# SOLAR ENERGY CONVERSION

## Making a Dye-Sensitized Solar Cell

## NGSS HIGH SCHOOL LESSON PLAN

How does a solar cell convert light into electricity? This lesson is designed to help teachers educate students about the chemistry of solar energy.

Juice from Juice
NSF Center for Innovation in Solar Fuels
California Institute of Technology

# Table of Contents



Image (cover): Each pane of these beautiful windows, found in the Swiss Federal Institute of Technology Convention Center, is composed of a dye-sensitized solar cell. The many colors allow for some artistic innovations when installing the cells.

Image Credit: *EPFL / Alain Herzog*

# Before You Start

## 1. What do I know about solar cells?

Evaluate your prior knowledge of solar cells and how they function. This short assessment is meant to help you identify what you *already* know about solar cells and what you might want to review.

Pre-lab Assessment

1. What are the types of energy into which efficient solar cells can convert light?
    a. Chemical
    b. Electrical
    c. Heat
    d. Both A and B
    e. Both B and C
    f. All of the above
2. Which of the following compounds allow plants to absorb light effectively?
    a. Titanium dioxide
    b. Chlorophyll
    c. Plant pigments
    d. Both B and C
    e. Both A and C
    f. None of the above
3. How does the size of a semiconductor's band gap affect the wavelength of light it absorbs?
    a. The larger the band gap, the shorter the wavelength of light needed to excite an electron in the semiconductor.
    b. The larger the band gap, the longer the wavelength of light needed to excite an electron in the semiconductor.
    c. The wavelength of light that a semiconductor absorbs is unaffected by the size of the band gap.
4. Assuming that you are presented with the same amount of each, what form of a semiconductor has the largest surface area?
    a. Bulk silicon (i.e. a thin piece of silicon)
    b. Silicon nanoparticles
    c. They should have the same surface area.
5. Mark each statement below as true or false.
    a. In a DSSC, an electrolyte must be present in the cell to return the semiconductor to its ground (unexcited) state.
    b. A DSSC is covered in metal to complete the circuit formed by the light absorber and semiconductor.
    c. While they are simple to fabricate, DSSCs are not used outside of the classroom due to their low conversion efficiencies.
    d. Attaching many DSSCs in parallel will result in the highest observable voltage when the cells are exposed to light.
    e. DSSCs are less expensive to make than silicon solar cells.

Once you have completed the assessment, please correct
your answers using the key on the next page!

## Assessment key:

1. D, solar cells convert light into chemical fuel or electricity. Inefficient cells can produce heat.

2. D, chlorophyll is the classic compound that leaves contain to absorb and convert light into energy. Other natural absorbers supplement chlorophyll and are called **accessory pigments**. These pigments include the dyes that make fruit multicolored, such as the anthocyanin dye found in blackberries.

3. A, shorter wavelengths mean higher energy photons. Remember that $E = h\nu = hc/\lambda$. Thus, when a semiconductor has a large band gap, it needs higher energy photons to excite an electron from the valence band to the conduction band.

*Not sure what a band gap is? Check out the background information below: What is a bandgap?*

4. B, nanoparticles are, as the name implies, very, very small particles. When given the same amount of bulk semiconductor and nanoparticle semiconductor, we would expect the nanoparticles to have a much larger surface area as the total surface area of the particles is the sum of the surface areas of each individual particle, whereas the total surface area of the bulk semiconductor is simply the surface of the wafer.

5a. False, the electrolyte must be present to regenerate the absorber (or dye) used in the DSSC, not the semiconductor.

5b. False, the DSSC is encased in conductive glass to ensure that the cell can still absorb sunlight. Metal would simply reflect the light and heat up the cell.

5c. False, while not as prevalent as their silicon counterparts, DSSCs are available commercially and used around the world.

5d. False, attaching the cells in series will yield the highest voltage. Attaching the cells in parallel yields the highest current.

5e. True, silicon solar cells are very expensive as the silicon used must be extremely pure. DSSCs typically do not have these cost limitations, although the organic components (i.e. the dye) will decompose over time, requiring more maintenance than a silicon solar cell.

How did you do? Identify the material you need to review
from the questions you missed and continue on to #2.

## 2. How does a solar cell work?

Now that you've identified what you need to review, take some time to read through the background information on the next few pages. This information along with the information provided in the accompanying prelab handouts should serve to fill in any knowledge gaps you may have identified in #1. Once you are done, continue on to #3.

## 3. Identify 3-4 learning objectives that connect the background information to the standards.

After reading through the four next generation science standards on page 13, what would you like your students to learn from this lab? To help prompt your thoughts, we've provided example objectives using language directly from the NGSS table.

**Example Objectives:**
Students should be able to:

- communicate how a dye-sensitized solar cell (DSSC) converts light waves into electricity
- design and build a dye-sensitized solar cell from basic components and blackberry juice dye
- refine their solar cell design through the comparison of various fruit dyes
- evaluate a dye-sensitized solar cell's performance in comparison to a silicon solar cell

**What objectives would you like your students to be able to complete?**

## 4. Read through the lab procedure.

After you read through the procedure, check out our demonstration videos for a quick refresher on how to make a DSSC. Any questions or concerns? Contact a Caltech scientist! We'd love to visit your classroom and help students fabricate their DSSCs.

## 5. Assess what you have learned.

At the end of this lab, your students (and you too!) should be able to fulfill all the objectives listed above in #3 along with any alternative or additional objectives you have identified from the NGSS standards. We have suggested some questions to assess what your students have learned. Feel free to use these questions or write your own.

**Before you instruct your students**, you may want to watch the DSSC videos to review the lab procedure: http://thesolararmy.org/jfromj/resources/ and click on "DSSC Playlist" under "Instructional Videos."

# Background Information

## *What is a solar cell?*

A solar cell is a light-sensitive material that collects solar energy and converts it into fuel: electrical or chemical. Nature's solar cell is a leaf on a plant as it undergoes ***photosynthesis***. In photosynthesis, the chlorophyll dye in a leaf absorbs light from the sun, solar energy, and converts it into sugar, source of chemical energy. Similarly, a manmade solar cell (Figure 1) takes solar energy but converts it into electrical energy rather than chemical energy.

*Figure 1*. Solar cells can be found scattered around Caltech's campus.

Recap Question #1:
Where does the power come from when we are using a solar cell?

## *How do we make a solar cell?*

*Figure 2*. A leaf is nature's solar cell, converting light into chemical fuel.

What components make up a solar cell? Let's look more closely at the example of the leaf (Figure 2). We can break down photosynthesis into two main processes: (1) absorption of solar energy by the leaf dye, chlorophyll, and any accessory pigments and (2) conversion of the absorbed solar energy into chemical fuel. We want our solar cell to mimic photosynthesis, where solar energy does all the work, but our cell will produce electrical energy. Just like the leaf, we need to ensure that our cell can complete both (1) absorption and (2) conversion.

Recap Question #2:
A leaf and a solar cell both convert solar energy into another type of energy. What type does a solar cell make, and what type does a leaf make?

