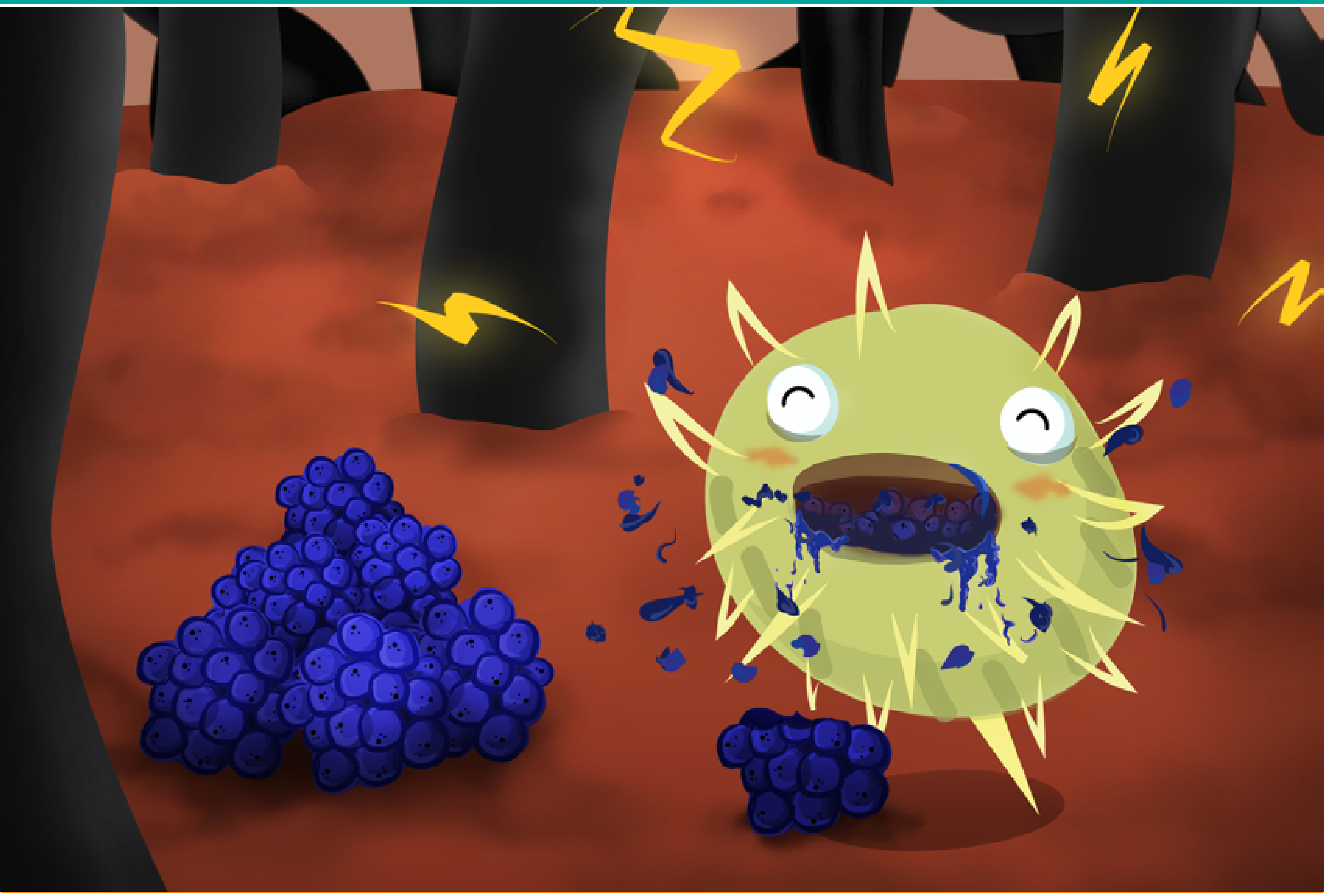
MAIN MODULE

MudWatt

NGSS TEACHER'S GUIDE



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INTRODUCTION

Teaching Rationale

Microbial fuel cells (MFCs) represent an exciting, emerging technology for generating electricity that is clean and reliable. In this module students will learn how electricity is produced by certain bacteria during their natural metabolic process and how a microbial fuel cell works.

The progression of lessons provided in this module has been designed to give students the background and instruction necessary to engage in their own exploration of microbial fuel cells. Each lesson builds upon the learning in the preceding activity and it is recommended that the lessons be done sequen tially.

The reading material and lab activities help provide concrete learning opportunities for abstract concepts. Students with minimal background knowledge in microbiology and electricity can perform these activities (see suggested prerequisites).

PREREQUISITES

Note: This module is intended for Middle School Students.

Prior to starting these investigations it is recommended that students have a basic understanding of:

- **Characteristics of all living organisms and microbes (specifically bacteria)**
- **Energy and electricity basics**

If additional background information is required prior to starting this module students may complete **Sub-Module 1: Meet the Microbes and Module 2: Electricity and Circuits.**

Learning Objectives

1. **Microbial fuel cells (MFCs)** are a clean energy source that can be used to generate electricity.
2. Natural metabolic processes of certain "electrogenic" bacteria can be used to **generate electricity**.
3. Nearly all soils, sediment and water contain **electrogenic bacteria**.
4. Energy can be transformed from one form to another: **chemical energy** (energy stored in the bonds of chemicals) into **electrical energy** (energy of moving electrons).
5. Conduct a scientific investigation in which certain variables are manipulated

Essential Questions

1. **How can we generate electricity from mud?**
2. **What are microbial fuel cells and how do they work?**
3. **What are the advantages to using a MFC as an energy source?**

By The End of This Lesson...

Students will understand that:

- Electron-releasing (electrogenic) bacteria exist in all types of soils and sediments worldwide
- Microbial fuel cells (MFC) generate electricity by directing electrons given off by certain, electrogenic, bacteria through a circuit
- Microbial Fuel Cells are a clean, renewable energy source because they are self-sustaining, do not require any external energy to operate and do not emit any excess greenhouse gases Microbial fuel cells convert organic matter into useable energy
- While producing electricity microbial fuel cells can also remove toxic materials from soil, sediment and waste water which lends itself for use in bioremediation projects to clean soil, sediment and wastewater

Students will be able to:

- Assemble a functional Microbial Fuel Cell
- Explain how a microbial fuel cell works
- Plan and conduct a scientific experiment using a MudWatt™ Microbial Fuel Cell Kit
- Measure the amount of power generated in a microbial fuel cell
- Explain how Microbial Fuel Cells are a clean, renewable energy source

NGSS Alignment

CORE IDEAS

Core Idea LS1: From Molecules to Organisms: Structures and Processes

LS1.A: Structure and Function

Core Idea LS2: Ecosystems: Interactions, Energy, and Dynamics

LS2.B: Cycles of Matter and Energy Transfer in Ecosystems

Core Idea PS3: Energy

PS3.B: Conservation of Energy and Energy Transfer
PS3.D: Energy in Chemical Processes and Everyday Life

Core Idea ETS1: Engineering Design

ETS1.A: Defining and Delimiting an Engineering Problem
ETS1.B: Developing Possible Solutions
ETS1.C: Optimizing the Design Solution

