The Arizona Science Lab (ASL): fieldtrip based STEM outreach with a full engineering design, build and test cycle

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ABSTRACT: Motivated by the declining interest of K-12 students in STEM courses and careers, the IEEE Phoenix chapter has founded the Arizona Science Lab (ASL) in Tempe, Arizona, the United States of America. The ASL conducts free hands-on science, technology, engineering and mathematics (STEM) workshops, e.g. on solar cars, with middle school students. The students visit the ASL for a full day during their fieldtrip day. The workshops provide students with a brief introduction to the science and engineering principles underlying the workshop topic, such as electric circuits and solar cells for the solar car workshop. Teams of two students then conduct a full design, build and test cycle that includes re-engineering and re-testing of their gadget, e.g. solar car. Teams, then, compete with their gadgets, e.g. solar cars, and take them home. Comparison of pre- and post-workshop survey ratings indicate that the workshops significantly improve the student perceptions of engineers as problem solvers and of engineers having a positive impact on the world. Also, the student self-perception of familiarity with engineering as well as general STEM interest and self-efficacy were significantly increased.

Keywords: Design, build and test cycle, middle school students, solar cars, STEM workshops, student attitudes

INTRODUCTION

Motivation

A number of recent initiatives have identified outreach to K-12 schools as a key mechanism for educating K-12 students about basic electrical engineering and raising awareness of electrical engineering as a field of study and a career choice [1-9]. As the University of Maryland physicist S. James Gates Jr., Co-chair of the President's Council of Advisors on Science and Technology (PCAST), has written:

> *If you look at U.S. performance on various international metrics, depending on which one you use, we come out something like 24th or 25th in the world. A lot of people might argue: Well, who cares? It's just science. The only problem with that theory is we're moving into a time in the development of the world economy when innovation and the formation of novel approaches will clearly come from countries best situated to create a population that can innovate in science and technology. We're not doing this because we want to make more scientists. The reason we are doing this with urgency is because it's connected to our country's future economy* [10].

Overview of Arizona Science Lab (ASL) Approach

In response to these needs, in 2009, the Phoenix chapter of the Institute of Electrical and Electronics Engineers (IEEE) founded the Arizona Science Lab (ASL, www.azsciencelab.org). The overall goal of the ASL is to reverse the widely acknowledged downward trend of students opting out of advanced science courses and consequently future careers in STEM. Consequently, the primary objective of the ASL is to encourage students to become interested in science, technology, engineering and mathematics (STEM) through experiential learning. The secondary objective is to provide an opportunity for retired engineers, employed engineers and university engineering students to become engaged with grade 4 - 9 students and share their knowledge, expertise and passion for engineering.

The ASL provides fully provisioned project-based STEM workshops for grade 4 - 9 students. The workshops are offered free of any charge to the schools, teachers and students. This *no cost* aspect has been found to be vital for the acceptance of the programme by the schools as for some years now, the schools and teachers have had limited resources to spend on activities outside the regular classroom, however advantageous they might be to the students. The workshops are marketed as a fieldtrip destination for the middle schools in the Phoenix metropolitan area. Throughout, the workshops emphasise the *Wow!* factor of the projects and are designed to impress the students about science and engineering principles at work.

Each workshop is conducted in a single four to five hour session in one day and includes a hands-on project for the students to build a gadget that reinforces the underlying STEM principles. The students get to keep what they build. An ASL workshop consists of three main phases: a) A demonstration phase that presents and demonstrates the underlying physical laws and engineering principles through rich student/workshop facilitator interactions; b) A design, build, and test phase where the students apply the principles they have learnt in the demonstration phase; and c) A wrap-up phase. Students work in two-person teams and they are challenged to engineer a working technology solution, with an emphasis on design, test, re-engineer and re-test to optimise their solution.

Related Work

A wide range of outreach activities for increasing awareness of engineering among K-12 students have been reported in the literature. A number of STEM outreach programmes have focused on improving STEM education through training for teachers or the design and preparation of teaching materials and Web sites supporting STEM instruction [11][12]. In contrast, many other programmes interact directly with K-12 students. Similar to [13][14], this review of related work classifies these programmes according to the setting where interactions take place. In-school programmes, such as Project Lead the Way, www.pltw.org [15], and the programmes described in [16-24], interact with the students in their regular classroom, e.g. during their regularly scheduled science class period.