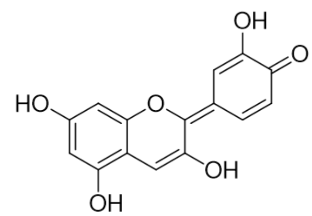
<u>Absorption</u>

First, we will need dye, such as chlorophyll, to absorb light from the sun (Figure 3). What makes something a good dye, or light absorber? Simply put, we want a molecule that can strongly absorb light. Logic tells us that if light must be absorbed by our solar cell in order to be converted into electricity, absorbing *more* light is better for the efficiency of our solar cell (i.e. more light in = more energy out).

In this lab, we will used the dye found in blackberry juice as our light absorber. Blackberries contain a strongly light-absorbing dye molecule called anthocyanin, which occurs in many types of fruits and berries (Figure 4). It is the compound that gives blackberries, raspberries, blueberries, and pomegranates their color.

*Figure 3.* The different dyes in this fabric absorb various wavelengths of light, giving the cloth its beautiful hue.

Chemical Formula: $C_{15}H_{10}O_6$




Anthocyanin (blackberry dye)

*Figure 4.* When crushed, blackberries release anthocyanin, the dye that gives the blackberry its dark purple color.

Once the dye absorbs light, the electrons in it get excited to higher energy levels, but having the cell absorb light is only part of the battle! What about converting what we absorb into electricity?

Recap Question #3:

The $TiO_2$ semiconductor paste used in this lab is <u>white</u> and used in many commercial products: white paint, toothpaste, powdered doughnuts, etc. Why do we need to use the <u>dark</u>-colored dyes from blackberries to make our solar cell work?

## What is a band gap?

A band gap is analogous to the energy gap between the highest *occupied* molecular orbital (HOMO) and the lowest *unoccupied* molecular orbital (LUMO) of a chain of conjugated carbon atoms, such as butadiene. In fact, as you add more and more carbons to the chain, the orbital arrangement of an organic molecule begins to approach the arrangement we can observe in a semiconductor (Figure 5). There are so many orbitals with similar energies on either side of the band gap that they are treated as a single **band** rather than individual orbitals. The HOMO becomes the valence band, and the LUMO becomes the conduction band.

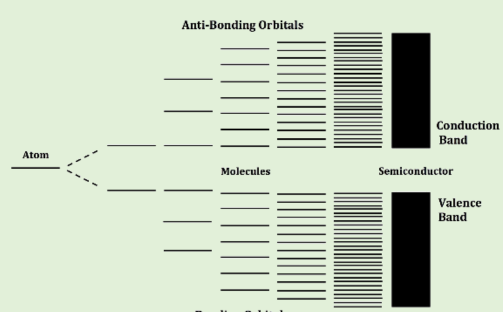



*Figure 5.* The HOMO-LUMO gap is analogous to the gap between the conduction band and valence band of a semiconductor.

Conversion

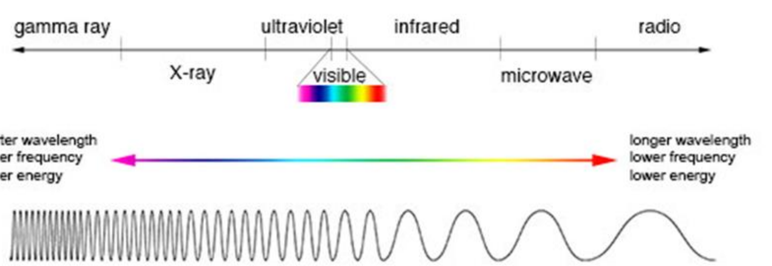
Conversion of the absorbed light proves to be the trickier half of the DSSC equation. We need a material that can take the light *absorbed* by the anthocyanin dye and *convert* it into a current, or moving electrons. To do this conversion, our material must be at the correct energy level to accept the high energy, excited electrons from the dye.

This is where semiconductors make their appearance (Figure 6)! Semiconductors are characterized by the size of their **band gap** (*What is a band gap? sidebar*) ideally between 0.5-3.0 eV for solar cell applications.

To put these values in perspective, remember that the longest wavelength of light that could excite an electron across the band gap of silicon, a 1.12 eV jump from the top of the valence band to the bottom of the conduction band, is about 1110 nm, a long, low energy wave in the infrared region of the electromagnetic radiation spectrum (Figure 7). However, what matters for our DSSC is the location of the **conduction band edge**, the very bottom edge of the conduction band.

Kemi Silicon, Inc.

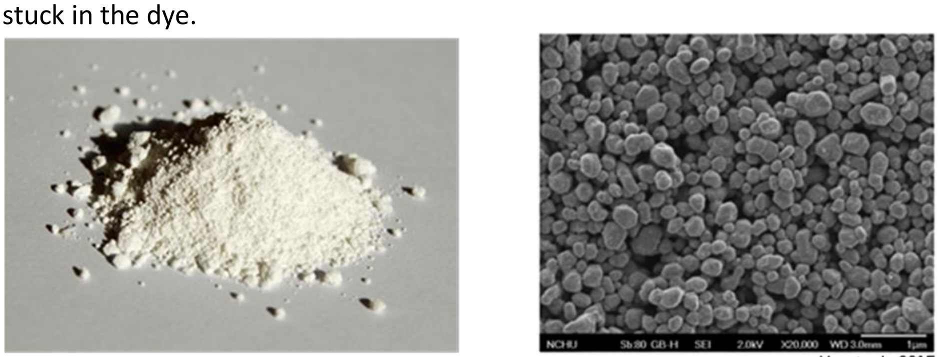
*Figure 6.* Small pieces of semi-conductor wafers like those shown above can be found in almost of our modern electronics as well as solar cells.




NASA's Imagine the Universe

*Figure 7.* Ultraviolet light, the type of light needed to excite an electron across the $TiO_2$ bandgap is shorter and higher energy than visible or infrared radiation.

For this lab, we will use the semiconductor titanium dioxide, $TiO_2$ with a band gap of 3.2 eV as its conduction band edge is at the appropriate level to move electrons through our circuit. After an electron is excited in the dye molecule by light, it can then fall **down** into the conduction band of the $TiO_2$. If the conduction band was too high in energy, the electrons would have nowhere to go and would get stuck in the dye.



Hu et. al., 2015

*Figure 8.* While a paste made of $TiO_2$ nanoparticles (left) may not look special, a scanning electron microscope can show us the tiny spheres that compose the paste.

To increase the number of dye molecules that can absorb light in our DSSC, we will use we will use **nanoparticle** $TiO_2$ instead of bulk $TiO_2$. These nanoparticles behave the same way the bulk $TiO_2$ does, but create a much larger surface area to which dye molecules can attach (Figure 8).

Recap Question #4:
Why is it important to use nanometer-sized particles for the film? Use the phrase "surface area" in your explanation.

## *What is an appropriate circuit?*

When we connect the dye and semiconductor in an appropriate circuit, we can collect these moving electrons, or electricity, to do work for us! Some components of our circuit we already know. We have discussed our absorber, blackberry dye, and converter, titanium dioxide, but in order to have a current flow, we need a complete circuit. In the same way that we can observe the reduction and oxidation of different metals through the creation of an *electrochemical cell*, we can create a similar, but more compact, circuit with our absorber and converter (*see our chemistry demonstration to learn more about electrochemistry and solar cells)*.

