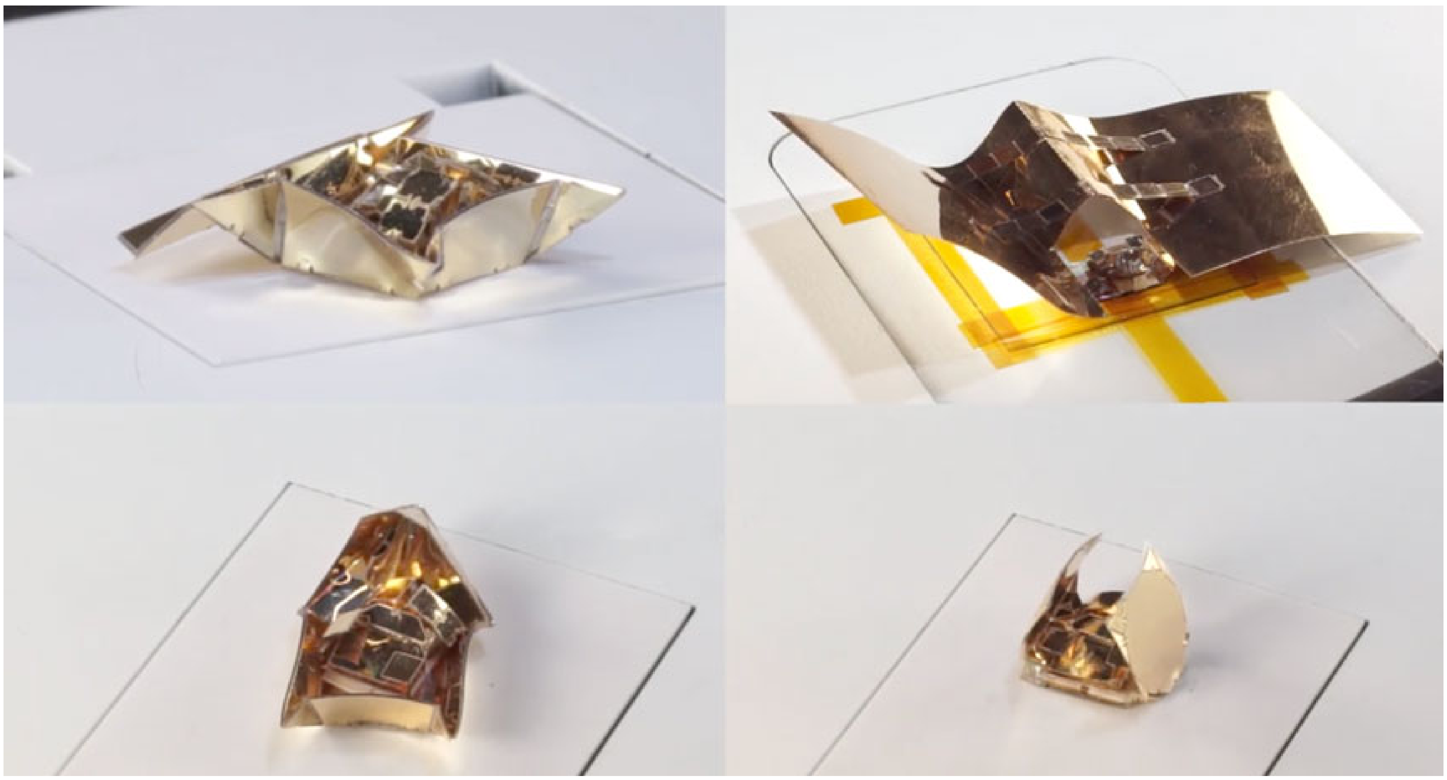
Science News

IN HIGH SCHOOLS | EDUCATOR GUIDE



MIT CSAIL

October 28, 2017

Origami Outfits Help Bots Retool

SOCIETY FOR SCIENCE & THE PUBLIC

EDUCATOR GUIDE

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About the Issue

***Science News* article(s):** "Origami outfits help bots retool"

Readability score: 13.6

***Science News for Students* article(s):** "These robots quickly swap 'origami' jackets — and tasks"

Readability score: 7.5

The article "Origami outfits help bots retool" describes how a cube-shaped mini-robot can wrap itself in different origami exoskeletons to perform various tasks while being driven by a solenoid. Students can focus on details reported in the articles, follow connections to earlier articles about robots and explore cross-curricular connections including the topics of solenoids, polymers, solubility and naturally occurring biological "transformers." In a related activity, students can make and test magnetic solenoids similar to those that were used to control the robot in this article.

