

# **BUILDING AN INEXPENSIVE MOTOR IN THE CLASSROOM**



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## A. Introduction

During my second year of my Research Experience for Teachers (RET) at Massachusetts Institute of Technology (MIT) I participated in the Science Teachers Enrichment Program (S.T.E.P). This program brings a group of teachers together to learn about electromagnetism and the engineering design process through the building of simple motors. During the week we learned about how motors work, the parts that make up the motor and how to produce these parts. We were able to use lathes, milling machines and various other tools to take pieces of plastic and produce a motor.

The picture to the right shows the motor that my teammate and I produced. Using a power supply that provided 10 volts and unlimited current, this motor spun at approximately 1200 rotations per minute (rpm). Other groups had motors that spun from 500 to 3500 rpms.

During the week we were tasked to come up with ideas on how to bring this experience back to our classroom. This ended up being a difficult task. As with most schools, we do not have the resources for milling machines or lathes classroom, nor do we want to tackle the safety issues involved with such equipment. I also don't have an unlimited budget to obtain all of the raw materials involved to make the motors.



After contemplating this problem for a few weeks I determined that I could apply what I learned through this week and build motors with my students using everyday materials that we normally throw away!!

The motor pictured below was built using a pill bottle, cardboard, a film canister, metal bar found at home depot, magnets, and some wire.



Using a 6 Volt battery and one extra magnet on each side of the motor I was able to get the motor to spin.

**B. Student Objectives** – Building these motors with your students will meet the following objectives.

National Science Standards –

“Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces, and moving magnets produce electric forces. These effects help students to understand electric motors and generators.”

Other Content Objectives –

- Understand how the right hand rule can be applied to determine the direction of the magnetic force on a wire.
- Calculate the magnetic force on a wire with measured values.
- Understand torque and be able to apply that understanding of torque to the design and construction of a motor.
- Understand why and how the current switches direction in a direct current motor.
- Be able to build a circuit so that current can flow through a motor.

Design and Engineering Standards – the following are laid out in the Massachusetts Science and Technology Frameworks.

- Identify and explain the steps of the engineering design process, i.e., identify the problem, research the problem, develop possible solutions, select the best possible solution(s), construct a prototype, test and evaluate, communicate the solution(s), and redesign.
- Interpret plans, diagrams, and working drawings in the construction of a prototype.

## C. What is a motor? How does it work?

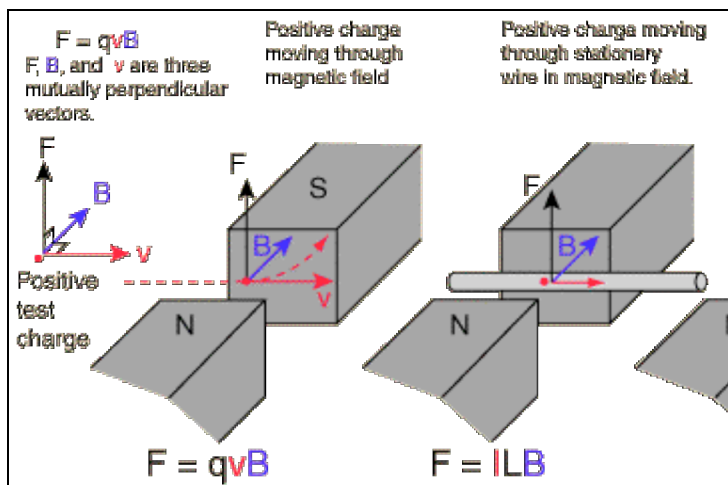
### A Look at the Electromagnetic Theory of Motors

A motor is a device that utilizes electromagnetism to convert electrical energy to mechanical energy.

Motors take advantage of the fact that an electric charge moving through a magnetic field will experience a magnetic force from that field.

The following diagram (<http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html>) shows a magnetic field between the north and south poles of two magnets. As shown in the diagram, the direction of the magnetic field is defined as from north to south.

The first picture in the diagram below shows a charge moving horizontally between the magnets. The positive charge will feel a force upward as shown in the diagram. The second picture shows current moving in a wire through the field. The charge moving through the wire will cause an upward force on the wire.



