# Electronic Materials and Devices

# 5 Semiconductor

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# 5.8 Bipolar junction transistor (BJT)

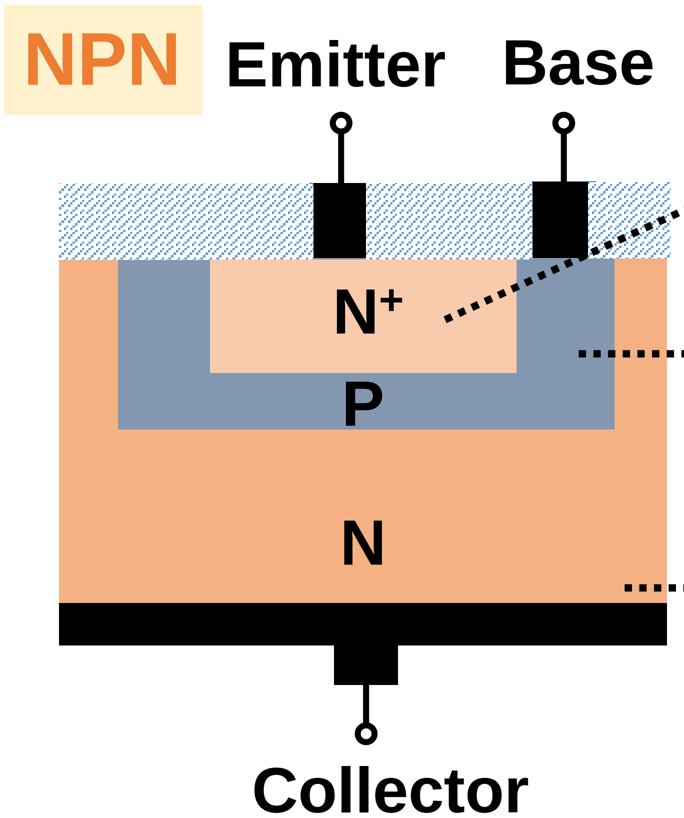
**Transistor is short for "Bipolar junction transistor"**

双极型晶体管，又称半导体三极管，简称为晶体管

The **amplification** and **switching** functions of transistors have promoted the leap of electronic technology

# Structure of BJT

**Transistor configuration: NPN or PNP -type**

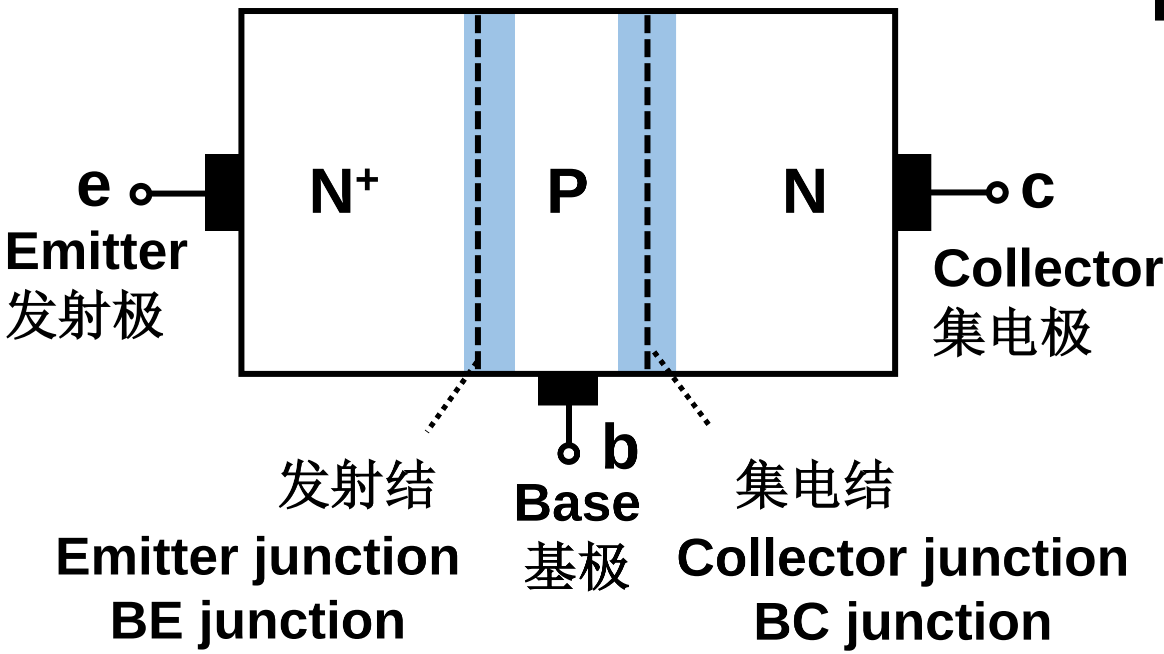



**N+:** heavily doped N-type semiconductor

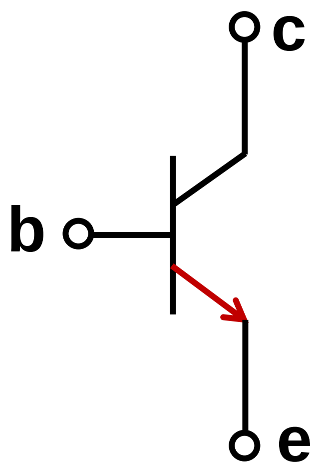
**P:** lightly doped P-type semiconductor

**N:** lightly doped N-type semiconductor

# NPN transistor

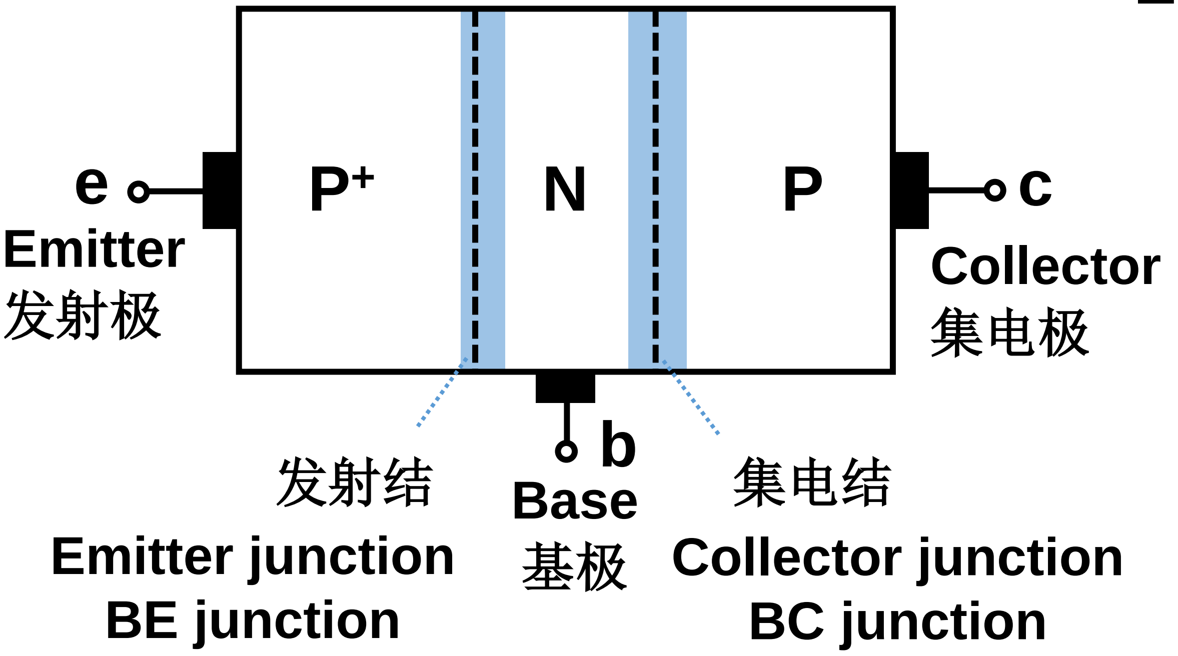



Electronic symbol

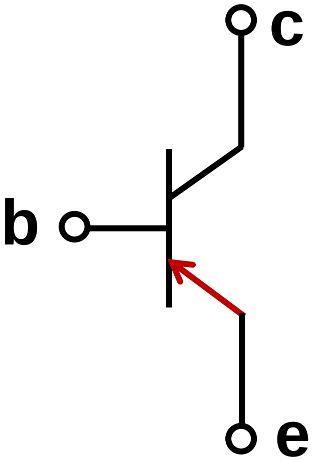



NPN

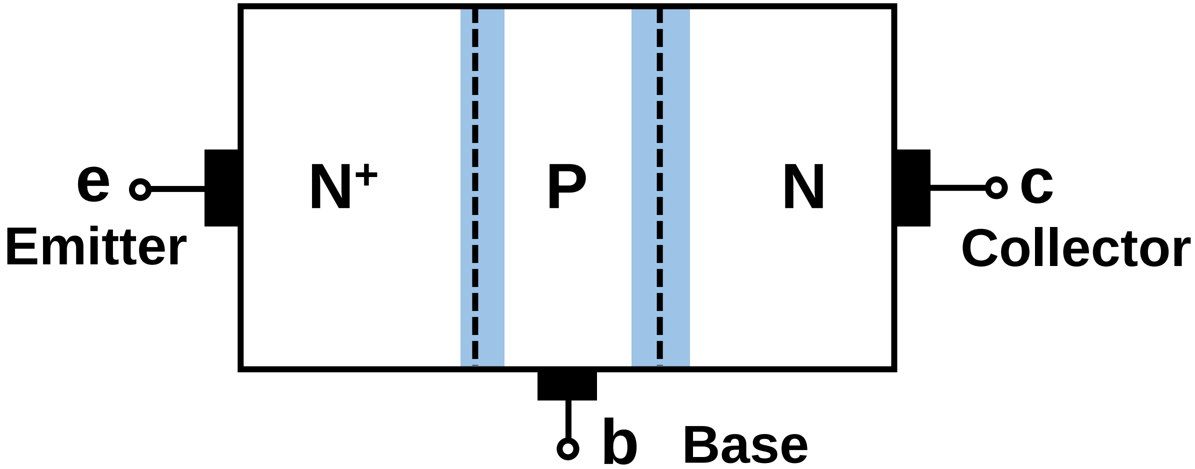
# PNP transistor

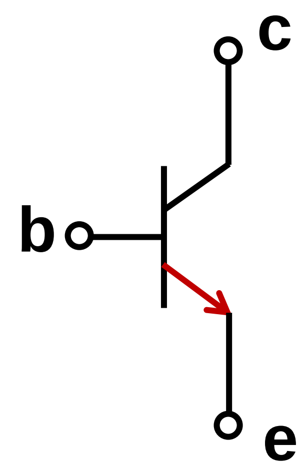



Electronic symbol




PNP




NPN

**Key features of transistor（for amplification）:**

Why?

（1）Emitter region: high doping, small area

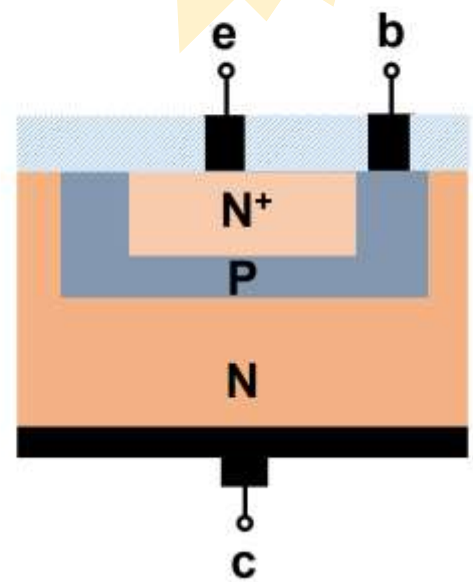
发射区掺杂浓度大，面积小。

（2）Collector region: low doping, large area

集电区掺杂浓度低，集电结面积大。

（3）Base region: low doping, very thin

基区掺杂浓度很低，且很薄。



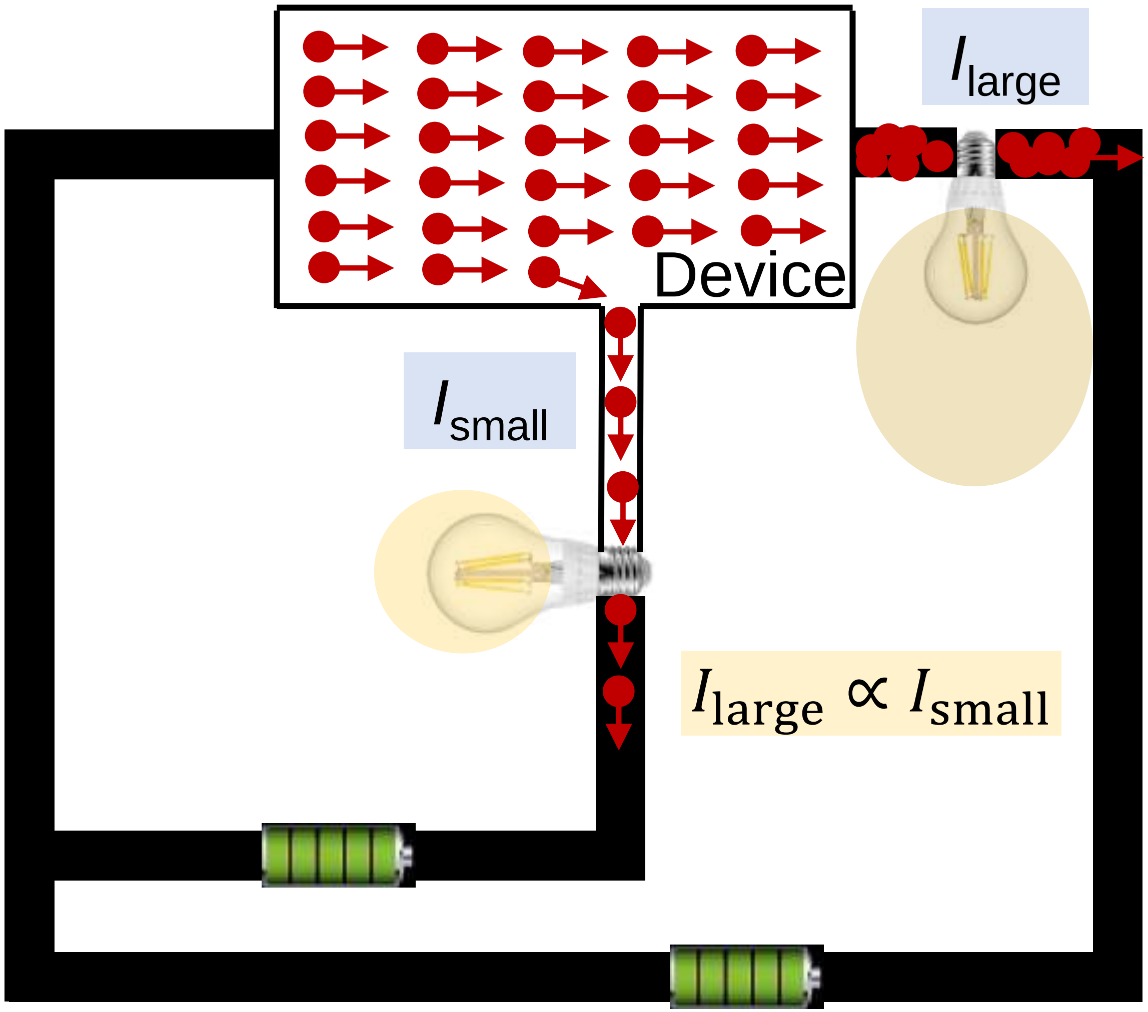
# Working principle of BJT (NPN)

Take **NPN-type** transistor as an example

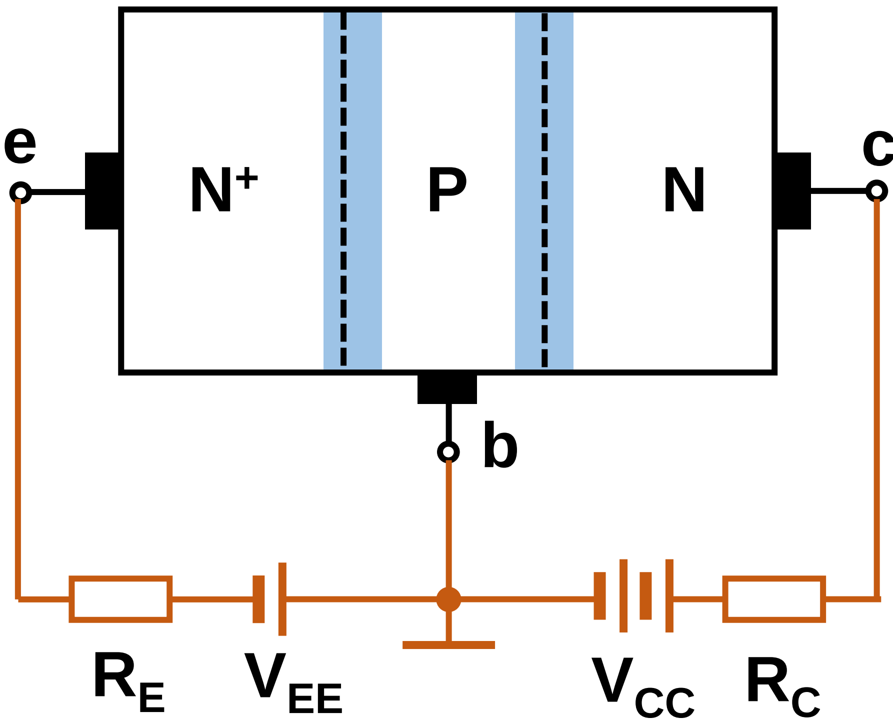
**Operating status of transistors**

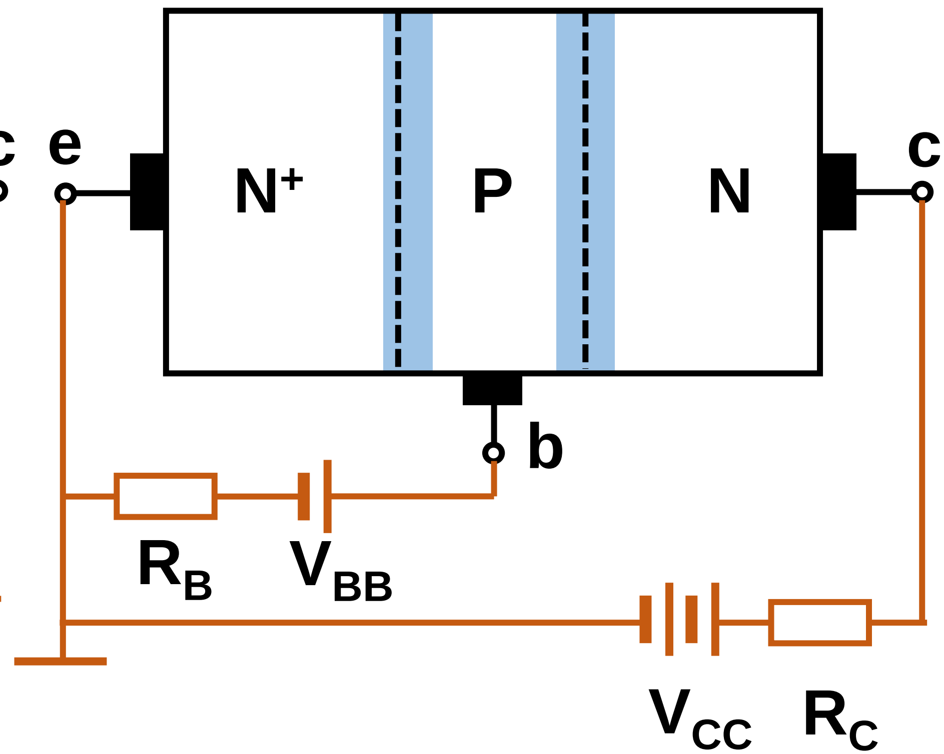
- **Amplification** 放大状态
- **Saturation** 饱和状态
- **Cut-off** 截止状态

