Solar Cell Classroom Set
User Guide
About the Solar Cell Classroom Sets

The Solar Schoolhouse makes Solar Cell Classroom Sets for hands-on explorations of solar power and electricity. This User Guide shows how to use & maintain this equipment, and includes a number of student exercises for developing an understanding of basic electric theory and the photovoltaic effect. There are also troubleshooting tips and suggestions for repairing solar cells.

Activities using the Solar Schoolhouse Solar Cell Classroom Set range from qualitative to quantitative experiences. Solar cells can be used with kindergarten classes to experience the photovoltaic effect (sunlight makes the motor spin) or with colleges and trade schools to plot the IV curves of solar modules.

Students can build simple circuits to power a variety of electrical loads. Radios, motors, a water pump, even model cars and homes can be powered with the Solar Cell Classroom Set. Some classes make solar power plants to run miniature “utility grids” in their classroom. Using this kit, students develop their scientific observation skills, meet the standards while studying electricity, and learn about renewable energy sources. Most importantly, these activities show students positive alternatives for our energy future, and foster optimism, excitement, and a sense of purpose.

Solar Cell Classroom Sets and video tutorials on their use are available from: www.solarschoolhouse.org

These video tutorials are also on the Teaching Solar DVD. Please check the website periodically for new activities, and consider sharing any new ones you’ve had success with.

What’s In the Solar Cell Set

The Solar Cell Set includes enough solar cells, motors, and equipment to engage a classroom full of students. Contents include:

- 30 Solar Cells each able to produce electricity at 0.5 volts and 0.4 amps (400 milliamps).
- 4 Solar Modules each able to produce electricity at 3 volts and 1 amp (or 3 watts).
- 16 motors that run at 0.5 volts to 5 volts - the motors come with wire leads attached.
- Assorted fan blades & wheels that attach to the motors.
- 1 - 3 volt radio with speakers.
- 1 Digital Multimeter (DMM).
- Assorted DC loads: 4.5V buzzer, 5V fan, 12V fan.
- 10 mini jumper wires with alligator clips.
- A sturdy case to organize and protect the equipment.

Before You Begin

Before you first use the Classroom Set, we recommend the following steps:

- Remove and dispose of all plastic covering the solar cells and modules (or the plastic will eventually melt permanently to the cell, reducing the amount of sunlight that enters).
• Mark the backs of the solar cells and modules with a permanent ink pen (e.g. Sharpie). Write your class or school name, and a number showing how many cells or modules there are (e.g. #1 of 30). This helps to keep track of all the cells after a day of use.

• Remove all plastic bags from around the motors. Consider using a piece of tape to hold the white wires to the body of the motor for strain relief. This keeps the wires from pulling out of the motor if the motors get swung about by the wires.

• Add a spot of solder to the jumper wires after sliding the boot back off the alligator clip. This will help reduce future troubleshooting if one of the jumpers has a weak connection at the clip. You can opt not to solder the clips before using the set, but consider doing it later on.

## Optional Tools & Materials to Add to the Solar Cell Set

Handy to have, but not absolutely necessary:

- Wire strippers & cutters
- Soldering iron (30 or 40 watt unit, e.g. Radioshack)

Other Accessories:

- Velcro strips for attaching solar cells & modules to small mounts (cardboard, thin wood)
- Wood or cardboard for making SOLRAD™ meter, & for small solar cell mounts
- Clear tape for strain relief on motors, &/or solar cells
- Additional multimeters, for SOLRAD™ meter & for additional stations
- Bilge Pump, 12VDC, pumping water. (e.g. Attwood T500)
- Other DC loads – e.g. LED lights (green, red, white), larger boom box. Small battery powered loads that can be powered using the solar cells & modules.
- Reflective Funnels - made of aluminum foil and manila folders.

## Potentiometers for use in the IV CURVETESTER (see page 145).

- Choose a Potentiometer (aka Rheostat or Variable Resistor) with an amp rating larger than the Isc (short circuit current) of the solar cell or module being testing. Since the amp rating is not always listed, one can calculate amps with Ohm’s Law:

\[
I = \sqrt{\frac{\text{Watts}}{\text{Resistance}}}
\]

- Ohmite makes a 12.5w 6 ohm potentiometer that can handle 1.44A, which would cover each of the solar cells and modules in this set. (Ohmite Part #RES6R0E). (www.ohmite.com)

## Packing up the Solar Set

It’s a good idea to inventory the set before and after each use to make sure all the parts are there. The Inventory List on the next page can be photocopied for this purpose. Get in the practice of putting away all components as neatly as possible. This makes it easier for the next use.

