McMaster University

Electrical and Computer Engineering Department

EE3EJ4 Electronic Devices and Circuits II - Fall 2025

Lab. 1 Device Characterization and Biasing Circuits

Lab Report Due on Sep. 21, 2025

Objective: These are the objectives of this lab.

- Review all available functions on the Analog Discovery 2 (or 3) (AD2/3)
- Simulate and characterize the bipolar junction transistors
- Analyze, simulate, and construct the constant current sources

Attributes Evaluated: These are the attributes you need to demonstrate in your solutions.

- **Competence in specialized engineering knowledge to simulate circuit performance using a SPICE-based circuit simulator and conduct analog circuit debugging;**
- **Ability to obtain substantiated conclusions as a result of a problem solution, including recognizing the limitations of the approaches and solutions and**
- **Ability to assess the accuracy and precision of results.**

Test Equipment:

- Analog Discovery 2 (or 3) (AD2/3)
- WaveForms from Digilent Link
- Analog Discovery 2 Quick Start Series Videos
- WaveForms Reference Manual

Components:

- Transistors: 1 × NPN-BJT 2N3904 1 × PNP-BJT 2N3906
- Resistors: 1 × 100 kΩ resistor 1 × 100 Ω resistor

Information of Components:

For a detailed description of these transistors, please check the following websites:

https://www.onsemi.com/pub/Collateral/2N3903-D.PDF

https://www.onsemi.com/pub/Collateral/2N3906-D.PDF

Reminder: Switch off the DC power suppliers first whenever you need to change the circuit configurations. Switch on the DC power suppliers only when you no longer have to change the circuit connection.

Part 1: DC Characterization of an NPN-BJT 2N3904

Description of DC Characterization

To use a bipolar junction transistor in circuit design, we need to know its I_C vs. V_{CE} characteristics and DC/AC parameters. These parameters include the common-emitter current gain $\beta = I_C/I_B$ (6.2), the turn-on base-emitter voltage V_{BEon}, the Early voltage V_A (as defined in Figure 6.18), the transconductance g_m (7.63), the input base-emitter resistance r_π (7.67), and the output resistance r_o (6.19). This section develops the characterization procedure to obtain I_C vs. V_{CE} characteristics and these parameters using the PSpice circuit simulator. It then verifies the results by measuring an NPN-BJT 2N3904 and a PNP-BJT 2N3906 using Analog Discovery 2 or Analog Discovery 3 (AD2/3).

Installation of PSpice Circuit Simulator

Note: PSpice only supports the Windows operating system. If you use a Mac operating system, please skip this installation and use the PC provided in the lab room for your simulation work.

Follow Steps 1 – 4 under *Lab 1: Device Characterization and Biasing Circuits*/*OrCAD PSpice*/*PSpice Installation Guide* in Avenue to Learn to register and install PSpice on your PC.

A. SPICE Simulation

1.1 In Avenue to Learn, *Lab 1: Device Characterization and Biasing Circuits*, use the tutorials under the submodule "OrCAD PSpice" to prepare the circuit diagram in Fig. 1 to characterize an NPN-BJT 2N3904. Because AD2/3 only measures voltages, we use R_1 and R_2 in Fig. 1 as the current sensors and obtain $I_B = -V(Q_{1B})/R_1$ and $I_C = [V_{CC} - V(Q_{1C})]/R_2$.

1.2 **DC Characteristics:** Set V_E = -5 V and run DC simulation by sweeping V_{CC} from 0.5 V to 5 V with a 0.5 V step. In the PSpice simulator window, (1) Edit -> Select All, and (2) Edit -> Copy. Open Excel and paste the data into an Excel sheet. Record the collector voltage $V(Q_{1C})$ and the base voltage $V(Q_{1B})$ in columns C and D in the sheet "Steps 1.2-1.4" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

1.3 Based on the definition of V_A in Fig. 6.18 in the textbook, use the I_C vs. V_{CE} plot for V_E = -5V in the Excel file, calculate the V_A value for V_E = -5 V, and record it in column L in the sheet "Step 1.2" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