CROSS CUTTING CONCEPTS

- ☐ Patterns
- ☑ Cause and effect: Mechanism and explanation
- ☑ Scale, proportion, and quantity
- ☑ Systems and system models
- ☑ Energy and matter: Flows, cycles, and conservation
- ☐ Structure and function
- ☐ Stability and change

PRACTICES

- ☑ Asking questions (for science) and defining problems (for engineering)
- ☑ Developing and using models
- ☑ Planning and carrying out investigations
- ☑ Analyzing and interpreting data
- ☑ Using mathematics, information and computer technology, and computational thinking
- ☑ Constructing explanations (for science) and designing solutions (for engineering)
- ☑ Engaging in argument from evidence
- ☑ Obtaining, evaluating, and communicating information

Vocabulary

Microbe	Photosynthesis	Cellular respiration
Electrogenic Bacteria	Electrons	Microbial Fuel Cell
Aerobic	Anaerobic	Metabolism
Bioremediation	Electrode	Electricity
Anode	Cathode	Power output
Voltage		

Glossary

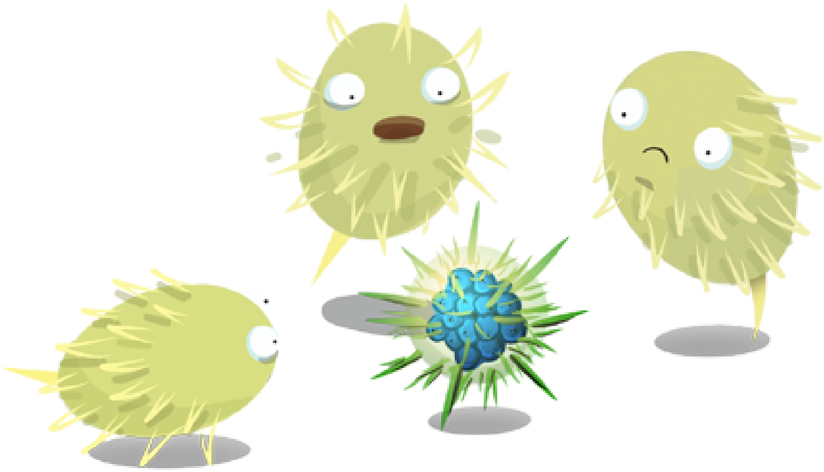
Aerobic Metabolic processes that occur in the presence of oxygen

Anaerobic Metabolic processes that occur in without the presence of oxygen

Anode The site at which electrons are collected (-)

Bioremediation The removal of harmful materials in the environment through natural biological processes

Cathode	The site at which electrons are released (+)
Cellular respiration	The process in which nutrients and sugars (e.g. glucose) are broken down and turned into useful energy within a cell
Electricity	The movement of electrons
Electrogenic bacteria	Bacteria capable of donating electrons to external receptors outside their bodies (e.g. an anode)
Electrons	Negatively charged particles of an atom which orbit around the atom's nucleus
Electrode	A general term for a conductive material that either accepts electrons (e.g. the anode) or gives them away (e.g. the cathode)
Metabolism	A process in which a series of chemical reactions release the energy stored in the chemical bonds of food eaten
Microbe	Short for microorganism, is used to describe any tiny organism that is too small individually to be seen with the naked eye
Microbial fuel cell	Devices which harness electrons given off naturally by bacteria within soil, sediment and wastewater, to create an electrical circuit
Neutron	Particles in the nucleus of an atom that have no electrical charge
Photosynthesis	A process used by plants where carbon dioxide and water are taken in to produce simple sugare (e.g. glucose) using energy from light (usually the sun). Oxygen is released as a waste product



Pre-Assessment: Free Response

Ask students to write down their ideas on the following questions using only what they already know:

1. What does "**metabolism**" mean?
2. How do **plants** get their energy?
3. How do **animals** get their energy?
4. How do **microbes** get their energy?
5. Do all **animals** require **oxygen** to survive?
6. Do all **microbes** require **oxygen** to survive?
7. What are **independent** and **dependent variables** in a scientific investigation?
8. What is a **control** in a scientific investigation?
9. What are **constants** in a scientific investigation?

Pre-Assessment: Multiple Choice

Ask students to answer the following questions using only what they already know:

1. **The process by which plants get their energy is called:**

   a. respiration

   b. photosynthesis

   c. breathing

   d. fermentation

2. **The process by which food is burned to release energy in organisms is called:**

   a. respiration

   b. photosynthesis

   c. breathing

   d. fermentation

3. **The term which describes the series of chemical reactions that result in the breakdown of complex organic molecules into simpler substances by living organisms is:**

   ____

4. **The term to describe respiration processes that occur in the presence of oxygen is:**

   a. anaerobic   b. aerobic

5. **The term to describe respiration processes that occur in when oxygen is not present is:**

   a. anaerobic   b. aerobic

6. **In a scientific investigation, the "control" is:**

   a. what is changed in the set up

   b. what is kept the same in all the set ups

   c. the set up that has not been changed

   d. what is measured and is used for comparison

7. In a scientific investigation, the "independent variable" is:

a. what is changed in the set up

b. what is kept the same in all the set ups

c. the set up that has not been changed and is used for comparison

d. what is measured

8. In a scientific investigation, the "dependent variable" is:

a. what is changed in the set up

b. what is kept the same in all the set ups

c. the set up that has not been changed and is used for comparison

d. what is measured

9. In a scientific investigation, "constants" are:

a. what is changed in the set up

b. what is kept the same in all the set ups

c. the set up that has not been changed and is used for comparison

d. what is measured

Teacher Background

Microbial fuel cells, also referred to as biological fuel cells, have been of interest to scientists as a source of electricity since the early 1900s. As our demand for energy continues to increase and our supply of energy resources continues to be stressed, we are constantly looking for alternative energy sources.

Criteria for alternative energy technologies is becoming more focused on finding clean, renewable sources that minimizes both the amount of energy needed to be put in and the amount of excess greenhouse gasses released during the electricity generating process.

Microbial fuel cells are an excellent candidate for including in a clean energy portfolio. They require no external energy source (unlike hydrogen fuel cells which require energy to generate the hydrogen), they do not produce any additional greenhouse gasses, they rely on naturally occurring processes, can be used anywhere in the world, and are self-sustaining.

Biological wastewater treatment

Currently, the U.S. spends roughly 5% of its energy budget on treating wastewater. Instead of consuming energy, wastewater treatment plants may actually be able to generate electricity while treating the wastewater, using microbial fuel cells. In addition, because while metabolizing organic material, the bacteria respire a variety of materials including iron, uranium and other toxic materials, MFCs can also be used for bioremediation (removal of harmful materials in the environment through natural biological processes). MFCs have been used to remove many different environmental pollutants including toxic heavy metals, petroleum and Uranium from contaminated soils and wastewater,

Using the **MudWatt microbial fuel cell** students are able to explore concepts in biology, physics and chemistry in a truly integrated manner.

The resources provided here will help students explore a wide range of design and experimental parameters that can influence the MudWatt's performance. Challenge your students to manipulate different variables to see if you can optimize power output or meet the engineering design challenge goals.

What are Microbial Fuel Cells?

What are microbes?

The term **microbe**, short for microorganism, is used to describe any tiny organism that is too small individually to be seen with the naked eye. To see a microbe you need to use a powerful microscope. Microbes are often associated with disease or illness, but microbes are also essential players in the recycling of nutrients on earth and in providing key ingredients necessary to support life. There are three main types of microbes: bacteria, fungi and viruses but in MFCs, bacteria are the key players, so we will limit our discussion to bacteria.

