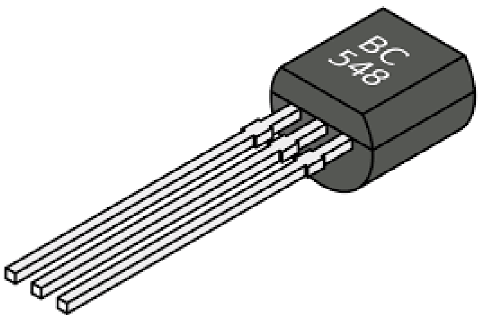
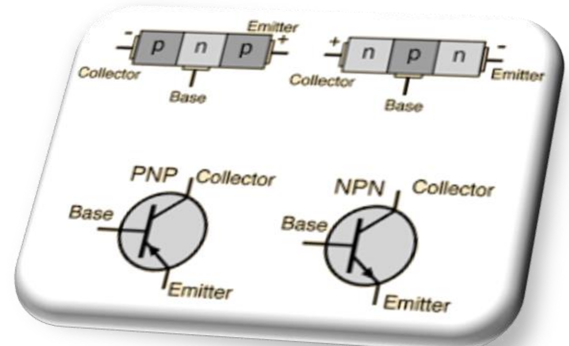
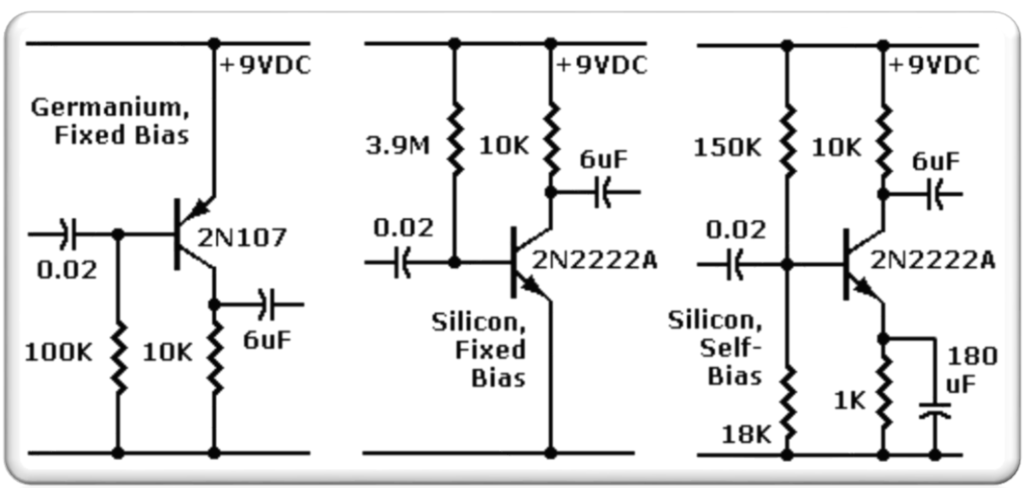
BJT Transistors







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

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

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

Note: For the *pnp* transistor, replace v_{BE} with v_{EB}.

$$i_C = \alpha i_E \qquad i_B = (1-\alpha) i_E = \frac{i_E}{\beta+1}$$

$$i_C = \beta i_B \qquad i_E = (\beta+1) i_B$$

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

$$V_T = \text{thermal voltage} = \frac{kT}{q} \simeq 25\ \text{mV} \text{ at room temperature}$$

First - BJTs

The transistor was probably the most important invention of the 20th Century, and the story behind the invention is one of clashing egos and top secret research.

Reference:
Bell Labs Museum
B. G. Streetman & S. Banerjee 'Solid State Electronic Devices', Prentice Hall 1999.

Interesting story…

Picture shows the workbench of John Bardeen (Stocker Professor at OU) and Walter Brattain at Bell Laboratories. They were supposed to be doing fundamental research about crystal surfaces.

The experimental results hadn't been very good, though, and there's a rumor that their boss, William Shockley, came near to canceling the project. But in 1947, working alone, they switched to using tremendously pure materials.

It dawned on them that they could build the circuit in the picture. It was a working amplifier! John and Walter submitted a patent for the first working **point contact transistor**.

Interesting story...

Shockley was furious and took their work and invented the **junction transistor** and submitted a patent for it 9 days later. The three shared a **Nobel Prize in 1955**. Bardeen and Brattain continued in research (and Bardeen later won another Nobel).

Shockley quit to start a semiconductor company in Palo Alto. It folded, but its staff went on to invent the integrated circuit (the "chip") and to found **Intel Corporation**.

By 1960, all important computers used transistors for logic, and ferrite cores for memory.

Point-Contact Transistor – first transistor ever made

The first transistor was a point-contact transistor

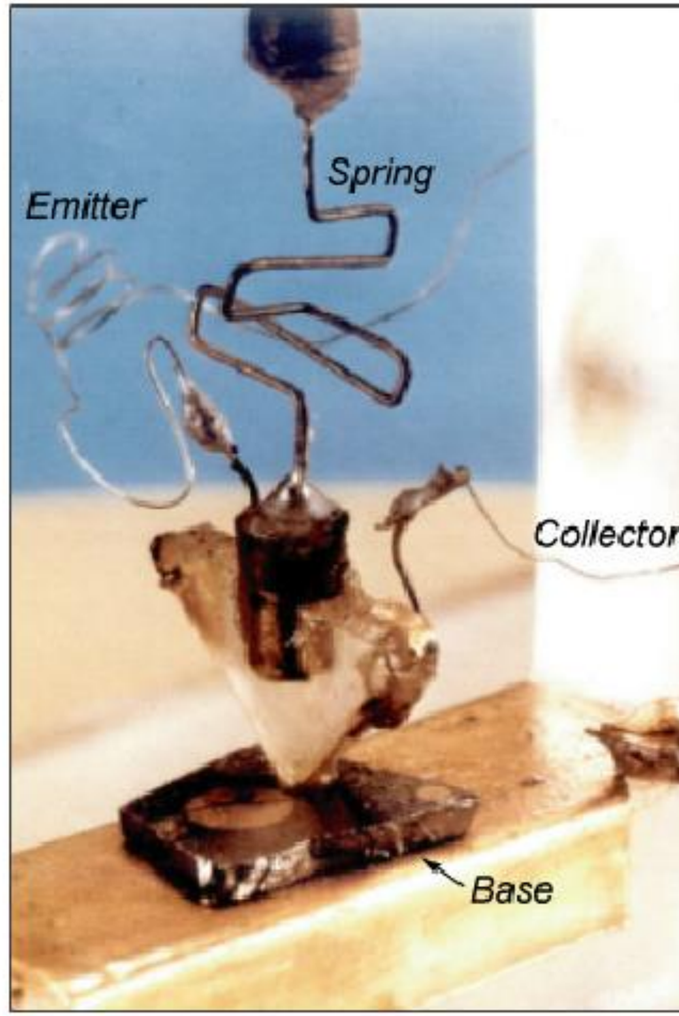
The first point-contact transistor

John Bardeen, Walter Brattain, and William Shockley

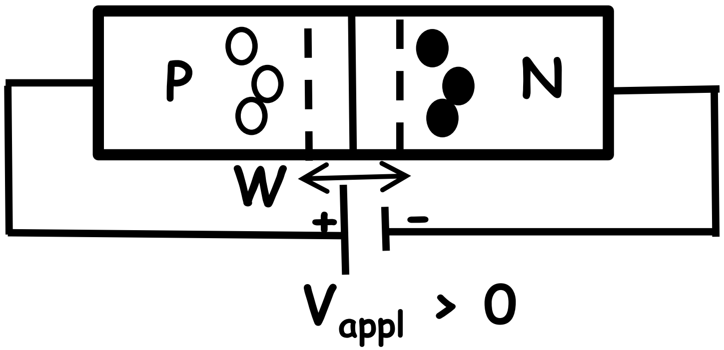
Bell Laboratories, Murray Hill, New Jersey (1947)

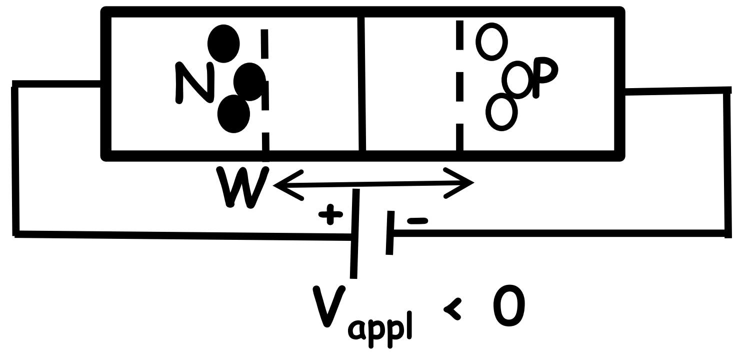
Bardeen *Brattain*

Shockley



Recall p-n junction



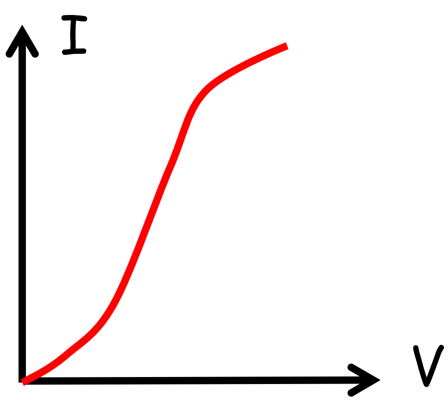


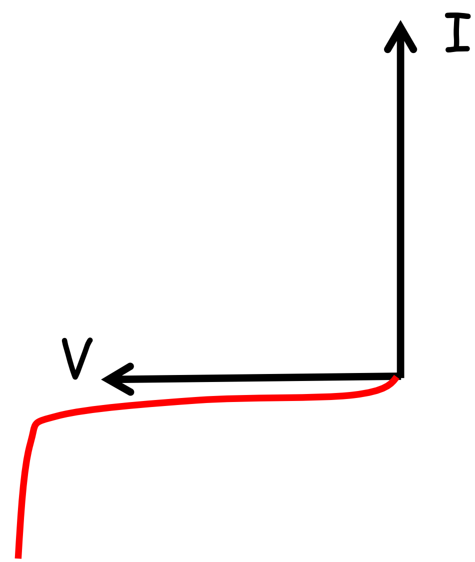
Forward bias, + on P, - on N
(Shrink, V_{bi})

Allow holes to jump over barrier
into N region.

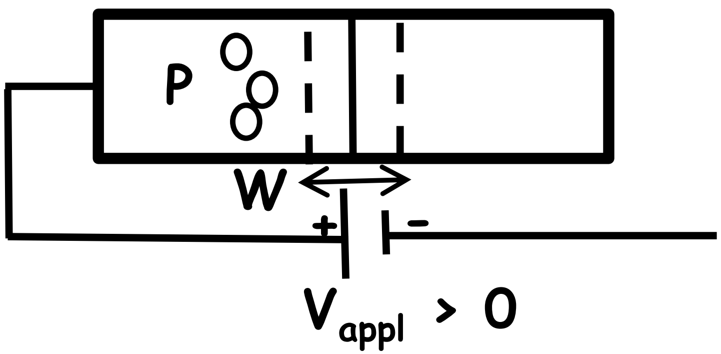
Reverse bias, + on N, - on P
(Expand, V_{bi})

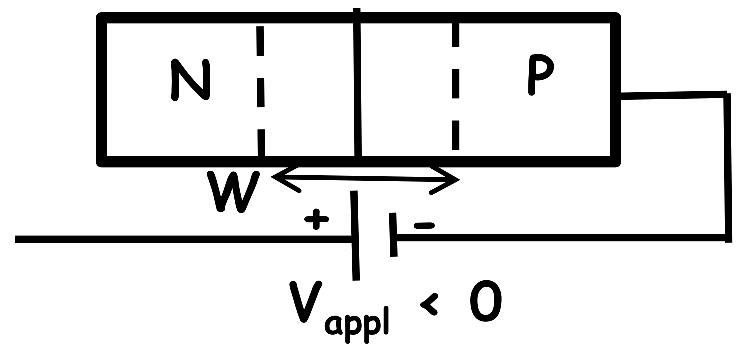
Remove holes and electrons away
from depletion region





So if we combine these by fusing their terminals…

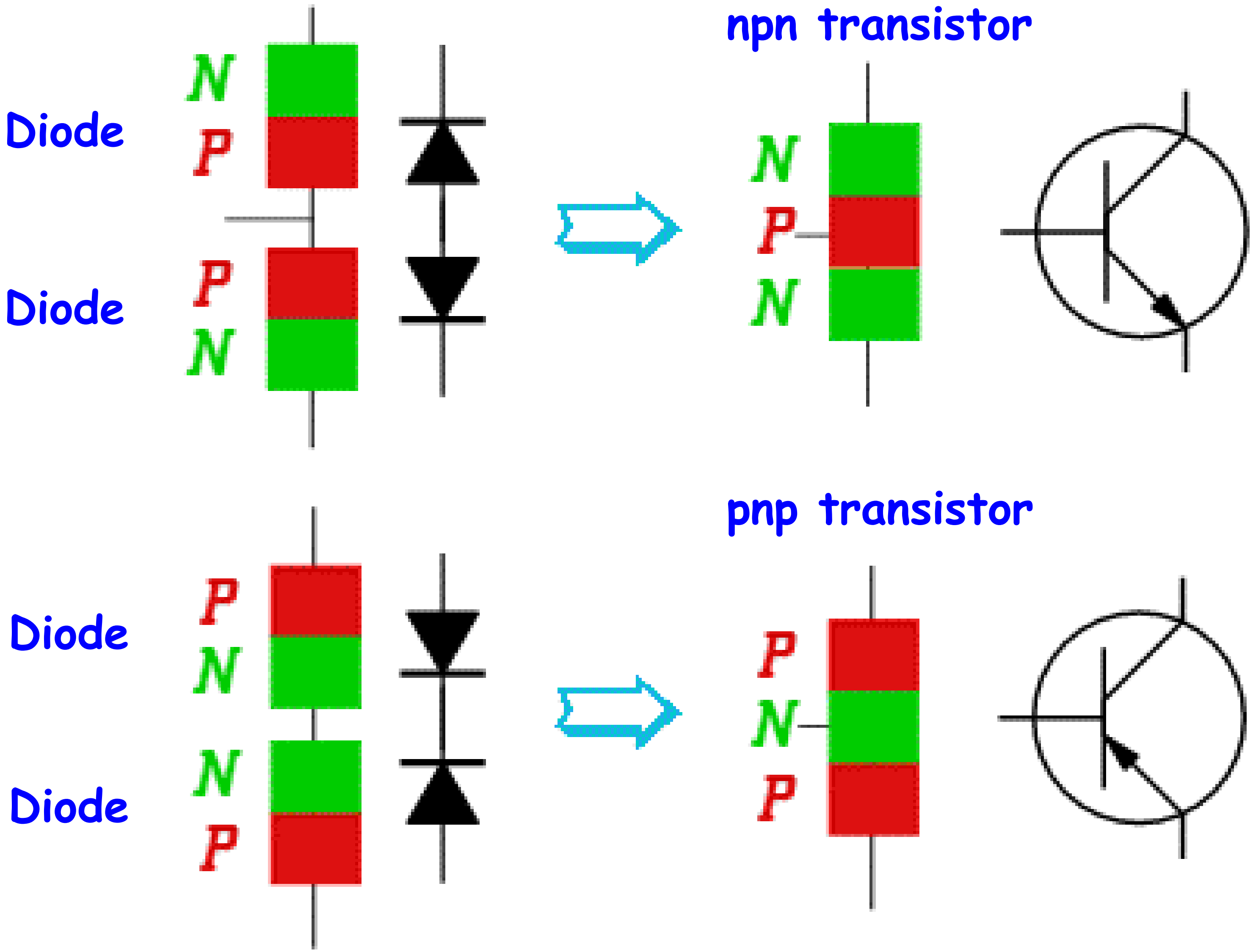




Holes from P region ("Emitter") of 1st PN junction are driven by Forward Bias of 1st PN junction into central N region ("Base")

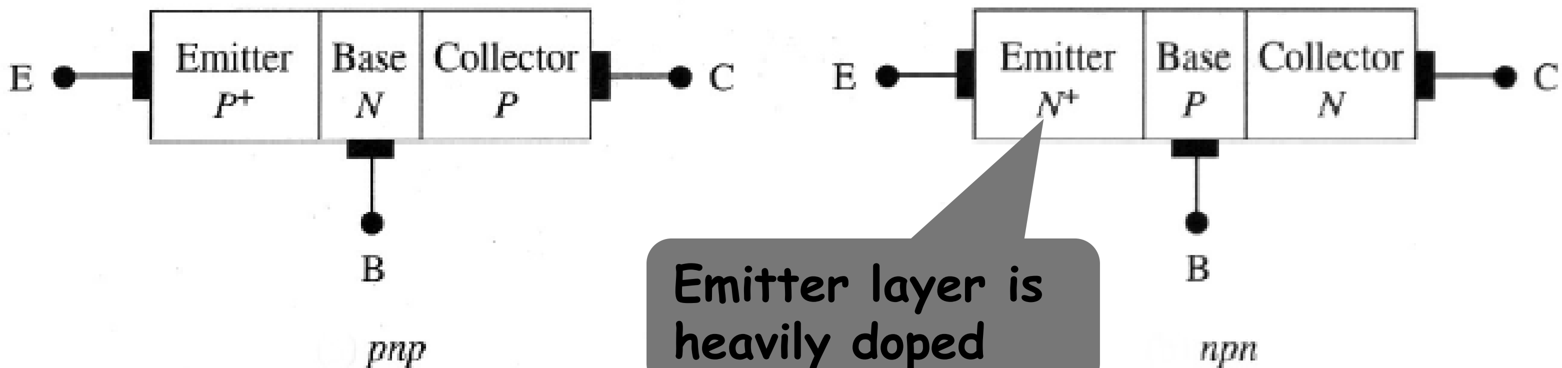
Driven by Reverse Bias of 2nd PN junction from Base into P region of 2nd junction ("Collector")

Basic models of BJT

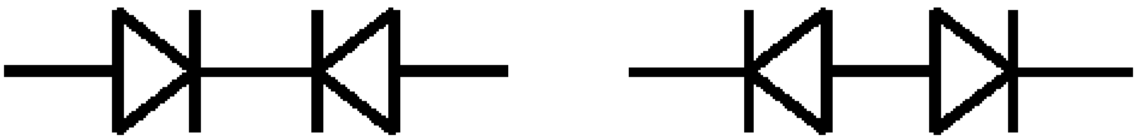


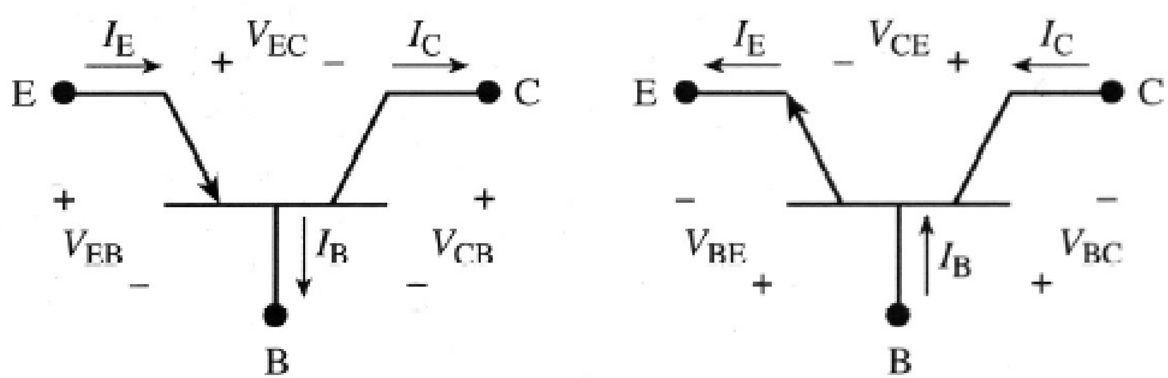
Basic models of BJT

Bipolar Junction Transistor Fundamentals

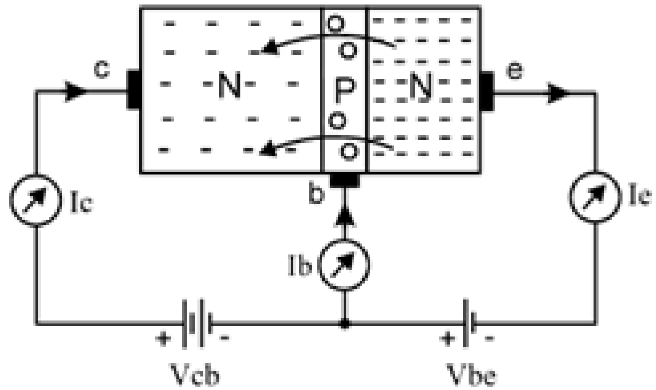


Looks sort of like two diodes back to back



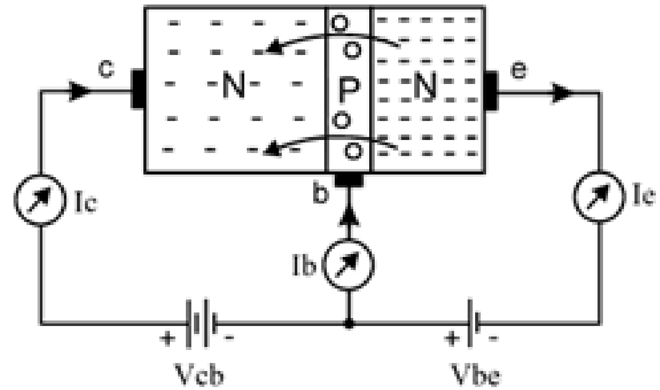


npn BJTs



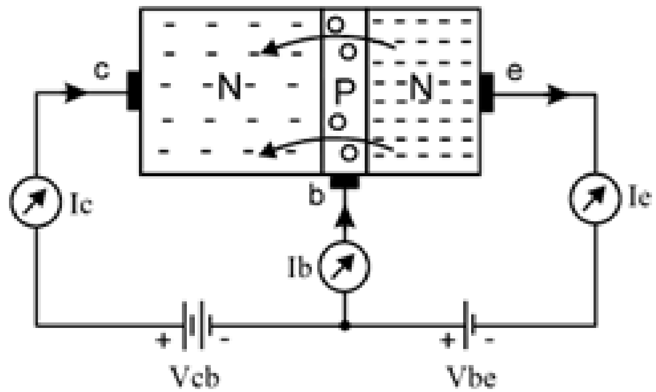
- It contains three semiconductor layers: one p-layer and two n-layers.
- The area of collector layer is largest. So it can dissipate heat quickly.
- Area of base layer is smallest and it is very thin layer.
- Area of emitter layer is medium.
- Collector layer is moderately doped. So it has medium number of charges (electrons).
- Base layer is lightly doped. So it has a very few number of charges (holes).
- Emitter layer is heavily doped. So it has largest number of charges (electrons).
- THE P-LAYER IS SANDWICHED BETWEEN TWO N-LAYERS.
- The junction between collector layer and base layer is called as collector-base junction or c-b junction.
- The junction between base layer and emitter layer is called as base-emitter junction or b-e junction.
- The two junctions have almost same potential barrier voltage of 0.6V to 0.7V, just like in a general purpose rectifier diode.

npn BJTs



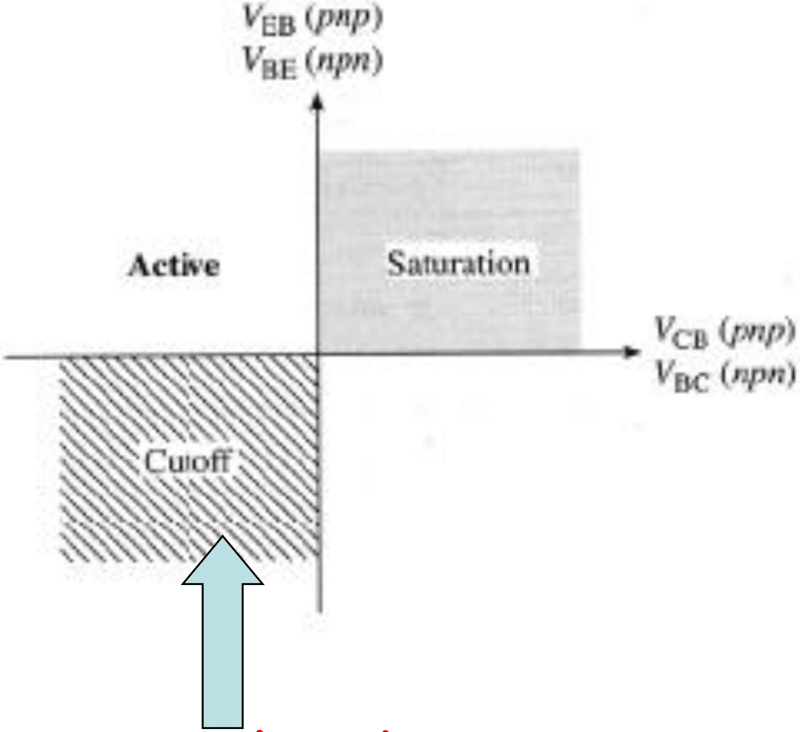
- The collector is connected to high positive voltage with respect to base i.e. Vcb is very high. So c-b junction is reverse biased.
- Vbe is low.When we increase Vbe ≥ 0.7V (the value 0.7V is a typical value of potential barrier voltage) the transistor is forward biased.
- Now large number of electrons in emitter layer is repelled by negative terminal of Vbe and they flow towards b-e junction.
- They cross the junction and enter into small base layer. Here some electrons combine with holes. Also some of them are attracted by positive terminal of Vbe and remaining maximum number of electrons flow into collector layer, crossing the second junction i.e. c-b junction.
- The resident electrons of collector are repelled by these (guest) electrons and thus, then all the electrons are present in collector layer are attracted by positive terminal of Vcb. Thus, all these electrons complete their journey back into emitter layer and produce conventional currents in the transistor as shown in the above circuit.

npn BJTs



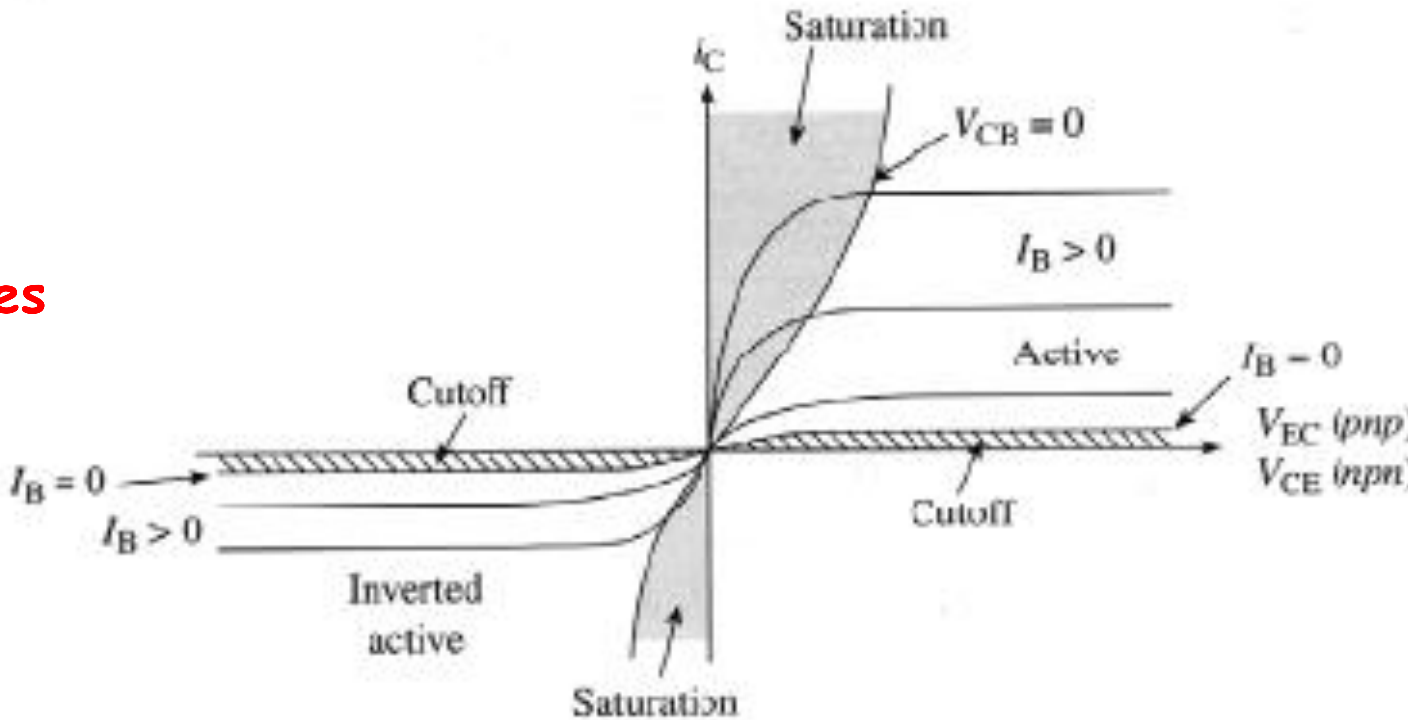
- Now when Vbe is still increased, more electrons are repelled by negative terminal of Vbe. So base-emitter junction is more and more forward biased. Thus the base current (Ib) increases, which in turn increases Ic.
- **Collector current (Ic) is controled by base current (Ib)**
- Hence, we can say that collector current (Ic) is the function of base current (Ib).
- In all this process, maximum number of electrons from emitter layer flow into collector layer. So collector current is ALMOST EQUAL to emitter current. Hence we say that, collector current is proportional to emitter current.

BJTs – Operation Modes
(BJT will operates in one of following three region)

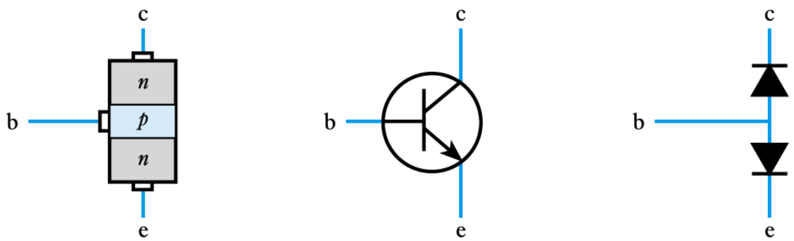


- When there is no I_B current almost no I_C flows
- When I_B current flows, I_C can flow
- <u>The device is a current controlled current device</u>

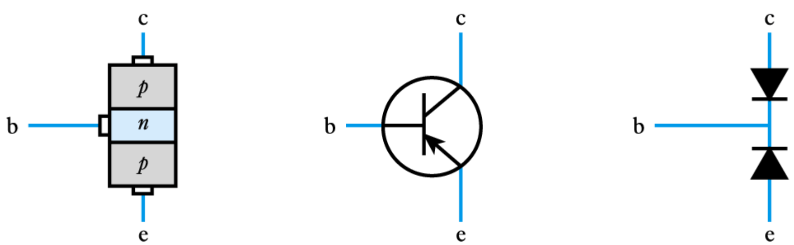
Operational modes can be defined based on V_{BE} and V_{BC}



Bipolar Junction Transistors: Operation Modes



(a) An *npn* transistor



(b) An *pnp* transistor

•**Saturation** : In this method both the junctions are forward biased. This method is not useful as the transistor is in "saturation" and the current cannot be controlled easily.

•**Cutoff**: In this method both the junctions are reverse biased. This method is also not useful as the transistor is in "cut-off" state since current is zero.

Bias Mode	*E-B Junction*	*C-B Junction*
Saturation	Forward	Forward
Active	**Forward**	**Reverse**
Cutoff	Reverse	Reverse

•***Active***: This is the most common and popular method used in transistor biasing. In this method, the base-emitter junction is forward biased and collector-base junction is reverse biased. So by adjusting base voltage we can control total current in the transistor easily.

