ECE 65 – Components and Circuits Lab

Lab 5 Report – BJT Circuits

Feb 13, 2025

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Abstract

The purpose of this lab is to explore the behavior of Bipolar Junction Transistors (BJTs) as a current source and as a switch in different circuit configurations.

We performed circuit analysis, simulations, and hands-on measurements to investigate how BJTs regulate current through a load and how they can be used to control external components like LEDs and buzzers. In Experiment 1, we analyzed and measured the transistor's ability to act as a current source, verifying at what load resistance values it maintains a constant current. In Experiment 2, we examined the BJT's switching behavior using an op-amp and light-dependent resistor (LDR) to activate a buzzer under different lighting conditions.

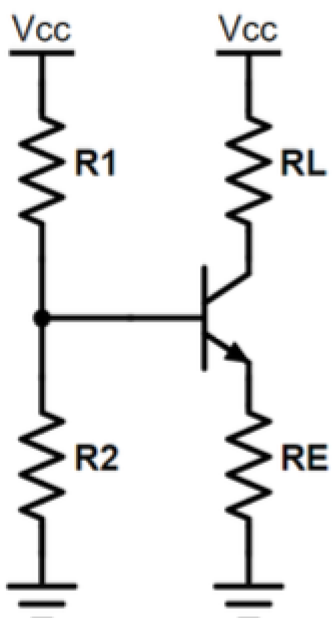
We concluded that the BJT operates as a stable current source within a specific range of load resistances but enters saturation at higher values, reducing current regulation. Additionally, we confirmed that the BJT can effectively act as a switch, but removing circuit components such as diodes affects its intended functionality. The experimental results closely aligned with our circuit analysis and simulations, with minor discrepancies attributed to real-world component tolerances.

Experimental Procedures and Results

In this lab, we use 2N3904 Si BJT, 1N4148 diodes, and LM741 op-amp for the experiments. Assume β = 200, V_{D0} = 0.7 V and V_{sat} = 0.2 V for BJT in the circuit analysis. Use the Q2N3904 BJT model and LM741/NS op-amp model in the PSpice libraries for simulations.

Experiment 1a: BJT as a Current Source

Consider the circuit below with a 2N3904 Si BJT transistor, $V_{CC} = 10\ V$, $R1 = R2 = 4.7\ k\Omega$ and $RE = 1\ k\Omega$. In this experiment, you will find out the range of RL, load resistor, for which BJT will act as a current source, i.e., constant current will flow through RL.



<u>Prelab:</u>

Circuit Analysis

1. Find the state of the transistor, I_B, I_C, I_E, V_{BE} and V_{CE} for RL = 0.5 $k\Omega$, 1 $k\Omega$ and 2.5 $k\Omega$.

In this prelab I am experimenting with using Overleaf as formatting is much easier using LaTeX. Below are screenshots from the compiled pdf, but I have the actual .tex files if they are necessary to show work.

Base and Emitter Voltages

The base voltage is given by the voltage divider:

$$V_B = V_{CC} \times \frac{R_2}{R_1 + R_2} = 10V \times \frac{4.7k\Omega}{4.7k\Omega + 4.7k\Omega} = 5V$$

Since $V_{BE} \approx 0.7V$, the emitter voltage is:

$$V_E = V_B - V_{BE} = 5V - 0.7V = 4.3V$$

Emitter and Collector Currents

Applying Ohm's Law with $R_E = 1k\Omega$:

$$I_E = \frac{V_E}{R_E} = \frac{4.3V}{1k\Omega} = 4.3mA, \quad I_C \approx I_E = 4.3mA$$

The base current is:

$$I_B = \frac{I_C}{\beta} = \frac{4.3mA}{200} = 0.0215mA$$

Collector Voltage and V_{CE} for Different R_L

The collector voltage is:

$$V_C = V_{CC} - I_C R_L$$

Case 1: $R_L = 500\Omega$

$$V_C = 10V - (4.3mA \times 500\Omega) = 7.85V, \quad V_{CE} = V_C - V_E = 3.55V$$

Since $V_{CE} > 0.2V$, the BJT is in **active mode**.

Case 2: $R_L = 1k\Omega$

$$V_C = 10V - (4.3mA \times 1k\Omega) = 5.7V, \quad V_{CE} = 1.4V$$

Since $V_{CE} > 0.2V$, the BJT remains in **active mode**.

