bacteria POWER

Pop quiz: Name three sources of electrical power.

By David C. Holzman

Before you read the title of this article, you may have thought of lightning, especially if you've already read the other articles in this issue. Perhaps you know that most of the electricity we use is produced in large generating plants from turbines powered either by burning a fossil fuel or using nuclear reactions. Or maybe you thought of a common battery that utilizes a chemical reaction to produce electricity. Perhaps you even thought of solar panels or windmills. You almost certainly never thought of bacteria. Bacteria!!!???

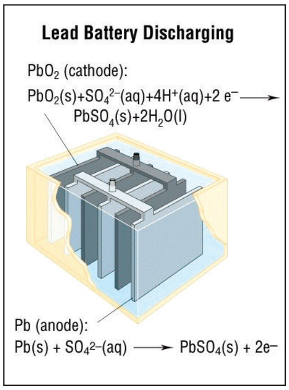
It may seem hard to believe that bacteria could produce electricity, yet some bacteria have managed to do just that. In Derek Lovley's laboratory at the University of Massachusetts *Geobacter sulfurreducens* displayed a talent that enabled them to produce tiny electrical currents. Don't get too excited. We're not about to use them to light up the skyline of a major American city, but Lovley thinks it may be possible to harness this power and use it to help bring electricity to remote locations.

The feedstock for these bacteria is decaying organic matter—the stuff of septic tanks.

You probably know that an electric current simply consists of electrons that are moving through or in a conductor. When we use electricity to power a motor or heat the filament of a light bulb, we don't actually "use up" any of these electrons. We just use some of their energy to do something we find useful.

Bacteria produce electricity in much the same way that a battery uses chemical reactions to produce electricity. Batteries have two poles, or terminals. Your textbook or teacher may have referred to these as electrodes. One is positive, and one is negative. Electricity flows from one terminal to the other. For example, when you start your car, turning the key connects the two terminals of the battery via an electrical pathway that goes through the starter motor's coils. Current–electrons immediately flow from the negative to the positive terminal. Here's how that works.

Like 60% of the batteries in the world, the car battery is what is called a lead acid battery. At each terminal, plates are bathed in sulfuric acid. The plates in the negative pole, which supply electrons for the current, are made of lead. The plates in the positive pole, which absorb the electrons, are made of lead oxide.



CHEMISTRY IN THE COMMUNITY © ACS

When the terminals are connected, at the negative pole the lead reacts with the sulfuric acid to produce lead sulfate and electrons.

$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

Those extra electrons make up the current that flows to the positive pole, where the following reaction takes place:

$$PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

The terminals of Lovley's bacterial fuel cells are two small slabs of graphite, a form of carbon, connected by a waterproof wire. "We use a slab of graphite typically one-fourth inch thick," says Lovley. One terminal is placed in the mud at the bottom of a body of water, where "the *Geobacter* are ubiquitous," Lovley says. The bacteria grow naturally on the surface, forming a highly stable colony called a biofilm, much like the colony that grows on your teeth when you forget to brush them. The other terminal is placed in the clear waters above.

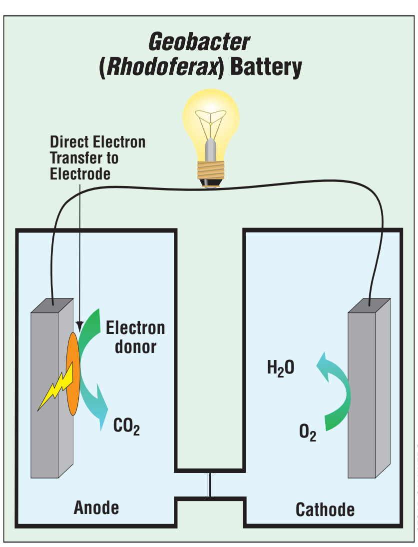
The bacteria on the anode, the negative terminal in the mud, feed off of decaying plant material. They oxidize acetate from the organic matter to carbon dioxide, also producing hydrogen ions and electrons. Normally, iron minerals act as electron acceptors for the bacteria, but in this case, the graphite electrode plays that role. The chemical equation for this is:

$$CH_3COO^- + 2H_2O \rightarrow 2\ CO_2 + 7H^+ + 8e^-$$

The resulting current flows through the wire to the positive pole, the cathode, where the electrons combine with protons and oxygen to produce water:

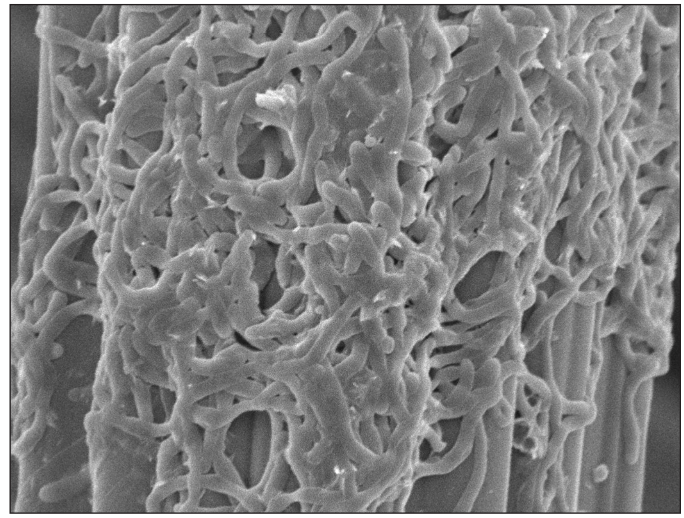
$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

In his experiments with the bacterial fuel cells, Lovley has seen them produce electricity steadily for a month (and they could have gone longer). But don't sell your shares in electric utilities. The current—65 milliamps per meter squared of electrode surface—is not going to charge up the nation. Caroline Harwood, a microbiologist at the University of Iowa, in Iowa City, envisions using bacterial fuel cells to power sensing devices, tiny gadgets that can be used for things like recording temperatures in remote locations for research on climate change.



CESAR CAMINERO

Lovley thinks it may have the potential to produce energy from wastes produced by farms and homes. For example, some farms make ethanol from corn for use as fuel, and others convert organic wastes to methane. *Geobacter* could convert either material to electricity, an energy source with many more applications, including cooking and powering devices such as lights, radios, and computers.



A scanning electron microscope image of the bacteria (*Rhodoferax ferrireducens*) growing on a graphite electrode.

To do that, it would be necessary to increase the power output of the bacterial fuel cells. "We've already increased the power output 5- to 10-fold," says Lovley. "We need to get maybe another 10-fold increase."

There are a variety of ways to approach such improvements. One route has to do with the pathway of transfer of the electrons from *Geobacter* to the surface of the electrode. There is a biochemical cascade as each electron gets handed off from one molecule to the next, until it reaches the electrode. The question is, how can that cascade be made to go faster? If researchers knew what enzyme catalyzed the final step of electron transfer, that "could help us in designing electrode materials," says Lovley.


ALL PHOTOS COURTESY OF UNIVERSITY OF MASSACHUSETTS, AMHERST, ENVIRONMENT BIOTECHNOLOGY CENTER

This working bacteria battery from Lovley's lab can power a red light emitting diode (LED).

Efficiency gains could also be made by "genetically engineering an organism that produces more of the enzyme for whatever the limiting step is," says Lovley. Toward that end, researchers have determined the complete genome of several species of *Geobacter*. Microarrays, devices that can be used to determine what genes are active in an organism at a specific moment in time, allow scientists to uncover each step of the cascade and to determine which step is slowest, in other words, which step limits the speed of the entire reaction.

Bacterial fuel cells would be environmentally benign. Although they would give off carbon dioxide as they generate power, unlike coal- and petroleum-powered machines, the car-

At this Colorado pilot site, a *Geobacter* food, acetate, was pumped into uranium(VI) contaminated ground. In a few months, the stimulated bacteria were able to reduce 70% of the uranium into an insoluble form that traps it in the soil and keeps it away from groundwater.

bon dioxide they produce comes from plant material, which would decay to carbon dioxide even if it were not used for electricity production. Thus, bacterial fuel cells would not add carbon dioxide to the atmosphere, a gas that is associated with global warming.

Lovley started conducting experiments to test bacterial electricity production after his program officer at the Office of Naval Research asked him to look into it. The phenomenon of producing current from marine sediments had been known, but at that time, no one knew how it worked or that bacteria were involved.

Besides producing electricity, the bacteria's talent may prove useful for removing uranium from groundwater. Like the electrode in the *Geobacter* fuel cell circuits and like-iron minerals, uranium can serve as an electron acceptor. The electron reduces it from a soluble form, uranium(VI), to an insoluble form, uranium(IV).