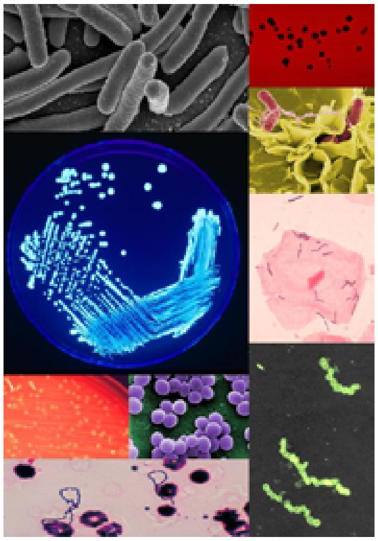


Photo by PeskyPlummer (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

Bacteria are the most dominant and diverse type of organism on Earth. Bacteria have dominated since life on Earth began and have been found in every imaginable type of environment, even those thought to be uninhabitable, like acid pools and super-hot thermal vents.

For more information see ***Sub-Module 1: Meet the Microbes***

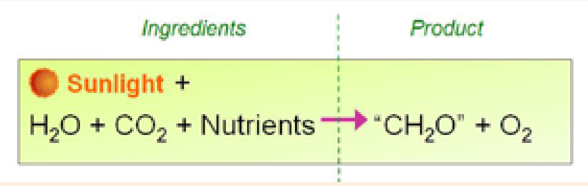
How do microbes get their energy?

All living organisms need energy to live. This energy comes from the energy stored in the chemical bonds of food that is released when we “burn” the fuel.

How different organisms get their food

Some organisms are autotrophs, meaning they take inorganic materials from the environment to make organic material, or food for themselves, from which they can then get energy to live.

Photosynthesis



Plants and certain bacteria photosynthesize. During **photosynthesis** plants take in carbon dioxide and water and use the sun’s energy to rearrange these molecules to make organic matter/food (simple sugars) and oxygen is given off as a waste product.

Some bacteria are also autotrophs but use a process called **chemosynthesis**. In chemosynthesis bacteria take in materials such as carbon dioxide and hydrogen sulfide, or iron or ammonia and process them to make organic material.

Chemosynthesis

$$6CO_2 + 12H_2S \rightarrow C_6H_{12}O_6 + 6H_2O + 12S$$

Finally, many other bacteria and organisms (like us) are **heterotrophs**, meaning they rely on external sources of organic matter from which they can get their energy. The bacteria that make the MudWatt work are heterotrophs. They take in organic matter that has been broken down to the right size and form by larger organisms, such as worms and fungi.

To learn more about nutrient cycling in soils, see ***Sub-Module 3: Soil Ecology and Nutrient Cycling****.*

How organisms break down food to release energy (Metabolic processes)

All organisms need to **metabolize**, or break down their food so that the stored energy can be converted into energy which can then be used to grow, repair and reproduce. There are several processes by which organisms are able to process food for energy but we will focus on cellular respiration.

> **Chemistry Connection!**
>
> In a chemical reaction **Oxidation** occurs when there is a loss of electrons and **Reduction** occurs when there is a gain of electrons.

Cellular respiration is the process by which organic matter is oxidized (burned) and the energy stored in the chemical bonds of the food is released. Cellular respiration occurs in the mitochondria of cells.

The details cellular respiration are complex and are beyond the scope of this module, but students should be aware that during respiration **electrons** are given off and are then taken up by electron acceptors.

When oxygen is present the electrons are taken up by the oxygen, and the process is referred to as **aerobic respiration**. When oxygen is not present, other materials such as iron or sulfur can accept the electrons. This process is called **anaerobic respiration**. For most organisms that occurs inside each cell but for a unique type of bacteria the electrons are actually given off externally. These specialized bacteria are called **electrogenic bacteria**. Electrogenic bacteria occur naturally in every type of soil, sediment and surface water environment where oxygen is limited. Two common types of electrogenic bacteria, **Shewanella** (a.k.a "Mr. Clean"), and **Geobacter** (a.k.a. "The Iron-Breather").

How microbial fuel cells harness energy from microbial metabolism

(Please refer to the MudWatt diagram on page 16.)

Microbial fuel cells work because **anaerobic bacteria** create a thin film on an **electrode** buried in soils or sediment. These **electrogenic bacteria** deposit their **electrons** onto the **anode** material (graphite fiber).

Electrons flow through the wire from the anode to the **cathode** where electrons combine with oxygen and hydrogen near the cathode to form water. The flow of electrons from the anode to the cathode and back into the soil completes a circuit and generates an electrical current.

A small circuit board with a capacitor and LED are visible indicators that **electricity** is being produced.

For more information on electricity and circuits, see ***Sub-Module 2: Electricity and Circuits****.*

MudWatt Explorer App

The **MudWatt Explorer App** (available for most smartphones and tablets) can be used to convert the number of blinks into current produced (in microWatts (μW)). Additionally, students are able to use the **MudWatt Power and Microbe Population Calculator worksheet** to estimate the number of electron-donating microbes around their MudWatt's anode.

Download the MudWatt Explorer App!

- Measure your MudWatt's power!
- Unlock chapters of a fun comic!
- Record and share your power data!

Available on the App Store

Get it on Google play

STUDENT HANDOUT

What are Microbial Fuel Cells?

Microbial fuel cells (MFCs) generate electricity using the natural ability of microbes to produce electrical power when they process food. To understand this process we need to understand how microbes get their energy.

You need microbes to make a microbial fuel cell work!

All living organisms need energy to live but where does that energy come from?

The energy organisms need to live comes from the energy stored in the "foods" they eat.

All organisms get their energy from the food they eat!

Some organisms, such as plants and some bacteria, make their own food. Other organisms must eat preexisting organic matter to get their energy.

To release the energy stored in the chemical bonds of the food organisms ***metabolize***, which means they use a series of chemical reaction to release the energy stored in the chemical bonds of the food they eat. Organisms differ in the way that they metabolize but the end result is the same: food is broken down and the stored energy is converted into energy that the organisms can use to grow, repair and reproduce in a process called ***cellular respiration***.

Respiration is a very complex process but what is important to understand is that **ALL** organisms respire, and during respiration, electrons are given off in a series of chain reactions.

Biology Connection!

The reason ***we*** breathe is to get oxygen to use in cellular respiration!

These electrons get picked up by an "electron acceptor" and are used in another series of chemical reaction. For humans, and many other animals and certain bacteria, oxygen is the electron acceptor. When oxygen is the electron acceptor the process is called ***aerobic respiration*** and the organisms that metabolize using oxygen are called **aerobes**.

Extension Idea!

Want to see what different types of bacteria use for food? Make a **Winogradsky Column**!

Other organisms, particularly certain types of bacteria, are able to respire **without oxygen** being present. This is called ***anaerobic*** (without oxygen) ***respiration***. Organisms that metabolize when oxygen is not present are called **anaerobes**. When oxygen is not present the electrons are taken up by elements other than oxygen, particularly metals like iron and sulfur.

Chemistry Connection!

Metals and other materials change their **chemical form** when used as electron acceptors, and become less toxic.

