Learning by Doing: Project-Based Science to Enhance Student Understanding of the Scientific Process

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Abstract

Using learning by doing methods (Dewey, 1916) via project-based science to support the learning goals of the Next Generation Science Standards (Krajcik, 2015), I engaged a classroom of twenty-two 11th grade students in a science project. I modeled the scientific process and instructed my students in introductory and radio astronomy to prepare them for this work. Students collected astronomical data by remotely controlling NASA's 34-meter Goldstone Apple Valley Radio Telescope (GAVRT). For their final project, students were given the option to create a scientific research poster report or an infographic as a summative assessment. Additionally, my data sources included a pre-assessment, student self-assessment, and final exam. Through this process, I learned that implementing a data-driven science project requires a high level of modeling and scaffolding for optimal student success. I also learned that teaching takes more than just passion and content knowledge, but also strong classroom management skills.

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In the winter of 2017, I began my full-time student teaching practicum as part of my master of education and single-subject teacher credential program at the University of San Diego. Before deciding on a research question for my action research assignment, I spent time observing the students I would be teaching at my student teacher site. I also interviewed my cooperating teacher, other faculty, and the site's special education coaches to better understand the school, its background, and my students and their needs. Time was also spent exploring and researching the local community. After learning about my teaching site and my students, I chose a research question that would allow me to explore the effectiveness of a research-backed lesson plan for them using a PBL (project-based learning) science unit doing real astronomical scientific research.

Context

My student teacher site was a PBL charter school in San Diego, CA. I focused my action research at this site within an 11^{th} grade science class composed of twenty-two students over the course of a seven-week quarter. I was given the freedom to choose a project in accordance to my interests, experience, and passion, but grounded in physics over the course of four weeks. My site, designated as a Title 1 school, had students ranging from lower to more affluent socioeconomic backgrounds. Being a school of choice, students are accepted based on a lottery system. A third-party organization runs the lottery to avoid conflicts of interest, and for the fairest selection procedure. However, children of staff members, faculty, or the board can be guaranteed admission. The goal set by the school, and shared with its third-party lottery organization, is to represent the socioeconomic and ethnic makeup of the greater San Diego area, and in accordance with the U.S. Census.

The group of twenty-two students I taught for this research, was evenly distributed between males and females. The class was diverse, and consisted of students who self-identified as Hispanic/Latinx, Caucasian, African-American, and Asian. Six students were Spanish speaking, but only two were English-language learners (ELLs). There was one student on an IEP (Individualized Education Plan), and one on a 504 plan.

It was discovered, from interviewing my cooperating teacher, that the students did not take any sort of science benchmark exam, or standardized science exam. The state school ranking in science was not able to be found through online data sites, such as the California Department of Education's partnered site, www.ed-data.org, nor was this information known by faculty asked at my site. I was also unable to find my students' previous scores in science courses taken before mine. Additionally, my cooperating teacher mentioned that state standards were followed much more loosely at this site, as compared to more traditional schools, but that the school did occasionally make use of the newer Next Generation Science Standards (NGSS).

Since I was not able to find any data on my students' achievement level in science, I delivered a background survey to discover something about their experience and achievement in previous science courses. Roughly 80 percent of my students reported to have taken previous science courses, such as biology, chemistry, and physics, and received average and above average grades. A few students stated that they had only taken middle school general science, and even fewer stated that they either never had a science course, were not sure, or did not provide an answer.

I also gave my students a self-designed pre-assessment. One of the questions was an open-ended question asking the students what they were interested in relating to the subject-matter. There was some excitement in their responses for wanting to know more about astronomy and physics. Their responses were genuine, well-thought-out, and showed that while they did not have much or any experience in physics or astronomy, knew generally about a few different concepts. Out of the eighteen responses received for this prompt, only one student explicitly said that she was not interested in the subject. A few students said they were "really interested" and "fascinated" by astronomy. Other students mentioned a desire to know more about black holes, the birth of the universe, formation of our solar system, the evolution of our Sun, gravity, and exoplanets. There was a lot of passion in their responses and I saw a genuine interest from them for learning about the cosmos.

