ECE3110J/VE311 Electronic Circuits

Bipolar Junction Transistor (BJT)

Microelectronic Circuit Design, Chapter 5
Fundamentals of Microelectronics, Chapter 4

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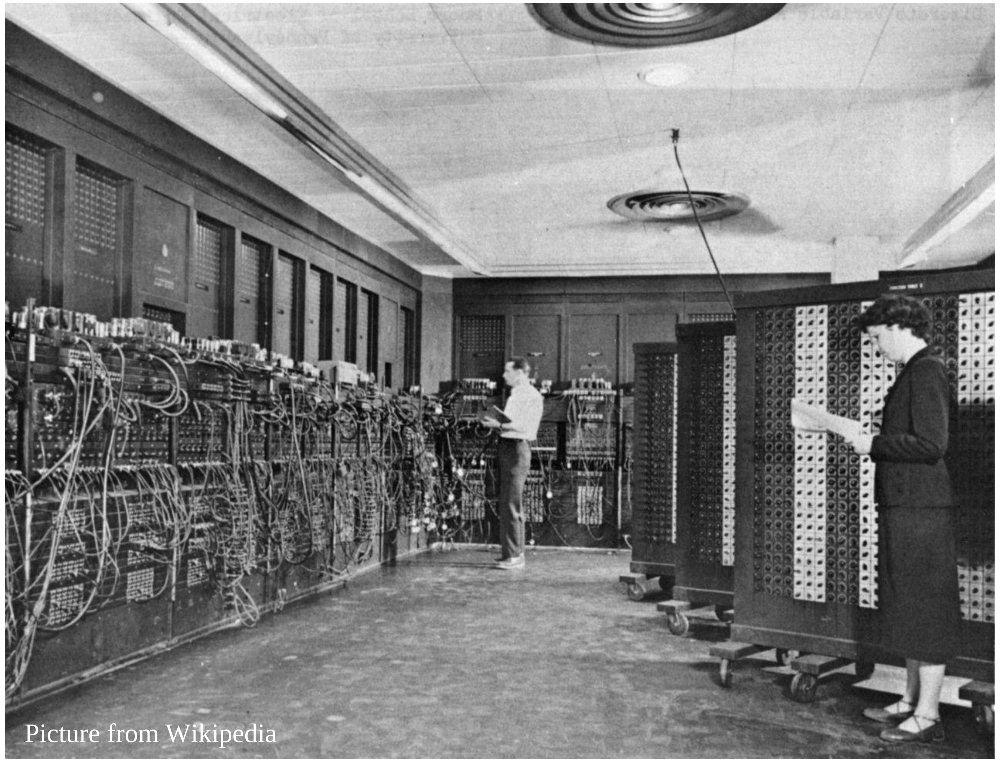
Before the invention of transistors


Picture from Wikipedia

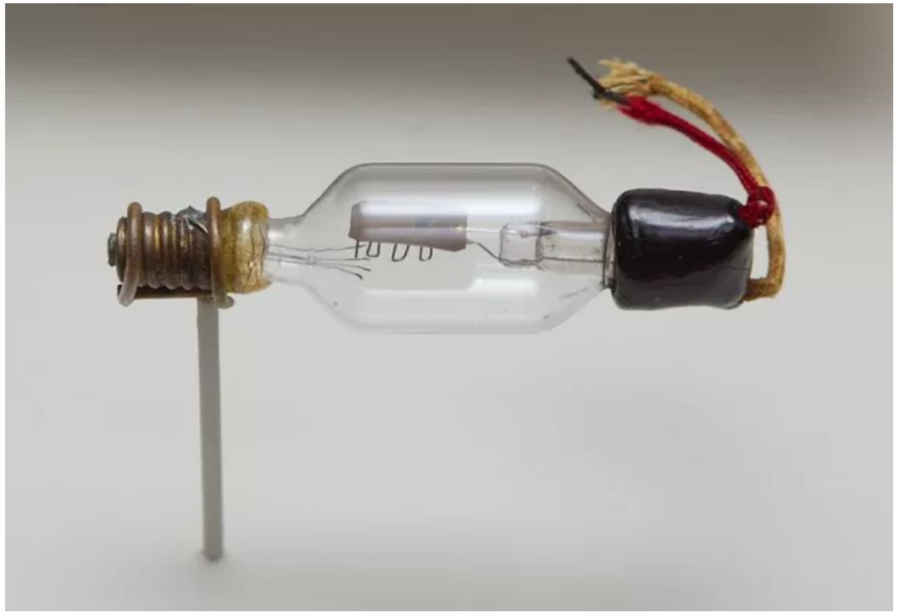
ENIAC is composed of

- **20,000 vacuum tubes**
- 7,200 crystal diodes
- 1,500 relays
- 70,000 resistors
- 10,000 capacitors
- Approximately 5,000,000 hand-soldered joints

Consumed **150 kW** of electricity, occupied **167 m^2**, weighed over **27 tones**

From Vacuum tube to Transistor

Instead of controlling an electron in **vacuum, transistor** controls it in **solid materials**



The original triode vacuum tube, the Audion, invented by Lee de Forest in 1906. (Image courtesy of Gregory F. Maxwell.)

A replica of the first transistor created in 1947.

BJT

In 1947, the world's first transistor was created, which was the beginning of the end for the vacuum tube. **The transistor could replicate all the functions of tubes, like switching and amplification, but was made out of semiconductor materials**.

BJT and Nobel Prize

nobelprize.org

Photo from the Nobel Foundation archive.
William Bradford Shockley

John Bardeen

Photo from the Nobel Foundation archive.
Walter Houser Brattain

Amoy, Xiamen

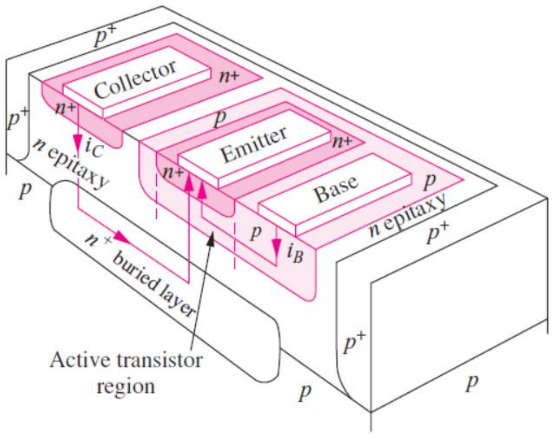
The transistors replaced the vacuum tubes and made a dramatic change in the world of electronics. Bardeen and Brattain together with William Shockley received the **Nobel Prize in Physics in 1956 “for their researches on semiconductors and their discovery of the transistor effect.”.**

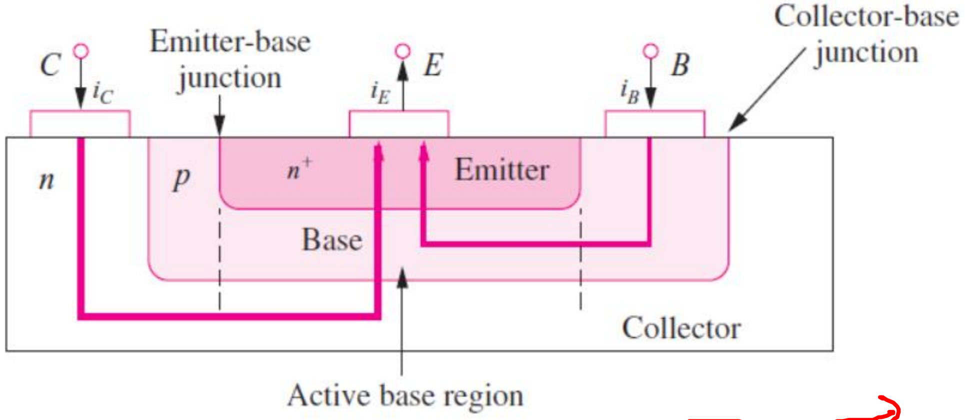
Device Schematics

MOSFET

S $\xrightarrow{e^-}$ D

S $\xleftarrow{e^-}$ D





e $\longrightarrow$

E	B	C
n+	p	n

W_b.

electron current

hole current.

BJT has **n$^+$-p-n** or **p$^+$-n-p** structure.

e.g. n$^+$-p-n structure

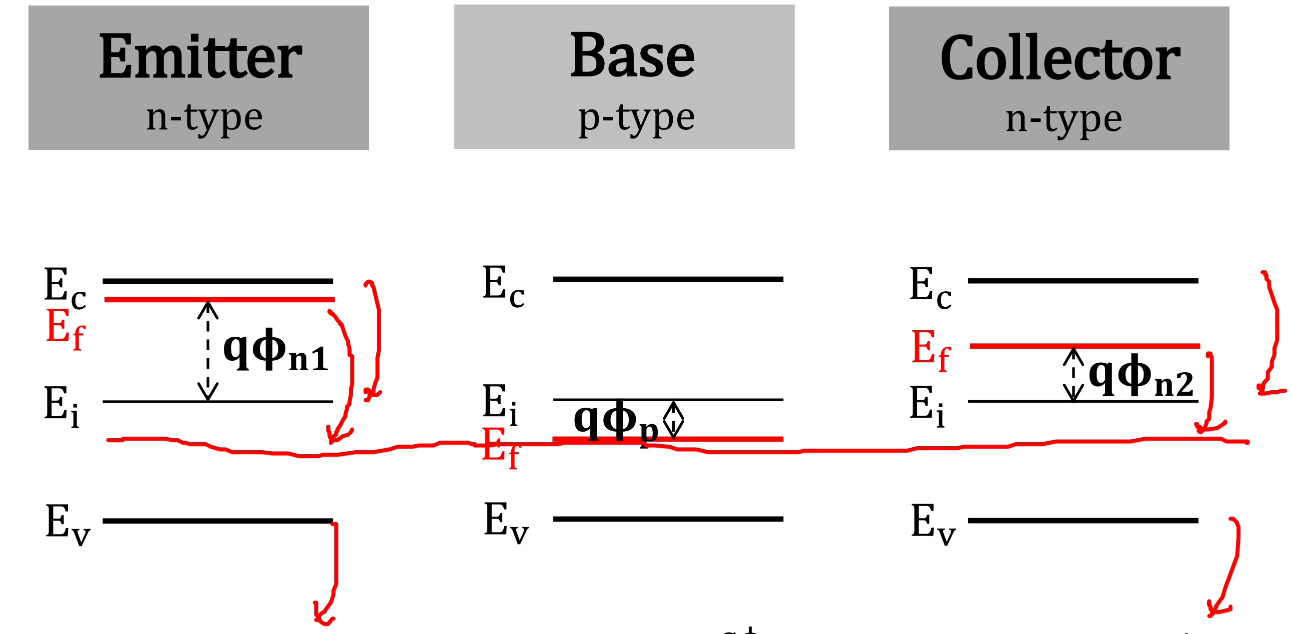
- Emitter: heavily doped n–type Source
- Base: p-region e^-
- Collector: lower n-region Drain
- Electron diffusion length (L_n) in base $\gg W_b$
- Emitter doping $N_{de} \gg$ base doping N_{ab} ($I_n \approx I$)

E B C

p+ n p.

*Energy Band of BJT

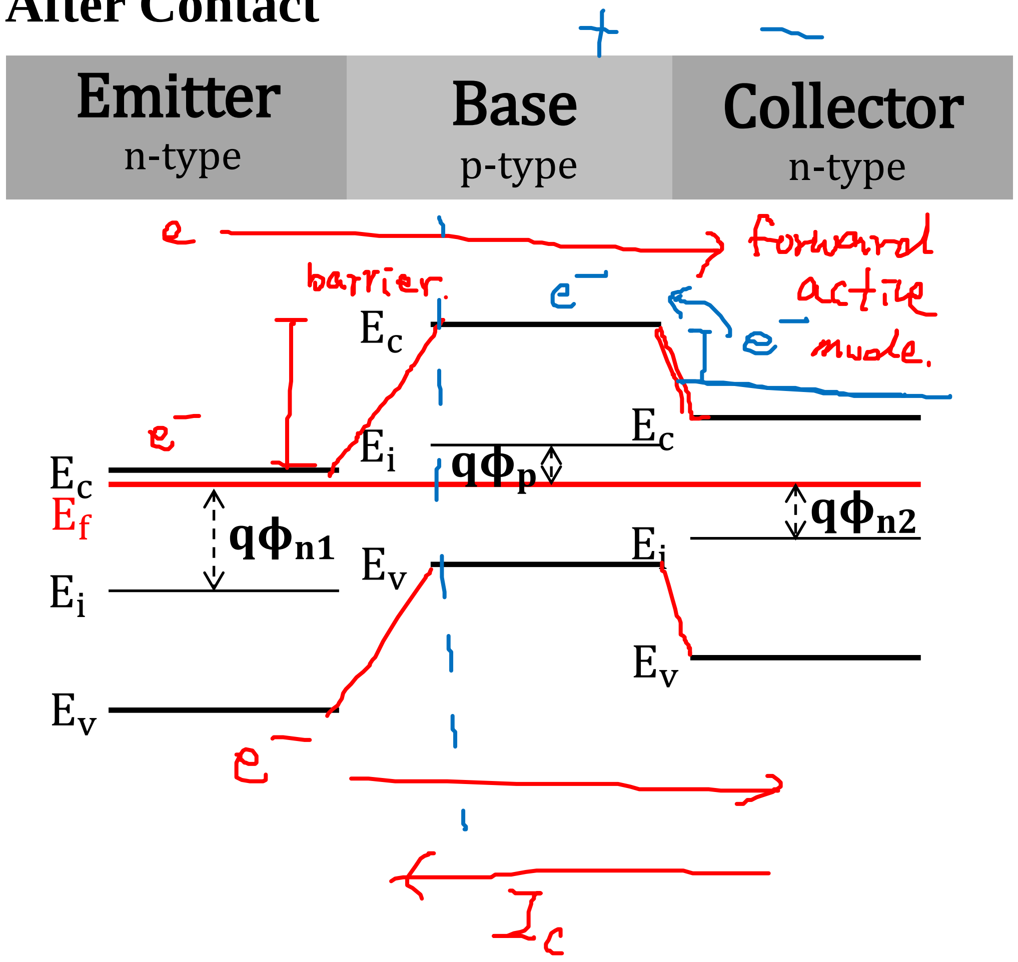
Before Contact



$$n \cong N_{d1} = n_i e^{\frac{q\phi_{n1}}{kT}} \qquad p \cong N_a = n_i e^{\frac{q\phi_p}{kT}} \qquad n \cong N_{d2} = n_i e^{\frac{q\phi_{n2}}{kT}}$$