Variables (units in parenthesis):

$F$  (black)  $\rightarrow$  Magnetic Force on the charge or wire (newtons)

$B$  (blue)  $\rightarrow$  Magnetic Field (teslas)

$v$  (red)  $\rightarrow$  velocity of the positive charge (meters/sec)

$q$   $\rightarrow$  magnitude of the charge (coulombs)

$I$   $\rightarrow$  electric current through the wire (amps)

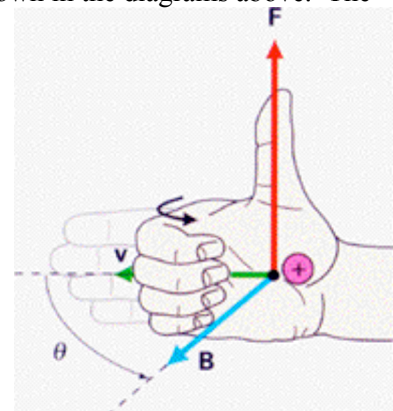
$L$   $\rightarrow$  Length of the wire perpendicular to the magnetic field (meters)

The magnitude of the magnetic force can be determined utilizing the equations shown in the diagrams above. The direction of the force can be determined using the following **right hand rule**:

1. Point your fingers in the direction of the positively charged particle's velocity (or direction of positive current).
2. Curl your fingers towards the direction of the magnetic field.
3. Your thumb will then point towards the direction of the magnetic force.

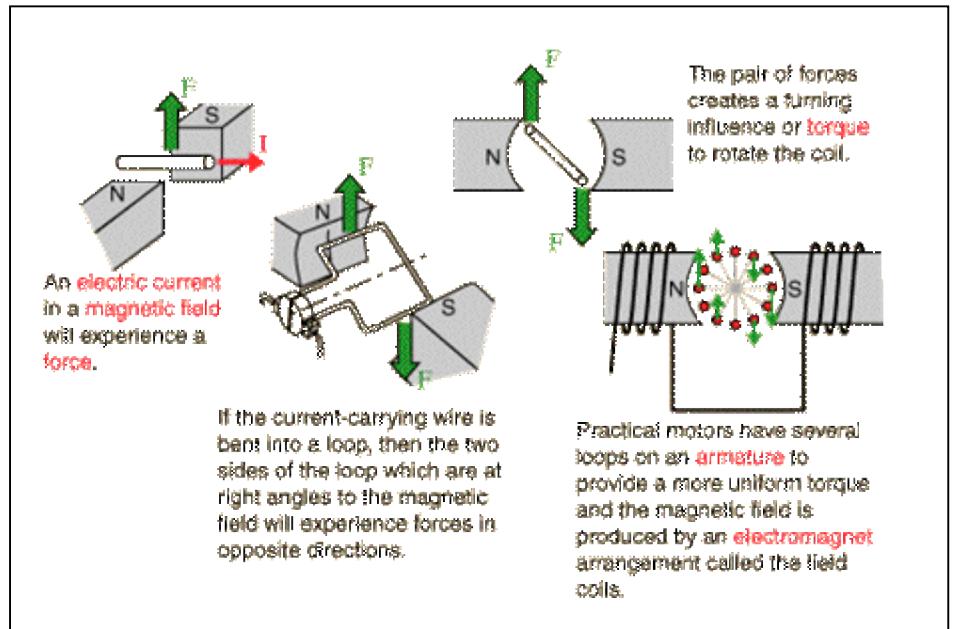
NOTE – Picture at the right found on

<http://www.physics.brocku.ca/faculty/sternin/120/slides/rh-rule.html>



**How can this magnetic force be used to produce a motor?**

As we saw above, a wire with a current moving through it will experience a force as it moves through a magnetic field. The text and diagrams to the right demonstrate how this force can be used to produce a rotating object.

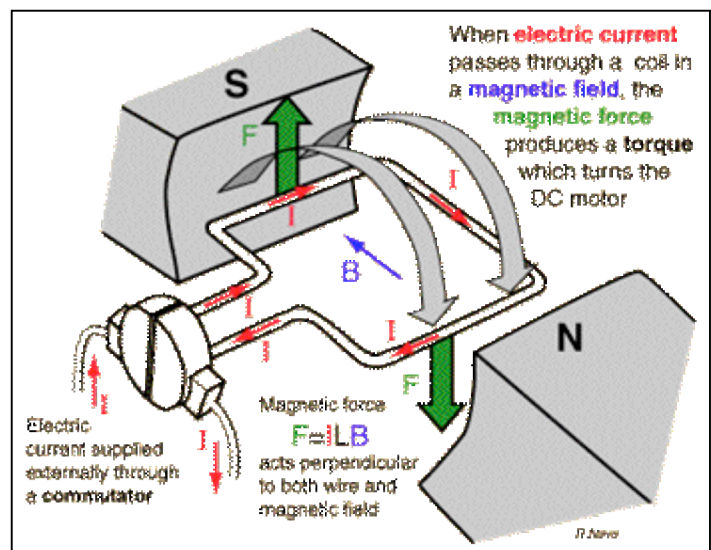


NOTE: Picture found on <http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html>

**Applying the right hand rule to the motor:**

The diagram to the right demonstrates why each side of the coil experiences a force in the opposite direction. As you can see the current near the south magnet flows away from the supply point. Now we can apply the right hand rule to determine the direction of the force. First we point our fingers in the direction of the current and then curl them in the direction of the field. Our thumb will point upward showing the direction of the force on the wire.

