Transistors
FETs and BJTs

Ch. 12 and Ch. 13 of Allan R. Hambley's Book

Brief Summary

In this lecture we will

- **Learn about FETs and BJTs**
- **Understand the basic operation of field effect transistors (MOSFETs in particular).**
- **Understand operation of bipolar junction transistors in amplifier circuits.**
- **Analize bias circuits for BJTs.**
- **And more…**

Basics

- **Field effect transistors** (FETs) are used in amplifiers and logic gates. There are several types of FETs but to simplify our discussion, in this course, we will focus on enhance-mode **metal-oxide-semiconductor field effect transistor** (MOSFET)

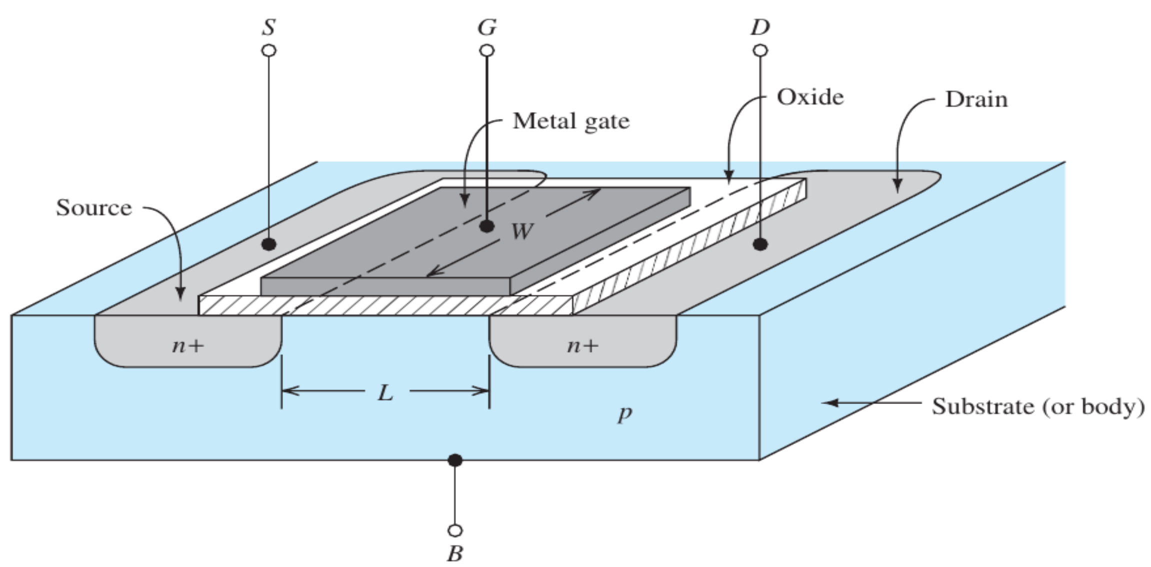
- Compared to BJTs, MOSFETs can occupy less chip area and can be fabricated with fewer processing steps. Therefore on most complex digital circuits, such as memories and microcontrollers, MOSFETs are commonly used.

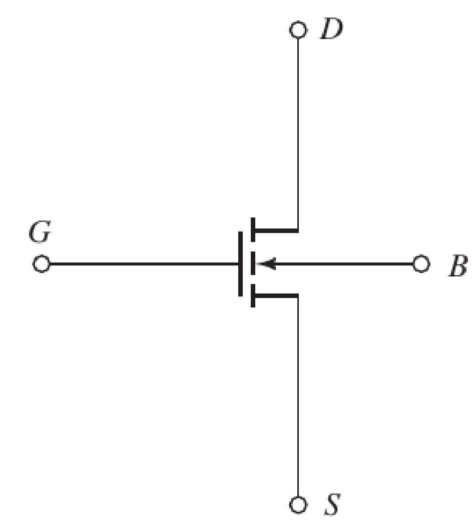
- On the other hand bipolar junction transistors are capable of producing large output currents that are needed for fast switching of a capacitive load

- Each type of device has some applications in which it performs better than the others

NMOS and PMOS transistors

- The figure illustrates the structure of an *n*-channel enhancement-mode MOSFET (also known as NMOS transistor). It is a chip of silicon crystal with impurities added to various regions to form *n*-type and *p*-type material.
- The device terminals are **drain** (D), **gate** (G), **source** (S) and **body** (B). In normal operation, negligible current flows through the body terminal. Sometimes the body is connected to the source so that we end up with a 3 terminal device.
- Drain current is controlled by the voltage applied to the gate.

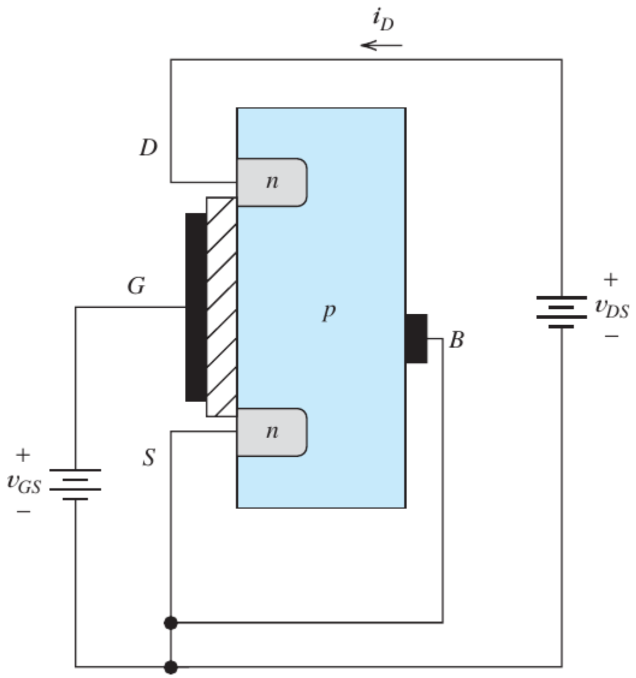


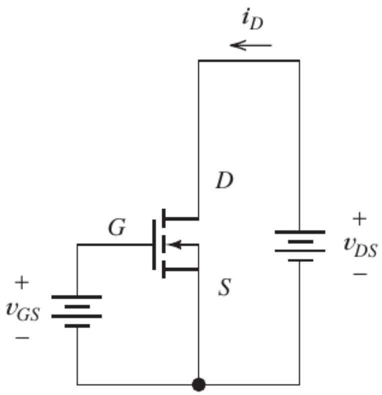


Operation modes of MOSFETs

Cutoff region

Consider a positive voltage v_{DS} is applied to the drain relative to the source and we start with v_{GS}=0. No current will flow into the drain terminal as the drain/body junction is reversed biased by the v_{DS} source. This region is called cutoff region. As v_{GS} increases the device will remain in cutoff until a threshold voltage is reached (we call this value V_{to})





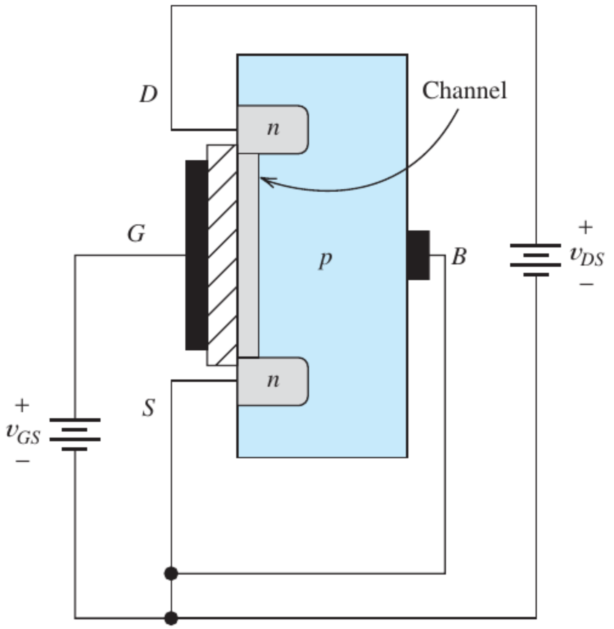
In cutoff we have

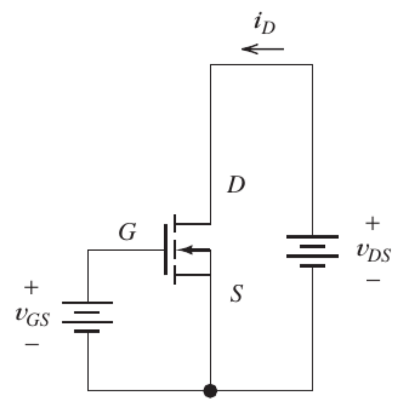
$$i_D = 0 \text{ for } v_{GS} \le V_{to}$$

