Chapter 4

Motors and BJTs

4.1 Section Overview

This section explores the function of two common types of semiconductors: diodes and Bipolar Junction Transistors (BJTs), This section also introduces the oscilloscope (oscope), an electric test instrument that allows observation of varying signals. As mentioned in Lab One, diodes allow current to flow only in one direction. They are used to convert AC to DC (rectification), provide voltage references, and to limit or ”clip” signals. BJTs are versatile devices, mostly utilized as switches, or small-signal amplifiers.

In this lab, we will observe the I-V characteristics of common diodes, zener diodes, BJTs, and the current draw of the Tekbot motors. We will also build a motor control circuit similar to the one on the motor control board. At the end of this lab, there is a challenge problem.

4.2 Procedure

To observe the characteristics of common as well as zener diodes, two diode experiments will be performed in this lab, followed by a BJT experiment. The motor board will then be examined to illustrate how transistors are utilized to create an H-bridge, and how they allow the motors to go forward and backward. The oscope will be introduced to observe the current draw of the Tekbot motors. Finally, a challenge problem is presented for building an amplifier using a BJT, to view voice waveforms on an oscilloscope.

4.3 Diode I-V Characteristics

To observe the I-V characteristics of a common diode, follow these steps:

1. Build the circuit, as shown in Figure 4.1. The $10K\Omega$ resistor (with an arrow pointing towards it), is a potentiometer (commonly called a ”pot”). Turning the potentiometer shaft will adjust the voltage across the diode. Use the blue, square, 10K pots in your circuit, and adjust them with a screwdriver.

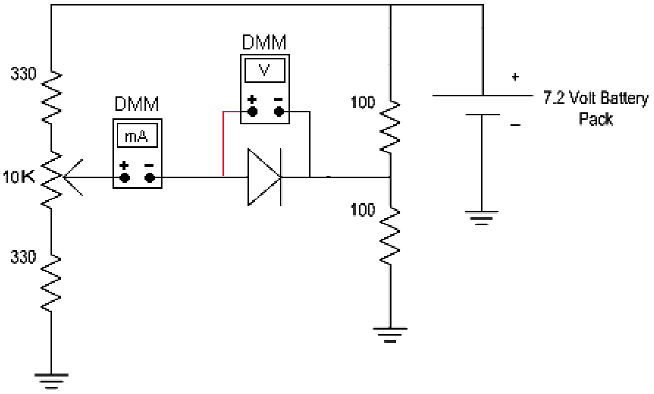

Figure 4.1: Schematic for testing the I-V characteristic of a diode

2. Adjust the voltage across the diode from the most negative value to the most positive value possible. Plot eight points on the graph alongside (Figure 4.2). Plot three negative diode voltages and five positive diode voltages to clearly illustrate the one-way nature of the diode.

> The scale of the negative diode voltages differs from the positive voltages, to make the curves look clearer.

