Build a Speedy Light-Tracking Robot (BlueBot Project #2)

https://www.sciencebuddies.org/science-fair-projects/project-ideas/Robotics_p022/robotics/light-following-robot (http://www.sciencebuddies.org/science-fair-projects/project-ideas/Robotics_p022/robotics/light-following-robot)

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Experimental Procedure

> **Note:** This engineering project is best described by the **engineering design process,** as opposed to the **scientific method.** You might want to ask your teacher whether it's acceptable to follow the engineering design process for your project before you begin. You can learn more about the engineering design process in the Science Buddies Engineering Design Process Guide (http://www.sciencebuddies.org/engineering-design-process/engineering-design-process-steps.shtml).

Assembling Your BlueBot Chassis

1. Follow the instructions in the video to assemble your robot chassis.
   a. Your kit comes with printed directions for assembling the chassis, but we recommend watching the video so you fully understand how all the parts fit together.
   b. The blue plastic parts come with a thin layer of protective plastic coating. Peel this coating off before assembling your chassis.
   c. We also recommend using double-sided foam tape to attach the battery holder to the top of the chassis, as shown in Figure 5. The printed directions recommend putting the battery holder in-between the two chassis plates, but this makes it harder to change the batteries.
   d. You will have some extra parts when you are done, including screws, nuts, and blue plastic gears. Put these parts aside for now; you will not need them for this project.

> https://www.youtube.com/watch?v=SBeGl_IgWwY (https://www.youtube.com/watch?v=SBeGl_IgWwY)
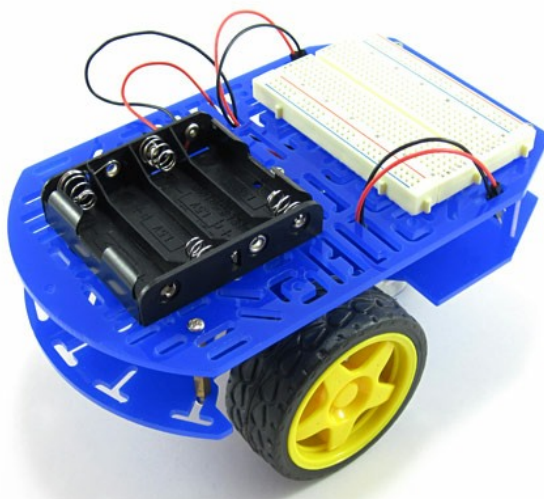

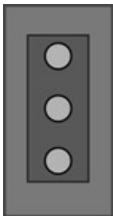**Figure 5.** A completed BlueBot chassis with breadboard and battery pack on top.
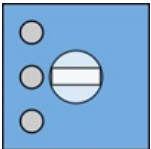
Assembling Your Circuit
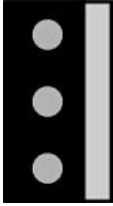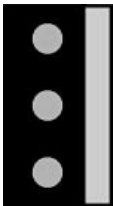
1. To build your circuit, you will need to know how to use a breadboard. Watch the video and see the Science Buddies reference How to Use a Breadboard (http://www.sciencebuddies.org/science-fair-projects/references/how-to-use-a-breadboard) to learn how to use a breadboard.

> https://www.youtube.com/watch?v=6WReFkfrUIk (https://www.youtube.com/watch?v=6WReFkfrUIk)

2. Now that you know how to use a breadboard, you are ready to assemble your BlueBot circuit. Table 2 shows a list of all the components in the circuit and where they go on the breadboard. You can download and print a PDF (https://www.sciencebuddies.org/science-fair-projects/breadboard-checklist.pdf) of this table—complete with checkboxes to track each step—to use while you are building your robot. You can also view a slideshow (#breadboard-slideshow) that shows breadboard diagrams of the circuit. Follow along in the table and/or slideshow to build your circuit one component at a time. Your finished circuit should look like the one in Figure 6 (#figure6). Pay attention to these notes:
   a. Remember to push all components *firmly* into the breadboard.
   b. All references to orientation (up, down, left, and right) assume you have the breadboard "right-side up," so the writing is facing you.
   c. Your jumper wire kit comes with an assortment of colors, and the colors may vary. It does not matter what color jumper wires you use. Your colors do *not* need to match the colors in the diagrams. In general, you should use the shortest wires possible, to help keep your circuit neat.

d. Insert the batteries *last.* If you see or smell smoke when you insert the batteries, you have a short circuit somewhere. Immediately remove the batteries and re-check your wiring.

Component	Picture	Symbol	Breadboard holes	Note
Power switch			F1, F2, F3	The direction in which it is facing does not matter, but make sure to slide the switch down (toward row 30, away from row 1), this is the "off" position.
Jumper wire			J2 to (+) bus	Color does not matter.
Jumper wire			J12 to (-) bus	Color does not matter.
Jumper wire			J19 to (-) bus	Color does not matter.
Jumper wire			Left side (+) bus to right side (+) bus	Color does not matter.
Jumper wire			Left side (-) bus to right side (-) bus	Color does not matter.
Potentiometer			G11, G12, G13	Direction matters; pins should be on the left.
Potentiometer			G18, G19, G20	Direction matters; pins should be on the left.

