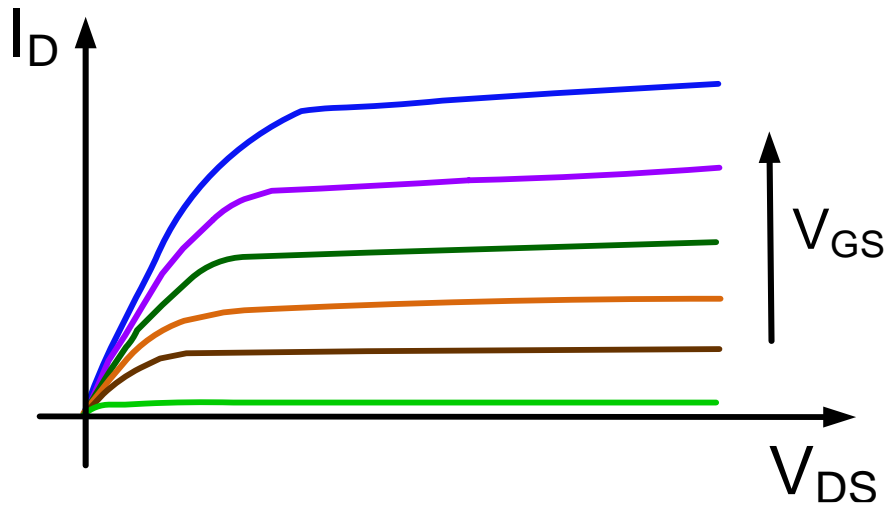


- Same general characteristics
- Spacings a bit different (Exponential vs square law)
- Slope steeper for small  $V_{CE}$  compared to small  $V_{DS}$

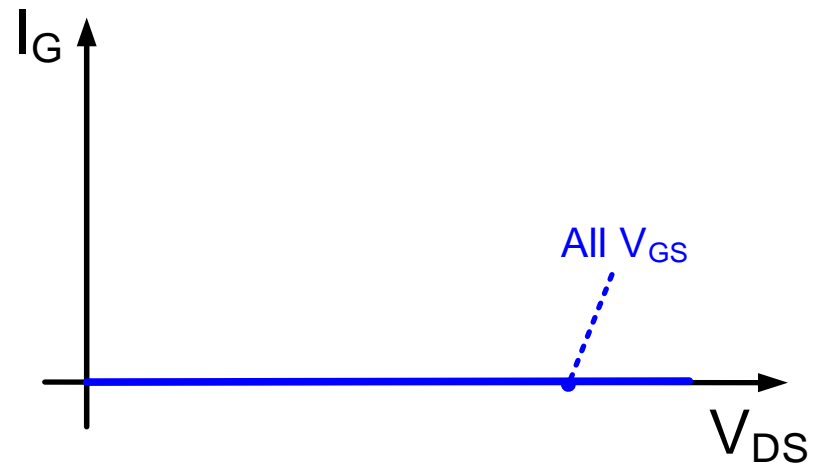
# Recall MOSFET Operation



Output characteristics



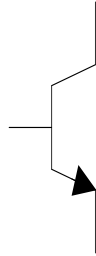
Input characteristics



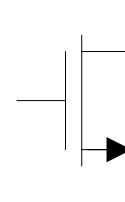
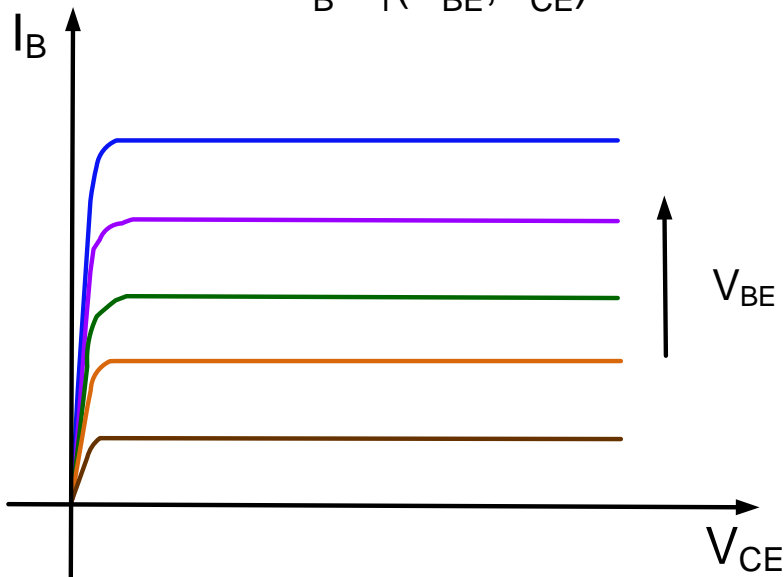
or equivalently:  $I_G = 0$

# BJT and MOSFET Comparison

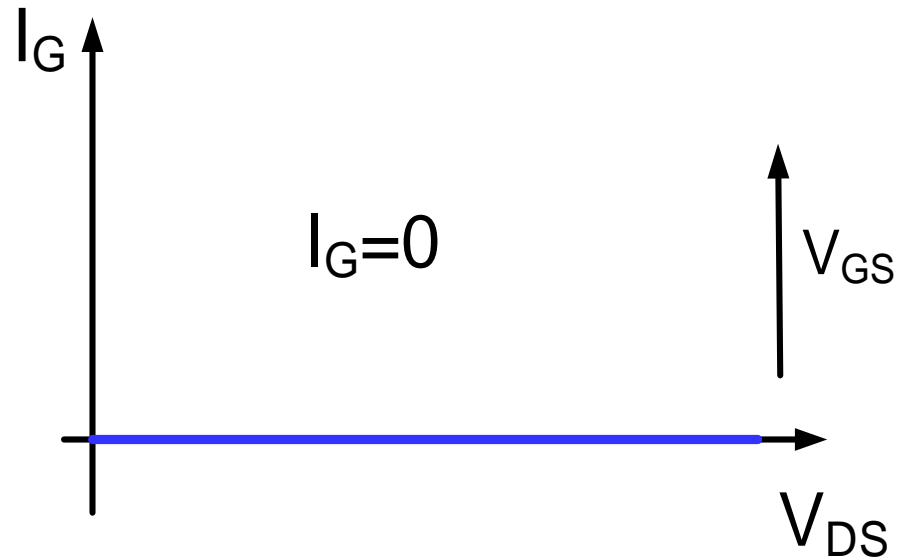
## Input Characteristics



$$I_B = f_1(V_{BE}, V_{CE})$$

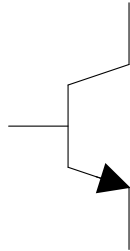


$$I_G = f_{1M}(V_{GS}, V_{DS})$$

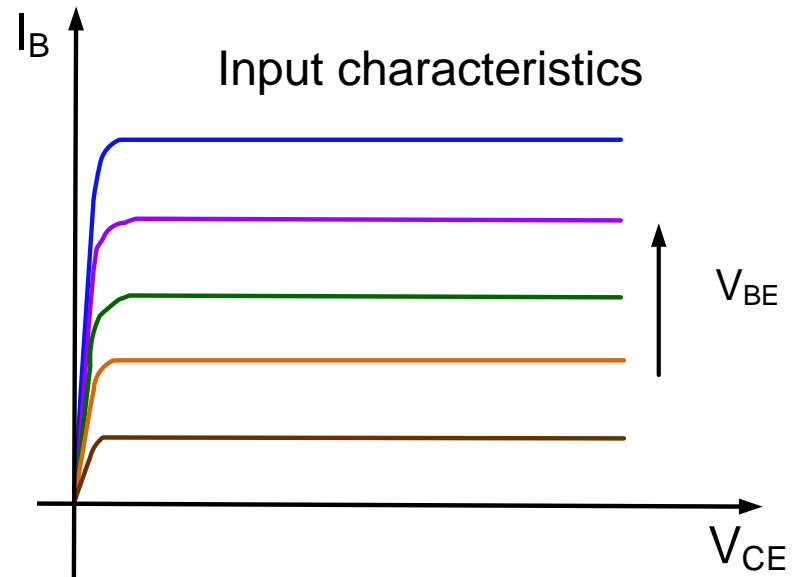
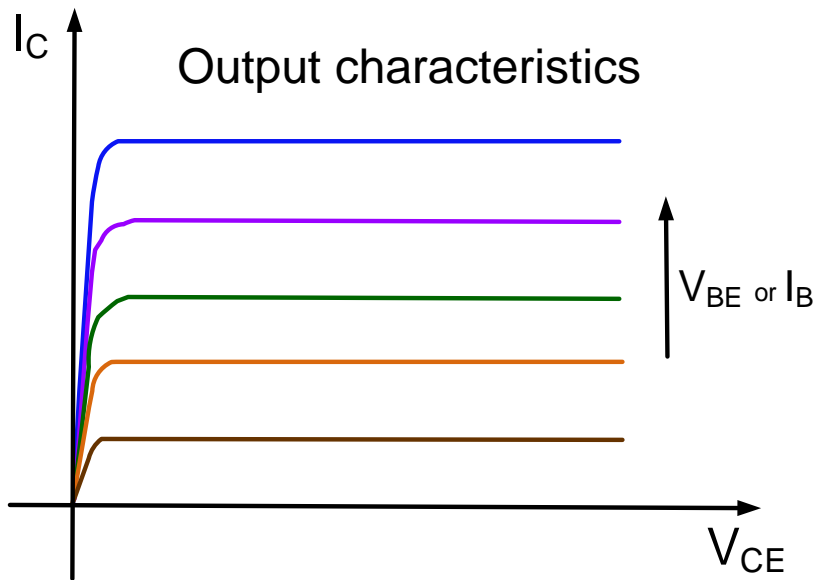


Did not need to graphically show input characteristics for MOS transistors since  $I_G = 0$

# BJT Model



$$I_B = f_1(V_{BE}, V_{CE})$$
$$I_C = f_2(V_{BE}, V_{CE})$$



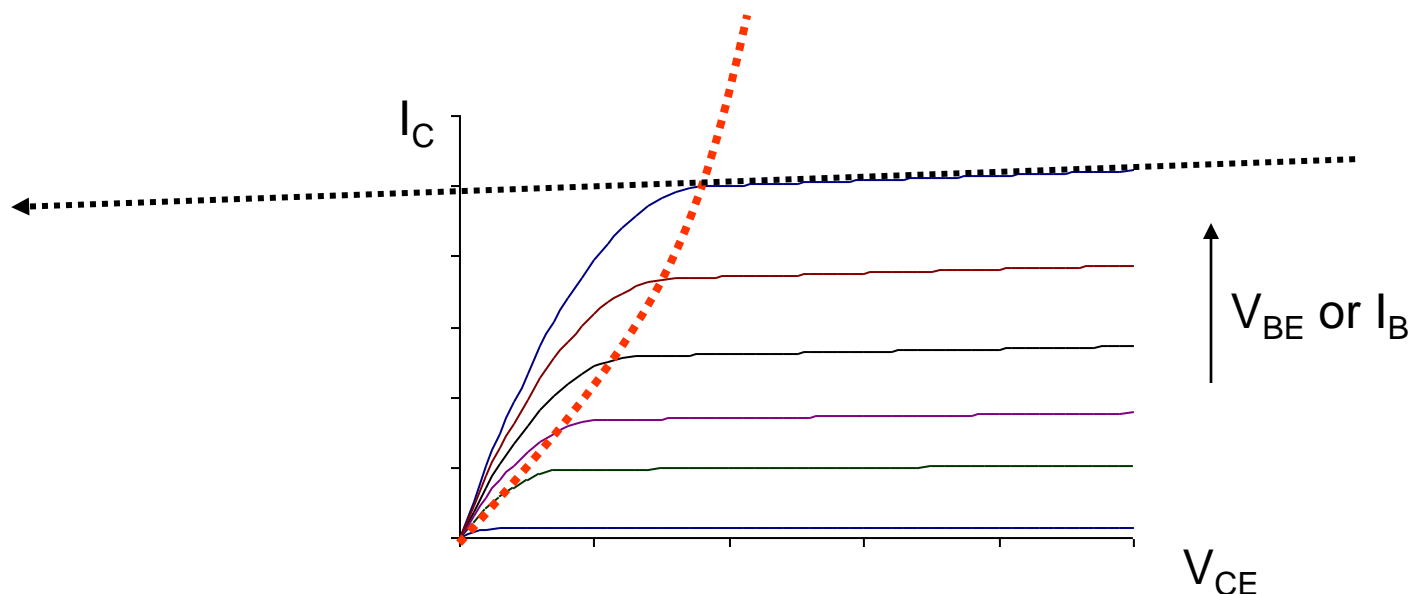
Require two graphical representations (or analytical expressions) though vertical axis scales different by factor of  $\beta$

