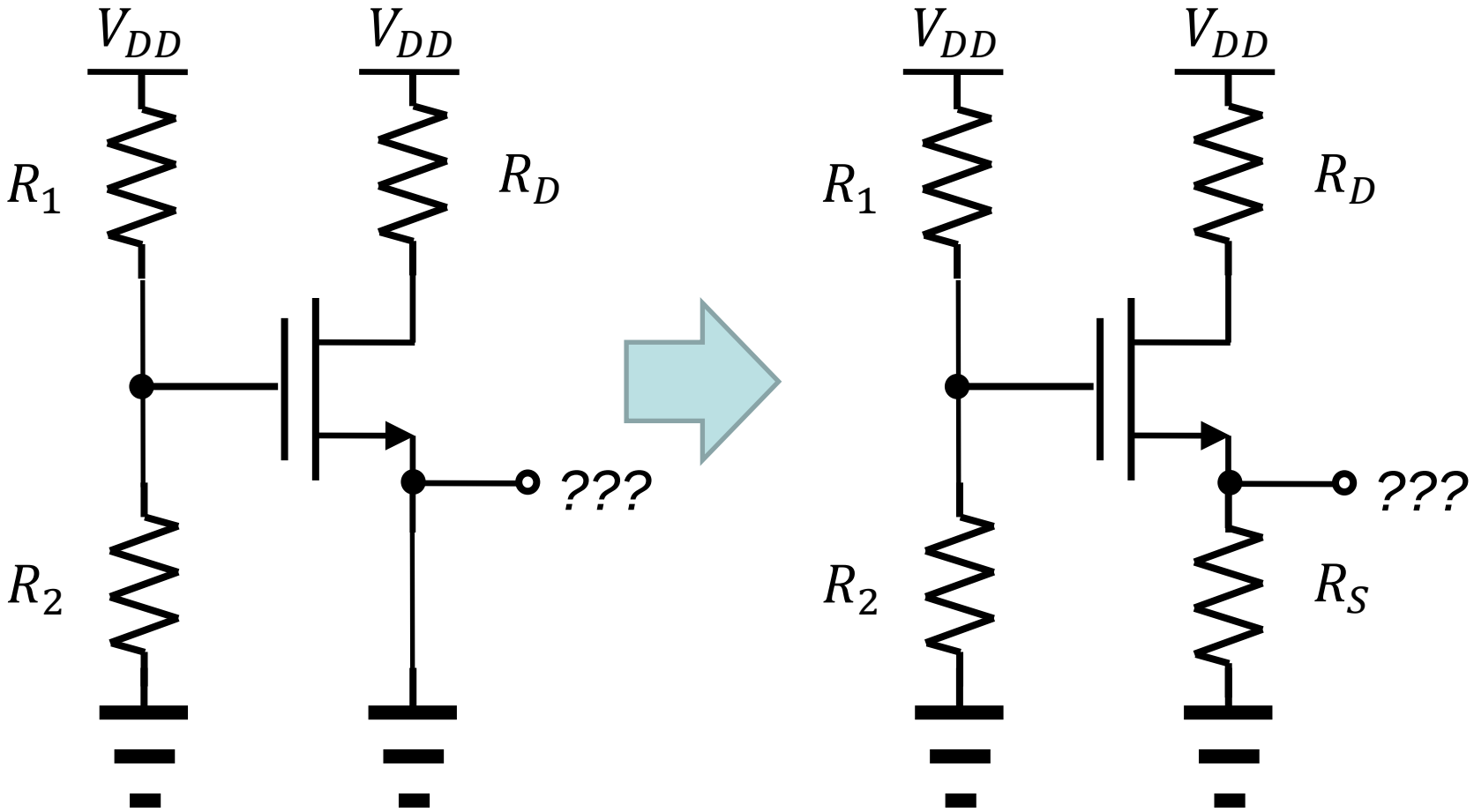
Homework#7 – The last one

- Razavi, 2nd edition (international)
  - Device parameters in p. 796
  - 1) P17.4
  - 2) G-SPICE excercise of P17.4
  - 3) P17.20 (Assume that the gate of M1 is also biased at 1 V.)
  - 4) G-SPICE exercise of P17.20
  - 5) P17.25
  - 6) P17.38
  - 7) P17.43
  - 8) P17.50

  - Due: Next Wednesday (Not Monday)

Source degeneration (1/2)

- A resistor placed in series with the source terminal



Source degeneration (2/2)

- Now we have to find the source voltage.
  - (Saturation current of the MOSFET) = (Current flowing through R_S)
  - After a simple manipulation, we can find

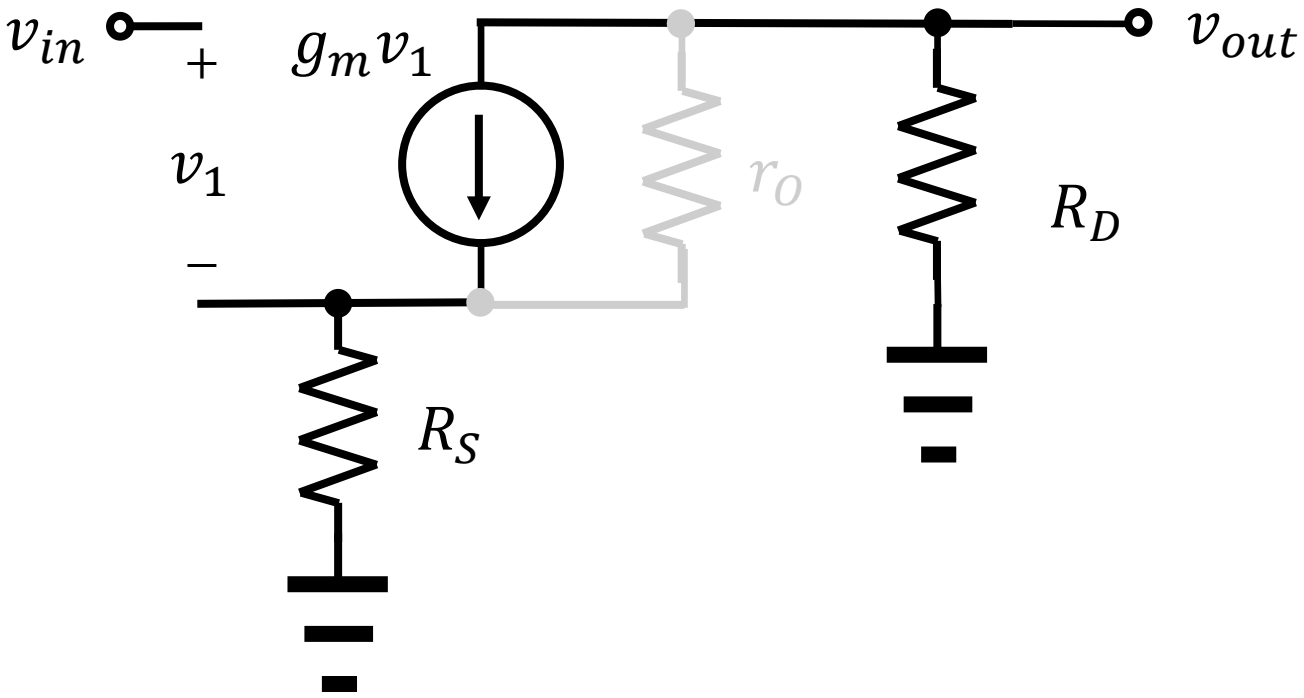
$$V_S = V_G + V_1 - V_{TH} - \sqrt{V_1^2 + 2(V_G - V_{TH})V_1}$$

  - Here,

$$V_1 = \frac{1}{\mu_n C_{ox} \frac{W}{L} R_s}$$

Effect of R_S (1/2)

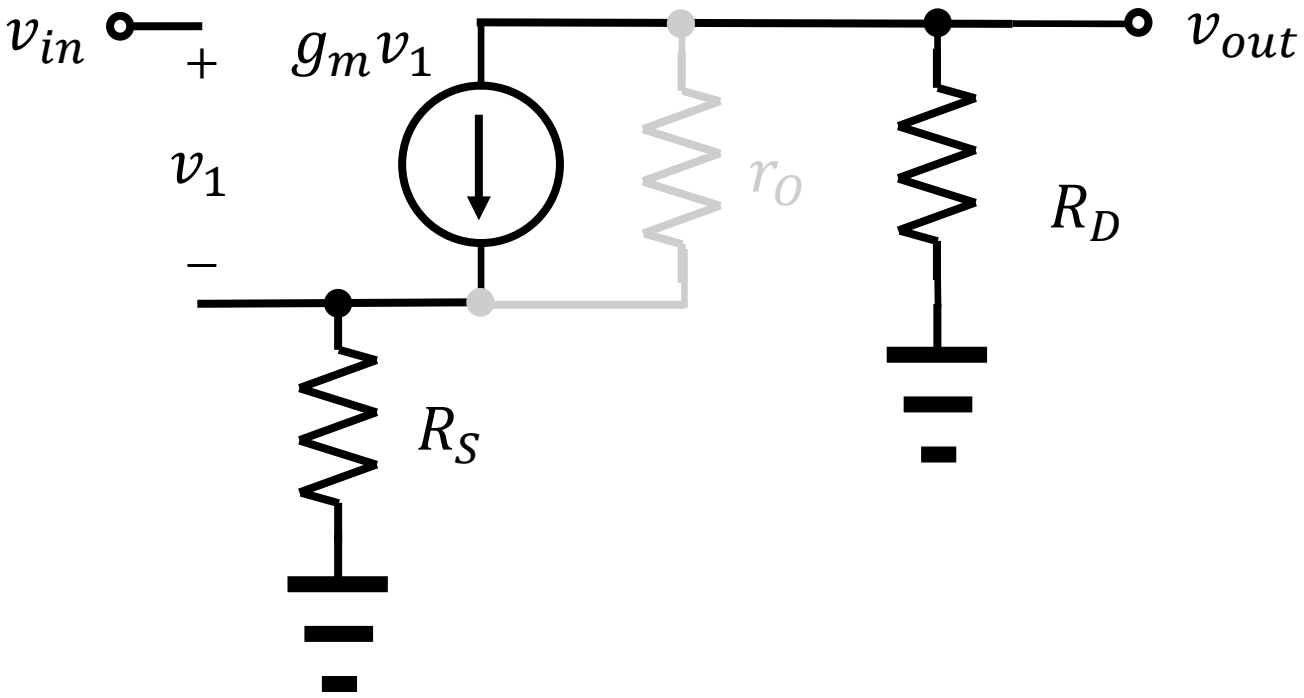
- Reduction of the gate-source voltage
  - Therefore, also reduction of the gain.
- For a while, neglect the channel-length modulation.