Let's review what we know so far. After a dye molecule, the blackberry juice, absorbs a photon, electrons are excited in the dye. It takes less than 1 picosecond ($10^{-12}$ s) to move an excited electron from the vacancy (or hole) that is left behind when excited, into a lower energy space on the $TiO_2$. When an electron is removed from the excited dye, a dye cation is left behind (Figure 9). To generate current, the electrons in $TiO_2$ must move through an external circuit and recombine with an oxidized electrolyte species (Figure 10). In our cell, the electrolyte solution is an iodide/triiodide solution ($I^-/I_3^-$).

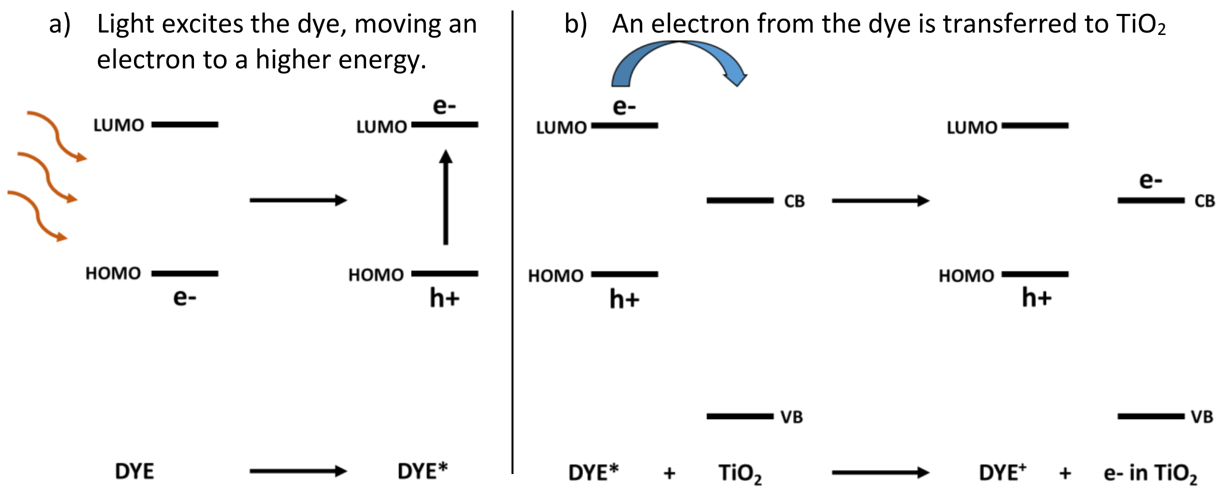



*Figure 9.* (a) Light excites an electron in the blackberry dye from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). The dye in the excited state is denoted as DYE*. This excitation leaves behind a positively-charged hole ($h^+$). (b) Once excited, the electron can fall back down to the original lower energy state to yield the original dye molecule (DYE) or it can be transferred into the adjacent low energy state on the $TiO_2$. This transfer leaves the dye with a positive charge, making it a dye cation ($DYE^+$).

In order to combine these components all together, we need a way connect the dye to this electrolyte solution that allows the collected electrons to travel through an external wire. In this way, we can place a LOAD, such as a small motor or other device, on our circuit. When we generate electricity for use by people around the world, we force the electricity to light lamps, turn on machines, and power technology by directing it through wires made of various metals. So why don't we put all our components on metal plates and connect them?

c) Electrons collected from the $TiO_2$ travel through a wire to reach the counter electrode, where they are used to reduce triiodide

d) Iodide is oxidized to release an electron back to the dye molecule.

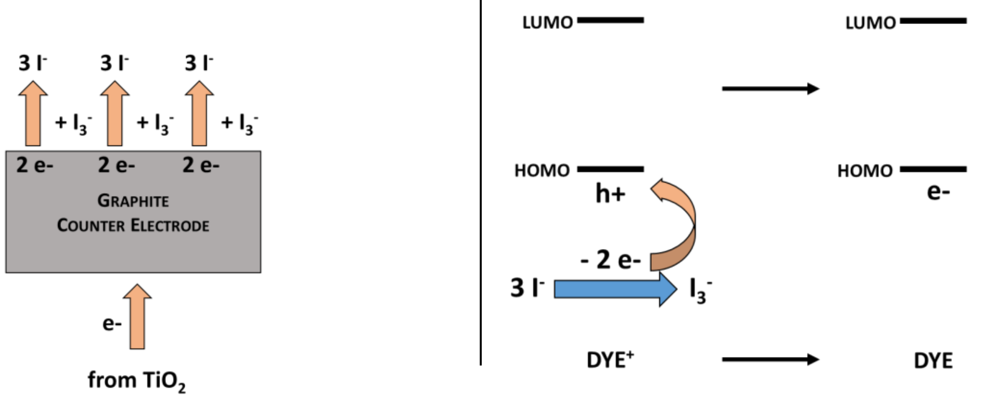



*Figure 10.* (c) Electrons are collected from the $TiO_2$ through a wire, which connects to the counter electrode. At the counter electrode, the graphite coating facilitates the transfer of electrons into solution by reducing triiodide to iodide. (d) When the several iodide molecules ($I^-$) come into contact with a dye cation ($DYE^+$), the iodide can be oxidized to reduce the dye molecule back to its ground state.

Remember that we need to *absorb* light still! Metal isn't transparent. As a substitute, we will use a special glass that behaves like a metal. This glass is coated with fluorinated tin oxide (or FTO) that greatly lowers the resistance of normal glass, allowing it to conduct electrons. To allow it to pass a large enough number of electrons across the liquid/glass interface, we will coat the FTO glass with a layer of graphite, a layered material made of carbon atoms. This carbon-coated glass acts as our counter electrode, the electrode which provides a balancing flow of electrons *into* the solution as they are *removed* from solution by the dye and $TiO_2$. We will make a FTO glass sandwich with our absorber, converter, and electrolyte as the filling to complete our circuit (Figure 11).

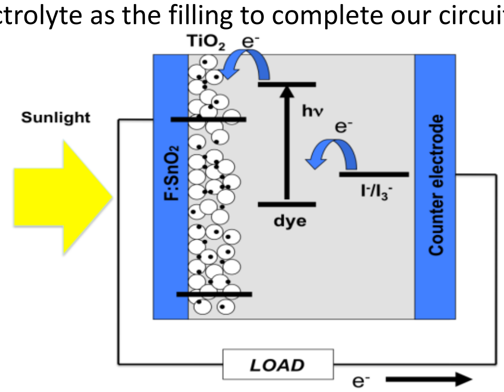



*Figure 11.* A working DSSC makes a complete circuit. Can you identify all of the elements necessary to complete the circuit? Note that the white circles represent $TiO_2$ nanoparticles while the black dots are dye molecules attached to the nanoparticles. In addition to the previously mentioned components, this figure also shows the sunlight as it illuminates the solar cell. To run a device off this solar cell, we would connect the device in the position in between the two halves of the cell, marked LOAD in the above circuit. In this lab, we will connect a multimeter at this position to test our DSSCs.

Recap Question #5:

Graphite is made up of layers of carbon. What do you think will happen to the performance of the DSSC if it was illuminated through this electrode rather than through the dyed side?

## *The origin of the dye-sensitized solar cell*

*Nature*, 2010

*Figure 12.* Michael Grätzel holding a panel of dye-sensitized solar cells.