Since  $I_B = f(V_{BE})$ , can use independent ( $V_{BE}$ ) or dependent ( $I_B$ ) variable for 2-D visualization of 3-dimensional  $I_C$  function



# Improved simple dc model

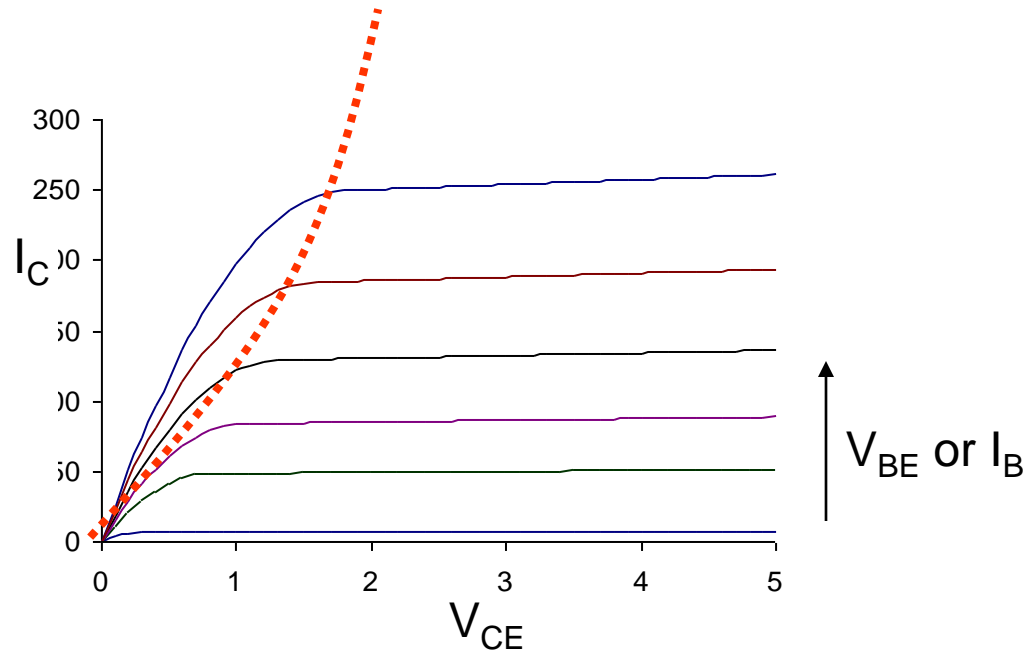
Typical Output Characteristics



- Projections of these tangential lines all intercept the  $-V_{CE}$  axis at the same place and this is termed the Early voltage,  $V_{AF}$  (actually  $-V_{AF}$  is intercept)
- Typical values of  $V_{AF}$  are in the 100V to 200V range
- Can multiply expression for  $I_C$  in Forward Active Region by term  $\left(1 + \frac{V_{CE}}{V_{AF}}\right)$  to account for slope

# Improved simple dc model

(graphically showing only output characteristics)

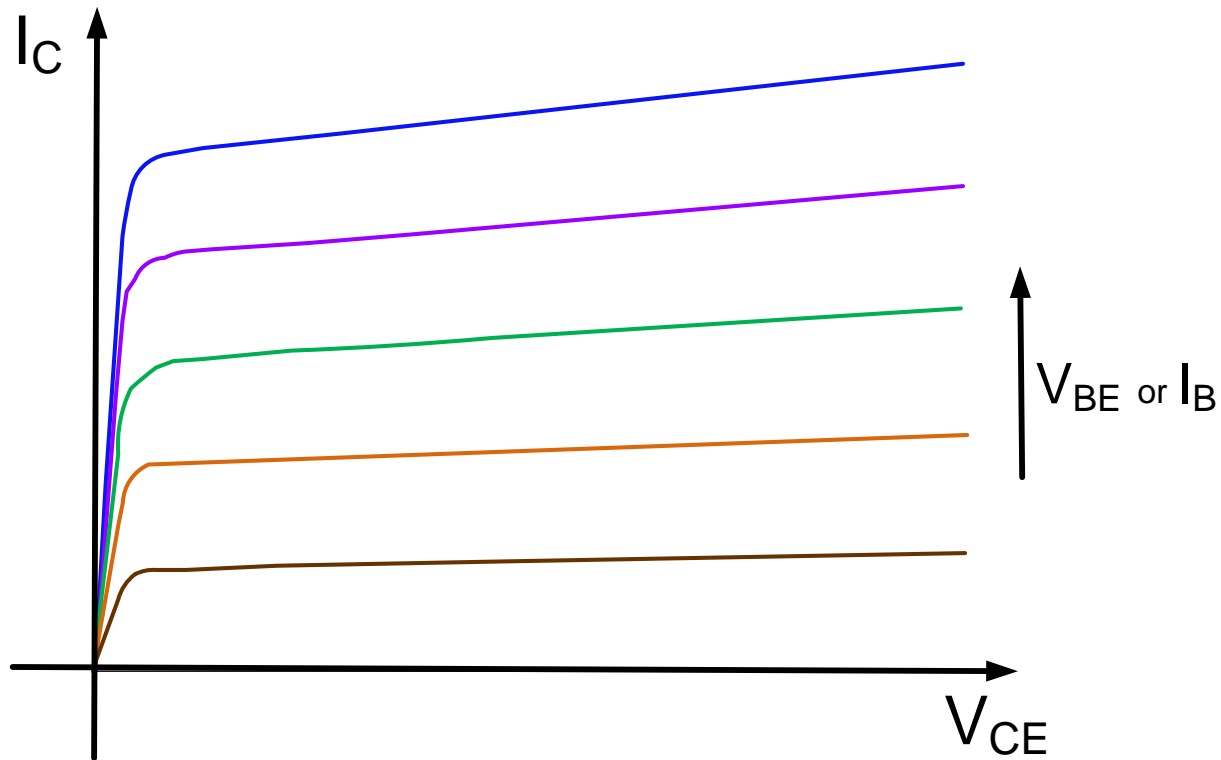


$$\left. \begin{aligned} I_B &= \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \\ I_C &= J_S A_E e^{\frac{V_{BE}}{V_t}} \left( 1 + \frac{V_{CE}}{V_{AF}} \right) \end{aligned} \right\} \text{Valid only in Forward Active Region}$$

