Fundamentals of Electronics
Week 11 — Review

Charles A. DiMarzio
EECE–2412
Northeastern University

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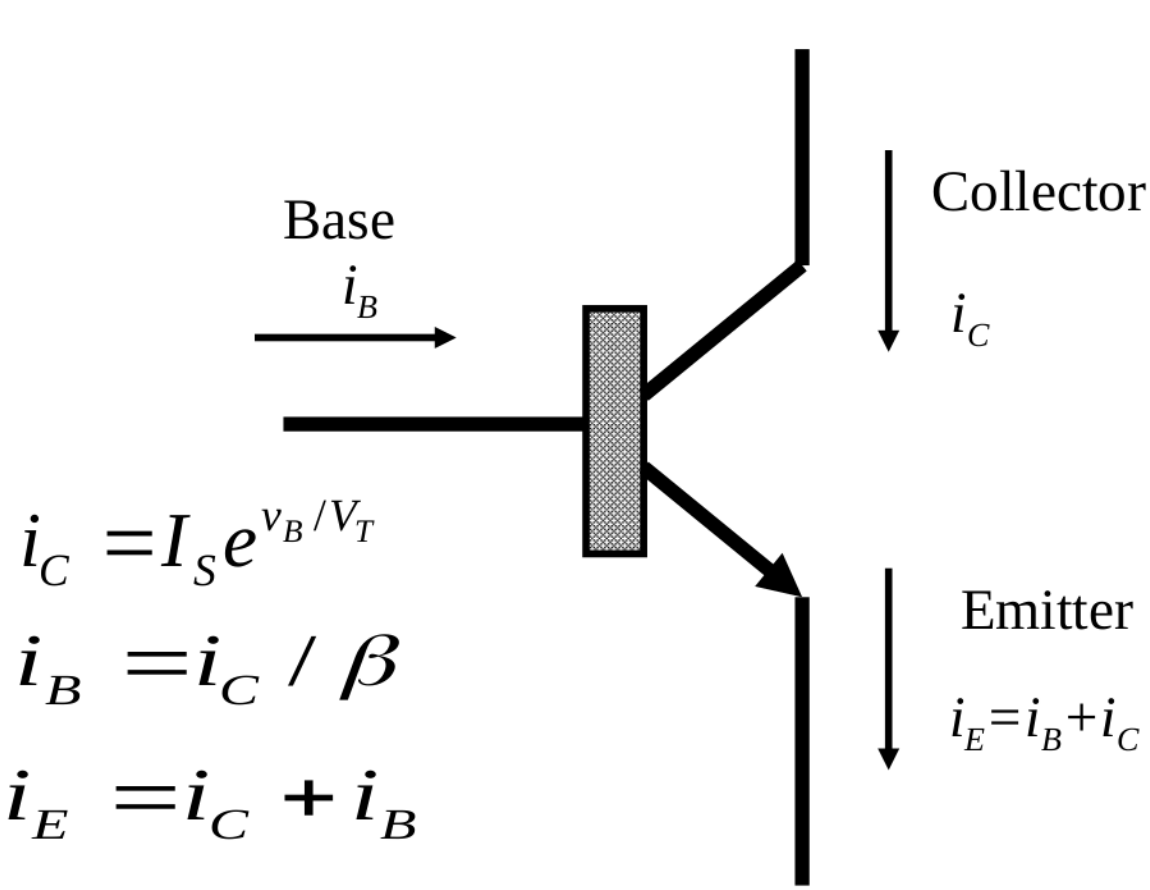
Agenda

- Modes of Operation
- DC Models
- DC Circuits
- AC Parameters
- AC Models
- Example AC Circuit for Amplifier
- Linearity
- Amplifier Circuits
- Frequency Analysis
- Cutoff and Saturation Regions
- Not, Nor, Nand