Brian O'Regan and Michael Grätzel at the École Polytechnique Fédérale De Lausanne in Switzerland made the first efficient DSSC (Figure 12). The approach used in DSSCs has many advantages over other solar energy conversion technologies because of its simple device construction and inexpensive $TiO_2$ particles and dyes that can be fine-tuned to increase their light-absorbing properties. Although there is still much room for improvement, state-of-the-art DSSCs convert solar energy into electricity with efficiencies over 11%, rivaling some silicon-based technologies (commercial silicon is typically around 20 – 30%). These devices use specially prepared dyes that absorb a great deal more sunlight than the anthocyanin dyes extracted from blackberries.

## *The basic procedure*

In this lab, we will make a DSSC using dyes extracted from a blackberry. The blackberry will be crushed, thus releasing its dyes (Figure 13). Then, electrodes that contain a thin layer of white $TiO_2$ paste will be soaked in the crushed blackberries so that the electrodes become colored and absorb visible light.

*Figure 13.* A crushed berry releases juice that we can use to dye our $TiO_2$ slide.

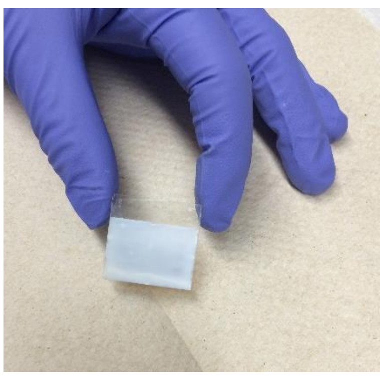


*Figure 14.* This slide is covered in tiny, white semiconductor nanoparticles.

The electrodes are made using a paste of $TiO_2$ nanoparticles that are spread out in a thin layer on transparent conductive glass electrodes (Figure 14). The thickness of the $TiO_2$ thin film ends up being roughly the thickness of a human hair. Remember that these particles provide a huge surface area for the dye molecules to bind and provide an electron pathway for the generated electrical current to be collected. Since the dyed electrode goes from white to dark purple when dyed, a significant portion of light is absorbed by the dye, even though only a single layer of dye molecules is attached to the surface.

The final steps include drying the electrode and then assembling the device with an additional counter electrode to form a "sandwich" solar cell (Figure 15). The device has a total of two electrodes, the dyed $TiO_2$ photoelectrode and a graphite counter electrode. The electrolyte solution is introduced between the two electrodes and is composed of potassium iodide and iodide/triiodide.

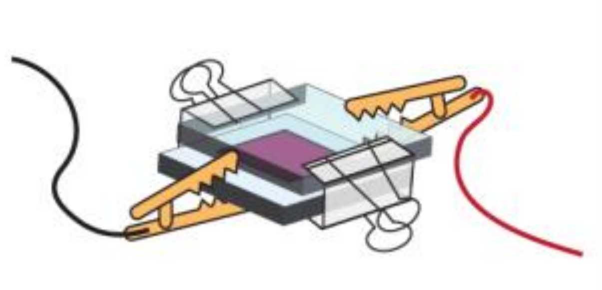


*Figure 15.* The completed DSSC is a $TiO_2$, blackberry, electrolyte, and graphite sandwich that converts sunlight into electricity.

### *What can you expect from the blackberry DSSCs?*

The solar power conversion efficiency of these types of berry-sensitized $TiO_2$ DSSCs can reach ~0.7% with demonstration cells attaining 200-600 μA/cm$^2$ of photocurrent (current observed under illumination) when using an overhead projector as a simulated sun illumination source. Students typically observe photovoltages (voltage observed under illumination) well over 400 mV and good photovoltaic cell stability (Figure 16). Attaching many cells electrically in series results in larger voltages as the voltages of the individual cells are additive; attaching them in parallel results in larger photocurrents.

*Figure 16.* A completed DSSC can be tested using a multimeter.

## Inquiry Opportunity: Renewable Energy

Help your students consider the importance of living sustainably. In what ways, other than installing solar panels, can we help make the world's energy use more sustainable? What is renewable energy and why is it important? Consider connecting a lesson to this lab, using the following NGSSs:

- HS.Human Sustainability
- HS.Weather and Climate

## Answers to Recap Questions

1. Where does the power come from when we are using a solar cell? (What causes the electrons in the dye to move?)

   The electrons in the dye are excited by photons, or light waves. This energy from the sun generates the current and voltage we can measure in a solar cell.

2. A leaf and a solar cell both convert solar energy into another type of energy. What type does a solar cell make, and what type does a leaf make?

   A leaf collects carbon dioxide and sunlight and converts them into glucose and water. These two products are chemical fuels. The energy from the sunlight is stored in the chemical bonds of the glucose and water. In contrast, a solar cell takes sunlight and converts it into moving electrons, or electricity.

3. The $TiO_2$ semiconductor paste used in this lab is white and used in many commercial products: white paint, toothpaste, powdered doughnuts, etc. Why do we need to use the dark-colored dyes from blackberries to make our solar cell work?

   When something appears white, it is reflecting all wavelengths of the visible spectrum that are hitting it. White is the reflection of all light. If we want our solar cell to work, we need to absorb sunlight rather than reflect it. Thus, we dye our solar cell dark colors, such as blue, purple, or red, to ensure that the cell is absorbing as much light as possible.

4. Why is it important to use nanometer-sized particles for the film? Use the words “surface area” in your explanation.

   Nanometer-sized particles are very small. One strand of human hair is about 100,000 nm wide! These tiny particles are important, because they increase the surface area of our solar cell. When we spread a thin layer of nanoparticles on our conductive glass, FTO glass, and then dye it with the blackberries, we have increased the surface area over which sunlight can be absorbed dramatically. Instead of a simple flat surface, we have a very bumpy, rough surface that allows more dye molecules to attach to the $TiO_2$ and then absorb sunlight for conversion into electricity.

5. Graphite is made up of layers of carbon. What do you think will happen to the performance of the DSSC if it was illuminated through this electrode rather than through the dyed side?

   The graphite is a dark gray so it would absorb sunlight. However, since the carbon cannot efficiently absorb sunlight and then subsequently excite electrons to move through a circuit, the DSSC would simply heat up and dry out.

## Next Generation Science Standards:

HS-PS3-3. Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.* [Clarification Statement: Emphasis is on both qualitative and quantitative evaluations of devices. Examples of devices could include Rube Goldberg devices, wind turbines, solar cells, solar ovens, and generators. Examples of constraints could include use of renewable energy forms and efficiency.] [Assessment Boundary: Assessment for quantitative evaluations is limited to total output for a given input. Assessment is limited to devices constructed with materials provided to students.]

| Science and Engineering Practices | Disciplinary Core Ideas | Crosscutting Concepts |
|---|---|---|
| **Constructing Explanations and Designing Solutions**<br>Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.<br>Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. (HS-PS3-3) | **PS3.A: Definitions of Energy**<br>At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HS-PS3-2) (HS-PS3-3)<br>**PS3.D: Energy in Chemical Processes**<br>Although energy cannot be destroyed, it can be converted to less useful forms—for example, to thermal energy in the surrounding environment. (HS-PS3-3),(HS-PS3-4)<br>**ETS1.A: Defining and Delimiting an Engineering Problem**<br>Criteria and constraints also include satisfying any requirements set by society, such as taking issues of risk mitigation into account, and they should be quantified to the extent possible and stated in such a way that one can tell if a given design meets them. *(secondary to HS-PS3-3)* | **Energy and Matter**<br>Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. (HS-PS3-3)<br>- - - - - - - - - - - - - - - - - - - - - - - - - - - - - -<br>*Connections to Engineering, Technology, and Applications of Science*<br><br>Influence of Science, Engineering and Technology on Society and the Natural World<br>Modern civilization depends on major technological systems. Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks. (HS-PS3-3) |