Before beginning any part of this guide, be sure to watch the origami bot video (scroll down to find the video at the end of the article) showing the exoskeleton transformations and the bot's performance of difference tasks. You could also start off with a simple origami math exercise as a warm-up, like folding a piece of paper into perfect thirds (explained in "Folding perfect thirds" by *Science News*).

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Article-based observation: Questions focus on how the cubic metallic robot is able to wrap itself in different exoskeletons and how it is able to perform different functions.

Quest through the archives: Use this short section to explore other articles about robots as reported by *Science News* since 1924.

Cross-curricular discussion:

Chemical Sciences questions address polymers, heat-shrinking materials and the general principles of solubility.

Physical Sciences questions concern magnetism and the properties and uses of solenoids.

Biological Sciences questions discuss some natural biological systems that function as adaptable "nano-robots," such as RNA polymerase, macrophage and mast cells, and complement proteins.

Engineering and Experimental Design questions deal with various applications of the technologies from the article, such as the transforming origami exoskeleton.

Activity: Solo for Solenoid

Purpose: To gain a better understanding of how solenoids work and to explore the uses of solenoids.

Procedural overview: Students construct their own simple solenoids and conduct experiments to measure solenoids' properties.

Approximate class time: 30-50 minutes.

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Standards

Next Generation Science	Common Core ELA
Structure and Properties of Matter: HS-PS1-1, HS-PS1-3, HS-PS1-5	Reading Informational Text (RI): 1, 2, 4, 5, 7
Forces and Interactions: HS-PS2-4, HS-PS2-5	Writing (W): 1, 2, 3, 4, 6, 7, 8, 9
Energy: HS-PS3-3, HS-PS3-4, HS-PS3-5	Speaking and Listening (SL): 1, 2, 4, 5, 6
From Molecules to Organisms: Structures and Processes: HS-LS1-1, HS-LS1-2, HS-LS1-3	Reading for Literacy in Science and Technical Subjects (RST): 1, 2, 3, 4, 5, 7, 8, 9
Engineering Design: HS-ETS1-1, HS-ETS1-2, HS-ETS1-3	Writing Literacy in History/Social Studies and Science and Technical Subjects (WHST): 1, 2, 4, 7, 8, 9

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Article-Based Observation: Q&A

Based on the article "Origami outfits help bots retool:"

1. In one sentence, what is the main idea of the article?

Possible student response: The same robot can wear different outfits, or shape-shifting exoskeletons, that allow it to perform different tasks.

2. What is described as the "heart" of the robot? How is this part of the robot controlled?

Possible student response: A magnetic metal cube a few millimeters across is the robot's heart, or control center. Researchers remotely control the small cube with magnetic coils called solenoids that attract and/or repel the magnetic cube.

3. How is the origami sheet made?

Possible student response: The sheet is a flat layer of heat-shrinking polymer (the same kind used to make Shrinky Dinks) that is covered on both sides with a layer of polyester. The polyester protects the heat-shrink layer by absorbing some of the heat from external sources. Wherever the researchers want the origami sheet to fold along a line as heat is applied to the exoskeleton, they peel away a thin strip of the polyester insulation.

4. How is the origami sheet converted into an exoskeleton for the robot?

Possible student response: Using the solenoids, the researchers position the metal cube on top of one of the origami sheets where the cube fastens to the sheet. A heating pad under the sheet is activated once the cube is in place and heats the origami sheet to 65° Celsius. The uninsulated regions, or creases, of the sheet start to shrink before the insulated regions do, causing the sheet to fold on the designated lines. The sheet surrounds the metal cube as it folds up into a three-dimensional shape.

5. How is each exoskeleton fastened in place and removed when desired?

Possible student response: Each exoskeleton is fastened into place with four latches made of water-soluble material. To remove the exoskeleton, researchers use the solenoids to guide the robot into water, which dissolves the latches. Then the researchers use the solenoids to move the metal cube away from the remains of the exoskeleton.