Case 3: $R_L = 2.5k\Omega$

$$V_C = 10V - (4.3mA \times 2.5k\Omega) = -0.75V, \quad V_{CE} = -5.05V$$

Since V_{CE} is negative (impossible), the transistor is in **saturation mode**.

Summary of Results

$R_L(\Omega)$	$V_C(V)$	$V_{CE}(V)$	**State**
500	7.85	3.55	Active Mode
1000	5.7	1.4	Active Mode
2500	-0.75	-5.05	Saturation Mode

2. How does the change in load resistor value affect the collector current and the mode of operation of the transistor?

As the load resistor R_L increases, the collector voltage V_C decreases. In **active mode**, the transistor acts as a **current source**, keeping I_C nearly constant regardless of R_L. However, if R_L becomes too large, V_C drops too low, reducing V_{CE} below V_{sat}. This forces the transistor into **saturation mode**, where I_C is no longer constant and instead decreases as R_L increases. Thus, the transistor remains a reliable current source only within a certain range of R_L.

3. To what value can RL be increased while the collector current remains unchanged? Note: BJT operates as a current source when the current through the load doesn't change while changing the load resistor value.

The transistor remains in **active mode** as long as:

$$V_{CE} > V_{sat}$$

Since:

$$V_{CE} = V_C - V_E, \quad V_C = V_{CC} - I_C R_L, \quad V_E = 4.3V$$

Setting $V_{CE} = 0.2V$ and solving for R_L:

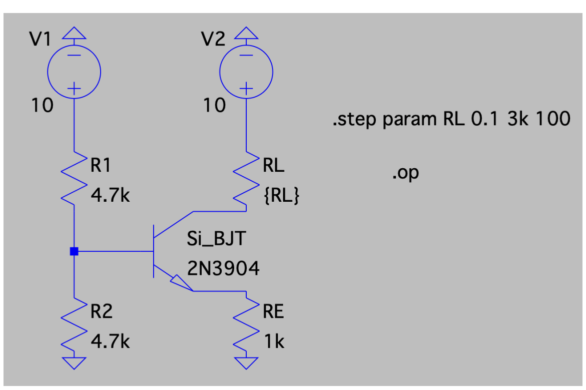
$$10V - (4.3mA \times R_L) - 4.3V > 0.2V$$

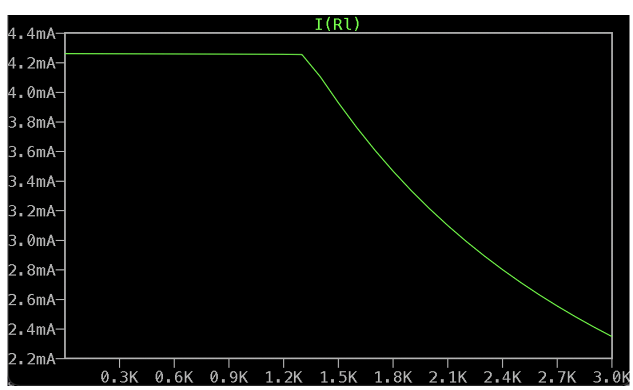
$$R_L^{\max} = \frac{10V - 0.2V - 4.3V}{4.3mA} = \frac{5.5V}{4.3mA} \approx 1.28k\Omega$$

Therefore, R_L can be increased up to **1.28kΩ** before the transistor enters **saturation mode** and I_C begins to decrease.

Simulation:

Simulate the circuit and generate a plot of I(RL) as a function of RL for RL ranging from 0.1 Ω to 3 kΩ (choose the increment in RL such that you have a meaningful plot, i.e., the curve looks nice and smooth). Is your plot consistent with the circuit analysis?



