Lecture 8: BJT Circuits

ECE3110J, Electronic Circuits

Xuyang Lu

2024 Summer

Recap of Last Lecture

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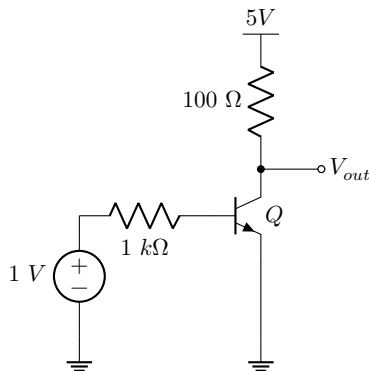SHANGHAI JIAO TONG UNIVERSITY

- Reviewed Op-amps
- BJT

Topics to Be Covered

- BJT

DC Condition Calculation

Given:

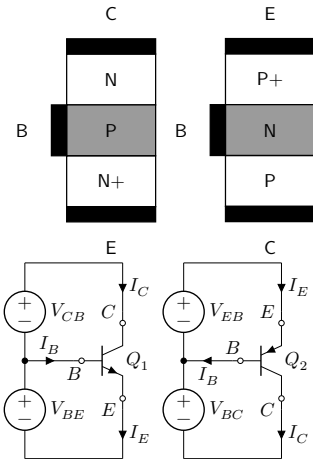$$\beta = 100, v_{BE,on} = 0.6V \qquad (1)$$

What is v_O? Assume FAR

$$i_B = \frac{1 - 0.6V}{R_B} = 0.4mA \qquad (2)$$

$$i_C = \beta i_B = 100 \cdot 0.4 \ mA = 40 \ mA \qquad (3)$$

$$v_O = 5V - 100 \ \Omega \cdot 40mA = 1V \qquad (4)$$

pnp Transistor

- For pnp, the basics of the operation are the same, except now instead of e^- crossing the base, h^+ cross the base.

- Because holes move a lot slower than e^-, there would be more recombination and fewer of them make it to the collector. Thus, the current gain is much lower for pnp than for npn.

- Note that all polarities are now different, for example for FAR operation, the BE junction has to be forward biased which means that the base-emitter voltage should be $-0.7V$, so the BE junction is forward biased.

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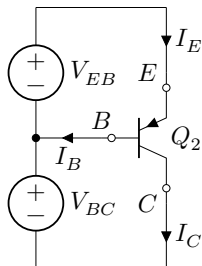
pnp Transistor

| Applied Voltages	B-E junction Bias (PNP)	B-C junction Bias (PNP)	Mode(PNP)
E < B < C	Reverse	Forward	Reverse-active
E < B > C	Reverse	Reverse	Cut-off
E > B < C	Forward	Forward	Saturation
E > B > C	Forward	Reverse	Forward-active

npn Transistor

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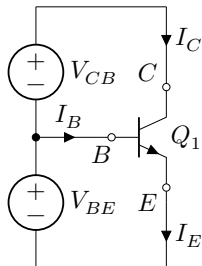
Applied Voltages	B-E junction Bias (NPN)	B-C junction Bias (NPN)	Mode(NPN)
E < B < C	Forward	Reverse	Forward-active
E < B > C	Forward	Forward	Saturation
E > B < C	Reverse	Reverse	Cut-off
E > B > C	Reverse	Forward	Reverse-active

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Large Signal Model: T-Model

• We can now easily establish large signal models for the transistor that describe the current-voltage relation ship

