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Let's Design a Better Electric Motor

Developed by Kai Van Horn

Description:
This lesson demonstrates the physical principles harnessed to drive the electric motor. Moreover, this lesson engages students in an activity to demonstrate the impacts of engineering design choices on motor performance through the comparison of rotor diameter and number of rotor turns.

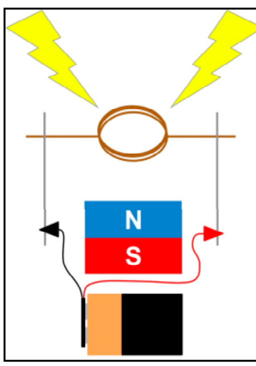
Prerequisites:
Students should have a basic understanding of electric circuits and magnetism.

Instruction Time:
120 minutes

Audience:
Middle school students (grades 6-8)

Lesson Objective:
The goal of this lesson is to introduce students to engineering design.

Page	**Contents**



Let's put magnetic forces to work and design a better electric motor!

Lesson Overview:

An electric motor is an electromechanical device that converts electrical energy (electricity) into mechanical energy (rotation). We use electric motors every day in appliances such as blenders, electric toothbrushes and mixers and even in our cars (and not just the radio-controlled electric ones). This lesson demonstrates the physical principles harnessed to drive the electric motor. Moreover, this lesson engages students in an activity to demonstrate the impacts of engineering design choices on motor performance through the comparison of rotor diameter and number of rotor turns.

This lesson is accompanied by a

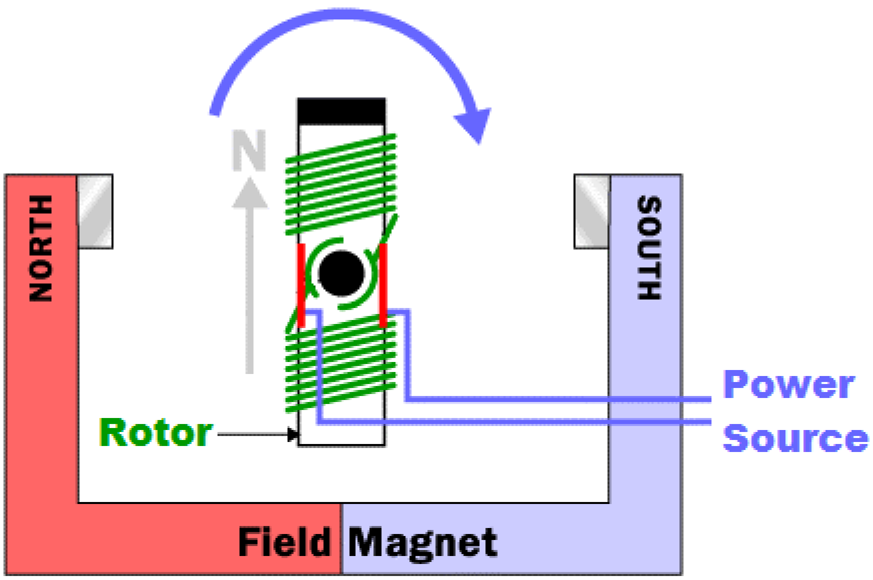
- A worksheet: The worksheet is a map to guide the students through the lesson and provides the key concepts and some exercises to test their knowledge as well as guidance for the performance tests, design tradeoff calculations and motor redesign.
- A set of PowerPoint slides: The slides present the basic concepts at work in an electric motor and provide examples of generators, motors, and electric appliances which rely on motors as well as their manually driven counterparts. The slides should be combined with question and answer with students to engage, build interest in the lesson, and evaluate the existing electricity and magnetism knowledge level of the students.

Background Information:

Electric motors harness the force of magnetism to create rotation. Motors use a combination of permanent magnets, the kind of magnets used for things like refrigerator magnets, and electromagnets, like those in cranes which lift and drop piles of metal at the junk yard. Electromagnets are made up of coils of insulated wire and a “core,” around which the wire is wrapped, and only produce magnetic forces when electricity flows through the electromagnet’s coils.

