Transistors

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The invention of the transistor was perhaps the most important development in electronics during the last century. John Bardeen, Walter Brattain and William Shockley, working at Bell Labs in New Jersey, are credited with the invention. The initial work that demonstrated the transistor effect was conducted in 1947 by Bardeen and Brattain. Further work on transistors ensued at the Bell Labs in which Shockley played an important role. All three men were jointly awarded the Nobel Prize in Physics in 1956 for their work on the transistor.

Transistors are found in nearly all modern electronic devices. Computers contain millions or even billions of transistors.

Two very important applications of the transistor are **switching** and **amplification**. A transistor can be used as an electronic type of switch to turn power on or off to a circuit. A transistor can also be used to amplify an electrical signal. A radio utilizes transistors to amplify the weak signal received from a radio station so that it contains enough power to drive a speaker, thus allowing you to hear the broadcast. The same can be said for TVs, cell phones and similar devices.

In this lesson you will use two transistors to switch the power on and off to the robot motors. Actually you will connect a motor to your breadboard in the next lesson. In this lesson you will substitute LEDs for the motors.

Recall from the last lesson that the IC chip, the “brains” of the robot, is limited to handling at most 20 milliamps of current. I tested a motor of the type you will use for your robot and found that it consumed 58 milliamps when supplied with 9 volts of DC power. When I put the motor under a heavy load, I found that it consumed about 150 milliamps. These current levels are well above the limit of the LM393 IC chip. Therefore, we cannot power the motors directly from the outputs of the IC chip. Instead, the outputs of the IC chip will be connected to transistors, which in turn will power the motors. A small amount of current from the IC chip output is capable of turning a transistor on, thus allowing a much larger amount of current to be supplied to a motor.

Recall that a diode contains a P-N junction. Also recall that there are two basic types of semiconductor material: P (positive) and N (negative). For a diode, the negative side of the DC power supply must be connected to the N type and the positive side to the P type. The magic of the diode happens at the junction of the P and N materials, where the two different types come in contact. When power is applied to the diode with the proper polarity, current will flow. If the power connections are reversed, then power will not flow though the diode.

There are a number of different types of transistors, and we will concentrate here on one type, the bipolar transistor. A bipolar transistor consists of a sandwich of three semiconductor layers. It can be

PNP or NPN. Thus, the bipolar transistor contains two P-N junctions. Figure 1 is a diagram of a PNP type showing the location of the junctions. In reality, the thickness of the base is so thin that you would need a microscope to see it.

The schematic symbols used for these transistors are provided in Figures 2 and 3 below.

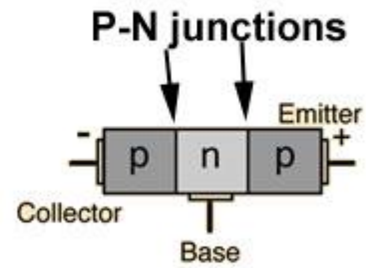

Figure 1 the two P-N junctions of a PNP bipolar transistor

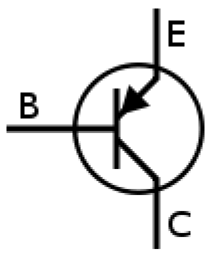

Figure 2 bipolar PNP transistor

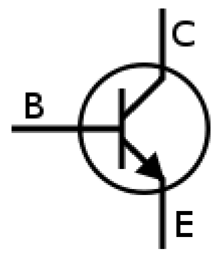

Figure 3 bipolar NPN transistor

The three wire leads for the bipolar transistor connect to the collector (C), the base (B) and the emitter (E). The arrow in the symbol reminds us of the direction of current flow. For the PNP type, current flows from the emitter to the collector. Therefore, the positive side of the power supply must be connected to the emitter and the negative side to the collector (of course there will be additional components besides the transistor in the circuit). The opposite is the case for the NPN type. The positive side is connected to the collector and the negative side to the emitter. For the PNP type the base is connected to the negative side of the power supply and for the NPN type the base is connected to the positive side of the power supply.

Keeping the above requirements in mind and reviewing the design of the LM393 IC chip used in lesson 3, we can determine that we need to use the PNP type of transistor for our application. How did I come to that conclusion? Well, remember that the output of the IC chip connects to ground, which is the same as the negative side of the power supply. If we intend to connect the output pin of the IC chip to the base of the transistor, the base will be connecting to the negative side of the power supply. The base in a PNP type transistor is of the N type material, which means it must connect to the negative side. That is a good rule to remember.

Remember our rule about current. It flows from the positive side of the power supply to the negative side. Take a look at the arrow in the symbol for the PNP transistor. It indicates the direction of current flow. Therefore, the positive side of the power supply must be connected to the emitter. After the current flows though the transistor and exits by way of the collector, then it can be directed to the robot motor. After flowing through the motor the current returns to the negative side of the power supply. The current that flows from the emitter to the collector is called the **collector current**.

