Beyond NXT Motors

The NXT has three output ports with variable power and polarity control that you can use to activate a variety of devices above and beyond the NXT motors. The sophisticated pulse width modulation circuitry behind these ports was already described in Chapter 3. The NXT output power is on the same two wires that we used for passive sensors: the black and the white wires in the NXT cable, or pin 1 and pin 2 on the output port connector. The white wire will be positive and the black negative when the motor output is set to forward. For most of the projects that follow, we'll only show only 18 gauge (0.8mm^2) speaker wires, and you can presume they are attached to these two NXT connections.

The Motor Block

Three NXT-G blocks control the output ports. The Move block is specifically designed for simultaneous control of two outputs for steering vehicles, and is not generally useful for controlling single outputs. The Motor block makes full use of the built-in NXT feedback, while the Motor* block is designed for the older, less-sophisticated LEGO 9V motors. Figure 12-1 shows the Motor block in its expanded form. In this form, a variety of data inputs and outputs are available, but most of these are concerned with the built-in angle feedback. For now, we're only interested in the Power and Direction inputs because they directly control the voltage on the output port.
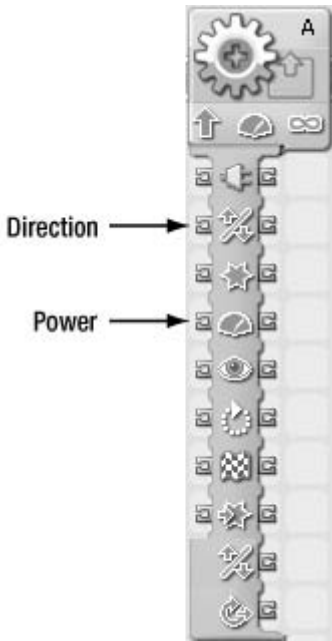
Figure 12-1. *Expanded Motor block*

Output Control Program

It would be nice if the NXT came with a control panel that allowed you to adjust the output power directly with a "Try Me"–type menu, but it doesn't. The NXT-G program laid out in Figures 12-2, 12-3, and 12-4 is handy for debugging the projects that follow. Pushing the right NXT button increases the motor power up to 100, and pushing the left button decreases the power to –100. A –100 power is actually a power of 100 in reverse.
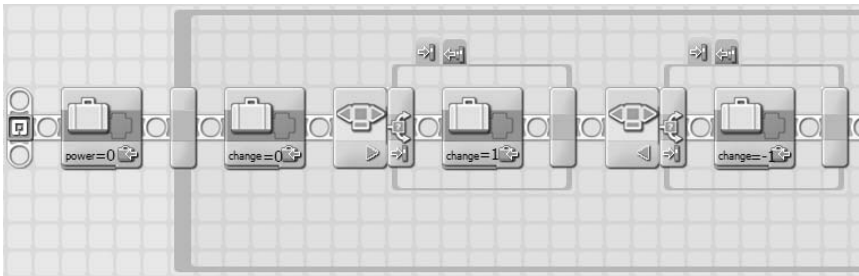

Figure 12-2. *Output control program—initalization and button detection*

The power level is stored in the variable *power*, and the increment amount—+1, 0, or –1—is stored in the variable *change*. When the value of *power* reaches +101 or –101, you need to set it back to the limit. The sign of the value of *power* is determined by comparing it to zero. The result of this comparison becomes the direction input for the Motor block.
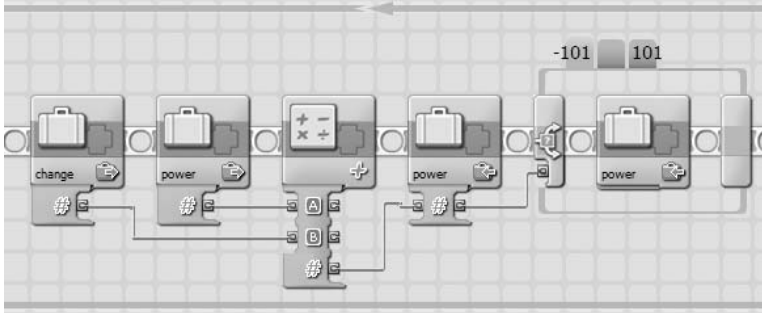

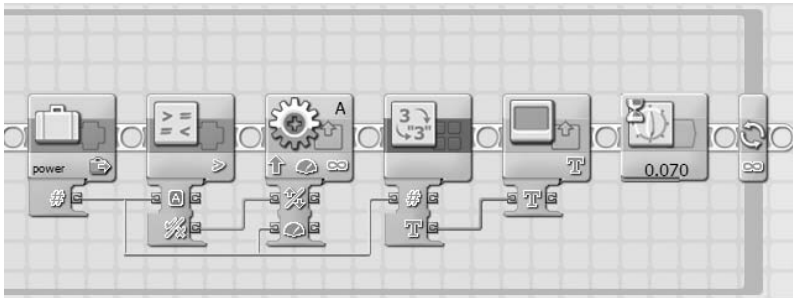**Figure 12-3.** *Output control program—change and limit*

Figure 12-4. *Output control program—output and display*

Lamps

By far, the simplest non-LEGO device you can connect to an NXT output port is an incandescent lamp. Lamps don't care about polarity, which means you can hook the black and white wires either way as shown in the circuit diagram in Figure 12-5. About the only problem is that the 9V output of the NXT is an uncommon voltage for lamps. Higher voltage lamps aren't very bright, while you can burn out lower voltage lamps by accidentally putting full power to the output.
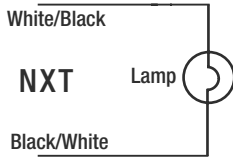
Figure 12-5. *Lamp circuit*

Figure 12-6 shows a small light bulb and plastic socket available at Radio Shack. The lamp is designed to operate from 7.5V, so you shouldn't set Motor block power to more than about 90 to keep from burning it out. Simply screw wires to the two terminals of the socket, and you're ready to create light on command.

Figure 12-6. *7.5V lamp in socket*

Muscle Wires

Muscle Wires are a type of shape memory alloy (SMA) made from an alloy of nickel and titanium called Flexinol. Due to their crystal structure, SMAs change shape at different temperatures. Below a critical transition temperature, Muscle Wires can stretch by as much as eight percent, but they recover their original length when heated. You can use this contraction to create motion without the usual need for motors. You can supply the heat externally or you can generate it internally by passing electrical current through the wire. The time it takes to heat or cool the wire is measured in seconds, and that greatly limits the places where it can be used.

