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The Solar Army: A Case Study in Outreach Based on Solar Photoelectrochemistry

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ABSTRACT

Over the last 5 years, researchers at the California Institute of Technology and several partner institutions have been executing a set of public outreach programs unified under the name "The Solar Army." These programs involve students of all ages, from those in primary school to adults, in the enterprise of cutting-edge solar energy research. Herein we present our experience as a case study, outlining the context, history, and structure of the Solar Army and providing perspectives from many of its leaders on their experiences in the program.

KEYWORDS: Solar Army, Outreach, Artificial Photosynthesis, Photoelectrolysis, Juice from Juice, Solar Hydrogen Activity Research Kit, SHArK, Solar Energy Activity Lab, SEAL.

CONTENTS

1. INTRODUCTION

On February 18, 2009, one of us (HBG) took the stage at Caltech's Beckman Auditorium to deliver the monthly Ernest C. Watson Lecture. The closing minutes of the presentation were devoted to demonstrating an apparatus designed for combinatorial screening of metal oxide semiconductors for photocatalytic oxygen evolution. This apparatus had been extensively developed and implemented as an undergraduate research experiment by our colleagues in the Parkinson research group.[1,2] The system was unique in that it made use of widely available components, including the popular LEGO Mindstorms® robotics building set, allowing it to be distributed widely and operated easily. The goal of the program was to develop a simple method to screen metal oxides as photocatalysts, such that the effort could be carried out by thousands of students all over the world. HBG concluded his lecture by inviting the audience to take a closer look at the apparatus, saying

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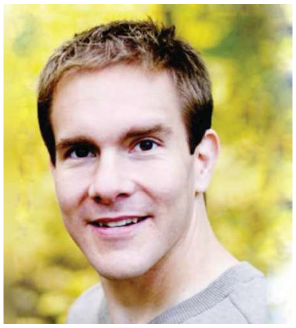
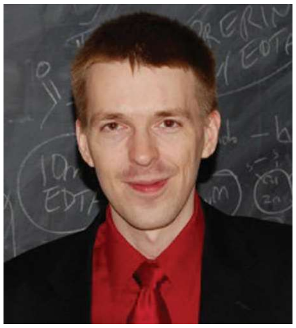
James R. McKone received a B.A. in chemistry and music from Saint Olaf College in 2008 and a Ph.D. from the California Institute of Technology in the Spring of 2013. His graduate studies involved characterization of non-noble catalyst and photoelectrodes for hydrogen evolution from water. He was also heavily involved in outreach as part of the CCI Solar program, mentoring undergraduate summer students and serving as a coordinator of the SHArK/SEAL program for several years. Currently Dr. McKone is pursuing studies on solar-driven batteries at Cornell University as a DOE EERE SunShot postdoctoral researcher.



Shane Ardo is an Assistant Professor of Chemistry, and Chemical Engineering and Materials Science, at the University of California, Irvine. He received his B.S. degree in mathematics from Towson University in 1999, M.S. degree in nutrition from the University of Maryland, College Park in 2005, and M.A. and Ph.D. degrees in chemistry from the Johns Hopkins University in 2008 and 2010, respectively. During his postdoctoral appointment at the California Institute of Technology, Shane was a DOE–EERE Postdoctoral Research Awardee through the EERE Fuel Cell Technologies Office. Shane is a recipient of a Harry and Cleio Greer Graduate Student Fellowship from the Johns Hopkins University and a Postdoctoral Research Award from the Physical Division of the American Chemical Society. Shane was also a high school teacher and community college instructor of mathematics and computer science for a total of three years, and led the Juice from Juice program at the California Institute of Technology for one year.

James D. Blakemore is currently a postdoctoral scholar in Harry Gray's group at the California Institute of Technology, and an active mentor in the Solar Army. James was raised in Kansas and earned an undergraduate degree from Wichita State University before graduating in 2007. James then enrolled at Yale University, where he completed the Ph.D. in Chemistry in 2012 as a student of Gary Brudvig and Robert Crabtree. James then took up a position at Caltech as a Postdoctoral Fellow with the NSF Center for Chemical Innovation in Solar Fuels. Most recently, in 2014, James was awarded a Caltech Resnick Institute Prize Postdoctoral Fellowship in Sustainability Science.



Paul J. Bracher is an Assistant Professor of Chemistry at Saint Louis University. He was a Morse and Beckman Scholar at New York University with David I. Schuster, an Origins Fellow and NSF Graduate Fellow at Harvard University under George M. Whitesides, and an NSF ACC Postdoctoral Fellow in the group of Harry B. Gray at Caltech. Paul's current research focuses on chemistry of prospective importance to the origin of life.

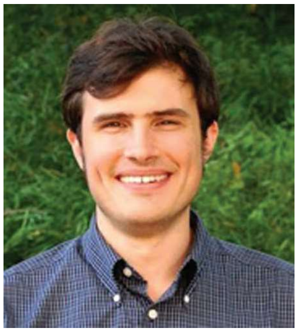
Jillian L. Dempsey received an S.B. in chemistry from the Massachusetts Institute of Technology in 2005 and a Ph.D. from the California Institute of Technology in 2011, where she worked with Harry Gray and Jay Winkler as an NSF Graduate Research Fellow. After carrying out postdoctoral research at the University of Washington with Daniel Gamelin as an NSF ACC Fellow, she joined the faculty at the University of North Carolina at Chapel Hill in 2012. Her research group studies fundamental charge transfer processes that dictate efficiency in solar energy conversion schemes.

Tania V. Darnton is a graduate student in the Gray group at the California Institute of Technology. Besides being an active mentor in the Solar Army, Tania researches the fundamental photophysical processes of diplatinate complexes and tutors local high school students in math, science, and Spanish. She is an NSF Graduate Research Fellow and earned a B.S. in chemistry from the College of Creative Studies at University of California, Santa Barbara.

Michelle C. Hansen works with CCI Solar as the group's Outreach Scientist. She previously worked in the molecular catalysis group at the Joint Center for Artificial Photosynthesis, researching earth abundant catalysts for the reduction of CO_2. She then moved on to pursue informal science education at the California Science Center and the Griffith Observatory before returning to Caltech for her current position. Michelle has a M.S. in chemistry from UCSD, where she worked in the Kubiak lab, and a B.S. from Harvey Mudd College.

W. Hill Harman is an Assistant Professor in the Chemistry Department at the University of California, Riverside. He received a B.S. in chemistry in 2004 from the University of Virginia. After completing his Ph.D. in chemistry from the University of California, Berkeley in 2010 under the direction of Professor Christopher J. Chang, he began an NSF CCI postdoctoral fellowship at Caltech, working in the laboratory of Professor Jonas Peters. In 2013, he assumed his current position. Hill's interests are in molecular inorganic and organometallic chemistry, especially as they relate to issues of energy and sustainability.

Michael J. Rose joined the Department of Chemistry at UT Austin in Fall 2012. His primary interests span several projects in the field of synthetic inorganic chemistry. He graduated from University of California, Davis in 2000 and proceeded to work in industry for two years at Roche Biosciences (Palo Alto, CA). He received his Ph.D. from UC Santa Cruz in 2009, advised by Professor Pradip Mascharak. From 2009–2012, Mike was a postdoctoral researcher at Caltech, advised by Professors Harry Gray and Nate Lewis. There he studied iron-based hydrogen evolution electrocatalysts and semiconductor surface chemistry. During that time, support from CCI-Solar and an NSF Fellowship spurred the development of his H_2 from H_2O program.