Effect of R_S (2/2)

- After a simple manipulation,

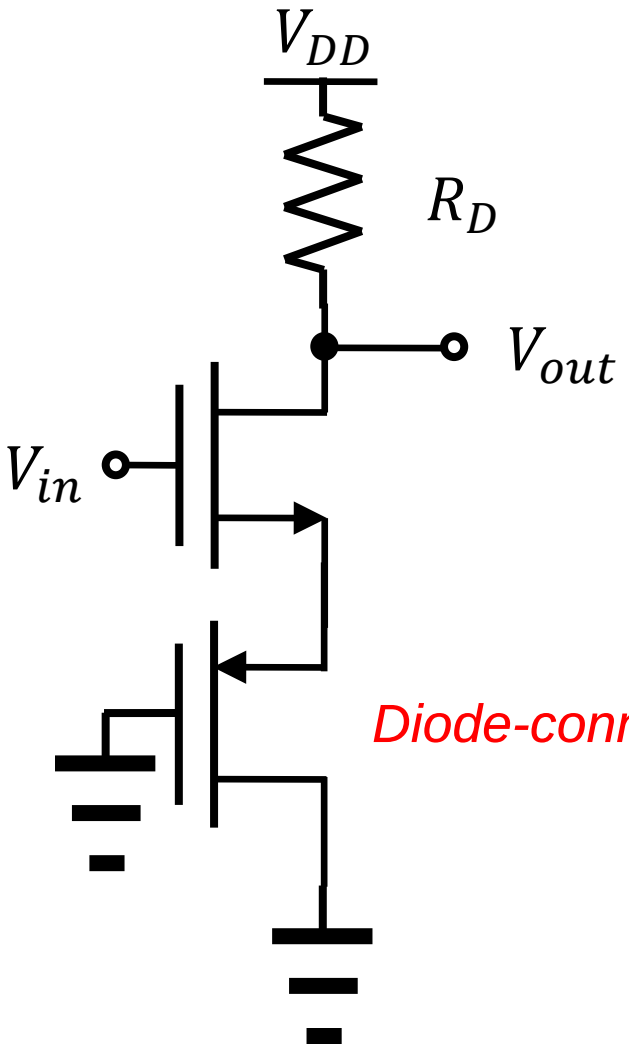
$$A_v = -\frac{g_m R_D}{1 + g_m R_S}$$



Example 17.20

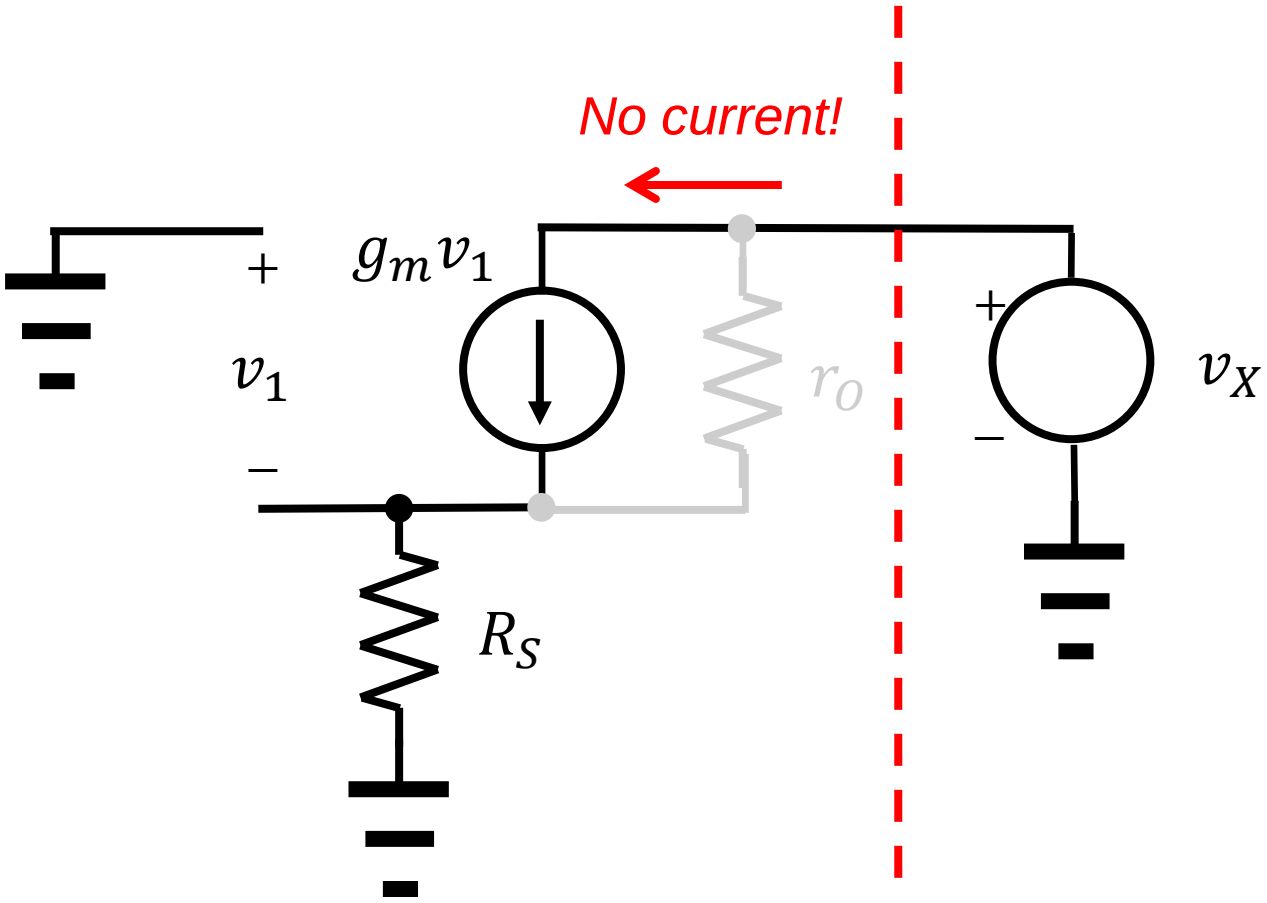
- CS with degeneration

$$A_v = -\frac{R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}}$$



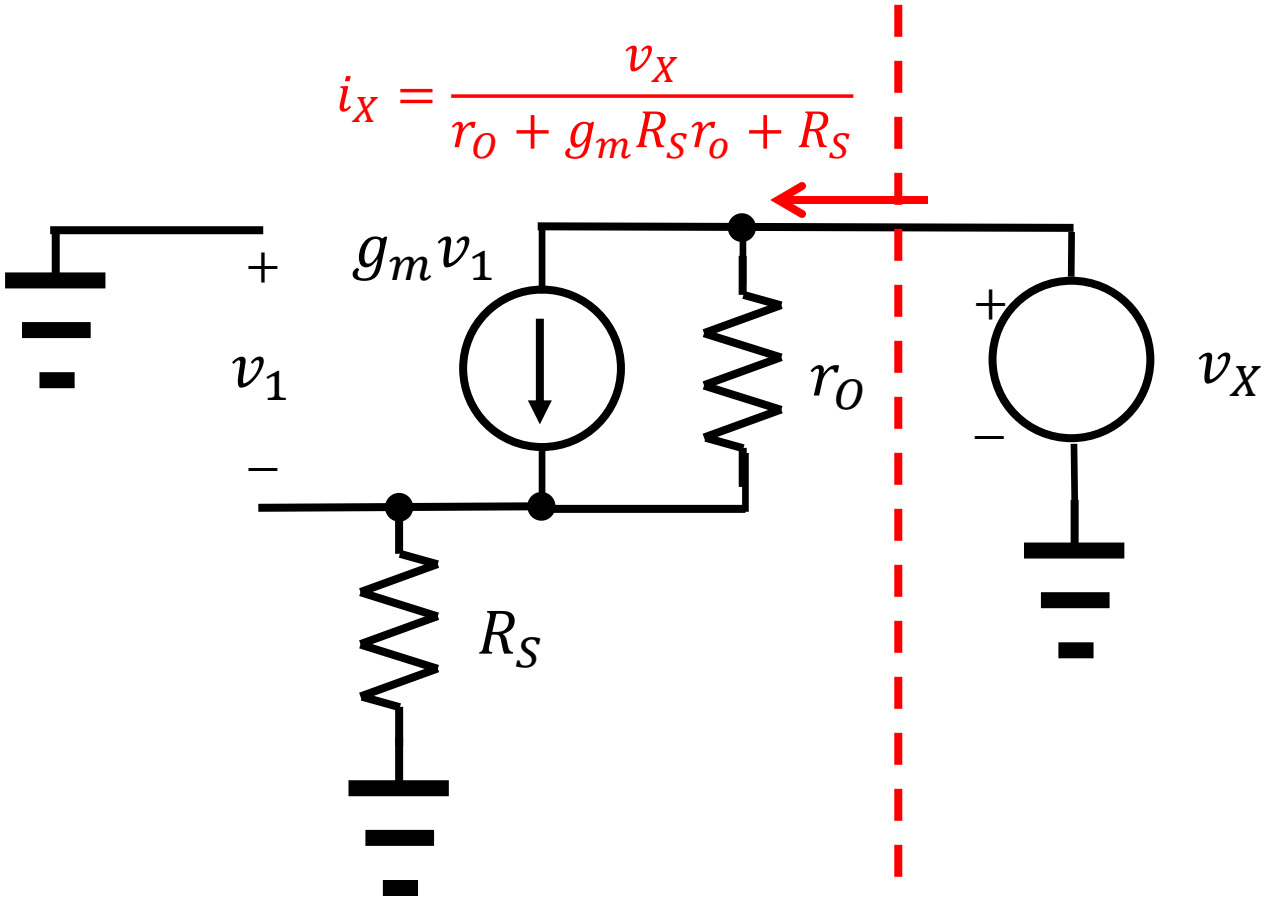
Output impedance of CS (1/2)

- Still neglecting the channel-length modulation
  - No current!