After-school programmes, such as the Mathematics, Engineering, and Science Achievement (MESA) programme and the programme presented in [25], organise students in clubs and interact with them on a regular basis, e.g. one afternoon for an hour for a quarter of the school year. The activities of these after-school programmes often are geared towards, and culminate in, a STEM competition [26]. Computer clubhouses [27][28] provide settings for after-school computer-based activities [29]. Summer camp programmes [30-33] engage students for several consecutive days, when regular school is on summer break. On-campus programmes [34-36] engage K-12 students on university campuses, through touring different laboratories and conducting short experimental laboratory sessions.

In contrast to these existing programmes, the ASL is focused on engaging students during their fieldtrip day, which usually is scheduled once or twice during a regular school year in the US. The fieldtrip day gives the students the opportunity to engage with STEM activities continuously for a full school day. The fieldtrip, therefore, provides a continuous time period that is longer than the typical in-school or after-school STEM programme, and shorter than the summer camp programmes. While usually only a few students from a class elect to participate in STEM after-school or summer camp programmes, the no-cost fieldtrip programme engages all students in a given class, similar to the in-class programmes.

The ASL fieldtrip programme is similar to on-campus programmes in that students engage with STEM content for a full school day. However, most on-campus programmes have students *sample* different laboratories and conduct only short activities on their own in some of the laboratories. In contrast, in the ASL programme, students stay focused on a topic area, such as solar cars, for a full day and experience the full design, build and test cycle. An additional advantage of the fieldtrip programme is that the students are transported by regular school buses to the ASL location, and do not need to rely on arranging their own transportation, as many summer programmes require. Thus, the ASL programme provides equal access by removing the barriers that are often presented by families' or schools' transportation or financial constraints.

ASL WORKSHOPS

Philosophy

The basic philosophy of the ASL workshops is that if students are to become interested in engineering, they have to see and understand how scientific principles and engineering relate to their everyday life. Hands-on activities, such as the workshop projects implemented in the ASL, allow students to directly manipulate the tools and materials, which are put to use by practicing engineers. According to situated cognition and constructivist perspectives, learning occurs in a specific social and physical context and individuals learn through social interactions, imitation and practice [37-39]. Learning contexts involving hands-on practice with expert practitioners (e.g. apprenticeships, guided hands-on experimentation) provide a greater degree of social interaction and authentic activity than traditional didactic instruction; thus, such informal learning approaches have great potential to promote learning. Specifically, the informal workshops in the ASL offer ideal conditions for the social interactions and authentic practice necessary for acquiring scientific principles and problem-solving skills involved in engineering. Therefore, the workshops:

- Use numerous simple hands-on demonstrations to illustrate scientific principles;
- Use authentic examples of everyday objects to illustrate how the scientific principles affect the engineering design and the operation of the gadget;

- Use a collaborative hands-on construction project to reinforce the science principles and the engineering design, build and test cycle.

Throughout, the ASL workshops emphasise the informal aspect of the learning experience. The ASL activities are not graded so as to avoid the performance pressures and related anxieties of the regular classroom. In contrast to graded classroom science experiments, failures and learning from failures are encouraged in the ASL activities.

Structure

The ASL workshops consist of a demonstration phase, followed by a design, build and test phase, and a wrap-up phase.

1. *Demonstration Phase:* The demonstration phase introduces students to the physical principles that are exploited in a given gadget that is to be built. The level of presented detail is adapted to the grade level of the students. The demonstration phase involves a combination of a slide presentation and hands-on demonstrations. Two facilitators are employed, one to concentrate on introduction of the principles through the slide presentation, and the other to conduct the demonstrations illustrating the principles. Both facilitators involve the students extensively through questions and answers, thought provocations, and student participation in the performance of the demonstrations.
2. *Design, Build and Test Phase:* In the design, build and test phase, the students work in two-person teams. There are typically up to 15 teams per workshop. Based on the principles they learnt in the demonstration phase, the students are challenged to engineer a working technology solution (gadget), with an emphasis on design, test, re-engineer and re-test so as to optimise their solution. A total of six facilitators (the two demonstration phase presenters, plus four additional facilitators) mentor the student teams. The facilitators only assist students having difficulties by asking questions and leading the students to a design solution; the facilitators do *not* divulge a solution. The facilitators prompt the teams to first design their solutions on paper and, then, judge whether a team is ready to proceed to the construction of the design. The students are encouraged to build their designs quickly, not worrying about making them *pretty*. A built design is tested with a facilitator to see how the design performs. During the testing, the students are encouraged to reflect on their design and how well it worked or did not work, and consider how it could be improved. Modifications or complete rebuilds are encouraged and the design - build - test - modify - retest cycle can be repeated as many times as the available time permits. At the end of the design, build and test phase, a competition between the teams is held to see who has the best design.
3. *Wrap-up Phase:* In the wrap-up phase, the students are encouraged to explain the different test results for the different designs and discuss tradeoffs. The students are also prompted to reflect on what they learnt and what they would do differently next time. The aim of the wrap-up session is to reinforce the key science principles and the engineering design, build and test cycle. The facilitators also initiate a discussion of studies and careers in STEM fields, emphasise that STEM careers are exciting, fun, and well paid, and answer any questions.