- Count the solar cells & use a rubber band to group them together in the case.
- Put radio, small fans, buzzer all in one box.
- Count the motors. Wrap the white wire around each motor & secure with a rubber band before putting in the case.
- Gather the jumper wires together. Tie together with an overhand knot or a rubber band.
- Leave the blue fans on the motors. They are easy to damage when removing.
Check the inventory before and after using this Solar Cell Set to make sure all the parts are there.

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<thead>
<tr>
<th>Date</th>
<th>Inventoried by</th>
<th>Item</th>
<th>Start ✔</th>
<th>End ✔</th>
<th>Comments</th>
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<td>30 single solar cells</td>
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<td>10 wheels for motors</td>
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<td>10 blue fans for motors</td>
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<td>1 digital multimeter &amp; leads w/ alligator clips</td>
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<td>1 - 5 volt fan</td>
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<td>1 - 4.5 volt buzzer</td>
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</table>
Electricity from the Sun
Congratulations! You’re about to change sunlight into electricity. The device that does this is called a photovoltaic cell. It’s also called a solar cell, or a PV cell. The term photovoltaic combines photo, from the Greek word for light, with voltaic, named after Alessandro Volta, a pioneer in the science of electricity.

Photovoltaic cells have no moving parts, need no maintenance, and run silently, without polluting the environment. They are made of a semiconductor material, typically silicon.

Invented in 1954 at Bell Labs, silicon solar cells were first developed for the space program. Many of the early cells still produce electricity, and photovoltaics continue to power the next generation of satellites and space technology. On Earth, they are the most cost-effective and reliable power source for many remote applications, like highway signs, navigation buoys and emergency call boxes. They also power an increasing number of homes and businesses.

How Solar Cells Work
Silicon is the most common element in the Earth’s crust. It’s also the main ingredient in beach sand, but it must be highly purified to make PV cells. The silicon in PV cells is treated chemically to create a negatively charged layer on top, and a positively charged layer on the bottom. Wires are usually attached to both sides of the cell.

When sunlight penetrates the solar cell, electrons are dislodged. The structure of the cell forces these loose electrons to flow through the wires, forming an electrical current. This is called direct current, or DC electricity because the current flows in only one direction. This is the same type of electricity available from batteries.

Several PV cells can be laid side-by-side to form a rectangular solar module (or photovoltaic module). The more PV cells in the module, the greater the current and voltage it delivers. Several solar modules together form a solar array.

Photovoltaic System Types
The simplest photovoltaic systems connect PV cells directly to the device being powered. A common example is a solar powered calculator. These are called PV Direct Systems, and they only work when light is falling on the solar cells.

To have power when the sun isn’t shining, one or more batteries are added to the circuit. This is called a Battery Backup or Stand Alone System, and it usually has a device called a charge controller to make sure the batteries are charged correctly.

The type of electricity we get from the utility grid changes direction, or alternates 60 times a second. It’s called alternating current, or AC electricity. To run most household appliances with solar panels, a device called an inverter is used to change the DC electricity from the solar array into AC electricity.

Some inverters can feed excess energy from a solar array into the utility grid. This is called a Grid Tie System, and batteries are not needed because the utility grid supplies power at night and on cloudy days.
Solar Electricity Challenges

These challenges start with simple qualitative explorations, and progress to complex quantitative projects. They work well individually or as part of series of increasingly more advanced activities.

Many teachers give students the elements of circuits - solar cells, motors and jumpers - and let them make their own systems. After this students are better prepared to understand the series-parallel handout on the next page. Once they’ve reviewed it, they can be challenged with the specific projects below. There are detailed activity guides in the following pages. We suggest working through the guides yourself before attempting the activities with students.

Where appropriate, we recommend giving students an opportunity to solve these challenges independently before presenting them with the project guides for each activity.

Simple Circuits with the Solar Cell Set:

- Individually, wire a solar cell and motor together. Notice speed. Point in different directions, reverse polarity, then add another cell in series and repeat. What happens when you shade one cell? Why?
- Build a parallel circuit using the 0.5v/0.4A solar cells with a motor & fan. Does the fan spin faster with 2 solar cells in series or 2 solar cells in parallel? What happens when you shade one cell? Why?
- Group circle circuit. Create a group series circuit – one person has a small 0.5V solar cell, and the next a motor, or see how many motors can run on a 3 watt module.

Powering a Radio with Sunlight:

- Radio Challenge - Build series circuits to power the 3 volt radio using 0.5 volt solar cells. Measure volts and amps. Show students that the mini radio requires 2 batteries that each produce 1.5 volts. The batteries are placed into the radio in series. Thus the radio needs 3.0 volts of power for proper operation. (1.5 volts + 1.5 volts = 3 volts).
- The challenge for the students is to create a 3-volt power source using the 0.5 volt cells. Have them predict how many solar cells will be needed (6) and have them sketch a diagram for how to wire it.
- Made in the Shade - create a circuit to power the radio when the solar cells are in the shade (diffuse sunlight). Build series/parallel circuits to power the 3 volt radio using 0.5 volt solar cells. The teacher can measure the amps and volts.