For most organisms these processes happen inside the organisms' cells but there is one type of bacteria that can actually give off electrons to something outside of their cells! These special bacteria are called ***electrogenic bacteria***. It is these electrogenic bacteria that are the key to how a microbial fuel cell works!!

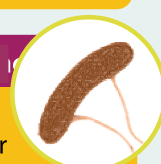
Electrogenic bacteria occur naturally and are abundant in nearly all types of soil, mud, sewage and waste water which is why microbial fuel cells can be made pretty much anywhere,

Two common types of electrogenic bacteria are: **Shewanella** (Mr. Clean), and **Geobacter** (The Iron-Breather):

Shewanella (Mr. Clean)

Known for their versatility, **Shewanella** species can be found almost everywhere on earth, from mountain dirt to ocean sediments. Due to their unique ability to **expel electrons** to compounds outside their bodies, Shewanella can metabolize a variety of substances and link together through conductive appendages, **transferring electrons** to their neighbors. They can even metabolize toxic compounds containing radioactive Uranium!

Geobacter (The Iron-Breather)



Geobacter species have the ability to respire iron compounds and use them in a way similar to the way humans respire oxygen. In fact, they prefer to live in environments where there is **no oxygen**, such as deep underground or within ocean sediments. Like Shewanella, due to their ability to **expel electrons**, they can metabolize many environmental pollutants, including petroleum and Uranium, and have been used to help clean up pollution.

Quick Recap!

1. When Microbes breakdown organic matter in **anaerobic** (lacking oxygen) environments, materials such as sulfur and iron are used as **electron acceptors**.
2. Certain bacteria **give off** their electrons outside of their body.
3. Metals and other materials **change their chemical form** when used as electron acceptors and become less toxic.

STUDENT HANDOUT

How does a microbial fuel cell work?

A microbial fuel cell takes advantage of ***electrogenic bacteria***'s ability to ***give electrons*** to external materials.

For a fuel cell to function there must be two electrodes, an ***anode*** and a ***cathode***, separated by a proton-exchange membrane (PEM), which allows very small ions (such as protons) to move through it but will not allow larger ions, such as oxygen, to pass through.

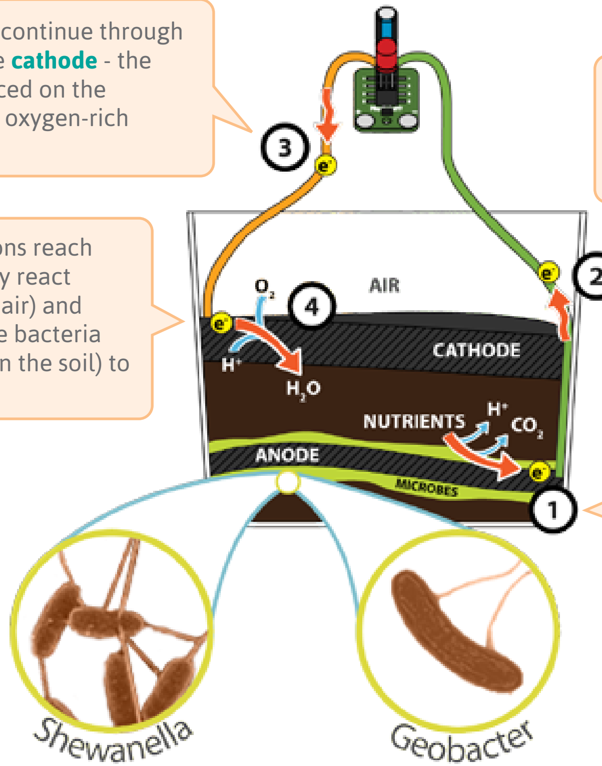
Physics Connection!

Anodes are electrodes that **accept** electrons and **cathodes** are electrodes the **release** electrons.

3 The **electrons** continue through the wire to the **cathode** - the other **electrode** placed on the top of the soil, in an oxygen-rich environment.

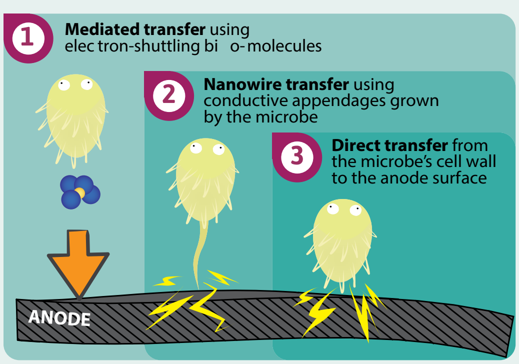
2 Electrons from the **anode** travel up through the wire to the Hacker Board, where they power the electronics.

4 Once the electrons reach the **cathode**, they react with oxygen (from the air) and hydrogen (made by the bacteria as it digests nutrients in the soil) to create water.



1 Inside the MudWatt, an **anode** is buried in the mud near the bottom. In this oxygen-poor environment microbes munch on sugars and other nutrients in the surrounding environment releasing electrons using **anaerobic respiration**. Over time these bacteria multiply and cover the anode with a biofilm. The anode acts as the electron acceptor for **electrogenic bacteria**, such as Shewanella and Geobacter.

How do the electrons get onto the anode?



Electrogenic bacteria are able to give electrons to the external electron acceptor in one of 3 ways:

1. A **secondary biomolecule** is used to shuttle the electron to the anode.
2. Electrons are transferred through **conductive appendages**, termed "**nanowires**", grown by the microbe. These nanowires can form vast conductive networks.
3. **Direct transfer** from the microbe's cell wall to the anode surface (microbe is touching the anode directly).

Power generation from an MFC will continue as long as there are **nutrients** readily available. Since mud is full of complex sugars and other nutrients from decaying plant and animal matter that have accumulated over millions of years, there is plenty of food for the microbes and thus the MudWatt can continue to produce power for **months to years**!

Quick Recap!

MudWatt Microbial Fuel Cell Operation

1. Microbes at the bottom of the MudWatt take in the **nutrients** in the soil and break them down without oxygen (**anaerobic respiration**).
2. **Electrogenic bacteria** give off electrons to an **external electron acceptor** when they respire.
3. Electrogenic microbes form a biofilm on the **anode** (an electron acceptor) and deposit their electrons onto it.
4. Electrons flow through the wire from the **anode** to the **cathode**.
5. Electrons combine with **oxygen** and **hydrogen** near the cathode to form **water**.
6. The flow of electrons from the **anode** to the **cathode** and back into the soil **completes a circuit** and generates an **electrical current**.

Activity 1: How does a microbial fuel cell work?

TEACHERS: In this lesson students gain familiarity with the assembly and operation of the MudWatt™ Microbial Fuel Cell. Students make a prediction of the expected outcome and then measure, record, and graph the voltage produced over time to see how the power production changes with time. Students are evaluated using the experimental and group work rubrics provided at the end of these investigations.

Time

1 class period for MudWatt assembly

Periodic monitoring over the course of 20 days

Materials

- MudWatt™ Microbial Fuel Cell kits (1 per class or 1 per group)
- Soil Sample (approximately 2 cups
- Smartphone with MudWatt™ Explorer installed
- Multimeter (optional)
  (Note: if using a multimeter see instructions for use on Educator's Resource page)

Investigation Question

How much power can a microbial fuel cell generate?