Curricula

The ASL currently offers four workshop topics that focus primarily on the basics of electrical engineering and related mechanical engineering topics. The workshops and the main covered topics are presented in Table 1. All workshops are aligned with US National Science Education Standards, which were produced by the US National Research Council and endorsed by the US National Science Teachers Association.

Table 1: Projects and essential principles of ASL workshops.

Workshop	Project	Science and engineering principles
Sail Away	Design and build a sail boat	Archimedes principle, forces and moments, Newton's laws
Here Comes the Sun	Build a solar-powered race car	Renewable energy, solar cells, electric circuits, sources/loads in series and parallel circuits
Working with Watermills	Design and build a water wheel	Renewable energy, kinetic/potential energy, simple machines
Rockets	Build and launch an air/water rocket	Newton's laws, rocket aerodynamics, using simulations

As a sample of the content covered in the workshops, the main principles covered in the demonstration phase of the *Here Comes the Sun* workshop on solar cars are summarised in Table 2. The solar cars workshop focuses on the application of solar panels in a solar powered model car. The workshop introduces solar panels and how solar powered cars operate as well as simple series and parallel electrical circuits using solar power and the application of Ohm's Law to simple electrical circuits. Students work in teams to design and build a solar powered model car and explore how the components work together. Students race their cars and suggest and test design enhancements to improve the cars' performance.

Table 2: Topic outline of demonstration phase of *Here Comes the Sun* solar car workshop.

Overview	Features of some professionally built solar cars; Overview of basic solar car students will build
Sun	What is the sun, fossil fuels versus solar energy, properties of sun light
Electricity	Uses and types of electricity, DC and AC current
Solar cell	Overview of structure and function of solar cell
Electrical circuits	Basic electrical quantities (voltage, current, resistance, power), open and closed circuit, Ohm's Law, parallel and series circuits, parallel and series arrangements of batteries or solar cells
Solar car	Components, assembling solar cells into panel, connecting panels to motor

EVALUATION

Methodology

1. *Participants and Design:* Participants in the study were a total of 307 grade 4 – 9 students from eight elementary and middle schools in the South-western US. Post-survey instruments were administered by teachers during class on a day following the workshop experience. A total of 224 post-surveys were collected, i.e. there was approximately 17% attrition (loss of completed participant surveys from pre- to post-survey). Of the participants from which post-survey data were obtained, 87 students participated in the Sail Away activity workshop; 60 participated in the Here Comes the Sun workshop; 44 participated in the Working with Watermills workshop; 33 participated in the Rockets workshop. In order to determine effects of the workshop experience on student perceptions of engineering and STEM disciplines, the average perception ratings (averaged across students) from pre-survey and post-survey were compared.
2. *Evaluation Instrument:* Student perceptions about STEM fields in general and engineering specifically were measured using a paper-based perceptions survey (pre-and post-survey were identical), comprised of 27 items developed by the research team. Each survey item was on a 5-point scale ranging from 1 - strongly disagree to 5 - strongly agree. Students responded to each item by circling the number associated with their level of agreement. Following Aiken, the construct validity of the survey was assessed with the judgment of subject matter experts in electrical engineering instruction [40].