Now let us take a look at the schematic for this lesson in Figure 4 below.

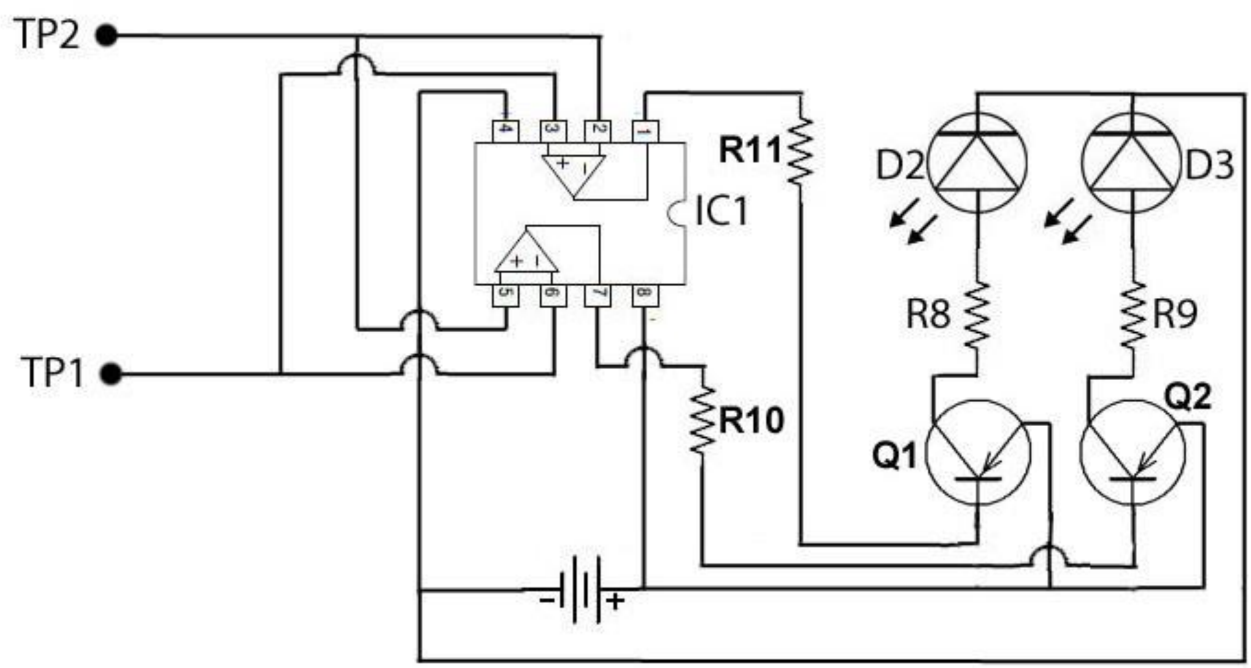

Figure 4 schematic for power transistors Q1 and Q2

The left side of the schematic should already be familiar because it contains the IC chip LM393 (IC1) that you wired in the last lesson. For this lesson you will remove the LEDs from the breadboard that were wired in lesson 3, add some resistors and two transistors, which connect to LEDs. The bipolar transistors are labeled Q1 and Q2. There is one transistor for each motor (or LED in this case). Notice that the transistors are the PNP type, as you can tell from the symbol. The base of Q1 is connected to output pin 7 of the IC chip through the current limiting resistor R10. The base of Q2 is connected to output pin 1 of the IC chip through the current limiting resistor R11. R10 and R11 are 2,200 ohm resistors. You will learn in a moment how that value was selected. R8 and R9 are the same resistors you used in lesson 3 when you powered the LEDs directly from the IC chip (also 2,200 ohms). D2 and D3 are the same LEDs you used in lesson 3 as well. The difference here is that now the LEDs are powered from the transistors, not the IC chip. The outputs from the IC chip are only used to turn the transistors on and off. Now we have a circuit that is capable of handling the current demands of the robot motors.

Taking a look at the data sheet for our bipolar transistors, which are the 2907A type, we find that the DC current gain at 150 milliamps collector current is 100 to 300 (it will vary between individual transistors). Suppose our specific transistor is running at a current gain of 100. What does that mean? It means that the transistor will allow 100 times more current to flow from the emitter to the collector than from the emitter to the base. Suppose we need to supply 100 milliamps of collector current to our motor. Then we only need to let 1 milliamp flow from the emitter to the base.

The current flowing from the emitter to the base is called the base current. After the base current exits the transistor it goes through the current limiting resistor (2,200 ohms) and then through the IC chip to the negative side of the power supply. Our IC chip can handle at most, 20 milliamps. Therefore a base current of 1 milliamp will be no problem at all. And that small amount of base current allows a current flow from emitter to collector, then to the motor, of 100 milliamps! That is the magic of the transistor!

