High School Laboratory Experiences and Science Achievement: Engaging Students in Integrated Laboratory Experiences

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This report will explore the link between high school science laboratory experiences and academic achievement in science. High school science performance in the United States has largely flatlined since 2009. Research suggests that integrating laboratory experiences with classroom learning leads to stronger learning outcomes in science. However, there are several challenges to their implementation such as teacher quality gaps, access to technology and science equipment, and the prevalence of inexperienced and Out-of-Field science teachers, with low-income schools feeling these challenges more acutely.

Science, technology and engineering permeate almost every facet of our modern lives. Rapid advances in science and technology offer solutions to humanity's most pressing issues and future challenges. The importance of STEM can also be seen in workforce projections, with the U.S. Bureau of Labor Statistics (BLS) projecting that STEM occupations to grow faster (8.0%) than all occupations (3.7%) between 2019 and 2029 (2020). To meet this need, it is imperative that K-12 schools ensure all students graduate science literate and well prepared to pursue the variety of STEM careers available to them.

The 2015 National Assessment of Educational Progress (NEAP) found no measurable improvement in 12^{th} grade science performance between 2009 and 2015, with only 22% of 12^{th} graders scoring at or above the proficient level. (McFarland, 2019, p. 114) However, the Program for International Student Assessment (PISA) results showed some gains in science literacy in the United States between 2006 and 2018. The 2018 PISA also found that the U.S. average score (502) was higher than the international average score (489) (Schleicher, 2019). While PISA results are encouraging, the NEAP results show there is still much work to do in improving science education in the United States.

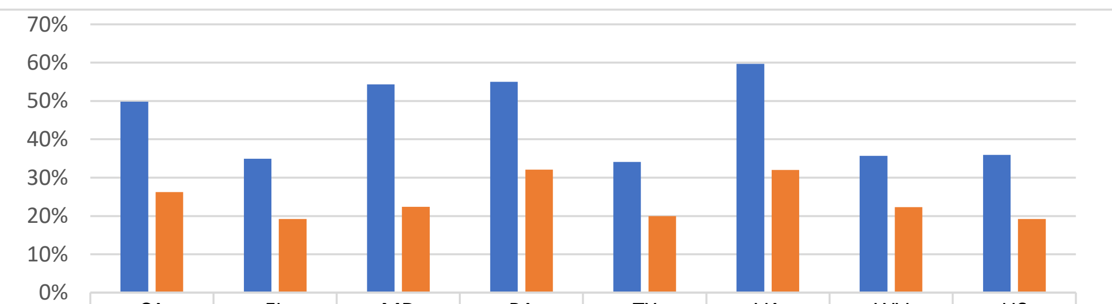
The National Science Teachers Association (NSTA) believes that "for science to be taught properly and effectively, labs must be an integral part of the science curriculum" (2007). The National Research Council offers that a few core science concepts can only be taught through laboratory experiences (2006, p. 4). However, many high schools face shortages of qualified, experienced teachers, limiting the ability of many urban, rural and low-income schools to provide students with critical laboratory experiences that help to contextualize science concepts. When students are better able to understand science and STEM, they are more likely to be interested in STEM careers.

The Center for Excellence in Education (CEE) is a nonprofit education organization whose mission is to nurture high school and university scholars to careers of excellence and leadership in STEM. CEE's Teacher Enrichment Program (TEP) helps to ensure a future talented and diverse U.S. workforce in science, technology, engineering and mathematics (STEM), by providing opportunities for urban and rural, low-income, middle and high school teachers to connect with leading experts from industry and academia to explore cutting-edge research and make meaningful professional links with direct benefits for their students. Since 2012, TEP has served teachers in Indiana, Illinois, South Carolina and Washington, D.C. and currently serves teachers in California, Florida, Maryland, Pennsylvania, Texas, Virginia, and West Virginia. The states TEP currently serves will be the focus of this report. Through increased teacher understanding of the practices and advancements in science research, teachers should be better prepared to integrate laboratory experiences within their classroom.