Stimulating the growth of geobacter can precipitate uranium out of contaminated surface waters before it gets into the groundwater, says Lovley. "We did a field experiment in Colorado, where by adding acetate to groundwater we could get *Geobacter* to grow. It worked really well."

"This problem is huge," says Lovley. The Colorado site had been contaminated by uranium mining. Other waters have become contaminated by uranium wastes that have been dumped into ponds during the manufacture of weapons. But big problems may yield to tiny creatures that have proven to be versatile chemists.

David Holtzman writes about science and technology in a variety of publications and lives in Lexington, MA.

Can You Build a Geobacter Battery?

Yes, you can. Success will require some extra research and experimentation. Here are some hints on what you will need.

- Anaerobic soil. Digging down in a riverbank, shallow pond, or other wetland to the black stinking mud is the best option. Anything characterized as "dirt'" probably doesn't have enough organic matter or anaerobic bacteria to work well.
- A container. Use a mason jar or an aquarium.
- Two wires, preferably a thick noncorrodible marine grade.
- Two graphite cylinders for the electrodes. Pencil "lead" is graphite, but it probably doesn't have enough surface area. Try getting large pieces at an art or specialty supply store.
- A voltage meter or small calculator to test your battery (Ah! But think about what you might be able to power if you were to hook a series of these batteries together?)

Some hints:

The picture above shows one possible battery. It is a mason jar half-filled with mud and then topped off with water. One graphite electrode hangs in the water connected to one of the wires. The second electrode is buried in the mud below and connected to the second wire. A key point: You must create a watertight connection between the graphite electrodes and the wire. If you don't, you risk creating an unwanted electrochemical reaction involving the copper wire. Aquarium sealant might be helpful in your quest.

That's it. The rest is up to you. If you have success, tell us how you did it and send pictures of your apparatus to chemmatters@acs.org. We'll give the new *ChemMatters* 20-year CD to the first five teachers who send us pictures of a working battery.

April 2004 Teacher's Guide

"Bacteria Power"

Student Questions

Bacteria Power

1. What unusual ability do the bacteria Geobacter sulfurreducens display?

2. Describe the basic structure of a battery and the general method by which it produces electricity.

3. Describe how Derek Lovley sets up an apparatus to use naturally occurring *Geobacter sulfurreducens* bacteria to produce electricity from a body of water.

4. Describe how the *Geobacter sulfurreducens* battery produces electricity, including the chemical reactions that occur.

5. Why are these kinds of electricity generating systems considered to be “environmentally benign?”

Answers to Student Questions

Bacteria Power

1. They are capable of producing electricity.

2. Batteries use chemical reactions to produce electricity. They have two poles—also called terminals or electrodes. One is positive and one is negative. Chemical reactions occur at the two electrodes and electrons flow from one terminal to the other. As the electrons flow between the two electrodes we can use some of their energy to do something that we find useful.

3. The terminals of the Geobacter sulfurreducens battery are slabs of granite about one-fourth of an inch thick. One terminal is placed in the mud at the bottom of a body of water. Geobacter bacteria are naturally present there. The other terminal is placed in the clear water above. The two terminals are connected by a waterproof wire.

4. The bacteria on the terminal that is in the mud feed off of decaying animal material. They oxidize acetate from the organic matter to carbon dioxide, also producing hydrogen ions and electrons:

   $CH_3COO^- + 2\ H_2O \rightarrow 2\ CO_2 + 7\ H^+ + 8\ e^-$

   The electrons released flow through the wire to the other terminal, where they combine with hydrogen ions and oxygen to produce water.

   $O_2 + 4\ H^+ + 4\ e^- \rightarrow 2\ H_2O$

5. Although they produce carbon dioxide as they generate power, the carbon dioxide that they produce comes from plant material. This plant material would decay to produce carbon dioxide anyway, so using the plant material to produce electricity really doesn't add any additional carbon dioxide to the environment. Carbon dioxide gas has been associated with global warming.