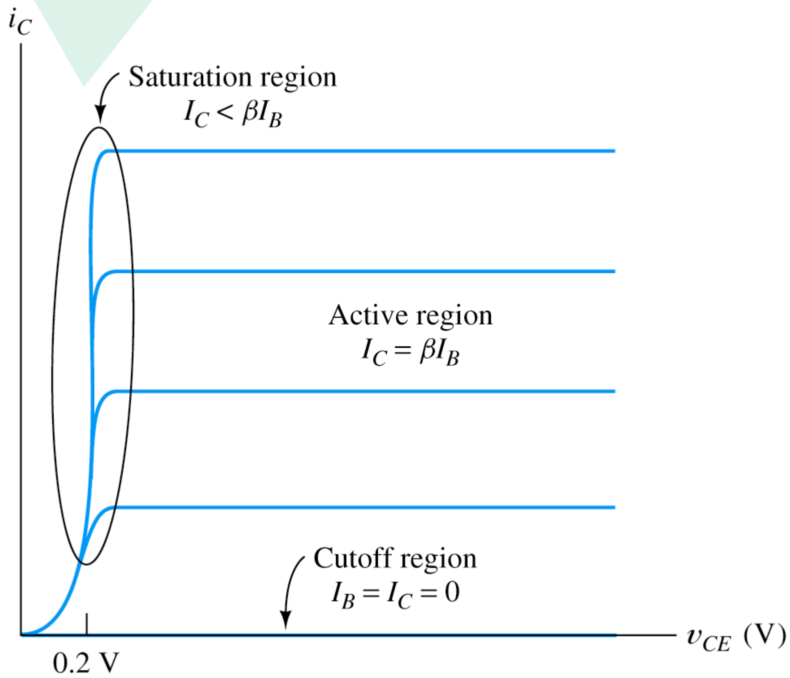
BJT Operating Regions and I V Curves

Output characteristics

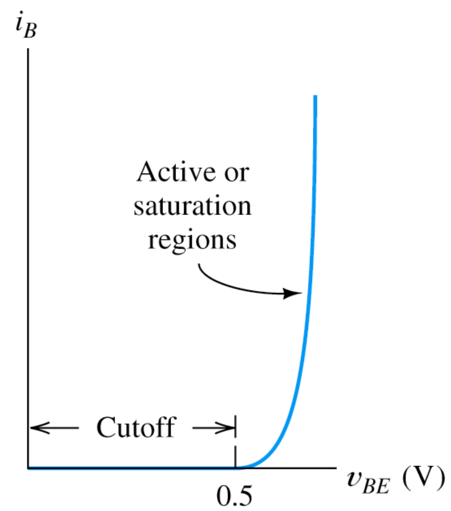
- region near to the origin is the saturation region
- this is normally avoided in linear circuits

Input characteristics

- the input takes the form of a forward-biased *pn* junction
- the input characteristics are similar to a semiconductor diode



(a) Output characteristic



(b) Input characteristic

Regions of operation on the characteristics of an *npn* BJT.

BJTs – Current & Voltage Relationships

Operation mode: v_{BE} is forward & v_{BC} is reverse (Active mode)

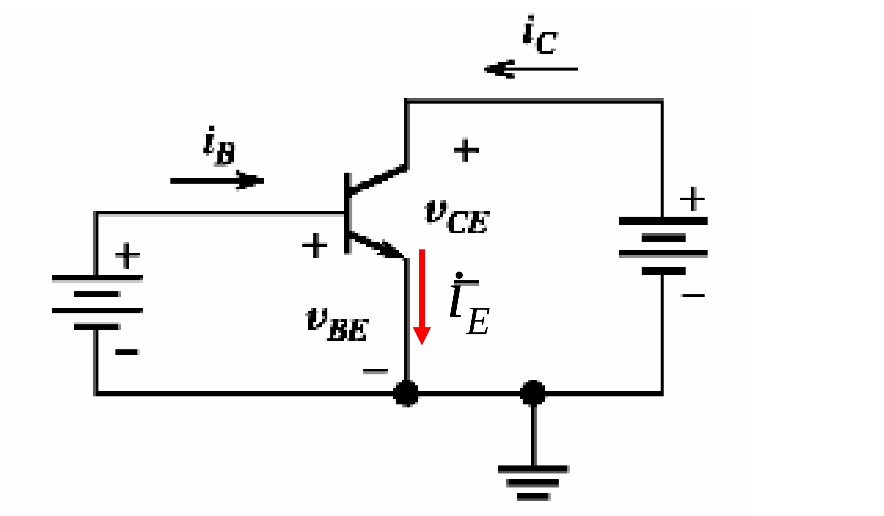
The Shockley equation

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

I_{ES}=saturation current (10^{-12}-10^{-16}A); V_T=kT/q -thermal V (26mV)

The Kirchhoff's laws

$$i_E = i_C + i_B$$



It is true regardless of the bias conditions of the junction

Useful parameter

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

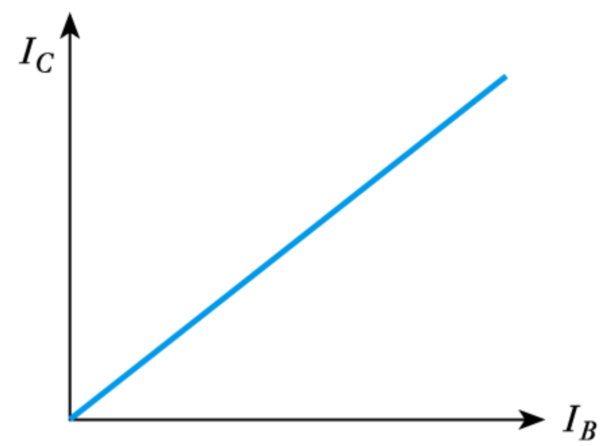
Relationship between the collector current and the base current

- characteristic is approximately linear
- magnitude of collector current is generally many times that of the base current
- the device provides **current gain**

It is true regardless of the bias conditions of the junction

Useful parameter

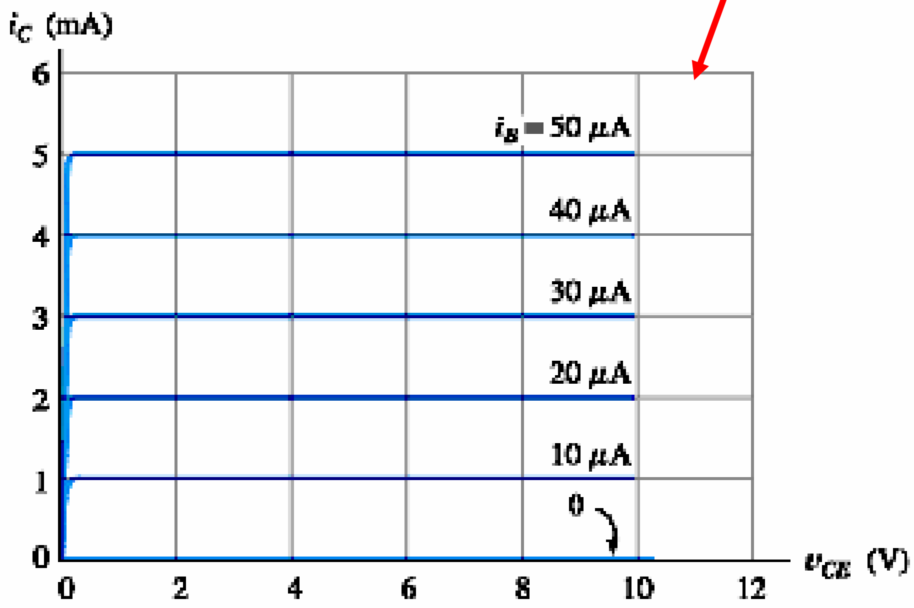
$$\boxed{\beta = \frac{i_C}{i_B}}$$



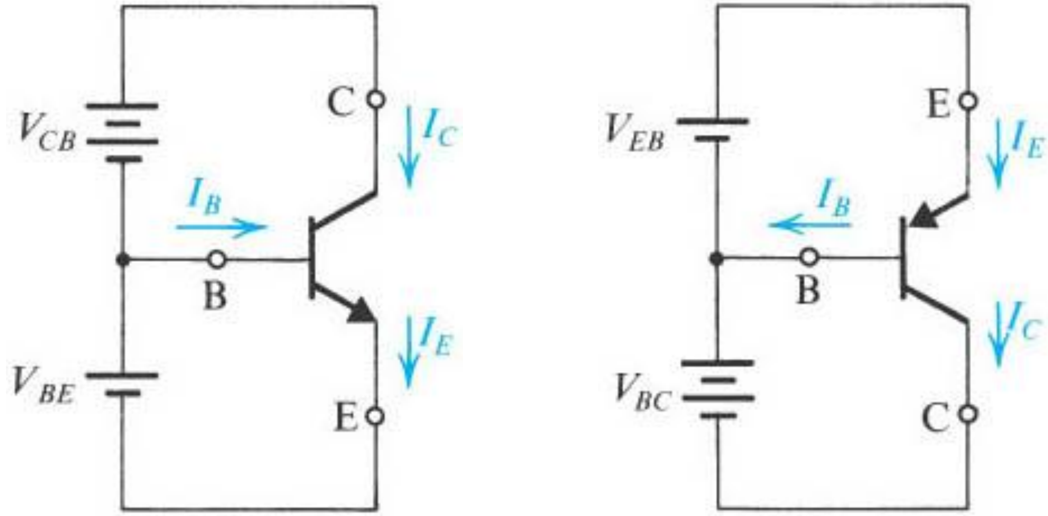
Example:

Please calculate the current gain (β) of this transistor

$$i_C = \beta i_B$$



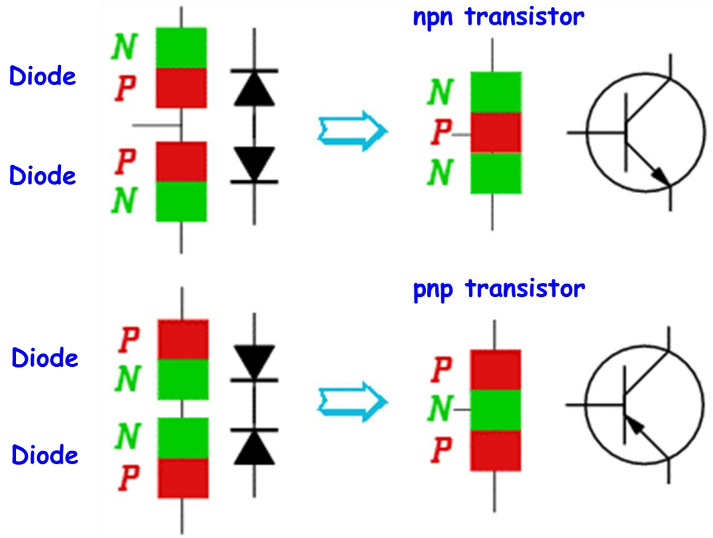
(b) Output characteristics



Voltage polarities and current flow in transistors biased in the active mode.

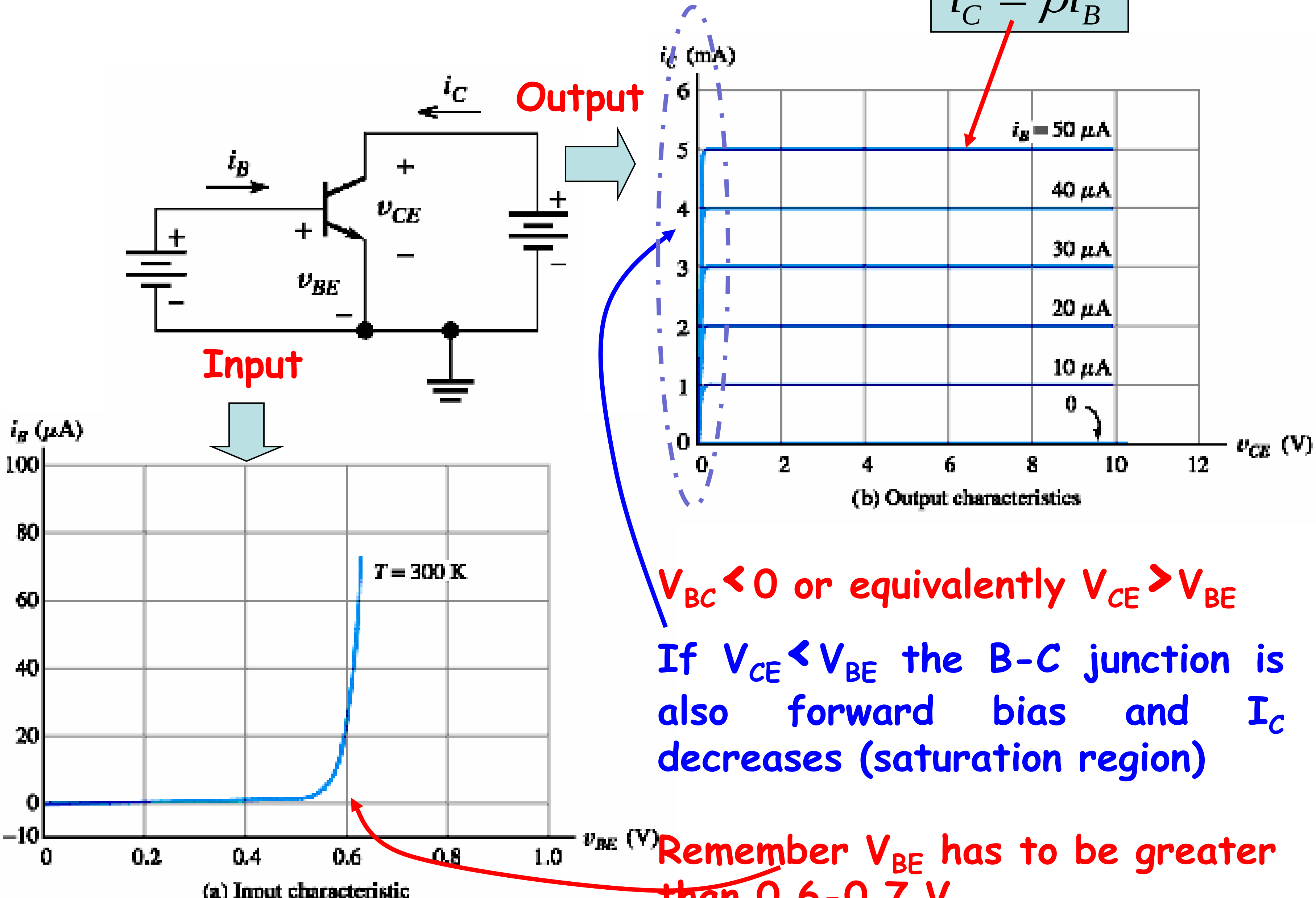
$$i_C = \beta i_B$$

$$i_E = i_B + i_C = i_B + \beta i_B = i_B(\beta + 1)$$



BJTs – Characteristics

$$i_C = \beta i_B$$

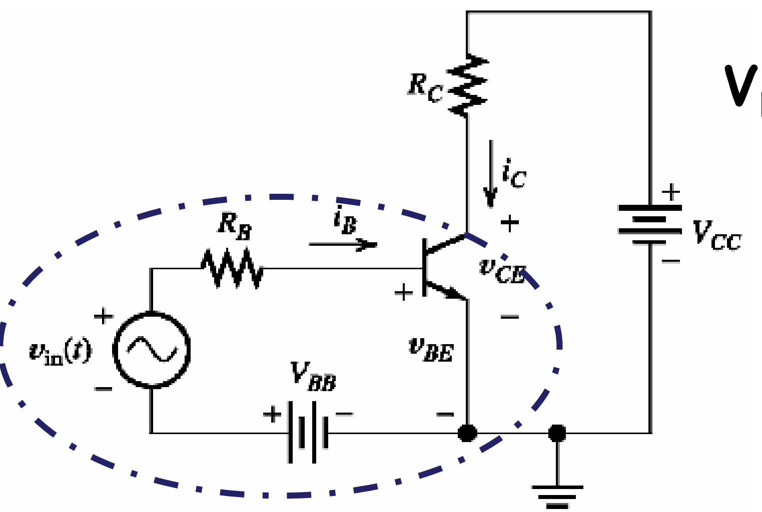


$V_{BC} < 0$ or equivalently $V_{CE} > V_{BE}$

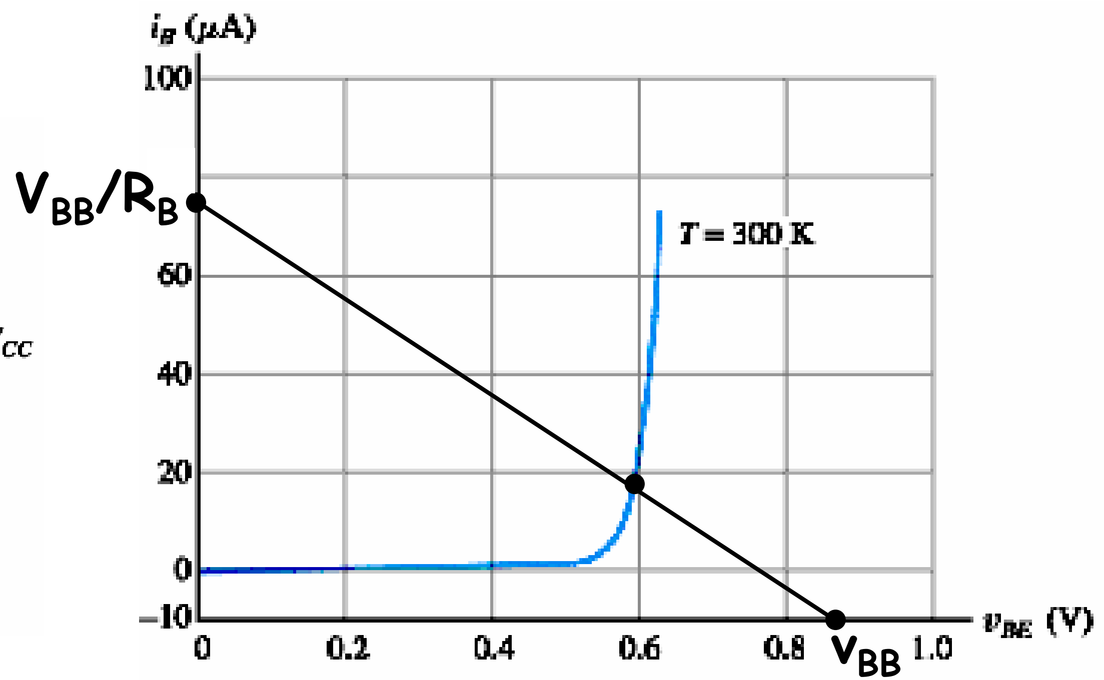
If $V_{CE} < V_{BE}$ the B-C junction is also forward bias and I_C decreases (saturation region)

Remember V_{BE} has to be greater than 0.6-0.7 V

BJTs - Load line analysis



Input loop



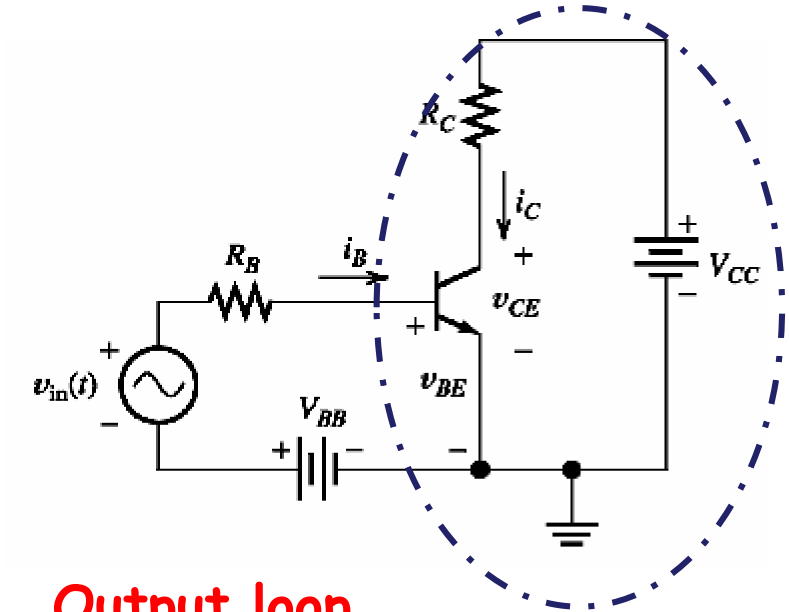
(a) Input characteristic

$$V_{BB} = R_B i_B + V_{BE}$$

if i_B=0 $\boxed{V_{BE} = V_{BB}}$

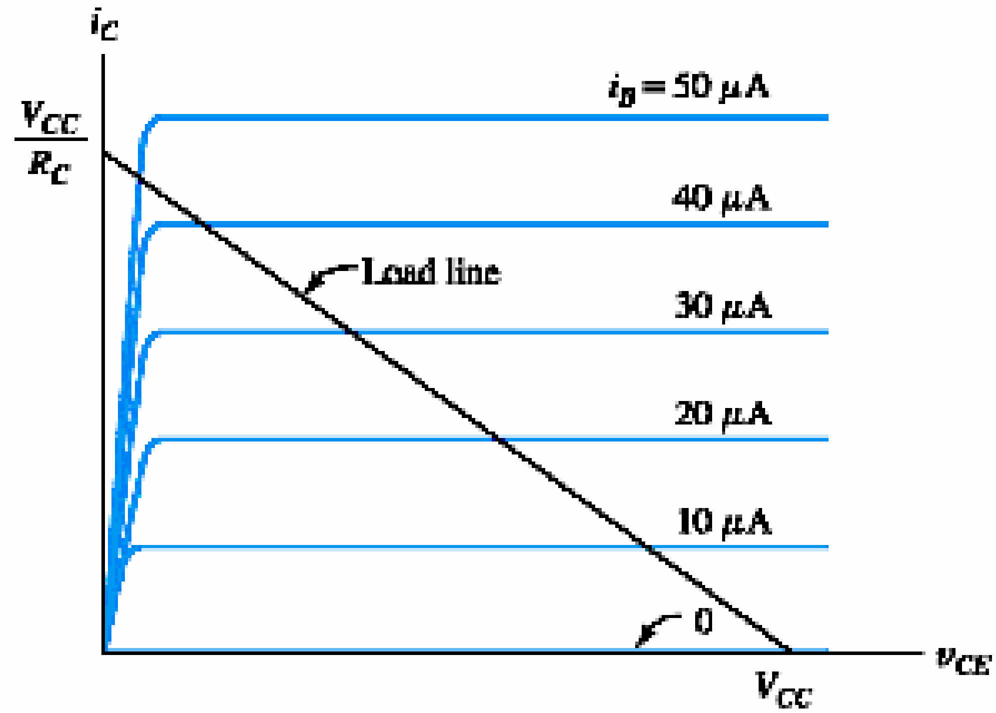
if v_{BE}=0 $\boxed{i_B = V_{BB} / R_B}$

BJTs - Load line analysis



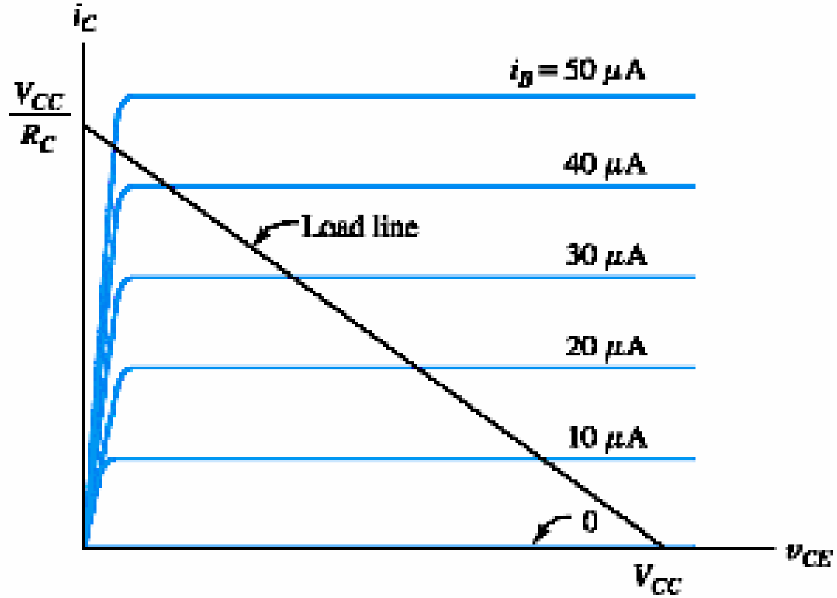
Output loop

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



Load Line Analysis:

Can be performed in order to determine $|V_{BE}|$ value of transistor in the active and saturation regions.



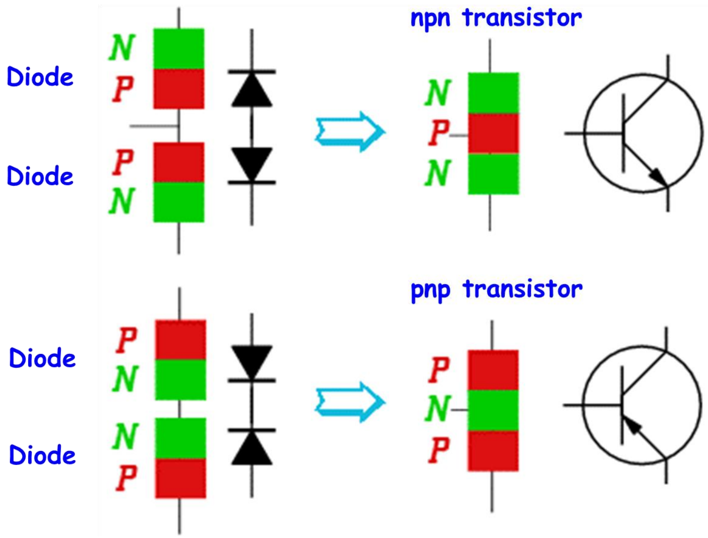
or

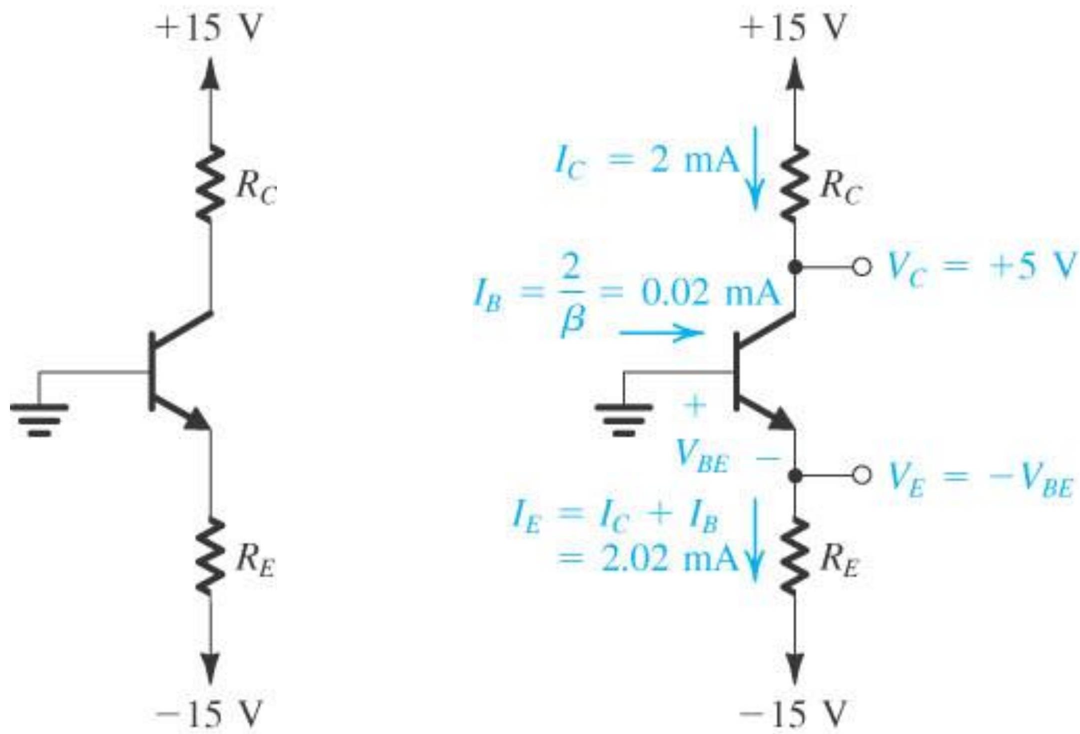
Assumption:

It is assumed that $|V_{BE}| = 0.7V$ in the active and saturation regions.

Problem :

Analyze the circuits shown in Figure (a) to determine I and V. For all transistors, assume that β = 100 and $|V_{BE}|$ = 0.7V in the active region. (R_C=5kΩ, R_E=7.07kΩ)

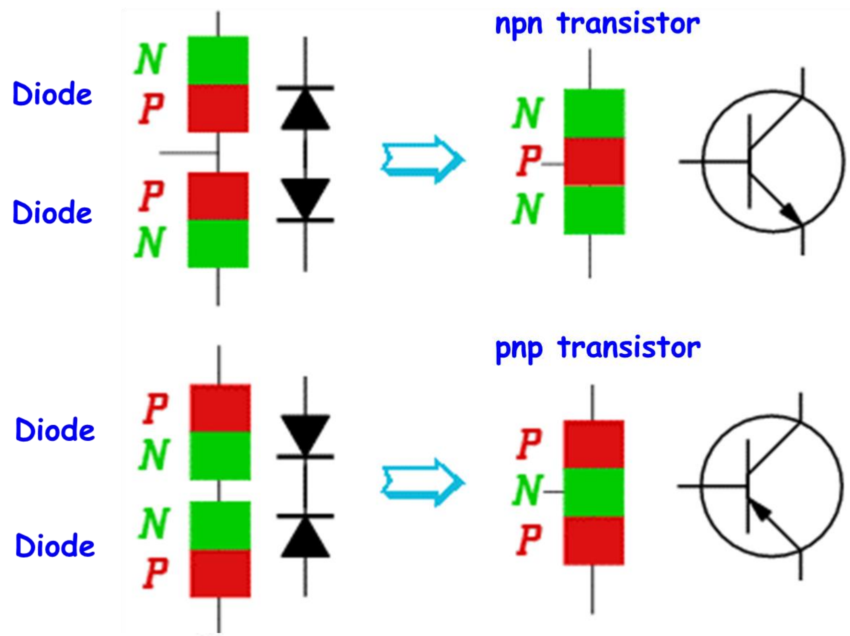


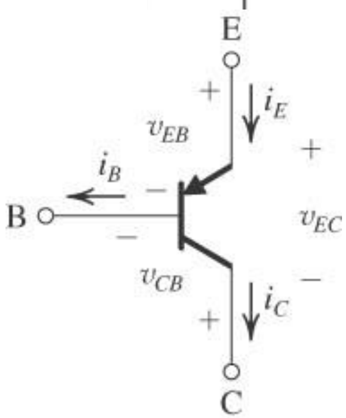


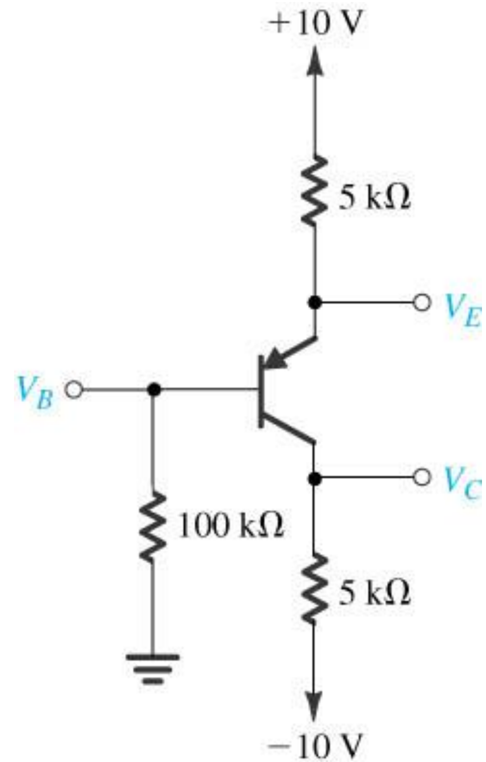
(a) (b)

Problem :

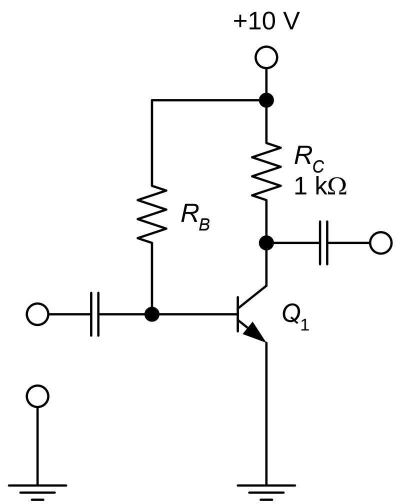
Analyze the circuits shown in Figure (a) to determine I and V. For all transistors, assume that β = 100 and $|V_{BE}|$ = 0.7V in the active region.