Component	Picture	Symbol	Breadboard holes	Note
Jumper wire			E11 to F11	Color does not matter.
Jumper wire			E18 to F18	Color does not matter.
MOSFET			C11, C12, C13	Writing should face to the left, large silver tab should face to the right. Note: the writing on your MOSFET may differ from the picture. This is OK.
MOSFET			C18, C19, C20	Writing should face to the left, large silver tab should face to the right. Note: the writing on your MOSFET may differ from the picture. This is OK.
Jumper wire			A13 to (-) bus	Color does not matter.
Jumper wire			A20 to (-) bus	Color does not matter.
Photoresistor			A11 to (+) bus	Direction does not matter.
Photoresistor			A18 to (+) bus	Direction does not matter.
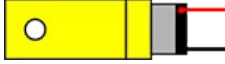
Component	Picture	Symbol	Breadboard holes	Note
Diode			A12 to (+) bus	Gray band must face to the left. Optional: Shorten the leads.
Diode			A19 to (+) bus	Gray band must face to the left Optional: Shorten the leads.
Top motor			Red lead to (+) bus Black lead to E19	When the robot is driving forward, this is the "right" motor.
Bottom motor			Red lead to (+) bus Black lead to E12	When the robot is driving forward, this is the "left" motor.
Battery holder			Red lead to J1 Black lead to (-) bus	Do not insert batteries until the circuit is complete.
AA battery			N/A	Insert into battery holder. Make sure (+) signs on batteries line up with (+) signs in battery holder.

Table 2. List of circuit components and locations. A printable PDF version (https://www.sciencebuddies.org/science-fair-projects/breadboard-checklist.pdf) is available.
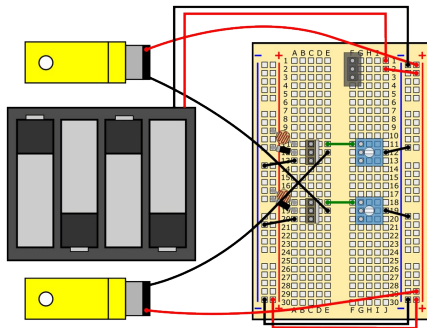
Slideshow with step-by-step instructions viewable online.
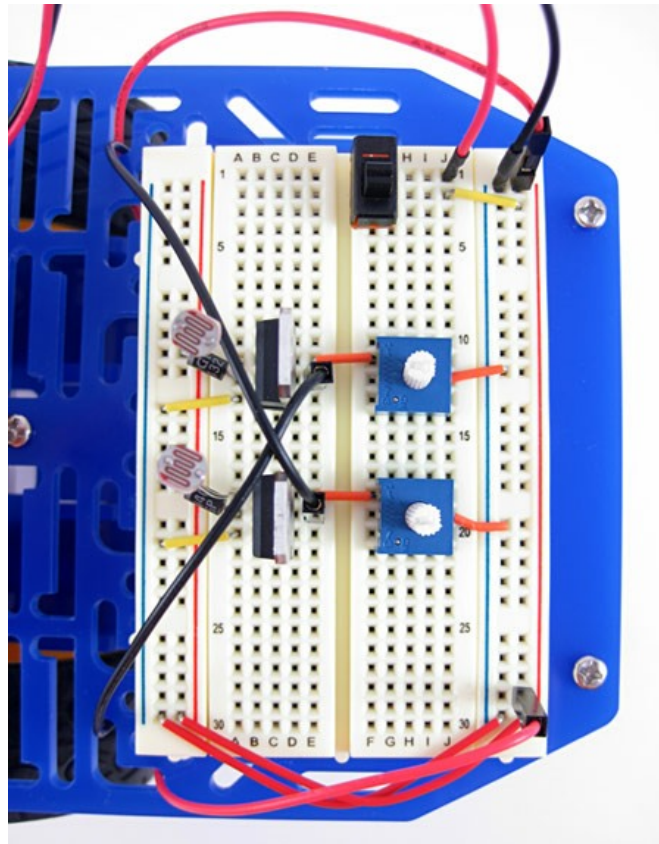
Figure 6. Your completed circuit should look like this.

Testing the Robot

You are finally ready to start testing your robot! Remember that now you will need to follow The Engineering Design Process (http://www.sciencebuddies.org/science-fair-projects/engineering-design-process/engineering-design-process-steps) to get your robot working. Follow these steps to learn how to use your robot.

1. Double-check your circuit against the breadboard diagrams in the previous section. Remember that just *one* misplaced wire can prevent the circuit from working properly.
2. Hold the robot's chassis in one hand so the wheels are off the ground. Turn the robot's power switch "on" by sliding it up, toward row 1 on the breadboard. Check Table 3 to see what you should do next.

Observation	What to do
I see or smell smoke.	Immediately turn your robot off. You have a short circuit somewhere. Re-check your wiring against the breadboard diagrams in the previous section.
The wheels spin forward.	Your robot works! Move on to the next step.
One or both wheels spin backwards.	Reverse the red and black wires for that motor if a wheel is spinning backwards.
The wheels do not spin at all.	Try holding the robot's light sensors up to a bright light. Turn the potentiometer knobs all the way clockwise. The wheels should start spinning.
The wheels still do not spin.	Part of your circuit is connected incorrectly. Re-check your circuit against the wiring diagrams, and see the Help (#help) section for more details.

Table 3. What to do the first time you turn on your robot.