6. What functions do the different exoskeletons perform?

Possible student response: When guided by the solenoids, the Walk-bot exoskeleton allows the cube to walk. The Wheel-bot exoskeleton allows the cube roll. The Boat-bot exoskeleton allows the cube to float on water. The Glider-bot exoskeleton has wings that carry the cube through the air.

7. What are some possible applications for such rapidly customizable robots? What tools could future exoskeletons provide for a robot?

Possible student response: Potential applications of these robots include surgery, space manufacturing and emergency response missions. Drills, scissors, shovels and grippers could all be included in future exoskeletons.

8. How could similar adaptable robots be useful for surgery? What about for space missions and for emergency responses?

Possible student response: For surgery, a patient could ingest a magnetic core and various exoskeletons, which a surgeon would then remotely control from outside the body. During space manufacturing, a single robot could perform a wide range of tasks that would normally require multiple robots or a lot of spare parts, which would reduce the weight of materials brought to space. In an emergency response operation, a robot could don different lightweight exoskeletons to perform different tasks while helping to find and rescue victims, again, without having to pack a lot of spare parts or completely different types of robots.

9. What general scientific principles were applied by the scientists when designing and constructing the robot?

Possible student response: In order to design and construct the robot, scientists used the concepts of electricity, magnetism, dynamics of movements, the structure and properties of materials (including solubility and the interactions of materials), heat transfer and thermodynamics, as well as mathematical principles of geometry.

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Article-Based Observation: Q

Directions: Read the article "Origami outfits help bots retool" and then answer these questions:

1. In one sentence, what is the main idea of the article?

2. What is described as the "heart" of the robot? How is this part of the robot controlled?

3. How is the origami sheet made?

4. How is the origami sheet converted into an exoskeleton for the robot?

5. How is each exoskeleton fastened in place and removed when desired?

6. What functions do the different exoskeletons perform?

7. What are some possible applications for such rapidly customizable robots? What tools could future exoskeletons provide for a robot?

8. How could similar adaptable robots be useful for surgery? What about for space missions and for emergency responses?

9. What general scientific principles were applied by the scientists when designing and constructing the robot?

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Quest Through the Archives: Q&A

1. The video showed that the origami robots could glide. Can you find an article about tiny flying beelike robots?

Possible student response: The article "Insect-sized bot is first to both fly, land," published 6/25/2016, discusses the RoboBee, a robot about the size of a real bee. It has flapping wings to fly and four pinlike legs to land. It can also use static electricity to cling to the underside of a leaf or other perches. By spending as much time perching as possible and only flying when necessary, the RoboBee can greatly extend how long it can operate before it has to recharge its energy supply. (Another *Science News* article that students may find is "Fleets of drones could pollinate future crops," published 3/18/2017, which shows how larger flying robots could act like bees to pollinate plants if too many real bees are killed by habitat loss, disease or pesticide exposure. There is also a *Science News for Students* version of the article, "Fleets of flying robots could pollinate crops.")

2. Can you find an article about a different origami robot that is operated by a laser?

Possible student response: The article "Laser light turns graphene paper into a microbot," published 11/6/2015, discusses how researchers made a simple origami robot out of graphene paper, a graphene and polymer composite material that absorbs water from humid air or a damp surface. The graphene paper flattens out when damp and folds into an arch shape when dry. Hitting it with a laser causes it to transition from its flat damp shape to its arched dry shape. When the laser shuts off, the graphene absorbs more moisture and flattens out again. Pulsing the laser on and off slowly causes the graphene paper to move like an inchworm, repeatedly arching up and flattening.

3. Another way for robots to transform their shape and function is for many smaller robots to join together in various configurations. Can you find an earlier article about "composite robots" with a "hive mind"?

Possible student response: The article "In these bot hookups, the machines meld their minds," published 9/12/2017, discusses composite robots made of many miniature robots. Each robot has its own wheels, sensors and computer processor, and can operate independently. However, groups of the robots can assemble into different shapes to perform different tasks as a single entity. When the robots are clustered together, one of them is selected to serve as the "brain unit" for all of the others in the cluster. That master robot receives data from all of the other robots' sensors and directs the actions of all the robots. Having one master robot per cluster yielded faster and better responses than having decentralized control, with every robot trying to function and coordinate with the other robots in the cluster.