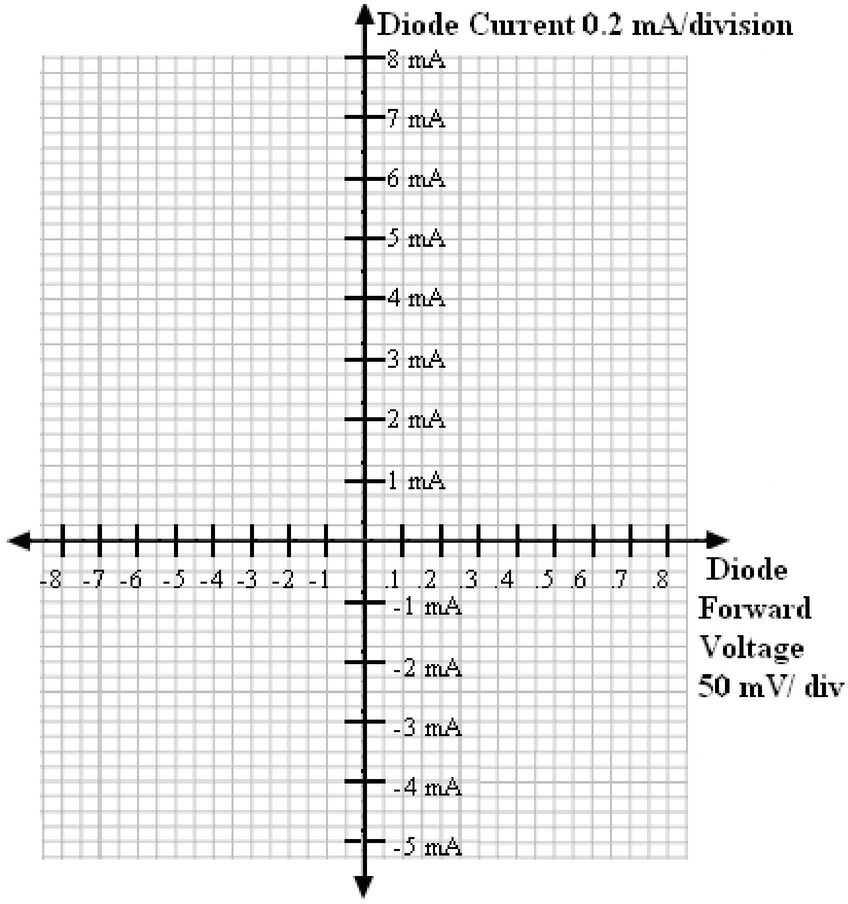

Figure 4.2: Diode I-V characteristic curve

4.4 Zener Diode Voltage Characteristics

To observe the zener diode I-V characteristics, follow these steps:

1. Replace the diode in the first experiment with a zener diode. See Figure 4.3.

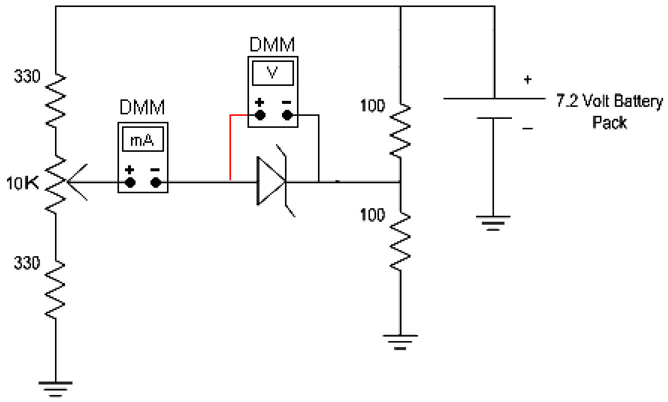

Figure 4.3: Schematic for testing the zener diode

2. Adjust the voltage from the smallest value possible, to the largest. Plot ten points on the graph in Figure 4.5. Plot five negative diode voltages and five positive diode voltages, so the conductive properties of a zener diode are clearly understood.

The scale of the negative diode voltages differs from the positive voltages, to make the curves look clearer.

