Evaluating Large-Scale STEM Outreach Efficacy with a Consistent Theme: Thermodynamics for Elementary School Students

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Abstract

A biannual chemistry demonstration-based show named “Energy and U” was created to extend the general outreach themes of STEM fields and a college education with a specific goal: to teach the First Law of Thermodynamics to elementary school students. The effectiveness of the program was analyzed using a clicker survey system. The fraction of the students that correctly answered the question “Is it possible to create energy?” increased from 14% immediately before the show to 89% immediately after the show. Students who had seen the show at least six months prior were twice as likely to correctly answer at the beginning of the show, demonstrating longer-term lesson retention. Interestingly, similar trends were observed for the adult chaperones that accompanied the students and participated in the clicker survey. A statistically significant difference (>99% confidence interval) was noted between the students’ responses to the questions “Can you create energy?” and “Can you destroy energy?”, revealing a potential effect of word choice on the interpretation of the First Law of Thermodynamics despite the two questions representing complementary concepts. Student performance, measured interest in science,
and desire to attend college were not correlated with standard economic indicators. This measurement is consistent with the postulate that economic biases surrounding interest in STEM fields are less pronounced in elementary school than later in high school.

**ABSTRACT GRAPHIC**

![Abstract Graphic](image)

**KEYWORDS**
General Public, Elementary Science, Chemical Education Research, Demonstration, Outreach, Multimedia-based Learning, Thermodynamics, Learning Theories

1. **INTRODUCTION**

Science outreach programs aimed at pre-college students have become more common as both academic and industrial scientists have increasingly come to acknowledge and understand the importance and impact of such efforts. From our general observations on university outreach efforts, a student or professor performs a variety of scientific demonstrations with the goal to promote pursuit of learning big ideas in science, technology, engineering, and mathematics (STEM), such as nanotechnology, polymers, or energy. These shows have become common in communities proximal to colleges and
universities, with many of the presenters able to trace their inspiration back to being an audience member themselves. One example is the renowned show developed and presented by former ACS President, Professor Bassam Shakhashiri at the University of Wisconsin.\textsuperscript{7} With a near inexhaustible library of attention-grabbing demonstrations,\textsuperscript{8-12} chemistry provides a uniquely effective playground for this format of scientific community engagement. From the seemingly endless expansion of the Elephant’s Toothpaste\textsuperscript{13} to the unexpected baritone after a breath from an invisible sea of SF\textsubscript{6} supporting an aluminum foil sailboat,\textsuperscript{14} chemical demonstrations are potent entertainment that fosters curiosity about the natural world and a passion to understand it.

In this report, we describe and evaluate a chemistry-based outreach show designed to extend the concept of promoting general interest in science to include a well-defined lesson. Evaluating the impact of this form of outreach in informal science education is uncommon,\textsuperscript{15} leaving most statements of impact to simple assumption or open ended. With a consistent and specific theme, the show is designed to teach one of the most important and poorly understood scientific principles, the First Law of Thermodynamics.\textsuperscript{16} Energy is a central concept in chemical education, most STEM disciplines, and it is the concept at the foundation of many of the greatest challenges faced by society today. The notion of energy and its conservation is identified as a cross-cutting concept for Next Generation Science Standards (NGSS) by the National Science Teachers’ Association (NSTA). From climate change to producing sufficient food and potable water, energy is the critical concept required to understand the sustainability of our future. At the same time,
misconceptions about energy are common among all ages and education levels.\textsuperscript{17-20} Given the immense energy-related challenges in advancing current technologies and shaping future governmental policies, cultivating an accurate conceptual understanding of energy can also provide a foundation when building toward the overarching goals of stimulating early interest in STEM fields and encouraging continual engagement in high school and college.