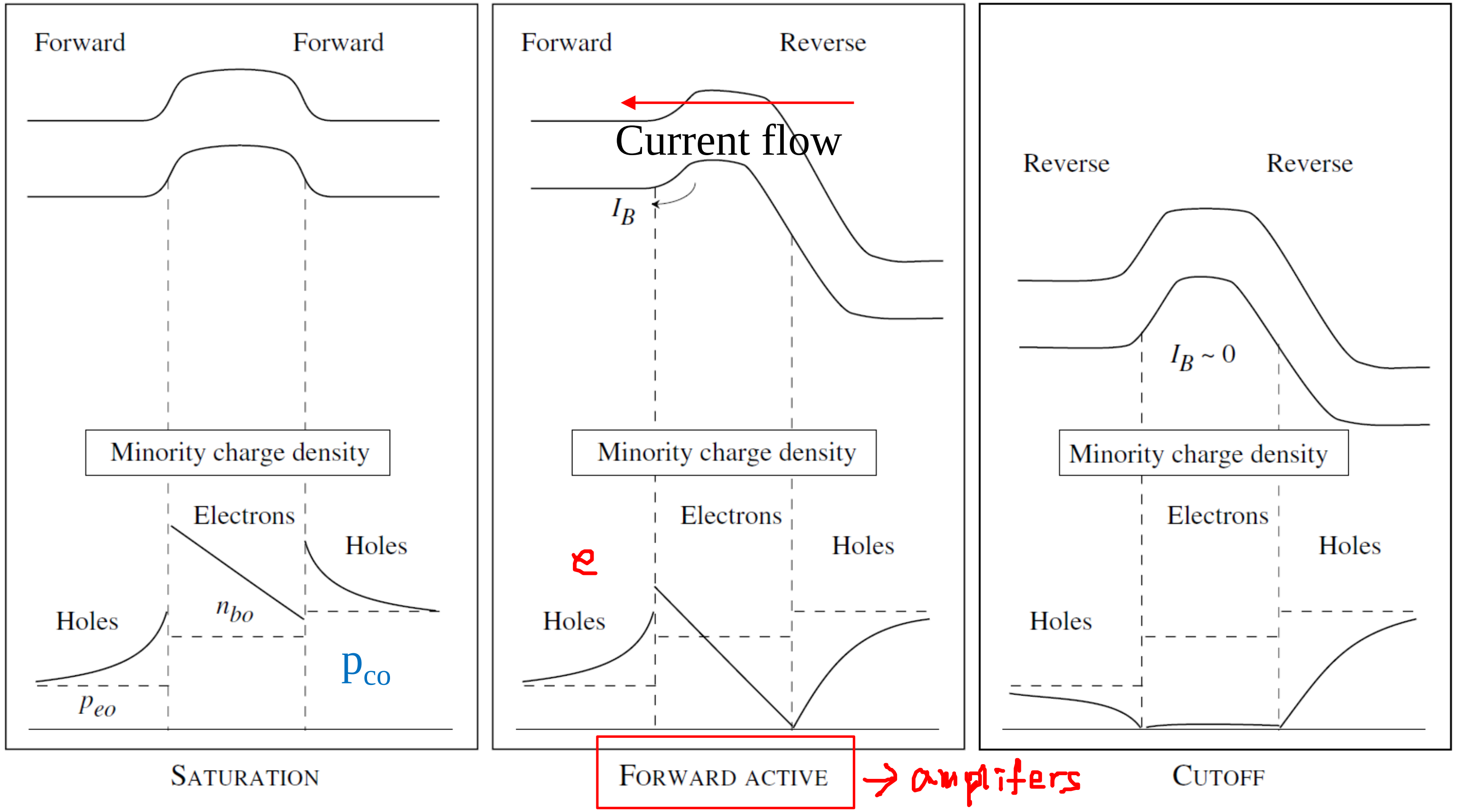
$$p \cong \frac{n_i^{\,2}}{N_{d1}} = n_i e^{\frac{-q\phi_{n1}}{kT}} \qquad n \cong \frac{n_i^{\,2}}{N_a} = n_i e^{\frac{-q\phi_p}{kT}} \qquad p \cong \frac{n_i^{\,2}}{N_{d2}} = n_i e^{\frac{-q\phi_{n2}}{kT}}$$

After Contact



How can we make the current flow in BJT from C to E, i.e. electrons flow from E to C

Modes in BJT



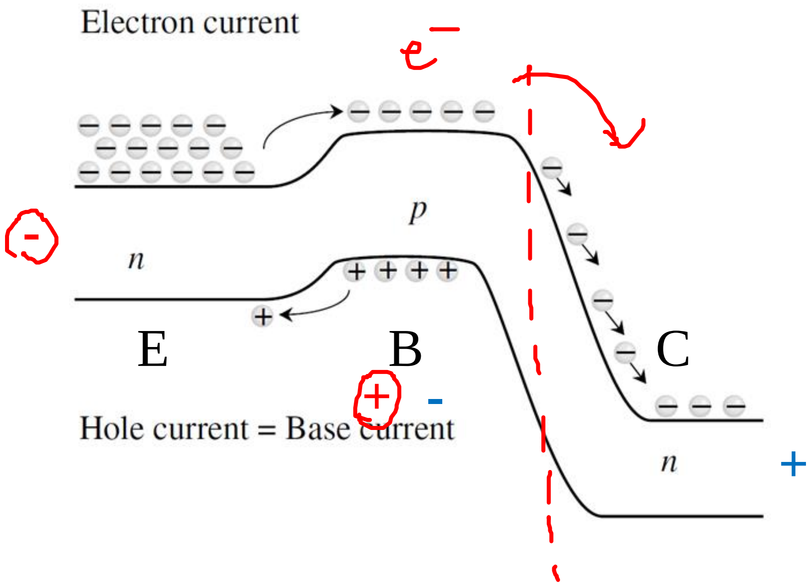
Saturation mode - both EBJ and BCJ are forward biased, for **switching**
Cutoff mode -both EBJ and BCJ are reverse biased.
Forward active mode - EBJ is forward biased, BCJ is reverse biased, for **amplifiers**

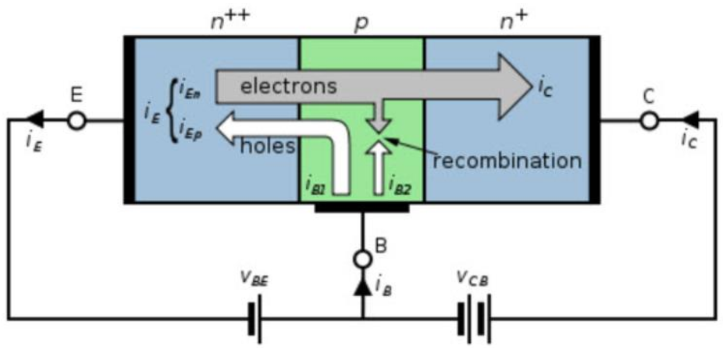
(Forward) Active Mode

EBJ (emitter base junction) – forward bias → reduce barrier

BCJ (base collector junction) – reverse bias / zero (built-in potential)

**Note: voltage notation*





$V_{BE} = V_B - V_E > 0$

EB diode (n^+-p) is forward biased ($V_{BE} > 0$ or $V_{EB} < 0$)

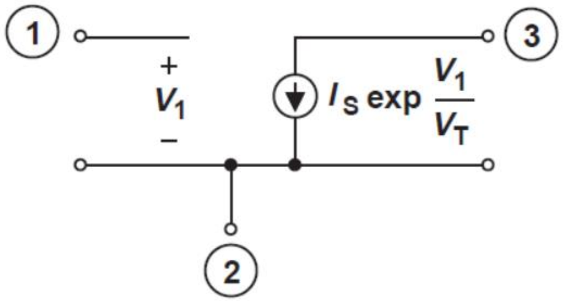
→ **diffusion of electrons into the p-side**

BC diode (p-n) is reversed biased ($V_{BC} < 0$ or $V_{CB} > 0$)

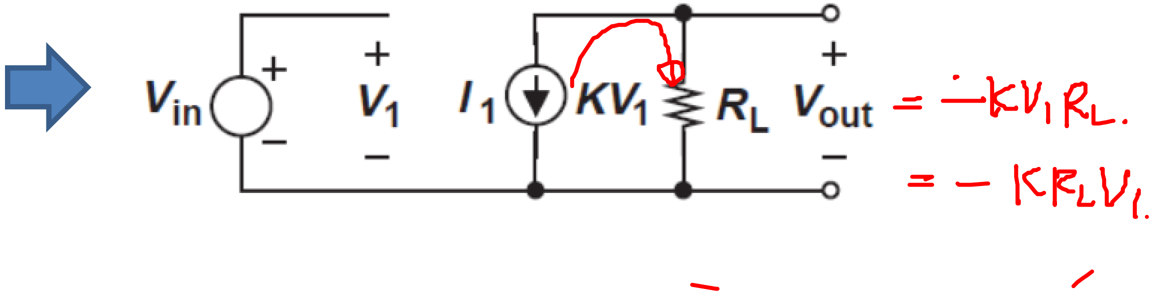
→ **transfer of injected electrons into the n-side**

BJT as Amplifier

In its simplest form, the bipolar transistor can be viewed as **a voltage-dependent current source**. We will see how a current source can **form an amplifier** and hence why bipolar devices are useful and interesting.



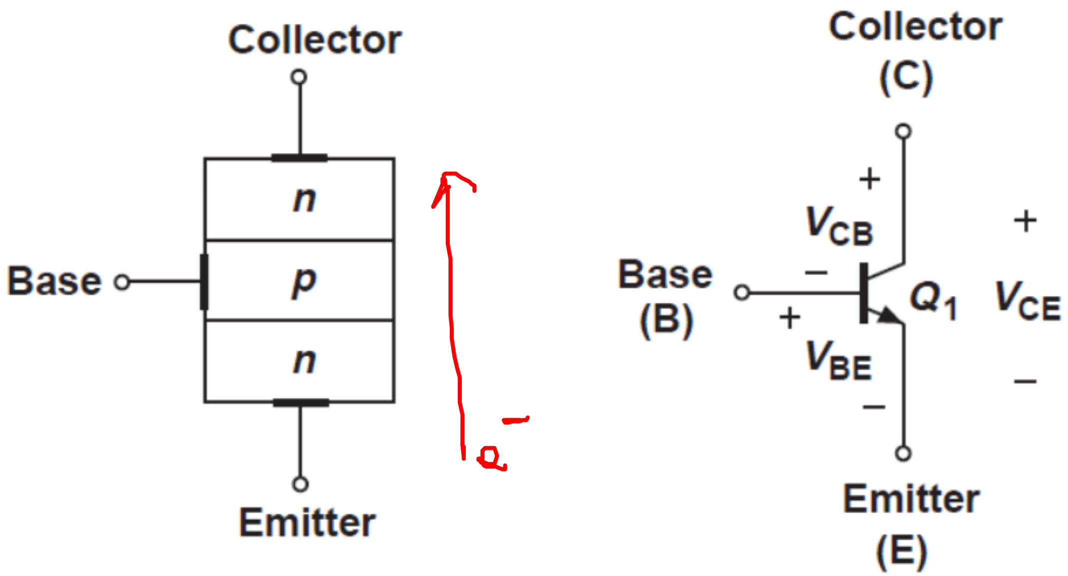
BJT circuit model



Since $V_1 = V_{in}$ and $V_{out} = -R_L I_1$, we have $V_{out} = -KR_LV_{in}$.
If $KR_L > 1$, then the circuit is an (inverting) amplifier.
The amplification factor, or voltage gain, of the circuit is $\boldsymbol{A_v = \frac{V_{out}}{V_{in}} = -KR_L}$

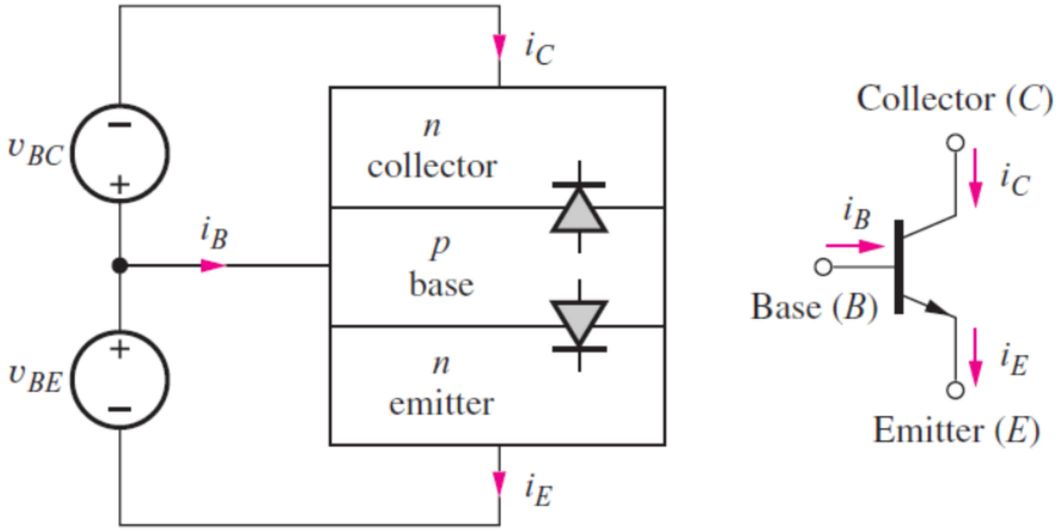
Structure of BJT

The BJT consists of three doped regions forming a sandwich. Below is an example comprising of a *p* layer sandwiched between two *n* regions and called an ***npn* BJT.**



There are three terminal voltages V_E, V_B, and V_C, and consequently the voltage differences between terminals V_{BE}, V_{CB}, and V_{CE}. Among various biasing conditions, **for amplification of BJT**, there is **only one biasing condition**. $V_{BE} > 0$ $V_{BC} < 0$

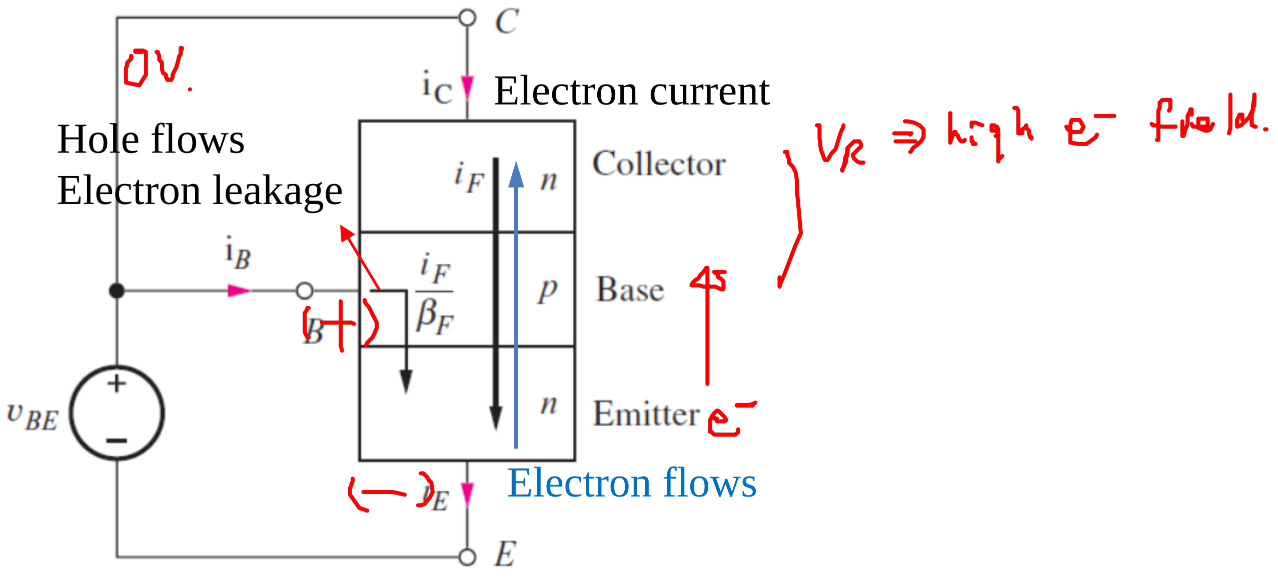
Transport Model for NPN BJT



There are also three terminal currents, **collector current i_C**, **emitter current i_E**, and **base current i_B**. The base-emitter voltage v_{BE} and the base-collector voltage v_{BC} applied to the two *pn* junctions **determine the magnitude of these three currents in the BJT** and are defined as **positive when they forward-bias** their respective *pn* junctions.