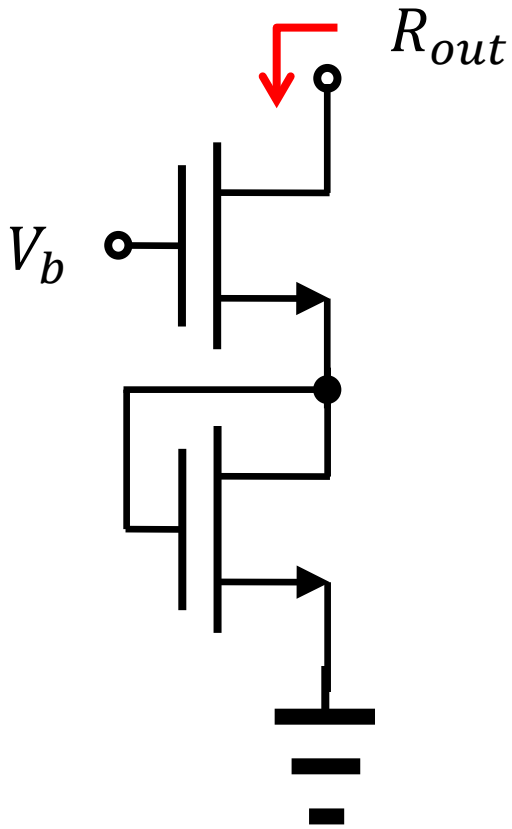
Output impedance of CS (2/2)

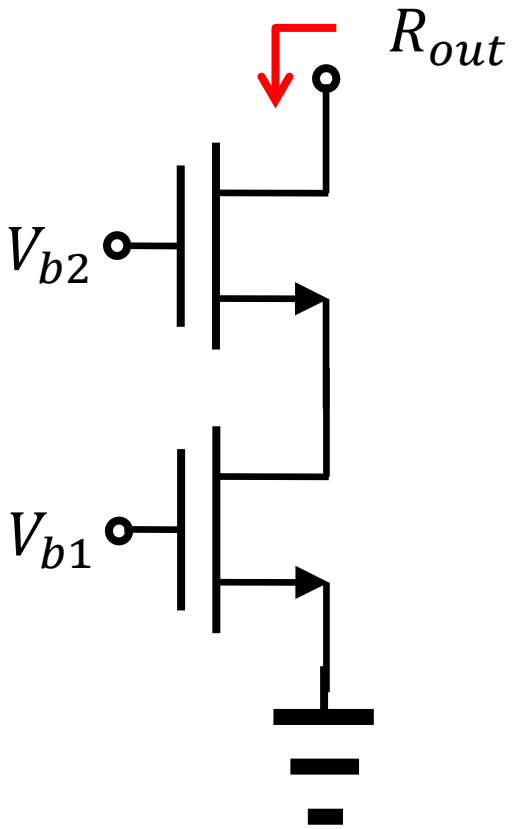
- Now considering the channel-length modulation
  - Output resistance is $r_O + (g_m r_O + 1)R_S$.



Examples 17.23 and 17.24

- Compute the output resistance.
  - What is the difference?





Lecture23:
Bipolar junction transistors

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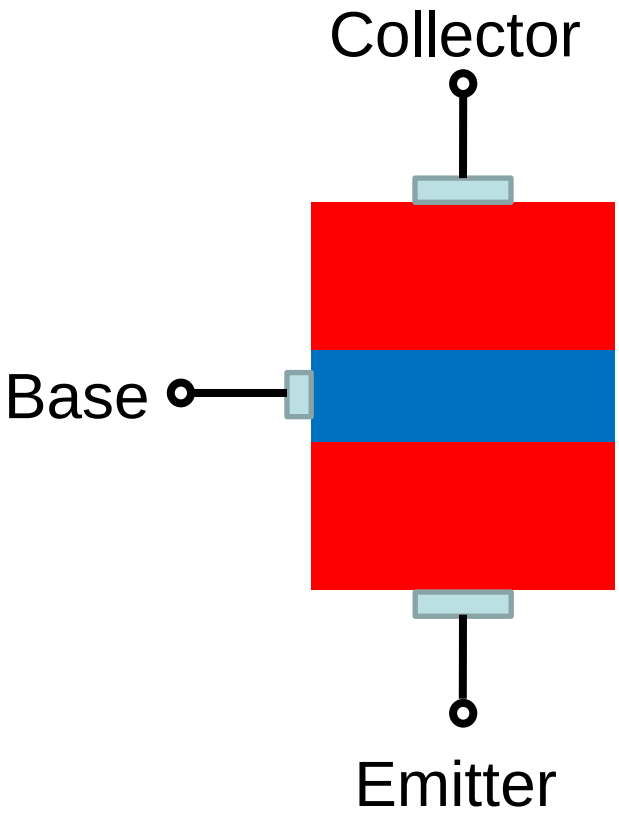
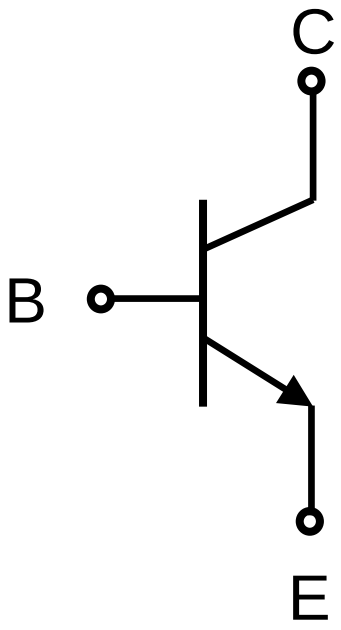
Bipolar transistor

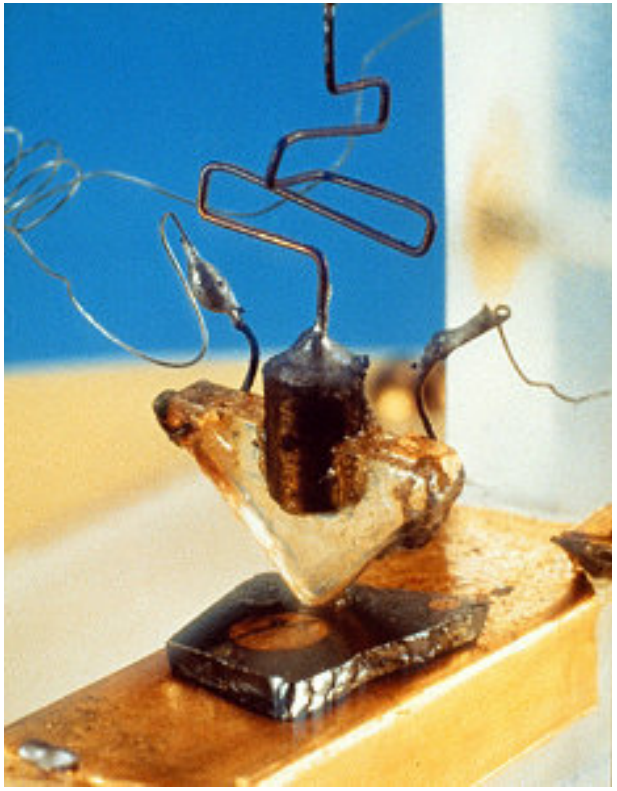
- Bipolar junction transistor (BJT)
  - Three doped regions forming a sandwich





The first transistor

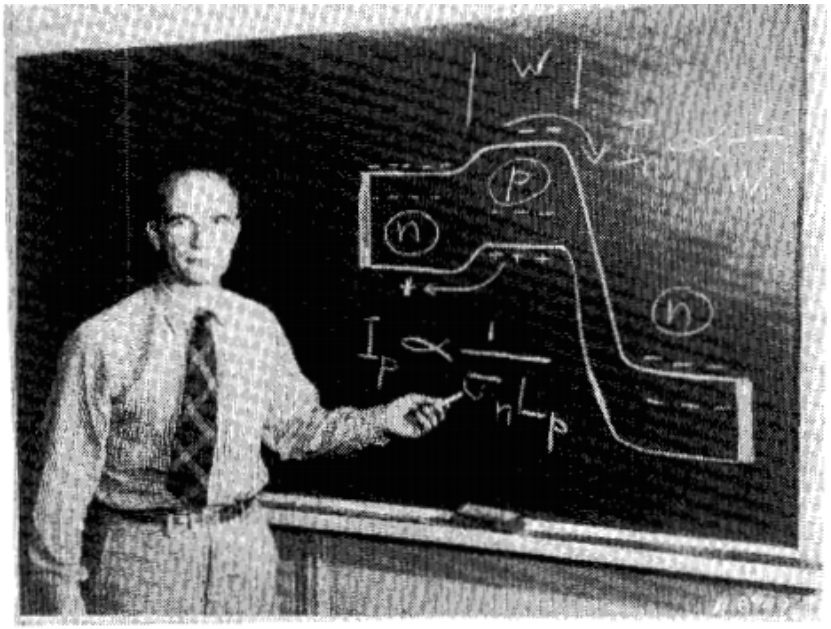
- Invented in 1947 by Shockley, Barttain, and Bardeen
  - To be specific, on December 16, 1947
  - Demonstrated to executives, on December 23, 1947
  - (Not 1945!)