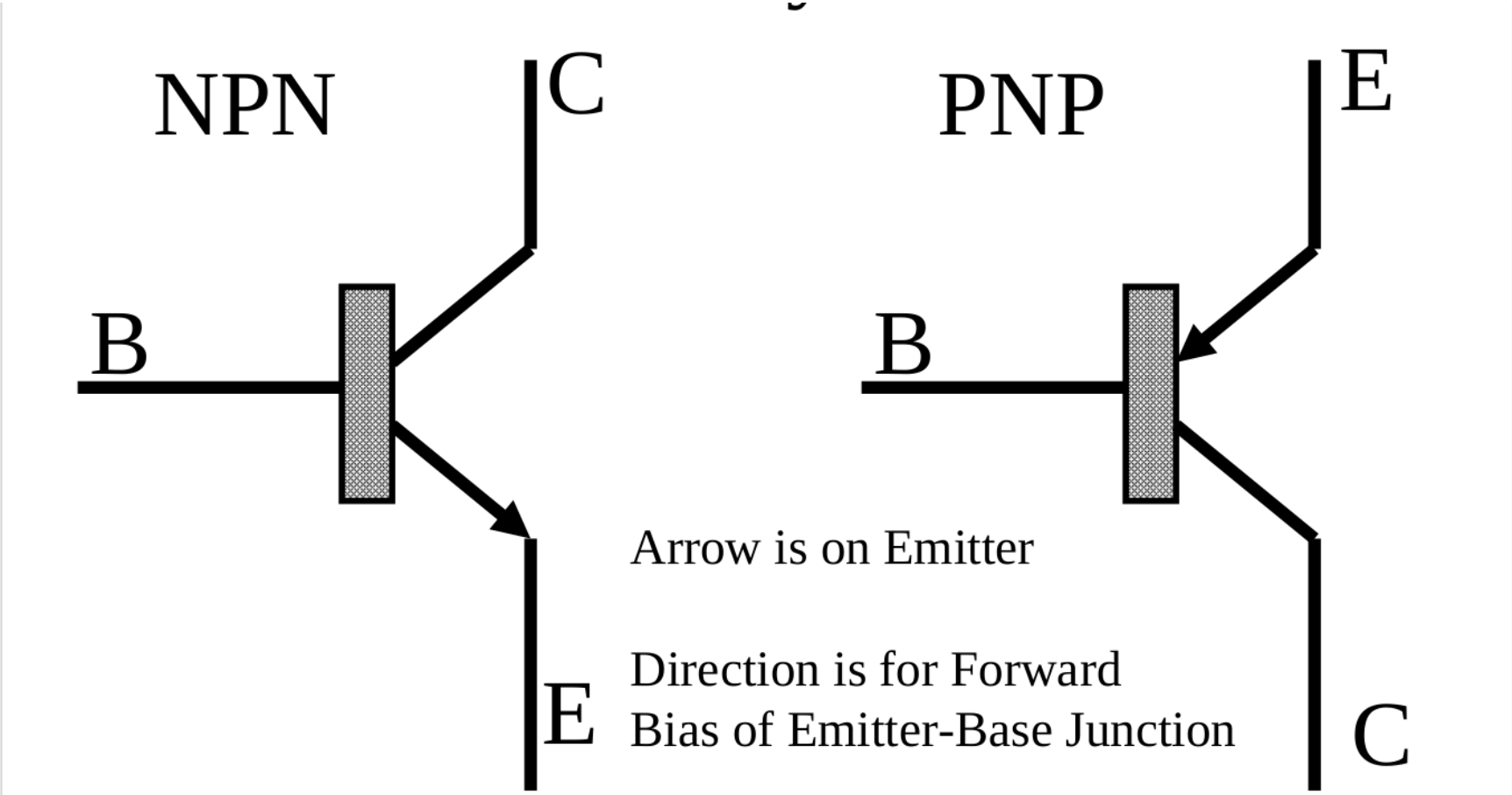
Slides 7

- Basics
- Modes of Operation
- DC Models

Transistor as 3–Terminal Device

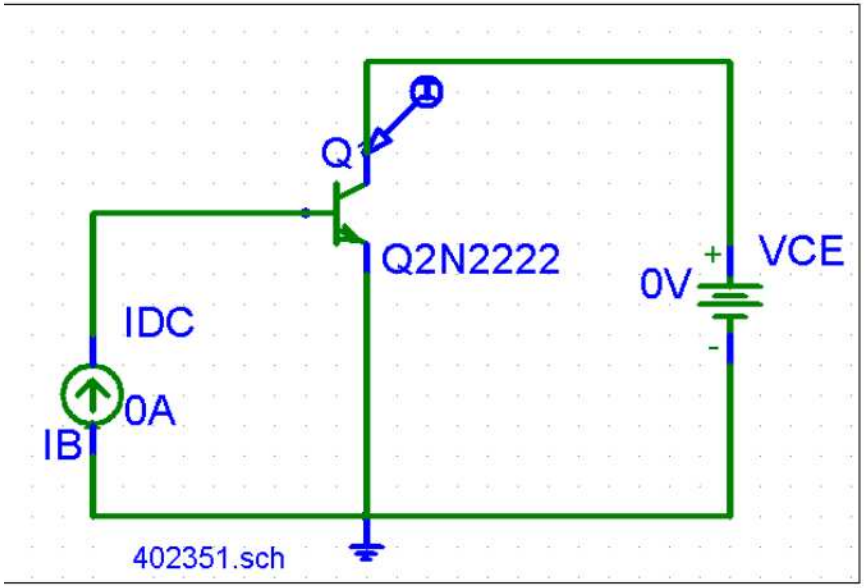


Circuit Symbols

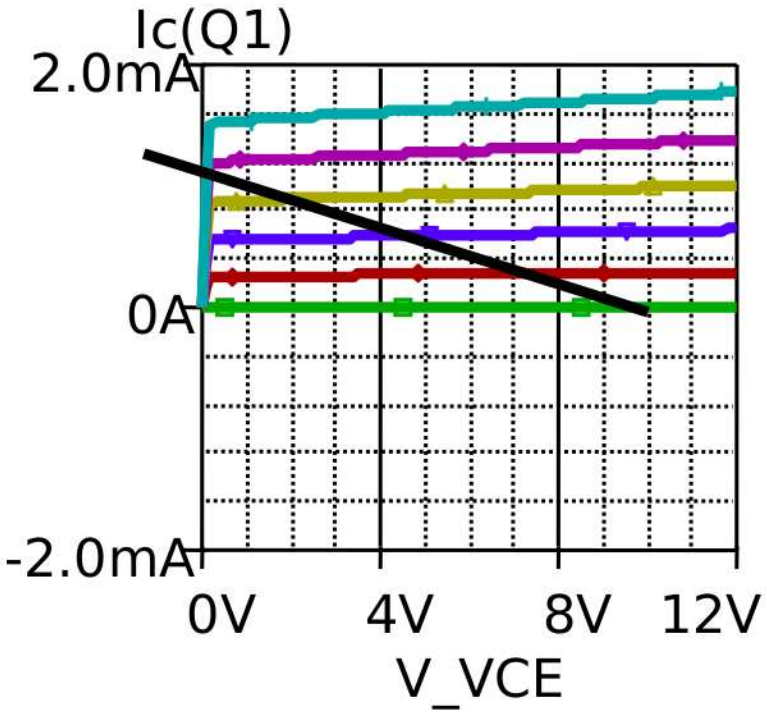


I–V Curves

- Test Circuit
  - Active Mode
  - Saturation
  - Cutoff

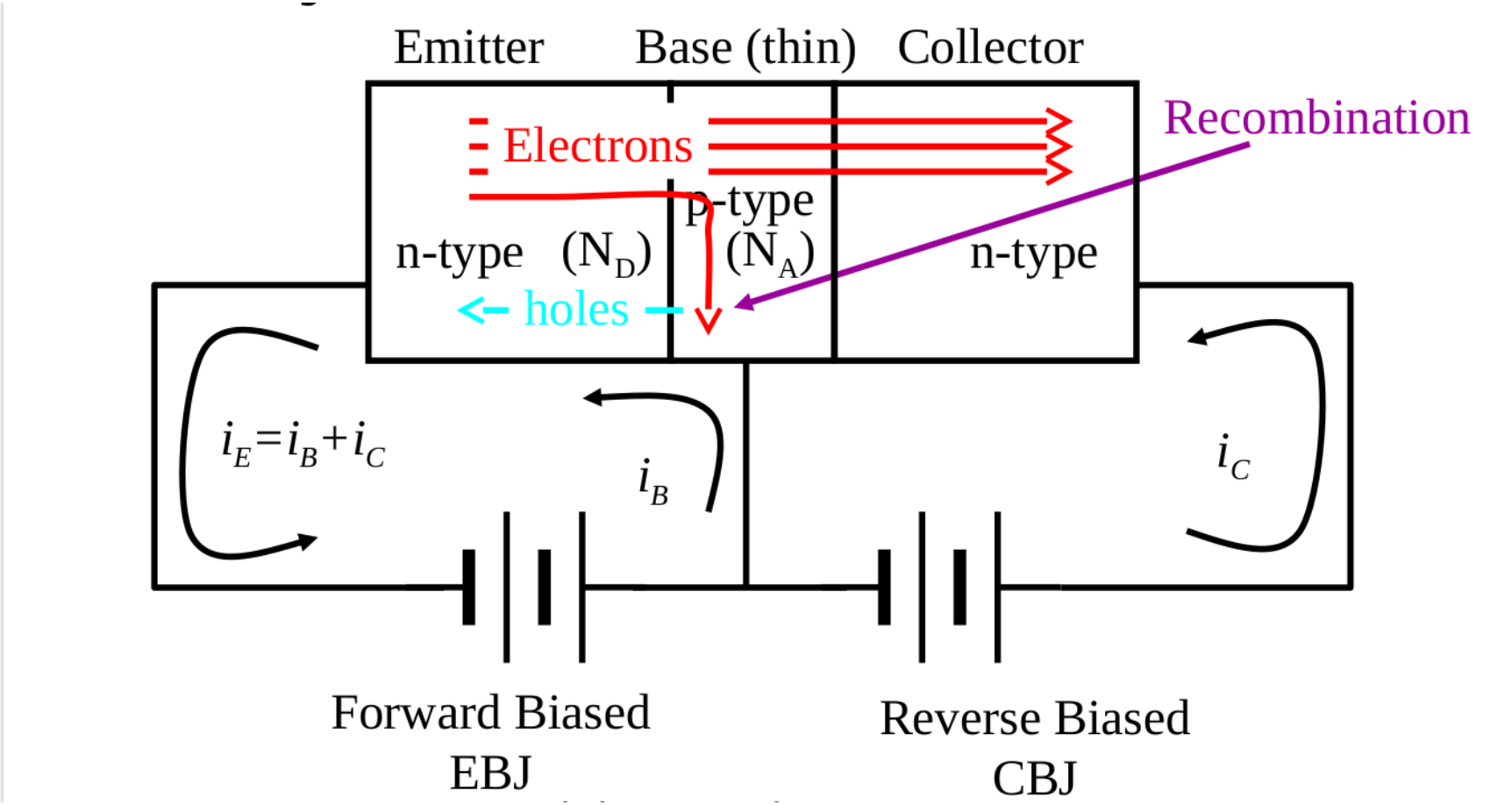


- I-V Curves
  - i_B=[0:2:10] microamperes



3 Modes: Active, Saturation, Cutoff

Physical Model: Active Mode

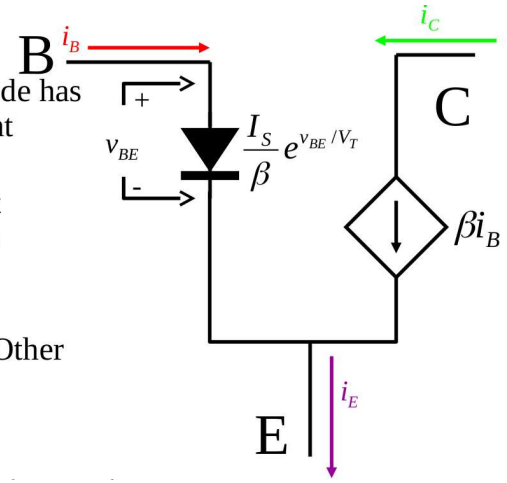


Modes of Operation

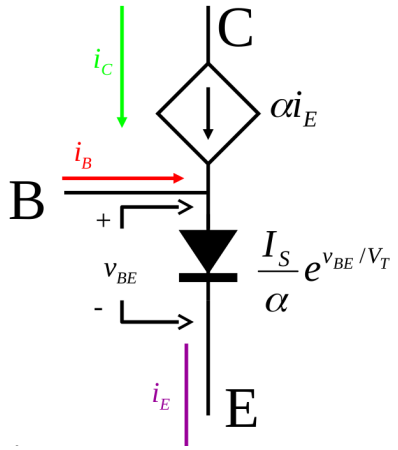
- Active Mode
  - EBJ Forward Biased
  - CBJ Reverse Biased
- Other Modes (Discussed Later)
  - Saturation Mode
    Both Forward Biased
  - Cutoff Mode
    Both Reverse Biased

DC Pi and T Models

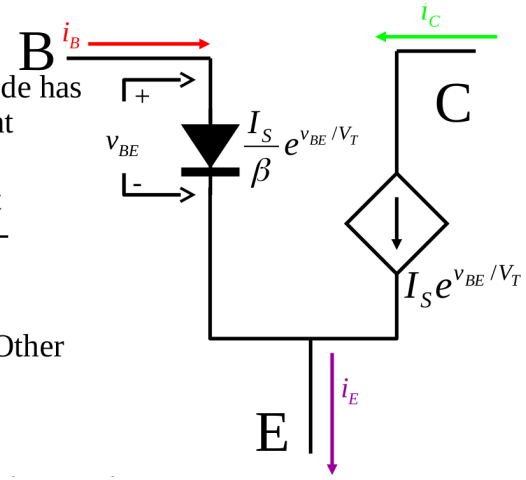
- Base-Emitter Diode has Saturation Current reduced by 1/β
- Collector Current Depends on Base Current.
- Emitter Current Calculated from Other Two
- Note that $i_E > i_C$



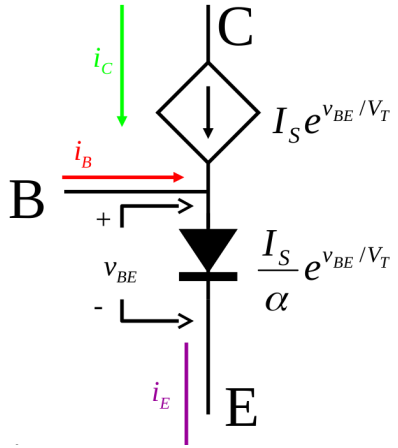
- Base-Emitter Diode has Saturation Current increased by 1/α
- Collector Current Depends on Emitter Current.
- Base Current Calculated from Other Two
- Note that $i_E > i_C$



- Base-Emitter Diode has Saturation Current reduced by 1/β
- Collector Current Depends on Base-Emitter Voltage.
- Emitter Current Calculated from Other Two
- Note that $i_E > i_C$



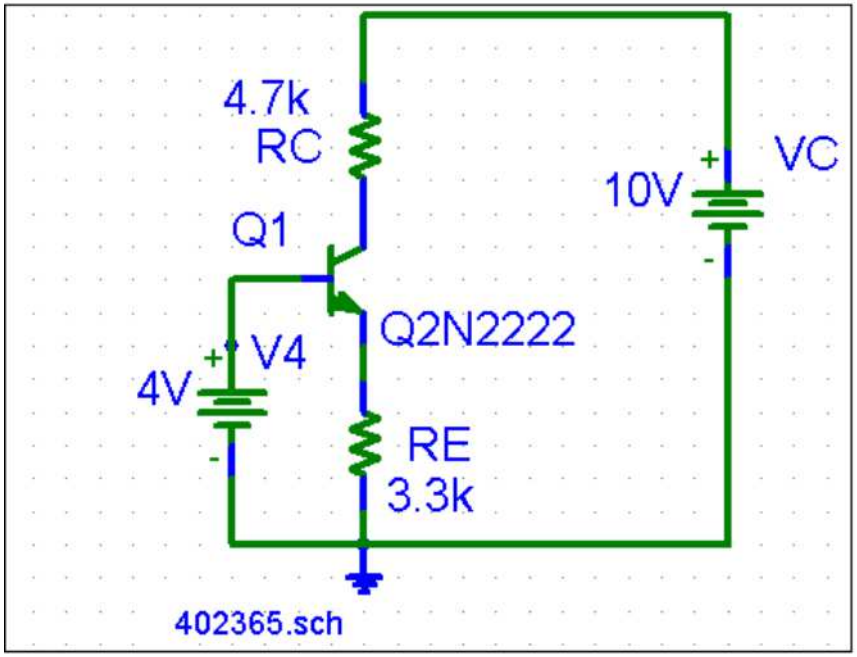
- Collector Current Depends on v_{BE}.
- Base-Emitter Diode has Saturation Current increased by 1/α
- Base Current Calculated from Other Two
- Note that $i_E > i_C$



Slides 8

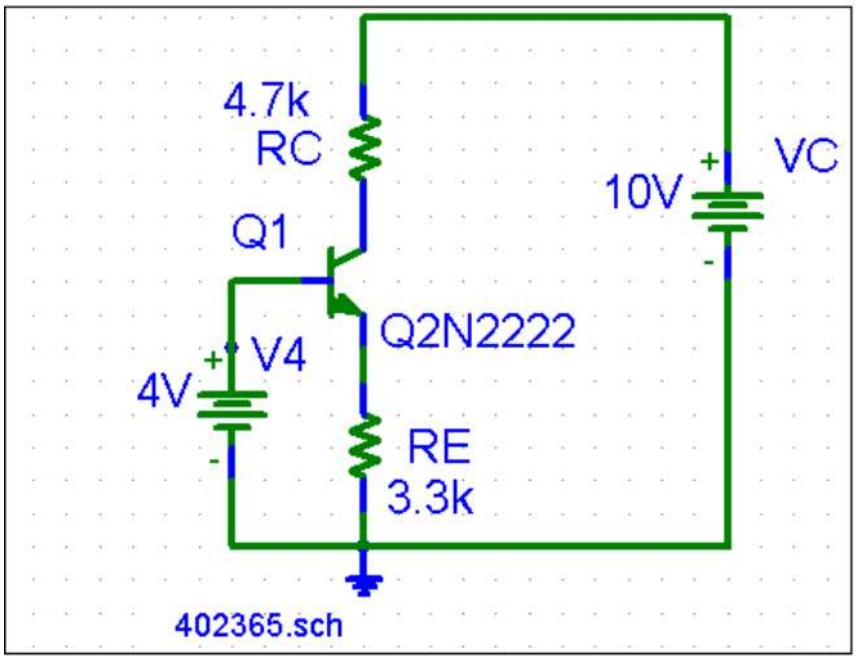
- DC Circuits
- AC Parameters
- AC Models

Example: 4.2 (1)



- Given
  - β=100
- Find Voltages and Currents

Example: 4.2 (2)



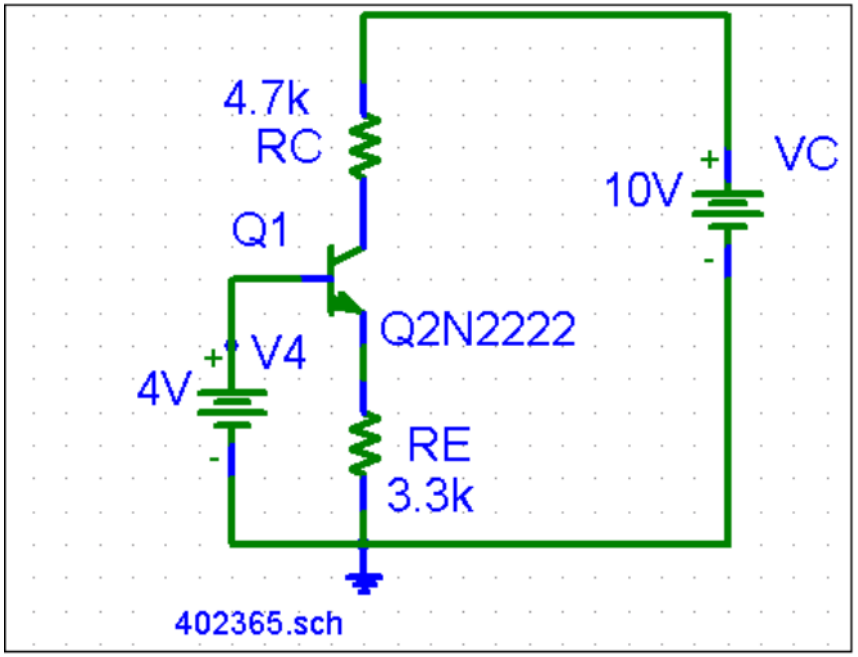
1. Assume $v_{BE} = 0.7\text{V}$

   $v_E = 3.3\text{V}$

2. $i_E = 1\text{mA}$

3. $i_C = \alpha i_E = 0.99\text{mA}$

Example: 4.2 (3)