It is difficult to accurately compare high school science achievement across states, given the differences in science standards and assessment between states. The National Assessment of Educational Progress science assessment breaks out state level data for 4^{th} and 8^{th} grade, however, does not do so for 12^{th} grade. The ACT is designed to measure college readiness in English, Reading, Mathematics and Science and provides a method for comparing high school science achievement between states. However, it is important to note that ACT student demographics do not provide a representative sample.

The ACT science section tests a student's ability to analyze, compare, and contrast graphs and models, understand experimental design, predict the results of experiments, generate hypotheses, and interpret data. These questions are asked in the context of life science, physical science and earth/space science. Students who achieve the prescribed benchmark have a 50% chance of earning a 'B' on the corresponding course and have a 75% chance of earning at least a 'C'. The benchmark for science in 2020 was 23 and is derived empirically through surveys of state science standards and introductory biology courses. To ensure the validity of the ACT as a college-readiness assessment tool, the ACT developed the College and Career Readiness Standards (CCRS), which are empirically derived essential college and career skills and knowledge. The CCRS give more meaning to test scores, with scores serving as a link between the skills and knowledge students have and what they are ready to learn next (Camara, 2015).

In Figure A below, the percent of 2020 graduates meeting the ACT science benchmark of the seven states TEP serves are shown. In Figure B, the number of students taking the ACT and the estimated percent taking the ACT in each TEP state are shown to add context to Figure A. In states such as California, Maryland, Pennsylvania, and Virginia, the percentage of students who meet the science benchmark is higher than other states both overall and when low-income students are broken out. However, the student sample is likely not representative, as fewer than 20% of graduating students took the ACT in each state. It is particularly striking that in states with a higher percentage of students meeting the science benchmark, there is a larger gap when comparing the overall and low-income percentage of students meeting the benchmark than in other states shown. More data and information would be needed to consider if this is a real trend and why it appears that way. Taken overall, these numbers show that many students in the United States are not adequately prepared to engage in post-secondary STEM education and career options and that low-income students are even less prepared than their peers.



	CA	FL	MD	PA	TX	VA	WV	US
Overall	49.8%	34.9%	54.3%	55.0%	34.1%	59.7%	35.7%	35.9%
Low Income	26.2%	19.2%	22.4%	32.1%	20.0%	32.0%	22.3%	19.2%

Figure A – Percent of 2020 high school graduates meeting ACT science benchmark in TEP states. Low income is defined by the ACT as a family earning less than $36,000 a year. (ACT)

	CA	FL	MD	PA	TX	VA	WV	US
# taking ACT	79,916	81,639	12,381	20,114	131,292	17,339	6,662	1,670,497
Est. % taking ACT	19%	46%	19%	15%	38%	19%	38%	N/A

Figure B - Number of students in the 2020 graduating class who took the ACT and the estimated percent of students in a state who took the ACT. (ACT)

Much of high school science education policy is based on the National Research Council's (NRC) *America's Lab Report*, which examined the status of high school laboratories in 2006 and provided a vision for the role of laboratories in science education. This report will use *America's Lab Report's* definition of labs when discussing laboratory experiences. This definition reads, "laboratory experiences provide opportunities for students to interact directly with the natural world (or with data drawn from the material world) using the tools, data collection techniques, models, and theories of science" (2006, p. 3). Laboratory attendance and laboratory grades have shown disproportionate effect on overall academic achievement in introductory biology courses (Moore, 2007).

America's Lab Report additionally identified common learning goals for laboratory experiences such as enhancing mastery of subject matter, understanding the nature of science, nurturing an interest in science and learning science, understanding the complexity of science research, and developing scientific reasoning, practical and teamwork skills (2006, p. 3). While no single laboratory experience is likely to teach all of these learning goals, integrating laboratory experiences throughout the school year makes reaching all the learning goals possible. Additionally, some of the learning goals, such as the understanding the complexity of science research and others, can only be attained through laboratory experiences (National Research Council, 2006).

According to the NSTA, the nature of science (NOS) "is a critical component of scientific literacy that enhances students' understanding of science concepts and enables them to make informed decisions about scientifically-based personal and societal issues" (2020). An important aspect of understanding the NOS is understanding the characteristics of science knowledge and uses of science knowledge as being both a reliable source of information, but subject to change with deeper research (National Science Teachers Association (NSTA), 2020). Lederman's research on teaching NOS finds that while understanding how the complexity of science research and its development is closely related to the characteristics of that science (NOS), they are different education concepts (2019).