On the opposite side of the coil, the current flows back to the supply point. Applying the right hand rule, we point our fingers in the direction of the current and then curl our fingers in the direction of the field. This time our thumb points downward indicating that the force is downward.



<http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html>

## Torque and the Commutator

Since the forces discussed above are on opposite sides of the axle they both cause the motor to twist in the same direction. This twisting force, which causes something to rotate, is called torque. Torque can be determined using the equation:

$$\tau = r_{\perp} * F \quad \text{where } F = \text{magnetic force on the coil (found from } F = BIL \text{ discussed on page 4)}$$

$r_{\perp}$  = the perpendicular distance from the axis of rotation to the magnetic force (called the lever arm in the diagram below)

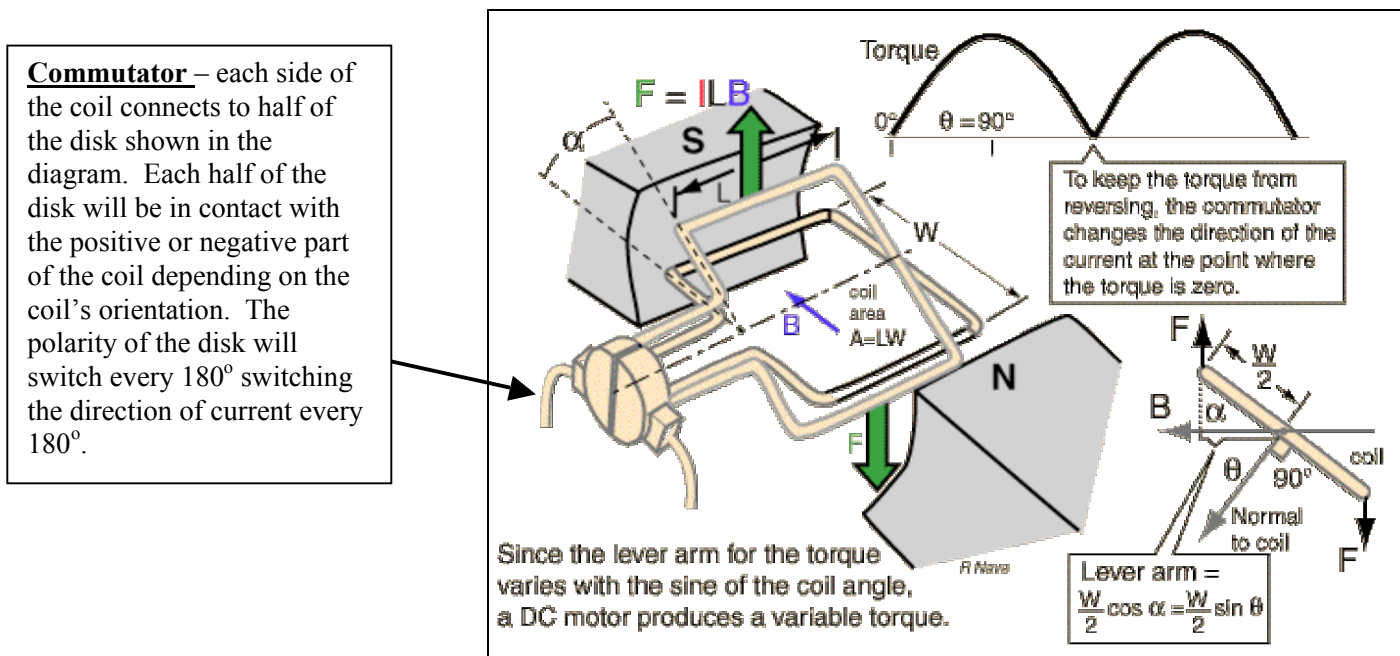
The diagram below shows the coil of a motor. The maximum torque on the coil will occur when the normal to the coil (i.e. the vector perpendicular to the plane of the coil) is at  $90^{\circ}$  with the field. This is also the point where the coils are closest to the magnets. The perpendicular distance from the axis of rotation to the magnetic force can be determined using the sine function:

$$r_{\perp} = (W/2)\sin_{\theta} \quad \text{where } W = \text{the width of the coil}$$

The torque on the coil can then be determined using the following expression:

$$\tau = (W/2)\sin_{\theta} * F$$

When the coil is perpendicular to the field ( $\theta = 0^{\circ}$ ) the torque will be zero. Unless something is done, after this point electromagnetic force will apply a torque in the opposite direction. To avoid this predicament, a device called a **commutator** is installed to switch the direction of the current flowing through the coil. Switching the direction of the current will switch the direction of the forces on the coil maintaining the original torque direction.