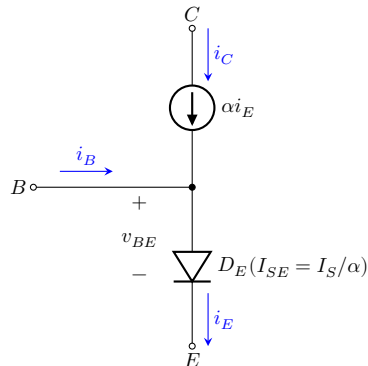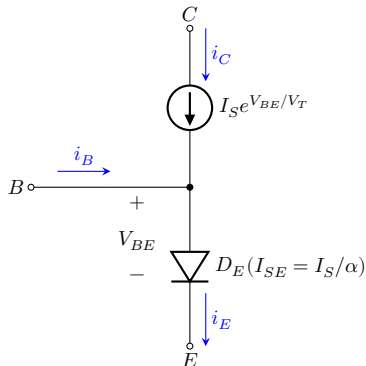$$i_C \approx I_S e^{V_{BE}/V_T} \qquad (5)$$

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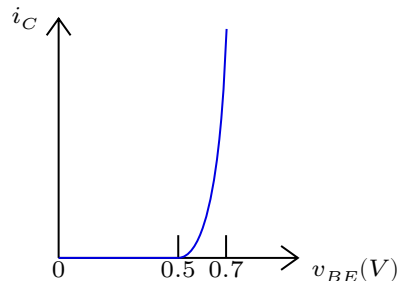
Large Signal Model: T-Model

- The base is shared between the input port (B-E) and the output port (B-C)

Hybrid-π Model

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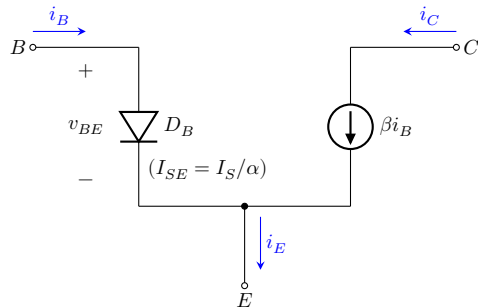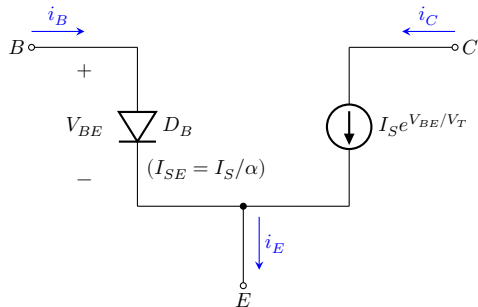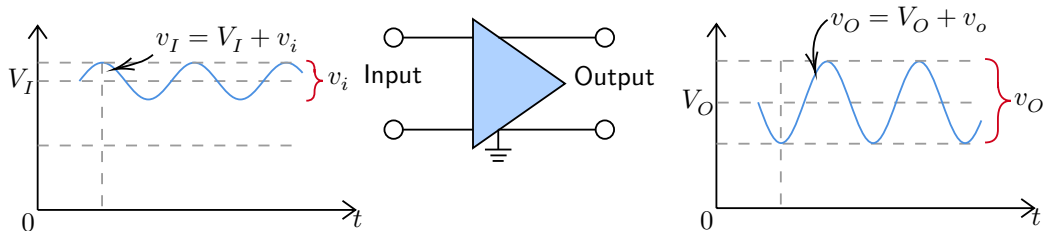
- In hybrid-π model, where the collector current is shown as a voltage controlled current source (VCCS).

- The hybrid-π model is more useful for analyzing the common-emitter amplifier. Notice that the emitter in this model is shared between the input port (B-E), and the output port (C-E).