The easiest way to start experimenting with Muscle Wires is to buy the "Muscle Wires Project Book and Sample Kit" from the Jameco Robot Store (Catalog Number: 3-141). Figure 12-7 shows a basic lever demonstration built with one of the Flexinol 150LT wires that comes in the kit. The Muscle Wire runs from the base of the tower to the short side of the lever, and a bag of coins on the long side of the lever provides the force to stretch it. When the NXT output passes current through the Muscle Wire it will be heated, causing it to contract and lift the bag.
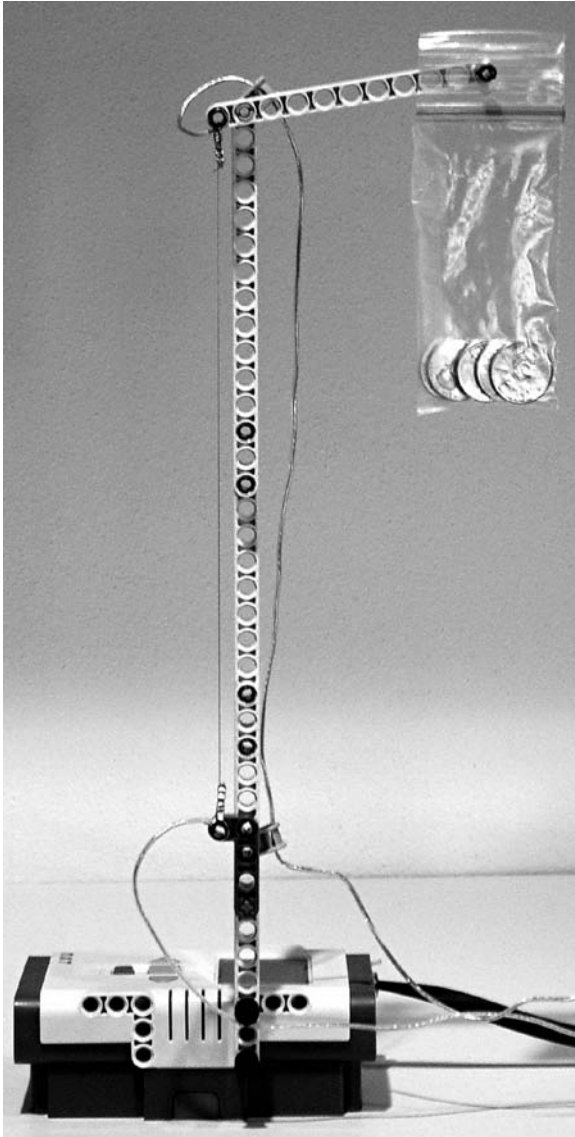
Figure 12-7. *Muscle Wire lever demonstation*

Making good connections to a Muscle Wire is challenging because it's brittle and cannot be soldered. The kit comes with little crimp connectors that are used to fasten the Muscle Wire to an anchor and an electrical wire. Crimp the Muscle Wire to one end of the connector and then crimp a loop of solid hook-up wire the same size as a Technic peg and a length of speaker wire on the other end. While holding the Muscle Wire end of the connector with needle nose pliers to keep it cool, solder the other end with the loop and speaker wire together. When you're done, the connector should look like Figure 12-8. Repeat this for the other end.

Figure 12-8. *Crimp assembly*

You attach the Muscle Wire to the base of the tower and lever using black Technic pegs, as in Figure 12-9. The NXT-G program in Figure 12-10 applies power to the output for five seconds. The power level only needs to be about 25 to get full contraction. The voltage on the wire should be less than 0.3V/cm to prevent it from overheating. Then the program waits five seconds to let the wire cool down and stretch. Audible "Start" and "Stop" sounds are generated with Sound blocks, so you can tell when the NXT is switching the power on and off.
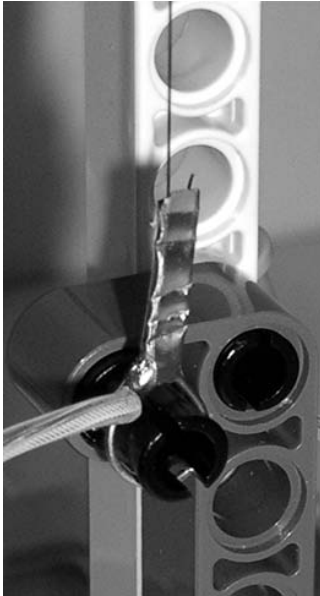
Figure 12-9. *Anchor at base of tower*

Figure 12-10. *Muscle Wire program*

Electromagnets and Solenoids

A motor is just a fancy kind of electromagnet, and it probably isn't too surprising that you can hook up an electromagnet to an output instead of the NXT motor. A *solenoid* is also an electromagnet that includes a metal rod that moves in and out of the winding, called the *armature*. It's like a motor that goes back and forth rather than around.

Kinetic Sculpture

Normally a swinging pendulum eventually stops due to friction. If a small amount of energy is pumped into the pendulum at the right time, like pushing a child in a swing, it will keep on going. That's the secret behind the kinetic sculpture shown in Figure 12-11. An electromagnet in the base is pulsed on to attract a small metal globe as it swings by. You control the timing by using an NXT Light Sensor to detect when the globe is in the correct position.
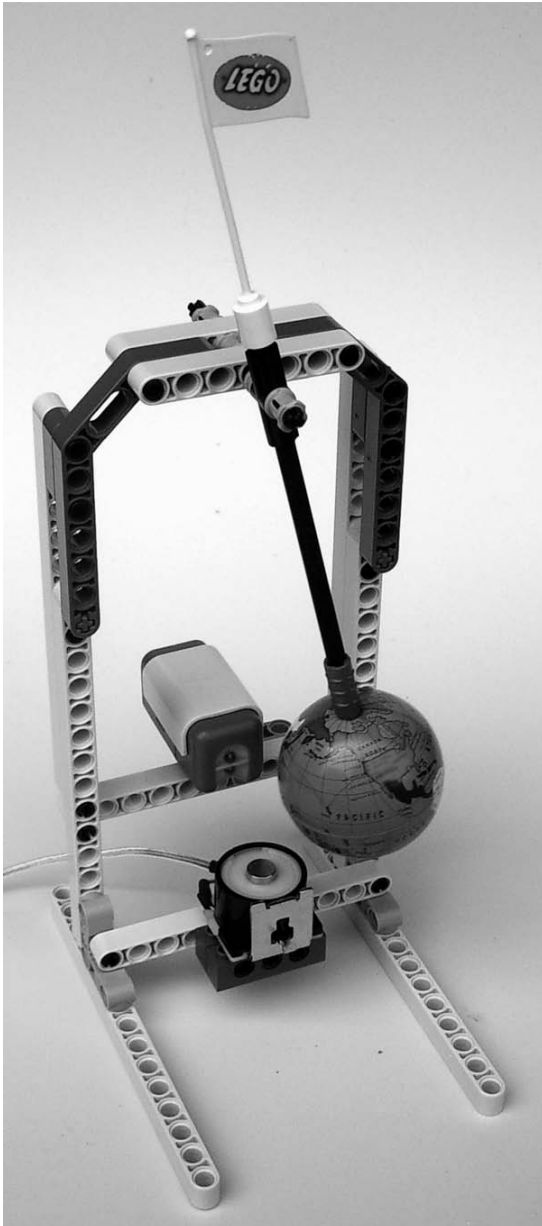

Figure 12-11. *Kinetic sculpture*

The metal globe is from the small toy pencil sharpener shown in Figure 12-12. You can probably find these in the stationery department of a variety store. The mounting hole in the North Pole of the globe is enlarged, and a blue Technic axle peg is pressed into it to allow it to be connected to Technic axle components.