Solar Powered Boombox:

- To reinforce student understanding, have them fill in the activity guide. Or, if materials are available, challenge them to analyze the power requirements of an actual boombox and power it with the 3 watt modules.

Using a Digital Multimeter & the Solar Cell Set:

Note: Use the reference guide when doing this project. Digital Multimeters can be damaged if used incorrectly.

- Measure Volts and Amps of single solar cells, and of series and parallel circuits.

Using the SOLRAD™ Solar Radiation Meter

Note: Use the reference guide when doing this project.

- Build a simple tool to measure the intensity of sunlight during solar energy experiments. This meter will be used to measure the efficiency of solar cells and modules in the next activity.

Making the IV CURVETESTER

Note: Use the reference guide when doing this project.

- Build a simple tool to measure the output characteristics of a solar cell or module. Graph an IV (Current & Voltage) curve, and, with a SOLRAD™ meter, measure the conversion efficiency of photovoltaic devices.

Solar Altitude & Module Tilt Angles:

- Find the sun’s altitude with a Sun Angle Quadrant (p.87). Then find the best module tilt angle for that altitude.

Other Challenges:

- Build Series and/or parallel circuits to power the fan (5v /0.1A) using 3V/1A or 0.5V/0.4A solar cells.
- Design a circuit to power the buzzer or the 12V fan.
Series & Parallel Wiring

Two basic units of electricity are **volts** & **amps**. Volts measure the force that pushes an electrical current through a wire. This current is a stream of electrical particles. **Amps** (or **amperes**) measure the number of particles moving in the stream. No matter what size a silicon solar cell is, it produces ~0.5 volts (at 25°C). Larger cells supply more amps than smaller cells. Wiring PV cells in series &/or parallel is done to increase the volts and amps to power a given load.

**Series Wiring** – When solar cells are connected in a string, from positive (+) to negative (−) between each cell, the voltage of the cells is added together. The total current (amperage) is the same as a single cell. Red wires are usually (+) & black wires (−).

**Parallel Wiring** – When PV cells are wired in parallel, the positives (+) of each cell are connected together, and the negatives (−) are connected together. The amperage of all the cells is added together; the voltage stays the same as a single cell.

**Series/Parallel Wiring** – Sometimes we need to combine both series and parallel wiring to get the voltage and amperage needed to power a given device. The circuit shown has two series “strings” providing 1 volt & 1 amp each. These strings are then wired in parallel to increase the current to 2 amps & keep the voltage at 1 volt.

**Series/Parallel Wiring Exercise** – Draw the needles on the meters to show the correct voltage and amperage in the circuit on the right. Record your answers below.

**Series** (+) to (−) adds volts.
**Parallel** (+) to (+) & (−) to (−) adds amps.

**Volts:** _______  **Amps:** _______
Simple Circuits with the Solar Cell Set

Explore series and parallel circuits with a photovoltaic cell (solar cell) and a DC motor. Find out how to make the motor turn faster, and which circuit works better on a cloudy day.

Record your results for the following experiments on a separate sheet of paper.

Materials
- Solar cells (also called PV cells)
- Direct current hobby motor
- Plastic fan

Simple Circuit to Motor
A simple circuit includes a power source (the solar cell), conductors to carry electricity (wires), and a load (the motor).

1. Clip the wires from the solar cell to the metal rings at the end of the motor wires. Aim the solar cell at the sun and observe. Change the angle of the solar cell to the sun. What angle makes the motor spin fastest?
2. Notice which way the motor spins. Reverse polarity by switching the alligator clip connections on the motor wires, and observe. What happens when you reverse polarity?

Set Up
1. Push a fan onto the motor shaft about 1/8” to 1/4.” Once attached, leave the fan connected to the motor; the blades might break if you try to remove the fan.

Series Circuit to Motor
Series wiring connects PV cells in a chain, from positive (+) to negative (–) between each cell. There’s only one path for the electricity to follow; through one cell after another & then through the load.

1. Connect the black (-) wire of one solar cell to the red (+) wire of another cell. Connect the remaining wire from each cell to the motor wires. Is the motor’s speed different than it was in the simple circuit? How?
2. What happens to the motor’s speed when you connect more cells in series?
3. What happens when you shade one cell? Why do you think this happens in a series circuit?