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Hybrid-π Model

Small Signal

- Amplifiers refer to circuits that amplify AC (time varying) signals; there is generally no interest in the DC component of a signal.
- Circuits that change the DC value of the input to produce an output with a different DC value are generally referred to as level shifters, or DC-DC converters.
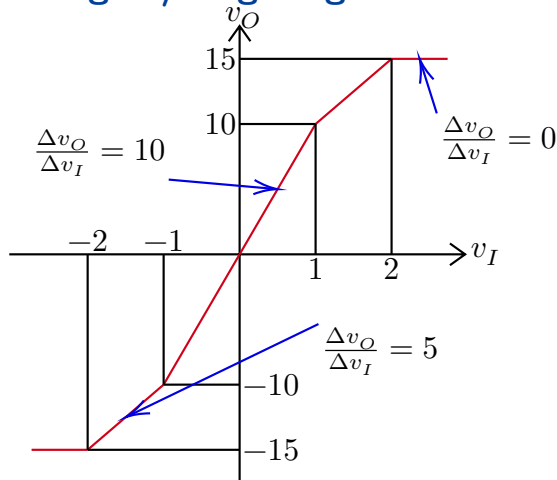
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AC-Coupled or DC-Coupled

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- AC-coupled, means only AC signals will pass through to the input of the next stage.

- DC coupled means there is no capacitor separating one part of a circuit from another part when the two are connected.

C

No V_I (No DC part)

$v_O = v_i$

V_I
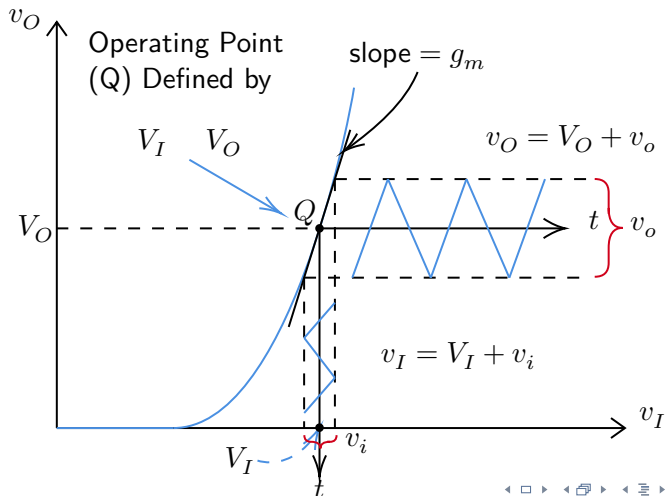
$v_I = V_I + v_i$

R

v_i
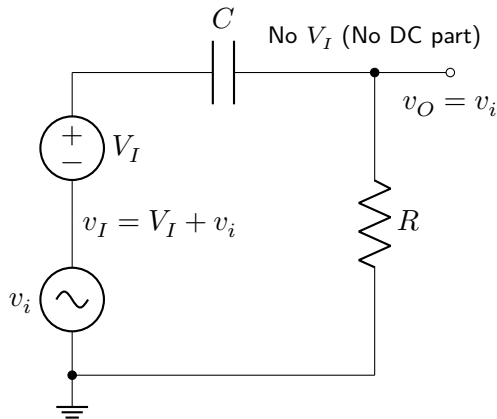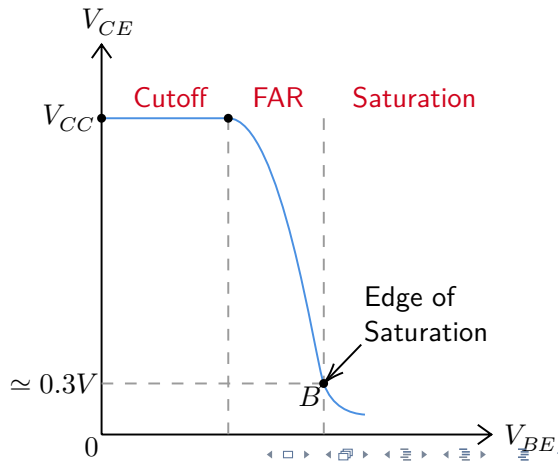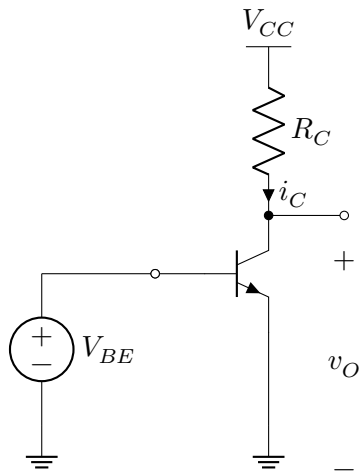
Small-Signal/Large-Signal