Figure 12-12. *Globe pencil sharpener*

The electromagnet (see Figure 12-13) is a coil removed from a device known as a *relay*. The relay is a Potter and Brumfield KRPA-11DG-6, which has a 6VDC coil (we'll discuss correct use of relays in the following section). It's all right to use a lower-voltage coil because the 9V of the NXT is only briefly applied to the coil, and the voltage is much less than 6V on average. You can attach the coil to the structure with a rubber band or double-face tape.

Figure 12-13. *Electromagnet coil from 6V relay*

The NXT-G program shown in Figure 12-14 loops till the globe casts a shadow on the Light Sensor, making its value less than 50. The program then gives the electromagnet a short pulse on with the Motor block and makes a little click with the Sound block. After that, it waits till the sensor is exposed to the light again as the globe swings past. It keeps looping till the globe swings back from the other direction, which starts the whole process over again.
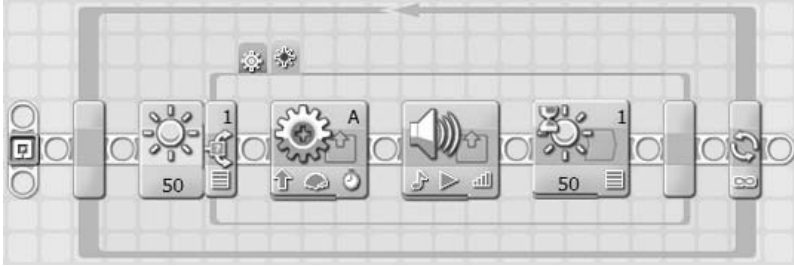

Figure 12-14. *Kinetic sculpture program*

There needs to be enough light in front of the sculpture so that the globe casts a shadow on the Light Sensor. Then you need to start the pendulum swinging by hand. After that, it keeps swinging and making a sound like a metronome. You can use it to provide animation for small objects such as flags or Minifigs.

Relays

Relays are controlled switches that use an electromagnet to move electrical contacts on and off. Usually relays have both normally open (NO) and normally closed (NC) contacts with a shared common connection. The common connection is also known as the *pole*. When the electromagnet is energized, the pole is pulled toward the NO contact to close it, and away from the NC contact to open it. Figure 12-15 shows the basic relay circuit. The load can be a device operating at a different voltage than the NXT, and also something that requires substantially more power than the NXT can deliver.

■**Caution** Although you could use a relay to control household electricity, we strongly advise you to stay away from it. Even the slightest mistake can be lethal. Stay safe by sticking with devices that operate from low voltages, and preferably from batteries.
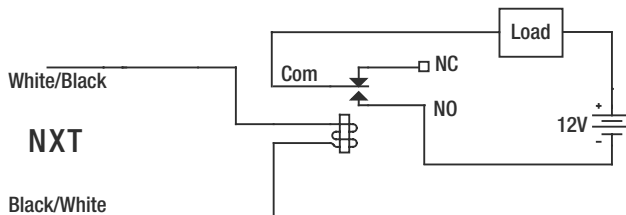

Figure 12-15. *Basic relay circuit*

One of the most important characteristics of a relay is its coil voltage. Just like with light bulbs, 9V is a fairly uncommon voltage for relay coils. Even if you could find a 9V relay, the output voltage of an NXT with weak batteries would be too low to operate it. Your best bet is to buy a 6V relay and operate the NXT output with less than full power. Limit the power value in the Motor block to 80 to keep the voltage on the relay coil around 6V.

The Potter and Brumfield KRPA-11DG-6 is an excellent choice for a relay, but it's expensive and requires an additional octal socket that will add a lot of cost to your project. A good alternative is the Potter and Brumfield PE014006, which is substantially smaller and cheaper. It's designed for mounting on a printed circuit board, but you can solder wires directly to the pins, as shown in Figure 12-16.
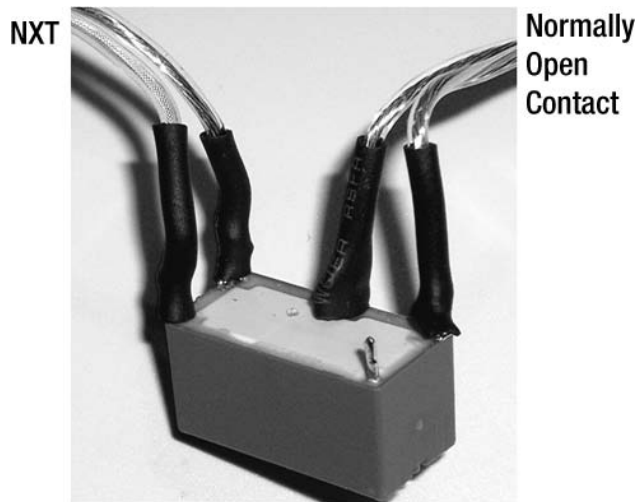

Figure 12-16. *Relay*

Relays are good for operating devices that were originally designed for automotive or marine applications. The NXT is a real weakling compared to equipment that operates at up to 13.8VDC with several amps of current. An automobile vacuum cleaner could be the basis of your own robotic vacuum cleaner. Portable air compressors can supply a constant source of pressure for pneumatics. Boat bilge pumps, as in Figure 12-17, can move liquids in hydroponic gardens or water fountains. It's more economical to run these devices with power supplies that deliver 12V from household electricity, but it's much safer to use batteries.

Figure 12-17. *Relay control of a 12V bilge pump*

Doubling Outputs

Diodes are the one-way valves of the electrical world. The physical package and circuit symbol are shown in Figure 12-18. They have two leads like a resistor, but unlike the resistor the leads are not interchangeable. A diode has an anode and a cathode lead, and a line is painted on the cathode end of the part. Electrical current can only flow from the anode to the cathode. In that direction, the diode looks about like a solid piece of wire. However, in the reverse direction, the diode looks like an open circuit.
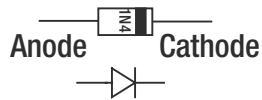

Figure 12-18. *Diode and circuit symbol*

If you connect a diode in series with a light bulb, as in Figure 12-19, then it will only light when the current flow is in one direction and not the other. Because you can control the polarity of the NXT output using the direction input on the Motor block, the bulb will light only in forward or reverse, but not both.
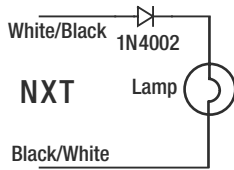
Figure 12-19. *Diode and lamp circuit diagram*

An inexpensive way to get small lights is to cut apart long strings of tiny Christmas tree lights. Up to 50 of these lights are connected in series, which means each light only operates on a few volts. You should only set the power in the Motor block to a low value such as 20, or you'll burn out the light.

