EE461g: Introduction to Electronic Circuits

Lecture 7

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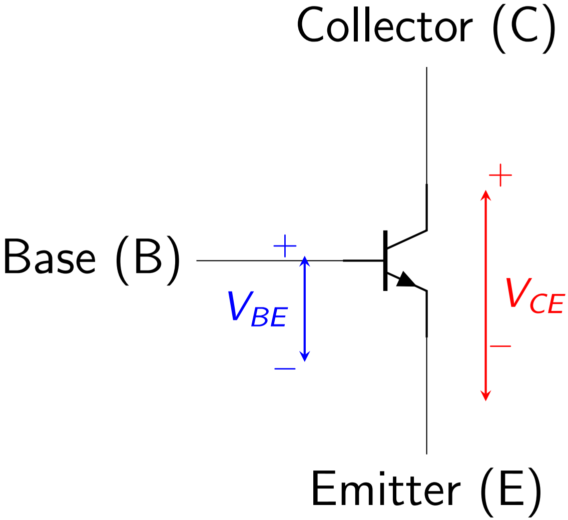
Outline

1. Bipolar Transistor Physics (Sec. 4.1–4.2)
2. BJT Output Characteristics (Sec. 4.3)
3. Common Emitter Amplifier (Sec. 4.4)
4. Operating Regions and Load Line
5. Concept of Transconductance (Sec. 4.4.3)
6. Small-Signal Model (Sec. 4.4.4)

NPN Bipolar Junction Transistor (BJT)



Before continuing with the bipolar transistor, it is instructive to study an interesting effect in *pn* junctions. Consider the reverse-biased junction depicted in Fig. 4.5(a) and recall from Chapter 2 that the depletion region sustains a strong electric field. Now suppose an electron is somehow "injected" from outside into the right side of the depletion region. What happens to this electron? Serving as a minority carrier on the *p* side, the electron experiences the electric field and is rapidly swept away into the *n* side. The ability of a reverse-biased *pn* junction to efficiently "collect" externally-injected electrons proves essential to the operation of the bipolar transistor.

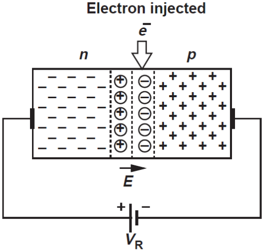


Figure 4.5 Injection of electrons into depletion region.

Source: B. Razavi, *Design of Analog CMOS Integrated Circuits*, 2nd ed., McGraw-Hill, 2017.

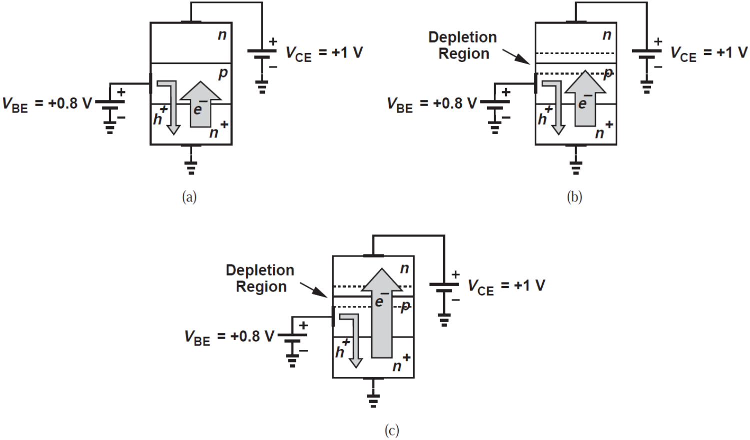
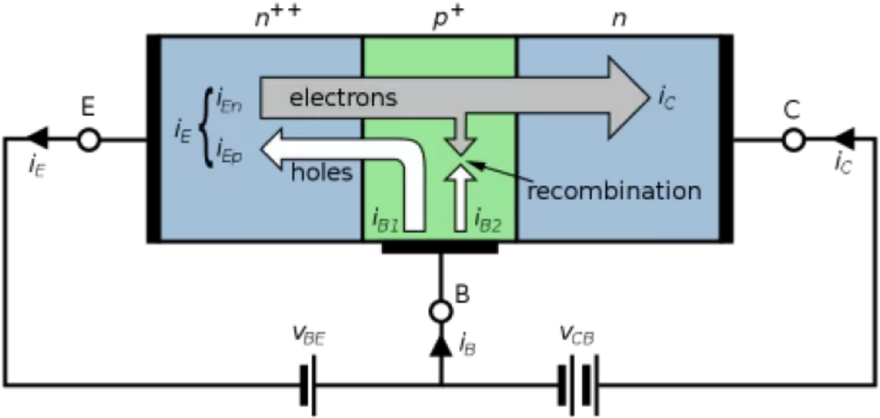