Parallel Circuit to Motor
When PV cells are wired in parallel, the positives (+) of each cell are connected to one side of the load, and the negatives (-) of each cell are connected to the other. This gives two paths for the current to follow through the load.

1. Clip the red wires from two solar cells onto the metal ring on one motor wire. Clip the black wires form the cells onto the other motor wire ring. What is the speed of the motor compared to the simple and series circuits?
2. What happens when you shade one cell? Why do you think this happens in a parallel circuit?

NOTE: Parallel circuits are useful for powering loads when there is less sunlight, like on a cloudy day.
You’re challenged to power a radio with solar cells. You need to figure out how many volts the radio needs, and how to connect the solar cells to provide the needed voltage.

You know the following:

- Each solar cell supplies 0.5 volts and 0.4 amps in full sun.
- Alkaline batteries supply 1.5 volts when fully charged.

Start by counting the number of batteries the radio uses, and multiply by 1.5 volts to get the voltage the radio needs. Then wire solar cells in series to supply that voltage.

**Example:**

The Solar Cell Set radio uses two 1.5 volt batteries for a total of 3.0 volts (1.5v x 2 = 3.0v)

6 solar cells wired in series deliver 3.0 volts (6 x 0.5v = 6.0v)

By stringing the solar cells together in series, connecting positive (+) to negative (–) between each cell, the voltage of the cells is added together. The total current (amperage) of the series string is the same as a single cell. Red wires are usually (+) and black wires (–). The positive wire at the end of the series string is clipped to the (+) wire from the radio. The negative wire is clipped to the (–) spring in the battery area.

**Troubleshooting: If there’s no sound:**

1. Make sure the volume knob is on.
2. Set the switch to “spk” (speaker) not phone.
3. Check for a short circuit caused by two alligator clips touching that shouldn’t be.
4. Check the polarity (+) & (–).
5. Check the voltage with a multimeter at the connections to the radio.

**Series-Parallel Wiring**

Suppose you’re in light overcast or shade (diffuse sunlight), and the circuit doesn’t have enough power to run the radio. Although the voltage is right, the cells can’t supply enough current (or amps).

You can wire six more cells in another series string, and connect both strings together in parallel. The positive wires (+) at the end of each string are connected to the (+) radio wire, and the negative wires (–) are connected together to one end of a jumper wire. The other end of the jumper is clipped to the (–) radio spring.

The current (amps) of both series strings is added; the voltage stays the same as a single string: 3 volts.

**Exercise:**

What is the maximum output of the series-parallel circuit on the right in full sun:

<table>
<thead>
<tr>
<th>Volts</th>
<th>Amps</th>
<th>Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.4</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Remember:** Power formula: watts = volts x amps

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You have several solar modules, and are challenged to power a boombox with them. Figure out how many volts the boombox needs, and decide how to connect the solar modules to provide the needed voltage.

**You know the following:**
- Each solar cell supplies 3.0 volts and 1.0 amp in full sun.
- Alkaline batteries supply 1.5 volts when fully charged.

**Exercise:**
The empty battery case of the boombox is shown below, along with a drawing of the first solar module in the circuit.

**Complete the following:**
1. Draw the remaining number of modules you decide will be needed to replace the alkaline battery voltage.
2. Label the positive terminals of the modules with a plus (+) and the negative terminals with a minus (−) as shown.
3. Draw lines between the module terminals and the boombox connections to represent wires.
4. Fill in the blanks at the bottom of the page.

**Draw the remaining modules & connecting wires to power the boombox.**

1. Final output of the solar electric circuit in full sun: Volts ________ Amps ________

2. What kind of wiring did you use? ____________________________

**Extra Credit:**
3. How much power (in watts) does the circuit produce in full sun? ________________

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**Using the Digital Multimeter & the Solar Cell Set**

**CAUTION:** DO NOT use a multimeter to test AC or household electric systems without proper supervision and instruction. DO NOT test battery *amperage* with a multimeter.

**Measuring the OPEN CIRCUIT VOLTAGE (Voc) of a single solar cell:**
This is the highest voltage reading the solar can give, measured when it’s not powering a load.
1. Put the black lead in the COM port, and the red lead in the VΩmA port. Set the dial to the number in the V range that is closest to and greater than the expected voltage of the solar cell. Silicon solar cells produce ~ 0.5 volts open circuit; set the meter to 2 volts.
2. Connect the black multimeter lead to the black wire from the solar cell, and the red multimeter lead to the red wire from the solar cell. Aim the cell toward the sun. Record the reading.

**Measuring the SHORT CIRCUIT AMPERAGE (Isc) of a single solar cell:**
This is the highest amperage reading the cell can give.
1. Move the red lead to the 10ADC port. Set the dial to 10A. The single cells produce ~ 0.4 amps.
2. Aim the cell toward the sun. Record the reading.