Need models in saturation and cutoff regions

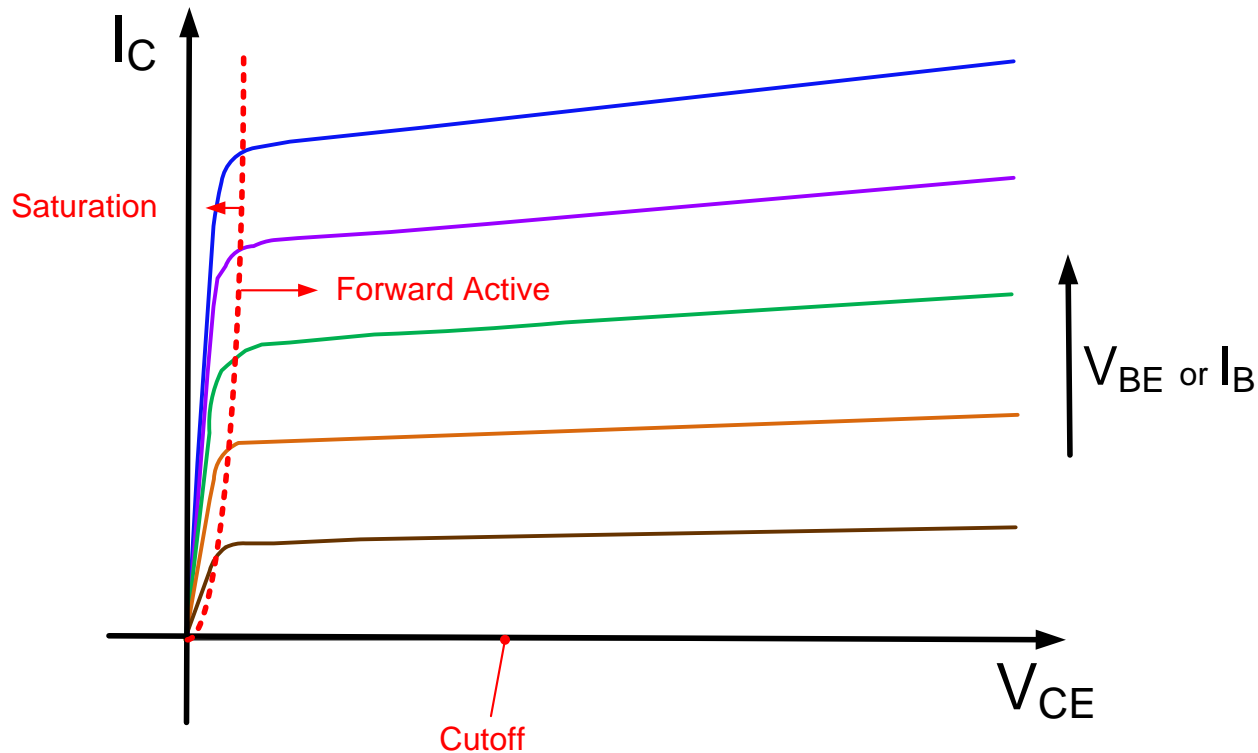
# Improved simple BJT dc model

Typical Output Characteristics



# Improved simple BJT dc model

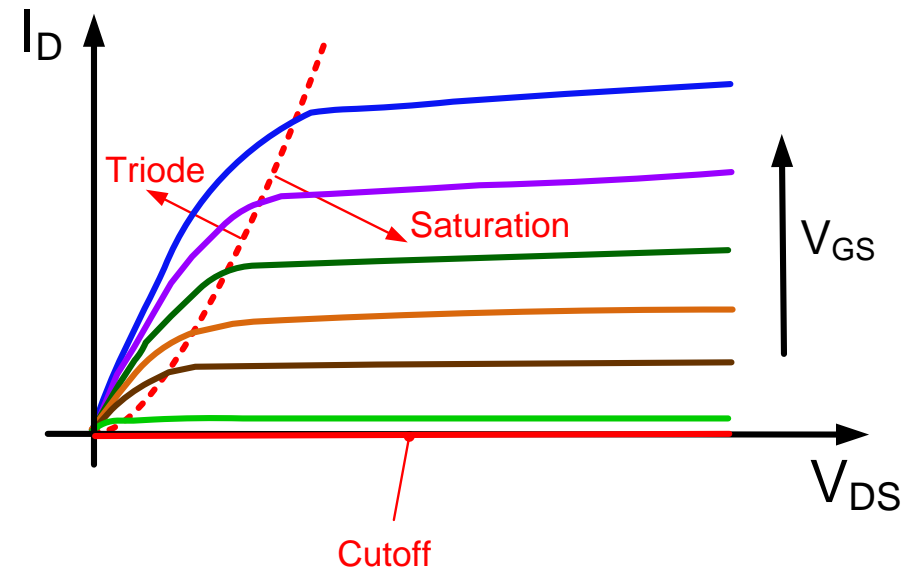
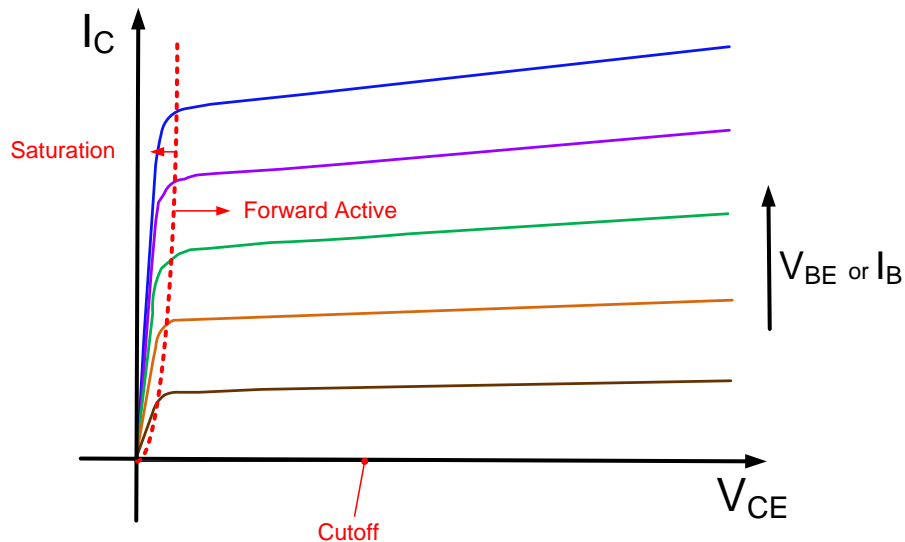
Typical Output Characteristics



Need analytical models in saturation and cutoff regions

# Improved simple BJT dc model

## Typical Output Characteristics



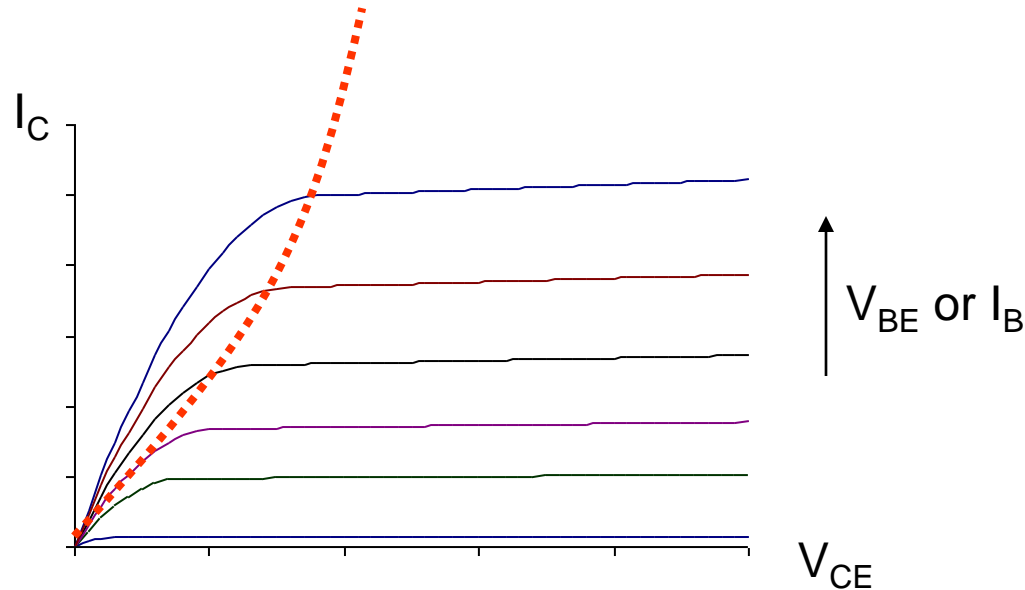
Recall:

Forward Active region of BJT is analogous to Saturation region of MOSFET

Saturation region of BJT is analogous to Triode region of MOSFET

# Improved dc model

(graphically showing only output characteristics)



$$V_t = \frac{kT}{q}$$

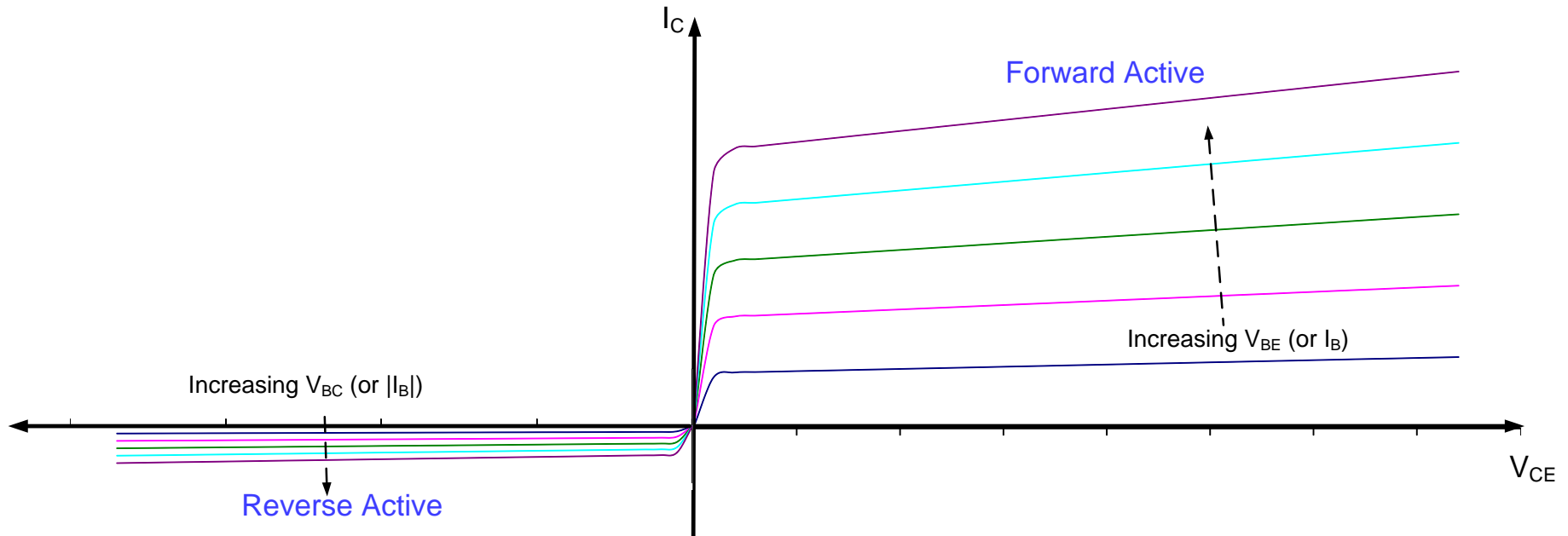
$$I_E = -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) + J_S A_E \left( e^{\frac{V_{BC}}{V_t}} - 1 \right)$$

$$I_C = J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right)$$

- Valid in All regions of operation
- $V_{AF}$  effects can be added
- Not mathematically easy to work with
- Note dependent variables changes  $\{I_E, I_C\}$
- Termed Ebers-Moll model
- Reduces to previous model in FA region
- Little use in Reverse Active Region

# Improved dc model

(graphically showing only output characteristics)



$$V_t = \frac{kT}{q}$$

$$I_E = -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) + J_S A_E \left( e^{\frac{V_{BC}}{V_t}} - 1 \right)$$

$$I_C = J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right)$$

- Model using  $I_E$  and  $I_C$  as dependent variables
- Valid in All regions of operation
- $V_{AF}$  effects can be added
- Not mathematically easy to work with
- Note dependent variables changes
- Termed Ebers-Moll model
- Reduces to previous model in FA region
- Little use in Reverse Active Region

# Ebers-Moll model

$$\left. \begin{aligned} I_E &= -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) + J_S A_E \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \\ I_C &= J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \end{aligned} \right\}$$

Process Parameters:  $\{J_S, \alpha_F, \alpha_R\}$        $V_t = \frac{kT}{q}$

Design Parameters:  $\{A_E\}$

$\alpha_F$  is the parameter  $\alpha$  discussed earlier  
 $\alpha_R$  is termed the “reverse  $\alpha$ ”

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F} \quad \beta_R = \frac{\alpha_R}{1 - \alpha_R} \quad \Longrightarrow \quad \alpha_F = \frac{\beta_F}{1 + \beta_F} \quad \alpha_R = \frac{\beta_R}{1 + \beta_R}$$

Typical values for process parameters:

$$J_S \sim 10^{-16} \text{ A}/\mu^2 \quad \beta_F \sim 100, \quad \beta_R \sim 0.4$$

Can substitute for  $\alpha_F$  and  $\alpha_R$  in Ebers-Moll model



# Ebers-Moll model

$$\left. \begin{aligned} I_E &= -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) + J_S A_E \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \\ I_C &= J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \end{aligned} \right\}$$

With typical values for process parameters in forward active region ( $V_{BE} \sim 0.6V$     $V_{BC} \sim -3$     $V_t \sim 26mV$ ) and if  $A_E = 100\mu^2$

$$I_C = 10^{-14} \left( 1.05 \times 10^{10} - 1 \right) - 3.6 \times 10^{-14} \left( 7.7 \times 10^{-14} - 1 \right)$$

Completely dominant

Makes no sense to keep anything other than  $I_C = J_S A_E e^{\frac{V_{BE}}{V_t}}$  in forward active region

# Ebers-Moll model

Ebers-Moll model

$$\left. \begin{aligned} I_E &= -\frac{J_S A_E}{\alpha_F} \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) + J_S A_E \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \\ I_C &= J_S A_E \left( e^{\frac{V_{BE}}{V_t}} - 1 \right) - \frac{J_S A_E}{\alpha_R} \left( e^{\frac{V_{BC}}{V_t}} - 1 \right) \end{aligned} \right\}$$

$$V_t = \frac{kT}{q}$$

Alternate equivalent expressions for dependent variables  $\{I_C, I_B\}$  defined earlier for Ebers-Moll equations in terms of independent variables  $\{V_{BE}, V_{CE}\}$  after dropping the “-1” terms