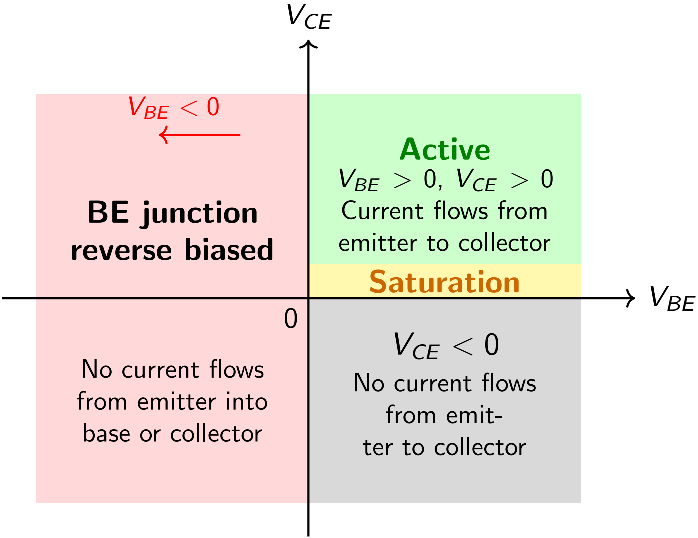
Figure 4.7 (a) Flow of electrons and holes through base-emitter junction, (b) electrons approaching collector junction, (c) electrons passing through collector junction.

Source: B. Razavi, *Design of Analog CMOS Integrated Circuits*, 2nd ed., McGraw-Hill, 2017.

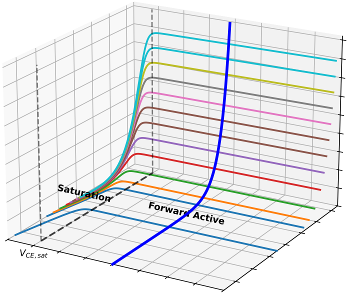


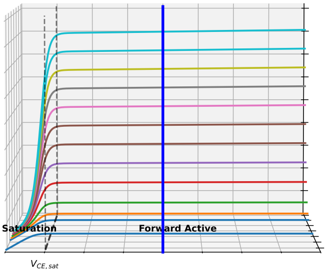
Source: https://www.emcourse.com/news-blog/bipolar-junction-transistors-what-are-they-what-do-they-do