Forward Characteristics

Forward bias
Barrier ↓ and charges flow

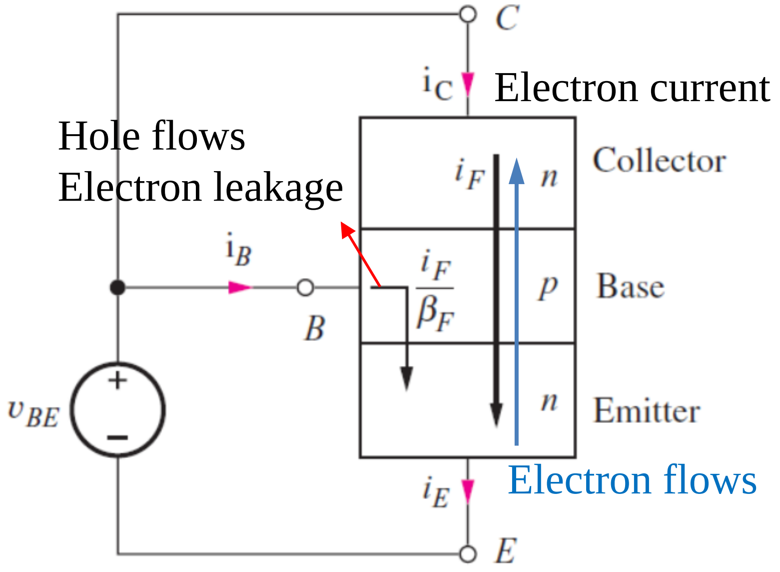


The base-emitter voltage establishes emitter current i_E , which equals the total current crossing the base-emitter junction.

$i_E = i_C + i_B$

$\mathbf{i_C = i_F = I_S[e^{v_{BE}/V_T} - 1]}$, I_S is the transistor saturation current $10^{-18} \sim 10^{-9}$ [A].

$i_B = {}^{i_F}/_{\beta_F} = {}^{I_S}/_{\beta_F}\left[e^{v_{BE}/V_T} - 1\right]$, β_F is Forward common-emitter current gain 10 ~ 500.



By KCL, $i_E = i_C + i_B$

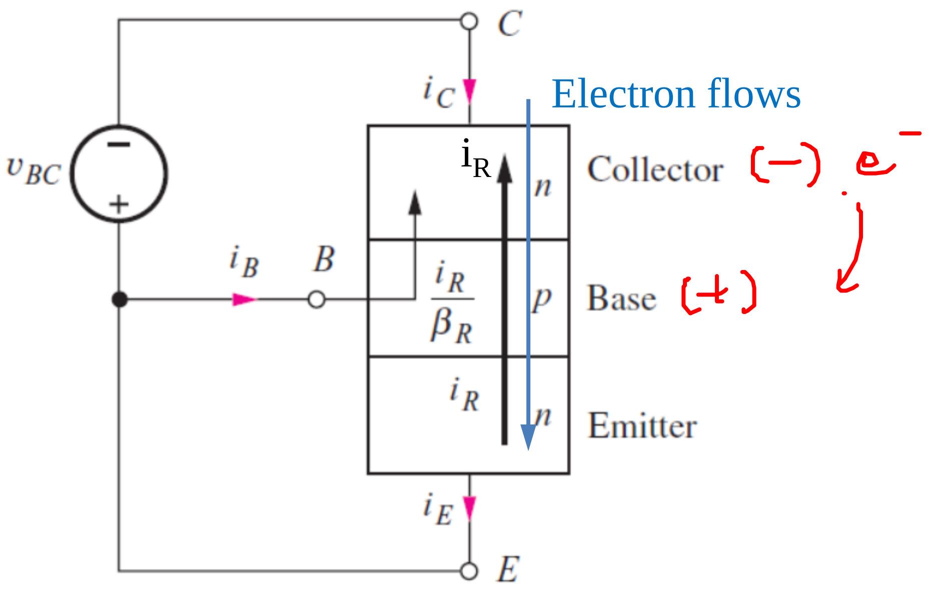
Therefore, $i_E = I_S\left[e^{v_{BE}/V_T} - 1\right] + {}^{I_S}/_{\beta_F}\left[e^{v_{BE}/V_T} - 1\right] = \boxed{\left(I_S + \frac{I_S}{\beta_F}\right)}\left[e^{v_{BE}/V_T} - 1\right]$

By defining $\boldsymbol{\alpha_F} = \frac{\boldsymbol{\beta_F}}{\boldsymbol{\beta_F+1}}$, $i_E = \frac{\boldsymbol{I_S}}{\boldsymbol{\alpha_F}}\left[e^{v_{BE}/V_T} - 1\right]$, α_F is the forward common-base current gain in the range of 0.95 ~ 1.0

Finally, $\frac{i_C}{i_B} = \boldsymbol{\beta_F}$, $\frac{i_C}{i_E} = \boldsymbol{\alpha_F}$

Reverse Characteristics

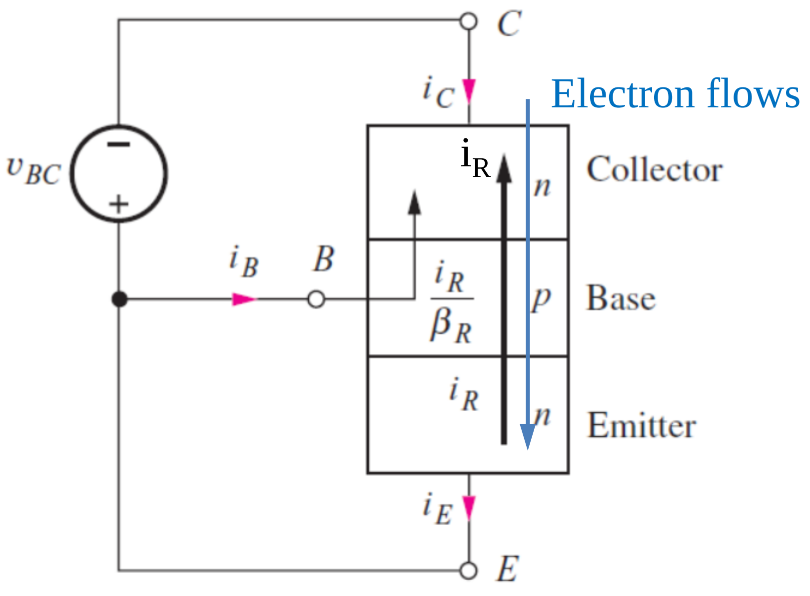
Forward bias
Barrier ↓ and charges flow



The base-collector voltage establishes the collector current i_C, now crossing the base-collector junction. The largest portion of the collector current, the reverse-transport current i_R, enters the emitter, travels completely across the narrow base region, and exits the collector terminal. Current i_R has a form identical to i_F :

$$i_R = -i_E = I_S[e^{v_{BC}/V_T} - 1]$$

Forward bias
Barrier ↓ and charges flo



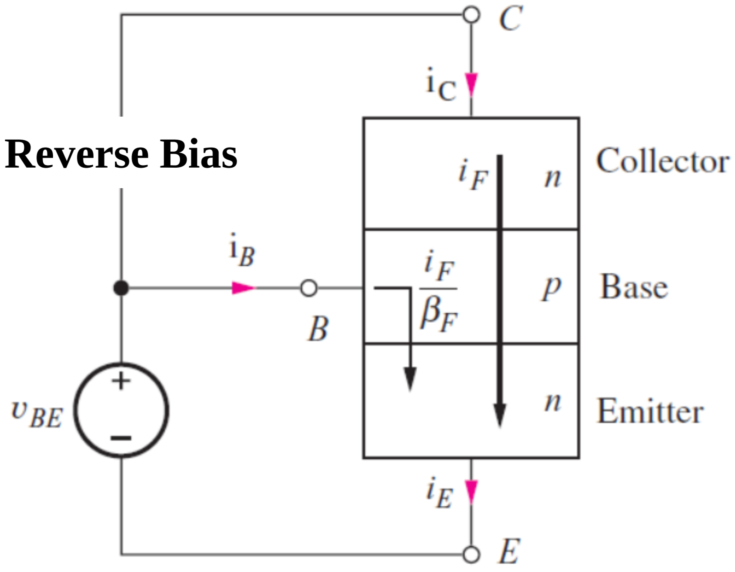
A fraction of the current i_R must also be supplied as base current through the base terminal:

$i_B = {}^{i_R}/_{\beta_R} = {}^{I_S}/_{\beta_R}\left[e^{v_{BC}/V_T} - 1\right]$, β_R is the reverse common-emitter current gain.

$i_C = \left(-\frac{I_S}{\alpha_R}\right)\left[e^{v_{BC}/V_T} - 1\right]$, $\boldsymbol{\alpha_R}$ is the reverse common-base current gain in the range of 0 ~ 0.95.

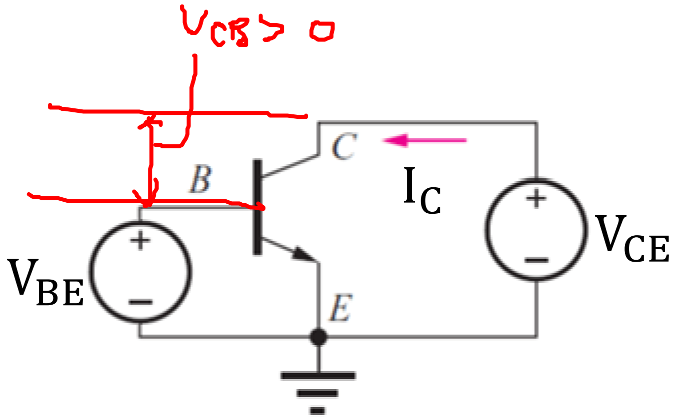
The bias condition for the Forward active mode of BJT (a normal BJT operation mode) is $\mathbf{v_{BE} > 0}$ **and** $\mathbf{v_{BC} < 0}$.

$= V_{CB} > 0$



Forward bias

Barrier ↓ and charges flow



① $V_{CE} \geq V_{BE}$

$\Rightarrow$ **Forward – Active**

② $V_{BE} > 0$, $V_{BC} < 0$

$$\mathbf{i_C = i_F = I_S\left[e^{v_{BE}/V_T} - 1\right]}$$

$$i_B = {}^{i_F}/_{\beta_F} = {}^{I_S}/_{\beta_F}\left[e^{v_{BE}/V_T} - 1\right]$$

$$i_E = I_S\left[e^{v_{BE}/V_T} - 1\right] + {}^{I_S}/_{\beta_F}\left[e^{v_{BE}/V_T} - 1\right] = \left(I_S + \frac{I_S}{\beta_F}\right)\left[e^{v_{BE}/V_T} - 1\right]$$

Example 1. Find the terminal voltages and currents

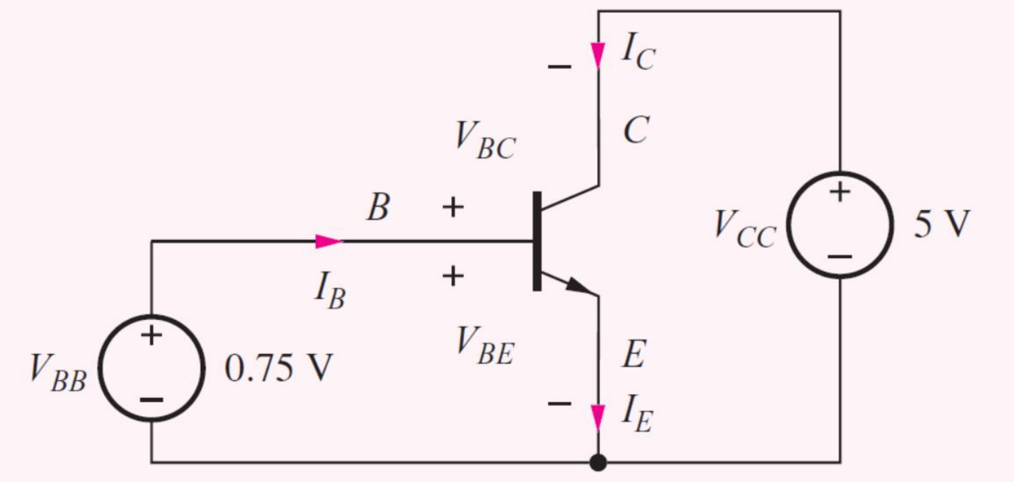


Figure 5.5 *npn* transistor circuit example: $I_S = 10^{-16}$ A, $\beta_F = 50$,

V_{BE} = 0.75 V and V_{BC} = -4.25 V thus Forward active

$i_C = i_F = I_S\left[e^{v_{BE}/V_T} - 1\right] = 0.00107$ A

$i_B = {i_F}/{\beta_F} = {I_S}/{\beta_F}\left[e^{v_{BE}/V_T} - 1\right] = 2.14\text{x}10^{-5}$ A

$$i_E = i_C + i_B = 0.00109\ A$$

Example 2. Consider the circuit shown below where $I_S = 5 \times 10^{-17}$ A and $V_{BE} = 800$ mV. Assume $\beta = 100$. (a) Determine the transistor terminal currents and voltages and verify that the device indeed operates in the active mode. (b) Determine the maximum value of R_C that permits operation in the active mode.