My students were very accustomed to PBL in their classrooms. Some of their previous science courses included projects in making soap (chemistry), and building model rockets (physics). However, I was not able to find any evidence that my students had any experience in the collection and analysis of scientific data, nor a project performing these tasks with professional scientists. Although they expressed much interest in learning about astronomy in the pre-assessment, and knew of many concepts, they did poorly in basic astronomy questions, such as the age of Earth or knowing the planets. They also did poorly in questions about the scientific process and did not seem to understand exactly what science was or how to conduct a scientific study. There was a general lack of confidence in their knowledge level in science. In addition to the pre-assessment, I also observed my class for a few weeks and found them to have a lack of motivation for being in the class and for learning about science. My hope, was to motivate and encourage their learning and curiosity in science through an engaging project-based science unit performing real scientific research in astronomy.

In an effort to increase my students' science literacy and understanding of science and its process, I decided on an action research question that would allow me to expose them to real scientific research and inquiry: *Will a project-based high school science course that involves the collection and analysis of real scientific data motivate and enhance my students' understanding of the scientific process? Additionally, will it support and enhance their understanding of subject-specific state standards within my discipline?*

Literature Review

In today's world, it is hard to go anywhere without noticing the impact and importance of science and technology in our lives. Students are surrounded by technology more than any other generation in the history of our species. They are entering a world that demands a skillset in science and technology to fulfill the jobs of tomorrow and drive innovation for its future economic success and prosperity (Committee, 2007).

In a report to President Barack Obama in 2010, his council of advisors on science and technology stated that the success of the United States in the 21st century will depend on the population's abilities in science, technology, engineering, and mathematics (STEM), and that this success directly correlates with the achievement of STEM education in our country (President, 2010). Several studies show that America's K-12 performance in STEM education is very near the bottom of the international rankings for industrialized nations (Committee, 2007; President, 2010). Additionally, student interest in pursuing STEM careers after high school are dismally low. In a 2006 study by the Association of American Universities, the United States ranked 16 out of 17 nations in the percentage of 24-years-olds who earned a bachelor degree in the natural sciences or engineering, relative to all first university degree recipients (Committee, 2007). More recent studies show that only about 33 percent of U.S. bachelor degrees are in STEM fields, as compared with 53 percent in China, and 63 percent in Japan; and less than half of science and engineering graduate students in the U.S. are American-born (President, 2010). Having foreign-born graduate students in STEM disciplines is important in that it supports the free flow of scientific ideas across borders, and it brings in the world's brightest minds who often stay and grow our economy (Committee, 2007; President, 2010). However, if the number of US-born STEM graduate students decreases, as well as the number of foreign-born STEM graduate students, then our nation's economy will be threatened by not having a scientifically skilled citizenry, and thus will not be able to compete on the world's modern technologically constructed stage (Committee, 2007; President, 2010). With America's future in science uncertain, and our previous educational efforts to increase STEM careers performing below expectations, perhaps our science education needs reformed. Perhaps we need more authentic scientific education and learning.

Experiential Learning

Learning by doing has been a subject of education research since John Dewey (1916) advocated for the use of experienced-based learning methods. Dewey (1938), argued that investigating real-world problems and teaching content relevant to students' lives was a highly beneficial method of education. Science, which is arguably more well-defined as a process, versus simply as a list of facts or body of knowledge, can be more effectively taught through a constructivist approach where students are active in their learning. According to notable astronomer and science educator, Carl Sagan: "The method of science, as stodgy and grumpy as it may seem, is far more important than the findings of science" (Sagan, 1996, p. 22). The

National Research Council (NRC) also realized the importance of teaching the scientific process when it drafted its *Framework for K-12 Science Education*: *Practices, Crosscutting Concepts, and Core Ideas* (Council, 2012), which lays the ground for the increasingly state adopted, Next Generation Science Standards (NGSS) (States, 2013). With NGSS, students are encouraged to be involved with developing questions, modeling, critical thinking, and project-based inquiry closely paralleling that of a professional scientist conducting research (Council, 2012; States, 2013). The drafters' of NGSS believe that placing more emphasis on critical thinking and problem solving has greater educational benefits, versus the traditional methods commonly in use by schools via memorization and rote procedures (Harris et al., 2015; States, 2013). This 'Teach Less, Learn More Initiative', which hails from the widely revered Singapore Educational System, moves instruction further away from rote memorization practices commonly found within direct instruction models, and closer to a deeper conceptual understanding of concepts through problem-based learning (States, 2013).