4. 4.7 V across RC

$$v_C = 5.3\text{V}$$

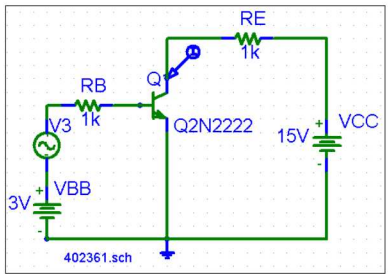
5. $$i_B = i_C / \beta = 0.01\text{mA}$$

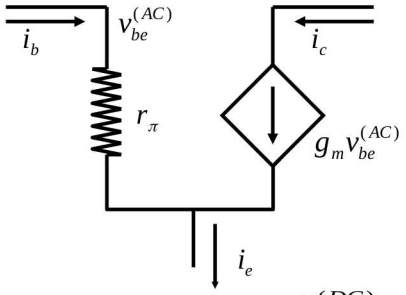
6. Check for Active Mode
   Fwd EBJ (0.7V)
   Rev CBJ (1.3V)

Small–Signal (AC) Model

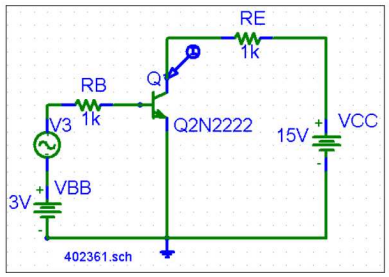
- Parameters
  - Transconductance: $g_m = \frac{I_C^{(DC)}}{V_T}$ from Taylor Series
  - Base Parameters: β given, $r_\pi = \frac{\beta}{g_m}$
    for Pi Models.
  - Emitter Parameters: $\alpha = \frac{\beta}{\beta+1}$,
    $r_e = \frac{V_T}{I_E^{(DC)}} = r_e/(\beta+1)$
    for T Models.

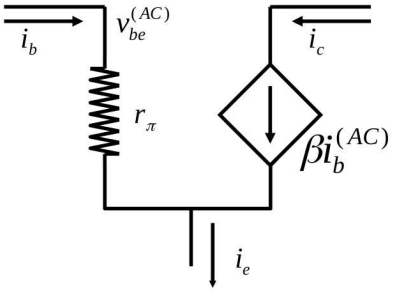
DC Pi and T Models



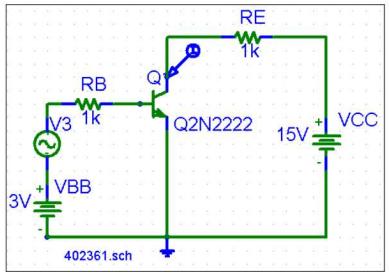


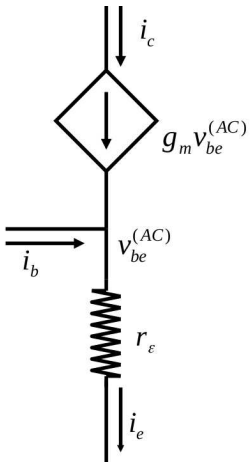
$$r_\pi = \beta / g_m \qquad g_m = \frac{I_C^{(DC)}}{V_T}$$



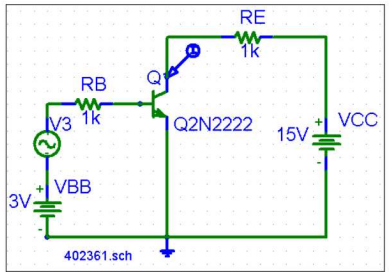


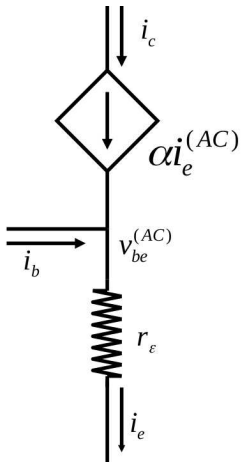
$$r_\pi = \beta \frac{V_T}{I_C^{(DC)}}$$





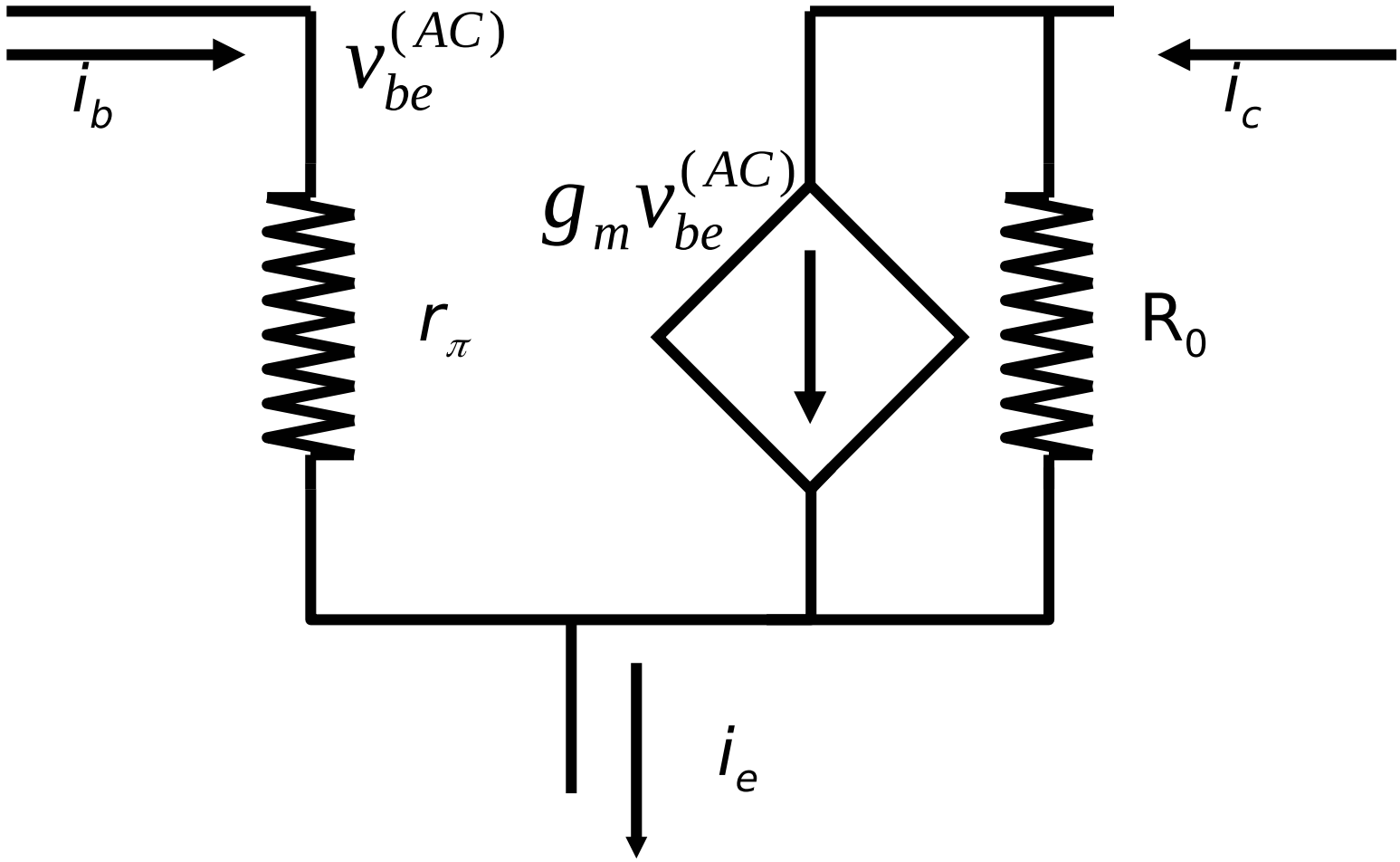
$$g_m = \frac{I_C^{(DC)}}{V_T} \qquad r_e = \frac{V_T}{I_E^{(DC)}}$$





$$g_m = \frac{I_C^{(DC)}}{V_T} \qquad r_e = \frac{V_T}{I_E^{(DC)}}$$

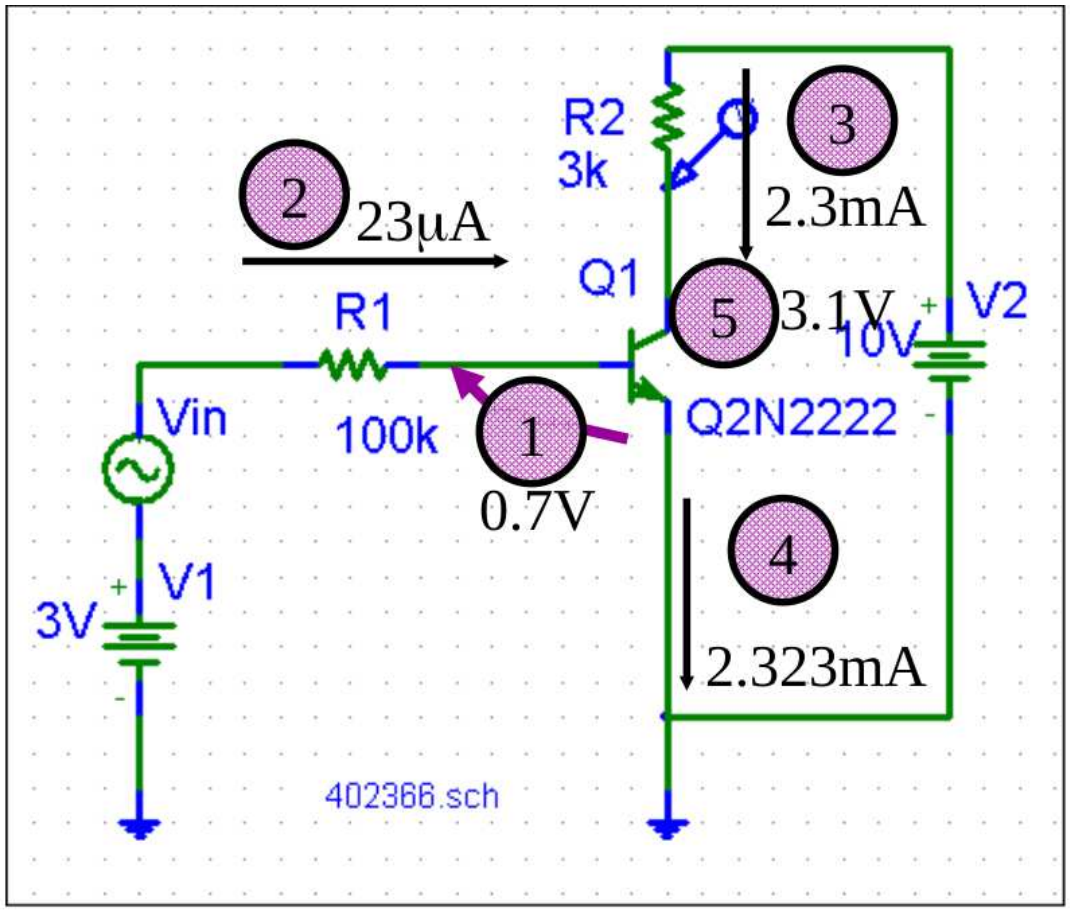
AC Pi Model with Early Voltage



Slides 9 (and 9b)