# How to realize amplification?



**Amplification mode: BE junction forward bias & BC junction reverse bias** 放大模式：发射结正向偏置，集电结反向偏置



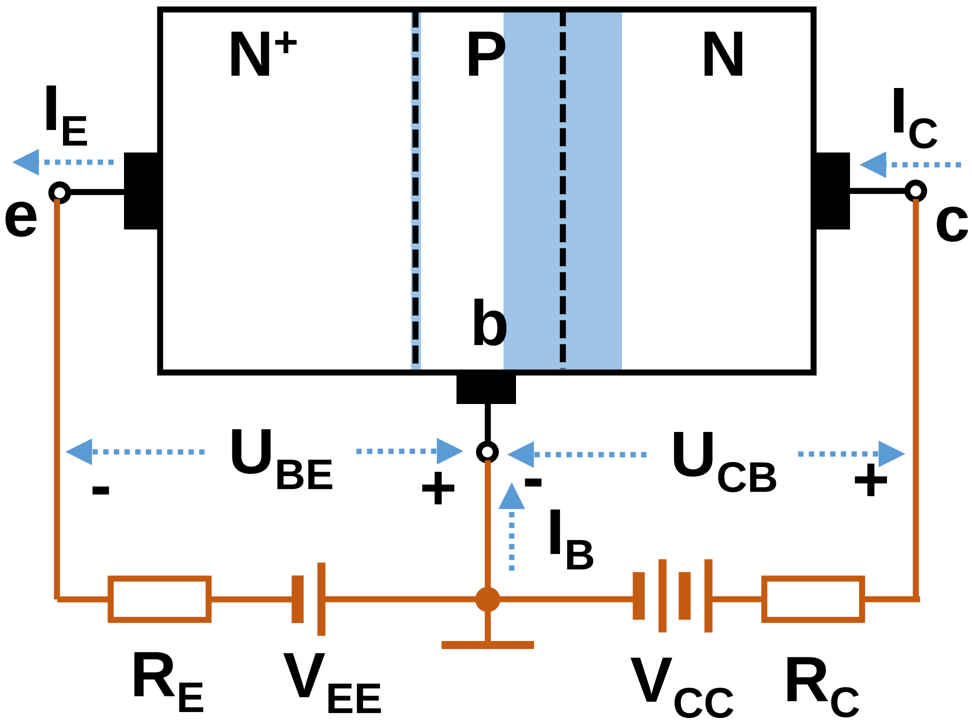



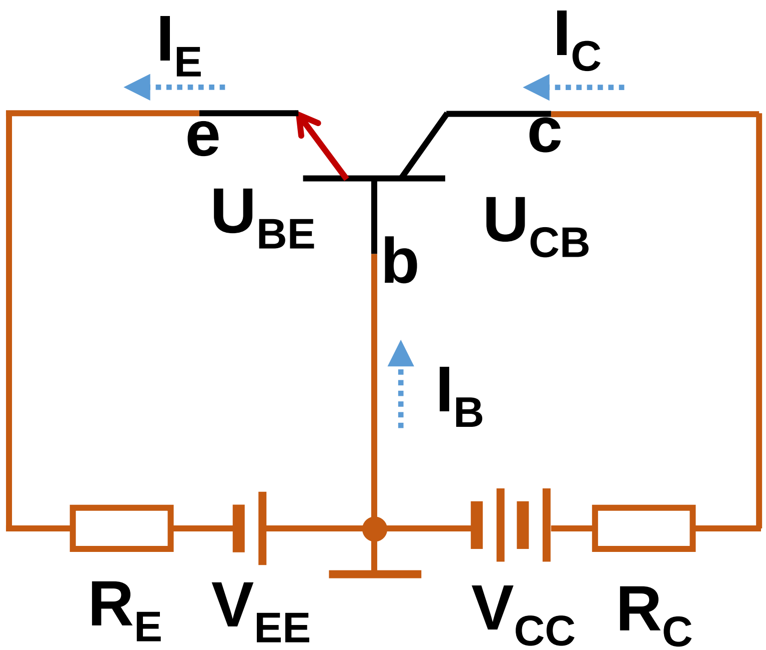

Common-base amplification circuit Common-emitter amplification circuit

共基极放大电路 共射极放大电路

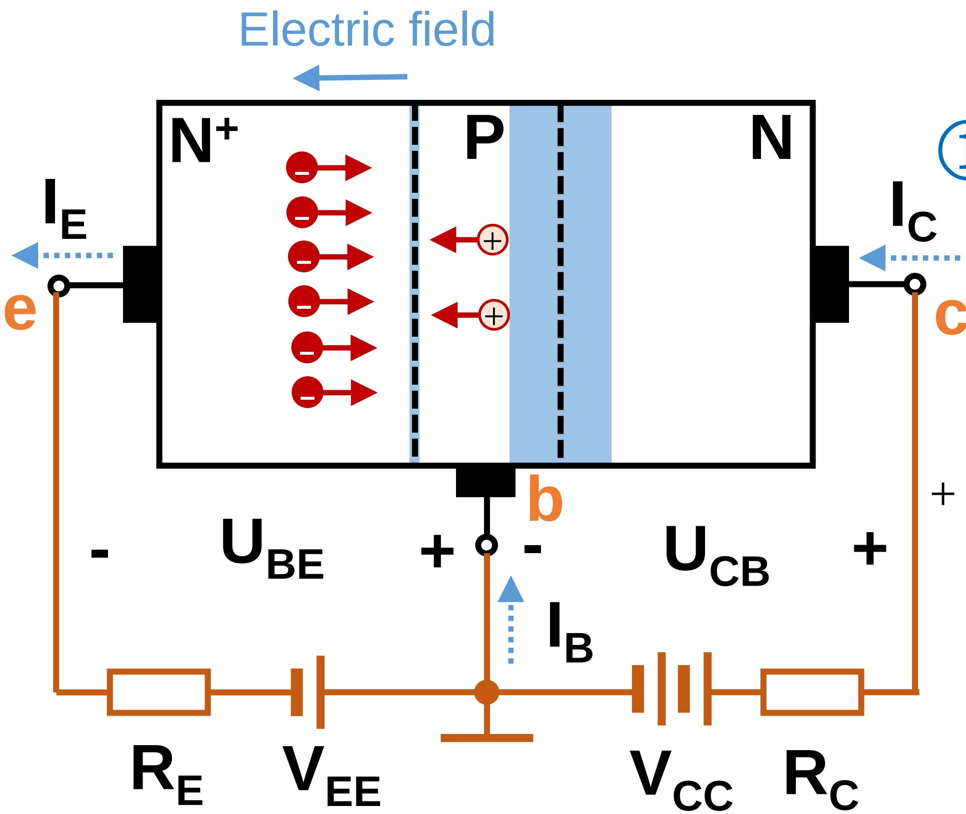
# Common-base amplifier circuit

共基极放大电路



# Forward bias of BE junction

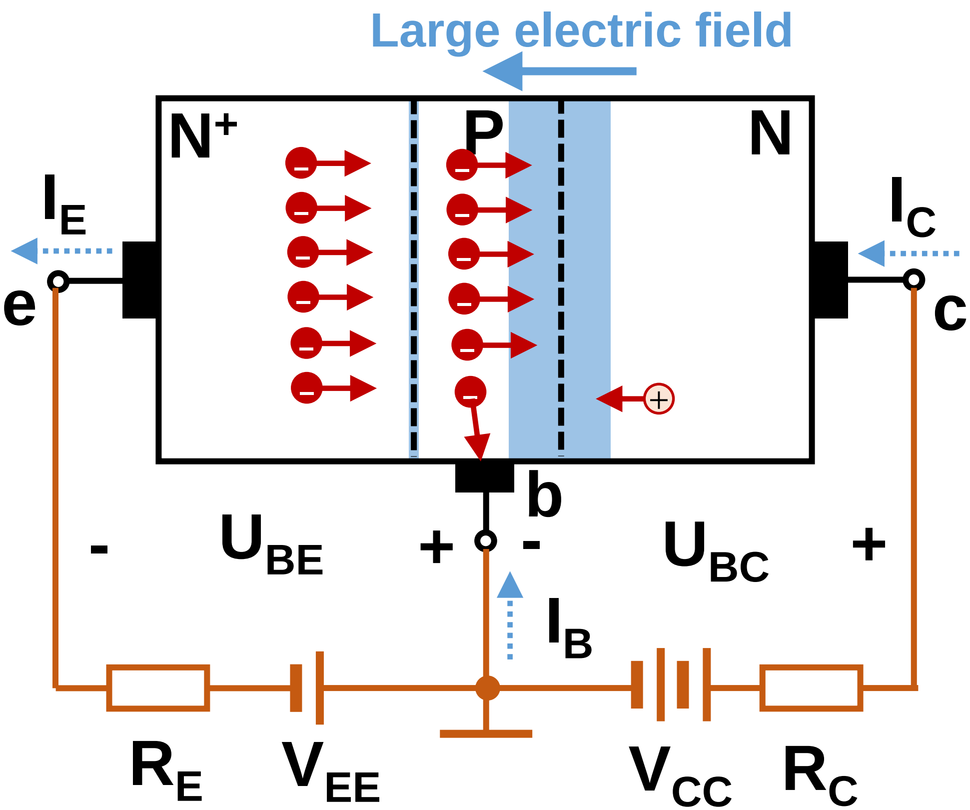



① **BE junction becomes thin.**

**BE junction**: The electron concentration in $N^+$ region is much higher than the hole concentration in P region.

② **Electrons (major carrier) in $N^+$ region drift to P region under electric field.**

# Reverse bias of BC junction




③ BC junction becomes thicker.

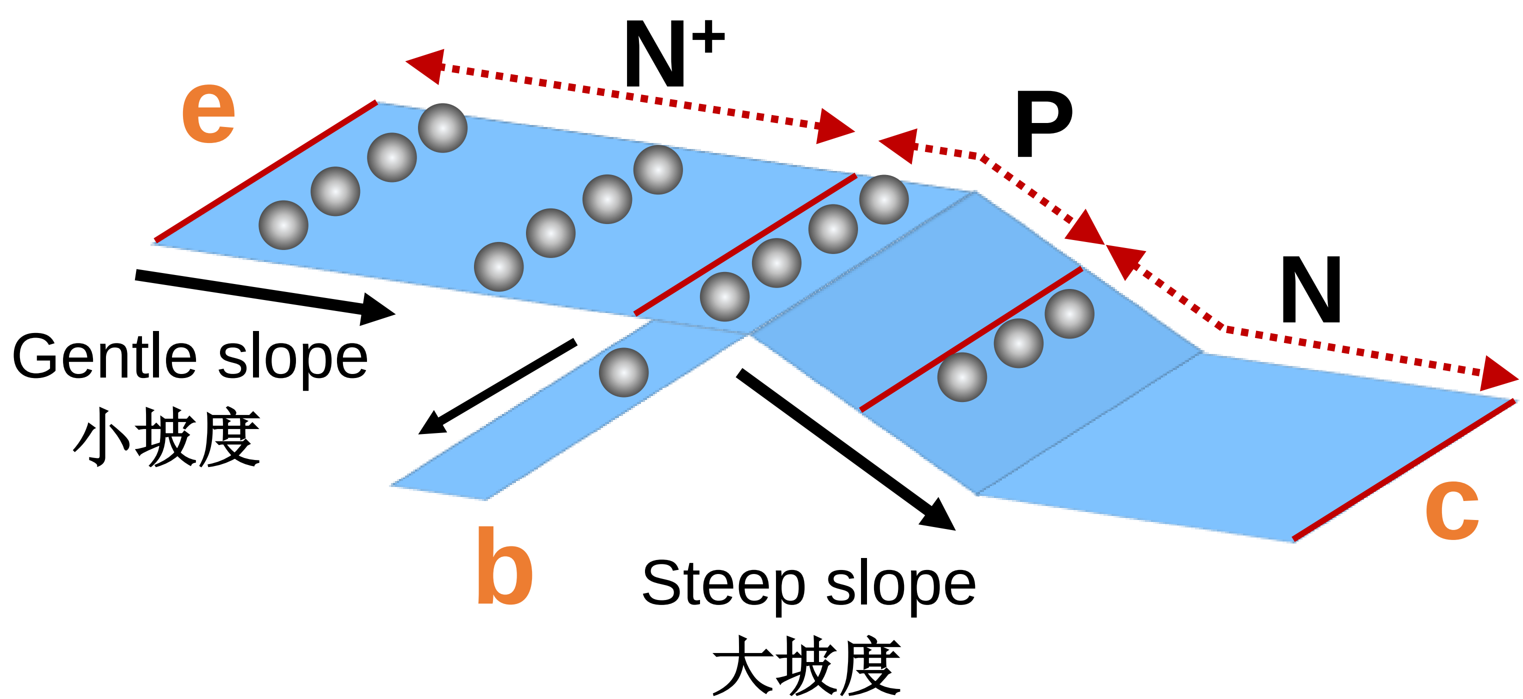
Internal electric field becomes stronger.

④ Most electrons are accelerated by the electric field of BC junction and collected by the collector. Only small portion is collected by base.