3. The potentiometers adjust your robot's sensitivity to *ambient* light levels (the normal light levels in a room). Your goal is to make sure the robot does *not* respond to regular ambient light, and that it *does* follow around a brighter flashlight beam.
   a. Turn both potentiometers all the way counterclockwise. This should turn the motors off (for more information on how the circuit works, see the Help (#help) section).
   b. *Slowly* turn the potentiometers clockwise, one at a time. This gradually increases the circuit's sensitivity to ambient light. Eventually, the motors should start spinning slowly.
   c. Turn the potentiometers slightly counterclockwise again, until the motors *just* turn off. You have set the motors just below the threshold for detecting ambient

light.

    d. Now, aim a flashlight directly at your robot's light sensors, or hold the robot very close to a light. This brighter amount of light should activate the sensors and cause the motors to spin.

    e. Depending on the lighting in the room, you may need to continue to adjust the potentiometers slightly. For example, an open window on a sunny day or a bright lamp in a corner might cause the robot to move. Your goal is to make sure the robot does *not* respond to these light sources, and that it only responds to your flashlight. If your potentiometers are adjusted asymmetrically (one is turned farther than the other), this may cause your robot to steer more in one direction.

4. Put the robot on the floor and try guiding it with a flashlight. Make sure you aim the flashlight *at the photoresistors* and not at the front of the robot or the floor in front of the robot. Can you control whether the robot goes forward, left, or right? It might be rather difficult to steer; go to the next step to find out why.

5. The photoresistors have long, flexible leads that let you adjust their aim. Which way they are facing can have a big impact on how easy the robot is to steer. If they are right next to each other, they will always get hit by the same amount of light, so it will be very hard to steer the robot left or right. If they are too far apart, it will be hard to illuminate them evenly, so it will be hard to make the robot go straight. You can also adjust whether they are aimed forward or up, straight ahead or outward, or even diagonally. Try adjusting the photoresistors to different positions, and see which position makes it the easiest to steer your robot. Figure 7 shows several different positions for the photoresistors.
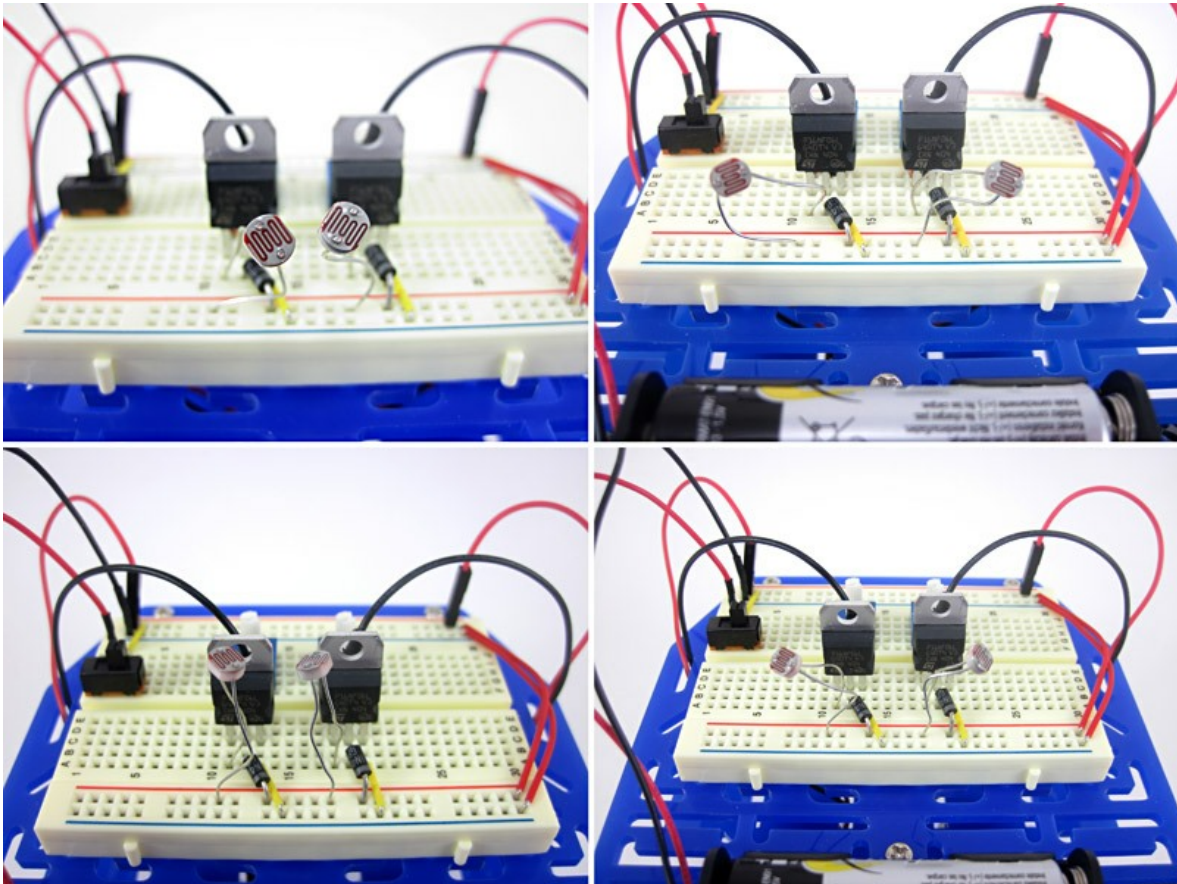
Figure 7. Different positions and orientations for the photoresistors. Top left: Photoresistors close together, facing forward. Top right: Photoresistors spaced apart, facing forward. Bottom left: Photoresistors spaced apart, facing upward. Bottom right: Photoresistors spaced apart, facing diagonally outward.