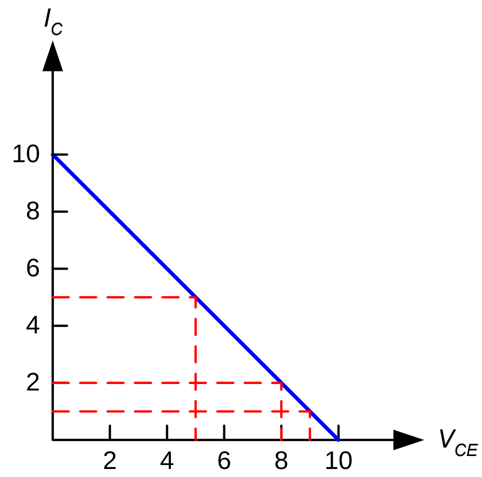


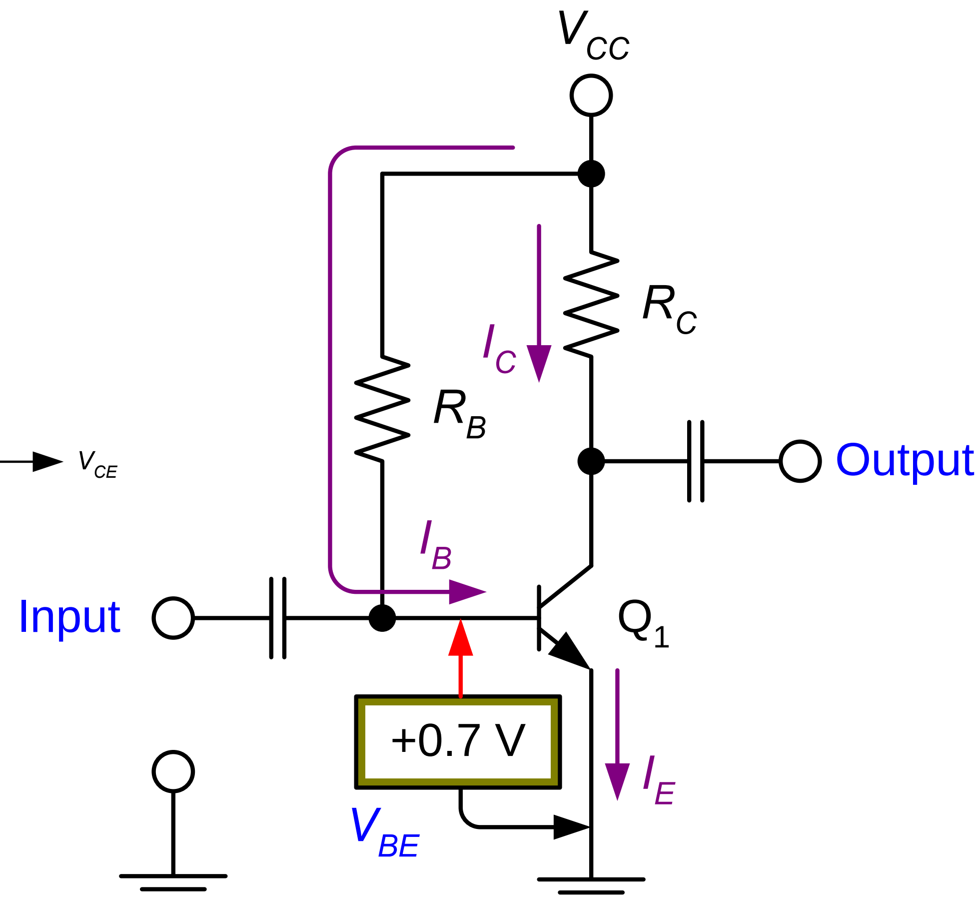




DC Biasing Circuits of BJTs





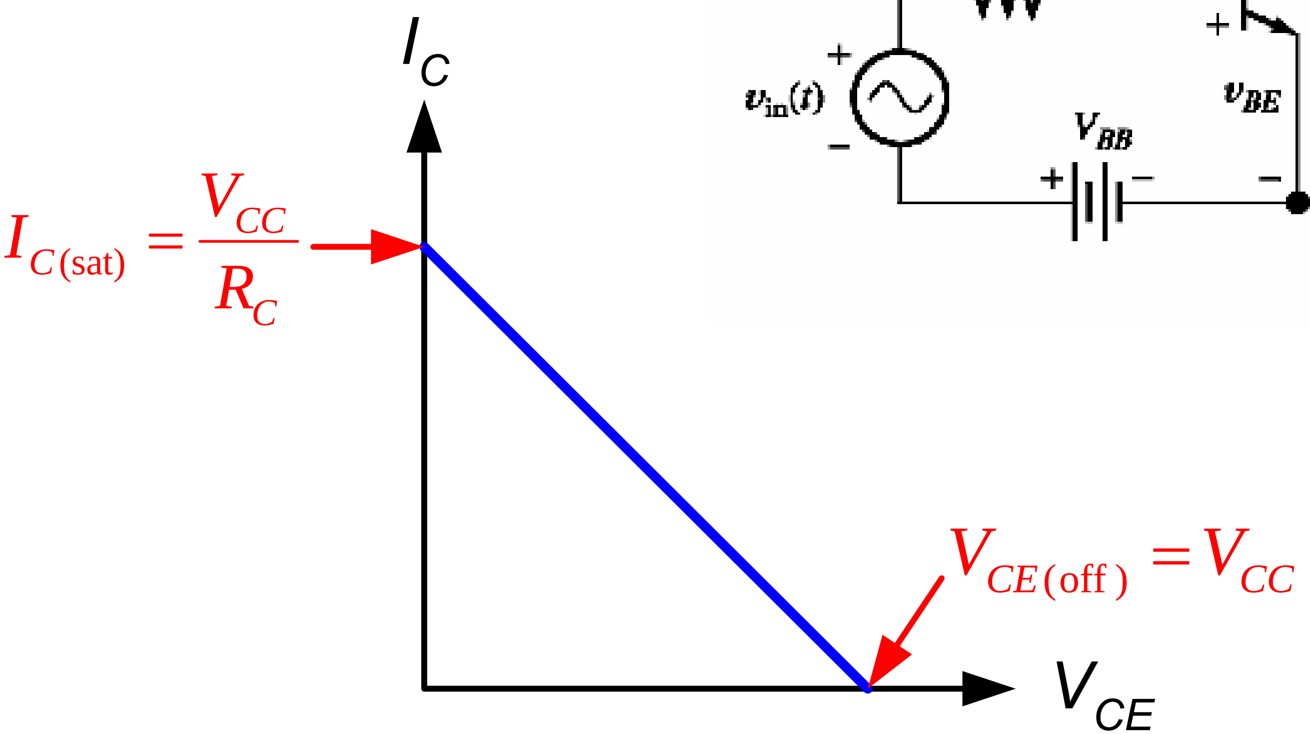


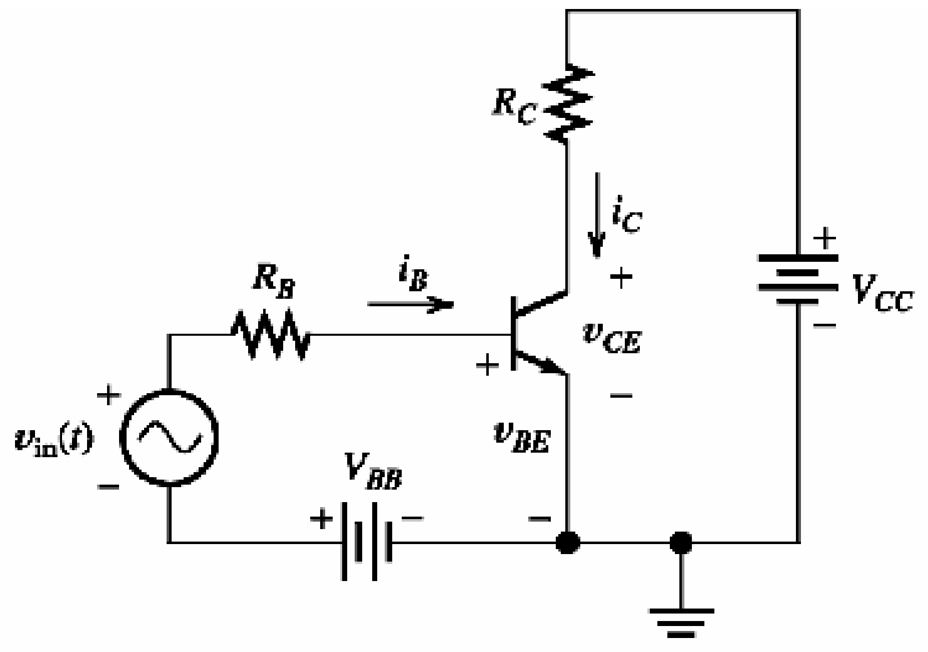
Objectives

- State the purpose of DC biasing circuits.
- Plot the DC load line given the value of V_{CC} and the total collector-emitter circuit resistance.
- Describe the Q-point of an amplifier.
- Describe and analyze the operations of various bias circuits:
  - base-bias circuits
  - voltage-divider bias circuits
  - emitter-bias circuits
  - collector-feedback bias circuits
  - emitter-feedback bias circuits

A generic DC load line.

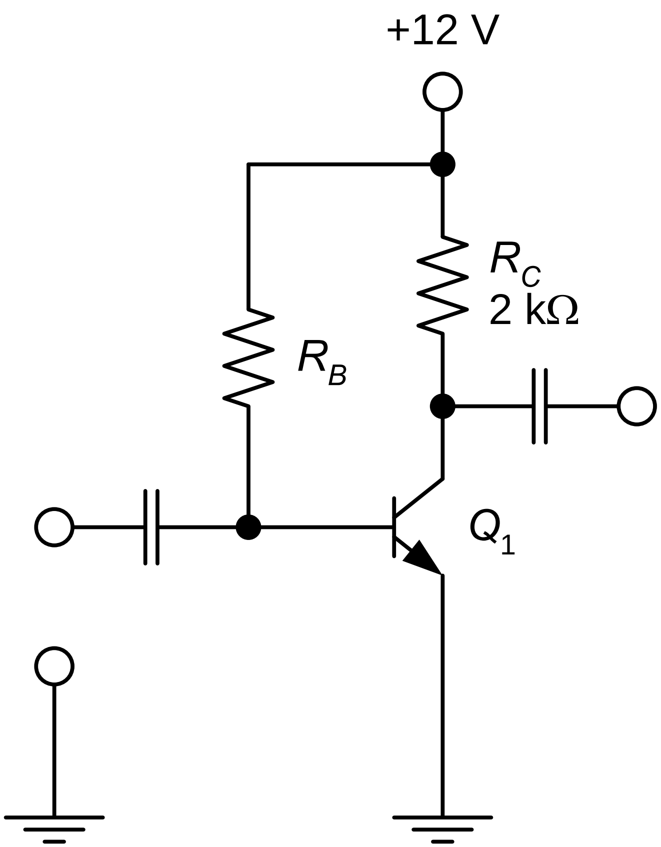
$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

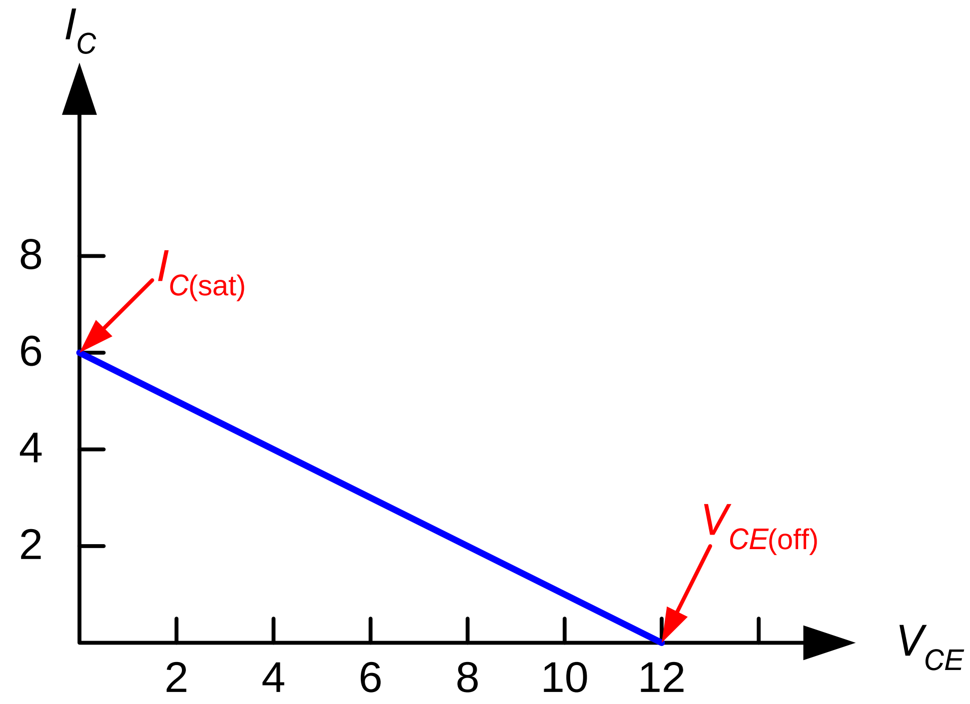




Example

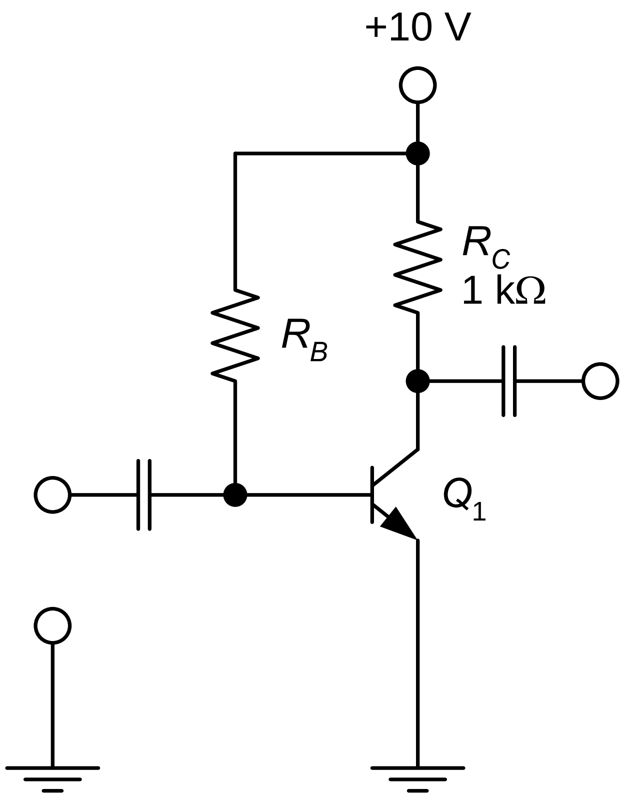
Plot the DC load line for the circuit shown in Fig.



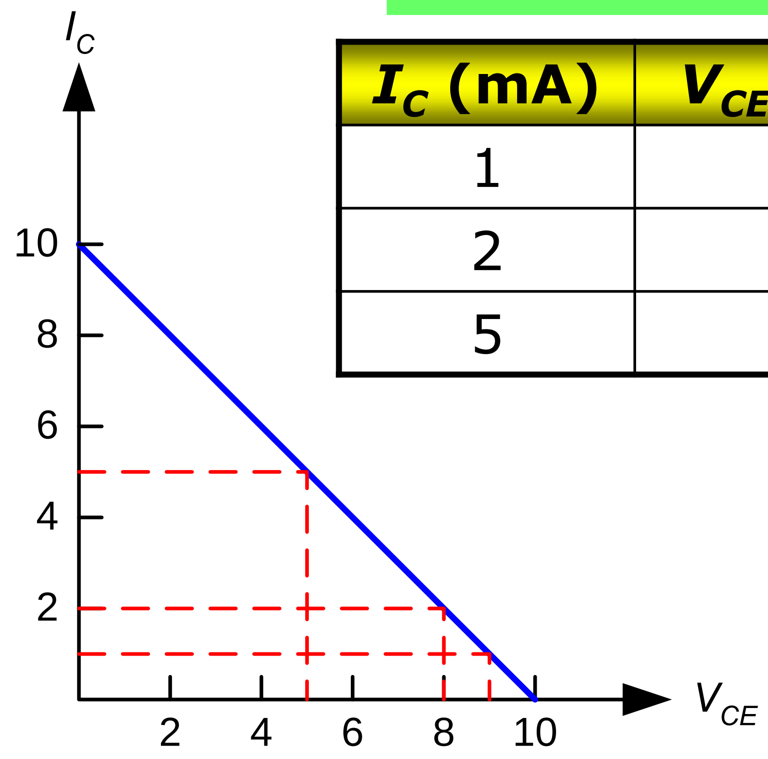


Example

Plot the DC load line for the circuit shown in Fig. Then, find the values of V_{CE} for I_C = 1, 2, 5 mA respectively.



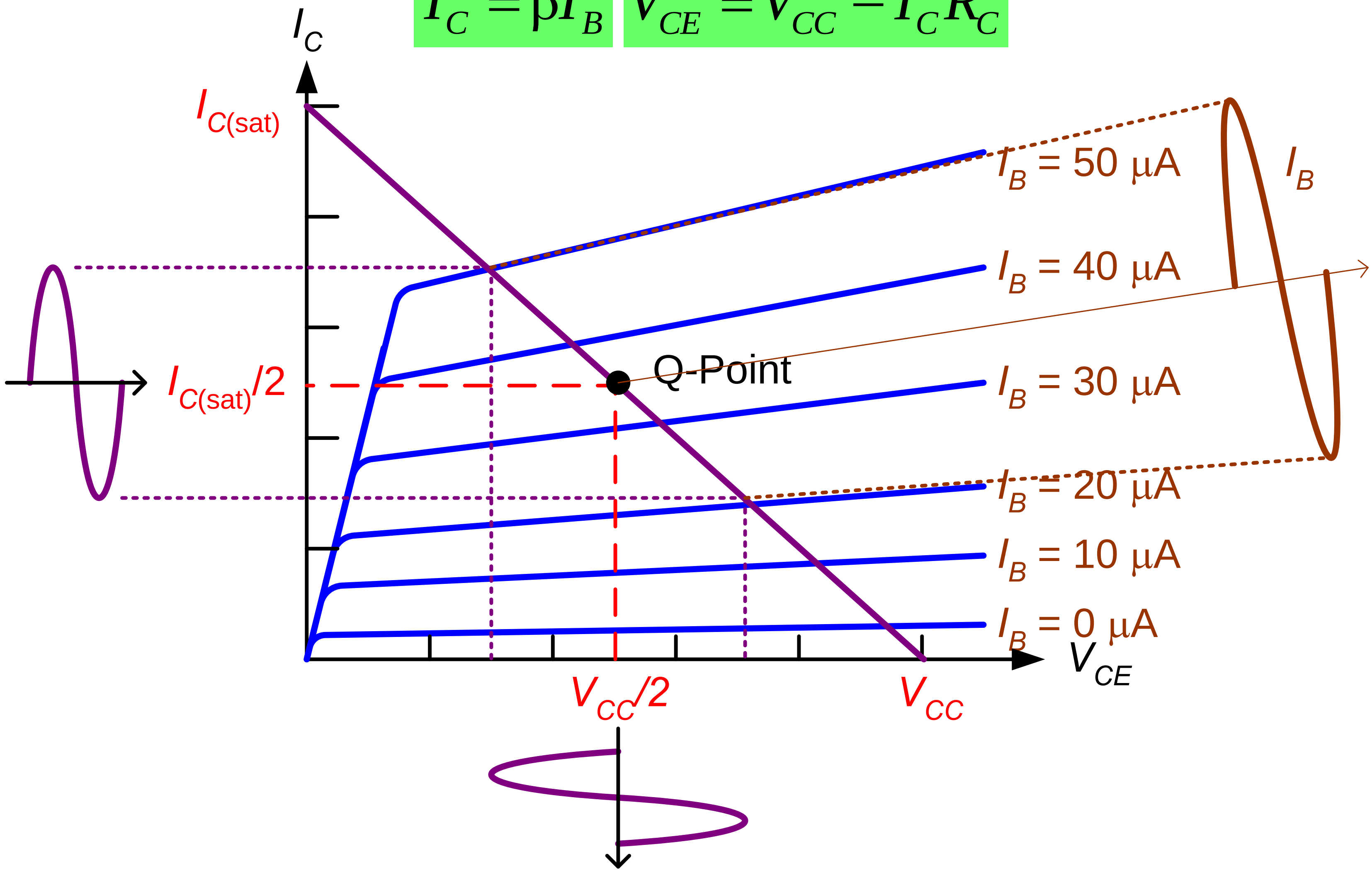
$$V_{CE} = V_{CC} - I_C R_C$$



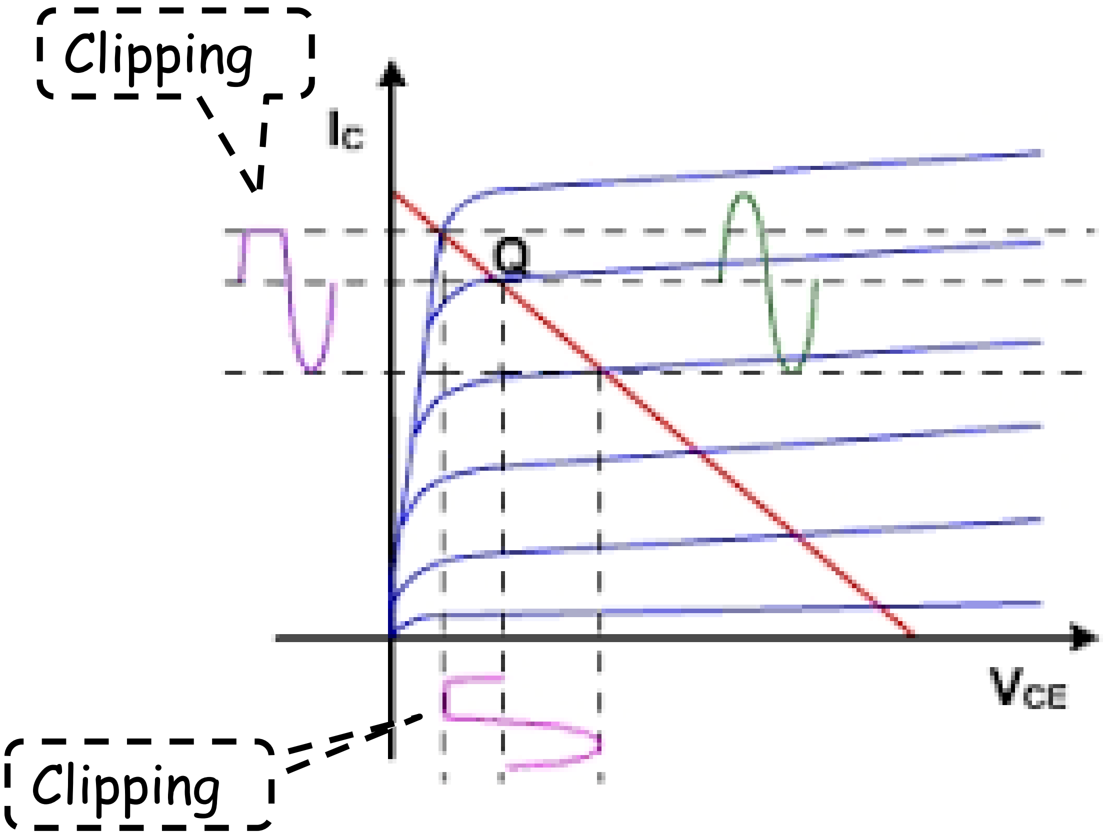
I_C (mA)	V_{CE} (V)
1	9
2	8
5	5

Optimum Q-point with amplifier operation.

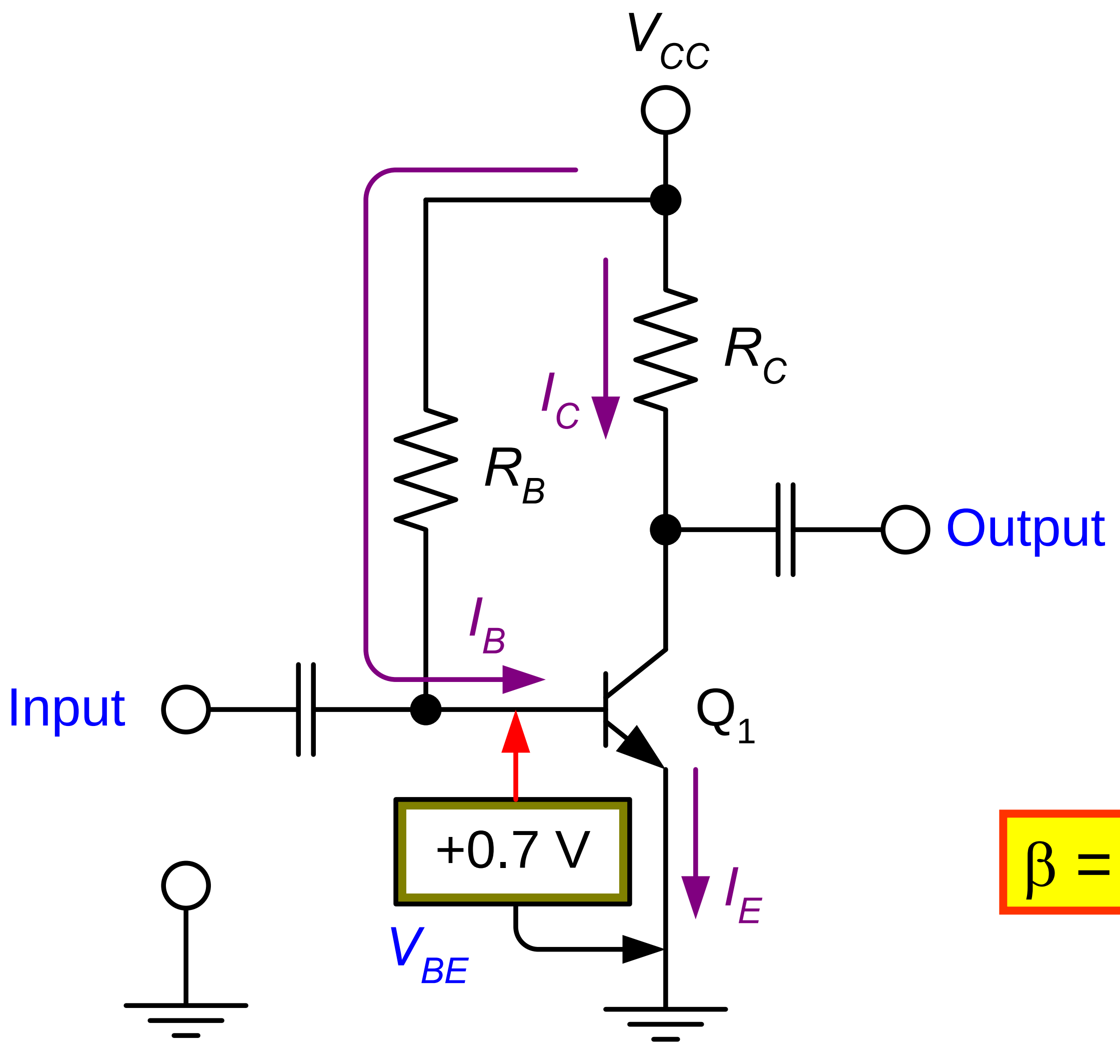
$$I_C = \beta I_B \qquad V_{CE} = V_{CC} - I_C R_C$$



Q-point is not at optimum location



1. Base bias (fixed bias).



$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

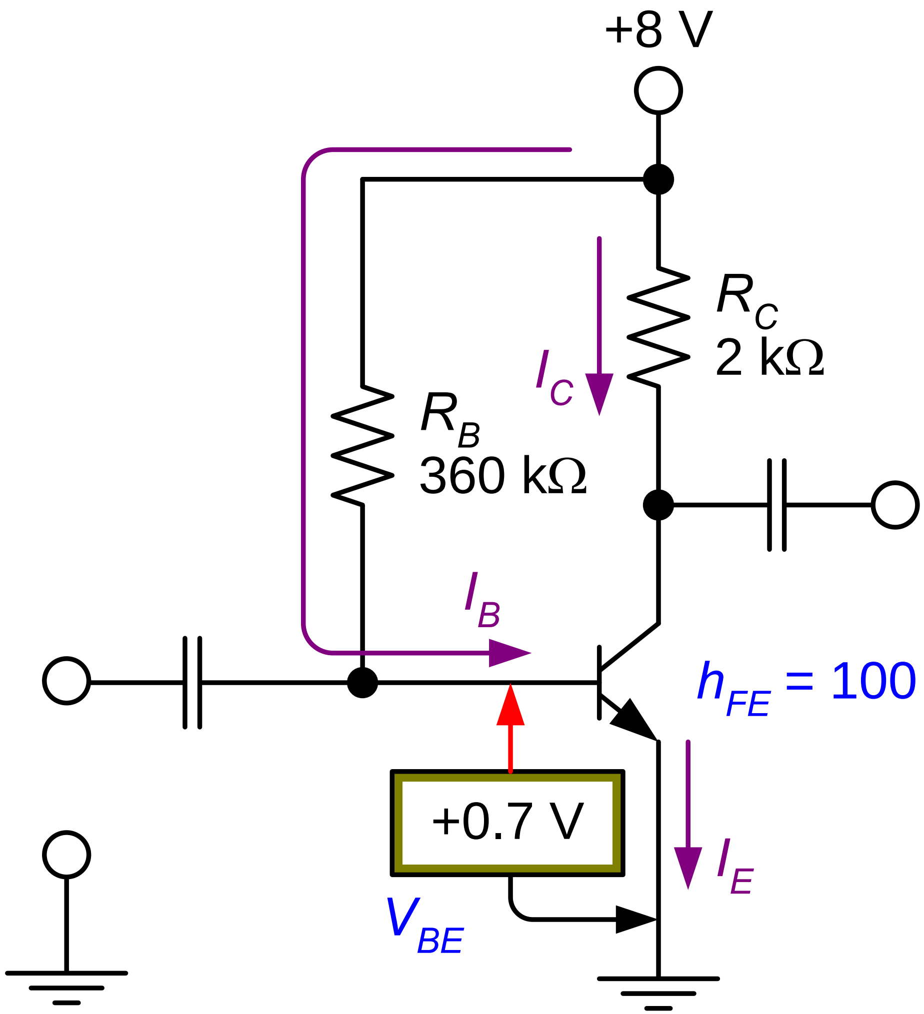
$$I_C = \beta I_B$$

$$V_{CE} = V_{CC} - I_C R_C$$

β = DC current gain = h_{FE}

Example

Construct the DC load line for the circuit and plot the Q-point.
Determine whether the circuit is midpoint biased.

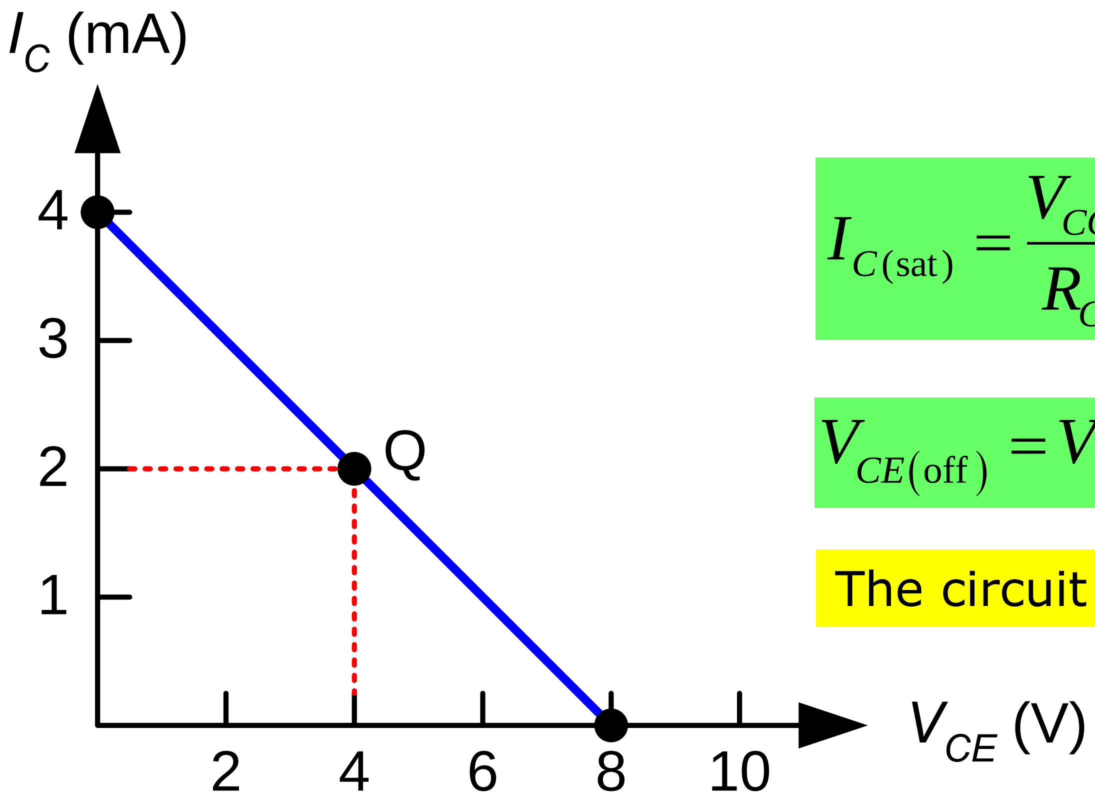


$$I_B = \frac{V_{CC} - 0.7\text{V}}{R_B} = \frac{8\text{V} - 0.7\text{V}}{360\text{k}\Omega}$$
$$= 20.28\mu\text{A}$$

$$I_C = h_{FE} I_B = (100)(20.28\mu\text{A})$$
$$= 2.028\text{mA}$$

$$V_{CE} = V_{CC} - I_C R_C$$
$$= 8\text{V} - (2.028\text{mA})(2\text{k}\Omega)$$
$$= 3.94\text{V}$$

Example



$$I_{C(\text{sat})} = \frac{V_{CC}}{R_C} = \frac{8\text{V}}{2\text{k}\Omega} = 4\text{mA}$$

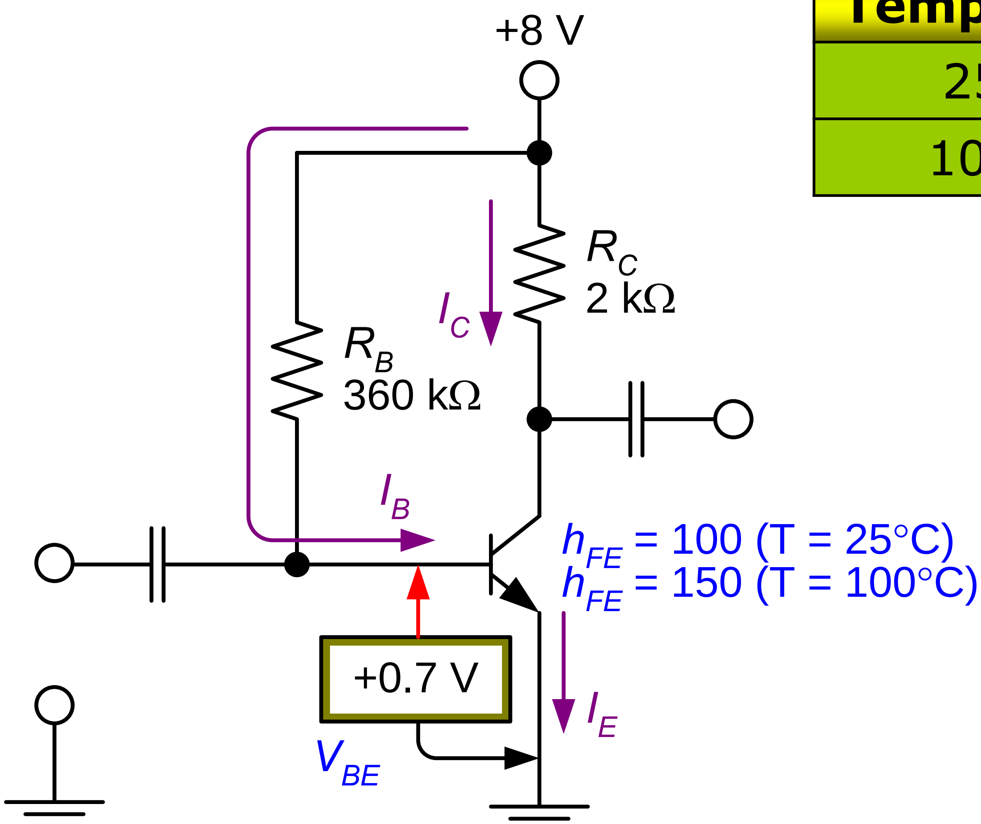
$$V_{CE(\text{off})} = V_{CC} = 8\text{V}$$

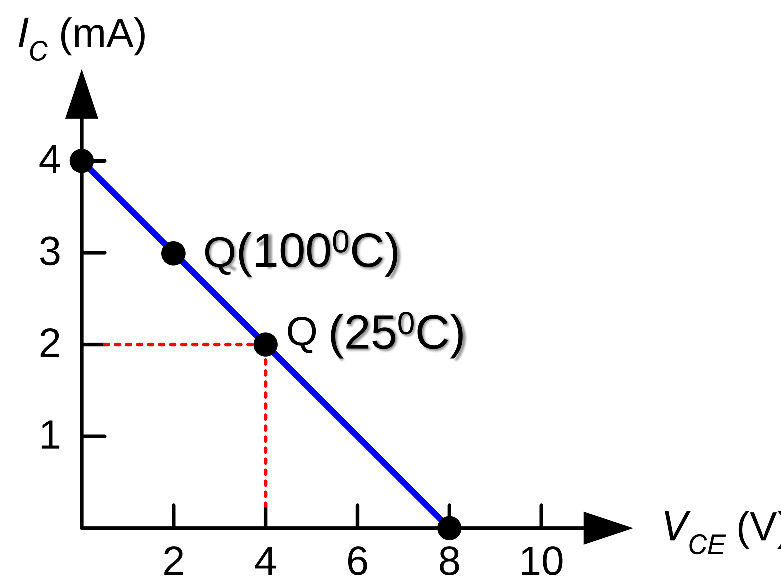
The circuit is midpoint biased.