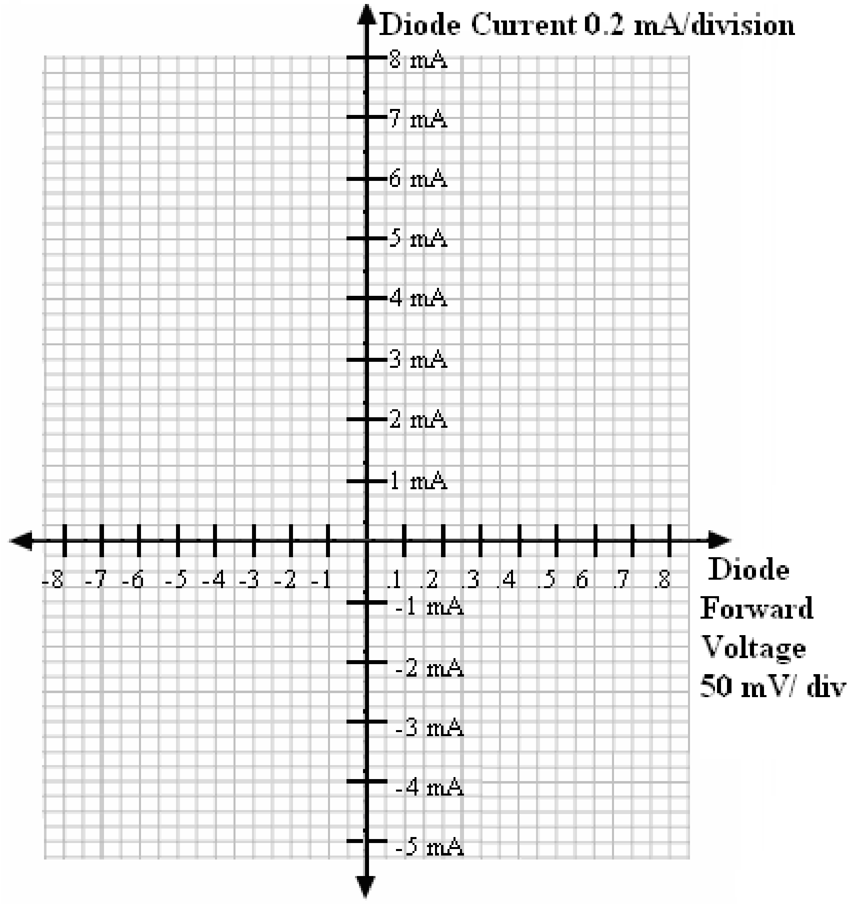

Figure 4.4: Zener Diode I-V Characteristic Curve

4.5 Bipolar Junction Transistors (BJTs)

The simplest way to use a BJT is as a switch. The ”contacts” of an NPN BJT switch are closed by injecting base current and are opened by removing base current. When sufficient base current is present and collector current is flowing, the collector and emitter terminals are essentially connected together with a voltage source of approximately 0.2V. The voltage source does not actually exist inside the transistor, but a potential difference of 0.2V still exists between the collector and the emitter. See Figures 4.5 and 4.6.

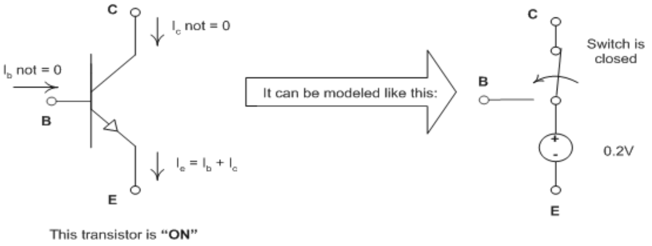

Figure 4.5: BJT as a switch (when the transistor is ON)

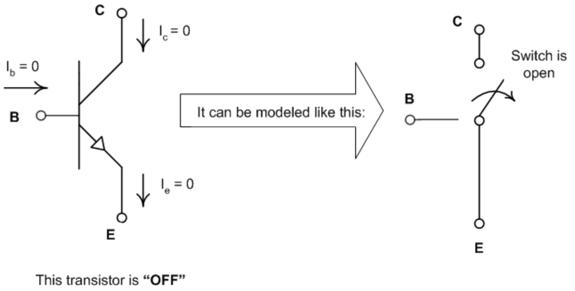

Figure 4.6: BJT as a switch (when the transistor is OFF)

In order to understand the BJT as a saturated switch, this section uses a BJT to switch the motor on and off, provides an explanation of the Light Emitting Diode (LED), and a few study questions towards the end.

1. ***With the wheels removed from the robot***, build the circuit as shown in Figure 4.7, on the protoboard. Create the switch using a movable wire.

2. ***With the switch open,*** measure the following:

   (a) The V_{be} and V_{ce} values of the transistor. V_{be} ______ [ ]; V_{ce} ______ [ ].

   (b) The I_b and I_c values of the transistor. (Hint: You dont have to actually measure these to know.) I_b ______ [ ]; I_c ______ [ ].

   (c) The **power dissipation** of the transistor (with the motor off). $PowerDissipated$ ______ [ ].

3. **With the switch contacts closed,** the motor should begin to run. Again, measure the following values:

   (a) V_{be} ______ [ ]; V_{ce} ______ [ ]; I_b ______ [ ]; I_c ______ [ ].

   (b) Using these measurements just taken, compute the **beta** of the transistor, using the formula $\beta \approx \frac{I_c}{I_b}$. $Beta$ ______

   (c) Neglecting the base current (that is, considering only I_c and V_{ce}), the **power dissipated** by the transistor is ______ [ ].