Permanent magnets and electromagnets have a north pole and a south pole. Which side is the north pole and which side is the south pole of the electromagnet depends on which way the electricity flows through the coils. If you have ever held two magnets together, you know that if you push the north or south poles of the two magnets together you feel the magnets push back, or *repel* each other, when they are close together. Similarly, if you push the north towards the south, you feel the magnets pull together, or *attract* each other, when they are close together.

The forces of attraction and repulsion which we feel between magnets are the driving forces behind the transformation of electricity into rotation in an electric motor. A basic motor, shown in the picture below, consists of a permanent magnet, called the stator or field magnet, a rotating electromagnet, called the rotor, and a source of electricity, the power source, usually a wall plug in the gadgets we use.



The rotor is fixed to an axle. When the power source energizes, or gives electricity to, the rotor, the rotor is magnetized and has north and south poles. These poles are attracted and repelled by the field magnet causing the rotor and the axle to rotate transforming electricity into rotational energy to turn the blades of the blender to make smoothie or the cooling fan to keep our computer cool while we surf the internet! When the north pole of the rotor is lined up with the south pole of field magnet, the electricity flow is reversed so that the rotor north pole becomes the south. Reversing the poles of the rotor keeps the motor from stalling, or stopping, when the rotor poles line up with the opposite field magnet poles.

The parameters of interest to engineers who work with electric motors and that are important for this lesson are the motor speed and the torque produced by the motor. In this lesson, the students will test various motor rotors, which are electromagnets made up of coils of wire with a core of air. They will investigate the impacts of modifications to the number of coils and the diameter of the rotor on the performance. The performance of the rotor can be tested by measuring the motor speed or the motor torque, though torque is easier to measure due to the size of the rotors and the speed of rotations.

We know from physics that the torque produced by a rotor is *direction proportional* to the number of coils and the diameter of the rotor, which means the more coils we have, or the larger our rotor, the more torque the rotor will produce. Conversely, the motor speed is *inversely proportional* to the number of coils and the rotor diameter. Consequently, large diameter rotors or those with more coils, will spin more slowly. The aim of this lesson is to guide the students to identify these relationships through experimental testing and apply them in the design of a rotor.

Learning Objectives & Assessment:

- Learning Goal 1: Students will build a simple DC motor and describe its function
  - Learning objectives: SWBAT
    - a) Students will be able to name force which is harnessed in an electric motor (magnetic)
    - b) Students will be able to name two types of magnets (permanent and electro magnets)
    - c) Students will be able to identify the engineering problem a DC motor solves (turns electric energy into mechanical energy)
    - d) Students will be able to name the three main components of the motor and describe their function (stator, rotor and power source)
- Learning Goal 2: Students will redesign the DC motor to improve performance
  - Learning objectives: SWBAT
    - a) Students will be able to perform the motor performance test and record the results
    - b) Students will be able to explain how modifications to the number of loops or diameter of the rotor impact the speed of the motor
    - c) Students will be able to apply the concepts learned in this lesson and their performance measure to identify at least one way to improve their motor design.

Learning objective: Students will be able to	Assessment
1a) name force which is harnessed in an electric motor (magnetic)	worksheet parts (a,b) and group discussion*
1b) name two types of magnets (permanent and electro magnets)	worksheet parts (c,d) and group discussion
1c) to identify the engineering problem a DC motor solves (turns electric energy into mechanical energy)	worksheet part (e) and group discussion
1d) name the three main components of the motor and describe their function (stator, rotor and power source)	worksheet part (f) and group discussion
2a) perform the motor performance test and record the results	Data table on the student worksheet
2b) explain how modifications to the number of rotor turns or diameter of the rotor impact the speed of the motor	Justify their custom rotor choices in section three and discussion about the results of the performance tests
2c) apply the concepts learned in this lesson and their performance measure to identify at least one way to improve their motor design.	group discussion

* Assessment during group discussion will be done using thumbs up/thumbs down or a similar method.