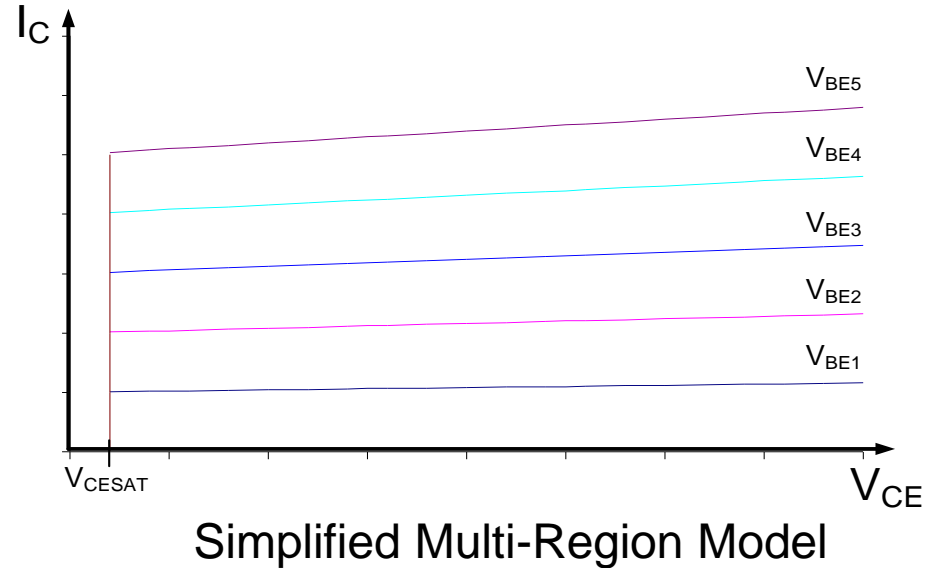
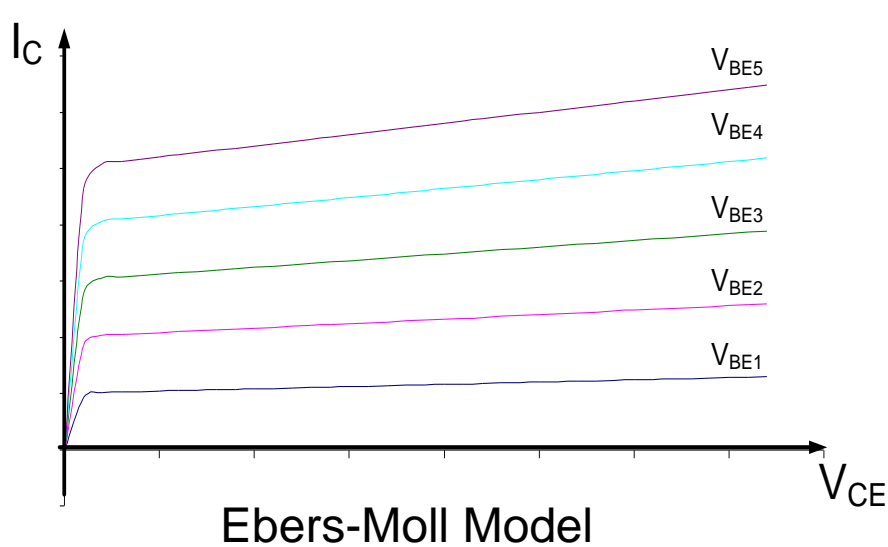
$$I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \left( 1 - \left[ \frac{1 + \beta_R}{\beta_R} \right] e^{\frac{-V_{CE}}{V_t}} \right)$$

$$I_B = J_S A_E e^{\frac{V_{BE}}{V_t}} \left( \frac{1}{\beta_F} - \frac{1}{\beta_R} e^{\frac{-V_{CE}}{V_t}} \right)$$

No more useful than previous equation but in form consistent with notation  
Introduced earlier

# Simplified Multi-Region Model

(graphically showing only output characteristics)

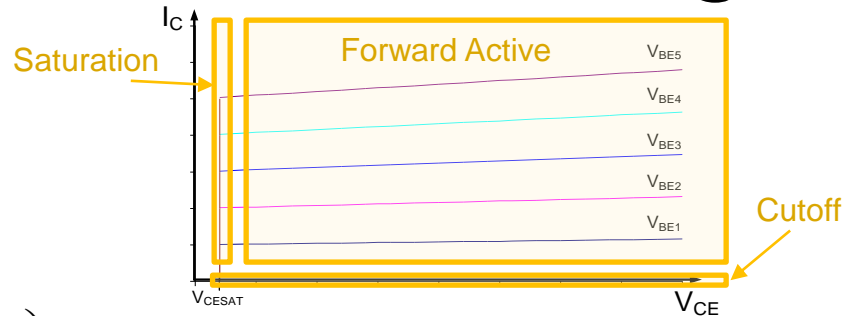


- Observe  $V_{CE}$  around 0.2V when saturated
- $V_{BE}$  around 0.6V when saturated
- In most applications, exact  $V_{CE}$  and  $V_{BE}$  voltage in saturation not critical

Simplified model in saturation:

$$\left. \begin{array}{l} V_{BE}=0.7V \\ V_{CE}=0.2V \end{array} \right\} \text{ Saturation}$$

# Simplified Multi-Region Model



$$I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \left( 1 + \frac{V_{CE}}{V_{AF}} \right)$$

$$I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}$$

$$V_t = \frac{kT}{q}$$

Forward Active

$$V_{BE} = 0.7V$$

$$V_{CE} = 0.2V$$

Saturation

$$I_C = I_B = 0$$

Cutoff

- This is a piecewise model suitable for analytical calculations
- Can easily extend to reverse active mode but of little use
- Still need conditions for operating in the 3 regions !!

# Simplified Multi-Region Model

“Forward” Regions :  $\beta = \beta_F$

$I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \left( 1 + \frac{V_{CE}}{V_{AF}} \right)$ $I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}$	<p>Conditions</p> <p><math>V_{BE} &gt; 0.4V</math>    <math>V_{BC} &lt; 0</math></p>	Forward Active
<p><math>V_{BE} = 0.7V</math> <math>V_{CE} = 0.2V</math></p>	<p><math>I_C &lt; \beta I_B</math></p>	Saturation
<p><math>I_C = I_B = 0</math></p>	<p><math>V_{BE} &lt; 0</math>    <math>V_{BC} &lt; 0</math></p>	Cutoff

Process Parameters:  $\{J_S, \beta, V_{AF}\}$   $\{V_{BESAT}, V_{CESAT}\}$   $V_t = \frac{kT}{q}$  Design Parameters:  $\{A_E\}$

- Process parameters highly process dependent
- $J_S$  highly temperature dependent as well,  $\beta$  modestly temperature dependent
- This model is dependent only upon emitter area, independent of base and collector area !
- Currents scale linearly with  $A_E$  and not dependent upon shape of emitter
- $V_{BESAT}$  and  $V_{CESAT}$  often not considered process parameters since change little with process
- A small portion of the operating region is missed with this model but seldom operate in the missing region

# Simplified Multi-Region Model

Alternate equivalent model

$$I_C = \beta I_B \left( 1 + \frac{V_{CE}}{V_{AF}} \right)$$

$$I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}$$

$$V_t = \frac{kT}{q}$$

$$V_{BE} = 0.7V$$

$$V_{CE} = 0.2V$$

$$I_C = I_B = 0$$

Conditions

$$V_{BE} > 0.4V$$

$$V_{BC} < 0$$

Forward Active

$$I_C < \beta I_B$$

Saturation

$$V_{BE} < 0$$

$$V_{BC} < 0$$

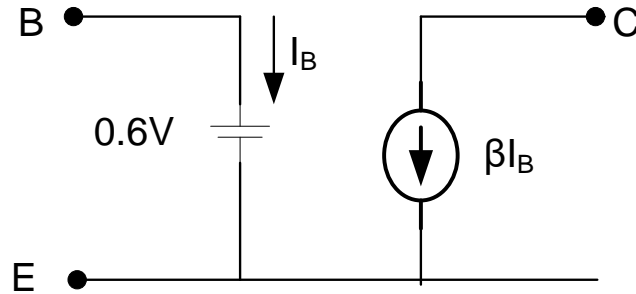
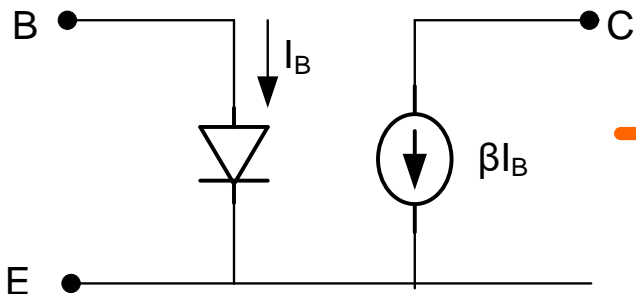
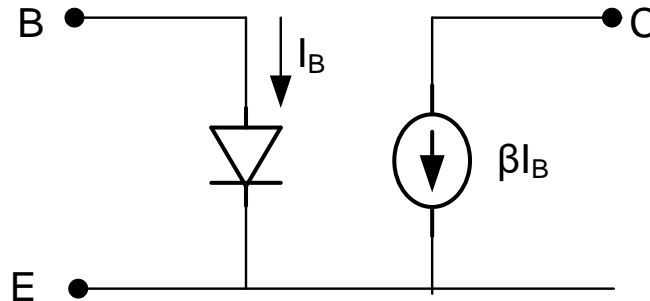
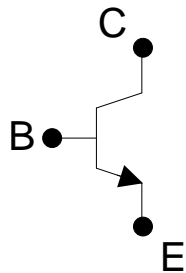
Cutoff

A small portion of the operating region is missed with this model but seldom operate in the missing region

# Further Simplified Multi-Region dc Model

(by neglecting  $V_{AF}$ )

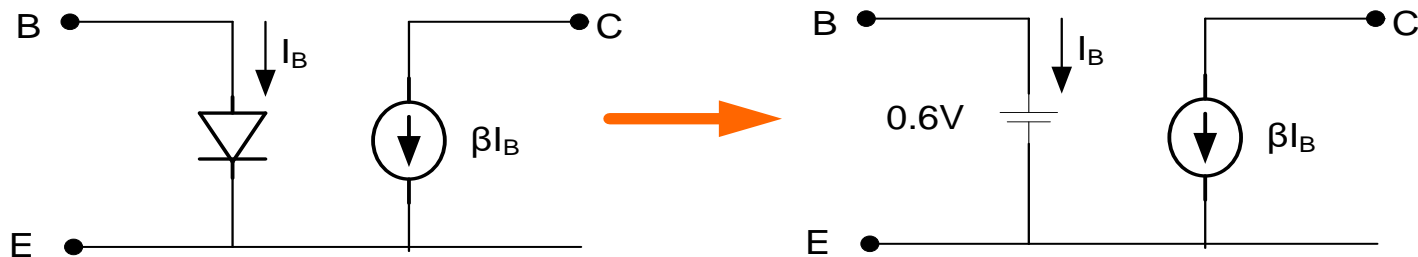
Forward Active



Adequate when it makes little difference whether  $V_{BE}=0.6V$  or  $V_{BE}=0.7V$