(Q-point shift)

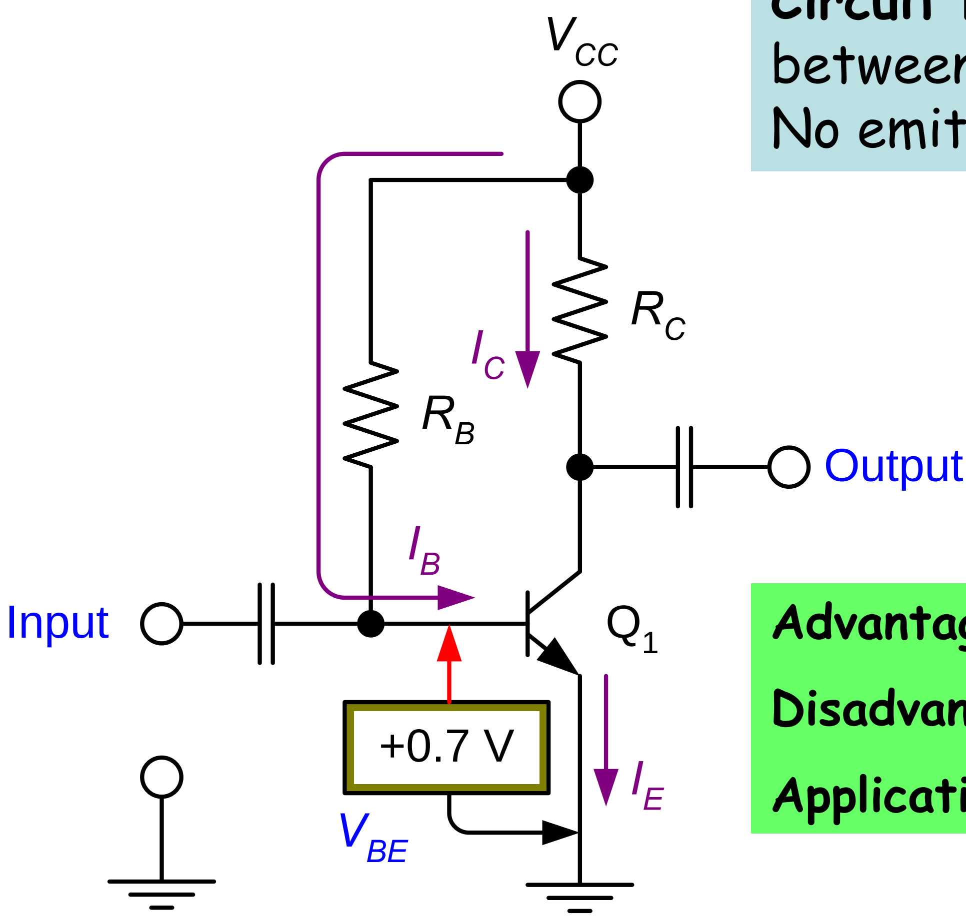
The transistor has values of h_{FE} = 100 when T = 25 °C and h_{FE} = 150 when T = 100 °C. Determine the Q-point values of I_C and V_{CE} at both of these temperatures.

Temp(°C)	I_B (μA)	I_C (mA)	V_{CE} (V)
25	20.28	2.028	3.94
100	20.28	3.04	1.92





Base bias characteristics.



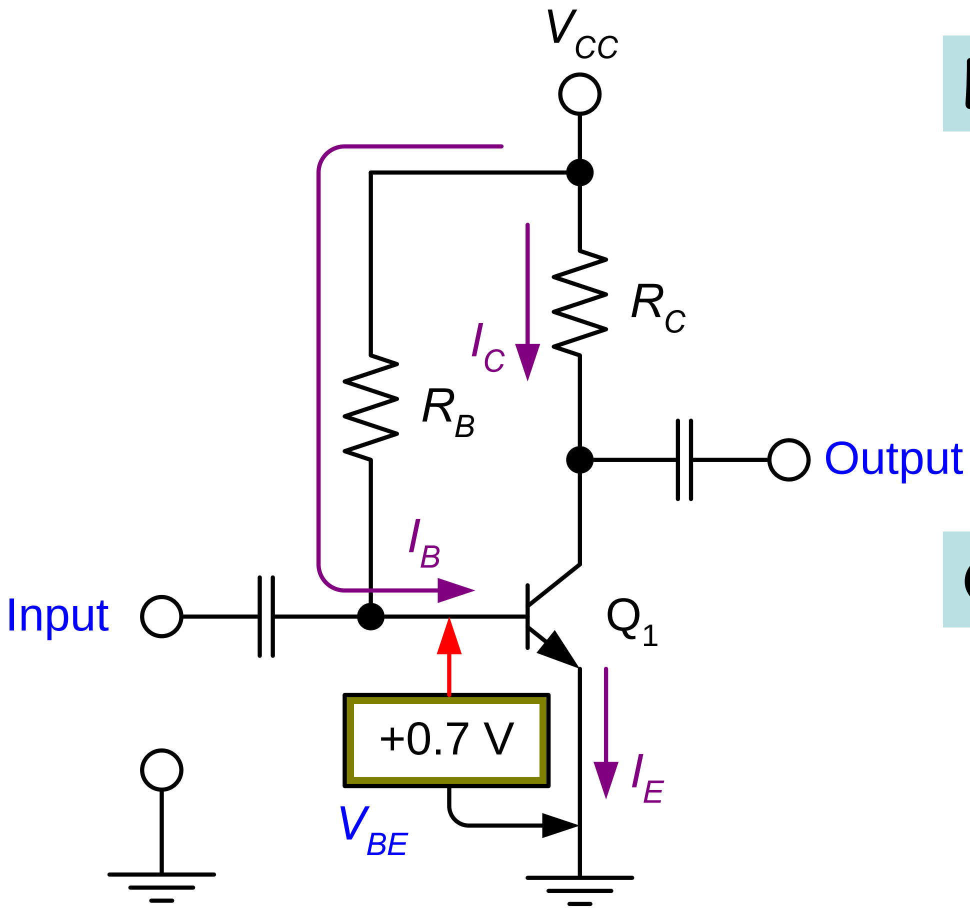
Circuit recognition: A single resistor (R_B) between the base terminal and V_{CC}. No emitter resistor.

Advantage: Circuit simplicity.

Disadvantage: Q-point shift with temp.

Applications: Switching circuits only.

Base bias characteristics.



Load line equations:

$$I_{C(\text{sat})} \cong \frac{V_{CC}}{R_C}$$

$$V_{CE(\text{off})} = V_{CC}$$

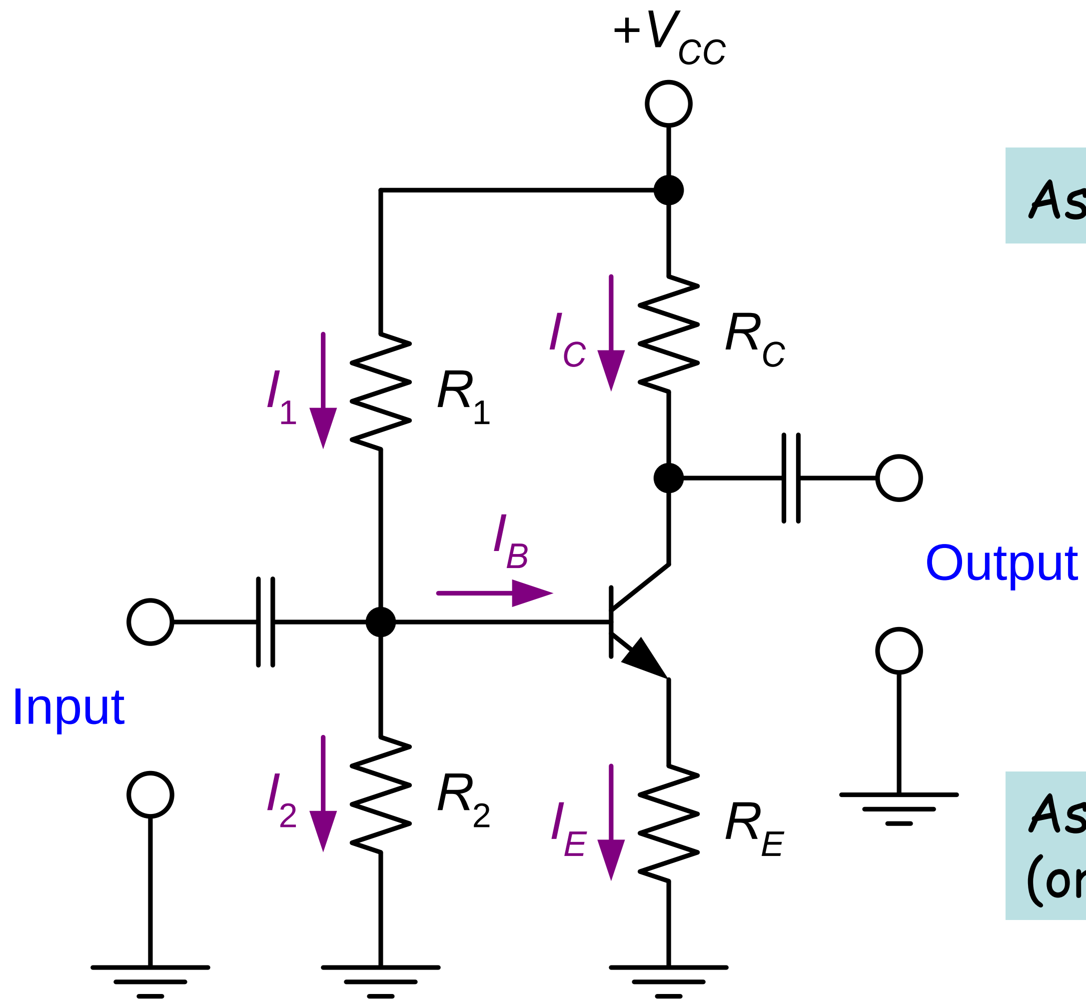
Q-point equations:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C = h_{FE} I_B$$

$$V_{CE} = V_{CC} - I_C R_C$$

2. Voltage divider bias.



Assume that $I_2 > 10I_B$.

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

$$V_E = V_B - 0.7\text{V}$$

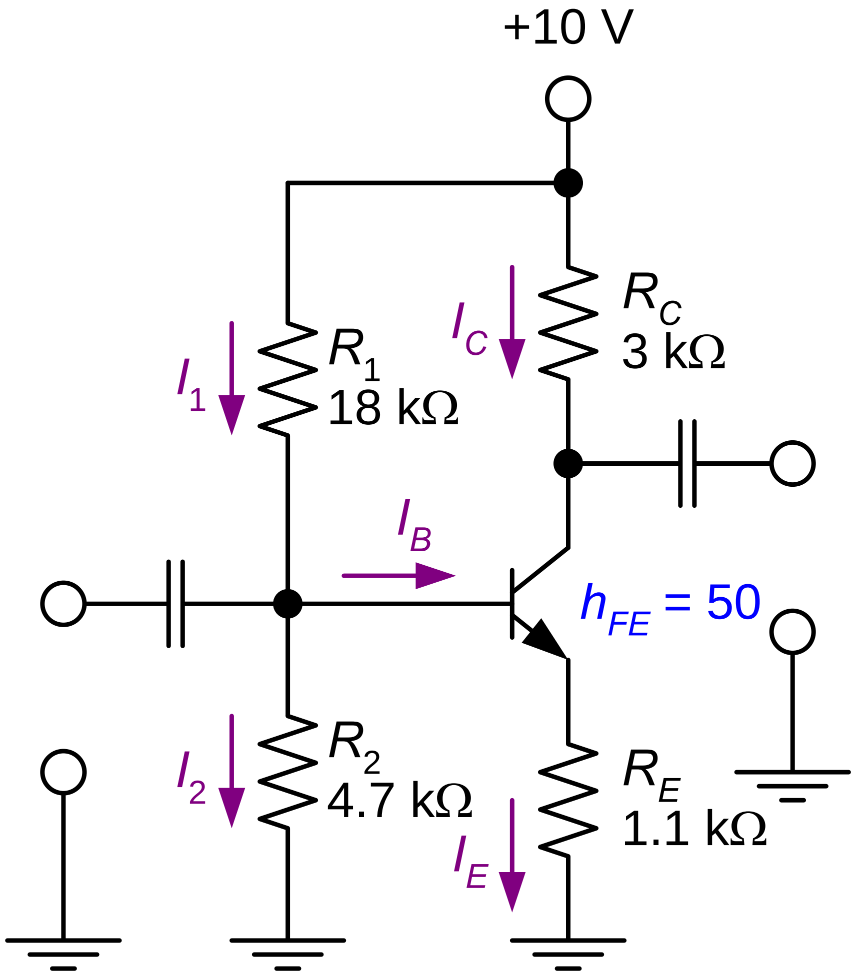
$$I_E = \frac{V_E}{R_E}$$

Assume that I_{CQ} @ I_E (or h_{FE} >> 1). Then

$$V_{CEQ} = V_{CC} - I_{CQ}\left(R_C + R_E\right)$$

Example

Determine the values of I_{CQ} and V_{CEQ} for the circuit shown in Fig.



$$V_B = V_{CC}\frac{R_2}{R_1 + R_2}$$
$$= (10\text{V})\frac{4.7\text{k}\Omega}{22.7\text{k}\Omega} = 2.07\text{V}$$

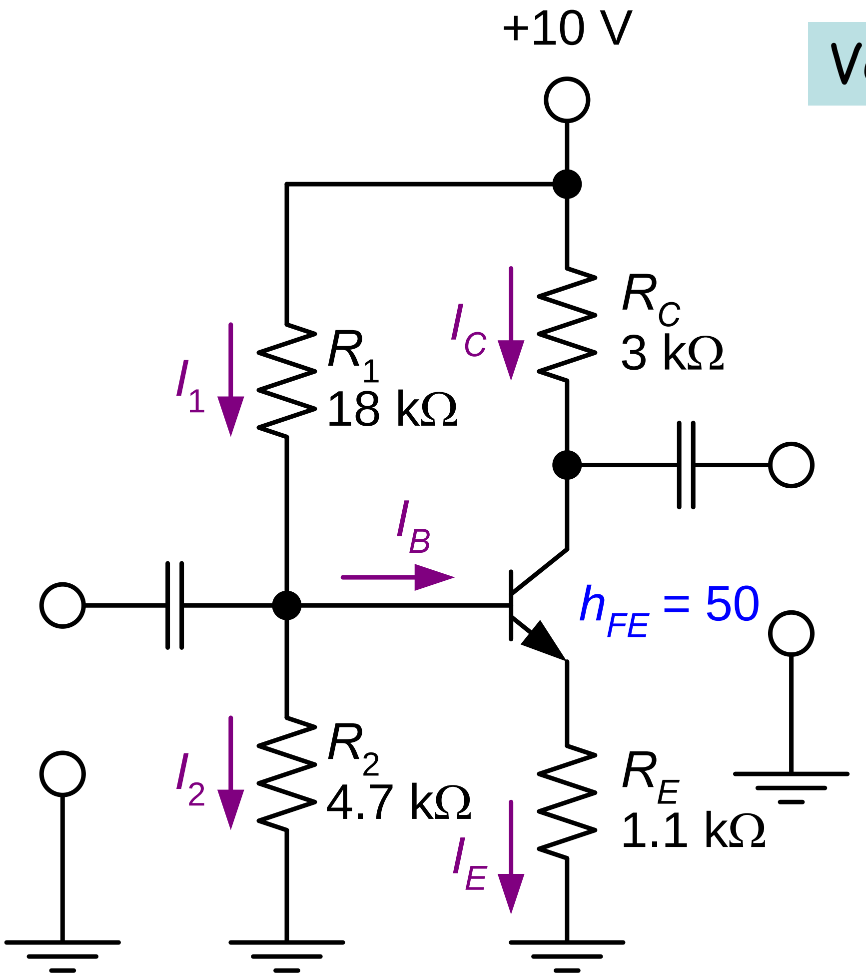
$$V_E = V_B - 0.7\text{V}$$
$$= 2.07\text{V} - 0.7\text{V} = 1.37\text{V}$$

Because I_{CQ} @ I_E (or h_{FE} >> 1),

$$I_{CQ} \cong \frac{V_E}{R_E} = \frac{1.37\text{V}}{1.1\text{k}\Omega} = 1.25\text{mA}$$

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C + R_E)$$
$$= 10\text{V} - (1.25\text{mA})(4.1\text{k}\Omega) = 4.87\text{V}$$

Example



Verify that I_2 > 10 I_B

$$I_2 = \frac{V_B}{R_2} = \frac{2.07\text{V}}{4.7\text{k}\Omega} = 440.4\mu\text{A}$$

$$I_B = \frac{I_E}{h_{FE}+1} = \frac{1.25\text{mA}}{50+1}$$
$$= 24.51\mu\text{A}$$

$$\therefore I_2 > 10 I_B$$

Which value of h_{FE} do I use?

Transistor specification sheet may list any combination of the following h_{FE} max. h_{FE} min or h_{FE} typ. Use typical value if there is one. Otherwise, use

$$h_{FE(\text{ave})} = \sqrt{h_{FE(\text{min})} \times h_{FE(\text{max})}}$$

Example

A voltage-divider bias circuit has the following values:

R_1 = 1.5 kW, R_2 = 680 W, R_C = 260 W, R_E = 240 W and V_{CC} = 10 V. Assuming the transistor is a 2N3904, determine the value of I_B for the circuit.

$$V_B = V_{CC}\frac{R_2}{R_1+R_2} = (10\text{V})\frac{680\Omega}{2180\Omega} = 3.12\text{V}$$

$$V_E = V_B - 0.7\text{V} = 3.12\text{V} - 0.7\text{V} = 2.42\text{V}$$

$$I_{CQ} \cong I_E = \frac{V_E}{R_E} = \frac{2.42\text{V}}{240\Omega} = 10\text{mA}$$

$$h_{FE(ave)} = \sqrt{h_{FE(\min)} \times h_{FE(\max)}} = \sqrt{100\times 300} = 173$$

$$I_B = \frac{I_E}{h_{FE(\text{ave})}+1} = \frac{10\text{mA}}{174} = 57.5\mu\text{A}$$

Stability of Voltage Divider Bias Circuit

The Q-point of voltage divider bias circuit is less dependent on h_{FE} than that of the base bias (fixed bias).

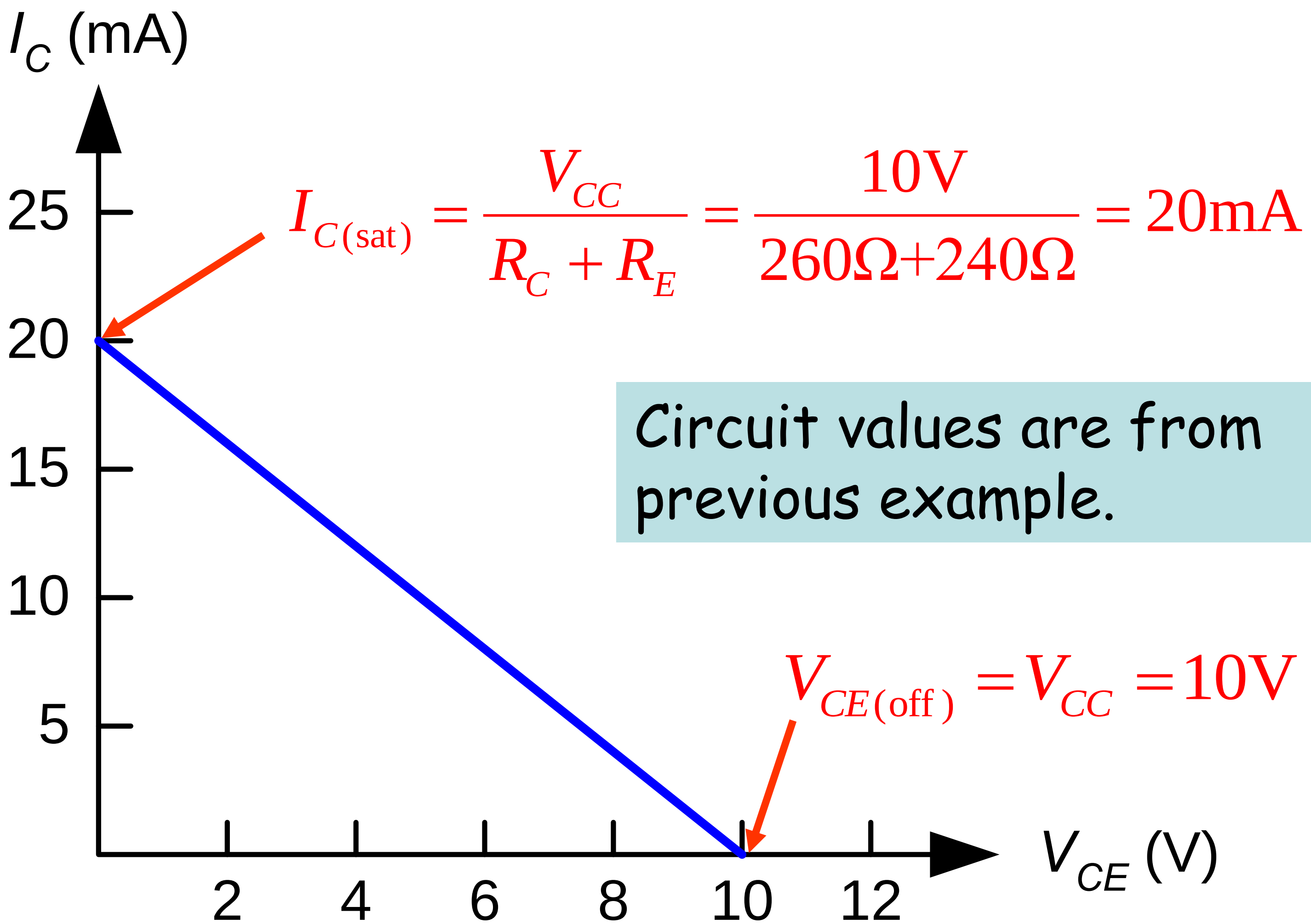
For example, if I_E is exactly 10 mA, the range of h_{FE} is 100 to 300. Then

$$\text{At } h_{FE} = 100,\ I_B = \frac{I_E}{h_{FE}+1} = \frac{10\text{mA}}{101} \cong 100\mu\text{A and } I_{CQ} = I_E - I_B \cong 9.90\text{mA}$$

$$\text{At } h_{FE} = 300,\ I_B = \frac{I_E}{h_{FE}+1} = \frac{10\text{mA}}{301} \cong 33\mu\text{A and } I_{CQ} = I_E - I_B \cong 9.97\text{mA}$$

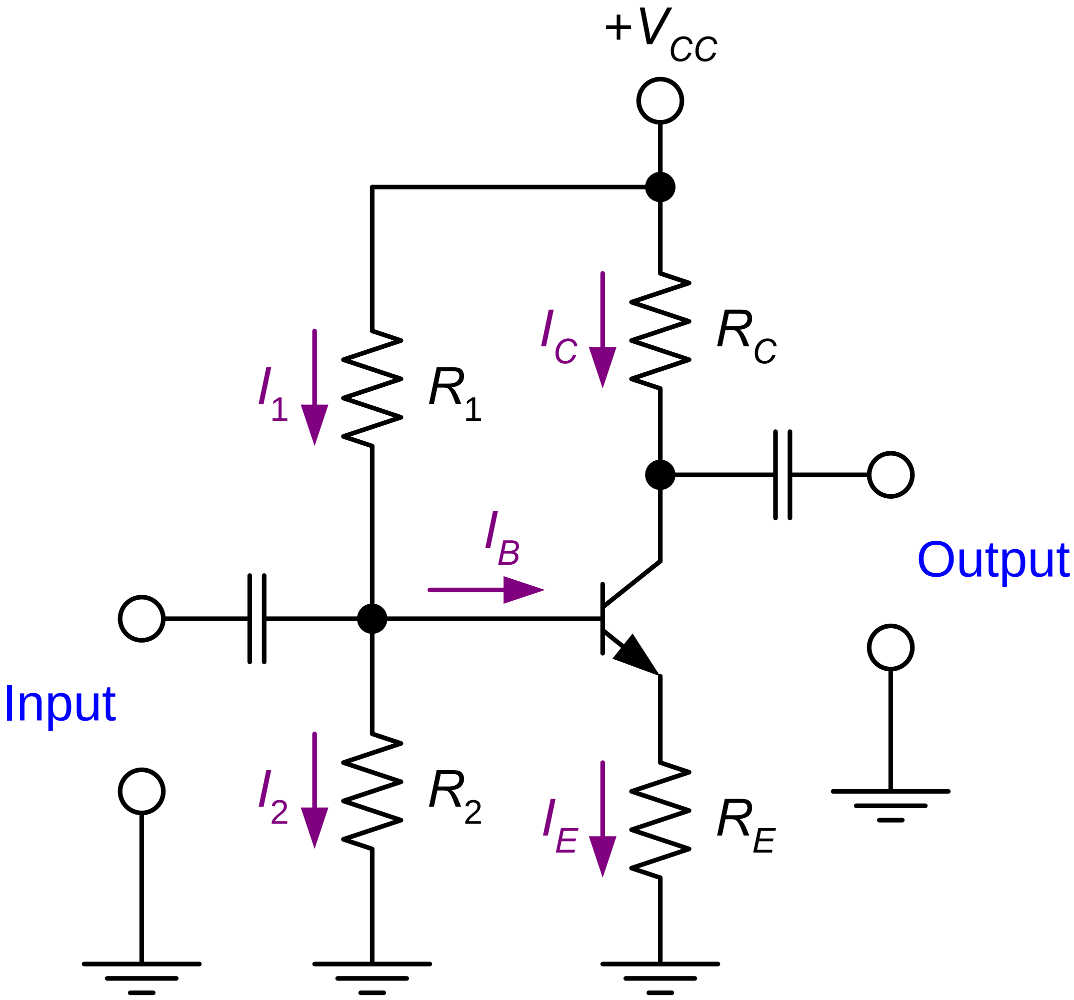
I_{CQ} hardly changes over the entire range of h_{FE}.

Load line for voltage divider bias circuit.



Circuit values are from previous example.

Voltage-divider bias characteristics.



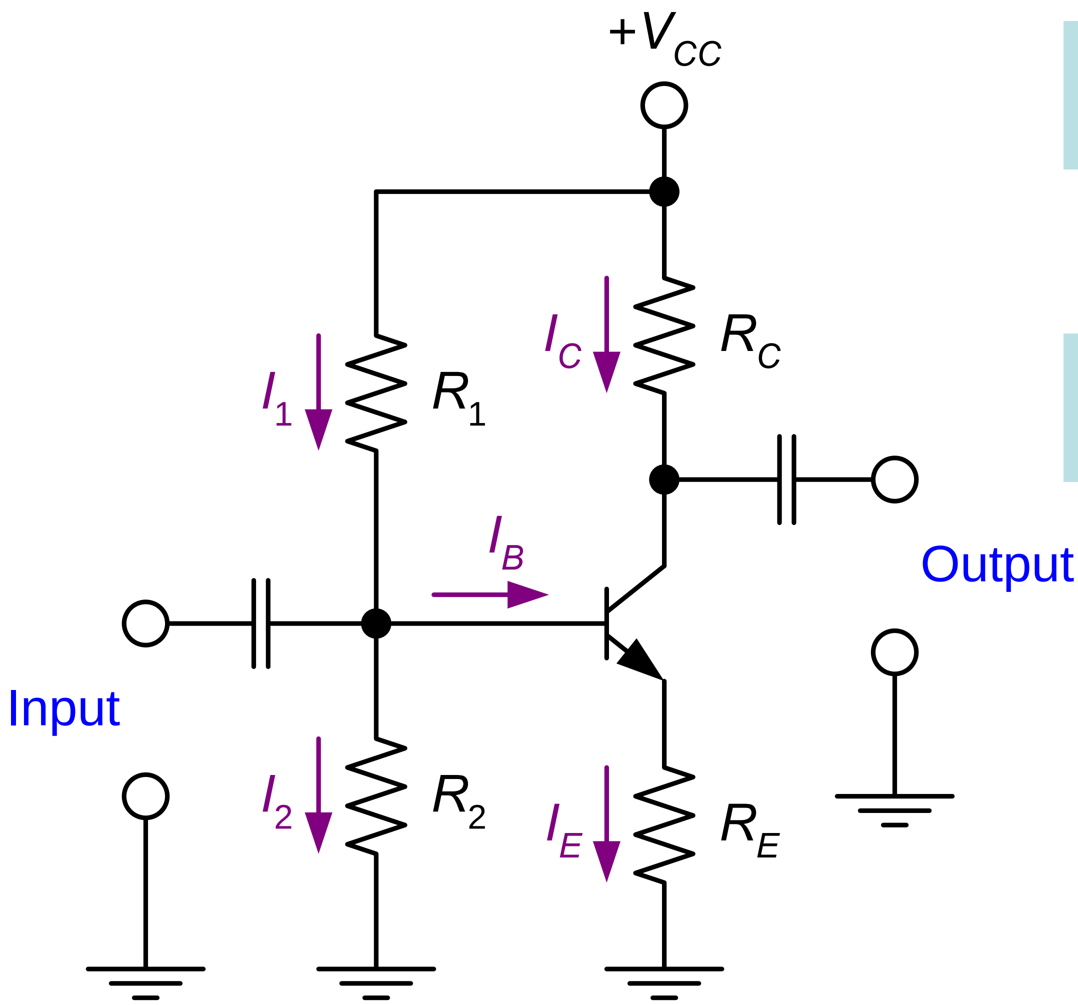
Circuit recognition: The voltage divider in the base circuit.

Advantages: The circuit Q-point values are stable against changes in h_{FE}.