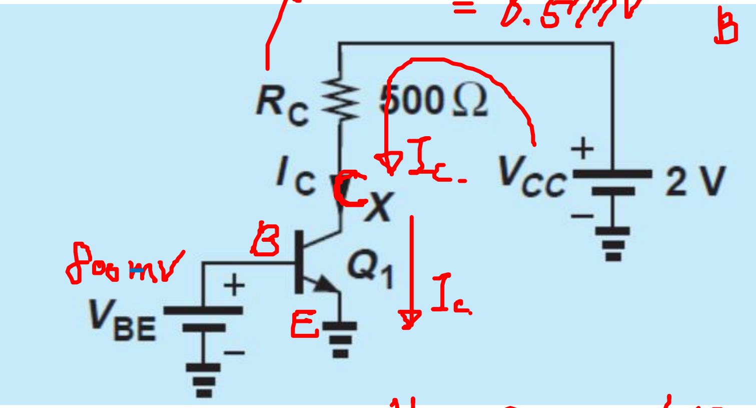
$V_B = 0.8\,V$

$V_E = 0\,V$

$V_C = ?$

Voltage drop $= R_C I_C$

$= 0.577\,V$

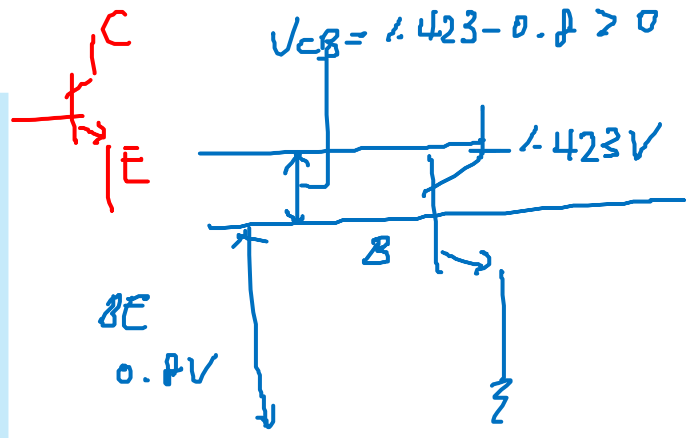


$V_{CB} = 1.423 - 0.8 > 0$

1.423V

B

BE 0.8V



$\Downarrow$ forward active mode.

$I_C = I_S\left[\exp\left(V_{BE}/V_T\right) - 1\right]$

$= 5\times10^{-17}\left[\exp\left(\dfrac{0.8}{0.026}\right) - 1\right]$

$= 0.001153$ A.

$V_C = 2 - 0.577 = 1.423\,V$

$V_{BE} > 0 \quad 0.8V$

$V_{BC} < 0, \; V_{CB} > 0.$

$I_B = I_C/\beta$

$I_E = I_B + I_C.$

$V_C = V_{CC} - R_C I_C \Rightarrow V_{CB} = V_{CC} - R_C I_C - V_B > 0$

$= 2 - R_C \times 0.001153 - 0.8 > 0.$

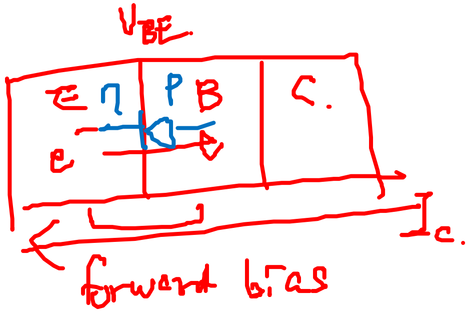
$R_C = 1040.76\,\Omega.$

Large-Signal Model

DC analysis → biasing

Large signal model can be used for **arbitrarily large voltage and current changes** in the BJT as long as the device operates **in the active mode**.

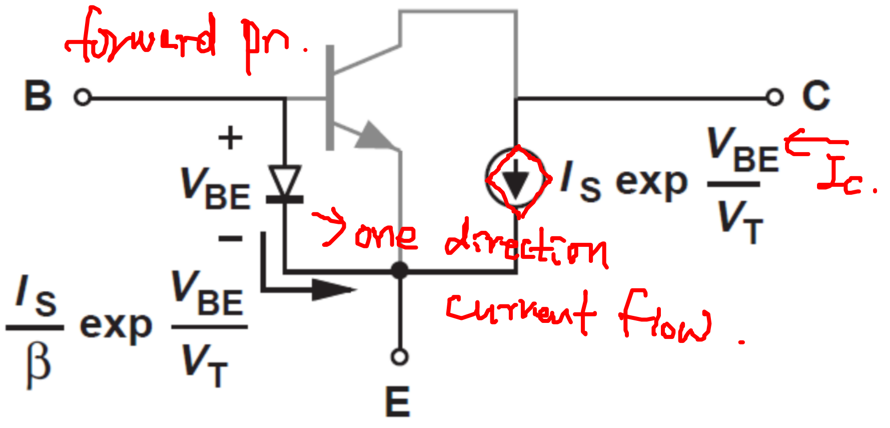
Since the B-E junction is forward-biased in the active mode, we can place **a diode between B-E**. Moreover, since I_C **flowing into the emitter depends on only V_{BE}**, we add **a voltage-controlled current source** between the collector and the emitter.



$V_{BE} \rightarrow 10\%\ I_c$

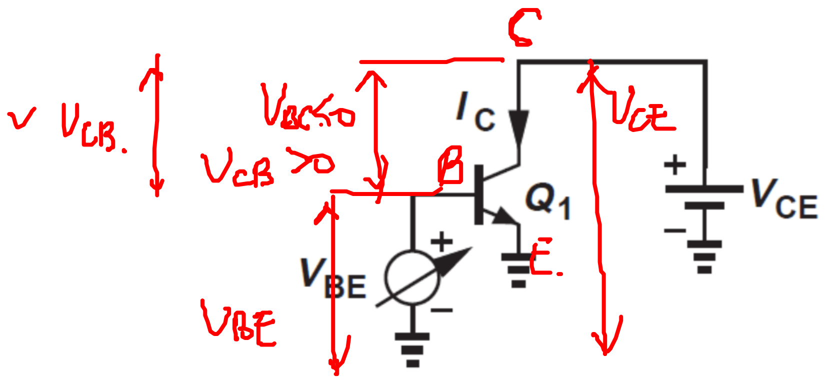
$V_{BE}' \rightarrow 30\%\ I_c.$

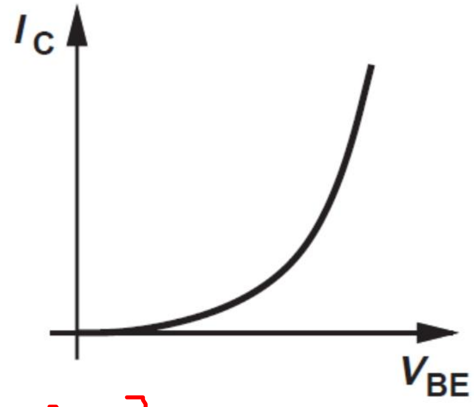
$I_c = I_s[\exp[V_{BE}/V_t) - 1]$



Large-signal model of BJT

IV characteristics – Transfer characteristic





$I_c = I_s[\exp(V_{BE}/V_t) - 1]$

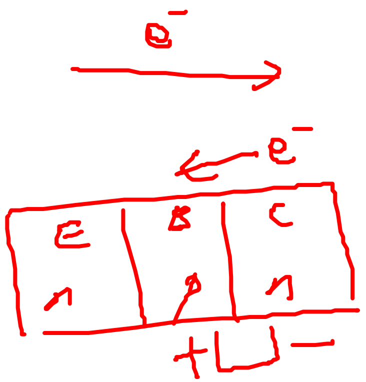
Transfer characteristic plots I_C vs V_{BE} with the assumption that the **V_{CE} is constant and no lower than the V_{BE}**. If $V_{CE} > V_{BE}$, then $v_{CB} > 0$ or $v_{BC} < 0$, meaning that v_{CB} is **reverse biased.** Thus, the BJT is in the forward active mode.

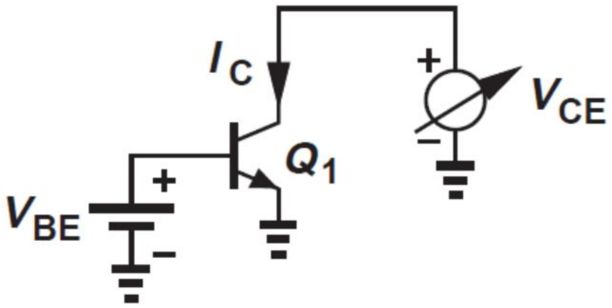
I_C is independent of V_{CE}; thus, different values of V_{CE} do not alter the characteristic.

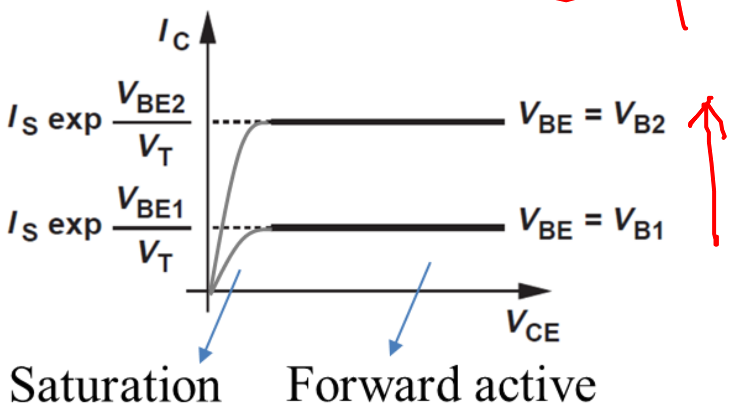
$i_C = I_S[e^{v_{BE}/v_T} - 1]$

IV characteristics – Output characteristic

$I_C = I_s\left[\exp(V_{BE}/V_T) - 1\right]$







Output characteristic shows **I_C for a given V_{BE} but with V_{CE} varying**.

$V_{BC} > 0 \Rightarrow$ BCJ forward.

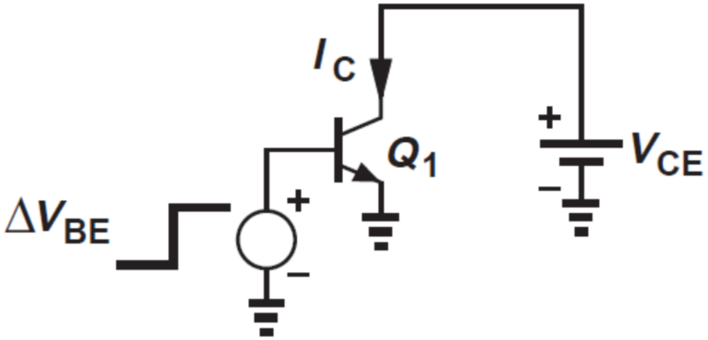
V_{CE} < V_{BE}, then $v_{CB} < 0$ or $v_{BC} > 0$, meaning that v_{CB} is forward biased. Both diodes (B-E and C-B) are on, which is called as saturation.

V_{CE} > V_{BE}, then $v_{CB} > 0$ or $v_{BC} < 0$, meaning that v_{CB} is **reverse biased** → Forward active. If V_{BE} increases I_C increases because $i_C = I_S[e^{v_{BE}/v_T} - 1]$

Transconductance

The BJT acts as **a voltage-dependent current source** when operating in the **forward active region**. What is the measure of the **goodness** of a voltage-dependent current source?

The transistor becomes a better amplifying device by producing larger changes in I_C in response to a given signal level (V_{BE}) applied (I_C/V_{BE}), i.e. **a better voltage-dependent current source or voltage-to-current converter**.



$dI_c = g_m dV_{BE}$

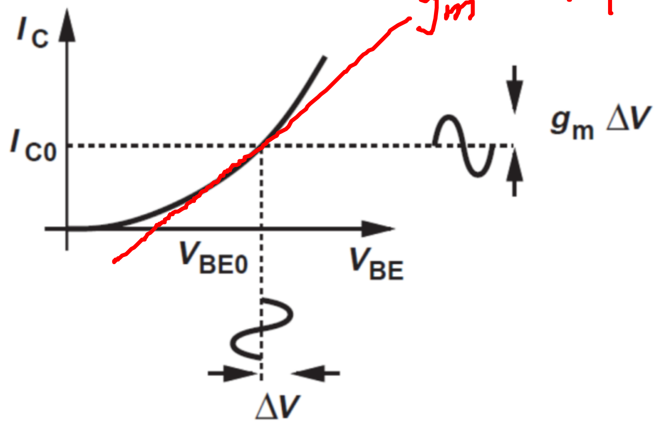
$$\boldsymbol{g_m} = \frac{dI_C}{dV_{BE}} = \frac{d}{dV_{BE}}\left(I_S exp\frac{V_{BE}}{V_T}\right) = \frac{1}{V_T} I_S exp\frac{V_{BE}}{V_T}$$

$$= \boldsymbol{\frac{I_C}{V_T}}$$

$g_m = dI_C/dV_{BE}$ simply represents the slope of I_C–V_{BE} characteristic at a given I_{C0}, and the corresponding V_{BE0}. In other words, **if V_{BE} experiences a small perturbation $\pm\Delta V$ around V_{BE0}, then the I_C displays a change of $\pm g_m\Delta V$ around I_{C0}.**

diode, BJT, MOSFET: → non-linear

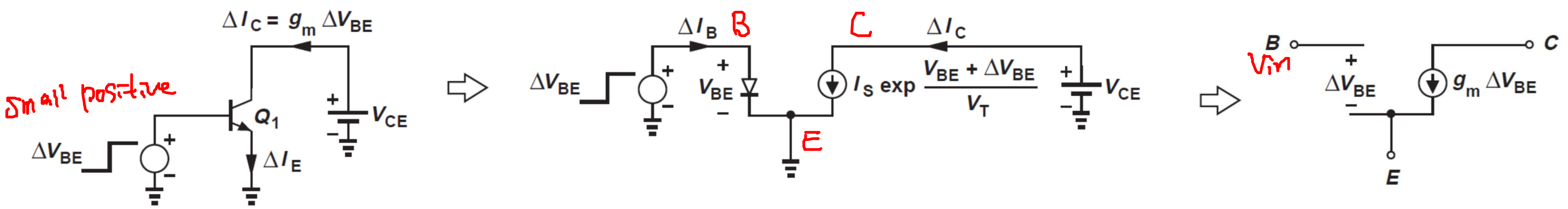
g_m = slope.



The transconductance is **fundamentally a function of the I_C** rather than the I_B. For example, if I_C remains constant but β varies, then g_m does not change but I_B does.