HS-PS4-5. Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.* [Clarification Statement: Examples could include solar cells capturing light and converting it to electricity; medical imaging; and communications technology.] *[Assessment Boundary: Assessments are limited to qualitative information. Assessments do not include band theory.]*

| Science and Engineering Practices | Disciplinary Core Ideas | Crosscutting Concepts |
|---|---|---|
| **Obtaining, Evaluating, and Communicating Information**<br>Obtaining, evaluating, and communicating information in 9–12 builds on K–8 and progresses to evaluating the validity and reliability of the claims, methods, and designs.<br>• Communicate technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically). (HS-PS4-5) | **PS3.D: Energy in Chemical Processes**<br>• Solar cells are human-made devices that likewise capture the sun's energy and produce electrical energy. *(secondary to HS-PS4-5)*<br>**PS4.B: Electromagnetic Radiation**<br>• Photoelectric materials emit electrons when they absorb light of a high-enough frequency. (HS-PS4-5)<br>**PS4.C: Information Technologies and Instrumentation**<br>• Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them. (HS-PS4-5) | **Cause and Effect**<br>• Systems can be designed to cause a desired effect. (HS-PS4-5)<br>- - - - - - - - - - - - - - - - - - - - - - - - - - - - - -<br>*Connections to Engineering, Technology, and Applications of Science*<br><br>**Interdependence of Science, Engineering, and Technology**<br>• Science and engineering complement each other in the cycle known as research and development (R&D). (HS-PS4-5) |

## Additional NGSS options for this lesson plan:

HS-ESS3-2. Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios.* [Clarification Statement: Emphasis is on the conservation, recycling, and reuse of resources (such as minerals and metals) where possible, and on minimizing impacts where it is not. Examples include developing best practices for agricultural soil use, mining (for coal, tar sands, and oil shales), and pumping (for petroleum and natural gas). Science knowledge indicates what can happen in natural systems—not what should happen.]

| Science and Engineering Practices | Disciplinary Core Ideas | Crosscutting Concepts |
|---|---|---|
| **Engaging in Argument from Evidence**<br>Engaging in argument from evidence in 9–12 builds on K–8 experiences and progresses to using appropriate and sufficient evidence and scientific reasoning to defend and critique claims and explanations about natural and designed world(s). Arguments may also come from current scientific or historical episodes in science.<br>• Evaluate competing design solutions to a real-world problem based on scientific ideas and principles, empirical evidence, and logical arguments regarding relevant factors (e.g. economic, societal, environmental, ethical considerations). | **ESS3.A: Natural Resources**<br>• All forms of energy production and other resource extraction have associated economic, social, environmental, and geopolitical costs and risks as well as benefits. New technologies and social regulations can change the balance of these factors.<br>**ETS1.B: Developing Possible Solutions**<br>• When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts. *(secondary)* | ***Connections to Engineering, Technology, and Applications of Science***<br><br>**Influence of Science, Engineering, and Technology on Society and the Natural World**<br>• Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks.<br>• Analysis of costs and benefits is a critical aspect of decisions about technology.<br>---------------------------------------------------<br>***Connections to Nature of Science***<br><br>**Science Addresses Questions About the Natural and Material World**<br>• Science and technology may raise ethical issues for which science, by itself, does not provide answers and solutions.<br>• Science knowledge indicates what can happen in natural systems—not what should happen. The latter involves ethics, values, and human decisions about the use of knowledge.<br>• Many decisions are not made using science alone, but rely on social and cultural contexts to resolve issues. |

HS-PS4-5. Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.* [Clarification Statement: Examples could include solar cells capturing light and converting it to electricity; medical imaging; and communications technology.] *[Assessment Boundary: Assessments are limited to qualitative information. Assessments do not include band theory.]*

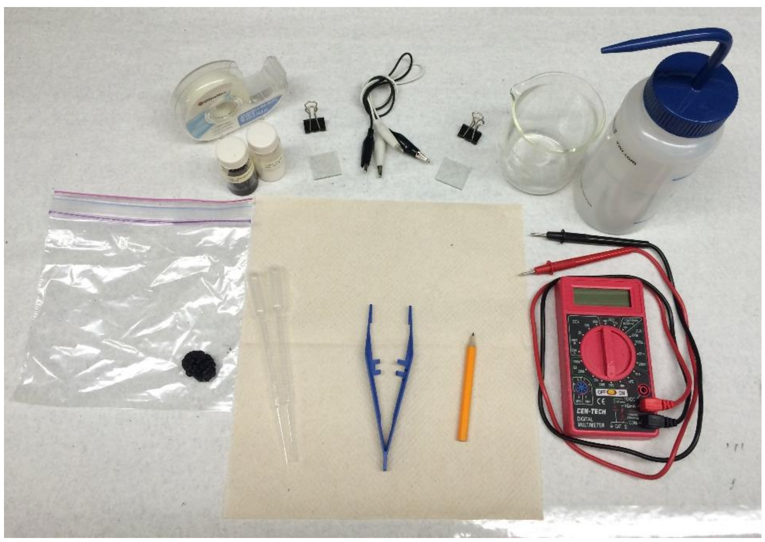
| Science and Engineering Practices | Disciplinary Core Ideas | Crosscutting Concepts |
|---|---|---|
| **Constructing Explanations and Designing Solutions**<br>Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific knowledge, principles, and theories.<br>• Design or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. | **ESS3.C: Human Impacts on Earth Systems**<br>• Scientists and engineers can make major contributions by developing technologies that produce less pollution and waste and that preclude ecosystem degradation.<br>**ETS1.B: Developing Possible Solutions**<br>• When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts. *(secondary)* | **Stability and Change**<br>• Feedback (negative or positive) can stabilize or destabilize a system.<br>-----------------------------------------------------<br>***Connections to Engineering, Technology, and Applications of Science***<br>**Influence of Science, Engineering, and Technology on Society and the Natural World**<br>• Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks. |

# Procedure

### *Materials and supplies*

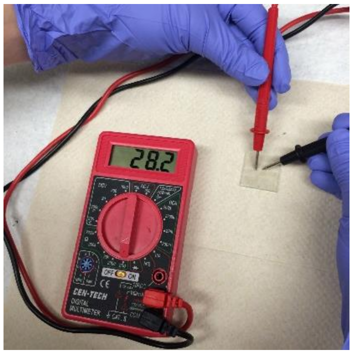
Per pair or group making a cell:

- 1x1" FTO glass (2)
- Small ziploc bag
- 1 Blackberry (fresh or frozen)
- Plastic pipette (2)
- Tweezers
- Paper towel
- Multimeter
- Alligator clips (2)
- Golf pencil
- 1" Binder clip (2)
- Water
- Cup/beaker (optional)
- TiO2 paste
- Iodide/triiodide electrolyte
- Scotch tape
- Hotplate (one or two for whole class)



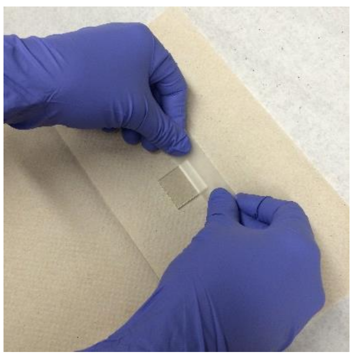
### *Preparing the $TiO_2$ electrode*

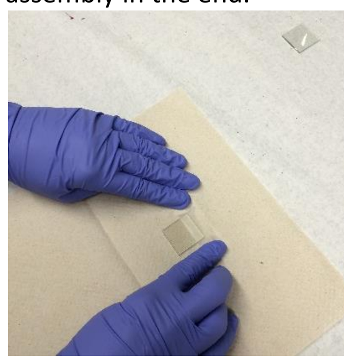

1. Take one piece of the FTO glass and use the multimeter to find the conductive side. Set the multimeter to the resistance setting denoted by the symbol ohm (Ω). If using the model included in the kit, the multimeter dial should just be pointing straight down pointing to 200 ohm.