Project-based science. NRC's *Framework* stresses that students must engage in the authentic practices of scientists to gain high proficiency levels in science content (Council, 2012; Harris et al., 2015). These practices involve the deep investigation and modeling of phenomena; they are not focused on the memorization of facts and information, which traditional science classrooms have historically utilized in their instruction (Harris et al., 2015). Additionally, traditional science classrooms mostly employ the notion that there is only one right answer to a question, whereas NGSS discourages this practice in place of more "open-ended questions that focus on the strength of the evidence used to generate claims" (Council, Education, & Education, 2015, p. 11). The American Association for the Advancement of Science (AAAS) offers supplementary insight into the scientific process and nature of its practitioners: "There simply is no fixed set of steps that scientists always follow, no one path that leads them unerringly to scientific knowledge" (Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005, p. 856). Therefore, the pathway to scientific knowledge is not best characterized through the memorization of facts, or by following a strict step-by-step procedure, but is rather a more open-ended quest that is based on scrupulously interrogating nature and basing newly gained knowledge on evidence acquired through that process. If we want our students to better understand science, then they need to be involved with these types of practices. Project-based science curriculum, which involves learning science by doing science (Bell, 2010; Krajcik, 2015), seems to fit perfectly with the goals of the NRC's *Framework* and the new Next Generation Science Standards. With project-based science, classrooms can be aligned with NGSS, and engage students in science practices, such as designing and participating in investigations, and discussing the validity of claims with evidence-based reasoning and critical thinking (Krajcik, 2015).

Project-based learning. Project-based instruction allows a classroom atmosphere to be full of inquiry-based problems, open-ended questions, and the use of more cognitive and metacognitive learning techniques (Blumenfeld et al., 1991). This not only supports NGSS, but also improves student motivation and learning outcomes. According to a study by the University of Michigan, there is an engaging and motivating nature in a project-based type of instruction when the projects employed are high-level and complex, and have no one right answer or specific pathway to completion (Blumenfeld et al., 1991). Additionally, motivation and engagement increases in students when the projects that they are involved with have benefits to society, real-world applications, value, are authentic, and/or are meaningful (Bell, 2010; Blumenfeld et al., 1991; Fortus et al., 2005). In project-based learning, the students are driving their own learning through inquiry (Bell, 2010). Empirical evidence has shown that this student-centered and interactive approach can also greatly improve student learning, problem solving, and analytical thinking skills in answering high-order questions (Hall & Miro, 2016) common in the field of science.

Not only have students involved in project-based science learning shown a deeper understanding of subject-matter (Blumenfeld et al., 1991), but they have also outperformed students in non-project-based science classes on standardized testing (Geier et al., 2008). In a study in Britain, three times as many students involved in a project-based learning program achieved the highest marks on a nation-wide exam, versus the students enrolled in a more traditional, non-project-based school setting (Bell, 2010). The benefits of project-based science were also found to be similar for both male and female students, students from various racial and ethnic backgrounds (Harris et al., 2015), and for students in more underserved and urban environments (Geier et al., 2008). This is important because women, African Americans, Hispanics, and Native Americans are extremely underrepresented in science and engineering fields (President, 2010), and this proves that "a central principle of the *Framework*—that all students can learn—is possible to realize at scale in a large urban school district" (Harris et al., 2015, p. 1381).

Science is perhaps the greatest achievement of the human species. It has delivered us a longer lifespan, defeated many diseases, given us flying machines, put the entirety of human knowledge at the touch of our fingertips within our pocket, and has allowed us to leave footprints on others worlds. These, and its many other achievements, have not only raised our quality of life, but have also driven our economies. The world and economy of tomorrow intrinsically depend on the advancement of science and technology, and if the United States wishes to remain highly competitive in this world, then it must produce a citizenry skilled in its practices (Committee, 2007; President, 2010). Through constructivist approaches made popular by John Dewey, and the current campaign by the National Research Council's Next Generation Science Standards, science education can mimic its profession more closely than ever and allow students to benefit from 'learning by doing'. The research presented here shows that this type of project-based learning allows students to learn science deeper through higher level metacognitive and critical thinking processes. It also shows that this type of learning can motivate students.

Implementation

In order to have a project-based lesson be successful and sustain student motivation, it is important that the instructor values and has passion for the project (Blumenfeld et al., 1991). For this reason, I chose a project aligned with the subject-matter that I am most passionate and knowledgeable about, astronomy. The Goldstone Apple Valley Radio Telescope (GAVRT) is a 34-meter radio astronomy telescope located at NASA's Deep Space Network (DSN) in Apple Valley, CA and is used in projects aimed at delivering "hands-on scientific discovery" to America's K-12 classrooms (Roller & Klein, 2003, p. 171). With GAVRT, students are able to remotely control a NASA, Jet Propulsion Laboratory (JPL), and Lewis Center for Education Research (LCER) partnered telescope to collect data from astronomical objects for real scientific research (Roller & Klein, 2003). Data that students collect with GAVRT is often found in published papers in scientific journals and shared at major science conferences, such as the American Astronomical Society, American Geophysical Union, and the International Astronomical Union (Roller & Klein, 2003).