- A circuit with linear behavior over a specific range of signals, could be used as a linear circuit, when/if the range of signals applied to it is limited to where response is linear
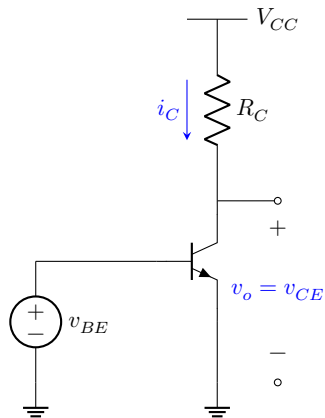
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Small-Signal/Large-Signal

Operating Point (Q) Defined by

V_I V_O

slope $= g_m$

$v_O = V_O + v_o$

$v_I = V_I + v_i$

Lecture 8: BJT Circuits

BJT CE Gain

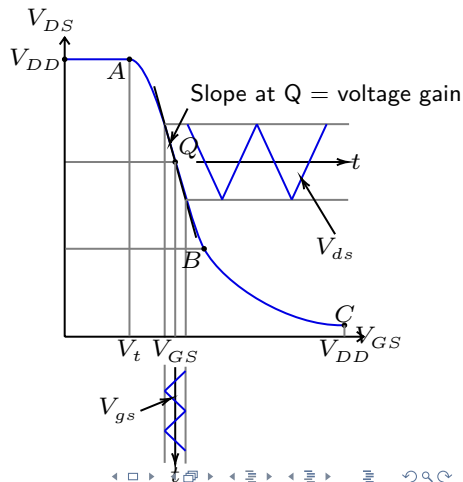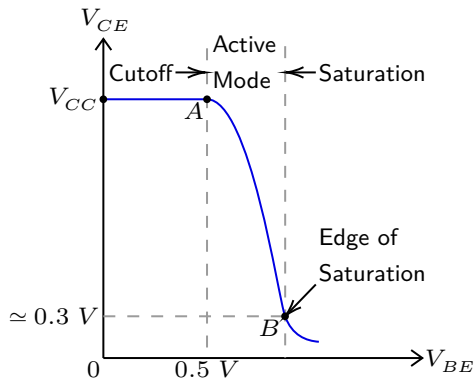# Small Signal Gain

$$A_v = \frac{dV_o}{dV_{BE}} \qquad (6)$$

$$A_v = -\frac{I_C}{V_T} R_C \qquad (7)$$
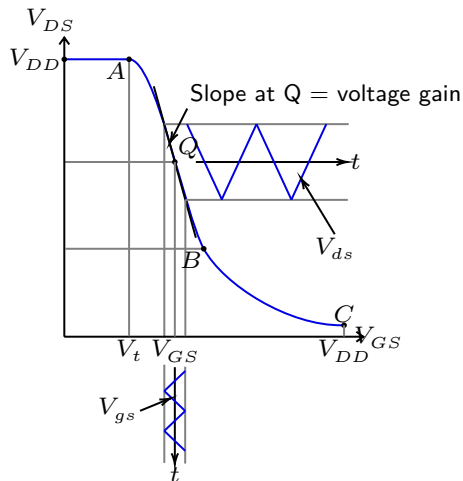
Small Signal Gain