Alignment to NRC Framework:

Scientific and Engineering Practices

- *analyzing and interpreting data* – students collect motor performance data and interpret the data to prove/disprove their initial hypothesis about the impacts of the design changes on motor performance

Crosscutting Concepts

- *cause and effect* – students will explore the relationship between rotor modifications (the cause) and motor performance (the effect) and develop an understanding of how engineers achieve desired effects by identifying and effectively addressing causes.

Disciplinary Core Ideas

- *engineering design (developing possible solutions)* – students redesign the motor to achieve better motor performance by developing their own rotors based on the performance testing.

Vocabulary:

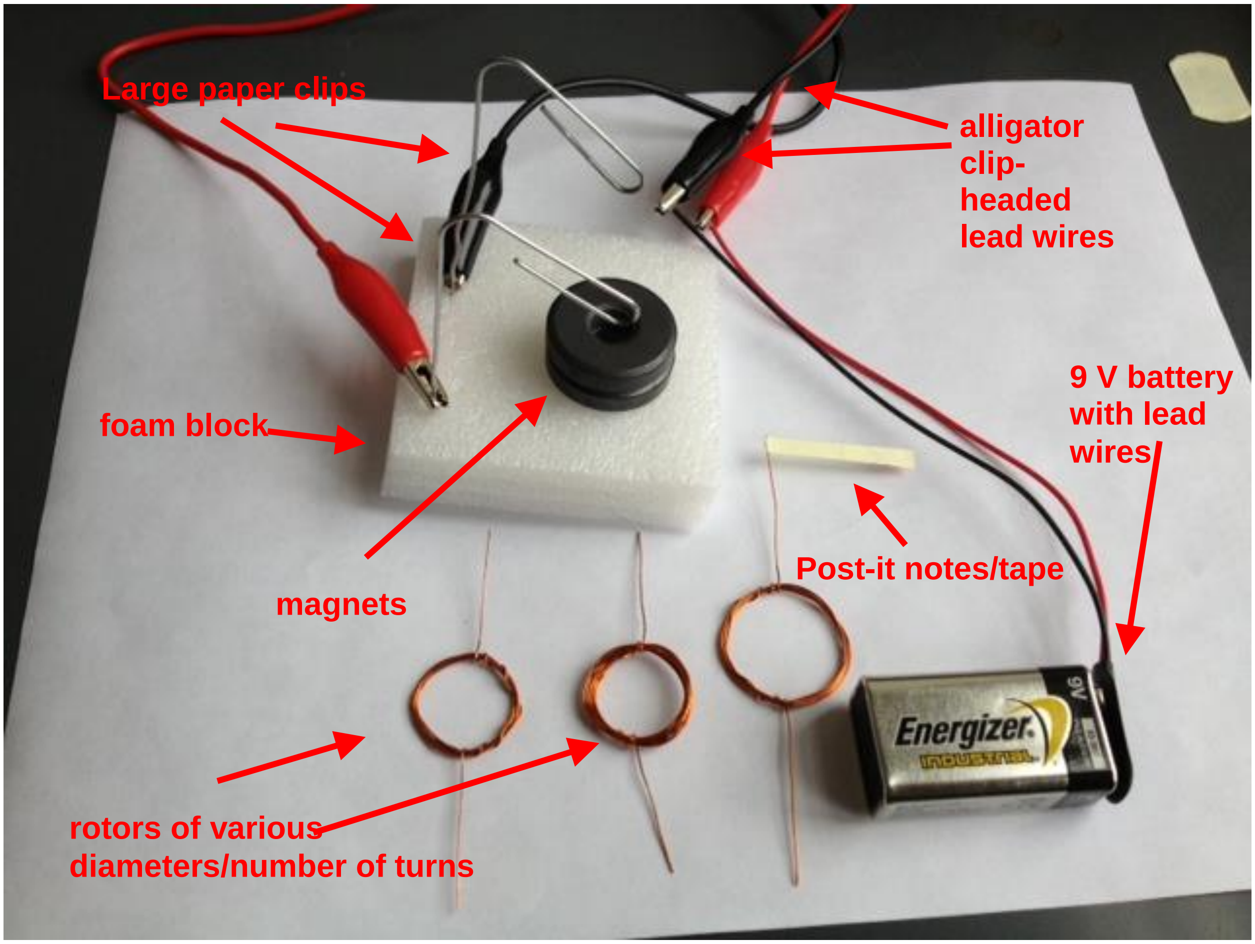
Rotor: The non-stationary part of a rotary electric motor. In this lesson, the rotor is an electromagnet.