6. Continue to make adjustments to the photoresistors and potentiometers until you can easily guide your robot around with a flashlight. Can you navigate the robot through a maze or obstacle course using the flashlight?

7. There are several other robotics projects you can do with your chassis. See the Variations (#makeityourown) section for some ideas.

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If you like this project, you might enjoy exploring these related careers:

Robotics Engineer (http://www.sciencebuddies.org/science-engineering-careers/engineering/robotics-engineer)

(http://www.sciencebuddies.org/science
-engineering-
careers/engineering/robotics-engineer)

Have you watched "The Transformers" cartoon series or seen the "Transformers" movies? Both shows are about how good and evil robots fight each other and the humans who get in the middle. Many TV shows and movies show robots and humans interacting with each other. While this is, at present, fantasy, in real life robots play a helpful role. Robots do jobs that can be dangerous for humans. For example, some robots defuse landmines in war-stricken countries; others work in harsh environments like the bottom of the ocean and on the planet Mars. At the heart of every robot is a robotics engineer who thinks about what a robot needs to do and works with several engineering disciplines to design and put together the perfect piece of equipment. Read more (http://www.sciencebuddies.org/science-engineering-careers/engineering/robotics-engineer)

Robotics Technician (http://www.sciencebuddies.org/science-engineering-careers/engineering/robotics-technician)

(http://www.sciencebuddies.org/science
-engineering-
careers/engineering/robotics-technician)

Robots are no longer futuristic machines. Robots are here and now and are used in manufacturing, health care, service industries, and military applications. They perform tasks that are repetitive and hazardous—things that humans don't want to do or are unsafe to do. But robots are still machines, which means they require humans to build, maintain, program, and keep them functioning efficiently. Robotics technicians work with robotics engineers to build and test robots. They are responsible for installing and maintaining robots and keeping them in working order for their employers. If you are interested in working with robots, your future is here and now. Read more (http://www.sciencebuddies.org/science-engineering-careers/engineering/robotics-technician)

Electrical & Electronics Engineer (http://www.sciencebuddies.org/science-engineering-careers/engineering/electrical-electronics-engineer)

(http://www.sciencebuddies.org/science
-engineering-
careers/engineering/electrical-
electronics-engineer)

Just as a potter forms clay, or a steel worker molds molten steel, electrical and electronics engineers gather and shape electricity and use it to make products that transmit power or transmit information. Electrical and electronics engineers may specialize in one of the millions of products that make or use electricity, like cell phones, electric motors, microwaves, medical instruments, airline navigation system, or handheld games. Read more (http://www.sciencebuddies.org/science-engineering-careers/engineering/electrical-electronics-engineer)

Mechanical Engineer (http://www.sciencebuddies.org/science-engineering-careers/engineering/mechanical-engineer)

(http://www.sciencebuddies.org/science
-engineering-
careers/engineering/mechanical-
engineer)

Mechanical engineers are part of your everyday life, designing the spoon you used to eat your breakfast, your breakfast's packaging, the flip-top cap on your toothpaste tube, the zipper on your jacket, the car, bike, or bus you took to school, the chair you sat in, the door handle you grasped and the hinges it opened on, and the ballpoint pen you used to take your test. Virtually every object that you see around you has passed through the hands of a mechanical engineer. Consequently, their skills are in demand to design millions of different products in almost every type of industry. Read more (http://www.sciencebuddies.org/science-engineering-careers/engineering/mechanical-engineer)

Variations

- There are three other projects you can do with your BlueBot kit. Since you have already assembled your chassis, all you need to do is build a new circuit.
  - Build a Zippy Line-following Robot (BlueBot Project #3) (http://www.sciencebuddies.org/science-fair-projects/project-ideas/Robotics_p023/robotics/line-following-robot)
  - Build a Motion-Activated Guard Robot (BlueBot Project #1) (http://www.sciencebuddies.org/science-fair-projects/project-ideas/Robotics_p024/robotics/guard-robot)
  - Build an Obstacle-Avoiding Robot (BlueBot Project #4) (http://www.sciencebuddies.org/science-fair-projects/project-ideas/Robotics_p028/robotics/obstacle-avoiding-robot)
- Use the long male-female jumper wires that came with your kit, and mount the light sensors to the front of your robot's chassis, angled down toward the floor. Can you now get the robot to "chase" a flashlight beam aimed at the floor in front of it (kind of like a cat chasing a laser pointer)?
- A "bristlebot" is a small robot that uses vibration motors instead of geared DC motors, and toothbrush heads instead of wheels. You can put the same circuit you used in this project on a bristlebot to build a miniature version of the robot. See the Science Buddies project Build a Light-Tracking Bristlebot (http://www.sciencebuddies.org/science-fair-projects/project-ideas/Robotics_p012/robotics/build-a-light-tracking-bristlebot) for directions.
- The Arduino (http://www.arduino.cc/) is a very popular type of *microcontroller* used in robotics. It lets you write a computer program that can read inputs from sensors and use them to control motors. This gives you more precise "control" over you robot's behavior. Can you build a programmable light-tracking robot by adding an Arduino to your chassis? See our Getting Started with Arduino (http://www.sciencebuddies.org/science-fair-projects/references/getting-started-with-arduino) page to learn more.

