Direct Current Motors

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You have arrived at the last lesson for the breadboard work on the line following robot. In this lesson you will attach a DC motor to your breadboard to demonstrate the functionality of the circuits in controlling the robot motors.

Before you start your wiring work, it would be a good idea to learn how a DC motor works. Electric motors utilize magnetic forces to convert electrical energy into rotating mechanical energy. Therefore, we should first review some things about magnetism.

I suspect you already have some experience with magnets and perhaps have learned something about them in science class at school. Magnets are said to be dipoles. That is, they have one end named the south pole and the opposite end named the north pole. If a magnet is suspended by its center with a thread, it will rotate until the north pole of the magnet points to the north magnetic pole of the Earth. We can actually use that method for distinguishing between the north and south poles of a magnet and is the principle upon which a compass operates. When the north pole of a magnet points to Earth's north magnetic pole, the south pole of the magnet points to the Earth's magnetic south pole.

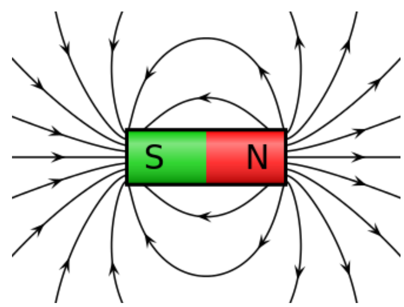
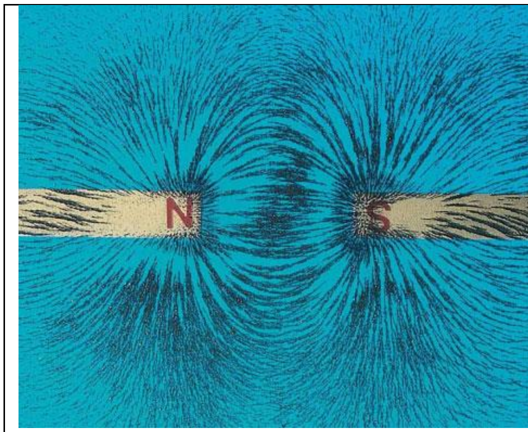
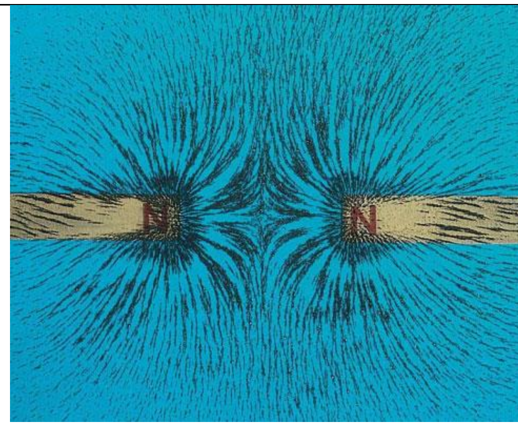


Figure 1 poles and field of a magnet

Figure 1 is a diagram of a bar magnet with the poles marked N for north and S for south. A magnetic field surrounds the magnet, which we can draw as lines with arrows. By convention, the magnetic lines point out from the north pole and point in toward the south pole.

It is actually possible to visualize a real magnetic field by using iron filings. Iron filings are fine particles of iron. When iron filings are sprinkled around the poles of magnets lying on a flat surface, the iron filings line up along the lines of the magnetic field (see Figures 2 and 3 on the next page).

 **Figure 2 iron filings showing field around opposing north and south poles of two magnets**	 **Figure 3 iron filings showing field around two opposing north poles of two magnets**

The north pole of a magnet will attract the south pole of another magnet. If you hold one magnet in each hand, with the north pole of one magnet pointing toward the south pole of the second magnet, as you move the magnets closer together, you will feel a stronger and stronger attractive magnetic force. If the magnets touch each other, they will stick to each other. Look at the magnetic field between the north and south poles in Figure 2. The iron filings allow you to visualize the attractive nature of the two poles. The magnetic field lines connect the two poles together.