Operation modes of MOSFETs

Triode Region

For $v_{DS} < v_{GS} - V_{to}$ and $v_{GS} \geq V_{to}$, we say the NMOS is operating in tripode region. The electric field resulting from the applied gate voltage has repelled holes from the region under the gate and electrons can easily flow from drain to source



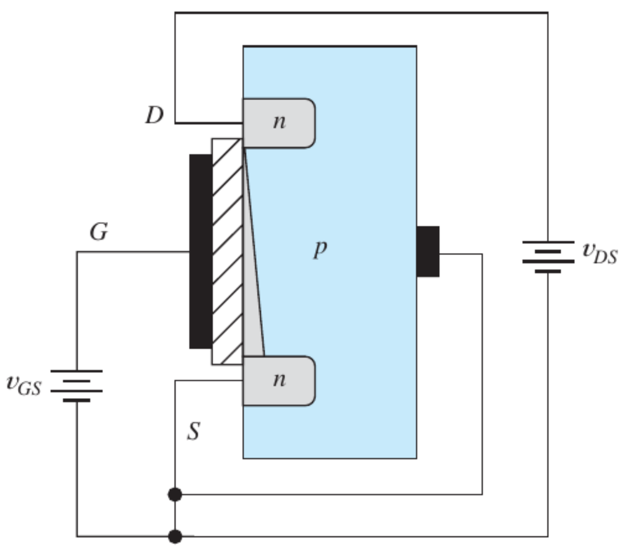


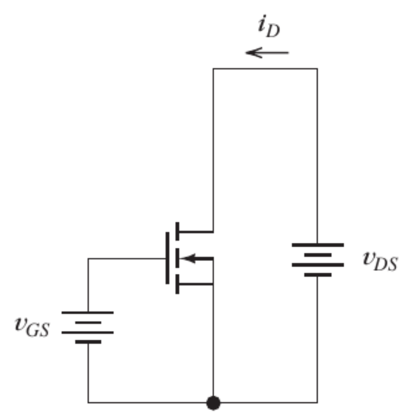
$$i_D = K\left[2(v_{GS} - V_{to})v_{DS} - v_{DS}^2\right]$$

Operation modes of MOSFETs

Saturation Region

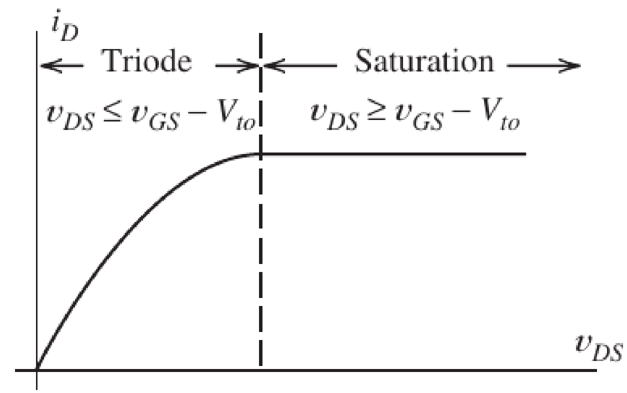
Now if increase v_{DS} the channel pinches down at the drain end and i_D increases more slowly. Finally, for $v_{DS} > v_{GS} - V_{to}$, i_D becomes constant. This is called saturation region



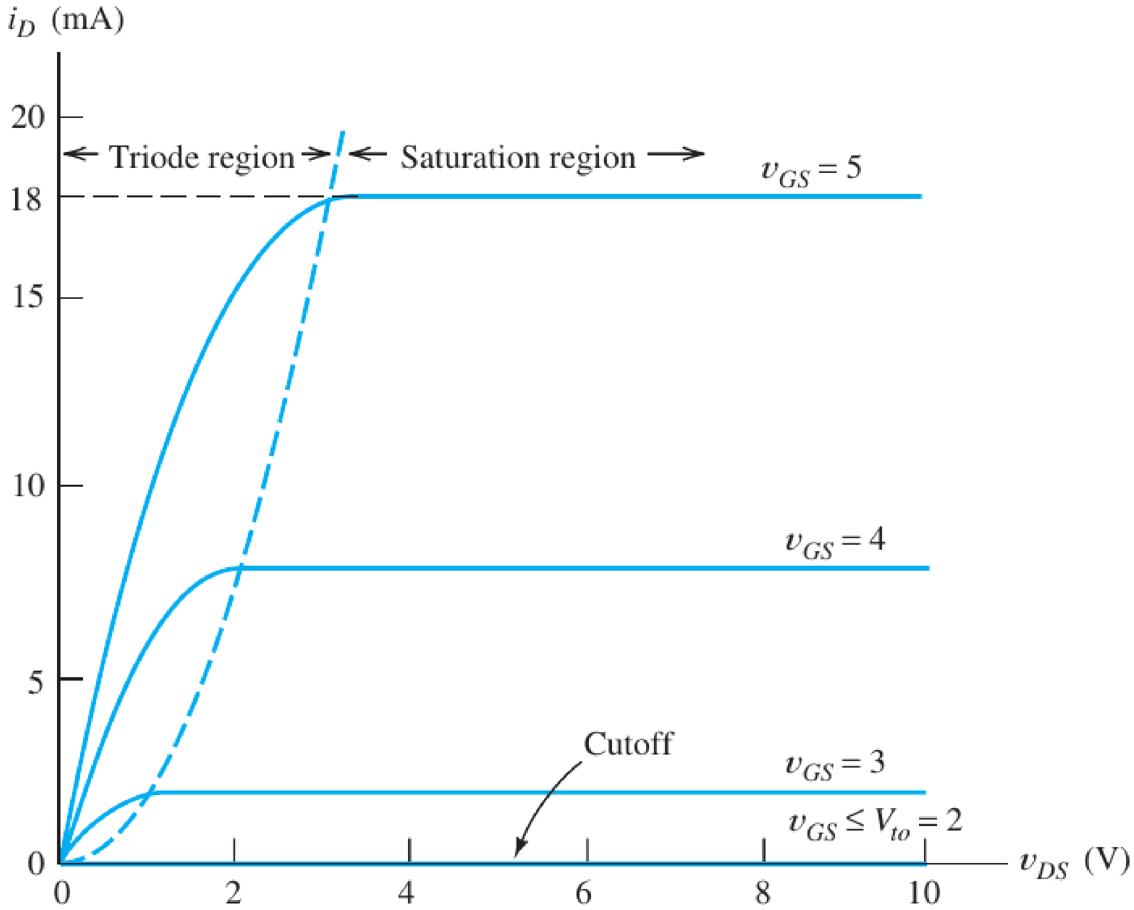


i_D behaviour

$$i_D = K(v_{GS} - V_{to})^2$$



Operation modes of MOSFETs

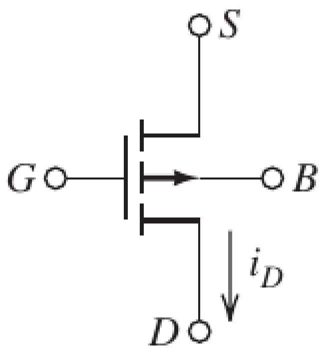


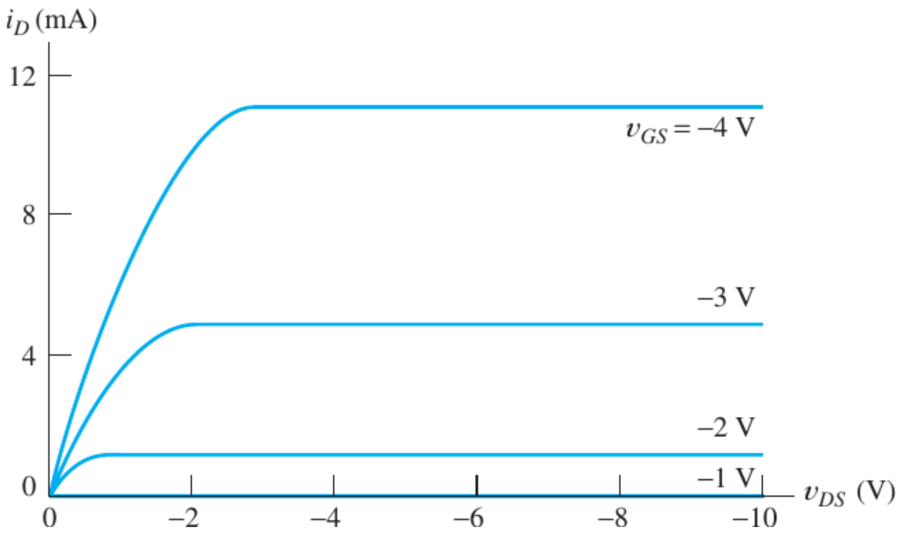
Characteristic curves for an NMOS transistor

PMOS transistors

MOSFETS can also be constructed by interchanging the *n* and *p* regions of n-channel devices, resulting p-channel devices (circuit representation is given below) PMOS symbol is same as NMOS symbol except for the orientation and the direction of the arrowhead.