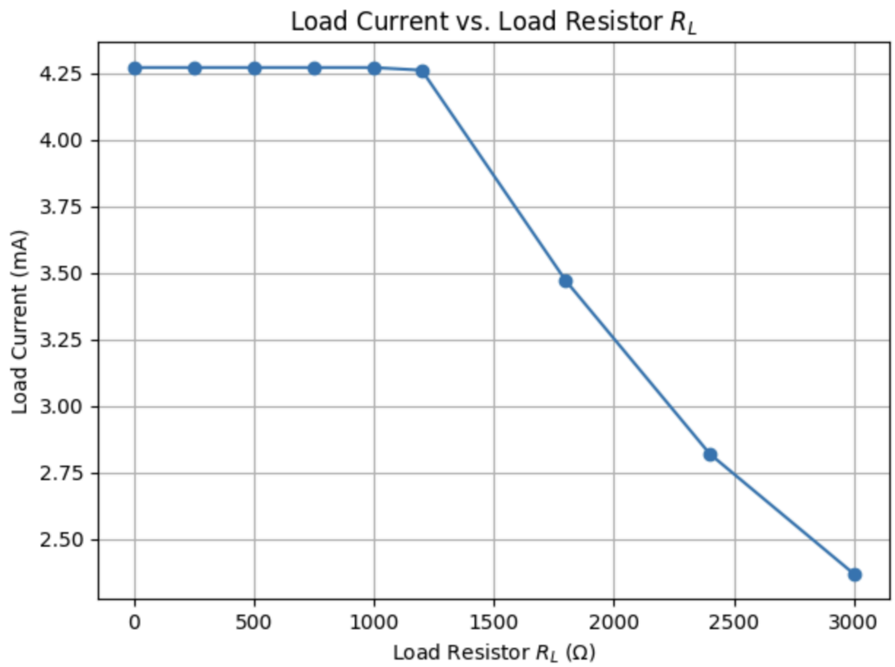


Yes our plot is consistent with our circuit analysis which gave us around 1.28kΩ.

Lab Exercise:

1. Assemble the circuit. Use a 1 kΩ potentiometer in place of RL.
2. Vary the potentiometer resistance from the lowest value (0Ω) to the highest value (1 kΩ) and measure load currents along with the corresponding resistances. Record the data for at least four different resistances in this step. Use a multimeter to measure the resistance.
3. Disconnect the 10V power supply. Replace the potentiometer with a 1.2 kΩ resistor. Reconnect the power supply and measure the load current.
4. Repeat step 3 for 1.8 kΩ, 2.4 kΩ and 3 kΩ resistors.
5. Plot load current vs. RL (use measured values in the previous steps). Compare the plot with your circuit analysis and simulation and explain any discrepancies.

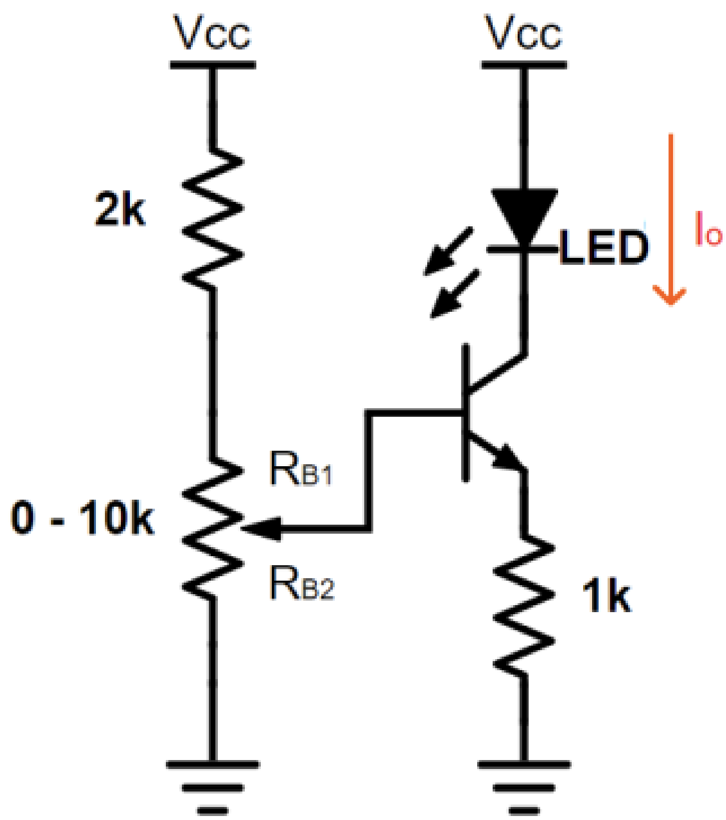
R_L	Load Current
0 Ω	4.27 mA
250 Ω	4.27 mA
500 Ω	4.27 mA
750 Ω	4.27 mA
1 kΩ	4.27 mA
1.2 kΩ	4.26 mA
1.8 kΩ	3.47 mA
2.4 kΩ	2.82 mA
3 kΩ	2.37 mA



Our in real life lab results are consistent with our prelab circuit analysis and our simulation analysis which shows the load current begins to drop off at around 1.28kΩ.