Disadvantages: Requires more components than most other biasing circuits.

Applications: Used primarily to bias linear amplifier.

Voltage-divider bias characteristics.



Load line equations:

$$I_{C(\text{sat})} = \frac{V_{CC}}{R_C + R_E}$$

$$V_{CE(\text{off})} = V_{CC}$$

Q-point equations (assume that $h_{FE}R_E > 10R_2$):

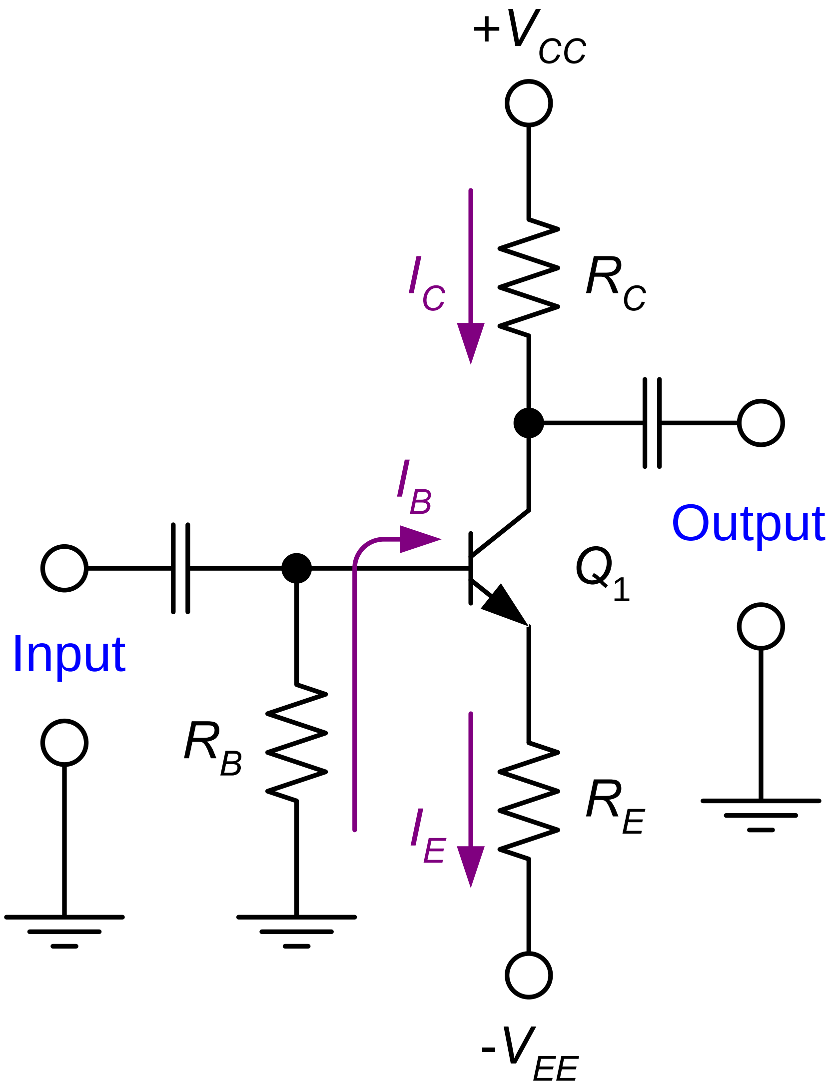
$$V_B = V_{CC}\frac{R_2}{R_1 + R_2}$$

$$V_E = V_B - 0.7\text{V}$$

$$I_{CQ} \cong I_E = \frac{V_E}{R_E}$$

$$V_{CEQ} = V_{CC} - I_{CQ}\left(R_C + R_E\right)$$

3. Emitter bias.



Assume that the transistor operation is in active region.

$$I_B = \frac{V_{EE} - 0.7\text{V}}{R_B + \left(h_{FE} + 1\right) R_E}$$

$$I_C = h_{FE} I_B$$

$$I_E = \left(h_{FE} + 1\right) I_B$$

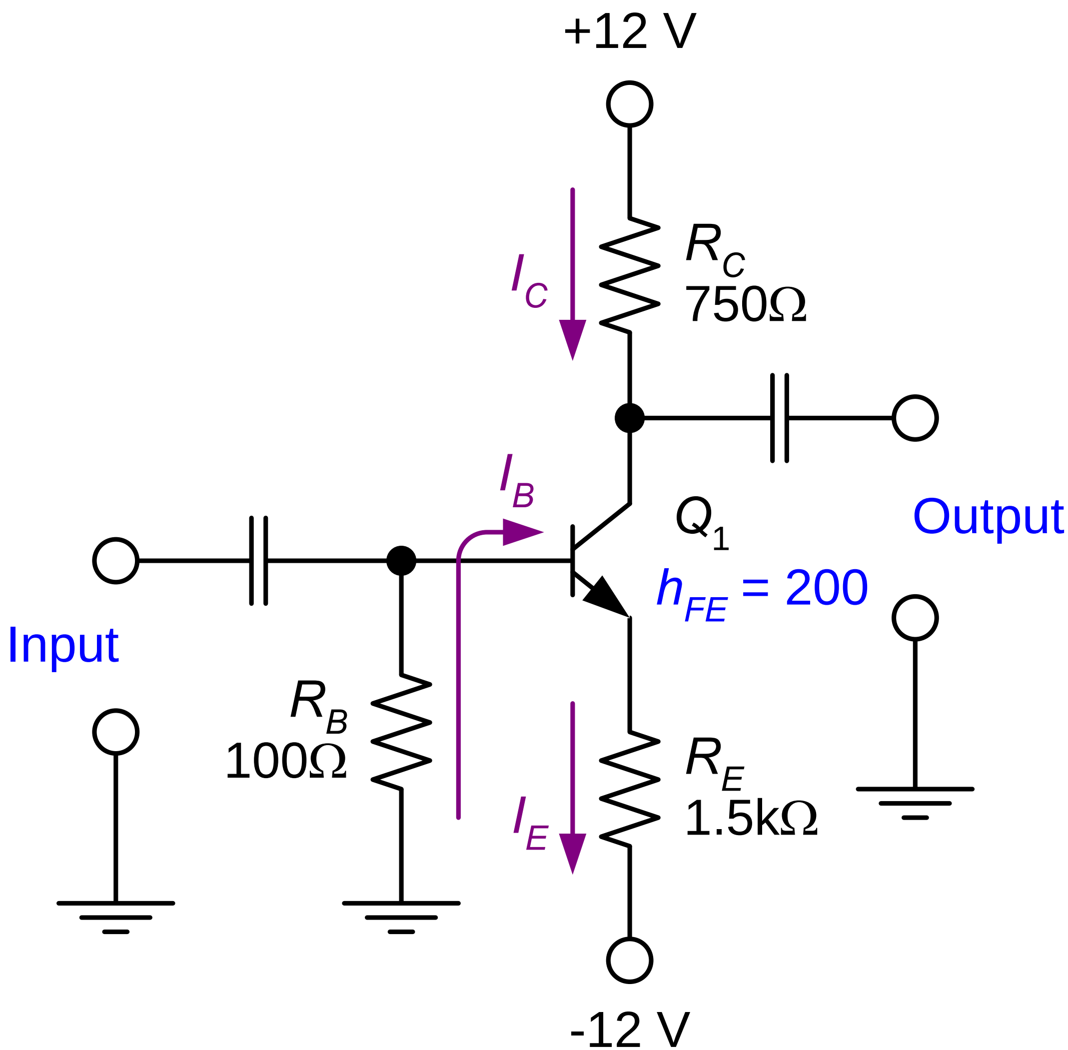
$$V_{CE} = V_{CC} - I_C R_C - I_E R_E + V_{EE}$$

Assume that $h_{FE} \gg 1$.

$$V_{CE} \cong V_{CC} - I_C \left(R_C + R_E\right) + V_{EE}$$

Example

Determine the values of I_{CQ} and V_{CEQ} for the amplifier shown in Fig.



$$I_B = \frac{12\text{V} - 0.7\text{V}}{R_B + (h_{FE}+1)R_E}$$

$$= \frac{11.3\text{V}}{100\Omega + 201 \times 1.5\text{k}\Omega} = 37.47\mu\text{A}$$

$$I_{CQ} = h_{FE} I_B = 200 \times 37.47\mu\text{A}$$

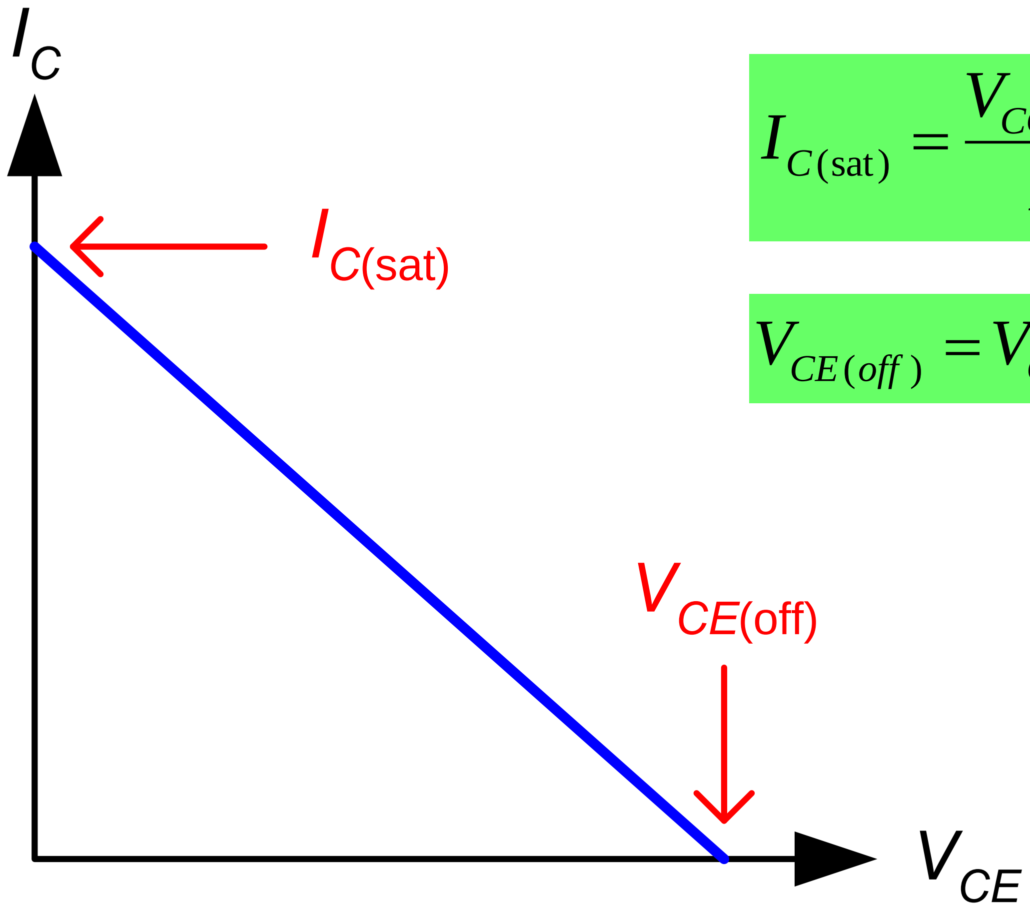
$$= 7.49\text{mA}$$

$$V_{CEQ} \cong V_{CC} - I_C\left(R_C + R_E\right) - (-V_{EE})$$

$$= 24\text{V} - 7.49\text{mA}\left(750\Omega + 1.5\text{k}\Omega\right)$$

$$= 7.14\text{V}$$

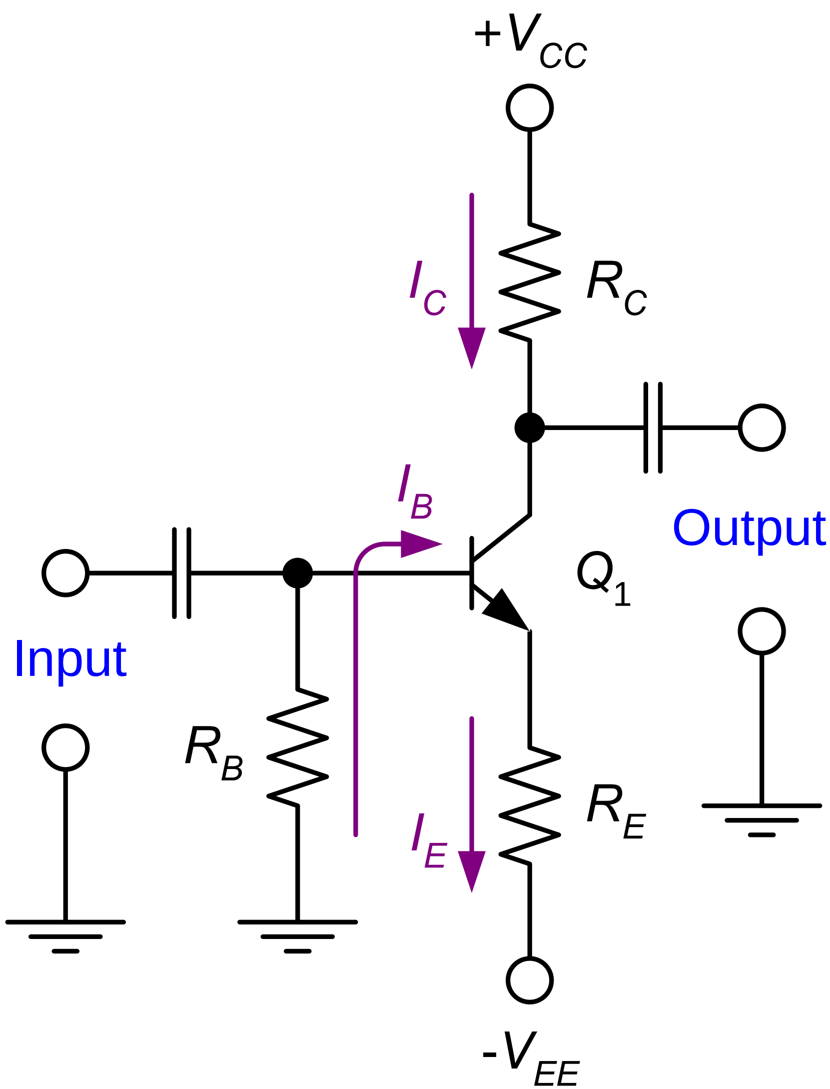
Load Line for Emitter-Bias Circuit



$$I_{C(\text{sat})} = \frac{V_{CC} - (-V_{EE})}{R_C + R_E} = \frac{V_{CC} + V_{EE}}{R_C + R_E}$$

$$V_{CE(off)} = V_{CC} - \left(-V_{EE}\right) = V_{CC} + V_{EE}$$

Emitter-bias characteristics.



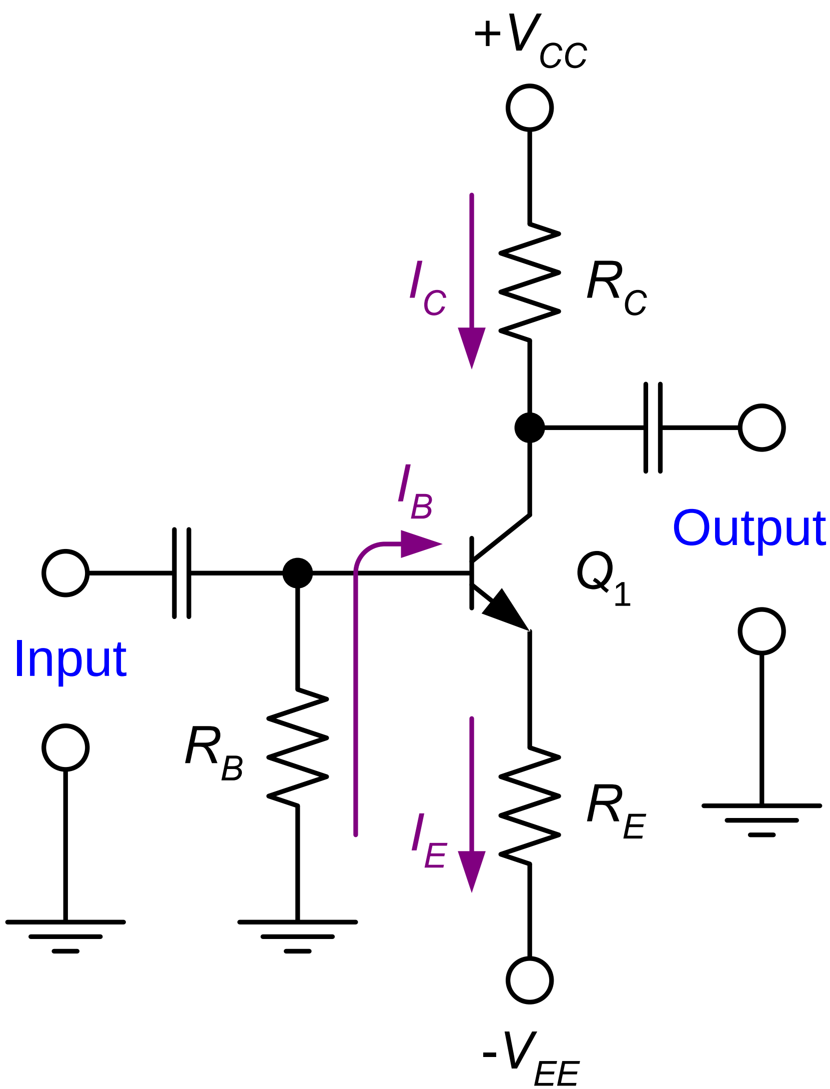
Circuit recognition: A split (dual-polairty) power supply and the base resistor is connected to ground.

Advantage: The circuit Q-point values are stable against changes in h_{FE}.

Disadvantage: Requires the use of dual-polarity power supply.

Applications: Used primarily to bias linear amplifiers.

Emitter-bias characteristics.



Load line equations:

$$I_{C(\text{sat})} = \frac{V_{CC} + V_{EE}}{R_C + R_E}$$

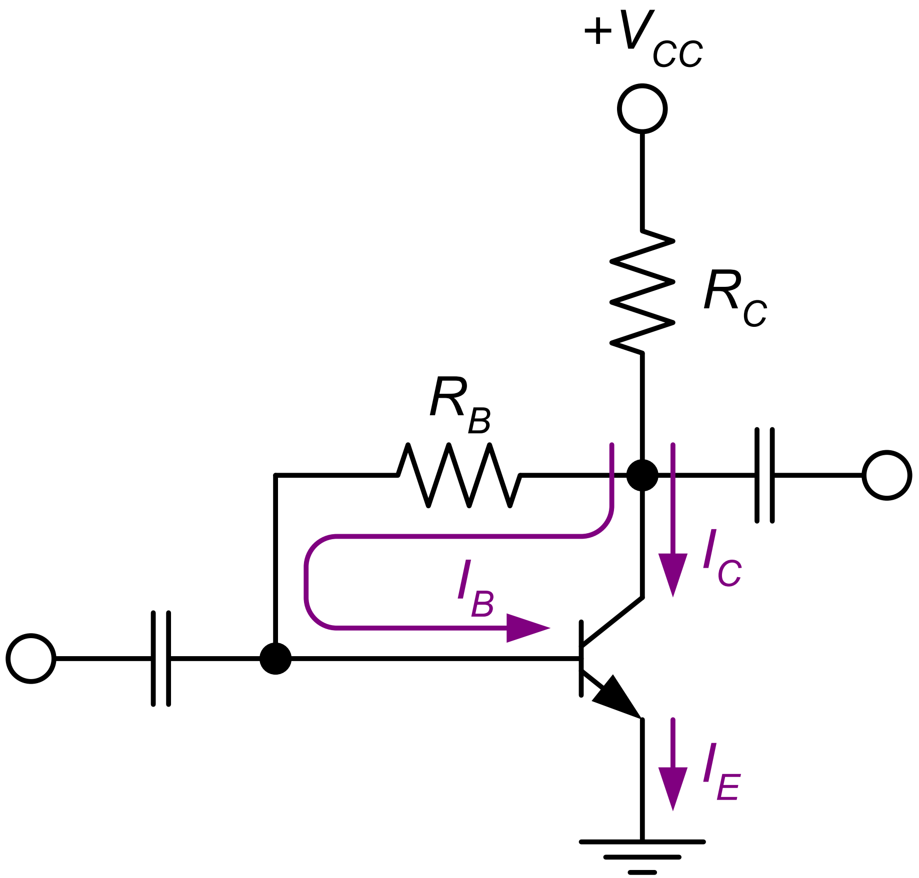
$$V_{CE(\text{off})} = V_{CC} + V_{EE}$$

Q-point equations:

$$I_{CQ} = \left(h_{FE}\right)\frac{-V_{BE} + V_{EE}}{R_B + \left(h_{FE} + 1\right)R_E}$$

$$V_{CEQ} \cong V_{CC} - I_{CQ}\left(R_C + R_E\right) + V_{EE}$$

4. Collector-feedback bias.



$$V_{CC} = \left(I_C + I_B\right)R_C + I_B R_B + V_{BE}$$

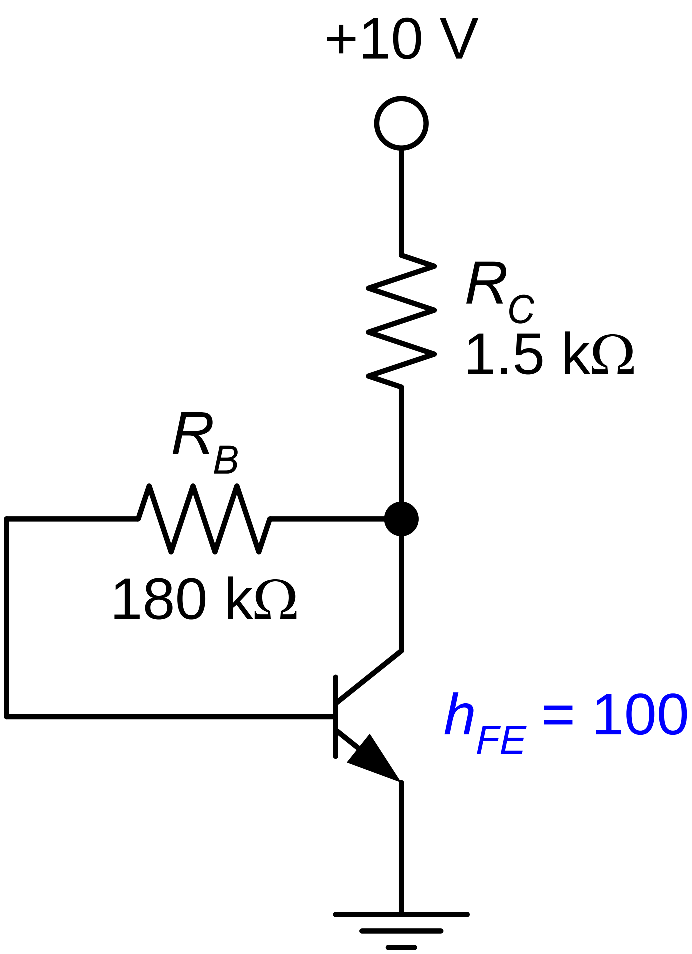
$$I_B = \frac{V_{CC} - V_{BE}}{(h_{FE}+1)R_C + R_B}$$

$$I_{CQ} = h_{FE} I_B$$

$$V_{CEQ} = V_{CC} - \left(h_{FE}+1\right) I_B R_C$$
$$\cong V_{CC} - I_{CQ} R_C$$

Example

Determine the values of I_{CQ} and V_{CEQ} for the amplifier shown in Fig.



$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (h_{FE} + 1) R_C}$$

$$= \frac{10\text{V} - 0.7\text{V}}{180\text{k}\Omega + 101 \times 1.5\text{k}\Omega} = 28.05\mu\text{A}$$

$$I_{CQ} = h_{FE} I_B = 100 \times 28.05\mu\text{A}$$

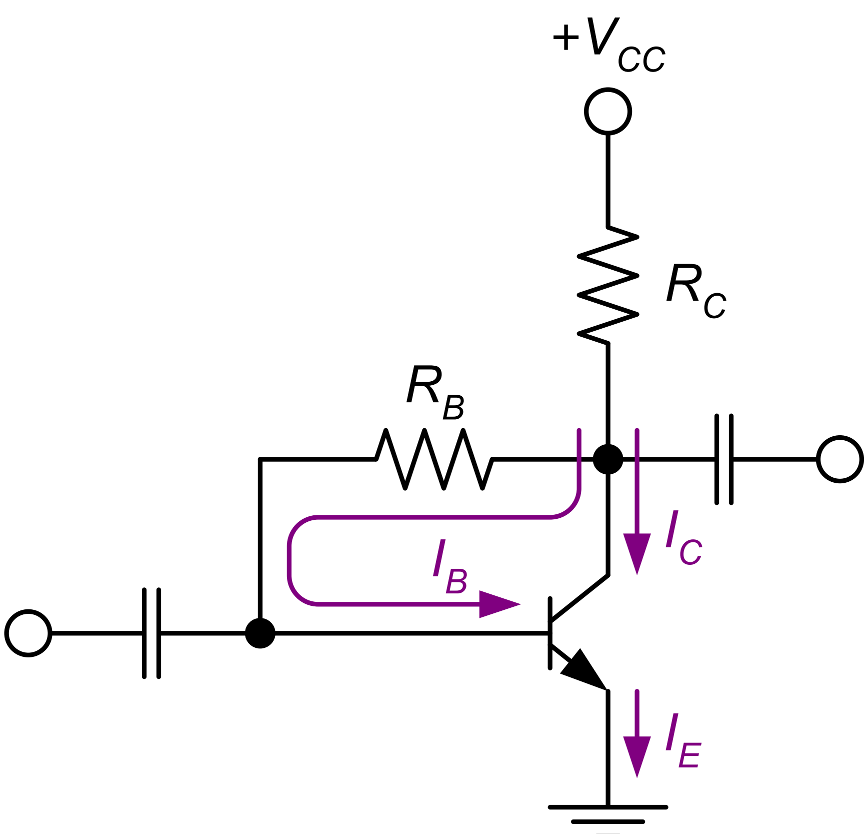
$$= 2.805\text{mA}$$

$$V_{CEQ} = V_{CC} - (h_{FE} + 1) I_B R_C$$

$$= 10\text{V} - 101 \times 28.05\mu\text{A} \times 1.5\text{k}\Omega$$

$$= 5.75\text{V}$$

Circuit Stability of Collector-Feedback Bias



h_{FE} increases

I_C increases (if I_B is the same)

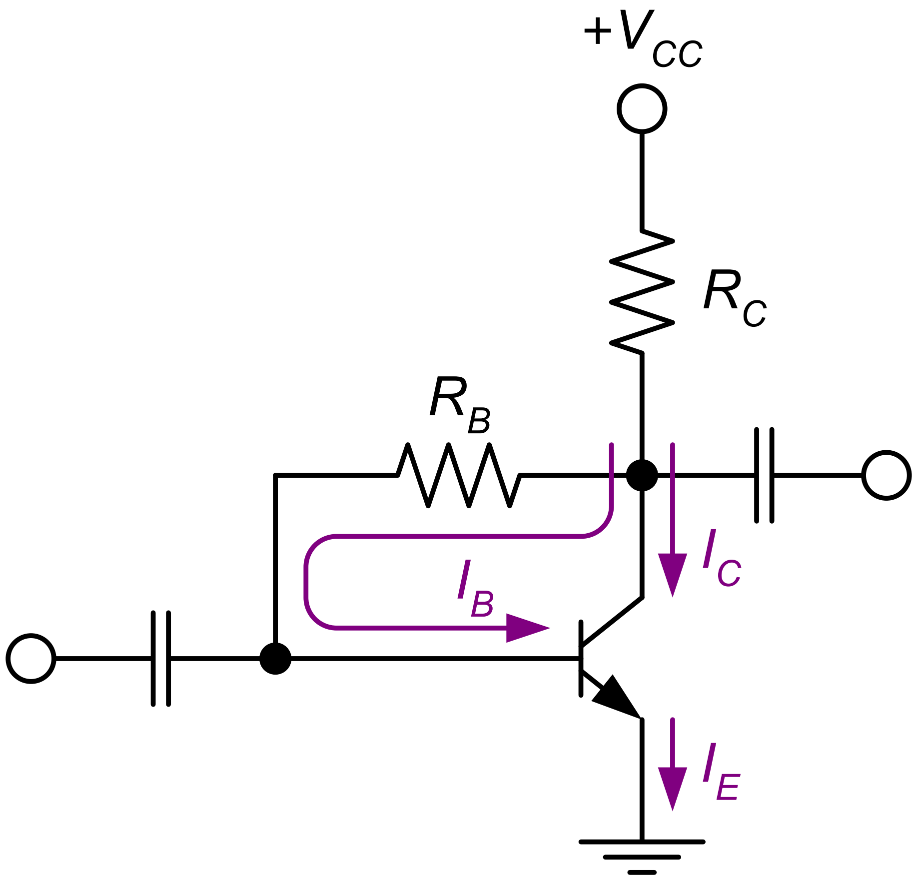
V_{CE} decreases

I_B decreases

I_C does not increase that much.

Good Stability. Less dependent on h_{FE} and temperature.

Collector-Feedback Characteristics



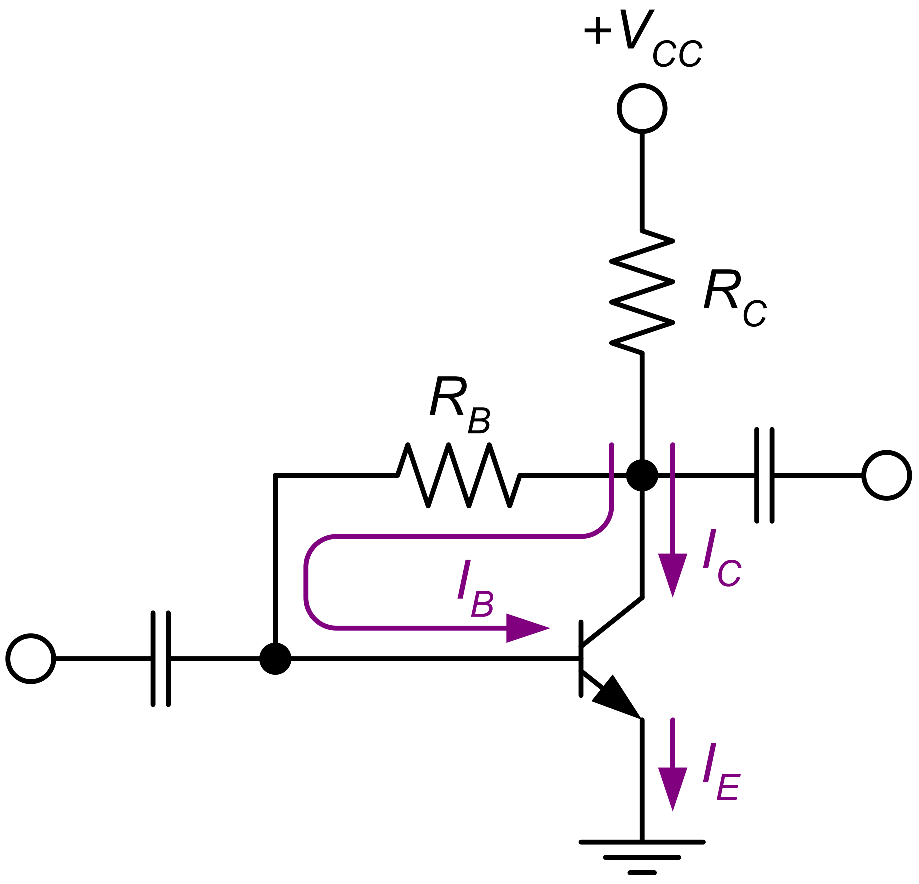
Circuit recognition: The base resistor is connected between the base and the collector terminals of the transistor.

Advantage: A simple circuit with relatively stable Q-point.

Disadvantage: Relatively poor AC characteristics.

Applications: Used primarily to bias linear amplifiers.