The perceptions survey was comprised of six subscales. Four subscales related specifically to engineering: *problem solvers*, *impact*, *stereotypes/misconceptions* and *familiarity*; two subscales related to STEM domains in general: *STEM interest* and *STEM self-efficacy*. Two items from the survey presented statements characterising engineers as *problem solvers* (e.g. *Engineers follow a problem solving process*). Four items included statements indicating that engineers *impact* the world (e.g. *Engineering affects people's lives* and *Engineering affects the world around us*). Eight items represented common student *stereotypes or misconceptions* about engineering (e.g. *Engineers are mostly men* and *Engineers work alone*). Two items evaluated students' perceptions of their own *familiarity* with engineering (*I know what engineers do at work* and *I understand how mathematics and science are a part of engineering*).

Four items comprised statements to measure student *interest* in STEM fields (e.g. *I find my science class interesting* and *I am interested in taking more mathematics classes*). Seven items presented statements to assess student *self-efficacy* in STEM (e.g. *I have an easy time solving science problems* and *I am confident in my ability to engage in mathematics questions*). Six composite variables were constructed using average ratings on the subscales: *Problem solvers*, *Impact*, *Stereotypes/misconceptions*, *Familiarity*, *STEM interest* and *STEM self-efficacy.*

Results and Discussion

In order to determine the effects of the workshop activities on students' perceptions about engineering and STEM disciplines, the average pre-survey ratings for the six subscales of the survey were computed and compared with the corresponding average post-survey ratings using a series of six one-sample *t*-tests. Descriptive statistics for pre-survey and post-survey ratings and inferential statistics associated with the one-sample *t*-tests are displayed in Table 3.

Results of the analyses on engineering perceptions indicated that participants had significantly higher ratings of engineers as *problem solvers* and as having *impact* on the world following the exposure to the workshop activities (i.e. post-survey > pre-survey). The analysis also indicated that students reported higher perceptions of *familiarity* with engineering following the workshops.

No significant differences were found between pre-survey and post-survey ratings for the *stereotypes/misconceptions* subscales. Results from the analyses on the STEM perceptions subscales demonstrated that students had significantly higher *STEM interest* and *STEM self-efficacy* following the exposure to the workshop activities (i.e. post-survey > pre-survey).

Table 3: Descriptive statistics for pre-survey and post-survey engineering and STEM perceptions ratings, as well as inferential *t*-test statistics for pre-post comparisons.

Engineering subscale	Pre-survey *M* (*SD*)	Post-survey *M* (*SD*)	*t*, *p*, Cohen's *d*
Problem Solvers	4.04 (0.80)	4.40 (0.78) [a]	5.23, < 0.001, 0.46
Impact	3.57 (0.91)	3.86 (0.90) [a]	3.58, < 0.001, 0.32
Stereotypes/ Misconceptions	2.29 (0.52)	2.24 (0.63)	0.93, 0.36
Familiarity	3.40 (1.05)	4.30 (0.85) [a]	10.58, < 0.001, 0.94
STEM subscale			
STEM interest	3.55 (0.87)	3.70 (0.89) [a]	1.96, < 0.05, 0.17
STEM self-efficacy	3.52 (0.70)	3.72 (0.73) [a]	3.17, < 0.005, 0.28

Note: [a] Significantly higher than pre-survey

These results demonstrate that the ASL workshops have a substantial positive impact on young students' attitudes toward engineering and STEM fields in general. The impact on participants' views of engineers as *problem solvers* is likely due to the problem-solving skills introduced and the hands-on project the students complete. The workshop facilitators present a simple, yet authentic engineering challenge (e.g. design and build a solar car) and provide the necessary assistance to students in solving the problem set before them. Through this process, students naturally come to recognise the fundamental steps involved in developing a solution to an authentic engineering problem (e.g. design, test, and refine solution). The workshops promote students' views of engineers as having positive *impact* on the world through the engineering artefacts the students construct. Participants are able to put to use the physical products of their designs, which are simplified versions of real-world engineering devices. Through this process, students are able to appreciate the potential impact they may have on the world as engineers.

The workshop activities strengthen students' self-perceptions of *familiarity with engineering* by introducing them to basic science and engineering principles and by demonstrating that, with a little help from others, they are capable of accomplishing engineering tasks. Although students' mean ratings of stereotypes and misconceptions regarding engineering were slightly lower at post-test, this difference was not statistically significant. The experience of working on authentic engineering projects may not be sufficient to challenge young students' pre-existing conceptions of engineers as absorbed in intellectual efforts and socially isolated. In fact, the exposure to the engineers during the workshop may actually serve to reinforce some children's stereotypes, as the workshop presenters interact with participants to develop students' understanding of, and interest in, STEM topics, not to develop social relationships. Also, the middle school students may find it difficult to relate socially to the facilitators, who are substantially older than the middle school students.