1.4 Repeat Steps 1.2 and 1.3 above with V_E from -4.5V and -1 V with 0.5 V step, respectively.

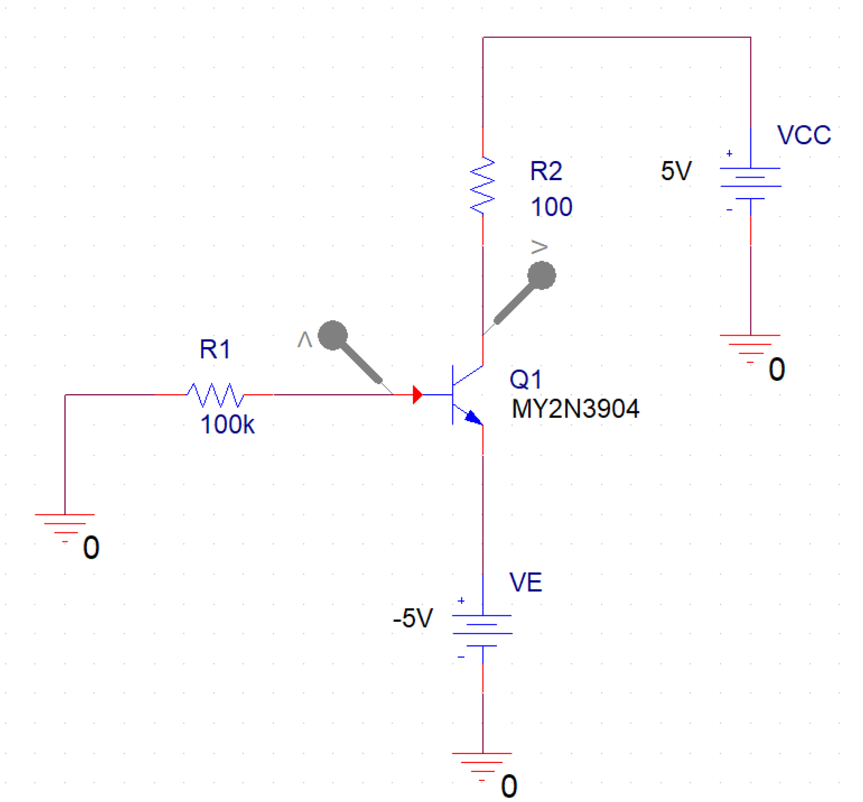


Fig. 1 The schematic diagram for the DC characterization of an NPN-BJT 2N3904

B. AD2/3 Measurement

1.5 As shown in Fig. 2, prepare the circuit using the same VE and VCC settings in Steps 1.2 to 1.4.

1.6 **DC Characteristics:** Start the WaveForms program, click Workspace, open the provided script function workspace file "Lab1_Step1.6.dwf3work", and press Run. This script function takes about 10 minutes to complete all sweep measurements automatically. Monitor the measurement progress by clicking the Supplies tag at the bottom of the Output window. The last measurement is done at V+ = 5V and V- = -1V. Click on the Script tag, select all data in the Output window, and right-click to save them into a text file "Lab1_Step1.6.txt".

1.7 Run Excel and open the text file "Lab1_Step1.6.txt". Choose Delimited as the file type, Comma in Delimiters, and General in Column data format to import the data. Select and copy the whole data. Go to a new sheet, right-click the destination cell A1, choose Paste Special from the context menu, and select Transpose.