Michael G. Walter is an Assistant Professor of Chemistry at the University of North Carolina at Charlotte in Charlotte, NC. He received a B.S. degree in chemistry from the University of Dayton in 2001 and as an undergraduate worked on conductive polymer syntheses at the Air Force Research Laboratory at Wright Patterson Air Force Base. He completed an M.S. degree in 2004 and Ph.D. degree in 2008 at Portland State University studying organic materials for solar cells under Carl Wamser. From 2009–2011, Michael was a NSF-ACC Postdoctoral scholar studying semiconductor-polymer interfaces under Nate Lewis at Caltech. During this time he spearheaded the development of the Juice from Juice program. His current research interests are primarily in organic material synthesis for solar energy conversion and medical applications, and he continues to participate actively in outreach efforts.

Siddharth Dasgupta is the Managing Director of the NSF Center for Chemical Innovation: Solar Fuels at Caltech, a 14 university 21 investigator consortium working on novel catalysts and membrane system for splitting water using solar energy. Prior to this position, he was at various times Associate Director of Industrial Relations and Technology Transfer for NSF Center for Neuromorphic Systems Engineering (CNSE), and Associate Director, NSF Center for Science and Engineering of Materials (CSEM), Member of the Beckman Institute (BI), and was the Director of Simulations for Materials and Process Simulation Center in the BI. Born in India, he got his Ph.D. in chemistry from Princeton University, and did a postdoc at Bell Labs and Caltech.

Jay R. Winkler received a B.S. in chemistry from Stanford University in 1978 and a Ph.D. from Caltech in 1984, where he worked with Harry Gray. After carrying out postdoctoral work with Norman Sutin and Thomas Netzel at Brookhaven National Laboratory, he was appointed to the scientific staff in the Brookhaven Chemistry Department. In 1990 he moved to Caltech, where he is currently the Director of the Beckman Institute Laser Resource Center, Member of the Beckman Institute, and a Faculty Associate in Chemistry.

Harry B. Gray is the Arnold O. Beckman Professor of Chemistry and the Founding Director of the Beckman Institute at the California Institute of Technology. In 1961, after study and research at Northwestern University and the University of Copenhagen, he was appointed to the faculty at Columbia University. In 1966, he moved to Caltech, where for over 40 years he has been doing research in biological inorganic chemistry and inorganic photochemistry. He received the National Medal of Science in 1986; the Priestley Medal in 1991; the NAS Award in Chemical Sciences in 2003; the Wolf Prize in 2004; the Welch Award in 2009; and the Othmer Gold Medal in 2013. He is a Fellow of the RSC and the ACS; a member of the National Academy of Sciences; the American Philosophical Society; a foreign member of the Royal Society of Great Britain; the Royal Swedish Academy of Sciences; and the Italian Accademia Nazionaledei Lincei.

spontaneously, "We will draft you into our army" of solar energy researchers.[3]

Over the next few days and weeks, the response to HBG's lecture was nothing short of stunning. We were deluged with phone calls and e-mails from community members asking how they could get their children involved in the "Solar Army." This unexpected and exciting reaction became the basis of an extensive suite of outreach programs incorporated into the National Science Foundation (NSF) Center for Chemical Innovation Solar Fuels (CCI-Solar) program at Caltech and its partner institutions.

At its core, the Solar Army consists of a group of thousands of individuals, assembled from many contexts, who are all involved in programs developed by CCI-Solar to facilitate education and research on solar energy capture and storage (Fig. 1). There are three core programmatic thrusts: one is called the Solar Hydrogen Activity Research Kit (SHArK) and later adapted into the Solar Energy Activity Lab (SEAL); another thrust is a program called Juice from Juice (JfJ); a third thrust is a set of informal science education (ISE) outreach efforts. All of these efforts were developed and administrated collectively by the authors, along with many coworkers, between 2009 and the present. Several extensions have now been developed that address other aspects of solar energy conversion and storage.

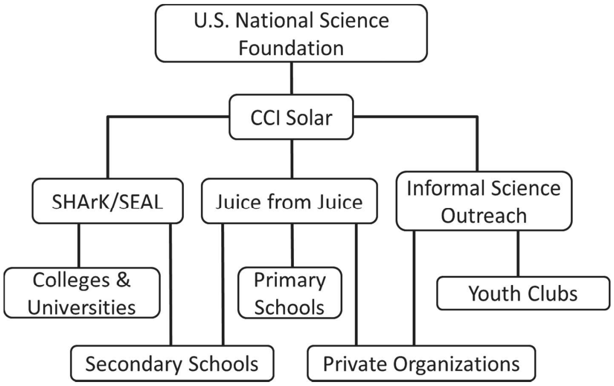


Fig. 1. Organization of the solar army thrust areas.

This account details the efforts we have made to bring modern and relevant science to diverse audiences through the Solar Army. We begin by describing specifics about the content and structure of our various thrusts. Then we address a series of questions that are representative of those we have received during the development of the Solar Army. We hope that this account will motivate and instruct others who are interested in teaching broader audiences—especially youngsters—about the beauty and excitement of scientific discovery.

2. CONTEXT AND HISTORY OF THE SOLAR ARMY

2.1. The SHArK and SEAL Experiments

Solar energy is the single source of renewable power that could completely satisfy humanity's current and anticipated energy needs.[4] However, solar energy only provides a small fraction of the global renewable energy portfolio.[5] A key challenge in scaling solar energy conversion technologies to supply a large proportion of global demand is finding a way to store intermittent solar photons so that their energy content may be transported and used when and where the Sun is not shining.[6] Many methods are available for electrical energy storage, which could be coupled to photovoltaics, solar thermal power generation, wind turbines, or any other energy conversion technology;[7] however, many of these methods are high in cost, low in efficiency, or suffer from very stringent land-use requirements.

The CCI-Solar program has focused on developing components for a unique approach to solar energy storage: using photoelectrochemical (PEC) redox reactions to drive water electrolysis for renewable generation of molecular hydrogen.[8] Devices of this type would in some ways resemble solar cells, but are better characterized as engineered mimics of natural photosynthesis.[9]

Several systems incorporating semiconductor absorbers and heterogeneous catalysts have been demonstrated to facilitate hydrogen evolution with high efficiency and stability.[10–18] However, materials capable of efficient and stable PEC oxygen evolution are not readily available. We consider semiconducting metal oxide materials to be the most likely candidates for PEC oxygen evolution due to their high abundance and thermodynamic stability.[19] Several metal oxides are already known to facilitate solar oxygen evolution, including TiO_2,[20,21] $SrTiO_3$,[22] Fe_2O_3,[23] WO_3,[24,25] and $BiVO_4$,[26] but each of them suffers from poor light absorption, low charge-carrier separation efficiency, low stability, or a combination of these.[27]

We believe that a viable approach for discovery of new materials for PEC water oxidation involves combinatorial experiments intended to identify one or more mixed metal oxide compounds that could facilitate the reaction efficiently and stably. For the CCI Solar SHArK/SEAL program, we drew inspiration from the literature on mixed oxide superconductors, where researchers have shown that superconducting materials with the highest critical temperature values can only be obtained by mixing three or more oxide components.[28] The landscape of available combinations of ternary and quaternary metal oxides is vast, which provides sound justification for a combinatorial research effort.

The SHArK program (where the lowercase "*r*" is used to allow the abbreviation to be assembled from the periodic table representations for sulfur, hydrogen, argon, and potassium) evolved from an experimental approach and apparatus pioneered by the Parkinson research group.[2,29–32] It was subsequently adopted as a primary outreach vehicle for the CCI-Solar program. The main focus of the outreach effort was a method for screening metal oxides for water oxidation activity using a kit incorporating a commercial inkjet printer and a basic photoelectrochemistry apparatus. The components of the SHArK kit were chosen to be inexpensive, readily available, and accessible to young scientists. As noted previously, the experiment made use of the popular LEGO Mindstorms® robotics kit.