Content Reading Materials

National Science Education Content Standard Addressed As a result of activities in grades 9-12, all students should develop understanding.	**Bacteria Power**
Science as Inquiry Standard A: and abilities necessary to do scientific inquiry.	✔
Science as Inquiry Standard A: about scientific inquiry.	✔
Physical Science Standard B: of the structure of atoms.	✔
Physical Science Standard B: of the structure and properties of matter.	✔
Physical Science Standard B: of chemical reactions.	✔
Physical Science Standard B: of interactions of energy and matter.	✔
Life Science Standard C: of the cell.	
Life Science Standard C: of the interdependence of organisms.	
Life Science Standard C: of matter, energy, and organization in living systems.	✔
Life Science Standard C: of the behavior of organisms.	✔
Earth and Space Standard D: of geochemical cycles.	
Science and Technology Standard E: and abilities of technological design.	✔
Science and Technology Standard E: about science and technology.	✔
Science in Personal and Social Perspectives Standard F: of personal and community health.	
Science in Personal and Social Perspectives Standard F: of natural resources.	✔
Science in Personal and Social Perspectives Standard F: of environmental quality.	✔
Science in Personal and Social Perspectives Standard F: of natural and human-induced hazards.	✔
Science in Personal and Social Perspectives Standard F: of science and technology in local, national, and global challenges.	✔
History and Nature of Science Standard G: of science as a human endeavor.	✔
History and Nature of Science Standard G: of the nature of scientific knowledge.	✔
History and Nature of Science Standard G: of historical perspectives.	

Reading Strategies

These content frames and organizers are provided to help students locate and analyze information from the articles. Student understanding will be enhanced when they explore and evaluate the information themselves, with input from the teacher if students are struggling. If you use these reading strategies to evaluate student performance, you may want to develop a grading rubric such as the one below.

Score	Description	Evidence
4	Excellent	Complete; details provided; demonstrates deep understanding.
3	Good	Complete; few details provided; demonstrates some understanding.
2	Fair	Incomplete; few details provided; some misconceptions evident.
1	Poor	Very incomplete; no details provided; many misconceptions evident.
0	Not acceptable	So incomplete that no judgment can be made about student understanding.

Bacteria Power

What are they?

How do they work?

Bacterial Fuel Cells

Advantages

Disadvantages and Future Research needed

Anticipation Guides

help engage students by activating prior knowledge and stimulating student interest. If you have time, discuss their responses to each statement before reading each article. Students should read each selection and look for evidence supporting or refuting their responses. Evaluate student learning by reviewing the anticipation guides after student reading.

Directions for all Anticipation Guides: In the first column, write "A" or "D" indicating your agreement or disagreement with each statement. As you read, compare your opinions with information from the article. Cite information from the article that supports or refutes your original ideas.

Bacteria Power

Me	Text	Statement
		1. Bacteria may be used to provide electricity for large cities.
		2. Bacterial fuel cells work by producing sulfuric acid, the same acid found in car batteries.
		3. Graphite electrodes are used in bacterial fuel cells.
		4. Researchers have determined the genome of several species of Geobacter so that they can develop a more efficient bacterial fuel cell.
		5. Bacterial fuel cells are harmful to the environment.
		6. Bacteria can be used to clean up sites contaminated by uranium mining.
		7. The materials needed for bacterial fuel cells are dangerous and not suitable for student experiments.

Bacteria Power

Background Information

More about Derek R. Lovley and his work

Although he is one of the most outstanding microbiologists in the country, Lovley never set out on that career path. When he was an undergraduate at the University of Connecticut in the 1970s, he was not a microbiology major. "I was mainly interested just in environmental science. I basically wanted to get a job working outdoors. That was the level of my sophistication at that age."

He tended to equate microbes with disease and microbiology with medical research.

"Most people think of microorganisms as pathogens, germs. Even a lot of microbiologists. I remember being in graduate school; there were still some professors who seemed to be amazed that microorganisms were important in the environment. But that's where 99.99 whatever percent of bacteria live, in natural environments. It's now being recognized that they live not only on the surface but also very deep in the earth."

Lovley points out that the weight of the planet's microorganisms far exceeds the total weight of all the plant life on earth!

Although the specific focus of the article centers around Lovley's work with *Geobacter sulfurreducen* bacteria and their ability to generate electricity, Lovley's research extends to several additional very significant areas. His general focus is on the physiology and ecology of novel anaerobic microorganisms. He approaches these at three levels--genetic, biochemical, and ecological. The range of his research projects is extremely impressive and includes:

microbial metabolism and community structure in the deep subsurface and hydrothermal zones
evolution of anaerobic respiration
mechanisms of electron transport to Fe(III) and humic acids
anaerobic bioremediation of petroleum-contaminated subsurface and aquatic habitats
bioremediation of metal contamination

The Dec. 2003 issue of *ChemMatters* contained an article on hydrothermal vents and giant tubeworms. Lovley and a co-researcher, Kazem Kashefi, discovered an extremophile (see *ChemMatters*, Dec. 1999) captured from a vent at the bottom of the Pacific Ocean that can survive a temperature of 130 ^{0}C (266 ^{o}F) and that can actually grow and reproduce at a temperature of 121 ^{o}C (250 ^{o}F). This is well above the normal boiling point of water and represents a temperature at which it was previously thought that no organism could possibly survive, let alone thrive. But when this organism (as of yet unnamed but for obvious reasons dubbed "Strain 121") was placed in an autoclave at 121 ^{o}C for 24 hours, it not only survived, but had doubled in number.