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Quest Through the Archives: Q

Directions: After reading the article "Origami outfits help bots retool," log in to your *Science News* in High Schools account and use the Search page to answer these questions. Make sure you adjust the filters to include articles written before 1999, if the question requires you to do so.

1. The video showed that the origami robots could glide. Can you find an article about tiny flying bee-like robots?

2. Can you find an article about a different origami robot that is operated by a laser?

3. Another way for robots to transform their shape and function is for many smaller robots to join together in various configurations. Can you find an earlier article about "composite robots" with a "hive mind"?

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Cross-Curricular Discussion: Q&A

Directions: After students have had a chance to review the article "Origami outfits help bots retool," lead a classroom discussion based on the questions that follow.

The last article-based observation question references the basic, interdisciplinary nature of the origami bot design and construction. After students have read the article, watched the video and completed the first section of questions, you could begin a discussion that allows students to express their own article-related interests. You could also encourage them to explore an idea for a simple project based on their interest. For example, if a student is fascinated by the origami designs of the exoskeletons, allow them to try to rebuild one of the origami exoskeletons and then allow them to try to design their own exoskeleton to perform a different task (see additional Engineering and Experimental Design questions below).

CHEMICAL SCIENCES

Discussion questions:

1. What is a polymer, and what are some examples of polymers in chemistry and biology?

A polymer is a chemical made of long chain-like molecules which themselves are made up of subunits called monomers. Some examples include polyethylene made of chains of ethylene subunits, polystyrene made of chains of styrene units, polyurethane made of chains of urethane subunits, nylon made of amide subunit chains and polyolefin made of olefin subunits. DNA and RNA are biological polymers made of nucleotide subunits, and proteins are biological polymers made of amino acid subunits. Sugars and lipids can also form polymers. For example, both cellulose and starch are made of glucose subunits.

2. What types of substances dissolve in water? Explain how water dissolves a substance.

Ionic compounds and polar molecules dissolve in water, which itself is made of polar molecules. Polar molecules have an overall neutral charge, but an uneven distribution of electrons between atoms within the molecules leads to partially positive and partially negative charged regions. These partially charged regions attract other molecules and ions with opposite charges. Take table salt, or sodium chloride, for example. Water's partially negative charged oxygen atoms attract salt's positive charged sodium ions. Meanwhile, the partial positive charge on water's two hydrogen atoms attracts salt's negative chloride atoms. Because of this attraction, when table salt is combined with water, water molecules surround the salt molecules and may completely dissolve the substance.

3. Other than the molecular composition of a solute, what other conditions affect the solubility of a solute and solvent?

Factors that affect the solubility of a solute in a solvent include: the temperature of the solute and solvent, the acidity or basicity of the environments, the amount of solute and solvent, particle size, the amount of applied mechanical motion and, for gases dissolving into liquids, the external pressure of the system.

Extension prompts:

4. What is heat-shrink material made of, and how does it work?

Heat-shrink material is a polymer that has been specially treated during manufacturing. First, the polymer is cross-linked, meaning that covalent bonds are created between different polymer chains. Those cross-links tend to make the polymer stiffer, like how tangling several strings together makes it harder to pull them apart. Then, the cross-linked polymer is heated enough to loosen it up and stretch it to a larger size. Finally, the polymer is cooled in that stretched shape until it is too rigid for the cross-links to pull it back together. (Imagine stretching a rubber band and then freezing it in the stretched state.) When heat-shrink material that has been manufactured that way is finally heated again its cross-links pull it back into its earlier more compact shape. (Likewise, heating up the rubber band that was stretched and then frozen would thaw out the rubber band and allow it to contract again.) For more information on heat-shrink materials, see [Hackaday, Heat Shrink Tubing and the Chemistry Behind Its Magic].