A schematic of the original SHArK kit is shown in Figure 2. The combinatorial experiment involved replacing the ink cartridges on a low-cost inkjet printer with modified cartridges filled with aqueous solutions of metal nitrate salts. The tray adapter intended for printing on compact discs was modified to accommodate transparent, conductive (fluorine-doped tin oxide, FTO) glass substrates,

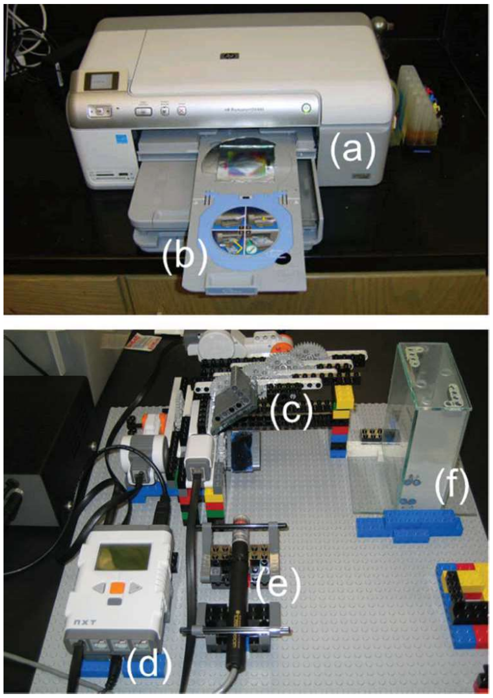


Fig. 2. Images of the original SHArK experimental kit, with the following components labeled: (a) commercial inkjet printer; (b) modified compact-disc adapter tray; (c) building block assembly to facilitate laser rastering; (d) LEGO Mindstorms® motor controller unit; (e) commercial green laser pointer; (f) custom vertically-oriented electrochemical cell.

and the printer was used to deposit a compositional gradient of mixed metal nitrate solutions onto the FTO substrates. The as-deposited solutions were dried and calcined in a furnace or kiln at 400–600 °C for several hours to oxidize the metal nitrates to metal oxides.

The metal oxides deposited on the FTO substrate could be tested for photoanodic activity using a simple potentiostat–coulometer circuit coupled to a rastering light source. The electronic components were designed and assembled in the Parkinson lab and interfaced to custom, distributable software built in the LabView environment. The light source was a class 3a commercial green laser pointer, and the rastering of the beam was facilitated by a pair of mirrors driven by a structure built from building blocks, gears, and stepper motors from the LEGO robotics kit. The metal oxide samples were placed in a vertically oriented electrochemical cell filled with alkaline electrolyte. The FTO substrate was contacted using an alligator clip and biased against a graphite counter electrode. Using this system, even very young researchers were able to collect meaningful data showing, for example, that hematite films are capable of absorbing visible light and producing an anodic photocurrent, and the photocurrent is enhanced by the addition of yttrium oxide (Fig. 3). The use of home-built components and the LEGO kit implicitly demonstrated the accessibility of research to scientists of all ages.

After several years of experimentation with the SHArK system, we developed and deployed a second type of PEC testing system (Fig. 4). This apparatus was based on a fixed array of 64 light-emitting diodes (LEDs) and a potentiostat–coulometer circuit similar to that of the original SHArK station. To differentiate the new testing apparatus from the old, the combinatorial experiment was renamed the Solar Energy Activity Lab (SEAL). A key benefit of the SEAL system was that it contained no moving parts. This feature made it somewhat more accessible for students who did not necessarily have adequate training to address electronic or mechanical errors. Additionally, using an array of 64 LEDs allowed us to transition to a simpler and more inexpensive deposition method involving manually mixing and pipetting metal nitrate solutions onto a pre-defined 8 × 8 square grid.[33] This was particularly useful for young researchers, as it allowed for more hands-on time and helped us teach key chemical concepts such as solution preparation, molarity, and pipette techniques.

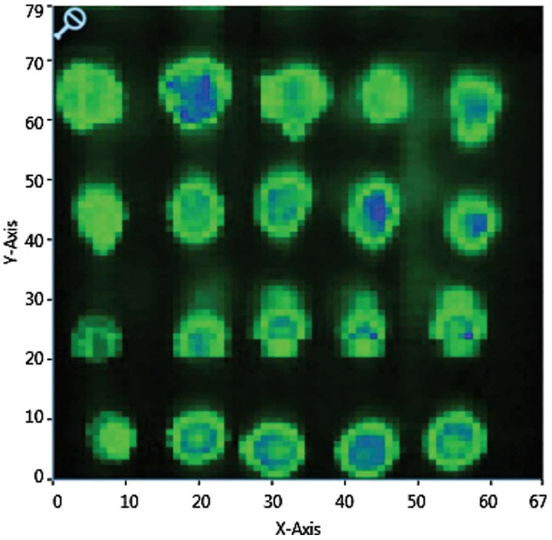


Fig. 3. False color image showing photoactivity for iron oxide (leftmost column) and mixed iron-yttrium oxides (remaining columns) obtained from the SHArK apparatus. Colors corresponding to relative current values are as follows: black < green < blue.

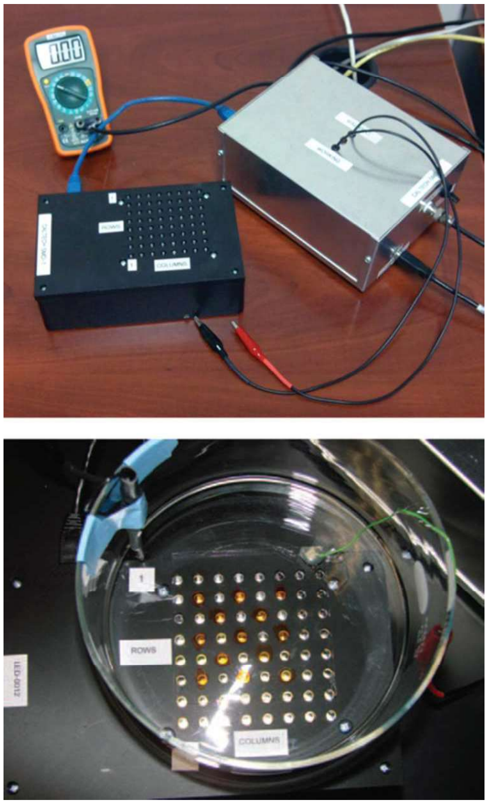


Fig. 4. Top: the main hardware components of the SEAL apparatus, including the LED array, the potentiostat unit, and a multimeter. Bottom: Close-up image of an electrochemical cell assembled for testing over the LED array. Adapted in part from [33], G. R. Winkler and J. R. Winkler, *Rev. Sci. Inst.* 82, 114101 **(2011)**. © 2011, The American Physical Society.