1.8 Copy the measured collector voltage V_C and the base voltage V_B for each V- (or V_E) to the corresponding cells in columns C and D in sheet "Step 1.8" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

1.9 Based on the definition of V_A in Fig. 6.18 in the textbook, use the I_C vs. V_{CE} plot for each V_E value in the Excel file, remove the outliers (right-click the data cell and choose Clear Contents) to have $R^2 \geq 0.9$, calculate their V_A values using the linear fitted dashed line, and record it in column L in the sheet "Step 1.8" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

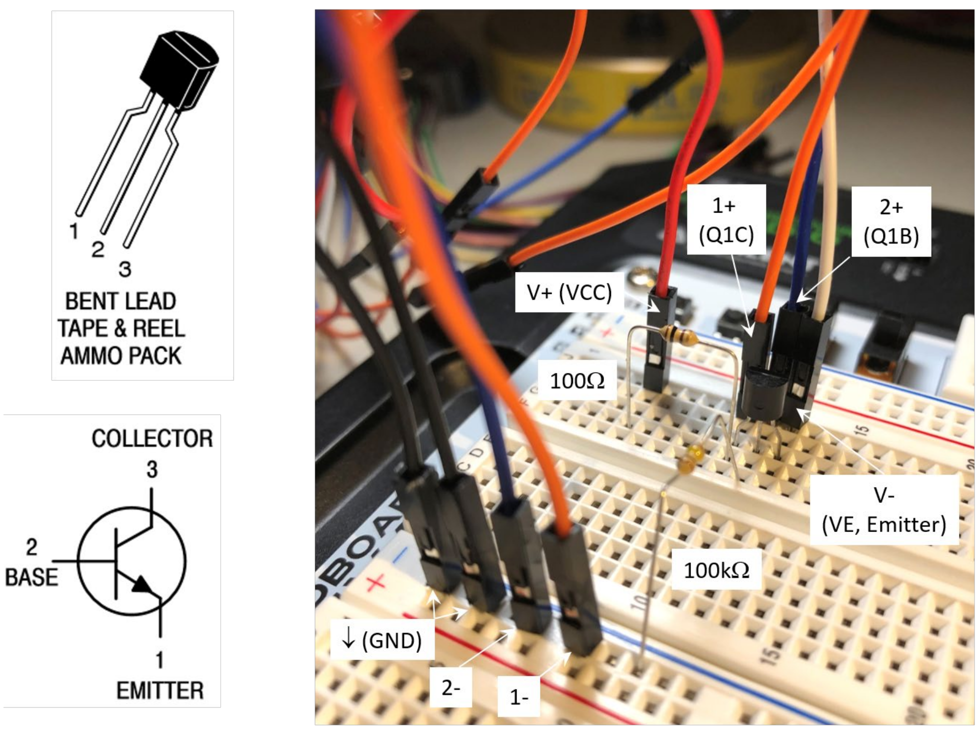


Fig. 2 Experimental setup for the DC characterization of an NPN-BJT 2N3904

C. Questions for Part 1

For the NPN-BJT 2N3904 characterized, if we want to bias this device to conduct a collector current I_C $\approx$ 1.0 mA at the lowest V_{CE} value, answer the following questions.

Q1. (7 Points) Based on the simulated data in Steps 1.2-1.4, use the bias condition giving the closest I_C value to the desired collector current, find out

(1) What are the simulated V_{BEon} in volts and the base current I_B in μA?

(2) What is the $\beta = I_C/I_B$ value at this I_C?

(3) What is the early voltage $|V_A|$ in volts?

(4) What is the output resistance r_o in kΩ?

(5) What is the transconductance g_m in mS?

(6) What is the input resistance r_π in kΩ?

Q2. (8 Points) Based on the measured data in Step 1.8, use the same bias condition found in Q1 (or the first reliable data if that bias condition is an outlier), find out

(1) How much is the measured collector current I_C in mA?

(2) What are the measured V_{BEon} in volts and the base current I_B in μA?

(3) What is the $\beta = I_C/I_B$ value at this I_C?

(4) What is the early voltage $|V_A|$ in volts?

(5) What is the output resistance r_o in kΩ?

(6) What is the transconductance g_m in mS?

(7) What is the input resistance r_π in kΩ?

Part 2: DC Characterization of a PNP-BJT 2N3906

A. SPICE Simulation

2.1 In Avenue to Learn, *Lab 1: Device Characterization and Biasing Circuits*, use the provided information to prepare the circuit diagram shown in Fig. 3 to characterize a PNP-BJT 2N3906.