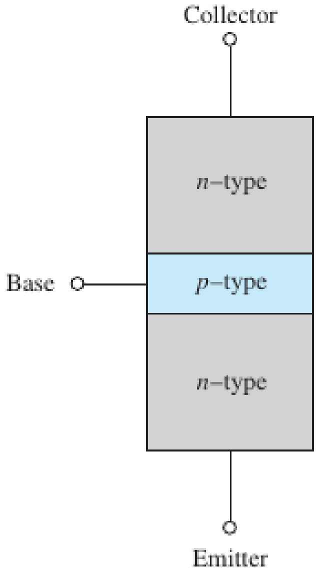
The characteristics of a PMOS transistor is very similar to that of an NMOS transistor except that the voltage polarities are inverted

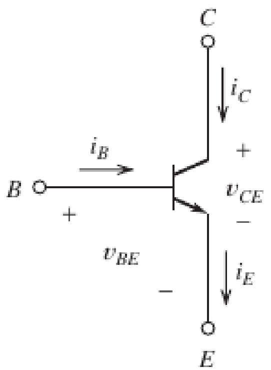




Bipolar Junction Transistors (BJTs)

- BJTs are constructed as layers of semiconductor materials doped with suitable impurities. Different types of impurities are used to create *n*-type and *p*-type semiconductors. In *n*-type material, conduction is due mainly to negatively charges electrons, whereas in *p*-type material conduction is due mainly to positively charges holes.
- An *npn* transistor consists of a layer of *p*-type material between 2 *n*-type materials. Each *pn* junction forms a diode. The three layers are called **base** (B), **emitter** (E) and **collector** (C).

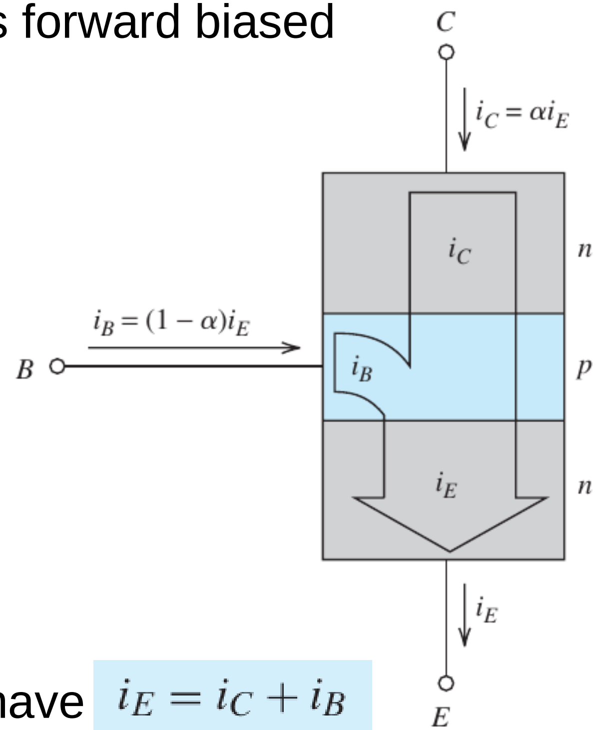




Operation modes of BJTs

Note that, a *pn* junction is **forward biased** by applying a positive voltage on the *p*-side, and **revered biased** if the positive polarity is applies to *n*-side

In **normal mode of operation** BJT is used as an amplifier, the base-collector junction is reverse biased and base emitter junction is forward biased



The Shockley equation gives the current I_E in terms of the base-emitter voltage v_{BE}

$$i_E = I_{ES}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$

where, the saturation current I_{ES} is in the range 10^{-12} to 10^{-16}, V_T is approximately 26mV at temperature of 300 K

Define $\alpha = \dfrac{i_C}{i_E}$ and from Kirchhoff's current law we have $i_E = i_C + i_B$

Solving for the base current we can obtain $\boxed{i_B = (1-\alpha) i_E}$

BJT in Active region

Using the definition of α. given previously we can define the ratio of collector current to the base current as

$$i_C = \beta i_B$$

Notice that

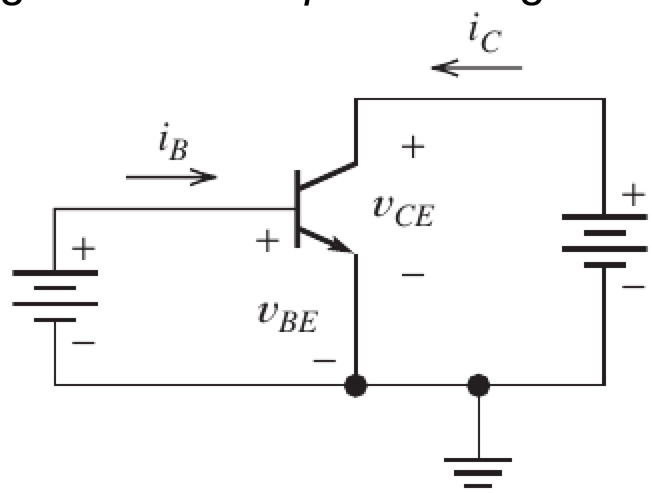
$$\beta = \frac{i_C}{i_B} = \frac{\alpha}{1-\alpha}$$

The value of α. is slightly less than unity (only a very small fraction of emitter current is supplied to the base) therefore the value of β ranges between 10 to 1000. A typical value is $\beta = 100$

That is : **the collector current is an amplified version of the base current**

Common-Emitter ch.

The common-emitter configuration of a *npn* BJT is given below.



The voltage between the base and emitter is positive enabling forward biasing of the base-emitter junction and the voltage supplied to the collector terminal produces a positive voltage at the collector with respect to the emitter
The voltage across the base-collector junction can be calculated as

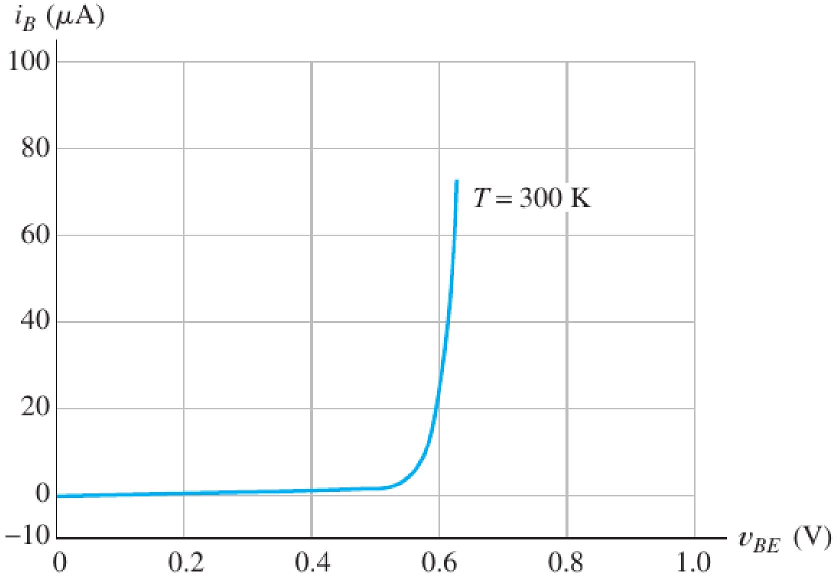
$$v_{BC} = v_{BE} - v_{CE}$$

Than when v_{CE} is greater than v_{BE} the base-collector voltage is negative (reverse bias)

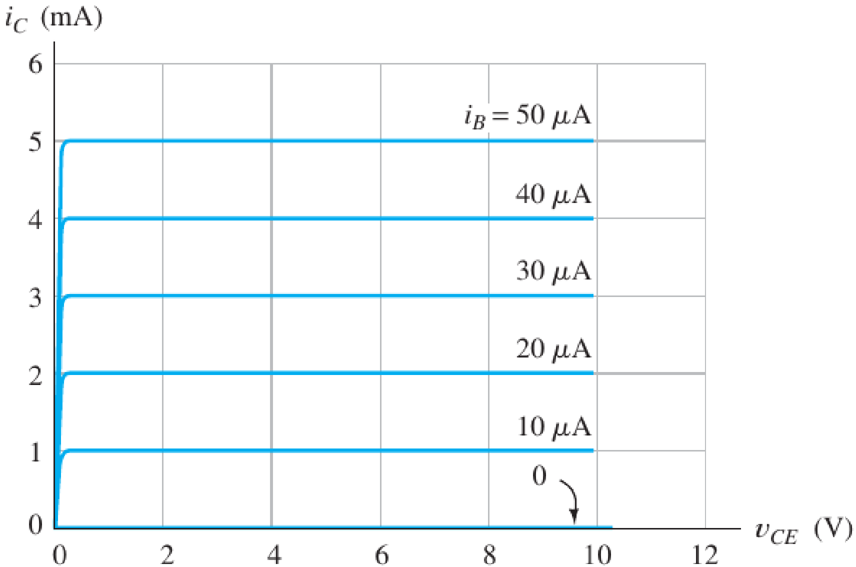
Common-Emitter ch.