On the other hand, two like poles of two magnets will repel each other (either two north poles pointing toward each other or two south poles pointing toward each other). As you hold a magnet in each hand and move like poles close to each other, you will experience a force of the magnets pushing against each other, trying to push your hands apart. The magnetic field displayed in Figure 3, of two opposing north poles, shows that the magnetic lines bend away from the opposite pole, revealing the repelling force between the poles.

An important effect of electric current flowing through a wire is that it produces a magnetic field around the wire. This effect was known to scientists in the nineteenth century, during which time early electric motors were invented.

Certain metals, like iron, can have magnetic properties even without electric current passing through them. These are known as **permanent magnets**. We can make an **electromagnet** by wrapping wire around a metal core (like a nail) and passing an electric current though it. The motors you will use for your robot are known as permanent magnet DC motors. The motors contain permanent magnets, but also utilize coils of wire to produce electromagnets. The electromagnets pull and push against the permanent magnets to cause the motor to spin. So that we can understand how that happens, we should now take a look at the parts of the robot motors.

Figure 4 is a photo of the motor with the end cap removed. This allows us to see the internal parts. The permanent magnets are attached to the inside surface of the motor case. The part that spins is called the rotor. The rotor contains three coils of wire, which become three electromagnets when electric current passes through the wire coils. We can see the rotor more clearly when it is removed from the motor case.

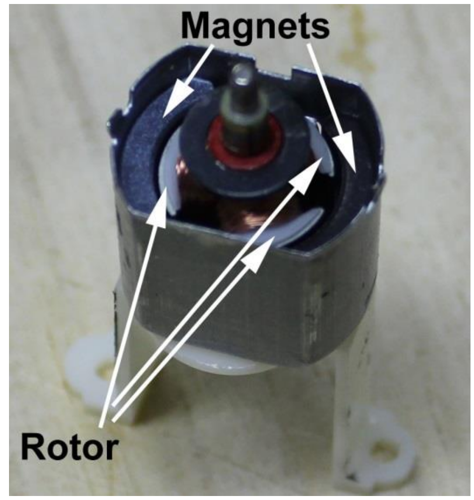


Figure 4 Interior of robot motor

The rotor contains three coils of wire, wound around an iron metal core (Figure 6). A metal rod runs through the center of the iron core and provides the axis for the rotor to spin upon. On the left the commutator is attached to the metal rod (the commutator surrounds the metal rod). The commutator is divided into three parts, with gaps between the parts. One of the gaps is barely visible in this photo (it looks like a dark line). The three parts of the commutator are made from metal and are insulated from the metal rod and also from each other by the gaps. The ends of the wire coils are attached to the commutator. Two metal brushes rub against the commutator. The brushes transfer electric current from the motor terminals to the coils of wire of the rotor. This is possible even when the rotor is spinning because the brushes only rub against the commutator, but are not physically bonded to the commutator (you can see the two brushes in Figure 5).