The reality that the students' work with GAVRT can contribute to real-world scientific discovery and progress has high benefits towards their motivation and learning in a science classroom (Bell, 2010; Blumenfeld et al., 1991; Fortus et al., 2005). Both the students and teachers involved with a GAVRT project are “doing real science as part of a team of national and international astronomers” (Jauncey et al., 2017, p. 281). Students involved with this work have amazing opportunities to contribute to cutting edge research in understanding quasars and black holes, the atmosphere of solar system planets, contribute to science done by NASA’s current Juno spacecraft orbiting Jupiter, and even comb the radio waves of our Milky Way Galaxy in an attempt to search for alien life with the GAVRT SETI (Search for Extraterrestrial Intelligence) project (Jauncey et al., 2017; Roller & Klein, 2003).

My instructional goal was to develop a unit using a project-based science approach so students could ‘learn science by doing science’. With GAVRT, the “goal is for students and teachers to learn about science by doing real science, instead of by reading about someone else’s results” (Jauncey et al., 2017, p. 286). GAVRT not only provides a project where goals align, but also one where students can gain real experience conducting NASA partnered astronomy research. Project-based science learning, such as done with GAVRT, allows students to gain important 21st century skills (Bell, 2010; Fortus et al., 2005; Hall & Miro, 2016) needed for tomorrow’s economy. With GAVRT, some of the skills students can learn include modeling, collaboration, and the collection and interpretation of data. The project-based science program with GAVRT allows students to not only learn science by literally involving themselves in rigorous astrophysics-based research, but it also motivates them through the fact that with GAVRT they are contributing to real scientific research and exploring the mysteries of the cosmos.

Instruction and GAVRT Experience

Before diving into an observation session with the GAVRT instrument, my students needed to learn about the scientific process, basic astronomy, radio astronomy, SETI, astrobiology, and some principles in physics (such as electromagnetism, waves, and frequency). My first lesson with my students was titled, *Science, Skepticism, and The Baloney Detection Kit*. This lesson gave a preview of our unit on astronomy, and the project we were beginning using GAVRT, however, its focus was helping students understand the scientific process and improve their critical thinking skills. This was imperative to my unit since the students would be conducting actual scientific research, collecting data, and sharing their results with NASA scientists. The lesson objectives where to (1) evaluate claims in an effort to determine their validity; (2) begin to understand the process of science, and the importance of skepticism and embracing of evidence; (3) learn Skeptic Magazine's Michael Shermer's version (Shermer, 2001a, 2001b) of Carl Sagan's Baloney Detection Kit (Sagan, 1996); and (4) use the Baloney Detection Kit to analyze a claim. Some of the claims explored included crop circles, recent fake news stories, chem trails, and the Moon landing hoax.

Next, I put my students through a unit on introductory astronomy, radio astronomy, and physics. In this unit, we covered the history of the universe, naked eye astronomy, how to navigate the night sky, astrobiology, the search for extraterrestrial intelligence (SETI), telescopes, radio astronomy, electromagnetism, the nature of light, waves, and frequency. It was important that my students had a basic understanding of these concepts before our first session booked with GAVRT, where they would be operating a 34-meter radio telescope collecting radio wave energy from a quasar, and searching the galaxy for candidate signals from extraterrestrial intelligence. Since I only had four weeks to deliver all the material I planned for my project with GAVRT, most of the lessons delivering this background knowledge were direct-instruction in nature. However, some lessons included group work, online virtual astronomy simulations, and student presentations.

After background lessons were complete, my students and I had two live sessions with the operators from the Lewis Center for Educational Research (LCER), who help administer the NASA GAVRT instrument. The operators at LCER connected with my classroom through a conference call and GoToMeeting online to give us access to the GAVRT instrument. Students were given control of the telescope and instructed on how to operate the instrument remotely and collect data in real-time as we observed astronomical phenomena. Students took turns acting as the lead GAVRT operator while the rest of the class recorded data from our observations both on provided data sheets, as well as on a GAVRT data website. As the lead GAVRT student operators in my class took control, the rest of the class was impressed to watch the million-pound radio telescope move in a live video feed on GAVRT's website, http://www.lewiscenter.org/gavrt/.