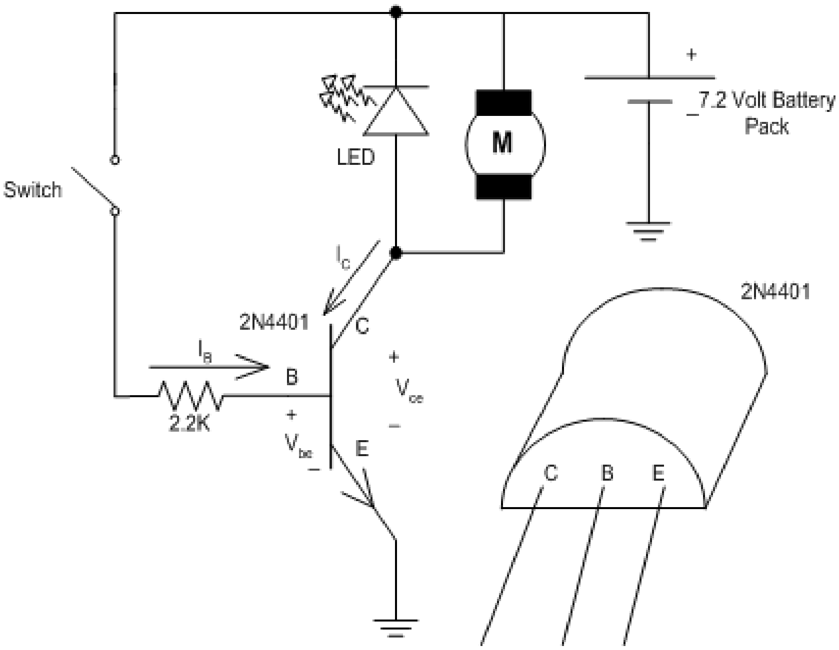

Figure 4.7: A switch using a NPN transistor and the pins of the 2N4401

4. With the switch contacts closed, as in Step 3, place another $2.2K\Omega$ resistor in **parallel** with the one connected to the base lead. Again, measure the following values:
   (a) V_{be} ______ [ ]; V_{ce} ______ [ ]; I_b ______ [ ]; I_c ______ [ ].
   (b) Does the motor run any faster? ______ (Yes/ No).

You will notice that I_b increased considerably and I_c increased slightly relative to its previous value in Step 3. Also, note the difference in V_{ce}. It should have changed only slightly.

When I_b is substantially increased with little increase in I_c, the transistor is still in saturation.

4.5.1 About the Light Emitting Diode (LED)

Internally, the motor consists of many windings of wire. When current flows through the windings, a magnetic field is produced in the motor that causes it to turn. But, when the motor drive current is removed, the collapsing magnetic field produces a very high voltage, (up to 200V), which will eventually destroy the transistor.

The high voltage created when the field collapses is oriented in the opposite direction to the original applied voltage. Therefore, the LED passes this *flyback* current and re-circulates it back through motor windings, thus protecting the transistor. It is this current spike that causes the brief flash of the LED when the power is removed. You may also see a dull glow of the LED while the motor is running.

4.6 Study Questions

1. Use the results of Steps 3 and 4 from the previous section (i.e. The BJT as a Saturated Switch), write out your own description of the condition of saturation. (It should include the relationship of I_b and V_{ce}).

2. Is the BJT an effective switch, as far as its own power dissipation is concerned? In other words, considering the power dissipated by the transistor (either on or off), is it effective in ensuring that most of the power is delivered to the load? Why? What characteristic feature about it being saturated makes the BJT an effective switch?

4.7 The Motor Control Board

The motor control board needs to be able to spin both motors in either direction to allow the robot to back up and turn. The motors are turned on or off by applying a high or low voltage level respectively to the motor drive circuits. These signals come from digital logic gates. The digital logic gates are implemented to keep the transistors from breaking. This protection block is called the current sequencer. The arrangement of the transistors in the motor drive circuit gives this circuit the name ”H-bridge”. Try to spot the ”H” in Figure 4.7.

This section describes the function of the H-Bridge, and testing of the motor control board.