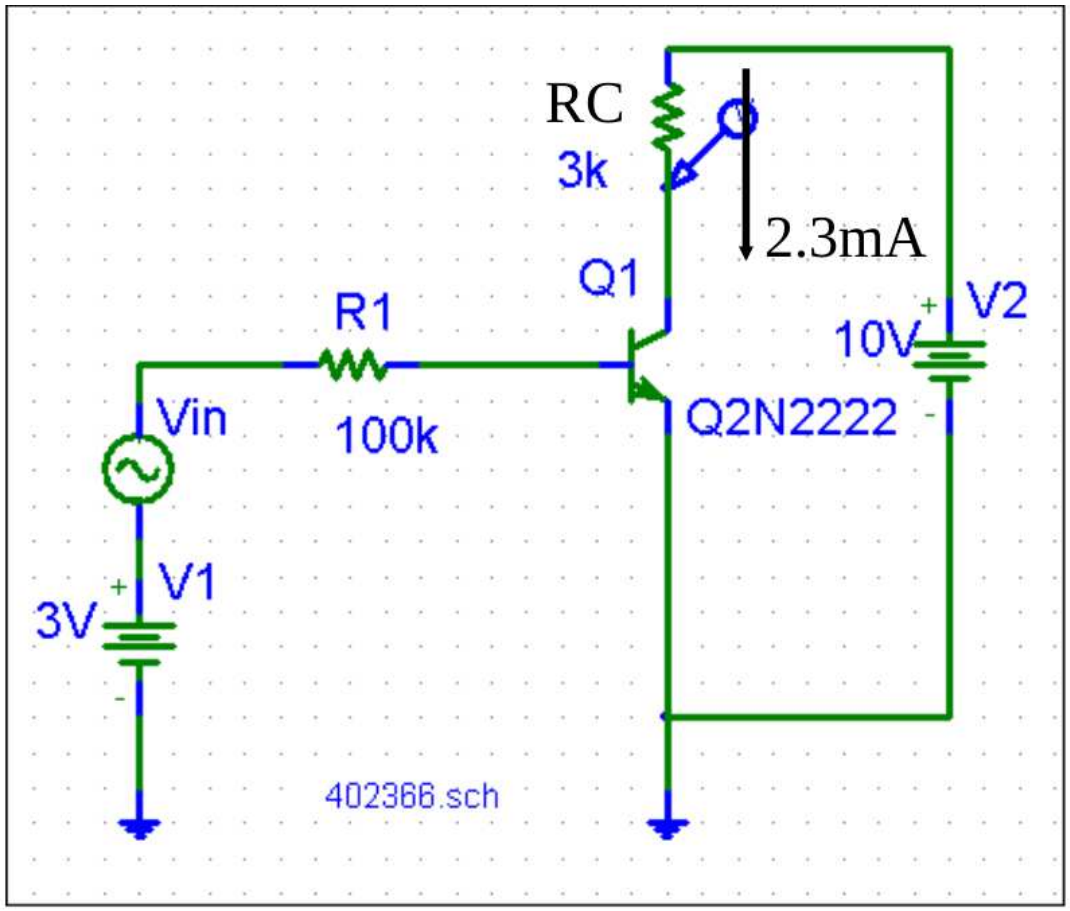
- Example AC Circuit for Amplifier
- Linearity
- Amplifier Circuits
- Frequency Analysis
- Cutoff and Saturation Regions
- Not, Nor, Nand

Example 4.9: DC Analysis



1. Guess
2. V/R
3. βi_b
4. $i_c + i_b$
5. $V_c = V_2 - i_c R_c$ $= 3.1\text{V}$
6. Active Mode OK

Example 4.9: AC Parameters



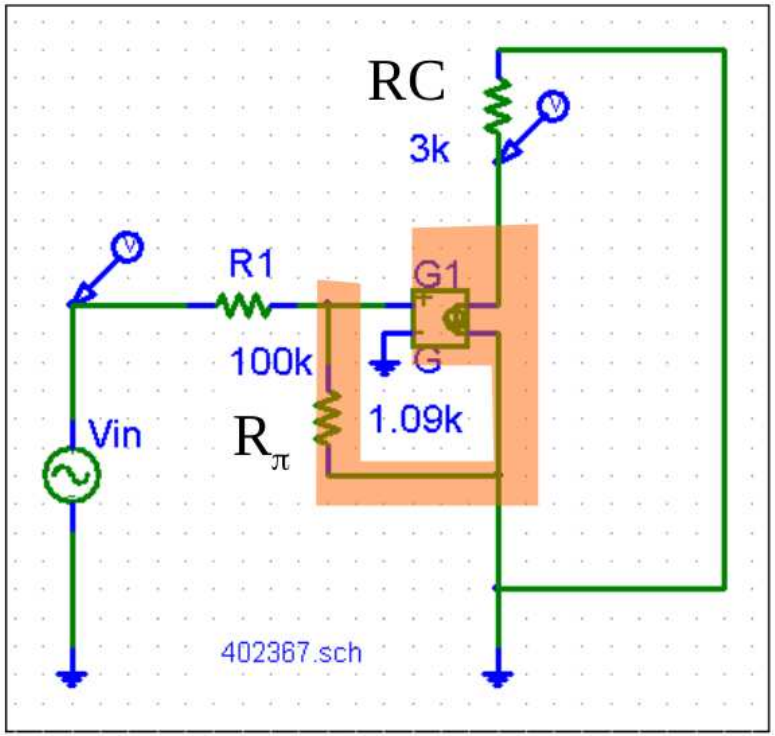
$$g_m = \frac{I_C}{V_T} = 92\text{mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = 1.09\text{k}\Omega$$

Base Current Depends Mostly on V1 and R1, so Collector Current is a Strong Function of β.

Thus, so is g_m, and r_π.

Example 4.9: AC Pi Model

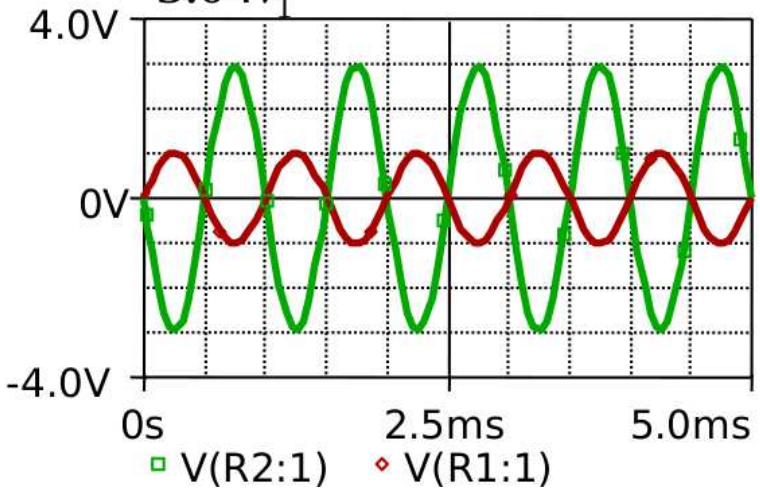


$$v_{be}^{(AC)} = v_{in}^{(AC)} \frac{r_\pi}{R_1 + r_\pi} = 0.011 v_1^{(AC)}$$

$$v_{out}^{(AC)} = - g_m v_{be}^{(AC)} R_C =$$

$$- 92\text{mA/V} \times 0.011 v_1^{(AC)} \times 3\text{k}\Omega$$

$$= - 3.04 v_1^{(AC)}$$



Example 4.9: Conclusion

- Amplifier Voltage Gain
  - g_v=-3.04
- Power Gain

$$dBm = 10\log\left[\frac{\left(v^{(RMS)}\right)^2}{50\Omega \times 0.001\text{W}}\right] = 20\log\left[\frac{\left|v^{(RMS)}\right|}{50\Omega \times 0.001\text{W}}\right]$$

  - *10 log(3.04²)=9.7* dB
- Example
  - Input = 7 mV RMS = 10 mV Peak = -30 dBm
  - Output = -30 dBm + 9.7 dB = -20.3 dBm

An Example: 4.10

- The AC Base Voltage Should Not Exceed About 10 mV

$$i_C = I_C^{(DC)} e^{v_{be}^{(AC)}/V_T}$$

$$i_C \approx I_C^{(DC)} \left[1 + \frac{v_{be}^{(AC)}}{V_T} + \frac{1}{2!}\left(\frac{v_{be}^{(AC)}}{V_T} \right)^2 + \cdots \right]$$

$$i_C \approx I_C^{(DC)} \left[1 + \frac{10\text{mV}}{25\text{mV}} + \frac{1}{2!}\left(\frac{10\text{mV}}{25\text{mV}} \right)^2 + \cdots \right]$$

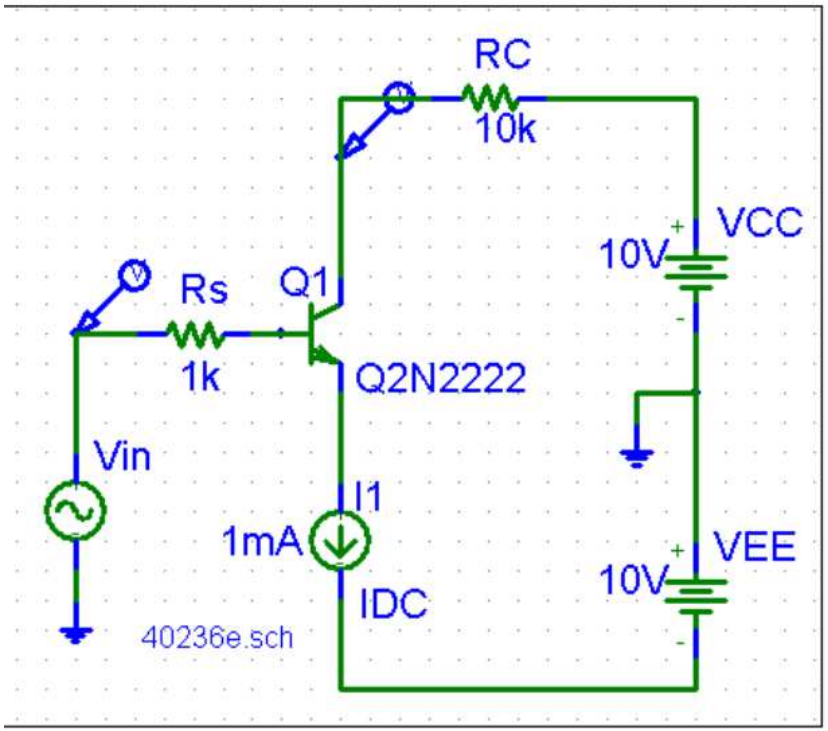
$$i_C \approx I_C^{(DC)} \left[1 + 0.4 + 0.08 + \cdots \right]$$

$$\text{distortion} = 0.08/0.4 = 20\%$$

Common Amplifier Circuits

- Common Emitter
  - Voltage Amplifier
- Common Emitter with Emitter Resistor
  - Lower Gain, Higher Input Levels
- Common Base
  - Current Buffer: Low input impedance
- Common Collector
  - Voltage Buffer: High input impedance

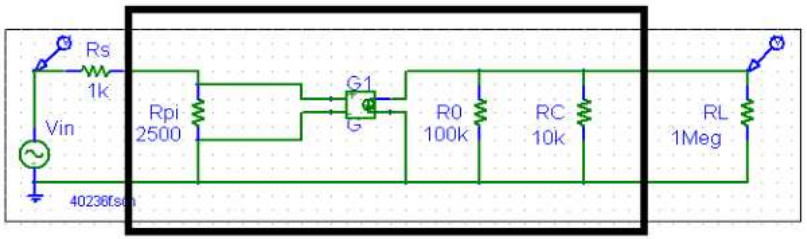
Common Emitter Amplifier



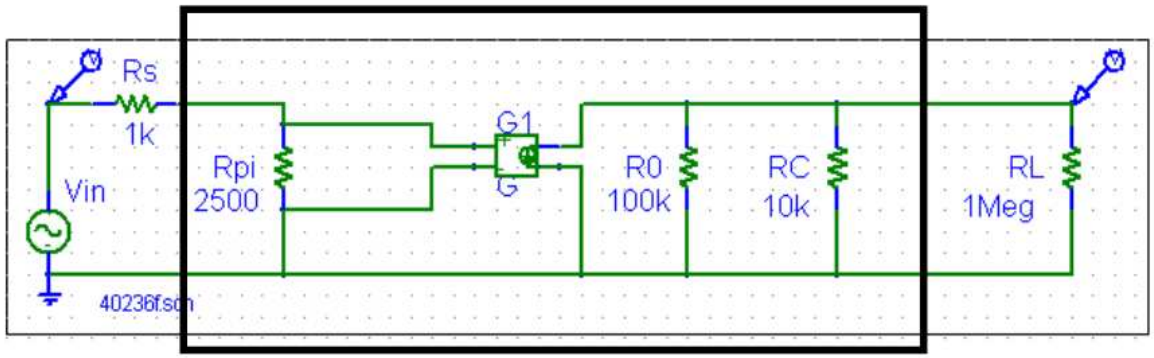
Voltage Amplifier

R_s is part of source?
R_L is the Load (not shown in original circuit).