$I_C >> I_B$

**Treat electrons as footballs** 把电子等效成皮球

**Treat electric fields as slope of hills** 电场强度等效为山坡的坡度



## Treat electrons as water molecules

**Emitter**

The source of a river

**Water flow**

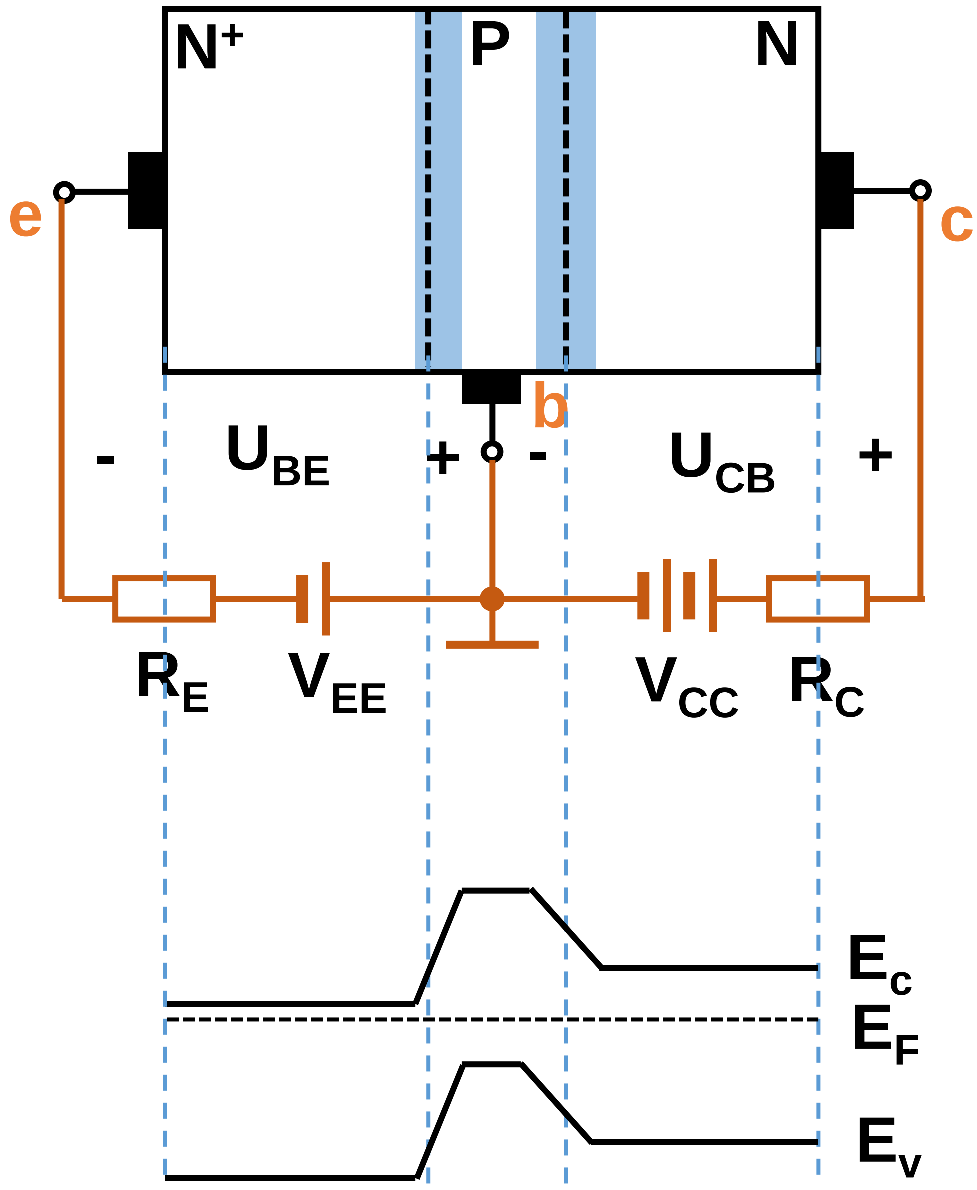
**Base** $I_B$

$I_C$ **Collector**

$$I_C >> I_B$$

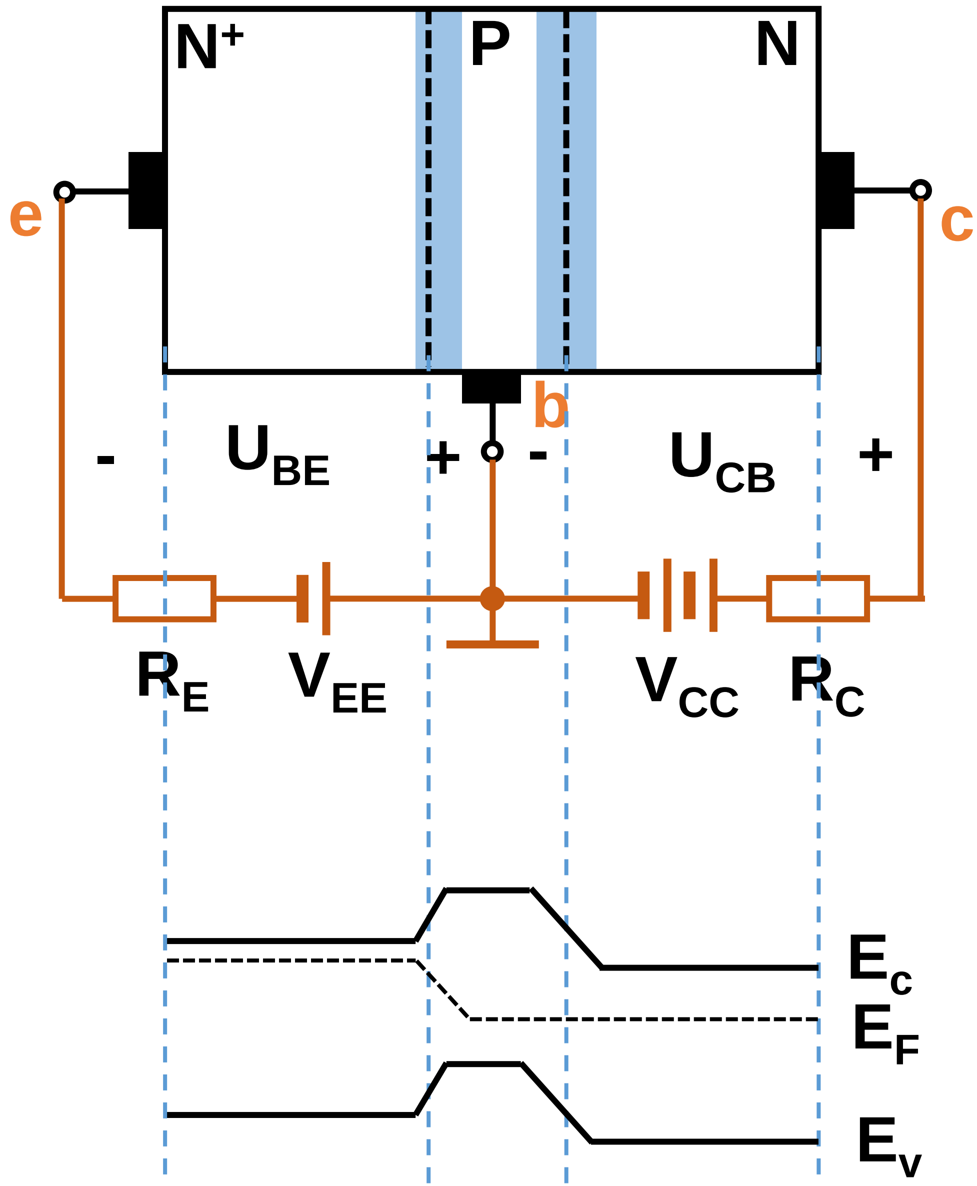
## Band diagram

① $V_{EE}=V_{CC}=0$



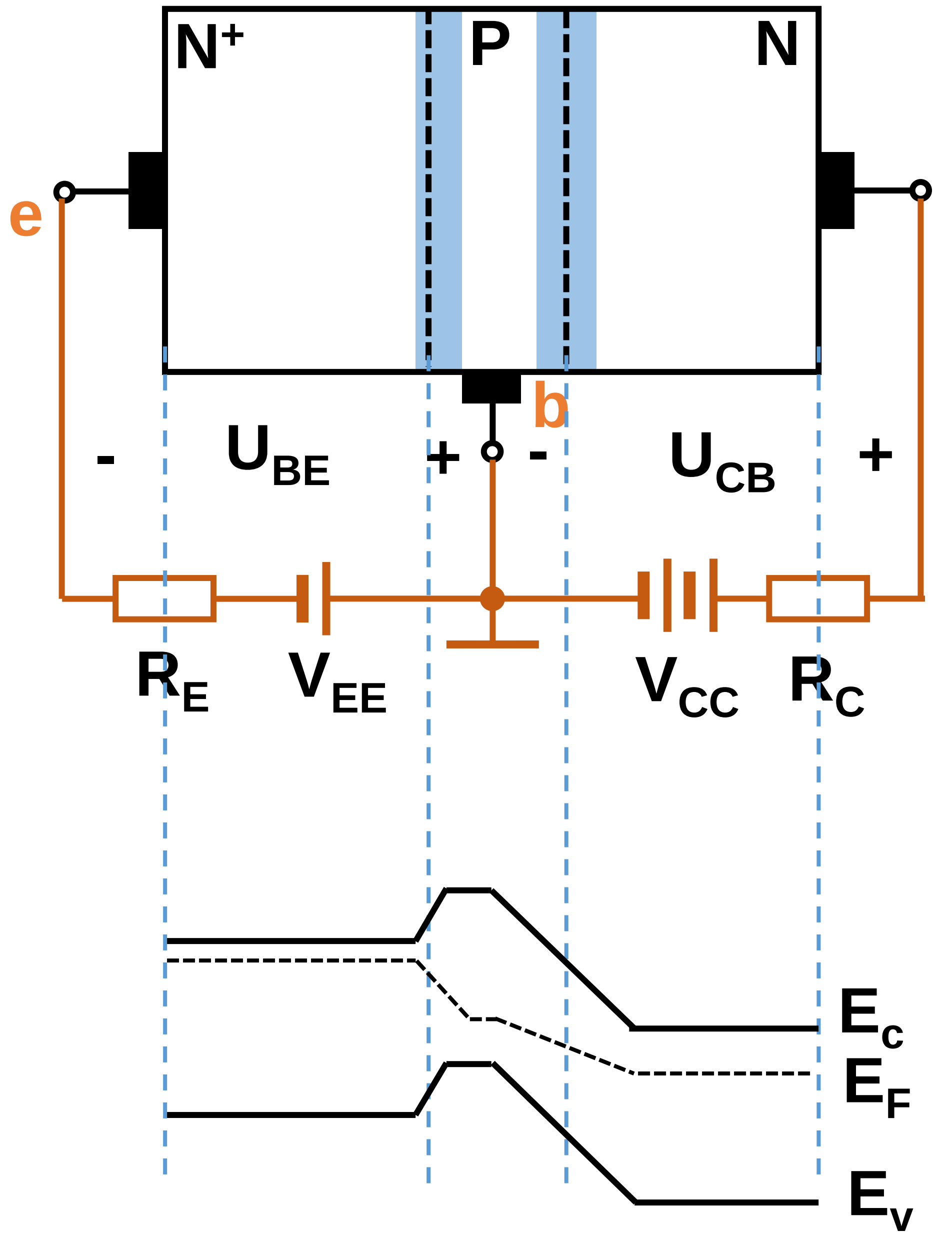
# Band diagram

② $V_{EE}>0$, $V_{CC}=0$



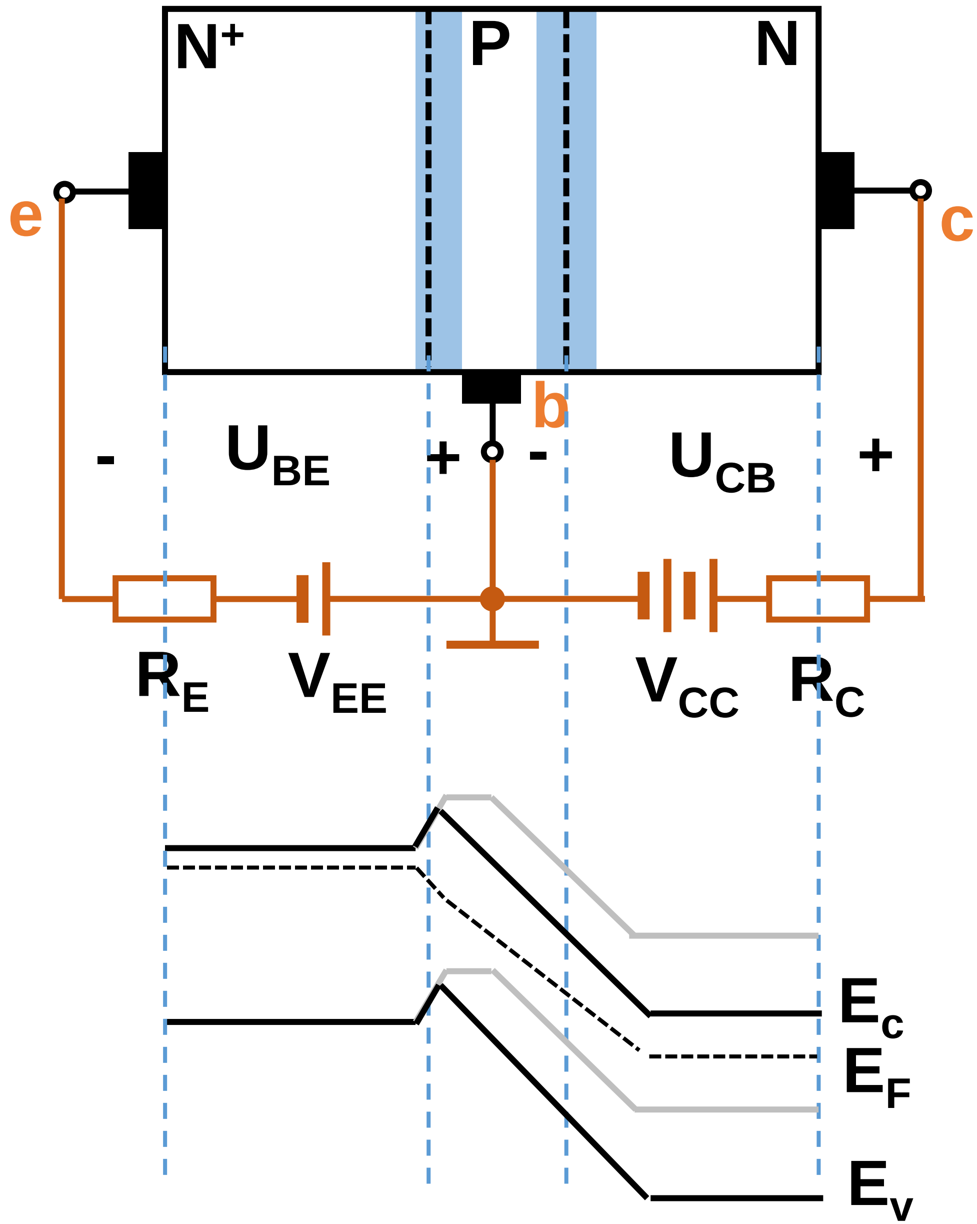
## Band diagram

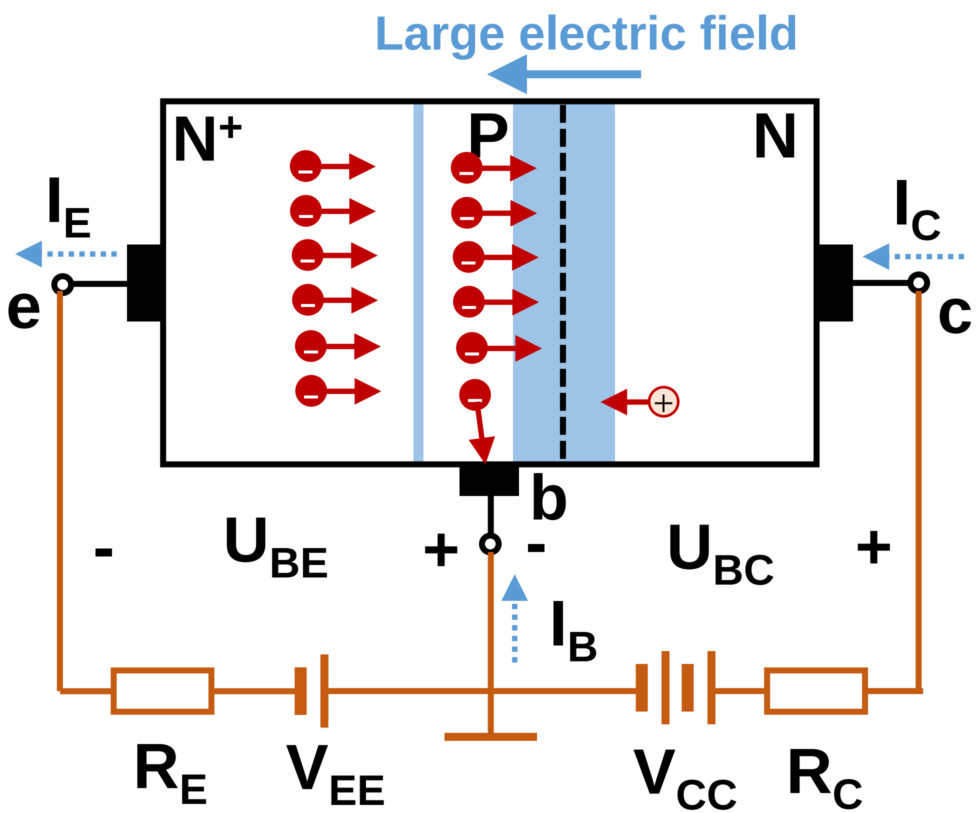
③ $V_{EE}>0$, $V_{CC}>0$

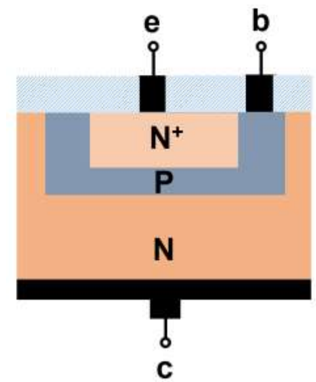


# Band diagram

④ $V_{EE}>0$, $V_{CC}>>0$





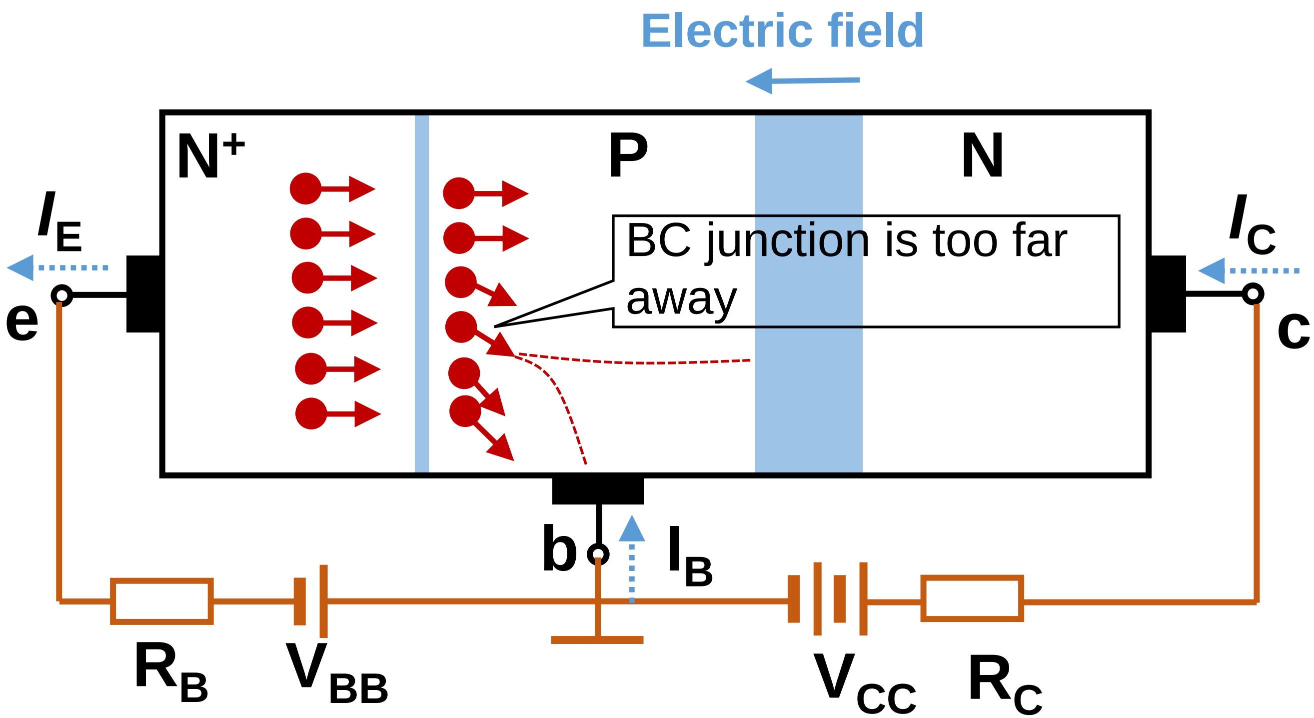

**Question!**

Why $N^+$ region should be highly doped (1)?

Why P region should be thin? (1)

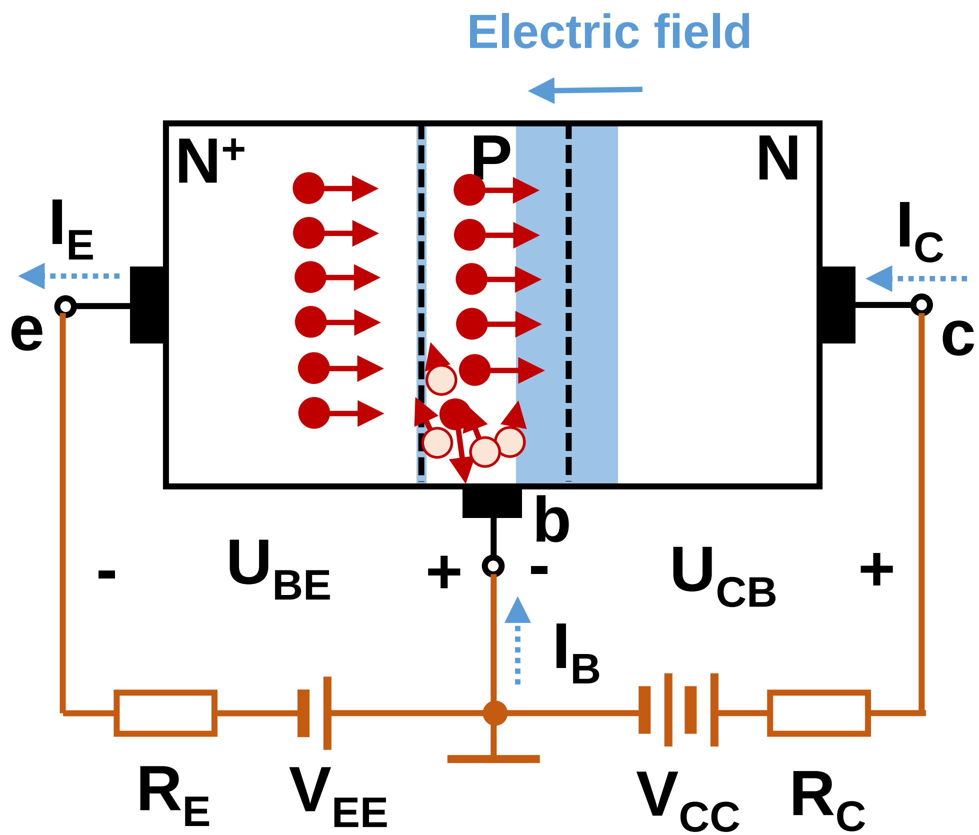
Why P region should be lightly loped? (1)

# Assume P-region was very thick

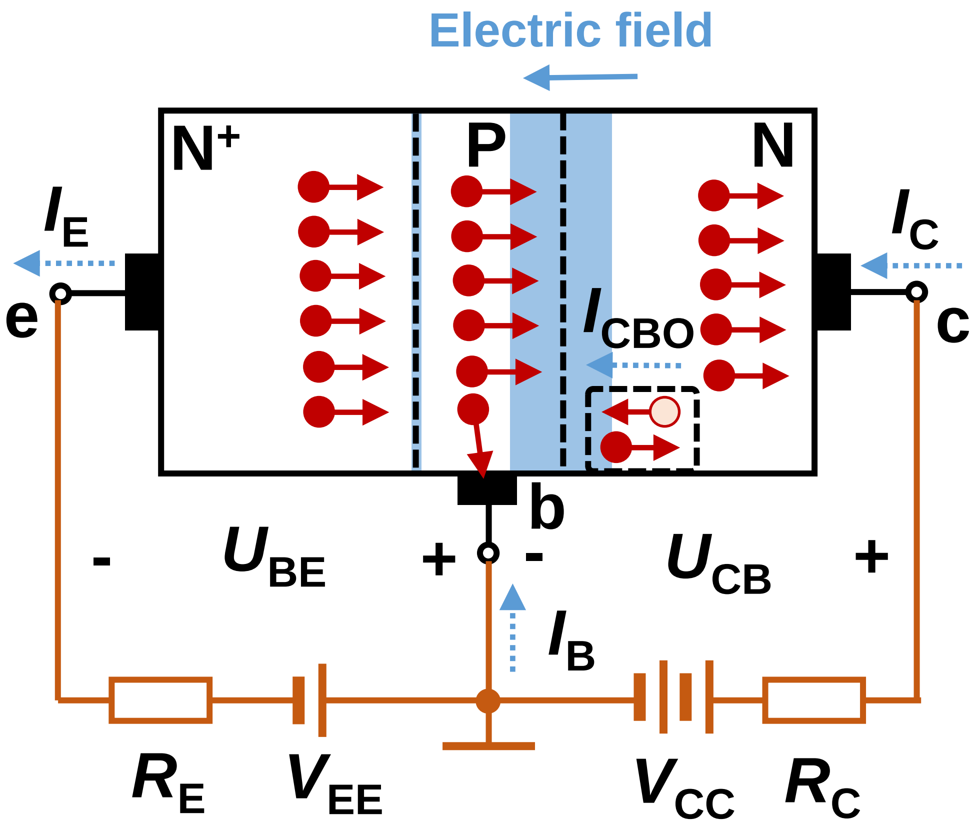



$I_B$ increases significantly!  $I_C/I_B$ decreases!

# Assume P-region was heavily doped




$I_B$ increases significantly! $I_C/I_B$ decreases!




$I_{CBO}$ : the reverse saturation current when emitter is open.

$I_E=I_C+I_B$

$$I_E \approx I_C \gg I_B$$

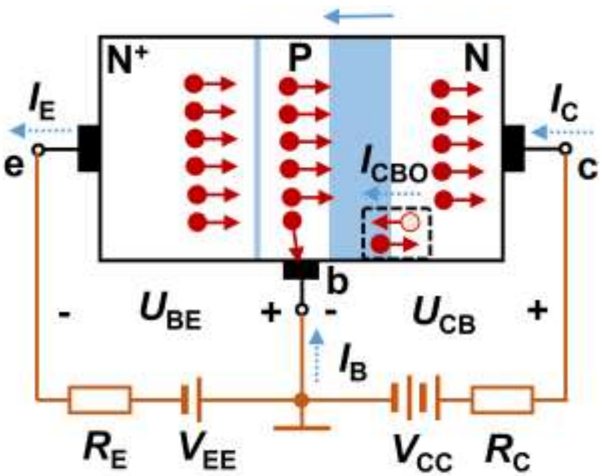
**Common-b DC amplification factor**

**共基极直流放大系数**

$$\bar{\alpha} = \frac{I_C - I_{CBO}}{I_E} \approx \frac{I_C}{I_E} < 1$$

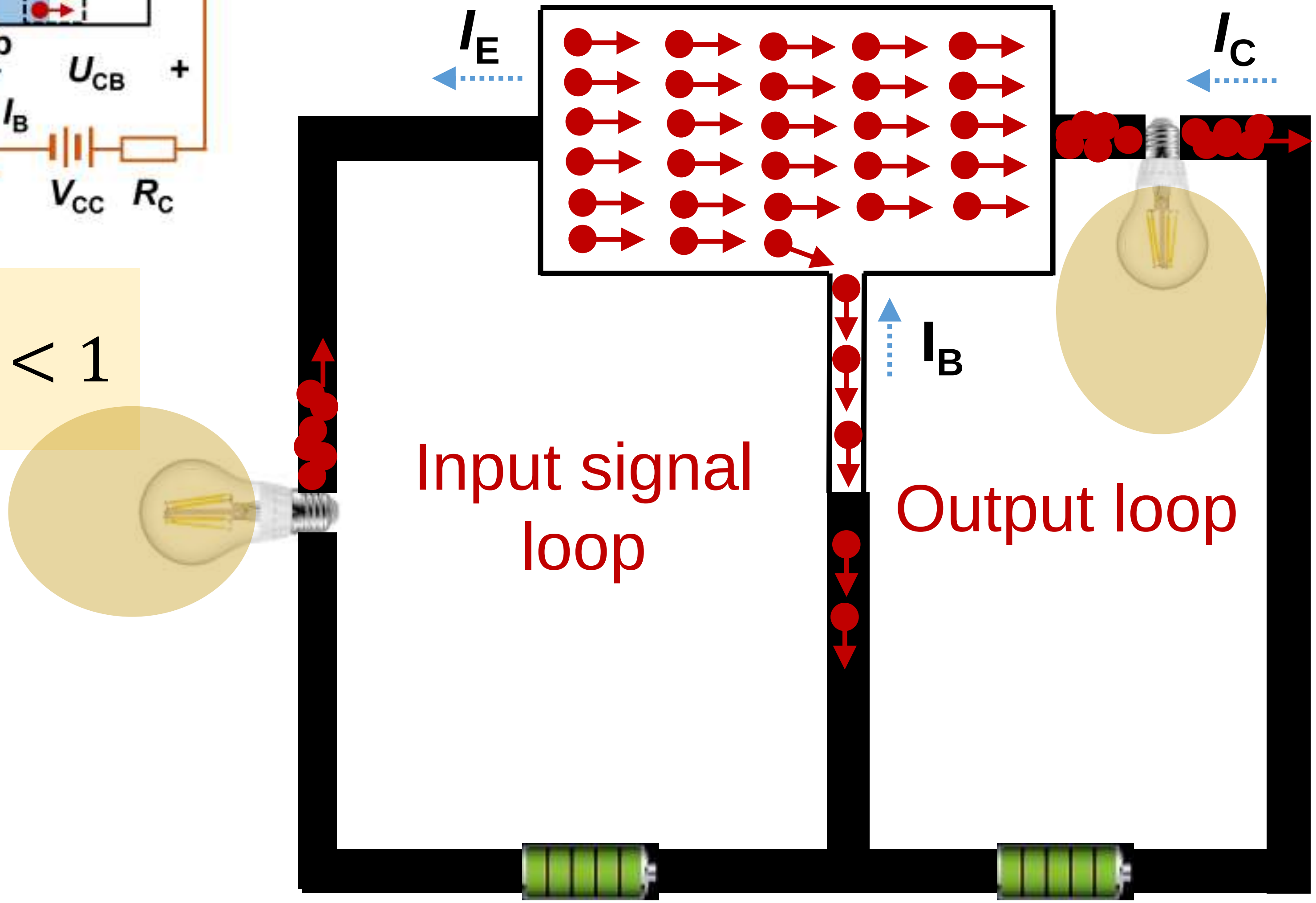
**Q: Why common-b amplification coefficient is not defined as:**