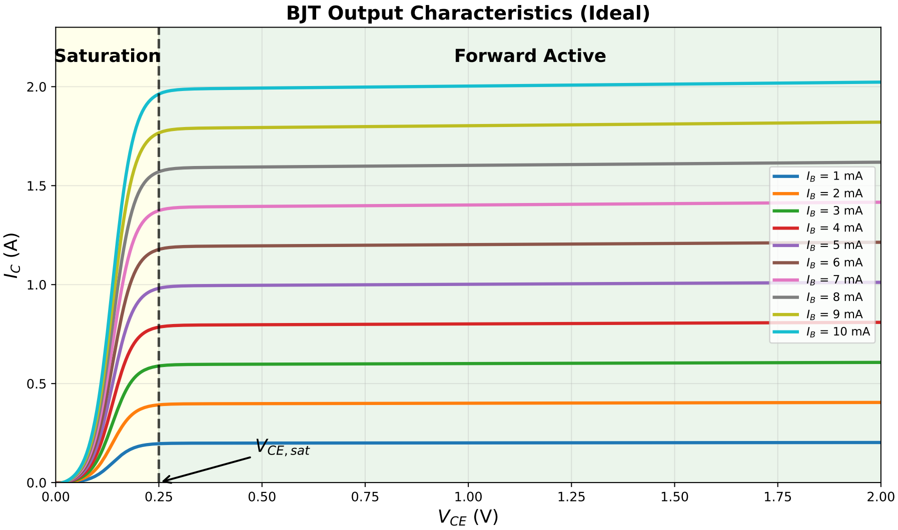
BJT Operating Space: V_{BE} vs V_{CE}



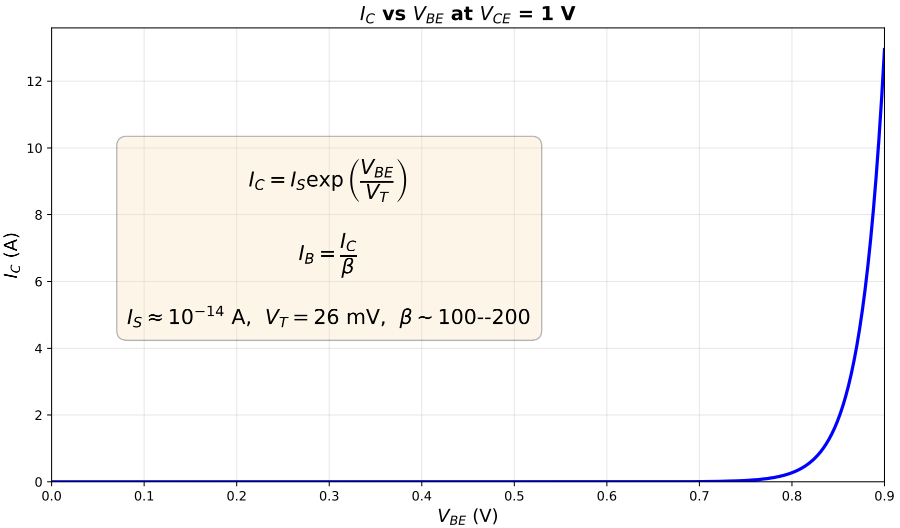
BJT Output Characteristics – Ideal



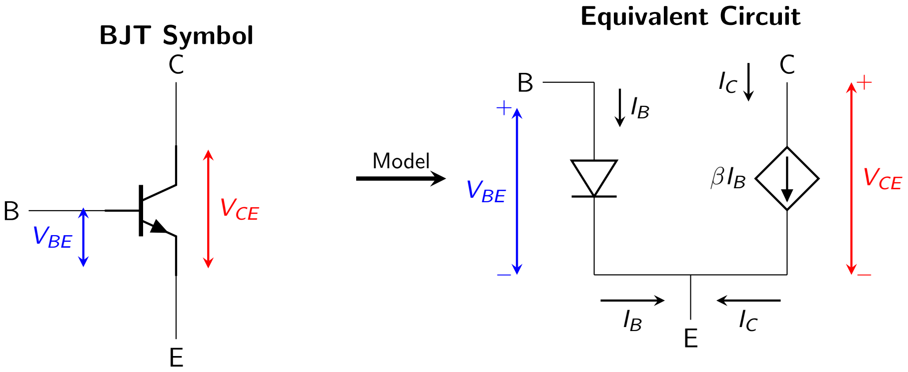



BJT Output Characteristics (Ideal)
Saturation
Forward Active
$V_{CE,sat}$
I_B = 1 mA
I_B = 2 mA
I_B = 3 mA
I_B = 4 mA
I_B = 5 mA
I_B = 6 mA
I_B = 7 mA
I_B = 8 mA
I_B = 9 mA
I_B = 10 mA
I_C (A)
V_{CE} (V)
0.0
0.5
1.0
1.5
2.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