<http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/motdct.html#c1>

To see how the current switches direction and changes the forces involved goto <http://www.walter-fendt.de/ph14e/electricmotor.htm>.

## D. Materials Needed

The materials I used to build my motor are shown below.



**Pill Bottle** – or any strong cylindrical bottle that can be used as a rotor (which you will wrap wires around).



**3/16" x 36" Round Steel Rod, Unthreaded, Zinc Coated** – I used this part as the axle of my motor. Any similar rods can be used for this purpose.

**Magnet Wire** – thin insulated magnet wire will be used to make the coils. I recommend using 18-22 gage wire.

**Magnets** – 2 ceramic magnets (magnet dimensions → thickness = 0.393", width = 0.875", length = 1.875"). Note – you may need to place one extra magnet on each side to increase the field so the motor will spin.

**Tape** – tape is always a helpful construction material. I recommend duct tape.



**Hot Glue** – used to help put materials together.

**Copper Tape** – used to make the commutator.

**Cardboard** – utilize scrap cardboard to make the box that holds the motor together.



**Film Canister** – provided the base for the copper tape in the commutator. Tape or any insulating circular object could be used that will go on the axle.

**Large Paper Clips** – to be used as brushes to connect with the commutator.

**Solder** – solder will be used to connect the coils to the commutator.



**E. Recommended Tools** → The following tools will be useful in constructing the motors.

**Glue Gun** – needed for hot gluing parts together.

**Electric Drill** – used to drill axle and coil holes in the pill bottles and in the cardboard.

**Drill Bits** – to be utilized with the drill.

**Hacksaw** – this saw will be needed to cut the axle rods as well as cardboard and other materials.

**Utility Knife** – this knife can be used to cut cardboard and plastic.

**Clamps/Vices** – clamps and vices should be used while cutting to ensure the safety of the students.

**Screwdriver Sets** – students may wish to build their supporting box out of wood and they will use this set to screw the wood pieces together.

**Pliers** – will be used for bending and shaping materials.

**Soldering Iron** – needed for soldering together electrical connections.

**Testing Materials** → These materials will be needed to test the motors.

**6 Volt Battery or 6-12 volt DC source** – provides the power needed to turn the motor.

**Stroboscope** – used to measure the rotational speed of your students' motors.

**F. Material and Tool Spreadsheet** → The following spreadsheet provides a cost estimate and a vendor for the materials listed above.

Material	Quantity	Unit Price (\$)	Total Cost (\$)	Where to Obtain Materials
Ceramic Magnets (CB60-2P)	100	0.6	60	Master Magnetics: 888-293-9399 ext 149
Pill Bottle (circular bottle)	27	0	0	Students bring from home
Cardboard	50	0	0	Obtained from school building or brought from home
60 Yds Duct Tape	5	3.35	16.75	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
10 Pc Electrical Tape	1	3.6	3.6	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
Magnetic Wire, 22 AWG (per 516 feet)	5	10	50	<a href="http://coaxman.com/webstore/Magnet_Wire_rated_@_200C.html">http://coaxman.com/webstore/Magnet_Wire_rated_@_200C.html</a>
File Cannister	27	0	0	Students bring from home
3/16 x 36 Round Rod, Unthreaded, Steel, Zinc Coated (122-316-36-01AAA)	15	0.72	10.8	<a href="http://www.barnhillbolt.com">http://www.barnhillbolt.com</a>
Copper Tape ((TAP) CU.125)	7	10	70	<a href="http://www.surplussales.com/RF/RFSilv-CoppS.html">http://www.surplussales.com/RF/RFSilv-CoppS.html</a>
Large Paper Clips (100 per pack)	3	2.49	7.47	<a href="http://www.staples.com">www.staples.com</a>
Glue (6 PC sticks)	10	0.5	5	<a href="http://www.brandsonsale.com/hot-glue-sticks.html">http://www.brandsonsale.com/hot-glue-sticks.html</a>
Soldering Wire	4	3.99	15.96	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
WW3082458 Bag of Plastic Gears, Pkg/20 Assorted Sizes	5	4.95	24.75	<a href="http://sciencekit.com/">http://sciencekit.com/</a>
<b>Materials Total</b>			<b>264.33</b>	

