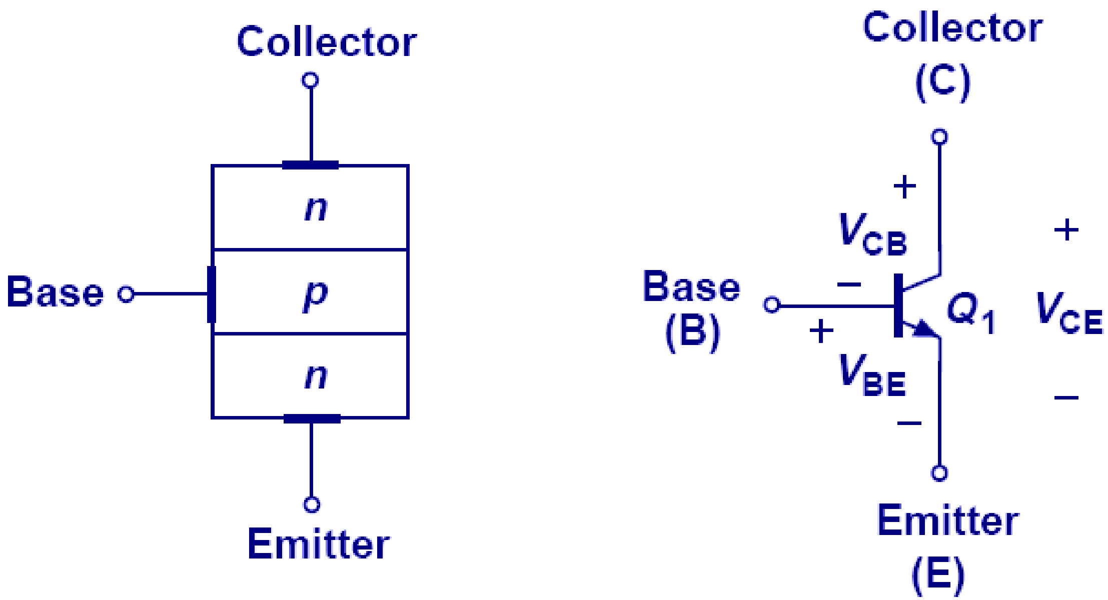
Lecture 4

OUTLINE

- Bipolar Junction Transistor (BJT)
  - General considerations
  - Structure
  - Operation in active mode
  - Large-signal model and I-V characteristics
  - Transconductance
  - Small-signal model
  - The Early effect

Reading: Chapter 4.1-4.4

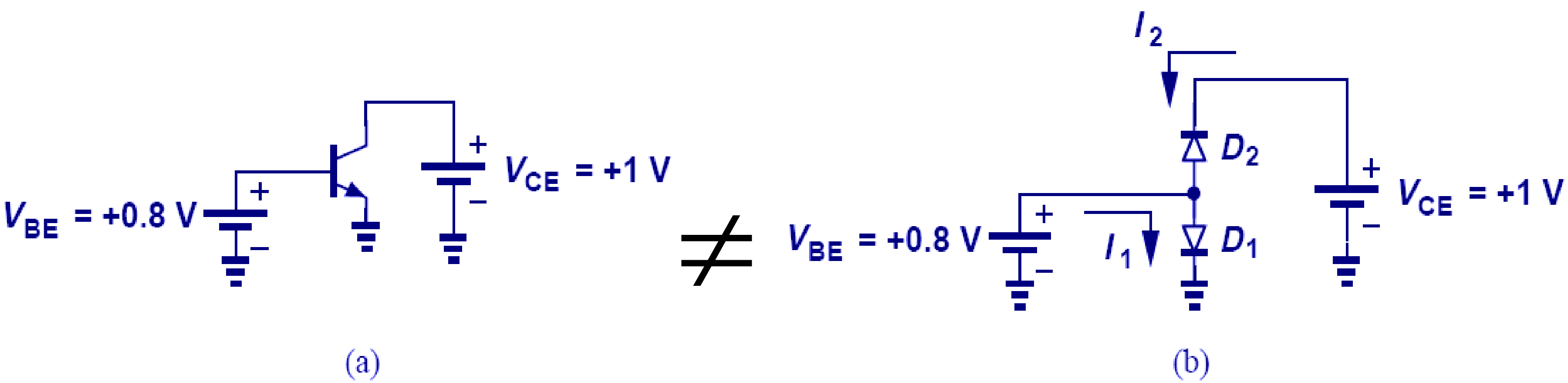
Structure and Symbol of Bipolar Transistor



(a) (b)

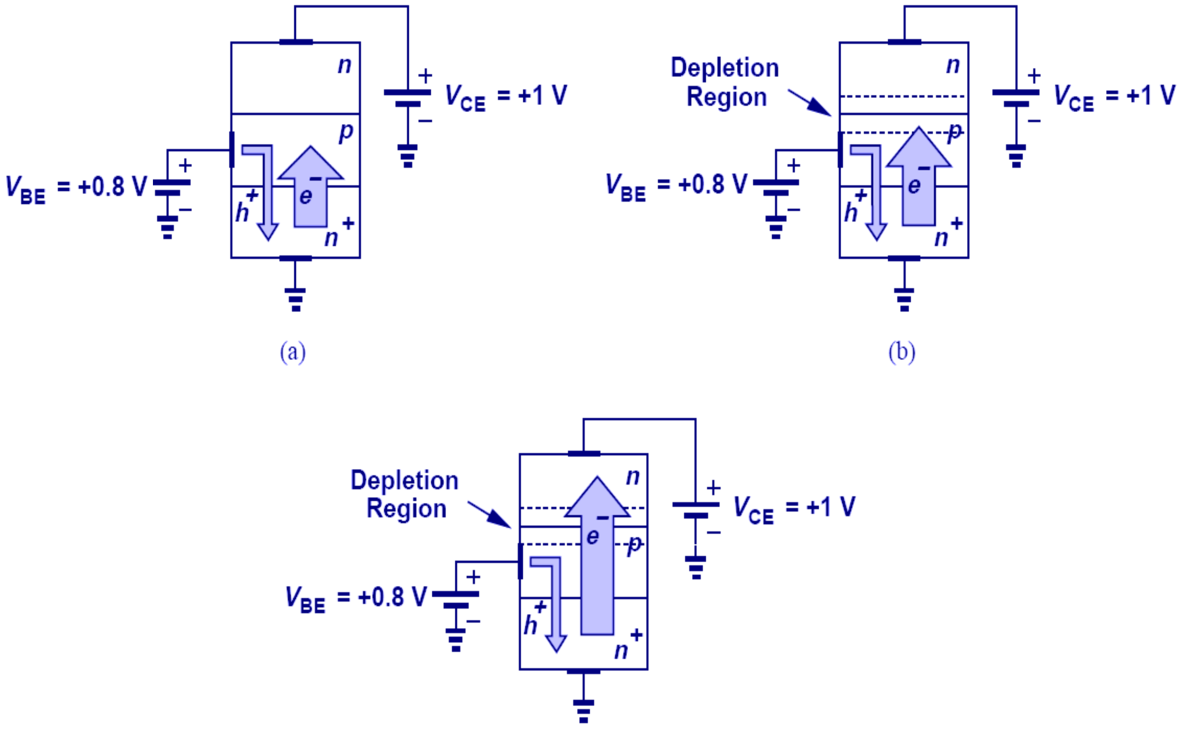
- Bipolar transistor can be thought of as a sandwich of three doped Si regions. The outer two regions are doped with the same polarity, while the middle region is doped with opposite polarity.