# Simplified Multi-Region dc Model

Forward Active



Mathematically

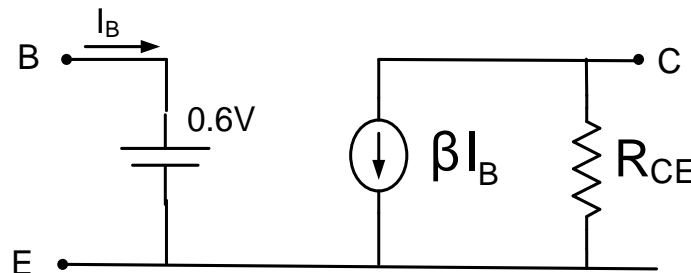
$$V_{BE} = 0.6V$$

$$I_C = \beta I_B$$

Or, if want to show slope in  $I_C$ - $V_{CE}$  characteristics

$$V_{BE} = 0.6V$$

$$I_C = \beta I_B (1 + V_{CE}/V_{AF})$$



$$R_{CE} = \frac{V_{AF}}{\beta I_{BQ}}$$

$R_{CE}$  highly nonlinear



# Further Simplified Multi-Region dc Model

Equivalent Further Simplified Multi-Region Model

$$I_C = \beta I_B$$

$$V_{BE} = 0.6V$$

$$V_{BE} > 0.4V$$

$$V_{BC} < 0$$

Forward Active

$$V_t = \frac{kT}{q}$$

---

$$V_{BE} = 0.7V$$

$$V_{CE} = 0.2V$$

$$I_C < \beta I_B$$

Saturation

$$I_C = I_B = 0$$

$$V_{BE} < 0$$

$$V_{BC} < 0$$

Cutoff

A small portion of the operating region is missed with this model but seldom operate in the missing region

# Conditions for Regions of Operation in Multi-Region Model

$$V_{BE} > 0.4V$$

Forward Active

$$V_{BC} < 0$$

$$I_C < \beta I_B$$

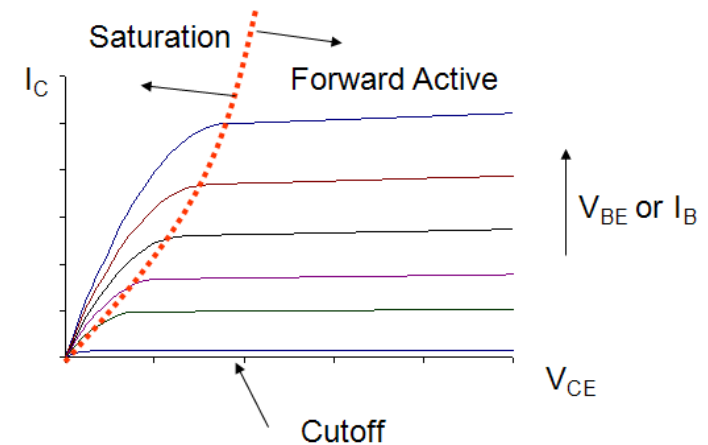
Saturation

$$V_{BE} < 0$$

$$V_{BC} < 0$$

Cutoff

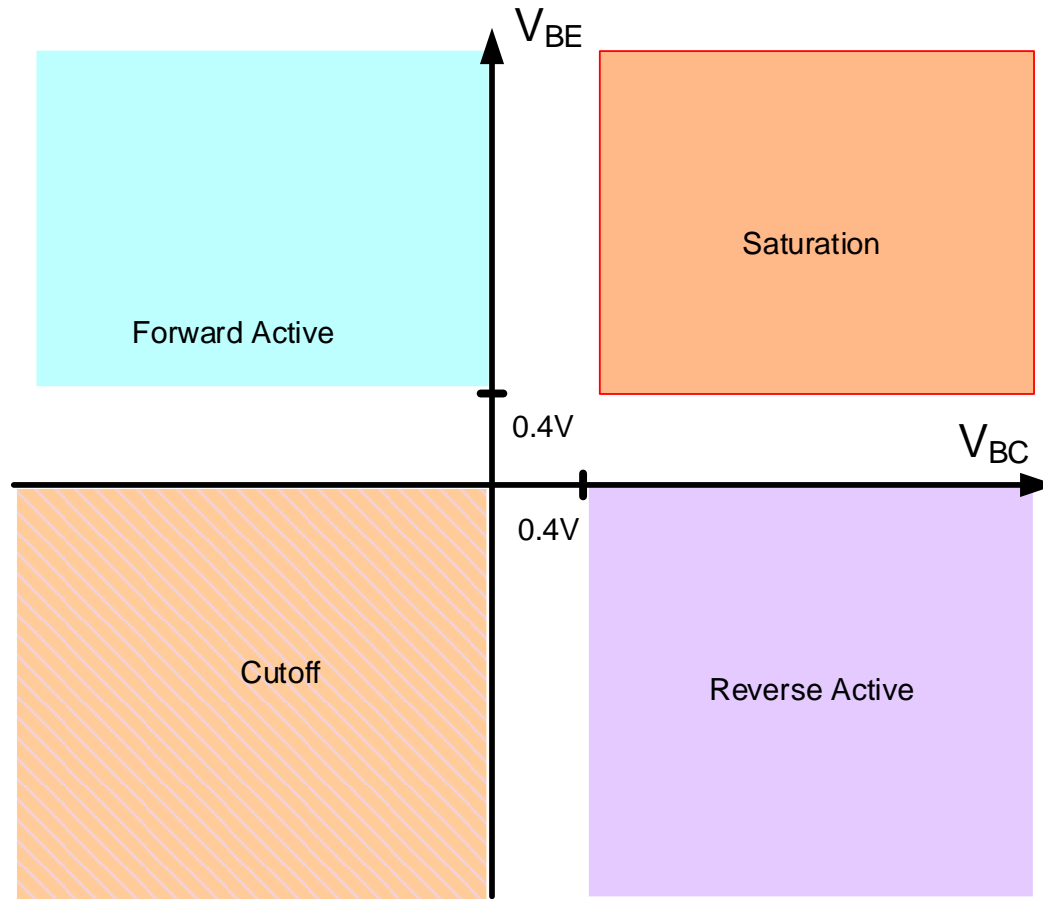
Note: One condition is on dependent variables !



Observe that in saturation,  $I_C < \beta I_B$

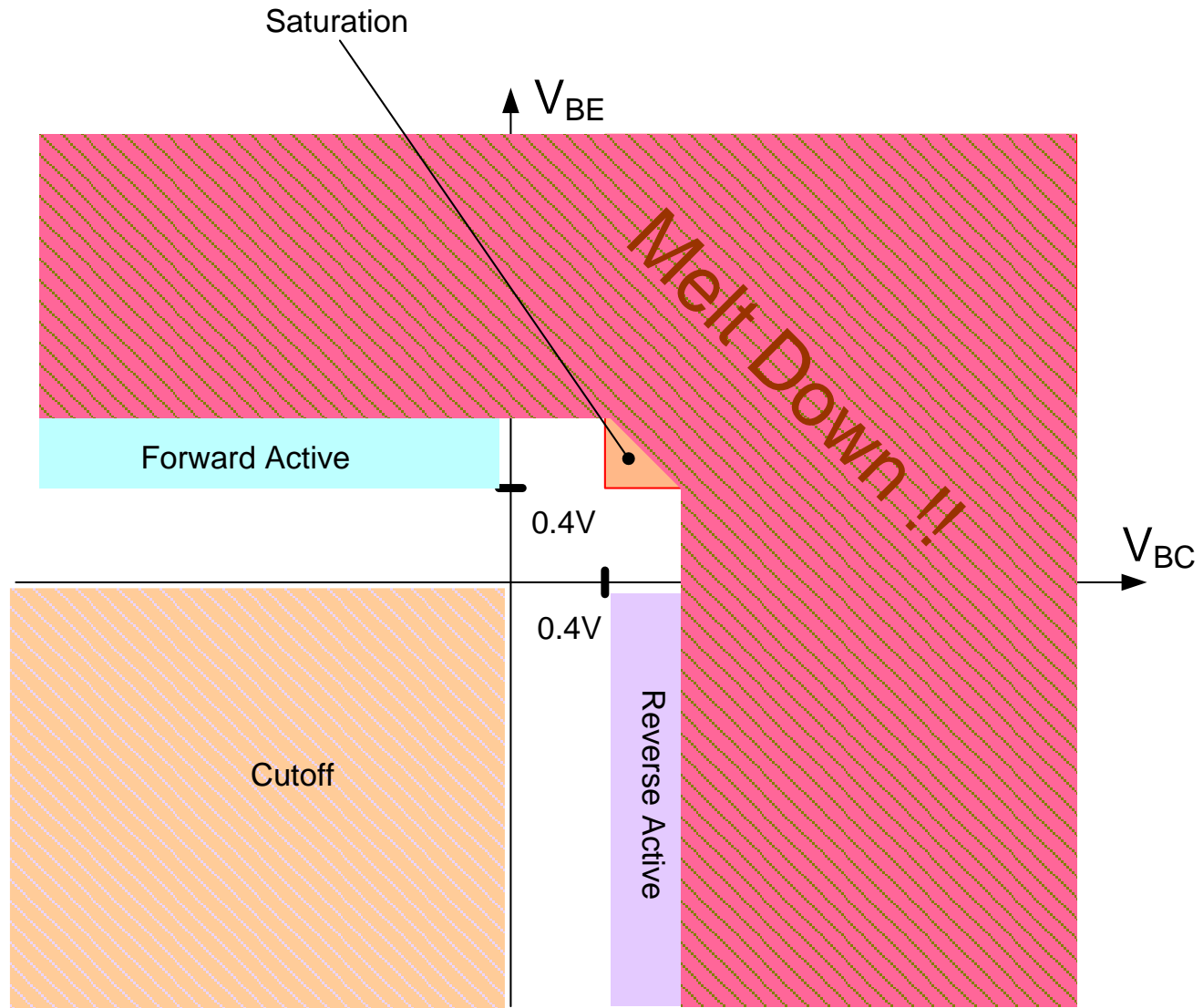
Can't condition on independent variables in saturation because they are fixed in the model

