Science News
IN HIGH SCHOOLS | EDUCATOR GUIDE

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Charging the Future

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Charging the Future

About this Issue

The article "Charging the future" describes the current scientific and technological pursuit for better batteries. Researchers are trying to develop long-lasting batteries that would have advantages over existing types of batteries, such as lithium-ion batteries that are currently used in most rechargeable electronic devices. After an introduction about the growing need for a longer-lasting, highly energy-efficient battery, a development that could lead to less dependence on fossil fuels, the article explains the general chemistry behind how batteries work. The article then discusses several different types of new batteries under development, how they function and the components researchers are striving to improve. Students can focus on the science of batteries, follow connections to earlier articles about battery research, explore the cross-curricular connections of battery technology and conduct their own experiments making batteries and measuring their performance. For additional information about batteries written at slightly lower Lexile levels, see the following *Science News for Students* articles: "Building a better battery," "This battery stretches without losing oomph," "Nanowires could lead to super-long-lived battery" and "Powered by poop and pee?" Also, *Science News for Students* offers an "Explainer" about Batteries and Capacitors.

Connections to Curricula

- Quantitative observations
- Reduction-oxidation (redox) reactions
- Electrochemistry
- Electric circuits
- Cellular respiration
- Photosynthesis
- Batteries
- Alternative energy sources

What's in this Guide?

- **Article-Based Observation:** These questions focus on reading and content comprehension by drawing on information found in the article "Charging the future." Questions focus on battery design, the mechanism and performance of lithium-ion batteries in comparison to new types of batteries and the nature of experimental design and modification.
- **Quest Through the Archives:** With Internet access and your school's digital access to *Science News*, your students can use this section to explore the history of battery research as reported by *Science News*.
- **Cross-Curricular Discussion:** These questions and extension prompts encourage students to think about ways that different elements create varied results in battery design and related redox reactions. The section is divided by subdiscipline for educators who would like to focus on a particular topic area. The extension prompts are either more topic-specific or more conceptually advanced. **Biological Sciences** questions involve biologically relevant reduction-oxidation (redox) reactions in respiration and photosynthesis and the energy production associated with these processes. **Chemistry and Physical Sciences** questions concern redox reactions, electrochemistry and electric voltage and current. **Engineering and Experimental Design** questions focus on designs, characteristics and applications of batteries.

- Activities: This section includes one teacher-led demonstration and two activities that students can perform. **Reduction-Oxidation Reaction Demonstration** is a straightforward introduction to reduction-oxidation reactions. **What Makes Different Type of Batteries Unique?** asks students to research specific battery types from "Charging the future" or other resources and report what they have found. **Building the Best Battery** allows students to build, test and optimize their own batteries using various metal electrodes and liquid electrolytes.

Standards Alignment

Next Generation Science	Common Core
Matter and Its Interactions: HS-PS1-1, HS-PS1-2, HS-PS1-3, HS-PS1-4	ELA Standards: Reading Informational Text (RI): 1, 2, 4, 7
Energy: HS-PS3-1, HS-PS3-3	ELA Standards: Writing (W): 1, 2, 4, 6, 7, 8, 9, 10
From Molecules to Organisms: Structures and Processes: HS-LS1-5, HS-LS1-7	ELA Standards: Speaking and Listening (SL): 1, 2, 3, 4, 5, 6
Engineering Design: HS-ETS1-3	ELA Standards: Reading for Literacy in Science and Technical Subjects (RST): 1, 2, 3, 4, 7, 9
	ELA Standards: Writing Literacy in History/Social Studies and Science and Technical Subjects (WHST): 1, 2, 4, 6, 7, 8, 9

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Article-Based Observation

Directions: After reading the article "Charging the future," answer these questions:

1. **According to materials scientist George Crabtree, how did the lithium-ion battery transform personal electronics?**

2. **What are current and potential future applications of batteries? Describe an environmental benefit to a future application.**

3. **How does a battery produce electricity? How does a battery recharge?**

4. **What is the best existing battery type, according to the article, and what is an advantage and disadvantage of it?**

5. **How do lithium-sulfur batteries work, and what are their potential applications, advantages and disadvantages? What are researchers doing to develop and improve them?**

6. **How do magnesium-ion batteries compare with lithium-ion batteries? What is a current drawback?**

7. **How do flow batteries work, and what are their potential applications, advantages and disadvantages? What are researchers doing to develop and improve them?**

8. **If you had 15 seconds to summarize this article to a classmate, what would you say?**

Responses to Article-Based Observation

1. **According to materials scientist George Crabtree, how did the lithium-ion battery transform personal electronics?** Possible student response: Cell phones became commonplace, making landline telephones less common for many people. Cell phones also made the internet, photography and even video recording readily accessible.