Stator: The stationary part of a rotary electric motor. In this lesson, the stator is a permanent magnet.

Power source: The source of power which energizes the coils of rotor. In this lesson, the power source is a 9-volt battery.

Torque: The tendency of a force to rotate an object about an axis. The amount of force that the rotor can overcome depends on the torque produced by the interactions between the magnetic forces of the stator and rotor.

Materials:
The following diagram shows the components of the simple DC motor the students will build and work with in this lesson.



Paper Resources	Technology & Multimedia Resources
Included student worksheet	Included PowerPoint presentation

You will require the following for each student or group of students unless otherwise noted:

Physical Resource	What's it for	Where to get it (cost)
¾ inch, 1 inch and 1 ½ inch wooden dowel rods (3 inches in length).	winding magnet wire into rotors (only one needed)	any hardware store/craft store (< $1)
16, 28 and 20 inch strands of 18 gauge copper **magnet wire (enameled wire)***	for the 5 and 10 turn rotors at ¾ inches diameter and the 5 turn rotor at 1 inch diameter**	readily available online and may be found at RadioShack (~$0.20/ft)
2 large metal paper clips	building motor base	office supply store (< $1)
2 one inch diameter disc/circle magnets (the stronger the better)	the motor stator	Craft store (~$0.50/magnet)
2 alligator clip-headed lead wires	to connect the battery to the motor base	RadioShack or online (~$1/wire though cheaper online)
1 nine-volt battery	the motor power source	cheapest bought in bulk online (~$1/battery)
1 piece of hard foam with approx. dimensions ½ inch X 2 inch X 3 inch	the motor base (must be hard enough to hold paper clips in place when poked through the foam)	packing materials make great motor bases and can usually be obtained free of charge
1 Scissors (only one needed)	to cut post-its/tape and remove enamel from one side of the rotor tips	
10 small circular stickers, tape or small post-it	to add load to the motor and measure the torque	office supply store (< $1)
Calculators (optional)	for extra activity on calculating rotor costs	
wire cutters	to cut magnet wire (only one needed)	hardware store (~$5)
ruler/yard stick/tape measure	to measure magnet wire (only one needed)	

*The wire length needed for each rotor is calculated using the following equation: (Rotor wire length) = (the number of turns) times (the diameter of the dowel rod) times (3.14) plus (5 inches for the rotor tips)

**Winding rotors is time-consuming. Pre-wind a number of rotors of each type to minimize the amount of time spent winding rotors during the lesson and to keep the students focused on the design aspects.

Lesson plan:

The students will work in design teams of two or three students each. There should be at least two design teams so that all of the rotor designs can be tested. There are three rotor designs to evaluate: a ¾ inch diameter rotor with 5 turns, a ¾ inch diameter rotor with 10 turns, and a 1 inch rotor with 10 turns. Each design team will evaluate the performance of the ¾ inch diameter rotor with 5 turns and half of the design teams (labeled group A) will evaluate the ¾ inch rotor with 10 turns while the other half of the design teams evaluates the 1 inch rotor with 5 turns (labeled group B).