Experiment 1b: BJT as a Current Source

In part b, you will use a 351-3230-RC LED as a load instead of the RL resistor in the BJT circuit of part a. You will explore how the brightness of LED can be controlled by varying the collector current of the transistor. The BJT will act like a variable current source. Consider the circuit below with a 2N3904 Si BJT transistor, a 351-3230-RC LED, a 10 $k\Omega$ potentiometer ($R_{B1} + R_{B2} = 10\ k\Omega$), a 1 $k\Omega$ resistor, a 2 $k\Omega$ resistor, and $V_{CC} = 10\ V$.



Prelab:

Circuit Analysis

Compute the value of R_{B2} and the corresponding V_B that turns the LED on (assume that the LED will light as soon as the transistor comes out of the cut-off region). Plot I_o as a function of R_{B2}. You can assume $I_C \approx I_E$ for an active mode BJT. I did this part of the prelab wrong because I imported the wrong photo (from part a) into the doc as can be seen in the prelab submission, so these calculations are on the wrong circuit, so I redid it during the lab time.

The LED turns on when the transistor exits cutoff, meaning the base-emitter junction is forward biased:

$$V_B = V_E + V_{BE}$$

Step 1: Compute V_E

Assuming $I_C \approx I_E$ in active mode and estimating $I_C = 1mA$:

$$V_E = I_E \times R_E = (1mA) \times (1k\Omega) = 1V$$

Thus,

$$V_B = V_E + V_{BE} = 1V + 0.7V = 1.7V$$

Step 2: Solve for R_{B2}

The voltage divider equation:

$$V_B = V_{CC} \times \frac{R_{B2}}{2k\Omega + R_{B1} + R_{B2}}$$

Given that $R_{B1} + R_{B2} = 10k\Omega$, the total denominator is $12k\Omega$, so we solve for R_{B2}:

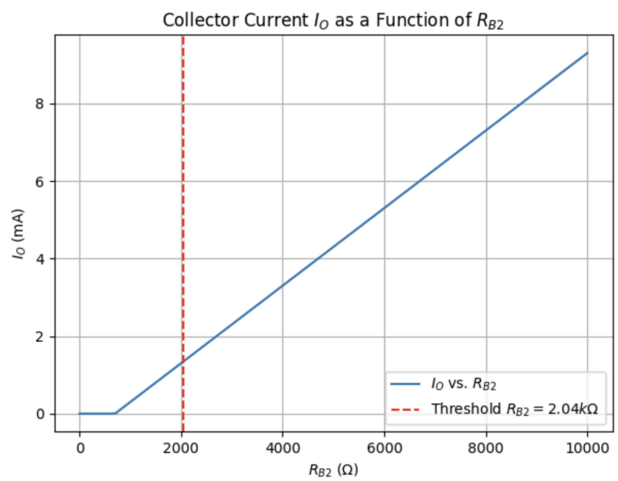
$$1.7V = 10V \times \frac{R_{B2}}{12k\Omega}$$

$$R_{B2} = \frac{1.7V}{10V} \times 12k\Omega$$

$$R_{B2} = 2.04k\Omega$$

Thus, the LED turns on when:

$$R_{B2} = \mathbf{2.04k\Omega}, \quad V_B = \mathbf{1.7V}$$



Lab exercise:

1. Assemble the circuit such that $R_{B2} = 0$. Measure V_B and I_o.

$V_B = 1.3$ mV, $I_o = 0.02$ mA, $R_{B2} = 0$

2. Slowly rotate the knob of the potentiometer (increase R_{B2}) until LED turns ON. Measure V_B and I_o of this point. From the measured V_B calculate R_{B2}. Does it match the circuit analysis?

$V_B = 0.693$ V, $I_o = 0.0547$ mA. Yes this matches our updated circuit analysis, as the current is still too low and the resistance is still below 1.7 kΩ.