2.2 **DC Characteristics:** Set V_E = 5 V and run DC simulation by sweeping V_{CC} from -5 V to -0.5 V with a 0.5 V step. In the PSpice simulator window, (1) Edit -> Select All, and (2) Edit -> Copy. Open Excel and paste the data into an Excel sheet. Record the collector voltage $V(Q_{1C})$ and the base voltage $V(Q_{1B})$ in columns C and D in the sheet "Steps 2.2-2.4" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

2.3 Based on the definition of V_A in Fig. 6.18 in the textbook, use the I_C vs. V_{EC} plot for V_E = 5V in the Excel file, calculate the $|V_A|$ value for V_E = 5 V and record it in column L in the sheet "Step 2.2" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

2.4 Repeat Steps 2.2 and 2.3 above with V_E from 4.5V to 1 V with -0.5 V step, respectively.

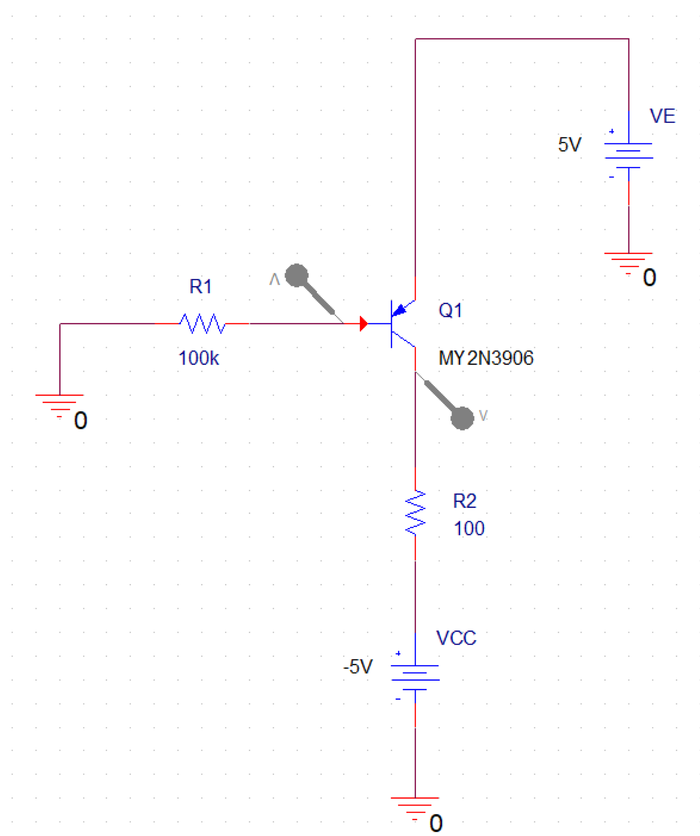


Fig. 3 The schematic diagram for the DC characterization of a PNP-BJT 2N3906

B. AD2/3 Measurement

2.5 As shown in Fig. 4, prepare the circuit using the same VE and VCC settings in Steps 2.2 to 2.4.

2.6 **DC Characteristics:** Start the WaveForms program, click Workspace, open the provided script function workspace file “Lab1_Step2.6.dwf3work”, and press Run. This script function takes about 10 minutes to complete all sweep measurements automatically. Monitor the measurement progress by clicking the Supplies tag at the bottom of the Output window. The last measurement is done at V+ = 1V and V- = -0.5V. Click on the Script tag, select all data in the Output window, and right-click to save them into a text file “Lab1_Step2.6.txt”.

2.7 Run Excel and open the text file “Lab1_Step2.6.txt”. Choose Delimited as the file type, Comma in Delimiters, and General in Column data format to import the data. Select and copy the whole data. Go to a new sheet, right-click the destination cell A1, choose Paste Special from the context menu, and select Transpose.

