

A. What You Already Know

Make a labeled drawing to show what you think is inside the motor. Write down how you think the motor works. Please do this independently.

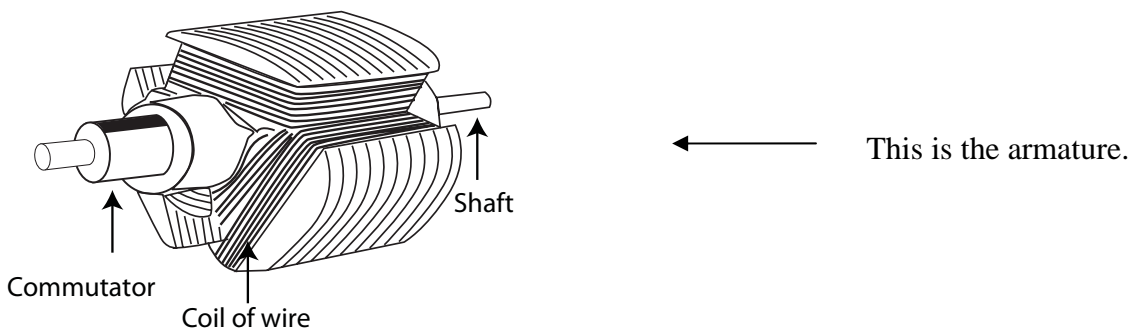
This important step forces students to create a preliminary mental model for the motor, which will be their starting point. Since they are writing it down, they can compare it with their answer to the same question at the end of the activity.

B. Observing and Disassembling the Motor

1. *Use the small screwdriver to take the motor apart by bending back the two metal tabs that hold the white plastic end-piece in place. Pull off this plastic end-piece, and then slide out the part that spins, which is called the armature.*
2. *Describe what you see.*
3. *How do you think the motor works? Discuss this question with the others in your group.*