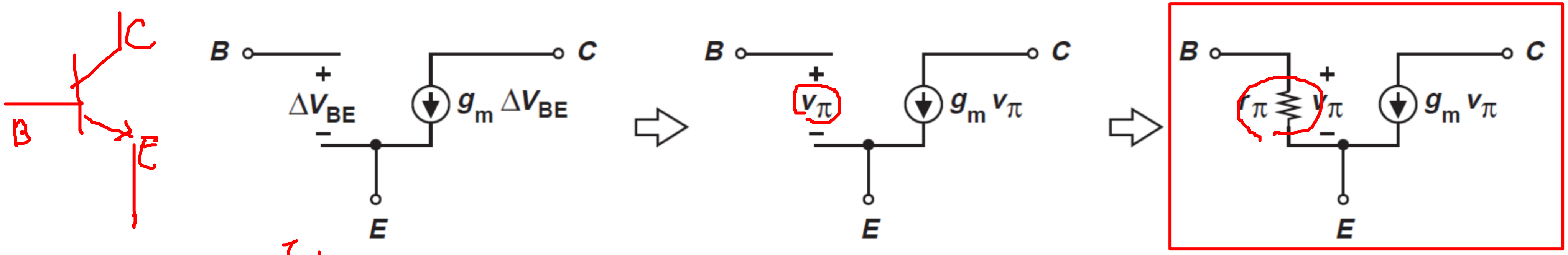
Small-Signal Model → small changes (ac)

To find a small-signal model of the BJT, we **perturb the voltage difference** between every two terminals while the third terminal remains at a constant potential. And we **determine the changes in the currents** flowing through all terminals, and **represent the results by proper circuit elements.**



(1) Begin with a change in V_{BE} while the V_{CE} is constant. By the definition of the transconductance g_m, $\mathbf{\Delta I_C = g_m \Delta V_{BE}}$ → **a voltage-controlled current source**

As $I_C = I_S[e^{V_{BE}/V_T} - 1]$, $\mathbf{\Delta I_C = I_S[e^{(V_{BE}+\Delta V_{BE})/V_T} - 1]}$



$I_B = I_c/\beta$

For simplicity, we denote V_{BE} by v_π and the change in the I_C by $g_m v_\pi$. The change in V_{BE} creates another change in I_B as well. $\Delta I_c = g_m \Delta V_{BE}$.

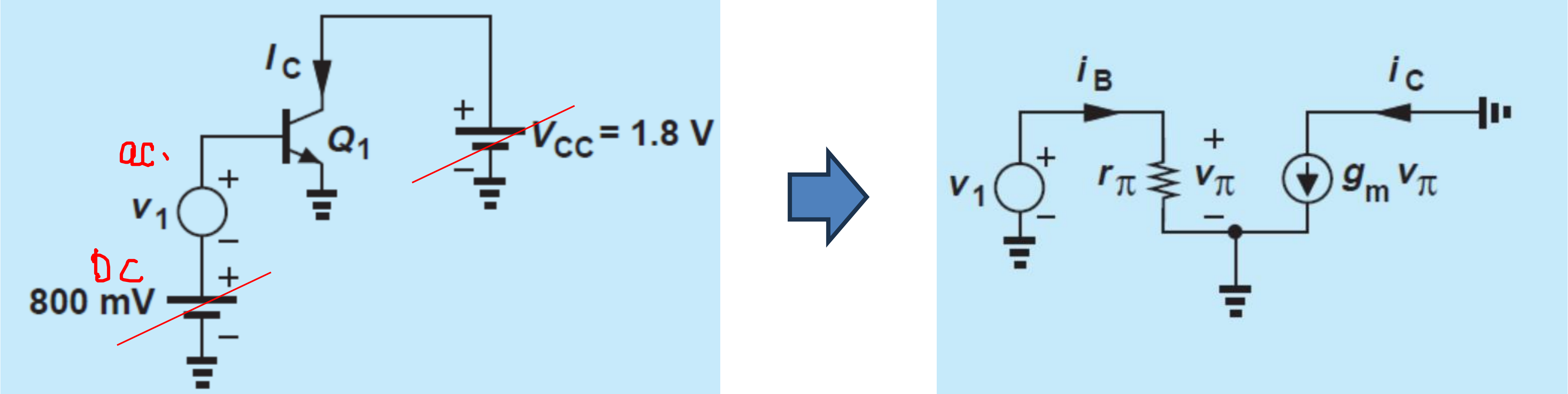
$$\Delta I_B = \frac{\Delta I_C}{\beta} = \frac{g_m}{\beta}\Delta V_{BE} \rightarrow \mathbf{r_\pi} = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{\boldsymbol{\beta}}{\mathbf{g_m}}$$

This represents a small signal model of the B-E diode as a resistance.

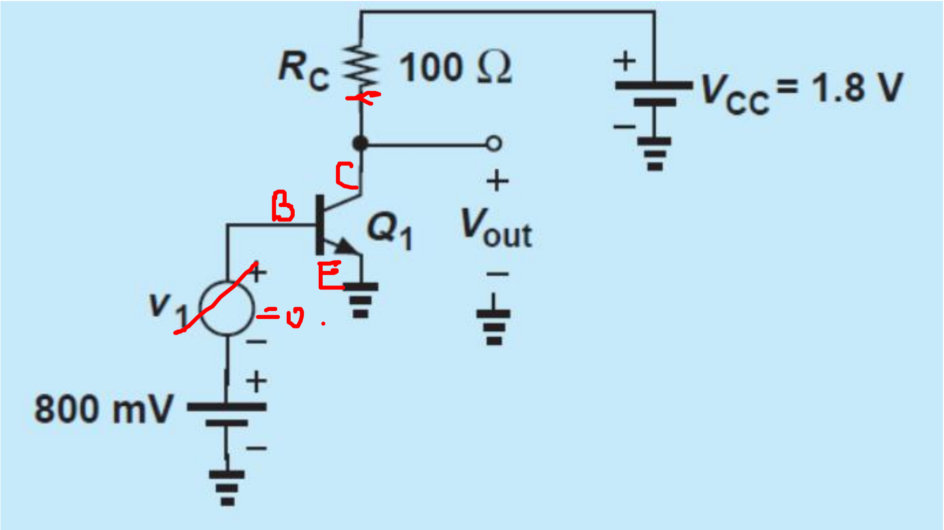
On the contrary, **V_{CE} and V_{BC}** do not result in any change of the small signal result as **I_C and I_B are the function of V_{BE}. The simple small-signal model serves as a powerful tool in the analysis and design of BJT circuits.**

Note that small-signal analysis deals with **only small changes** in voltages and currents in a circuit around their quiescent values. Thus, **all constant sources, i.e., voltage and current sources that do not vary with time, must be set to zero for small-signal analysis**.

e.g., the supply voltage is constant and, while establishing proper bias points, plays no role in the response to small signals. **We therefore ground all constant voltage sources and open all constant current sources while constructing the small-signal equivalent circuit**.



Example 3. $I_S = 3 \times 10^{-16}$ A, $\beta = 100$, $V_T = 0.026$ V (a) When $v_1 = 0$, verify that the transistor operates in the active mode. (b) Determine the voltage gain of the circuit if the v_1 changes by +1 mV (c) suppose we raise R_C to 200 and V_{CC} to 3.6 V. Verify that the device operates in the active mode and compute the voltage gain.



(a) $V_B = 0.8V$

$V_E = 0V$

$V_C = ?$

$$I_C = I_S\left[\exp\left(V_{BE}/V_T\right) - 1\right]$$

$$= 3\times 10^{-16}\left[\exp\left(0.8/0.026\right) - 1\right]$$

$$= 6.92\text{mA}$$

$$V_{R_C} = I_C R_C = 100 \times 6.92\times 10^{-3} = 0.692V$$

$$V_C = V_{CE} = V_{out} = 1.8 - 0.692 = 1.108\ V$$

$V_{CE} > V_{BE}$ ⇒ forward active mode.

(b) $V_{BE} = 0.801\ V$

$I_C = 0.00719\cdots$

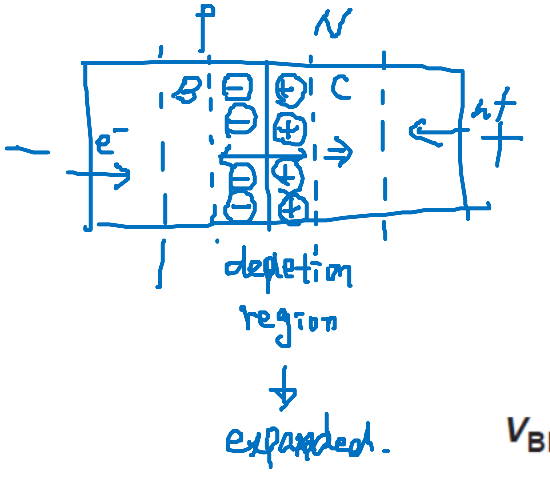
$V_{R_C} = 100 \times I_C = 0.719\ V$

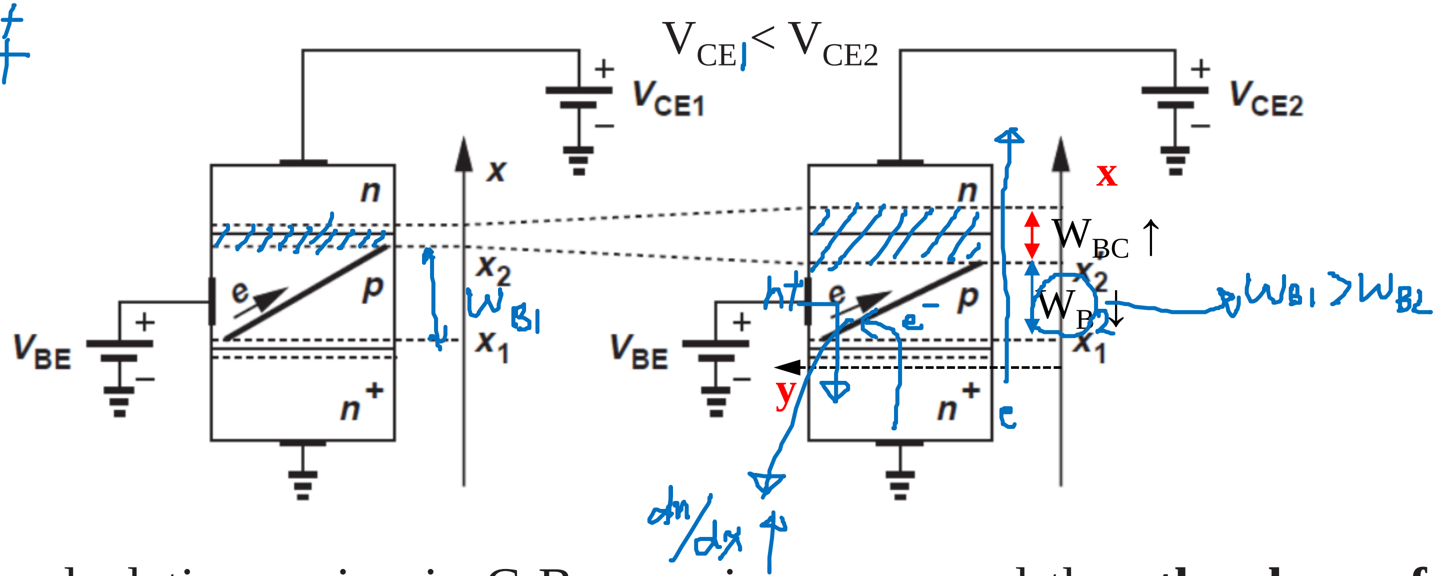
$$V_C = V_{CE} = V_{out} = 1.8 - 0.719 = 1.081V$$

$$A_v = \left|\frac{\Delta V_{out}}{\Delta V_{in}}\right| = \left|\frac{1.081 - 1.108}{0.801 - 0.8}\right| = 27$$

Early Effect

Example 3 points to an important trend **if $R_C \to \infty$ would the gain also grows indefinitely**? **The Early effect** translates to a nonideality in the device which **limits the gain of amplifiers**.



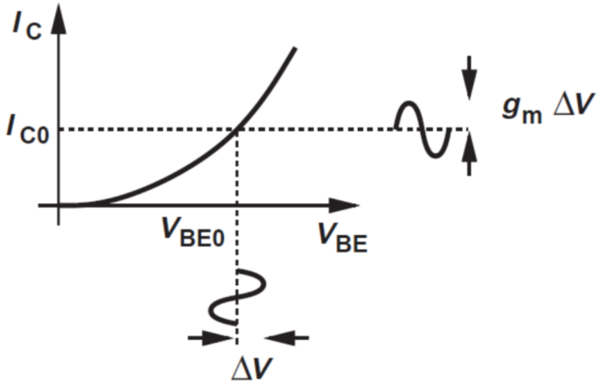


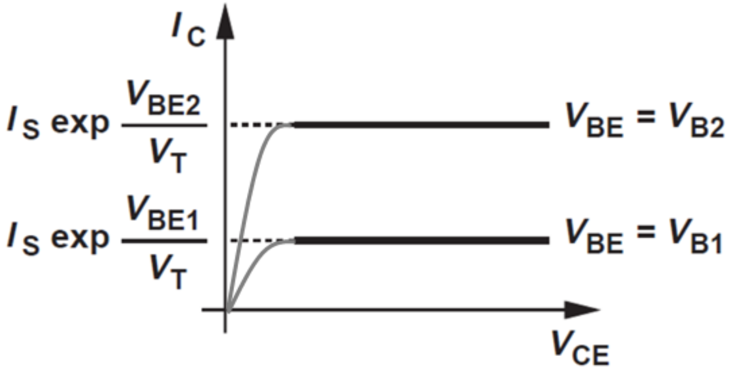
As $V_{CE} < V_{CE2}$, the depletion region in C-B areas increases, and thus **the slope of the profile increases.** Equivalently, the effective **W_B decreases**, thereby **increasing I_C. Early effect indicates that the V_{CE} does affect the I_C.**

$I_S = \frac{\quad}{W_B}$

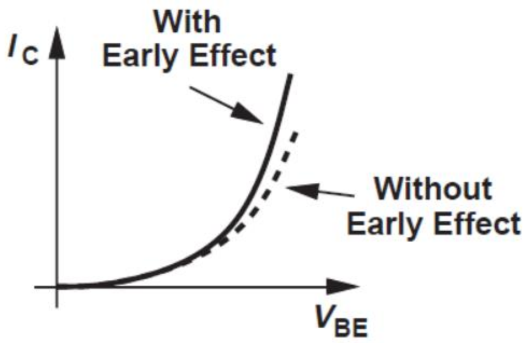
With the Early effect, $I_C \approx \left(I_S exp\frac{V_{BE}}{V_T}\right)\left(1+\frac{V_{CE}}{V_A}\right)$ V_A = Early voltage

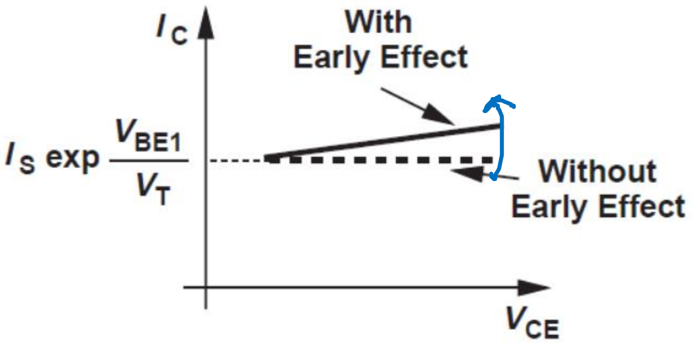
Without the Early effect, $i_C = I_S[e^{v_{BE}/V_T} - 1]$





With the Early effect, $I_C \approx \left(I_S exp\frac{V_{BE}}{V_T}\right)\left(1 + \frac{V_{CE}}{V_A}\right)$





With the Early effect, $I_C \approx \left(I_S exp\frac{V_{BE}}{V_T}\right)\left(1 + \frac{V_{CE}}{V_A}\right)$

$$\frac{\delta I_C}{\delta V_{CE}} = I_S\left(exp\frac{V_{BE}}{V_T}\right)\left(\frac{1}{V_A}\right) \approx \frac{I_C}{V_A}$$

If $\mathbf{V_A} \gg \mathbf{V_{CE}}$, we can see that

$$I_C \approx \left(I_S exp\frac{V_{BE}}{V_T}\right)\left(1 + \cancel{\frac{V_{CE}}{V_A}}\right) \to 0.$$

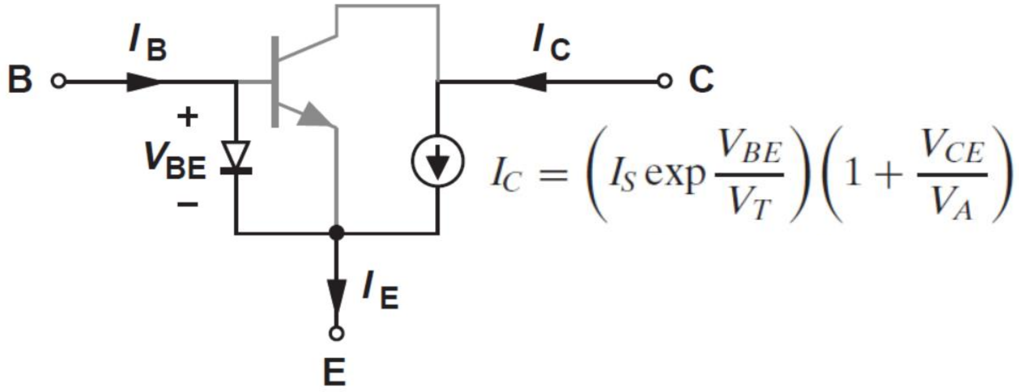
∞.