2.8 Copy the measured collector voltage V_C and the base voltage V_B for each V+ (or V_E) to the corresponding cells in columns C and D in sheet “Step 2.8” of the Excel file “Lab 1 – DC Characterization and Current Sink.xlsx”.

2.9 Based on the definition of V_A in Fig. 6.18 in the textbook, use the I_C vs. V_{CE} plot for each V_E value in the Excel file, remove the outliers (right-click the data cell and choose Clear Contents) to have $R^2 \geq 0.9$, calculate their V_A values using the linear fitted dashed line, and record it in column L in the sheet “Step 2.8” of the Excel file “Lab 1 – DC Characterization and Current Sink.xlsx”.

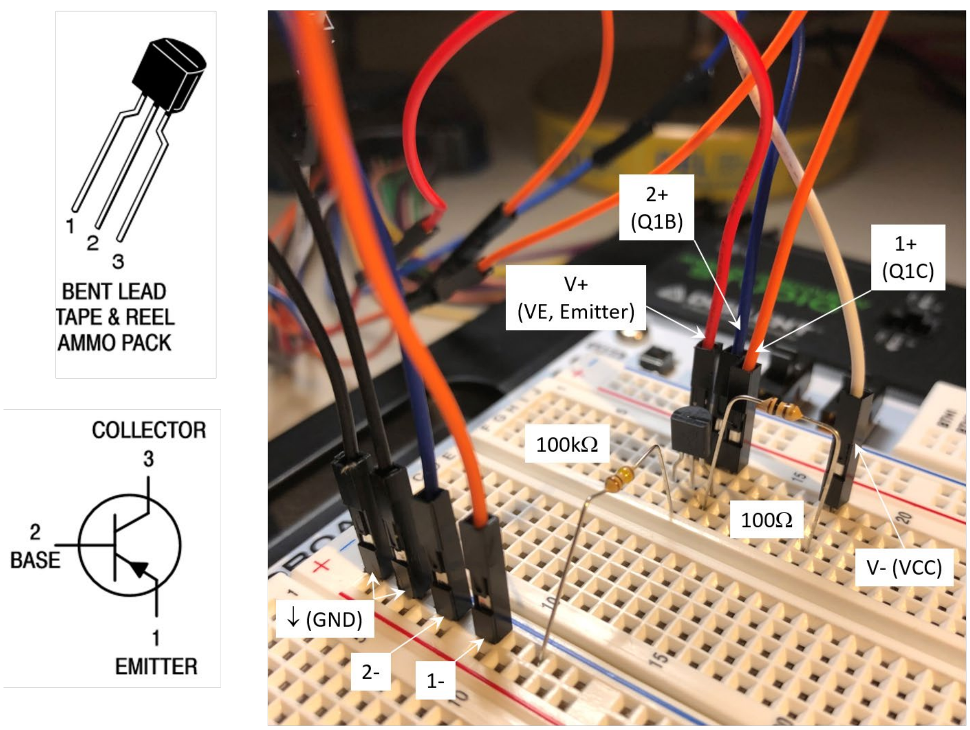


Fig. 4 Experimental setup for the DC characterization of a PNP-BJT 2N3906

C. Questions for Part 2

For the PNP-BJT 2N3906 characterized, if we want to bias this device to conduct a collector current $I_C \approx 1.0$ mA at the lowest V_{EC} value, answer the following questions.

Q3. (7 Points) Based on the simulated data in Steps 2.2-2.4, use the bias condition giving the closest I_C value to the desired collector current, find out

(1) What are the simulated V_{EBon} in volts and the base current I_B in μA?

(2) What is the $\beta = I_C/I_B$ value at this I_C?

(3) What is the early voltage $|V_A|$ in volts?

(4) What is the output resistance r_o in kΩ?

(5) What is the transconductance g_m in mS?

(6) What is the input resistance r_π in kΩ?

Q4. (8 Points) Based on the measured data in Step 2.8, use the same bias condition found in Q3 (or the first reliable data if that bias condition is an outlier), find out

(1) How much is the measured collector current I_C in mA?