I_C vs V_{BE} at $V_{CE} = 1$ V

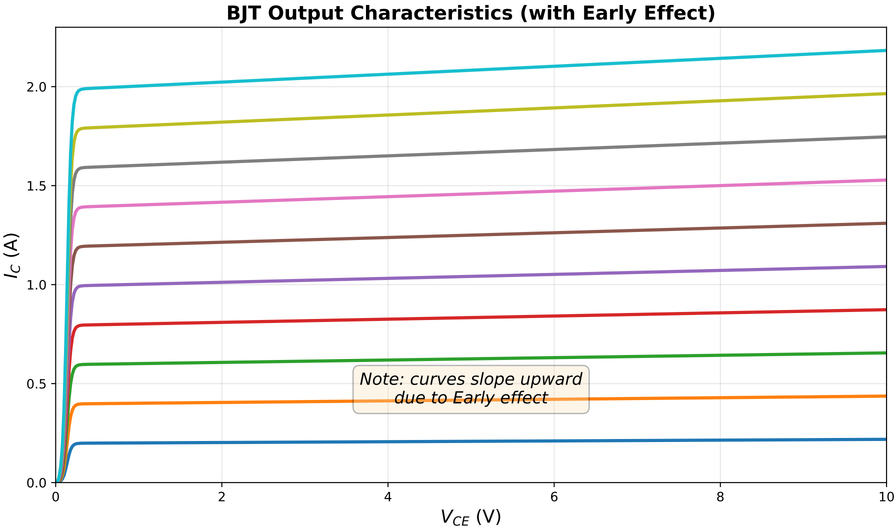


NPN BJT Large-Signal Model

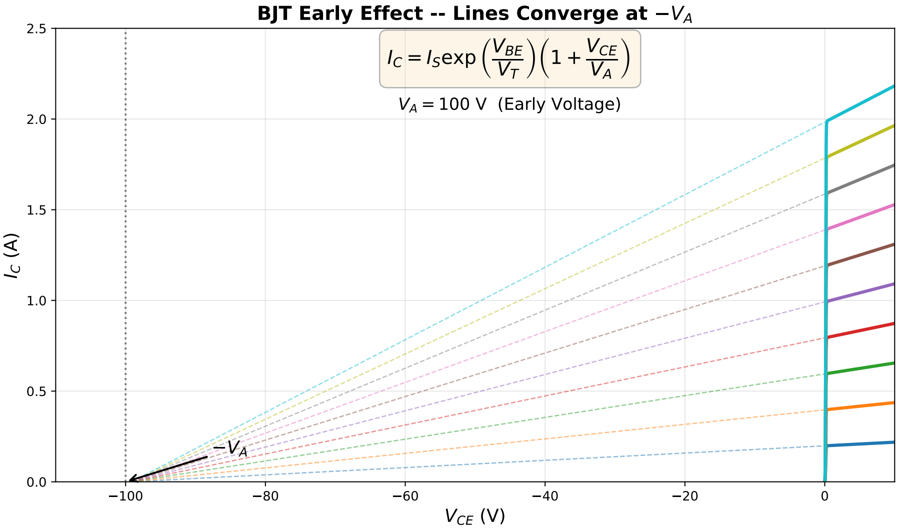


$$I_E = I_B + I_C$$

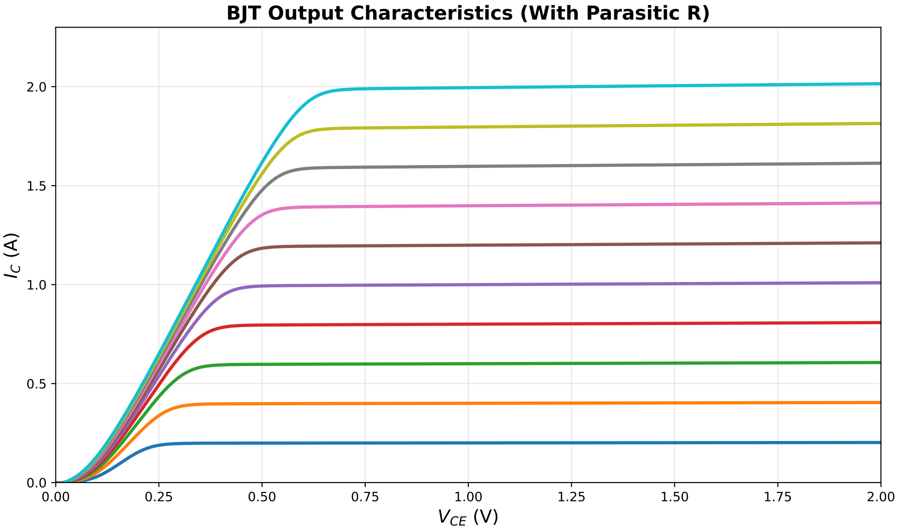
BJT Output Characteristics (with Early Effect)



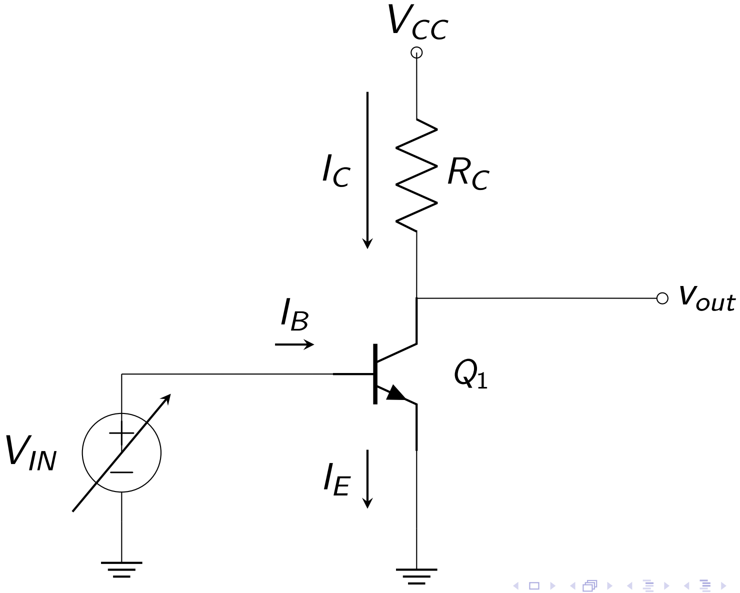
BJT Early Effect – Lines Converge at $-V_A$