3. Starting from the R_{B2} value at which the LED just turns ON, slowly increase R_{B2} while monitoring the value of I_o. For $I_o = 1mA$, $3mA$, $5mA$, and $7mA$, measure V_B and calculate R_{B2}. Explain your observations about LED's brightness.

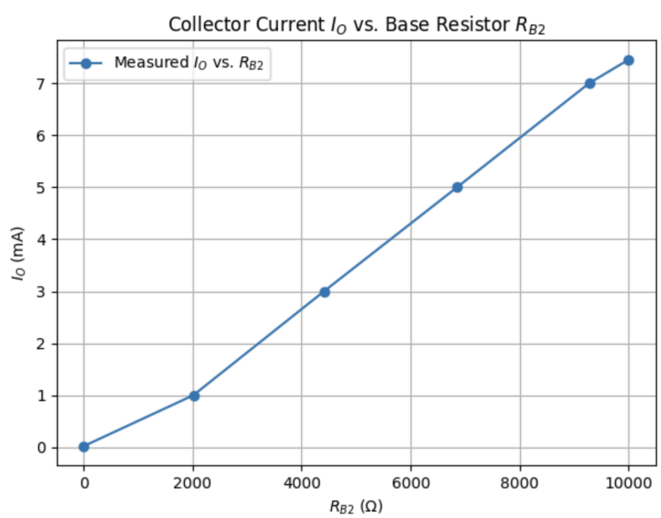
I_o	V_B	Calculated R_{B2}
1 mA	1.678 V	2013.6 Ω
3 mA	3.677 V	4412.4 Ω
5 mA	5.711 V	6853.2 Ω
7 mA	7.73 V	9276 Ω

Our LED becomes more and more bright as we increase the potentiometer.

4. Now, set R_{B2} at the highest possible value. What happens to the brightness of LED? Measure V_B and I_o of this point.

V_B = 8.18 V, I_o = 7.453 mA, $R_{B2} = 10\ k\Omega$

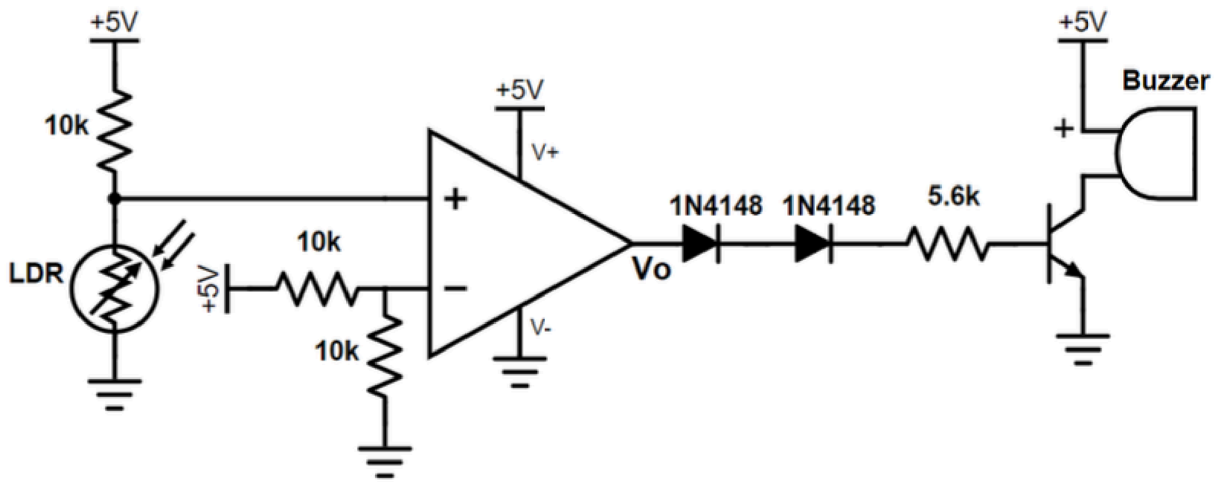
5. Plot I_o vs. R_{B2} (use measured values in the previous steps). Compare the plot with your circuit analysis and explain any discrepancies. What are your conclusions?