Vocabulary

Scientific process: the process scientists carry out find answers to questions or test ideas

Hypothesis: what you think is going to happen (using prior knowledge)

Independent variables: the variable that is manipulated or changed on purpose

Dependent variables: the variable that responds

STUDENT HANDOUT

Activity 1: How does a microbial fuel cell work?

How does a microbial fuel cell work? In this activity you and your partner will assemble a MudWatt™ Microbial Fuel Cell. You will be monitoring the MudWatt over 20 days to see how much power it generates over time. You will be evaluated using the experimental and group work rubrics provided.

Procedure

1. Gather MudWatt™ kit and a few cups of dirt (1 kit per group).
2. Assemble MudWatt™ according to the instructions included in the kit.

Questions

1. **What are the parts of a Microbial Fuel Cell?**
   In the space provided sketch what the MudWatt set up looks like.

Label the following parts on the drawing:

anode cathode circuit board LED capacitor soil

Predictions

1. **When will the MudWatt LED begin blinking?**

2. **What will be the maximum amount of power (in µAmps) produced in 20 days?**

Data Collection

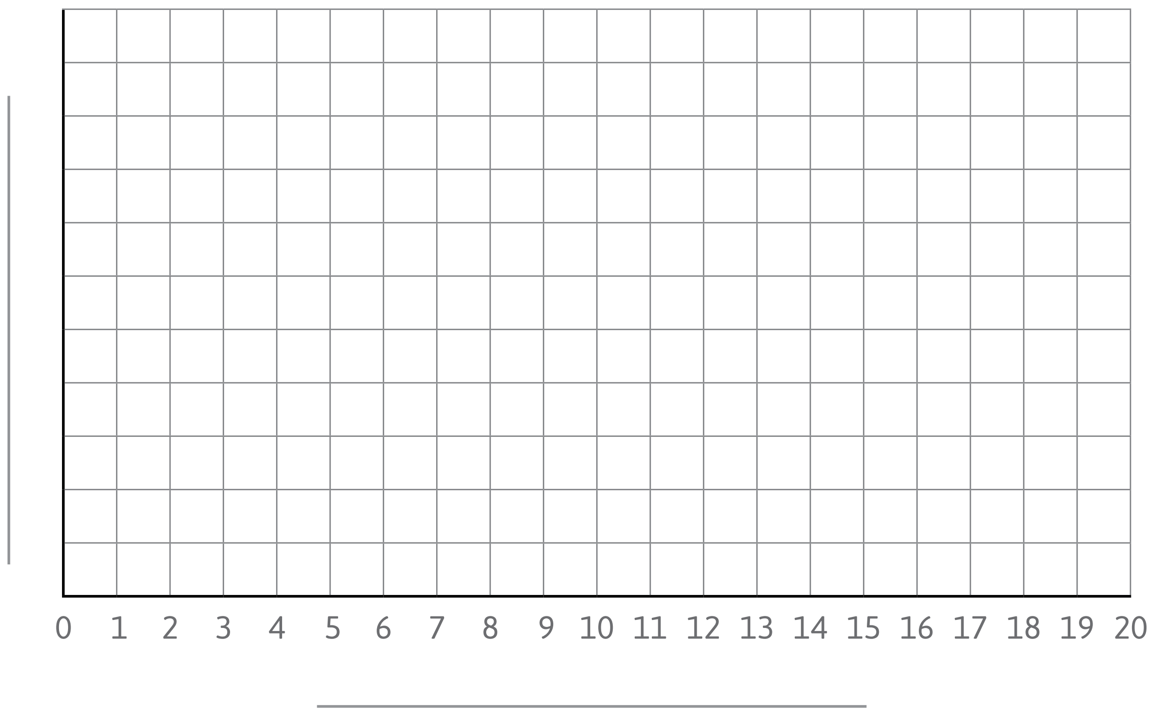
1. Check the MudWatt™ each day to see if the LED light is **blinking**.
2. Use the **MudWatt Explorer app** to measure and record the amount of current being produced (the app converts the number of blinks per minute the LED light produces into power in microWatts (µW)).
3. Record the **power output** each day for 20 days in the data table. If the light is not blinking, record the value as 0.

Day	1	2	3	4	5	6	7	8	9	10
Power output (µW)										
	11	12	13	14	15	16	17	18	19	20

Graphing

Once all the data have been collected make a graph of the **voltage** (y axis) versus **time** (x axis). Be sure to include a title, axes labels, and units.

Title: ____



Analysis

1. An independent variable is something that is changed on purpose during the experiment. **What was the independent variable in this investigation?**

2. The dependent variable is what is measured. **What was the dependent variable in this investigation?**

Analysis (cont.)

1. **Describe the results.**

2. Examine the graph and describe any trends, patterns, or interesting changes in the data over time. **How (in what ways) did the amount of power change over time?**

Critical Thinking

1. **What evidence did you have that electricity was being generated in the MudWatt™?**

2. **Can you think of an explanation for why the power output changed the way that it did?**

Critical Thinking (cont.)

3. **In a MFC what type of energy is being converted into electricity?**

4. **Write 4 questions that you still have after doing this investigation:**

   1. ______________________________
   2. ______________________________
   3. ______________________________
   4. ______________________________

5. **What changes could you make to the MudWatt™ to increase its power production?**

   I could change:

   1. ______________________________
   2. ______________________________
   3. ______________________________

6. **What else besides power output could you make on the MudWatt™?**

   I could measure:

   1. ______________________________
   2. ______________________________
   3. ______________________________

7. **Use your ideas from #5 and #6 above to conduct another investigation with the MudWatt in Activity #2.**

Activity 2: Maximizing Power Output in a MudWatt

TEACHERS: In this investigation students manipulate variables to determine cause and effect between the variables with the goal of optimizing the amount of power output from the MudWatt™.

Two MudWatts™ per group are used to conduct an experiment using a control. Students select one independent variable (of their own choosing) to change in one MudWatt™ while keeping the second MudWatt™ unchanged to serve as the **control**. Students may also select the dependent variable to measure and record.

Using their selection of independent and dependent variables students develop a testable question for their investigations. Students may design their own investigations using **Activity 2** or the **Experiment Design Template**, depending on their previous experience with experimental design. Students are evaluated using the experimental and group work rubrics provided at the end of these investigations.

Objectives

In this lesson, students will:

- Gain familiarity with how MFCs respond to different conditions
- Conduct a controlled experiment while manipulating variables
- Make accurate observations and record data
- Use indirect evidence to make predictions
- Practice analyzing data results
- Evaluate data for a cause and effect relationship

Science as Inquiry Practices

- ☑ Asking questions (for science)
- ☑ Developing and using models
- ☑ Planning and carrying out investigations
- ☑ Analyzing and interpreting data
- ☑ Using computer technology, and computational thinking
- ☑ Constructing explanations (for science)
- ☑ Engaging in argument from evidence
- ☑ Obtaining, evaluating, and communicating information

Vocabulary

Control: part of an experiment in which the scientist does not manipulate the variable

Independent variables: the variable that is manipulated or changed on purpose, or

Dependent variables: the variable that responds or what results or is measured

Testable question: a question that can be answered through scientific investigations

STUDENT HANDOUT

Activity 2: Maximizing Power Output in a MudWatt

In this investigation you are trying to find ways to modify the MudWatt so that it will produce the greatest amount of power. Your team will have **two MudWatts**. Both MudWatts should be identical except you will change one thing in one of the MudWatts.