Collector-Feedback Characteristics



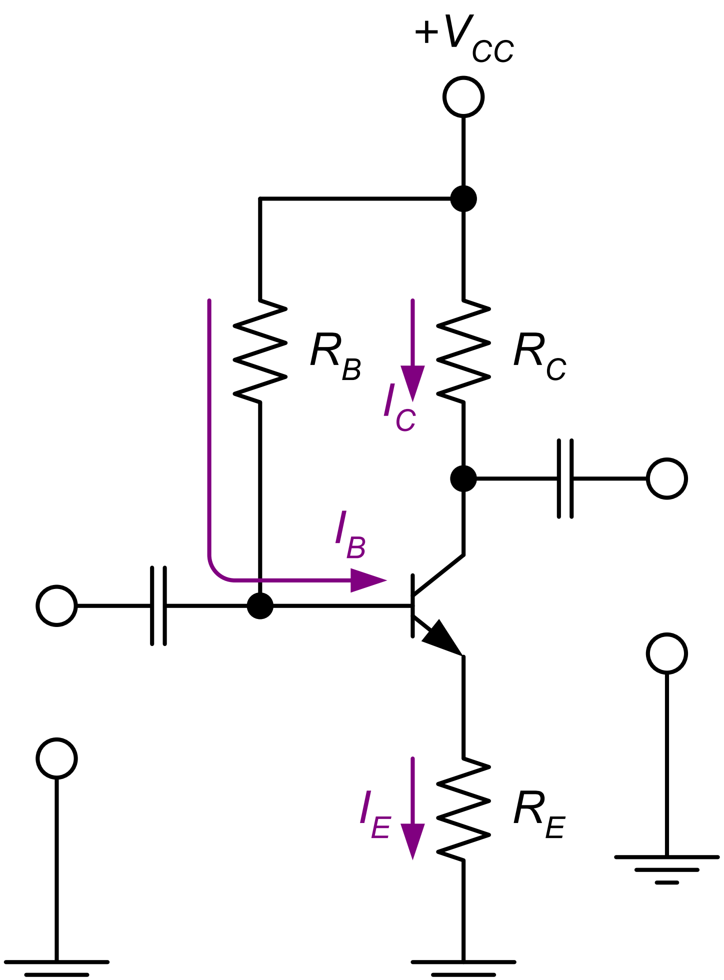
Q-point relationships:

$$I_B = \frac{V_{CC} - V_{BE}}{(h_{FE}+1)R_C + R_B}$$

$$I_{CQ} = h_{FE} I_B$$

$$V_{CEQ} \cong V_{CC} - I_{CQ} R_C$$

5. Emitter-feedback bias.



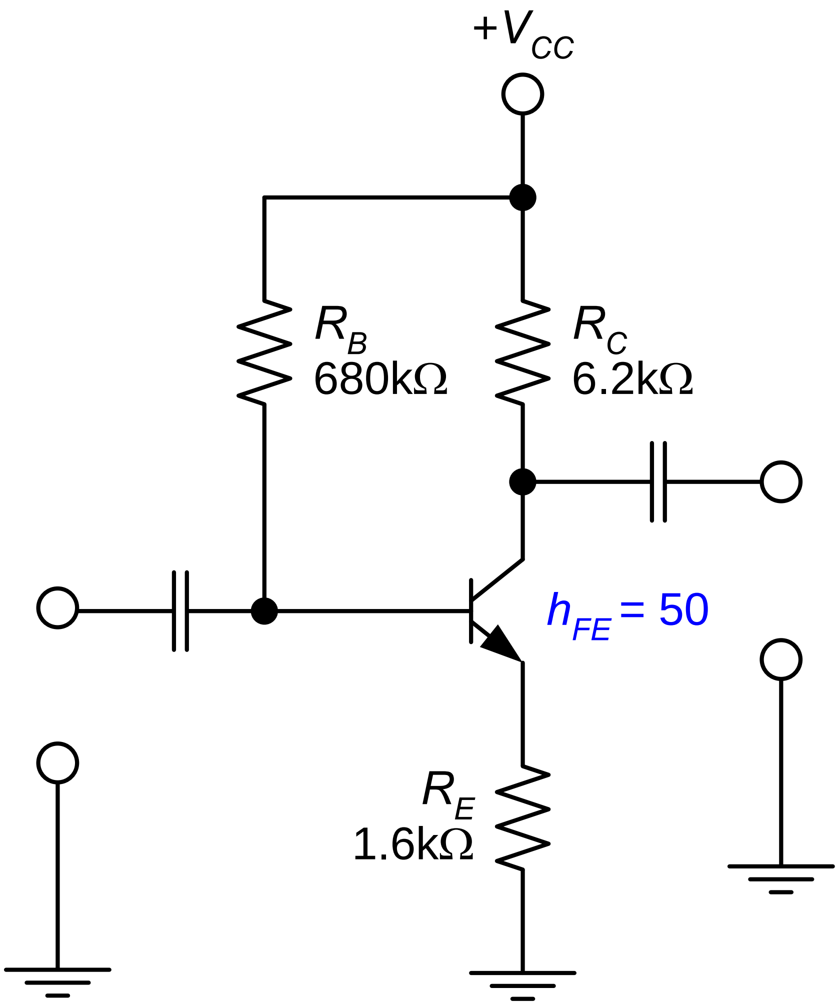
$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (h_{FE} + 1) R_E}$$

$$I_{CQ} = h_{FE} I_B$$

$$I_E = (h_{FE} + 1) I_B$$

$$\begin{aligned} V_{CEQ} &= V_{CC} - I_C R_C - I_E R_E \\ &\cong V_{CC} - I_{CQ}(R_C + R_E) \end{aligned}$$

Example

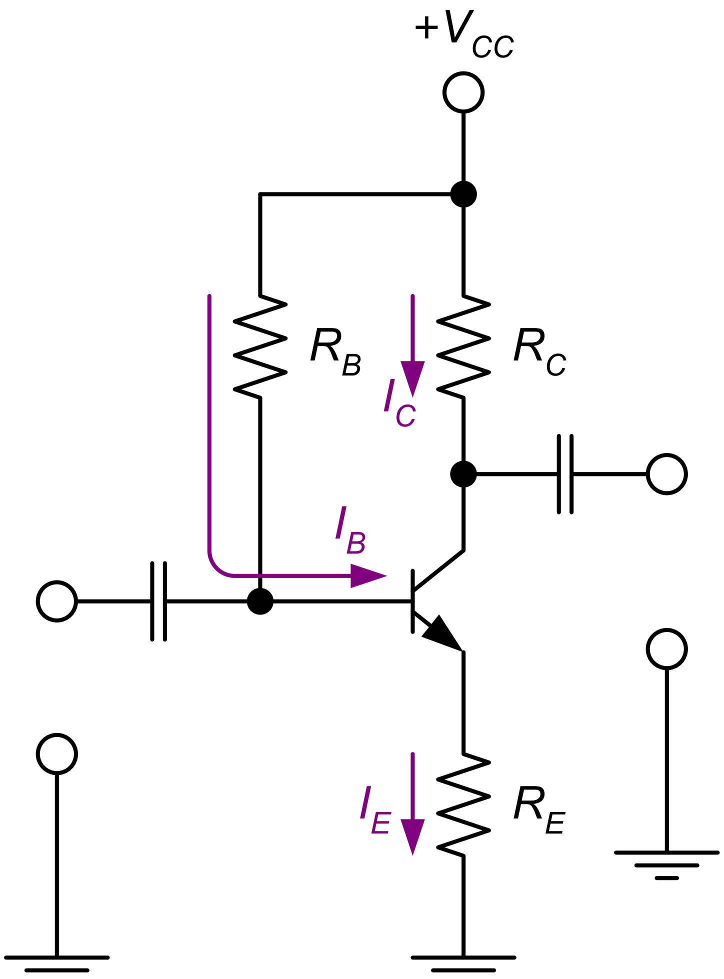


$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \left(h_{FE} + 1\right) R_E} = \frac{16\text{V} - 0.7\text{V}}{680\text{k}\Omega + 51 \times 1.6\text{k}\Omega}$$
$$= 20.09\mu\text{A}$$

$$I_{CQ} = h_{FE} I_B = 50 \times 20.09\mu\text{A} = 1\text{mA}$$

$$V_{CEQ} \cong V_{CC} - I_{CQ}\left(R_C + R_E\right)$$
$$= 16\text{V} - \left(1\text{mA}\right)\left(7.8\text{k}\Omega\right) = 8.2\text{V}$$

Circuit Stability of Emitter-Feedback Bias



h_{FE} increases

↓

I_C increases (if I_B is the same)

↓

V_E increases

↓

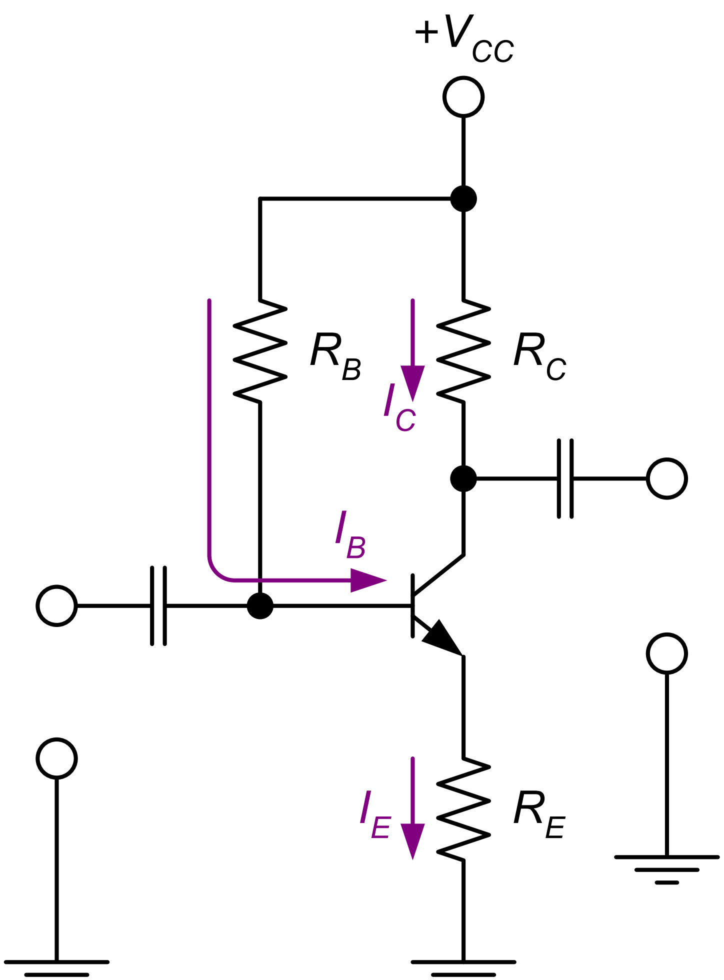
I_B decreases

↓

I_C does not increase that much.

I_C is less dependent on h_{FE} and temperature.

Emitter-Feedback Characteristics



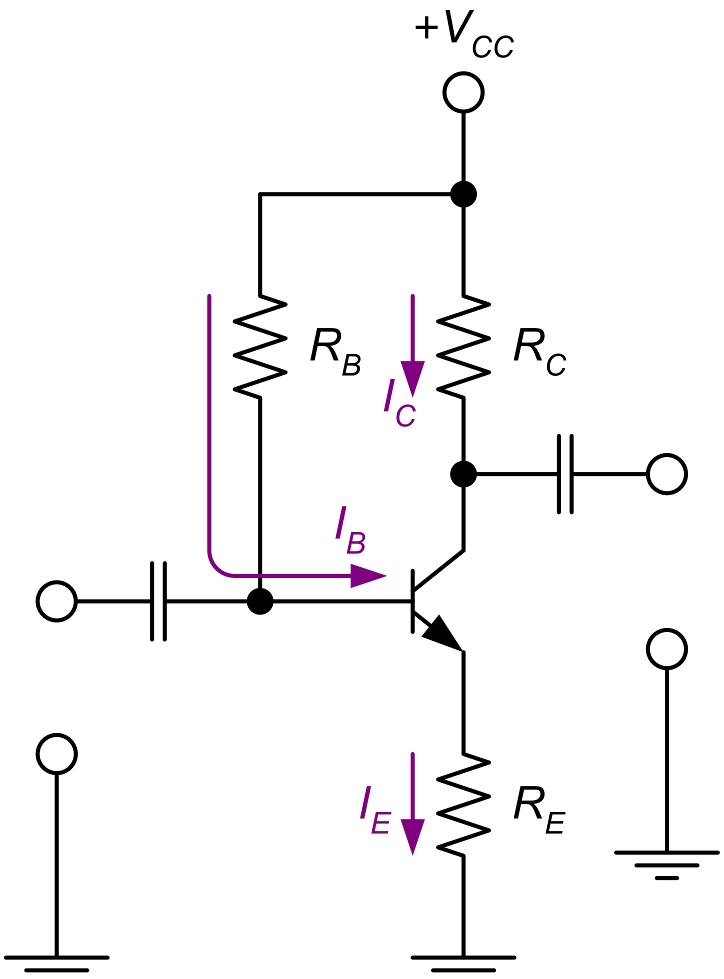
Circuit recognition: Similar to voltage divider bias with R_2 missing (or base bias with R_E added).

Advantage: A simple circuit with relatively stable Q-point.

Disadvantage: Requires more components than collector-feedback bias.

Applications: Used primarily to bias linear amplifiers.

Emitter-Feedback Characteristics



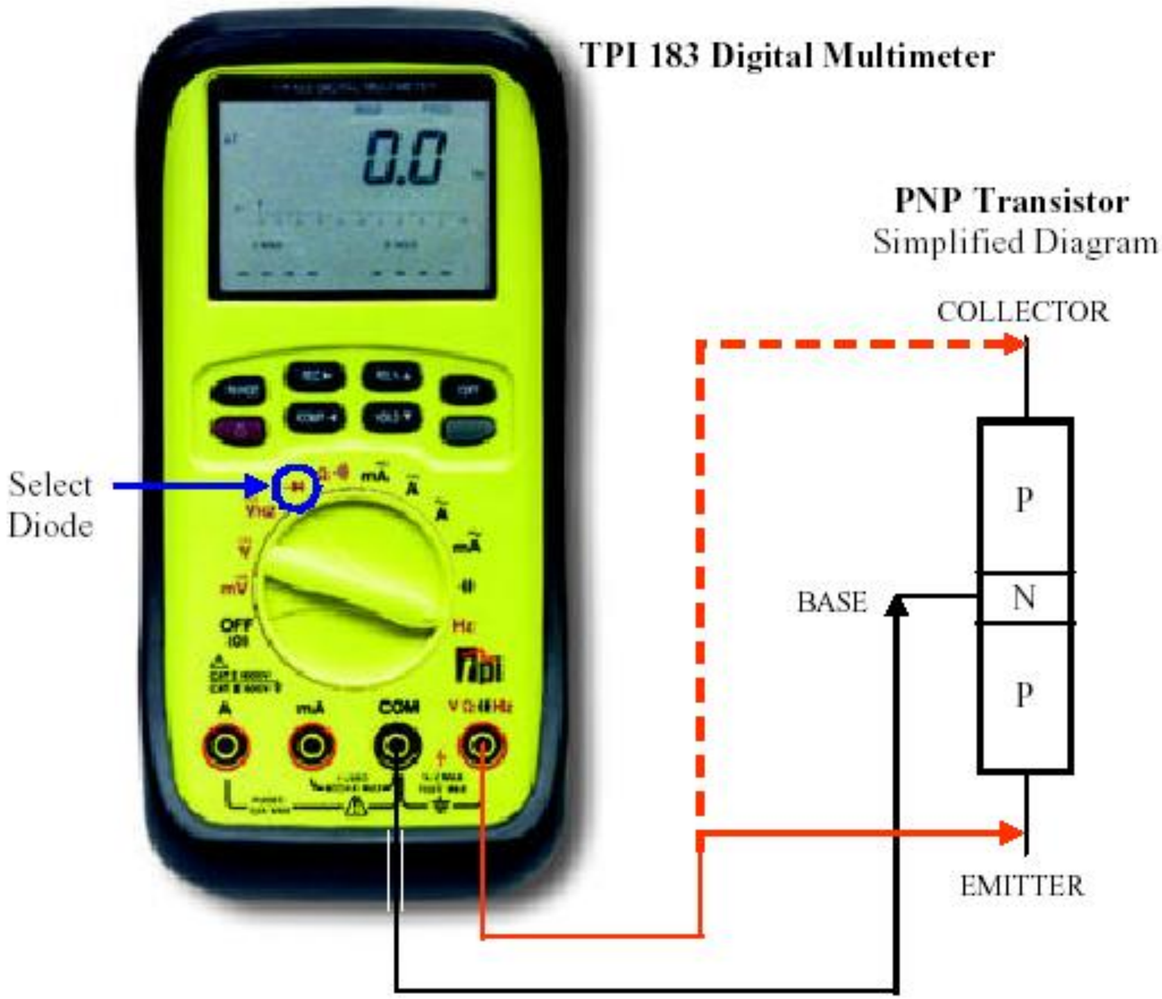
Q-point relationships:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (h_{FE} + 1)R_E}$$

$$I_{CQ} = h_{FE} I_B$$

$$V_{CEQ} \cong V_{CC} - I_{CQ}\left(R_C + R_E\right)$$

BJTs - Testing



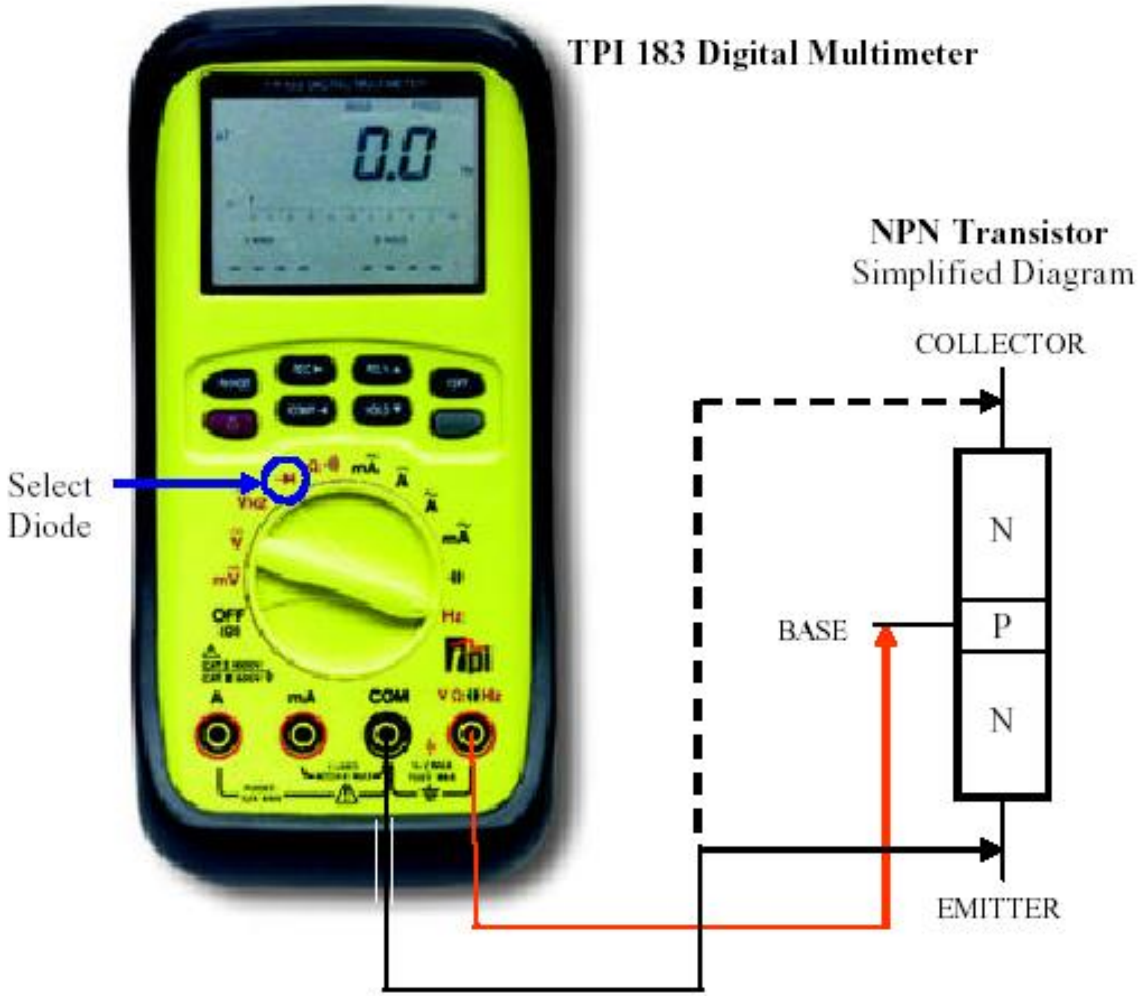
PNP Test Procedure

Connect the meter leads with the polarity as shown and verify that the base-to-emitter and base-to-collector junctions read as a forward biased diode: 0.5 to 0.8 VDC.

Reverse the meter connections to the transistor and verify that both PN junctions do not conduct. Meter should indicate an open circuit. (Display = OUCH or OL.)

Finally read the resistance from emitter to collector and verify an open circuit reading in both directions. (Note: A short can exist from emitter to collector even if the individual PN junctions test properly.)

BJTs - Testing



PNP Test Procedure

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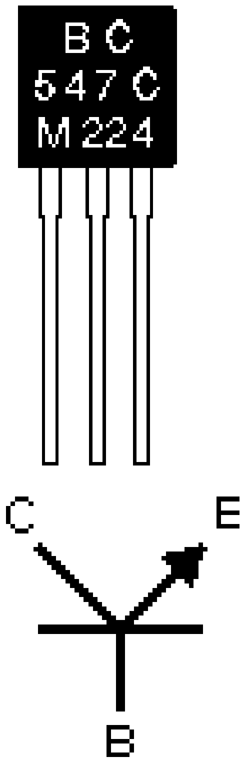
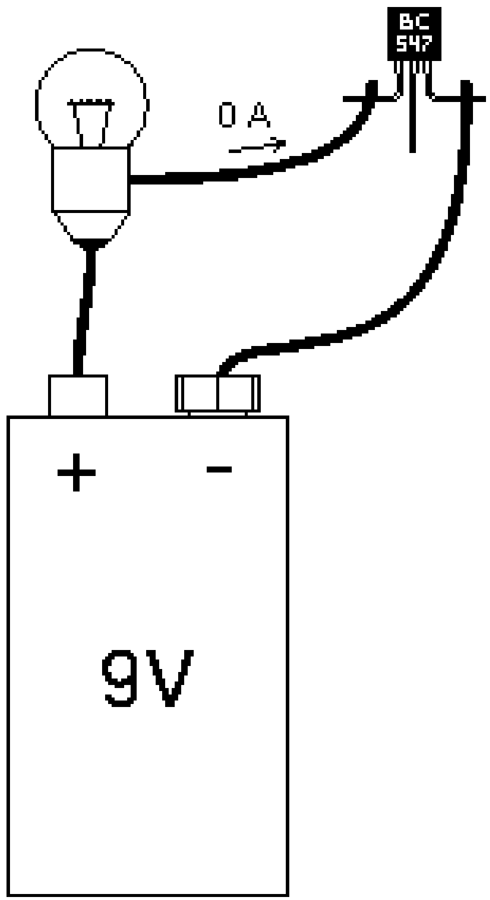
Reverse the meter connections to the transistor and verify that both PN junctions do not conduct. Meter should indicate an open circuit. (Display = OUCH or OL.)

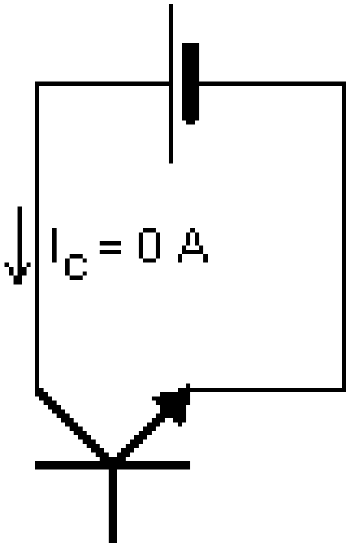
Finally read the resistance from emitter to collector and verify an open circuit reading in both directions. (Note: A short can exist from emitter to collector even if the individual PN junctions test properly.)

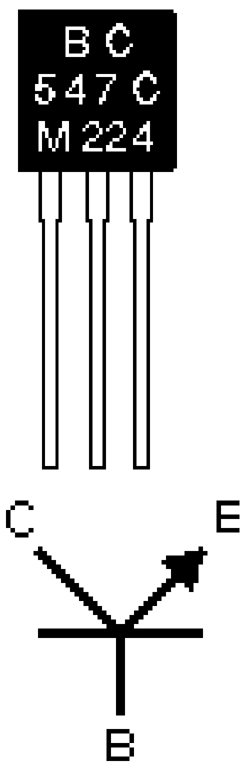
BJTs - Practical Aspects

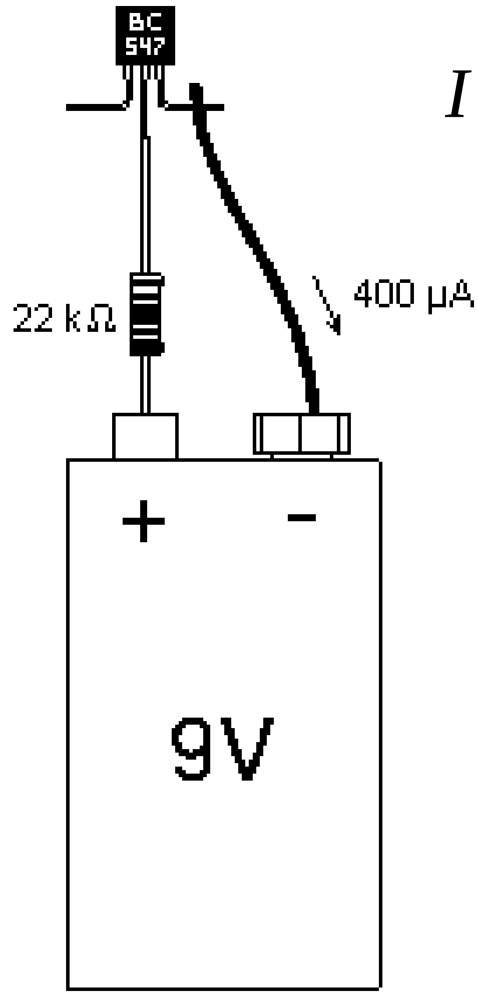


npn

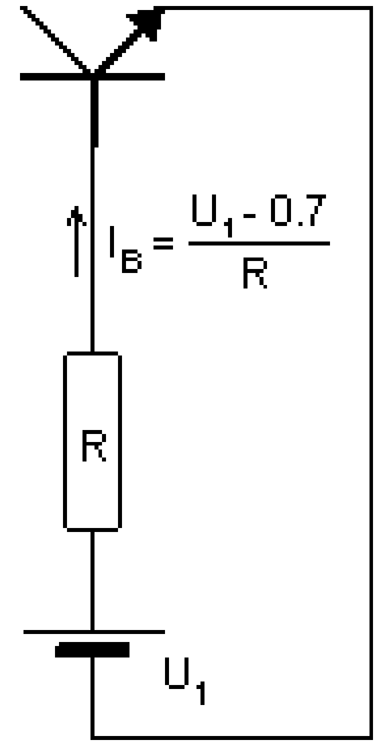


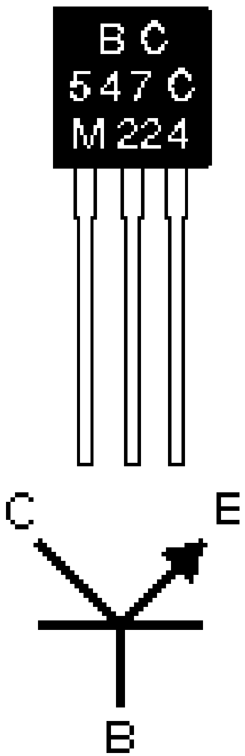




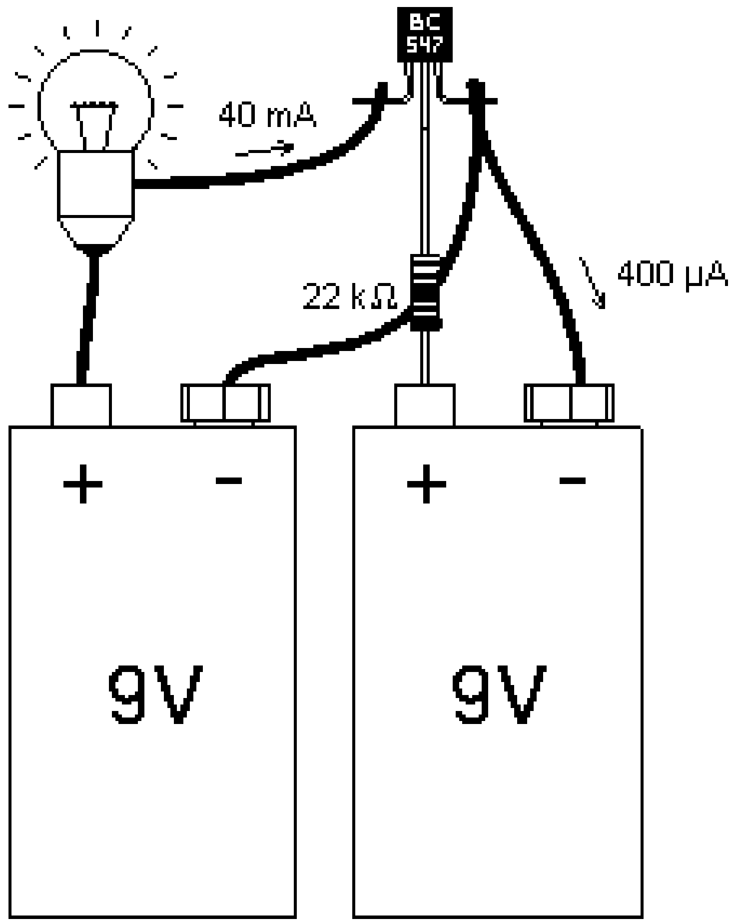


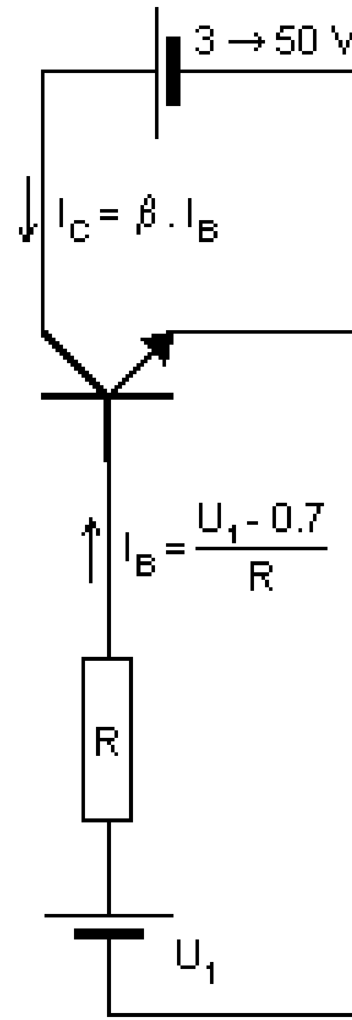
$$I = \frac{V}{R}$$

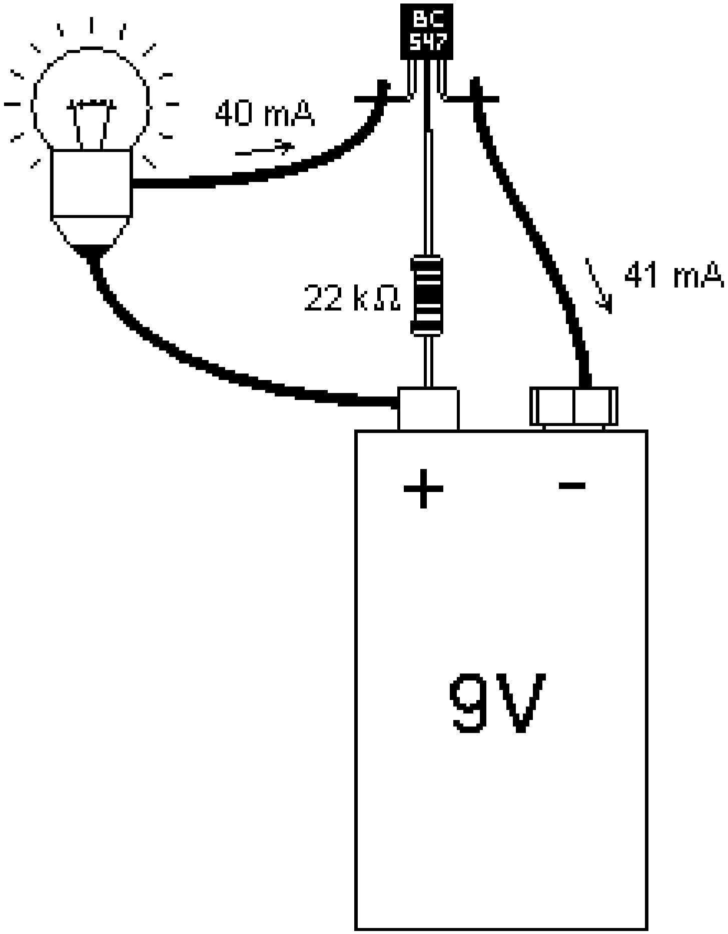


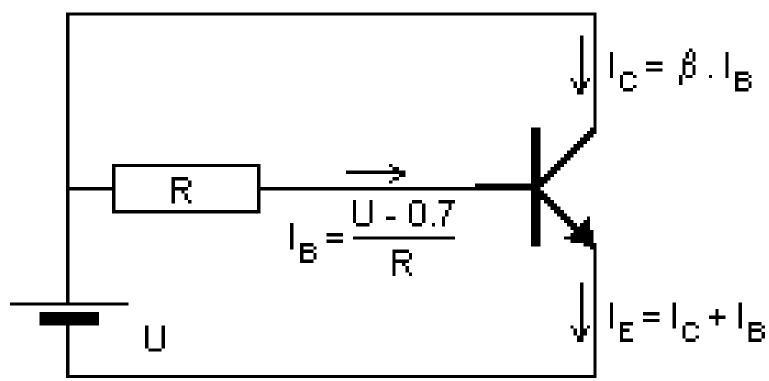

BC
547C
M224
C
E
B

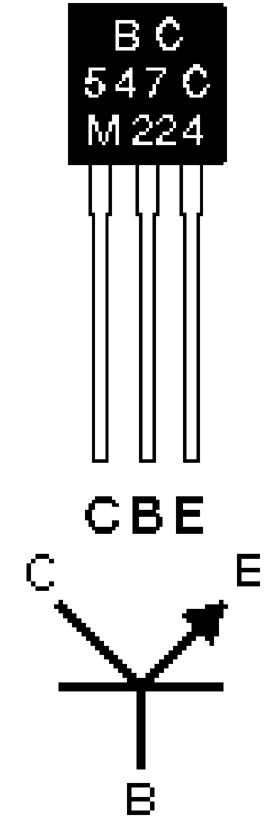
npn


BC
547
40 mA
22 kΩ
400 μA
+
-
9V
+
-
9V


3 → 50 V
$I_C = \beta . I_B$
$I_B = \frac{U_1 - 0.7}{R}$
R
U_1


BC
547
40 mA
22 kΩ
41 mA
+
-
9V

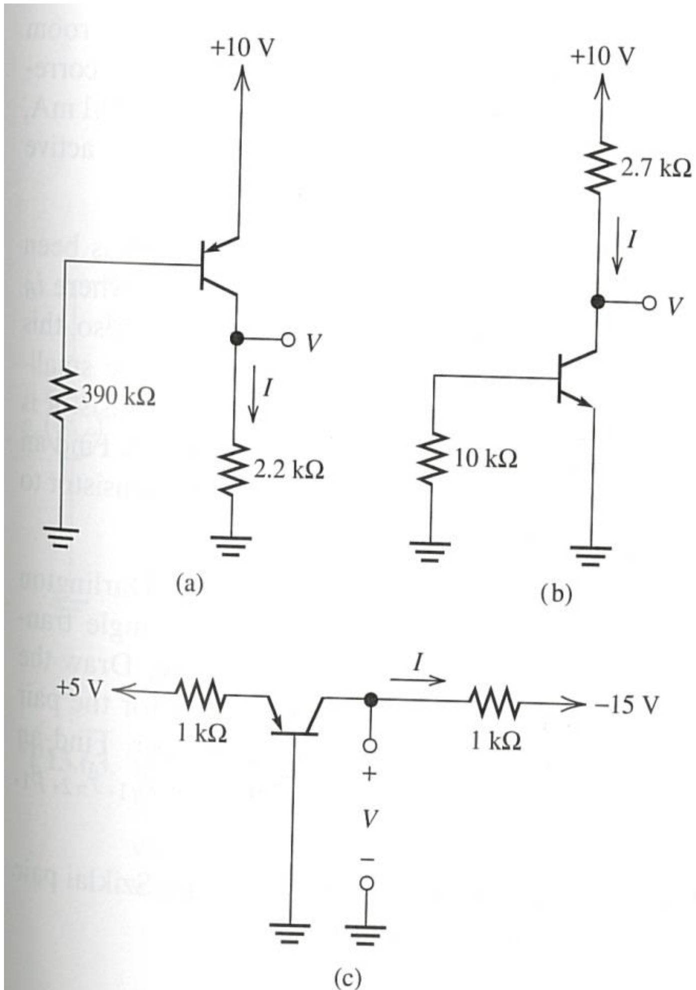

$I_C = \beta . I_B$
R
$I_B = \frac{U - 0.7}{R}$
U
$I_E = I_C + I_B$


B C
547 C
M 224
C B E
C
E
B

npn

Problem :

Analyze the circuits shown in Figure to determine I and V. For all transistors, assume that β = 100 and $|V_{BE}| = 0.7V$ in both the active and saturation regions.