**Measuring the OPEN CIRCUIT VOLTAGE (Voc) of two solar cells in SERIES:**
1. Place the black lead in the COM port, and the red lead in the VΩmA port. Set the dial to the number in the V range closest to and greater than the expected voltage of the solar cells. Series wiring ADDS the voltage of cells together. Set the meter to 2 volts.
2. Connect the red (+) wire from one solar cell to the black (-) wire of the next.
3. Connect the black multimeter lead to the remaining black wire from the two solar cells, and the red lead to the remaining red wire. Aim the cells toward the sun. Record the reading.

**Measuring the SHORT CIRCUIT AMPERAGE (Isc) of two solar cells in SERIES:**
1. Move the red lead to the 10ADC port. Set the dial to 10A.
2. Aim the cells toward the sun. Record the reading.

**Measuring the OPEN CIRCUIT VOLTAGE (Voc) of two solar cells in PARALLEL:**
1. Place the black lead in the COM port, and the red lead in the VΩmA port. Set the dial to the number in the V range closest to and greater than the expected voltage of the solar cells. Note: In parallel wiring, the voltage stays the same as the voltage of a single solar cell.
2. Connect the red (+) wires from both cells together, and the black (-) wires from both cells together.
3. Connect the black multimeter lead to both black wires from the two solar cells, and the red multimeter lead to both red wires. Aim the cells toward the sun. Record the reading.

**Measuring the SHORT CIRCUIT AMPERAGE (Isc) of two solar cells in PARALLEL:**
1. Move the red lead to the 10ADC port. Set the dial to 10A.
2. Aim the cells toward the sun. Record the reading.

If a reading is negative, the polarity is reversed: Switch the connections to the PV cells.
Turn the dial to OFF when the meter is not in use, and put the red lead in the VΩmA port.

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*Cells wired in series*

*Solar cells connected to multimeter probes in parallel: the positives (+) of each cell are clipped together, and the negatives (-) are clipped together.*

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Measuring the Sun’s Power

Pyranometers measure the amount of solar radiant energy striking a surface. This solar radiation (also called insolation) is measured in Watts per square meter (W/m²). Pyranometers can be used to gauge the intensity of sunlight during solar energy experiments. This data lets us calculate how efficiently a solar cell or module used in an experiment converts sunlight into electricity (see p.146). Insolation data can be collected at your location over the course of a day, a season, or a whole year. Yearly solar radiation data is useful for predicting how much energy a household solar system will produce.

Typical pyranometers can be expensive: usually several hundred dollars. Fortunately, we can make a low-cost solar radiation sensor using the digital multimeter and a solar cell from the Solar Schoolhouse Solar Cell Classroom Set.

Materials needed for the SOLRAD™ Meter:
- Digital multimeter
- Small mounting board of wood or cardboard.
- Solar cell from the Solar Cell Classroom Set
- Bubble level

Calculating Insolation with the SOLRAD™ Meter

Set up a multimeter and solar cell to measure current (see p.10), and put them on a board with a bubble level. To measure the amount of sunlight hitting a level surface, adjust the board until the bubble is centered, and record the meter’s amp reading. Next we need to convert the solar cell’s amp reading into the units used for insolation (W/m²). To do this we use a conversion equation developed from comparison tests.

A Solar Schoolhouse experiment* compared the output of a solar cell (units of amps) and a pyranometer (units of W/m²) in the same amount of light. It found a linear relationship between amps and Watts/m² (see graph below). The graph charts pyranometer readings on the y-axis in Watts/M², and solar cell output in amps on the x-axis. Solving for y in terms of x to the nearest integer, the conversion equation becomes: $y = 2850x - 52$

Example:
The SOLRAD Meter reads 0.30 amps. Plugging this number into the equation gives a measurement of the insolation at this location:

$2850(0.3Amps) - 52 = 803$ Watts/m²

Note: This specific equation is for use with the mini solar cells found in the Solar Cell Classroom Set. If using a different solar cell, you should repeat the experiment using a pyranometer (e.g. LiCor).

Exercise:
The SOLRAD Meter shown above reads 0.32 amps. The insolation (solar radiation) available is:

$\text{Watts/m}^2$

* Check the Solar Schoolhouse website for cell conversion factor updates: www.solarschoolhouse.org
All solar cells (or modules and arrays) provide a variety of voltages and current flows, depending on the available sunlight, temperature, connected loads, and other factors. At any given moment, a cell’s output voltage times its operating current equals its power output (in watts). This is represented by the Power Formula:

\[ P \text{ [watts]} = I \text{ [amps]} \times V \text{ [voltage]} \]

The output characteristics of a solar cell or module are shown by a performance curve called an IV (Current & Voltage) curve. This curve graphs the relationship between current and voltage output. Most solar modules sold include their IV curves as part of their technical specifications.