Forward Active Region



- Forward active region: $V_{BE} > 0$, $V_{BC} < 0$.
- Figure b) presents a wrong way of modeling Figure a).

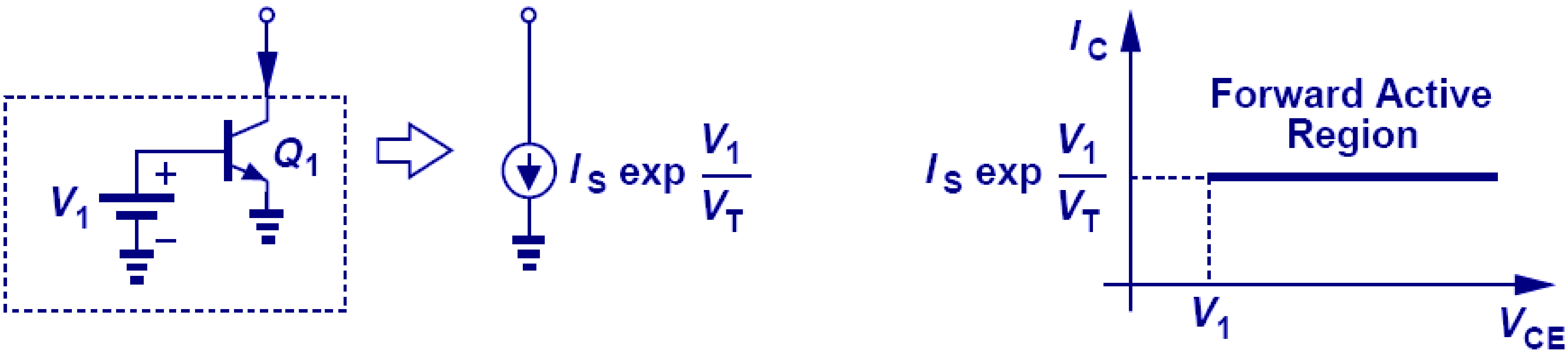
Accurate Bipolar Representation



(a) (b) (c)

- Collector also carries current due to carrier injection from base.

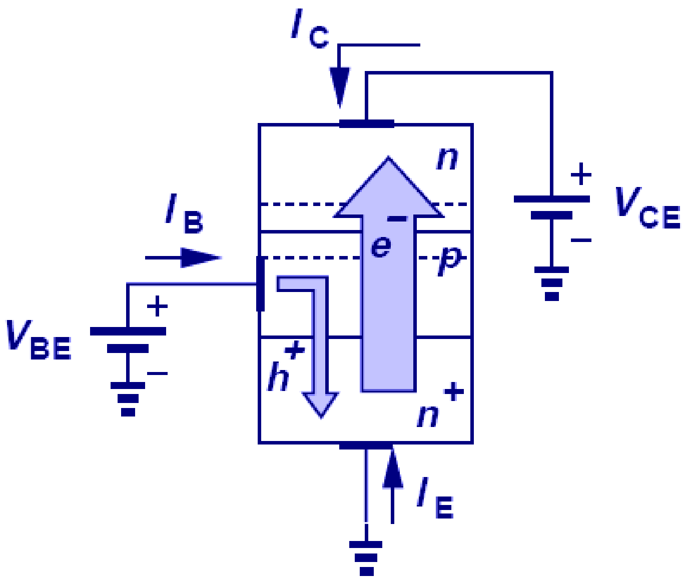
Constant Current Source



(a) (b)

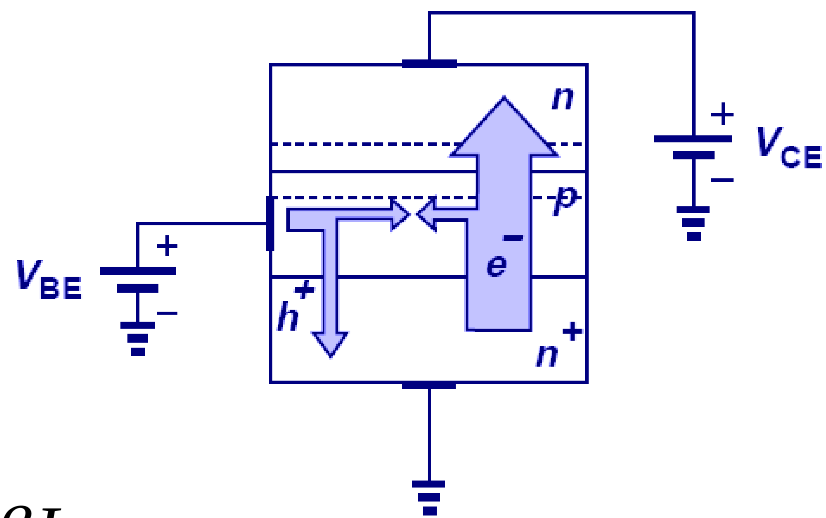
- Ideally, the collector current does not depend on the collector to emitter voltage. This property allows the transistor to behave as a constant current source when its base-emitter voltage is fixed.

Base Current



(a)

$$I_C = \beta I_B$$



(b)

- Base current consists of two components:
  - Reverse injection of holes into the emitter and
  - Recombination of holes with electrons coming from the emitter.

Emitter Current

$$I_E = I_C + I_B$$

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

$$\beta = \frac{I_C}{I_B}$$

- Applying Kirchoff's current law to the transistor, we can easily find the emitter current.