2. **What are current and potential future applications of batteries? Describe an environmental benefit to a future application.** Possible student response: Smartphones, tablets, laptops, cameras, video recorders, clocks, smoke alarms, electric cars, electric airplanes and storing energy for the power grid are all current or potential applications of batteries. With better batteries that deliver more energy and last longer, the grid could run on greener fuels, such as sunlight, because energy could be stored and used on cloudy days.

3. **How does a battery produce electricity? How does a battery recharge?** Possible student response: A chemical reaction in a battery produces an external flow of electrons (electricity) that can be used to power a device. Batteries have three main components: a negative anode, a positive cathode and an electrolyte. Oxidation reactions occur at the anode and release electrons to the cathode where the reduction reactions takes place. The electrolyte passes the ions created by these reactions back and forth to complete the circuit. Batteries are recharged by supplying a current that forces the electrons to flow in the opposite direction. Essentially the chemical reaction occurs in reverse.

4. **What is the best existing battery type, according to the article, and what is an advantage and disadvantage of it?** Possible student response: Today's lithium-ion batteries have a graphite anode containing loose lithium atoms, an electrolyte and a cathode. Lithium-ion batteries can store at least twice as much energy as previous battery technologies and thus have become widely used in modern devices. However, they are not practical for storing and releasing enough energy to compete directly with gasoline in vehicles, and they drain too quickly to be useful for the electric power grid.

5. **How do lithium-sulfur batteries work, and what are their potential applications, advantages and disadvantages? What are researchers doing to develop and improve them?** Possible student response: Lithium-sulfur batteries have a lithium metal anode, a mainly sulfur cathode and a liquid electrolyte. They could be useful for electric cars and electronic devices. Sulfur can bond to twice as many lithium ions as existing cathodes and is much lighter, so a lithium-sulfur battery might store four or five times as much energy per mass as a lithium-ion battery. Unfortunately, the lithium and sulfur can form unwanted polysulfide compounds that gum up the inside of the battery after a few dozen cycles of discharging and recharging the battery. To minimize that problem, researchers are

improving the electrolyte composition and amount, as well as using membranes or nanotubes to protect the anode and/or cathode.

6. **How do magnesium-ion batteries compare with lithium-ion batteries? What is a current drawback?** Possible student response: Magnesium-ion batteries are similar to lithium-ion batteries but use magnesium instead of lithium. Magnesium ions have twice the electric charge of lithium ions, so this substitution should allow the batteries to produce twice as much electrical current. They could be useful for electric cars and electronic devices. Presently, the charged magnesium ions travel too slowly through the electrolyte (thereby limiting the electric current flow), but researchers are trying to improve the electrolyte.

7. **How do flow batteries work, and what are their potential applications, advantages and disadvantages? What are researchers doing to develop and improve them?** Possible student response: Flow batteries have two tanks of liquid (one positively charged and one negatively charged) that are separated by a membrane. A flow battery "seesaws," allowing electrochemically active material to flow and create a current. Adjusting the angle can speed up or stop the flow. Because the tanks can be scaled up, flow batteries can store large amounts of energy, making them especially useful for electric cars and the power grid. Researchers are trying to simplify the mechanical design of flow batteries to eliminate pumps and other complex components. Yet-Ming Chiang of MIT and his team are working on an hourglass concept to this end. Another group is working on a way to replace expensive and toxic materials such as vanadium with better choices such as sulfur, and optimize the battery liquids and/or membranes to prevent unwanted leaks between the tanks.

8. **If you had 15 seconds to summarize this article to a classmate, what would you say?** Possible student response: Researchers are trying to develop batteries that would store more energy, last longer, be cheaper, safer and/or easier to recharge than existing lithium-ion batteries.

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Quest Through the Archives

Directions: After reading the article "Charging the future," use the archives at www.sciencenews.org to answer these questions:

1. **Search for an article discussing unusual materials that might be used to make batteries. Explain how the material could be beneficial in a battery.**

2. **Find an article that discusses the revamping of an early battery technology. Explain it.**

3. **Find an article that talks about alternatives to batteries for powering personal electronic devices. Describe what you find.**

Responses to Quest Through the Archives

1. **Search for an article discussing unusual materials that might be used to make batteries. Explain how the material could be beneficial in a battery.** Possible student response: https://www.sciencenews.org/article/idea-new-battery-material-isn't-nuts. In 2015, an article discussed the use of packing material peanuts to enhance the charging and discharging performance of a lithium-ion battery. Carbon-containing packing peanuts were baked and compressed into microsheets, which were then placed into the battery's anode.