Section one: Introduction and background, form design teams, begin motor building

Engage: (10 minutes) Begin with the interactive presentation and demo of the motor to whet the student's appetites for the lesson to come. Introduce the students to the engineering design process (slides 2-4) and the concepts of magnetic forces (slides 5-8). During the presentation, the following key ideas and questions should be raised:

Key ideas:

- What is an engineer and what do engineers do?
- The engineering design process is something we already do every day!
- There are magnets which always produce magnetic forces and some which only do when they are supplied with electricity (electro magnets).
- Electro magnets are coils of energized wire.

Questions and discussion (these questions are intended to accompany the slide presentation included with this lesson):

- What is different between the two objects pictured? (manual vs. electric drive)
- Where else do we find electric motors?
    - potential answers: cars, blenders,
- Are there ways we can "create" magnets?

Demonstrate magnetic forces (do this demo after slide 7 of the presentation)
Have a helper hand out two disc magnets to each group of two students. Ask the students to push the magnets towards each other. What happens? Now, ask them to turn one magnet around and push the magnets together again. What happens this time? Have the students record their findings on the worksheet and share their observations with the class. This demo is intended to familiarize the students with the magnetic forces which are harnessed to create electric motors.

Demonstrate the DC motor

Gather the students around a table and demo a version of the motor they will design and build. Use the motor to demonstrate how the rotor is only magnetized when the power supply is attached (i.e., it is an electromagnet). What happens when we use a rotor without the insulation removed? Why doesn't it turn? Have the students record their observations on the worksheet.

Give an outline of the rest of the lesson:

- Divide students into design teams of two to three students
- Give an overview of the basic parts of an electric motor and the physical principals involved.
- Describe the parts of the motor which we can change in the design. If we increase the number of coils or the size of the coils we increase the force the coil produces. Similarly if we increase the strength of the permanent magnet we increase the force.
- Students build the motor
- Students evaluate the performance of the pre-wound rotors and discuss which rotors performed best and why.
- Students redesign a "best" rotor using the knowledge of the performance.

Explore (10 minutes): Divide the students into design teams and hand out materials for motor base only. Walk around with the helper to assist the students in bending the paperclips and creating the motor base. The students should have the motor base built by the end of section one. When groups finish building their motor base, demo the electric motor using their base.

Evaluate (5 minutes): *Students should meet learning objectives 1a and 1b by the end of section one.* Assessment should be undertaken throughout this section of the lesson using thumbs up/thumbs down or a similar method to gauge concept understanding.

Section two: Motor building and testing

Engage: (5 minutes) Form the students into their design teams. Recap the ideas about magnetic forces from section one. Introduce the students to the basic components of a motor, the parts of the motor which we can change to affect performance and the impacts of those changes (slides 9 and 10). The electric motor solves the engineering problem of how to convert electricity into mechanical energy.

Key ideas:

- An electric motor is an electromechanical device that converts electrical energy into mechanical energy
- Electric motors consist of permanent magnets and electromagnets
- The permanent magnet is the stator and the electro magnet the rotor in our simple motor
- The repulsive and attractive force of the magnet causes the motor to spin
- Which rotor do you think will be best? Why? Students indicate their hypothesis with activities g and h on the worksheet

Explore: (20 minutes) Demo the construction of the motor components with the base. Form the students into their groups from the previous section and hand out the pre-wound rotors and other remaining motor materials.

Key ideas:

- The rotor has to complete the circuit between the paperclips to become an electromagnet
- A performance test has to be repeatable and consistent

Questions and Discussion:

- Will the motor produce more torque if we put the coil closer or further away from the permanent magnet? Why?

Activity: Performance testing

1. The performance test successively add more load to the rotor and see how much can be added before it can no longer turn. Each group needs two testers and one recorder.
2. Student complete performance test for the two rotors assigned to their group and record results in the table on their worksheets and report the results to be aggregated on the table in the slideshow.