Recap
BJT small signal model
BJT hybrid-π model

Small Signal Gain
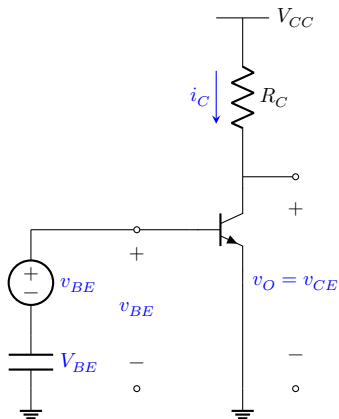
$$v_{CE}(t) = V_{CE} + v_{ce}(t) \qquad (8)$$

$$v_{BE}(t) = V_{BE} + v_{be}(t) \qquad (9)$$

Quiescent Point (Q)
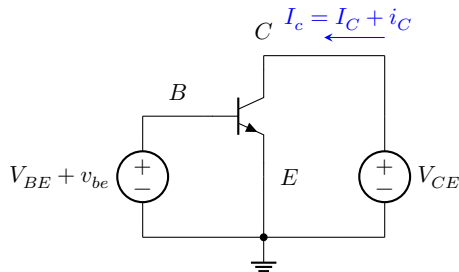
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- Operating point for circuit
- Often called "bias" point

$$A_v = \frac{v_o}{v_{be}} \qquad (10)$$

$$V_o = V_{CC} - R_C I_S e^{V_{BE}/V_T} \qquad (11)$$

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Recap
BJT small signal model
BJT hybrid-π model

Hybrid-π Model (g_m and r_π)

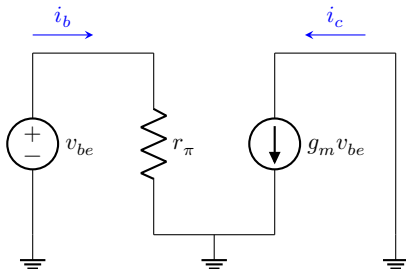$V_{CE} \geq V_{BE} \Rightarrow \text{Forward}-\text{Active}$

$$I_C = I_S \left(e^{\frac{q V_{BE}}{kT}} - 1 \right) \left(1 + \frac{V_{CE}}{V_A} \right) \qquad (12)$$

Hybrid-π Model (Derivation of g_m and r_π)

Small-signal circuit:

$$r_\pi = \frac{dV_{BE}}{dI_B} = \frac{1}{\frac{dI_C}{\beta dV_{BE}}} \qquad (13)$$

$$= \frac{1}{\frac{g_m}{\beta}} = \frac{\beta}{g_m} \qquad (14)$$

$$g_m = \frac{dI_C}{dV_{BE}} \cong \frac{I_C}{kT/q} \qquad (15)$$
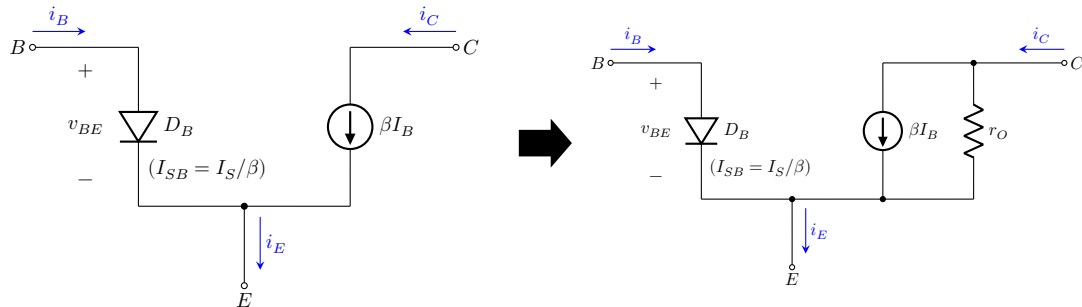
Models with the Early Effect Included