2. **Find an article that discusses the revamping of an early battery technology. Explain it.** Possible student response: https://www.sciencenews.org/article/old-battery-gets-high-tech-makeover. This 2012 article discusses the redesign of Edison's nickel-iron battery, which was originally patented in 1901.

3. **Find an article that talks about alternatives to batteries for powering personal electronic devices. Describe what you find.** Possible student response: https://www.sciencenews.org/article/double-charging-material-makes-run-sun-extra-powerful. This 2016 article discusses a lightweight material that can capture and store solar as well as mechanical energy in a supercapacitor to power personal electronic devices.

Cross-Curricular Discussion

After students have had a chance to review the article "Charging the future," lead a classroom discussion based on the questions that follow. From the question bank, you can copy and paste only the questions that apply to your classroom out into a different document for your students. Before starting the discussion, you may want to supplement their introduction to batteries with one or more of the following videos listed below. Also, the first activity is a simple reduction-oxidation reaction demonstration that might be useful for student understanding.

Possible video resources

- A TED-Ed video titled "How batteries work" by Adam Jacobson. This video is approximately four minutes and shows an animated history of batteries.
- A CNBC video posted at the Joint Center for Energy Storage Research (JCESR) about the life-changing potential of advanced energy storage.
- A LiveScience video that gives a quick introduction to flow batteries.

CHEMISTRY AND PHYSICAL SCIENCES

Discussion Questions:

1. What is an oxidation reaction? What is a reduction reaction? [*Oxidation: an atom or group of atoms loses one or more electrons. Reduction: an atom or group of atoms gains one or more electrons.*]
2. What determines which atoms or groups get oxidized, and which get reduced? [*Order in list of standard reduction potentials.*]
3. What is a battery? Using the diagram on the second page of "Charging the future," define the major parts of a battery and explain their importance. [*Show the students a diagram with labeled anode (where oxidation occurs), cathode (where reduction occurs), electrolyte (helps ions move within the battery so electrons will continue to flow from the anode to the cathode) and electrons flowing through an external circuit. Point out that electrodes are conductors through which the electrons enter or exit the battery. Show students a diagram of a typical electrochemical cell and explain that the anode and cathode must be separated and that the electrolyte is contained in the salt bridge.*]
4. What is voltage and how do you determine the voltage of a battery? [*Voltage: the potential difference in charge between the anode and cathode (as determined by how badly electrons want to go someplace). It's measured in volts, where one electron with one volt of potential energy has approximately* 1.6×10^{-19} *Joules of potential energy. Battery voltage: determined by the difference between reduction potentials (show students a reduction potential table) at the anode and cathode, the number of identical cells put in series to make a large battery and so on.*]

5. Using your knowledge of atomic reactivity based on an atom's location on the periodic table, which atom would you expect to have the largest reduction potential? Looking at a common reduction potential table, what combination of elements would you use in a battery? Why? [*Largest reduction potential: fluorine, because it is the most electronegative element (located in the upper right corner of the periodic table). Student element combinations will vary, but they may choose fluorine (easily reduced) and lithium (easily oxidized) to get a large overall cell potential.*]

Extension Prompts:

6. What is electric current? [*Essentially how many electrons (or other charges) per second are going someplace, measured in amps, where 1 amp ≈ 6.2×10^{18} electrons/second.*]
7. What is electroplating? What are some applications of electroplating? [*Electroplating: using electrochemical reactions to coat one metal with a thin layer of another metal, generally by putting electrical energy into a system. It's very much like operating a battery in reverse. Applications: depositing thin layers of silver or gold on jewelry, coating electrical connectors with gold, zinc-plating iron or steel hardware.*]
8. What is electrolysis? What are some applications of electrolysis? [*Electrolysis: putting electric current into a liquid to decompose molecules in the liquid into their components at the electrodes, such as electrolysis to split water molecules into hydrogen and oxygen gases. Applications: production of hydrogen and oxygen by the electrolysis of water, production of pure chlorine, aluminum and other elements by electrolysis of liquid or molten solutions containing them.*]
9. What is corrosion? How can corrosion be minimized? [*Corrosion: oxidation of a metal, usually forming a metal oxide, such as iron oxide (rust). Corrosion can be limited by minimizing salt buildup on metal car parts to prevent electrochemical reactions when wet, minimizing contact between dissimilar metals in the dishwasher, putting a "sacrificial anode" of a less noble metal such as magnesium, zinc or aluminum on ship hulls or pipelines to prevent rusting of iron in the main structure, zinc-coated ("galvanized") iron or steel hardware to prevent rusting of the iron, coating electrical connectors with gold and so on.*]

Chemistry and Physical Sciences Question Bank:

What is an oxidation reaction? What is a reduction reaction?