Replica of the first transistor, the point-contact transistor (Google images)

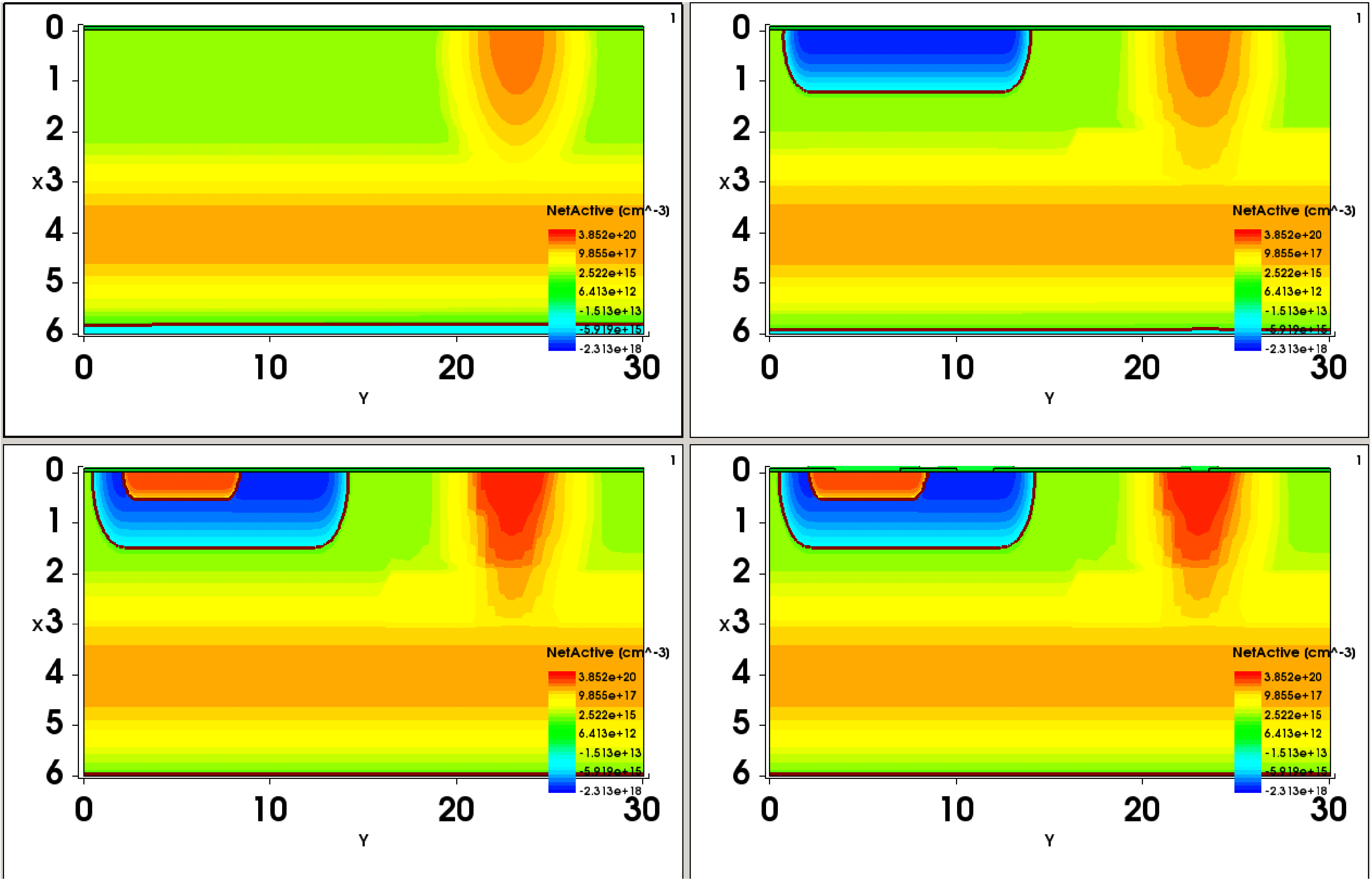
Three key concepts of BJT

- Emphasized by the inventor of the junction transistor
  - 1) Minority carrier injection into the base layer which increases exponentially with forward emitter bias
  - 2) Application of reverse voltage at the collector junction
  - 3) Favorable geometry and doping levels so as to obtain good emitter to collector efficiency



William Shockley, the inventor of the BJT
(IEEE TED, vol. 23, p. 597, 1976)

How to fabricate it



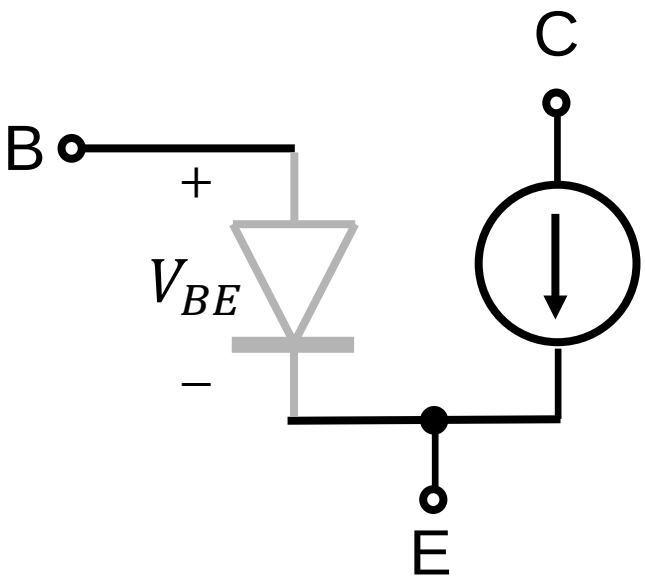
CMOS versus BJT

- Why do we still study the BJT? (Taken from Sedra and Smith)
  - The MOSFET is undoubtedly the most widely used electronic device.
  - CMOS technology is the technology of choice in the design of integrated circuits.
  - The BJT remains a significant device that excels in certain applications.
  - For instance, the reliability of BJT circuits under severe environmental conditions makes them the dominant device in certain automotive applications.
  - The BJT is the preferred device in very-high-frequency applications.
  - Finally, the BJT can be combined with MOSFETs. (BiCMOS)

We will show that…

- (a) The current flow from the emitter to the collector can be viewed as a current source tied between these two terminals.
- (b) This current is controlled by the voltage difference between the base and the emitter.

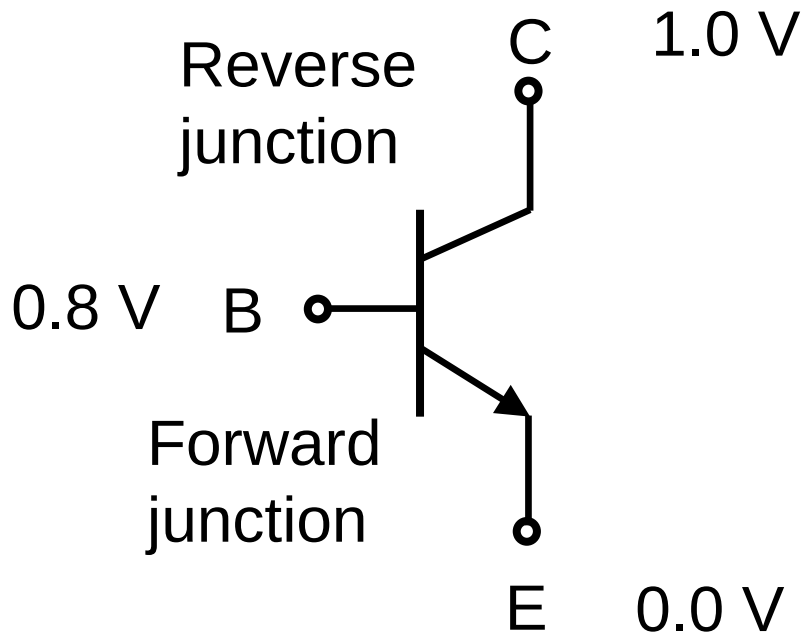
- In other words,
  - A voltage-controlled current source!



Assumption

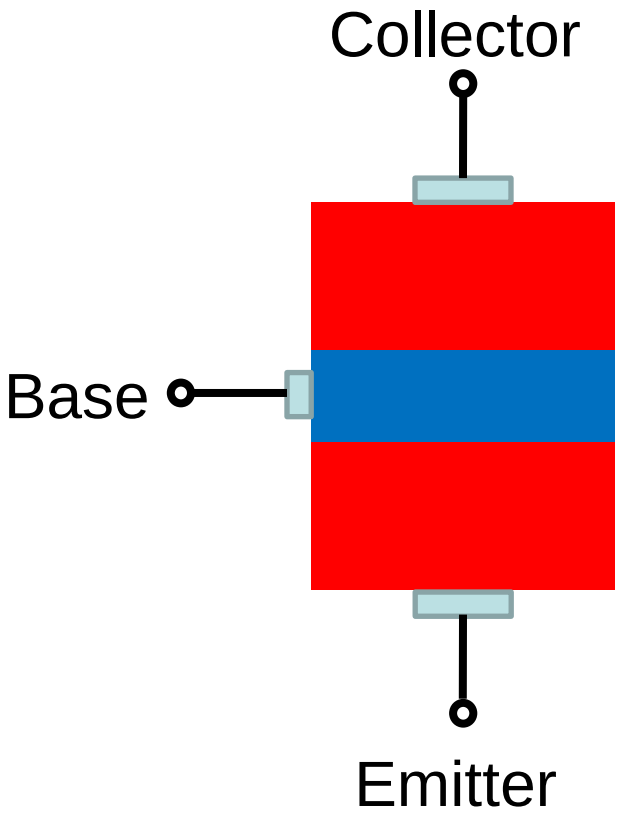
- Forward active region
  - Positive V_{BE}
  - Negative V_{BC}

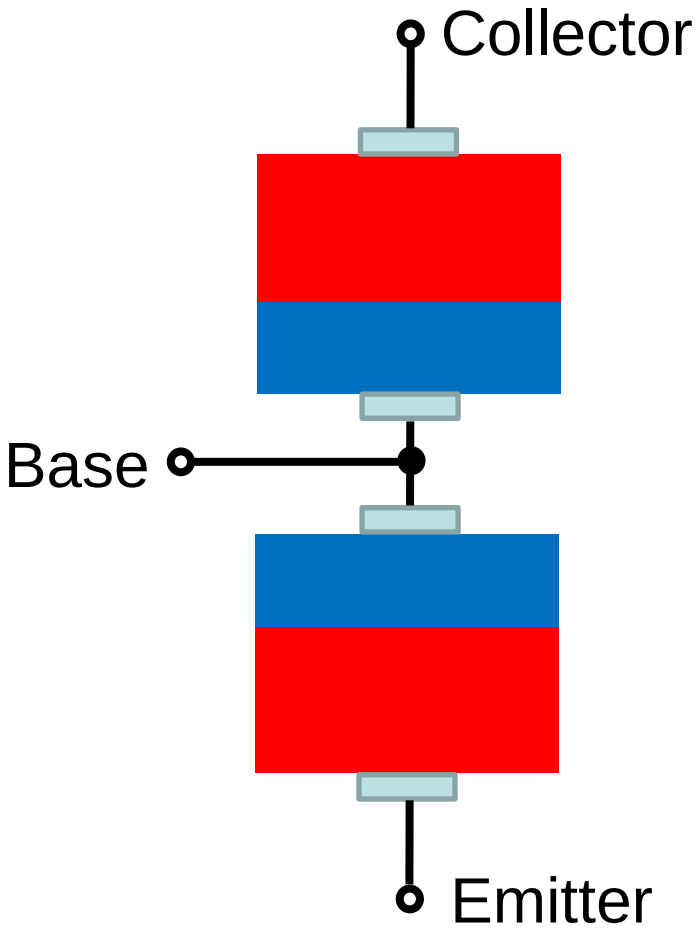
  - For example, in the figure,
$V_{BE} = 0.8\ \mathrm{V}$
$V_{BC} = -0.2\ \mathrm{V}$



Linux is not Unix.