The graph we get is not quite the same as what we expected in the circuit analysis, but partly because our calculations for the R_{B2} were wrong because of how we initially understood the voltage divider. We can see now after the lab that as R_{B2} increases, the base voltage V_B rises, allowing more base current I_B to flow into the transistor. This, in turn, increases the collector current I_C , which is approximately equal to the emitter current I_E . Since the LED is in the collector path, a higher I_C means more current flows through the LED, making it brighter. At lower R_{B2} , V_B is too low to fully turn on the transistor, keeping I_C minimal and the LED dim or off. At very high R_{B2} , the transistor reaches saturation, limiting further increases in brightness.

Experiment 2: BJT as a switch

Consider the circuit below with an LM741 op-amp, a 2N3904 Si BJT transistor, a light-dependent resistor (LDR) and a buzzer. Generally, LDR has a very high resistance ($M\Omega$) in the dark and a very low resistance ($\approx 100\ \Omega$) in bright light. Notice that, here, the op-amp is powered only by a <u>single</u> supply voltage (i.e., the V+ terminal is connected to a 5V source, and V- terminal is grounded) instead of a differential supply used in previous labs.



Prelab:

The above circuit can be used as a dark and light indicator. Assume the resistance of the LDR is 50 $k\Omega$ in the dark and 1 $k\Omega$ in room light. Use a 200 Ω resistor to model the buzzer for circuit analysis and simulation. Turn on voltage for the buzzer is 1.4V, i.e., the buzzer works when the voltage drop across the buzzer is more than 1.4V.

Circuit Analysis

1. Calculate the output voltage, V_o, of the op-amp for both conditions (dark and light). For LM741, $V_{sat+} = V_+ - 1$ and $V_{sat-} = V_- + 1$.

For an LM741 op-amp:

$$V_{\text{sat}+} = 4V, \quad V_{\text{sat}-} = 1V$$

Using the voltage divider equation:

$$V_A = V_{CC} \times \frac{R_{\text{LDR}}}{R_{\text{LDR}} + 10k\Omega}$$

Case 1: Darkness (LDR = 50k)

$$V_A = 5V \times \frac{50k\Omega}{50k\Omega + 10k\Omega} = 4.17V$$

Since $V_A > V_B = 2.5V$, the op-amp output is:

$$V_O = 4V$$

Case 2: Bright Light (LDR = 1k)

$$V_A = 5V \times \frac{1k\Omega}{1k\Omega + 10k\Omega} = 0.45V$$

Since $V_A < V_B = 2.5V$, the op-amp output is:

$$V_O = 1V$$

Condition	V_A (Non-inverting)	V_B (Inverting)	V_O (Op-Amp Output)
Dark (LDR = 50k)	4.17V	2.5V	4V
Light (LDR = 1k)	0.45V	2.5V	1V

2. Find out the state of the transistor (cut-off/active/saturation) and I_C for both conditions. When will you hear the sound from the buzzer (dark/light)? Show your calculation.

The transistor's base voltage is given by:

$$V_B = V_O - 1.4V$$

Case 1: Darkness (LDR = 50k)

$$V_B = 4V - 1.4V = 2.6V$$

Since $V_B > V_{BE} = 0.7V$, the transistor is in **saturation**, turning the buzzer ON. The voltage across the buzzer:

$$V_{\text{buzzer}} = 5V - V_{CE} = 5V - 0.2V = 4.8V$$

Thus, the collector current:

$$I_C = \frac{4.8V}{200\Omega} = 24mA$$

Case 2: Bright Light (LDR = 1k)

$$V_B = 1V - 1.4V = -0.4V$$

Since $V_B < V_{BE}$, the transistor is **cut off**, meaning $I_C = 0mA$ and the buzzer is OFF.

Condition	V_O (Op-Amp)	V_B (Transistor)	BJT State	I_C (mA)	Buzzer
Dark (LDR = 50k)	4V	2.6V	Saturation (ON)	24mA	Yes
Light (LDR = 1k)	1V	-0.4V	Cutoff (OFF)	0mA	No

3. Remove the diodes and repeat step 2. Can the circuit work as a dark and light indicator without the diodes? Explain your conclusions.

Without the diodes, $V_B = V_O$.