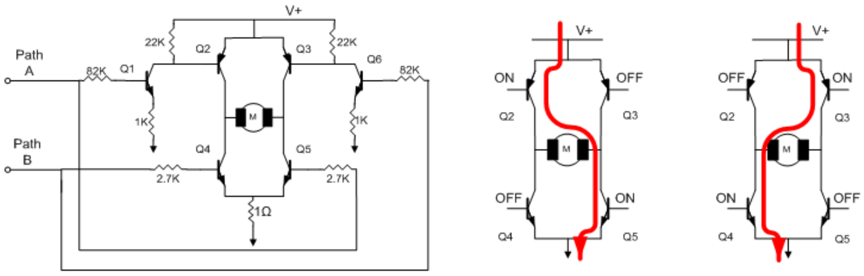

Figure 4.8: Motor Control Board H-Bridge

4.7.1 The H-Bridge

Figure 4.8 shows the H-bridge that controls the direction of current flowing through the motors, and therefore, the direction of rotation as well, notice:

- This circuit is actually a combination of the NPN and PNP switch circuits we just built.
- The current flows from left to right through the motor when Q2 and Q5 are turned on.
- The current flows from right to left through the motor when Q3 and Q4 are turned on.
- Q1, Q6, and the various resistors are used to correctly bias the H-bridge transistors to work with logic-high ”on” input signals.

4.7.2 The Current Sequencer

The H-bridge of the motor control board is what determines if the motors run foward or backward. However an issue can arise if the change of direction is too quick. When the direction of the motors changes too quickly the current can shoot through from Q2 to Q4, bypassing the motors entirely and damaging the transistors. See figure 4.9.

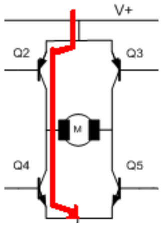

Figure 4.9: Shoot Through Current

The current sequencer, figure 4.10 is used to protect the H-bridge. The digital logic provides a delay so the direction of the H-bridge current does not switch over too fast. As you can see in figure 4.11 as the directioin input changes (dark line) from high to low there is a very quick period where the tekbot motors are not moving at all. The same thing happens again when the tekbot moves foward.