(2) What are the measured V_{EBon} in volts and the base current I_B in μA?

(3) What is the $\beta = I_C/I_B$ value at this I_C?

(4) What is the early voltage $|V_A|$ in volts?

(5) What is the output resistance r_o in kΩ?

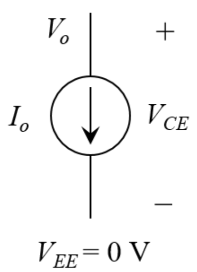
(6) What is the transconductance g_m in mS?

(7) What is the input resistance r_π in kΩ?

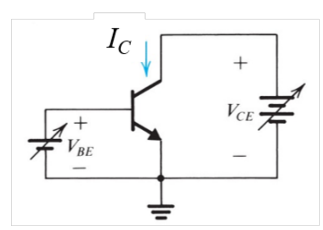
Part 3: Design of a Current Source/Sink

The function of a current source/sink is to deliver a constant current, regardless of the voltage drop across its terminals, as shown in Fig. 5. The current source is located between the V_{CC} (the highest voltage used in the system) and the supporting circuit, while the current sink sits between the supporting circuit and the ground (or $V_{EE} < 0$, the lowest voltage used in the system). In this section, we need to consider the following to implement this function using a BJT.

1. **Biasing:** We need to bias the BJT to work in the active region to deliver a constant current, assuming its $|V_A|$ is infinite. According to Fig. 6.14 in the textbook, it requires that we set its $|V_{BE}| = V_{BEon} \approx 0.7\text{V}$ and $|V_{CE}| \geq 0.3\text{V}$.
2. **Current:** Since the BJT works as a current amplifier, we need to control I_B to deliver a constant current $I_C = \beta \cdot I_B$.
3. **Output Resistance:** To provide constant current, we need to reduce the current change due to the Early effect $|V_A|$. To evaluate the Early effect, we calculate the output resistance R_o of the current source. If the BJT has no Early effect, the output resistance R_o of the current source is infinite.
4. **Maximum/Minimum Output Voltage:** Since $|V_{CE}| \geq 0.3\text{V}$ is required for a BJT to work in the active region, the minimum output voltage, $V_{o,min}$ of a current sink is $V_{o,min} = V_{EE} + 0.3$ V, and the maximum output voltage of a current source is $V_{o,max} = V_{CC} - 0.3\text{V}$.



(a)



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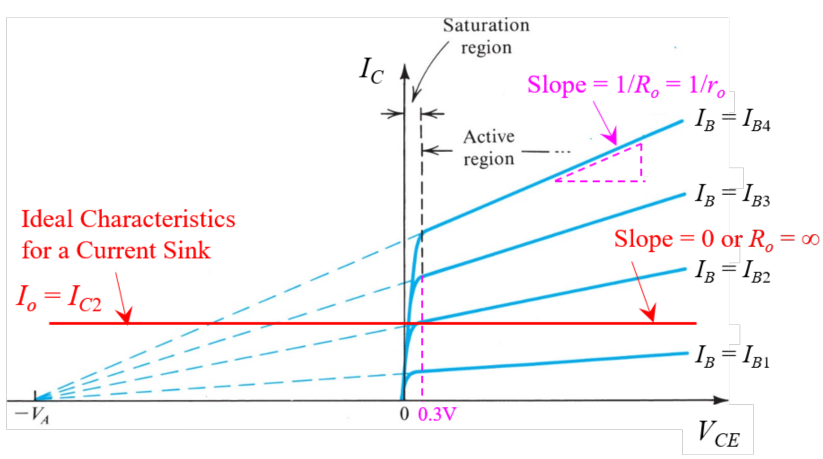

(c)

Fig. 5 (a) Ideal current sink, (b) implementation of a current sink using an NPN-BJT, and (c) ideal and actual characteristics of a current sink.

A. SPICE Simulation

3.1 In PSpice, construct a current sink as shown in Fig. 6 and load the SPICE 3 model parameters for Q1 following the same procedure as in Step 1.1.