America's Lab Report found that integrating laboratory experiences into the classroom learning sequence is critical to the effectiveness of laboratory experiences in supporting science education. Laboratory experiences that have clear learning outcomes, are thoughtfully sequenced into classroom instruction, integrate classroom content with learning the process of science, and incorporate ongoing student discussion, help to ensure achievement of intended learning goals (2006, p. 6). This definition of integrated laboratory experiences will be used to explore the challenges in providing all students with the integrated laboratory experiences that are critical to their science education and achievement.

One of the biggest challenges in both middle and high school science education are teacher quality gaps and shortage of science teachers. Low-wealth urban and rural districts with inadequate resources must pay lower salaries and generally have poor working conditions (Adamson, 2012) leading to high turnover rates. A summary of the available data on teacher characteristics found that "[d]isadvantaged students were more likely to have lower-quality teachers in every year of available data and under every definition of student disadvantage and teacher quality" (Goldhaber, 2019).

One way to measure teacher quality is to look at out-of-field (OoF) teaching, which has a number of definitions. OoF can generally be defined as teachers teaching at least one class outside of their degree or state teaching license. Taylor's analysis of the 2018 National Survey of Science and Mathematics Education (NSSME+) found that life sciences courses were the only high school science course where a majority of teachers had a subject matter degree (2020). The 2018 NSSME+ survey also found that 42% of high school chemistry teachers and only 24% of physics teachers held a degree in that field (Smith, 2020). Taylor's analysis also revealed that high poverty districts had a higher percentage of OoF teachers and an uneven distribution of OoF teachers within individual schools. Classes with high achieving students had an OoF teacher half of the time while classes with low achieving students had an OoF teacher over two thirds of the time. Taylor suggests that this creates a "*de facto* tracking mechanism where, because of a lack of qualified teachers, students who need qualified teachers the most are the least likely to be assigned one" (Taylor, Banilower, & Clayton, 2020).

Lack of high-quality science instructional materials are often a challenge to implementing integrated laboratory experiences in low-income schools. During the 2014-2015 school year, 94% of public school teachers spent their own money on school supplies, and the mean amount of spending was $479 non-reimbursed expenditure (U.S. Department of Education, 2018). The 2018 NSSME+ survey revealed that 33% of high school teachers did not have adequate consumable supplies such as chemicals, living organisms, and batteries. It also found that 30% of high school science teachers lacked instructional technology (computers, probes/sensors), 27% lacked equipment (thermometers, microscopes, beakers), and 28% lacked facilities (lab tables, outlets, sinks) (Smith, 2020).

However, even when a low-income school has the high-quality instructional materials needed, students are likely to have an inexperienced or OoF teacher lacking the content knowledge to fully integrate the laboratory experience into the classroom. Furthermore, low achieving students are more likely to have an inexperienced or OoF teacher, compounding the impact of these students at low-income schools. There are many kits available to assist teachers in creating a classroom where students regularly engage in integrated laboratory experiences, however, they often require specific replacement parts and consumables, otherwise a kit is rendered useless. There are many free, online resources to help teachers conduct low-cost laboratory experiences of varying levels of quality and curriculum inclusion or standards information. To use these, a teacher needs to determine if it aligns with district curriculum and state standards, a harder task for inexperienced and OoF teachers.

Research about high school laboratory experiences has shown that to be effective at helping students to learn science, they must be integrated and related to classroom learning. While the state science standards set expectations of science education for the state, they often lack information needed to guide the critical step of integrating laboratory experiences with classroom learning sequences. Even when the science standards seek to provide that guidance, there is still work that needs to be done on how to integrate laboratory experiences to ensure that students make connections to the natural world, classroom learning and other science disciplines. As science and technology advances and becomes more interdisciplinary, the task of integrating laboratory experiences becomes increasingly important as a means to ensure that students understand the complexity of science research and the nature of science.