Figure 5 shows an image of an FTO-coated glass substrate onto which Fe_2O_3 spots were deposited in specific positions on the 8 × 8 grid, along with the corresponding three-dimensional bar graph demonstrating the activity of those spots relative to the FTO background activity. Using this system, students have been able to verify the high photoanodic activity of iron oxides and bismuth-based oxides. More recently, students using the SEAL system have shown that adding alcohols to the alkaline test solution significantly increases photocurrent yields for metal oxides, consistent with the known current-doubling phenomena

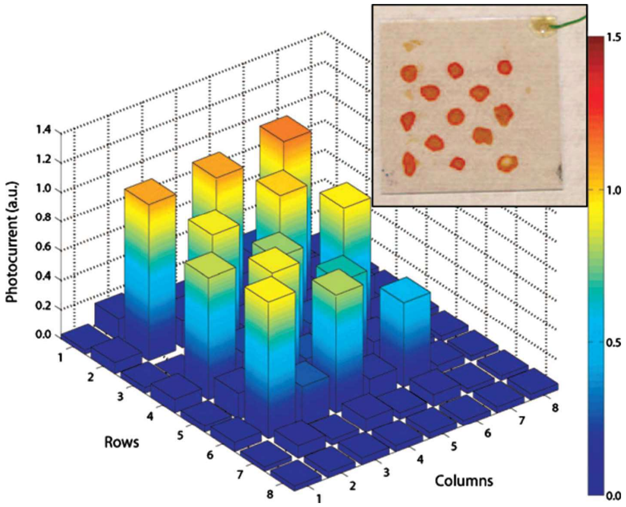


Fig. 5. Data output from a SEAL experiment involving hematite thin films deposited in alternating positions over diodes in the test array. The *x*- and *y*-axes correspond to position on the plate, whereas the *z*-axis corresponds to normalized photocurrent during a light pulse. Inset: image of the sample used for this experiment. Adapted from [33], G. R. Winkler and J. R. Winkler, *Rev. Sci. Inst.* 82, 114101 (**2011**). © 2011, The American Institute of Physics.

for photoanodic alcohol oxidation.[34] In fact, experiments carried out by SEAL researchers have formed a strong complement to ongoing efforts in the CCI-Solar program on development of $BiVO_4$ photoanodes.[35–37] Additionally, undergraduate research at Gonzaga University and recent follow-up experiments by the Parkinson lab have shown that a *p*-type mixed Fe–Cr–Al oxide gives very large negative photovoltages upon illumination in aqueous alkaline solution.[38]

2.2. SHArK/SEAL Outreach Efforts

The first students to experiment with the SHArK kit were summer researchers at primarily undergraduate institutions (PUIs).[1] They worked closely with CCI-Solar researchers in the Parkinson group to test and benchmark the system, and to begin the search for viable metal oxide photoanode materials. The SHArK scanning system was the apparatus that HBG unveiled at the Watson Lecture at Caltech. After the ensuing wave of interest, we adapted the undergraduate program into one that would be amenable for secondary-school students.

The approach that emerged for the high-school SHArK/SEAL program involved small groups of 3–6 students working after school with one or two CCI-Solar graduate student or postdoc mentors. During the first year of the program, teams of students were assembled at three local high schools, and these teams met once per week for several hours to undertake the combinatorial experiments described above. The experimental approach was unique in that there were no predetermined outcomes, no lab reports, and no quizzes or examinations. Rather, the students were considered to be an extension of the CCI-Solar research efforts.

The structure of the SHArK/SEAL program has remained substantially the same since its inception, but it has grown greatly in the number of school sites and in the number of students and mentors involved. We estimate that hundreds of secondary school and undergraduate students from all over North America, and in several locations in Europe, have now participated in the SHArK and SEAL programs. For the Southern California program, we have facilitated a local conference (known internally as SHArK-CON and then SEAL-CON), held on the Caltech campus in the spring, as a culmination of the students' work over the course of the school year. Additionally, many students from a variety of locations have participated in the CCI-Solar annual meeting, held in Southern California each January. In the last few years, we have devoted a full afternoon or evening session at this meeting to our outreach efforts, including presentations and posters delivered by the student researchers themselves.

High school students who have participated in the SHArK/SEAL programs have reported a substantially greater degree of efficacy and excitement about science research. Many of our program alumni have gone on to pursue undergraduate studies in science, technology, engineering, and mathematics (STEM) disciplines. Program mentors have also generally expressed very positive sentiments about their involvement. The second section of this account details some of the positive outcomes for the authors, which are broadly representative of the Solar Army "mentor corps" as a whole.

It is worth noting that the high school SHArK/SEAL program has not yet discovered a mixed metal oxide composition that significantly improves on Fe_2O_3 or $BiVO_4$ as a water oxidation photoelectrode. This fact has not dulled the enthusiasm of our students, who have been unflappable in their excitement for performing research that is real and meaningful to their lives.

Efforts are ongoing to develop and improve the SHArK/SEAL experimental apparatus. For several years, we have involved high school and undergraduate students in summer research projects intended to increase the utility and accessibility of our distributed combinatorial efforts. In fact, the development of the SEAL apparatus was largely a product of these summer research efforts. Several of us have developed teaching materials intended to make the project easier to deploy at high school and undergraduate campuses without local mentor availability. A new generation of SHArK laser scanning systems is also currently under development, which we expect will significantly improve on the reliability and throughput of the original system, while still allowing for the high degree of accessibility for young scientists.

Recently, several programs have developed that are closely related to the SHArK/SEAL program. CCI-Solar collaborators at the University of Wisconsin have developed a companion project called Heterogeneous Anodes Rapidly Perused for Oxygen Overpotential Neutralization (HARPOON).[39] This system uses a fluorescent probe where emission can be detected using a consumer digital camera. The emission is quenched by oxygen, thereby allowing easy detection of oxygen evolution activity for a compositional spread of mixed metal oxides. Already researchers involved in HARPOON have discovered a mixed aluminum-iron-nickel oxide material that shows higher oxygen-evolution activity than iron, nickel, and mixed iron-nickel oxides under alkaline conditions.[40] Also, researchers at the Joint Center for Artificial Photosynthesis (JCAP), a DOE Energy Innovation Hub located at Caltech and Lawrence Berkeley Labs, have developed a sophisticated combinatorial screening system for photocatalysts of all types.[41–44] This effort draws directly from the experience of the Parkinson and Lewis research groups,[29–32, 45, 46] our SHArK/SEAL efforts, and other previous efforts in combinatorial electrochemistry.[47–49]

2.3. The Juice from Juice Program

The Juice from Juice (JfJ) program is a series of discovery-based learning experiments designed for students as young as primary school, built around the concept of the dye-sensitized solar cell (DSSC). DSSCs are a current topic of intense research for practical applications in solar energy conversion. This technology rapidly rose to research prominence in 1991 when a 7% efficient solar cell was reported.[50] Just two years later, a 10% efficient solar cell was demonstrated.[51] These efficiencies rivaled those of state-of-the-art thin-film solar cells, and the exquisite control of properties excited many in the solar research community.

Like natural photosynthesis, DSSCs use chromophores to absorb light and separate charge. In photosynthesis, this separated charge subsequently takes part in a cascade of redox reactions with other molecules, ultimately reducing/oxidizing a final electron acceptor/donor to store electrochemical potential energy. In the DSSC, after initial photo-excitation the separated charges are collected in an external circuit through electron hopping and conduction in a mesoporous thin-film of TiO_2 in concert with the drift of molecular species in an electrolyte solution to an auxiliary/counter electrode to "complete the circuit." The fundamental difference between DSSCs and natural photosynthesis is that electricity is the final product in the former, and not the storage of chemical potential in chemical bonds like in the latter. Figure 6 shows a schematic of the processes involved in the operation of a DSSC.

Chemists have been particularly interested in DSSCs, since they rely on sensitization of metal oxide particles with, e.g., molecular absorbers (dyes) and molecular redox couples to facilitate charge transfer.[52] One can tune the light-absorbing properties of the dyes as well as the solar-cell performance through chemical modification and introduction of additives into the electrolyte. To date, the world-record efficiency has improved to ~12%,[53] but these devices are not currently prevalent in the commercial solar-cell market. Notwithstanding, exciting research into their operation and optimization still exists. The multidisciplinary research involved in these types of solar cells makes them exciting to people with diverse backgrounds, expertise, and interests.