At the heart of the First Law is the conversion and conservation of energy. In the context of an energy demonstrations show, the examples converting between forms of energy that take center stage, and chemistry is a well-suited platform for this. The most common and convenient form of energy storage is the potential energy in molecules. Chemical transformations are excellent examples of the First Law, converting chemical potential energy directly into a range of other forms of energy including heat, electrical, potential, work, and light.\textsuperscript{21} Chemical storage and transformation also provide a temporally and spatially controllable starting point for access to many forms and subsequent transformations of energy. This makes chemistry a natural toolkit when attempting to educate a K-12 audience about the First Law while simultaneously building excitement and interest in science.

Despite its familiarity from common use of the term “energy,” the concept of energy differs connotatively in meaning through everyday dialogue: we may panic at the depletion of energy in our mobile phones, schedule regular payments for energy utilities at home during frigid winters, or consume energy drinks that are marketed to increase mental
alertness and physical performance. Moreover, media publications that discuss “creating” sustainable or alternative energy sources further obfuscate the general public’s perception of energy. For educators, this ambiguity complicates the instruction of a concrete definition of energy that reconciles competing meanings derived from everyday usage.

At first, teaching the First Law of Thermodynamics to elementary school students may seem to be a mismatch between content and student grade level. However, as we will demonstrate below, even students in the third grade can understand and retain a simplified version of the First Law that omits the underlying mathematical formulation but retains the foundational concept of energy conservation conveyed through example. In fact, qualitative descriptions of energy transfer from one form to another has been identified as a Disciplinary Core Idea for elementary school students in the NGSS by the NSTA. The “Energy and U” show was designed to be a demonstration-oriented performance with a continuous running theme built around the First Law. During this show, several demonstrations were performed, each showing a conversion between different forms of energy such as heat, electrical, and chemical. Examples are presented in Figure 1-a. We deconstructed the First Law into two main questions, referred to throughout this report as Question A and Question B:

- Question A: Can you create energy?
- Question B: Can you destroy energy?
Figure 1. (a) Representative photographs of the University of Minnesota Energy and U show, which presents conversion between different forms of energy with explosive experiments and interactive demonstrations. (b) Timeline of the development and growth of the Energy and U program.

Figure 1-b shows the progression of the Energy and U show, which was originally conceived in late 2006 and performed at the University of Minnesota for the first time in the summer of 2007 to a group of visiting K-12 students. After this initial success, continuous development of the show followed, and in May 2015 it was expanded and improved in collaboration with the Theater Arts and Dance Department at the University of Minnesota to include many of the trappings of professional theater, such as professional stage management, sound, visual effects and lights. The show has been performed for over 60,000 students, and currently serves ~12,000 students per year. From January of 2014 to
January of 2015, audience participation using clicker devices was incorporated to both enhance student engagement and allow the collection of real-time student feedback. This report presents an analysis of the data collected during that time.

We present here the results of a comprehensive study aimed at not only teaching the conservation of energy to elementary school students, but also evaluating the effectiveness of an outreach program in a quantitative manner. The student audience was surveyed before and after the show. Responses demonstrate that the show positively affects both short- (immediately after the show) and long-term (>6 months) understanding of the First Law of Thermodynamics. We further identify a disparity between student retention of the inability to create energy compared to that of the inability to destroy energy. This may be linked to the presentation of these lessons or a result of preconceptions about the creation of energy. While the focus of the show is the First Law and general promotion of STEM education, the survey data was also analyzed for correlations with student socioeconomic status indicators based on access to free and reduced cost lunch.

2. METHODS

2.1 Student Population

The authors have contacted and worked with the University of Minnesota IRB office to verify that this activity does not fall under human research according to DHHS regulations. Survey responses collected according to this protocol were not classified as identifiable information.

Survey data was collected over a two-year period of performances from the Minneapolis-Saint Paul metropolitan area; 8605 and 4059 students attended the 2014 and 2015 performances.
2015 shows, respectively. The elementary schools represented a diverse range of student populations. The racial and socioeconomic makeup of the survey population was estimated from the data collected by the state of Minnesota for each of the schools that attended the show, and was not assessed directly at the show. Based on this data, the survey population was made up of 56% students of color and 56% economically disadvantaged as defined by the percentage of students eligible for reduced cost or free lunch.