A representative common-emitter characteristics of a BJT would be similar to the figures given below.

Notice that a small change in the base-emitter voltage can result in an appreciable change in the base current



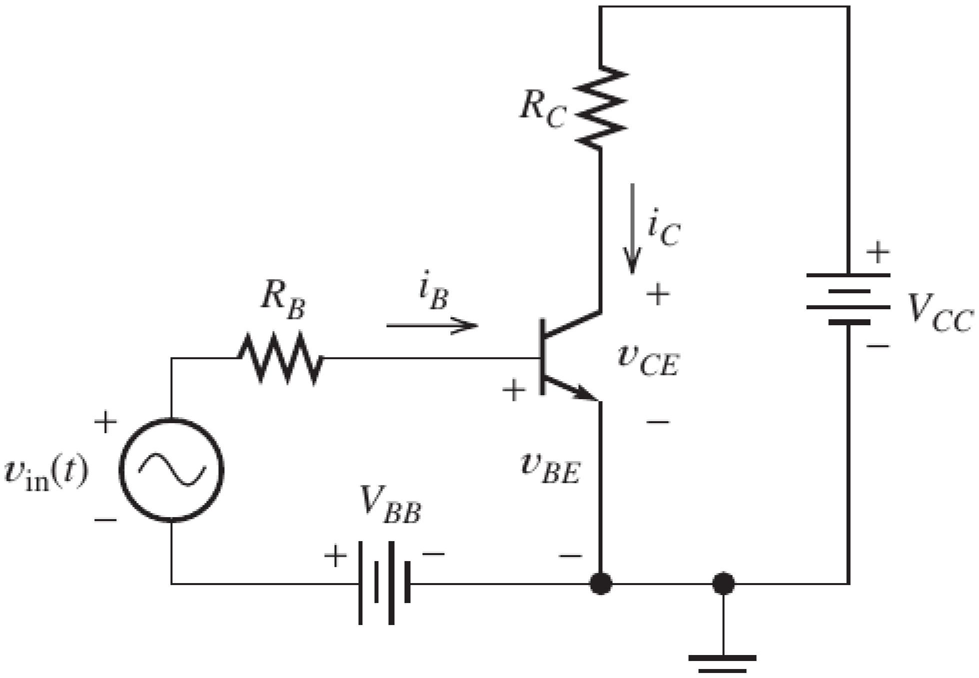
(a) Input characteristic



(b) Output characteristics

Example

For the circuitry given, analyze the input and output characteristics, find the operation point and comment on the type of the amplifier.