We must limit the amount of current flowing from the base of the transistor to the IC chip. That is done with the current limiting resistors (R10 and R11). We can use Ohm's Law to calculate the necessary resistance. But first, we should consult the transistor data sheet once again. There we find that the transistor has a maximum of 500 milliamps collector current. That is well above the requirements of our robot motors, but let us calculate out the resistance required for 500 milliamps collector current. If our transistor is indeed operating at a current gain of 100, then we need to provide a base current of 5 milliamps (divide 500 milliamps collector current by the gain of 100 to calculate required base current).

Just like an LED, these transistors also consume some voltage when they operate. Consulting the data sheet for the transistor again, we find that the maximum Collector-Emitter Saturation voltage is 0.4 volts with a collector current of 150 milliamps and a base current of 15 milliamps. At a collector current of 500 milliamps and base current of 50 milliamps the collector-emitter saturation voltage is 1.6 volts maximum. These are the voltage drops we can expect across the transistor under the current conditions listed. We should keep in mind that the transistor consumes some voltage, but it depends on the amount of current flowing through the transistor. As a test I connected a robot motor to one of the transistors and measured the voltage drop between the collector and emitter. I found it was about 0.1 volts with the motor running without a load and about 0.2 volts under a heavy motor load. Suppose we have a fresh 9 volt battery that actually supplies 9.4 volts. Then the voltage left after passing through the transistor would be about 9.2 volts. We know the volts and current, so can now calculate the resistance required.

Resistance = Voltage/Current

R = 9.2 volts/0.005 amps base current = 1840 ohms

Therefore, we can use an 1840 ohm resistor to limit the base current of the transistor to 5 milliamps and provide up to 500 milliamps current to the collector. Well, I happen to have a large stock of 2200 ohm resistors but not many 1800 ohm ones. So let us see what base current we will get using 2200 ohms.

Current = Voltage/Resistance

Current = 9.2 volts/2200 ohms = 0.004 amps or 4 milliamps

How much collector current can we expect when the base current is 4 milliamps and the transistor has a current gain of 100? Then we can expect a maximum collector current of 400 milliamps (100 gain X 4 milliamps base current). This is well above the requirements for our robot motor and will work just fine.

Wiring the transistors

1. Before you begin wiring the transistors, you must remove some components from your breadboard. Refer to Figure 5. Remove the wires labeled 1 and 7. Also remove the two red wires marked with black arrows. Remove resistors R8 and R9 and LEDs D2 and D3.
2. Now you are ready to begin wiring the transistors. Go to the next page.