What can you think of to change? Use your imagination. Create a competition with another group to see which group can produce the highest amount of power!

Selecting Variables

1. **What could you *change* in the MudWatt™ set up to try to *maximize power output*?**

List all possible ideas here:

Soil ________ ________ ________

________ ________ ________

________ ________ ________

Choose one item from this list that you will change in the MudWatt.
This will be your **independent variable**:

____

2. **What are all the parameters you could *measure* on the MudWatt™?**

List all possible ideas here:

Voltage ________ ________ ________

________ ________ ________

________ ________ ________

Choose one item from this list that you will measure in the MudWatt.
This will be your **dependent variable**:

____

Selecting Variables (cont.)

Here are a few suggestions to get you started:

- Try **different soil types** from different locations to see which soil type produces more power
- Add something **creative** to the soil in one Mudwatt™ to see if power production increases (Think, what would a microbe like to eat? *Hint: what molds or goes bad quickly?*)
- Determine if the **voltage**, or **current**, or **time** to reach a maximum amount of power is affected by the changed variable
- Change the **temperature** of the soil
- Change the **distance** between electrodes

3. Create a testable question from your choice of independent and dependent variables:

Example: Does the type of soil used affect how much voltage is produced in a MFC?

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4. Hypothesis: Before beginning your experiment make a prediction.

Do you think changing the independent variable will affect the dependent variable? Why do you think this?

Example: Soil type will affect the voltage produced by the MFC. I think that the soil from the forest will produce more electricity than the soil from the garden because the forest has more decaying material in it.

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Activity 2: Maximizing Power Output in a MudWatt

Time

1 class period for MudWatt assembly

Periodic monitoring over the course of 20 days

Materials

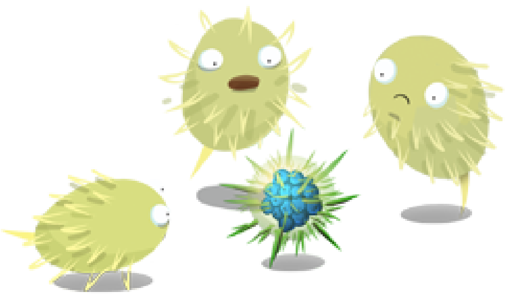
- 2 MudWatt™ Microbial Fuel Cell kits per group (2 per class or per group of 2-4 students)
- Soil Samples (approximately 2 cups)
- Smartphone with MudWatt™ app installed or multimeter

  (Note: if using a multimeter see "MaxTracker" instructions for use on Educator's Resource page)
- Other materials as determined by your selection of an independent variable to be changed

Procedure

1. Gather MudWatt™ kits (2 per group) and a 5-6 cups of dirt.
2. Acquire materials needed for manipulated variable.
3. Add appropriate amount of the material selected as the independent variable to the mud in a beaker and mix thoroughly or make change to one MudWatt™ set up as determined by your choice of independent variables.

   *(Note: Record the volume fractions of the soil and the special ingredient. You will need these later when you share your data. For **solid supplemental materials**: use a ratio of about **3 parts soil to 1 part special ingredient** by volume. For **liquid supplemental materials**: just mix a few drops of the liquid ingredient into the mud that you place below the anode during MudWatt construction. The soil that is placed above the anode should not have the special ingredient.)*
4. Assemble both MudWatts™ (Don't forget to label them accordingly).
5. Clean lab station and rinse beakers
6. Before starting the experiment **record your observations of the two MudWatts™** (the control and the one with the manipulated variable). Be sure to **identify any differences** seen between the two units.
7. Gather data according to instructions on the next page.



Data Collection

1. Check the MudWatt™ each day to see if the LED light is **blinking**.
2. Use the **MudWatt Explorer app** to measure and record the amount of current being produced (the app converts the number of blinks per minute the LED light produces into power in microWatts (μW)).
3. Record the **power output** each day for 20 days in the data table. If the light is not blinking, record the value as 0.

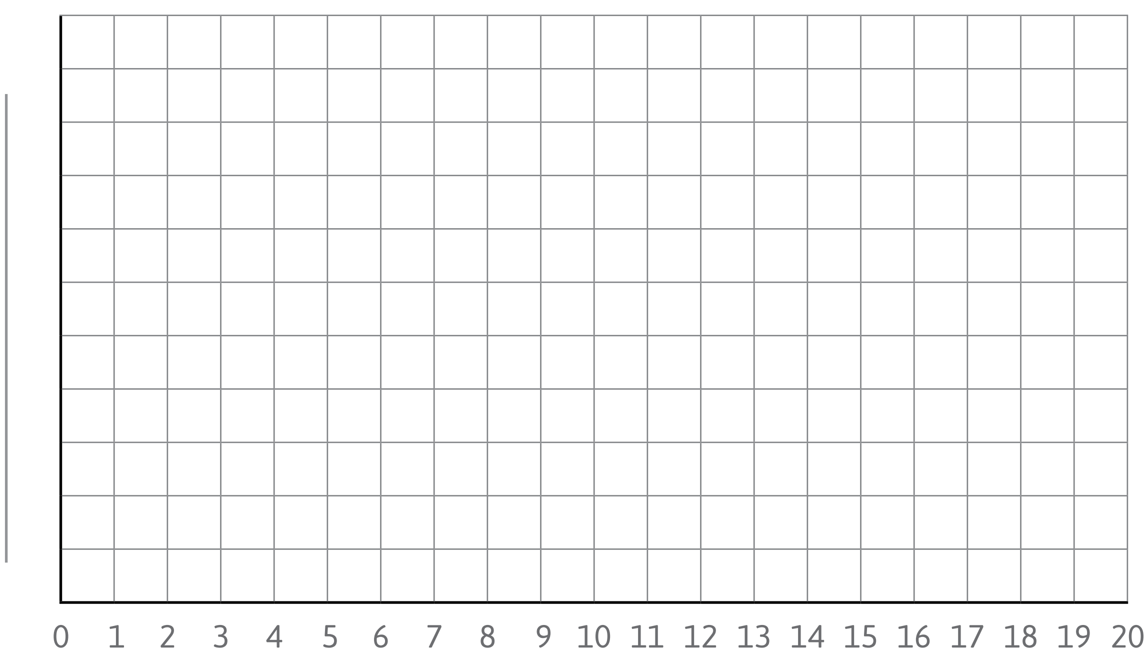
Day	1	2	3	4	5	6	7	8	9	10
Power output (μW)										

	11	12	13	14	15	16	17	18	19	20
Power output (μW)										

Graphing

Once all the data have been collected make a graph of the **voltage** (y axis) versus **time** (x axis). Be sure to include a title, axes labels, and units.

Title: ______________________________



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Analysis

1. Describe the results. Examine the graph to see any trends, patterns, or interesting changes in the data and record those observations below.

2. What was similar about each of the Mudwatt™ set ups in this investigation?

3. What was different in each of the Mudwatt™ set ups in this investigation?

4. Was there a difference in the amount of power produced by the two MudWatts™ in your investigation? What was the highest and lowest amount of power, voltage and/or current recorded for each Mudwatt™?

MudWatt Name	Highest power Recorded (uW)	Lowest Power Recorded (μW)

Analysis (cont.)

5. Can you provide a scientific explanation for why the Mudwatts™ produced different amounts of power? What evidence can you provide to support your answer? (refer to your data)

6. Compare your results with those of another team. Which group's MudWatt™ produced the most power? What was the highest and lowest amount of power, voltage and/or current recorded for each Mudwatt™?