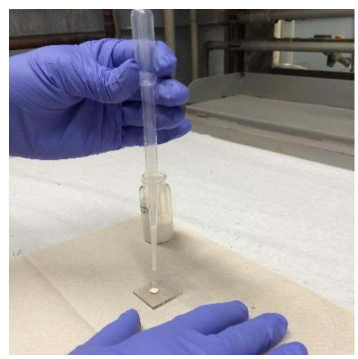

Press the points of the two metal probes onto the surface of the glass, careful that the metal points don't touch. The conductive side will have a reading around 30 ohms. If you don't get a reading (i.e. still see the overflow value of "1"), flip the glass over and try the other side.

2. Once you have found the conductive side of the glass (the side with a resistance reading), set that side face up on the table. Take a piece of scotch tape and cover approximately 1/8" of the surface of the glass as shown here. The remaining open surface area will be covered with the TiO2 paste. The taped off strip will be blank glass which is necessary for assembly in the end.

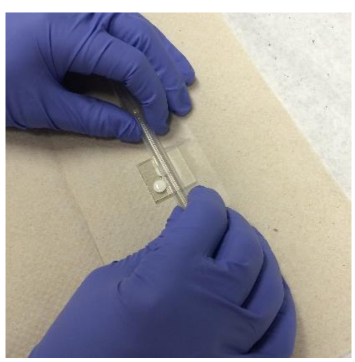


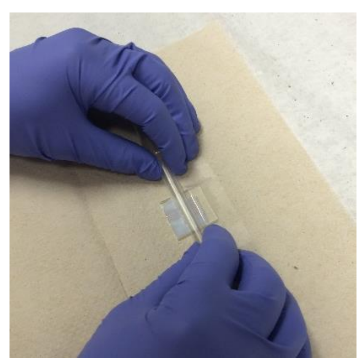


3. Using the plastic pipette, drip a couple drops of the $TiO_2$ solution in the center of the exposed glass. Don't add too much!

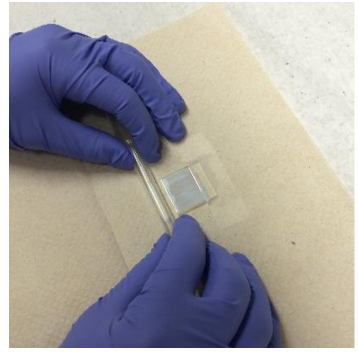


Use the smooth side of the pipette (i.e. no engraved numbers or seam) and immediately squeegee the solution down and up once or twice with the side of the pipette. Aim for a thin, even coating of the paste.





If the $TiO_2$ does not coat the entire exposed surface, quickly add another drop of $TiO_2$ paste and re-squeegee the whole plate. It should be a slightly transparent white color. Allow the paste to dry, undisturbed, for a minute or two. Once dry, remove the tape from the glass.



4. Transfer the glass to a hotplate and leave the $TiO_2$ film face up. The exact temperature of the hotplate is not important. Simply the hotter the plate, the faster it will be done.

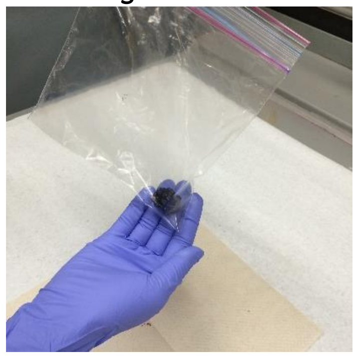


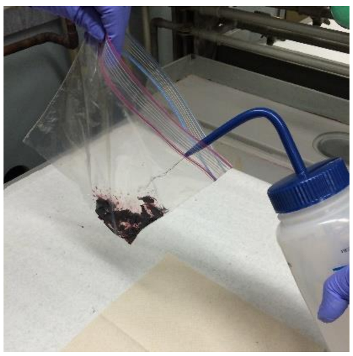
The surfactant and solvent in the paste will evaporate while on the hotplate, leaving behind just the TiO2 nanoparticles. The glass will appear to turn brown or burned, and then white again.

5. When the glass is done (i.e. the slide turned brown and then back to white), turn off the hotplate and let the glass cool down slowly. If the glass is moved too quickly from hot to cold it will crack. Even touching it with the tweezers can sometimes be enough of a temperature shock to cause cracking. A small crack usually won't cause problems with the effectiveness of the cell, but best to avoid. The plastic tweezers can also melt so wait for the plate to cool mostly.

## *Dyeing the $TiO_2$ electrode and assembling the DSSC*

6. Prepare the dye by thoroughly (but gently) crushing 1 blackberry inside a closed plastic bag by squeezing the outside of the bag.

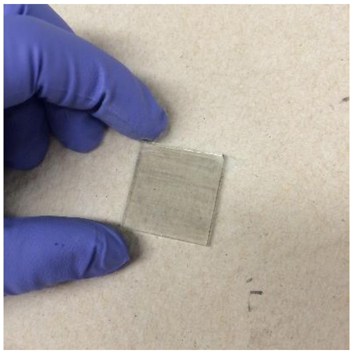




Careful not to poke any holes! Open the bag and add approximately 1 tsp of water to make it a little "juicier".

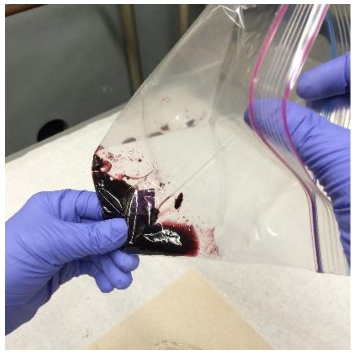
7. Take the $TiO_2$ coated piece of glass and place it into the blackberry juice in the bag for 1-5 minutes. Be sure that the glass is completely covered. The white $TiO_2$ paste should turn completely purple so there is no white left. The darker the better!

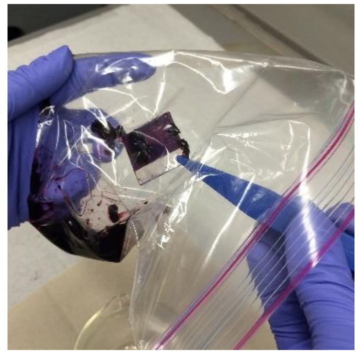
8. While you wait, take your other piece of FTO glass and find the conductive side as in step 1. Set the conductive side face up and use the pencil to coat the entire surface with graphite (pencil lead).