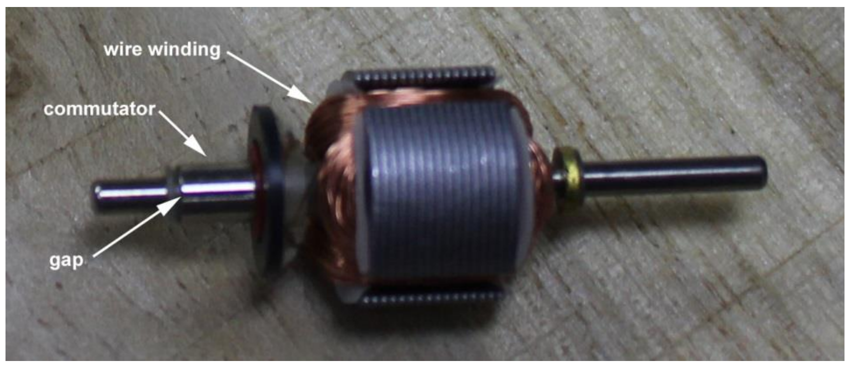


Figure 6 motor rotor

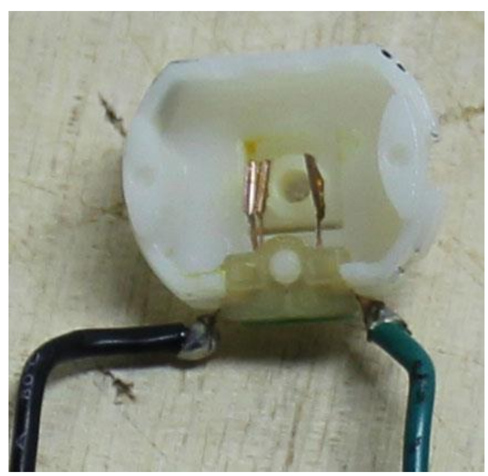


Figure 5 motor end cap containing brushes

A series of drawings can help us visualize how the motor works. In Figure 7 the yellow parts represent the motor brushes which rub against the commutator, which is a red circle with three gaps. The three electromagnets of the rotor are labeled 1, 2 and 3. You can see that these have red wires wrapped around them with the wire ends connected to the commutator. The north (N) and south (S) poles of the electromagnets are also labeled. The permanent magnets are on the left and right sides of the diagram, which also have their poles labeled. Notice that the permanent magnet on the left has its south pole pointing toward the rotor and the permanent magnet on the right has its north pole pointing toward the rotor. In Figure 7 the brush on the right is shorting between the two commutator sections that contain the wire connections to the coil for the number 2 electromagnet. Therefore, no current is flowing through this electromagnet and it does not have any magnetic properties at this position. The rotor is turning in a clockwise direction, which means the north pole of the number 3 electromagnet is approaching the south pole of the left permanent magnet. This makes sense because opposite poles attract each other. At the same time electromagnet number one's south pole is moving away from the south pole of the left permanent magnet. This also makes sense because the two south poles are pushing against each other, forcing the south pole of electromagnet one to move away from the left permanent magnet.

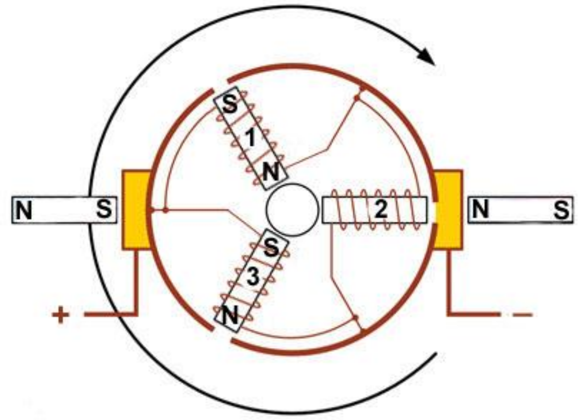


Figure 7 motor diagram 1

In Figure 8 the rotor has rotated 40 degrees clockwise compared to Figure 7. Now we notice that the right brush is not shorting between commutator parts and all three electromagnets have current flowing through them. The south pole of electromagnet one is now approaching the north pole of the right permanent magnet, the north pole of electromagnet two is moving away from the north pole of the right permanent magnet, and the north pole of electromagnet 3 is approaching the south pole of the left permanent magnet. All of this is consistent with what we know about the attractive and repelling forces of magnets.