The previous extremophile record holder had been *Pyrolobus fumarii*, which stops growing at 113 ^{o}C and is killed in a 121 ^{o}C autoclave after about an hour.

The discovery of Strain 121 represents more than just an interesting example of an unusual organism. The vent where Strain 121 was discovered sits about two miles under the ocean's surface. Since no oxygen is available at that depth, Strain 121 uses iron for its metabolism. The early Earth was iron-rich and oxygen poor, and it is speculated that perhaps early forms of life might have utilized metabolic mechanisms similar to that used by Strain 121. The fact that there is at least one organism capable of surviving such high temperatures in the absence of oxygen also increases the possibility that life might exist on other planets, either in our own solar system or elsewhere in the universe. As Lovley says, "No one had ever seen a bug like this before."

Strain 121 was obtained from a "black smoker" like the kind described in the *ChemMatters* article. John A. Baross of the University of Washington in Seattle and his crew sent an unmanned submarine to the ocean floor and removed part of the chimney with a remotely controlled chainsaw. It was quickly transferred to an oxygen-free container. Lovley was able to culture Strain 121 from part of this chimney.

Some general information about the metabolism of *Geobacter sulfurreducen*

The *geobacter sulfurredeucen* discussed in the article represent only one of an entire family of *geobacteraceae* (Latin for "earth" and "rod," which relates to where they live and their shape) bacteria. At least fifty species have been isolated and it is thought that many more may exist. The family was discovered by Dr. Lovley.

We are so accustomed to biological systems that utilize oxygen gas for their metabolic activities that it may be somewhat difficult to "understand" biological systems that use other reducible substances. But the principle is relatively straightforward.

There is nothing "magical" about oxygen, but it is a very suitable substance upon which to base metabolic activities. First, it is plentiful. Second, it is a good oxidizing agent, meaning that it is readily reduced. Third, the products of reduction are typically carbon dioxide and water, easily released after metabolism.

What is important is that the metabolic oxidation process and the accompanying reduction release energy the organism needs in order to survive. In principle, any material that is capable of undergoing reduction might conceivably be used.

Geobacter sulfurreducen can use iron(III). Substances taken from their surroundings, such as decaying plant material, are oxidized. The electrons removed, instead of being picked up by oxygen, are picked up by Fe(III) that is contained in materials like Fe(III) oxide. The process releases the energy which the organism needs to survive. Geobacter can actually sense the presence of iron in their environment and will move towards it. Genetic and biochemical studies have shown that Geobacter specifically produce flagella and/or pili (relatively short, hollow protein rods that are important in binding the cell to solid surfaces) in response to growth on insoluble electron acceptors such as Fe(III) and Mn(III). Geobacter are naturally present in soil and mud, and their growth can be easily stimulated by simply adding an acetate-containing material such as vinegar.

In one experiment, Dr. Susan Childers set up a series of microscope slides. In order to survive, the Geobacter would have to move across the slide to reach the metal required for their survival, and that's exactly what they did. They grew the required flagella and swam towards the metal source. Once they got there, they grew pili which allowed them to anchor themselves to the metal. To quote Dr. Childers, "The Geobacter doesn't waste energy growing flagella or pili unless it genuinely needs them. But if it's not located near metal, it somehow senses that it better get up and start moving, and the gene that governs the growth of flagella comes into play."

The process described in the article is slightly different. Instead of iron(III) accepting the electrons, the electrons are picked up by the graphite electrode and then sent through wires to the water's surface, where they are picked up by oxygen in the presence of hydrogen ions.

It turns out that hyperthermophiles can anaerobically oxidize not only acetate, but aromatic compounds and long-chain fatty acids as well. They can also reduce not only Fe(III) and U(VI), as described in the article, but also Mn(IV), Tc(VII), Au(III) and some other metals.