Frequently Asked Questions (FAQ)

If you are having trouble with this project, please read the FAQ below. You may find the answer to your question.

- My wheels do not spin at all. What should I do? (#question1)
- Only one of my robot's wheels is spinning. What is wrong? (#question2)
- My robot is going backwards! What should I do? (#question3)
- I have double-checked everything and my robot still does not work. How can I check if something is broken? (#question4)
- How does the light sensor work? (#question5)
- How does a MOSFET work? (#question6)
- How does the circuit work? What is the circuit diagram? (#question7)
- What are the circuit diagram symbols for the components in this project? (#question8)
- How did you make the breadboard diagrams for this project? (#question9)

Q: My wheels do not spin at all. What should I do?

A: If your wheels do not spin at all when you turn the robot on and expose it to light, there are several troubleshooting steps you can try:

- Double-check your circuit to make sure that it exactly matches the breadboard diagrams from the Procedure (#procedure).
- Make sure all of your jumper wires and component leads are pressed firmly into the breadboard. You can read about other common breadboard mistakes in the the Common Mistakes (http://www.sciencebuddies.org/science-fair-projects/breadboard-tutorial#common-mistakes) section of the Science Buddies reference How to Use a Breadboard.
- Make sure your batteries are properly inserted into the battery pack, and that the "+" symbols on the batteries line up with the "+" symbols on the battery pack.
- Make sure the power switch for your robot is toggled "on" (the slider should be pushed toward row 1 at the top of the breadboard).
- Turn both potentiometers all the way clockwise, then hold the robot directly up to a bright light source. Do the wheels spin?
- If not, turn both potentiometers all the way counterclockwise (just in case you put them in the breadboard backwards). Hold the robot directly up to a bright light source. Do the wheels spin?
- If you have been using your robot for a long time, or did some of the other BlueBot projects first, your batteries may be dead. Try putting fresh batteries in your robot if none of the other steps work.
- If your robot still does not turn on, follow these steps to see if the problem is with your power switch:
  - Remove the power switch from the breadboard, flip it around, and put it back into the same breadboard holes (F1, F2, and F3). If you are confused about which way to rotate the switch, see this video (https://youtu.be/zkGBW5JSqls).
  - Slide the power switch to the "on" position ("up" towards row 1 of the breadboard) and try testing your robot again. If your robot works after making this change, you can continue with the project, but please contact us at scibuddy@sciencebuddies.org (mailto:scibuddy@sciencebuddies.org?subject=Light%20BlueBot:%20switch%20worked%20when%20flipped) to let us know this happened.
  - If your robot still does not work after flipping the power switch around, bypass the power switch entirely. Connect the battery pack's red lead directly to the breadboard's power bus instead of hole J1. This connects the battery pack directly to the rest of the circuit. To turn the robot off again, you will have to temporarily disconnect this wire.
  - Now, re-try testing your robot. If your robot works, you can continue with the project, but please contact us at scibuddy@sciencebuddies.org (mailto:scibuddy@sciencebuddies.org?subject=Light%20BlueBot:%20switch%20did%20not%20work%20at%20all) to let us know the switch did not work in either direction.
  - If your robot still does not work, even after you have tried the previous steps, the problem is elsewhere in your circuit and not with the power switch. If you are having trouble figuring out what is wrong with your robot, you can ask a question in our Ask an Expert: Answers to Your Science Questions (http://www.sciencebuddies.org/science-fair-projects/ask-an-expert-intro) forums.

Q: Only one of my robot's wheels is spinning. What is wrong?

A: Your robot's circuit consists of two identical halves that drive the two motors. If only one wheel is spinning, chances are you just have something placed incorrectly on the breadboard in one half of the circuit. Very carefully double-check all of your writing on the side of the motor that is not working. It only takes *one* misplaced component or jumper wire to prevent the motor from spinning!

Q: My robot is going backwards! What should I do?