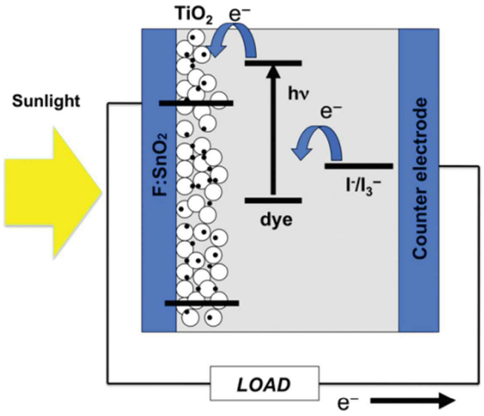


Fig. 6. Basic schematic of a dye-sensitized solar cell used as part of the JfJ workshop.

The high variability of the structure of the dye molecules allows one to fabricate solar cells that absorb over different regions of the solar spectrum. This is very important in artificial photosynthesis research where two light-absorbing solar energy conversion devices are often wired in series to generate the voltage required to drive hydrogen and oxygen evolution. For example, the tunability of DSSCs has allowed them to be incorporated in a device with a >3% efficiency for unassisted solar-driven water electrolysis when coupled to a WO_3 photoanode.[54]

2.4. Juice from Juice Outreach

The original motivation for the JfJ program was to develop a platform to promote understanding of the photophysics of solar energy conversion for students at every level; however, after initial consulting with partner teachers, it became clear that there was a need for a multidisciplinary kit that could be permanently incorporated into the high school science curriculum and would draw on already established science activities. We decided to develop a kit that could be provided to biology, chemistry, and physics teachers, where all of the experiments could relate to a unifying solar-cell activity.

At the heart of the JfJ outreach program is a DSSC module that functions as a multifaceted learning tool and helps to develop concepts of electricity, electrochemistry, nanotechnology, biology–photosynthesis, surface chemistry, and general materials development. There are clear overlaps among the principles encountered in biology, chemistry, and physics, as shown in Figure 7.

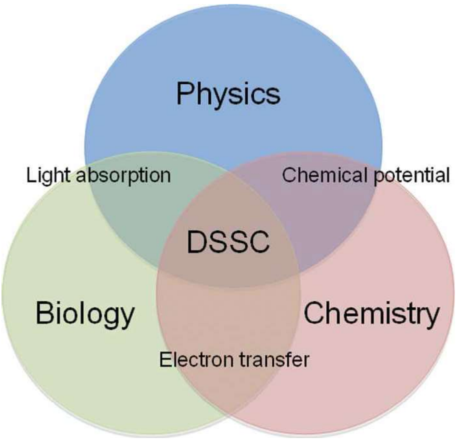


Fig. 7. Venn diagram depicting examples of topics covered in the JfJ program that span the range from chemistry to physics to biology.

Fig. 8. Images of part of an early version of the assembled JfJ kits, which included multimeters, well plates, pipettes, tweezers, binder clips, and vials of chemical compounds that were used for the chemistry and solar cell modules.

The DSSC lesson itself includes building and testing a DSSC using the dyes from blackberries (anthocyanin), pomegranates (anthocyanin), or beets (betalain) as the light-absorbing chromophores. This activity was modeled after one reported previously by Smestad and Grätzel.[55] The complete solar cell also requires a TiO_2 thin film, FTO-coated glass substrates, graphite as a triiodide reduction catalyst, I^-/I_3^- electrolyte, and binder clips to hold the cell together. A key aspect of the experiment is that nearly all of the components involved can be observed in everyday life. For example, TiO_2 is used as a white colorant in paints and toothpaste, transparent conductors are used ubiquitously in flat panel displays and window treatments, graphite is found in pencils, and iodine is used as an antiseptic.

The students cast their own TiO_2 films using a previously prepared paste, add a layer of dye (e.g., from crushed blackberries) to the thin film, deposit the graphite catalysts by physically scratching with a pencil, assemble the cell, and introduce electrolyte via capillary action. The open-circuit photovoltage and short-circuit photocurrent of the assembled DSSC can be measured under illumination from the Sun or another suitable light source using a digital multimeter and alligator clips. All of the required components, except the light source and fruit juices for dyes, are included as part of the kit (Fig. 8). The DSSC activity is meant to be inquiry-based and thus the lesson is flexible and can be tailored to answer questions the students pose, such as *what is the best dye?*, *what is the best electrolyte*?, etc. The lesson includes pictures and a description of the required supplies and instruments, as well as an assessment activity consisting of a laboratory report and post-laboratory questions. We have also developed online instructional videos for each activity.

Three other "lead-in" modules are also included in the JfJ program, each of which can be coupled to the DSSC lab activity. One of these modules is based on biology with the introduction of the role of chlorophyll and the electron transfer processes responsible for photosynthesis. Students conduct a lead-in lab that involves crushing up spinach leaves and examining the various dyes found in the plant pigment by paper chromatography. The students can use the dyes obtained from the chromatography experiment in a DSSC with comparisons being made between chlorophyll and anthocyanin dye obtained from crushed berries or pomegranate seeds. This lab helps to provide substantial overlap between the energy producing processes in a leaf with those occurring in the DSSC.

The JfJ chemistry module includes a galvanic cell lead-in experiment where potential differences between dissimilar metals in aqueous electrolyte solutions are measured. This lab helps relate concepts of chemical potential generated between two metals to the chemical potential generated by the dye-sensitized TiO_2 solar cell. The main concepts for this lab include electrochemical potential, solution phase redox reactions, and the concepts of cathode/anode with corresponding reactions occurring at their surfaces. The third physics-based module explores the properties of a silicon solar cell in comparison to a DSSC, and teaches more about concepts of voltage, current, and power by varying parameters such as incident light intensity and the range of incident wavelengths.

Contained within each lead-in lab and the DSSC lab are several basic lesson plans that take students through several paths to help them discover what basic scientific principles and concepts are being developed. For example, in the physics module, the importance of the light absorption in the DSSC module includes a wavelength-dependent study where only red light is used to illuminate the cell. Students are encouraged to think about other parameters that might be tested, like varying actual fabrication details or testing conditions.

Presenting these coupled activities described above is central to the JfJ program and part of its novelty. The program also caters to the needs of the high school teachers, and it is impacted by their impression about what helps students succeed in the sciences. The high school teachers that participate continually stress the importance of having hands-on activities that the students can explore. It is also important that the modules can be tied to science education standards in order to justify their incorporation into existing curricula.

The JfJ outreach program is structured to provide quarterly workshops where high-school science teachers are invited to come to the Caltech campus to learn about the four modules. The outreach also involves follow-up visits to various sites to help implement the activities in science classrooms. The first high school teacher workshop was held at Caltech in December of 2010 and included a daylong training session with all four science modules presented. The day included hands-on activities and a JfJ kit for the high school teachers to take back with them to try out in their own classrooms.

Feedback about the workshops and the kits has been overwhelmingly positive with a great deal of constructive suggestions for increasing the effectiveness of the laboratories and adjusting the curriculum to fit various class sizes. The teachers who attended the workshops agreed to help further develop the DSSC curriculum through online website resources that included dissemination of lesson plans and instructional videos demonstrating the activities.

Due in part to the significant interest and resulting growth of the JfJ program, we partnered with a commercial supplier, Arbor Scientific, to assemble and distribute kits. Sustained growth of the program has relied on this partnership, as it allows mentors and administrators to focus on developing and executing the teacher training workshops. Feedback from teachers on the quality of the teacher-training program has been generally very positive; however, follow-on evaluations have shown that very few teachers have actually implemented the JfJ curriculum in their own classrooms. Work is underway to address this challenge, as described in a later section of this account.