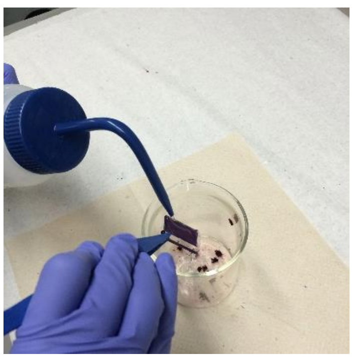


It can be hard to see but as long as you colored there should be graphite on the surface. Set it aside but keep the conductive side face up.

9. Using the tweezers grab the dyed $TiO_2$ piece of glass out of the blackberry juice (try to avoid scratching the film with the tweezers as it will chip off).

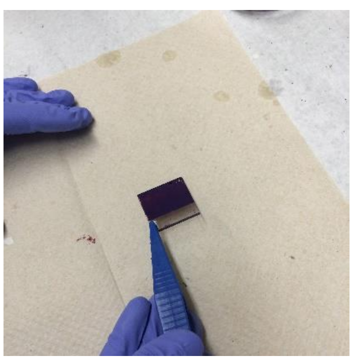


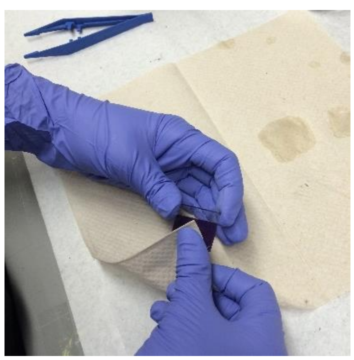


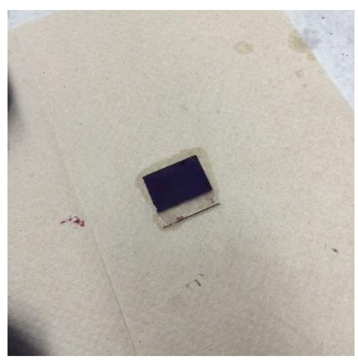


Holding the glass over the opening of a cup or beaker, rinse off the excess blackberry pieces and juice with a squirt bottle of water. Catch the drippings in the cup or beaker. (You can also rinse over the bag being held open by your partner to minimize supplies needed).

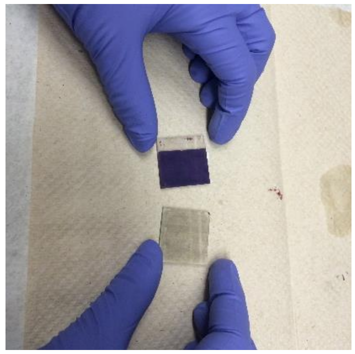
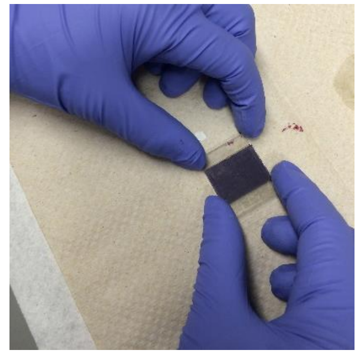
10. Set the rinsed glass onto a paper towel and very gently dab it with the towel to dry it off. DO NOT WIPE the glass as the $TiO_2$ coating will come off.



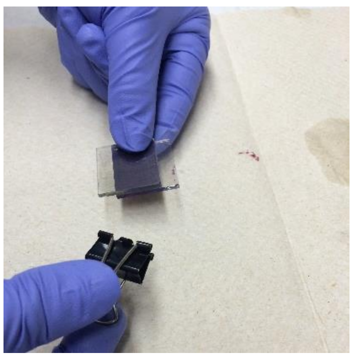
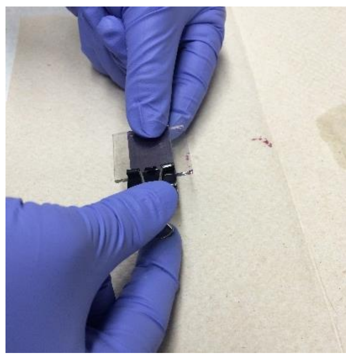
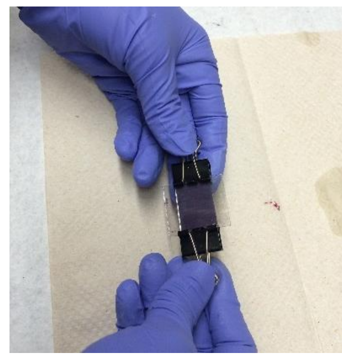




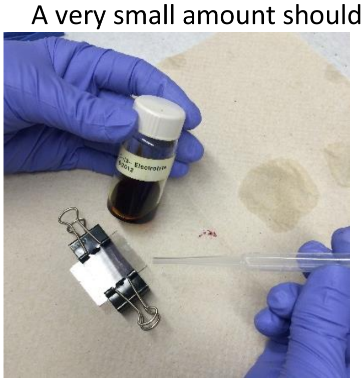
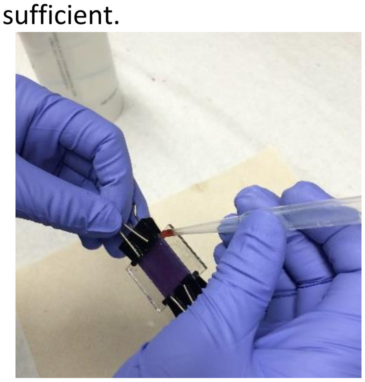
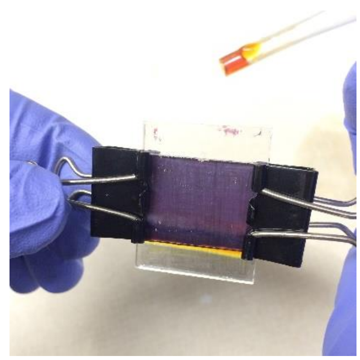
11. Take the two pieces of glass and assemble them into a sandwich with the two conductive and coated sides facing in. Think of a PB&J sandwich: the coated sides face in.

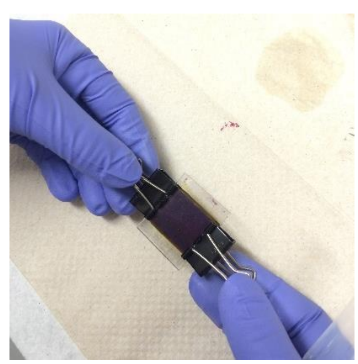
Then, slide the graphite glass out so that its edge aligns with the beginning of the purple $TiO_2$ coating on the other piece. Then using binder clips, clip together the two sides of the glass that are not offset.

12. Lastly, add the iodide/triiodide ($I^-/I_3^-$) electrolyte solution using a pipette to the seam of the glass. A very small amount should be sufficient.