10W Electric Glue Gun	10	1.36	13.6	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a> (or <a href="http://www.brandsonsale.com/cheap-hot-glue-gun.html#description">http://www.brandsonsale.com/cheap-hot-glue-gun.html#description</a> )
1/2 inch 2 Speed Reversible Electric Drill	5	7.6	38	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
8 Pc Masonry Drill Bit Set	10	1.2	12	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
HackSaw w/ Blade	5	1.36	6.8	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
3 Pcs Snip-Off Utility Knife Set	10	1.38	13.8	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
10 inch Quick Clamp	10	2.18	21.8	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
12 Pc Screwdriver Set	2	2.79	5.58	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
Long Nose Plier	10	1.2	12	<a href="http://www.nationalwholesaletools.com">www.nationalwholesaletools.com</a>
Vector Travel Mate 6.0 Amp AC/DC Converter (VEC004)	1	24.99	24.99	<a href="http://www.bestbuy.com">www.bestbuy.com</a>
Electric Soldering Iron	5	3.11	15.55	
Technika Digital Stroboscope	1	196	196	<a href="http://www.technika.com/Sper/s840009.htm">http://www.technika.com/Sper/s840009.htm</a>
<b>Tool Totals</b>			<b>360.12</b>	

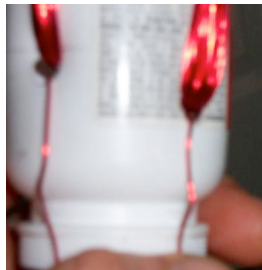
<b>Total Cost of Project (Materials + Tools)</b>	<b>624.45</b>
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**G. Construction Hints** – Since there are many ways students can build their motor I have chosen not to provide step-by-step instructions. Instead I am providing the following suggestions which may be helpful during the construction process.

1. **Drilling Holes** – When drilling axle holes in the pill bottle, be sure that the holes are drilled in the center of the bottle. The motor will spin best if the holes are right at the center of the bottle. Along the same lines, be sure that the holes in the cardboard box are aligned correctly as well.
2. **Notching the Pill Bottle** – While wrapping my coils around the pill bottle I found that the wires slipped out of location very easily. To solve this problem, I put notches at the ends of the bottle where I turned the wires. This kept the wires in place without weakening the structure of the bottle.



3. **Putting Wires through the Bottle** – Instead of wrapping the whole pill bottle I found that I saved wire and kept the motor more compact by inserting the wire through holes in the bottle. In order to do this, I drilled holes through the side of the bottle on opposite sides. Then I inserted the wire through one hole and pulled it out the other side. With the axle already installed I found I needed to bend the wire so that I could get it around the axle and through the hole on the other side of the bottle.



4. **Stripping the Wire** – The magnet wire is insulated. Before connecting the coils to the commutator the coating on the wire needs to be stripped using the utility knife or sandpaper.
5. **Soldering the Commutator** – While making the commutator, I glued the copper pieces to the film canister and then tried to solder the coils to the copper. Unfortunately, after many attempts I had had little luck getting the solder to adhere the wires to the copper. After some discussion with others I found that the copper needs to be heated in order for the solder to adhere to it. However, trying to heat the copper while it was glued to the film canister would not work because that would melt the canister. Based on my difficulty, I recommend that people solder the wire to the copper before attaching the commutator pieces to the structure material.

6. **Paper Clip Brushes** – I utilized two additional paper clips to keep the paper clip brushes in position. This also allowed me to attach the power source to the motor without disturbing the brushes. The picture to the right shows how this was done.
7. **Making the Box** – The magnets should be as close to the rotor as possible without hitting it. I recommend planning out the box and dry fitting all of the pieces together to ensure a good fit that allows the rotor to rotate.



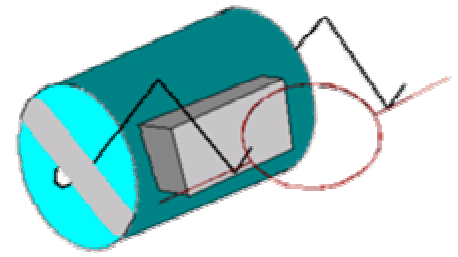
**H. Possible Variations** – There are a variety of ways students can approach building their motor. Here are some of the variations that you may see.