- A bipolar transistor is not two connected diodes.
  - Positive





Analogy

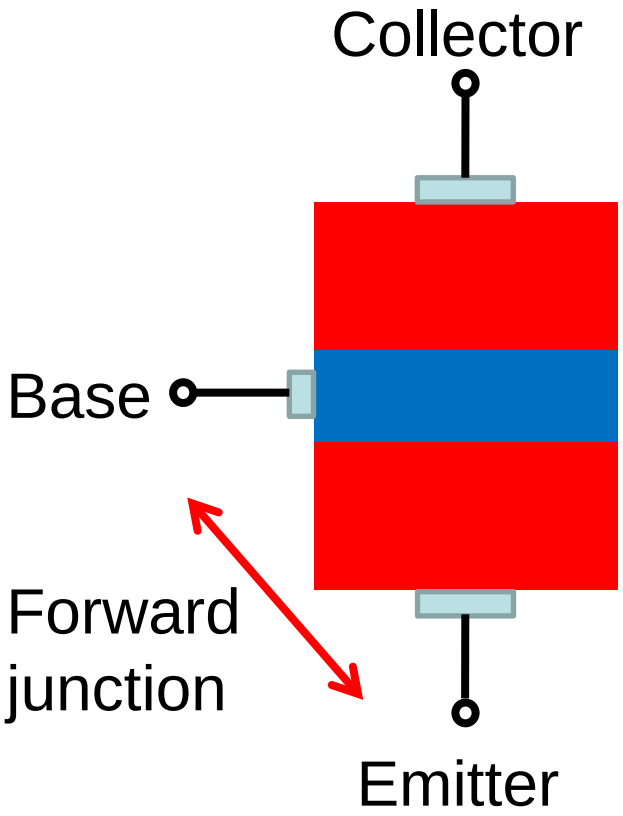
- A cliff
  - Potential barrier seen by electrons

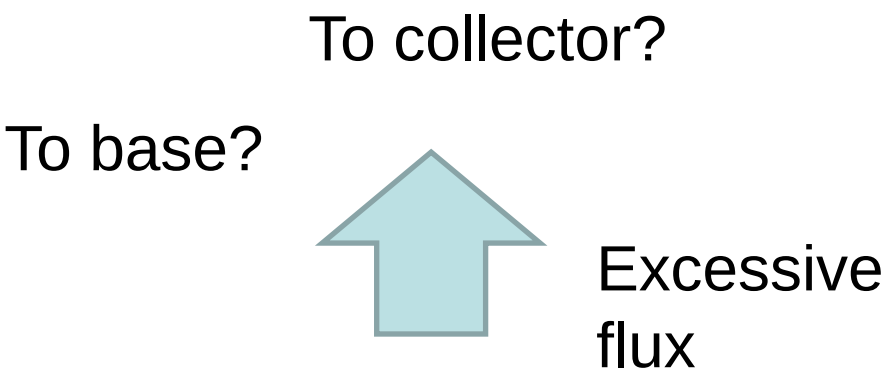
- Two ways on top
  - Narrow path (to base)
  - Broad path (to collector)

(Both taken from Google images)

Electron flux

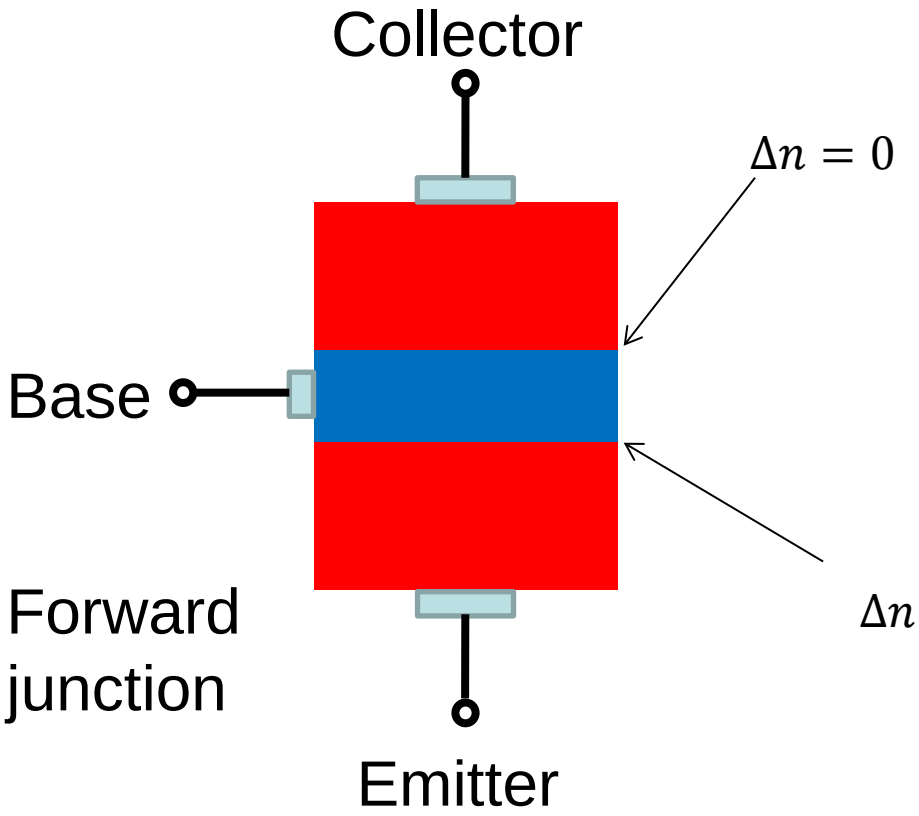
- First, consider the electron flux.
  - There will be the flux generated by a positive V_{BE}.





Collector current

- Calculate it using the diffusion current.



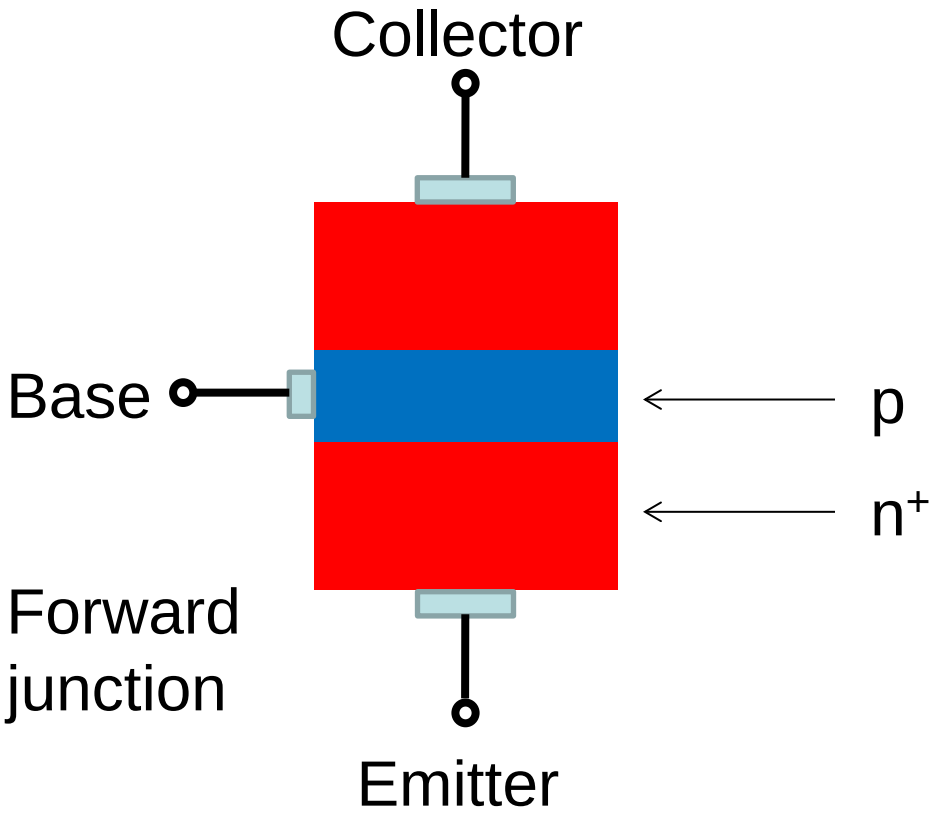
$$J_n = qD_n \frac{dn}{dx}$$

$$I_C = \frac{A_E q D_n n_i^2}{N_B W_B}\left(\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right)$$

Check your (4.5)!