13.45

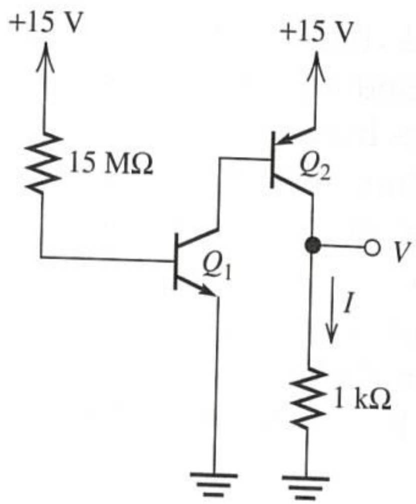
$$(a) \quad for\, \beta = 100$$

$$|V_{BE}| = 0.7 \quad => \quad V_B = 9.3V$$

$$I_B = \frac{9.3}{390k} = 23.8\mu A$$

$$I_C = \beta I_B = 2.38mA \quad => \quad V = I_C * 2.2k = 5.236\,V$$

Problem:



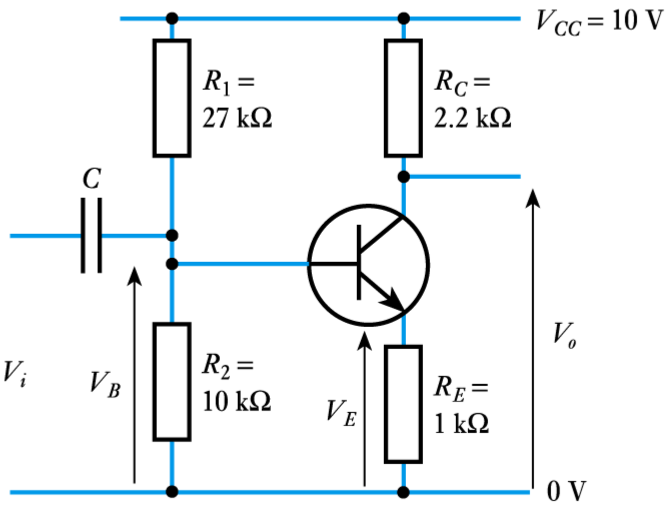
$$For\ \beta = 100$$

$$I_{B1} = \frac{14.3}{15M\Omega} = 0.9533\mu A \qquad I_{C1} = \beta I_{B1} = 95.33\mu A = I_{B2}$$

$$I = I_{C2} = I_{B2} * \beta = 9.533mA \quad => \quad V = I * 1k = 9.533V$$

Problem:

Suppose that npn transistor has VBE = 0.7V. Determine I_C and V_{CE} for transistor and output voltage.



Base current is small, so

$$V_B \approx V_{CC}\frac{R_2}{R_1+R_2} = 10\frac{10\,\text{k}\Omega}{27\,\text{k}\Omega + 10\,\text{k}\Omega} = 2.7\text{ V}$$

Emitter voltage

$$V_E = V_B - V_{BE} = 2.7 - 0.7 = 2.0\text{ V}$$

Emitter current

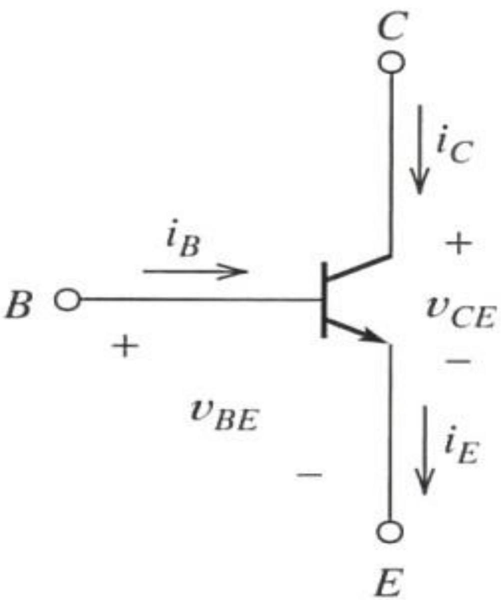
$$I_E = \frac{V_E}{R_E} = \frac{2.0\text{ V}}{1\text{k}\Omega} = 2\,\text{mA}$$

Since I_B is small, **collector current** $I_C \approx I_E = 2$ mA

Output voltage = $V_{CC} - I_C R_C = 10 - 2\text{ mA} \times 2.2\text{ k}\Omega = 5.6$ V

Problem:

Suppose that a certain *npn* transistor has V_{BE} = 0.7V for I_E =10mA. Compute V_{BE} for I_E = 1mA. Assume that V_T = 26mV.



$$I_E = I_{ES}\left(\exp\left(\frac{V_{BE}}{V_T}\right)-1\right) \approx I_{ES}\exp\left(\frac{V_{BE}}{V_T}\right)$$

$$10\text{mA} = I_{ES}\exp\left(\frac{0.7}{0.026}\right) \quad \textit{and} \quad 1\text{mA} = I_{ES}\exp\left(\frac{V_{BE}}{0.026}\right)$$

$$\textit{divide both sides} \quad \Rightarrow \quad 10 = \exp\left(\frac{0.7 - V_{BE}}{0.026}\right)$$

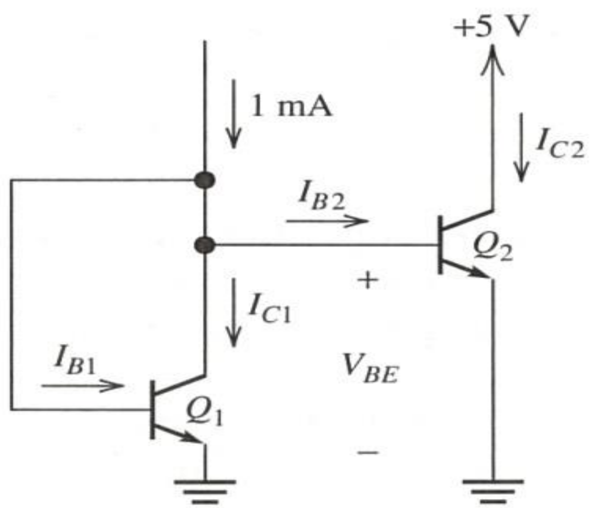
$$\Rightarrow \quad 0.026 * \ln 10 = 0.7 - V_{BE}$$

$$\therefore V_{BE} = 0.7 - 0.026 * \ln 10 = 0.64[V]$$

Problem:

Consider the circuit shown in Figure. Transistors Q_1 and Q_2 are identical, both having $I_{ES} = 10^{-14} A$ and $\beta = 100$. Calculate V_{BE} and I_{C2}. Assume that $V_T = 26mV$ for both transistors.

Hint: Both transistors are operating in the active region. Because the transistors are identical and have identical values of V_{BE}, their collector currents are equal.



$$I_{B1} + I_{B2} + I_C = 1mA \quad \& \quad I_C = \beta I_B$$

$$\Rightarrow \quad I_C\left(\frac{2}{\beta} + 1\right) = 1mA \quad \Rightarrow \quad I_C = \frac{1mA}{1.02} = 0.98mA$$

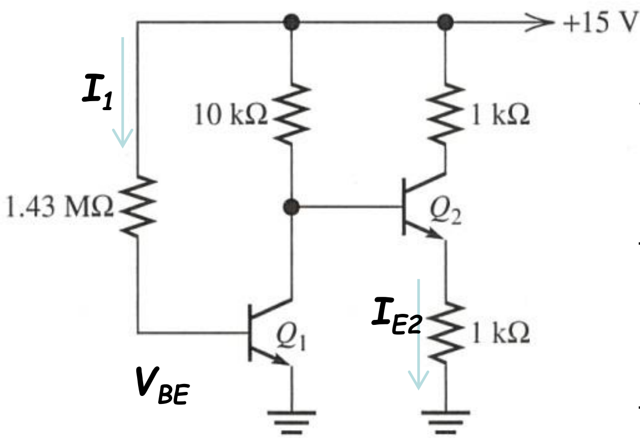
$$I_E = \left(1 + \frac{1}{\beta}\right) I_C = 0.99mA$$

$$\sin ce \quad I_E \approx I_{ES} \exp\left(\frac{V_{BE}}{V_T}\right) \quad we\ have$$

$$\therefore V_{BE} = V_T \ln \frac{I_E}{I_{ES}} = 0.026 * \ln\left(0.99 * 10^{11}\right) = 0.658V$$

Problem:

The transistors shown in Figure operate in active region and have β = 100, V_{BE}=0.7V. Determine I_C and V_{CE} for each transistor.



$$I_1 = \frac{14.3}{1.43M\Omega} = 10\mu A \qquad I_{C1} = \beta I_1 = 1mA$$

$$\frac{(15-(I_{E2}*1k+0.7))}{10k} = I_{C1} + \frac{I_{E2}}{\beta+1}$$

$$\frac{14.3}{10k} - \frac{I_{E2}}{10} = 1mA + \frac{I_{E2}}{101}$$

$$0.43mA = I_{E2} * \left(\frac{1}{101} + \frac{1}{10}\right)$$

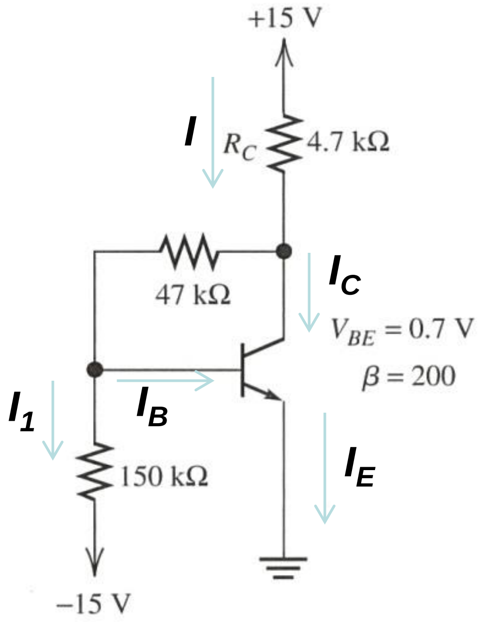
$$I_{E2} = 3.9126mA \quad => \quad I_{C2} = 0.99 I_{E2} = 3.8735mA$$

$$V_{CE2} = 15 - 1k*(I_{C2} + I_{E2}) = 15 - 1.99k * I_{E2} = 7.213V$$

$$V_{CE1} = 15 - 10k * \left(1mA + \frac{I_{C2}}{\beta}\right) = 4.6126V$$

Problem:

Analyze the circuit of Figure determine I_C and V_{CE}.



$$I = I_1 + I_E \qquad I_C = \beta I_B$$

$$I_1 = \frac{(0.7+15)V}{150K\Omega} = 0.1047mA \qquad I_E = (\beta+1)I_B$$

$$(I_1 + I_B)*47k\Omega + 0.7 + I*4.7k\Omega = 15V$$

$$I_1*47k + I_B*47k + 0.7 + I_1*4.7k + (\beta+1)*I_B*4.7k = 15V$$

$$I_1*(47k+4.7k) = 15 - 0.7 - I_B*(47k + 201*4.7k)$$

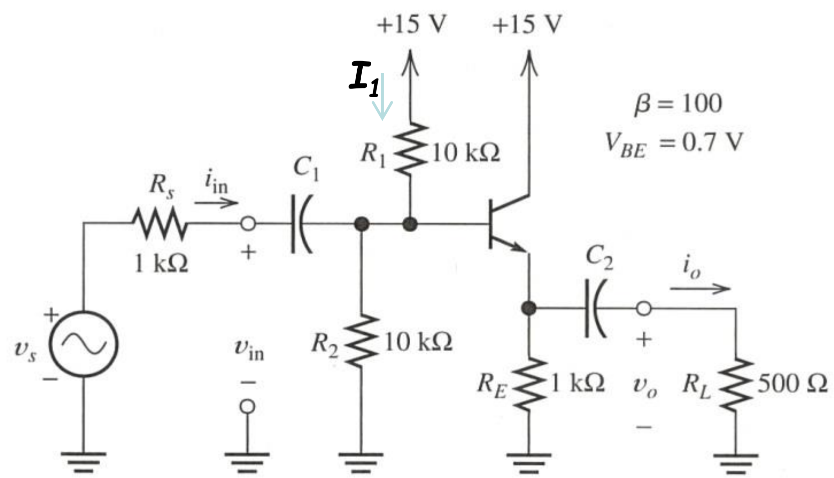
$$I_B = \frac{14.3 - 0.1047mA*51.7k}{47k + 944.7k} = \frac{14.3-5.413}{991.7k} = 9.0\mu A$$

$$I_C = \beta I_B = 1.8mA$$

$$V_{CE} = V_{BE} + 47k*(I_1 + I_B) = 0.7 + 47k*0.1137mA = 6.04V$$

Problem:

Consider the emitter-follower amplifier of Figure. Draw the DC circuit and find I_{CQ}.



DC Analysis

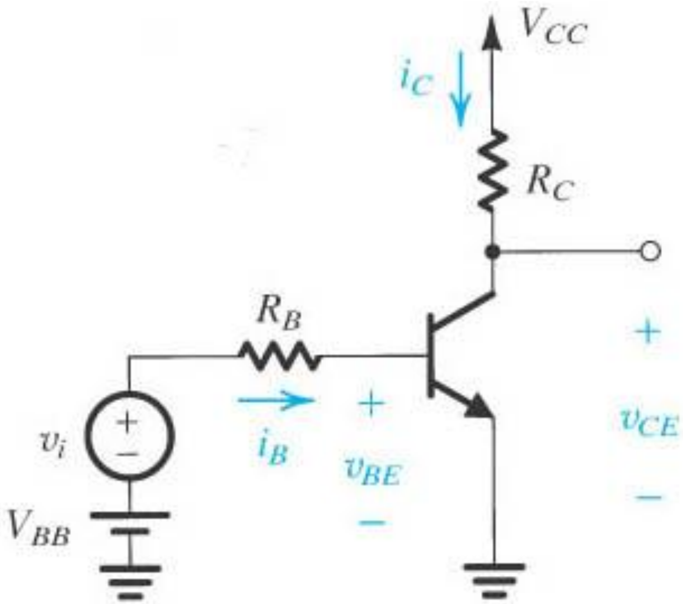
$$I_1 * 10k + (I_1 - I_{BE}) * 10k = 15V \quad \Rightarrow \quad I_1 * 20k - I_B * 10k = 15V$$

$$15 - I_1 * 10k - 0.7 = (1+\beta) * I_B * 1k\Omega \quad \Rightarrow \quad I_1 * 10k + I_B * 101k = 14.3V$$

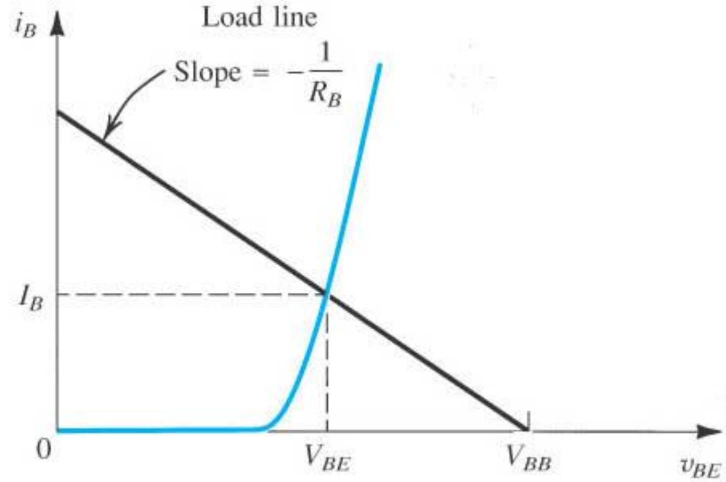
multiply 2nd *equation by* 2 *and subtract the first one*

$$I_B * (202k + 10k) = 28.6 - 15 \qquad I_B = \frac{13.6}{212k} = 64.2\mu A$$

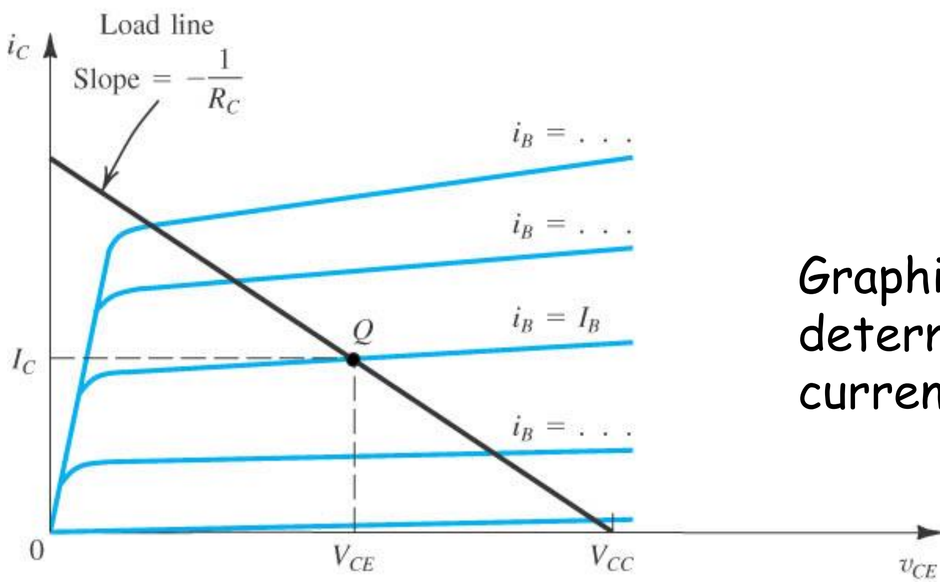
$$I_{CQ} = I_B * \beta = 6.42mA$$



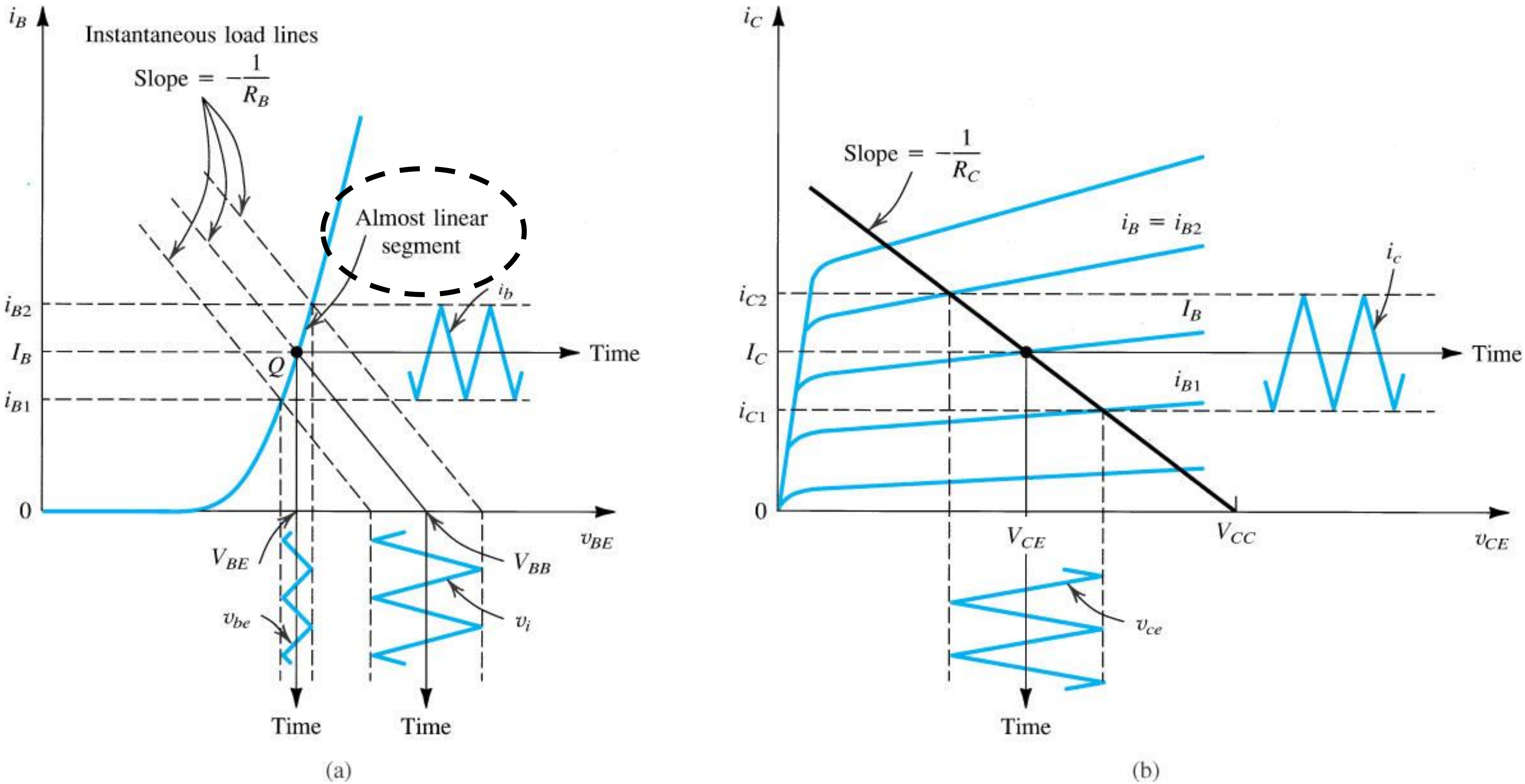
Circuit whose operation is to be analyzed graphically.



Graphical construction for the determination of the dc base current in the circuit (input)



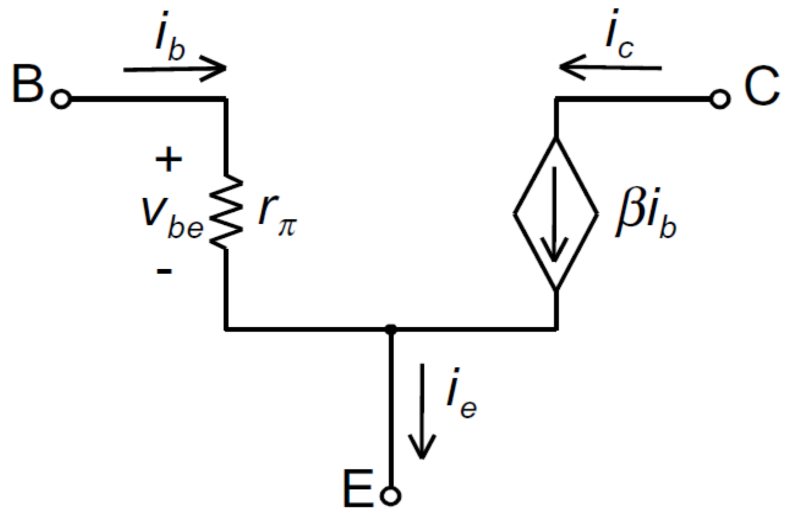
Graphical construction for the determination of the dc base current in the circuit (output)



Graphical determination of the signal components v_{be}, i_b, i_c, and v_{ce} when a signal component v_i is superimposed on the dc voltage V_{BB}

Small-Signal Equivalent Circuit

Small signal equivalent circuit for BJT:



$$i_B = I_{BQ} + i_b(t) =$$

$$= (1-\alpha) I_{ES}\left[\exp\left(\frac{v_{BEQ} + v_{be}(t)}{V_T}\right)\right]$$

$$= I_{BQ}\left[\exp\left(\frac{v_{be}(t)}{V_T}\right)\right]$$

$$\exp(x) = 1 + x,$$

$$I_{BQ} + i_b(t) = I_{BQ}\left(1 + \frac{v_{be}(t)}{V_T}\right)$$

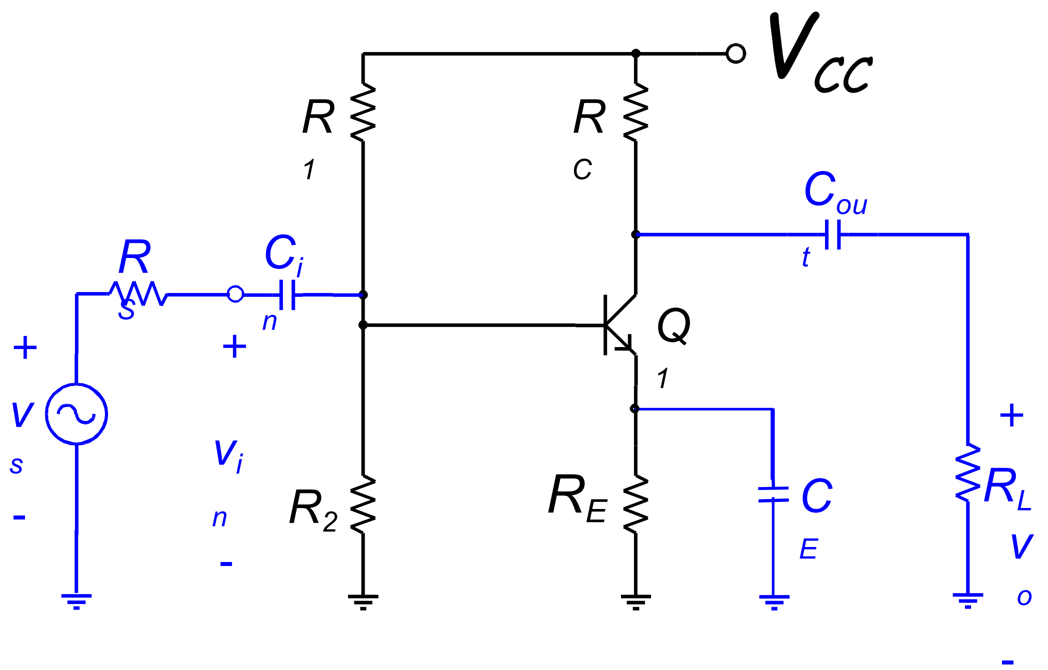
so

$$i_b(t) = I_{BQ}\frac{v_{be}(t)}{V_T} = \frac{v_{be}(t)}{r_\pi}$$

and

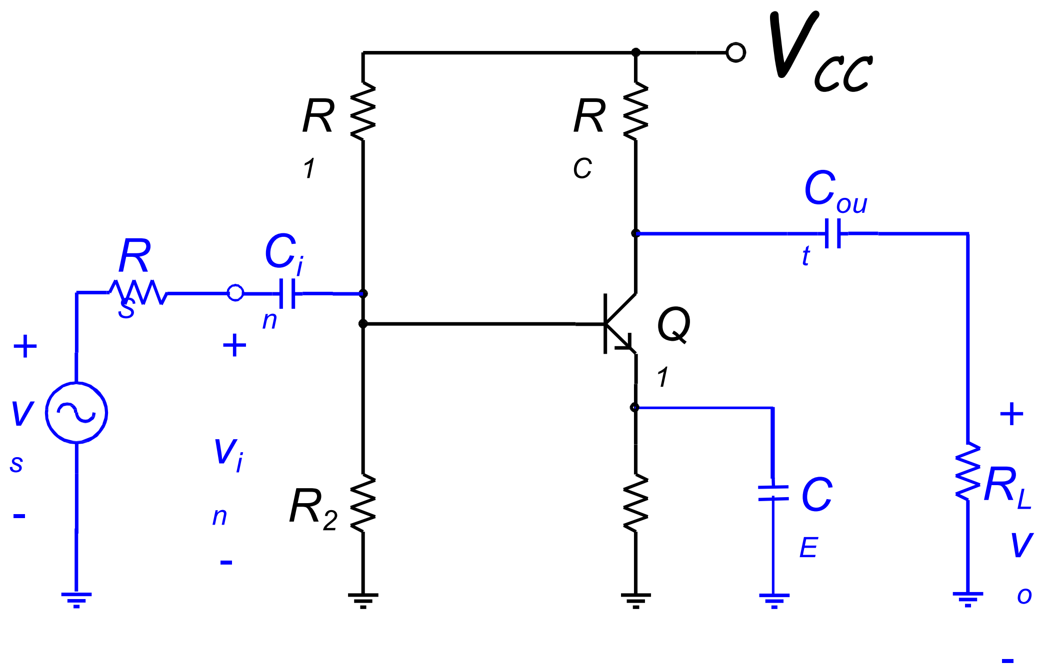
$$r_\pi = \frac{V_T}{I_{BQ}}$$

DC ANALYSIS



1. Replace all capacitors with OPEN circuits.
2. Set all *AC* sources to zero, *because they have zero signal component*!!!

Constructing the Small-Signal Equivalent Circuit

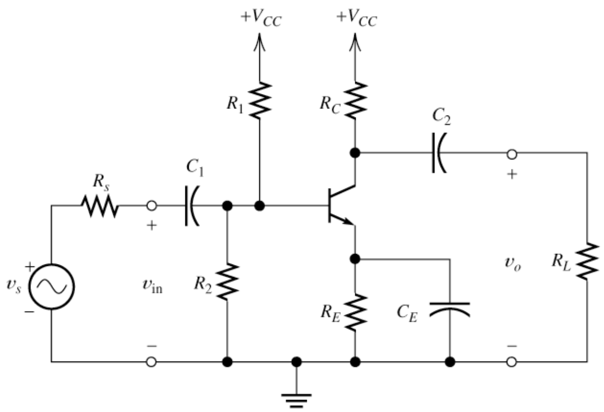


To construct small-signal equivalent circuit for entire amplifier, we:

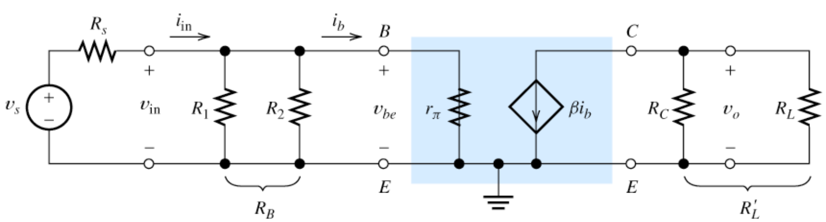
1. Replace the BJT by its small-signal model.
2. Replace all capacitors with short circuits.
3. Set all DC sources to zero, <u>*because they have zero signal component*</u>!!!