As with the SHArK/SEAL program, JfJ has motivated extensions for other teaching/outreach efforts that are built on the same kit and teacher-training model. One of us (MJR) developed an inquiry-based electrochemical water splitting kit called "H_2 from H_2O." The idea of this kit is to show, in a simple way, that potential sources of renewable energy, such as solar photons, are readily available. Additionally, the experiment is meant to visually demonstrate a few basic concepts relevant to secondary-school chemistry such as stoichiometry, the ideal gas law, and decomposition reactions. The H_2 from H_2O program involves distributing many (10–15) self-contained kits to a classroom. The students work in small teams to execute the experiment, increasing engagement relative to a teacher-led demonstration activity.

The content of the H_2 from H_2O kit is a home-built electronic circuit capable of controlling the DC power output from a battery, wall socket, or solar cell, and a simple electrochemical cell employing aqueous electrolyte and two nickel electrodes enclosed in inexpensive plastic burets (Fig. 9). Along with these hardware components are included a complete set of teaching instructions, handouts, and materials, so that teachers can have "turn-key" access to a working solar electrolysis laboratory experiment. Teachers have responded very positively to this kit–particularly its ease of implementation in a classroom.

2.5. Out of the Classroom: Informal Science Education

Drawing from our very positive experiences and successes with school-based solar energy outreach, we have recently developed companion programs for informal science education (ISE) outreach outside of the classroom setting. One area of ISE outreach we have pursued is a close partnership among CCI-Solar, the Wildwood School (a Southern California private high school), and the Westside Science Club (WSSC). The WSSC is a club for primary-school aged children that meets every other Saturday morning for two hours in the recreation room of a low-cost housing complex in Venice, California. Most of the students live in this complex and are from under-represented groups in the sciences.

Our work with the Wildwood School and the Westside Science Club is intended as a partnership to provide out-of-school science education to otherwise under-represented groups. Caltech scientists provide expertise in planning activities to communicate understanding about the mission and science of CCI-Solar. Wildwood students serve as "near-peer mentors" to help bridge the age gap and make a more enjoyable and impressionable experience for the science club members. Our intention has been to use this partnership as a platform to develop a generalizable

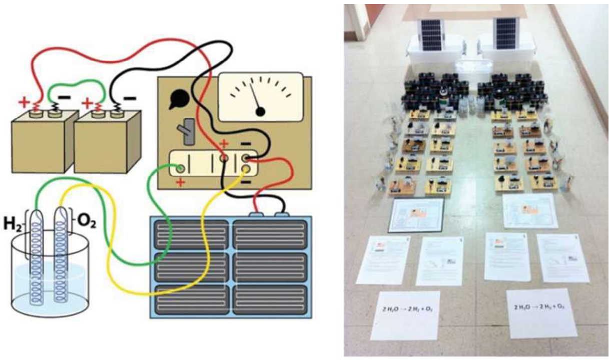


Fig. 9. Schematic (left) and actual (right) H_2 from H_2O experimental kits, including batteries, small solar modules, electrode assemblies, a custom-built electrical control unit, and the associated handouts.

approach to facilitate science outreach for young people outside of the classroom setting.

This program has recently completed its second year, and has been fruitful in yielding useful lessons and teaching/learning materials. During the first year, we planned and maintained 15 experiments. We also wrote lesson plans in anticipation of replicating the experiments in other clubs. Every club meeting included 1–3 activities related to a central theme. For instance, for the "carbon" meeting, we provided dry ice and let the students observe how it sublimated and expanded upon heating and how it acidified water. We also observed how a plastic bottle filled with CO_2 became warmer while sitting in sunlight than one filled with air. These activities helped communicate the importance of CCI Solar's mission in finding cleaner alternatives to fossil fuels.

While most of the Solar Army outreach programs target middle and high school students, the Solar Army has participated in events that widen the audience even more. Specifically, we have facilitated events with the Los Angeles Natural History Museum, where families participated in the JfJ experiment. Very young children and adults were able to learn and participate. Recently we ran a similar event at the Los Angeles Department of Sanitation Earth Day celebration, which had thousands of attendees. We also offer tours of Caltech's labs for students and their families at our annual conference, engaging adult and school-aged audiences simultaneously.

3. NARRATIVE ACCOUNT FROM "FIVE-STAR GENERALS"

This section is structured as answers to a series of questions that we are often asked about our experience in science outreach. The questions are posed as section headings, and the answers are provided in a narrative form from those authors who have served as "five-star generals" (i.e., lead mentors) in the Solar Army. JLD, JRM, WHH, and JDB were heavily involved in the SHArK/SEAL program. Lead mentors for the Juice from Juice program were MGW, SA, and TVD. MCH recently took on administration of the entire Caltech Solar Army outreach effort as a dedicated outreach scientist. PJB was heavily involved in work with our informal science outreach, and he has previously written and presented on the importance of outreach in the scientific enterprise.[56] MJR was responsible for the H_2 from H_2O offshoot from the JfJ program.

3.1. What Were Some of the Successes of Your Program?

JLD: We were successful at engaging high school students, introducing them to new science while at the same time reinforcing concepts they were learning in their courses (stoichiometry, molarity, solution chemistry, etc.) and training them in laboratory skills. We were also quite successful at introducing them to what "research" involves, connecting them to Caltech, and making them more competitive college applicants. Finally, we were successful at providing Caltech graduate students and postdocs with mentorship and teaching opportunities and helping them learn to effectively communicate with the general public and non-specialized audiences.

JRM: I think we were really very successful at making an impact in young people's knowledge and efficacy about science and energy. We also were able to expose high-school-age students to details of university research and what is the job of a scientist. Further, we had some success encouraging students from under-represented populations to consider science as viable career option.

WHH: The high-school students that participated in SHArK/SEAL obtained direct access to some of the most talented young scientists working in renewable energy research. The role model aspect of this experience is terrific. Also, the program is sufficiently open-ended to give students a realistic picture of research progress, emphasizing aspects of troubleshooting, technical skill, and creativity that may not be obvious aspects of science to students primarily educated in a normal classroom. Graduate students were also in an excellent position to provide useful advice to graduating high school seniors on the best ways to get involved in research at the university level and position oneself for acceptance to an elite graduate program. In general, the program raises the profile of graduate level studies in science for students who may not have considered it.

JDB: One particularly successful component of the SEAL program has been the summer program for high school students. In 2013, we ended up with 11 students on campus for five full weeks of full-time laboratory research. Some students worked on new metal oxide combinations, including preparation of samples, screening photo-response with the SEAL kit, and also characterizing the materials with mentor assistance using techniques like cyclic voltammetry and X-ray photoelectron spectroscopy. One group of students started a very different type of experiment looking at photo-oxidation of compounds other than water in the SEAL kit. Their experiment was to look at photo-driven oxidation of more readily oxidized compounds like alcohols. The students indeed found that the more easily oxidizable alcohols gave higher photocurrents. We plan to expand on this effort in the future. This is also a nice example of how we are able to use the kit-based approach in a modular way. The students come up with things they'd like to investigate, and we can use the tools at hand to find a way that they can do it.

We have also seen remarkable diversity in the experiments being run by the students within the framework of the program's emphasis on sustainability, solar energy, and STEM topics. For example, my students at Duarte HS this past semester built a homemade solar-powered water electrolyzer with burets and some old solar panels they had lying around. It was great fun to watch them engineer it!

MGW: Working with teachers was crucial to the success of JfJ; they provided the know-how for two of the modules that really helped tie in the DSSC experiment. The availability of the kit was expedited by the efforts at Arbor Scientific. Also, having support staff at Caltech made the whole operation a success; they were particularly invaluable with the first series of workshops. The most successful part about these kits is the fact that it ties in with commonly used science activities, all in one kit. It's a nice model for future projects that aim to integrate new technologies/principles into a low cost series of activities.