PHYSICAL SCIENCES

Discussion questions:

1. What is magnetism? Why are some materials magnetic and other are not?

Magnetism is a physical phenomenon produced by the motion of electric charges that results in attractive and repulsive forces between objects. Moving charges create an electric current, and anywhere there is an electric current, there is a magnetic field present. Atoms have charged electrons moving around them, and that motion, called orbital motion, can give their atoms magnetic fields. Electrons within a material also have a quantum mechanical property called spin, which makes them behave as if they are spinning around like a top, giving each electron a tiny magnetic field. In order for an atom to have a magnetic field, however, the magnetic fields of its electrons must not cancel each other out (point in opposite directions). If the tiny magnetic fields from many atoms in a material line up with one another, they can add together to produce an overall magnetic field. Iron, cobalt and nickel atoms, for instance, have relatively large numbers of unpaired electrons occupying different energy levels — the spins of these unpaired electrons will align and give the atoms an overall magnetic field. (Paired electrons in orbitals cancel each other's individual magnetic field, so atoms that contain only paired electrons are not magnetic.) When the magnetic fields of many atoms are allowed to align in a material, the overall object has a large-scale magnetic field.

2. What is a solenoid?

A solenoid is a coil of wire. Passing an electrical current through the coil creates a magnetic field down the center of the coil. The magnetic field can be made stronger if a magnetizable metal (such as iron) core is placed inside the coil, making it an electromagnet.

Extension prompts:

3. How can a solenoid be used to move things?

Using the solenoid as an electromagnet, it can attract or repel other magnets or magnetic metal. Alternatively, the solenoid coil's magnetic field can be used to exert a push or pull on a magnetic metal core inside the coil, like an electrically operated bolt lock.

3. How can a solenoid be used to make sparks?

Electrical energy from current flowing through the solenoid coil is converted into magnetic energy emanating from the solenoid. If the wire to the solenoid coil is disconnected, the magnetic energy will resist losing the connection, creating a high-voltage spark that jumps to the disconnected wire and tries to keep current flowing.

BIOLOGICAL SCIENCES

Discussion questions:

1. How does an RNA polymerase enzyme adapt itself to make RNA copies of different DNA genes under different circumstances, essentially acting like a natural transformer or origami bot?

RNA polymerase is an enzyme that makes RNA copies of DNA genes. Which genes RNA polymerase copies, when the enzyme copies them and how many copies the enzyme makes depend on various factors sensed by the cell, including what the genes control — cell division, inflammation or hormone production, for example. To do these various jobs under different circumstances, RNA polymerases depend on a collection of protein subunits, transcription factors and regulatory proteins. Called holoenzymes, RNA polymerases will add or subtract these gene-copying helpers based on signals from the cell, similar to how the origami bots can change their exoskeletons based on the task at hand.

Extension prompts:

2. How do macrophage and mast cells, certain types of white blood cells in the immune system, adapt themselves to detect different intruders in your body?

Antibodies are proteins shaped like two-pronged forks; the tip of each prong has a specific shape to bind to a particular pathogen (germ) or allergen (something that your body should not react to, but does). Antibodies are made by one type of white blood cell, B lymphocytes. But other types of white blood cells, such as macrophage and mast cells, can also pick up and use those antibodies. The back end of the antibody (called the Fc domain) plugs into a socket (called the Fc receptor) on the surfaces of macrophage and mast cells. Using those plugged-in antibodies, macrophage and mast cells can adapt themselves to detect whatever pathogens or allergens the antibody tips selectively bind to. When macrophage cells detect a pathogen that way, the cells try to eat it to destroy it. When mast cells detect an allergen that way, the cells release histamine, which causes inflammation (which is why you take an antihistamine if you have an allergic reaction).

3. How do complement proteins act like a swarm of self-assembling nano-robots?

Complement proteins are another part of the immune system. Complement proteins bind to intruders in your body, but not to cells or other normal components in your body. When some complement proteins bind to an intruder, they attract more and more complement proteins, producing a swarm that attacks the intruder (the membrane attack complex) and release complement protein fragments that attract other parts of your immune system.

ENGINEERING AND EXPERIMENTAL DESIGN

Discussion questions:

1. What improvements would you like to see made to the origami robot research?

Robots that can do more themselves without being dependent on externally controlled heating pads to fold the origami materials, water to detach itself from an origami exoskeleton or solenoids to move the robots. Also, robots with sensors added so the bots can detect and respond to stimuli instead of having to be guided by human operators for every step.

Extension prompts:

2. What are some possible extensions and applications you can think of for remote-controlled magnetic manipulation?

Precise remote-controlled magnetic manipulation of objects for surgery, repetitive lab experiments, manufacturing, printing and food harvesting and processing are a few possible examples.