2.2 Show Description

The show was held twice a year for a week each time (January and May in 2014, and January in 2015) in a classroom outfitted for chemical demonstrations on the University of Minnesota–Twin Cities campus. There were three shows each day for a total of 15 shows per week. Three to five local elementary schools were invited to each show with a typical total attendance of 300 students and chaperones. At the beginning of each show, demographic information such as grade level and school, and a pre-evaluation of the students’ understanding of the First Law of Thermodynamics were collected and assessed using clickers provided to every audience member (see Section 2.3). The first question asked was unrelated to the topic of energy, “Who is the better singer? A) Justin Timberlake, B) Taylor Swift.” This was used to help orient the students to the use of the feedback device. Figure 2 shows representative slides from the show.

Following initial assessments, the show followed a consistent, connected, and running theme of the conversion of energy from one form to another. As one illustrative example we describe the content related to combustion. A more comprehensive description of the
show is provided in the Supporting Information. The students were introduced to the oxidation of organic molecules with a live demonstration of the combustion of a gummy bear, including real-time monitoring of the temperature. The chemistry is shown on a slide graphically, and symbolically, with conversion of stored chemical energy to energy in the form of heat. When each new form of energy is introduced, heat in this case, the students are invited to stand up and dance to excerpts of popular songs. This is designed to engage the students as they identify with each form of energy. Next the students are told that cars run on energy in the form of heat. As one might expect, they are a bit confused, since this is not their natural response when confronted with the question, “What do cars run on?” It leads directly to the questions, “If cars run on heat, and you cannot create or destroy energy, where did the heat come from? What do cars run on?” The audience routinely shouts “Gas!”, and then the connection can be made to the full energy conversion of hydrocarbon combustion to heat to work to motion (kinetic energy). Later in the show, the question is raised, “Where did the energy stored in the gas come from?” With the audience helping, the energy conversions are walked back to light from the sun.

The first half of the show is focused on energy in the form of work, heat, and potential energy while the second half of the show describes converting energy between electricity, chemical energy, and light. For each demonstration, emphasis was placed on showing the conversion of energy from one form to another. Student volunteers from the audience are involved in many of the onstage demonstrations. The First Law of Thermodynamics is introduced to the students during the show as the statement, “You can’t create energy, and
you can’t destroy energy.” This concept of energy conservation is stated twice during the show, near the beginning and then about half way through. Student retention of the concepts is then measured at the end of the show.

Figure 2. Representative slides shown during the Energy and U show. Students were familiarized with clickers at the beginning of each show and were surveyed in their understanding of the First Law of Thermodynamics. Understanding of the First Law was evaluated at the end of the show.

2.3 Student Evaluation and Analysis
All students were surveyed using i>clicker 2 response devices\textsuperscript{23} (clickers), and collective responses were compiled in the i>Grader (TenTal Software\textsuperscript{24}) program. Table 1 presents the questions asked at the beginning and end of the show, and a set of representative student response. After familiarizing students with using the clickers by asking them Question 1, we collected demographic information, including school location, grade, and previous attendance of the show with Questions 2-4. In this manner, student
responses could be separated from chaperone responses and retention from a prior experience with the show can be assessed. At the beginning of the show we asked Question 5, “Is it possible to create energy?” to assess students’ prior knowledge about The First Law of Thermodynamics. At the conclusion of the show, we asked both questions A and B to evaluate the immediate impact of the show. Students were instructed to remain silent during this time. We switched the ordering of the last two questions for 1593 of the 12,664 students in order to identify any potential bias created by one preceding the other.
Table 1. Energy and U Clicker Questions and Rationale.