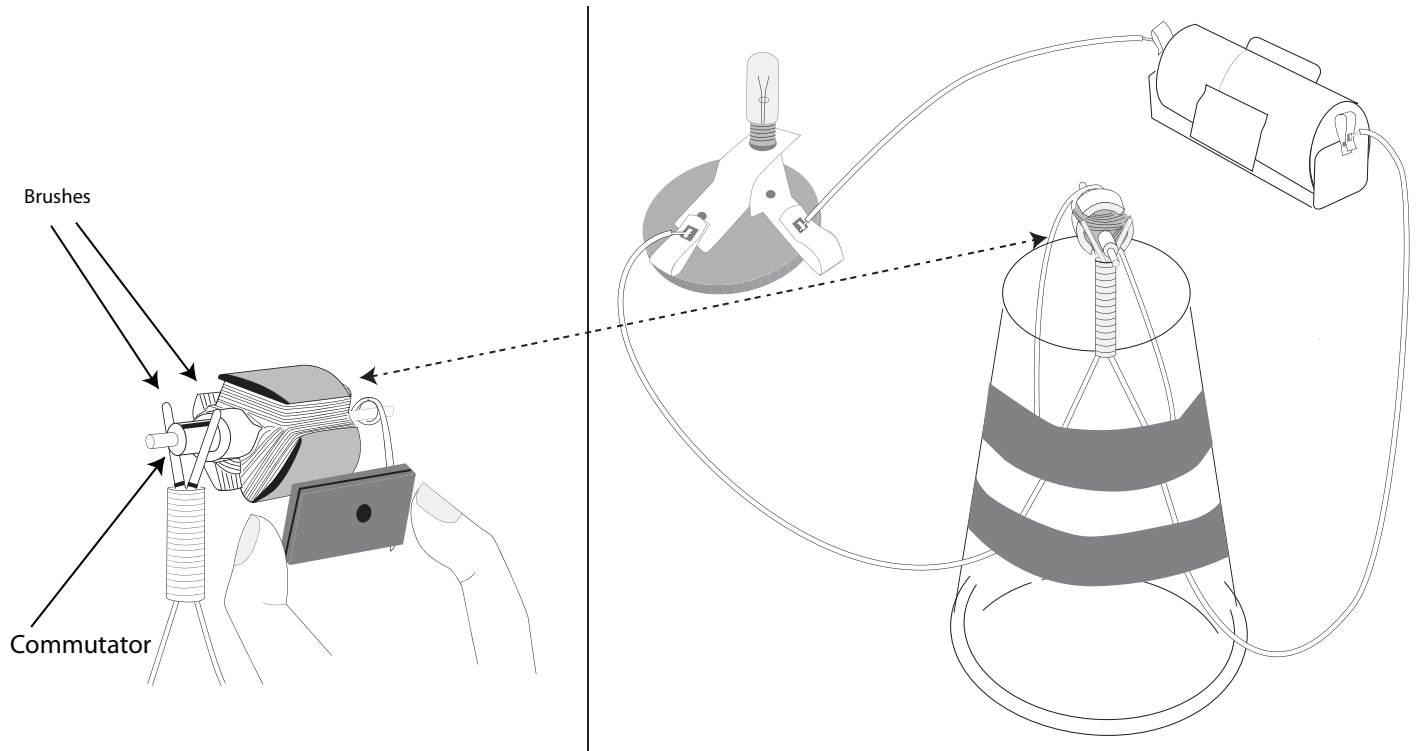
C. Mounting the Armature

1. *Use the diagram below to locate the commutator—the split ring around the motor shaft.*



2. *Look at the drawing on the next page and find the brushes—two short ends of bare wire that make a "V". The brushes will make electrical contact with the commutator, and gravity will hold them together. In addition the brushes will support one end of the armature and cradle it to prevent side-to-side movement.*

- Using the cup, the two rubber bands, the piece of bare wire, and the three pieces of insulated wire, mount the armature as in the diagram below.
- You will have to tape together the two #20 insulated wires to make the brushes. The commutator—the split ring on one end of the motor shaft—will rest on the brushes.
- Using the rubber bands, mount the wires on the plastic cup as shown in the drawing.



Nancy Bennett-Karasik/American Physical Society © 2009

- Use the small compass to find the north and south poles of the ceramic magnets.

The north and south poles of the ceramic magnets are on the large faces.

- Hook up the battery and bulb to the commutator leads. How does the bulb help you understand if the circuit is working?

If the bulb is lit, current is flowing in the armature.

- With the armature mounted as in the diagram above, bring up the two magnets—stuck together—and get the armature spinning.

D. Observing How the Motor Operates

1. *Observe what happens when the armature spins.*

- The armature spins in one direction only.
- Reversing the battery reverses the direction of spin.

2. *Explore how the position of the magnet affects the operation of the motor.*

- Flipping over the magnet reverses the direction of spin.
- Bringing the magnet closer to the armature increases the rate of spin.
- Holding the magnet above the armature stops the spinning, and the armature may jump up and stick to the magnet—the armature spins much better with the magnets held slightly below, rather than above.

E. Changing the Motor Speed and Load

1. *With the armature spinning, carefully bring the magnet closer to the spinning armature, and then further away. What do you observe? (Look at everything in the circuit.)*

As the magnet is brought closer, the armature spins faster, and the bulb dims.

2. *So far, the spinning armature has been unloaded--it has not been doing any work, except against its internal friction. As the armature turns, gently squeeze the armature shaft. What do you observe?*

When the shaft is squeezed, the armature spins more slowly and the bulb brightens.

F. How the Armature Makes Contact with the Brushes

1. *Take the cardboard tube and cradle it in your hands-- as shown in the drawing on the next page-- and let gravity keep it in place. Hold your forearms vertically, almost touching. Tilt your hands outward, but keep your wrists close together.*
2. *Imagine that your hands are the brushes and the three black lines on the cardboard tube are the three gaps in the commutator (these gaps prevent electrical contact between adjacent segments).*
3. *Work together to turn this commutator model so you can find out how the parts of the commutator make contact with the brushes.*

The drawing below shows the commutator, resting on the brushes. To power the motor, current must enter and leave the armature. The drawing at the right shows an armature orientation when it is conducting. In fact, the commutator, with its very small gaps, conducts almost all the time as it spins.