Figure 12-20 shows how to connect the diode in series with the light. It's a good idea to solder the connections to make them more permanent. Figure 12-21 shows how you can cover the entire diode and the connections with heat shrink tubing to insulate and protect them.
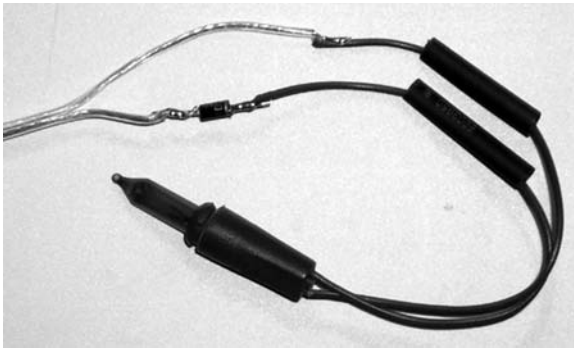

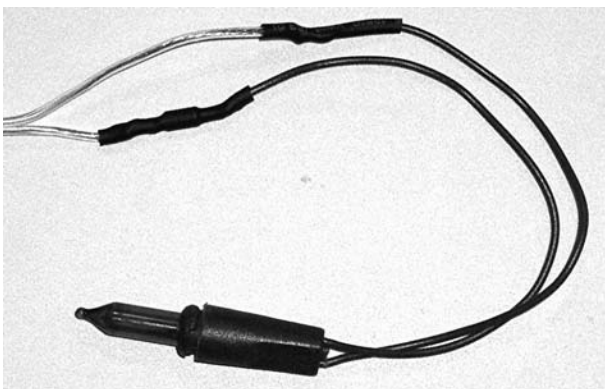**Figure 12-20.** *Christmas tree light with diode*

Figure 12-21. *Heat shrink tubing covers the diode and connections*

The whole idea of connecting a diode in series might sound pretty useless, but there is a method to our madness. If you connect two lights to the same output with diodes facing in opposite directions, like the schematic in Figure 12-22, one lamp will light in forward and the other in reverse. In a way, you've doubled the number of NXT outputs because you can control six different lights. The only drawback is that you can only light one light per output at a time.
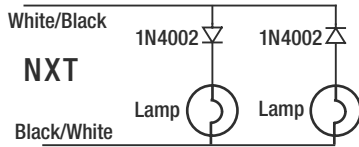

Figure 12-22. *Two lights connected to one output*

Many different types of diodes are available. The best ones to use for NXT outputs are the 1N400X rectifier diodes. The X in the model number has to do with the voltage capability of the part, and the higher the number, the higher the voltage. All of them can handle the current and voltages present on an NXT output. In this book we show the 1N4002, which is good to 100V.

When controlling anything but a resistive load such as a lamp or Muscle Wire, the circuit gets a little more complicated. Figure 12-23 shows how you should add an additional diode to the circuit when operating motors or relays. It's beyond the scope of this book to explain exactly why this diode is necessary, but it has to do with diverting energy that's stored in motors and electromagnets when they get turned off. Not using it will probably damage the other diode. Just like with the lights earlier, now you can control six different motors or relays.
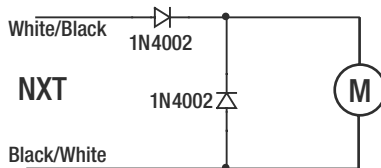

Figure 12-23. *Motor or relay circuit diagram*

You can combine the contacts from two relays controlled by the same output to get voltage polarity control on an output. Figure 12-24 has two of the circuits in Figure 12-23 and an arrangement of relay contacts that switch 12V on the motor to make it go forward with Relay 1 energized, or reverse with Relay 2.
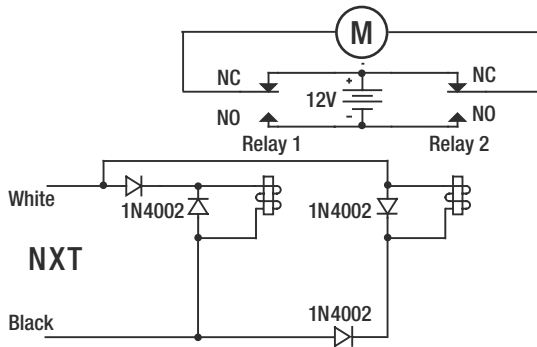
Figure 12-24. *Directional voltage control using two relays*

Although you could use the point-to-point wiring schemes shown so far, it's better to build the circuit shown in Figure 12-24 on a printed circuit board (PCB). Figure 12-25 shows how you can connect the relays and diodes in a sturdy and compact way on a prototype PCB. Speaker wires are used to input the 12V and NXT signals and output the load voltage.
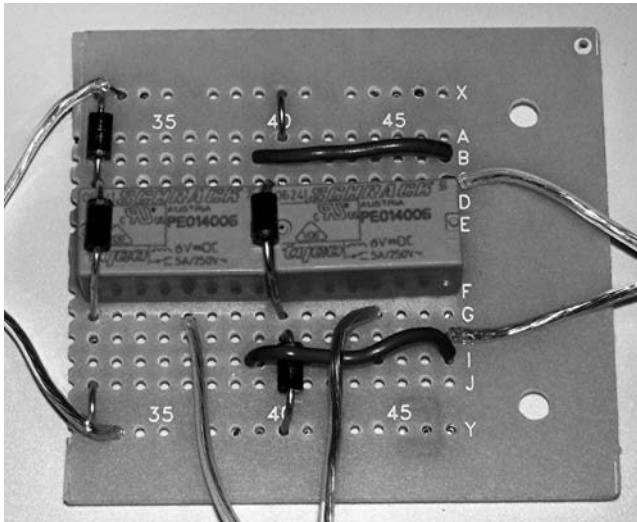

Figure 12-25. *Directional voltage control assembly*

Light Emitting Diodes

Figure 12-26 shows the typical package of a Light Emitting Diode (LED) and its electrical circuit symbol. The symbol is the same as the diode we've already discussed, except for two little arrows that symbolize the light being emitted. Instead of a painted line to signify the cathode end of the LED, like a conventional diode, the LED has a flat space in the flange directly next to that lead. The anode lead is also a little longer than the cathode lead.
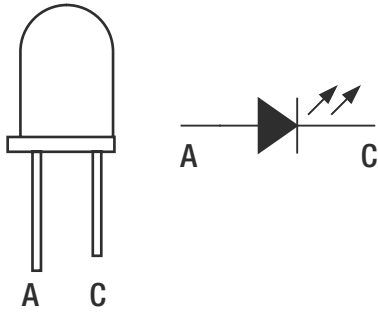
Figure 12-26. *LED outline and circuit symbol*

An LED needs a resistor connected in series with it to limit the amount of current flowing through it. Unlike an incandescent lamp, the voltage across the LED is fixed and only about two volts. If you connect an LED to a voltage greater than that, it won't just shine brightly, it will be permanently damaged.