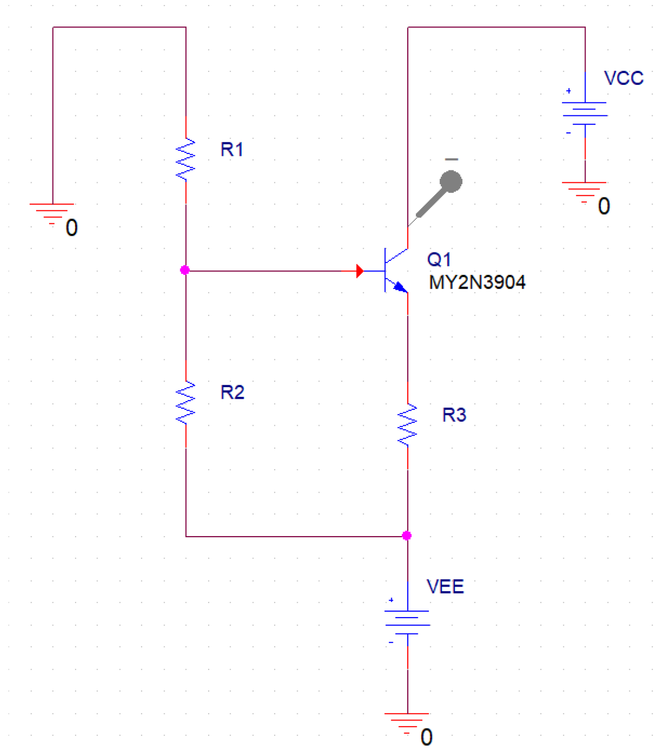

Fig. 6 Constant current sink using an NPN-BJT 2N3904

3.2 Simplify the base circuit using Thevenin's theorem and calculate the equivalent based voltage V_{BB} and resistance R_{BB} by

$$V_{BB} = V_{EE} + \frac{R_2}{R_1 + R_2}(0 - V_{EE}) = V_{EE} - \frac{R_2}{R_1 + R_2}V_{EE} = \frac{R_1}{R_1 + R_2}V_{EE} < 0 \tag{1}$$

and

$$R_{BB} = R_1 \,||\, R_2 = \frac{R_1 R_2}{R_1 + R_2}. \tag{2}$$

Fig. 7 shows the equivalent circuit of the constant current sink using V_{BB} and R_{BB}. If $R_3 = 0$, based on the V_{BEon} obtained in Part 1, we could obtain the base current I_B by

$$I_B = \frac{V_{BB} - (V_{EE} + V_{BEon})}{R_{BB}} = \frac{R_2}{(R_1 + R_2)}\frac{(-V_{EE})}{R_{BB}} - \frac{V_{BEon}}{R_{BB}} > 0. \tag{3}$$

Note that $-V_{EE} > 0$ and $V_{BB} < 0$ in (3). From (1) and (3), we notice that if there is a change in the supply voltage V_{EE}, the base current I_B will also change by a proportional amount. Here, we apply a feedback technique to stabilize the transistor's base current (or Q-point).

To avoid the change in I_B, we connect R_3 to the emitter of the BJT, as shown in Fig. 6, to work as a feedback resistor. For example, if $|V_{EE}|$ reduces, which causes I_B to be smaller than the designed value, the resulting I_E will produce a smaller voltage drop across R_3 and reduce V_E at the emitter terminal of Q_1. This reduced V_E will increase the V_{BE} of Q_1 and, therefore, I_B.