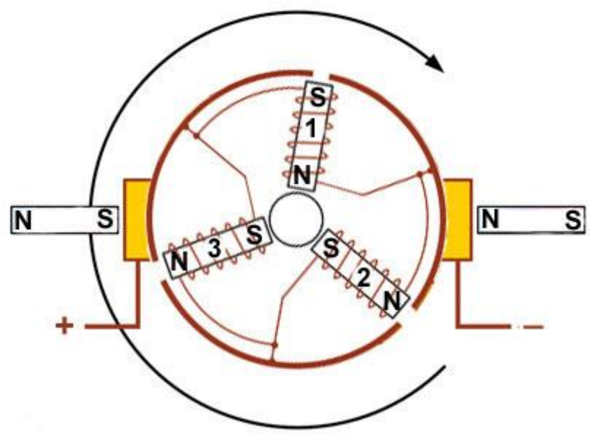


Figure 8 second motor diagram, rotation 40 degrees clockwise

In Figure 9 the rotor has now rotated 80 degrees clockwise from the position in Figure 7. There is one interesting change at this point, which reveals the secret of the electric motor design. You should notice that the outer pole of electromagnet 3 has changed from a north pole to a south pole. This is due to the fact that the direction of current flow in this electromagnet has changed. That is caused by the way the electrical contacts of the commutator have changed due to rotation. While at the position in Figure 8, the outermost end of the wire coil of electromagnet 3 was connected to the negative side of the power source. But in Figure 9, the top end of the coil is now connected to the positive side of the power source. This is because the commutator part that has the connection to the outermost end of the coil has changed from being connected to the right brush to being connected to the left brush. This is the key to this motor design. As the rotor spins, the outermost poles of the electromagnets must change back and forth, becoming south poles and then north poles. In order to keep the motor spinning, an electromagnet must have the opposite type of pole compared to the permanent magnet as it approaches the permanent magnet and must have the same type of pole as it moves away from the permanent magnet (opposite type poles attract, like type poles repel). You may have to study the diagrams carefully to understand the operating principles. It is a rather difficult thing to visualize.

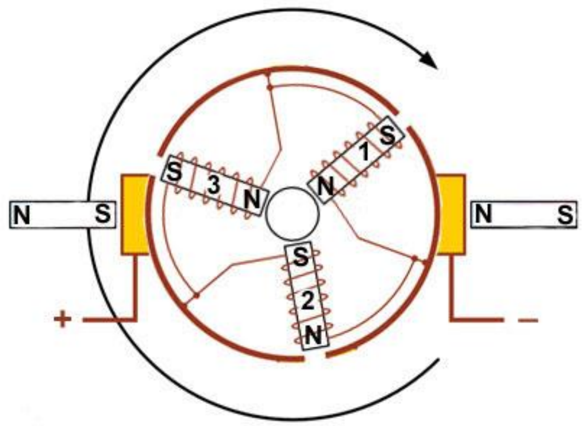


Figure 9 third motor diagram, rotation 80 degrees clockwise

When nine volts are applied to the terminals of our robot motors, they will spin at a rate of approximately 15,000 revolutions per minute (RPM). That is much too fast if we connect the motor directly to the robot wheel. In fact, if our robot wheel spun at a rate of 15,000 RPM, the robot would exceed the speed limit of any public road in America. At the end of this lesson you will actually calculate the speed.

In order to solve the excessive speed problem, our robot motors have a gear box attached. The gears reduce the rate of revolutions from 15,000 to an output rate of 67 RPM. That is just about the right rate of rotation for our robot wheels. You will find a photograph of the motor gear box in Figure 10 on the next page.

The motor is attached to the right side of the gear box. There is a gear with 8 teeth attached to the end of the motor shaft. That gear meshes with a gear containing 36 teeth. The 8-tooth gear must turn 4.5 times in order to turn the 36-tooth gear one turn. This is how the gearing reduces the rate of rotation of the motor. The 8-tooth/36 tooth combination reduces the rate of rotation by a factor of 4.5 and this is commonly expressed as a ratio like this: 4.5:1.