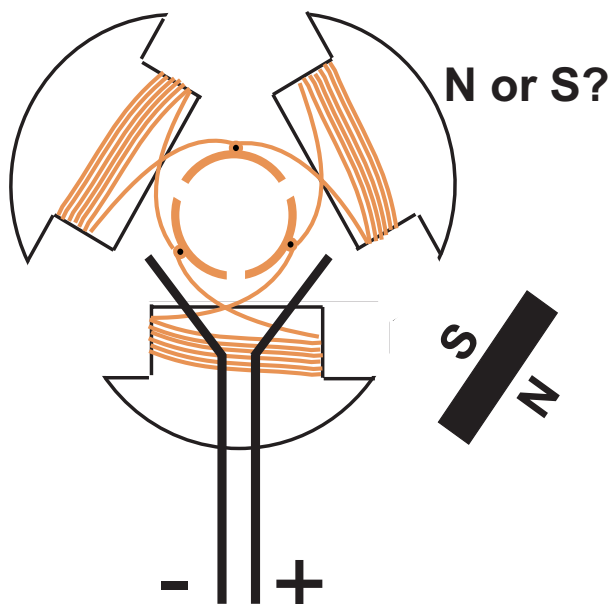
- Notice that you can rotate the cardboard tube almost 120° and maintain contact between your hands and the same two segments of the commutator.
- The commutator has three segments. Whenever the brushes are in electrical contact with *two* of the commutator segments, current flows through the armature. See diagram just below showing the commutator and the brushes.

4. The drawing at the right shows the commutator, resting on the brushes. To power the motor, current must enter and leave the armature. The drawing shows an armature orientation when it is conducting. In fact, the commutator, with its very small gaps, conducts almost all the time as it spins.

commutator orientation when coils are conducting

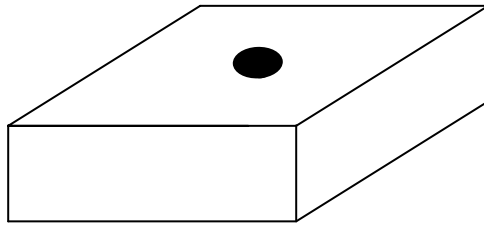


G. Why the Armature Spins: Relative Polarity of Motor Coils



- In this drawing, we are again looking along the motor shaft, so we see the commutator end-on. To enable us to see all the wiring, the brushes have been lowered.
- The ceramic permanent magnet is on the right and seen edge-on, with the orientation of its magnetic poles indicated. (This orientation is arbitrary.)
- If we knew the relative polarity of these three electromagnets, perhaps we could explain how the armature spins. For instance, look at the pole labeled "N or S?". If that were a north pole, it would be attracted to the permanent magnet; if a south pole, it would be repelled.

1. *With the compass, you can determine the relative polarity of the three armature electromagnets. To get started, set the white cardboard box on the table so the hole faces up (see the drawing below).*

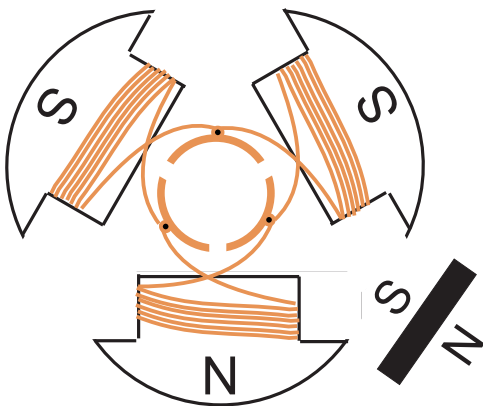


The box-top provides a platform for the compass so that it's reasonably close to the heights of the three electromagnets on the armature.

2. *Remove the brushes from the plastic cup, but keep them taped together.*
3. *Hold the armature vertically, with the commutator above the coils, and push the armature shaft through the hole in the tray so the commutator is on top. Touch the brushes to the commutator and investigate the magnetic field with the compass. Record what you have found.*

- Two of the electromagnets have the same polarity, and the third is opposite. (see drawing below)
- Some students will provide the sentence just above as a statement of their observations, but it is not the whole story. It's crucial to consider the orientation of these poles—if the results are to be useful, the relative polarity must be specified with respect to the position of the brushes and the armature electromagnets: Two electromagnets have the same polarity, and the one below the brushes is opposite.