An IV CURVETESTER can be used to plot a module’s IV curve. Two meters are connected to a module at the same time; one meter measures voltage, the other amperage (current). The module is also connected to a potentiometer: a variable resistor. The potentiometer is set to several different resistances, and voltage and current readings are taken. These data points are then graphed to plot the IV curve. A SOLRAD™ meter (see previous page) can be used to assure consistent insolation during the tests.

Materials for the IV CURVE TESTER:
- 2 Digital multimeters
- Small mounting board of wood or cardboard
- Screws
- Wire: black and red
- Potentiometer, i.e. variable resistor. See page 2 of this guide for specifications and more information on potentiometers.
  Or use various loads (fan, radio, motors from the Solar Cell Set)

Using The IV CURVETESTER
Tests should be conducted in consistent sunlight. Face the solar module or cell directly toward the sun (perpendicular to the sun’s rays) for the best test. The SOLRAD Meter should also face the same direction. Adjust the potentiometer until the AMPS show 0. The other meter shows the maximum voltage (or open circuit voltage: Voc).

Record current and voltage. Adjust the potentiometer slightly to increase the AMPS and record IV again. Adjust and record the values until you’ve maxed out the amps and voltage is near zero. Then you can finish your data table by multiplying Volts x Amps to get Power (see the table on next page).
To find PowerIN (i.e., solar radiation shining on the solar module): record the SOLRAD™ meter amp reading. Then convert the SOLRAD™ amps to Watts/m² using the following equation:

\[ \text{PowerIN [in W/m}^2\text{]} = 2850(\text{SOLRAD Amps}) - 52 \]

To find PowerOUT: use the maximum power (\(P_{\text{MAX}}\)) from the IV curve tests. Measure the area of the solar cell or module in units of meters. Then solve for PowerOUT using the following equation:

\[ \text{PowerOUT [in W/m}^2\text{]} = \frac{P_{\text{MAX}} \text{ [in Watts]}}{\text{Cell or Module Area [in meters}^2\text{]}} \]

**Example:**

The SOLRAD™ meter reads: 0.36 amps. PowerIN = 2850(0.36) - 52

PowerIN = 974 Watts/m²

Area of solar module = 0.375m \times 0.405m = 0.152m²,

\(P_{\text{MAX}} = 20\) Watts

\[ \text{PowerOUT [in W/m}^2\text{]} = \frac{20 \text{ Watts}}{0.152 \text{ meter}^2} \]

PowerOUT = 131.6 Watts/m²

\[ \text{EFF} = \frac{131.6 \text{ Watts/M}^2}{974.0 \text{ Watts/M}^2} = 13.5\% \]

**Exercise - Calculating Efficiency**

Using data from the IV CURVETESTER table on this page, and a SOLRAD™ meter reading of 0.35 amps, calculate the efficiency of a 55 watt module measuring 1.293 meters long by 0.329 meters wide.
Solar Altitude & Module Tilt Angles

Solar cells and modules provide the most electricity when oriented (or facing) at a 90° angle toward the sun. You can use the Sun Angle Quadrant (p. 87) to find the sun’s altitude (elevation angle above the horizon). Then use simple geometry to find the correct tilt angle for a solar cell or module. Finally test your calculations by measuring the module’s output at various angles with multimeter.

Finding the Best Module Tilt Angle

1. Measure and record the sun’s altitude angle using the Sun Angle Quadrant.
2. Determine the angle at which a solar module must be tilted up from the ground plane to be perpendicular to the sun’s rays.
   - \( a \) = the sun’s altitude
   - \( b = 90° \) module angle to the sun
   - \( c \) = module tilt angle from ground plane

The earth’s surface for our purposes is a level plane, so the sum of the three angles equals a line, or 180°. We know that the optimum module angle to the sun is 90°, and we’ve measured the sun’s angle up from the ground (altitude). So the equation for the module’s best tilt angle from the ground plane is calculated as follows:

\[
a \ [\text{the sun’s altitude}] + b \ [90° \text{ module angle to the sun}] + c \ [\text{module tilt angle from ground plane}] = 180°
\]

Thus: \( c = 90° - a \)

Example:
The sun’s altitude as measured by the Sun Angle Quadrant is 47°.

\( c = 90° - 47° \)

The best module tilt angle for this solar altitude = 43°

Exercise:
Use a Sun Angle Quadrant to measure the sun’s altitude and calculate the best module tilt angle for that altitude.