The potential uses to which microorganisms might be put is extremely broad. To help direct research efforts to areas with a higher probability of success, computer models of genomes have been created in order to see how an organism might function in a given environment. According to Lovley, this represents the strategy of the future. We can "tweak" the genome by moving genes around. There is the potential to design organisms to accomplish a certain task.

Other studied Fe(III)-reducing microorganisms exist, such as *Shewanella* and *Geothrix*, but microorganisms in the *Geobacteraceae* family represent the predominant metal-reducing microorganisms in a wide diversity of subsurface sediments. The mechanism by which they access Fe(III) oxides and transfer electrons onto Fe(III) surfaces differs significantly from that of these other microorganisms. Furthermore, *Geobacteraceae* contains a high percentage of genes that are devoted to sensing its environment and then allowing it to regulate its metabolism in response to the environmental conditions.

Connections to Chemistry Concepts

No matter how technologically or chemically complex it might be, the basic concept behind the operation of any electrochemical cell, or battery, is quite simple. Oxidation-reduction reactions involve the transfer of electrons from one substance to another. When a redox reaction occurs in a beaker, for example, the reactants make contact with each other, and the electrons are transferred directly. Slightly oversimplified, the reason the transfer occurs is basically because the electrons are in a lower energy state when they are on one substance vs. being on the other substance. The substance that loses electrons is said to be oxidized while the substance gaining the electrons is said to be reduced. Oxidation and reduction always occur together.

An electrochemical cell is simply a technological “trick” that forces the electrons to travel through a wire (or other conductor) in order to get from the substance oxidized to the substance that is going to be reduced. As the electrons travel through the wire we can use some of their energy to light a light bulb, power a laptop computer, start a car, or whatever.

For example, let’s consider a very simple electrochemical cell, one that utilizes the reaction between copper metal and silver ions to produce copper ions and metallic silver:

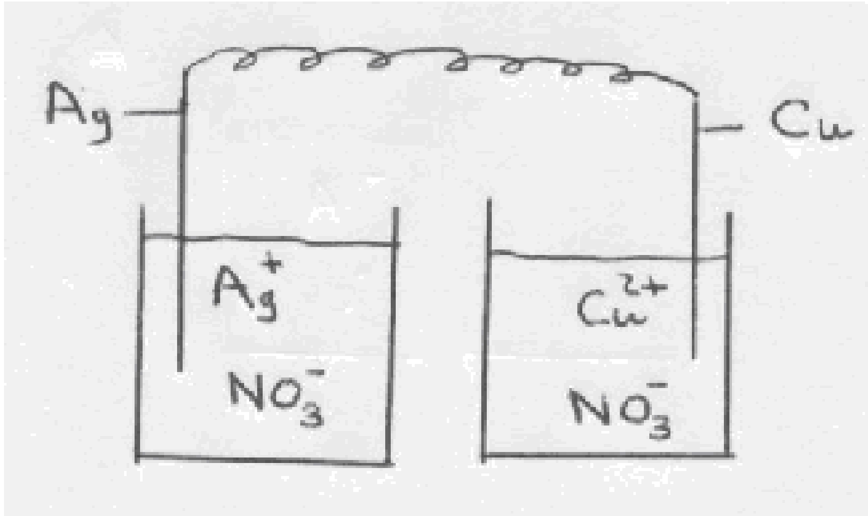
$$Cu(s) + 2\ Ag^+ (aq) \rightarrow Cu^{2+}(aq) + 2\ Ag(s)$$

The copper metal is being oxidized and the silver ions are being reduced.

If we simply dip a piece of copper metal into a solution containing silver ion, the electron transfer will occur directly and we won’t be able to make much use of the energy of the electrons that are being transferred.

But suppose we place a copper electrode into a solution that contains some $Cu(NO_3)_2$, which in solution will exist as Cu^{2+} and NO_3^-. We actually don’t need the Cu^{2+}, since it isn’t one of the reactants, but we do need some ions that won’t react directly with the Cu electrode, so $Cu(NO_3)_2$ will do fine (we could have used $NaNO_3$ or any other salt that wouldn’t react with the Cu electrode). In another beaker we place a silver electrode in a solution of $AgNO_3$, which will contain Ag^+ and NO_3^- ions. Here we actually don’t need an electrode made of Ag, since Ag isn’t a reactant. We could have used any nonreactive electrode, like graphite or platinum.