The calculation of the resistor value is a little mathematical. The first thing you need to know is the power supply voltage from which you intend to run the LED. In the case of the NXT, the output voltage is 9V. The second thing you need to know is the LED voltage drop, and that depends on the particular LED you have. Table 12-1 shows typical values, but it's better to check the datasheet for your particular device. Finally, you need the amount of current that should flow through the LED. That should also come from the datasheet, but Table 12-1 also has typical values.

Subtract the LED voltage from the power supply voltage and then divide the result by the LED current. For example, suppose you have a 9V power supply, a 2V LED voltage drop, and you want 20mA (0.020A) of current. The calculated resistor value is 350Ω, but you would need to use a 330Ω resistor because that's the closest standard resistor value.

$$R = \frac{V - VDrop}{I} \ [\Omega]$$

$$R = \frac{9 - 2}{0.02} = 350 \ [\Omega]$$

Table 12-1. *Typical LED Data*

Color	V Drop	Current	R
Red	1.7 V	20mA	330Ω
High-efficiency red	1.9	20	330
Orange and yellow	2	20	330
Green	2.1	20	330
White, blue, and pure green	3.4	25	220

LEDs only produce light when they are *forward biased*. That means the current needs to flow in the same direction as the arrow of the diode in the LED symbol. This also means the anode voltage must be positive with respect to the cathode. LEDs don't produce light when they are connected backwards or reverse biased. In fact, they can be damaged if the reverse voltage is greater than about 5V. Because the NXT output voltage polarity can be positive or negative, you must protect the LED with another diode to prevent it from being damaged this way.

Figure 12-27 shows the circuit diagram of an LED output, and Figure 12-28 shows the assembly. The value of resistor R is computed using the equation, and the 1N4148 is a small diode used to protect the LED from reverse voltage. You could use a 1N4002, but the 1N4148 is smaller and more appropriate for the current in the LED. Hooking the white NXT cable wire to the resistor and the black to the LED cathode will make an LED that lights when the Motor block output is set to forward. Reversing the white and black connections will make an LED that lights when the Motor block is in reverse.
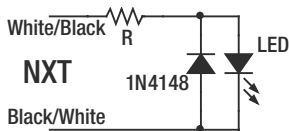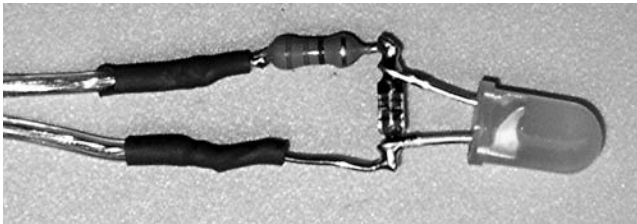
Figure 12-27. *Basic LED circuit*

Figure 12-28. *LED assembly*

You can also use another LED in place of the 1N4148, as shown in the circuit in Figure 12-29. They can share the same series resistor if the LEDs are similar enough. Only one LED will light at a time: LED1 when the Motor block output is in forward and LED2 when it is in reverse. Use LEDs in the T13/4 package, which is about 5mm in diameter, because they can be pushed part way into Technic holes for mounting, as in Figure 12-30.
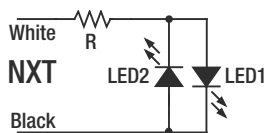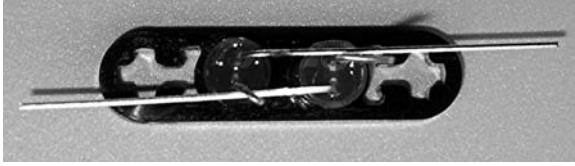
Figure 12-29. *Two-LED circuit*

Figure 12-30. *T13/4 LEDs in Technic beam*

It's easier to create the parallel connection between the LEDs by bending one lead of each LED over to the other LED. Make sure the LEDs are mounted with the cathode flat spot on opposite sides. This gives you two leads to connect to that are separated by enough distance that they won't easily touch and short. Figure 12-31 shows the parallel connection, while Figure 12-32 shows the addition of the series resistor. Finally, Figure 12-33 shows heat shrink covering the connections.
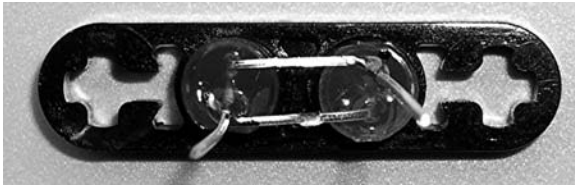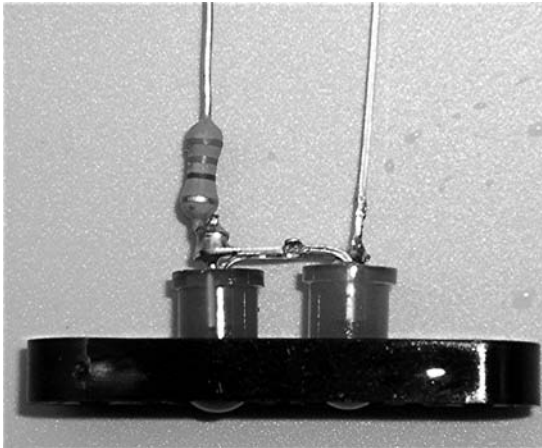

Figure 12-31. *LEDs connected in parallel*

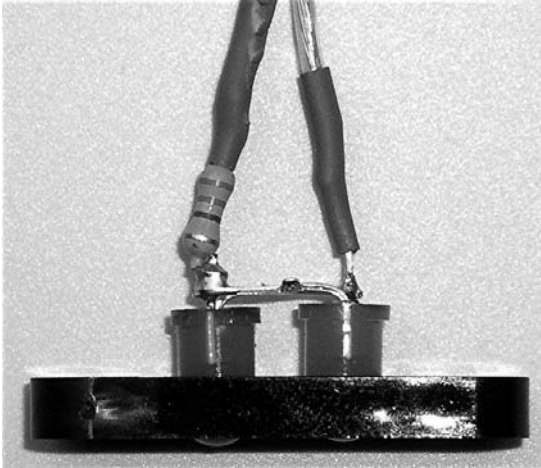**Figure 12-32.** *Add common series resistor*