BJT Output Characteristics – With Parasitic R

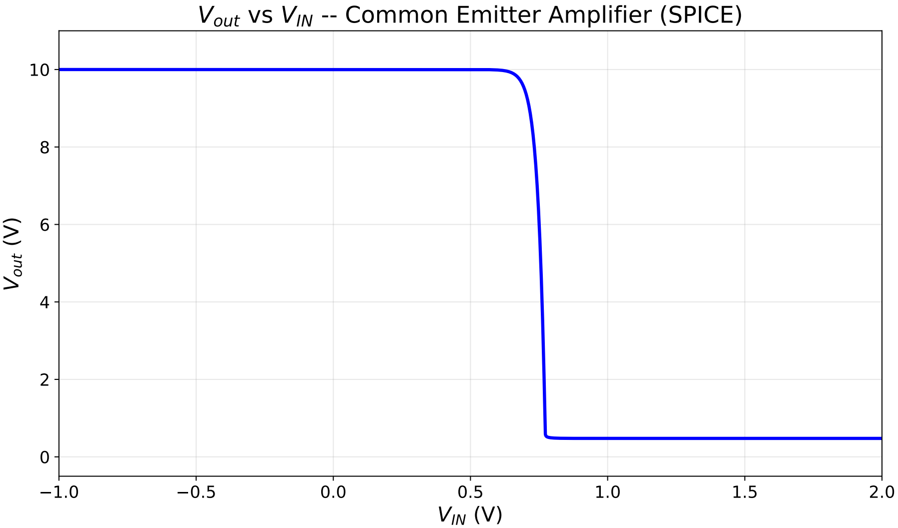


Common Emitter Amplifier



Common Emitter Amplifier – SPICE Simulation

$V_{CC} = 10$ V $\qquad R_C = 100\ \Omega \qquad \beta = 100$



Understanding the V_{out} vs V_{IN} Shape

- From the large-signal model and I_C vs V_{BE} relationship:

$$\boxed{V_{out} = V_{CC} - R_C\, I_C} \qquad \boxed{I_C = I_S\, e^{V_{BE}/V_T}}$$

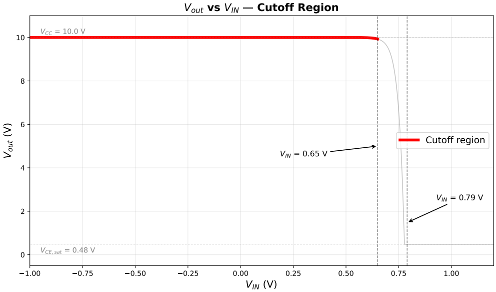
- Since the emitter is grounded: $V_{BE} = V_{IN}$
- As V_{IN} increases, I_C grows exponentially
- V_{out} drops from V_{CC} until the transistor saturates at $V_{CE,sat}$

$$V_{CC} = 10\ \text{V} \qquad R_C = 100\ \Omega \qquad \beta = 100$$

Cutoff Region

- $V_{IN} <\sim 0.65$ V
- V_{BE} too small to turn on the BJT
- $I_C \approx 0$
- $V_{out} = V_{CC} - R_C \cdot 0 = V_{CC}$

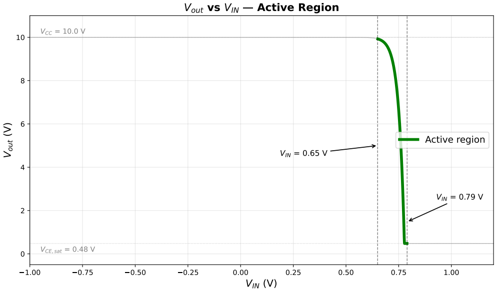
Output stays flat at V_{CC}
(transistor is OFF)