<table>
<thead>
<tr>
<th>No.</th>
<th>Question</th>
<th>Purpose</th>
<th>Answers</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>“Who is the better singer?”</td>
<td>To acclimate students towards using the Clicker devices.</td>
<td>(A) Justin Timberlake  (B) Taylor Swift</td>
<td>(A) 1525 (B) 2442</td>
</tr>
<tr>
<td>2</td>
<td>“What school are you from?”</td>
<td>To associate responses with specific school groups and demographics.</td>
<td>(A) School 1 (B) School 2 (C) School 3 (D) School 4 (E) School 5</td>
<td>44 schools were surveyed over the course of the show.</td>
</tr>
<tr>
<td>3</td>
<td>“What grade are you in?”</td>
<td>To categorize the students’ grade and separate student and chaperone responses.</td>
<td>(A) 3rd  (B) 4th  (C) 5th  (D) 6th  (E) Teacher, chaperone, other</td>
<td>(A) 759 (B) 713 (C) 1606 (D) 404 (E) 284</td>
</tr>
<tr>
<td>4</td>
<td>“Have you been to the show before?”</td>
<td>To monitor the retention of students who are returning to the show.</td>
<td>(A) Yes  (B) No</td>
<td>(A) 920 (B) 2923</td>
</tr>
<tr>
<td>5</td>
<td>“Is it possible to create energy?”</td>
<td>To assess the understanding of the conservation of energy before the show.</td>
<td>(A) Yes  (B) No</td>
<td>(A) 3496 (B) 563</td>
</tr>
<tr>
<td>A</td>
<td>“Can you create energy?”</td>
<td>To assess the understanding of the conservation of energy after the show.</td>
<td>(A) Yes  (B) No</td>
<td>(A) 213 (B) 3477</td>
</tr>
<tr>
<td>B</td>
<td>“Can you destroy energy?”</td>
<td>To assess the understanding of the conservation of energy after the show.</td>
<td>(A) Yes  (B) No</td>
<td>(A) 406 (B) 3565</td>
</tr>
</tbody>
</table>

Questions 1-5 were asked at the beginning of the show, and questions A and B were asked at the end of the show, with the order of questions A and B reversed in some of the shows.

In addition to the assessment associated with the conservation of energy, 3300 of the students were surveyed regarding their overall interest in college and science. The results are presented in Table 2. A five-point Likert-type scale was initially chosen and used with 1561 students with responses ranging from “very untrue” to “very true.” As a comparison,
a simplified three-point Likert-type scale with options of “Yes,” “No,” or “Maybe” was used for a different 1739 students.

### Table 2. Likert scale and multiple choice survey questions (January 2015 Show). $^a$

<table>
<thead>
<tr>
<th>No.</th>
<th>Question</th>
<th>Purpose</th>
<th>Answers</th>
<th>Responses</th>
<th>Simplified Likert-type Scale</th>
<th>Answers</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>“I want to go to college.”</td>
<td>To gauge general interest in attending college.</td>
<td>(A) Very untrue (B) Somewhat untrue (C) Neither true nor untrue (D) Somewhat true (E) Very true</td>
<td>(A) 111 (B) 35 (C) 102 (D) 190 (E) 1568</td>
<td>(A) Yes (B) No (C) Maybe</td>
<td>(A) Yes</td>
<td>(A) 1599 (B) 64 (C) 342</td>
</tr>
<tr>
<td>2</td>
<td>“I want to take more science classes.”</td>
<td>To assess general interest in science.</td>
<td>(A) Very untrue (B) Somewhat untrue (C) Neither true nor untrue (D) Somewhat true (E) Very true</td>
<td>(A) 279 (B) 89 (C) 243 (D) 395 (E) 927</td>
<td>(A) Yes (B) No (C) Maybe</td>
<td>(A) Yes</td>
<td>(A) 1063 (B) 404 (C) 563</td>
</tr>
</tbody>
</table>

$^a$ Answer choices were switched mid-way through shows.