4. *Let's go back to your observations of the spinning armature. Using what you have learned about the pattern of magnetic poles on the armature, as shown in the drawing below, explain as many of these observations as you can. Which observations are you so far unable to explain?*



This drawing shows the armature spinning. The brushes are not shown, but they are below the commutator, as before, and the orientation of the armature is the same as in the drawing on page 4.

Observation: The armature spins, and in one direction only.

- The drawing above shows the pattern of magnetic poles that you observed with the compass.
- We neglect the effect of the electromagnet that is furthest from the permanent magnet—the electromagnet at the upper left in the diagram above.
- We know that like poles repel and unlike poles attract. Therefore the south pole at the top right repels the south pole of the permanent magnet, and the north pole at the bottom attracts the south pole of the permanent magnet. Both of these forces exert torques on the armature *in the same direction*—counterclockwise—so the armature spins in that direction.

Observation: Flipping over the magnet reverses the direction of spin.

- Flipping over the magnet reverses both forces and thus reverses the direction of both torques.

Observation: Reversing the battery reverses the direction of spin.

- Reversing the battery reverses the direction of the current, which reverses the poles of the electromagnets, which reverses the forces that the permanent magnet exerts.
- Therefore, the torques reverse.

Observation: Bringing the permanent magnet closer increases the rate of spin.

- Bringing the permanent magnet closer increases the magnetic field at the electromagnets, which increases the magnetic forces and thus the torques.

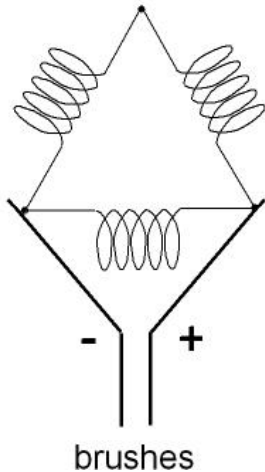
Observation not yet explained: When the permanent magnet moves closer to the armature, the armature spins faster, *and the bulb dims*.

Observation not yet explained: When you squeeze the spinning armature shaft, *the bulb brightens*.

H. How the Armature Poles Switch

1. *With the magnifier, observe carefully how the commutator sections of the armature are wired to the coils.*
2. *Make a drawing of how you think the three coils are connected to the three parts of the commutator. Assume the armature is oriented as in the drawing on page 4.*

How the three coils are wired

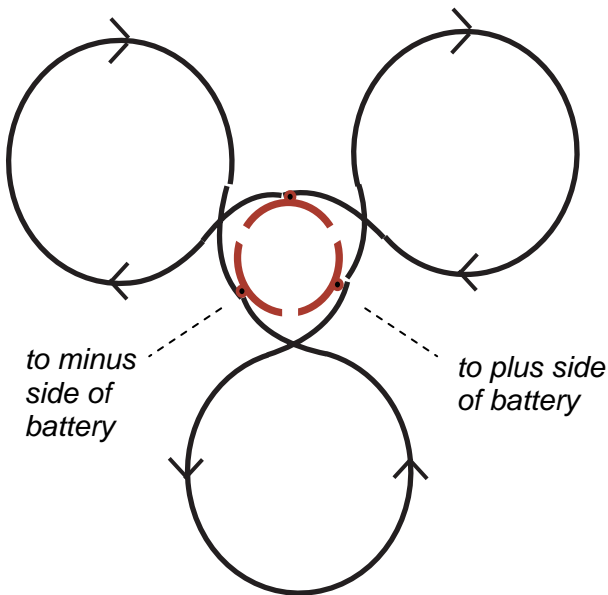


- The drawing shows how the electromagnet coils are connected to the commutator when two electromagnets are above and one is below.
- The three coils form a series-parallel circuit.

3. *When the armature conducts electricity through the brushes, are all three armature electromagnets on?*

Yes, all three coils conduct whenever current flows through one of them. In fact, you observed this when you use the compass to measure the relative polarity of the three electromagnet coils, since all three were conducting at the same time. Also, if you examine the commutator, you can see where the current divides between two adjacent coils, and then recombines on the other side of the commutator (see the drawing above).