$$\bar{\beta} = \frac{I_C}{I_B} \gg 1?$$



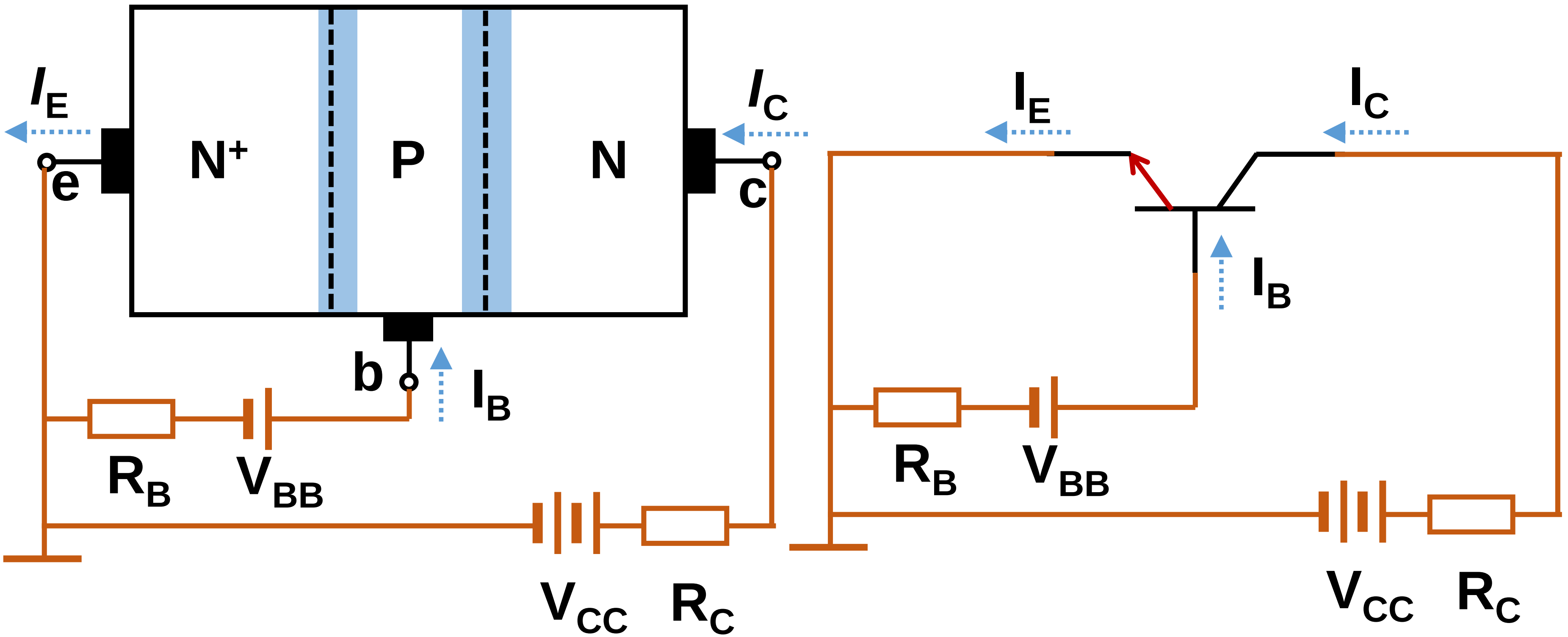

# Common-base amplifier

$$\bar{\alpha} = \frac{I_C}{I_E} < 1$$

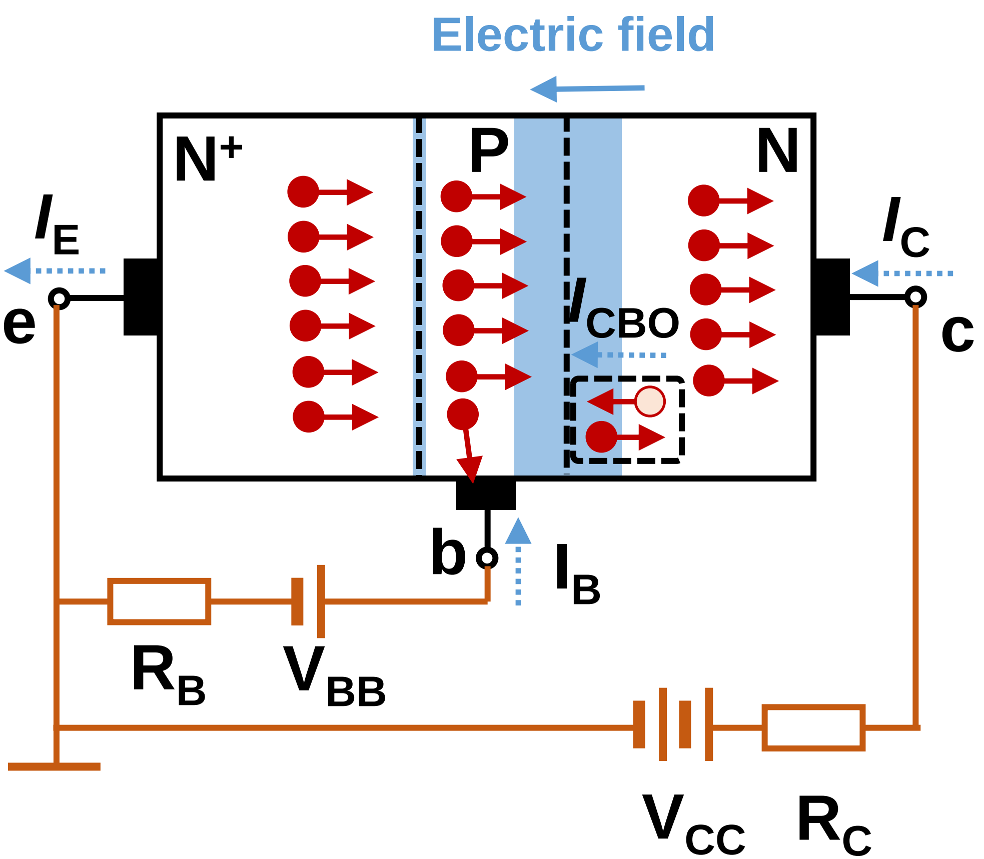


# Common-emitter amplification circuit

## 共射极放大电路




$V_{CC} > V_{BB}$




$I_E = I_C + I_B$

$I_E \approx I_C \gg I_B$

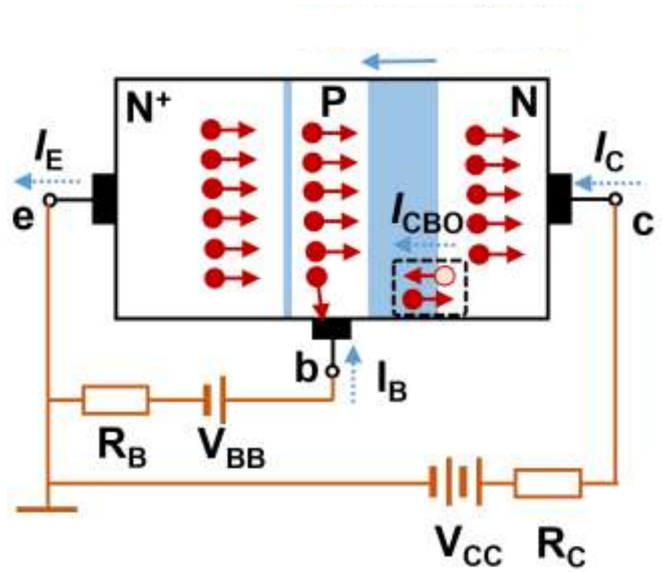
**Common-e DC amplification factor**

**共射极直流放大系数**

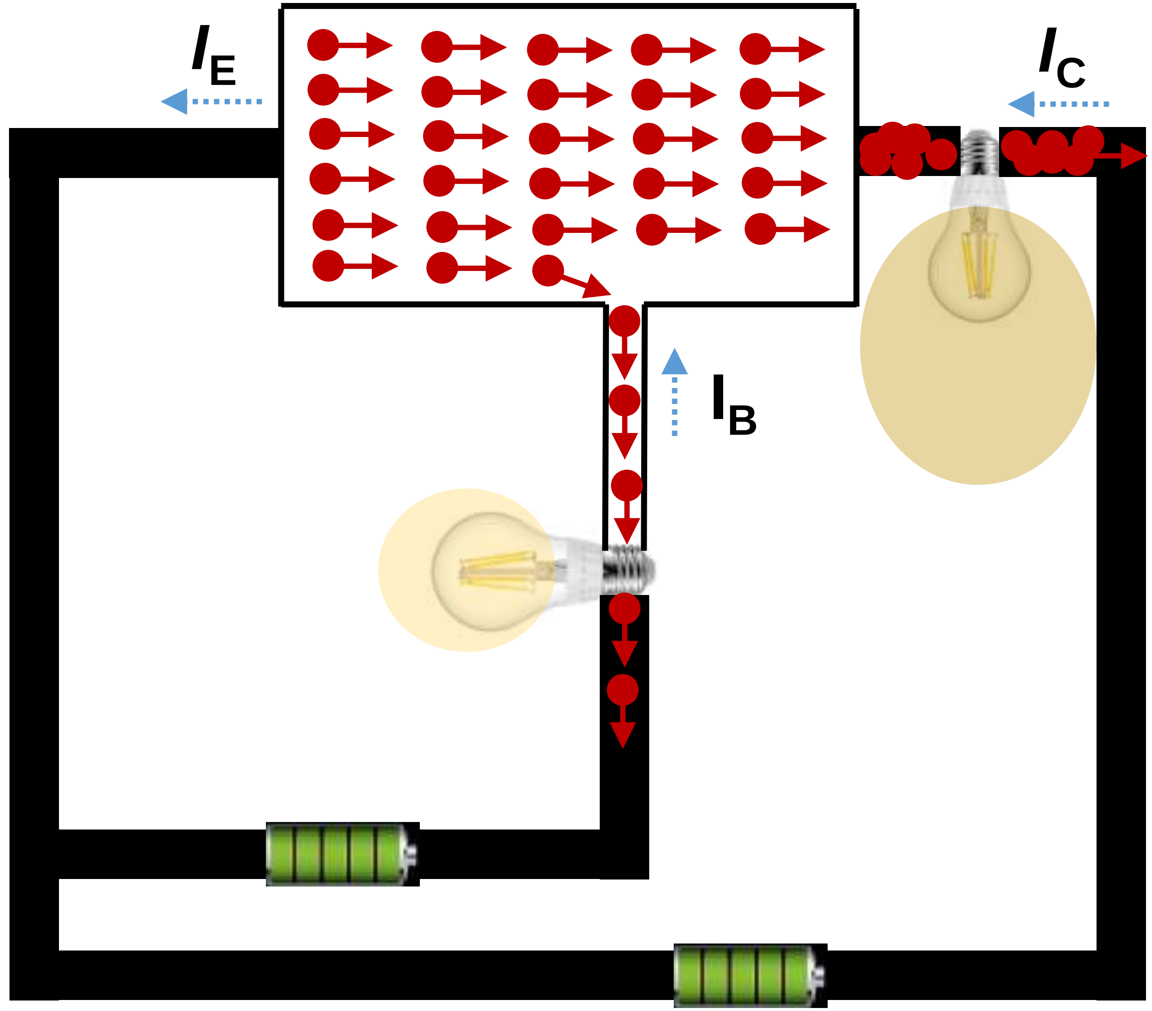
$$\bar{\beta} = \frac{I_C - I_{CBO}}{I_B + I_{CBO}} \approx \frac{I_C}{I_B}$$

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

# Common-emitter amplifier




$$\bar{\beta} = \frac{I_C}{I_B} \gg 1$$



## Common-b amplification coefficient

$$\bar{\alpha} = \frac{I_{\mathrm{C}}}{I_{\mathrm{E}}}$$

$$\bar{\alpha} < 1, \bar{\alpha} \approx 1$$

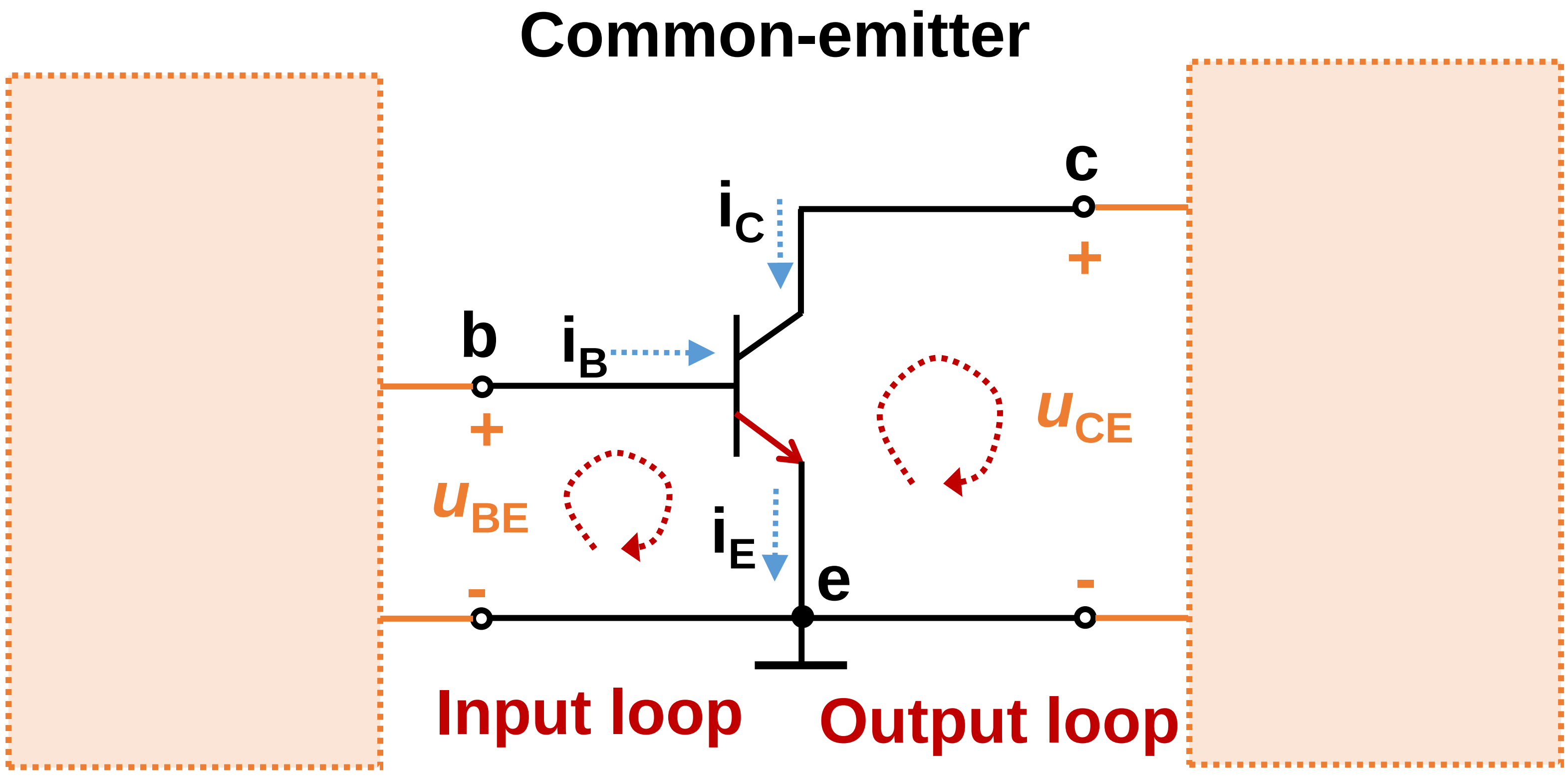
## Common-e amplification coefficient

$$\bar{\beta} = \frac{I_{\mathrm{C}}}{I_{\mathrm{B}}}$$

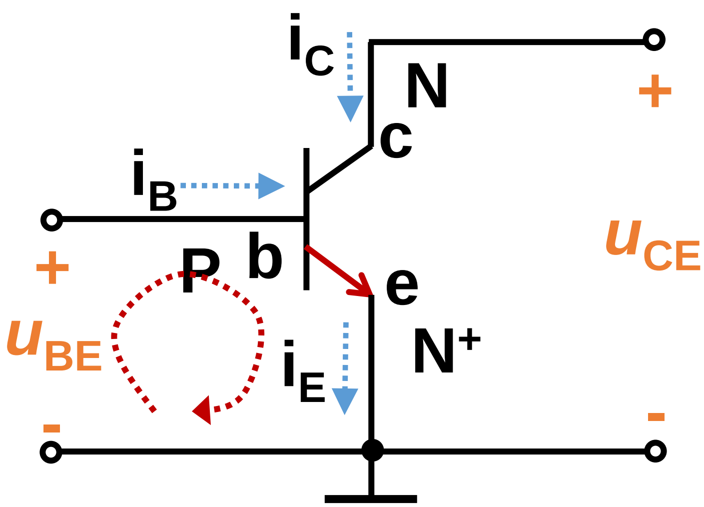
$$\bar{\beta} \gg 1$$

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

# The input and output I-V characteristics



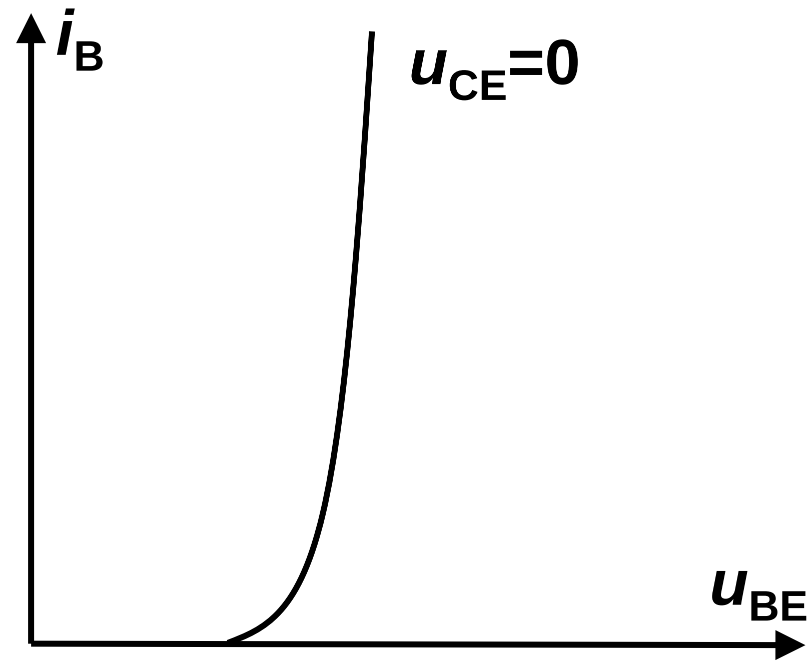
## Common-emitter



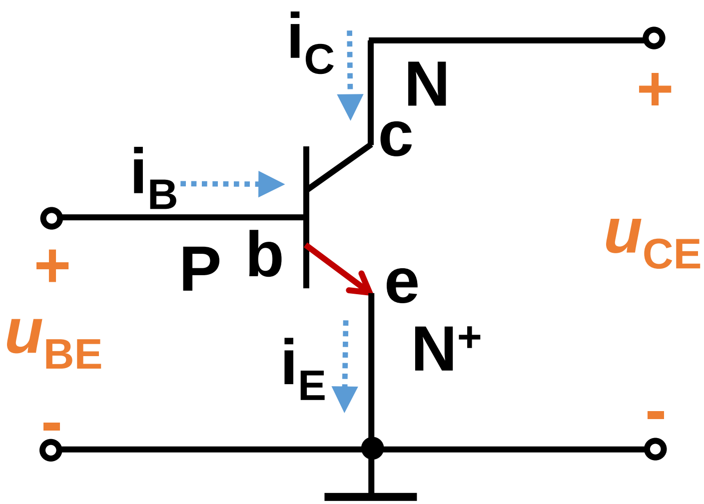

1) When $u_{CE}$=0, BE and BC junction are forward biased by $u_{BE}$. The internal electric field is in BC junction is weak, most electrons are collected by the **Base**. The I-V curve is similar to that of PN junction.