Case 1: Darkness (LDR = 50k)

$$V_B = 4V \Rightarrow \text{BJT turns ON, buzzer ON}$$

Case 2: Bright Light (LDR = 1k)

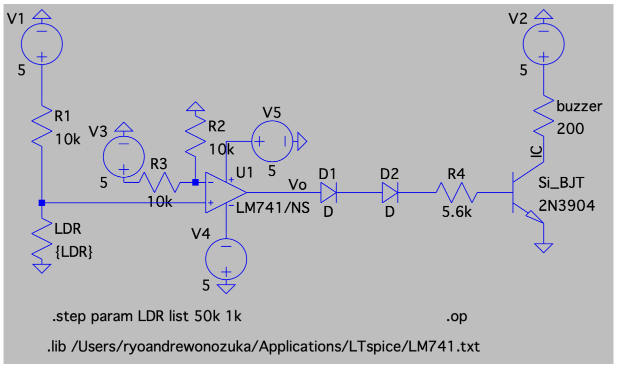
$$V_B = 1V \Rightarrow \text{BJT may still turn ON since } V_B > 0.7V$$

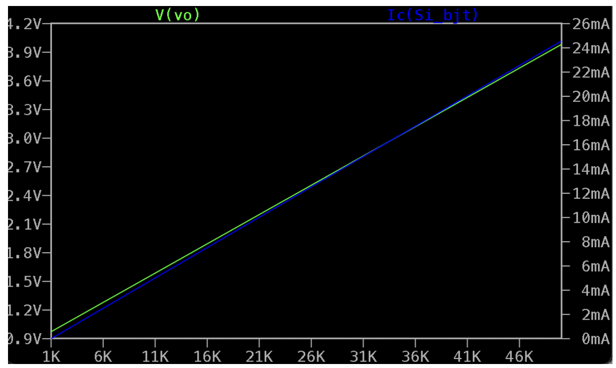
This **prevents proper cutoff**, making the circuit unreliable.

Conclusion: Removing the diodes affects the switching threshold, causing the circuit to potentially **fail as a dark/light indicator**.

Simulation:

Simulate the circuit and attach the circuit with bias-point details for both dark and light conditions. Clearly show the value of V_o and I_C . Compare simulation results with the circuit analysis.





The graph confirms that the transistor operates as a current source for a range of R_L, but once it enters saturation, I_C begins to decrease. This behavior is consistent with our circuit analysis predictions.

Lab exercise:

1. Assemble the circuit in a way such that you can measure the collector current of the transistor.
2. Use your finger or any object to darken the surroundings of the LDR. Measure I_C and V_o. Explain your observation.

I_C = 19.998 mA, V_o = 4.245 V

3. Move your finger/object away from the LDR and measure I_C and V_o again. Explain your observation.

I_C = 0.291 mA, V_o = 1.248 V

4. Repeat step 2 and 3 without the diodes. What are your conclusions?

DARK: I_C = 20.464 mA, V_o = 4.229 V

LIGHT: I_C = 7.400 mA, V_o = 1.231 V

Even though we get a difference in I_C and V_o, we can see that taking out the diodes breaks our intended functionality of the circuit, as the buzzer continues to beep in both situations. This and the 4V and 1V mark is roughly equivalent to the circuit analysis and simulations we did for the prelab.

Helpful Tips for LTspice:

- Add an "npn" to your schematic. Then, right-click on the BJT to pick a new transistor. Choose '2N3904'.
- Use the steps described in lab 1 to use LM741 op-amp in your simulation. The model file LM741.txt is uploaded on Canvas.
- Check out the instructions from lab 3 for simulating circuits with a parametric sweep.

Conclusion

In this lab, we investigated the behavior of BJT-based circuits, including current source configurations and switching applications, analyzing their performance through both simulations and experiments. By varying the load resistor and base resistance, we observed their impact on transistor operation, current regulation, and external component activation.

For the BJT current source, we confirmed that the transistor maintains a stable collector current across a range of load resistances but enters saturation at higher values, limiting current regulation. In the switching circuit, we demonstrated that the transistor effectively controls an LED or buzzer, with the op-amp comparator determining activation based on an LDR. Removing key components, such as diodes, affected proper circuit functionality, reinforcing the importance of voltage thresholds in transistor operation.

Overall, this lab demonstrated the practical applications of BJTs in analog circuits, validating their use as current sources and switches. While our simulations aligned with theoretical predictions, experimental results highlighted real-world deviations due to component tolerances and non-ideal behavior, emphasizing the need for careful measurement, troubleshooting, and circuit design considerations.