Evaluate (5 min): *Students should meet learning objective 1c, 1d, and 2a by the end of section two.* Assessment should be undertaken throughout this section of the lesson using thumbs up/thumbs down or a similar method to gauge knowledge retention and concept understanding.

Section three: Motor redesign

Explain/Extend (10 min): Form the students into their design teams. Ask the students to share the results of their motor performance tests to assess the differences between the different rotors they built. Discuss which rotor performed best and why. Encourage students to use the terminology, such as magnetic field, rotor, stator, they learned in the previous parts of the lesson to describe why they observe performance differences among the rotors. It will save a lot of time to pre-wind a few of the custom rotors for each diameter-number of turns combination.

Key ideas:

- Increasing the number of coils or the size of the coils increases the force created by the interaction of the electromagnet and the permanent magnet
- Increasing the number of coils or the size of the coils also increases the weight of the rotor and force needed to it keep the rotor turning. This is an engineering design trade-off!

Questions and Discussion:

- Which rotor performed best? Why?
- How did the impacts on performance of increasing the number of loops or the diameter compare with our predictions?
- What factors may have contributed to the differences in the results between the groups?

Extend/Explore (15 min): Students then apply the knowledge and skills they have learned over the previous two sections to design a "better" rotor. The students first design the rotor in activity (i) of their worksheet and justify their design decisions specifying the diameter and number of turns.

Activity: custom rotor design

1. Students design custom rotor on worksheet in activity (i)
2. Students explain their decision to obtain the pre-wound custom rotor
3. Students performance test the rotor and record the values in the table on their worksheets
4. Students compare their design's performance the other rotors they tested

Key ideas:

- Increasing the number of coils increases the cost of the coils

- The cost of the coils must be balanced with the performance of the rotor. This is a design tradeoff.

Questions and Discussion:

- How did the custom rotor compare with the other rotors tested?

Clean-up (10 minutes)

Evaluate (5 min): *Students should meet learning objective 2b and 2c the end of section three.* Assessment should be undertaken throughout this section using thumbs up/thumbs down or a similar method to gauge knowledge retention and concept understanding. At the end of this final section, go back to the basic concepts of magnetic forces, motor components, and what engineers are and what they do. Use this final 5 minutes to assess the student's post activity knowledge level and reinforce these concepts where necessary. Discuss with the students how the activity relates to the engineering design process described at the beginning of the lesson

Extra Activity: Rotor cost and design tradeoffs

This additional component of the lesson can be added in section three after the discussion of the section two rotor test results and at the end of section three when evaluating the custom rotors against the rotors tested duration section two.

Extend/Explore (15 min): Introduce the concept of a design tradeoff by bringing up a "cost per turn." Students calculate rotor costs and reassess which rotor is best. Students then apply the knowledge and skills they have learned over the lesson to design a "better" rotor taking cost as well as performance into account. The students first design the rotor on their worksheet and justify their design decisions specifying the diameter and number of turns.

Activity: rotor costs

1. Perform an example calculation of the rotor cost (number of turns times cost per turn)
2. Students calculate the costs of the rotors and record them in the table on their worksheets

Key ideas:

- Increasing the number of coils increases the cost of the coils
- The cost of the coils must be balanced with the performance of the rotor. This is a design tradeoff.

Questions and Discussion:

- How does the increase in cost between the rotors compare to the performance?
- Which rotor design is best if we consider cost *and* performance?
- How does the custom design performance and cost compare to the designs we previously tested?