Summary of Currents

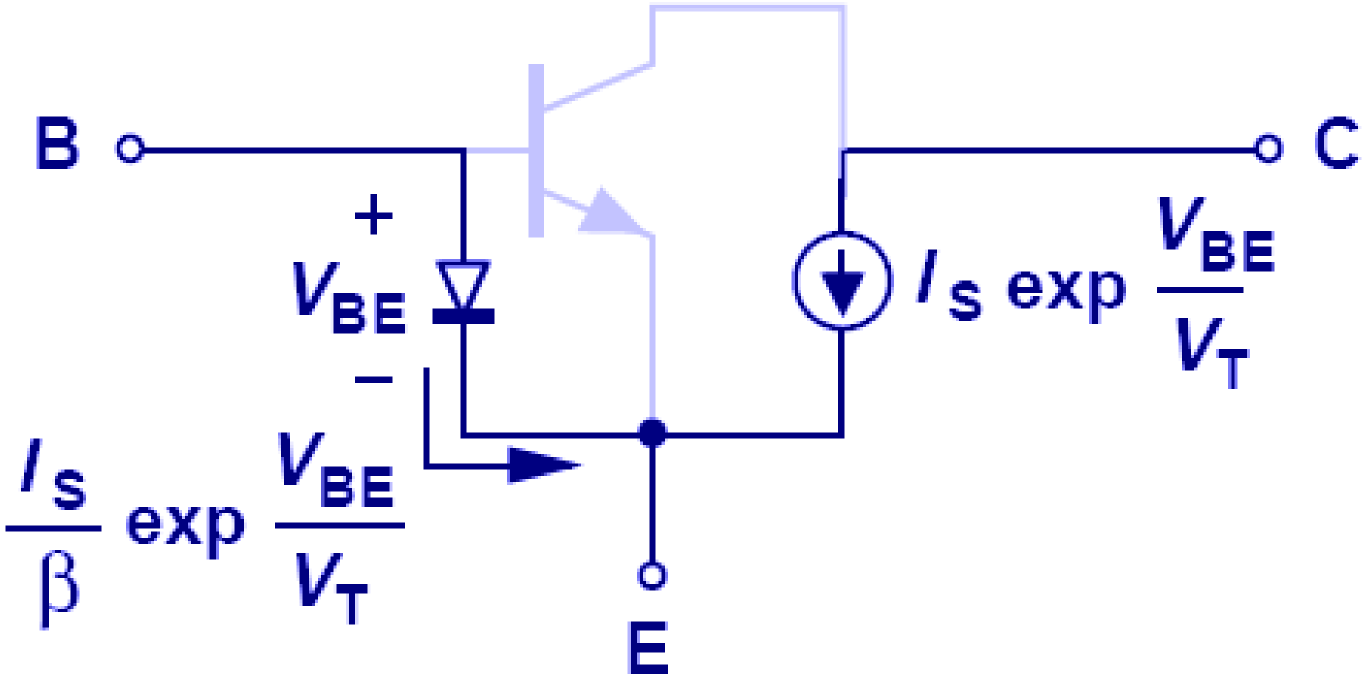
$$I_C = I_S \exp\frac{V_{BE}}{V_T}$$

$$I_B = \frac{1}{\beta} I_S \exp\frac{V_{BE}}{V_T}$$

$$I_E = \frac{\beta+1}{\beta} I_S \exp\frac{V_{BE}}{V_T}$$

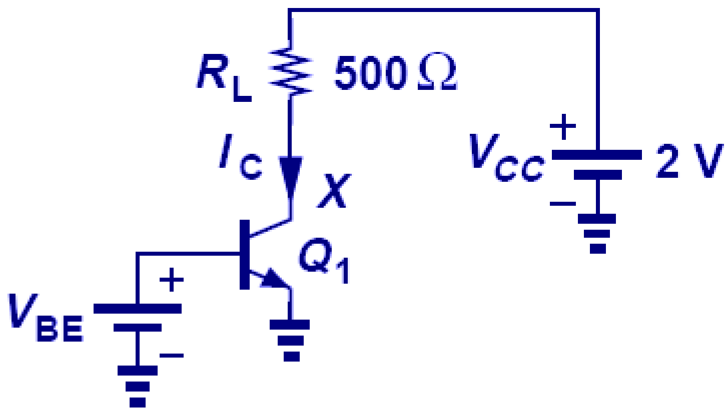
$$\frac{\beta}{\beta+1} = \alpha$$

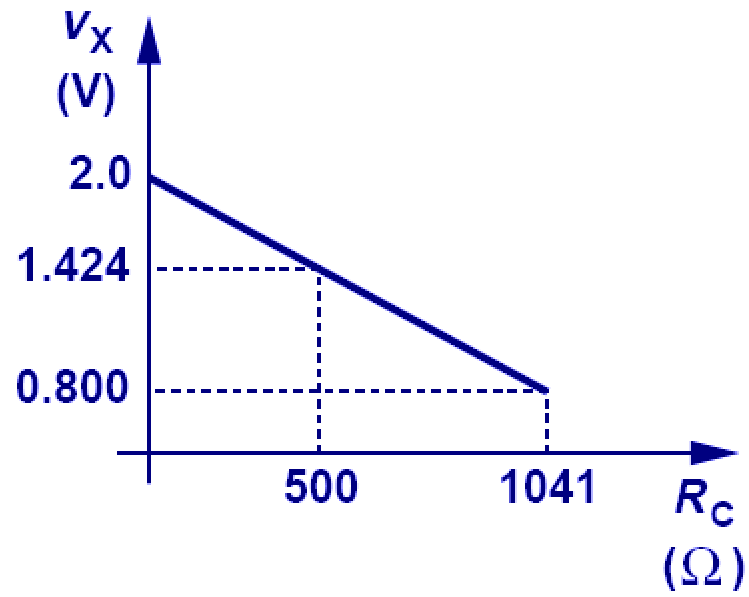
Bipolar Transistor Large Signal Model



- A diode is placed between base and emitter and a voltage controlled current source is placed between the collector and emitter.