Figure 12-33. *Heat shrink to insulate connections*

Assuming executives make important decisions that are about as good as flipping a coin, you can make a contraption that makes yes/no decisions at the push of a button (see Figure 12-34). You make the yes/no indicator using the circuit shown in Figure 12-28, with one red and one green LED.
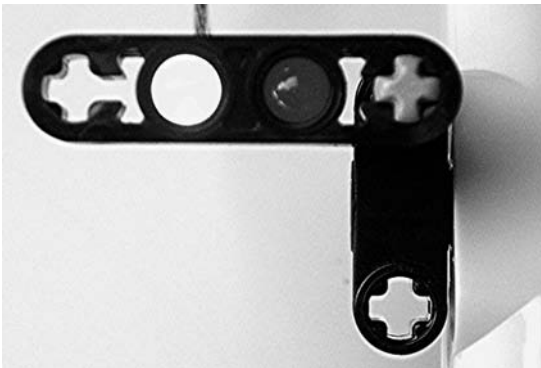

Figure 12-34. *A favorable decision*

The NXT-G program is shown in Figure 12-35. Pushing the center button on the NXT turns the output off, clearing the previous decision. When the button is released, the Random block picks a number 0 or 1, with equal probability. Depending on the number, the output is either turned on in forward or reverse, making either the green/yes or the red/no light up. If you reduce the power level in the Motor block, you could also use two Christmas tree lights connected as in Figure 12-22.
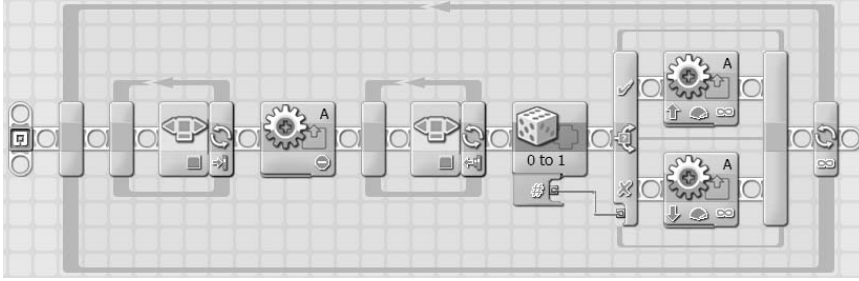
Figure 12-35. *Decision maker program*

More Power

Relays are great for turning on and off equipment that requires power beyond the capability of the NXT. The NXT creates variable power by turning on and off the output thousands of times a second, but relays are way too slow to be operated this way. You can use a solid-state device known as a metal oxide semiconductor field effect transistor (MOSFET) like a relay, but it can switch as fast as the NXT. Unlike relay contacts, the MOSFET only conducts in one direction, so it's only useful for DC applications.

One MOSFET Amplifier

Figure 12-36 shows the basic N-channel MOSFET amplifier using the IRF510. The MOSFET is the complicated symbol in the center of the drawing. It has three leads: the gate, source, and drain. The diode in the symbol is usually not drawn for simplicity, but it's always a part of the device. When the voltage between the gate and source is greater than about 4V, the MOSFET will switch the connection between the drain and the source on. The 10k resistor prevents the gate voltage from floating around when it isn't connected to anything, and the 1N4002 is there to divert the power stored in the motor when it is turned off.
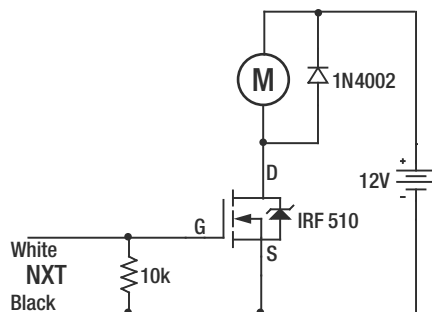

Figure 12-36. *MOSFET unipolar amplifier circuit*

The IRF510 comes in the TO-220AB package shown in Figure 12-37. The drain is connected to both the center lead and the large flange. You can use a small screw and nut to turn the flange into a handy terminal for connecting the load. However, if you need for the IRF510 to carry more than about 2A, you'll need to attach a heat sink to the flange.
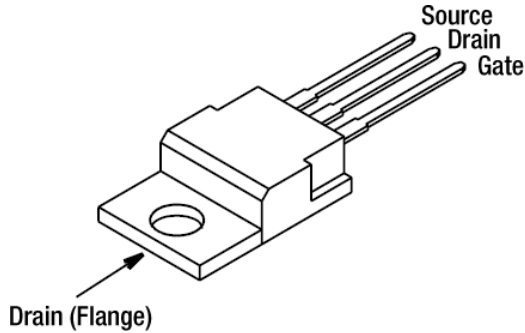

Figure 12-37. *MOSFET package*

A terminal strip version of the MOSFET amplifier is shown in Figure 12-38. The drain lead is bent up and out of the way because the flange is used to make the connection. The wires to the load are soldered to the leads of the 1N4002 to make connecting easier. Make sure you have the cathode (end with the band) of the diode toward the positive power terminal.
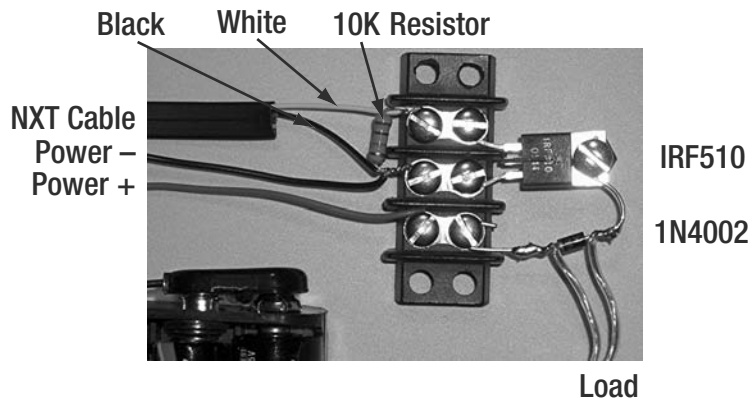