SA: The JfJ project was unique because it focused on training teachers and not the students. If a single teacher could be taught the lessons and if the lessons were then implemented in his/her classroom then that teacher could engage, influence, and educate many more students than any set of organizers from Caltech. The exponential educational growth of the teacher-training model was well-conceived and the greatest strength of the program.

TVD: We have been very successful lately in expanding the scope of JfJ beyond the day-long workshops at Caltech. We still hold regular workshops at Caltech, but JfJ has also become heavily involved with informal science education (ISE) opportunities. We now annually visit the Natural History Museum as well as East Los Angeles College to participate in ISE activities.

MJR: CCI-Solar was incredibly supportive, and allowed me the time to develop the H_2 from H_2O kits and get them plugged into various programs and schools nearby. More importantly in a global sense, I think, is that CCI-Solar created an atmosphere where outreach was a recognized and lauded goal, so actions could be taken on this basis.

MCH: First, the idea to offer school visits to teachers who take our Juice from Juice workshops was brilliant. We have more teachers interested in attending the workshop, and most importantly, teachers are actually implementing the lessons in their classrooms. Another success was revamping both the SEAL kits and the JfJ kits. Each kit now includes crucial items that were missing before, making it easier than ever to participate in the projects. Instructions and resources for both kits are also more readily available. Feedback for these changes has been very positive. The other great success would have to be expansion of the outreach program to more institutions involved with CCI-Solar. More outreach nodes are being established in Texas, Wisconsin, Illinois, and Boston, with hopefully even more to come!

PJB: In our ISE efforts, the kids were very engaged and retained a fair amount of information that was presented. Also, much like the SEAL program, a big part of the success of the ISE program is having students interact with scientists and perform scientific experiments themselves. These students—most of whom are underprivileged—are learning that science is something that they can do.

3.2. What Were Some of the Aspects of Your Program That Were Particularly Challenging?

JLD: One of my personal goals was to really unify and develop the educational materials available to make SHArK more accessible to those without Caltech graduate students nearby to help out, and that did not happen while I was involved. Communication among the different SHArK research sites was also particularly challenging early on in the development of the program.

JRM: We made some efforts to create online learning materials (including videos and print materials) to instruct new sites on how to properly execute the SHArK/SEAL experiments. But we found in general that the presence of a Caltech mentor at least a few times per month was required in order to keep the students engaged and to work through troubleshooting issues. I think this was probably a function of this program being "real science" with no predetermined outcomes, which meant that we couldn't create a kit or packet that could successfully guide students from start to finish. There were a few exceptional cases where students or teacher partners were able to step in and facilitate most of the program without consistent input from the Caltech mentor, but these cases were limited.

WHH: We found that providing enough content to carry the students through the week was often challenging. This was compounded by the need for equipment, such as a furnace, that the school did not possess. Ultimately, time spent on the SHArK program in the absence of a CCI mentor gave mixed results. Additionally, although the summer research program we implemented for students was a positive experience, the personnel requirements to run such a program successfully simply can't be reasonably met by postdoctoral scholars and graduate students.

The biggest drawback of the program is its dependence on the time and talent of the graduate student and postdoc mentors. It simply could not function without them, and the vast majority of the knowledge related to executing the program remains for the most part in their minds and imaginations and not formally schematized. This renders the program not amenable to export. A revised experimental platform that produced easily reproducible, quantitative data in a more or less fool proof manner would be a major step forward.

JDB: As the school year ended in spring 2013, we lost a large group of students and postdocs that were serving as SEAL mentors to graduation and new academic positions. I estimate that we lost around 15 people, which was a large percentage (~75%) of our total current mentor pool. This was a serious challenge for us, since we recruit purely on a volunteer basis from groups around Caltech. Luckily we were able to recruit the needed new talent to keep the program running for the next year. 2014 has been going great so far!

SA: Unfortunately, the percentage of teachers that implemented the JfJ program at their schools was very small.

The teachers learned a lot during the time they spent at a workshop, but they often remarked that they felt overwhelmed and intimidated when tasked with the job of implementing the activities on their own. This obstacle was being addressed around the time that I transitioned away from Caltech.

TVD: We have found that it is difficult to get teachers to actually implement the JfJ project/technology in their own classrooms. Teachers are quite willing to attend a day-long professional development workshop, but less willing to spend a lot of time and effort implementing a completely new experiment in their classroom.

MCH: The only unsuccessful thing I have seen so far is that one of our high schools dropped the SEAL project. This has happened before and will likely happen again. A group has to have a strong enough desire from both students and teachers to participate in the outreach program for it to work.

PJB: Initial efforts in building up the ISE program were a lot of work. Each two-hour outreach session would be preceded by multiple conference calls, lesson planning sessions, supply gathering, experiment testing, and travel time. For all of this planning time, sometimes only 6 to 8 kids showed up to the event. Hopefully, these lessons have longer legs and can be used to fuel the creation of similar science clubs. If not, a lot of time and resources will have been spent on a rather modestly-sized audience.

3.3. Were There Any Noteworthy Lessons You Learned During Your Experience in the CCI Solar Energy Outreach Efforts?

JLD: I think the most important lesson I learned was the value of being able to communicate with general and non-specialized audiences. I found SHArK to be incredibly rewarding on many levels and the whole experience really increased my own personal standards for broader impacts.

JRM: There were so many lessons I took away from my experience with SHArK and SEAL. First, I learned that mentorship is incredibly rewarding. One of the most rewarding aspects was realizing how it is possible for youngsters to understand what I would otherwise think are incredibly subtle scientific concepts if they are motivated to think about a problem carefully. Additionally, I was surprised at how hard it is to bore young people when they feel motivated. I also learned firsthand how hard primary and secondary school teaching can be, and that having a good teacher partner is critical to success in a school-based outreach program. Finally, I think we learned collectively that growth of outreach and mentorship programs needs to be managed carefully in order to ensure that it is sustainable growth.

WHH: Above all, the program demonstrated to me the real value in dedicated outreach efforts as a part of nationally competitive funding opportunities. Despite the various frustrations associated with finding time for all of the demands of graduate student and postdoc life, incentivizing the best and the brightest to take the fundamental messages of their research both to young people and the citizenry at large is incredibly important. I feel like we still know very little about what works and what does not work in these venues, however, which leads me to another valuable lesson: learning about the existence of and interacting with outreach and informal science education experts and inviting independent evaluation of outreach programs. I see these efforts as empirical means to achieve important nationwide social outcomes, and as such, they must be empirically validated. I look forward to a time when practitioners of academic science interact more thoroughly with this research and the findings of education research generally.

MGW: Follow-up is a very important aspect of training the teachers at the workshop. If we want them to continually use the kit, they need support to implement the activities into their labs. For instance, several colleagues and I traveled to a high school site after the first workshop in 2010 to help implement the JfJ activity for 60 high school students. The chemistry instructors there were extremely appreciative of our help to get the experiment going and to see how it "works." Also, because of the rapidly expanding numbers of teachers who became involved, a way for the teachers to interact with one another would be an exciting development to maintain the enthusiasm the teachers experience when they first come away from the workshops.

SA: I learned that while training teachers may be a better use of one's time, performing hands-on work with students is much more exciting and rewarding, especially when working with students that are particularly inquisitive or shy. I find it a challenge to engage, reach, entertain, and excite both of these personality extremes.

TVD: I think the most important thing I've taken away from my time with CCI Solar is that outreach is really important and rewarding. When I was an undergraduate I had plenty of opportunities to be involved with outreach but I generally saw it as a waste of time. Since being here I have seen firsthand the difference it can make for people (particularly young people) and I am proud to be a part of the Solar Army's efforts.