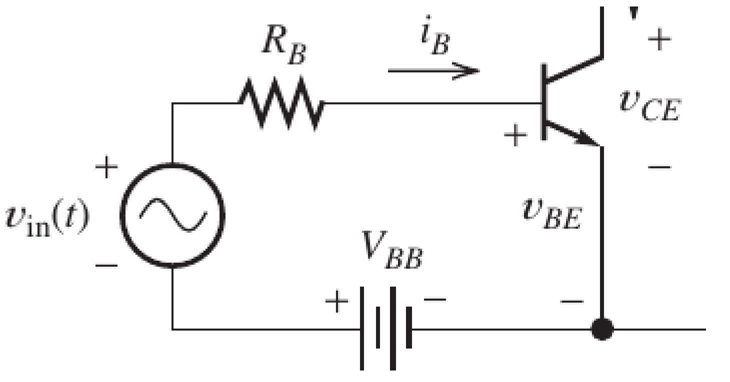


Example

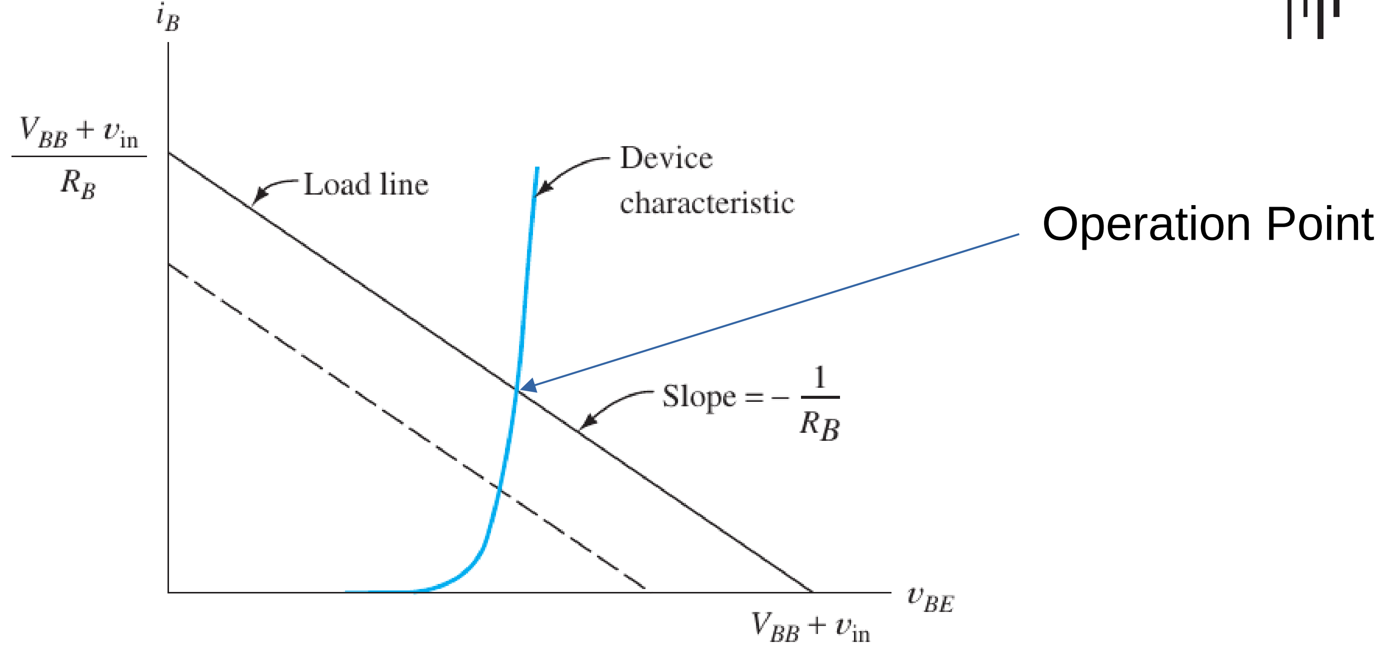
Input Circuitry

Using Kirchhoff's voltage law

$$V_{BB} + v_{\text{in}}(t) = R_B i_B(t) + v_{BE}(t)$$



Plot i_B versus v_{BE}



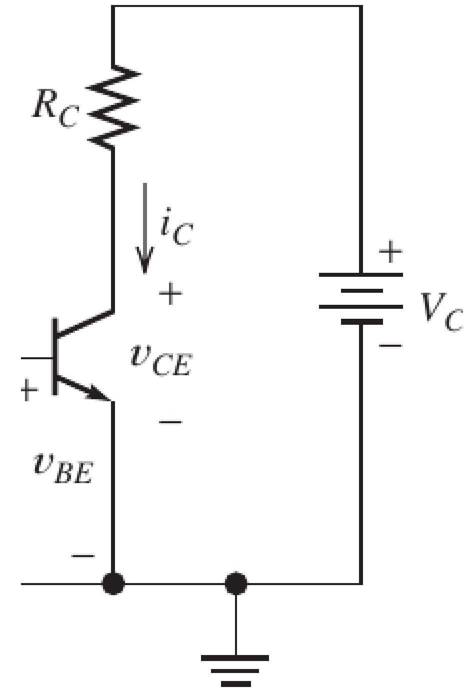
Example

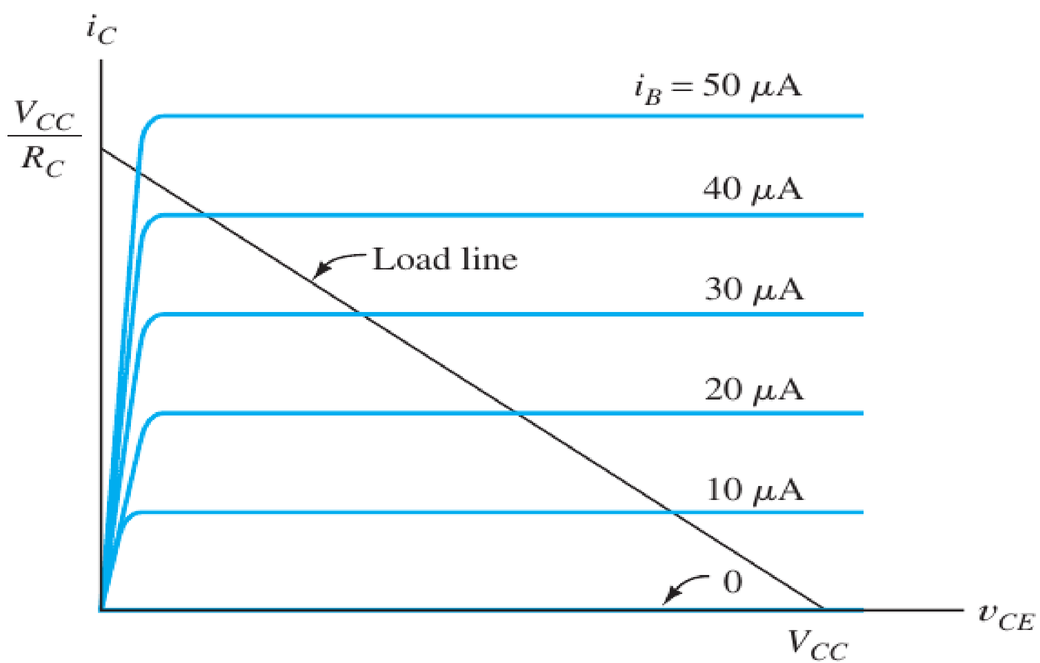
Output Circuitry

Using Kirchhoff's voltage law

$$V_{CC} = R_C i_C + v_{CE}$$

Plot i_C versus v_{CE}

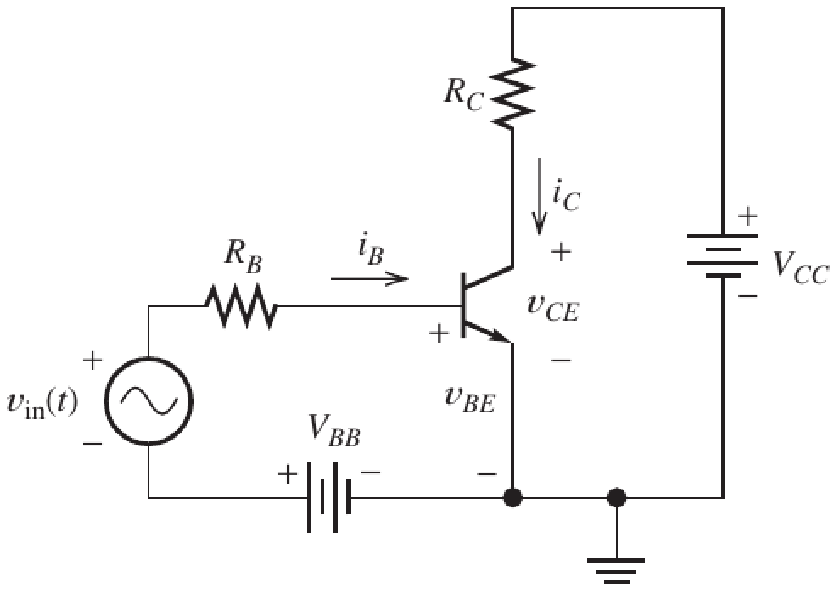




i_B should be inserted from the input circuitry load line

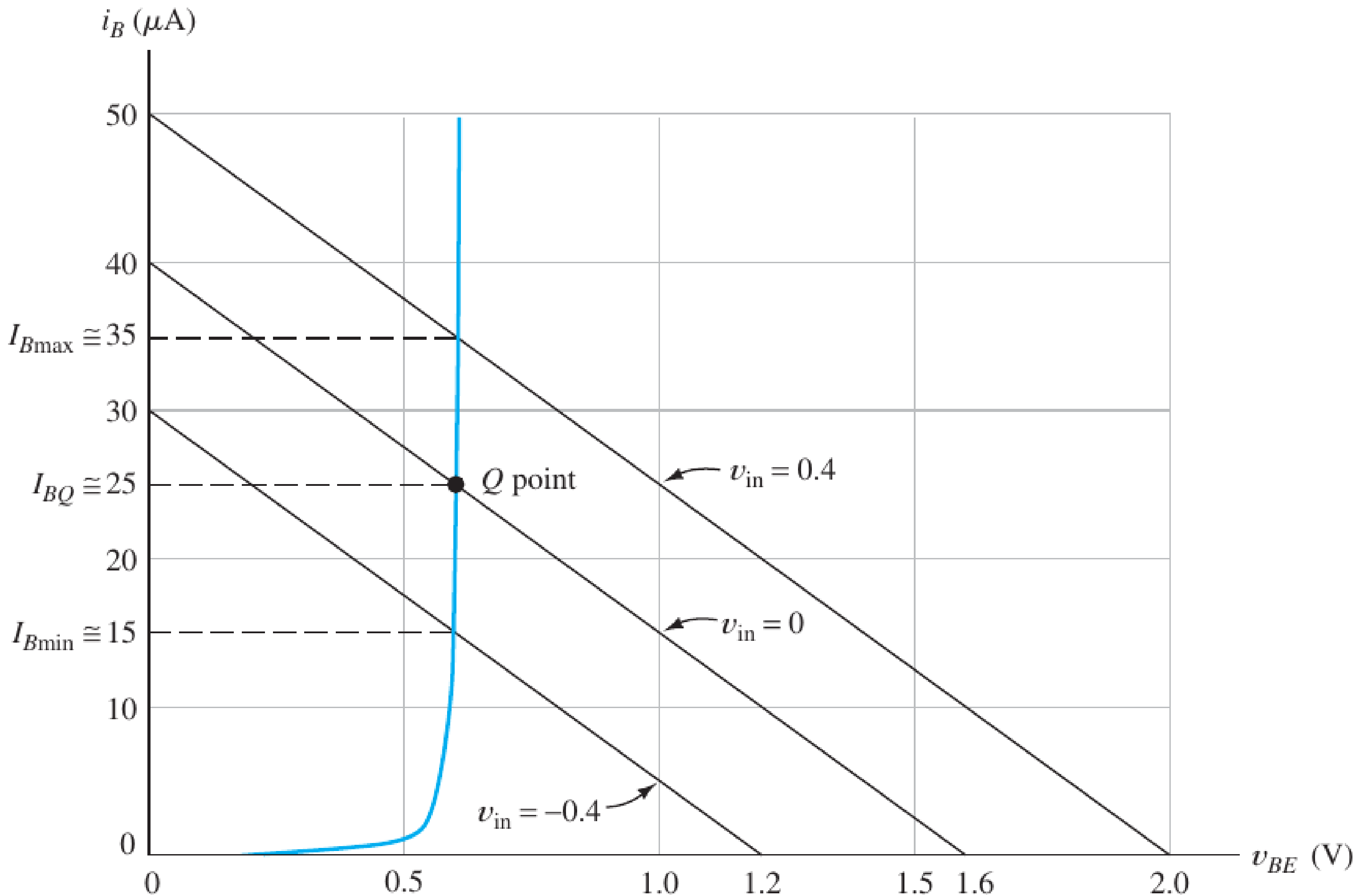
Numerical Example

For the circuit given below $V_{CC} = 10\text{ V}, V_{BB} = 1.6\text{ V}, R_B = 40\text{ k}\Omega,$ and $R_C = 2\text{ k}\Omega$. The input signal is $v_{\text{in}}(t) = 0.4\sin(2000\pi t)$