The result is the small-signal equivalent circuit of the amplifier:

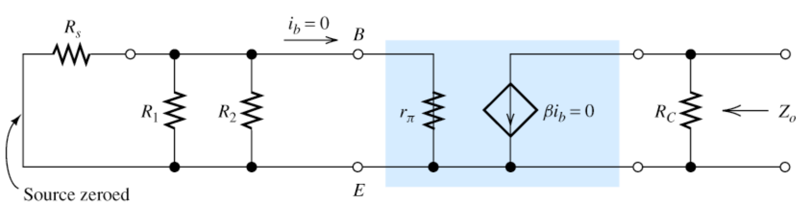
Common Emitter Amplifier



(a) Actual circuit



(b) Small-signal ac equivalent circuit



(c) Equivalent circuit used to find Z_o

First perform DC analysis to find small-signal equivalent parameters at the **operating point**.

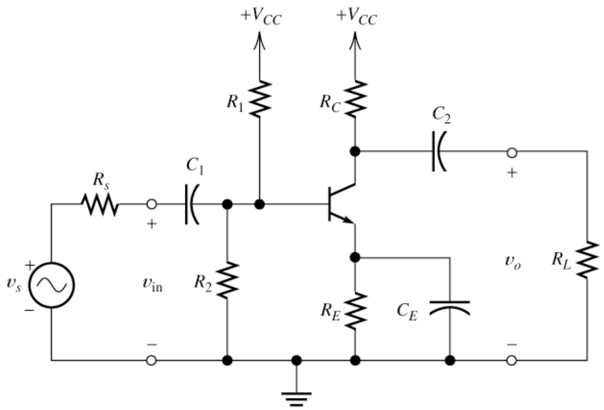
Then:

To construct small-signal equivalent circuit for entire amplifier, we:

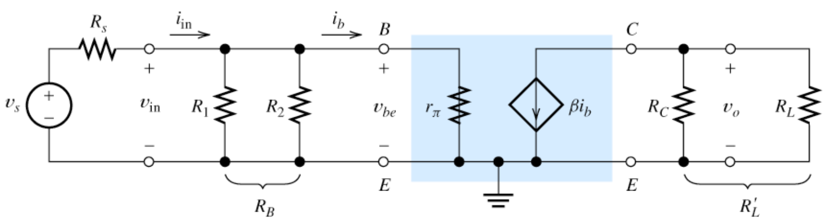
1. Replace the BJT by its small-signal model.
2. Replace all capacitors with short circuits.
3. Set all *DC* sources to zero, <u>because they have zero signal component</u>!!!

The result is the small-signal equivalent circuit of the amplifier:

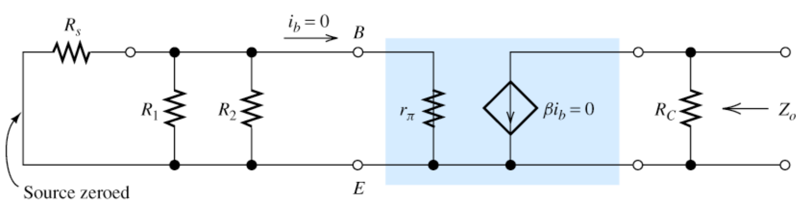
Common Emitter Amplifier



(a) Actual circuit



(b) Small-signal ac equivalent circuit



(c) Equivalent circuit used to find Z_o

Find voltage gain:

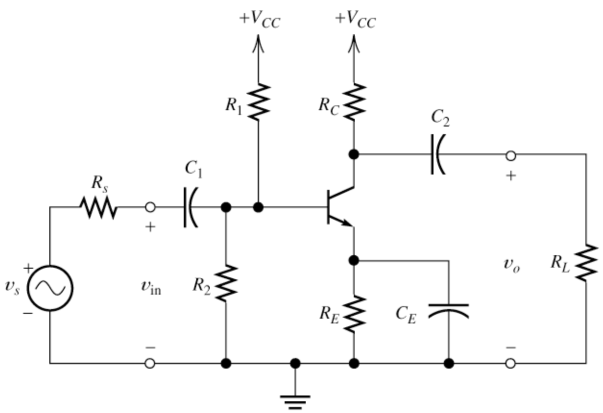
$$v_{in} = v_{be} = r_\pi i_b$$
$$v_o = -R'_L \beta i_b$$

$$A_v = \frac{v_o}{v_{in}} = -\frac{R'_L \beta}{r_\pi}$$
$$A_{voc} = \frac{v_o}{v_{in}} = -\frac{R_C \beta}{r_\pi}$$

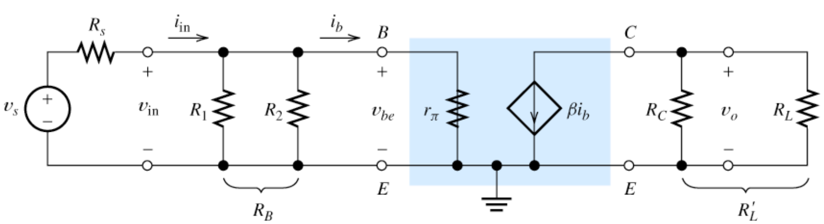
Find input impedance:

$$Z_{in} = \frac{v_{in}}{i_{in}} = \frac{1}{\dfrac{1}{R_B} + \dfrac{1}{r_\pi}}$$

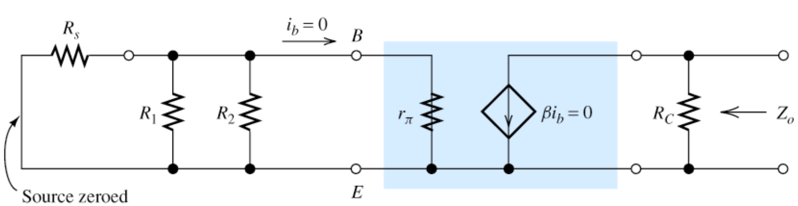
Common Emitter Amplifier



(a) Actual circuit



(b) Small-signal ac equivalent circuit



(c) Equivalent circuit used to find Z_o

Find current gain

$$A_i = \frac{i_o}{i_{in}} = \frac{A_v Z_{in}}{R_L}$$

Find power gain:

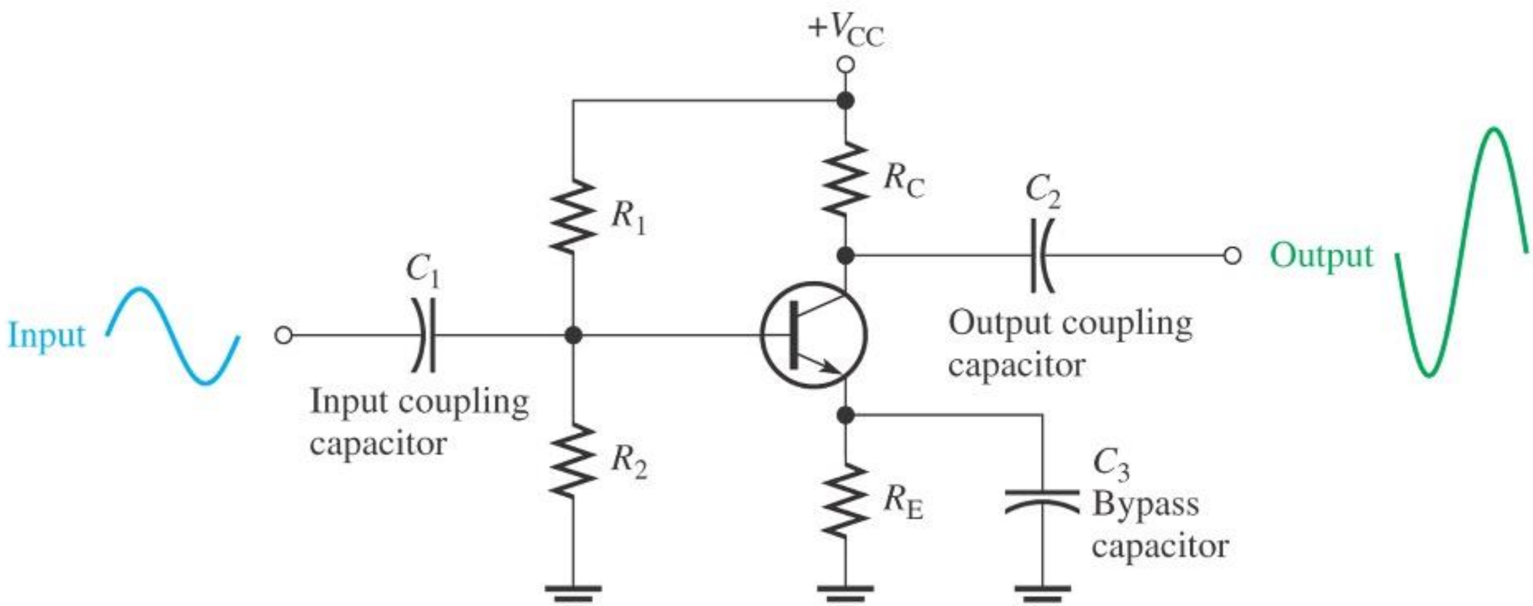
$$G = A_i A_v$$

Find output impedance:

$$Z_o = R_C$$

Transistor as an amplifier:

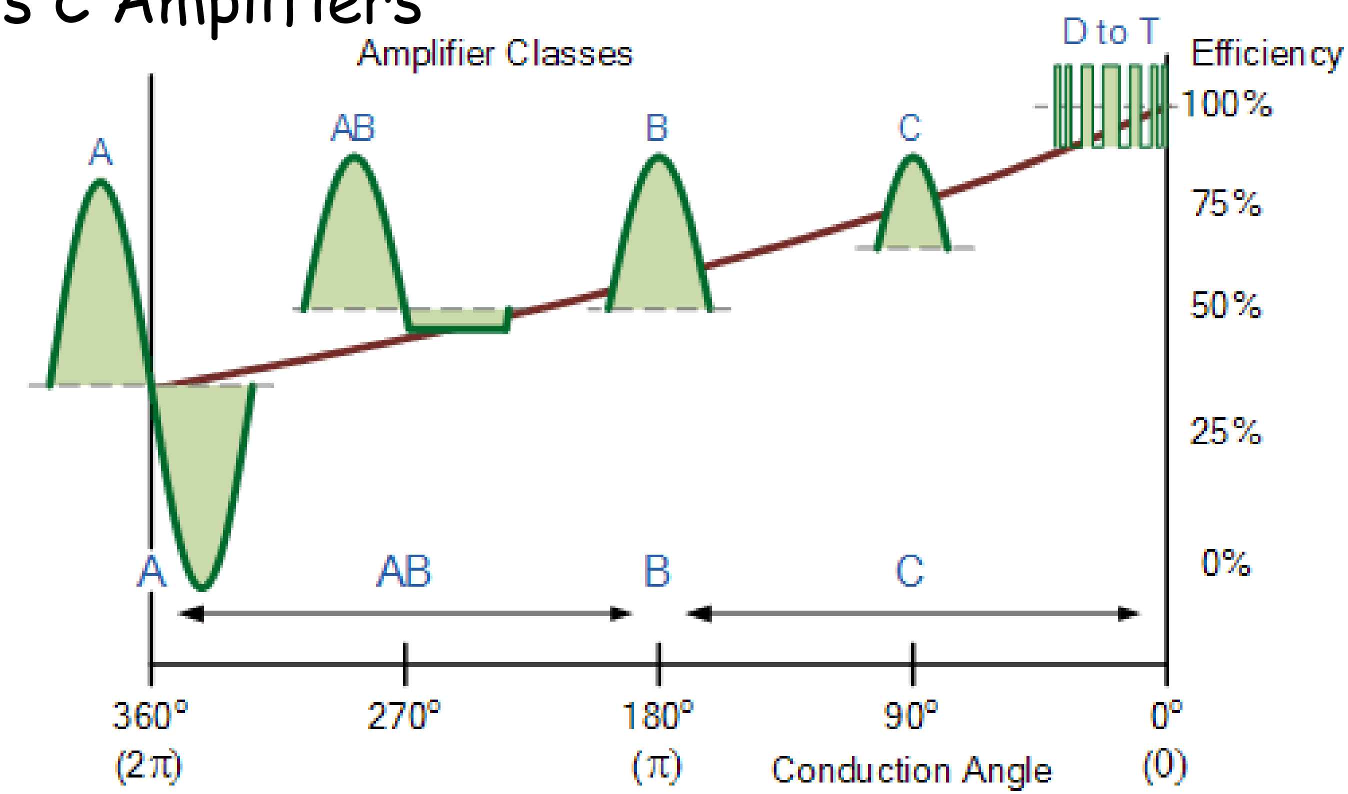
Transistors are often used as amplifiers to increase input signal in radios, televisions and some other applications .The circuit may be designed to increase the current or voltage level.



Amplifier Classes:

Class A Amplifiers
Class AB Amplifiers
Class B Amplifiers
Class C Amplifiers

They are defined by the length of their conduction state over some portion of the output waveform.



BJT Class A Amplifiers

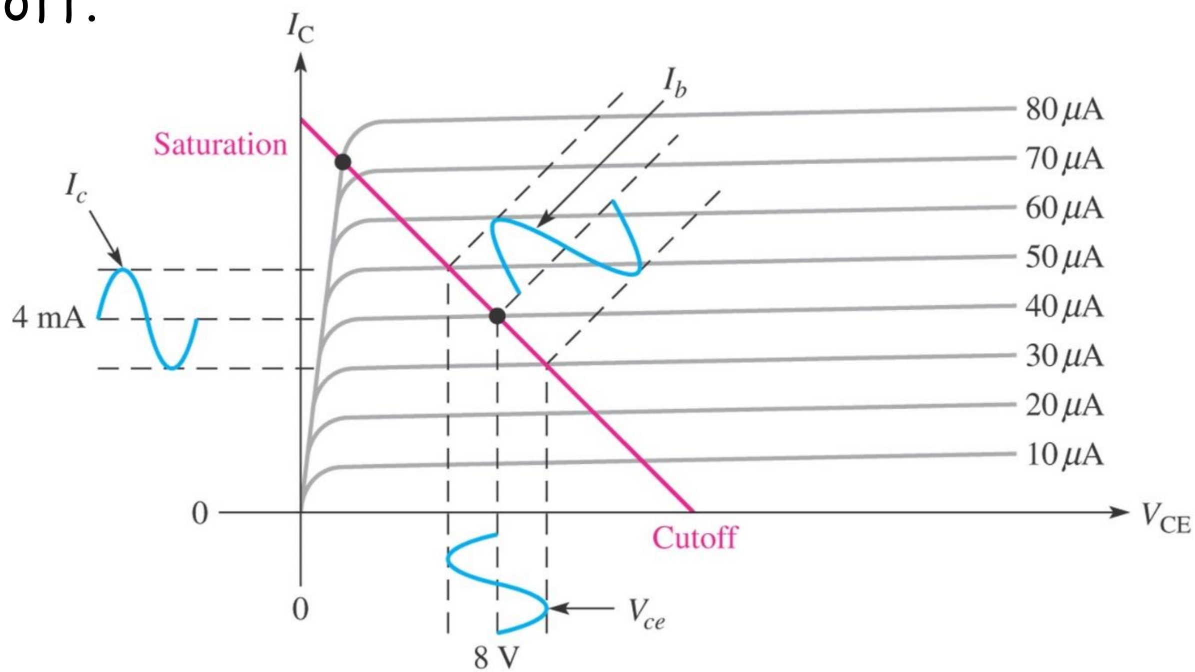
In a class A amplifier, the transistor conducts for the full cycle of the input signal (360°)

–used in low-power applications.

The transistor is operated in the **active region**, between saturation and cutoff.

–saturation is when both junctions are forward biased. the transistor is in cutoff when $I_B = 0$.

The *load line* is drawn on the collector curves between saturation and cutoff.



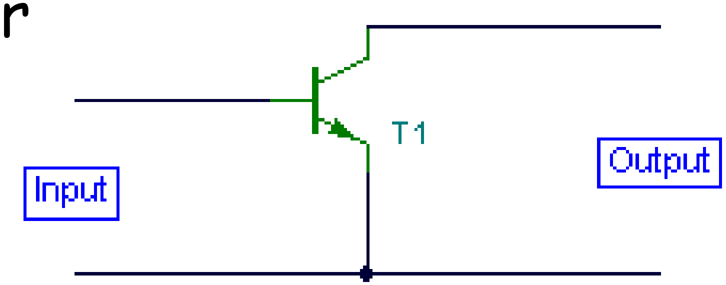
BJT Class A Amplifiers

Three biasing mode for class A amplifiers

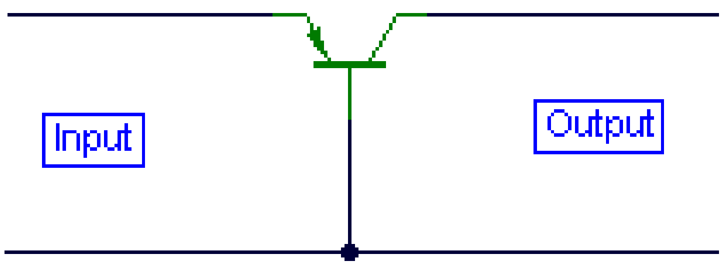
–**common-emitter** (CE) amplifier

–**common-collector** (CC) amplifier

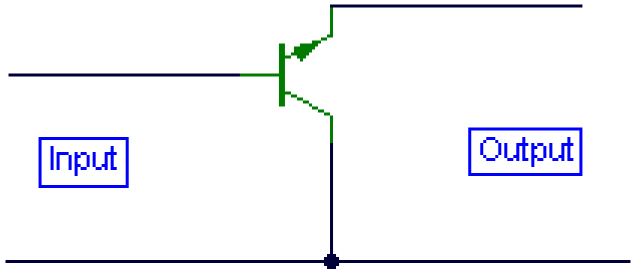
–**common-base** (CB) amplifier



Common-emitter (CE) amplifier

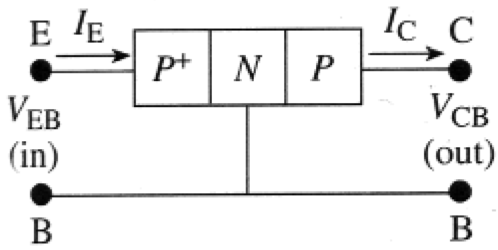


Common-base (CB) amplifier



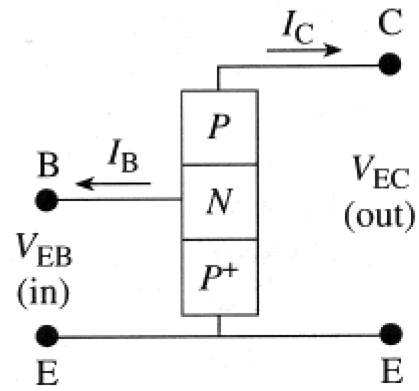
Common-collector (CC) amplifier

BJTs – Basic configurations



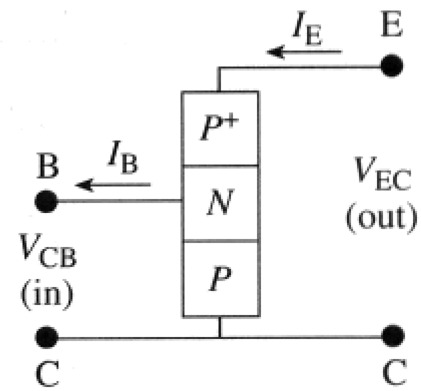
Common base

Both the input and output share the base "in common"



Common emitter

Both the input and output share the emitter "in common"



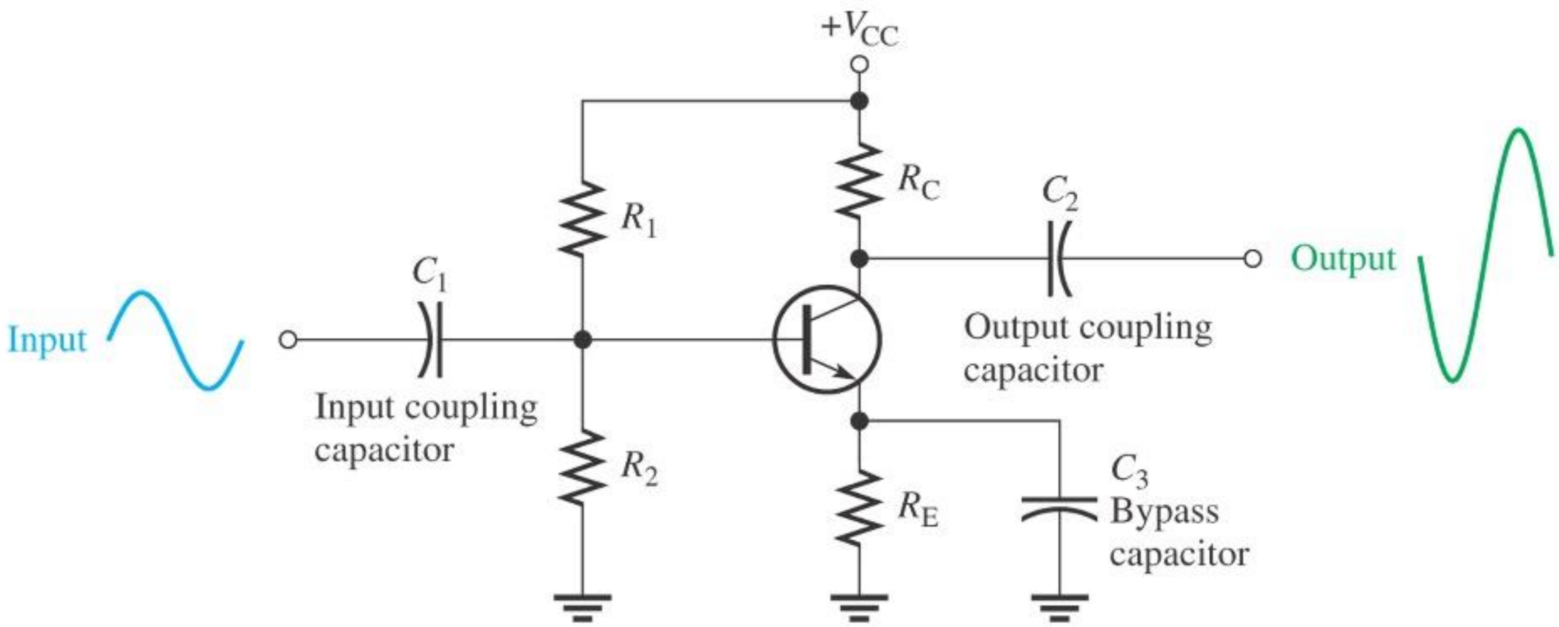
Common collector

Both the input and output share the Collector "in common"

BJT Class A Amplifiers

A **common-emitter** (CE) amplifier

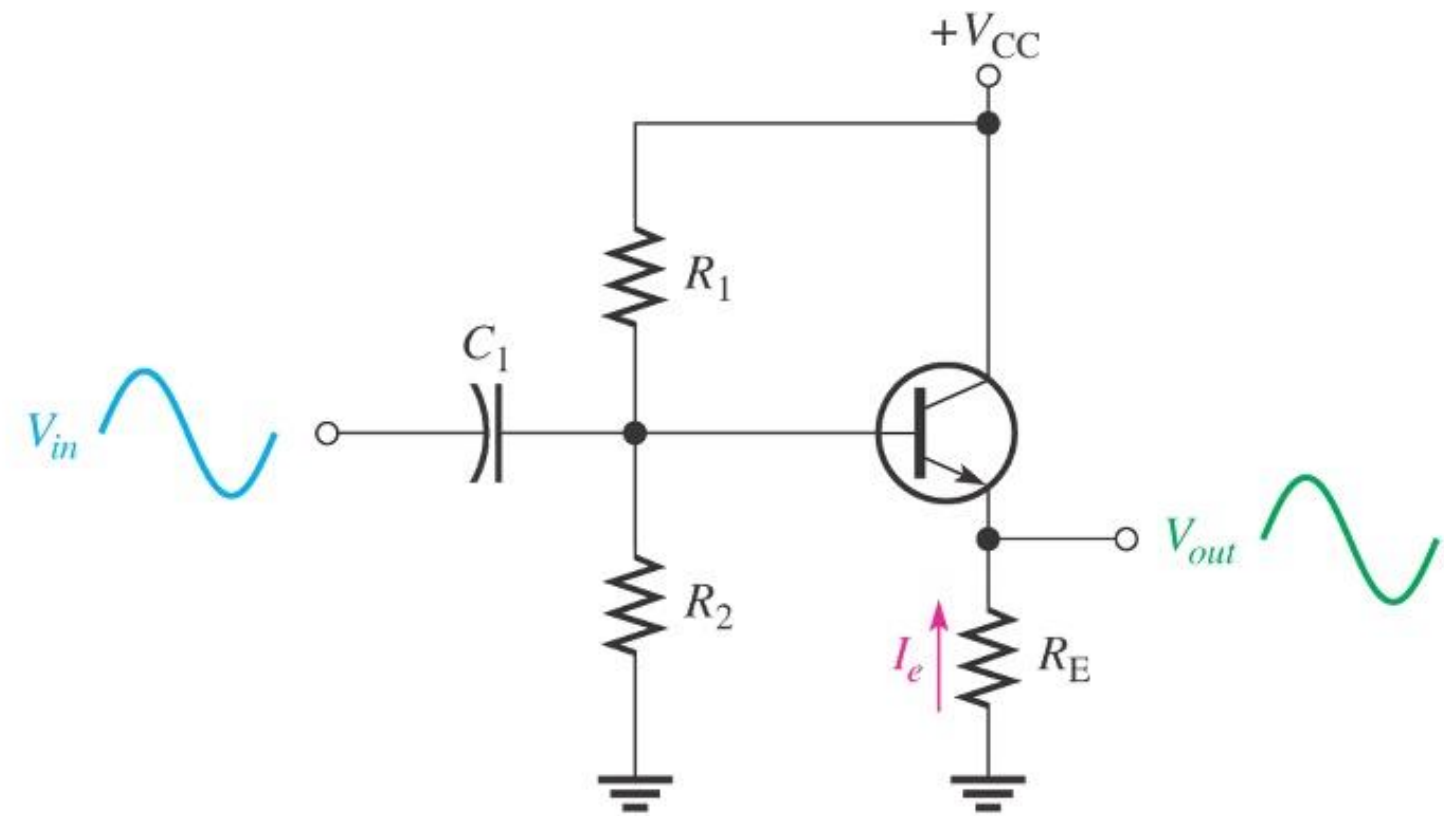
–capacitors are used for coupling AC without disturbing dc levels



BJT Class A Amplifiers

A **common-collector** (CC) amplifier

–voltage gain is approximately 1, but current gain is greater than 1



BJT Class A Amplifiers

Common-base (CB) amplifier

–the base is the grounded (common) terminal. The input signal is applied to the emitter. Output signal is taken off the collector

–output is in-phase with the input

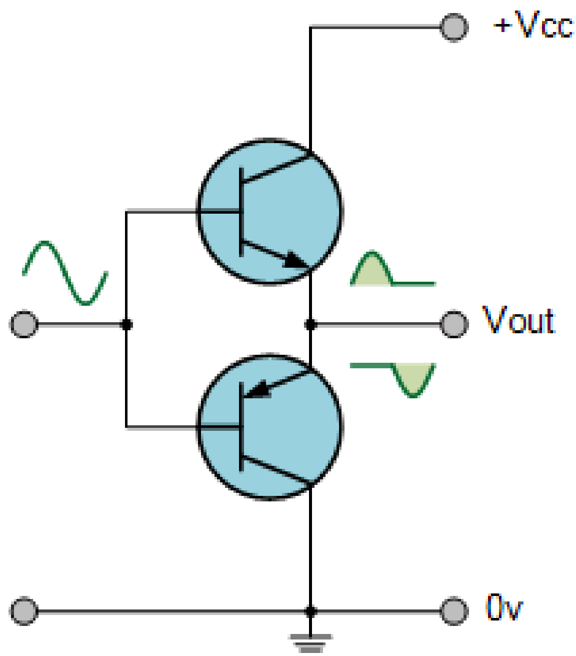
–voltage gain is greater than 1

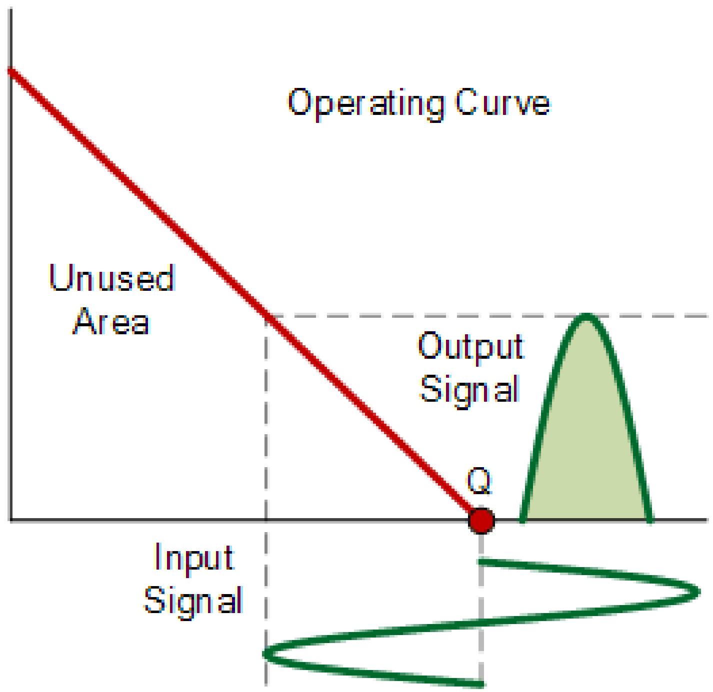
–current gain is always less than 1

BJT Class B Amplifiers

When an amplifier is biased such that it operates in the linear region for 180° of the input cycle and is in cutoff for 180°, it is a class B amplifier.

–Class B amplifier is more efficient than a class A. The transistors in a class B amplifier must be biased above cutoff to eliminate crossover distortion.



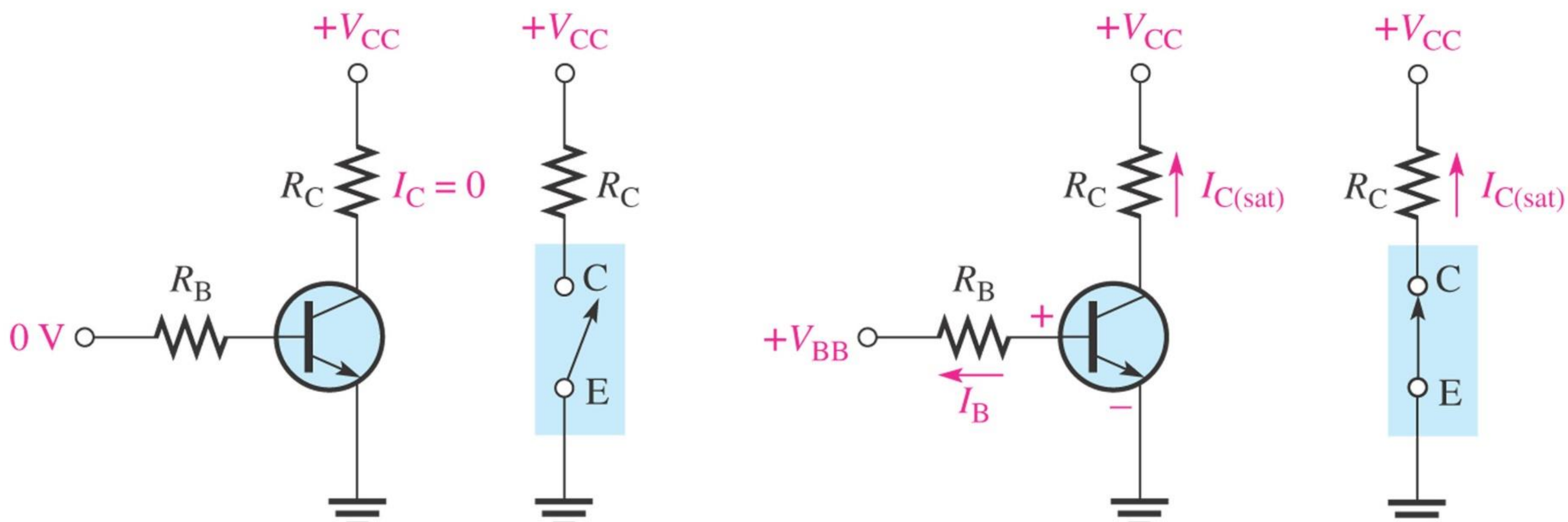


The BJT as a Switch

When used as an electronic switch, a transistor normally is operated alternately in cutoff and saturation

–A transistor is in cutoff when the base-emitter junction is not forward-biased. V_{CE} is approximately equal to V_{CC}

–When the base-emitter junction is forward-biased and there is enough base current to produce a maximum collector current, the transistor is saturated



(a) Cutoff — open switch

(b) Saturation — closed switch