$\underline{V_A = \infty.}$

and thus $I_C \approx \left(I_S exp\frac{V_{BE}}{V_T}\right)$

The variation of I_C with V_{CE} reveals that **the BJT in fact does not operate as an ideal current source**, requiring modification of the perspective.

Large-Signal and Small-Signal Models with Early Effect



The presence of Early effect alters the BJT’s large signal model as follows:

$$I_C = \left(I_S \exp\frac{V_{BE}}{V_T}\right)\left(1+\frac{V_{CE}}{V_A}\right)$$

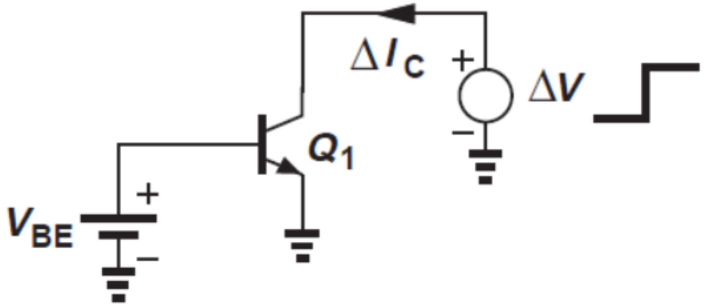
$$I_B = \frac{1}{\beta}\left(I_S \exp\frac{V_{BE}}{V_T}\right)$$

$$I_E = I_C + I_B.$$

For the small-signal model, $\mathbf{g_m}$ **and** $\mathbf{r_\pi}$ are expressed as below. Thus, **the controlled current source remains unchanged**.

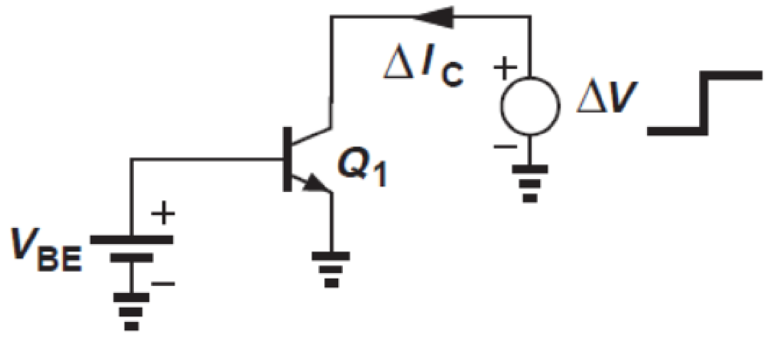
$$\boldsymbol{g_m} = \frac{dI_C}{dV_{BE}} = \frac{d}{dV_{BE}}\left(I_S exp\frac{V_{BE}}{V_T}\right)\left(1+\frac{V_{CE}}{V_A}\right) = \frac{1}{V_T} I_S exp\frac{V_{BE}}{V_T}\left(1+\frac{V_{CE}}{V_A}\right)$$
$$= \frac{\boldsymbol{I_C}}{\boldsymbol{V_T}}$$
$$\boldsymbol{r_\pi} = \frac{\boldsymbol{\beta}}{\boldsymbol{g_m}} = \boldsymbol{\beta}\frac{\boldsymbol{V_T}}{\boldsymbol{I_C}}$$

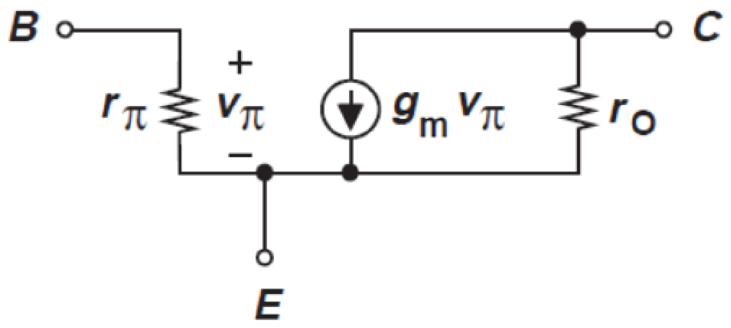
Considering that the $\mathbf{I_C}$ **does vary with** $\mathbf{V_{CE}}$, we apply a voltage change at the collector and measure the resulting current change



$$\boldsymbol{I_C} + \Delta\boldsymbol{I_C} = \left(I_S exp\frac{V_{BE}}{V_T}\right)\left(1+\frac{V_{CE}+\Delta V_{CE}}{V_A}\right)$$

Thus, $$\Delta\boldsymbol{I_C} = \left(I_S exp\frac{V_{BE}}{V_T}\right)\frac{\Delta V_{CE}}{V_A}$$



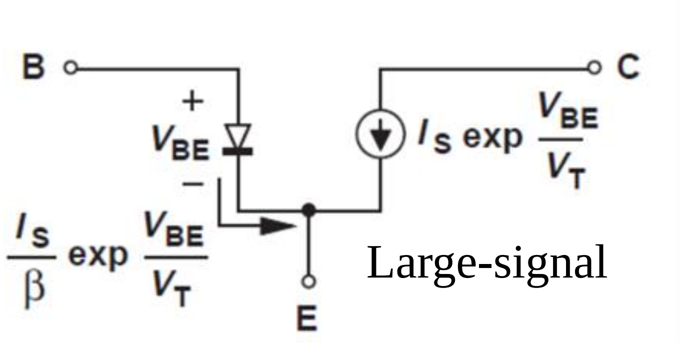


Since the voltage and current change correspond to the **same two terminals**, they satisfy Ohm's law, **yielding an equivalent resistor r_O**

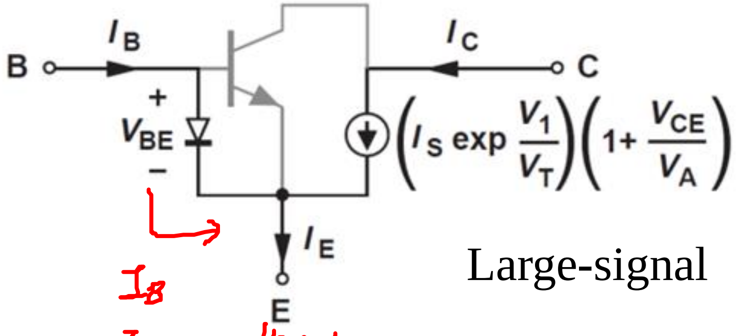
$$\boldsymbol{\Delta I_C} = \left(I_S exp\frac{V_{BE}}{V_T}\right)\frac{\Delta V_{CE}}{V_A} \rightarrow \boldsymbol{r_O} = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{V_A}{I_S exp\frac{V_{BE}}{V_T}} \approx \frac{\boldsymbol{V_A}}{\boldsymbol{I_C}}$$

The small-signal model contains **only one extra element r_O to represent the Early effect**. This **output resistance r_O** plays a critical role in high gain amplifiers

Summary



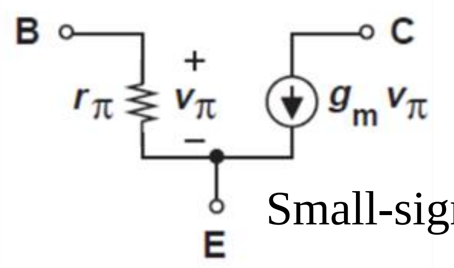
Large-signal



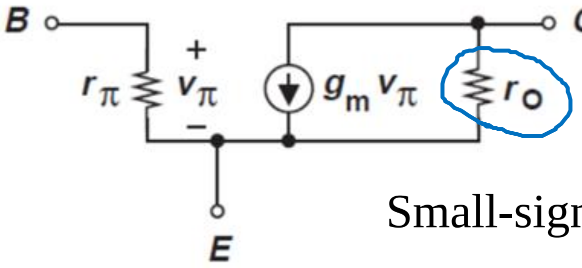
Large-signal

$I_B = I_S/\beta \exp V_{BE}/V_T$

Without Early Effect **With Early Effect**



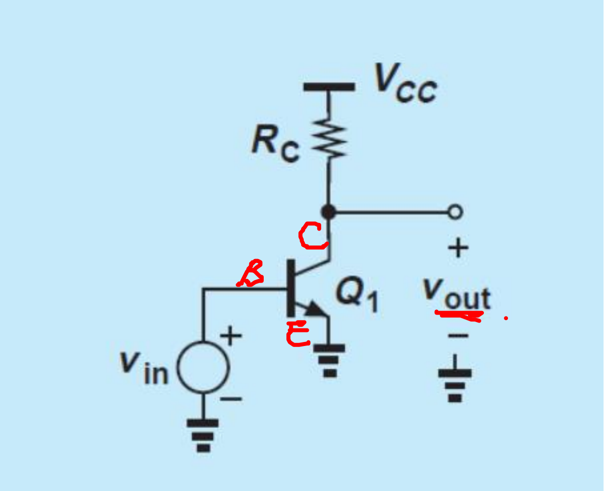
Small-signal

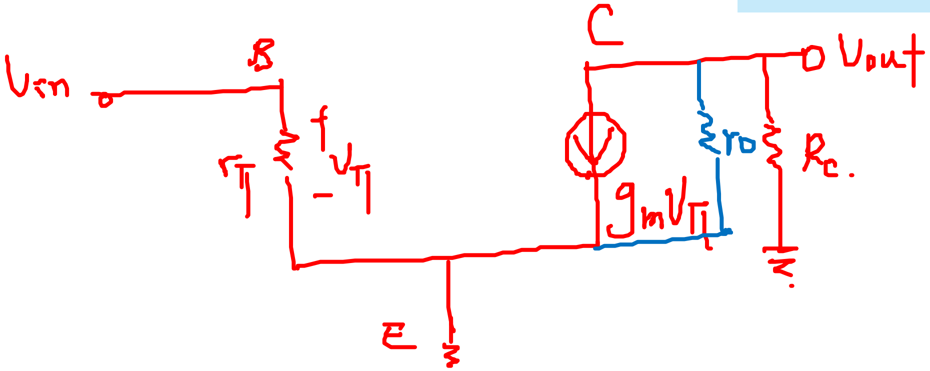


Small-signal

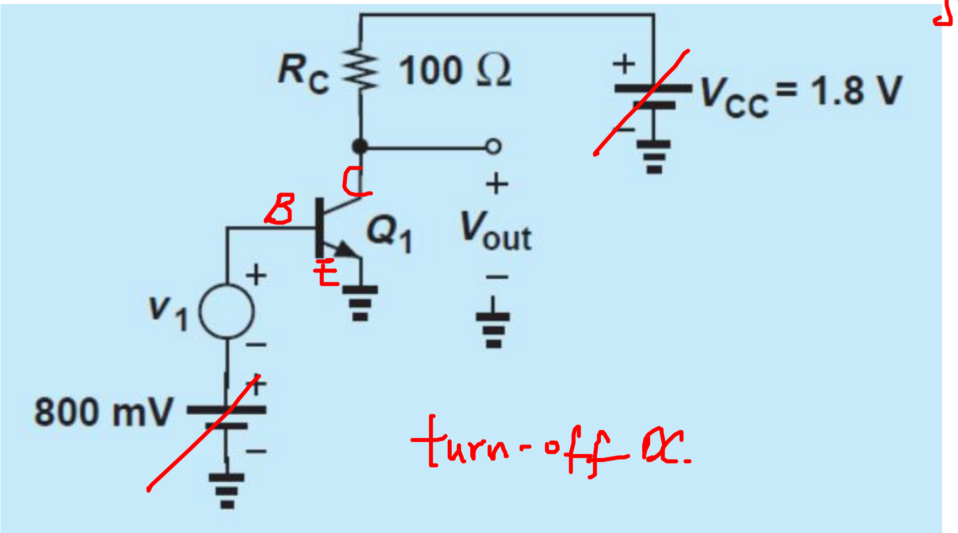
We must create **proper DC voltages and currents at the device terminals to accomplish two goals**: (1) guarantee **operation in the active mode** (e.g. for npn BJT $V_{BE} > 0$, $V_{CE} \geq 0$); (2) establish the I_C that yields the required values for the **small signal parameters g_m, r_O, and r_π**.

Example 4 Draw the small-signal equivalent circuit. Please include the Early effect.