3. What are some possible extensions and applications you can think of for the origami materials?

Origami materials for sensing heat and moisture; changing your clothing for appearance, function or in response to changing environmental conditions; changing your vehicle or your home for appearance, function or in response to changing environmental conditions.

4. What are some possible extensions and applications you can think of for such robot research?

Robots that configure themselves for surgery, for finding people in collapsed buildings, for space exploration or even for cleaning your house.

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Cross-Curricular Discussion: Q

Directions: The following list of discussion questions is provided to help you take notes, brainstorm ideas and test your thinking in order to be more actively engaged in class discussions related to this article. All questions in this section are related to topics covered in "Origami outfits help bots retool."

CHEMICAL SCIENCES

Discussion questions:

1. What is a polymer, and what are some examples of polymers in chemistry and biology?

2. What types of substances dissolve in water? Explain how water dissolves a substance.

3. Other than the molecular composition of a solute, what other conditions affect the solubility of a solute and solvent?

Extension prompts:

4. What is heat-shrink material made of, and how does it work?

PHYSICAL SCIENCES

Discussion questions:

1. What is magnetism? Why are some materials magnetic and other are not?

2. What is a solenoid?

Extension prompts:

3. How can a solenoid be used to move things?

4. How can a solenoid be used to make sparks?

BIOLOGICAL SCIENCES

Discussion questions:

1. How does an RNA polymerase enzyme adapt itself to make RNA copies of different DNA genes under different circumstances, essentially acting like a natural transformer or origami bot?

Extension prompts:

2. How do macrophage and mast cells, certain types of white blood cells in the immune system, adapt themselves to detect different intruders in your body?

3. How do complement proteins act like a swarm of self-assembling nano-robots?

ENGINEERING AND EXPERIMENTAL DESIGN

Discussion questions:

1. What improvements would you like to see made to the origami robot research?

Extension prompts:

2. What are some possible extensions and applications you can think of for remote-controlled magnetic manipulation?

3. What are some possible extensions and applications you can think of for the origami materials?

4. What are some possible extensions and applications you can think of for such robot research?

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Activity Guide for Teachers: Solo for Solenoid

Purpose: To gain a better understanding of how solenoids work and to explore the uses of solenoids.

Procedural overview: Students construct their own simple solenoids and conduct experiments to measure the solenoids' properties.

Approximate class time: 30-50 minutes.

Materials:

- Activity Guide for Students: Solo for Solenoid
- Copper wire
- Wire cutters
- Empty toilet paper tubes
- Empty paper towel tubes
- Empty kitchen spice bottles
- Large glass or plastic test tubes
- Small corks that will freely slide inside the test tubes
- Small steel or iron nails
- Magnetic compasses small enough to fit inside the tubes/bottles
- Bar magnets small enough to fit inside the tubes/bottles
- Other strong magnets of assorted shapes and sizes
- Steel rods that can fit inside the tubes/bottles
- Voltmeter (electrical multimeter)
- 1.5 volt batteries (any size, AA to D) and holders for them
- Paper clips
- Meter sticks
- Water

Notes to the teacher:

Note that the research in this week's article, "Origami outfits help bots retool," could be implemented with the resources that a high school student can find — a metal cube, heat-shrink material, a remote control provided by moving around magnet solenoids and a heating pad under the table. Encourage your students to pursue a research idea even if they do not immediately have access to professional laboratories.

Some good sources for small magnetic compasses, magnets, battery holders and electrical multimeters are: Home Science Tools, American Science and Surplus and Educational Innovations.

Students can work in small groups and each group should have an identical set of supplies. Encourage students to be creative with their own designs — there is no one right way to build or use a solenoid!

Procedure and questions for students, with possible answers:

1. Make a solenoid: Cut a piece of wire 1 meter in length and strip the insulation off the ends. Wrap the wire around a paper, glass or plastic tube, with all the loops of wire going the same way around the tube. What is the diameter of the tube and the number of loops in the coil around the tube? You can keep the solenoid coil on the tube, or pull it off if it will keep its shape.

Answers will vary.

2. Hold a small magnetic compass level. Which way is north? Put the compass a short distance inside the wire-wrapped tube and keep the compass level. Does the direction of the compass needle change or stay the same?

The compass should still point to north inside the tube.