1. Number of Coils – My motor utilizes two coils in the rotor. Students may choose to build motors with 1 to 3 coils. Additional coils can provide more torque to the rotor since each coil allows more current to flow through the magnetic field. However, as more coils are added, the construction of the motor becomes more difficult.
2. Number of times each coil is wrapped – Students will probably put as many wraps as they can fit on their motor.
3. Number and Placement of Magnets – Students may decide that they want to alter the shape of the magnets. Some participants in the S.T.E.P. program placed the magnets in a U-shape so that the coils will be in the strongest field at all times. I recommend that instructors be vigilant against handing out magnets. Magnets can be expensive so the instructor should look for creative alternatives before handing out additional materials.
4. Motor Size – The size of the motor will depend on the size of the bottle that students decide to use. The amount of wire and the box will depend on the bottle. The larger the radius of the bottle the larger the possible torque that can be produced by the magnetic force (since the coils will be a larger distance from the axis of rotation). However, a larger bottle size will increase the distance between the magnets decreasing the strength of the magnetic field. This is just one of the myriad of tradeoffs that students will need to consider.
5. Choice of Box – I built my supporting box out of cardboard. However, your students may want to build a stronger box using wood or other materials. I recommend cardboard because it can usually be found for free and is easily cut. However, if students choose to build a wooden box they can certainly bring in materials from home.
6. Size of the Commutator – My motor utilizes a film canister for the commutator. However, a smaller commutator would provide less frictional torque allowing the motor to spin faster. Students may factor this in and decide to use tape or a smaller circular object to make the commutator. However, a smaller commutator may be more difficult to construct.

To be successful in this project, students will need to apply their understanding of the physics of a motor and make decisions based on their understanding. At first, students will have difficulty making decisions but they will be excited to see all of the different approaches that can be taken to tackle this task.

## I. Classroom Sequence - Recommended sequence for classroom implementation.

1. Before designing and building these motors, students should be familiar with what a motor is and how it works. To introduce motors to students, direct them to <http://fly.hiwaay.net/~palmer/motor.html> where they will find instructions on how to build the simple motor pictured to the right.
2. As students experiment with this motor pose the following questions to guide their inquiry. Students should respond to these questions in their log and be prepared to discuss their responses as a class. You may also choose to have them write up their results in a lab report format.
  - a. Why does the motor spin? *Students will say that some magnetic force causes the motor to spin. However, they probably won't be able to discuss torque or the right hand rule yet. You can leave that to the class discussion.*
  - b. What happens when you turn the magnet around? *Students should observe that the motor will spin in the opposite direction.*
  - c. Try making different shaped coils and seeing how they work. Is the circle the best shape? Try squares, ovals, etc. *Students will find that a symmetrical shape works the best because the rotor needs to be balanced. Torque will be maximized with a square shaped coil since the side closest to the magnet will be the same distance from the center of rotation at all times.*
  - d. Does the number of coils make a difference? *Students should find that the number of coils increases the speed of the motor. However, if they make too many coils it may become difficult to keep it balanced and it will not rotate properly.*
  - e. Turn the coil slowly by hand and feel the magnetic attraction at each position of the coil. Make drawings showing the different coil positions and describe how the attractions vary at each position. *Students will find different areas that have stronger magnetic forces than others. This will lead them towards the understanding of the commutator.*
  - f. Why do the instructions tell you to shave off half of the coil on one side? *This acts as a rough commutator. Shaving off only half the side will turn off the current during the half of the armature's rotation that would provide torque in the opposite direction.*
3. Discuss the results of the questions above with the class. During this discussion you should introduce the ideas of torque and the right hand rule (from page 4). The diagrams and websites shown will help your students visualize what is happening.
4. After students become comfortable with the theory behind the simple motor you should present motor samples for the students focusing on the coils, the commutator, and the brushes. You can show them small DC motors, fan motors, and other types that are available.
5. You should next show them the inexpensive motor that I built (shown at the beginning of this write-up) and explain to the students that each team will be building their own motor. To provide some incentive I recommend having the students compete to see who can build the fastest motor. Again, make sure that the students understand that there are many different ways to tackle this idea and the motors that were shown to them are just samples.
6. Now that the students understand the task, each group should get together to develop a drawing of what they plan to build.
7. After a copy of the drawing is turned into you (and not before!!) you can have the students begin to build their motor. I recommend that you require the students develop written daily update of their work on the motor. This will help you keep abreast of their progress and provide a record of their activities.



## **J. Building a Motor: Student Handout**

### **1. Build a simple motor →**

You will be provided with some insulated wire, a permanent magnet, paper clip, and battery. Go to <http://fly.hiwaay.net/~palmer/motor.html> for directions.