With the improvements in computing and sensor technology, it has become easier to capture, store and analyze increasingly large data sets. There is an increasing need for people with the ability to work with data not just in STEM fields, but also across industries, making the field of data science is inherently interdisciplinary (Finzer, 2012). The interdisciplinary nature of data science combined with the increase in publicly accessible data sets provides both opportunities and challenges for science teachers to integrate laboratory experiences in the classroom. Having students work directly with big data sets, often referred to as messy data, provides students with an opportunity to better understand how scientists use data to understand the natural world around them by going through the process themselves. This also provides students an opportunity to engage with the interdisciplinary nature of STEM, as the creation of a data set is grounded in a scientific process, but also requires technology to collect, store and interact with. The growing field of data science offers science teachers an opportunity to engage students around the critical step in science of data analysis, without needing the materials to develop data sets. However, these opportunities come with some significant challenges.

For science teachers to seize these opportunities, they must understand both how the data was collected and the process of analyzing large data sets, as data was not collected or made available with K-12 science educators in mind (Lee & Wilkerson, 2018). Additionally, there is little guidance offered to teachers on how to engage their students in analyzing data sets that are publicly available. A final challenge to science teachers engaging students in this type of laboratory experience is the availability of computers with adequate internet access to conduct data analysis on large data sets. A 2019 report found that 46% of high school science teachers did not have adequate internet bandwidth for classroom use that is reliable and consistent. This report also found that 77% of high school students had access to a tablet, laptop or Chromebook to support in school learning, while 23% needed a computer lab or library to access a computer (Evans, 2019). An increase in the percentage of students with access to an in-classroom device is expected with the 2020 pandemic that forced many schools to teach remotely, with many schools quicky working to ensure all students in their district had access to a computer for remote learning.

There are many challenges that schools and districts face in providing their students with the science education needed to not only pursue a STEM career, but also be an informed citizen with an understanding of the impacts of science, technology and engineering in our world. The condition of laboratory facilities and funds to purchase science instructional materials vary widely within states and across the country, with rural and/or low-income school districts facing these barriers more often. Without proper facilities and materials to engage in laboratory experiences, teachers are unable to meet the science standards and curriculum expectations set for them. High school science teachers at rural and/or low-income school districts are more likely to be teaching out of field or lack critical college level science courses than teachers in suburban districts. Combined, this is a huge challenge for science education in low-income and rural districts, as they are more likely to have both out of field teachers and poor laboratory facilities. Lastly, there are not enough professional development opportunities for science teachers to learn how to better integrate laboratory experiences with classroom learning. There are many models for STEM teacher professional development, unfortunately the variability in state standards and what teachers need to learn makes implementing one STEM teacher professional development model impractical.

The integration of laboratory experiences with classroom content is critical to student science learning and is a pathway to higher science achievement. The lack of professional development opportunities for teachers around this issue presents an opportunity for CEE and TEP to better serve our teachers and students. CEE and TEP could be the provider of the additional professional development STEM teachers need to better integrate laboratory experiences within their classroom teaching. TEP's Bite of Science programming certainly works towards building teacher's content knowledge and understanding of how scientists conduct research, which can help teachers to better integrate laboratory experiences. One possibility is to provide teachers with online content knowledge courses taught by college professors or industry experts that focus on building teachers' content knowledge of emerging STEM topics such as bioinformatics, artificial intelligence, molecular genetics, material science, and biophysics. This model could also be used with TEP's industry partners to focus on the industrial applications of classroom content knowledge such as data science, industry uses of math and 3-D modeling, science communication, and iterative processes (i.e., engineering design process and scientific method).

The findings in this report make it clear that all TEP programming must help STEM teachers develop stronger background content knowledge, understand how research and data analysis is conducted, and develop a deeper comprehension of the interdisciplinary nature of science, technology, engineering, and math that together make STEM. By helping teachers develop stronger content knowledge and make connections across science disciplines and to the real-world, teachers are better equipped to integrate laboratory experiences into their classroom, as they have a deeper understanding of how the lab fits into their student's content learning and how the lab parallels science research. Teachers can more explicitly help students make those same connections, hopefully increasing interest and passion for STEM subjects and for a career in a STEM field.

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