Active (Forward-Active) Region

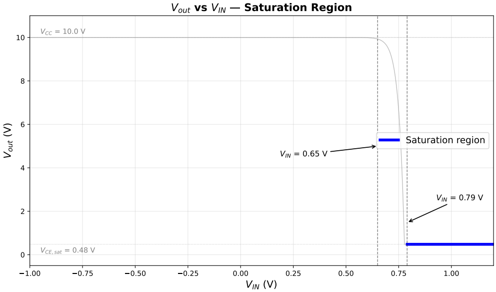
- $V_{IN} \approx 0.65$ V to 0.79 V
- V_{BE} crosses threshold $\Rightarrow I_C$ rises exponentially
- $V_{out} = V_{CC} - R_C I_C$ drops rapidly

Output drops steeply
(high voltage gain region)



Saturation Region

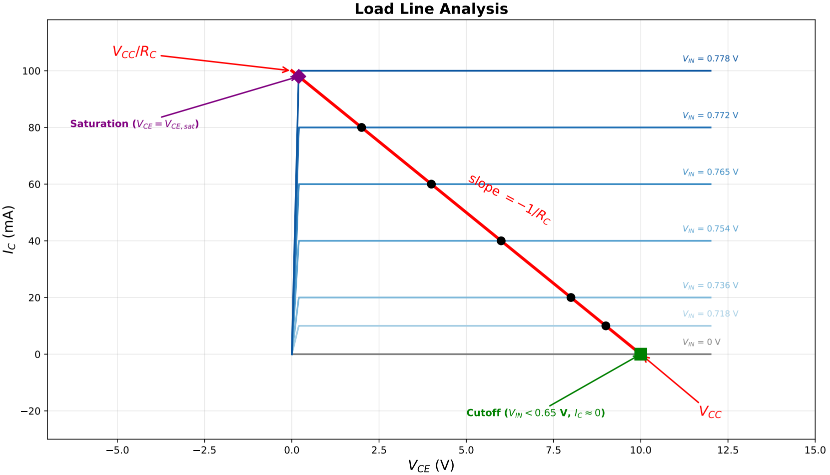
- $V_{IN} >\sim 0.79$ V
- V_{CE} reaches $V_{CE,sat} \approx 0.48$ V
- Collector–base junction forward biases
- I_C can no longer increase freely
- As $V_{IN} \to \infty$, $V_{out} \to V_{CE,sat} \approx 0$ V



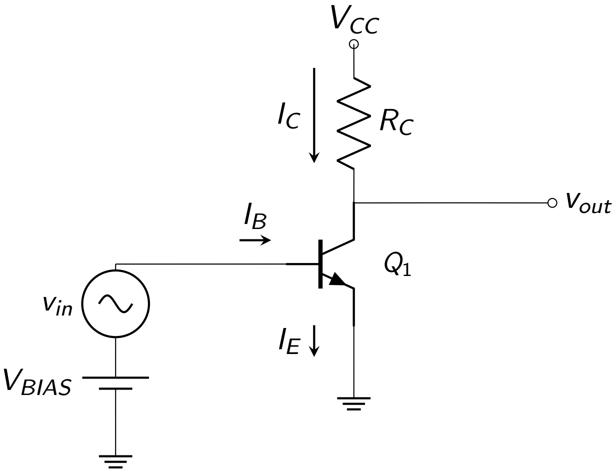
Output levels off at $V_{CE,sat}$ (transistor is fully ON)

Load Line Analysis

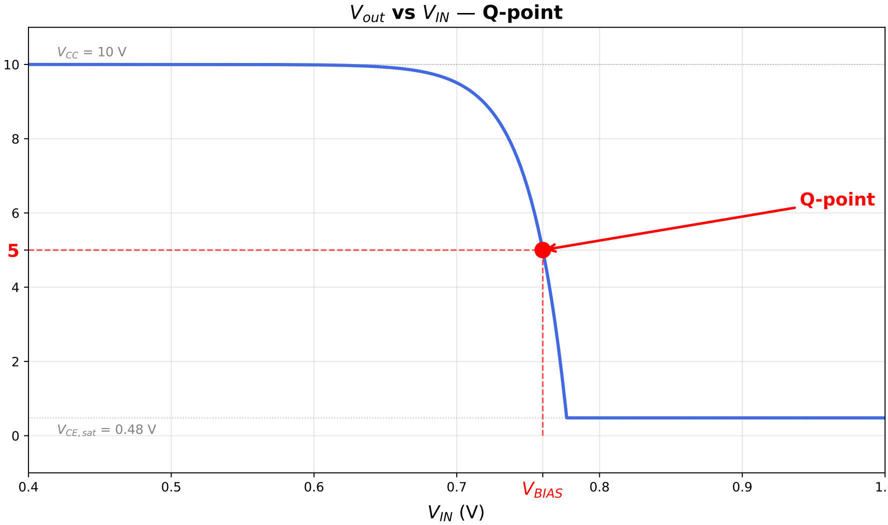
Load line equation: $$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$