Pi Model Below



CA Amp: AC Characteristics



Input Resistance

$$r_{in} = r_\pi = \frac{\beta}{g_m} = \frac{\beta V_T}{I_E^{(DC)}\alpha} = (\beta + 1)\frac{V_T}{I_E^{(DC)}}$$

Output Resistance

$$r_{out} = R_C \parallel R_0$$

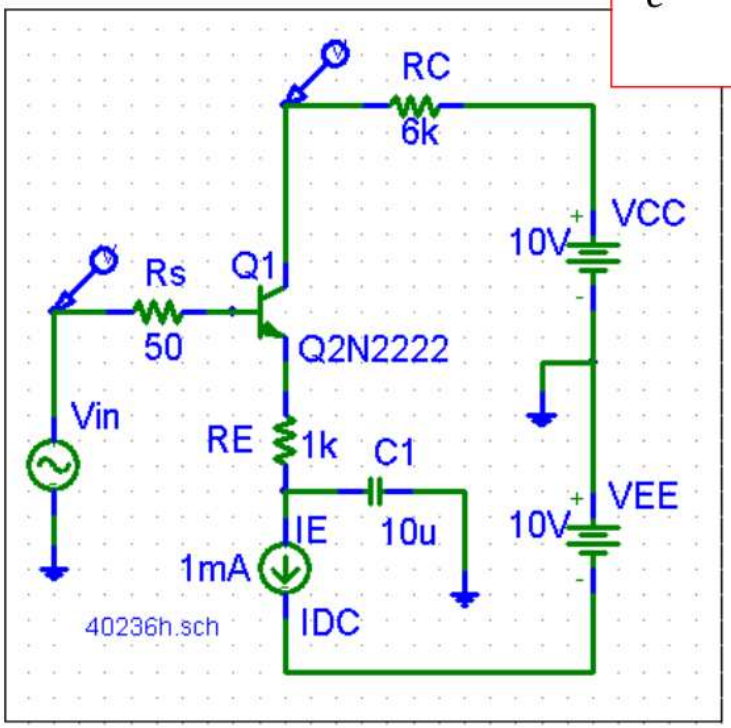
Voltage Gain

$$A_v = \frac{v_{out}^{(AC)}}{v_{in}^{(AC)}} = - g_m \frac{r_\pi}{R_s + r_\pi}(R_C \parallel R_0 \parallel R_L)$$

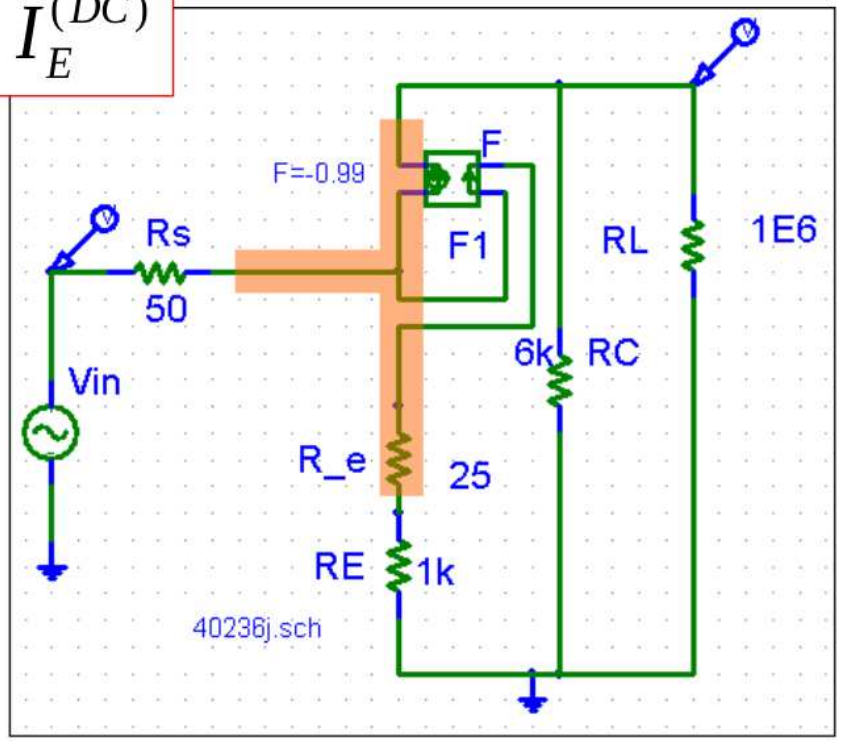
CE Amp with Emitter Resistor

$$r_e = \frac{V_T}{I_E^{(DC)}}$$

Circuit



AC Tee Model with Load



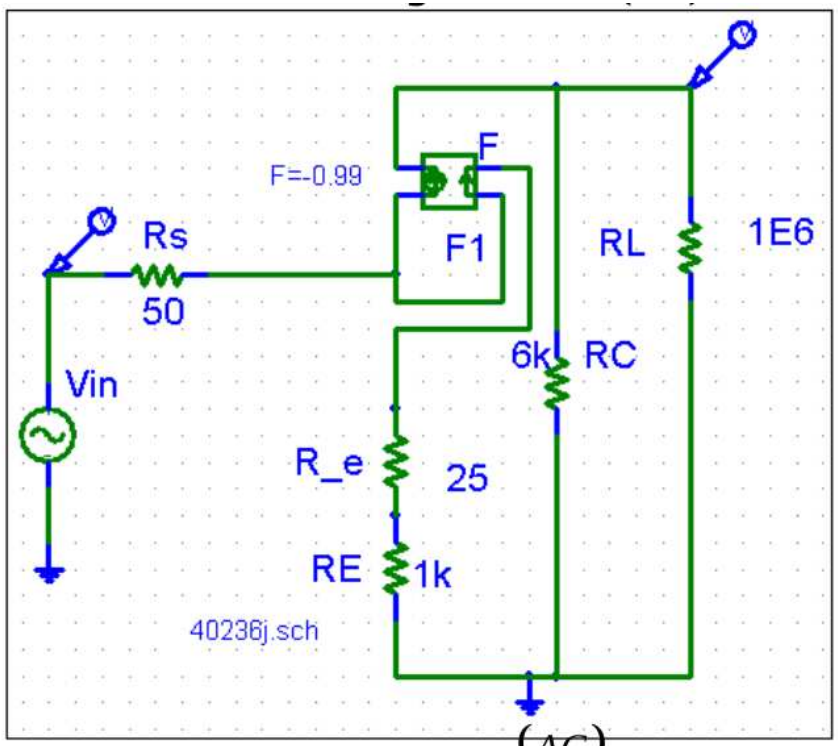
CE/R: Circuit Analysis (1)

Input Impedance

$$v_b^{(AC)} = i_e^{(AC)}(r_e + R_E)$$

$$i_b^{(AC)} = (1-\alpha) i_e^{(AC)} = \frac{i_e^{(AC)}}{\beta+1}$$

$$r_{in} = \frac{v_b^{(AC)}}{i_b^{(AC)}} = (\beta+1)(r_e + R_E)$$

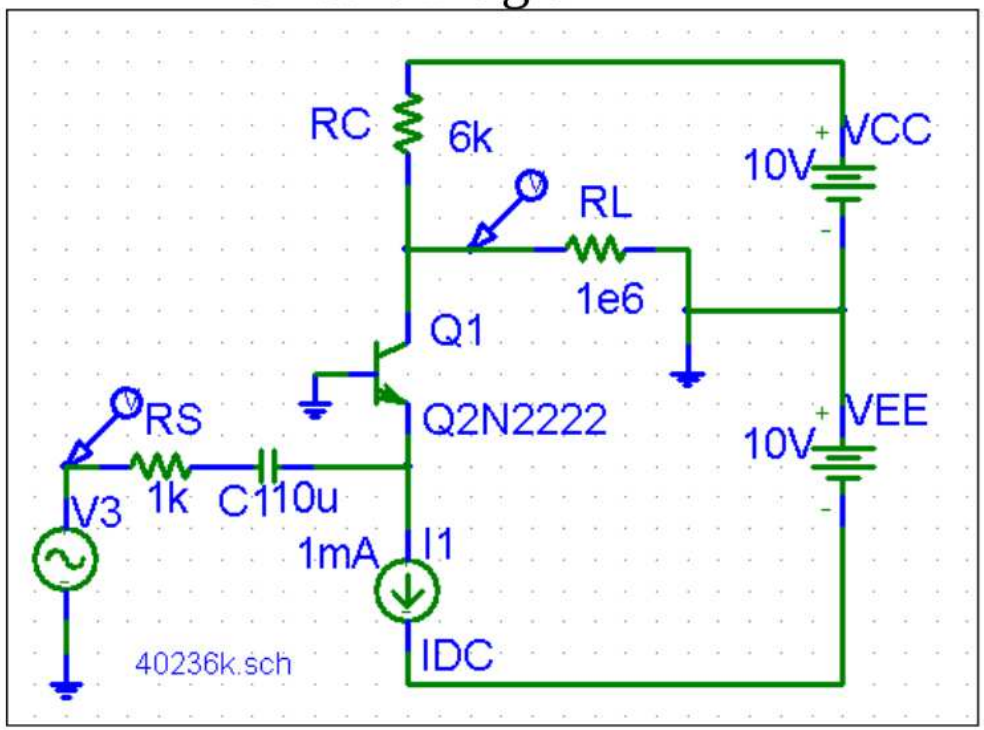


Gain

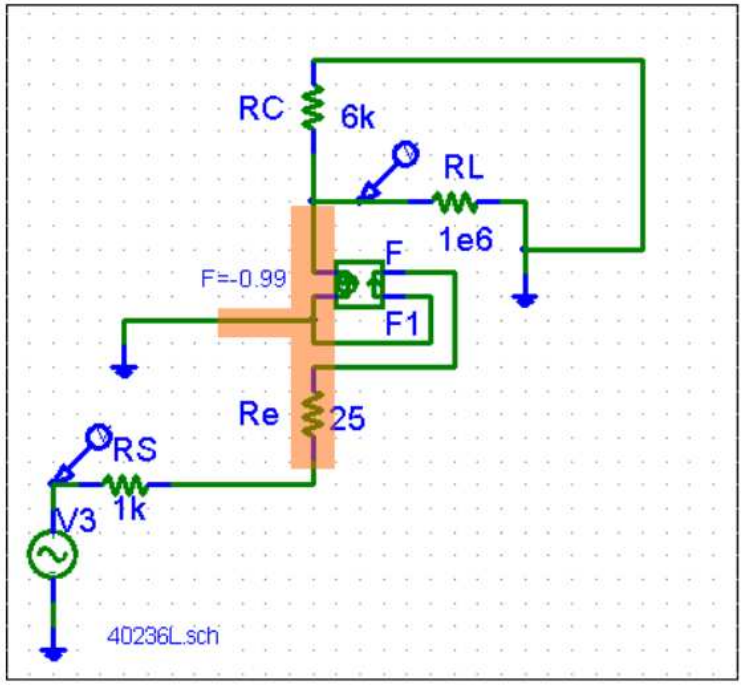
$$v_{out}^{(AC)} = -i_c^{(AC)}(R_C \parallel R_L) = -\alpha i_e^{(AC)}(R_C \parallel R_L) = -\alpha \frac{v_b^{(AC)}}{r_e + R_E}(R_C \parallel R_L)$$