A: If your robot is driving away from light instead of toward it, all you need to do is switch the breadboard connections of the red and black leads from each motor. This is shown in Figure 8.
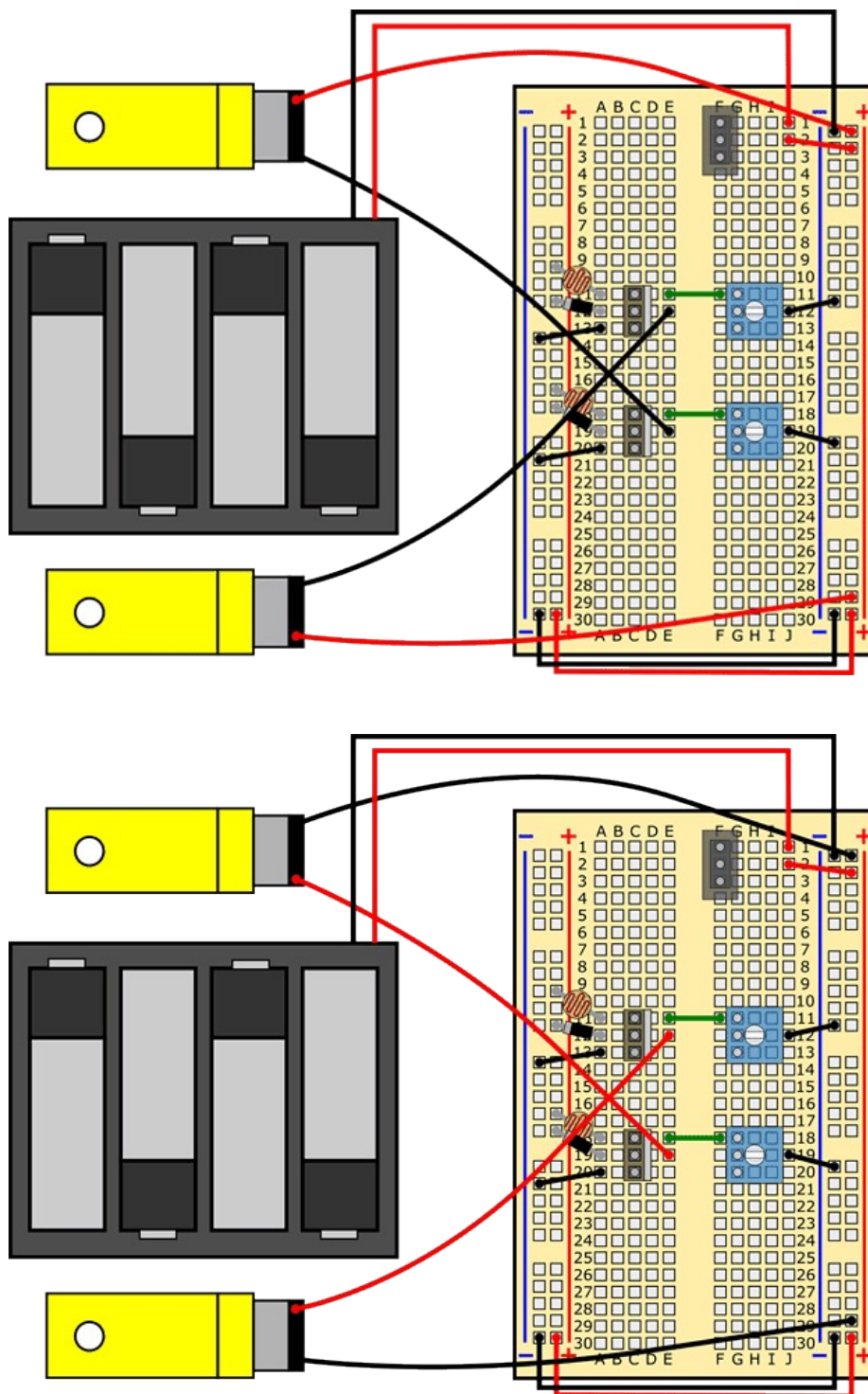
Figure 8. On the top, the motor's red wires are connected to the power bus, and the black wires are connected to the MOSFET's drain pins (holes E12 and E19). If this configuration makes your robot drive backwards, just switch the red and black wires for each motor, to match the image on the bottom. Connect the black wires to the power bus, and the red wires to the MOSFET drains. Do not worry about violating standard color-coding conventions; all this does is reverse the direction in which the motors spin.

Q: I have double-checked everything and my robot still does not work. How can I check if something is broken?
A: If you are having trouble figuring out why your robot will not work, you can try asking a question in our Ask an Expert: Answers to Your Science Questions (http://www.sciencebuddies.org/science-fair-projects/ask-an-expert-intro) forums. If you have access to a multimeter, you can also use that to help troubleshoot your circuit. See the Science Buddies reference How to Use a Multimeter (http://www.sciencebuddies.org/science-fair-projects/references/how-to-use-a-multimeter) if you need help using a multimeter. There are several steps you can take to check individual parts of your circuit (depending on your multimeter's probes, you may need alligator clips and additional jumper wires to take these measurements).

- Try plugging your motor's leads directly into the buses on your breadboard (for each motor, one lead to the power bus, one lead to the ground bus). If the motors turn on, then you know that they are working, and the problem is elsewhere in your circuit. If the motors do not turn on, that does not necessarily mean they are broken. There might be a problem with your power supply (see next point).
- Check your breadboard's power supply.

- Set your multimeter to measure DC volts. Four fresh AA batteries should provide just over 6 V.
- Turn your power switch on and measure the voltage between the breadboard's buses. If you do not read a voltage, there may a problem with your power switch (see the first question in this FAQ), but you should also double check that your power switch and the red jumper wire from hole J2 to the power bus are in the right place.
- Unplug the red and black battery pack leads and measure the voltage of the battery pack directly. If you get a reading, then you know your battery pack is working, and the problem is with your breadboard connections or the power switch. If you do not get a reading, make sure all the batteries are in the correct orientation in your battery pack, and that none of the metal clips and springs that hold the batteries in place are loose.
- Check the output of the light sensor.
  - Measure the voltage between the first MOSFET's gate (row 11 on the left side of the breadboard) and ground. This is the output of the light sensor. The voltage should change when you turn the potentiometer. It should also change when you shine bright light on the photoresistor. If the voltage does not change at all, then your photoresistor and potentiometer may be wired incorrectly. Repeat this for the second half of the circuit (MOSFET gate at row 18).
  - If the voltages changes, and goes above roughly 3–4 V with bright light, then your motors should turn on. If you previously checked to make sure your motors work (see above), and they still will not turn on, then the problem is elsewhere in your circuit. You know the individual components are functioning so nothing is "broken." Double and triple-check all your breadboard connections. Remember that just one misplaced wire can prevent the whole circuit from working.