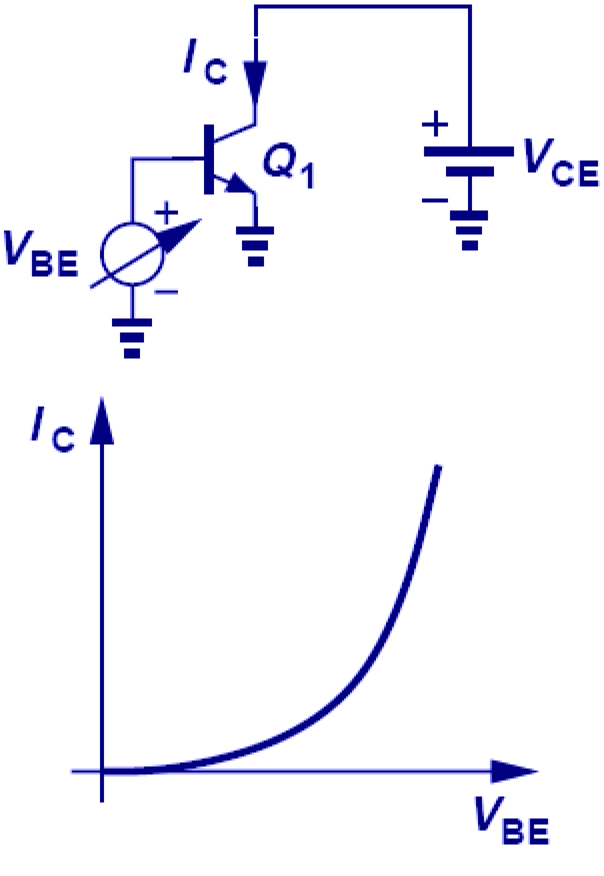
Example: Maximum R_L



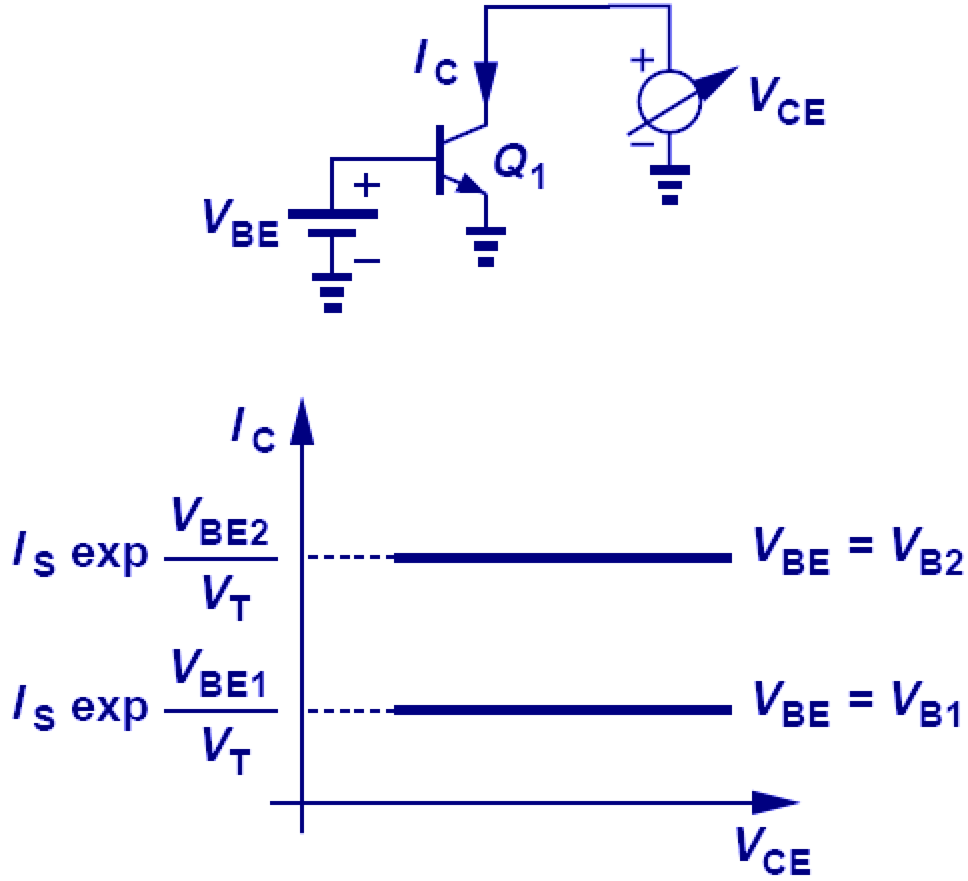


- As R_L increases, V_x drops and eventually forward biases the collector-base junction. This will force the transistor out of forward active region.
- Therefore, there exists a maximum tolerable collector resistance.

Characteristics of Bipolar Transistor



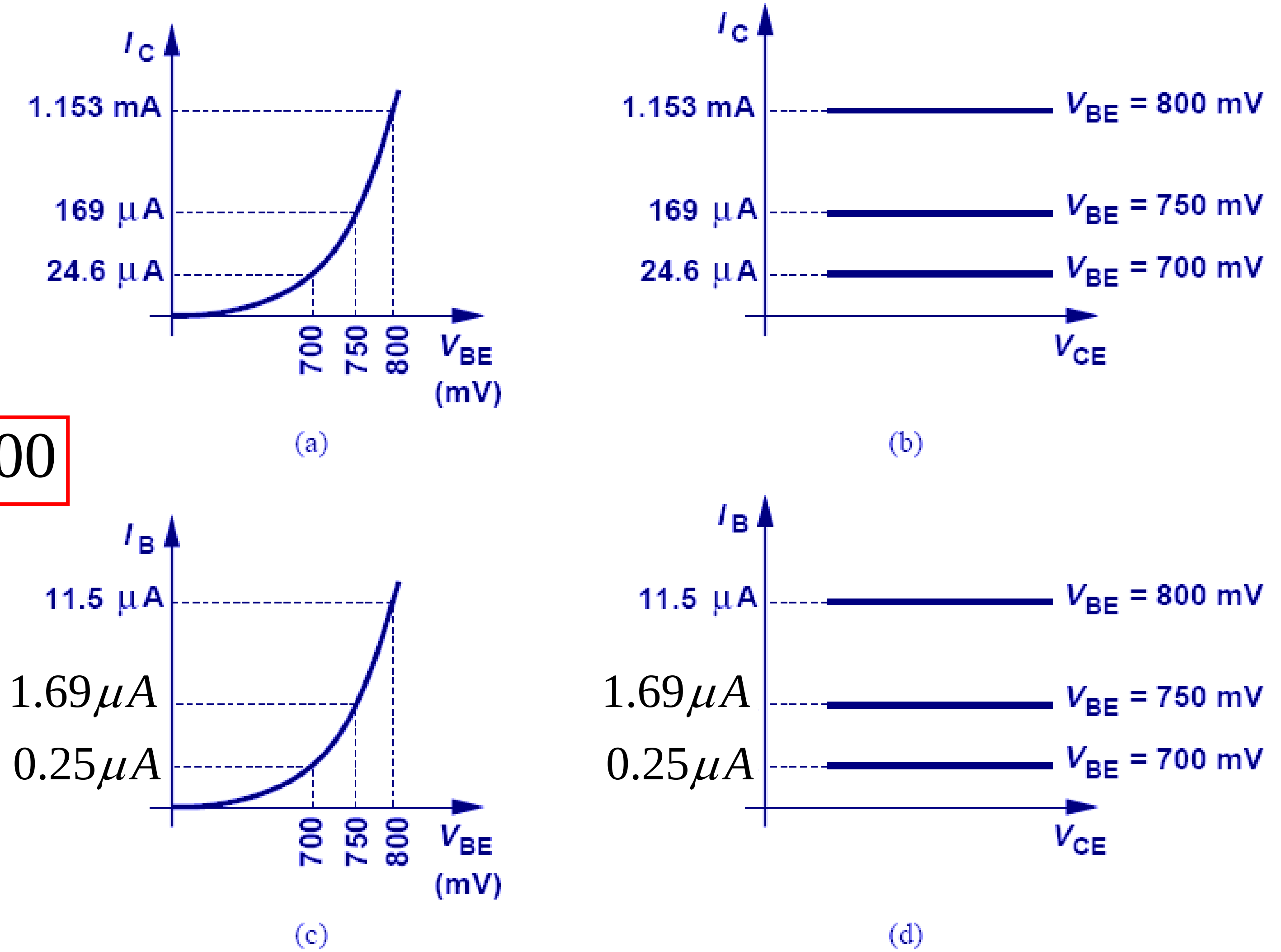
(a)



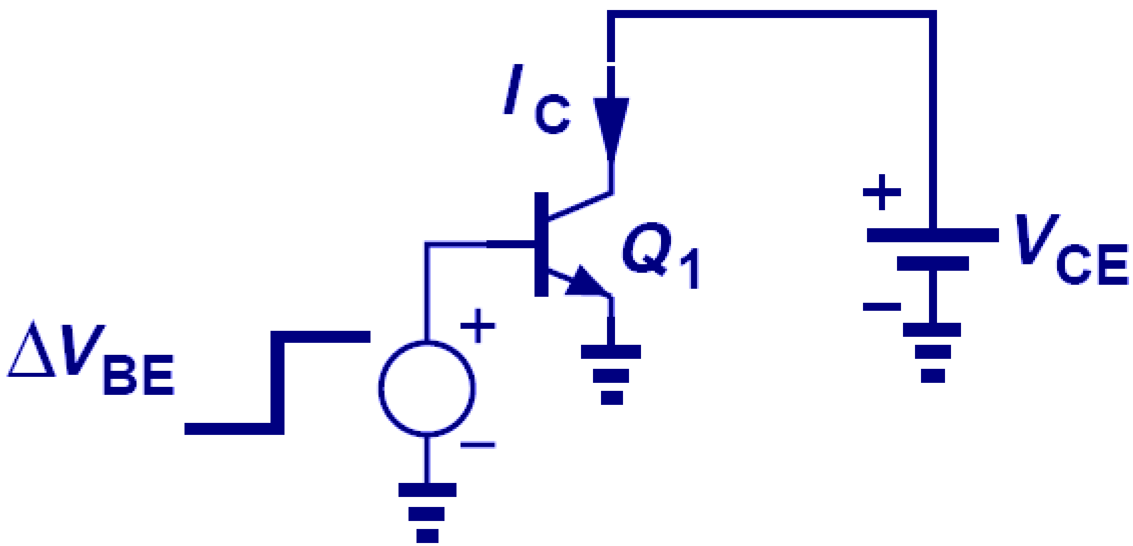
(b)