Date: ___________ Time: ___________

Sun’s altitude: _______ Best module tilt angle: _______

Testing the Calculation

1. Connect a solar module to a digital multimeter.
2. Attach a Sun Angle quadrant to the module with a small binder clip, or removable tape, as shown. Use this to hold the module at the tilt angle found in the above equation.
3. Record the voltage and amperage output by the module.
4. Repeat for higher and lower tilt angles.

The tilt angle at which maximum power is produced should match the one found by the above calculation.

For Extra Credit:
Check sun angle chart for your location to confirm the sun’s altitude at the current date & time.
**Helpful Facts & Figures**

**VOLTS** measure the force that pushes an electrical current through a wire.

**AMPS** (or amperes) measure the number of electrical particles in an electric current.

**WATTS** measure electrical power: the rate at which electricity is generated or used. Volts x amps = watts.

**SERIES WIRING** – Connected in a string: (+) to (−) between each cell or module. The voltage of all the cells is added together; the current stays the same as a single cell.

**PARALLEL WIRING** – All the (+) are connected together, all the (−) are connected together. The amps of all the cells are added together; the voltage stays the same as a single cell.

**THE POWER FORMULA:** Volts x Amps = Watts

**The Power Triangle**

The Power Triangle can calculate all forms of the power formula. Just cover the value to be calculated, and the other values show how to do the calculation.

**Example:**
You have a 60 watt, 12 volt light, and you want to know how many amps it’s drawing. Cover the “I” and you’re left with “P” over “V”, or watts divided by volts:

\[
\frac{60 \text{ watts}}{12 \text{ volts}} = 5 \text{ amps}
\]

**SOLAR CELL & BATTERY COMPARISON CHART**

<table>
<thead>
<tr>
<th>Feature</th>
<th>SILICON SOLAR CELL</th>
<th>BATTERY CELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Function of its chemistry</td>
<td>Function of its chemistry: Fully charged batteries: Alkaline batteries = 1.5V per cell NiCad batteries = 1.2V per cell NiMH batteries = 1.2V per cell Li-ion batteries = 3.7V per cell</td>
</tr>
<tr>
<td></td>
<td>Silicon Cells =~0.5V per cell</td>
<td></td>
</tr>
<tr>
<td>Amps (Current)</td>
<td>Function of the AREA of the cell &amp; the available sunlight. The larger a solar cell</td>
<td>Function of the SIZE of the battery. All energy is stored inside the cell. The larger the battery cell is the more amps it can deliver.</td>
</tr>
<tr>
<td></td>
<td>is, the more amps it can deliver in the same amount of light.</td>
<td><strong>D cell</strong> can deliver more current than <strong>AA cell.</strong></td>
</tr>
<tr>
<td></td>
<td><img src="image1.png" alt="A1" /> <img src="image2.png" alt="A2" /> <strong>A2 can deliver more current than A1</strong></td>
<td></td>
</tr>
<tr>
<td>DC or AC? (Direct Current or Alternating Current)</td>
<td>DC</td>
<td>DC</td>
</tr>
<tr>
<td>Stores Energy</td>
<td>NO (Needs sunlight)</td>
<td>YES</td>
</tr>
</tbody>
</table>
## TROUBLESHOOTING

<table>
<thead>
<tr>
<th>Issue</th>
<th>Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Digital Multimeter (DMM)</strong></td>
<td></td>
</tr>
</tbody>
</table>
| DMM is on but there is no AMP reading | • Make sure the RED (+) lead is in the 10ADC port, & the BLACK (-) lead in the center (COM) port.  
• The Dial should point to 10A.  
• Connect the two DMM leads to the matching color solar cell leads.  
• Point the solar cell toward the sun (or light). |
| DMM is on but there is no VOLT reading | • Make sure the RED (+) lead is in the VΩmA port, & the BLACK (-) lead in the center (COM) port.  
• The Dial should point to 20V or 200V.  
• Connect the two DMM leads to the matching color solar cell leads.  
• Point the solar cell toward the sun or light. |
| The DMM doesn’t work | Change the battery &/or the fuse:  
1. Turn the DMM dial to OFF position  
2. Remove Test Leads from ports.  
3. Slip the protective boot off the DMM.  
4. Remove 2 screws in back & remove cover.  
5. Unsnap contacts, remove & replace 9V battery.  
6. Check & replace the fuse if it’s blown.  
(replacements are available @ Radio Shack)  
7. Reattach contacts, replace the back cover & boot |
| **Solar Cells** | |
| No Volt or Amp reading from the solar cell | Be sure to clip to metal parts of the connectors, not the outer insulator. Make sure your circuit is not creating a Short Circuit. This happens when the + and – clips on the solar cell touch each other, creating a path of least resistance back to the cell, and bypassing the load or DMM. |
| Solar Cell wires detach from the wires | Reattach the wires with a soldering iron. Add a dab of silicone on the wires for strain relief &/or tape the wires to the back of the cell. |
| 2 solar cells wired in series produce no voltage | Instead of + to – series wiring, one cell may be wired from + to the + of the next solar cell. When a positive and negative voltage combine in this manner, they cancel each other out, producing zero voltage. |
| Series wiring doesn’t power the radio | For radios & other electronics, polarity matters, meaning that the + and – wires must match correctly for it to work. Motors will simply spin the other way if the + & – wires are switched. For radios make sure that the last + wire (red) from the solar cells is connected to the + terminal on the radio, and the – (black) solar cell wire is connected to the – terminal on the radio. The connections between the solar cells should still be + to – for series wiring to increase the voltage. |
# Fixing Disconnected Wires on Solar Cells