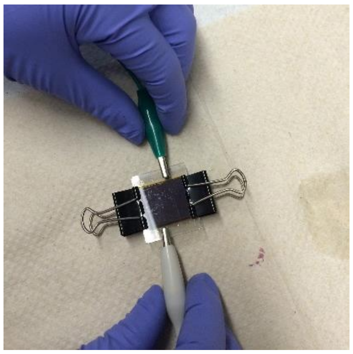




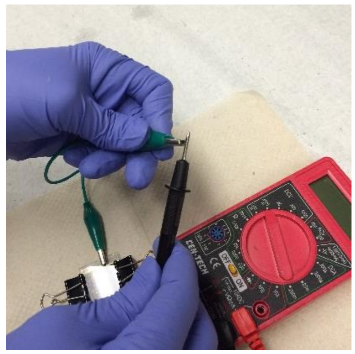
The purple area of the glass should turn darker as it is filled with the electrolyte. If there are any spots that don't get coated, try removing a binder clip and then clipping it back on to move the liquid around. If that doesn't fix it, add a little more electrolyte to the seam.

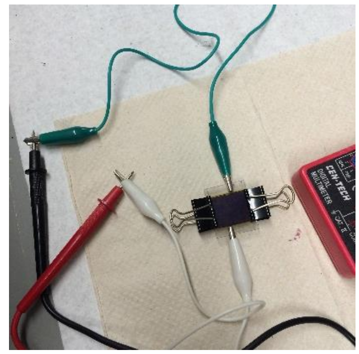


### *Testing the DSSC*

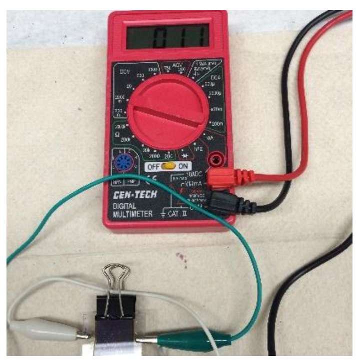
13. The DSSC is ready to generate electricity. All it needs is some sunlight and a way to measure its output! Think of the DSSC as a battery. It has the capacity to generate electricity but you can’t see it until it is used to power a device or tested with a multimeter, which is what you will do.
14. To test your solar cell, clip one end of an alligator clip to one of the overhanging pieces of glass. Clip the other end of the alligator clip to one of the metal multimeter probes. Use the second alligator clip and clip it to the other piece of overhanging glass and the other multimeter probe.







15. Switch the multimeter setting to DCV (Direct Current Voltage) to measure the voltage of the DSSC. The 2000m setting is usually sufficient to measure the output in millivolts. An average reading in full sunlight is around 350 mV.


If the reading is negative, this just means the meter is measuring electricity flowing in the opposite direction. Simply switch which electrode the alligator clips are attached to and the reading will become positive.

* Flipping the DSSC over so the dye is closer to the sun can sometime increase voltage dramatically.

16. Then switch the multimeter setting to DCA (Direct Current Amperage) to measure the current. The setting of 2000µ is usually sufficient to measure the current output. A typical reading in full sunlight is about 700 µA.

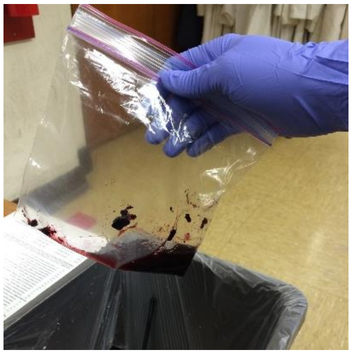
Finally, the voltage and current readings can be multiplied together to obtain the overall power of the cell. Power is defined as follows: P = current*voltage = I*V. Be sure to convert the voltage from mV to V and µA to A before multiplying. See the lesson on scientific notation for help with this process. Remember to record the weather conditions (sunny, cloudy, etc.) and light source!

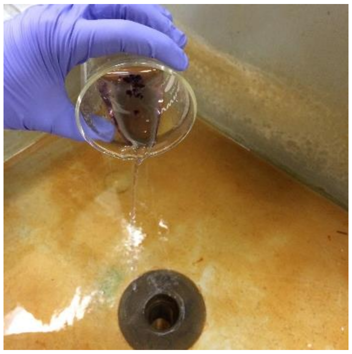
| **Data Table (include units for voltage and current)** | |
|---|---|
| | DSSC<br>dye: |
| Voltage | |
| Current | |

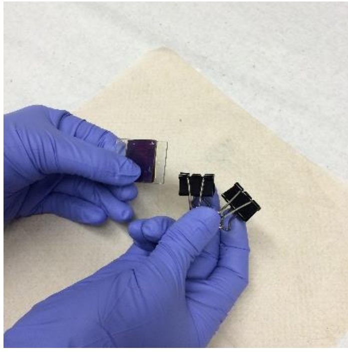
**Light Source (room light, projector light, sun):**
**Weather conditions (sunny, cloudy, rainy):**

### *Cleaning up*

17. Bags of blackberry juice can go in the trash and any rinsing of juice in a cup can go down the sink. Paper towels go in the trash. You can choose to toss plastic pipettes or rinse and reuse them for future classes.







18. Save the FTO glass and simply wipe clean with water and a towel. Graphite is easily removed by a rubber eraser.

19. All other parts are reusable and should be packed away for future use.

## Optional analysis

How do we evaluate whether or not students can successfully fulfill the objectives we set out at the beginning of the lesson? Here are some sample assessment activities based on our example objectives.

**Example Objectives:**
Students should be able to:

1. Communicate how a dye-sensitized solar cell (DSSC) converts light waves into electricity

   In groups of 2-4, draw a diagram of a dye-sensitized solar cell, label the components, and explain on how the cell converts light into electricity. Remember to consider the absorber and converter in your explanation. Make sure your solar cell forms a complete circuit.

2. Design and build a dye-sensitized solar cell from basic components and blackberry juice dye

   Before or after introducing the information from the background section, provide your students with a list of the basic components necessary to make a DSSC. Have them try to place them in the correct order and present their design to the class. Discuss the designs as a class or in small groups. Then, give them the lab procedure and let them build a DSSC.

3. Refine their solar cell design through the comparison of various fruit dyes

   The day before you have the class perform the lab, ask them to vote on one other fruit besides a blackberry to test as a DSSC. Have them list what makes a good absorber in a solar cell. While students fabricate their own blackberry DSSCs, make one DSSC with the class's fruit of choice. Have students compare the data of both DSSC. Return to the initial list of characteristics of good absorbers. Let the class decide if the new DSSC is better or worse than the blackberry DSSC.

4. Evaluate a dye-sensitized solar cell's performance in comparison to a silicon solar cell

   Have your student complete the same analysis they performed on their DSSCs on a commercial silicon solar cell by taping off a similar area as the DSSC and measuring voltage and current with a multimeter. Ask your students to complete a table as shown on the next page and compare these values to that of their blackberry DSSC and other fruit DSSC. Calculate the power ($P = I*V$) and conversion efficiency (below) of the silicon solar cell. Which solar cell performs best? Why?

Calculating solar cell efficiency:
Efficiency is defined as the ratio of power in to power out. That is, the efficiency of a solar cell is determined as the amount of power input to the defined area that is then converted into output power.

$$\text{Efficiency} = P_{max}/P_{IN} = I*V/P_{IN}$$

$P_{IN}$ is generally assumed to be 100 mW/cm$^2$. For a 1 cm x 1 cm solar cell (area of 1 cm$^2$), the input power is 100 mW. $P_{max}$ is the product of the measured voltage and current of your solar cell.

Example expanded data table:

| **Data Table (include units for voltage and current)** | | | |
|---|---|---|---|
| | DSSC<br>dye: | DSSC<br>dye: | Silicon Solar Cell |
| Voltage | | | |
| Current | | | |

## References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