• As we see from this relationship, the collector current should change when the collector-emitter voltage changes:

$$i_C \approx I_S e^{V_{BE}/V_T} \left(1 + \frac{V_{CE}}{V_A} \right) \tag{16}$$

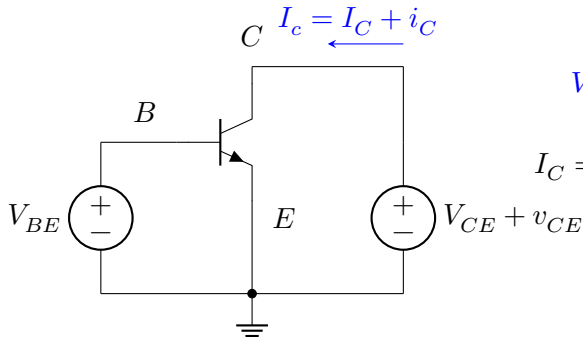• So, this effect is included in the model shown below where:

$$r_o = \frac{V_A}{I_C} = \frac{\Delta v_{CE}}{\Delta i_C} \tag{17}$$

Models with the Early Effect Included
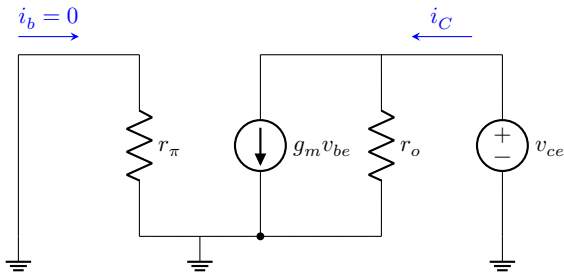
Hybrid-π Model (how to get r_o)

$V_{CE} \geq V_{BE} \Rightarrow \text{Forward}-\text{Active}$

$$I_C = I_S \left(e^{\frac{qV_{BE}}{kT}} - 1 \right) \left(1 + \frac{V_{CE}}{V_A} \right) \qquad (18)$$
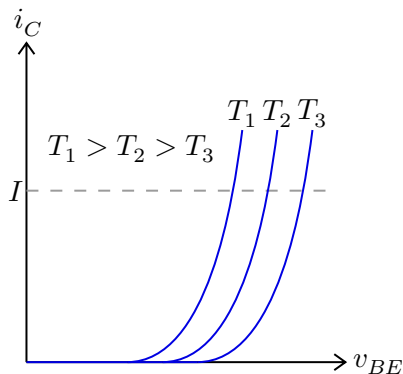
Hybrid-π Model (Derivation of r_o)

$$r_o = \frac{1}{\frac{dI_C}{dV_{CE}}} \cong \frac{V_A}{I_C} \qquad (19)$$
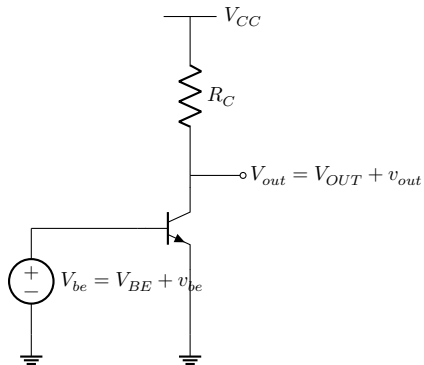
Temperature Variation

$$i_C = I_S e^{V_{BE}/V_T} \qquad (20)$$

- Both I_S and V_T are temperature dependent

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Common-Emitter Amplifier

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- Sedra 7.1,7.2.2, 7.2.3

V_{CC}

R_C

$V_{out} = V_{OUT} + v_{out}$

$V_{be} = V_{BE} + v_{be}$
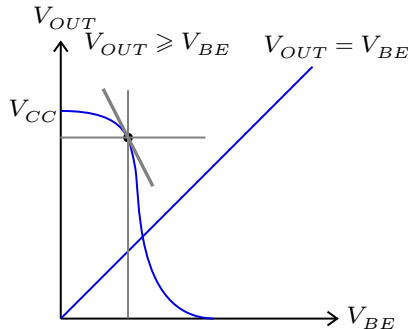
Common-Emitter Amplifier