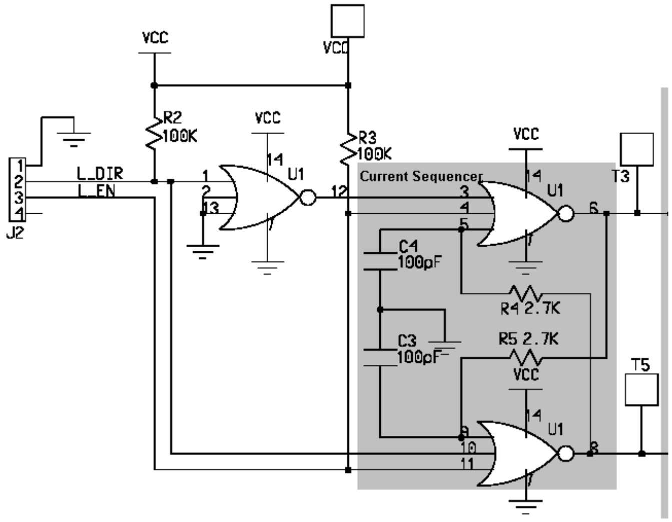

Figure 4.10: The Current Sequencer

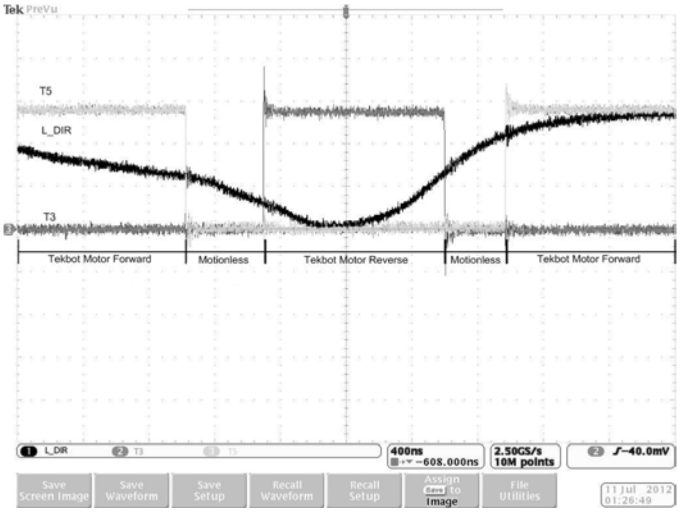

Figure 4.11: Current Sequencer In Action

4.7.3 Testing the Motor Control Board

Power the motor controller board with a 4-pin keyed power wire from the power distribution area of the charger board. Use all four pins so that if the plug is put in backwards, there will only be NC (No Connection) plugged into $+$ and GND. The motor controller board inputs are ”active low”. This means that when an input signal is zero volts, it is logically asserted or true. When EN is connected to GND, an H-bridge passes current. When DIR is connected to GND, then the H-bridge passes current in the reverse direction.

Since the motor controller has digital gates, a reference to EN being grounded or at 0V potential does not apply here. Instead, the term for grounded is ’0’. When the inputs to the motor controller aren’t grounded, they are being pulled hihg to Vcc by R2 and R3 are called ’1’. Thus, the inputs are essentially referred to as just 0 or 1.

Use some stripped wires to connect the motor board, as shown below in Figure 4.12.

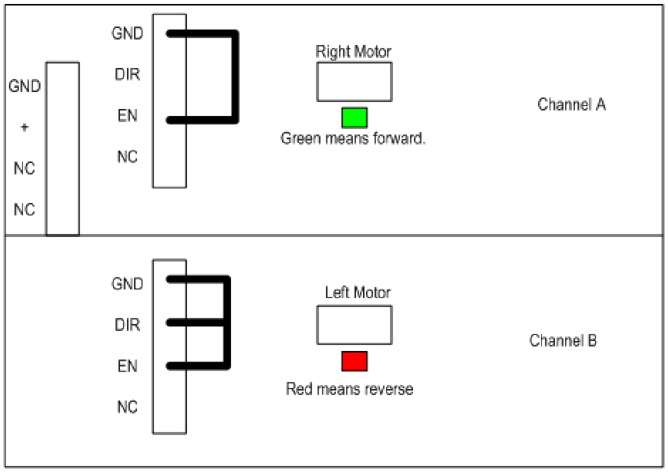

Figure 4.12: Diagram of the Motor Control Board

In table 4.1, write the appropriate motor actions. Indicate which LED is on: *red* or *green*.

Table 4.1: **Control-Table for Tekbots Motor Board**

Enable	Direction	Motor State	LED Color
1	1	Stopped	
1	0	Stopped	
0	1	Forward	
0	0	Backward	

Try each switch combination and observe the resultant motor state. If the motor runs on a direction opposite to the one indicated, just reverse the motor connections to the board. Refer to the schematic for the motor controller in *Appendix C: Schematics.*

4.7.4 Motor Current and the Oscilloscope

Motors will draw varying current depending on the physical resistance. When the motors have to overcome a greater force to turn, a greater current will be drawn. For example, if the Tekbot needs to drive uphill it will draw greater current. To observe the current being drawn by the motors an oscilloscope will be used. The oscilloscope is an electric test instrument that allows the user to monitor a system with varying voltages.

Due to the cost of oscilloscopes there are a limited number. Working in groups of two is advised.