Common Base Amplifier

Circuit Diagram



AC Tee Model



CB Amp: Simplified AC Model

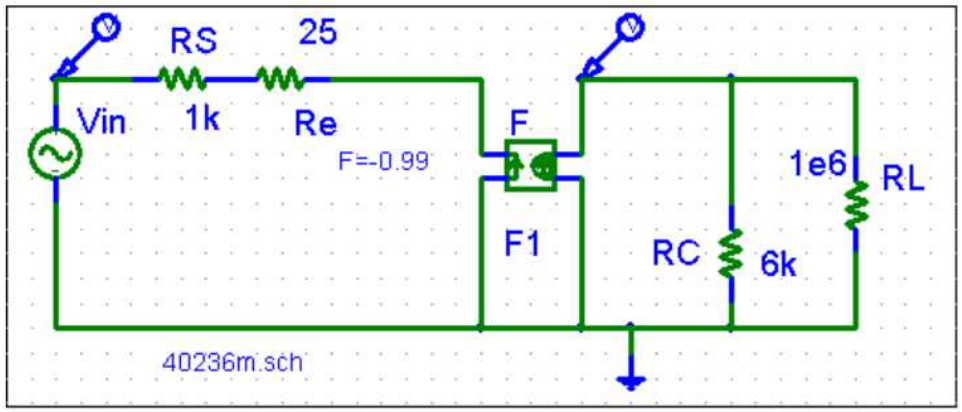
Voltage Gain

$$v_{out}^{(AC)} = -\alpha i_e^{(AC)} (R_C \parallel R_L)$$

$$v_{out}^{(AC)} = -\alpha \left(- \frac{v_{in}^{(AC)}}{r_e + R_s} \right) (R_C \parallel R_L)$$

$$A_V = \alpha \frac{R_C \parallel R_L}{r_e + R_s}$$

$$A_V = \frac{\beta}{\beta + 1} \frac{R_C \parallel R_L}{R_s + \frac{V_T}{I_E^{(DC)}}}$$



Current Gain

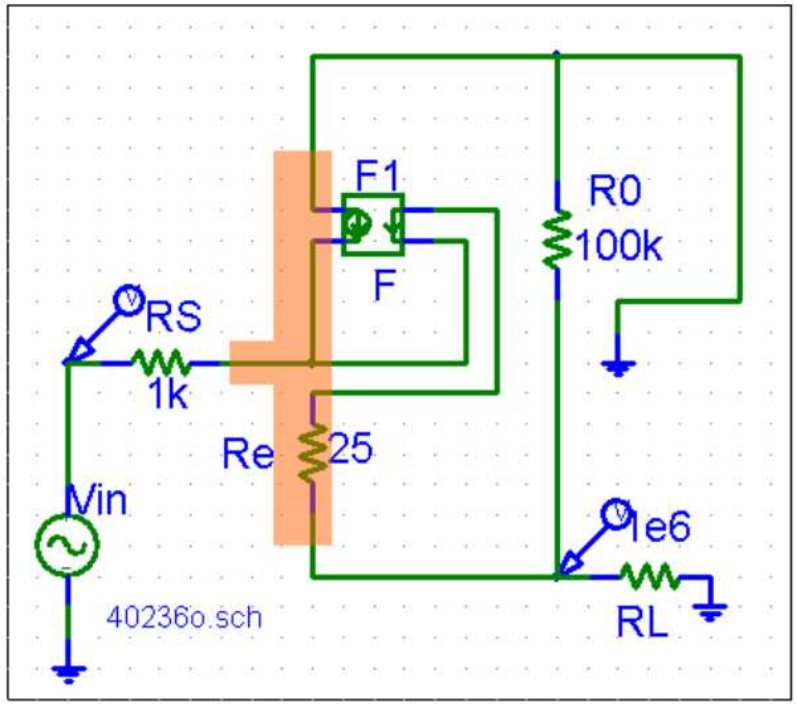
$$A_i = \frac{\beta}{\beta + 1} \frac{R_C}{R_L + R_C}$$

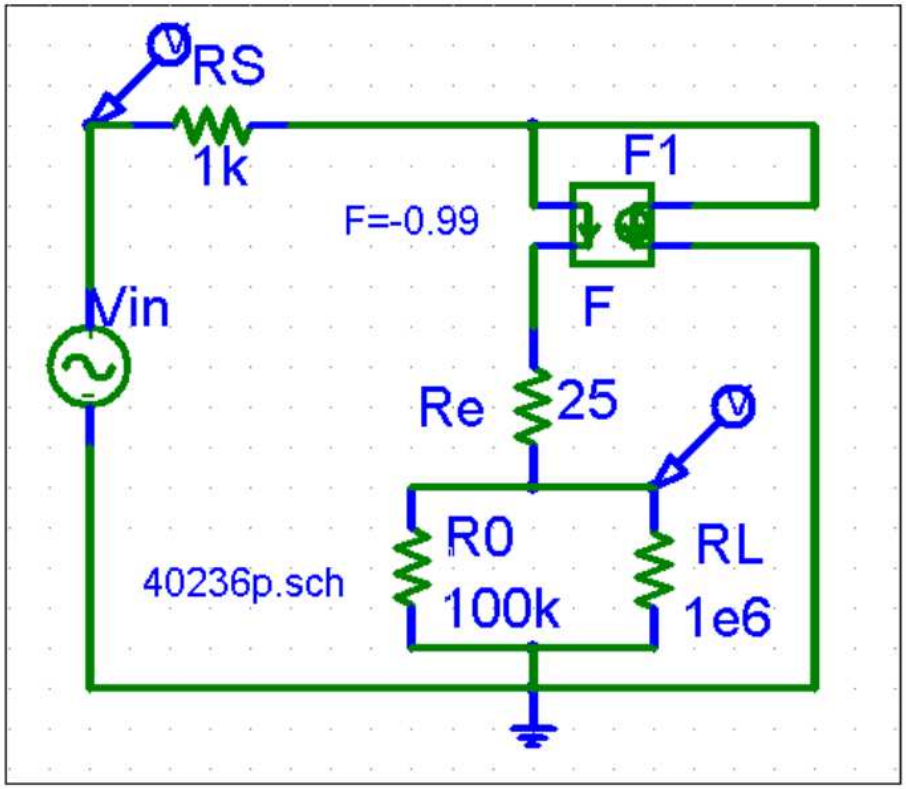
$$A_i \xrightarrow{R_L \to 0} 1$$

Output Impedance

$$R_{out} = R_C$$

CC Amp: Simplified AC Model





BJT Amplifier Parameters

	Voltage Gain	Current Gain	Input Resistance	Output Resistance
CE	$-\dfrac{\beta(R_C \parallel R_0 \parallel R_L)}{R_s + \dfrac{(\beta+1)V_T}{I_E^{(DC)}}}$	$-\beta\dfrac{R_C \parallel R_0}{(R_C \parallel R_0)+R_L}$	$(\beta+1)\dfrac{V_T}{I_E^{(DC)}}$	$R_C \parallel R_0$
CER	$-\dfrac{\beta}{\beta+1}\dfrac{R_C \parallel R_L}{R_S + \dfrac{V_T}{I_E^{(DC)}} + R_E}$	$-\beta\dfrac{R_C}{R_C+R_L}$	$(\beta+1)\left(\dfrac{V_T}{I_E^{(DC)}}+R_E\right)$	R_C
CB	$\dfrac{\beta}{\beta+1}\dfrac{R_C \parallel R_L}{R_s + \dfrac{V_T}{I_E^{(DC)}}}$	$\dfrac{\beta}{\beta+1}\dfrac{R_C}{R_L+R_C}$	$\dfrac{V_T}{I_E^{(DC)}}$	R_C
CC	$\dfrac{R_0 \parallel R_L}{\dfrac{V_T}{I_E^{(DC)}}+(R_0 \parallel R_L)+\dfrac{R_s}{(\beta+1)}}$	$\beta+1$	$(\beta+1)\left[\dfrac{V_T}{I_E^{(DC)}}+(R_0 \parallel R_L)\right]$	$R_0 \parallel \left(\dfrac{V_T}{I_e^{(DC)}}+\dfrac{R_s}{\beta+1}\right)$

Typical Applications

CE

High Gain

CER

Lower Gain, Higher Inputs

CB

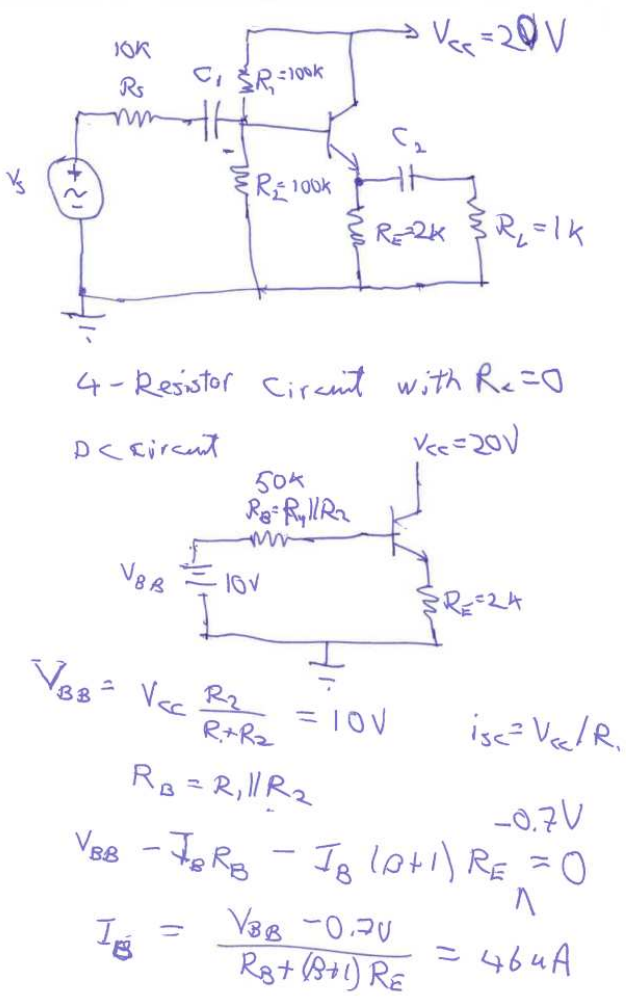
Current Buffer: Input looks like a short, output like a current source

CC

Voltage Buffer: Input looks like $R_L\ \beta$, Output like $R_s/\ \beta$

Common Collector Example (1)

- Goal: $A_V = 1$ for AC
- Solve DC
- AC Parameters: r_π
- Solve AC "Midband"
- Solve AC vs. Frequency

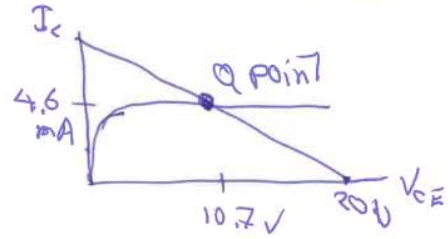


Common Collector Example (2)

- Finish DC

$I_C = \beta I_B = 4.6\,mA$ (Good!)

$V_{CE} = V_C - (\beta+1) I_B R_E = 10.7\,V$



- AC Parameters: r_π

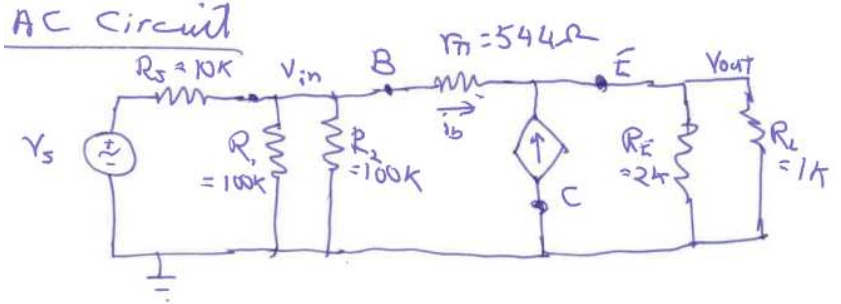
Small signal model

$r_\pi = \frac{\beta V_t}{I_C} = \frac{100 \times 25mV}{4.6\,mA} = 544\,\Omega$

$\beta = 100$

- Start AC Solution

AC circuit



Common Collector Example (3)

- Midband AC Analysis
- Then vs. Frequency

$$Z_S = R_S + \frac{1}{j\omega C_1}$$

$$Z_L = R_L + \frac{1}{j\omega C_2}$$

New $A + v$ multiplied by . . .