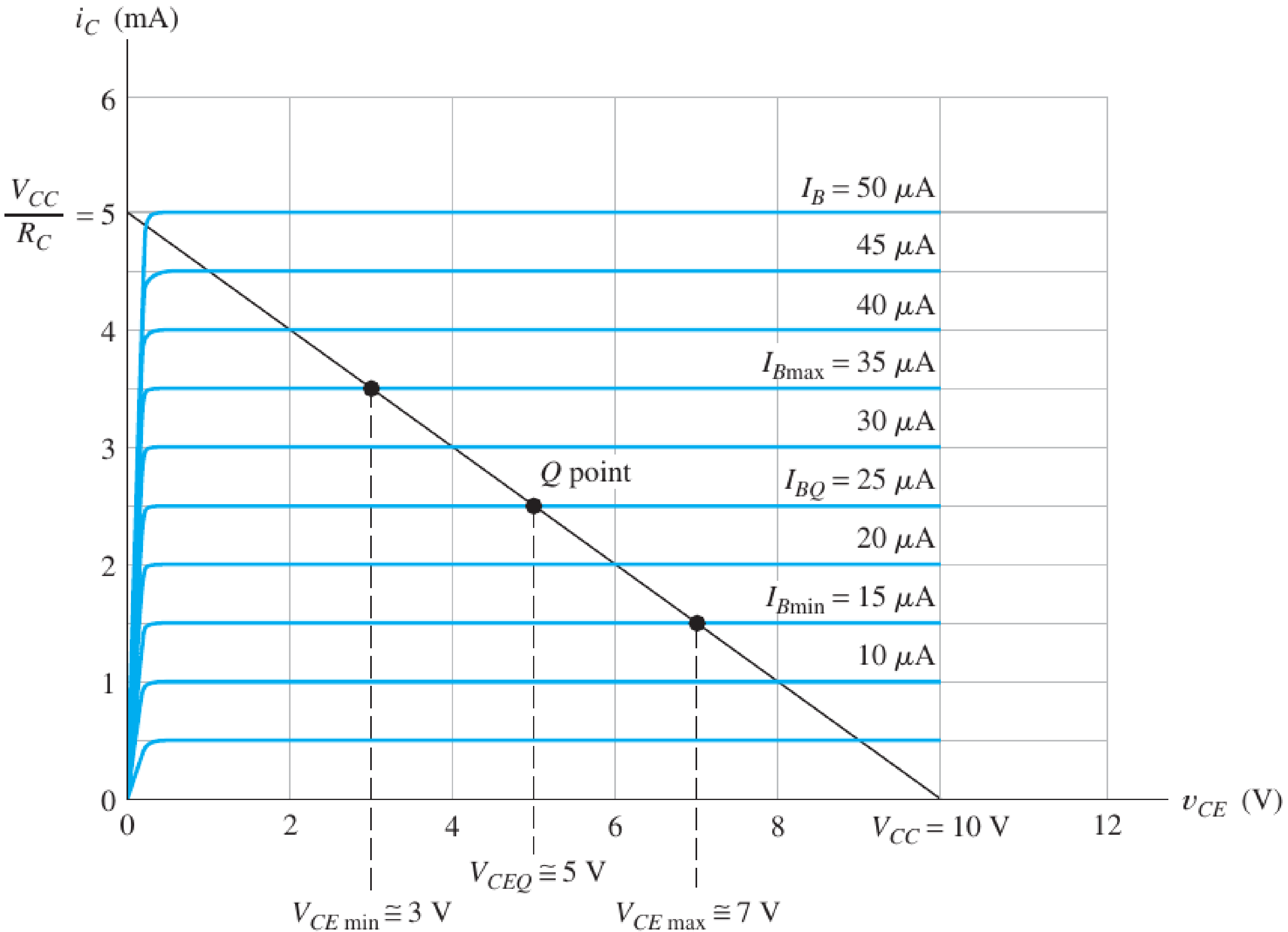
Plot the input and output characteristics. Find the minimum and maximum values of the for the base current and collector-emitter voltage.

Solution:

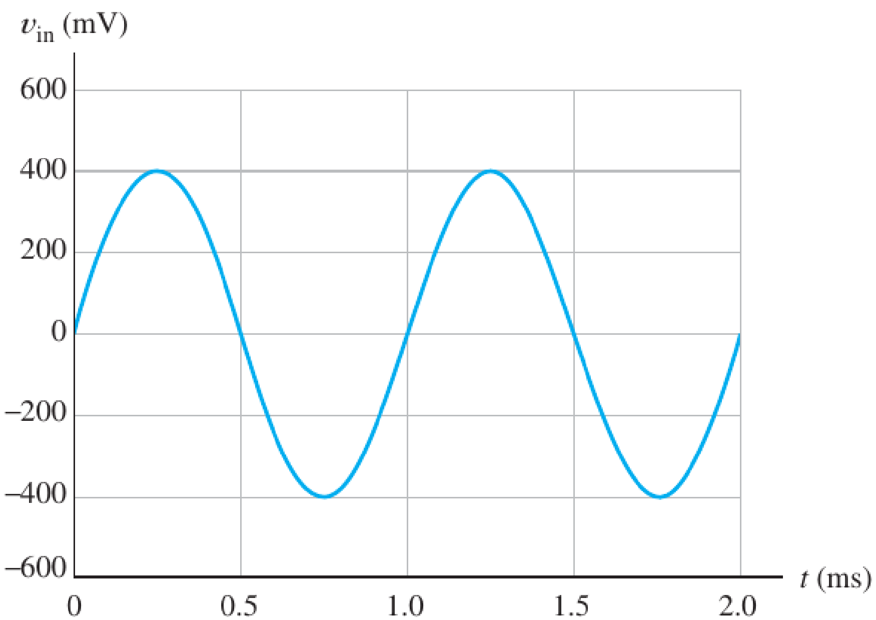


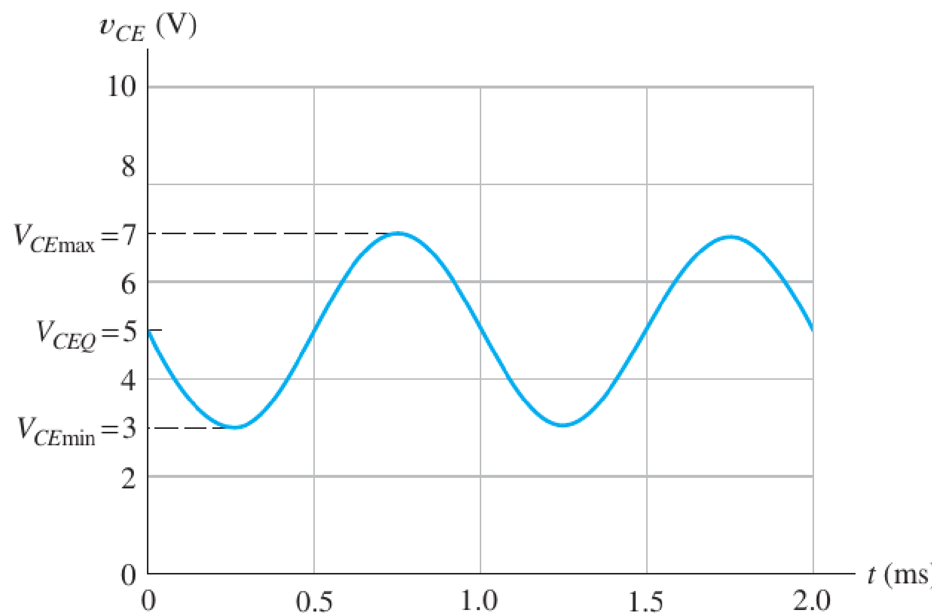
Input characteristics (we need the device plot !!!! use data sheet here)