In the first session, for GAVRT's Black Hole Patrol project, we observed the celestial object, J0217+7349, a quasar powered by a supermassive black hole 12 billion light years away. Students collected electromagnetic radio energy data from this object in their Black Hole Patrol data sheets in real-time. In the second GAVRT session, for their SETI project, we pointed the instrument at a swath of the Milky Way Galaxy to listen for narrow-band radio signals that could be candidate signals in the search for extraterrestrial intelligence (SETI). In these sessions, students also got to control the telescope, watch it move through the online live feed, and collected data in real-time. For the GAVRT SETI project, they were led by LCER operators through the GAVRT SETI website, http://galileo.gavrt.org/seti/, and instructed on how to mask out narrow-band radio signals in GAVRT SETI waterfall data plots collected directly from our observations that day. Students found several candidate signals that will be shared with NASA SETI scientists for further follow-up.

For my students' final project, they were tasked with creating either an infographic educational poster on a concept they learned from the course, or a scientific research poster reporting and analyzing the data collected by the GAVRT sessions. Most students opted for creating infographics covering the scientific process, radio astronomy, SETI, and other topics covered in the course. However, three groups of students chose to create scientific research posters analyzing the GAVRT data. The students making research posters modeled their work after undergraduate and graduate level research posters commonly seen in scientific conferences; they included an introduction, methods, results, and conclusion section, as well as data tables and graphs.

Future work. If I were to reteach this course, I would give my students more time to be involved in group work constructing the background knowledge needed for the GAVRT sessions, versus much of the direct-instruction I delivered up to the GAVRT sessions. Unfortunately, although more effective, constructivist techniques that allow students to build their own knowledge can take much more time than direct-instruction and I only had two and half weeks to teach my students introductory astrophysics and radio astronomy before our first GAVRT session. Time was not on my side. In hindsight, I believe I may have tried to put too much into my overall plans with these students given the short amount of time that I had to deliver. To more effectively deliver my GAVRT project, I believe I would need at least a full 6-7 week quarter, but an entire 12-15 week semester is even more realistic.

If I had a more reasonable amount of time to deliver my project, I would also want to spend more time covering electromagnetism, waves, and quantitative analysis. Electromagnetism and waves are tough subjects, but are deeply important to radio astronomy and the GAVRT sessions. Additionally, I had no time to cover quantitative analysis, such as creating data tables, graphs, and using probability and statistics with the collected data. This made the research posters very challenging for the students that chose that option. The lack of data analysis skills developed by my class may also be why so few students chose to make a science research poster for their project.

Another important factor I would add to GAVRT prep lessons in the future, is more scaffolding, modeling, and lessons on scientific writing for research papers and posters. I feel that many of my students felt intimidated by this project because they were not given the adequate skills needed to write a scientific research paper/poster. If I were to have had them practice writing a science paper (complete with an intro, methods, results, and conclusion section) early in the course, then maybe more students would have chosen the research poster project, and those who did would have been more successful with it.

Assessment Plan

Students were assessed via various informal and formal methods throughout the course. At the beginning of the course, I gave my students a self-designed pre-assessment titled, *Pre-Assessment: Scientific Process & Astronomy*. This exam tested their current and previously acquired knowledge in astronomy, physics, and the scientific process and method. Given before the start of the course, it was meant to test what they already knew, or did not know. It was administered via the online assessment platform, Socrative, and was mostly multiple choice and true and false questions, with a few short answer questions. Students scored very poorly on this pre-assessment, with 95 percent not at proficiency (see Table 1). I was surprised at how low the overall scores were and that 50 percent of students did not know the age of the Earth, and 20 percent of them incorrectly answered a question about Earth's revolution about the Sun. This assessment was very informative and helped me to know where my students stood in their knowledge in the subject-area.

Table 1

Assessment	Percentage of Students		
	Not Yet at Proficiency	**At Proficiency**	**Exceeding Proficiency**
Pre-Assessment	95%	5%	0%
Post-Assessment	14%	41%	45%

One example of informal methods used with my students was during their lessons on electromagnetism, waves, and light. After lectures on the subject material, students were instructed to complete an interactive online tutorial on the electromagnetic (EM) spectrum, and had to draw an EM spectrum in their notebooks. Later in the lesson, the whole class was presented with a series of challenging questions on electromagnetism, waves, and light via PowerPoint slides. Students were chosen at random to answer these questions as part of an informal assessment, but before called upon where given thirty seconds to think, and then one minute to share ideas about their answers. Similar think-pair-share activities were combined with informal assessments throughout the course. Even when given time to think and share with their neighbor, students still often struggled with the questions, but most eventually got the correct answers. However, students still seemed much more confident and excited to answer questions in this style, versus cold calling students with no time to think out their answer or share with a classmate.