Statistical significance of the differences between the students who have or have not seen the show previously for their responses to the Likert-type scale questions was evaluated using t-tests of independent means. Reported 95% confidence intervals for Likert-type scales indicate certainty evaluated from a Student’s-t analysis. For all other reported analyses, Z-tests of proportions were used to determine the statistical significance of measured differences between two populations (e.g. those who have or have not seen the show). Unless otherwise mentioned, all results using Z-tests of proportions were observed to be statistically significant with over 99% confidence because of the large sample size of over 4000 students for each session.
3. RESULTS AND DISCUSSION

3.1 Evaluating the Effectiveness of Teaching Conservation of Energy Principles

The results of the evaluations are presented in Figure 3. There is substantial contrast between the perception of energy before and after the show. The percentage of the audience (12,664 students) who gave correct responses to Question A increased dramatically from the beginning of the show to the end of the show, from 15% to 91% (Figure 3a). The faction of students that correctly answered Question B was 94%. These results provide two important conclusions. First, the percentage of students that know the concept of energy conversion prior to the show is very low. Second, the show has very high efficacy in delivering the lesson of energy conversion when evaluated for short-term retention.

Although elementary school students are the primary targets of the show, it is interesting to note that a similar trend was observed for the responses of 178 adult chaperones. The correct response to Question A increased from 30% to 90%. This large increase reveals that (i) the misconception that energy can be created is still present in adult populations and (ii) the immediate effect of the show on lesson retention also upholds for chaperones. Additionally, this may yield a secondary impact on the students through education of the primary set of adults that have the opportunity influence their understanding over a much longer contact period.
Figure 3. Comparison of responses when asked. “Is it possible to create energy?” (pre-show, Question 5), “Can you create energy?” (post-show, Question A), or “Can you destroy energy?” (post-show, Question B) for (a) total students and (b) January 2015 chaperones. All differences between correct (green solid bars) and incorrect (red dashed bars) answers were statistically significant to over 99% confidence.

Longer-term retention of the primary concept was assessed by comparing the performance of 2135 first-time and 701 returning students (the minimum time between
shows was 5 months) on Question 5 asked the beginning of the show. The fraction of students who correctly answered Question 5 was a factor of 2.5 larger for those who have seen the show previously than those who have not (24% and 9%, respectively), providing direct evidence of longer-term retention. The observed increase in retention of those who have previously seen the show is upheld even when the students are separated into two age groups with similar population sizes: 3rd/4th graders, consisting of 1090 students, and 5th graders or older, comprising 1746 students (Figure 4). The similar increase in both age groups suggests that the measured retention is an effect of the show and not simply increasing age (59% of returning students are 5th graders or older). Additionally, 26% of the chaperones present who have not seen the show previously answered Question 5 correctly at the beginning of the show while 39% of the chaperones who have seen the show previously answered correctly, demonstrating that the show is effective even among adults (Figure 4).
3.2 Wording Effect and Comprehension.

Given the ongoing cognitive development in logic, interpretation, and communication skills for children, questions that are intended to be standardized can elicit biased responses or compromise reliability (stability or repeatability over time) in the question-answer process. Borgers et al. discussed how cognitive factors can affect objectivity in responding to survey questions for children from ages 8 to 16 years old.\textsuperscript{25} They report that the number of answer choices has a particularly strong effect on response reliability, while negatively-worded question interpretation was not a key factor in response consistency. The ordering of multiple questions targeting the same learning outcome, such as comprehension of the conservation of energy, may influence the question’s responses. For example, Questions A
and B at the end of the presentation address conservation from the complementary perspectives of the inability to create and the inability to destroy energy. There are two issues to consider: (1) Does the first question bias response to the second question? (2) Do the students interpret the ideas of create and destroy differently in this context?

To study the effect of question order, we reversed the order of the post-show Questions A and B for different sessions of the show: 2289 students were asked Question A first, and 1476 students were asked Question B first. For Question A, 88.2% of students responded correctly when this question was asked first. After the ordering switch, this increased slightly to 90.3% correct responses. In comparison, for Question B, 95.4% of students responded correctly when asked first, and 95.9% of students responded correctly when asked this second. These differences were statistically different from each other to a 99% confidence level. However, there does appear to be modest differences in how the students interpreted the concepts of create and destroy in the context of energy conservation. The larger residual population that did not change their answer to Question A from the beginning to the end of the show suggests a larger barrier to acceptance of the idea that you cannot create energy compared to the idea that you cannot destroy energy. We postulate that the observed discrepancy may have its roots in ubiquitous usage of phrases such as “creating new sources of energy” found in a wide variety of common media.15,16
Figure 5. Comparison of correct and incorrect student responses when asked Questions A and B at the end of the show before and after switching the question ordering. All differences between correct responses before the switch (blue dashed bars) and after the switch (green solid bars) were statistically significant with greater than 99% confidence.