## Regions of Operation in Independent Parameter Domain used In multi-region models

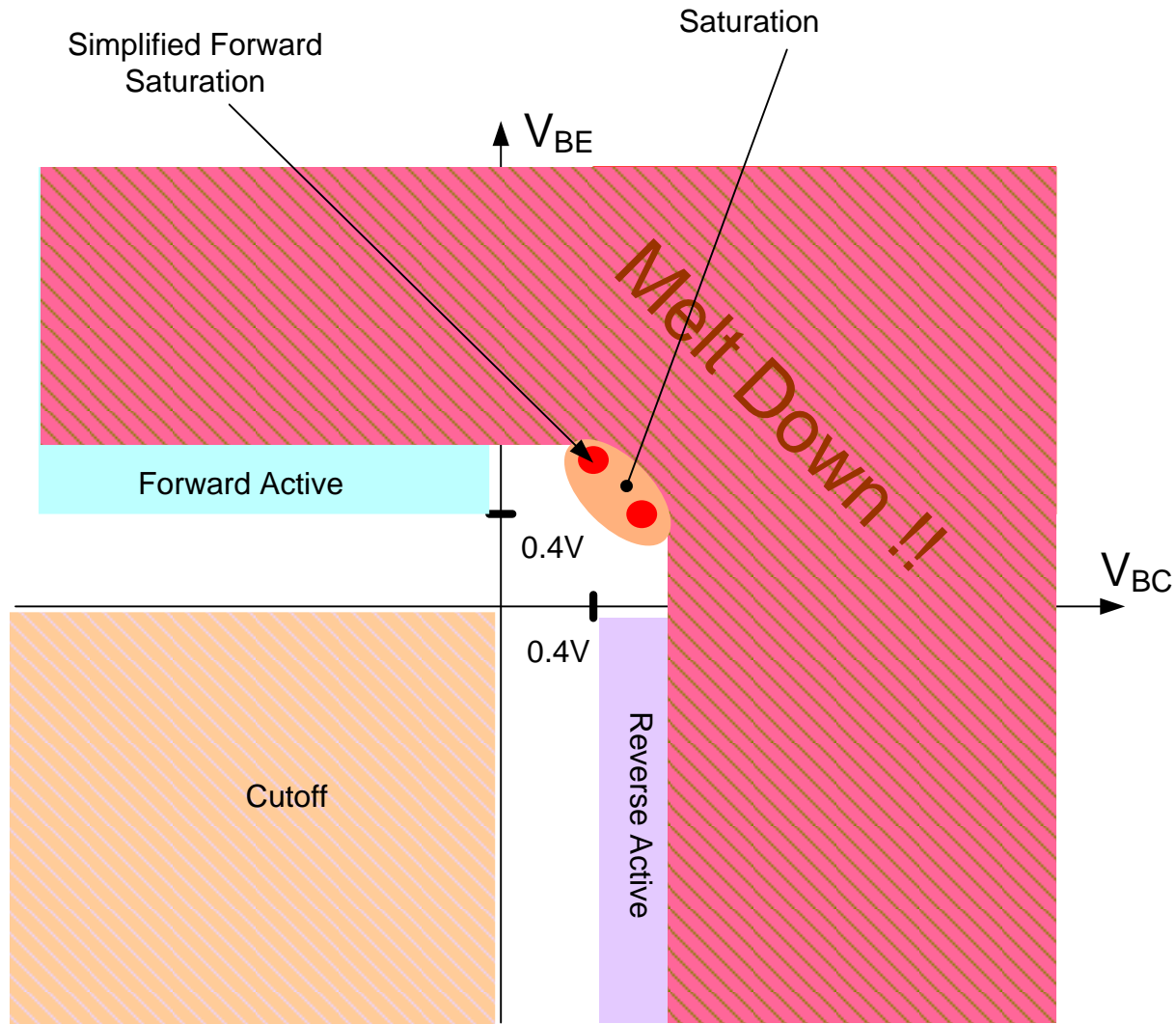


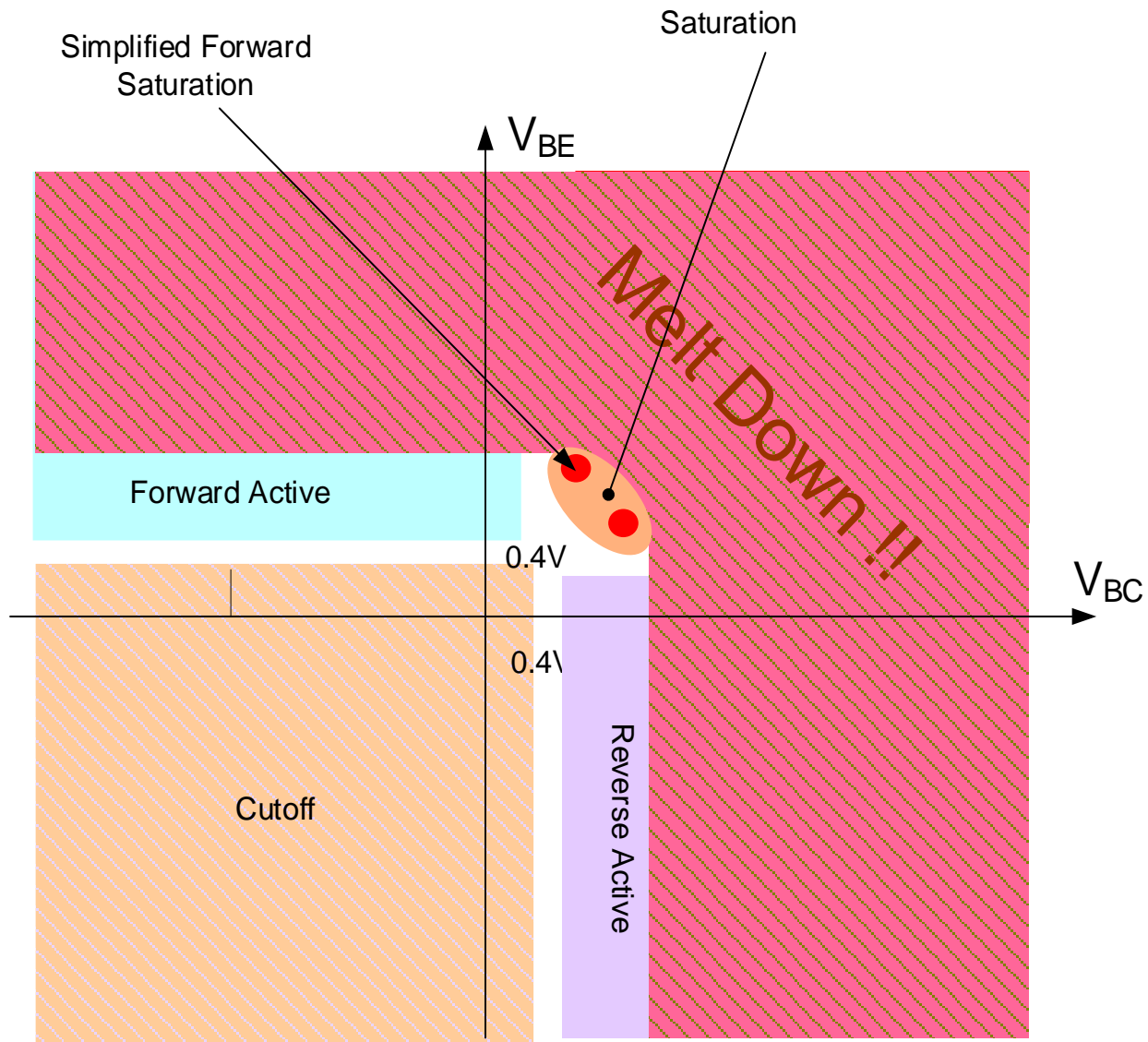
- Seldom operate in regions excluded in this picture
- Limited use in Reverse Active Mode

Excessive Power Dissipation if either junction has large forward bias



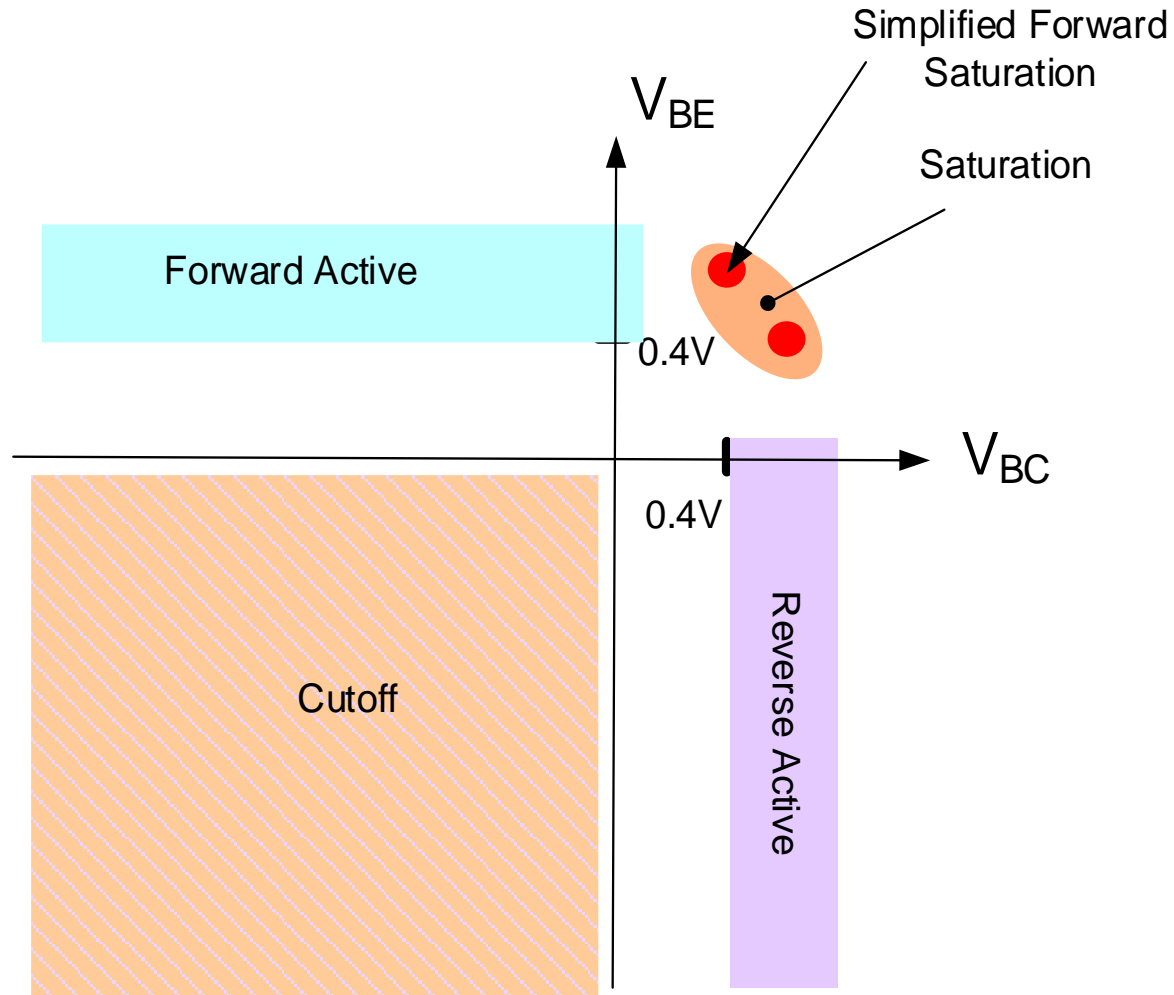
# Safe regions of operation



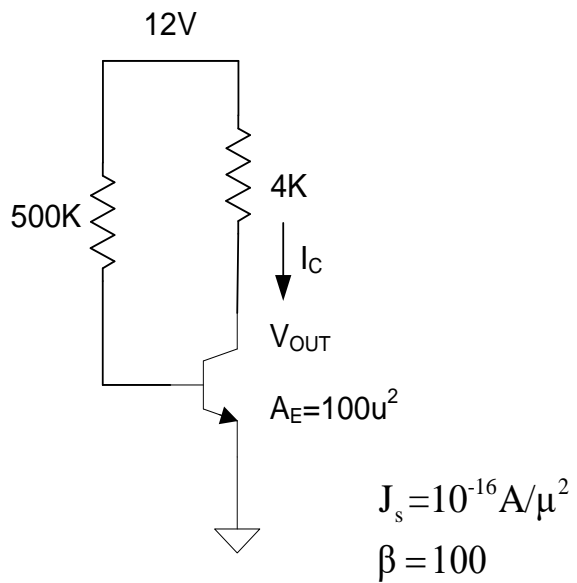


Actually cutoff, forward active, and reverse active regions can be extended modestly as shown and multi-region models still are quite good