What factors determine which atoms or groups get oxidized, and which get reduced?

What is a battery? Using the diagram on the second page of "Charging the future," define the major parts of a battery and explain their importance.

What is voltage and how do you determine the voltage of a battery?

Using your knowledge of atomic reactivity based on an atom's location on the periodic table, which atom would you expect to have the largest reduction potential?

What is electric current?

What is electroplating? What are some applications of electroplating?

What is electrolysis? What are some applications of electrolysis?

What is corrosion? How can corrosion be minimized?

BIOLOGICAL SCIENCES

Discussion Questions:

1. How do your cells extract energy from the food you eat? How are the reactions involved similar to those in a battery? [*Students may discuss the set of metabolic reactions and processes involved in cellular respiration. Similar to a battery, redox reactions occur throughout these processes. During cellular respiration, electrons are transported through carrier molecules until the energy of the reactions is used to drive ATP synthesis.*]

2. The article discussed how batteries work by converting chemical energy into electrical energy to power a device. How does your body store energy (in what forms) and how is it converted to energy during exercise? How can you relate the process of storing and using energy in the body to a battery? [*Energy is stored as carbohydrates (short-term storage) or fat (long-term storage). Students might discuss how through the processes of aerobic/anaerobic respiration, the body creates ATP which is used by the muscles to contract. Carbs/fats are converted into ATP to power our muscles, just as the chemical energy in batteries is converted to electrical energy to power devices.*]

Extension Prompts:

3. How do NADH, NADPH and $FADH_2$ accept or donate electrons in biological redox reactions? [*Show the students images of NADH, NADPH and $FADH_2$ losing or gaining electrons and protons from Campbell Biology or other references.*]

4. What specific roles do redox reactions play in respiration in cellular mitochondria? [*Show the students images from Campbell Biology or other references.*]

5. What roles do redox reactions play in photosynthesis in plant chloroplasts? [*Show the students images from Campbell Biology or other references.*]

6. How can redox reactions be used to quantitatively measure concentrations of compounds such as ascorbic acid (vitamin C)? [*Since there are many acids and bases in food, acid/base titration reactions cannot often be used to measure the amount of ascorbic acid in food. A redox reaction can be used where ascorbic acid is oxidized and 2,6-dichloroindophenol is reduced. See the related lab activity from the University of California, Santa Cruz here*.]

Biological Sciences Question Bank:

How do your cells extract energy from the food you eat? How are the reactions involved similar to a battery?

The article discussed how batteries work by converting chemical energy into electrical energy to power a device. How does your body store energy (in what forms) and how is it converted to energy during exercise? How can you relate the process of storing and using energy in the body to a battery?

How do NADH, NADPH and $FADH_2$ accept or donate electrons in biological redox reactions?

What specific roles do redox reactions play in respiration in cellular mitochondria?

What roles do redox reactions play in photosynthesis in plant chloroplasts?

How can redox reactions be used to quantitatively measure concentrations of compounds such as ascorbic acid (vitamin C)?

ENGINEERING AND EXPERIMENTAL DESIGN

Discussion Questions:

1. How many different types of batteries and their applications can students think of? [*Non-rechargeable alkaline batteries in small electronic devices; rechargeable Ni-Cd batteries in household tools; lithium-ion batteries in personal electronic devices, computers and household tools; lead-acid batteries in cars and so on.*]
2. How does gravity play a role in the design of a flow battery? How might a flow battery work on another planet with a gravitational pull that is greater or less than that of Earth? [*Students also may pick a planet, research, then draw a model of a flow battery on that planet.*]

Extension Prompts:

3. What are desirable characteristics for a battery for portable electronic devices? [*Very small mass, very small volume, high energy density, low heat output, very large number of recharging cycles, very impact-resistant, does not explode during airline flights, etc.*]
4. What are desirable characteristics for a battery for electric cars? [*Very high energy density, very impact-resistant, rapid recharging, etc.*]
5. What are desirable characteristics for a battery for electric power grid storage? [*Very large capacity, storage times of many days or weeks, widely variable discharge rate depending on the needs, etc.*]
6. How would an engineer consider desired battery characteristics to determine the basis for new battery designs? Discuss engineering design and how essential characteristics drive a product's design. What other considerations affect design decisions?
7. Using Blackline Master 3, examine the table of battery types from "Charging the future." If funding were not an issue, what type of battery would you choose to power a device that you use regularly? Name the device and explain your reasoning.

Engineering Question Bank:

How many different types of batteries and their applications can students think of?

How does gravity play a role in the design of a flow battery? How might a flow battery work on another planet with a gravitational pull that is greater or less than that of Earth?