3.3 Factors Affected by Socioeconomic Diversity

Aschbacher, Li, and Roth reported that only 20% of the surveyed students that the authors categorized as having a low socioeconomic status were interested in STEM fields at the end of high school, compared to 62% of those of a higher socioeconomic status.26 With the ability to correlate our survey data with socioeconomic indicators, we decided to examine the potential for correlation between socioeconomic status and exposure to a fundamental scientific concept, energy conservation, in elementary school students. We compared the percent of students at each school that were eligible for free and reduced lunch (%F&RL) to the performance on Question 5 at the beginning of the show. No
correlation was observed, as shown in Figure 6 ($R^2 = 0.0594$). Similarly, when measuring the correlations between %F&RL and interest in attending college and in taking more science classes, as measured using the Likert-type scales (see Table 2 for questions), the $R^2$ values were 0.0014 and 0.0022, respectively, Figure 7.

**Figure 6.** Percentage of the students of each school that correctly answered “Is it possible to create energy?” as a function of %F&RL for that school for the January 2015 show. Error bars represent the 95% confidence intervals as determined using a Students-t analysis. The dashed line shows a linear regression of the plotted data.
Figure 7. Students’ Likert-type responses to (a) “I want to go to college” and (b) “I want to take more science classes” as a function of %F&RL for each school for the January 2015 show (the Y-axis shows an average of all responses was measured using the following: Very Untrue/No = 1, Somewhat Untrue = 2, Neither True nor Untrue/Maybe = 3, Somewhat True = 4, and Very True/Yes = 5). Error bars represent the 95% confidence intervals as determined using a Students-t analysis. The dashed line shows a linear regression of the plotted data.
4. **Conclusions**

   Energy and U, a demonstration-based show with a consistent theme based on the First Law of Thermodynamics, was developed and then evaluated using direct audience feedback collected from over 10,000 elementary school students. Survey data collected at the start and end of the show demonstrated a low level of understanding when the students (and chaperones) arrived and a high level of efficacy imparting the correct understanding of the conservation of energy. The percentage of students that correctly answered Question 5 at the start of the show, 14%, increased to 90% correct answers on Question A. Students across both analyzed age groups (3rd/4th and 5th grade and older) who had previously seen the show were twice as likely to correctly answer Question 5 at the beginning of the show than students who had not seen the show before. These measurements demonstrate the effectiveness of the show to promote both short- and long-term retention of the First Law of Thermodynamics among elementary school students. The increased lesson retention was also observed for adults/teachers/chaperones who attended the show. Reports of quantitative evaluation of the impact of this type of community outreach are scarce. This study demonstrates that positive learning outcomes for targeted scientific content can successfully accompany a more general theme promoting pursuit of learning and careers in STEM-based disciplines.

   At the end of the show, more students correctly answered Question B than Question A, irrespective of the order the questions were posed. This observation demonstrates an inherent bias among elementary school students for the ability to create energy compared with destroying energy. This bias may reflect common usage of terminology that often
incorrectly states or infers the creation of energy. No correlation was observed between the percent of the student population eligible for free and reduced cost school lunches (%F&RL) and the propensity for the students of each school to correctly answer Question A. Student interest in science and future pursuit of a college education, measured using a Likert-type scale, were independent of %F&RL, revealing that elementary school students are less affected by economic biases than has been demonstrated for older students. This study provides one of the first examples of incorporating real-time feedback into large-scale chemistry-based outreach events for elementary school students in order to quantify and better understand the broader impact and learning outcomes.

**ASSOCIATED CONTENT**

**Supporting Information**

The Energy and U presentation, demonstration descriptions, Likert-type scale analysis, and supplemental photographs from the show. This material is available free of charge via the Internet at http://pubs.acs.org.

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