MCH: I have learned that what we do for the community is highly valued and respected. We have received very positive feedback from funding agencies and colleagues. I have heard from teachers that they are so grateful to be included in our programs and honored that Caltech would want to collaborate with their schools. I have heard from students that they have learned so much about alternative energy and being a scientist. I have also learned that our outreach program is filling a great need and desire in the community for science education, especially in a hot field like alternative energy.

MJR: My experience with the various outreach efforts reinforced the idea that it is critical to make and maintain connections and working relationships over long periods (years) to really make an outreach program function properly, and to be recognized as valuable.

PJB: I learned many lessons on many levels. At the top-level, I gained a deep appreciation for the importance of public outreach and communicating the value of scientific research to the public.

3.4. How Did Your Research/Outreach Program Grow and Change While You Were Involved?

JLD: The SHArK program seemed to grow exponentially—the first time I saw a LEGO laser scanner it was at the Renewable Energy: Solar Fuels Gordon Research Conference in Ventura, CA in January 2009. Over the next year, more kits were sent out to undergraduate colleges and the high school program kicked off at Caltech. The following summer we had a cadre of high school students working in a Caltech lab, improving SHArK. I would say the major driving force was the concerted effort of all the individuals involved in the program who allowed it to be successful and grow organically.

WHH: During my involvement with the SHArK/SEAL programs, we expanded in Southern California area high schools significantly, with interest in the program significantly exceeding our personnel levels. We also experimented with different outreach group configurations, such as working with a group of student in an engineering elective course at Duarte High School. We also piloted a program in which several more remote high school groups came to Caltech. We also attempted to regularize a summer program in which area high school students came to work at Caltech for several days a week to extend their investigations in solar energy conversion while gaining exposure to the instrumentation capabilities and intellectual atmosphere of a research university.

JDB: To me, one of the main driving forces behind the success of the SHArK/SEAL programs is the sustained emphasis that we place on mentoring the kids involved in the program through our dedicated Caltech mentor pool that currently numbers around 20. This is complicated to organize, and also a testament to the good will of everyone involved! It is their effort to stay engaged with the students and their research effort that keeps the program going. They have the expertise to understand the experiments taking place and guide the students. Moreover, they provide leadership, career advice, life experience, and general mentoring beyond science to the students. Certainly, at this point, we are still limited only by the number of mentors that we have. Schools are still on waiting lists for getting involved.

TVD: Recently, the JfJ program has greatly increased its scope and reach through ISE activities. Furthermore, we have developed a "travel" JfJ kit that makes it much easier to give workshops anywhere. We are now fully equipped to give a workshop at any location. We also now have much more of a support structure in place for teachers that take the workshop. We have established an extensive outreach system where teachers who take a workshop may have a JfJ mentor visit their school to help implement the experiments in their classroom for the first time.

MCH: While I've only been here a short time, the outreach program has changed and grown quite a bit. Having a staff member dedicated to outreach really has helped the program. Resources and supplies are centralized and organized, making it easier for mentors to focus on mentoring. I am also able to act as a representative for the program, developing more collaborations and expanding the scope and impact of our outreach.

PJB: Interestingly, over the course of the first year, the ISE program might have shrunk to a certain extent and benefitted as a result. In our first meeting, we had over 6 mentors from Caltech participate, and the students seemed a bit overwhelmed. We made a conscious decision to use fewer mentors and to have these mentors make a real commitment to coming every week so that the mentors and kids could form stronger/deeper relationships. Operationally, the major area of growth in this outreach effort was in the development of a curriculum. From day 1, we focused on writing complete lesson plans such that any success we generated could be subsequently replicated.

3.5. What Are Some Ways in Which You Plan to Incorporate or Have Incorporated Your Mentorship Activities Into Your Academic Experience Beyond Caltech and the NSF CCI?

JLD: During my postdoc at the University of Washington (2011–2012), I adapted SHArK to be a four-session laboratory experiment for students enrolled in North Seattle Community College's Nanotechnology program. Now that I am at the University of North Carolina, I have been working with my graduate students and the Morehead Planetarium to design hands-on activities that highlight our research efforts in solar energy conversion. We showcase these activities at local science museums, local schools and the annual NC Science Expo. Unfortunately it has been hard to balance the demands of being an assistant professor with doing outreach activities at the same level as SHArK.

JDB: Going forward beyond Caltech, I plan to build a small mentoring-based outreach effort in my independent laboratory. Initially, I hope that my students and I will find interested students/teachers/schools/classes to partner with to explore sustainability-themed chemistry and general science experiments. The model of inviting the community into your labs for meetings or materials characterization is also very appealing, so hopefully I will incorporate this aspect as well.

MGW: In 2011, I presented the efforts of the team and this program in general at the ACS National Meeting in Anaheim, CA to a group of High School teachers at the

ACS High School day. Since moving to UNC Charlotte, I have conducted JfJ workshops in Charlotte, NC with numerous High School teachers. I also helped to facilitate a teacher workshop and several student workshops. Moving forward at UNC Charlotte, one of my goals is develop a similar polymer outreach kit that will highlight some of the new materials used in polymer optoelectronics (photovoltaics, PLEDs, OFETs). I think the model of JfJ can be used for any science implementation strategy to bridge the gap between University level research and K-12 science education.

SA: Based on what I learned from my outreach experience through CCI Solar, I have formulated a specific plan to increase the implementation success rate of the teacher-training model. My plan requires less time from the organizers, albeit in a more concentrated time period. Before coming to graduate school, I was a high-school teacher, and leveraging my past personal experiences in that job has helped guide my design of this new program.

MJR: The H_2 from H_2O program is resetting at UT Austin and beginning to partner with on campus education organizations and local teachers. The NSF ACC-F and CCI Solar support also served as a form of seed funding, in that we have received continued funding from the Dreyfus Foundation to grow the program locally here in Austin. A large roll-out of the program to the central Texas area is planned for over the next several years, hopefully with continued support from national funding agencies that place emphasis on such efforts. The experience of participating in and learning from the successful SHARK/SEAL and JfJ programs, have highlighted the importance of continually bringing in new people (collaborators, teachers, schools) as well as maintaining a few core personnel over multiple years.

4. CONCLUSIONS

Modern technological innovations have empowered citizens to access information and contribute opinions with ease. Therefore, scientists must recognize the vital importance of engaging the public. Apathy toward public outreach by scientists can only lead to scientific illiteracy and the erosion of support for our work. While the research of CCI Solar aims to harness the energy of the Sun, our outreach efforts have sought also to harness the energy of the public.

Although the specifics and expense of our laboratory experiments are broadly inaccessible to youngsters and lay citizens, we have found that research is a fantastic tool for invigorating their hearts and minds. People are naturally curious, and inquiry-based activities like SHArK/SEAL and JfJ have allowed our audiences to immerse themselves in the fundamental concepts of solar energy research and to gain a better understanding of work that needs to be done. The SHArK/SEAL programs, for example, have empowered students to conduct "real" research that could lead to the discovery of new materials for water oxidation. While the odds of finding a commercially viable catalyst are low, the mere possibility invigorates students with the knowledge that hard work and creativity are the price of a lottery ticket for the chance to make a substantial positive impact in their world. Regardless of the outcome of the experiments, there is value in communicating that scientific research is an avenue for smart, motivated people to solve the greatest challenges facing humanity.

Here we have shared the success stories of our outreach activities in the hope they would stimulate new ideas from researchers across the scientific spectrum. Our program is only one example of how scientists can take specific research problems and use them to engage a public hungry for information. From our perspective, CCI-Solar's outreach efforts have been challenging, exciting, and incredibly satisfying to develop and deploy. Working with citizens of all ages and professions has been a very rewarding aspect of our lives as scientists. While we have primarily served as teachers, we have learned a lot from our experiences—especially about the tenacity of young people when they are motivated by meaningful topics to study.

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