Solution: Output



Solution: vin vs vout



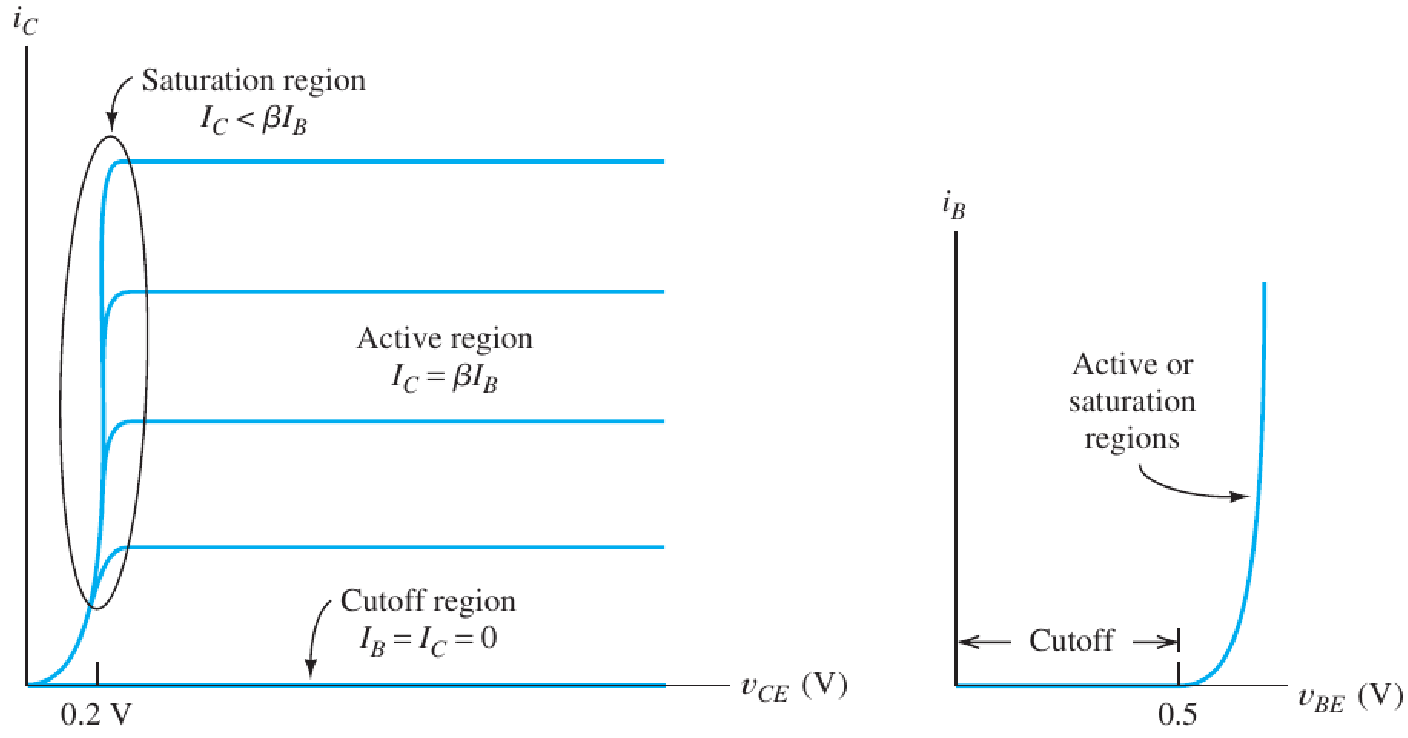


Inverting Amplifier !!!

Other modes ?

When the collector current becomes zero, the transistor will enter into **cut off** region

And When the collector-emitter voltage drops below a small value (semiconductor material dependent value, for example for silicon its below approximately 0.2V) the transistor will enter into saturation.



Example

(find the operation region of BJTs)

For a npn type BJT that has $\beta = 100.$ Determine the operation region for

1) $I_B = 50\,\mu\text{A}$ and $I_C = 3\,\text{mA}$

1) $V_{BE} = -2\text{V}$ and $V_{CE} = -1\,\text{V}.$

1) $I_B = 50\,\mu\text{A}$ and $V_{CE} = 5\text{V}$

Solution :
1) Since base current and collector current are positive device is either in the acitve Mode or in saturation mode : Check $\beta I_B > I_C$ (True) device is in **saturation**

2) We have $V_{BE} < 0$ and $V_{BC} = V_{BE} - V_{CE} = -1 < 0$ both junctions are reversed biased. Operation is in **cutoff** region.

3) As $I_B > 0$ and $V_{CE} > 0.2,$ transistor is in **active** region

Exercise

(find the operation region of BJTs)

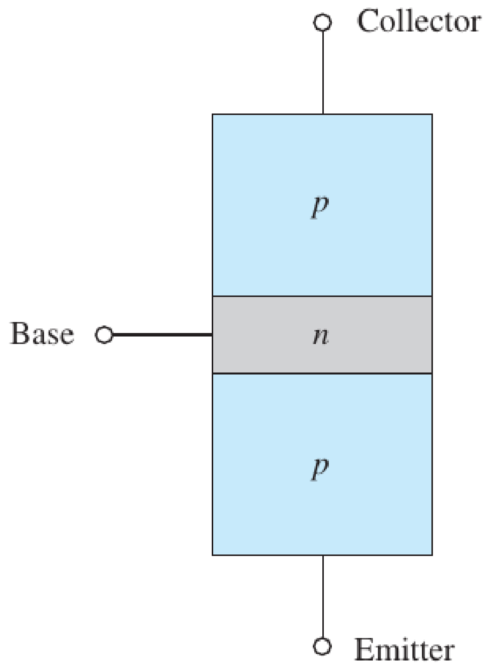
Exercise A certain *npn* transistor has $\beta = 100$. Determine the region of operation if **a.** $V_{BE} = -0.2\,\text{V}$ and $V_{CE} = 5\,\text{V}$; **b.** $I_B = 50\,\mu\text{A}$ and $I_C = 2\,\text{mA}$; **c.** $V_{CE} = 5\,\text{V}$ and $I_B = 50\,\mu\text{A}$.

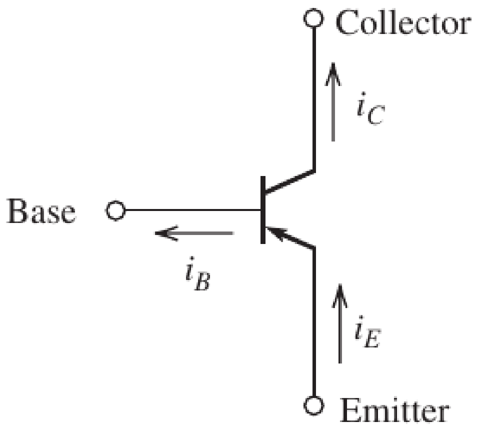
Answer **a.** cutoff; **b.** saturation; **c.** active.

pnp BJT

So far we have only considered *npn* BJTs. An equivalently useful device results if the base is a layer of *n*-type material between *p*-type emitter and collector regions.

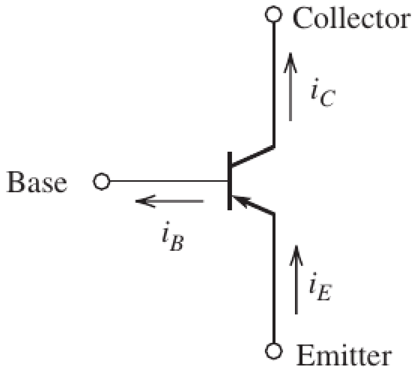
For proper operation as an amplifier the polarities of the dc voltages applied to the *pnp* device must be opposite to those of *npn* device





pnp BJT

For the *pnp* transistor similar equations for terminal currents can be obtained.



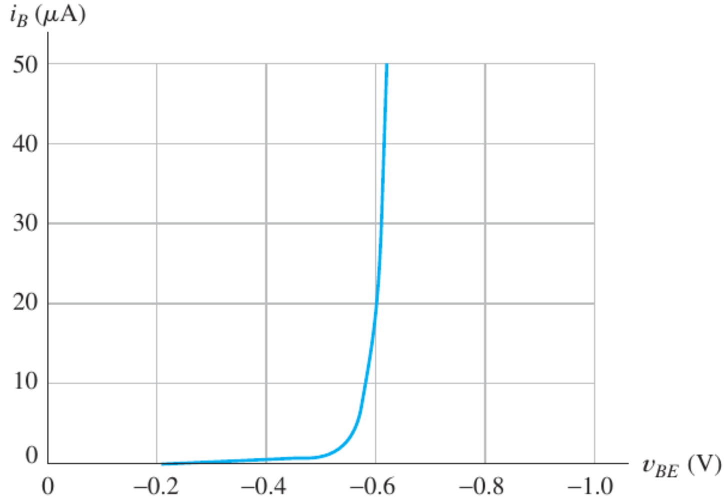
$$i_C = \alpha i_E$$

$$i_B = (1-\alpha) i_E$$

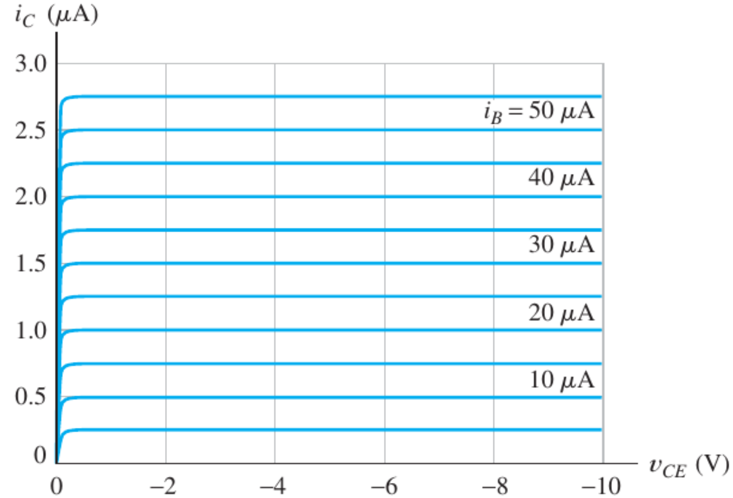
$$i_C = \beta i_B$$

$$i_E = i_C + i_B$$

The common emitter characteristics are also similar (note the sign on the x-axis)