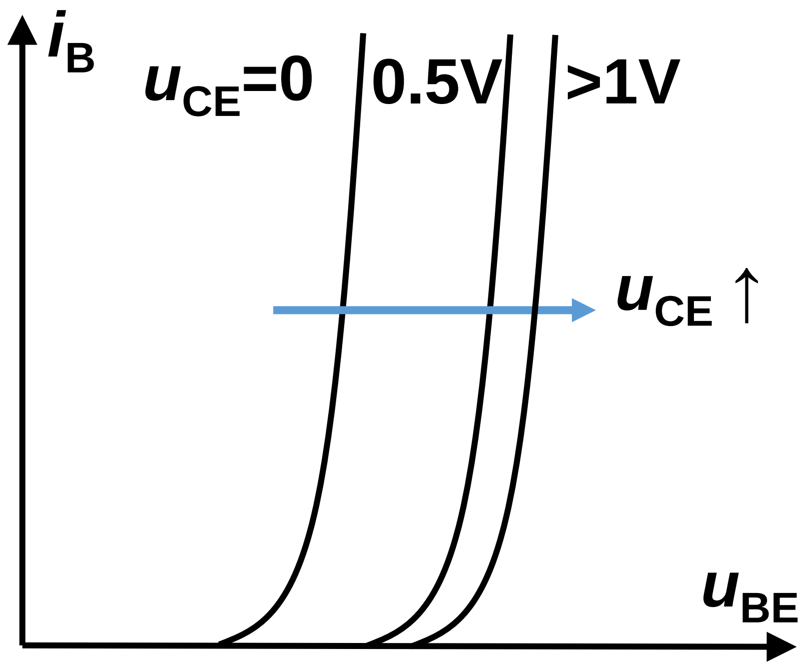
## Input I-V characteristics:

$$i_B = f(u_{BE})\Big|_{u_{CE} = \text{Constant}}$$



## Common-emitter

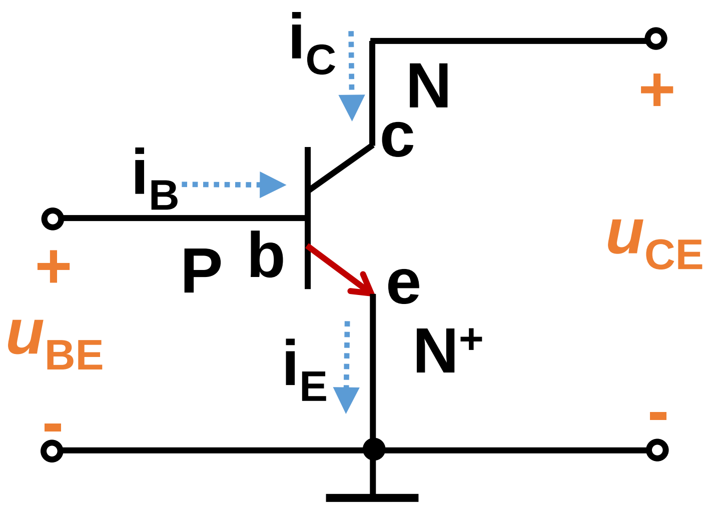



2) When $u_{CE}$ increase (<1V), the electric field in BC junction increase. Some electrons are collected by **Collector**, and the left are collected by **Base**. To reach the same value of $i_B$, $u_{BE}$ should be larger. Hence the I-V curve shifts to right.

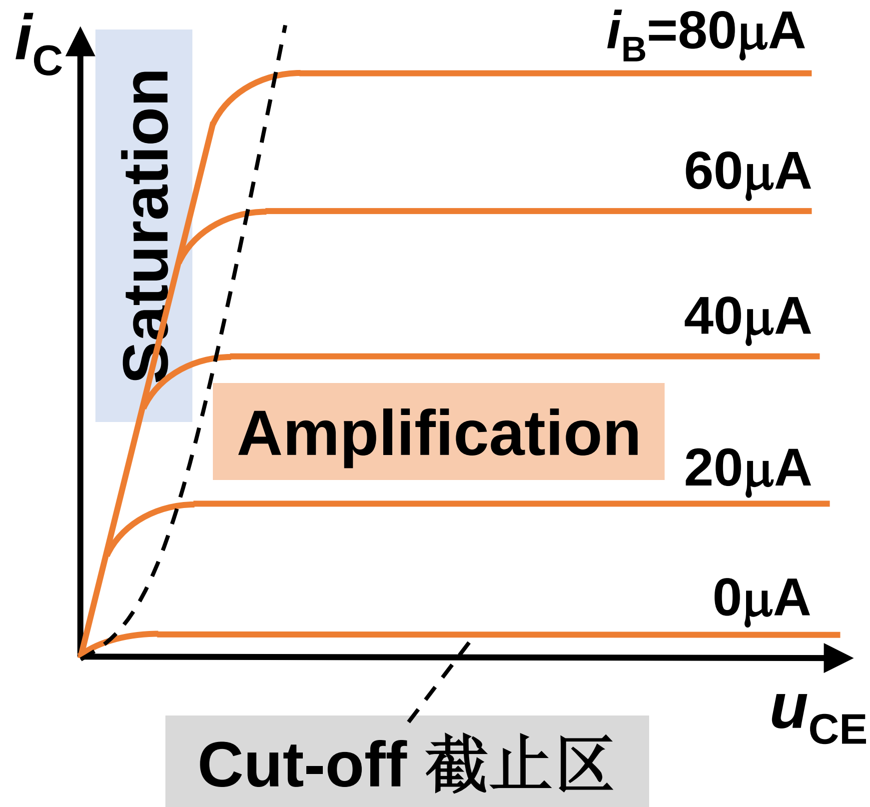
3) When $u_{CE}$ is large enough (>1V), the electric field in BC junction is strong enough, and most electrons are collected by **Collector** and **Collector** is saturated. Even further increase $u_{CE}$, the curve does not shift any more.

## Common-emitter




## Output I-V characteristic

$$i_C = f(u_{CE})\Big|_{i_B = \text{Constant}}$$



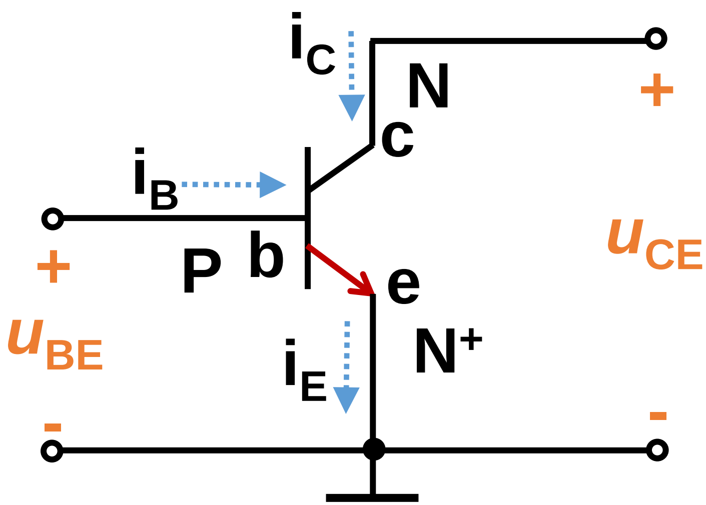

### 1) Cut-off region：

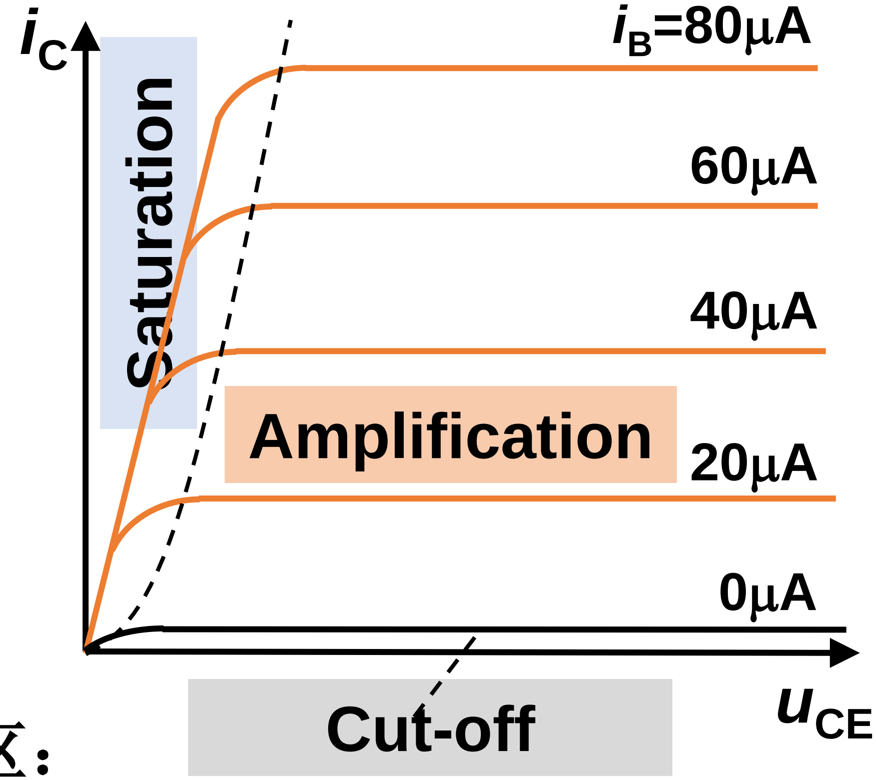
$u_{BE} < U_{ON}$ threshold voltage

$u_{CE} > u_{BE}$

$i_B \approx 0 \quad i_C \approx 0$

Common-emitter




**2) Amplification region放大区：**

$$u_{BE} > U_{ON}$$

$$u_{CE} > u_{BE}$$

BC junction is reverse biased

**$i_C$ is almost a constant**

**3) Saturation region饱和区：**

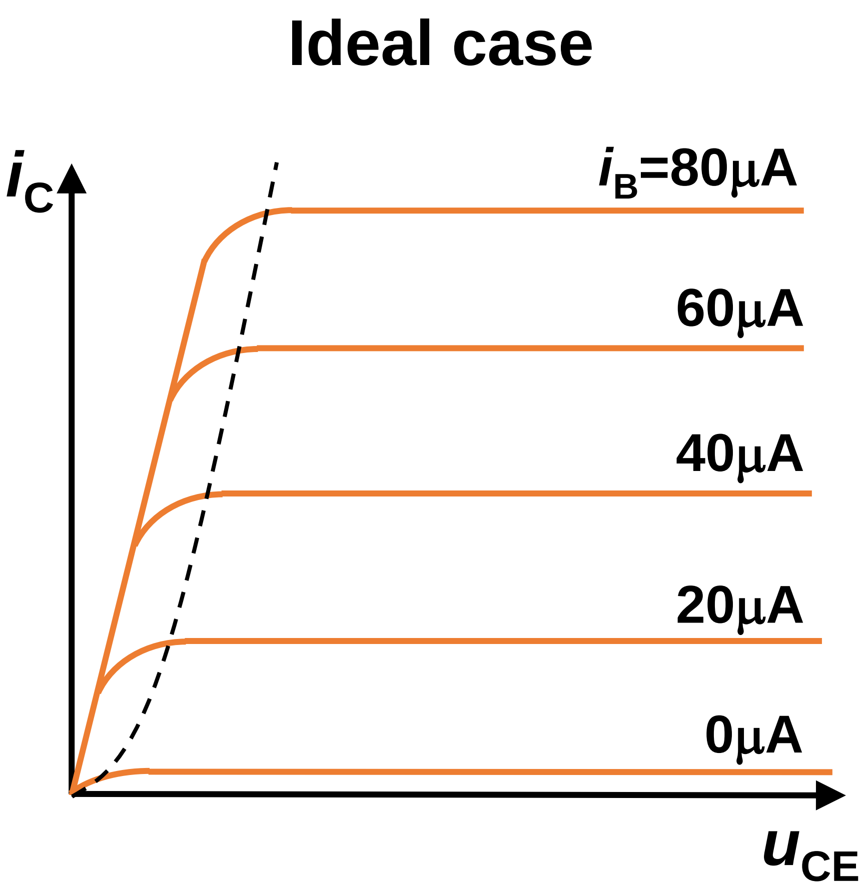
$$u_{BE} > U_{ON}$$

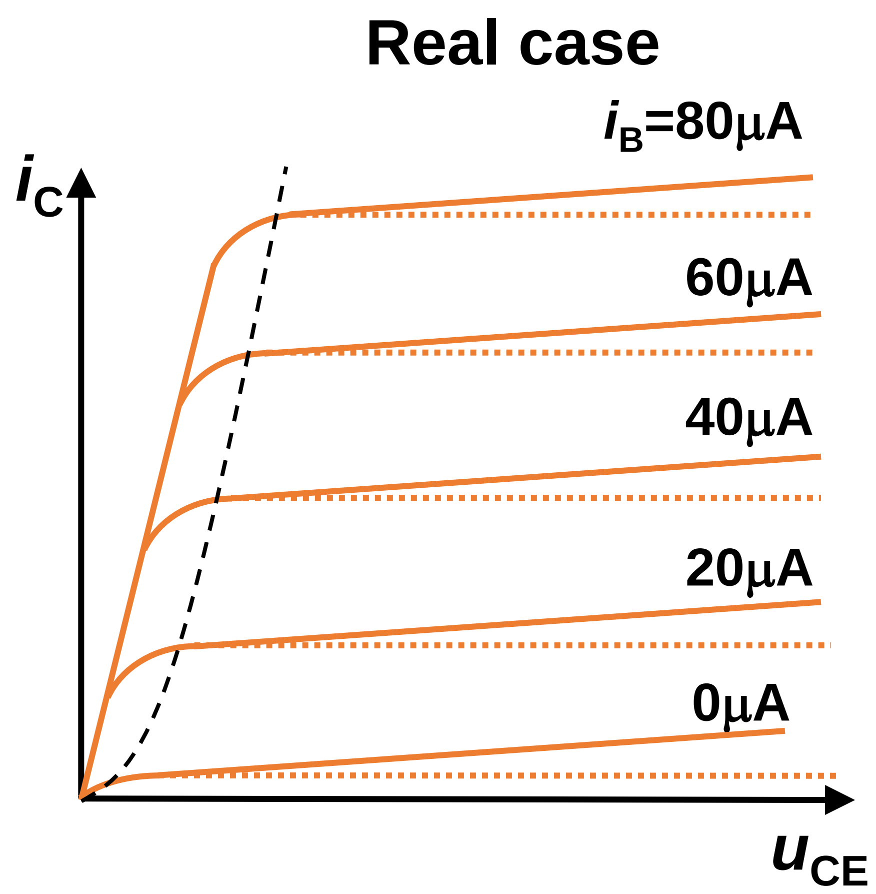
$$u_{CE} < u_{BE}$$

BC junction is forward biased

**$i_C$ increase with $u_{CE}$**

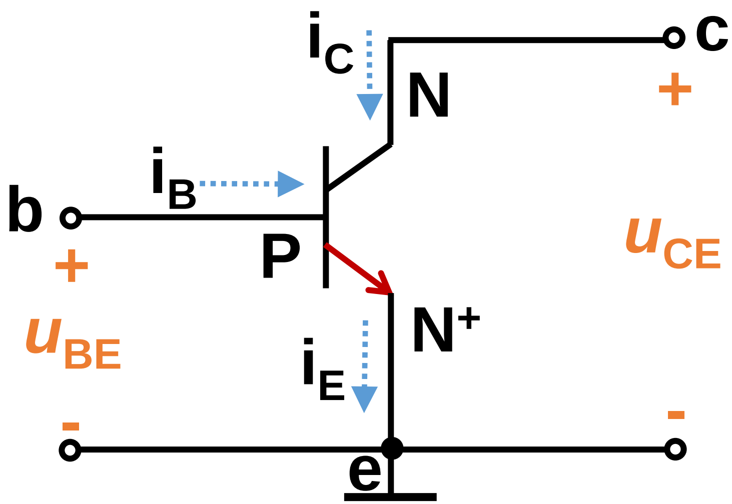
# Output I-V characteristic Common-emitter



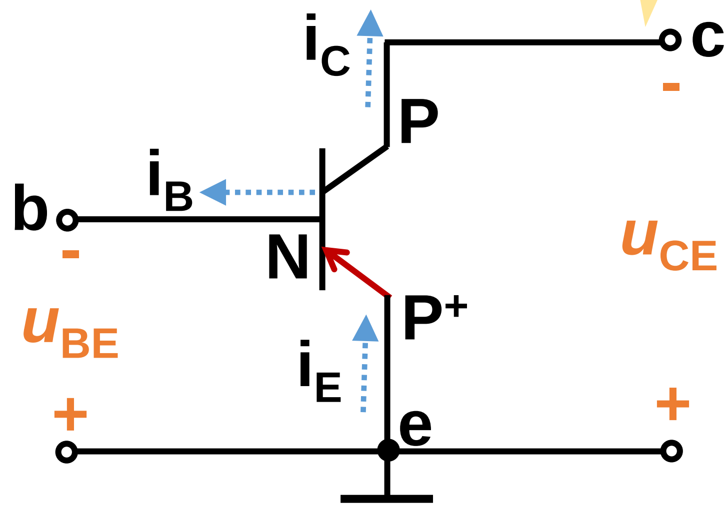
**Question!**

## NPN




Amplification mode

## PNP




Amplification mode

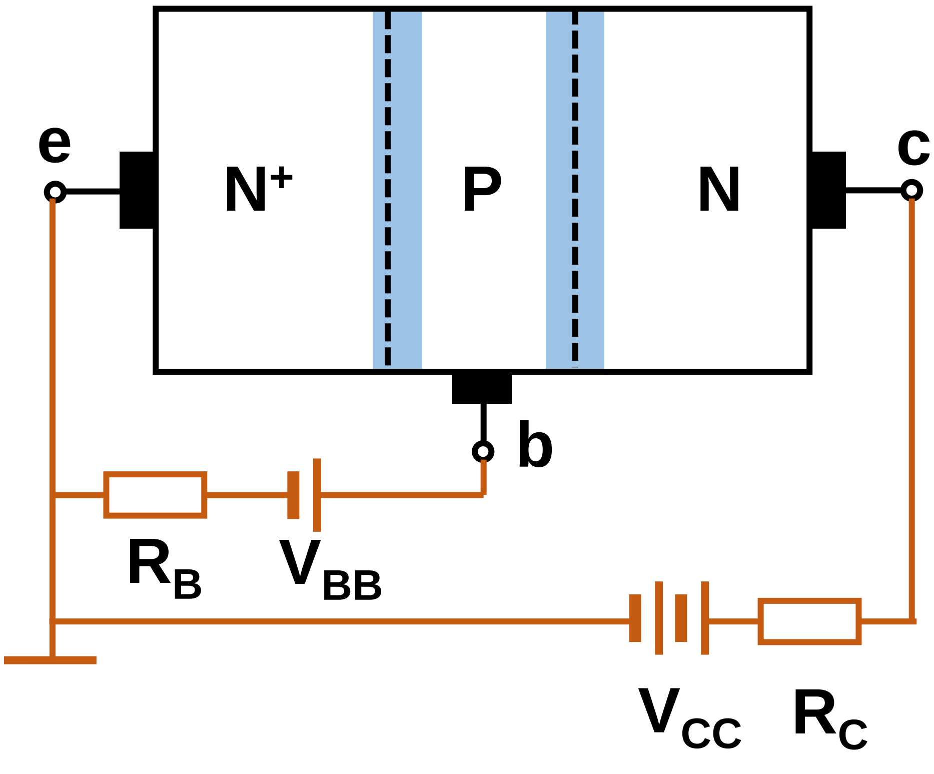
$$|u_{\mathrm{BE}}| < |u_{\mathrm{CE}}|$$

## Homework1-5: Draw the energy band diagram of N$^+$PN transistor

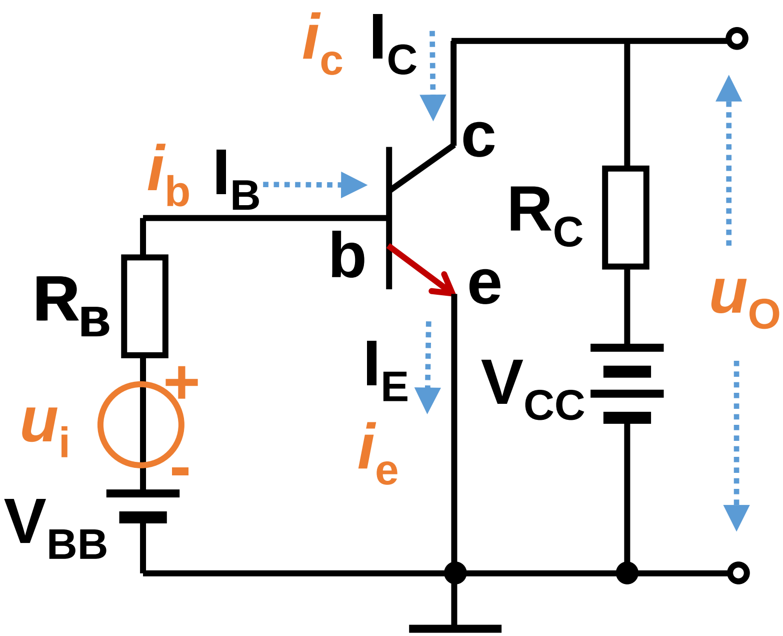
(1) $V_{BB}$ = $V_{CC}$ = 0.