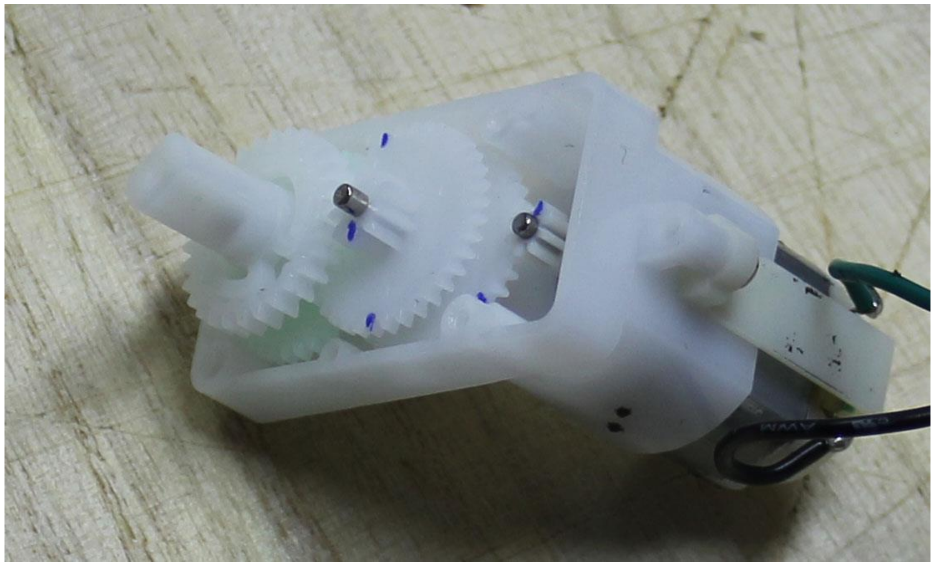


Figure 10 motor gear box

Well, we can't see all of the gears clearly while they are inside the gear box, so let's remove them and align them in a manner that makes it easier for us to understand how they work. That is what I have done for you in Figure 11. The gear attached to the motor shaft is the one on the right and the gear that attaches to the robot wheel is on the left. There are eight gears that mesh in four pairs to reduce the rate of the motor at 15,000 RPM to 67 RPM at the wheel. The ratio of each gear pair is labeled in the figure. In order to calculate the gear reduction of the combined gears, we simply multiply the reductions together: 4.5 X 4 X 4 X 3.111 = 224. The gear ratio of the gear box is 224:1. That means the motor must make 224 turns for each turn of the wheel. If we divide 15,000 RPM by 224, we get an answer of 67 RPM. That is the rate of the rotation of the wheel.

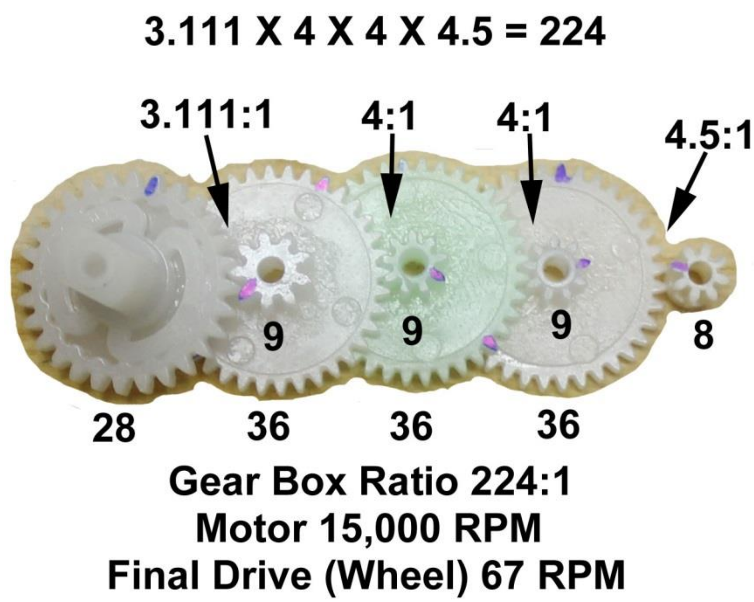


Figure 11 gears removed from gear box

There is another advantage to using a gear box. As the rate of rotation is reduced the amount of torque delivered to the wheel increases. Torque is a measure of the amount of twisting force applied to the wheel. The more torque applied, the more driving force applied to move your robot forward. If you want your robot to go uphill, the wheels must have more torque applied than if running on a flat surface. Even on a flat surface, your robot must have enough torque applied to the wheels to overcome the frictional forces experienced by the robot. Also, to accelerate the robot from a standstill to a certain speed, it is necessary to apply a certain amount of torque in order to accelerate the mass of the robot.