Team	Highest power Recorded (uW)	Lowest Power Recorded (μW)

7. If you ran this experiment again what would you do the same as this experiment? Explain why you would keep that part of the experiment unchanged.

Analysis (cont.)

8. What would you change or do differently if you ran this experiment again? Explain why you would make that change.

Critical Thinking

1. Using what you learned about ways to increase power output in a microbial fuel cell, describe how microbial fuel cells could be used as an energy source in your community or in a different part of the world?

Scientific Investigation Design Template

What are you curious about? Design your own investigation using a MudWatt™ Microbial Fuel Cell! Develop a **testable question** and design and run your own investigation using a MudWatt™. Use the following template to help you through the steps involved in designing your own experiment.

Name: ______________________________ **Date:** ______________

Lab Partner(s): ____

Experiment Design Template
Purpose What do you want to learn about or find the answer to? What do you already know about this idea?
Testable Question Pose your idea in the form of a question that can only be answered by experimentation (it should be able to be answered with a yes/no or true/false answer)
Independent Variable What variable will be changed in this experiment?
Dependent Variable What variable will be measured/observed in this experiment?
Hypothesis What do you think will happen based on what you already know about this idea? State your prediction to show what you think will happen or change? (If this... then this... will result)

Experiment Design Template	
Materials List all the materials and supplies you will need to conduct this investigation	**Procedure** Write out each step in enough detail that someone else could do the same experiment from your directions.

Experiment Design Template

Data Collection

Record what happened. (Include units, times of measurements, sketches, etc.)

Data Display

Find the best way to display the data for ease of interpretation and viewing. Options include graphs (line, bar, circle, scatter) or time series of sketches

Experiment Design Template

Analysis

Examine the data and describe any patterns, trends, changes you can see.

Conclusions

Were you able to answer the investigation question from the results of this experiment? What did you find out? Did you get the results you expected? Why or why not?

Did anything go wrong along the way? Identify anything that went wrong or that had to be changed during the experiment.

Identify any new ideas or new questions that have arisen as a result of running this experiment (what new questions do you have?

Experiment Evaluation Rubric

Name: ______________________________ **Section:** ____ **Date:** ____________

	3	2	1	0
Problem	☐ Is clearly testable and is written in a clear and concise manner	☐ Is not clearly testable or not written in a clear manner	☐ Is not testable and is not written in a clear manner	☐ No problem given
Hypothesis	☐ Relationship or trend predicted. ☐ Reason /support given for hypothesis	☐ Relationship or trend prediction not clear and /or reason /support not clearly given	☐ Relationship or trend not predicted. ☐ No reason / support given	☐ No Hypothesis given
Variables	☐ Variables clearly identified	☐ Some but not all variables identified	☐ Variables not identified	☐ No variables given
Procedure	☐ Well organized, ☐ presented in a logical sequence, ☐ enough information given so another could repeat procedure	☐ Somewhat organized, ☐ Information provided is not complete enough to allow another to repeat procedure	☐ Not organized ☐ Sequence is not logical sequence, ☐ Not enough information given so another could repeat procedure	☐ No procedure given
Observations	☐ All drawings and written observations detailed and accurately reflect results	☐ Drawings and written observations not detailed enough to accurately reflect results	☐ Drawings and written observations lack detail, difficult to understand results	☐ No observations made
Analysis/ Conclusion	☐ All data discussed and interpreted ☐ Trends in data explained and interpreted ☐ All statements must be supported by the data	☐ Some data discussed and interpreted ☐ Trends in data explained and interpreted ☐ Some statements supported by the data	☐ All data not discussed and interpreted ☐ Trends in data not explained or interpreted ☐ Statements not supported by the data	☐ No analysis or conclusion given

Group Experiment Evaluation Rubric

Name: ______________________________ **Section:** _______ **Date:** ____________

Skills	Basic 1	Sound 2	Thorough 3	Extensive 4
Contributions/ Participation/ Attitude	☐ Seldom cooperative, rarely offers useful ideas. Is disruptive.	☐ Sometimes cooperative, sometimes offered useful ideas. Rarely displays positive attitude.	☐ Cooperative, usually offered useful ideas.	☐ Always willing to help and do more, routinely offered useful ideas. ☐ Always displays positive attitude.
Working with others/ Cooperation	☐ Did not do any work – does not contribute, does not work well with others, usually argues with teammates.	☐ Could have done more of the work – has difficulty, requires structure, directions and leadership, sometimes argues.	☐ Did their part of the work – cooperative. ☐ Works well with others, rarely argues.	☐ Did more than others – highly productive
Focus on task/ Commitment	☐ Often is not a good team member. Does not focus on the task and what needs to be done. Lets others do the work.	☐ Sometimes not a good team member. Sometimes focuses on the task and what needs to be done. Must be prodded and reminded to keep on task.	☐ Does not cause problems in the group. ☐ Focuses on the task and what needs to be done most of the time. Can count on this person.	☐ Tries to keep people working together. Almost always focused on the task and what needs to be done. Is very self-directed.
Team role fulfillment	☐ Participate in few or no group meetings. Provided no leadership. Did little or no work assigned by the group.	☐ Participated in some group meetings. Provided some leadership. Did some of the work assigned by the group.	☐ Participated in most group meetings. Provided leadership when asked. Did most of the work assigned by the group	☐ Participated in all group meetings, assumed leadership role as necessary. Did the work that was assigned by the group.
Communication/ Listening/ Information sharing	☐ Rarely listens to, shares with, or supports the efforts of others. Is always talking and never listens to others. Provided no feedback to others. Does not relay any information to teammates.	☐ Always listens to, shares with, and supports the efforts of others. Provided effective feedback to other members. Relays a great deal of information – all relates to the topic.	☐ Usually listens to, shares with, and supports the efforts of others. Sometimes talks too much. Provided some effective feedback to others. Relays some basic information – most relates to the topic.	☐ Always listens to, shares with, and supports the efforts of others. Provided effective feedback to other members. Relays a great deal of information – all relates to the topic.

Source: questgarden.com/60/13/2/080123185936/files/Group_work_rubric.doc

Teacher's Guide: MudWatt Experiment Ideas

Note: For all of experiments mentioned below, you can use the "MudWatt Soil Standard" (aka the "MudWatt DirtBag") to ensure you have a viable soil.

Beginner Level Experiments

Experiment A

Experiment Question: Does the type of soil used impact how much power is produced?

Independent Variable: Soil Type, as varied by color, texture, depth, and/or smell

Dependent Variable(s) / Measurables: Voltage, Current, Power

Experiment Notes:

- The color, texture, and/or smell can tell you a lot about a soil. Typically darker soils and more rich with decayed plant material and organic carbon molecules, a food source for microbes, and therefore are likely to produce more power.
- Typically, the smellier the soil, the more microbial respiration is present. If the soil smells like rotten eggs, that means there are a lot sulfur compounds present, which electrogenic microbes often use during their respiration. Try not to smell this too much, as it can make you feel sick! In terms of power, the smellier the soil, the better.
- Try to keep all other variables constant, such as electrode position, temperature, and the water saturation level of the soil. One way of keep the saturation level constant between different soil types is to over saturate of the soils, let them settle for a few minutes, and then decant any excess liquid resting on top of the soil.
- Note, you can use the "MudWatt Soil Standard DirtBag" available at www.mudwatt.com as a "control" soil in your experiment.