Base current

- Hole flux of the base-emitter junction
  - Doping levels, diffusion constants, diffusion lengths



$$I_C = \beta I_B$$

Gummel plot

- IV curves for the BJT
  - Collector and base currents

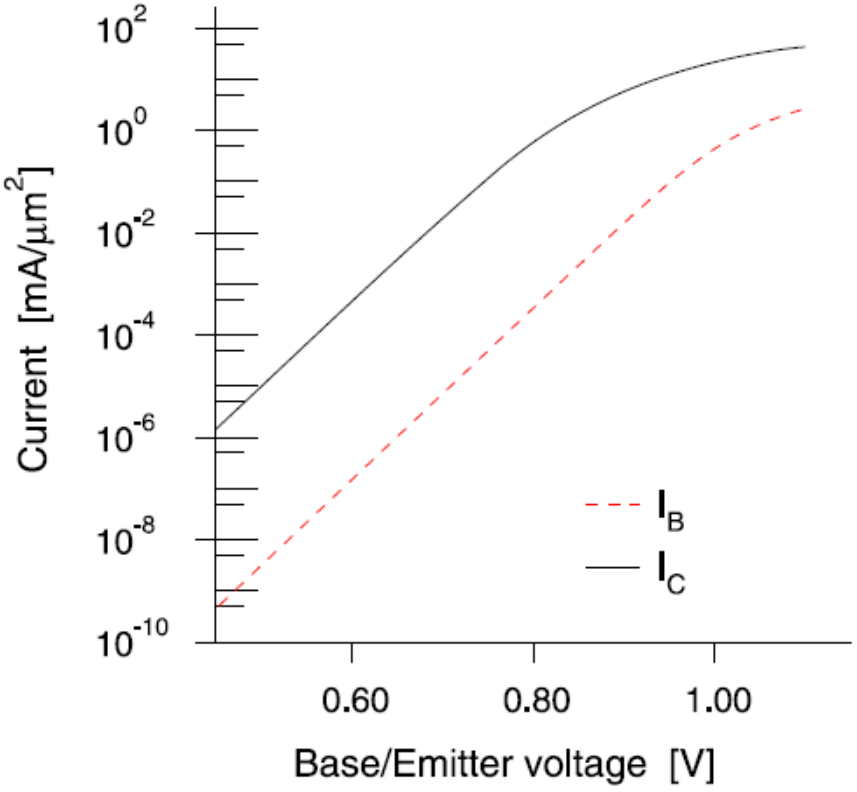


Fig. 19 Gummel plot. $V_{CB} = 0.1$ V

Simulated Gummel plot of a HBT
(Taken from Hong, JCE, vol. 8, p. 225, 2009)

Compare g_m

- Transconductance is given by $g_m = \frac{dI_C}{dV_{BE}}$.

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

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

- How about the MOSFET?

$$I_D = ???$$

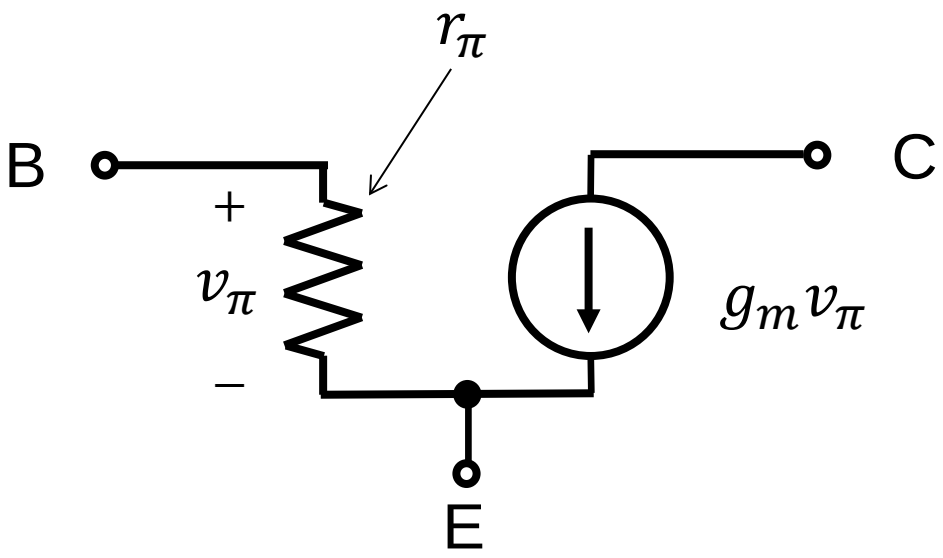
$$g_m = ???$$

- For a given current, which one has higher g_m?

Small-signal model

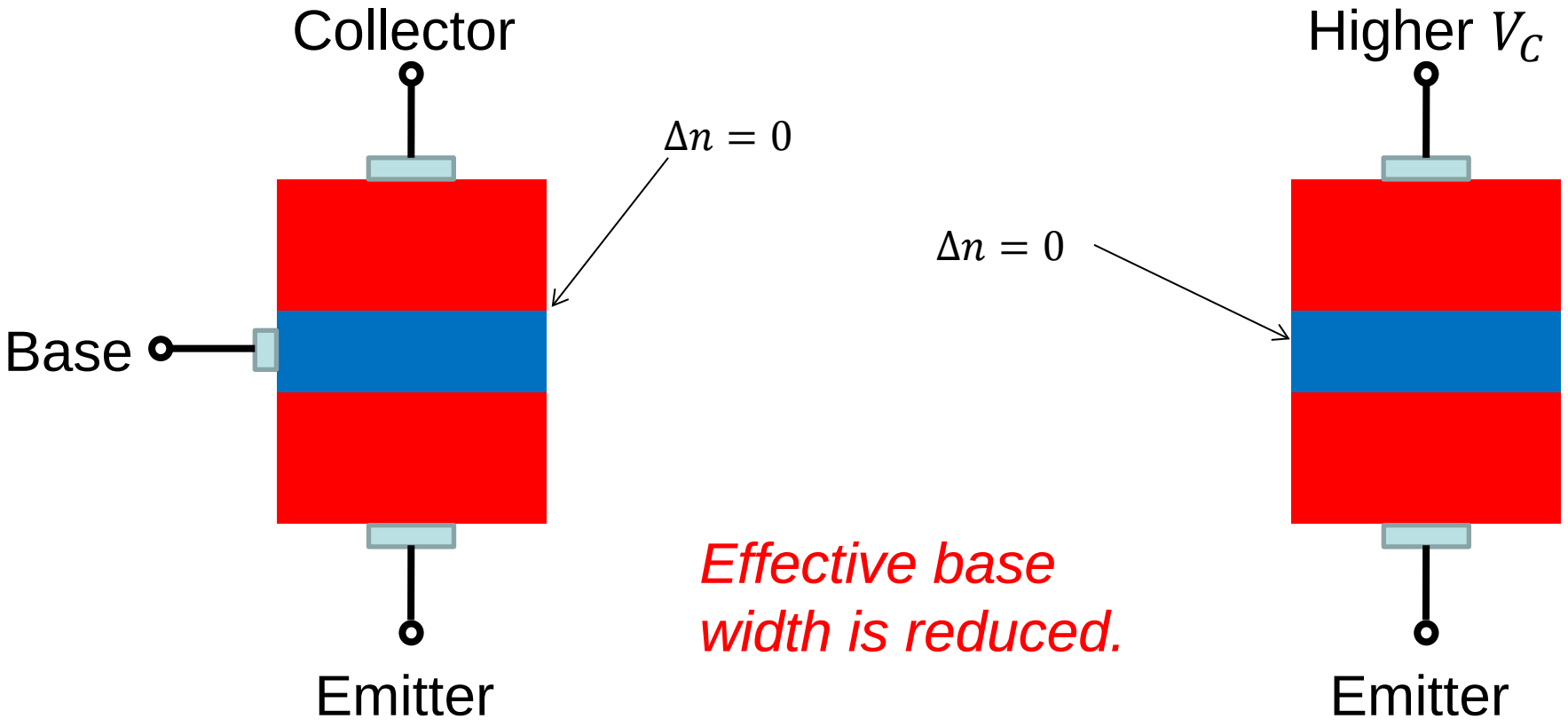
- Quite similar with the MOSFET model
  - Finite resistance between the base and emitter

$$r_\pi = \frac{\beta}{g_m}$$



Early effect (1/2)

- For higher V_{CE},
  - The depletion region between the base and collector is widened.

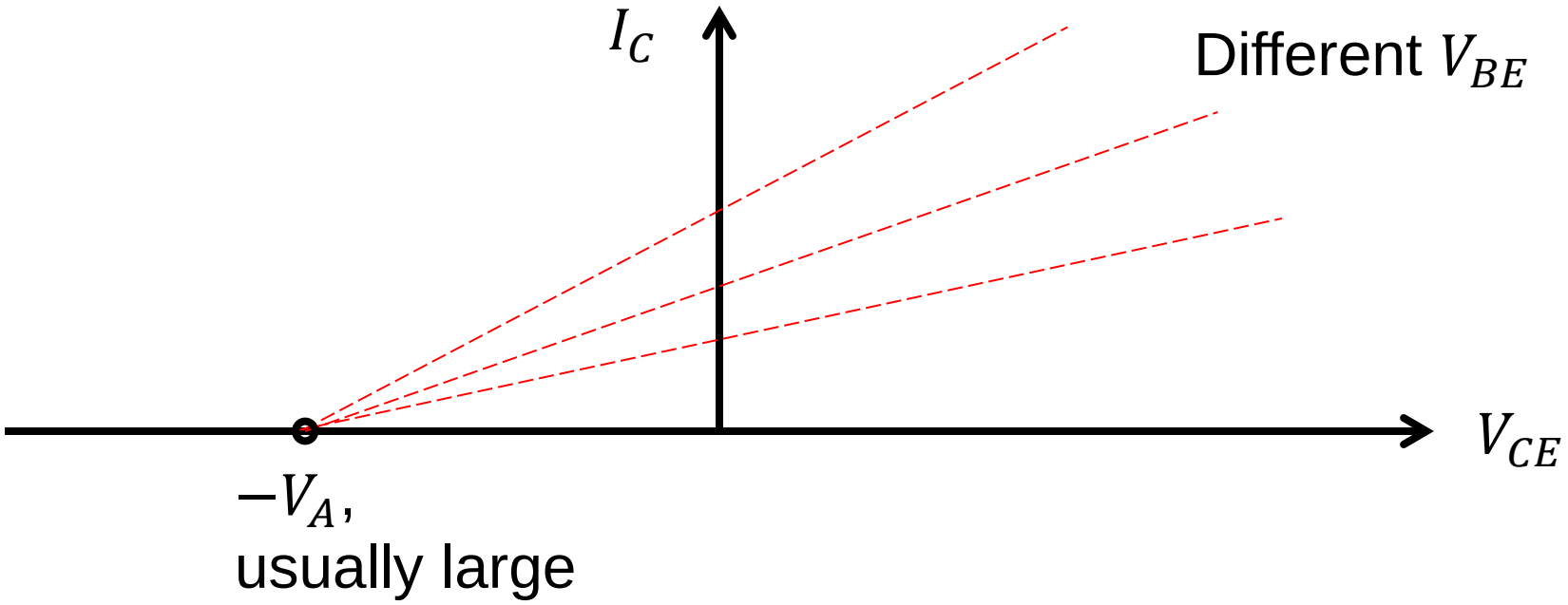


Effective base width is reduced.