The amount of torque output by the motor itself is not sufficient to run the robot. If we actually connected the motor directly to the wheel, the motor could not spin due to a lack of sufficient torque. By reducing the rotation rate by a factor of 224, we also increase the torque by a factor of 224. Then the torque is more than enough to run our robot.

In reality, the foremost reason for using the gear box is to increase the amount of torque. Otherwise, our robot could not move. If our motor had enough torque to actually move the robot, then the only reason for using the gear box would be to reduce the speed to an acceptable rate. Reducing speed and increasing torque are both important features of the gearbox, but without sufficient torque, reduction of speed becomes a moot point (if the motor can't turn, then there is no speed to reduce).

Protecting the power transistors with flyback diodes

When the motor is disconnected from electrical power, it produces brief, but powerful voltage spikes due to inductance of the rotor wire coils. The high voltage can damage the power transistor. In order to prevent this damage, we can connect a diode across the motor terminals. The diode is connected in the reverse direction. In other words, it is connected so that the battery current applied cannot flow through the diode. But current can flow in the opposite direction when the voltage spike starts to build. This application of a diode is known as a flyback diode. The diode prevents large voltage spikes by allowing current to circulate in a circle between the diode and motor, thus protecting the power transistor.

A special type of diode, called a Schottky diode, is a good choice for use as a flyback diode. Schottky diodes operate as very fast switches. This is what we want when the voltage spike begins. The Schottky diode turns on quickly before much voltage can build up. You will be using a 1N5818 Schottky diode and I have included the data sheet for it in this lesson.

Now let us study the circuit schematic for the motor, which is on the next page.

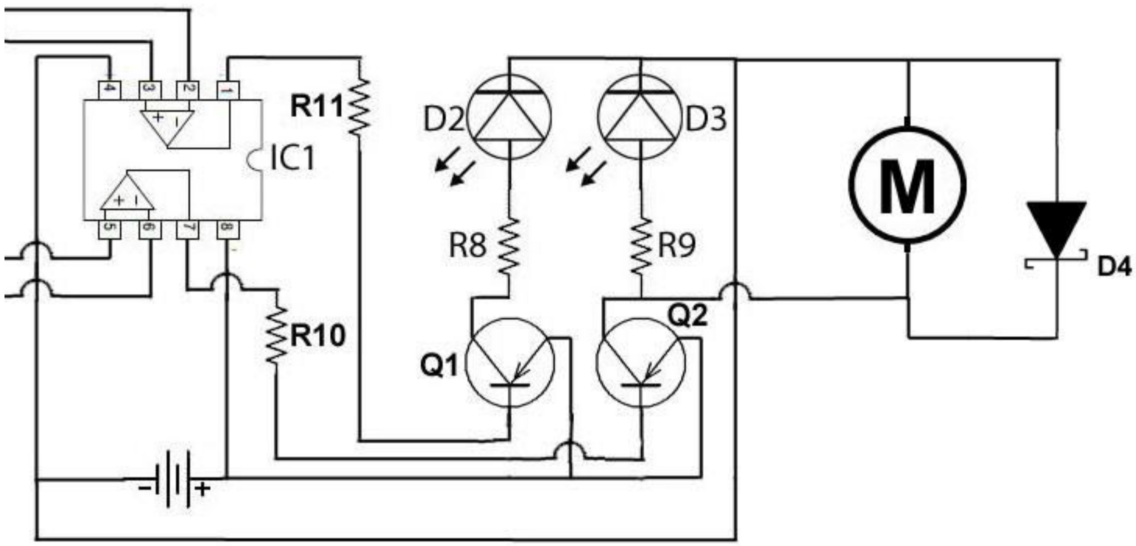


Figure 12 motor circuit schematic

The motor is represented in the schematic above by a circle containing the letter M inside. The Schottky diode is D4 in the schematic. Notice that the diode symbol is slightly different than a regular diode. The line against the arrow is bent at its ends into a U-shape. Also notice that the diode is positioned in a reverse direction to current flow through the motor. The bottom terminal of the motor is connected to the positive side of the battery through the transistor Q2. Therefore, current flows through the motor in the upward direction on the schematic. We can see that the arrow of the diode is pointing down, indicating that the direction of allowed current flow is opposite to the flow through the motor. Therefore, the diode is placed in a reverse position and won't allow current to flow through it while current from the battery is flowing through the motor. This is what we want. We don't want to have the diode taking away current from our motor.