(2) Saturation region.

(3) Amplification region.



# Common-emitter AC amplification circuit

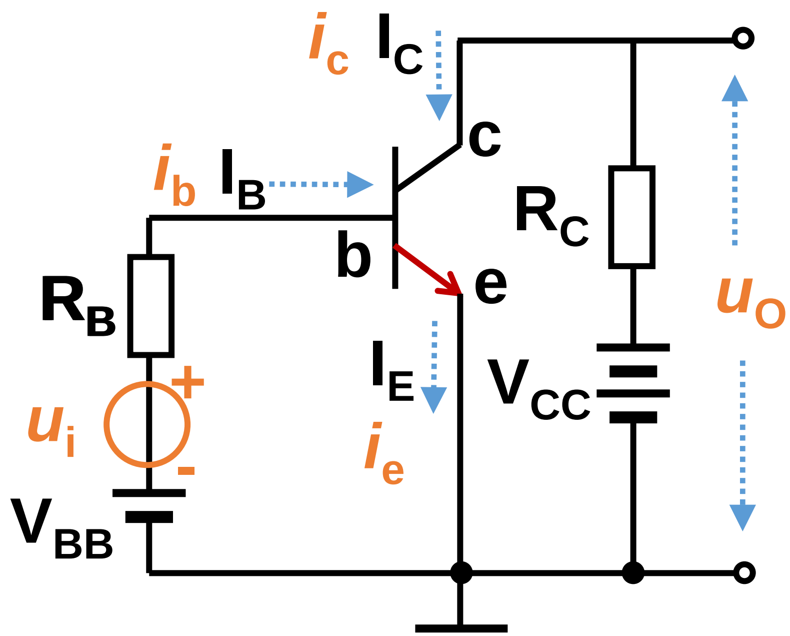



**Direct current**
直流电流

$$i_B = I_B + i_b$$

**Total current**
总瞬时电流

**Alternating current**
交流瞬时电流




**Input AC voltage signal** $u_i$

$$i_B = I_B + i_b$$

$$i_C = I_C + i_c$$

**Output voltage (DC+AC):**

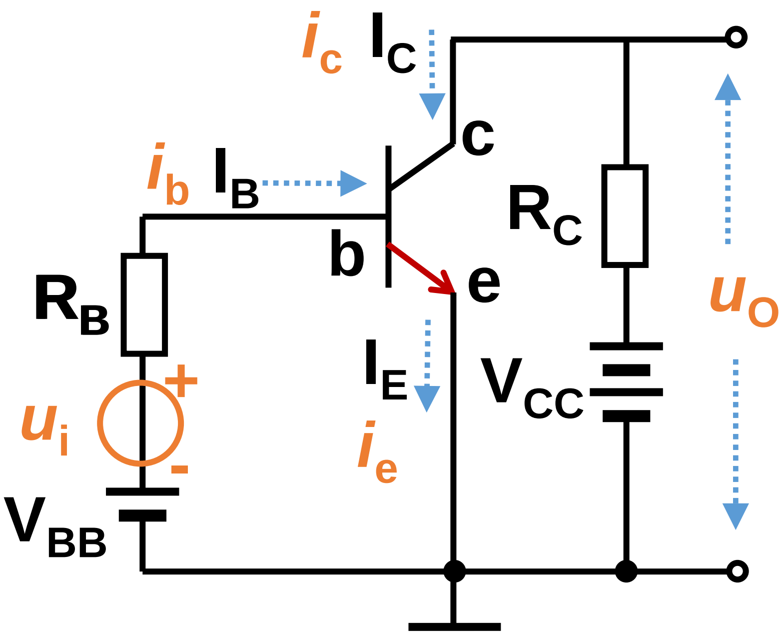
$$u_O = V_{CC} - i_C R_C$$
$$= V_{CC} - I_C R_C - i_c R_C$$

**Output DC voltage:** $U_O = V_{CC} - I_C R_C$

**Output AC voltage:** $u_o = -i_c R_C$

# AC amplification factor

## 共射交流放大系数




**Common-e:** $\beta = \dfrac{i_c}{i_b}$ **?**

**Common-b:** $\alpha = \dfrac{i_c}{i_e}$ **?**

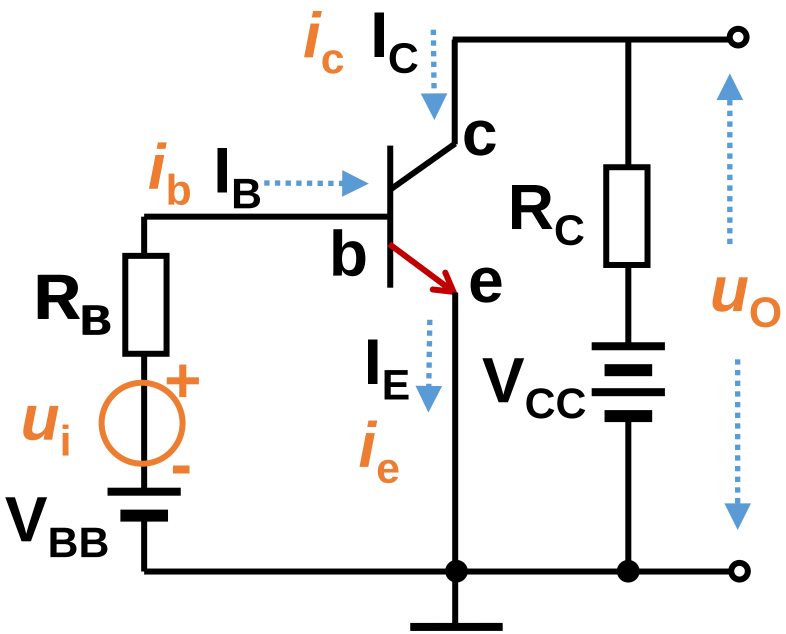
**In general case:**

$$\alpha \approx \bar{\alpha} \qquad \beta \approx \bar{\beta}$$

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

# AC amplification factor

## 共射交流放大系数




Total current:

$$i_C = \beta i_B$$

$$I_C + i_c = \beta(I_B + i_b)$$

$$I_C = \beta I_B$$

$$i_c = \beta i_b$$

$$\beta = \bar{\beta}$$

$$\alpha = \bar{\alpha}$$

**AC voltage/current：dynamic working parameter**

交流电压/电流：动态工作参数

$i_{\mathrm{b}}, i_{\mathrm{c}}, u_{\mathrm{be}}, u_{\mathrm{ce}}$

**Signal 信号.**

**DC voltage/current：static working parameter**

直流电压/电流：静态工作参数

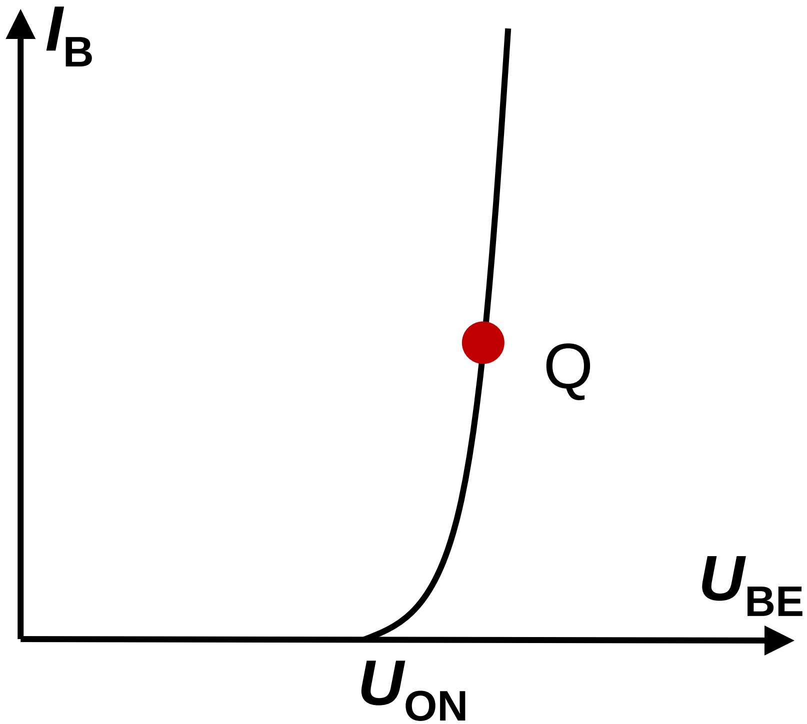
$I_{\mathrm{BQ}}, I_{\mathrm{CQ}}, U_{\mathrm{BEQ}}, U_{\mathrm{CEQ}}$

**Make transistor work in amplification region.**

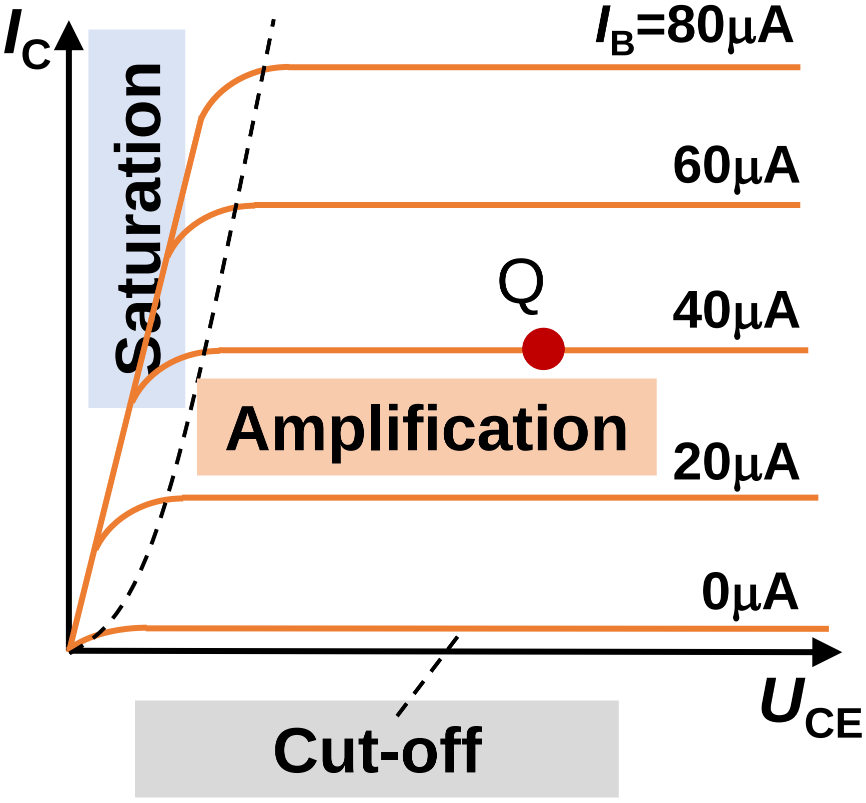
**To amplifier AC signal, transistor much work in amplification region.**

**To work in amplification region, transistor must have proper static working parameters:** $I_{\mathrm{BQ}}, I_{\mathrm{CQ}}, U_{\mathrm{BEQ}}, U_{\mathrm{CEQ}}$**.**

**Input curve of transistor**

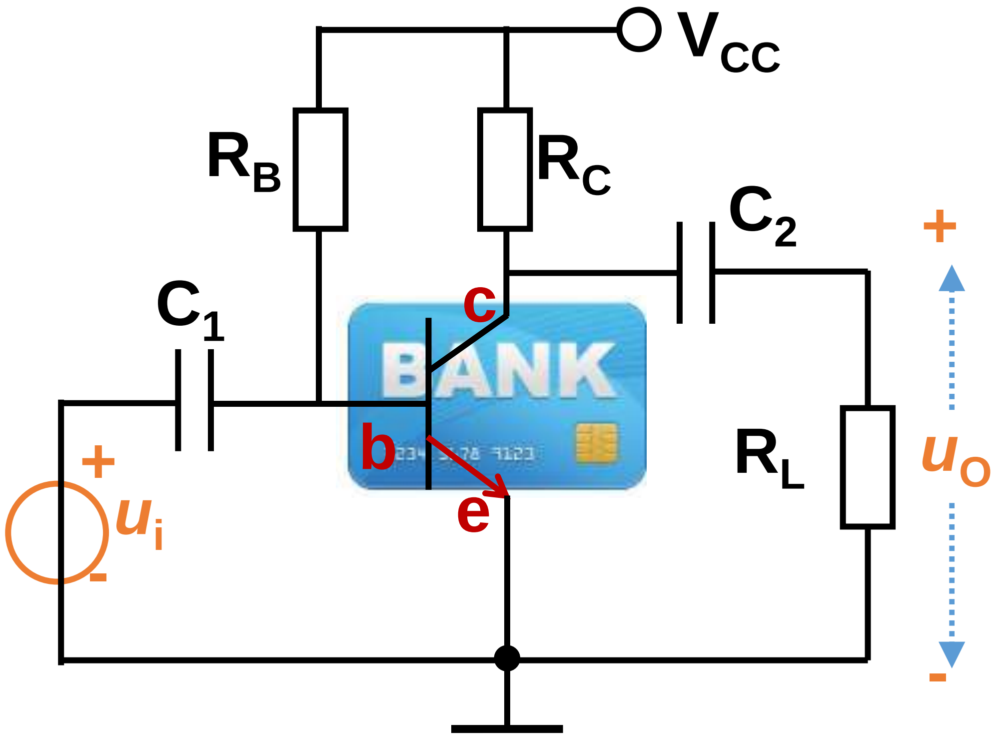



**Output curve of transistor**



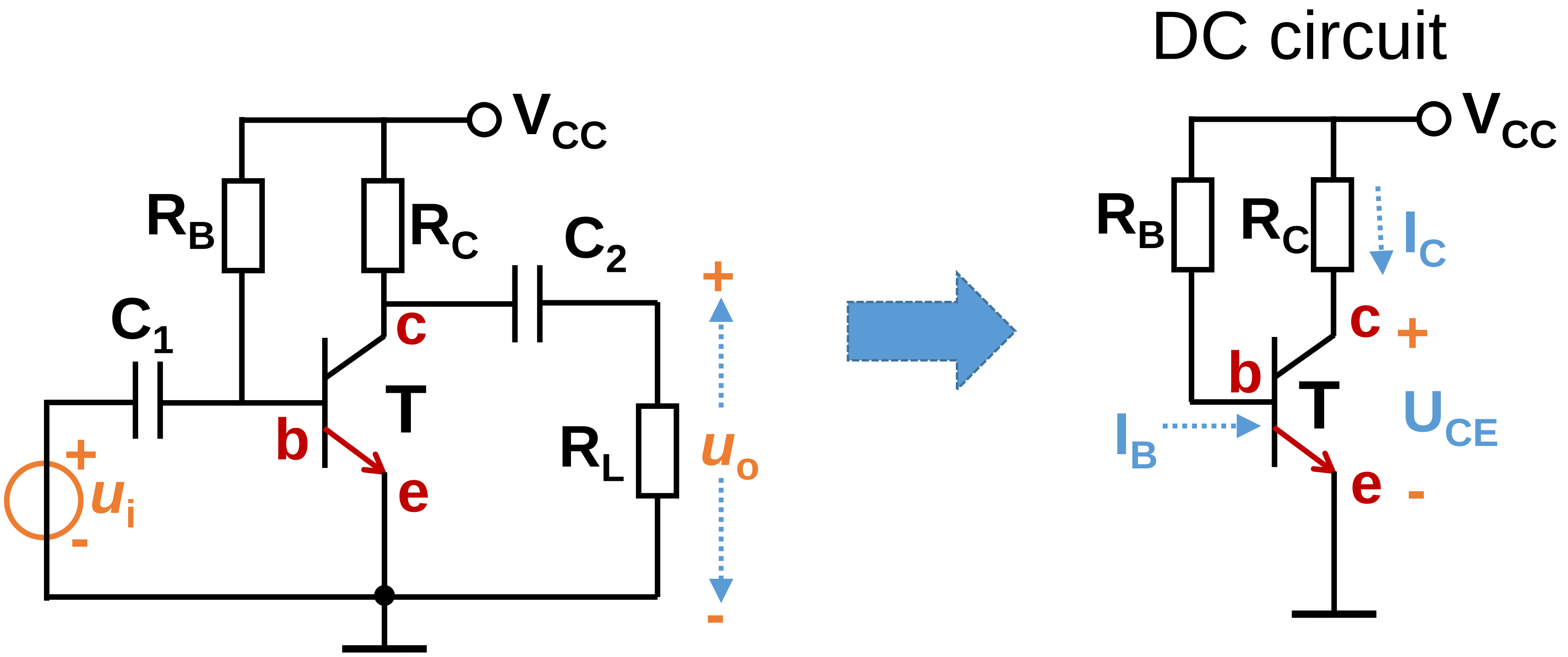

Choose $V_{CC}$, $R_B$ and $R_C$, set a proper $U_{BE}$, $U_{CE}$, $I_C$ and $I_B$, to make transistor work in the amplification region ($U_{BE} > U_{ON}$, $U_{CE} > U_{BE}$ ).

Usury 高利贷

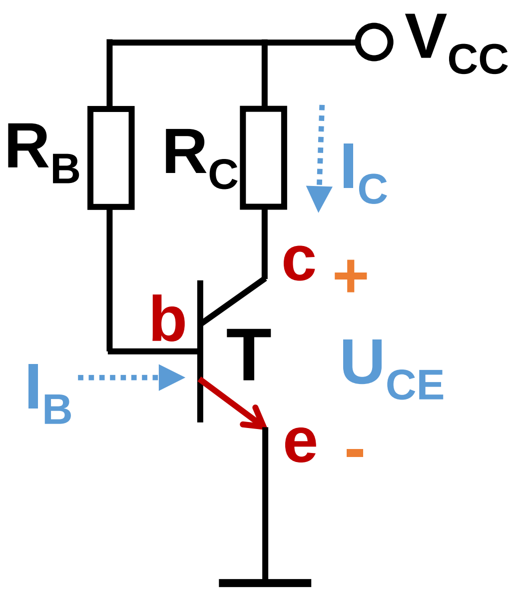




# Analyze quiescent working parameters

Get the static working parameters $I_{BQ}, I_{CQ}, U_{BEQ}, U_{CEQ}$ through analyzing its **DC circuit**.