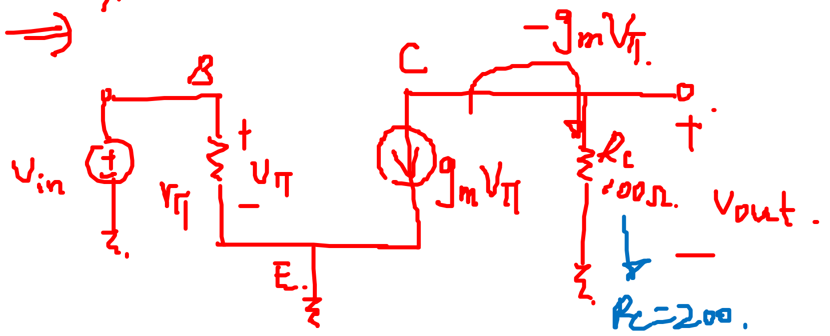




Example 3. $I_S = 3 \times 10^{-16}$ A, $\beta = 100$, $V_T = 0.026$ V (a) When $v_1 = 0$, verify that the transistor operates in the active mode. (b) Determine the voltage gain of the circuit if the v_1 changes by 1 mV (c) suppose we raise R_C to 200 and V_{CC} to 3.6 V. Verify that the device operates in the active mode and compute the voltage gain.



small-signal mode
⇒



$V_{out} = -g_m v_\pi R_c \quad , \quad v_\pi = v_{in}$

$= -g_m R_c v_{in}$

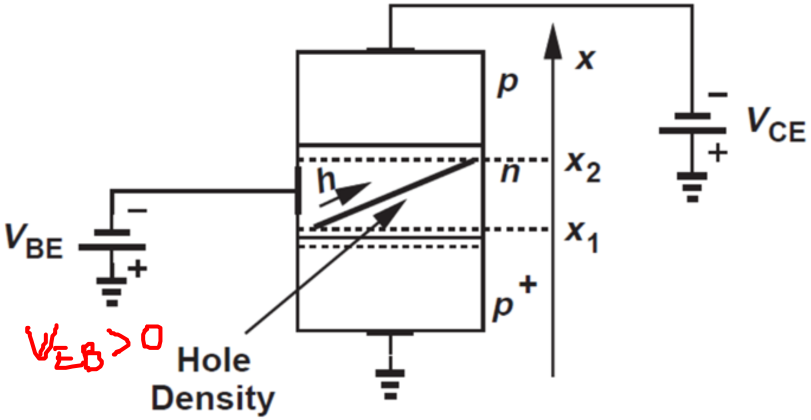
$\frac{V_{out}}{V_{in}} = -g_m R_c = -26.66\cdots \simeq |27|$

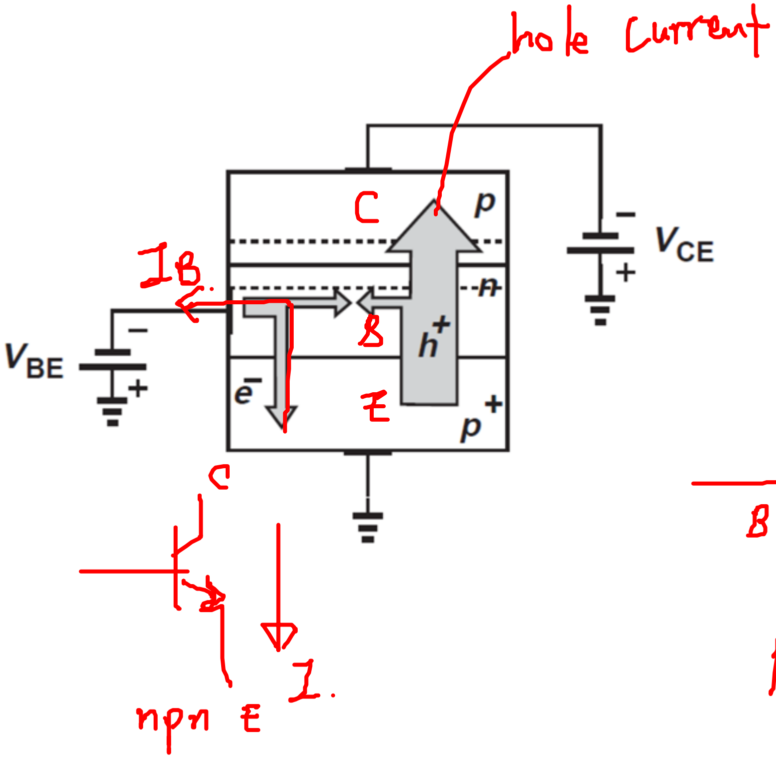
$g_m = I_c / V_T = \frac{0.00692}{0.026} = 0.266\cdots$

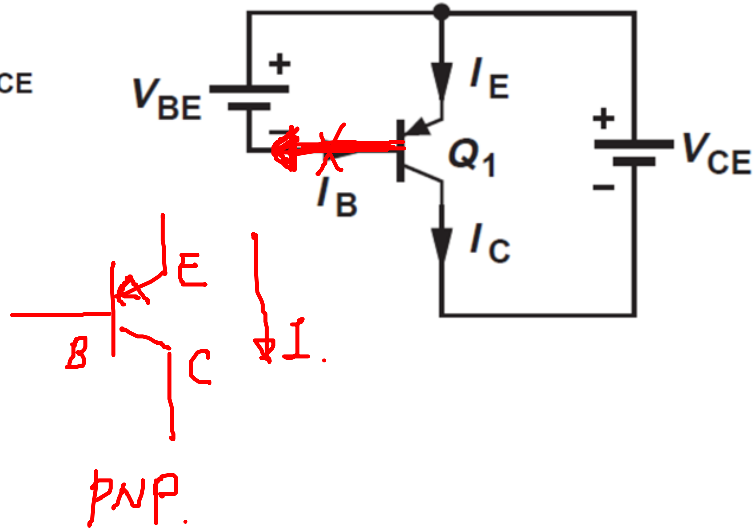
(c) $A_v = -g_m R_c$

$= -0.266\cdots \times 200 = |-53.2|$

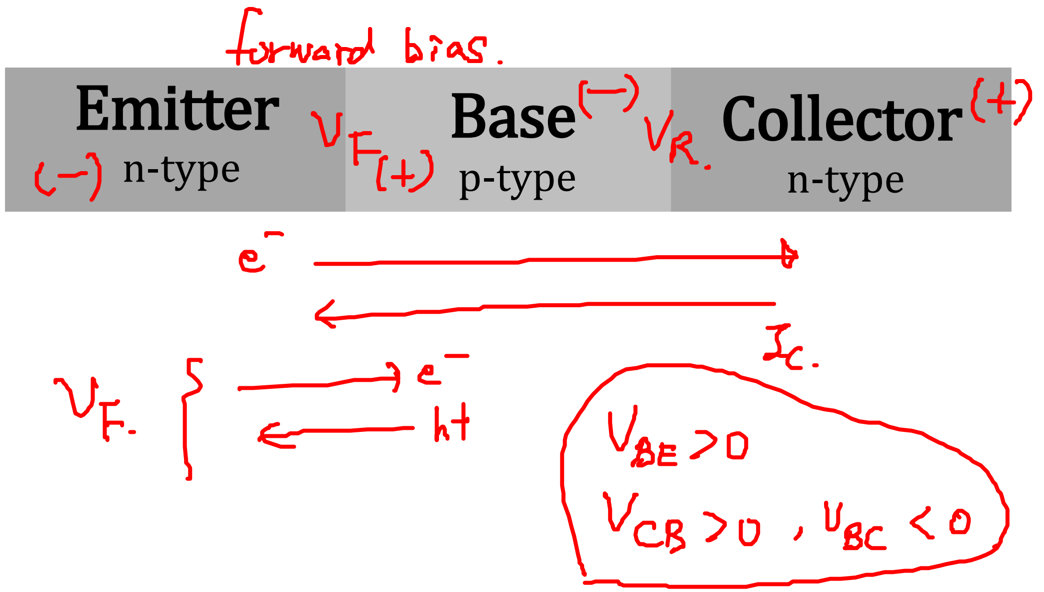
PNP BJT →hole current.







Operation of PNP in the active region requires forward biasing the base-emitter junction and reverse-biasing the collector junction. Thus, **V_{BE} < 0 (Forward) and V_{BC} > 0 (Reverse)**. All of the operation principles and equations described for npn transistors apply to pnp devices as well.

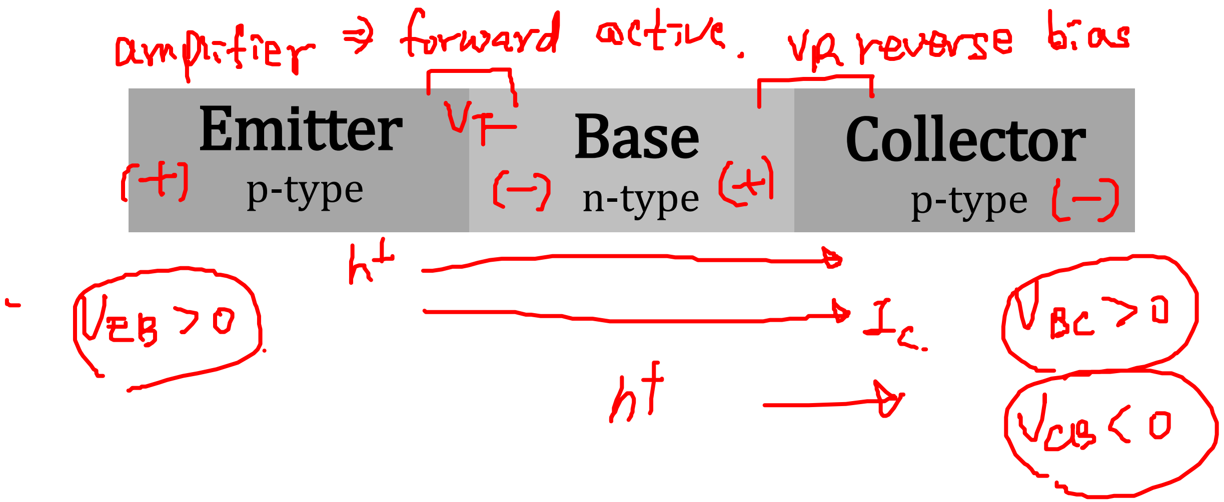


$$i_C = i_F = I_S\left[e^{v_{BE}/v_T} - 1\right]$$

$$i_B = {}^{i_F}/_{\beta_F} = {}^{I_S}/_{\beta_F}\left[e^{v_{BE}/v_T} - 1\right]$$

$$i_E = \left(I_S + \frac{I_S}{\beta_F}\right)\left[e^{v_{BE}/v_T} - 1\right]$$

$= I_c + I_B$



$$i_C = i_F = I_S\left[e^{v_{EB}/v_T} - 1\right]$$

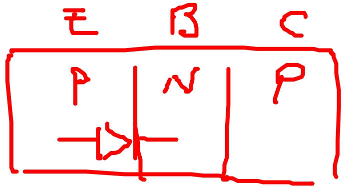
$$i_B = {}^{i_F}/_{\beta_F} = {}^{I_S}/_{\beta_F}\left[e^{v_{EB}/v_T} - 1\right]$$

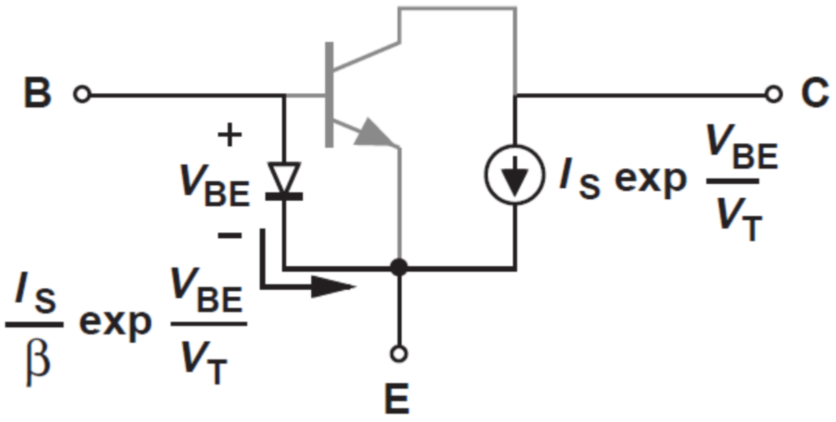
$$i_E = \left(I_S + \frac{I_S}{\beta_F}\right)\left[e^{v_{EB}/v_T} - 1\right]$$

$= I_c + I_B$

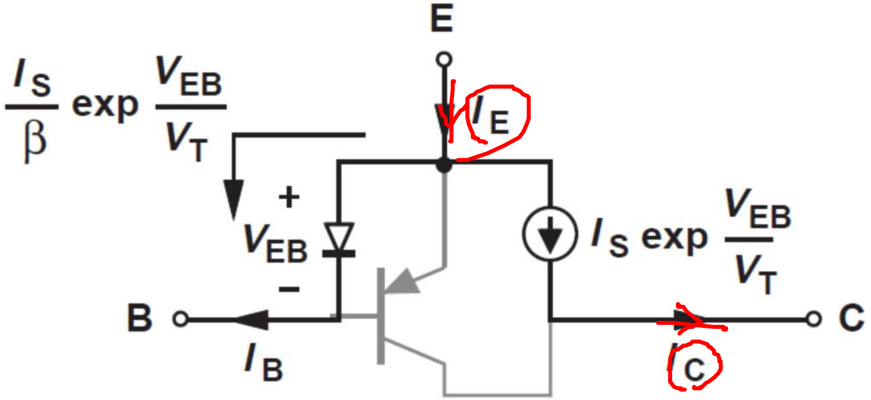
PNP BJT Large Signal model

DC analysis.





Large-signal model of NPN BJT



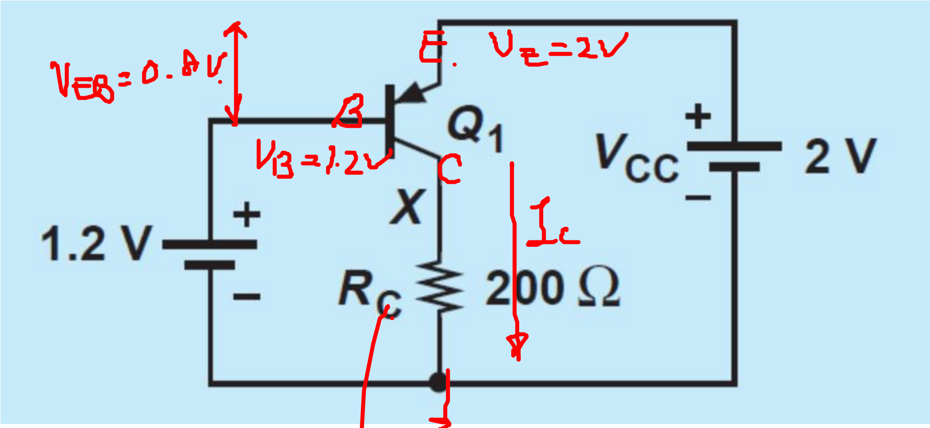
Large-signal model of PNP BJT

The difference between the npn and pnp equations relates to the base-emitter voltage that appears in the exponent, and the direction of current flow.

Also, the Early effect can be included as $I_C = \left(I_S \exp \frac{V_{EB}}{V_T}\right)\left(1 + \frac{V_{EC}}{V_A}\right)$

Example 5. Determine the terminal currents of Q_1 and verify operation in the forward active region. Assume $I_S = 2 \times 10^{-16}$ A and $\beta = 50$ where $V_A = \infty$ and $V_T = 0.026$ V.

no early effect.