1. Begin with the motor plugged in but with switch of the charger board in the off position.

2. Strip both ends of a small wire and solder one end to the test point T12 of the motor control board.

3. Turn on the oscilloscope, the button is on the top of the scope in the bottom left hand corner. Open the oscilloscope probe and connect it to channel one, toward the bottom of the oscilloscope. Before continuing, the probe attenuation must be on the appropriate setting. Press the channel one button and be sure it says ”10X” under the ”probe” setting.
4. The alligator clip needs to connect to GND and the probe clip needs to connect to the other end of the wire soldered to T12.
5. Oscilloscopes have auto set buttons that try their best to set up the display in the best possible way. Use auto set to begin and adjust the display accordingly.
6. When using only one channel it is a good idea to make sure the wave is centered on the x-axis.Using the vertical position dial adjust the waveform until it is centered on the x-axis.
7. The VOLTS/DIV knob is used to adjust the voltage scale of the display. T12 is measuring the voltage across a 1ohm resistor, therefore the current being drawn by the motors is determined using a simple Ohm’s Law calculation. The current equals the voltage across R12. The scale of the display should be set to either 100mV or 200mV for the best view.
8. The oscilloscope is very powerful and can sample voltages at incredibly fast speeds. For the purpose of this lab we want to be able to see the increase and decrease of the voltage, so the SEC/DIV needs to be changed. This will change the time scale. Setting it to 1.00 seconds per division will allow for a steady capture speed.
9. The RUN/STOP button allows you to pause the display and capture what you currently have recorded. The SINGLE button allows you to capture one time interval of data and freezes after that.
10. Play with the oscilloscope settings and the resistance of the wheels to generate different wave forms of on the display. This oscilloscope exercise will help with the first study question.

4.8 Study Question

1. The following oscilloscope graph is of the test point T12. Identify what is happening to the motor in the five regions.

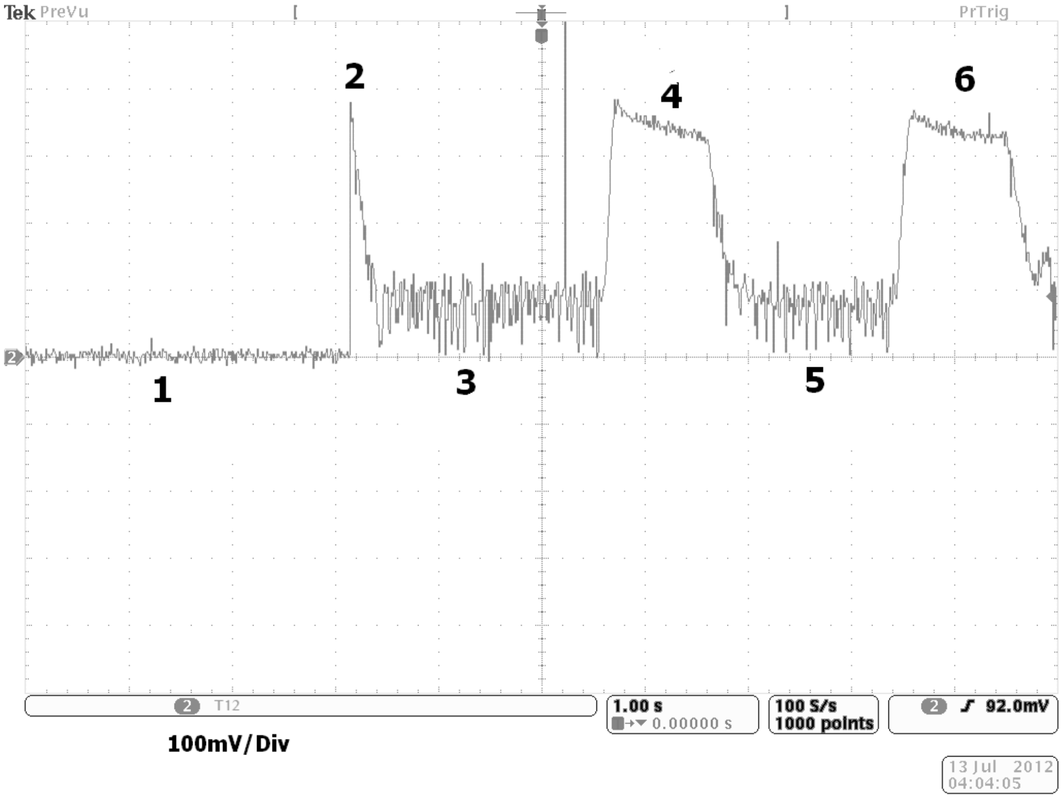

Figure 4.13: T12 Voltage

2. In figure 4.13 what is the maximum current draw of the motor.

3. What is the motor doing in figure 4.11.

4.8.1 Challenge

An NPN BJT acting as a linear amplifier is more like a dimmer switch than an on/off switch. In this mode, a small base current is able to control a much larger current flowing from the collector to the emitter. The big difference with the BJT amplifier is that a large collector resistor is used to convert the varying collector current to a varying voltage at the output.