Q: How does the light sensor work?
A: In order to make a light sensor, the photoresistor and potentiometer are combined to make a **voltage divider**. A voltage divider is a simple circuit made from two resistors, R_1 and R_2 (Figure 9). It takes an input voltage (V_{in}) and outputs a different voltage (V_{out}), according to Equation 1 (which can be derived based on **Ohm's law**—see the Bibliography (#bibliography)):

Equation 1:

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$$

- V_{in} is the input voltage in volts (V).
- V_{out} is the output voltage in volts (V).
- R_1 is the first resistance in ohms (Ω).
- R_2 is the second resistance in ohms (Ω).
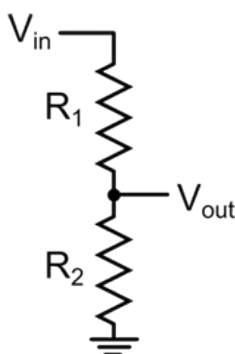

Figure 9. Circuit diagram for a voltage divider.

In your circuit, the photoresistor will be R_1 and the potentiometer will be R_2. Remember that the resistance of a photoresistor *decreases* when it is exposed to bright light. From Equation 1, we can see that when R_1 is very large ($R_1 >> R_2$), V_{out} gets very small ($V_{out} << V_{in}$). When R_1 is very small ($R_1 << R_2$), V_{out} is roughly equal to V_{in} ($V_{out} \cong V_{in}$). This means that the light sensor outputs a high voltage when it detects light, and a low voltage when it does not.

Q: How does a MOSFET work?
A: MOSFET stands for *metal-oxide-semiconductor field-effect transistor* (so you can see why it is a lot easier just to say "MOSFET"). The three pins of a field-effect transistor are called the **gate**, **drain**, and **source**. Unlike a *bipolar* transistor, which is controlled by a small current applied to the base pin, a *field-effect* transistor is controlled by a voltage applied to the gate pin, but the gate does not actually draw any current. A voltage applied to the gate causes current to flow between the drain and source pins.

Figure 10 shows a simplified explanation of how a MOSFET works. A votage is applied to the gate pin in order to control the flow of current between the drain and source pins. When the voltage between the gate and source pins (V_{GS}) is below a certain limit, called the **threshold voltage** (V_{th}), no current flows. When V_{GS} exceeds V_{th}, the MOSFET begins to conduct, allowing current to pass through. This is what allows you to use the gate voltage of a MOSFET to turn a DC motor on and off. For this robot, the MOSFET's gate voltage is controlled by the voltage divider.
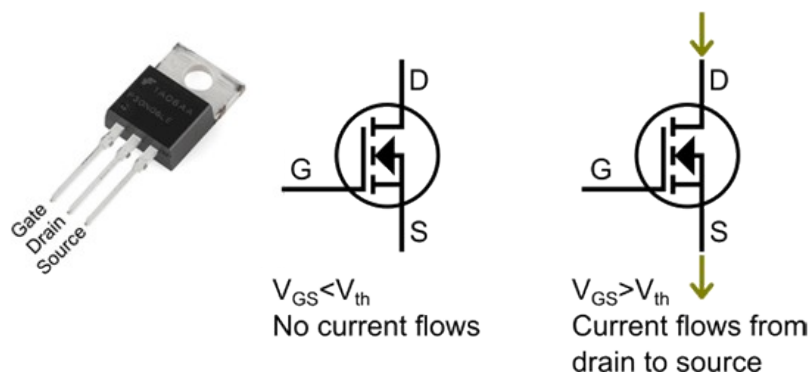
Figure 10. Simplified explanation of a MOSFET's operation.

The exact description of how a MOSFET works is more complicated than this. As V_{GS} increases past V_{th}, the current through the MOSFET will continue to increase. Eventually the MOSFET will reach **saturation**, where no additional current can flow, even if V_{GS} continues to increase. The MOSFET's behavior will also depend on the type of **load** to which it is attached. The MOSFET used in this project is an **N-channel MOSFET**, which requires a positive gate voltage to turn on. A **P-channel MOSFET** requires a negative gate voltage to turn on. Advanced users can refer to the Bibliography (#bibliography) for more information on MOSFETs.