Now you are ready to start wiring the motor circuit. See the instructions on the next page.

Wiring the motor circuit

1. Insert a green wire (labeled #1 in photo), with one end in the same row as the right wire of the transistor.
2. Insert the Schottky diode (D4) with one wire lead in the same row as the right side of the green wire. Insert the other end of the diode in a row above the gap in the board. Make sure the diode is positioned with proper polarity. The end of the diode marked with a gray band must be down as in the photo (the arrow in the photo points to the gray band).
3. Connect a black wire (labeled #2 in photo) to the same row as the top lead of D4. The other end of the wire should connect to the negative power bus.
4. Using two wire jumpers with alligator clips, attach one clip of each jumper to a lead of the Schotkky diode (Figure 14). Connect the other ends of the wire jumpers to the wires of the motor (not shown). Your wiring is now complete and ready for testing. But first, have an adult check your wiring. It is especially important that you have inserted the diode properly. Otherwise you may damage the transistor when testing your circuit.
5. To test your circuit, turn the power switch on. The power LED light should be glowing. The motor may also start to run. Now cast a shadow on one set of the photoresistors and then the other set. Alternate back and forth and you should find that the robot motor turns off and on at the same time as the LED attached to transistor Q2. If this is

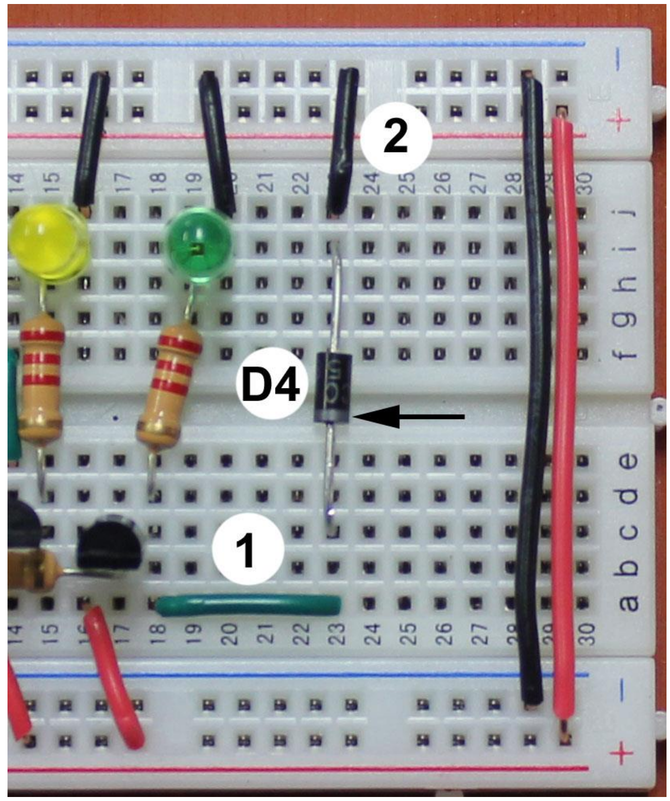


Figure 13

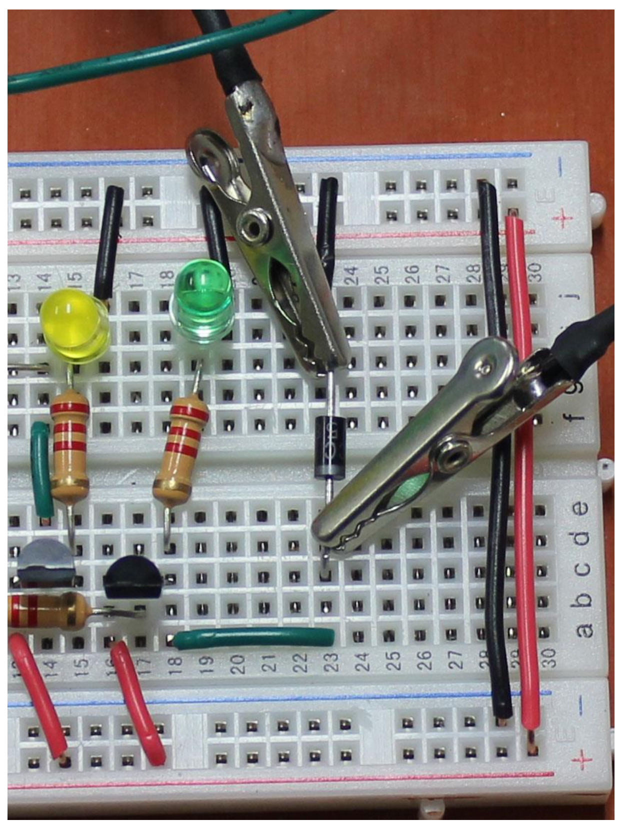


Figure 14

what you observe, you have successfully completed the wiring for the robot on the breadboard. Congratulations!

Calculating the speed of your robot

It is time now to do some engineering calculations. Remember that I said you would calculate the speed of the robot earlier in this lesson. First you will calculate the speed of the robot assuming the motor is connected directly to the wheel. We will assume the motor can develop enough torque to rotate the wheel at the unloaded speed of the motor (15,000 RPM). I have already said that this is not possible, but just for fun let us assume it is possible.

First we need to measure the diameter of the wheel. I have already done this for you. The diameter of the wheel is 2.7 inches. As the wheel rotates, it is the circumference of the wheel that contacts the floor. If the wheel makes exactly one turn, the robot will move forward the same distance as the circumference of the wheel. Therefore, we need to calculate the circumference of the wheel. The circumference of a circle can be calculated by multiplying the diameter by the value of pi (approximately 3.14).