What are desirable characteristics for a battery for portable electronic devices?

What are desirable characteristics for a battery for electric cars?

What are desirable characteristics for a battery for electric power grid storage?

How would an engineer consider desired battery characteristics to determine the basis for new battery designs? Discuss engineering design and how essential characteristics drive a product's design. What other considerations affect design decisions?

Using Blackline Master 3, examine the table of battery types from "Charging the future." If funding were not an issue, what type of battery would you choose to power a device that you use regularly? Name the device and explain your reasoning.

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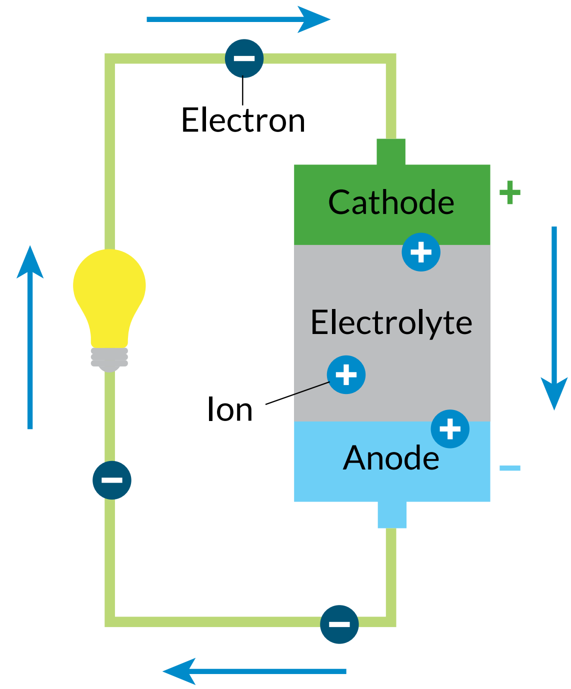
Cross-Curricular Discussion

Directions: Use the diagram and chart below from "Charging the future" to answer the related discussion questions assigned by your teacher.



Battery	How it works	What it's used for	Advantages	Obstacles
Lithium-sulfur	Lithium ions from the anode react with sulfur held in the cathode to produce electric current	Cars, cell phones, laptops	Sulfur is cheap and very light, good for packing more capacity into a lighter package	Current versions have short lifetimes and the electrolyte needs work — it tends to dissolve the cathode and react with the anode
Magnesium-ion	Similar to lithium-ion batteries, but magnesium ions do the work	Cars, cell phones, laptops	Magnesium, more plentiful than lithium, provides two electrons (vs. lithium's one) so it could provide twice as much juice	Chemistry not well understood yet; batteries have short lives
Flow batteries	Two tanks of liquid, one positively charged and one negative, are separated by a membrane. Where they meet, the ions react, generating electrons	Cars, grid, backup power	Separating the two parts of the battery makes it easier to design batteries with maximum power or lighter weight; some new designs eliminate pumps and use gravity to adjust speed of energy flow	Current versions can't hold as much energy as lithium-ion; when pumps are used, maintenance remains a problem
Lithium-air	Oxygen molecules from the air react with lithium ions in the anode to release energy. Recharging forces out the oxygen atoms, and the lithium is ready to start again	Cars	Could make a very light battery	Finding electrolytes that don't react with other components is a challenge; batteries have very short life span and may need extra safety engineering
Sodium-sulfur	A molten sodium core exchanges ions with sulfur through a solid electrolyte barrier	Large-scale energy storage (holding power generated from wind or solar)	Materials are cheap and abundant; fairly long lifetime	Must operate at high temperatures, so not possible to use in a car

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Reduction-Oxidation Reaction Demonstration

Class time: About 15 to 20 minutes.

Purpose: This is a simple demonstration for introducing reduction-oxidation (redox) reactions.

Notes to the teacher: Please handle and dispose of copper(II) sulfate solution in accordance with federal, state and local environmental control regulations.

Materials:

- Copper(II) sulfate (available from chemical supply companies — sold as a hydrate, or sold as root killer at hardware stores)
- A large steel or iron nail/screw/bolt (or more than one if you want)
- A beaker or clear plastic cup
- A stirring rod

Directions:

1. Fill the beaker with hot water, pour in a few grams of copper(II) sulfate and stir until it dissolves. Show the students that the blue crystals of copper sulfate turn the water blue (due to Cu^{2+}). Show the students the steel (iron alloy) or iron nail, then put it in the beaker. After a few minutes, pull out the nail and show it to the students. The nail should be coated with a thin layer of reddish-bronze copper atoms, which can be easily scraped off with a paper towel. If you use more than one nail, or have a dilute enough copper(II) sulfate solution, your students may be able to notice that the blue solution gets lighter in color due to the decreasing concentration of Cu^{2+} ions.