4. *Use the diagram on the next page to predict the relative direction of current flow in the three electromagnet coils. The brushes are not shown, but they are underneath the commutator, as before.*



Note that the convention for current flow here is the flow of positive charge.

- In the diagram, one turn of each coil is shown, and these coils have been rotated 90° towards your line of sight.
- Follow the direction of the positive current, which enters the commutator on the right and then splits, with part going into the lower coil and the rest into the upper right coil (the brushes are not shown). These two currents recombine when they exit the commutator on the left side.
- Already you can see that the circulation in the lower coil is opposite to the circulation in the other two, so their magnetic fields will point in opposite directions. To use the right-hand rule, if your thumb points along the direction of the positive current, your fingers will curl in the direction of the field. Try this for all three coils.

5. When current flows through the commutator and the coils, what relative polarity of the coils would you expect? How does this prediction compare with your observations?
6. Imagine following one of the electromagnets on the armature all the way through one revolution. Identify where it reverses polarity, and explain how you found your answer.

- In the drawing on page 7, suppose the armature is spinning counterclockwise.
- When the electromagnet on the armature at the top left rotates down to the bottom, its polarity reverses, because the current through it has reversed.
- When this electromagnet rotates to the top right, its polarity reverses again.
- When this electromagnet rotates to the top left, its polarity stays the same.

I. Energy Conservation in the Battery-Bulb-Armature Circuit

1. If the bulb dims, what can you say about the current flowing through it? Also, what can you say about the voltage across it?

If the bulb dims, the current through it has decreased. If the bulb brightens, the current through it has increased. Note, though, that the light bulb does not obey Ohm's law—that's because as the current through the bulb increases, the filament gets hotter, so its resistance goes up.

2. If you bring the magnet closer to the armature, and the armature spins faster, and less current is flowing through the circuit, does that violate conservation of energy?

- No, this does not violate conservation of energy. In moving the magnet closer the armature, you have changed the motor design to make it more efficient.
- Efficiency equals the power out divided by the power in. Since the armature spins faster when the magnet is closer, the power out is greater. Since the armature draws less current when the magnet is brought closer, the power in is less.
- Since the motor spins faster and draws less current, it is more efficient.

3. How can Lenz's Law explain the dimming of the bulb as the motor spins faster?

- Lenz's Law says that the electromotive force (EMF) induced by a changing magnetic flux (magnetic field times area of a current loop) produces a current that flows in the direction *that opposes the change in flux*. This is a statement of the law of conservation of energy, because if the induced current instead reinforced the change, the larger change would make a larger induced current, which would make a larger change, etc., and we would get a lot of energy for nothing.
- The spinning armature is a generator. As an electromagnet coil sweeps by the ceramic magnet, the magnetic flux through the coil changes, inducing the "back EMF." This "back EMF" produces a current whose direction is opposite to the direction of the current produced in the coil by the battery.
- Since the induced current has the opposite direction to the current from the battery, the net current through the bulb is reduced.

4. *The battery supplies power equal to the voltage across it times the current through it. How does this relationship help explain the observation that squeezing on the motor shaft made the bulb burn brighter? (Let's assume the battery is ideal, producing a constant 1.5 V.)*

- Since the current through the bulb went up, the battery was therefore doing more work per unit time—supplying more power. (Power is equal to current times voltage.)
- Where did that extra work done by the battery go?
 - Some became the extra work that the armature shaft had to do against friction as you squeezed the shaft—winding up as heat.
 - Some went into the extra power dissipated by the lightbulb as it burned more brightly.
 - And some was dissipated inside the motor itself.
- If an electric motor has so large a load that it cannot turn, the motor can draw so much current that it burns out.

J. What You Know Now

Once again, make a labeled drawing to show what you think is inside the motor. Write down how you think the motor works. Please do this independently.