Figure 12-38. *MOSFET amplifier assembly built on a terminal strip*

Because you often need variable speed, motors are the natural application for the MOSFET amplifier. Figure 12-39 shows an automobile electric window motor connected to the amplifier. A variety of motors such as this are used in automobiles for power equipment and windshield wipers. They are geared down much like the NXT motor, but they often use a worm gear that locks the shaft when the motor isn't turning.
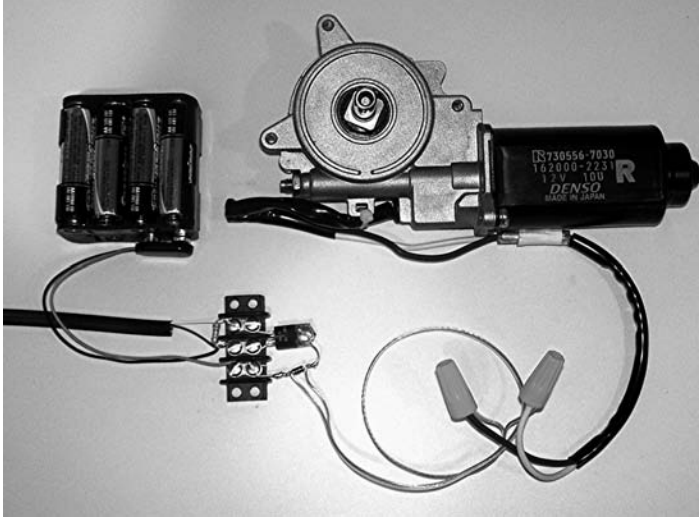
Figure 12-39. *MOSFET amplifier controlling an automotive electric window motor*

Bipolar MOSFET Amplifier

You can vary motor speed with the one MOSFET amplifier, but not the direction. This can be a serious shortcoming for vehicle designs where you need to go both forward and reverse. Extending the design to control both speed and direction requires the more complicated bipolar amplifier shown in Figure 12-40. See Table 12-2 for the bill of materials.
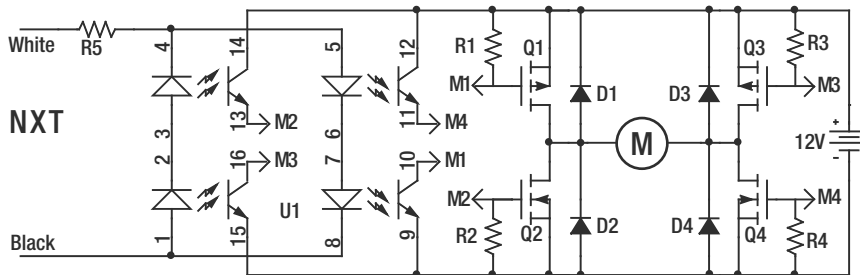

Figure 12-40. *Bipolar amplifier*

Table 12-2. *Bill of Materials*

Component	Part Number	Description	Digi-Key
Q1, Q3	IRF9530PBF	P Chan MOSFET	IRF9530PBF-ND
Q2, Q4	IRF520NPBF	N Chan MOSFET	IRF520NPBF-ND
R1–R4	330 Ohm	1/2 W Resistor	PPC330BCT-ND
R5	100 Ohm	1/4 W Resistor	P100CACT-ND
U1	PS2501-4	NEC Quad Optoisolator	PS2501-4A-ND
D1–D4	STTH2R06RL	Fast Recovery Rectifier Diode	497-4409-1-ND

The heart of the design is the H-bridge made from four MOSFETs. You can see the H pattern where the motor symbol M is in the middle of the horizontal line of the letter H. The upper MOSFETs—Q1 and Q3—are P-channel, while the lowers—Q2 and Q4—are N-channel like the IRF510. P-channel MOSFETs work like their N-channel brothers, but have a negative gate voltage. The arrow in the gate part of the symbol is reversed to differentiate it from the N-channel.

You use the MOSFETs in pairs to connect either the positive voltage or ground to either end of the motor. The forward pair is Q1 and Q4, and the reverse is Q3 and Q2. U1 is an optoisolator that contains four LEDs and four phototransistors. When the light from an LED shines on a corresponding phototransistor, it turns on. The LEDs are cleverly arranged to turn on the right pairs of MOSFETS to preserve the polarity of the NXT output voltage.

You should first build the bipolar amplifier on a solderless prototype board, and then transfer the working design over to a matching prototype PCB. Figure 12-41 shows the first step in populating the prototype board. Follow Table 12-3 for step-by-step construction, making sure every part is in the correct hole. The MOSFET legs fit tightly in the prototype board and require gentle rocking to minimize the insertion force. Pay special attention to the direction of the diodes—it's easy to connect them backwards accidentally.
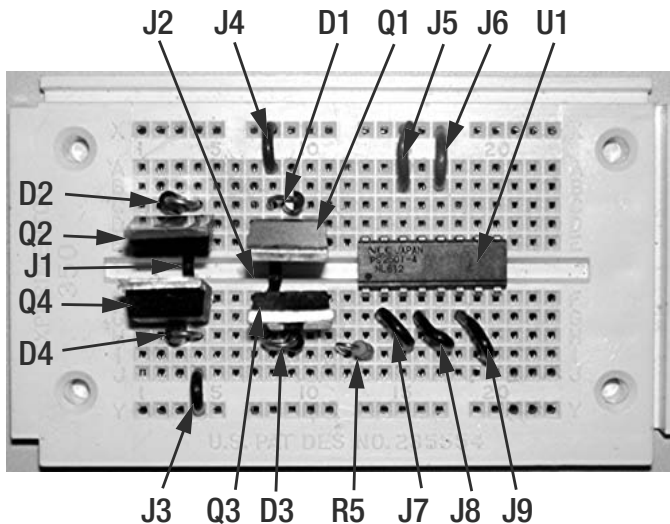

Figure 12-41. *Step one*

Table 12-3. *Component Placement Step One*

Component	Start	End
Q2 Gate Drain Source	D2	D4
J1	E4	F4
Q4 Gate Drain Source	G2	G4
D2 Anode Cathode	C4	C3
D4 Anode Cathode	H4	H3
Q1 Gate Drain Source	D10	D8
J2	E8	F8
Q3 Gate Drain Source	G10	G8
D1 Anode Cathode	C9	C8
D3 Anode Cathode	H9	H8
J3	X8	A8
U1 Pin 1	F13	
J4	J4	Y4
R5	I12	I13
J5	X15	B15
J6	X17	B17
J7	G14	H15
J8	G16	H17
J9	G18	H19

Figure 12-42 shows additional parts, with Table 12-4 giving the step-by-step construction that goes with it. Notice that resistors R1–R4 need to be the larger 1/2 W type because of the power they dissipate. Finally, Figure 12-43 shows the complete circuit with connections to 12V, the NXT, and the load. Again, step-by-step instructions are in Table 12-5.
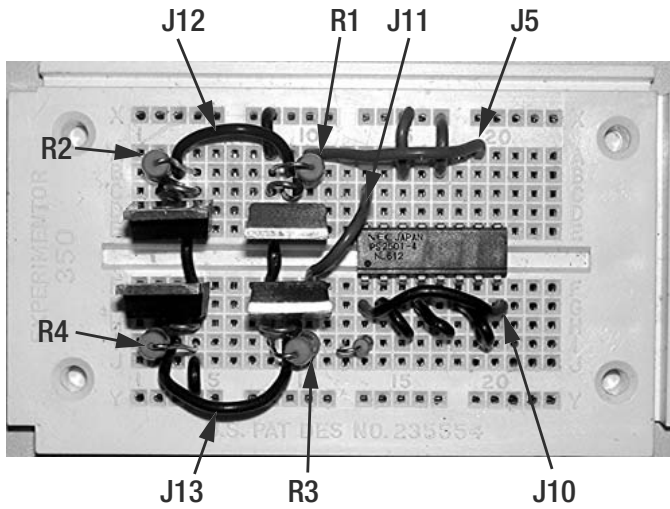
Figure 12-42. *Step two*