Students were also informally assessed throughout the course via random, and often unplanned, questioning during lectures. However, much of the time, being that these were not as structured as the think-pair-share styled assessments, they seemed to lack a level of seriousness or accountability that came with that more structured style of informal assessment. If I were to reteach these students this course again, I would include more structured and rigorous informal assessments during class. Using Google Classroom, Socrative, or if available, a SMART Response or other clicker-based assessment system, I could engage them in challenging questions directly after learning a concept to test their understanding, and to determine if I need to reteach the material or not.

Additionally, students were given an informal student self-assessment after their lessons on radio astronomy and their first GAVRT session. They were asked what they learned and how they knew they learned what they had learned. Student responses to this assessment were very informative and revealed some misunderstanding in the concepts, but also revealed some exciting motivational successes in some students. One student wrote about her experience with GAVRT: “We can talk about it all we want, but until we see it then it’s like whoa, that’s super cool!” In the future, I would like to have more student self-assessments, as I found them to be very effective for both student and teacher. Weekly, if not daily, self-assessments would not only help students retain information, but also give students more time to develop their literacy and writing skills.

In the conclusion of this course, my students were given two formal assessments. The first formal assessment was a final exam testing them on the scientific process, astronomy, radio astronomy, GAVRT, and some of the physics concepts learned. The exam was administered via Socrative, and was composed mostly of multiple choice and true and false questions, but with some short-answer questions. The format was very similar to their pre-assessment, and in fact, many of the same questions appeared on this exam. Fortunately, my students scored much better on the final exam than their pre-assessment. 45 percent of my students scored above proficiency levels (see Table 1), 100 percent got the age of Earth correct, and only one student missed the question about Earth's revolution about the Sun (I learned that he only answered incorrectly as a joke). Although these scores were much higher than their pre-assessment scores, I did offer many bonus point opportunities on the exam, and made the exam much easier than I had liked. If I were to administer it again, I would make it slightly more challenging and offer less extra credit opportunities on it.

The culmination of the course was the second formal assessment administered. Students were given a choice between creating either an infographic educational poster on a concept they learned from the course, or a scientific research poster reporting and analyzing the data collected by the GAVRT sessions. Most of my students opted for creating infographics covering the scientific process, radio astronomy, SETI, and other concepts we covered in the course. However, three groups of students chose to create scientific research posters with the GAVRT data from the Black Hole Patrol and SETI sessions. Modeling their work after undergraduate and graduate level research poster examples, students drafted highly technical pieces that included an introduction, methods, results, and conclusion section, as well as data tables and graphs displaying their collected GAVRT data. Students creating infographics made graphic rich science communication pieces explaining complex concepts, such as electromagnetism, black holes, and quasars. In the end, all my students did extremely well with their posters, regardless of which format they chose to complete, and over 90 percent scored at an above level proficiency (Table 2).

Table 2

Assessment	**Percentage of Students**		
	Not Yet at Proficiency	**At Proficiency**	**Exceeding Proficiency**
Final Project – Posters	0%	9%	91%

I was so impressed with one group's infographic on The Baloney Detection Kit, that I submitted it to the Editor in Chief of Skeptic Magazine and Sagan Baloney Detection Kit modifier, Michael Shermer. Astonished by their work, Shermer published it in an April 26 electronic issue of notable science magazine, Skeptic Magazine's *eSkeptic* (Society, 2017). Since this publication occurred after the quarter with these students concluded, my communication with them was limited, however, I can imagine that this must have been very inspiring and exciting news for them. I am currently working to contact these students to get feedback on how getting published may have affected their motivation for future scientific study. It would be interesting to find out how the students generally felt about getting published, and if it has had any effect on their future academic interests and goals.

Reflection and Future Work – Assessment

From my students creating infographics, I learned that they were very talented in drafting eye-appealing graphic posters, but their content was mostly rehashed information from their notes and my slides. From my students creating research posters, I learned that they had a very hard time with the analytical portion of creating data tables and graphs, were not confident in analyzing the data, and had trouble understanding the differences in the four sections of the poster (intro, methods, results, and conclusion). Students creating infographics were able to work mostly independently, and many finished early. Students working on research posters required almost constant assistance and worked right up until the deadline. The infographics needed to be more challenging for the students. The research posters were challenging enough, but required more scaffolding, skill-development, lessons, and modeling by me for my students to feel prepared to undertake its challenge.