$$V_{OUT} = V_{CC} - I_C R_C \qquad (21)$$

$$= V_{CC} - \frac{A q D_n {n_i}^2}{N_a W_B} \left(e^{\frac{q V_{BE}}{kT}} - 1 \right) R_C \qquad (22)$$

$$A_V = \frac{d V_{OUT}}{d V_{BE}} \qquad (23)$$

$$\cong -\frac{I_C}{kT/q} R_C = -g_m R_C \qquad (24)$$

Common-Emitter Amplifier
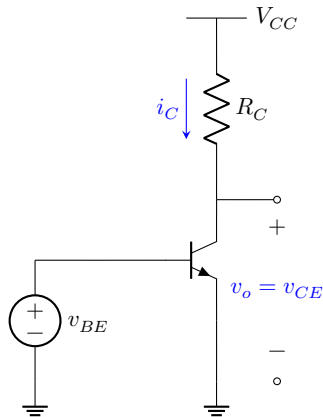
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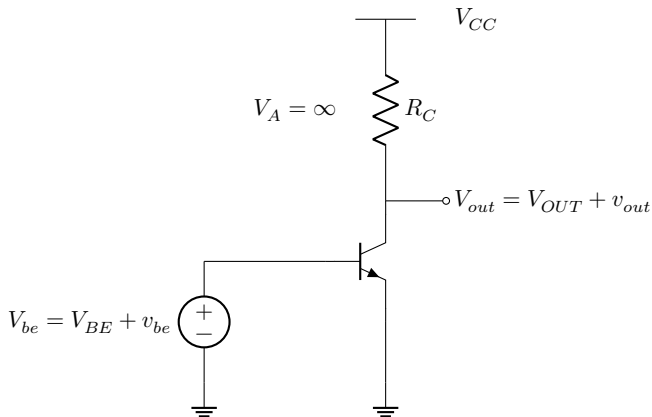SHANGHAI JIAO TONG UNIVERSITY

Gain varies a lot in the FAR region.

$$A_V = \frac{dV_o}{dV_{BE}} \qquad (25)$$
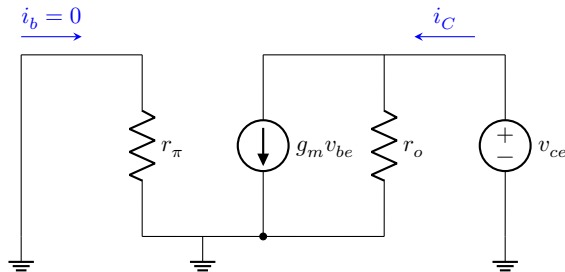
$$A_V = \frac{dV_{OUT}}{dV_{BE}} \qquad (26)$$

$$\cong -\frac{I_C}{kT/q}R_C = -g_m R_C \qquad (27)$$

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Common-Emitter Amplifier ($V_A = \infty$)
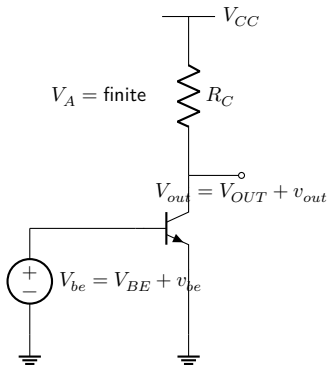
Common-Emitter Amplifier ($V_A = \infty$)

$$A_v = \frac{v_{out}}{v_{be}} = -g_m \left(R_C \parallel r_o \right) \qquad (28)$$

$$= -g_m R_C \quad (\text{since } r_o = \infty) \qquad (29)$$

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Common-Emitter Amplifier ($V_A = $ finite)