Example: IV Characteristics

$\beta = 100$



Transconductance



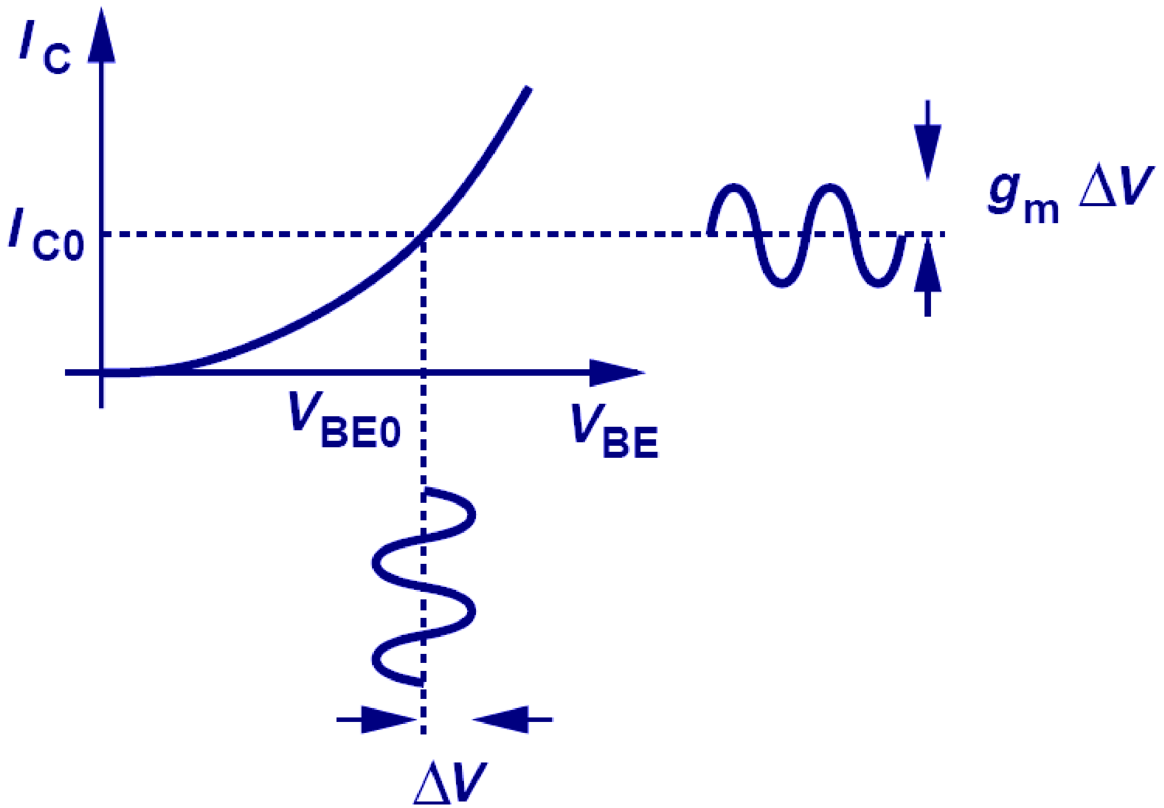
$$g_m = \frac{d}{dV_{BE}}\left(I_S \exp\frac{V_{BE}}{V_T}\right)$$

$$g_m = \frac{1}{V_T} I_S \exp\frac{V_{BE}}{V_T}$$

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

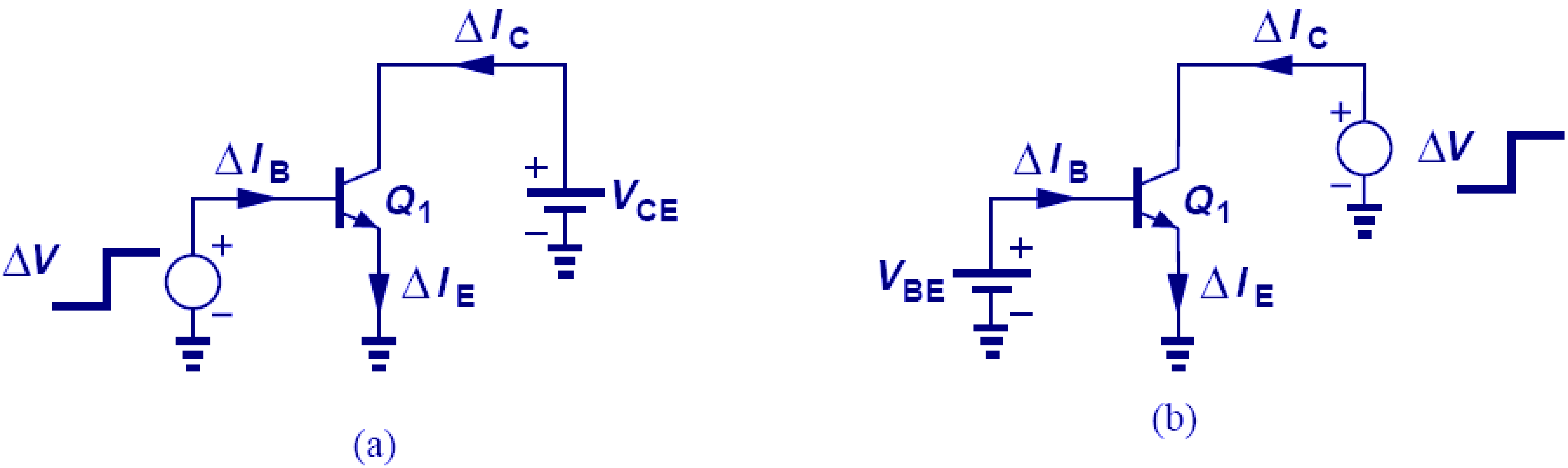
- Transconductance, g_m shows a measure of how well the transistor converts voltage to current.
- It will later be shown that gm is one of the most important parameters in circuit design.

Visualization of Transconductance



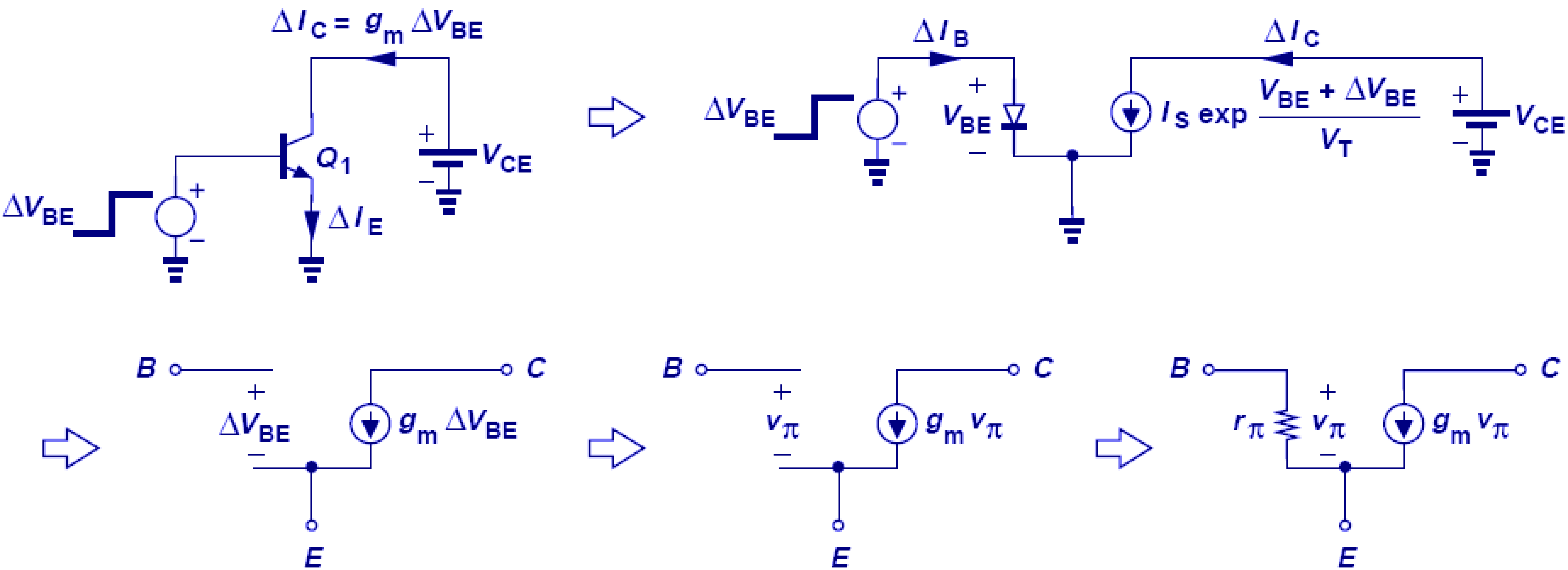
- g_m can be visualized as the slope of I_C versus VBE.
- A large I_C has a large slope and therefore a large g_m.