In the future, for infographics, I will require students to include one original metaphor and/or analogy for each concept explained. This will safeguard against students producing derivative work with unoriginal content, as well as make the posters better science communicating tools. Additionally, I will have students develop questions intending to probe the fringes of what is currently known for that topic in the field of science, as well as share their own idea(s) on how that question could be explored through scientific experiment and inquiry to drive the field of science into further advance. These additions would make the infographic version of this assignment more challenging and academically rewarding for students. For research posters, I will do a better job in modeling and scaffolding students in science research paper writing throughout the course. Students will also need to be taught additional skills, such as analytical data reporting, using Excel, and some introductory statistics and probability. Developing more research skills with my students will ensure that they are more confident in doing this type of work when confronted with it in the future. It may also be best to not give the students the choice to create an infographic poster for the final project, but rather make the infographic a shorter project to complete earlier in the course. If the goal was to get all my students to participate in real science inquiry, then I believe I fell somewhat short of that goal since most students chose the easier final project (i.e. the infographics). Even if I fell short of that goal, I believe it was still a worthwhile experience for all my students to be involved with collecting data from the GAVRT instrument and to have seen how the scientific process really works.

Self-Reflection

Overall, this experience was very rewarding in many ways. I have grown not only as an educator, but as a person. I feel more impassioned to go into science education and confident in undertaking the challenge of inspiring new careers in STEM. Our country's future in science and technology is in danger of losing its front seat as the world's leaders and innovators. I am encouraged by my experience with this action research that when you show students that they can change the world with science, that they will want to learn. I saw this first hand with my students and our project with GAVRT. My students were very excited to be a part of this project, as evident in my student's self-assessment response: "We can talk about it all we want, but until we see it then it's like whoa, that's super cool!" This is testament to the power of project-based science and its engaging and motivating factor. Additionally, and possibly from me mentioning the need for more women and people of color in STEM in my lessons, I had several female students communicate a newfound interest in entering the field of science. When students show this type of excitement, it can also affect the teacher, as it has definitely inspired and motivated me. It is moments like this that we learn from and that drive us forward.

Confidence and Flexibility

From being in this classroom I also learned the importance of confidence and flexibility. When teaching my students, I found a huge increase in their engagement and attention when I was more confident in my lessons. On off days, when I came off as less confident, students were much more likely to misbehave and loose attention. It is therefore extremely important to come into to class everyday with confidence and readiness to deliver strong and passionate lessons. It may also help to practice delivery the night before, and make use of briefly drafted notecards. In addition to being confident, I also found that being flexible was of vital importance in the classroom. The classroom can take many different turns, and sometimes what I planned was not working. However, when I was able to think on my feet and improvise in these situations, I could then turn a dull and/or failing lesson into one of success. In the future, I will do my best to come into the classroom prepared not only with a confident outlook, but also with openness to improvise, if needed.

Classroom management. One of the greatest struggles I had also helped me to learn the most about me as a teacher. This struggle was with classroom management. I thought that since I was knowledgeable, and extremely passionate about my subject-material, that everything would fall into place, and my students would also fall in love with the subject matter and give me their full attention. This was not the case. Yes, being passionate about a subject is of extreme importance, and was and is a valuable asset to me as a teacher, but I learned that I also had to be thoughtful in how I managed the classroom. Too often, I would find myself too afraid to practice some classroom management techniques when the class was misbehaving out of fear of not being liked or sounding mean, and occasionally I would let a student slack off while I was busy helping another group of students.

In the future, I want to work on my classroom management skills and not let any student slack off, and find fun and interesting ways to gain my classrooms respect and attention throughout the year. It will also be important for me to be mindful of my passion for my subject. It is possible that my passion could blind me to the base needs of my students. It is also possible that my passion for the subject may drive me to speak of content or material above their knowledge levels. It will be important to find a healthy balance with my passion, be mindful of my students needs and background knowledge, as well as push myself in practicing effective classroom management techniques in my future classrooms.