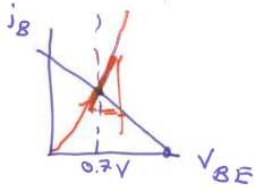
$$\frac{R_L}{Z_L}$$

$v_{in} = i_b r_\pi + (\beta+1) i_b (R_E \| R_L)$

$v_{out} = (\beta+1) i_b (R_E \| R_L)$

$A_v = \frac{v_{out}}{v_{in}} = \frac{R_E \| R_L}{R_E \| R_L + \frac{r_\pi}{\beta+1}} = \frac{666\,\Omega}{666\,\Omega \; \frac{544}{101}}$

$A_v = 0.992$



input impedance

$Z_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{i_b} = r_\pi + (\beta+1)(R_E \| R_L)$

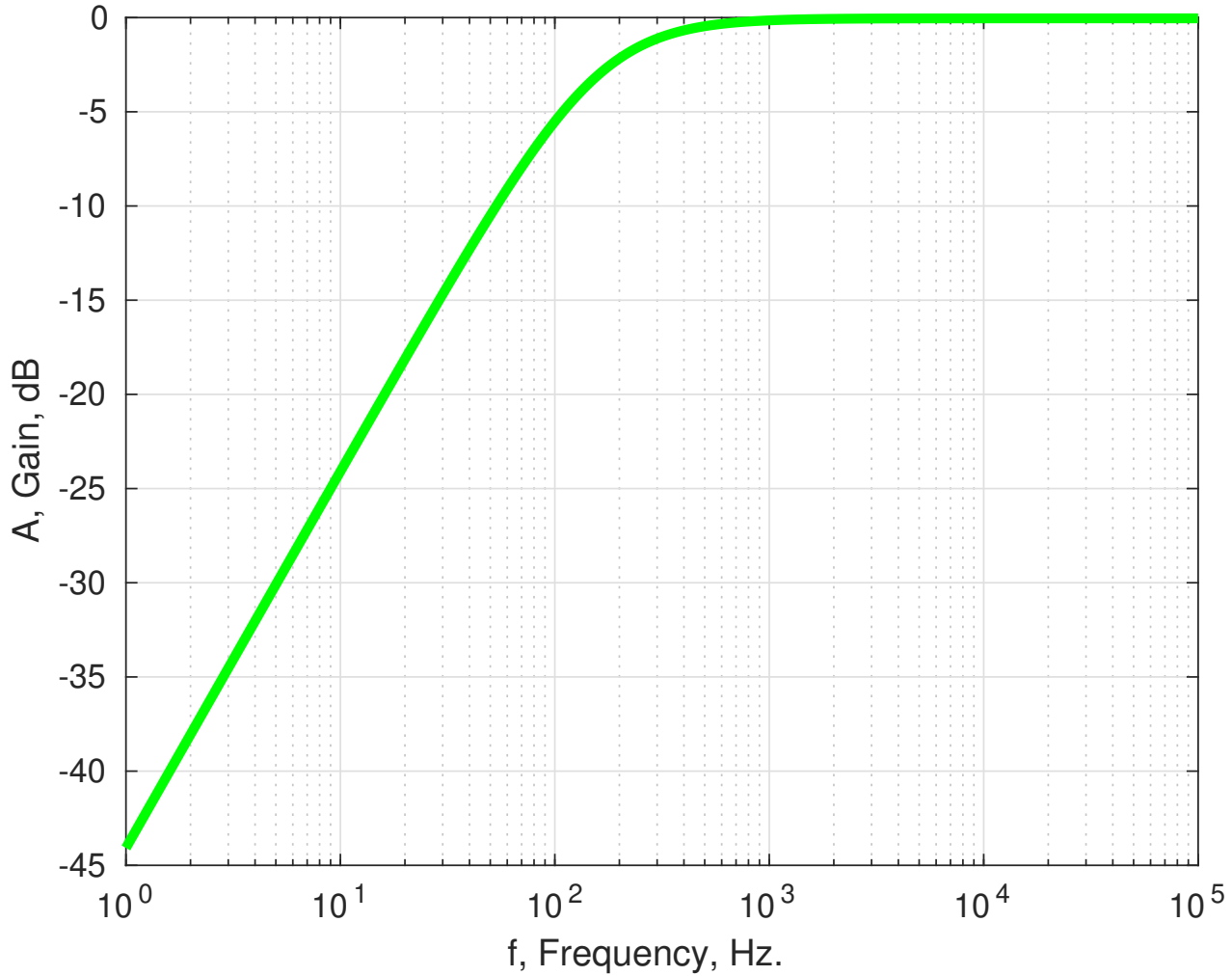
$= 544 + 101 \times 666 = 67.3k$

output impedance.

$z = R_E \| \frac{r_\pi + (R_S \| R_1 \| R_2)}{\beta+1} \approx 2k \| \frac{10k}{101}$

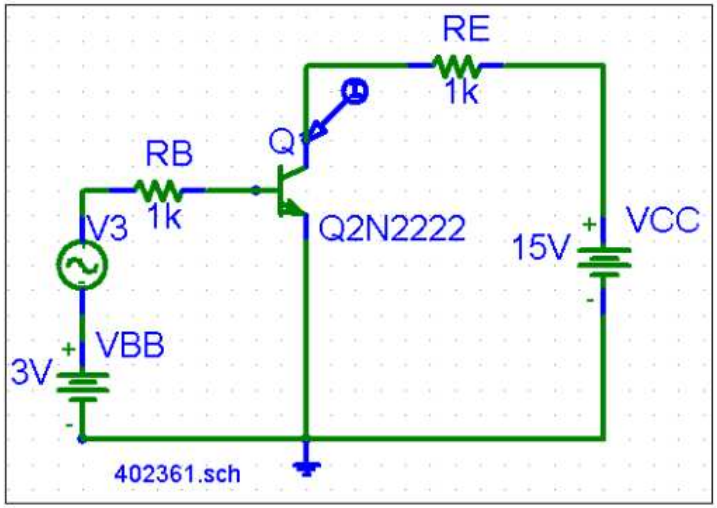
$z \approx 100\,\Omega$

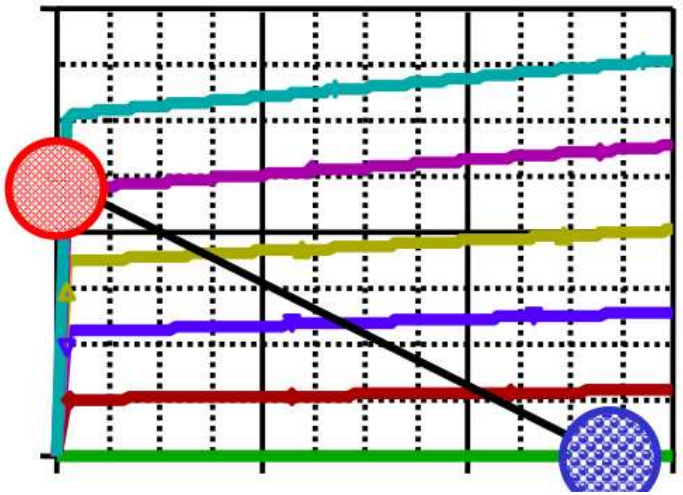
Common Collector Example (4)



Transistor Modes

- Active Mode
  - Forward Biased BE Jct
  - Reverse Biased BC
- Cutoff Mode
  - Zero or Reverse BE
  - Zero or Reverse BC
- Saturation
  - Forward Biased BE
  - Forward Biased BC





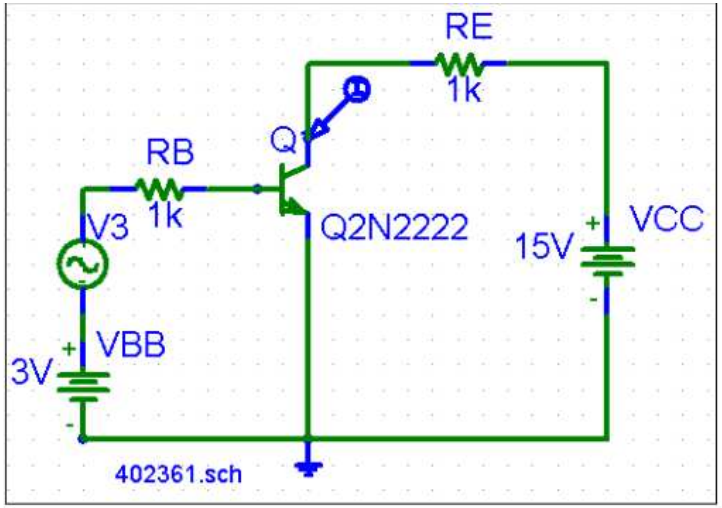
Cutoff

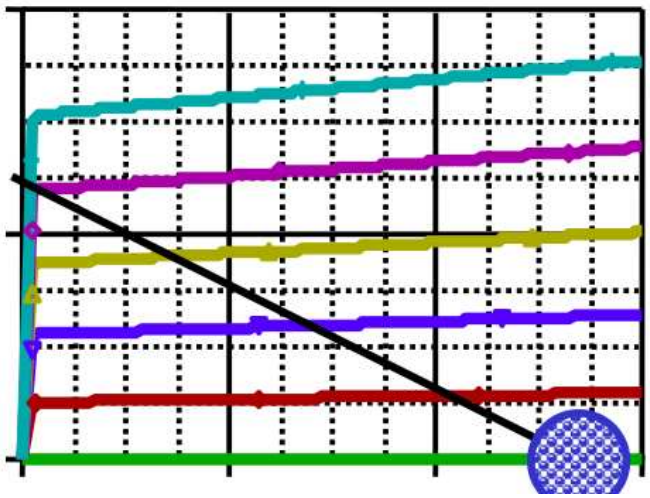
- Zero or Reverse BE Junction
- Zero or Reverse BC Junction

$$i_B = 0$$

$$i_C = 0$$

$$V_C = V_{CC}$$



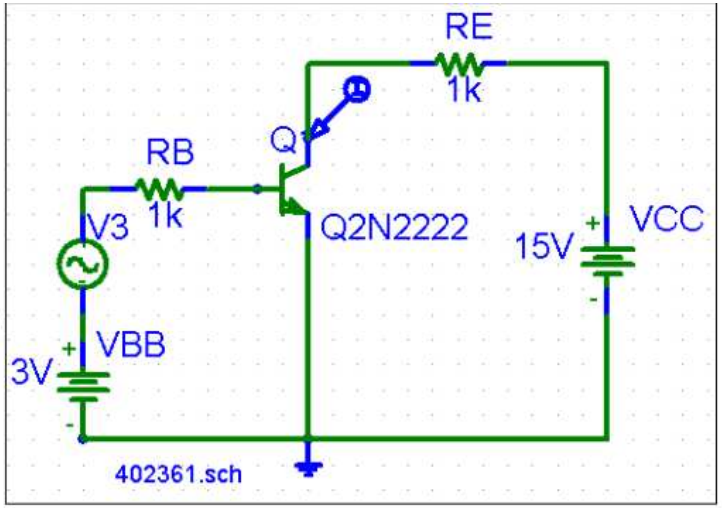


Saturation

$$V_{BC} = 0.5 \text{ Volts}$$

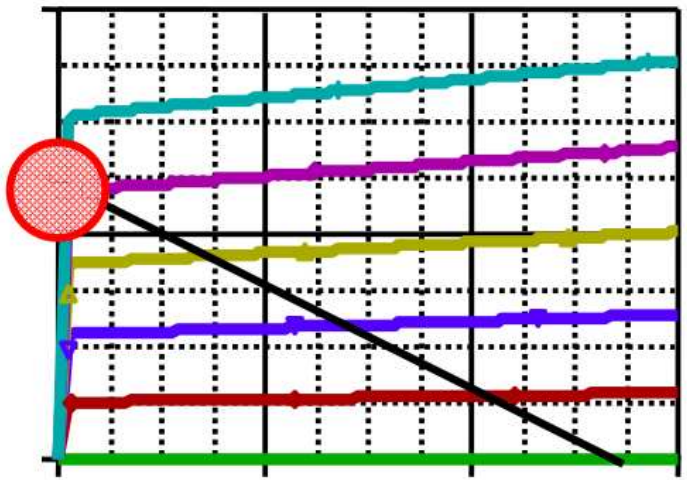
$$V_{BE} = 0.7 \text{ Volts}$$

$$\hat{I}_C = \frac{V_{CC} - V_{CEsat}}{R_C} \approx \frac{V_{CC} - 0.2\,\text{V}}{R_C}$$