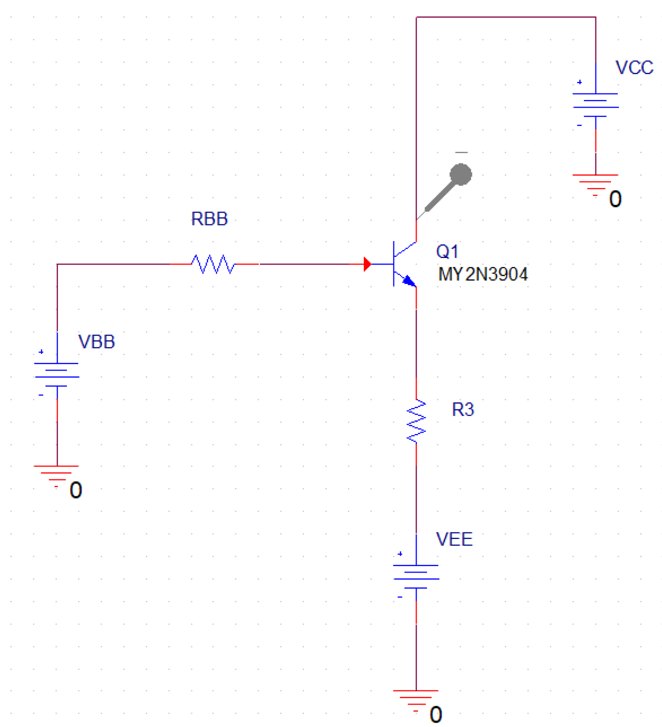

Fig. 7 The equivalent circuit for the constant current sink in Fig. 6 with R_1, R_2, and power supply replaced by its Thevenin equivalent circuit V_{BB} and R_{BB}.

B. Questions for Part 3

Based on the equivalent circuit in Fig. 7, answer the following questions.

Q5. (10 Points) Express the base current I_B as a function of V_{BB}, R_{BB}, V_{BEon}, R_3, V_{EE}, and β.

Q6. (10 Points) Comparing the I_B expressions obtained in Q5 and in (3), what is the difference between these two equations? For a change ΔV_{EE} in the power supply V_{EE}, derive equations for the resulting change in the base current ΔI_B using the I_B expressions obtained in Q5 and in (3). Show that the emitter resistor R_3 reduces the change in the base current ΔI_B as a result of the change ΔV_{EE} in the power supply V_{EE}.

Q7. (15 Points) Inserting the feedback R_3 at the emitter of the BJT not only stabilizes the I_B but also improves (or increases) the output resistance R_o of the current sink shown in Fig. 6/Fig. 7 (i.e., I_o is more stable when there is a change in V_{CE}). Using a π-model for the BJT, prove that the output resistance of the current sink is $R_o = r_o + \left[R_3 \,||\, \left(R_{BB} + r_\pi\right)\right]\left[1 + g_m r_o \left(\frac{r_\pi}{R_{BB} + r_\pi}\right)\right]$.

Q8. (10 Points) Inserting the feedback R_3 at the emitter of the BJT improves the stabilization of the Q-point at the cost of increased $V_{o,min}$. What is the $V_{o,min}$ of the constant current sink when $R_3 \neq 0$? Express $V_{o,min}$ as a function of I_o, which is the I_C of Q1.

Q9. (15 Points) For V_{EE} = -5V, if we want to design a current sink with I_o = 1.0 mA and $V_{o,min}$ = -1 V using the NPN-BJT 2N3094 characterized in Q1, what is the resistance value for R_3? To reduce the DC power consumption of R_1 and R_2, we usually choose large resistance values (in tens or hundreds of kΩ) for R_1 and R_2. Suppose we choose R_2 = 100 kΩ, calculate R_1 in kΩ. Verify the I_o vs. V_{CC} characteristics of the design by sweeping V_{CC} from -5V to 5V with a 0.05V step and post the waveform of the simulated I_o vs. V_{CC} characteristics using the command "Window -> Copy to Clipboard" in the PSpice simulator window.

Q10. (10 Points) When designing the constant current sink shown in Fig. 6, we assume that $|V_{CE}| \geq$ 0.3V and Q_1 works in the active region. Based on the resistance values obtained in Q9, sweep V_{CC} in Fig. 6 from -5 V to +5 V with a 0.05 V step and measure V_E and I_C to determine the $|V_{CE}|$ required for Q_1 to work in the active region.