Setting the stage. Some of the most amazing discoveries in science have come from creative minds exploring the unknown. My students have these type of creative minds, but I have been thinking that I may not have done the best job at giving them the opportunity to do the exploring. If I can find ways to challenge my students' higher-level critical thinking and problem solving skills, and in the same assessment, give them the opportunity to be creative, then who knows what amazing things—besides content and standards—that they will uncover or create. I would love to begin to incorporate opportunities in my lessons for students to create questions about exploring unknown aspects of our universe, such as dark matter, dark energy, the spooky nature of quantum mechanics, the accelerating expansion of the universe, inflation, how we should search for life elsewhere in the universe, how we should be exploring our solar system, what should we be doing with our human space exploration programs, and much more.

Some of the greatest discoveries of our time have also only come from asking the right questions about the universe. For example, Albert Einstein's curiosity about what it would be like to ride on a wave of light (Topper, 2012). Every one of the students that I had in this class, and in any future class that I will have, has the ability to answer and create challenging and creative questions, such as "What is it like to ride on a wave of light?" However, I as the teacher must scaffold, differentiate, and lead them to the creation of these questions and finding answers. For example, I should have had a prompt in the directions for the infographics or rubrics requiring them to create original copy to explain their chosen scientific topic using analogies, similes, and/or metaphors. I'm confident that they all would have come up with amazing ways to communicate the science, and I probably would have also learned a thing or two from them on how to better communicate some of the topics. I also need to think about how I can better lead my students to the creation of questions about the universe's unsolved problems and developing experiments and investigations in finding their answers.

However, to fully give my students the opportunity to utilize their creativity, and apply what they learned to challenging activities, I need to give them the stage to perform from. That takes planning by me to build the stage, showing them how to get onto the stage, and prudence for me to step back and let them perform. Too often, I noticed that I would interject too soon when helping a student with an informal question in class. I need to give students more time to think about their answer, or give more probing questions to help them along their way. I also need to let go a little more to let the students construct their own knowledge, and to find new creative ways for them to do this, even if time is against us.

Social-emotional learning. I have learned through this experience the importance of knowing every student's individuality, personal story, and background. For me to serve my students the universe, I first had to know them, and them to know me. We had to trust each other, and I had to know about each one of their strengths, weaknesses, and learning styles so that I could accommodate their individual needs and differentiate my lessons so that every student could access the universe I so desperately wanted to share with them. To address the need of truly knowing my students in future instruction and assessment, I will make it a point to create a positive and enriching classroom culture in the first few weeks of instruction with my students, to share cultural backpack items, to encourage creativity, questioning, skepticism, and always give every student a chance to be heard. It will also be important for me to be vulnerable in sharing a little about myself with my students. I found that when I shared stories with my students about how I came to be a teacher, and fun stories about my background (e.g. I used to be in a rock band), that they grew to respect me more and improved their behavior in the class.

Saving the world. No longer do we live in a world where simply knowing information will get you ahead. In fact, it is dangerous to have an education system built on an assembly line system machined with rote procedures and memorization, and not building our citizenry's critical thinking and problem solving skills. It is imperative that we encourage students to be curious, question authority, and demand evidence for claims—skepticism fueled by wonder and backed by peer-reviewed evidence. The world of tomorrow demands a scientifically literate populous. The process of science can teach our future world *how* to think, rather than *what* to think, as well as make them more scientifically literate.

The benefits of project-based science education helping our students learn how to think go beyond the classroom, their future economic success, and being scientifically literate in a technology driven world. The ability to critically think and decide on the validity of claims also help protect democracy from takeovers from charlatans and tyrants alike:

> If we can't think for ourselves, if we're unwilling to question authority, then we're just putty in the hands of those in power. But if the citizens are educated and form their own opinions, then those in power work for us. (Sagan, 1996, p. 434)

Through project-based science curriculum, the new NGSS standards, and passionate and informed teachers, I believe we can achieve a scientifically literate populous with the gift of critical thinking and an open mind ready to uncover the mysteries of the universe.

To help prep the next generation of our species with the tools to save the world from charlatans and tyrants, and be scientifically literate citizens of Earth ready to drive our economic future and uncover the mysteries of the universe, I must continue to learn from experiences such as this. Moving forward, my greatest challenge to accomplish this goal will be to inspire my students and thoughtfully engineer lessons that guide my students to create their own knowledge and grow in wisdom. Inspired, I will move forward as a science educator following Kahlil Gibran's own words of wisdom: "If a teacher is indeed wise he does not bid you enter the house of his wisdom, but rather leads you to the threshold of your own mind" (Gibran, 2015, pp. 33-34). If I can accomplish this as an educator, show students the importance and process of science, and through project-based science practices teach students how to think, rather than what to think, then I will certainly help to change the world.

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