3. Connect the ends of the solenoid wire to one 1.5-volt battery. What happens to the compass needle? Which way does it point? What does that tell you? Which direction can you point the solenoid to make the change as large as possible? Disconnect the battery after a few seconds or it will start to overheat.

If the solenoid is oriented perpendicular to north, the compass needle will point to north when the battery is disconnected, and point away from north one way down the length of the solenoid when the battery is connected. That demonstrates that current flowing through the solenoid coil creates a magnetic field inside the coil pointing in one direction.

4. Connect the ends of the solenoid wire to one 1.5-volt battery in the opposite direction. What happens to the compass needle? Which way does it point? What does that tell you? Disconnect the battery after a few seconds or it will start to overheat.

When the battery is reversed, the compass needle should point the opposite direction down the length of the solenoid. That demonstrates that current flowing in the opposite direction through the solenoid coil creates a magnetic field inside the coil pointing in the opposite direction.

5. When the solenoid is on, use the same or a similar compass inside the solenoid coil versus in various positions outside the coil. What do you learn about the strength of the magnetic field? Disconnect the battery after a few seconds or it will start to overheat.

The magnetic field is strongest inside the coil, and outside the coil it gets rapidly weaker as you get farther from the coil in any direction.

6. Try connecting two or more batteries to the solenoid. Try batteries in series or in parallel. Check the magnetic field strength at various positions inside and outside the solenoid, and notice how much the compass needle deflects in each case. What do you learn? Remember to disconnect the batteries after a few seconds.

Increasing the current flowing through the coil, especially by using batteries in parallel, should increase the magnetic field strength.

7. Make an identical solenoid but use a much longer piece of wire. How long is the wire and how many loops does it make around the tube? Using a magnetic compass, what do you notice about the effect of the number of loops on magnetic field strength?

The more loops there are, the stronger the magnetic field strength should be.

8. Make a similar solenoid but use a tube with a smaller diameter, and the same number of coils as in one of your previous solenoids. What is the tube diameter and how many loops are around the tube? Using a magnetic compass, what do you notice about the effect of the tube diameter on magnetic field strength?

For the same number of loops, the smaller the diameter, the stronger the magnetic field strength should be (inside and close to the ends of the solenoid).

9. Especially for the smaller diameter solenoid, what happens to the magnetic field strength if you put a steel rod through the center of the solenoid?

Iron in the steel rod should help to concentrate the magnetic field, creating an electromagnet.

10. Connect a straight piece of wire to a battery for a few seconds and then disconnect it. Now connect a solenoid to the battery for a few seconds and then disconnect it. Which case creates a larger spark when you disconnect from the battery?

The solenoid should create more of a spark than the straight wire, since so much energy is stored in the solenoid's magnetic field.

11. Connect a solenoid to a multimeter or voltmeter instead of a battery. How much voltage does the solenoid have? How much current?

The solenoid should have zero voltage and zero current.

12. With the solenoid still connected to a multimeter or voltmeter, pass a bar magnet back and forth through the coil very quickly. What happens to the voltage and current on the meter?

The voltage and current readings should show fluctuations when the magnet is moving.

13. Can you use a solenoid to make a nearby object (other than a compass needle) move when the solenoid is connected or disconnected from a battery? The stronger you can make the solenoid, the better for this purpose.

A small but strong magnet or a paper clip near the end of the solenoid may move when the solenoid is turned on or off.

14. Can you make a solenoid coil move when the solenoid is connected or disconnected from a battery? Make the solenoid as light as possible by removing the cardboard/glass/plastic tube and just keeping the coiled wire shape.

If a strong magnet is held fixed near the end of the solenoid coil, the solenoid coil may flex toward or away from the magnet when it is turned on or off.

15. Fill a test tube most of the way with water. Stick a steel or iron nail through a small cork, and let it float freely on top of the water inside the test tube. Wrap the test tube with as many loops as possible to make a solenoid. What happens when you connect the solenoid to a battery, and then disconnect it?

If the solenoid is strong enough, turning it on can pull the floating nail and cork downward in the water toward the center of the coil. Turning it off lets the nail and cork bob back up to the top of the water.