# Parametric estimating method 估算法




1. Input circuit: $V_{CC}=I_{BQ}R_B+U_{BEQ}$

$$I_{BQ}=\frac{V_{CC}-U_{BEQ}}{R_B}$$

$U_{BEQ}$=0.7V for Si, 0.3V for Ge

2. $$I_{CQ}=\bar{\beta}I_{BQ}$$

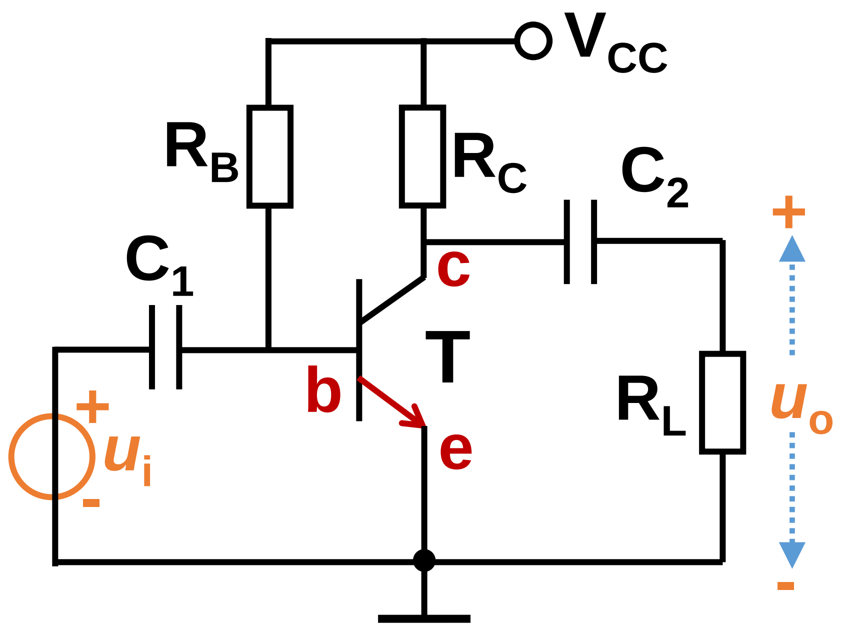
3. Output circuit

$$U_{CEQ}=V_{CC}-I_{CQ}R_C$$

# Dynamic analysis of the amplification circuit

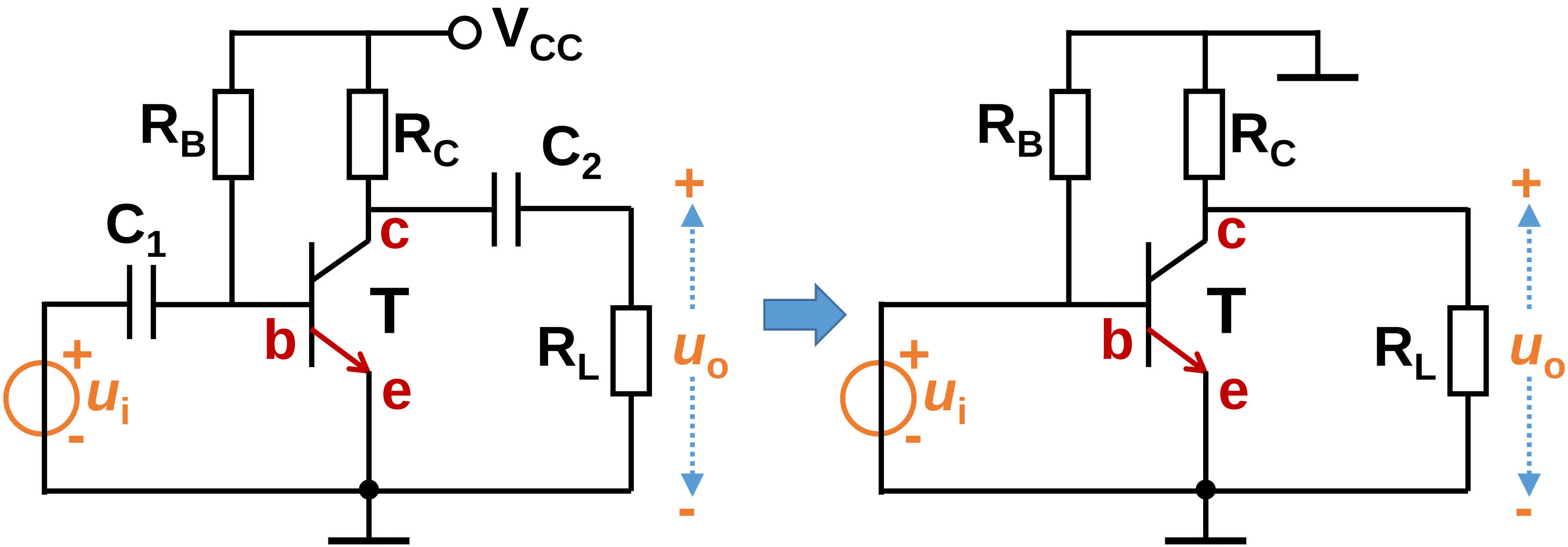
**Dynamic analysis: analyze the AC signal based on the quiescent/DC circuit.**

动态分析：在静态电路的基础上分析各交流信号的关系



# How to obtain the AC circuit

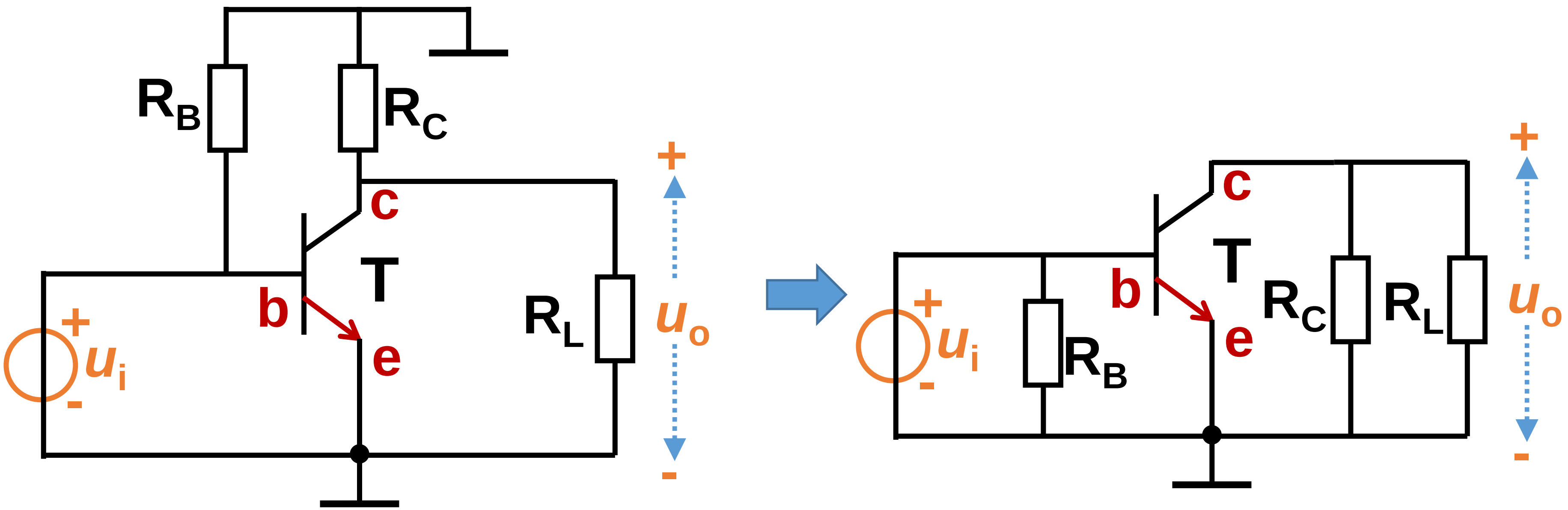
## AC circuit 交流通路




1. Short the DC voltage source (Connect DC voltage source to ground) 直流电压源接地.

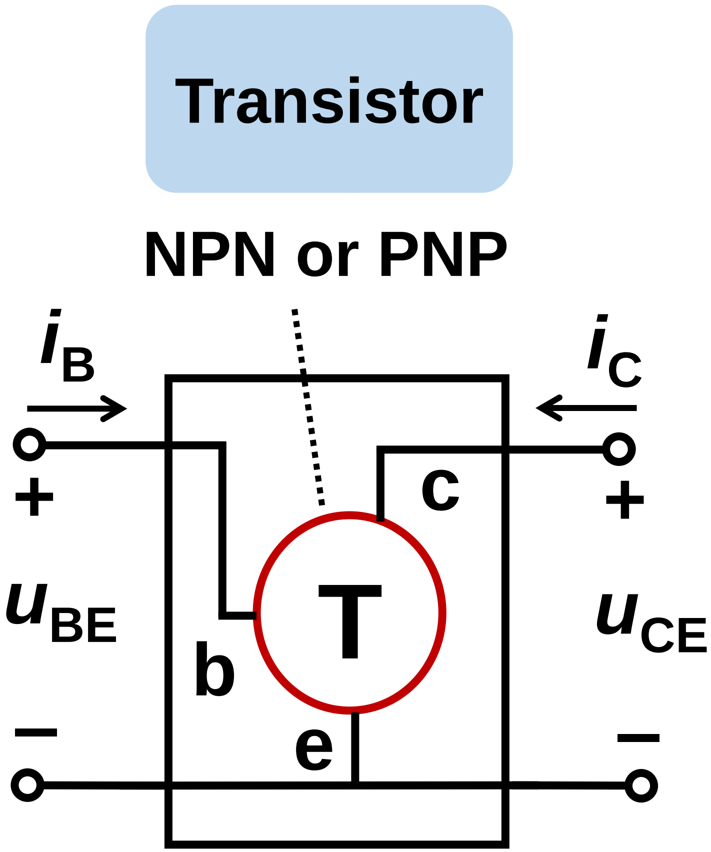
2. Short the capacitor if its impedance is very small 工作频率下如果电容阻抗很小的话，近似电容短路.

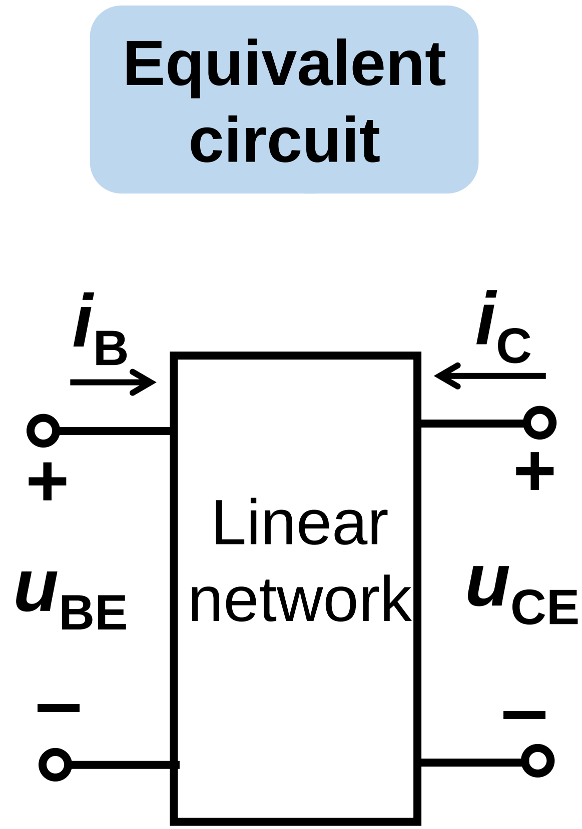
# AC circuit 交流通路

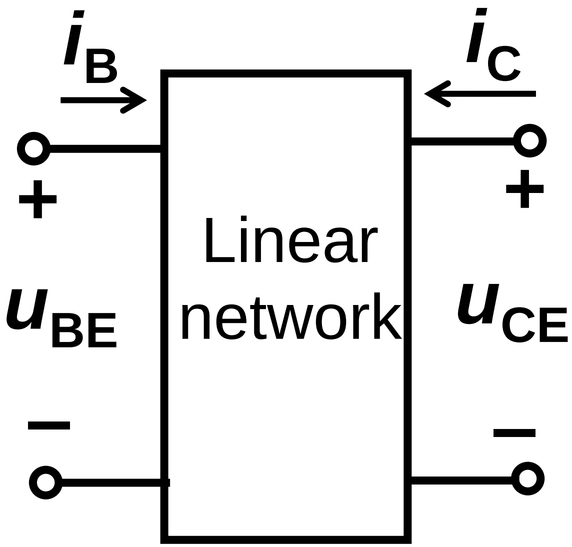


# Equivalent circuit method (*h*-model)

**To replace transistor with a linear network**






1
$$\begin{cases} u_{BE} = f(i_B, u_{CE}) \\ i_C = f(i_B, u_{CE}) \end{cases}$$

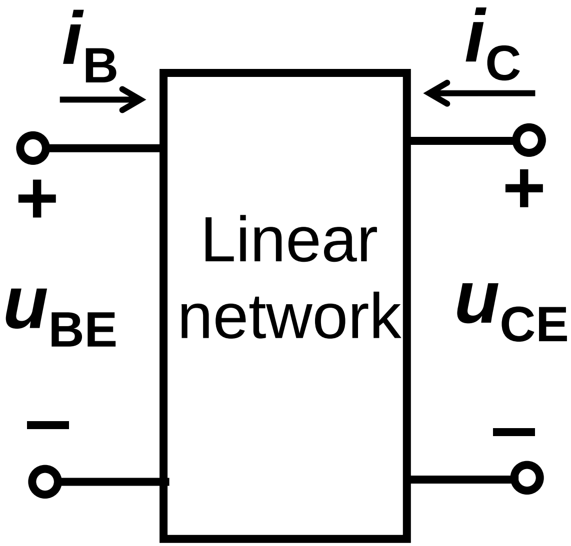
2
$$\begin{cases} du_{BE} = \dfrac{\partial u_{BE}}{\partial i_B}\Big|_{U_{CEQ}} di_B + \dfrac{\partial u_{BE}}{\partial u_{CE}}\Big|_{I_{BQ}} du_{CE} \\ di_C = \dfrac{\partial i_C}{\partial i_B}\Big|_{U_{CEQ}} di_B + \dfrac{\partial i_C}{\partial u_{CE}}\Big|_{I_{BQ}} du_{CE} \end{cases}$$

$$u_{BE} = U_{BE} + u_{be} \qquad du_{BE} = du_{be}$$

**Input signal $u_{be}$ is small**

$du_{BE}$ can be replaced by a small quantity: $u_{be}$ or $\dot{U}_{be}$

$$\begin{pmatrix} h_{11e} = \dfrac{\partial u_{BE}}{\partial i_B}\Big|_{U_{CEQ}} = \dfrac{\dot{U}_{be}}{\dot{I}_b}\Big|_{U_{CEQ}} & h_{12e} = \dfrac{\partial u_{BE}}{\partial u_{CE}}\Big|_{I_{BQ}} = \dfrac{\dot{U}_{be}}{\dot{U}_{ce}}\Big|_{I_{BQ}} \\ h_{21e} = \dfrac{\partial i_C}{\partial i_B}\Big|_{U_{CEQ}} = \dfrac{\dot{I}_c}{\dot{I}_b}\Big|_{U_{CEQ}} & h_{22e} = \dfrac{\partial i_C}{\partial u_{CE}}\Big|_{I_{BQ}} = \dfrac{\dot{I}_c}{\dot{U}_{ce}}\Big|_{I_{BQ}} \end{pmatrix}$$

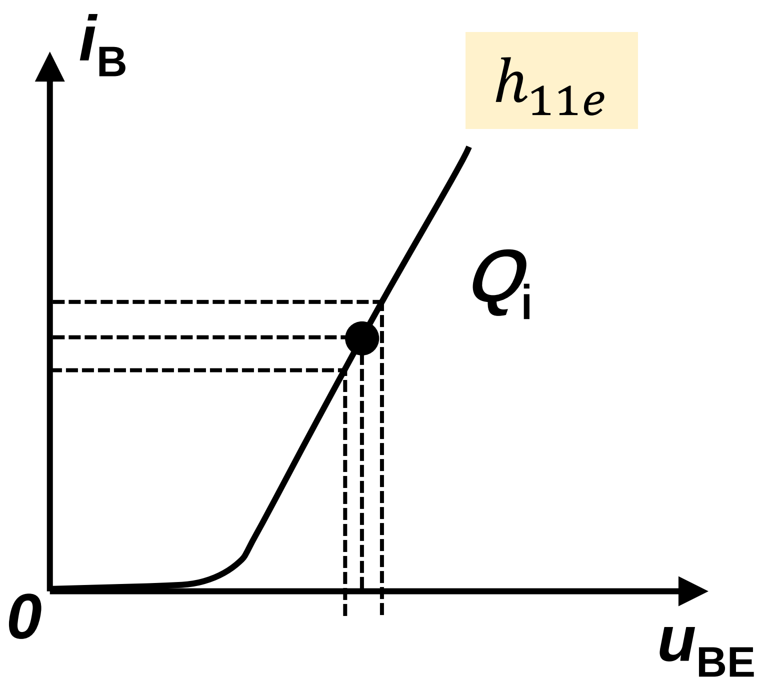


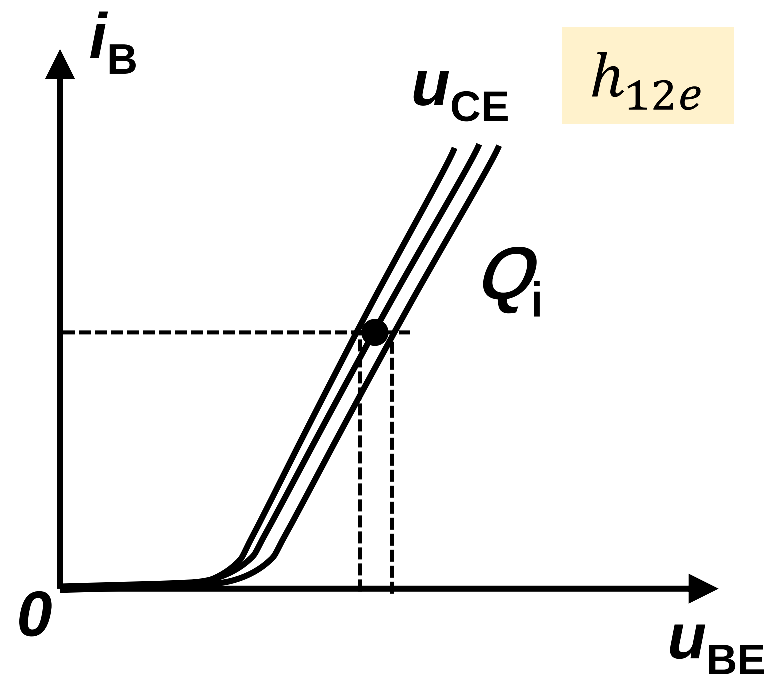

$$\begin{cases} \dot{U}_{\mathrm{be}} = h_{11\mathrm{e}}\dot{I}_{\mathrm{b}} + h_{12\mathrm{e}}\dot{U}_{\mathrm{ce}} \\ \dot{I}_{\mathrm{c}} = h_{21\mathrm{e}}\dot{I}_{\mathrm{b}} + h_{22\mathrm{e}}\dot{U}_{\mathrm{ce}} \end{cases}$$

$$\begin{cases} u_{\mathrm{be}} = h_{11\mathrm{e}} i_{\mathrm{b}} + h_{12\mathrm{e}} u_{\mathrm{ce}} \\ i_{\mathrm{c}} = h_{21\mathrm{e}} i_{\mathrm{b}} + h_{22\mathrm{e}} u_{\mathrm{ce}} \end{cases}$$

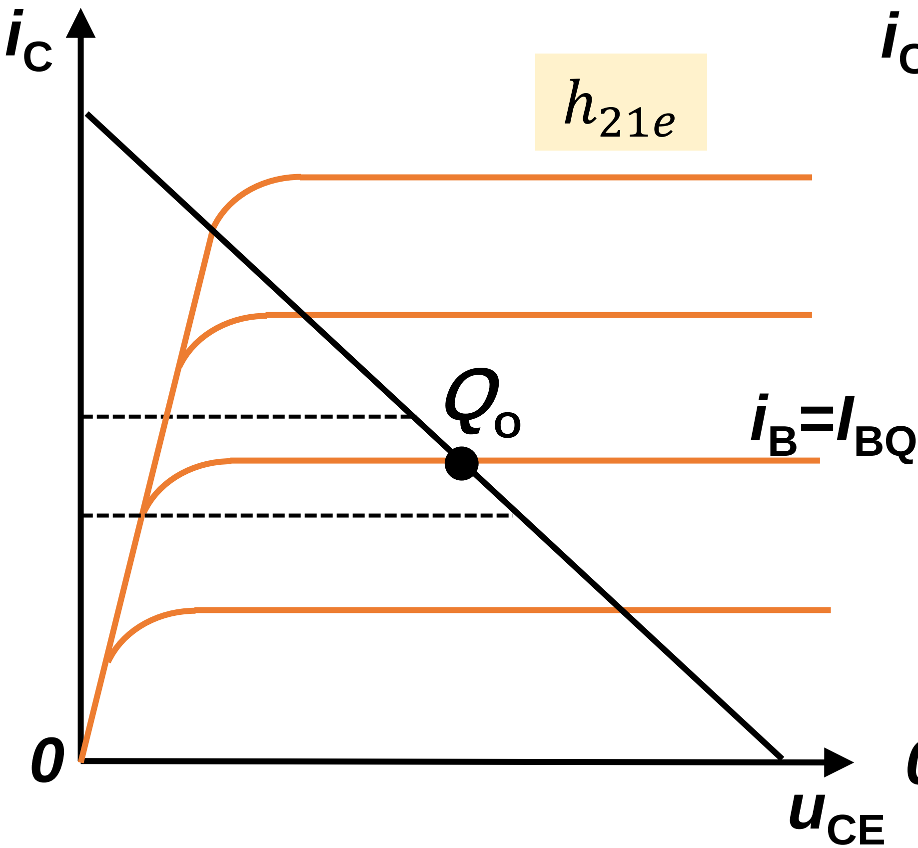
$$\left( \begin{array}{ll} h_{11\mathrm{e}} = \dfrac{\partial u_{\mathrm{BE}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CEQ}}} = \dfrac{\dot{U}_{\mathrm{be}}}{\dot{I}_{\mathrm{b}}}\Big|_{U_{\mathrm{CEQ}}} & h_{12\mathrm{e}} = \dfrac{\partial u_{\mathrm{BE}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{BQ}}} = \dfrac{\dot{U}_{\mathrm{be}}}{\dot{U}_{\mathrm{ce}}}\Big|_{I_{\mathrm{BQ}}} \\ h_{21\mathrm{e}} = \dfrac{\partial i_{\mathrm{C}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CEQ}}} = \dfrac{\dot{I}_{\mathrm{c}}}{\dot{I}_{\mathrm{b}}}\Big|_{U_{\mathrm{CEQ}}} & h_{22\mathrm{e}} = \dfrac{\partial i_{\mathrm{C}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{BQ}}} = \dfrac{\dot{I}_{\mathrm{c}}}{\dot{U}_{\mathrm{ce}}}\Big|_{I_{\mathrm{BQ}}} \end{array} \right)$$