Early effect (2/2)

- Its modeling
  - The IV characteristics is now modified:

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

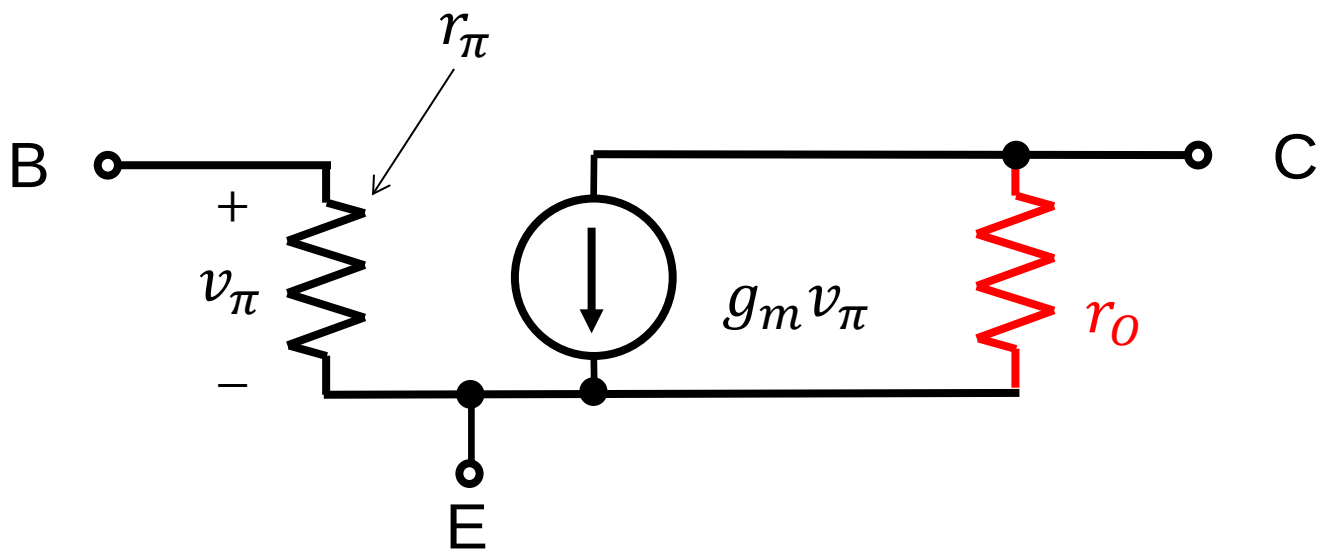


Output resistance

- It is easy to show that

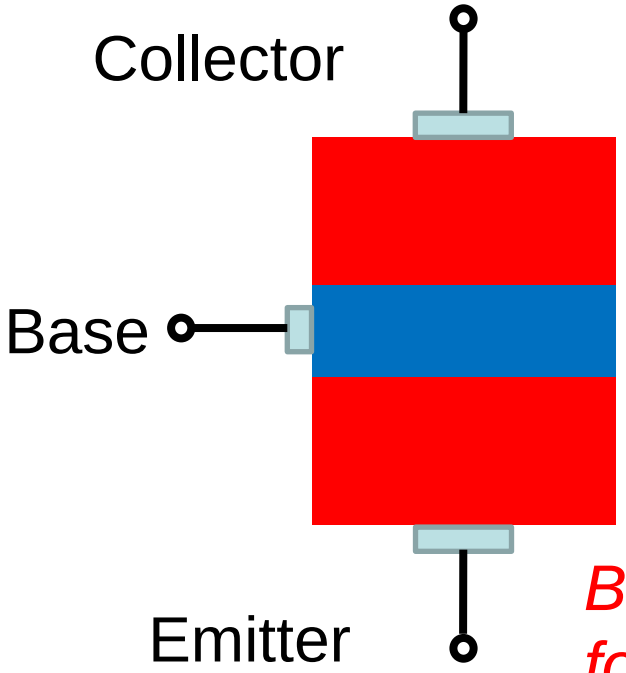
$$\frac{dI_C}{dV_{CE}} = \left(I_S \exp\frac{V_{BE}}{V_T}\right)\frac{1}{V_A}$$

$$r_O \approx \frac{V_A}{I_C}$$

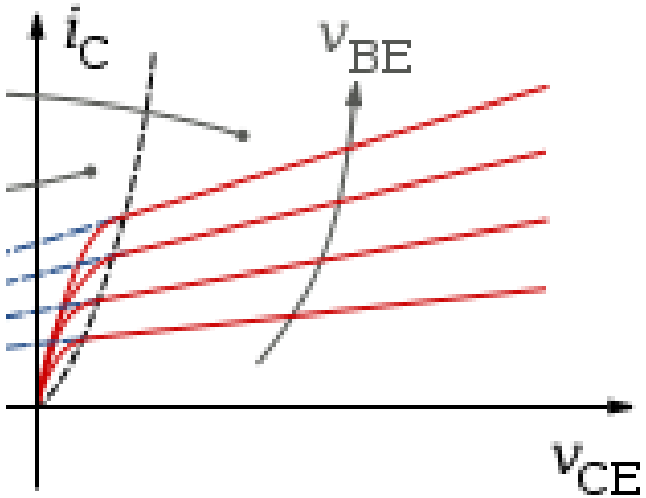


Saturation?

- What was the saturation in the MOSFET?
  - Saturation of the drain current, as the drain voltage increases.
- What is the saturation in the BJT?
  - Saturation of the collector current, as the base current increases.



Both junctions are forward biased.



Typical output characteristics (Taken from Wikipedia)

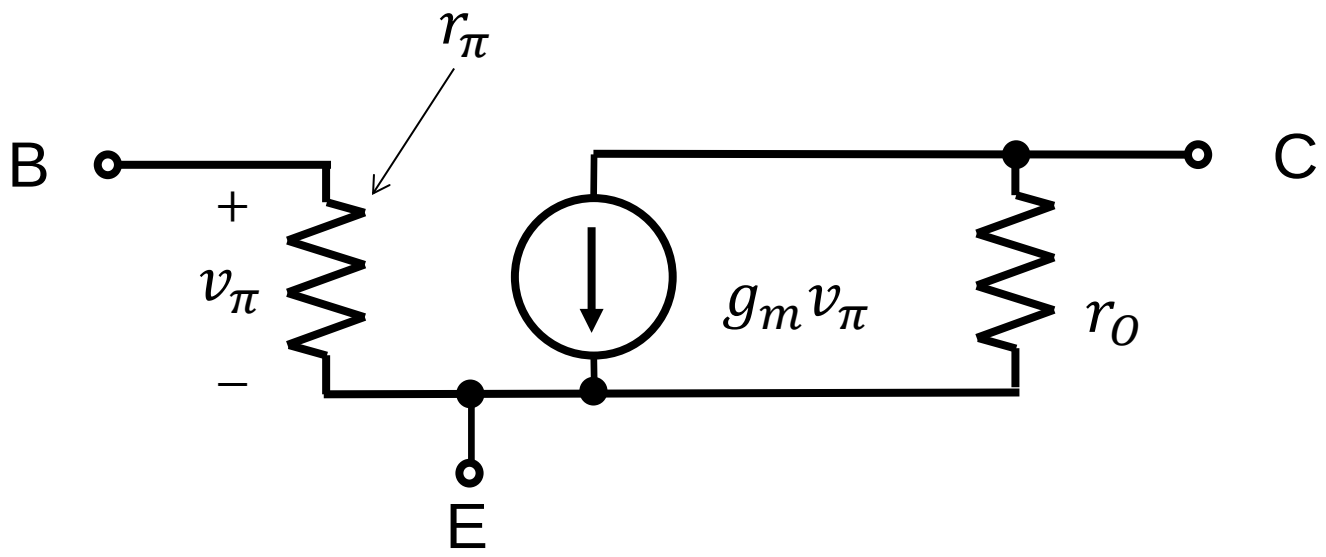
Small-signal model

- Useful expressions

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

$$r_\pi = \frac{\beta}{g_m}$$

$$r_O \approx \frac{V_A}{I_C}$$

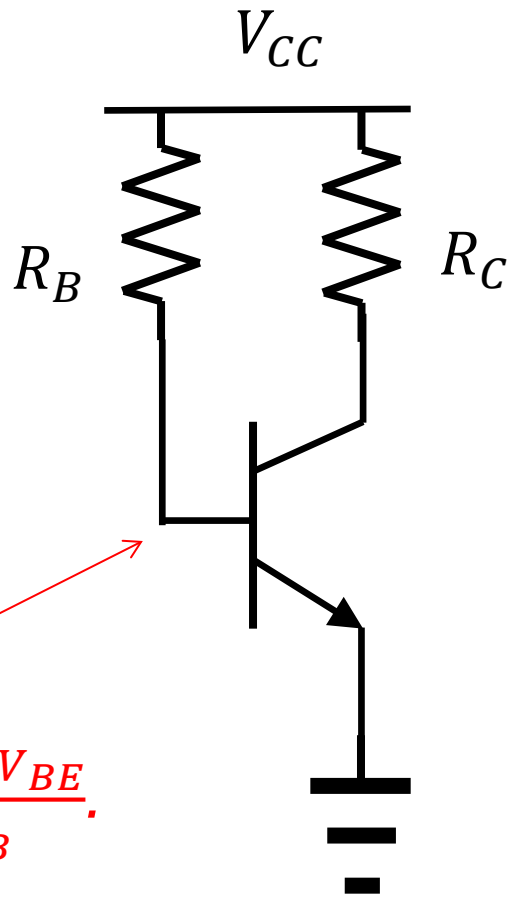


Biasing

- Example 5.7
  - DC analysis?
  - (Recall its MOS counterpart.)