Shown below in Figure 4.14, is the schematic for a small signal audio amplifier. The amplifier consists of two single transistor amplifiers in series. By doing so, the two stages of amplification can together boost the microphone output level over 150 times. The microphone output level is only about 20mV peak-to-peak. The composite gain of the amplifier is simply: $gain\ of\ the\ first\ stage \times gain\ of\ the\ second$

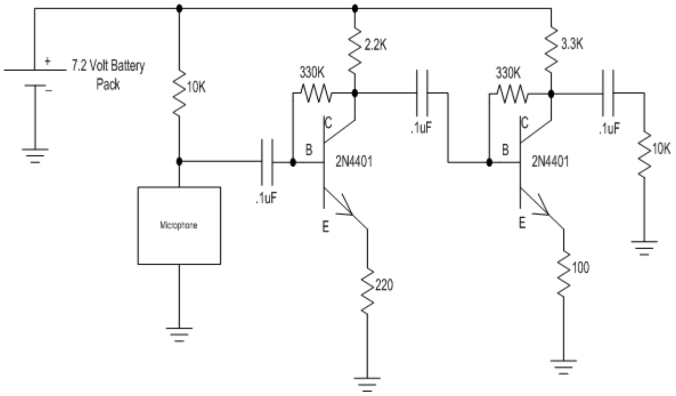

Figure 4.14: Schematic for a two-stage audio amplifier.

The output voltage of both the microphone as well as of the amplifier can be measured with an oscilloscope. The oscilloscope plots a waveform of voltage versus time on its screen. Your TA will set up the oscilloscope at your workstation appropriately. (Please share the oscilloscope with your neighbor). In order to implement this challenge, follow these steps:

1. First analyze the amplifier circuit in Figure 4.14 and determine its collector voltage, and its collector current. (Hint: Write the KVL loop from the supply through R_c, R_b, V_{be}, and finally R_e). Do this for both stages of the amplifier. Use a beta of 100. Outline your work below.

   First stage computed value: V_c _______ [ ]; I_c _______ [ ]. **Second stage computed value:** V_c _______ [ ]; I_c _______ [ ].

2. Build the amplifier on the protoboard and apply power to the circuit. Confirm that the voltages just computed are identical in the amplifier. The voltages and currents should be within about 30% of computed values. If they are not, check your circuit for errors.

Actual Value: V_c ______ [ ]; I_c ______ [ ].

3. If your amplifier voltages match, adjust the knob labeled ”CH 1 VOLTS/DIV” to the setting 50mV for the 10x probe. Attach the ground lead of the oscilloscope probe to the circuit ground. Touch the oscilloscope probe tip to the junction of the microphone and the 10K resistor. Whistle or hum into the microphone and note the voltage level.
   Average Microphone Output-Voltage Level: ______ mV (Should be $\approx$ 20mV peak-to-peak)

4. Next, touch the probe to the collector of the transistor Q1. Adjust the knob labeled ”CH 1 VOLTS/DIV” to the setting 0.1 for the 10x probe. Now hum or whistle into the microphone again at about the same level and notice the output signal in Q1. It should be significantly bigger. From the relative size of both the input and output voltages, estimate the voltage gain of the amplifier.
   Approximate amplifier gain of Q1 (observed) ______

5. Given the values of the resistors in the amplifier, what would you estimate the gain to be?
   Approximate amplifier gain of Q1 (rule of thumb estimate) ______

6. Finally, touch the probe to the collector of the second transistor Q2. Adjust the knob labeled ”CH 1 VOLTS/DIV” to the setting 5 for the 10x probe. Now hum or whistle into the microphone again at about the same level and notice the output signal in Q2. It should be significantly bigger than that seen at Q1s collector. From the relative size of Q1s and Q2s output voltages, estimate the voltage gain of the amplifier. (Hint: The input to Q2 is simply the output of Q1.)
   Approximate amplifier gain of Q2 (observed) ______

7. Given the values of the resistors in the amplifier, what would you estimate the gain to be?
   Approximate amplifier gain of Q2 (rule of thumb estimate) ______