16. What have you learned about how solenoids create magnetic fields?

The magnetic field runs down the length of the solenoid inside the coil, is strongest at the solenoid's center and weaker outside. The direction of the magnetic field depends on the direction current runs through the solenoid from the connected battery. Larger currents, more wire loops and smaller solenoid diameters create stronger magnetic fields.

17. What have you learned about how solenoids can be used to control motion?

Students have used several configurations of solenoids to cause motion of the solenoid or a nearby object. When the solenoid is turned on, it produces a magnetic field, and if a magnetic object is close, it will interact with the magnetic field produced by the solenoid.

18. Now that you know more about the properties of solenoids, what are some of their applications?

Solenoids can produce quick and powerful linear motion and are used in inductors, electromagnets and antennas. Some applications include power car locks and other simple locking devices, medical clamping equipment, dishwasher cycle switch mechanisms and air conditioning units.

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Activity Guide for Students: Solo for Solenoid

Purpose: To gain a better understanding of how solenoids work and to explore the uses of solenoids.

Procedural overview: Construct your own simple solenoids and conduct experiments to measure their properties.

Procedure and questions:

1. Make a solenoid: Cut a piece of wire 1 meter in length and strip the insulation off the ends. Wrap the wire around a paper, glass or plastic tube, with all the loops of wire going the same way around the tube. What is the diameter of the tube and the number of loops in the coil around the tube? You can keep the solenoid coil on the tube, or pull it off if it will keep its shape.

2. Hold a small magnetic compass level. Which way is north? Put the compass a short distance inside the wire-wrapped tube and keep the compass level. Does its direction change or stay the same?

3. Connect the ends of the solenoid wire to one 1.5-volt battery. What happens to the compass needle? Which way does it point? What does that tell you? Which direction can you point the solenoid to make the change as large as possible? Disconnect the battery after a few seconds or it will start to overheat.

4. Connect the ends of the solenoid wire to one 1.5-volt battery in the opposite direction. What happens to the compass needle? Which way does it point? What does that tell you? Disconnect the battery after a few seconds or it will start to overheat.

5. When the solenoid is on, use the same or a similar compass inside the solenoid coil versus in various positions outside the coil. What do you learn about the strength of the magnetic field? Disconnect the battery after a few seconds or it will start to overheat.

6. Try connecting two or more batteries to the solenoid. Try batteries in series or in parallel. Check the magnetic field strength at various positions inside and outside the solenoid, and notice how much the compass needle deflects in each case. What do you learn? Remember to disconnect the batteries after a few seconds.

7. Make an identical solenoid but use a much longer piece of wire. How long is the wire and how many loops does it make around the tube? Using a magnetic compass, what do you notice about the effect of the number of loops on magnetic field strength?

8. Make a similar solenoid but use a tube with a smaller diameter, and the same number of coils as in one of your previous solenoids. What is the tube diameter and how many loops are around the tube? Using a magnetic compass, what do you notice about the effect of the tube diameter on magnetic field strength?

9. Especially for the smaller diameter solenoid, what happens to the magnetic field strength if you put a steel rod through the center of the solenoid?

10. Connect a straight piece of wire to a battery for a few seconds and then disconnect it. Now connect a solenoid to the battery for a few seconds and then disconnect it. Which case creates a larger spark when you disconnect from the battery?

11. Connect a solenoid to a multimeter or voltmeter instead of a battery. How much voltage does the solenoid have? How much current?

12. With the solenoid still connected to a multimeter or voltmeter, pass a bar magnet back and forth through the coil very quickly. What happens to the voltage and current on the meter?

13. Can you use a solenoid to make a nearby object (other than a compass needle) move when the solenoid is connected or disconnected from a battery? The stronger you can make the solenoid, the better for this purpose.

14. Can you make a solenoid coil move when the solenoid is connected or disconnected from a battery? Make the solenoid as light as possible by removing the cardboard/glass/plastic tube and just keeping the coiled wire shape.

15. Fill a test tube most of the way with water. Stick a steel or iron nail through a small cork, and let it float freely on top of the water inside the test tube. Wrap the test tube with as many loops as possible to make a solenoid. What happens when you connect the solenoid to a battery, and then disconnect it?

16. What have you learned about how solenoids create magnetic fields?

17. What have you learned about how solenoids can be used to control motion?

18. Now that you know more about the properties of solenoids, what are some of their applications?

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