# Sufficient regions of operation for most applications



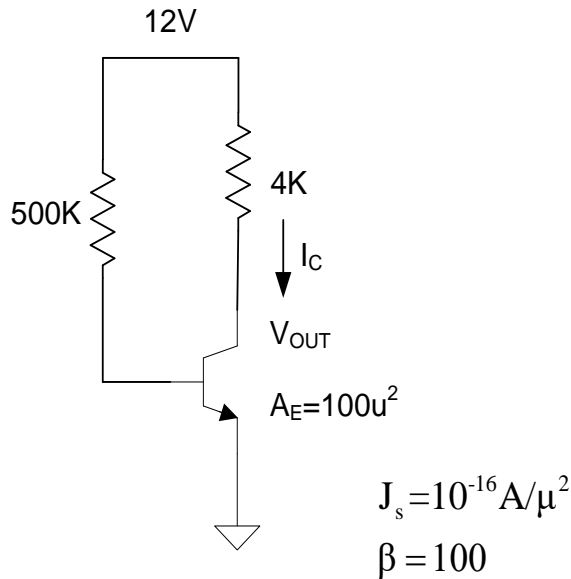
Example: Determine  $I_C$  and  $V_{OUT}$



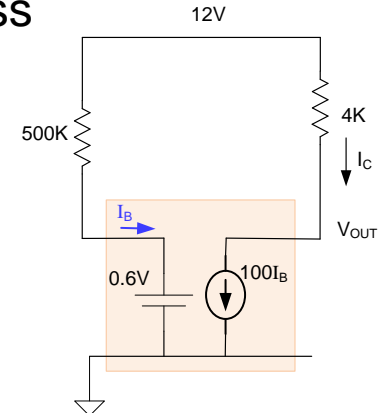


Example: Determine  $I_C$  and  $V_{OUT}$

Solution:



1. Guess Forward Active Region (and model)
2. Solve Circuit with Guess
3. Verify model (if necessary)



$$I_B = \frac{(12 - 0.6)}{500K}$$

$$I_C = \beta I_B = 100 \frac{(12 - 0.6)}{500K} = 2.28 \text{ mA}$$

$$V_{OUT} = 12 - I_C \cdot 4K = 2.88 \text{ V}$$

4. Verify FA Region

$$V_{BE} = 0.6 \text{ V} > 0.4 \text{ V}$$

$$V_{BE} > 0.4 \text{ V} \text{ and } V_{BC} < 0$$

$$V_{BC} = 0.6 \text{ V} - 2.88 \text{ V} = -2.28 \text{ V} < 0$$

Verify Passes so solution is valid

$$I_C = 2.28 \text{ mA}$$

$$V_{OUT} = 2.88 \text{ V}$$

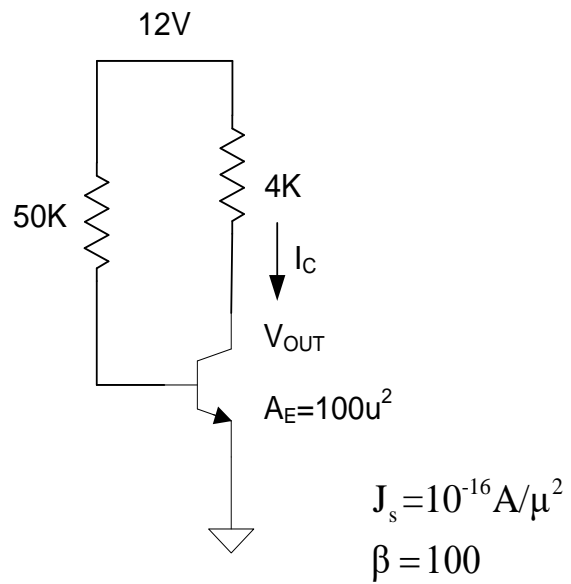
5. Verify model (if necessary)

Solve again with  $V_{BE} = 0.7 \text{ V}$

Will show  $V_{OUT} = 2.96 \text{ V}$  so difference is small

Note solution independent of  $J_s$  and  $A_E$

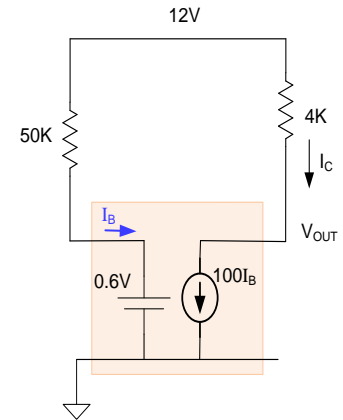
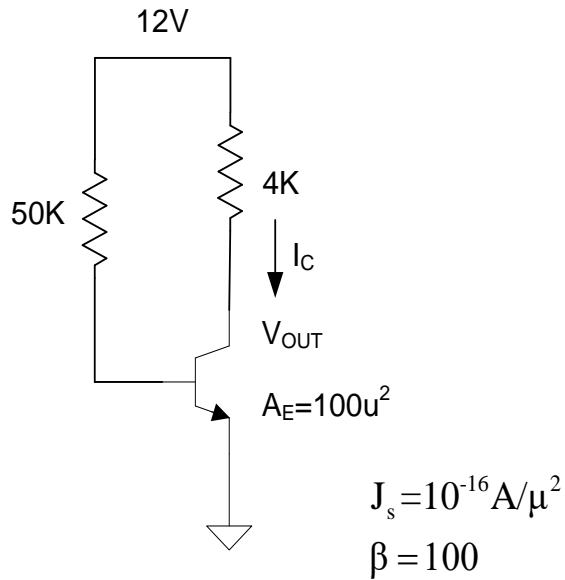
Example: Determine  $I_C$  and  $V_{OUT}$ ,



Example: Determine  $I_C$  and  $V_{OUT}$ .

Solution:

1. Guess Forward Active Region
2. Solve Circuit with Guess
3. Verify model (if necessary)



$$I_B = \frac{(12 - 0.6)}{50K}$$

$$I_C = \beta I_B = 100 \frac{(12 - 0.6)}{50K} = 22.8 \text{ mA}$$

$$V_{OUT} = 12 - I_C \cdot 4K = -79.2 \text{ V}$$

4. Verify FA Region  $V_{BE} > 0.4 \text{ V}$  and  $V_{BC} < 0$

$$V_{BE} = 0.6 \text{ V} > 0.4 \text{ V}$$

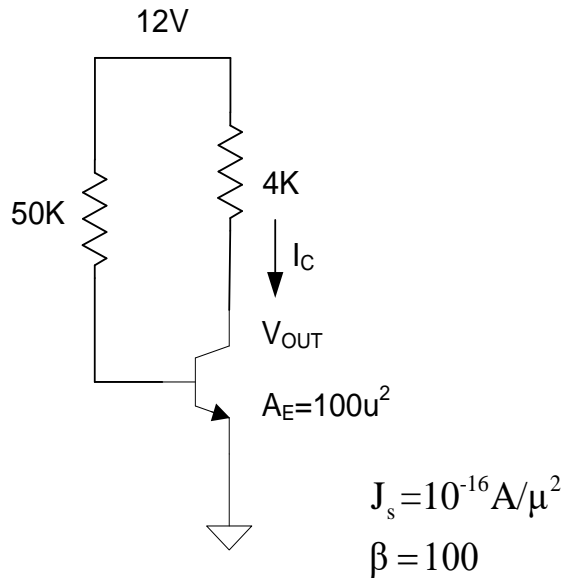
$$V_{BC} = 0.6 \text{ V} - (-79.2 \text{ V}) = +79.8 \text{ V} > 0$$

Verify Fails so solution is not valid

Example: Determine  $I_C$  and  $V_{OUT}$

Solution:

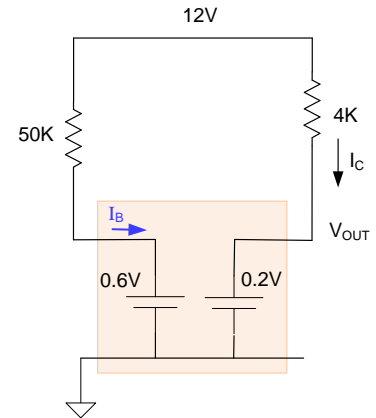
5. Guess Saturation
6. Solve Circuit with Guess
7. Verify model (if necessary)



$$I_B = \frac{(12 - 0.6)}{50K} = 228 \mu A$$

$$I_C = \frac{(12 - 0.2)}{4K} = 2.95 \text{ mA}$$

$$V_{OUT} = 0.2V$$



8. Verify SAT Region

$$I_C < \beta I_B$$

$$\beta I_B = 100 \cdot 228 \mu A = 22.8 \text{ mA}$$

$$I_C = 2.95 \text{ mA}$$

$$I_C = 2.95 \text{ mA} < \beta I_B = 22.8 \text{ mA}$$

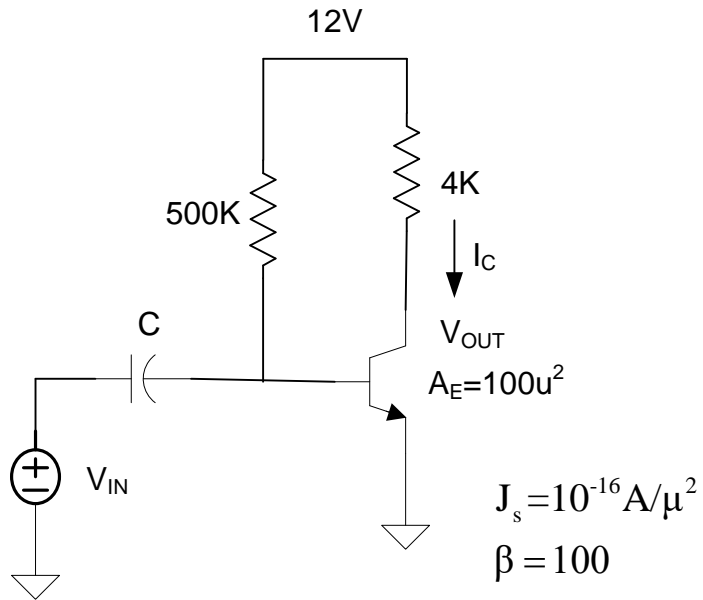
Verify SAT Passes so solution is valid

$$I_C = 2.95 \text{ mA} \quad V_{OUT} = 0.2V$$

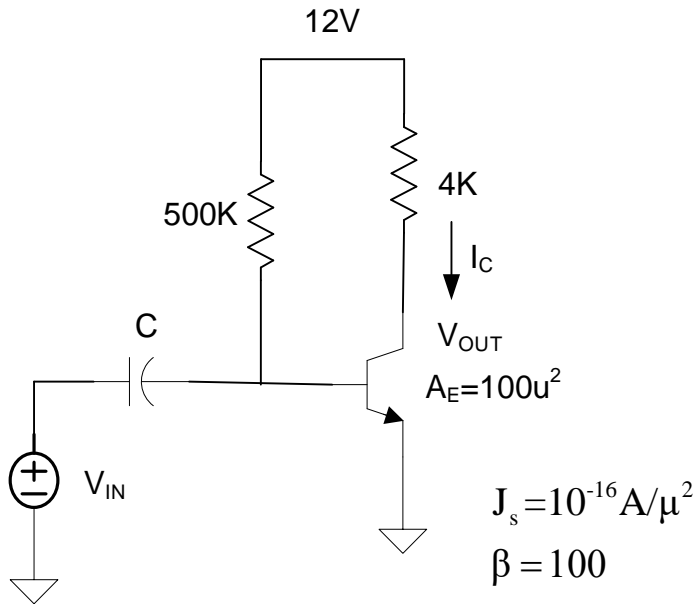
9. Verify model (if necessary)

(use  $V_{BE} = 0.7V$ , no change in output)

Example: Determine  $I_C$  and  $V_{OUT}$ . Assume  $C$  is large and  $V_{IN}$  is very small.