Experiment B

Experiment Question: What food items from the fridge would increase power generation in a MudWatt?

Independent Variable: Special ingredient from a the fridge

Dependent Variable(s): Voltage, Current, and/or Power

Experiment Notes:

- With any special ingredient, you'll want to add just a modest amount, and mix it well into the soil. We recommend using 1-part of special ingredient for every 5-parts (or more) of soil.
- We recommend using liquid special ingredients. If you are using a solid special ingredient (e.g. banana peels), you'll want to grind/mush it up first, so that it mixes well with the soil.
- Think: what would microbes like to eat? You'll want to get something that is very "bioavailable", meaning something that is easily broken down by microbes. Things that mold/rot quickly are typically very "bioavailable"
- Acetate is very nice energy source for microbes – you can create it by taking a half cup of vinegar (acetic acid) and adding in baking soda (bicarbonate) until it stops fizzing. What remains is acetate.
- For more advanced users, you could create your own special bacteria media much like that used in research labs, using items from the grocery store. For this you'll want to mix 1 teaspoon of yeast extraxt (e.g. Marmite), 1 teaspoon of corn syrup, and a pinch of salt into 2-3 cups of water.
- To prevent mold from forming on top of your soil, only fill up your MudWatt half way with the soil that has the special ingredient in it (with the anode buried). Then top it off with regular soil before putting on the cathode.

Experiment C

Experiment Question: Does the temperature of the soil affect how much power is produced?

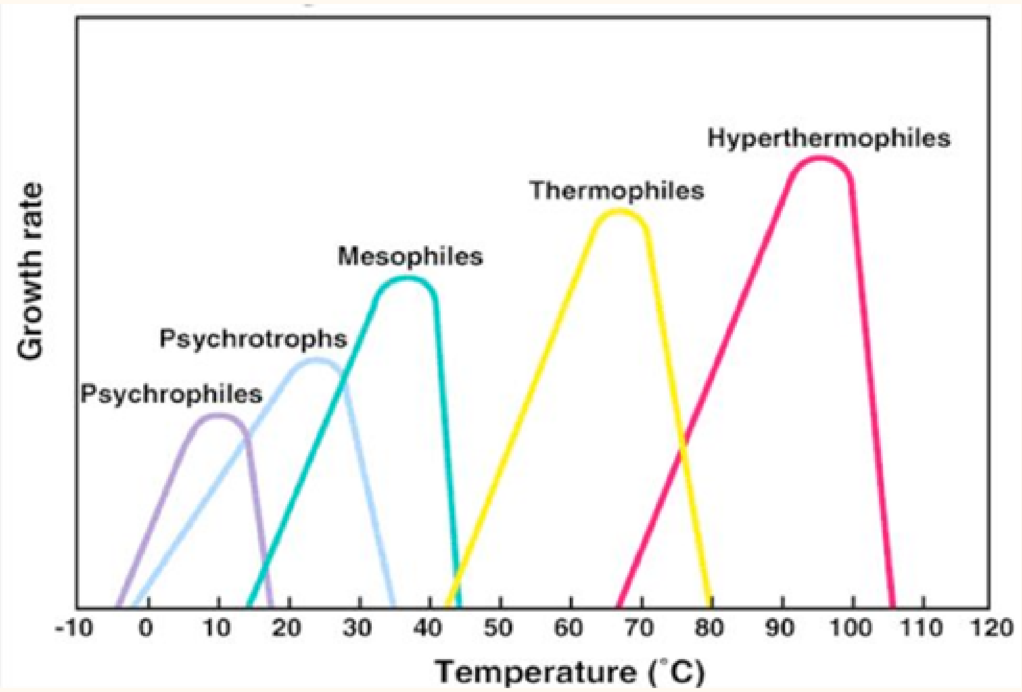
Independent Variable: Temperature

Dependent Variable(s): Voltage, Current, Power

Experiment Notes:

- The easiest way to implement this experiment is to place a thermometer in the soil (try to get the tip between the anode and cathode) and place the MudWatt in a bath of hot water to heat it up. Take measurements of the temperature and your dependent variable(s) at very various time points until the temperature has stabilized (higher limit). Then place the MudWatt in an ice bath or refrigerator and do the same thing until the temperature has stabilized again (lower limit).

- Be sure to compare your graphed results to known relationships of microbial growth vs temperature that can be found on the web (also copied below). It's an interesting comparison! Based on your data, can you determine if your electricity-generating bacteria are psychrophiles (cold loving), mesophiles (warm loving), or thermophiles (hot loving)?



Experiment D

Experimental Question: How can multiple MudWatts be configured to increase the amount of Voltage or Current, or both, in order to power different things? More broadly, how can the power being generated by the MudWatts be manipulated to do useful things? *(Note: the MudWatt Teacher Pack is designed to facilitate this exploration)*

Independent Variable: The method of connecting multiple MudWatts together (in series vs parallel)

Dependent Variable(s) / Measurables: Voltage, Current, Power

Experiment Notes:

- When hooking up MudWatts in series (i.e. The (+) end of one to the (-)

end of another), their voltages will be added, and the current will be averaged between them all.

- When hooking up MudWatts in parallel (i.e. All the (+) ends together and all of the (-) ends together) their current will be added, and the voltage will be averaged between them all.

Advanced Level Experiments

Experiment A

Experimental Question: Does the distance between electrodes affect the amount of voltage, current or power being produced?

Independent Variable: The distance between the electrodes (i.e. the amount of soil between them)

Dependent Variable(s) / Measurables: Voltage, Current, Power

Experiment Notes:

- The amount of soil between the anode and cathode has a couple of effects. Firstly, the deeper the anode is buried, the less oxygen it will be exposed to. This is because as oxygen diffuses down through the soil, it is likely to get consumed by aerobic microbes in the soil. The less oxygen the anode is exposed to, the lower its redox potential will be. Since the MudWatt's voltage is a function of the cathode redox potential minus the Anode redox potential, burying the anode deeper in the soil should increase the total voltage created by the MudWatt.
- Secondly, remember that for every electron donated by microbes at the anode, a positive ion is released into the soil (this is a called a "proton equivalent" – it can refer to a H+, K+, Na+, or any other positive ion). Increasing the distance between the anode and cathode will make it harder for these proton equivalents to diffuse all the way to the cathode, where they interact with the electron again to form new compounds, like H2O. So, increasing the distance between anode and cathode may actually hurt the power generation from the MudWatt in the long-run, because you may build up proton equivalents at the anode, which in turn make the environment around the anode more acidic, which the microbes don't like.

Experiment B

B) Experimental Question: How can you find a MudWatt's Maximum Power Point? (The art of Potentiometry)

Independent Variable: The resistor value that is placed within the MudWatt's Hacker Board

Dependent Variable(s) / Measurables: Voltage, Current, Power

Experiment Notes:

- Microbial Fuel Cells behave much like solar panels do, in that they have a "Maximum Power Point" that is achieved when you apply an external resistance (i.e. a resistor) that is equal value to the MudWatt's own internal resistance (which is a function of how well proton equivalents can travel from the anode, through the soil, to the cathode).
- The methodology for this is explained in the MaxTracker Kit.

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