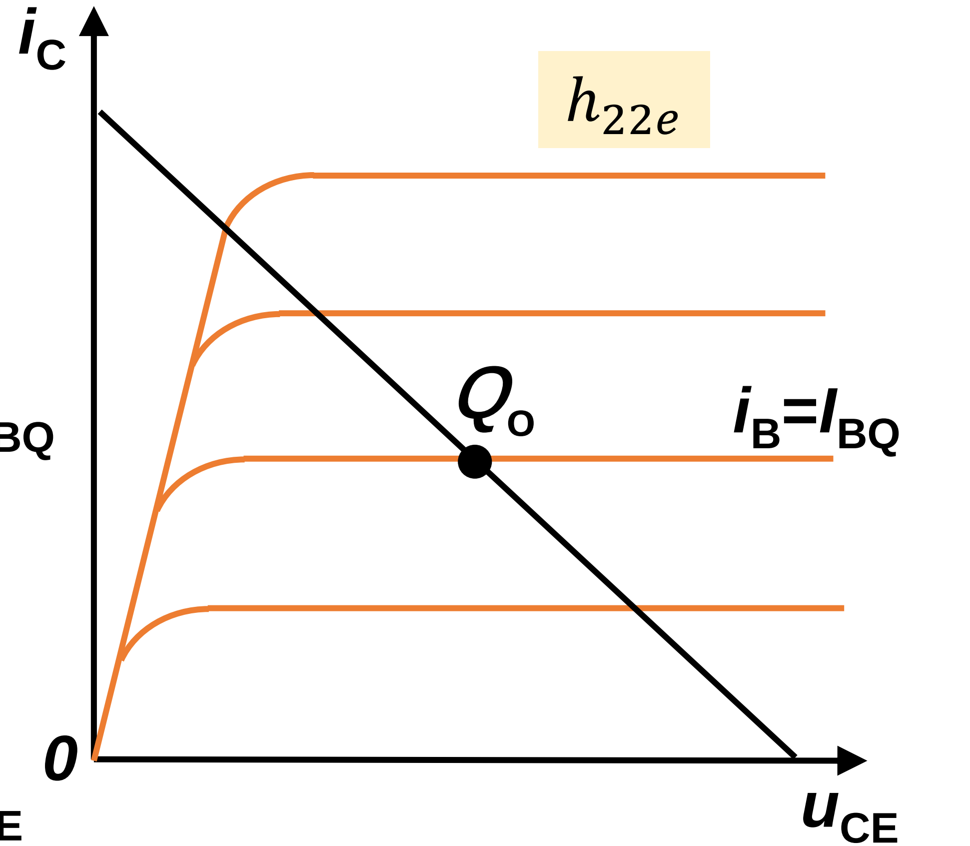
# The physical interpretation of *h*



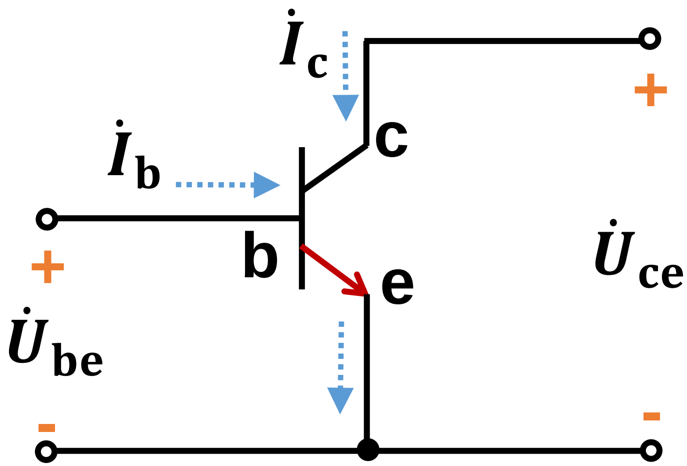

$$\begin{cases} h_{11\mathrm{e}} = \dfrac{\partial u_{\mathrm{BE}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CEQ}}} = \dfrac{\dot{U}_{\mathrm{be}}}{\dot{I}_{\mathrm{b}}}\Big|_{U_{\mathrm{CEQ}}} & h_{12\mathrm{e}} = \dfrac{\partial u_{\mathrm{BE}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{BQ}}} = \dfrac{\dot{U}_{\mathrm{be}}}{\dot{U}_{\mathrm{ce}}}\Big|_{I_{\mathrm{BQ}}} \\ h_{21\mathrm{e}} = \dfrac{\partial i_{\mathrm{C}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CEQ}}} = \dfrac{\dot{I}_{\mathrm{c}}}{\dot{I}_{\mathrm{b}}}\Big|_{U_{\mathrm{CEQ}}} & h_{22\mathrm{e}} = \dfrac{\partial i_{\mathrm{C}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{BQ}}} = \dfrac{\dot{I}_{\mathrm{c}}}{\dot{U}_{\mathrm{ce}}}\Big|_{I_{\mathrm{BQ}}} \end{cases}$$



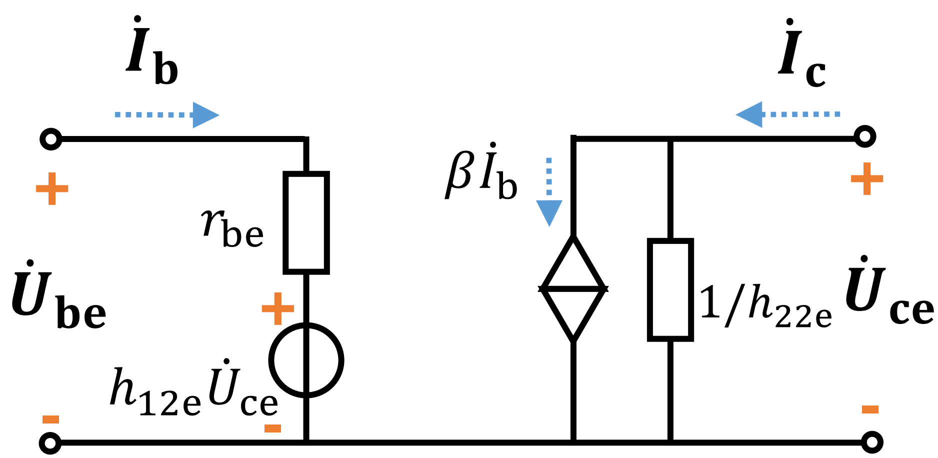



$$\begin{cases} h_{11\mathrm{e}} = \dfrac{\partial u_{\mathrm{BE}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CEQ}}} = \dfrac{\dot{U}_{\mathrm{be}}}{\dot{I}_{\mathrm{b}}}\Big|_{U_{\mathrm{CEQ}}} & h_{12\mathrm{e}} = \dfrac{\partial u_{\mathrm{BE}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{BQ}}} = \dfrac{\dot{U}_{\mathrm{be}}}{\dot{U}_{\mathrm{ce}}}\Big|_{I_{\mathrm{BQ}}} \\ h_{21\mathrm{e}} = \dfrac{\partial i_{\mathrm{C}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CEQ}}} = \dfrac{\dot{I}_{\mathrm{c}}}{\dot{I}_{\mathrm{b}}}\Big|_{U_{\mathrm{CEQ}}} & h_{22\mathrm{e}} = \dfrac{\partial i_{\mathrm{C}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{BQ}}} = \dfrac{\dot{I}_{\mathrm{c}}}{\dot{U}_{\mathrm{ce}}}\Big|_{I_{\mathrm{BQ}}} \end{cases}$$

# Common-emitter

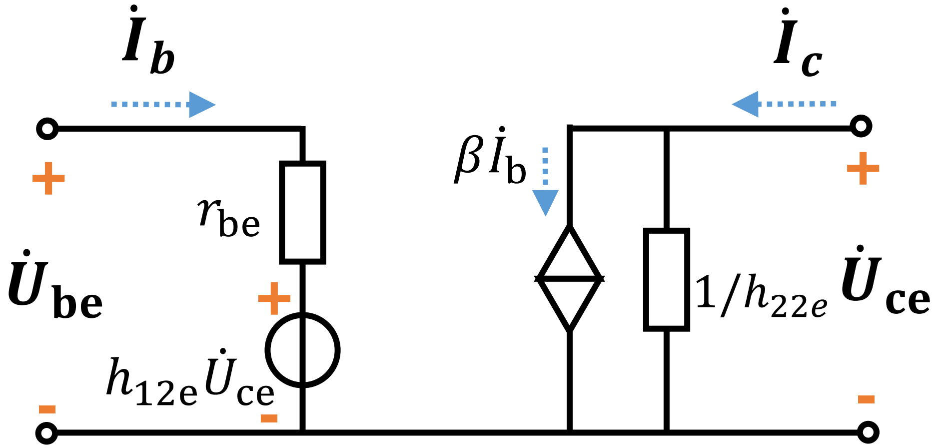



$$\begin{cases} \dot{U}_{\mathrm{be}} = h_{11\mathrm{e}}\dot{I}_{\mathrm{b}} + h_{12\mathrm{e}}\dot{U}_{\mathrm{ce}} \\ \dot{I}_{\mathrm{c}} = h_{21\mathrm{e}}\dot{I}_{\mathrm{b}} + h_{22\mathrm{e}}\dot{U}_{\mathrm{ce}} \end{cases}$$




$$r_{\mathrm{be}} = h_{11\mathrm{e}}$$

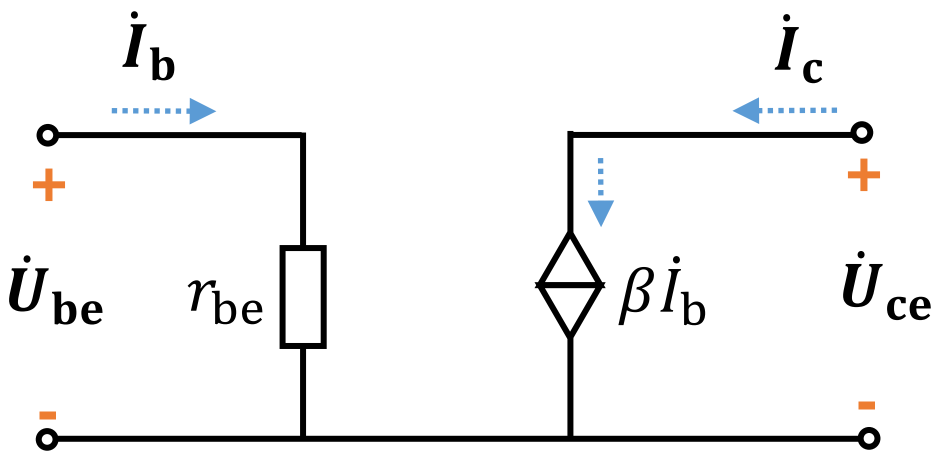
$$h_{21\mathrm{e}} = \beta$$




$$r_{be} = h_{11e}$$

$$h_{21e} = \beta$$

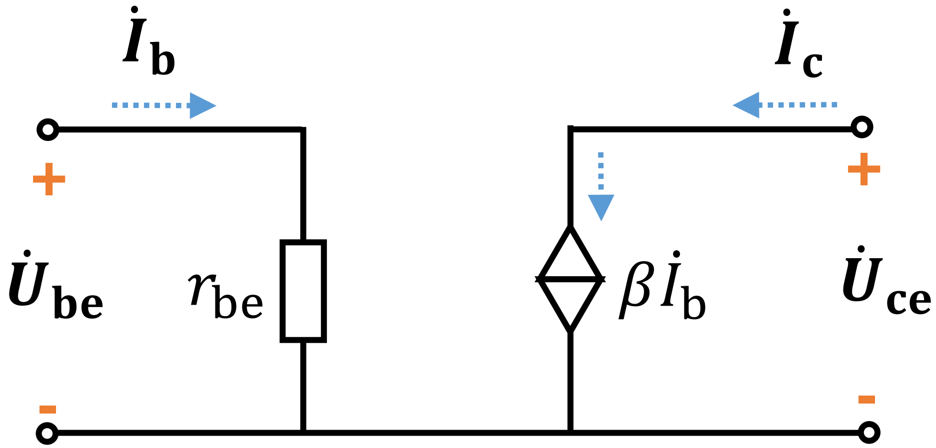
Because $h_{12e}$ and $h_{22e}$ is very small, we can simplify the circuit




$$r_{be} \approx \beta \frac{U_T}{|I_{CQ}|}$$

$$U_T = 26\text{mV}$$

## Question: What's the h-model of PNP transistor?

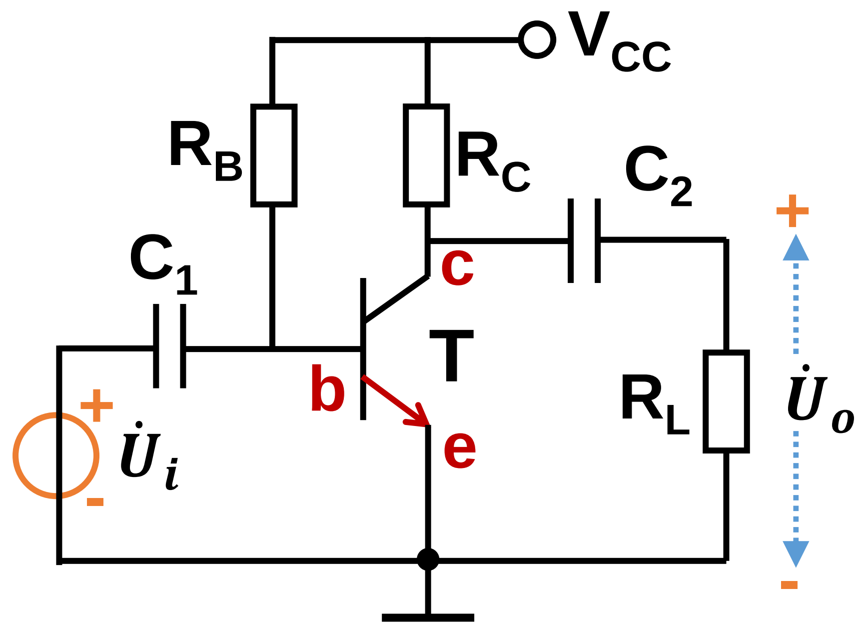



$$r_{be} = r_{bb'} + \beta \frac{U_T}{|I_{CQ}|}$$

$$U_T = 26\text{mV}$$

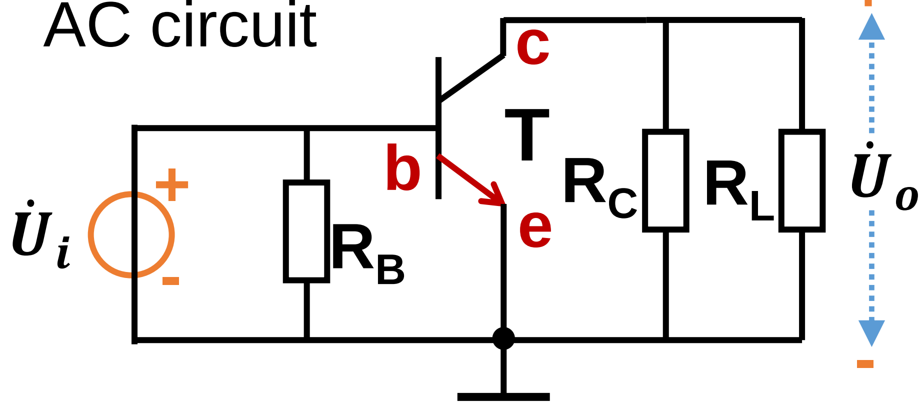
**This equivalent circuit is for both NPN and PNP transistors.**

# Example:

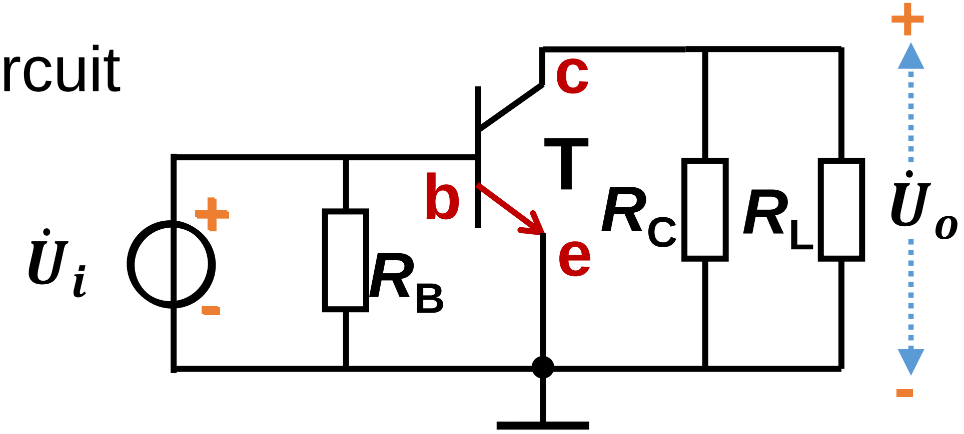



(1) What's the equivalent circuit of *h*-model?

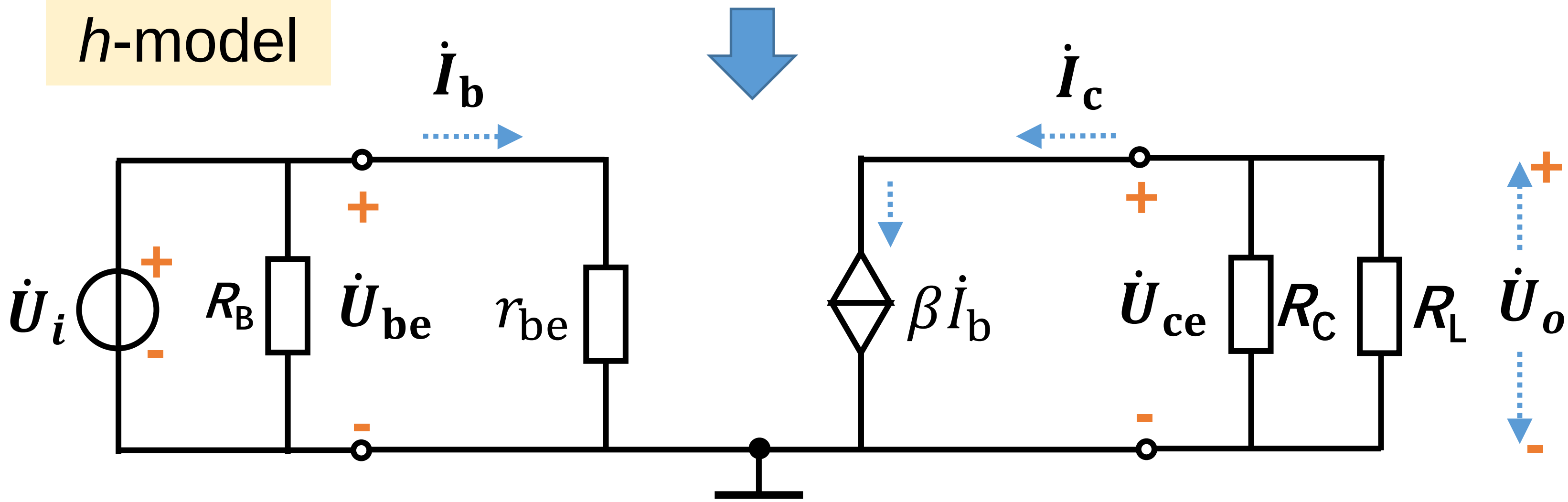
AC circuit



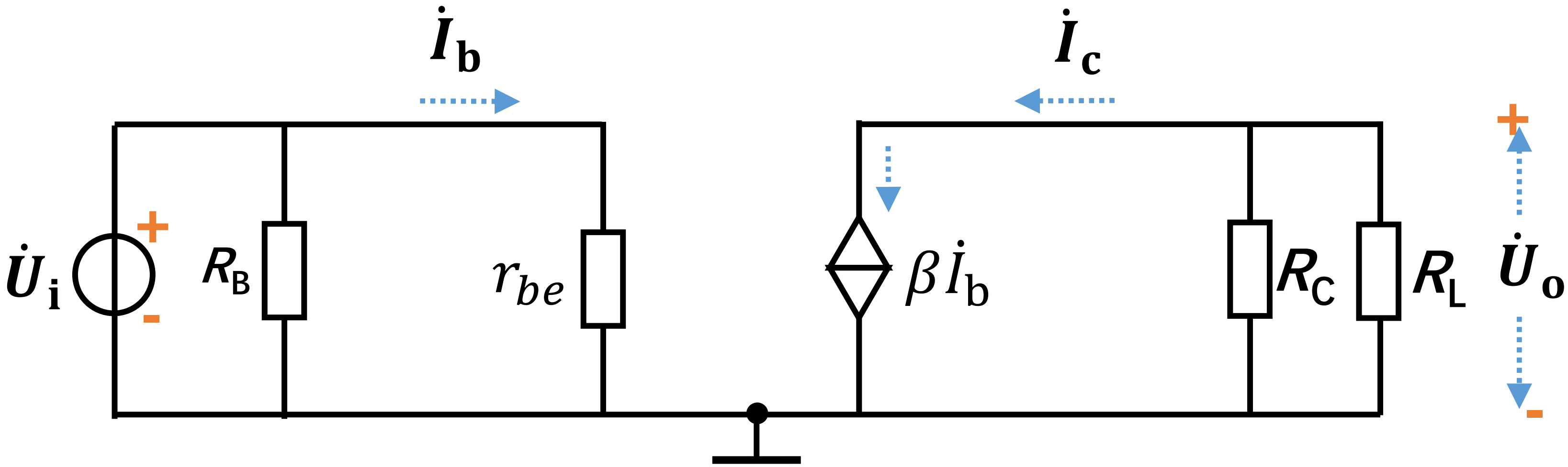
AC circuit




*h*-model




(2) Voltage gain?




**Voltage gain:** $$\dot{A}_u = \frac{\dot{U}_o}{\dot{U}_i}$$

$$\dot{U}_i = \dot{I}_b r_{be}$$

$$\dot{U}_o = -\dot{I}_c (R_C || R_L) = -\beta \dot{I}_b R_L{}'$$

$$\dot{A}_u = -\frac{\beta R_L{}'}{r_{be}}$$