After you build the motor, answer the following questions in your notebook. Be prepared to discuss your responses with your classmates.

- a. Why does the motor spin?
- b. What happens when you turn the magnet around?
- c. Try making different shaped coils and see how they work. Is the circle the best shape? Try squares, ovals, etc. Make a display showing each of the coils you tried with a short summary of the results underneath them.
- d. Does the number of coils make a difference?
- e. Turn the coil slowly by hand and feel the magnetic attraction at each position of the coil. Make drawings showing the different coil positions and describe how the attractions vary at each position.
- f. Why do the instructions tell you to shave off halve of the coil on one side?

### **2. Building a more advanced motor →**

After the group discussion you should be familiar with concepts such as the right hand rule, torque, and the purpose of a commutator.

Utilizing your understanding, you and your group members will build a motor similar to the following:



You and your team will try to produce the motor with the fastest rotational speed when connected to a 6 V battery.

Your team will submit the following products to your instructor:

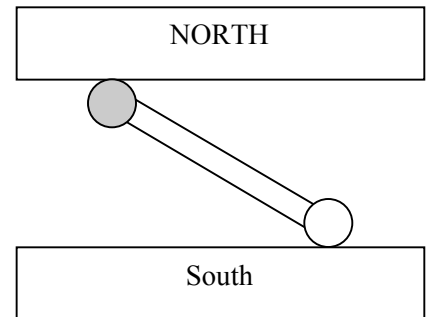
1. Daily report of your group's progress. This includes what you did that day and why. At the end of your report you should include your plans for the next day.
2. The working motor
3. Engineering Summary
  - Explain the parts that make up a motor and how a motor works
  - Discussion of your engineering process –
    - What was your original design?
    - How did your design evolve into the final product and why?
    - How did you apply the theory to the design and construction of your motor?
    - Review the final parameters of your motor (i.e. number of coils, dimensions, etc.)
  - Torque Calculation – Calculate the estimated torque produced by your motor.
  - Conclusion
    - Are you happy with your design?
    - What are you most proud of? What would you change if you had to do it again?

## K. Rubric for Students

Description	Wow!!	Good	Fair	Poor
Daily Reports	Professional daily reports are completed and provide details on what you did, the decisions you made, your thought processes, and your plans for the next day.	Daily reports are completed and provide most of the details on your group's process. However, a few additional details would have been helpful.	Daily reports are completed and provide some details as to your group's process. Much of the details are missing or the reports are unprofessional.	Daily reports are incomplete or do not provide the required detail in provide an effective summary of your group's progress.
The Motor	The motor works!!	The motor works with some additional help (i.e. additional magnets, some modifications by your instructor, etc.)	Your motor is completed but does not work.	Your motor demonstrates that no real effort was made to produce a working motor.
Engineering summary	Someone unfamiliar with physics will <b>understand the physics</b> involved in the motor and understand how your group applied those concepts to your final product.  The calculation is accurate, clear and organized.  The conclusion demonstrates careful reflection of your motor.	Someone unfamiliar with physics <b>will understand most of the physics</b> involved in the motor and understand how your group applied those concepts to your final product. <b>Some clarifications may have been helpful.</b>  The calculation is accurate, clear and organized.  The conclusion demonstrates careful reflection of your motor.	Someone unfamiliar with physics will <b>have much difficulty</b> in understanding the physics involved in the motor and understanding how your group applied those concepts to your final product.  The calculation is accurate but not clearly presented.  The conclusion demonstrates some reflection on your motor.	Someone unfamiliar with physics <b>will not gain an understanding</b> of the physics involved in the motor and an understanding how your group applied those concepts to your final product.  The calculation is in accurate and not clearly presented.  The conclusion demonstrates little reflection of motor.

**L. Assessment Questions** – The following questions can be used to assess your students’ understanding of the physics of motors.

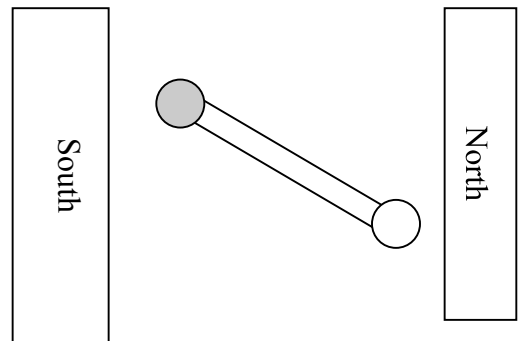
1. The diagram to the right shows a cross section of a motor.
- The two circles at the end of the rod indicate the conventional current.
  - The filled in dot signifies current going into the page.
  - The empty circle signifies current coming out of the page.
  - The armature rotates about the center of the rod.
  - The normal to the armature is  $45^\circ$  below the horizontal axis.
- a. Which direction is the motor designed to spin – clockwise or counter clockwise? Explain with a diagram.