2. Explain that the copper starts off in the solution as ions with two positive charges (having donated two electrons to sulfate), and the iron starts off as a solid composed of neutral iron atoms with the same number of protons as electrons in each atom. Since the copper has a greater affinity for electrons than the iron does, the iron loses two electrons and gets dissolved into solution. Each Cu^{2+} ion gains two electrons and becomes a solid where the iron had been. In chemistry notation, the reactions are:

   Oxidation: $Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2\ e^-$

   Reduction: $Cu^{2+}_{(aq)} + 2\ e^- \rightarrow Cu_{(s)}$

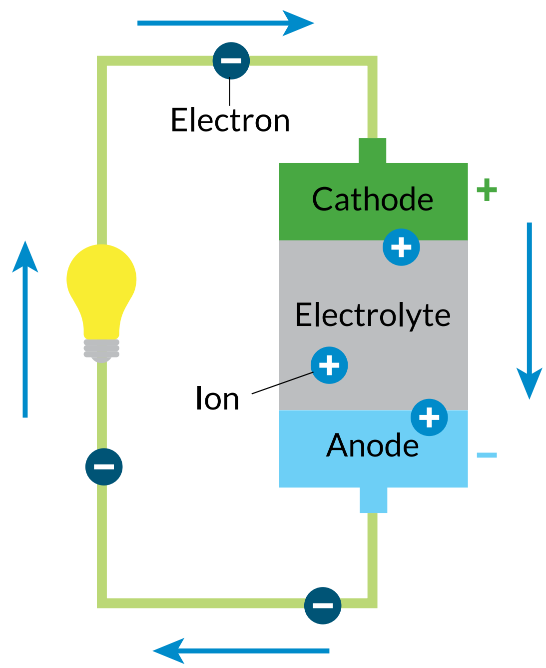
   Net reaction: $Fe_{(s)} + Cu^{2+}_{(aq)} \rightarrow Fe^{2+}_{(aq)} + Cu_{(s)}$

   The sulfate and the water were innocent bystanders in this reaction and did not directly participate. Explain that the ions, such as sulfate (SO_4^{2-}), are called spectator ions.

3. Explain that this is just one example of an oxidation and reduction reaction, but there are many others. Reduction and oxidation reactions are a mouthful to say and always occur together (electrons have to come from someplace and go to someplace), so they are called "redox reactions" for short. Also, it is important to note that the number of electrons lost in a reaction must be equal to

the number of electrons gained, so the chemical equation may need to be balanced. To remember the difference between oxidation and reduction reactions, use the mnemonic **OIL RIG**: **O**xidation **I**s **L**oss of electrons, **R**eduction **I**s **G**ain of electrons.

4. Copper wanted electrons more than iron did in this demonstration. Scientists can make a list of atoms or molecular groups in order from those that are least determined to hang on to their electrons (or in other words, those most likely to be oxidized) to those most determined to keep their electrons (or in other words, those most likely to be reduced). This difference in affinity for electrons may be expressed in terms of volts of electric potential energy, or the standard reduction potential of each material. Show an example of your favorite reduction potential table such as this one given by California State University at Dominguez Hills.



5. Using the diagram above, which also appears on Blackline Master 3, explain that a battery is a device that converts the chemical energy of a redox reaction to usable electrical energy. A battery has an anode made of one material, a cathode made of another material, an electrolyte allowing ion flow between the anode and cathode and an external electrical circuit allowing electron flow between the anode and cathode. Ignoring real-world inefficiencies and imperfections, the voltage of the battery is the difference in the standard reduction potentials of the anode and cathode materials. You may want to demonstrate calculating the difference in reduction potentials from the demonstration materials. A Khan Academy video gives a brief summary of how to calculate the overall redox reaction potentials under standard conditions from a standard reduction potential table.

Teacher Guide: What Makes Different Types of Batteries Unique?

Class time: One or two class periods plus homework

Purpose: Different student groups find and report information about different battery types

Notes to the teacher: You can adapt this activity to your preferences by including more or fewer battery types, setting the number of students per battery type, providing specific references for the students or encouraging them to do more independent research, choosing how extensive the students' research and reporting should be, and selecting how the students report their findings (public service announcement, written paper, graphical poster, oral presentation in class, computer slide presentation, etc.).

Use Blackline Master 4 to help guide your students through the battery research and summary.