Table 12-4. *Component Placement Step Two*

Component	Start	End
R2	B2	B4
J12	B3	B9
R1	B8	B10
R4	I2	I4
J13	I3	I9
R3	I8	I10
J11	A10	A19
J10	G13	G20
J14	C13	F10
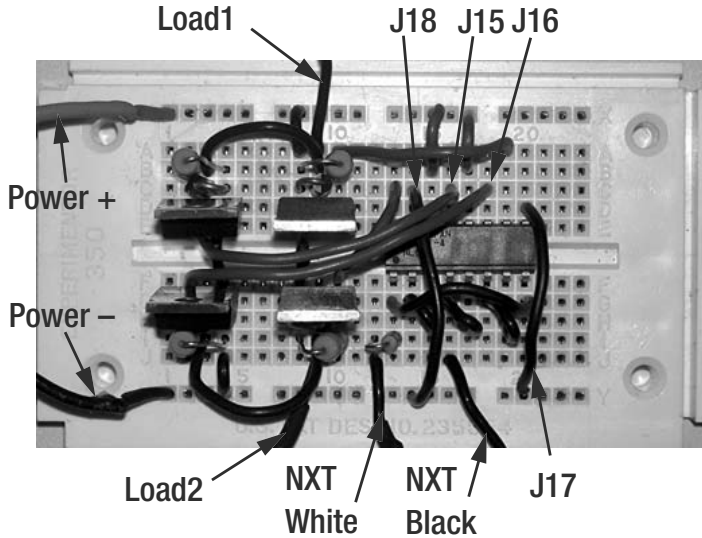
Figure 12-43. *Step three*

Table 12-5. *Component Placement Step Three*

Component	Start	End
Power +12V GND	X1	Y1
Load 1 Load 2	A9	J9
J18	C14	Y14
J17	D20	Y20
J15	C16	E2
J16	C18	F2
NXT White Black	J12	J16

Double-check your connections before connecting the 12V to the circuit. Connect the motor and then the 12V, but not the NXT. The motor should not run and the circuitry should remain cool. When the circuit passes that test, connect the NXT and run the power control program discussed earlier. With a power level of about 10, you should hear the high-pitched noise of the PWM coming from the motor. By the time you advance the power to 50, the motor should be turning. The circuit should operate the same way for negative power, except that the motor will turn in the opposite direction.

You could use the amplifier built on the prototype board, but moving it to a PCB will make it much more reliable. Figure 12-44 shows the final assembly, where components were moved one at a time from the prototype board. The amplifier is capable of controlling up to 15V at 2A without additional heat sinks.
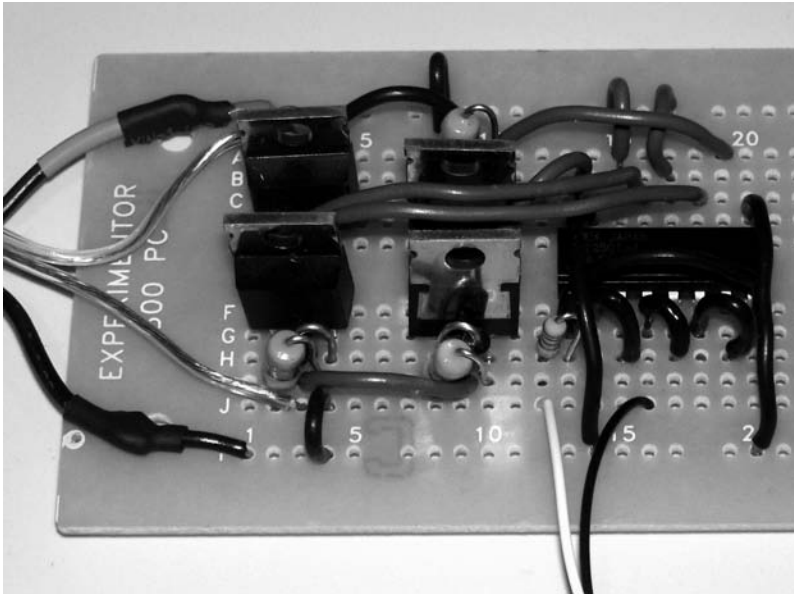

Figure 12-44. *Step four*

The bipolar amplifier is well suited for controlling motors for vehicle propulsion. Figure 12-45 shows a good-sized 24VDC motor that runs nicely on 13.8V from a lead acid battery–based power supply. Generally you don't need the high speed of a DC motor, so it's better to buy motors with built-in gear reduction, called *gear head motors*, because they already have lower speed and higher torque. However, you can lower the ratio externally with drive belts where the smaller pulley, like the one in Figure 12-45, is on the motor and the larger one is on the axle connected to the wheel.
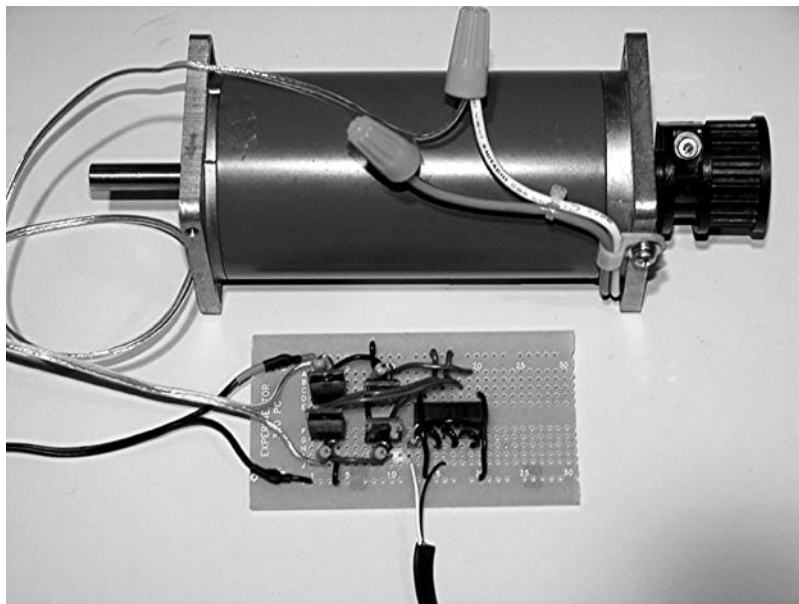
Figure 12-45. *Bipolar amplifier connected to DC motor*