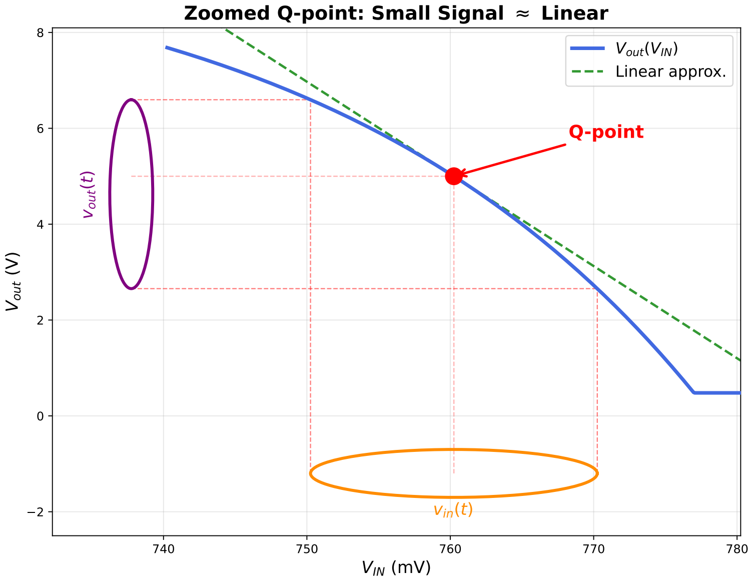
Common Emitter Amplifier with Small-Signal Input



V_{out} vs V_{IN} — Choosing a Q-point



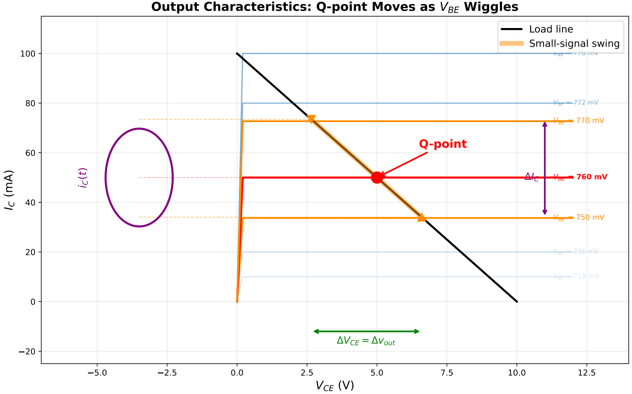
Zoomed Q-point: Small Signal ≈ Linear



What Happens on the Output Characteristics?

$$\boxed{V_{out} = V_{CC} - R_C\, I_C} \qquad \boxed{I_C = I_S\, e^{V_{BE}/V_T}}$$

As V_{BE} wiggles around V_{BIAS}, I_C changes $\Rightarrow$ Q-point slides along the load line:



From Exponential to Linear: Transconductance g_m

Recall Lecture 1: for the square-law device we linearized I vs V and got a small-signal **resistance** r.