Small-Signal Model: Derivation

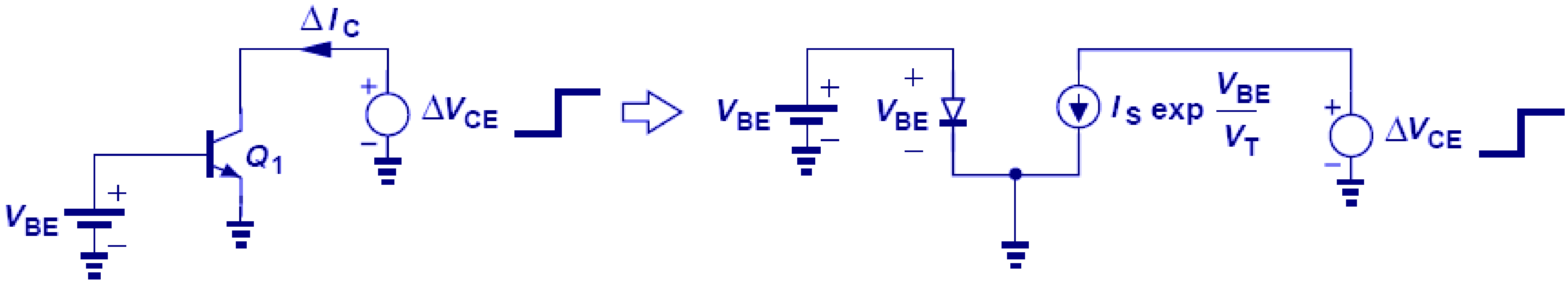


- Small signal model is derived by perturbing voltage difference every two terminals while fixing the third terminal and analyzing the change in current of all three terminals. We then represent these changes with controlled sources or resistors.

Small-Signal Model: V_{BE} Change

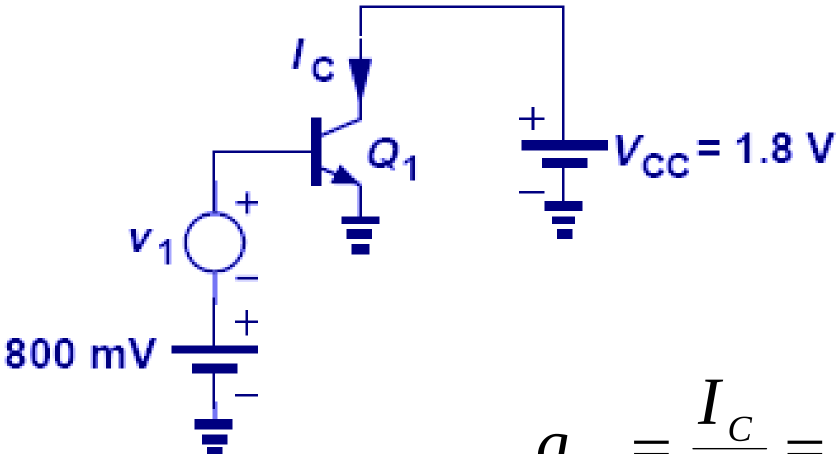


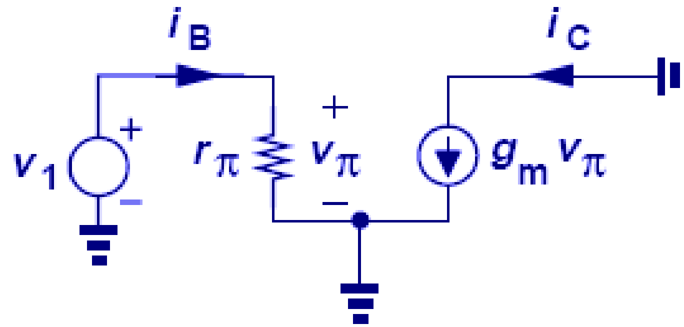
Small-Signal Model: V_{CE} Change



- Ideally, V_{CE} has no effect on the collector current. Thus, it will not contribute to the small signal model.
- It can be shown that V_{CB} has no effect on the small signal model, either.

Small Signal Example I



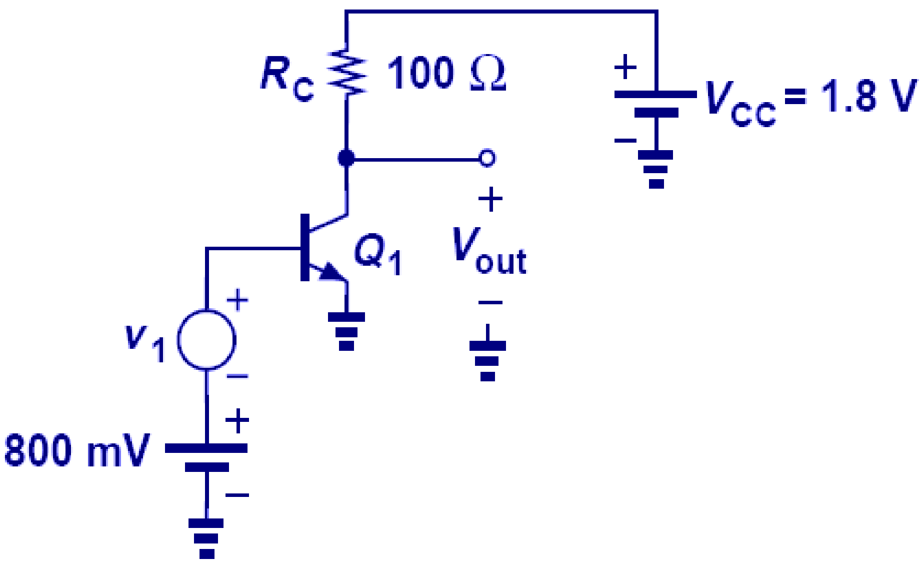


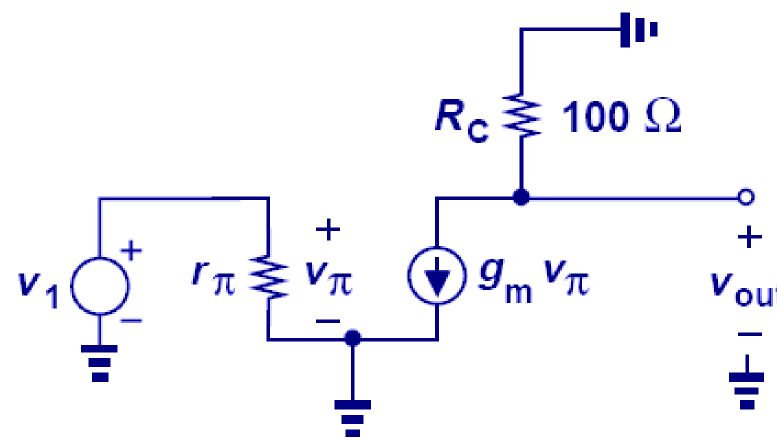
$$g_m = \frac{I_C}{V_T} = \frac{1}{3.75\Omega}$$

$$r_\pi = \frac{\beta}{g_m} = 375\,\Omega$$

- Here, small signal parameters are calculated from DC operating point and are used to calculate the change in collector current due to a change in V_{BE}.