Materials:

- List of battery types to research
- Books or websites for students to research battery types
- Materials for students to create posters, papers or presentations

Directions:

1. Assign different battery types to different students or groups of students. Battery types could include:
   a. Carbon-zinc batteries (older non-rechargeable batteries)
   b. Alkaline batteries (newer non-rechargeable batteries)
   c. Lead-acid batteries
   d. Nickel-cadmium batteries
   e. Lithium-ion batteries
   f. Lithium-sulfur batteries
   g. Magnesium-ion batteries
   h. Flow batteries
   i. Lithium-air batteries
   j. Sodium-sulfur batteries
   k. Hydrogen-oxygen fuel cells (similar to batteries)
2. Give students Blackline Master 4 , which lists the information they should find for their battery types.
3. Direct students to specific references for battery information, or let them do more open-ended self-directed research in the library or online. References include:
   - Online sources: Battery University and JCESR.
   - Carl H. Snyder, *The Extraordinary Chemistry of Ordinary Things*. 4th ed. New York: Wiley. 2002. Chapter 11.

- Theodore E. Brown *et al.*, *Chemistry: The Central Science*. 14th ed. New York: Pearson. 2017. Chapter 20.
- *Encyclopedia Britannica*
- Wikipedia articles on specific battery types might provide a starting point to look for links to more reputable source material.

4. Let the students report their findings in the format(s) of your/their choice.

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Student Guide: What Makes Different Types of Batteries Unique?

Directions: Your group should take ownership of one battery type. Using the resources recommended by your teacher, find the following information for your battery (elaborate in areas where a lot of information is accessible) and summarize your findings according to your teacher's instructions.

Please be sure to include the following information:

1. Type of battery
2. Is it a primary or secondary cell (one time use or rechargeable)?
3. What is the overall redox reaction?
4. What gets oxidized (oxidation half reaction) and what gets reduced (reduction half reaction)?
5. What is the common electrolyte/ionic compound (to neutralize charge buildup)?
6. What is the voltage per cell?
7. What is the overall battery voltage, and how many cells are required to produce that voltage?
8. What is the maximum energy density in Joules per kilogram (and/or milliliter) for this electrochemical reaction? For reference, how does that compare to the energy density in Joules per kilogram (and/or milliliter) for gasoline?
9. What are the advantages of this battery type, and what aspects of the electrochemistry and battery design give it those advantages?
10. What are the disadvantages of this battery type, and what aspects of the electrochemistry and battery design give it those disadvantages?
11. What are the major applications of this battery type, and what aspects of the electrochemistry and battery design make it suitable for those applications?
12. What are the environmental concerns for the use and/or for the disposal of your battery type?
13. What is the best method of disposal for your battery type? Can it be recycled and, if so, how?
14. When and where was this battery type first developed?
15. What characteristics of this battery type could be improved, and what changes in the electrochemistry or the battery design might yield those improvements?

Teacher Guide: Building the Best Battery

Class time: 40 to 65 minutes

Purpose: Students create, test and optimize batteries using various electrodes and electrolyte compositions.

Notes to the teacher: If you have more time, you can allow the students more design options and let them figure out more things themselves. If you have less time, you can allow the students fewer design options by giving more guidance. You can order electrodes such as these from Home Science Tools or buy materials made from or coated with suitable metals from Home Depot or similar stores. Ideally students should be able to find the configurations that produce the most voltage, and then use those to light a lightbulb. If your time is limited, you could have the students focus on either the voltage measurements or lighting the bulb. This activity would work well for pairs of students working together.

Use Blackline Master 5 to help guide your students through building their batteries.

Materials:

- Beakers or clear plastic cups (about 250 ml)
- Copper electrodes (or copper tubing or stripped copper wire)
- Zinc electrodes (or zinc or zinc-plated hardware)
- Iron or steel electrodes (or iron or steel hardware)
- Aluminum electrodes (or aluminum foil or strips cut from disposable aluminum pans)
- Vinegar (5% acetic acid, sold by the gallon at many grocery stores)
- Table salt (NaCl, not iodized)
- Optional: other ionic solids to use as electrolytes such as KCl or $NaNO_3$
- Scales or balances and weigh boats or weigh paper
- Graduated cylinders
- Water (distilled if you have it, otherwise tap water)
- Stirring rods
- Electric multimeter (inexpensive models are sold at Walmart or similar stores)
- 1.5 volt incandescent lightbulbs and sockets (see this example from Home Science Tools)
- Wires with alligator clips (see for example these from American Science & Surplus)
- Table of standard reduction potentials
- Goggles
- Gloves and other protective equipment such as aprons
- Paper towels
- Sandpaper or steel wool

Directions:

1. Have the students wear goggles and gloves (and other protective equipment such as aprons, if available).
2. Show the students how to use the table of standard reduction potentials to predict the voltage difference between two different electrode materials. A Khan Academy video gives a brief summary of how to calculate the overall redox reaction potentials under standard conditions from a standard reduction potential table.
3. Show the students how to use the multimeter to measure voltage. Remind students that the multimeter leads must be in direct contact with the battery electrodes in order for the circuit to be complete. Also, when the voltage is positive, the metal electrode connected to the red lead is considered the positive terminal of the battery (the cathode) and the metal electrode connected to the black lead is the negative terminal (the anode). If the voltage is negative, the student should reverse the leads so that the voltage is positive.
4. Ideally students should determine battery configurations that produce the most voltage, and then use those to light a lightbulb. But if time is limited, determine which variables they should focus on. Students can start with determining the largest possible voltage from different combinations of electrodes (theoretically and experimentally). Once the maximum voltage is determined, students can use this electrode combination to test other variables such as the type and/or concentration of the electrolyte (how much vinegar, salt, water is in solution), the approximate distance between electrodes and the number of cells (depending on available supplies). Students can ultimately test their battery with a lightbulb. If students are more advanced, have them calculate the molarity of their electrolyte solutions.

Note the following:

Tap water may have enough impurities to make a fairly good electrolyte by itself; distilled water is less conductive and would show the students the importance of adding ions to the electrolyte. Salt (especially about 1 to 2 g per 200 ml of water) makes the water function as a much better electrolyte. Vinegar has enough ions to serve as a good electrolyte. Vinegar plus salt can be even better.

The specific electrode combination chosen will have a large effect on the voltage, generally in the ballpark of the standard reduction potentials but with some variation due to the electrolyte. (Standard conditions for the reduction potential table are defined as 25 degrees Celsius, 1 atm for any gas participating in the reaction, and 1 M concentration for each ion participating in the reaction.) The electrolyte chosen will have a smaller but still significant effect on cell potential. The spacing between the electrodes may have a small but measurable effect, depending on the electrodes, electrolyte and volume.

Show the students that they can use the alligator clip leads to connect multiple batteries in series if necessary to light a lightbulb.

Charging the Future

Student Guide: Building the Best Battery

You can make a simple battery using a beaker or clear plastic cup partially filled with a liquid electrolyte, and with two different types of metal electrodes partially immersed in the electrolyte but not touching. You can connect the battery to a multimeter to measure voltage, or even to light a lightbulb. You can choose the electrode types, electrolyte composition, electrode spacing and other design details to optimize your results. Listen to your teacher for more specific instructions for your class.

1. Fill the beaker at least halfway with water. What is the approximate volume of water as shown on the beaker (or measure the amount of water with a graduated cylinder)?
2. Weigh out a small amount of salt between 1 and 2 grams and record the value. Stir it into the water in the beaker until it is fully dissolved. How much salt did you add?
3. Use sandpaper or steel wool to clean the electrodes before your experiment. Note how each electrode material looks before and after cleaning.
4. Using the chart below, write down the theoretically predicted voltage for each pair of electrodes using a standard reduction potential table (provided by your teacher). Note that the table is for standard cell conditions which are defined as 25 degrees Celsius, 1 atm for any gas participating in the reaction, and 1 M concentration for each ion participating in the reaction. Then put the pair of electrodes in the beaker (not touching each other) and use the multimeter to record the actual voltage between the electrodes. How much does that differ (in %) from your theoretical prediction? Make sure the distance between the electrodes remains approximately the same among all trials.

Electrode 1	Electrode 2	Theoretical voltage	Measured voltage	% difference
Copper	Copper			
Copper	Zinc			
Copper	Iron			
Copper	Aluminum			
Zinc	Zinc			
Zinc	Iron			
Zinc	Aluminum			
Iron	Iron			
Iron	Aluminum			
Aluminum	Aluminum			

5. What factors could account for differences between your measured voltages and the theoretically predicted voltages?

6. Closely observe the surfaces of the electrodes after you remove them from the electrolyte. What do you see? What caused what you see? After your experiments, be sure to dry the electrodes and then clean them with sandpaper or steel wool.

7. Can you improve the performance by adjusting the spacing between electrodes? Record your results.

8. Can you improve the performance by using a different electrolyte? Try larger or smaller amounts of salt, different mixtures of water and vinegar ranging from pure water to pure vinegar, etc. Refer to your teacher for more specific instructions. Record your results.

9. Can you light a lightbulb with your battery? If one battery cannot produce enough voltage, you can connect two or more batteries in series (the positive terminal of one battery to the negative terminal of the next battery). Record what setup works best.

10. Summarize your results. What conditions were optimal for creating a battery that produced the highest voltage?

11. Reflect on your experimental quest for making the best battery. What did you enjoy about it? What made it difficult? After reading "Charging the future," how do you think your experience compares to the challenges battery scientists face?