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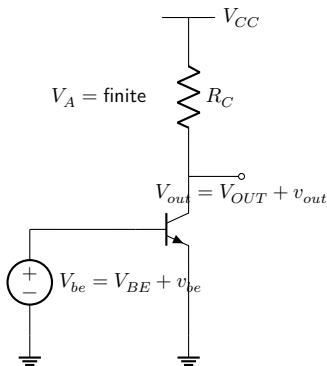SHANGHAI JIAO TONG UNIVERSITY

$$V_{OUT} = V_{CC} - I_C R_C \qquad (30)$$

$$= V_{CC} - I_S \left(e^{\frac{q V_{BE}}{kT}} - 1 \right) \left(1 + \frac{V_{OUT}}{V_A} \right) R_C \quad (31)$$

$$\frac{d V_{OUT}}{d V_{BE}} = -\frac{q}{kT} I_S e^{\frac{q V_{BE}}{kT}} \left(1 + \frac{V_{OUT}}{V_A} \right) R_C \quad (32)$$

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Common-Emitter Amplifier (V_A = finite)

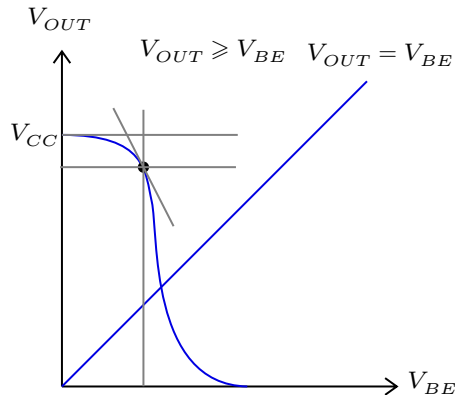$$-I_S \left(e^{\frac{qV_{BE}}{kT}} - 1 \right) \frac{1}{V_A} \frac{dV_{OUT}}{dV_{BE}} R_C \qquad (33)$$

$$\cong -g_m R_C - \frac{1}{r_o} \frac{dV_{OUT}}{dV_{BE}} R_C \qquad (34)$$

Common-Emitter Amplifier ($V_A =$ finite)

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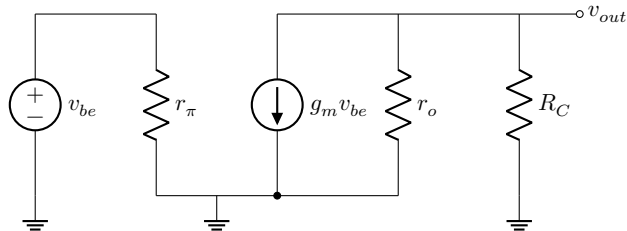
$$A_V = \frac{dV_{OUT}}{dV_{BE}} \qquad (35)$$

$$\cong g_m(R_C \parallel r_o) \qquad (36)$$

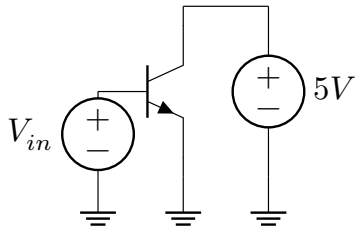# Common-Emitter Amplifier ($V_A =$ finite)

- Small-Signal Analysis

$$A_v = \frac{v_{out}}{v_{be}} = -g_m(R_C \parallel r_o) \tag{37}$$

Example 1: $I_S = 1e{-}15, \beta = 100, V_{AF} = 50$

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- What is current?
- What is small signal gain?
- What is the output if input $= 2 + 0.001\sin(2 \cdot \pi \cdot 100t)$

$$I_C = I_S \left(e^{\frac{qV_{BE}}{kT}} - 1 \right) \left(1 + \frac{V_{CE}}{V_A} \right) \quad (38)$$
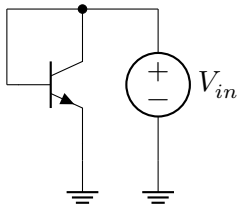
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Example 1

Example 2: $I_S = 10^{-15}, \beta = 100, V_{AF} = 50$

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Find the output if input $= 2 + 0.001 \sin(2\pi 100t)$

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Example 2