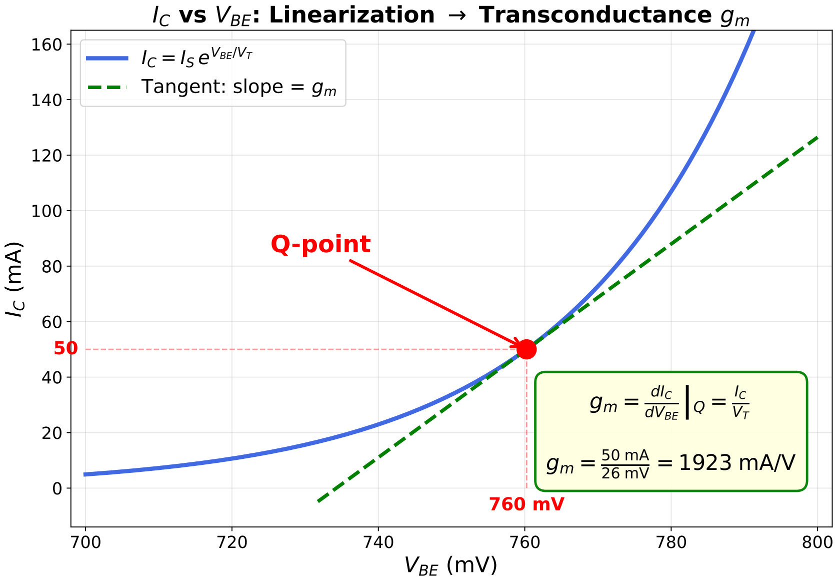
Here: we linearize I_C vs V_{BE}. The slope has units of current / voltage — a **conductance**:

$$\boxed{g_m = \left.\frac{dI_C}{dV_{BE}}\right|_Q = \frac{I_C}{V_T}}$$

We call g_m the **transconductance** because the input voltage (V_{BE}) controls the output current (I_C) — they are at different ports.

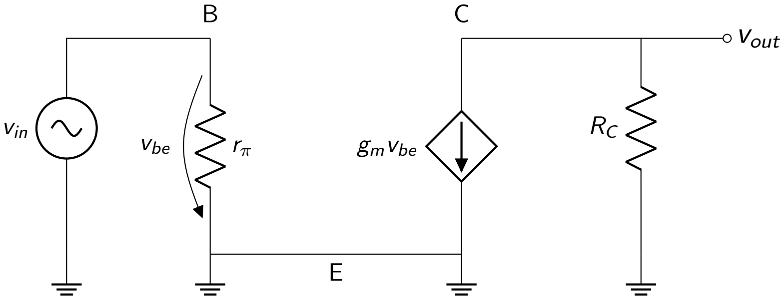
g_m tells us: *how much does I_C change for a small change in V_{BE}?*

I_C vs V_{BE}: Linearization at the Q-point



Small-Signal Equivalent Circuit

Short all DC sources ($V_{BIAS} \rightarrow$ short, $V_{CC} \rightarrow$ short) and replace BJT with small-signal model:



$v_{be} = v_{in}$ $\qquad$ $v_{out} = -g_m\, v_{be} \cdot R_C$

$$A_v = \frac{v_{out}}{v_{in}} = -g_m R_C$$

Early Effect $\Rightarrow$ Output Resistance r_o

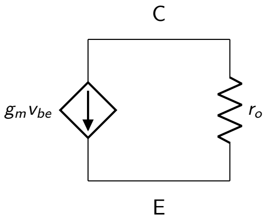
Recall from Lecture 7: with the Early effect, I_C depends on V_{CE}:

$$I_C = I_S\, e^{V_{BE}/V_T} \left(1 + \frac{V_{CE}}{V_A}\right)$$

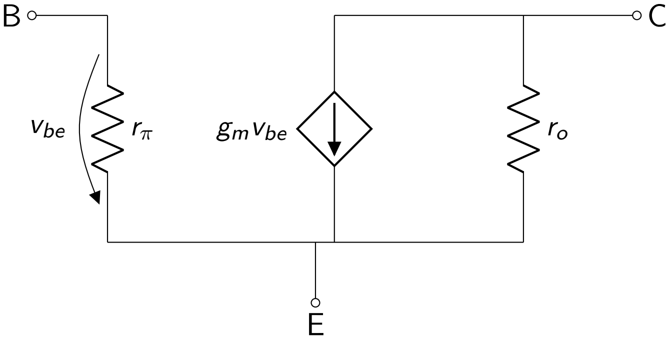
The output characteristics are **not perfectly flat** — I_C increases slightly with V_{CE}. This slope is a **conductance** between C and E:

$$\left.\frac{\partial I_C}{\partial V_{CE}}\right|_Q = \frac{I_C}{V_A} \qquad \Longrightarrow \qquad \boxed{r_o = \frac{V_A}{I_C}}$$

Physical meaning: wiggling V_{CE} by a small amount changes I_C a little. This behaves like a **resistor** r_o in parallel with the current source $g_m v_{be}$.



Complete Small-Signal Model of the BJT



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

$$r_\pi = \frac{\beta}{g_m} = \frac{\beta\, V_T}{I_C}$$

$$r_o = \frac{V_A}{I_C}$$