  - Specific values

$V_{CC} = 2.5\ \text{V}$
$R_B = 100\ k\Omega$
$R_C = 1\ k\Omega$



Voltage?
It would be $\frac{V_{CC}-V_{BE}}{R_B}$.

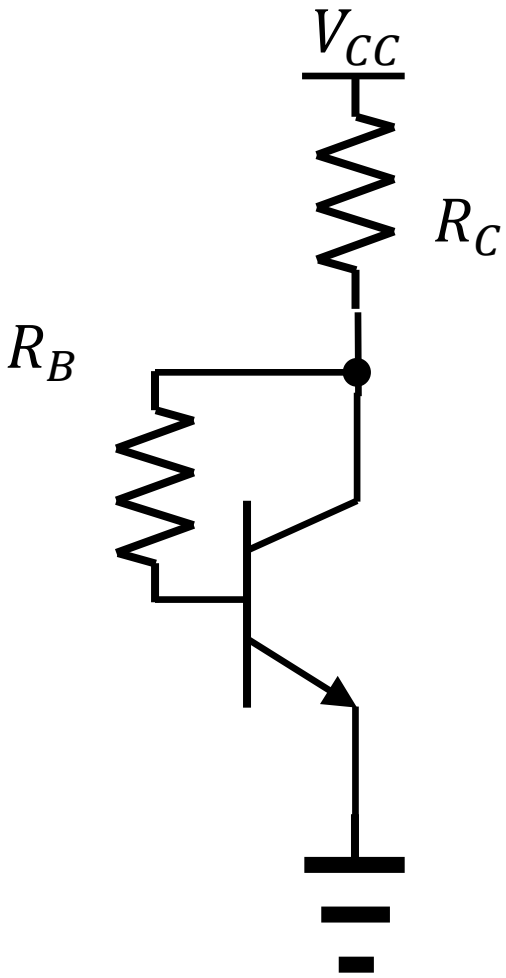
Self-biased stage

- Which one is higher?
  - Collector voltage or base voltage?
  - In the forward active region!

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{\beta}}$$ ← *Why?*

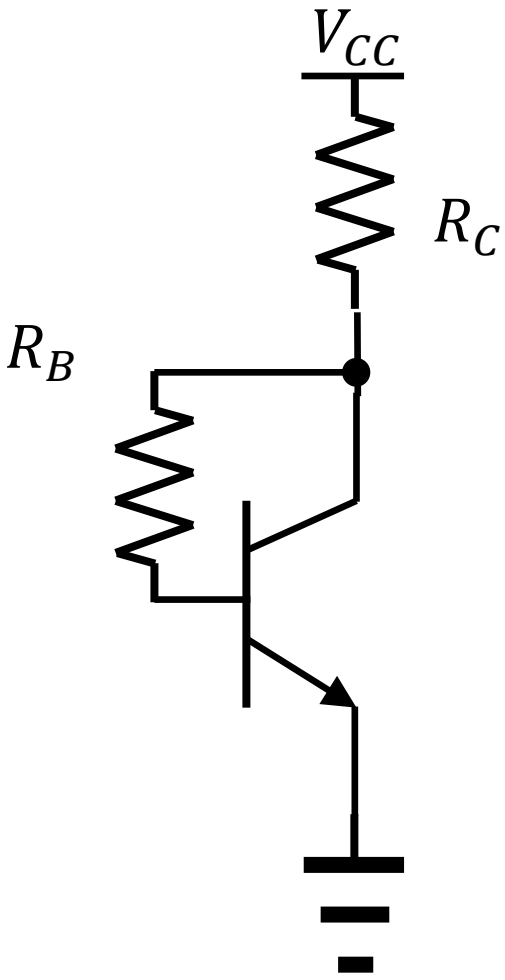
  - Uncertain V_{BE} and β
  - What can we do?

$$R_C \gg \frac{R_B}{\beta}$$



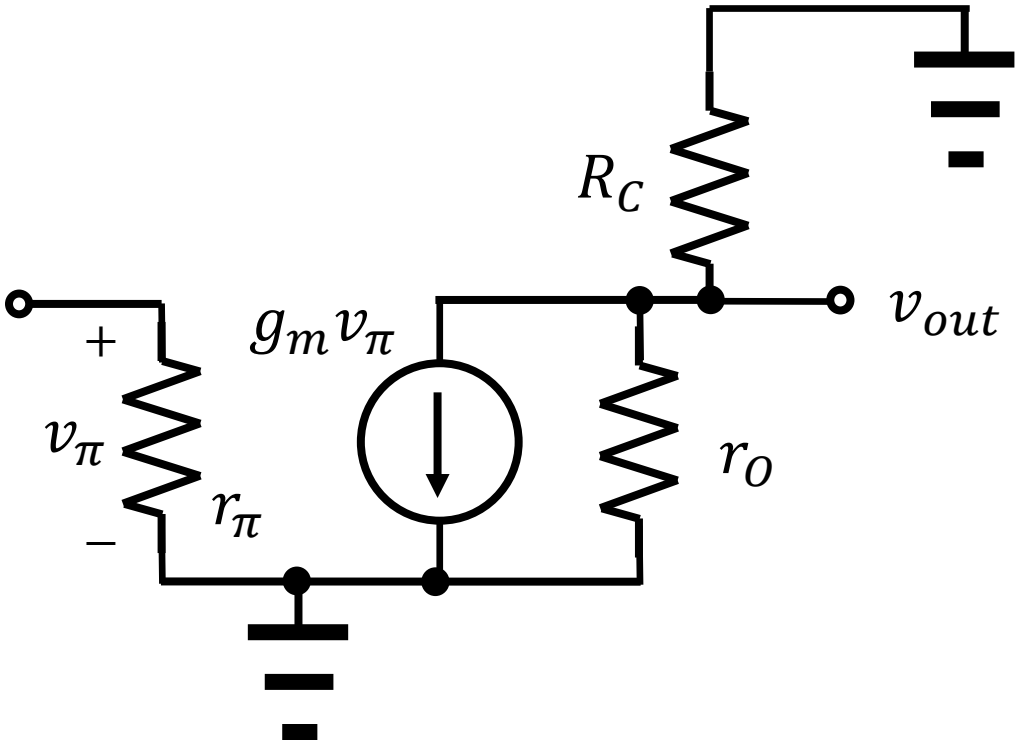
Example 5.14

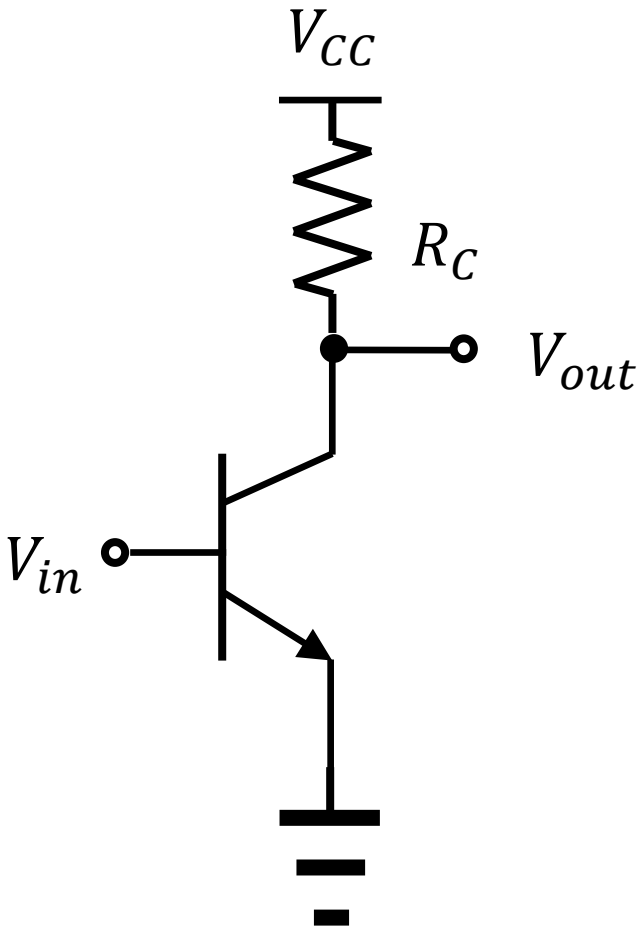
- Design the self-biased stage.
  - In this example, we assume
$$R_C \approx 10\frac{R_B}{\beta}$$
  - It means $I_C = \frac{V_{CC}-V_{BE}}{1.1R_C}$.
  - We want to have g_m of $\frac{1}{13\ \Omega}$ in this example.
  - For BJTs, $g_m = \frac{I_C}{V_T}$. Therefore, $I_C = 2\ \mathrm{mA}$.
  - Then,
$$R_C \approx \frac{V_{CC} - V_{BE}}{1.1\ I_C} = 475\ \Omega$$



Common-emitter (1/2)

- You can easily imagine that
  - There is a common-emitter configuration.





Common-emitter (2/2)

- Voltage gain?
  - Same with the CS stage:

$$A_v = -g_m(R_C||r_O)$$

- Impedances?
  - Input impedance

$$R_{in} = r_\pi = \frac{\beta}{g_m}$$

  - Output impedance

$$R_{out} = R_C||r_O$$

Common-emitter (2/2)

- Voltage gain?
  - Same with the CS stage:
$$A_v = -g_m(R_C||r_O)$$
  - When we have a very large R_C, $A_v \rightarrow -g_m r_O$.
  - For BJTs, $g_m = \frac{I_C}{V_T}$ and $r_O = \frac{V_A}{I_C}$.

- Impedances?
  - Input impedance
$$R_{in} = r_\pi = \frac{\beta}{g_m}$$
  - Output impedance
$$R_{out} = R_C||r_O$$

Example 5.21

- Collector current of 1 mA and $R_C = 1\ k\Omega$.
  - Then, g_m is readily available.

$$g_m = \frac{1}{26\ \Omega}$$

  - When, the Early voltage is 10 V, $r_O = \frac{10\ \text{V}}{1\ \text{mA}} = 10k\Omega$.
  - Overall, $R_C || r_O = \frac{1}{1.1} k\Omega \approx 0.91\ k\Omega$.