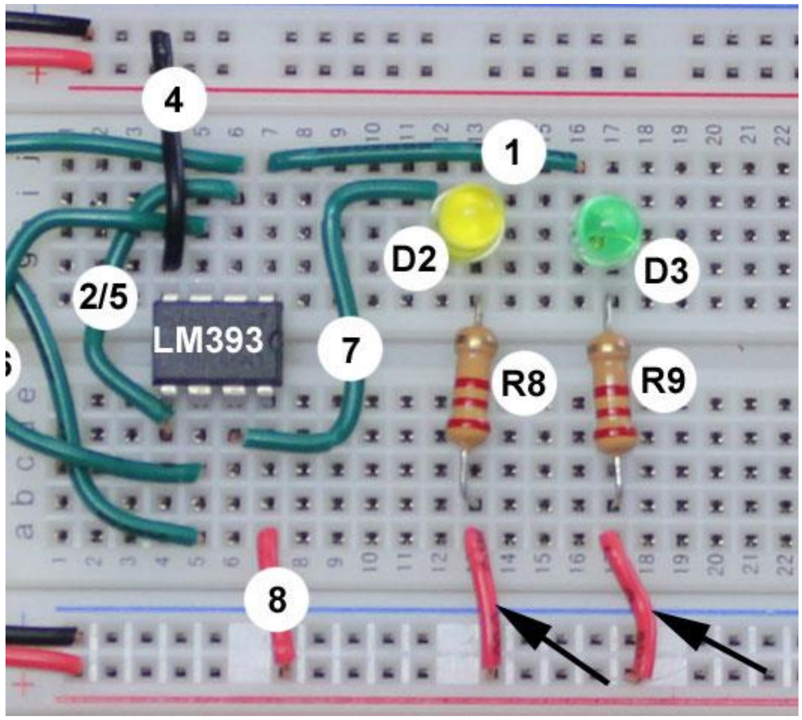

Figure 5

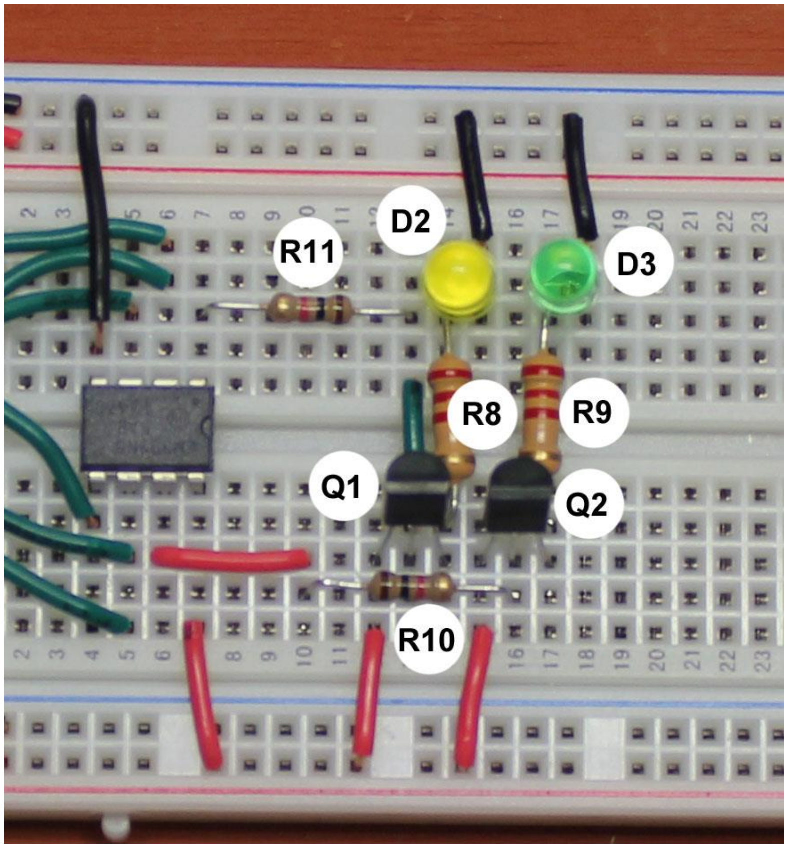

Figure 6

3. Insert R11 into the board, with one lead in the same row as pin #1 of the IC chip (Figure 6 – you may notice that the resistor in the photo is 1000 ohms but you will use a 2200 ohm resistor)
4. Connect a green wire to the same row as the right side of R11. This wire should cross over the divide in the middle of the board to a row on the bottom.
5. Connect the middle wire of transistor Q1 to the same row that contains the green wire you just inserted. The transistors have polarity just like LEDs so you need to insert them properly. The flat face of the transistor should be facing the bottom of the board as in the photo. Then the emitter will be the left wire and the collector the right wire (see Figure 7).
6. Connect a red wire from the positive power bus to the same row as the emitter of Q1 (emitter is on the left in photo).
7. Connect R8 to the same row as the collector of Q1 and the other end over the gap to a row at top of board.
8. Then connect the anode of LED D2 to the same row as R8 (the anode is the longer wire). Make sure the cathode of the LED is in the next row to the right of the anode, not in the same row.
9. Connect a black wire from the row containing the cathode of LED D2 to the negative power bus. You have now completed the wiring for Q1 circuit.

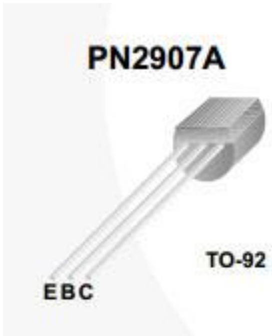

Figure 7

10. Connect a red wire to the same row containing pin #7 of the IC and jump over 4 rows to the right.
11. Connect one side of R10 to the same row that contains the right side of the red wire you just inserted.
12. Insert transistor Q2 into the board with its middle wire (the base) in the same row as the right side of resistor R10 (make sure the flat face of transistor faces toward bottom of board).

13. Connect a red wire from the positive power bus to the same row containing the left wire (emitter) of Q2.
14. Connect resistor R9 to the same row containing the right wire (collector) of Q2 and the other end across the gap to a top row.
15. Connect the anode of LED D3 to the same row as R9 (make sure the cathode is in the next row to right of the anode)
16. Connect a black wire from the row containing the cathode of D3 to the negative power bus.
17. You wiring is now finished. Have an adult check your wiring before you apply power to the circuits.

If all of your wiring is correct, then you should observe the following. When you shade one set of photoresistors, one LED should be on and when you shade the other set of photoresistors the other LED should be on. If this is what you observe, then you have successfully wired your circuits.

Congratulations! You have finished this lesson. You have one lesson remaining to complete the wiring of the robot on the breadboard. Then you will learn how to solder and assemble the actual working robot!