Example: Determine  $I_C$  and  $V_{OUT}$ . Assume  $C$  is large and  $V_{IN}$  is very small.



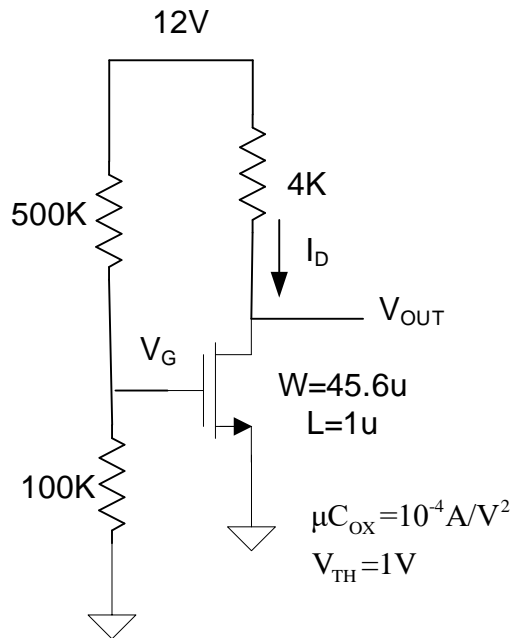
Solution:

Assume  $V_{IN} = 0$ , then no current flows through  $C$  so circuit is identical to circuit of previous-previous example so

$$I_C = 2.28 \text{ mA} \quad V_{OUT} = 2.88 \text{ V}$$

Note: If  $C$  is large and  $V_{IN}$  is small sinusoidal signal of sufficiently high frequency, the voltage across  $C$  will not change the input so  $V_{IN}$  is from an ac viewpoint coupled directly to base. In this case, the circuit will amplify  $V_{IN}$  and the gain will be very large due to the exponential relationship between  $I_C$  and  $V_{BE}$ .

Example: Determine  $I_D$  and  $V_{OUT}$



Solution:

Since  $I_G=0$ ,

$$V_G = \frac{100K}{600K} 12V = 2V$$

Guess Saturation Region for MOSFET

$$V_{GS} > V_{TH} \quad V_{DS} > V_{GS} - V_{TH}$$

$$I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_{TH})^2$$

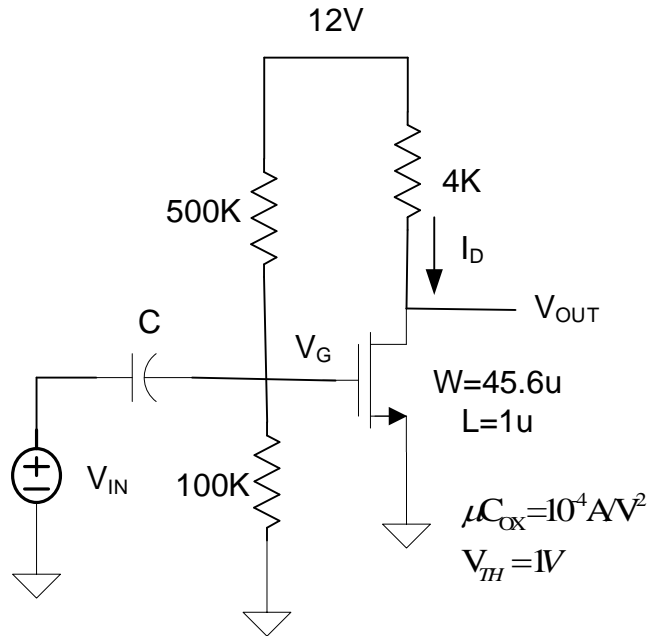
$$I_D = 10^{-4} \frac{45.6}{2} (2 - 1)^2 = 2.28mA$$

$$V_{OUT} = 2.88V$$

Verify saturation  $2V > 1V$   $2.88V > 2V - 1V$

Note: solution dependent upon  $W, L, V_{TH}$ , and  $\mu C_{ox}$

Example: Determine  $I_D$  and  $V_{OUT}$ . Assume C is large and  $V_{IN}$  is very small.



Solution:

Assume  $V_{IN}=0$ , then no current flows through C

$$V_G = \frac{100K}{600K} 12V = 2V$$

Guess Saturation Region for MOSFET

$$V_{GS} > V_{TH} \quad V_{DS} > V_{GS} - V_{TH}$$

$$I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_{TH})^2$$

$$I_D = 10^{-4} \frac{45.6}{2} (2 - 1)^2 = 2.28mA$$

$$V_{OUT} = 2.88V$$

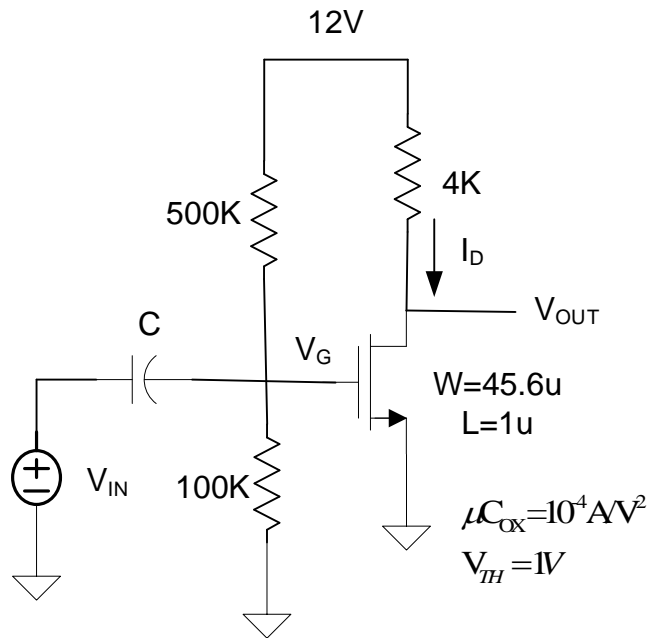
Verify saturation  $2V > 1V$   $2.88V > 2V - 1V$

Note: This circuit has the same current and same  $V_{OUT}$  as the previous circuit

Note: solution dependent upon  $W, L, V_{TH}$ , and  $\mu C_{ox}$



Example: Determine  $I_D$  and  $V_{OUT}$ . Assume  $C$  is large and  $V_{IN}$  is very small.



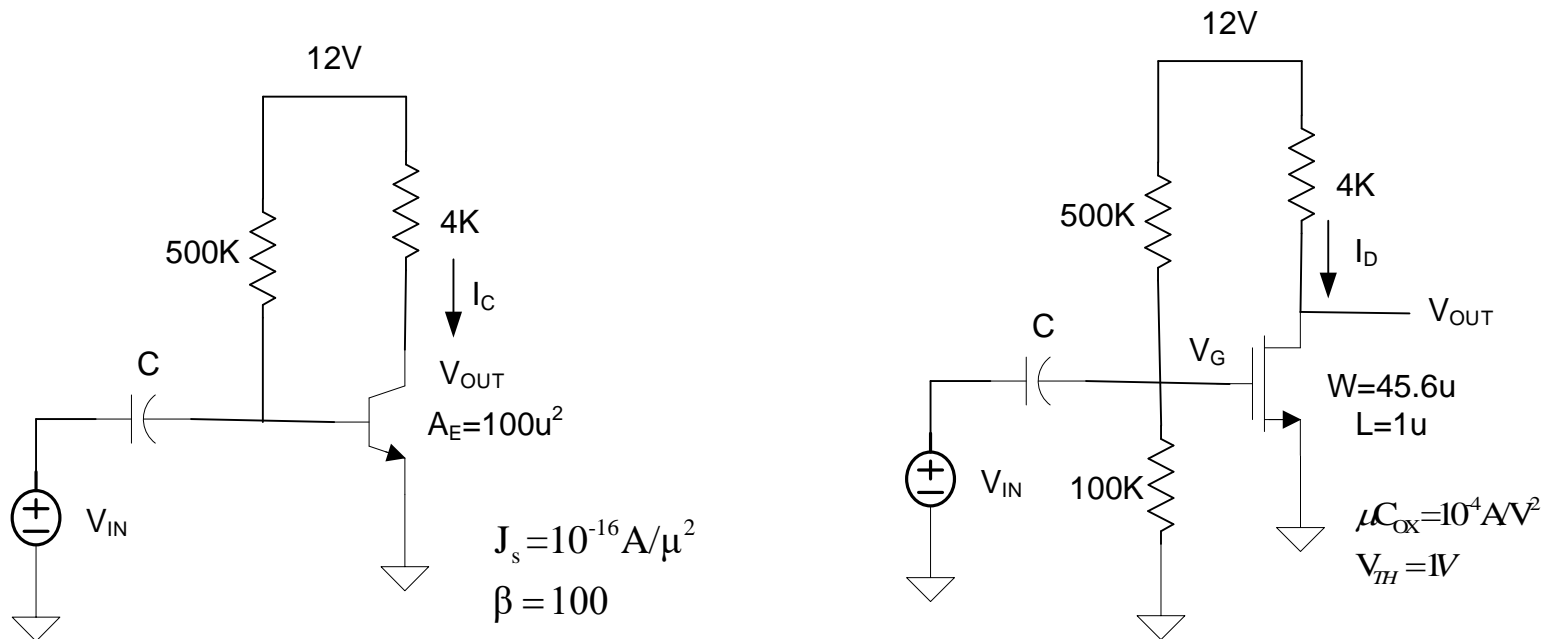
Solution:

Assume  $V_{IN}=0$ , then no current flows through  $C$  so circuit is identical to circuit of previous-previous example so

$$I_D = 2.28\text{mA} \quad V_{OUT} = 2.88\text{V}$$

Note: If  $C$  is large and  $V_{IN}$  is small sinusoidal signal of sufficiently high frequency, the voltage across  $C$  will not change so  $V_{IN}$  is from an ac viewpoint coupled directly to gate. In this case, the circuit will amplify  $V_{IN}$  and the gain will be large due to the square-law relationship between  $I_D$  and  $V_{GS}$ .

# Comparison



$$I_C = I_D = 2.28 \text{ mA} \quad V_{OUT} = 2.88 \text{ V}$$

- Both circuits can serve as amplifiers
- Architectures very similar
- MOS circuit dependent upon model parameters, BJT independent of model parameters
- Will be shown later that the bipolar circuit has larger gain because exponential vs square law relationship



Stay Safe and Stay Healthy !

End of Lecture 20