Wheel Diameter X π = Wheel Circumference

2.7 inches X 3.14 = ___________________

Now you know how far the robot will travel with each complete turn of the wheel. Your next calculation will determine how far the robot will travel in one minute. We know the motor turns 15,000 times in one minute.

Wheel Circumference X 15,000 RPM = distance traveled in one minute (in inches)

Wheel Circumference ___________ X 15,000 RPM = ______________ inches

Let us now convert inches to feet by dividing by 12.

Distance traveled in inches / 12 = Distance traveled in feet

Distance traveled in inches _________ / 12 = _________________ feet

Now you will calculate the distance traveled in one hour by multiplying by 60 (minutes per hour)

Distance traveled in one minute X 60 minutes per hour = Distance traveled in one hour

Distance traveled in one minute___________ X 60 = ____________________feet per hour

The distance traveled in one hour in feet will be a very large number. Let's reduce that by calculating the distance traveled in miles in one hour, which will be the same as miles per hour or MPH.

Feet traveled in one hour / 5,280 feet per mile = miles traveled in one hour

Feet traveled in one hour _________ / 5,280 = ___________ MPH

Your figure for the speed of the robot should be very fast, quite a bit more than 100 MPH. Ask me and I will tell you the exact speed. Then you can check against the answer you calculated.

Well, we know our robot motor is not capable of moving the robot at a speed of over 100 MPH. We also know that the rotation rate of the motor is reduced by the gear box by a factor of 224. Therefore, if you divide the calculated speed above by 224, you will know the actual speed obtained by your robot. It should be much less than one mile per hour.

Speed of robot at 15,000 RPM / 224 = Actual speed of robot

Speed of robot at 15,000 RPM________________ / 224 = ______________ MPH true speed.

You have now completed all lessons covering the breadboard work of the robot circuits. You should also understand how all circuits of the robot work together to allow the robot to follow a line. If there is something you don't understand, please ask questions at our meetings. It is my goal that every member should understand how the robot works. That is the most important thing.

You are now ready to start assembling your actual robot! But first you need to learn how to solder. That will be your next lesson.