More generally, the workshop activities increased student interest in STEM fields and self-efficacy toward STEM topics. STEM interest and self-efficacy were likely promoted through the active involvement of the students in the hands-on activity. Rather than sitting idly through didactic lessons on science and mathematics, the students actively utilised the principles and concepts in an authentic context, thereby elevating interest and self-efficacy in STEM. Most students desire to view themselves as capable problem solvers and having an impact on the world. By increasing children's feelings of familiarity with engineering and associating problem solving and local/global impact with engineering, hands-on, expert-guided activities such as those offered in the ASL workshops can encourage student pursuit of engineering disciplines. Furthermore, by elevating students' interest in, and self-efficacy toward, STEM domains more generally, such activities have the potential to promote student engagement in various STEM courses.

CONCLUSION

The findings from this study demonstrate that the ASL workshops have a significant positive influence on students' perceptions of engineering and STEM fields. The expert-guided, hands-on activities may promote student attitudes through three primary mechanisms. First, by carrying out simple, authentic engineering projects, children are able to understand the problem-solving steps undertaken in developing real-world engineering solutions. Second, by putting to use the physical products of these engineering projects in the real world, students come to recognise the local and global impact of engineering solutions. Third, by showing students that they can achieve engineering solutions themselves, the activities increase the students' feelings of familiarity with engineering. Each of these factors not only elevates attitudes toward engineering, but also increases students' interest in, and self-efficacy toward, STEM fields more generally.

Overall, the results support further efforts to supplement traditional, didactic approaches to STEM education through hands-on experiential learning as authentic learning contexts offer the social interactions and opportunities for imitation and practice necessary for deeper immediate engagement, lifelong practical learning and interest in the domain [37-39]. As students develop interest and positive attitudes, they will engage more meaningfully in STEM coursework and be more likely to pursue careers in STEM disciplines. This is essential for advancing the capable workforce needed to sustain the United States in the global economy that is driven by science and technological innovations.

There are a number of important directions for future research on fieldtrip based STEM outreach. First, the current study employed pairs of students working on projects. A future study may investigate whether pairs, triads, or larger groups have the greatest impact on student attitudes. Also, specific scaffolding techniques of facilitators during the hands-on activities can be investigated. Overall, the present field-trip based study represents an essential first step in demonstrating the beneficial outcomes of engineering workshops on the attitudes of K-12 students toward engineering and STEM fields.

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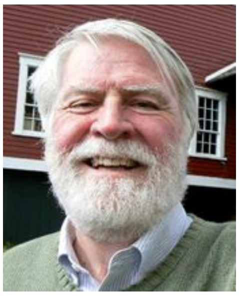
BIOGRAPHIES



Tom Innes had a successful career as an electrical engineer and business development manager. He is a Life Member of the IEEE and a member of Eta Kappa Nu. Tom received his BS degree in Engineering from Case Institute of Technology in 1966. He worked for Intel Corp. for over 30 years in many of their locations, including Santa Clara CA and Chandler AZ. Tom retired in December 1998 after several years as General Manager of a number of business and development operations at Intel's Chandler facilities. He was responsible for establishing successful microprocessor design centres in Israel and in Arizona, and managed the Embedded Microprocessor business and Intel's Arizona site operations team. Tom is active on a number of corporate boards, including AZ Science Center Board of Trustees: Life Member; AZ Tech Incubator: charter member of the Board of Directors; 1999-2008: Co-founder, director of Primarion Inc, Tempe, AZ; and 2008 - present: Director of Deepdive Tech. Inc, Scottsdale AZ.

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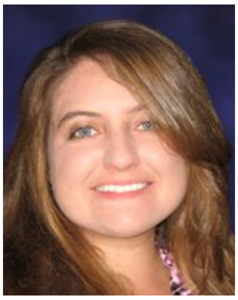

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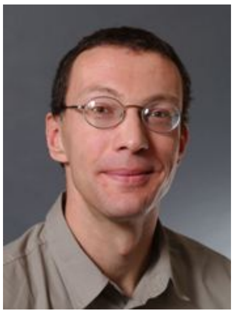
Justin Harvey is an undergraduate student in electrical engineering at Arizona State University (ASU), Tempe, Arizona, USA.



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