## Materials Needed
- Solar Cell
- Alligator clips with plastic boots
- Wire strippers
- Soldering iron & solder
- Thin gauge red & black wire
- Needle nose pliers
- Electrical tape
- Solder Sucker or similar tool

## Resources
- *The Art of Soldering*, R. Brewster

## Procedure

| Note: An online search for “How to solder” will bring up many tips and best practices for novice solderers. |

### Attaching Alligator Clips
1. Cut short lengths of red and black thin gauge wire (~18 - 20 AWG)
2. Strip about ¼" of the insulation off both ends of both wires.
3. Feed a wire into the hole in the end of an alligator clip, & crimp the tabs onto the wire's insulation with needle nose pliers (or just crimp the end if there's no hole).
4. Hold down the wire on the inside of the clip with the hot tip of a soldering iron.
5. When the wire and clip are heated, melt new solder onto the joint.

### Attaching Alligator Clip Boots
*Do this before soldering wires to solar cells!*
1. Feed the boot onto the wire.
2. Clamp the clip jaws onto a screwdriver to hold them open, and slip the boot over the clip.

### Soldering New Wires
1. Use a hot soldering iron to melt old solder off the solar cell.
2. Use a “solder sucker” tool to suck up old melted solder. Visit your local hardware store or search online for available sources of this and other solder removing tools.
3. Place clip wire on contact point on solar cell. Hold the wire down with the hot tip of the soldering iron.
4. When the wire is heated, melt new solder over wire.
5. Hold the soldering iron in place until the solder is evenly displaced along the end of the wire and contact point. Let cool.

*Note: it is recommended that if both wires need to be replaced, run the new wires back over the solar cell. Use duct tape or electrical tape to hold the wires to the back of the cell.*
**Directions**

1. Cut on the outside dotted line (A).
2. Cut **HALFWAY** on the dotted line (B).
3. Punch holes for string with a pencil.
4. Fold over on solid line (C) with the printed side out.
5. Fold in half on solid line (D) with the printed side out.
6. Tape the sides of the quadrant together, & tape along line (E).
7. Roll the square section over a pencil to make a tube & tape it to the quadrant.
8. Thread 1 foot of string thru the hole. Enlarge the hole with a pencil if needed.
9. Thread the string thru 2 paperclips & tie the ends.
10. When the tube’s shadow is a circle read the sun’s altitude on the gauge. **DON’T LOOK AT THE SUN THRU THE TUBE!**

**Sun Angle Quadrant**

**NEVER STARE AT THE SUN!**

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**Answer Key**

**Series/Parallel Wiring Exercise, p.6**
Volts = 1.0, Amps = 3.0

**Simple Circuits with the Solar Cell Set, p.7**
Simple Circuit to Motor:
1. 90 degrees or perpendicular
2. The motor spins the other way

Series Circuit to Motor:
1. Yes, the motor spins faster.
2. It spins faster still
3. The motor stops; the current must flow through each cell to get to the motor. If one is shaded the current can’t flow through it.

Parallel Circuit to Motor:
1. The motor spins faster with two cells in series.
2. The motor keeps spinning. There are two parallel paths for the current to follow to the motor.

**Powering a Radio with Sunlight, p.8**
Volts = 3.0, Amps = 0.8, Watts = 2.4

**Solar Powered Boombox, p.9**
Add three more modules (@ 3 volts & 1 amp each) for a total of four modules wired in series.
1. Final output = 12 volts, 1 amp
2. Series wiring
3. 12 watts

**Using the SOLRAD Solar Radiation Meter, p.11**
860 watts/m2

**Making the IV CURVETESTER, p.12**
Exercise - Calculating Efficiency:
PowerIN = 945.5 watts, PowerOUT = 128.9 watts/m2, EFF. = 13.6%