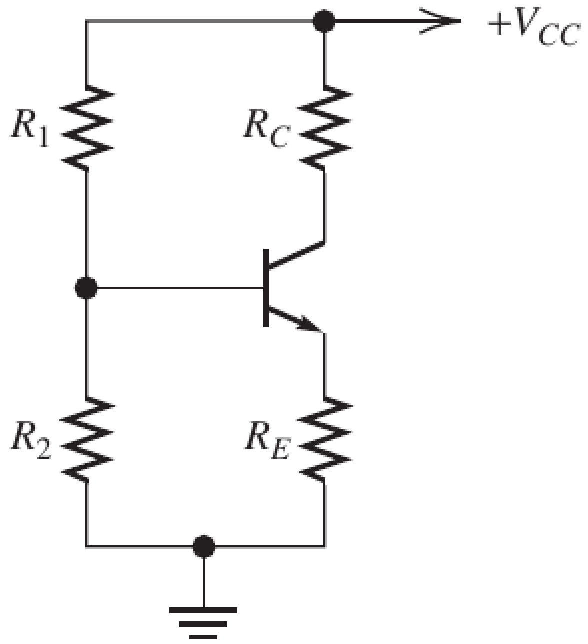
(a) Input



(b) Output

Bias Circuits (4 resistor example)

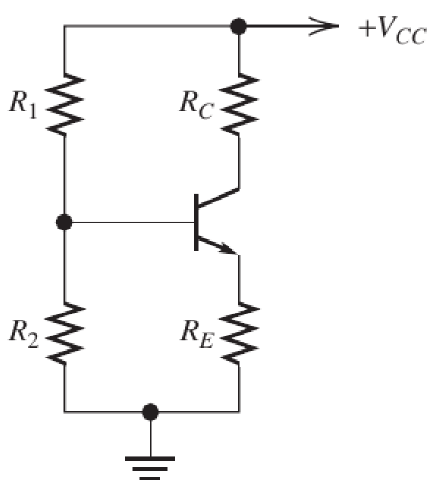
A commonly used bias circuit for BJT transistors is the 4-resistor bias circuit given in the figure



Notice that R1 and R2 form a voltage divider, intended to provide a constant base voltage resulting a constant collector current and collector to emitter voltage

Bias Circuits (4 resistor example)

To ease the analysis this circuit apply the following conversion



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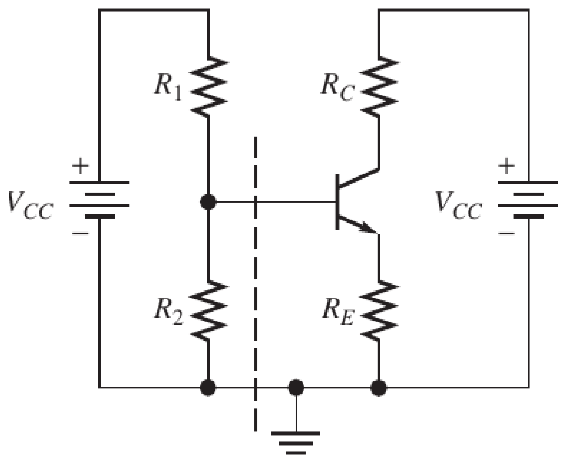
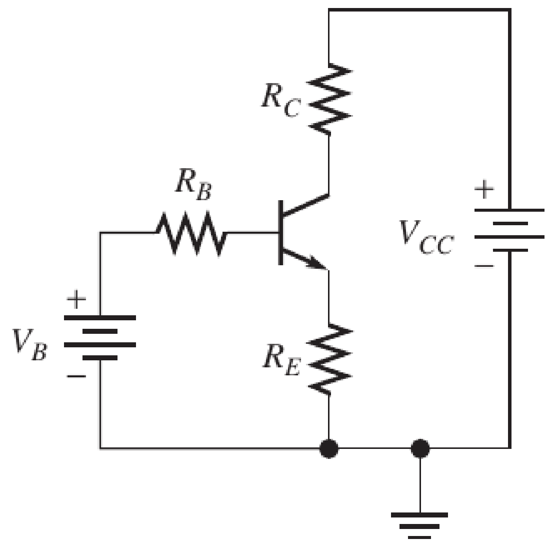


Two source equivalent

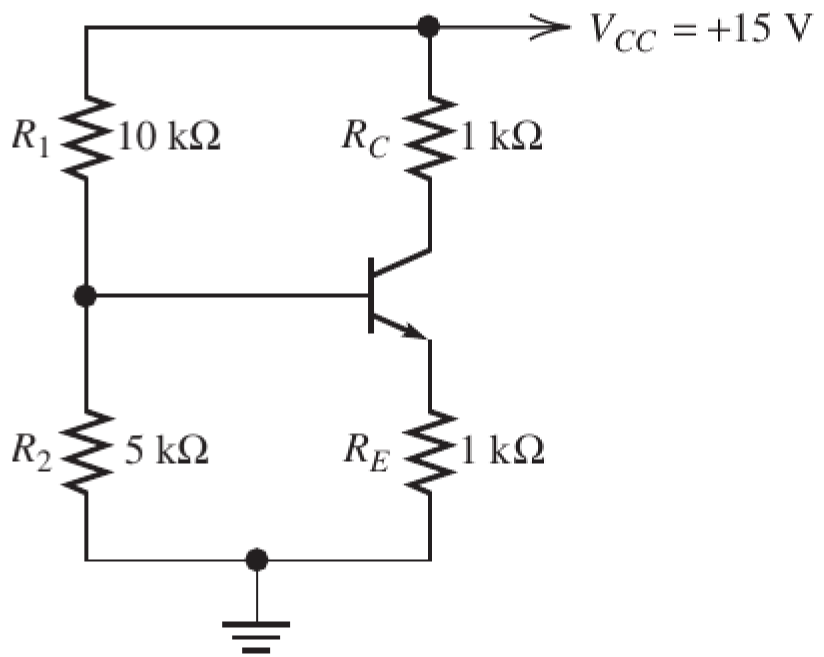


Thevenin equivalent
of the input side

Notice that $R_B = \dfrac{1}{1/R_1 + 1/R_2} = R_1||R_2$ and $V_B = V_{CC}\dfrac{R_2}{R_1 + R_2}$

Exercise

For the circuit given, find the values of I_C and V_{CE} for $\beta = 100$
Assume that $V_{BE} = 0.7$ V.



Exercise cont.

Solution :

Use the equivalent circuit. Need the resistance and voltage values

$$R_B = \frac{1}{1/R_1 + 1/R_2} = 3.33\ \text{k}\Omega$$

$$V_B = V_{CC}\frac{R_2}{R_1 + R_2} = 5\ \text{V}$$

Note that the base to emitter loop will give us

$$V_B = R_B I_B + V_{BE} + R_E I_E \quad \text{with} \quad I_E = (\beta + 1)\, I_B$$

Therefore

$$I_B = \frac{V_B - V_{BE}}{R_B + (\beta + 1) R_E} = 41.2\ \mu\text{A}$$

Now we can calculate collector current using $I_C = \beta I_B$ and emitter current using $I_E = I_C + I_B$.

Finally the collector emiter voltage can be obtained using $V_{CE} = V_{CC} - R_C I_C - R_E I_E$

Exercise

Find the β value for the transistor given in the figure