Now let’s place the two beakers next to each other and connect the two electrodes with a conducting wire:



Since the two electrodes are now connected, one might assume that the electrons could travel from the Ag electrode to the Cu electrode. If this were to occur, then oxidation would be occurring at the Ag electrode, and reduction would be occurring at the Cu electrode. We have basically broken the entire reaction into what are called two "half-reactions." If these two half-reactions were to occur we would have:

<u>At the Ag electrode:</u>

$Ag(s) \rightarrow Ag^{+}(aq) + e^{-}$

<u>At the Cu electrode:</u>

$Cu^{2+}(aq) + 2\ e^{-} \rightarrow Cu(s)$

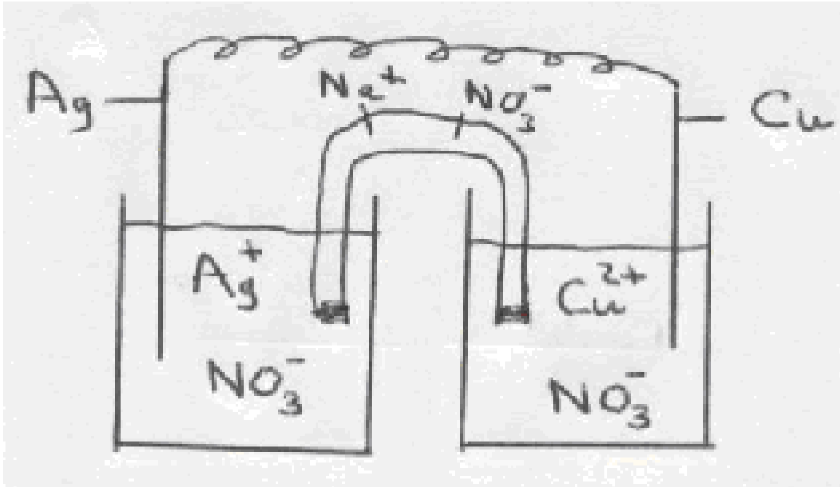
But there is one major problem. If these two half-reactions were to occur, the two solutions would no longer be electrically neutral. Positive ions (Ag+) would be produced in the $AgNO_3$ solution while positive ions (Cu^{2+}) would be removed from the $Cu(NO_3)_2$ solution. This would leave the $AgNO_3$ solution with a net positive charge and the $Cu(NO_3)_2$ solution with a net negative charge.

This is not allowed. Solutions must be electrically neutral at all times.

To solve this problem we can use something called a *salt bridge*. There are other ways to solve this problem as well, but this is one good way.

A salt bridge is nothing more than a U-tube filled with a solution that contains unreactive ions. A solution of something like $NaNO_3$ will work well. The ends of the U-tube are plugged with cotton. This keeps the solution from falling out or mixing with the solutions in the beakers, but still allows ions to move in and out of the U-tube.

Once the salt bridge is in place the cell looks like this:



Now the cell will work. As Ag^+ ions are produced in the left-hand beaker they can migrate into the salt bridge, keeping the $AgNO_3$ solution electrically neutral. As Cu^{2+} ions are removed from the right-hand beaker, Na^+ ions can migrate into the solution to replace them and keep that solution electrically neutral also.

And most importantly, as the electrons flow from the Ag electrode to the Cu electrode, we can use some of their energy. That was the whole idea behind building this electrochemical cell in the first place.

And that's what the Geobacter are basically doing. They are oxidizing acetate from organic matter in the mud. The electrons released in the oxidation process travel from one graphite electrode at the bottom of the pond to another electrode placed in the clear water above, where they are picked up by oxygen molecules and hydrogen ions. As the electrons travel, we can use some of their energy.

Possible Student Misconceptions

The article briefly mentions that Geobacter can reduce U(VI), a "soluble form" to U(IV), an "insoluble" form. It is conceivable that some students may draw a couple of invalid conclusions from these statements. First, it isn't "uranium" that is soluble or insoluble. It is compounds of uranium. What the 'soluble form' and 'insoluble form' refer to in this instance is that the compounds typically formed by U(VI) in the environment are salts of the UO_2^{2+} ion, which are generally soluble, while U(IV) forms insoluble UO_2. Some students may even incorrectly think that in some way this is eliminating or reducing the radioactivity. This, of course, is not the case at all. Radioactivity is a nuclear phenomenon, and no chemical process can remove or reduce it. But by changing the oxidation state of uranium from VI to IV, it transforms it into insoluble compounds that precipitate out rather than remain in solution. These compounds can then be collected and taken to a proper storage site instead of remaining in solution where they have the potential of migrating to other areas.