Q: How does the circuit work? What is the circuit diagram?
A: The two questions above explain two key components of the circuit: voltage dividers and MOSFETs. How do you combine these, along with all the other components listed in Table 1, into a single circuit that can control two motors to allow a robot to steer left and right in response to light? Figure 11 shows the complete circuit diagram for the entire robot (refer to the reference "How to Read a Schematic" in the Bibliography (#bibliography) if you are not familiar with circuit diagrams). Look closely and you will see that it is actually two copies of the same circuit, one for each motor.
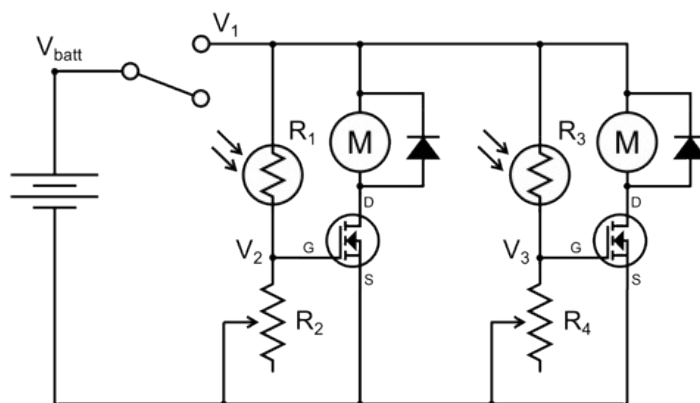
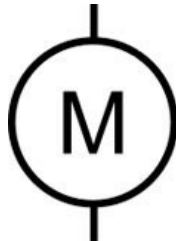**Figure 11.** A complete circuit diagram for the light-following rbot.
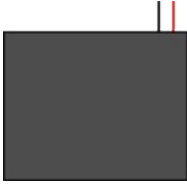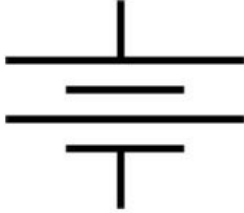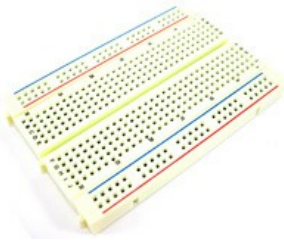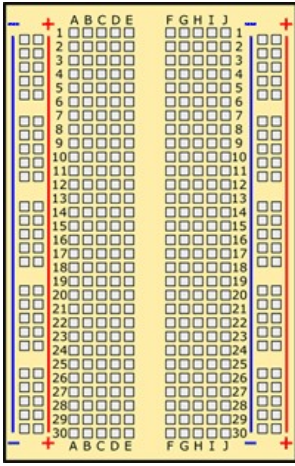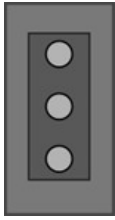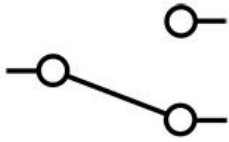
The circuit diagram might look confusing at first, but if you look closely (refer to the symbols in Table 3 if necessary), you will see that it just consists of things you have already read about. Let us just look at the left-hand side of the circuit (the same explanation applies to the right-hand side):

- The battery pack supplies a voltage V_{batt} to the circuit. For this project, you will use four AA batteries, which provide about 6 V.
- The switch controls whether or not the battery pack's positive terminal is connected to the circuit. When the switch is open, V_1 is "floating" (not connected to anything), so the circuit has no power. When the switch is closed, V_1 is equal to the battery voltage.
- The photoresistor (R_1) and potentiometer (R_2) form a voltage divider. The input to this voltage divider is V_1, and the output is V_2.
- The potentiometer can be used to tune the voltage divider's output (can you figure this out by examining how Equation 1 depends on R_2?). This allows you to adjust the robot's sensitivity to ambient light levels.
- The output of the voltage divider is connected the input (the gate) of the MOSFET. The source of the MOSFET is connected to ground (0 V). So, for this circuit, $V_{GS} = V_2$. When V_2 exceeds the threshold voltage V_{th}, the MOSFET will turn "on."
- The motor is connected between the positive voltage supply and the MOSFET's drain pin. When the MOSFET is "off", the drain pin's voltage is close to the battery voltage, so no current can flow through the motor. When the MOSFET is "on", the drain pin's voltage drops, allowing current to flow through the motor, into the MOSFET's drain pin, then out of its source pin to ground.
- Finally, each motor has a diode connected across its terminals. Motors can create large voltage spikes when they abruptly come to a stop (this has to do with the relationship between electrical current and magnetic fields, if you want to do more research on the explanation). The diodes help prevent damage to the MOSFET by safely discharging the current generated by the voltage spike.

Q: What are the circuit diagram symbols for the components in this project?
A: Table 4 shows a picture, a breadboard diagram symbol, and a circuit diagram symbol (when applicable) for each component in the project.

Item name	Picture	Breadboard Diagram Symbol	Circuit Diagram Symbol

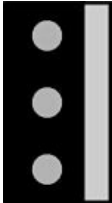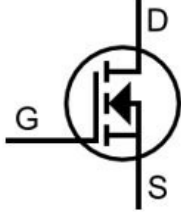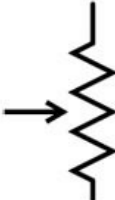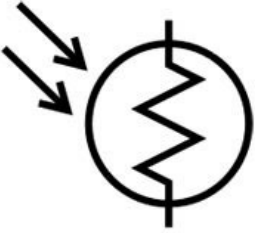|			
Battery pack			
Breadboard			n/a
Switch			
Jumper wire			
DC Motor			
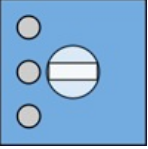
Item name	Picture	Breadboard Diagram Symbol	Circuit Diagram Symbol
MOSFET			
Diode			
Potentiometer			
Photoresistor			

Table 4. A picture, a breadboard diagram symbol, and a circuit diagram symbol for each of the components used in this project.

Q: How did you make the breadboard diagrams for this project?
A: The breadboard diagrams for this project were created using Inkscape (http://inkscape.org/en/), a free vector graphics program. You can find free scalable vector graphic (SVG) files for many circuit components on Wikimedia Commons (http://commons.wikimedia.org/wiki/Main_Page). There are other free programs specifically for making breadboard diagrams, such as Fritzing (http://fritzing.org/home/).

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