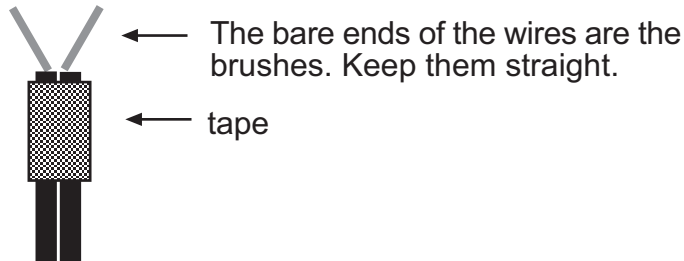
>>>> Also, see the DC motor video on the American Physical Society website at <http://www.aps.org/> ; search on the keyword "dc motor".

[Please note that parts B, C, and D of this activity were adapted from lessons 14 and 15 of *Magnets and Motors*, produced by Science and Technology for Children, National Science Resources Center.]

Suggestions for Motor Assembly

1. Making the brushes:

- Use the two #20 insulated wires
- Apply tape over the ends of the insulation, as shown in the drawing below. If possible, use fiberglass tape (black electrical tape will work, but it stretches easily).
- Keep the bare ends straight. Bend them so they make about a 60° angle. Keep the bare ends perpendicular to the motor axis and in a vertical plane.



The tape does not extend beyond the vinyl insulation of the wires.

2. Making the coil that supports the other end of the motor shaft (this coil provides mechanical support only)

- Make a small coil in the middle of the #20 bare wire, about .5 cm in diameter. You can wind it around a pen. Don't make the coil so small that it binds the motor shaft.

3. Mounting the motor

- Keep the plane of the brushes (the “V”) and the plane of the loop of bare wire perpendicular to the motor axis.
- The coil and brushes need to be close enough together so the commutator cannot fall off the brushes, but far enough apart so there is no binding.

4. If you tape the cup to the tabletop, it may be easier to build the motor.

Materials for DC Motors

Item	Possible Sources	Cost
Economy motor #21471	The Science Source	@ \$1.35
[Carolina Biological sells a slightly larger motor, with wire leads, as part of the STC "Magnets and Motors" kit. The motor is available separately.]		
Bulb, #41, #020-5842	Delta Education	Pkg. of 10 for \$4.95
Bulb-socket, #97-2632	Carolina Biological Supply	Pkg. of 30 for \$21.95
Battery-holder #11F	Acme Model Engineering Co.	10 for \$26
D-cell battery	hardware store	
Compass, #032-2629	Delta Education	Pkg. of 10 for \$4.95
2 rubber bands, #84	office supply company	
Plastic cup, 10-ounce	grocery store	
2 ceramic magnets	Radio Shack	\$.50 each
Cardboard box-top	Container or jewelry store (or make them)	
#20 copper wire, bare #WLS85135-D, ¼ lb.	Sargent Welch (CENCO)	\$6.55
#20 copper wire, vinyl #WLS85135-30F, ¼ lb.	Sargent Welch (CENCO)	\$7.40
Hookup wire (# 22)	hardware store	
Jewelers screwdrivers	hardware store	
Fiberglass tape	hardware store	
Cardboard tube commutator models	Quaker oats containers (small, for students, and large, for teacher demo); cover with brown wrapping paper and draw thick black lines at 120° to represent the commutator gaps	

Materials notes:

- The bulb-holder and battery-holder are particularly durable, and both have Fahnestock clips.
- Thanks to the low resistance of the #41 light bulb, only one battery is needed.
- Be sure to double up the ceramic magnets.
- You will use the piece of fiberglass tape on the battery to tape together two #20 wires to make the motor brushes (black electrical tape will work, but the fiberglass tape stretches less).

>>> Also, see the DC Motor video on the American Physical Society website at <http://www.aps.org/>, keyword "teachers day."

National Science Standards Addressed by DC Motor

National Science Education Standards (NSES)

Abilities Necessary to Do Scientific Inquiry

- Design and conduct scientific investigation: use evidence, apply logic, and construct an argument for... the proposed explanations.

Motion and Forces

- Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces...

Benchmarks for Science Literacy

Scientific Inquiry

- [Scientific investigations] all have in common certain basic beliefs about the value of evidence, logic, and good arguments.

Forces of Nature

- Magnetic forces are very closely related to electric forces and can be thought of as different aspects of a single electromagnetic force. Moving electric charges produce magnetic forces... the interplay of electric and magnetic forces is the basis for electric motors...