Additional Information and Links:

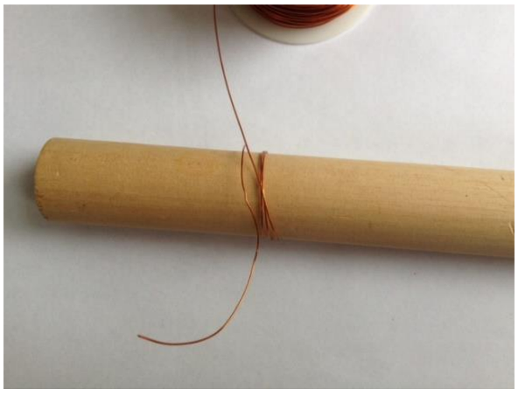
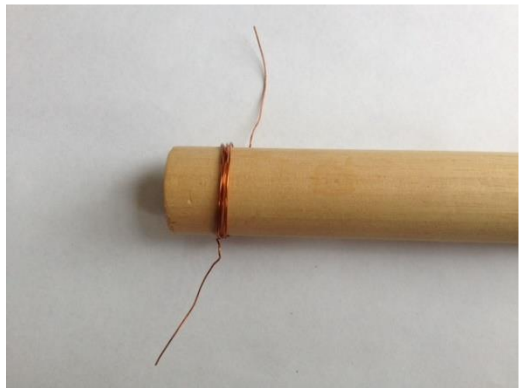
- Electrical engineering:
  - http://en.wikipedia.org/wiki/Electrical_engineering
- Motor physics
  - http://en.wikibooks.org/wiki/GCSE_Science/The_motor_effect
- Motor Activities
  - http://www.engineeringinteract.org/resources/parkworldplot/flash/concepts/magneticforces.htm
  - http://www.magnet.fsu.edu/education/tutorials/java/dcmotor/index.html

Appendix:

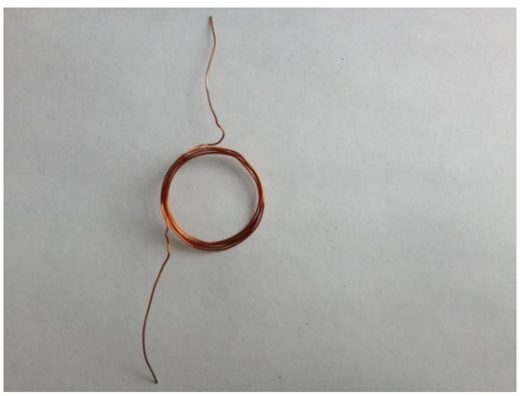
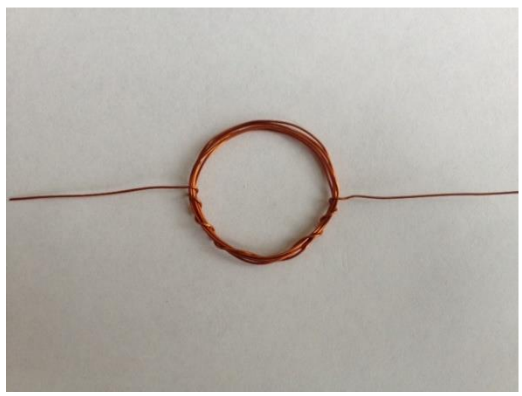
The following provides instructions for winding the rotors and building and testing the motor.

Wind a rotor!

1. Wrap the appropriate length wire around the dowel rod making sure to leave ~2 inches of extra wire on each side.

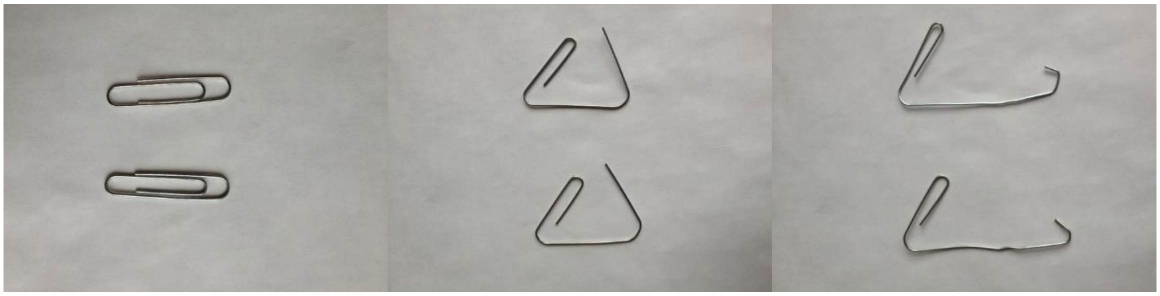
2. Wrap the extra wire ends through the loop two or three times on each side of the rotor to hold the loops of the rotor together