Small Signal Example II



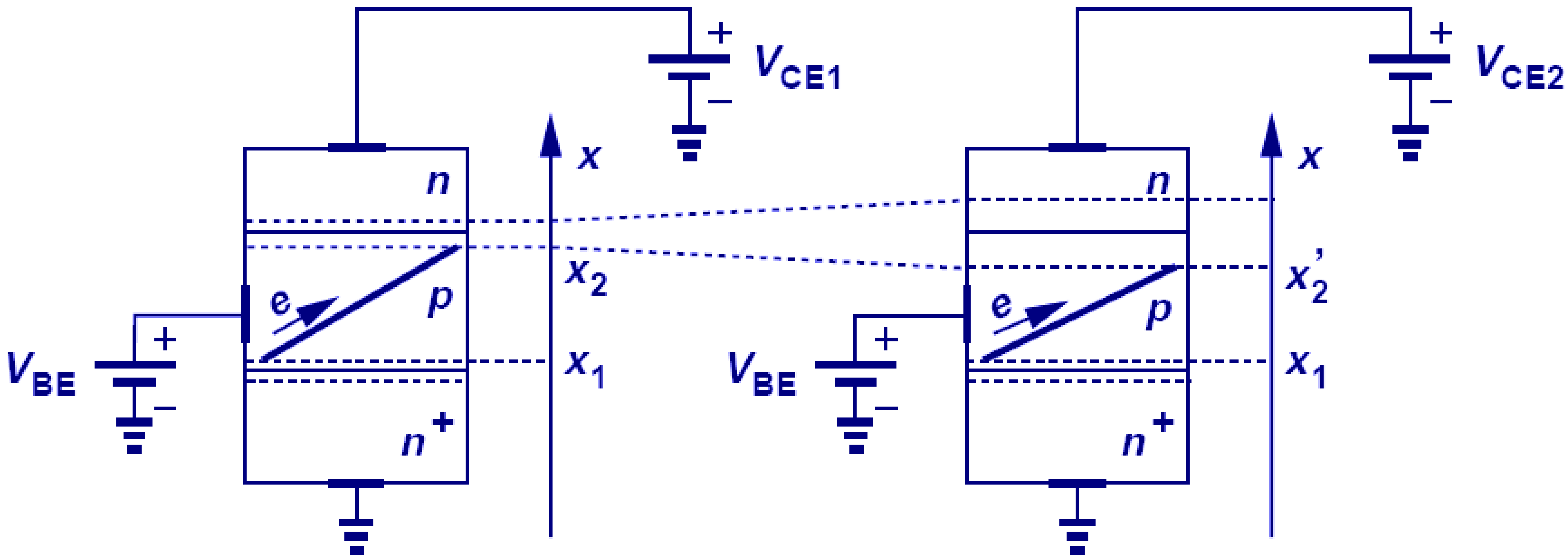


- In this example, a resistor is placed between the power supply and collector, therefore, providing an output voltage.

AC Ground

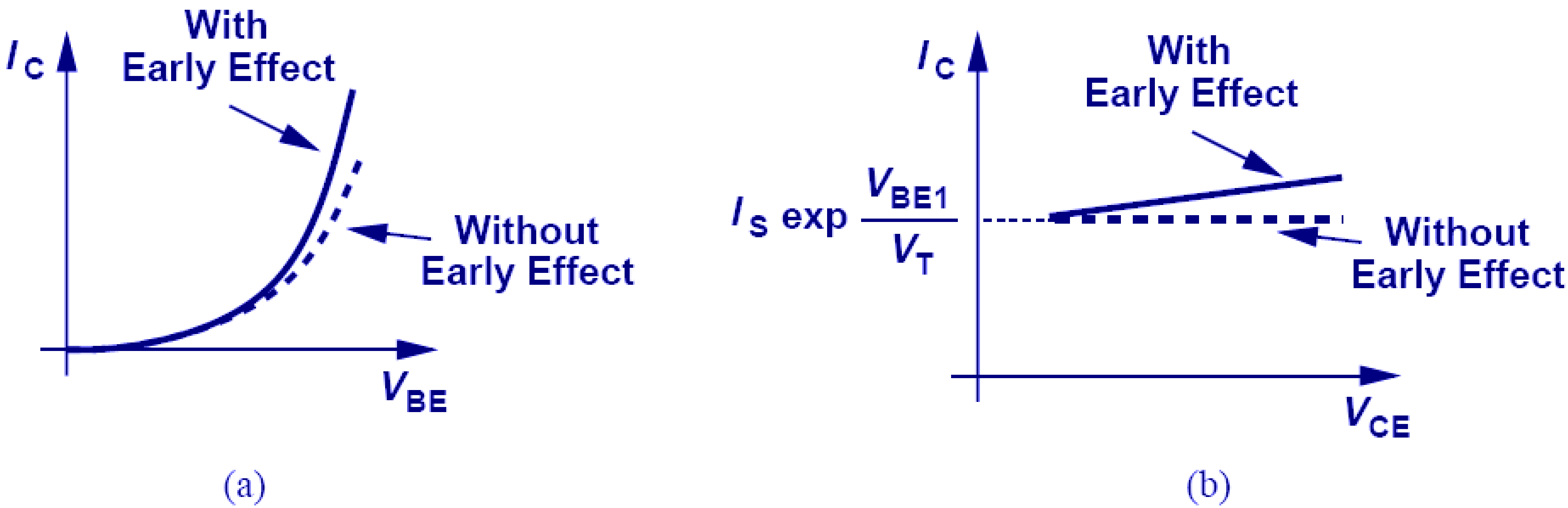
- Since the power supply voltage does not vary with time, it is regarded as a ground in small-signal analysis.