*The right hand rule shows that the magnetic force on the filled in circle will be to the right. The force on the open circle will be to the left. The torque will cause the motor to rotate in a clockwise rotation.*

- b. At which point(s) in the motion of the armature does the current need to switch directions?  
*The current going through the motor will need to change whenever the rod in the diagram is horizontal (i.e. the normal to the rod is parallel to the magnetic field).*
- c. Calculate the torque at the point pictured in the diagram if  $I = 3 \text{ A}$ ,  $B = 100 \text{ T}$ , distance from the rotation point =  $50 \text{ cm}$ , and the length of the wire perpendicular to the field is  $70 \text{ cm}$ .  
*Using  $F = BIL$  the magnetic force each end of the rotor is  $210 \text{ N}$ . Torque can be found using the equation  $\tau = (W/2)\sin_\theta F$ , where  $W = 1 \text{ m}$ ,  $\theta = 45^\circ$ , and  $F = 210 \text{ N}$ . Note: since each side of the coil experiences a torque, you need to multiply this number by 2  $\rightarrow \tau = 148.5 \text{ N-m}$*
- d. If the motor above turns at a constant  $1000 \text{ rpms}$ , what will be the frictional torque opposing the motion of the motor?  
*This question helps to review Newton’s First Law of Motion. If something moves at constant speed then the sum of the forces must be equal to zero. Since it is spinning at a constant rotational speed the frictional torque must be equal to the torque provided by the magnetic field.*

2. The diagram to the right shows a cross section of a motor. The rotor (rod) makes a  $30^\circ$  angle with the horizontal.
- a. Which direction is the motor designed to spin – clockwise or counter clockwise? Explain with a diagram.



*The right hand rule shows that the magnetic force on the filled in circle will be downward. The force on the open circle will be upward. The torque will cause the motor to rotate in a counter-clockwise rotation.*

- b. At which point(s) in the motion of the armature does the current need to switch directions?  
*The current going through the motor will need to change whenever the rod in the diagram is vertical (i.e. the normal to the rod is parallel to the magnetic field).*
- c. Calculate the torque at the point pictured in the diagram if  $I = 2 \text{ A}$ ,  $B = 50 \text{ T}$ , the coil diameter is  $10 \text{ cm}$ , and the length of the wire perpendicular to the field is  $20 \text{ cm}$ .

*Using  $F = BIL$  the magnetic force each end of the rotor is  $20 \text{ N}$ . Torque can be found using the equation  $\tau = (W/2)\sin_\theta F$ , where  $W = 1 \text{ m}$ ,  $\theta = 60^\circ$  (NOTE – the angle for the normal is the complement to the*



angle of the rotor), and  $F = 20 \text{ N}$ . Note: since each side of the coil experiences a torque, you need to multiply this number by 2  $\rightarrow \tau = 1.73 \text{ N-m}$

3. Engineers have found they can get motors to turn faster if they decrease the radius of the commutators. Explain why decreasing the radius of the commutator will allow the motor to turn faster.

*The brushes that make contact with the commutator provide frictional torque to the motor. By decreasing the radius, you decrease the frictional torque on the commutator because you decrease the distance the force is applied from the axis of rotation.*

4. Explain the benefits and drawbacks of using a larger pill bottle to make your motor.

*Benefits – A large pill bottle will allow you to build the motor so that coils are farther from the axle of rotation which will increase the torque on the coil.*

*Drawbacks – The larger the pill bottle is the farther the magnets will be from the coil, therefore decreasing the strength of the electromagnetic field which decreases the force on the wire. Also, having a larger pill bottle will also increase the amount of wire that is in your motor that does not contribute to the torque on the motor.*

5. Explain the benefits and drawbacks of increasing the number of coils in your motor.

*Benefits – Additional coils will provide additional torque since the magnetic force is applied to each coil.*

*Drawbacks – Additional coils may make the mass of the motor difficult to turn. Also, there may be some construction difficulties to installing additional coils.*

## **M. Possible Extensions**

1. Challenge students to get their motor to perform work. This could include lifting or pulling an object, working as a fan or whatever the students come up with.
2. Turn the motor into a generator. Since any motor can also be used as a generator, students can use gears or other materials to produce voltage with their motor. You can see which student group can produce the most voltage. In the materials spreadsheet on page 10 I included a vendor for plastic gears that can be used to convert your motor to a generator.

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