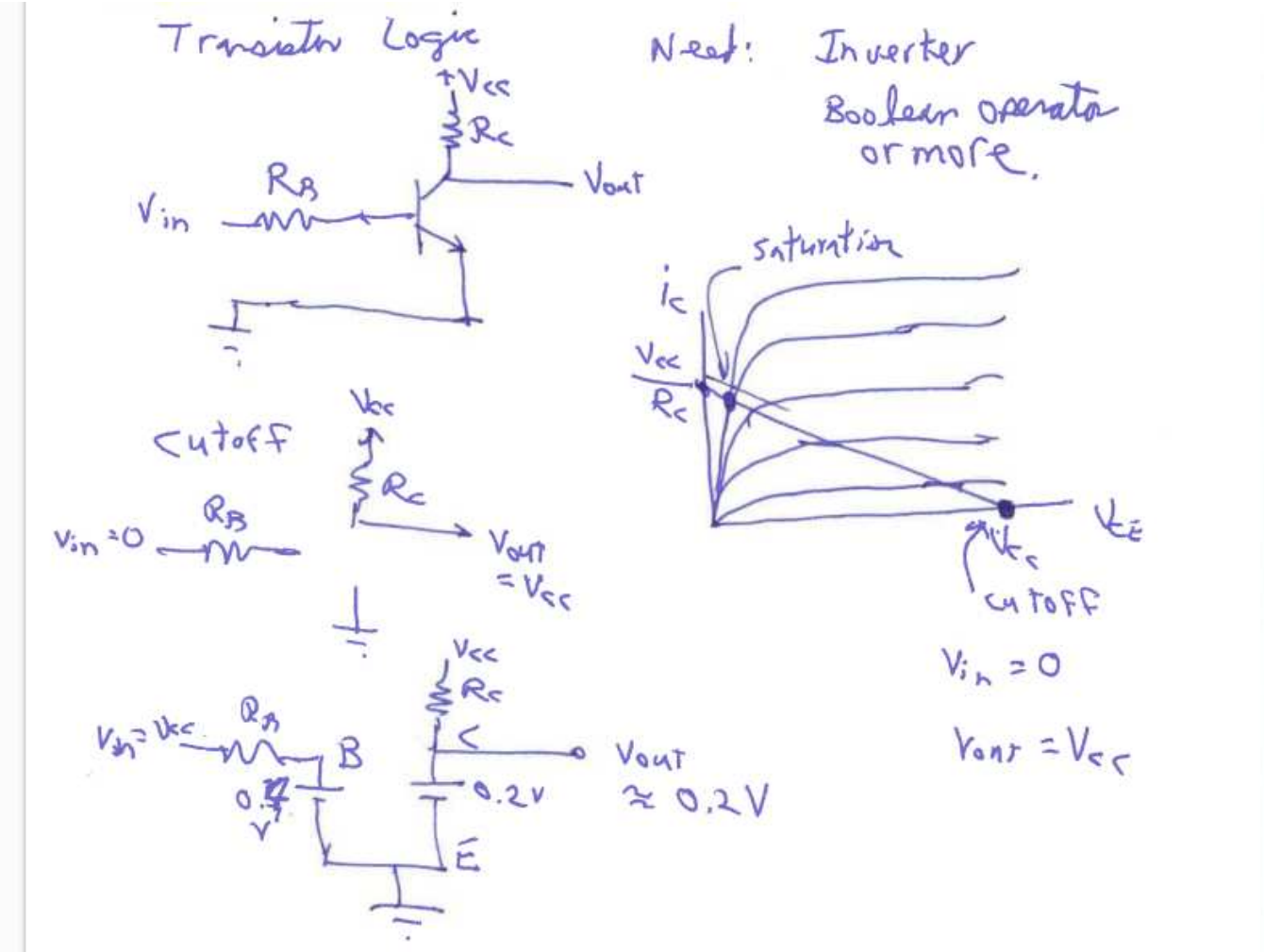


Edge of Saturation

$$I_{Beos} = \frac{I_{Csat}}{\beta}$$



Resistor-Transistor Logic



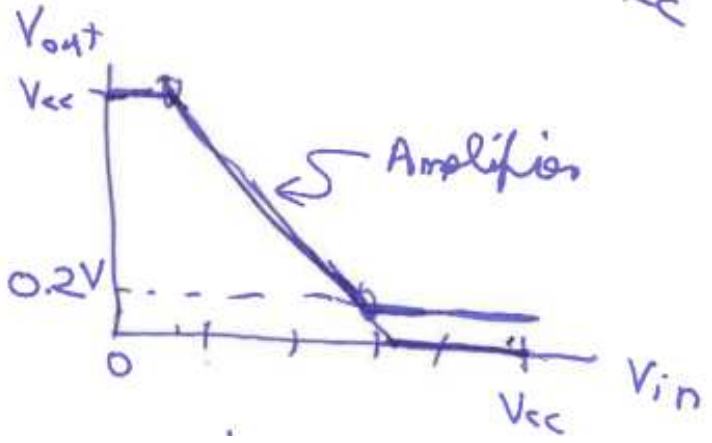
Logic Inverter

$V_{out} = 5V$

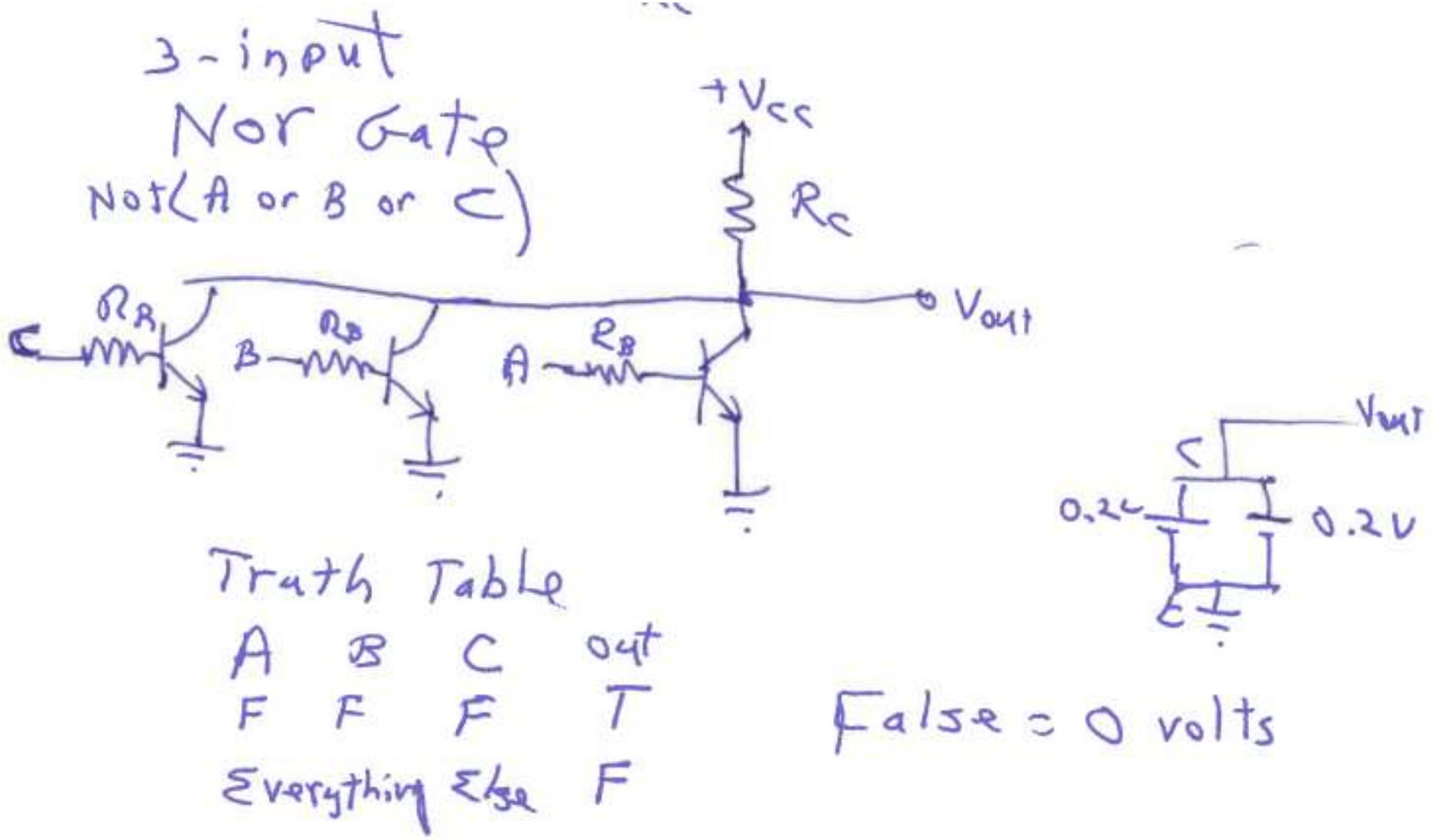
$P = \frac{V_{out}^2}{R_{load}} = \frac{25V^2}{R_{load}}$

$V_{out} = 0$

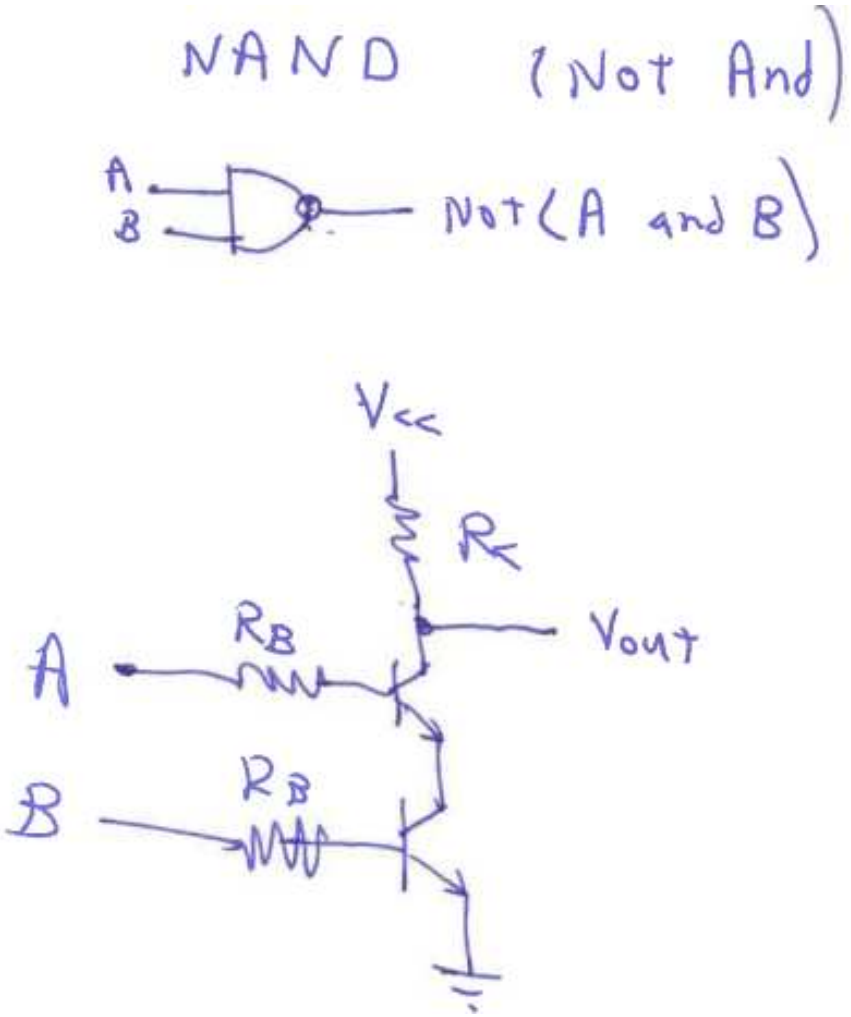
$P = \frac{V_{cc}^2}{R_c} = \frac{25V^2}{R_c}$



Logic NOR Gate



Logic NAND Gate



A	B	out
T	T	F
T	F	T
F	T	T
F	F	T