$V_B = 1.2V$

$V_E = 2V$

$V_{EB} = 0.8V$

$$I_c = I_s\left[\exp\left(V_{EB}/V_T\right) - 1\right]$$

$$= 2\times10^{-16}\left[\exp\left(\frac{0.8}{0.026}\right) - 1\right]$$

$$= 0.0046A.$$

Voltage drop $= I_c R_c = 200 \times 0.0046$

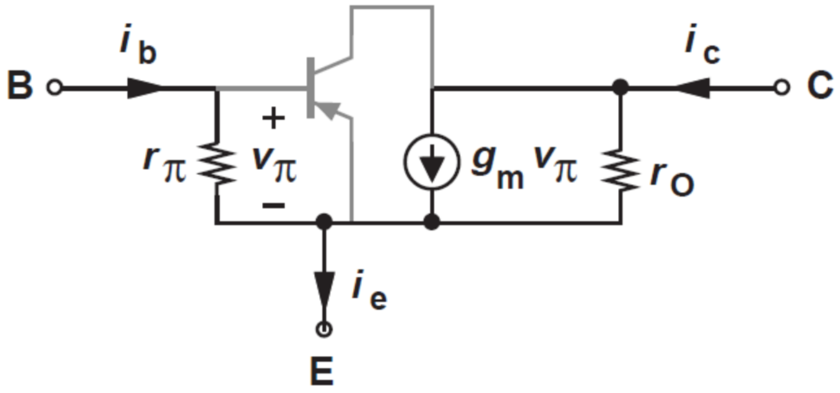
$= \underline{0.92V}$

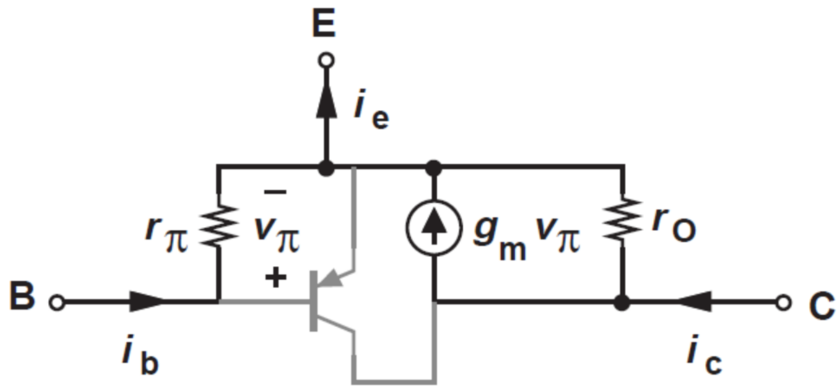
$V_c = 0.92V.$

$V_{BC} = 1.2 - 0.92 > 0.$ $V_{CB} < 0.$

$V_{EB} > 0$

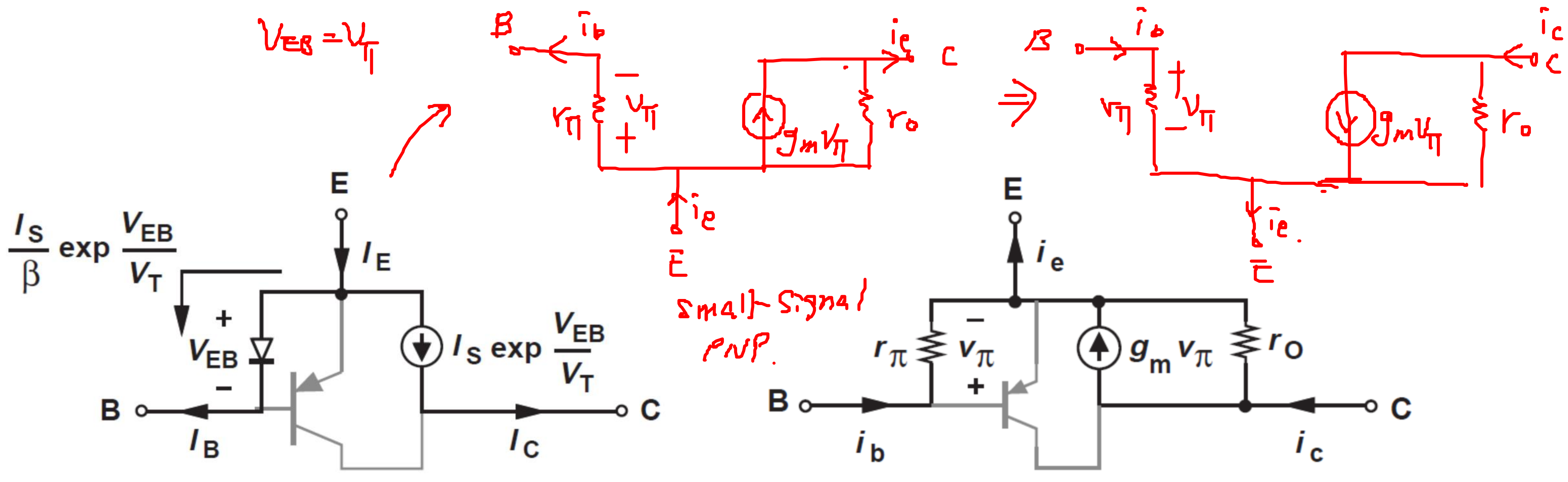
PNP BJT Small Signal model





small-signal model
of PNP.

Since the small-signal model represents changes in the voltages and currents, we expect npn and pnp transistors to have similar models. **The small signal model of the pnp transistor is indeed identical to that of the npn device.**



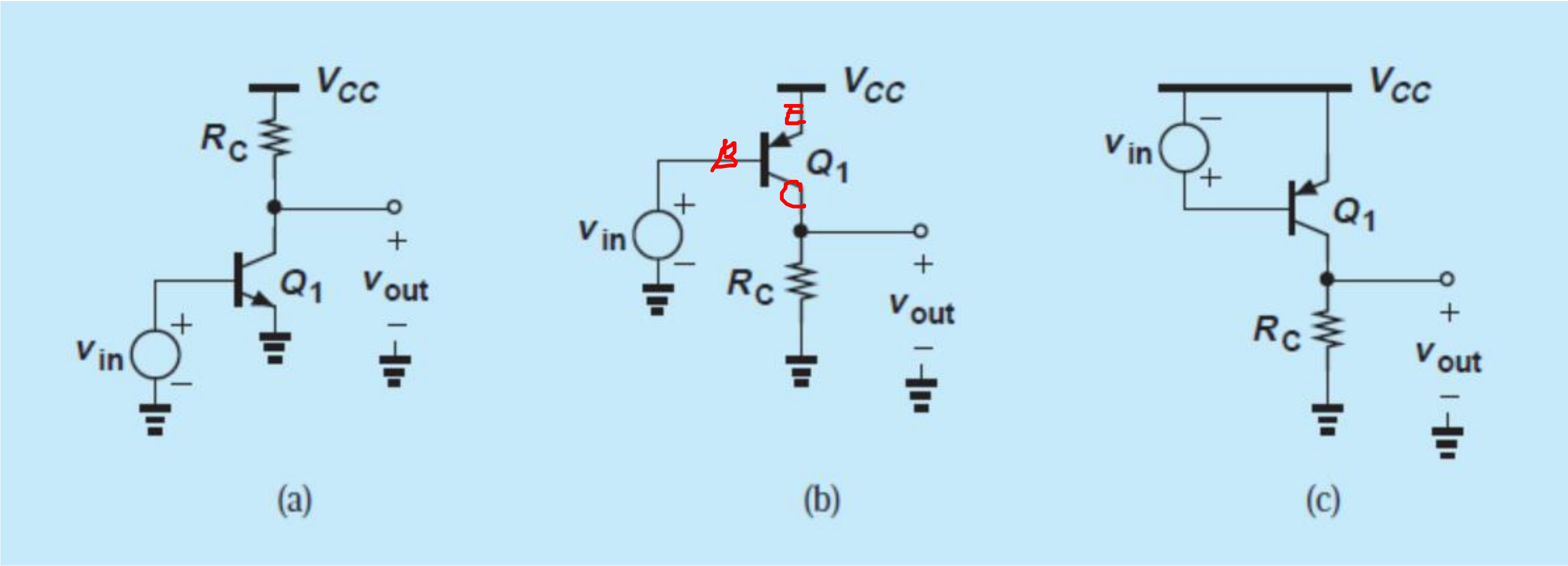
Large-signal model of PNP BJT

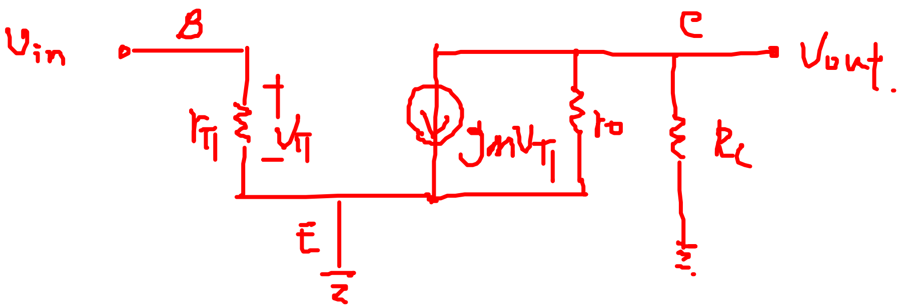
Small-signal model of PNP BJT

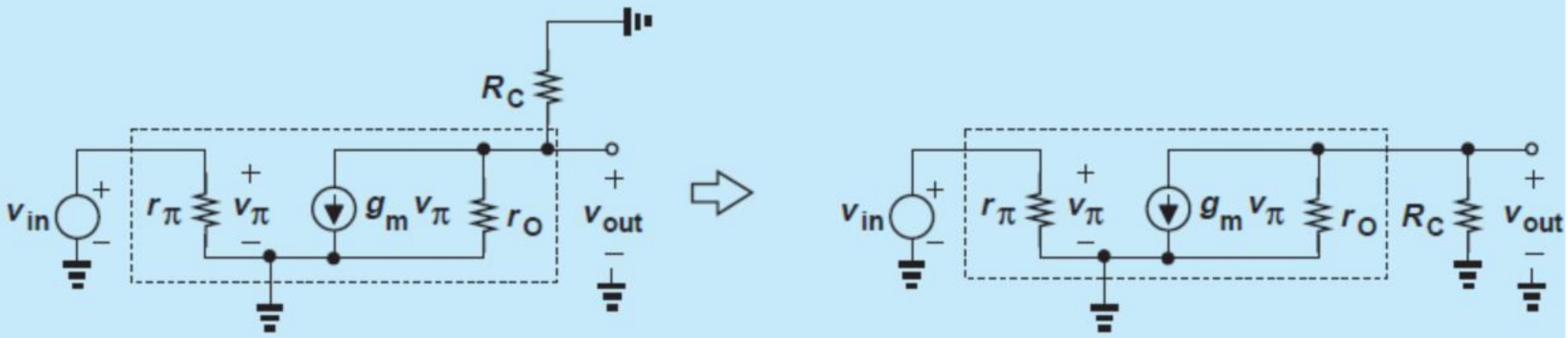
The direction of currents in the **large-signal model** shows how currents could flow when the pnp transistor is **properly DC biased**.

The direction of currents in the **small-signal model** shows how the ac currents flow when ac voltage **across base-emitter increases**.

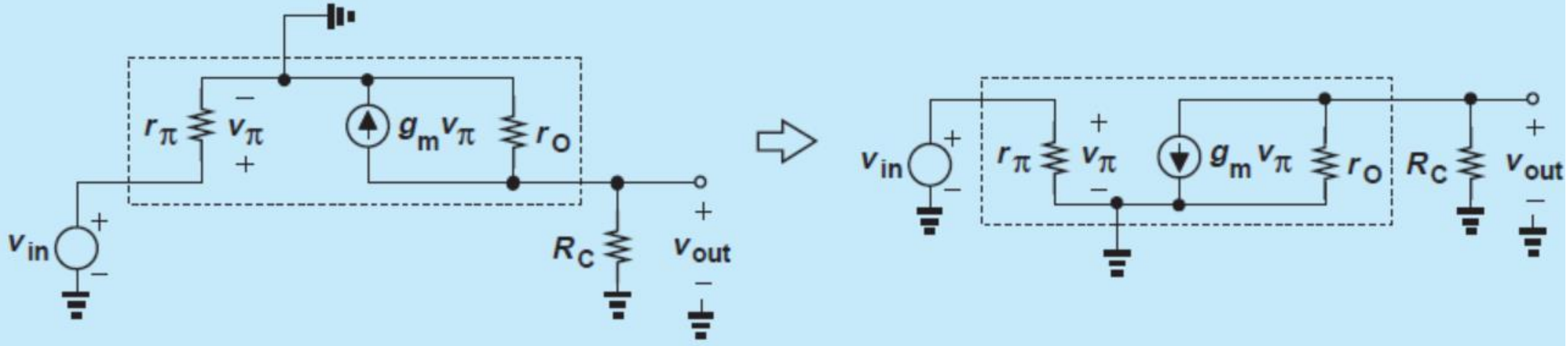
Example 6 Draw the small-signal equivalent circuits for the topologies shown below.



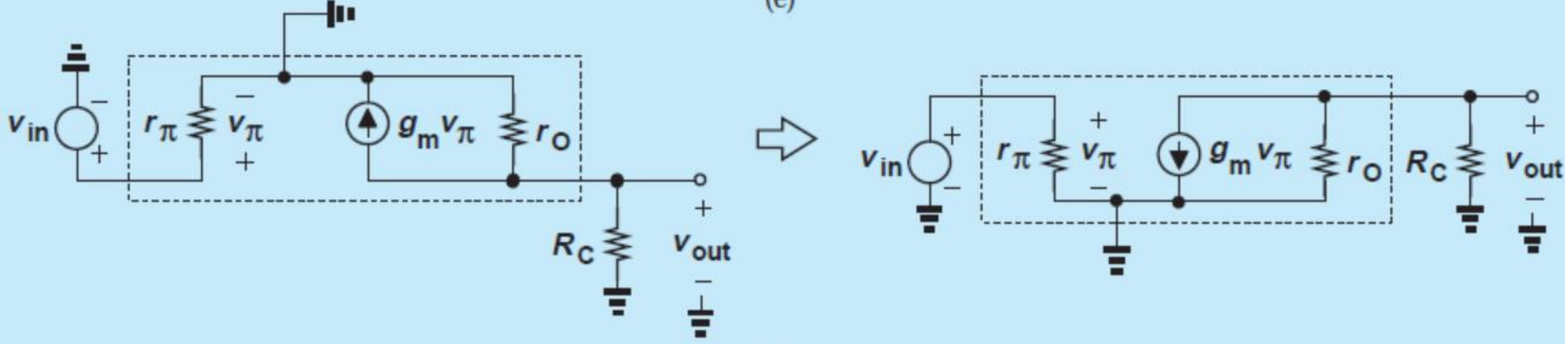



R_C
v_in
r_π
v_π
g_m v_π
r_O
v_out

(d)


r_π
v_π
g_m v_π
r_O
v_in
R_C
v_out

(e)


v_in
r_π
v_π
g_m v_π
r_O
R_C
v_out

(f)