Because the article discusses the use of *Geobacter sulfurrenducens* to produce electricity, students may assume that this is the only bacterium that is capable of engaging in this kind of activity. This is hardly the case. See *Background Information*.

Demonstrations and Lessons

National Public Radio conducted an interesting interview with Dr. Lovley and Barbara Methe, a coresearcher. It runs to just over 30 minutes and provides a nice "science for the general public" discussion of Dr. Lovley's work and its potential. Audience members call in with questions, which range from fairly knowledgeable and thoughtful to some that may be a bit off-base. It might be interesting to have students listen to this broadcast and then react to both its content and the posed questions. Dr. Lovley and Dr. Methe handle all the questions nicely and never insult or talk down to the audience. The program can be accessed at:

http://www.npr.org/rundowns/rundown.php?prgId=5&prgDate=12-Dec-2003

Connections to the Chemistry Curriculum

This article connects particularly strongly with the topic of oxidation-reduction and electrochemical cells (see *Connections to Chemistry Concepts*). There are additional connections to the concept of oxidation states and how they affect the solubility of metallic compounds. The biological connections are obvious.

Suggestions for Student Projects

1. Although most organisms utilize oxygen for their metabolic processes, in principle any substance that readily undergoes reduction could conceivably be the basis for an organism's metabolic requirements. It might be both challenging and fun to have knowledgeable and creative students consider different possible reduction reactions (from a table of reduction potentials, for example) and then try and create a theoretically viable metabolic system that might be used by an organism. Some considerations would include the availability of the requisite materials, the energy release that might be anticipated, and the properties of the metabolic products.

2. Dr. Lovley's research includes studies of what are called extremophiles (see *Background Information*). *ChemMatters* published two articles that connect to Dr. Lovley's work. The Dec. 2003 issue contained an article on hydrothermal vents, and the Dec. 1999 issue contained an article on extremophiles. Students could learn more about Dr. Lovley's research in these areas, read both of the *ChemMatters* articles and the accompanying Teacher's Guide materials and then prepare a report that connects all of the information.

3. The use of microbes for bioremediation extends to many more areas than are mentioned in the article. For example, microbes can be used to clean up gasoline spills. Every day enormous quantities of gasoline are pumped into American motor vehicles. Inevitably some of this ends up in the environment. It has been demonstrated that microbes can be used to clean up much of this mess, and reporting on how this is done and the progress which has been made to date might provide a good topic for a student report.

Anticipating Student Questions

1. Since Geobacter react with iron and uranium in the soil could they also react with an undesirable metal like mercury, Hg, to remove it from the soil?

   It hasn't been done yet, but it might be possible. Geobacter contain genes similar to other organisms that can remove mercury.

2. Could the kind of process described in the article be patented?

   It already has been patented.

3. Is there a danger that by feeding these bacteria so they become prevalent enough to accomplish some useful activity we run the danger that they may grow out-of-control?

   Not really. When you remove the acetate upon which they feed, their growth drops off.

4. Since these bacteria can feed on iron, is there a danger that they might feed off the iron in the hemoglobin in our blood and kill us?

   No. Geobacter have no genes for pathogenicity. They cannot attack the blood.

5. Could Geobacter be used to clean toxic substances from humans?

   No. They cannot grow in the human body. If we wanted to try and get them to accomplish something like this we'd have to alter their genome.

6. Is there a "microorganism for everything?"

   No, but the potential that exists is awesome. For example, we have added chemicals to the environment, such as PCBs, that do not naturally exist. Nevertheless, organisms have emerged that are capable of biodegrading these kinds of materials.

Websites for Additional Information and Ideas

National Public Radio contains an interview with Derek Lovley and Barbara Methe from the Institute for Genomic Research. The interview and the accompanying call-in questions from listeners runs a bit over 30 minutes. It can be accessed at:

http://www.npr.org/rundowns/rundown.php?prgId=5&prgDate=12-Dec-2003

A much more thorough scientific paper published by Dr. Lovley and Daniel R. Bond on electricity production by Geobacter sulfurreducens can be found at:

http://www.geobacter.org/publications/12620842.pdf

Check out an article on "Plugging into the power of sewage" from The New Scientist magazine.
http://www.newscientist.com/news/news.jsp?id=ns99994761