Early Effect



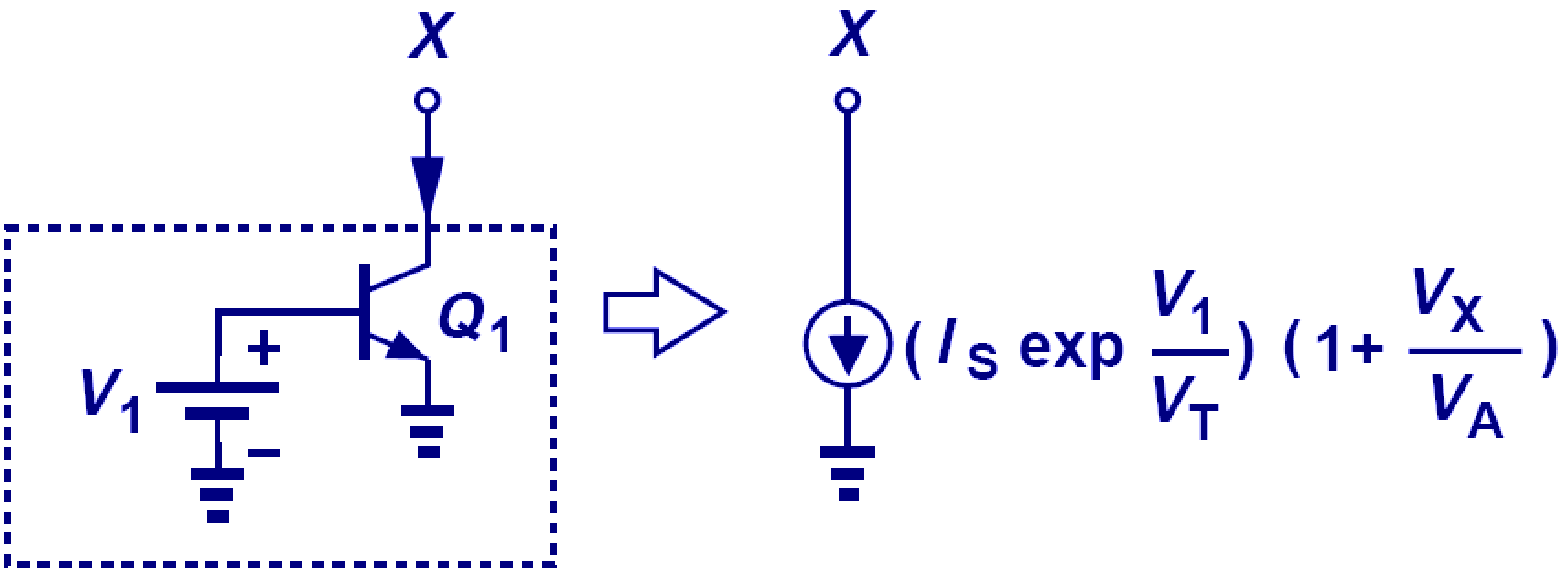
- The claim that collector current does not depend on V_{CE} is not accurate.
- As V_{CE} increases, the depletion region between base and collector increases. Therefore, the effective base width decreases, which leads to an increase in the collector current.

Early Effect Illustration

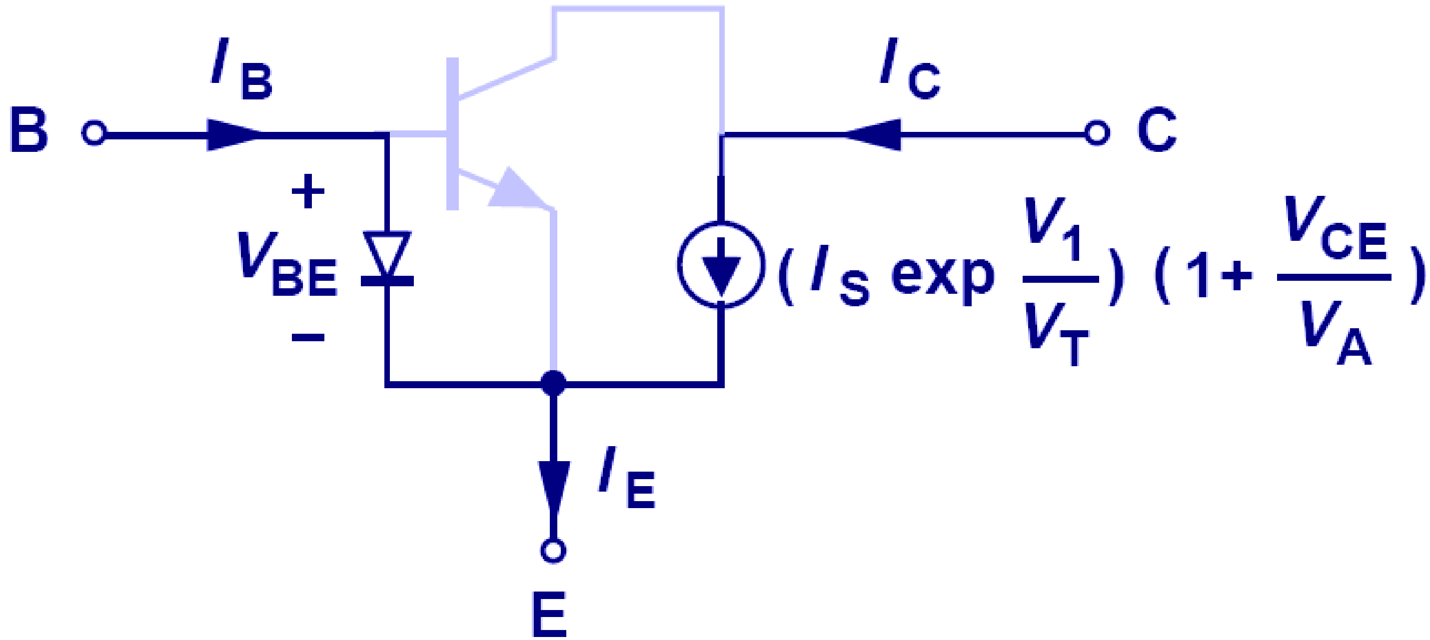


- With Early effect, collector current becomes larger than usual and a function of V_{CE}.

Early Effect Representation

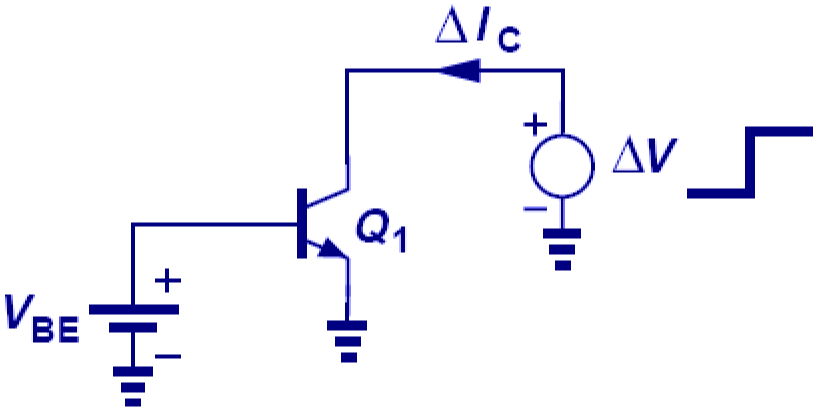


Early Effect and Large-Signal Model

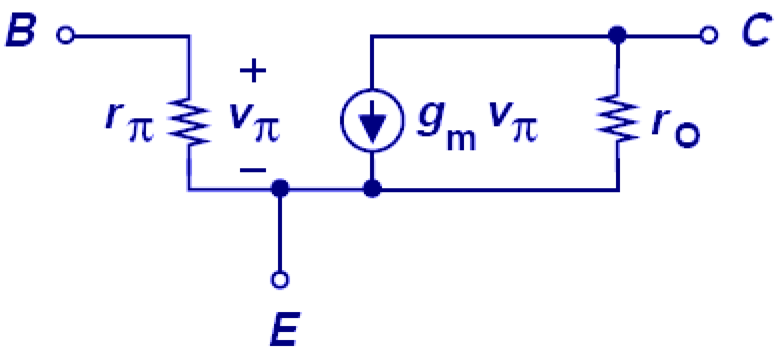


- Early effect can be accounted for in large-signal model by simply changing the collector current with a correction factor.
- In this mode, base current does not change.

Early Effect and Small-Signal Model



(a)



(b)

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{V_A}{I_S \exp\frac{V_{BE}}{V_T}} \approx \frac{V_A}{I_C}$$

Summary of Ideas