3. Scrape the insulation off one side of the wire on each end (it should be the same side on each end). The edge of a scissors work well for this. If the motor doesn't turn, this is likely the cause and the rotor ends may need to be scraped again.

Build a motor base!

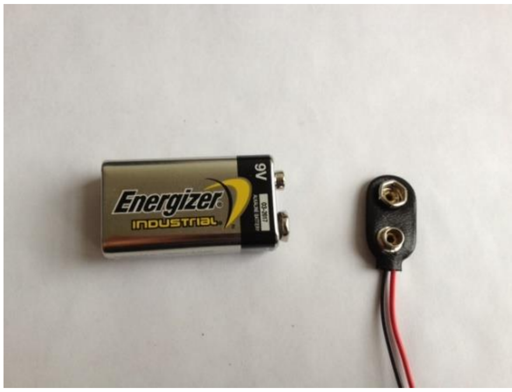
1. Bend paper clips open and form the open end into a small hook



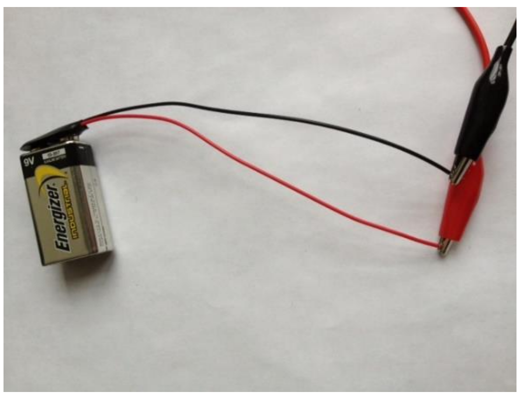
2. Poke paper clips through the hard foam so they are about 1.5 inches apart.

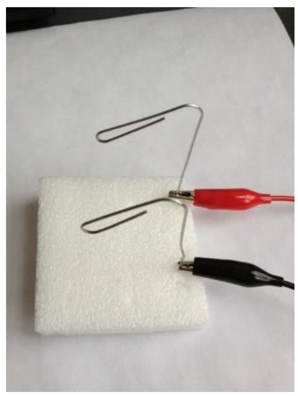
Build a motor!

1. Connect the battery to the batter leads by snapping the black battery lead cap onto the end of the battery

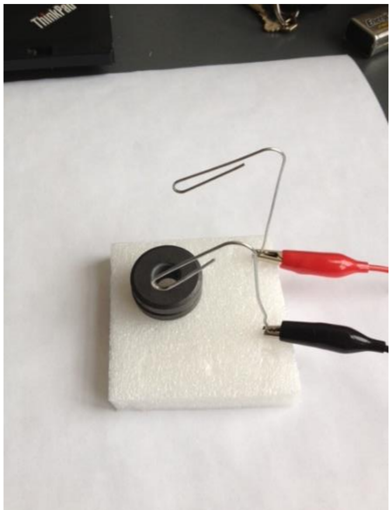


2. Connect the ends of the red alligator clip wire to the red battery lead and the other to one of the paperclips. Connect one end of the black alligator clip wire to the black battery lead and the other to the other paperclip.





3. Place magnets on the foam base between the paper clips



4. Place the rotor into the loops of the paper clips so that it is centered between the paper clips. Remove the rotor from the paper clips after the 5-second test.