A Brief History of U.S. Science Education—Leading to Modeling Instruction

Author's Note: This article came from Chapter 2 of my dissertation. Please see nathantbelcher.com/edd-program-writings for the full dissertation.

Prior to the mid-1800s, science and science education in the United States existed in an unstructured manner. However, the public's interest in science increased in the late 19th century (Bybee, 2010), partially due to scientific progress and technological advances associated with the industrial revolution. In addition, high school attendance increased drastically between 1890 and 1900, with enrollment more than doubling during this decade. In 1892, the National Education Association formed the Committee of Ten on Secondary School Studies (Spring, 2014). The final report from the Committee of Ten established a general framework for discussion of the goals of secondary education, including information about science education. All students—whether they intended to go to college or enter the workforce—were expected to participate in science courses and the scope of the science courses was expanded to include laboratory work. To specify which type of scientific experiments were expected from secondary students, Charles Eliot (President of Harvard and Chairman of the Committee of Ten) asked the physics department at Harvard to develop an entrance requirement that emphasized the laboratory as part of high school physics courses (Bybee, 2010). In 1889, these laboratories were compiled into a list and published as the *Harvard University Descriptive List of Elementary Physical Experiments*. This list—along with information from other universities—became the first set of national standards for science (Bybee, 2010; Richardson, 1957).

Era of Scientific Management

The era between 1900 and the end of World War II may be considered a time of scientific management in the American school system. In a system with a focus on scientific management, success depended on the implementation of standardization. District and school administrators were preoccupied with standardizing all aspects of the school experience, including hiring procedures, evaluations of teachers and students, and curriculum, instruction, and assessment (Spring, 2014). During this quest for standardization, administrators became obsessed with cost-effectiveness; taking a cue from the business world, administrators began to approach every program with cost-benefit analysis. Through the implementation of standardization, science—along with many other disciplines—became a set of facts to be memorized rather than experiences to be understood (Bybee, 2010). This sterilization eliminated the process of science, producing students who were unaware of the foundational meaning of the "facts." John Dewey, widely known for his progressive ideas about education, discussed the role of scientific process in an address at a meeting for the American Association for the Advancement of Science. Dewey (1910) argued that science "has been taught too much as an accumulation of ready-made material with which students are to be made familiar, not enough as a method of thinking, an attitude of mind, after a pattern of which mental habits are to be transformed" (p. 122). Further in the discussion, Dewey states, "surely if there is any knowledge which is of most worth it is knowledge of the ways by which anything is entitled to be called knowledge instead of being mere opinion or guess work or dogma" (Dewey, 1910, p. 125). This sentiment of helping students understand the ways by which anything may be taken as "knowledge" was counter to standardization because it required experimentation and use of the scientific process. Laboratory work is often messy—intellectually and materially—whereas standardization strives for perfectly predictable results. In an ironic twist, Dewey's ideas about the scientific process as a method of inquiry about a topic were taken by those seeking standardization and changed into a rigid structure called the scientific method. "Soon the scientific method was included in textbooks, thus becoming part of the knowledge that students had to memorize" (Bybee, 2010, p. 71). Even today—more than 100 years after Dewey's ideas—some textbooks begin with the scientific method; beginning with this formal structure as the only way to perform the scientific process presents an incorrect idea.

Establishing the National Science Foundation

Global events after World War II directly affected American schools (Spring, 2014); the Cold War between the United States and the Soviet Union caused many to question the existing K-12 school curriculum. "In the early 1950s the school curriculum, in particular, came under intense scrutiny and became an important ideological battleground on which partisan groups clashed as the nation's survival seemed to hang in the balance" (Rudolph, 2002, p. 10). To increase the quantity and quality of science and technology workers in the United States, the federal government slowly began to provide funding to K-12 education. One application of funding for science was the National Science Foundation (NSF); established in 1950, its primary mission was to initiate, support, and promote basic scientific research and education (Mazuzan, 1994). Four divisions were created in the NSF: "Medical research; mathematical, physical, and engineering sciences; biological sciences; and scientific personnel and education" (Mazuzan, 1994, p. 6). Alan Waterman, chief scientist at the Office of Naval Research and previously a physics professor at Yale, became the first Director of the NSF; his appointment created a dependable link between the scientific elite and government funds from the NSF.

Waterman and other leaders quickly positioned the organization as the preeminent science—and science education—organization in the United States. Leaders of the NSF focused their efforts at improving K-12 science education by funding summer institutes for teachers and updating curricula. As the NSF engaged in K-12 education, science education professional organizations were excluded; this exclusion "demonstrates the overriding influence of both national security and the scientific elite in redefining the school curriculum in the 1950s" (Rudolph, 2002, p. 58). Leaders at the NSF were frustrated by approaches to science education taken by science educators and science education professional organizations; to direct curriculum and instruction developments funded by the NSF, the leaders wanted a first-rate scientist. A scientist would approach curriculum and instruction initiatives with the same techniques that were successfully used to conduct wartime research and development projects, leading to full implementation of the curriculum and instruction.

Legislators in Congress moderately increased federal funding to all divisions of the NSF during the early and mid-1950s, but sentiments of the legislators changed dramatically when the Soviet Union launched *Sputnik I* in 1957. In response, Congress passed the National Defense Education Act (NDEA) in 1958; Title III of the NDEA "appropriated $70 million for each of the next four fiscal years to be used for equipment and materials and for the expansion and improvement of supervisory services in science, mathematics, and modern foreign languages" (Spring, 2014, p. 370). Funding for education could have been awarded to other agencies;

instead, resources went to the Divisional Committee of Scientific Personnel and Education of the NSF. To lead the curricular reform efforts, leaders of the NSF could have partnered with professional science education organizations; however, leaders of the NSF wanted "someone very much like themselves, who shared the interests of the hard-science elite that dominated the NSF hierarchy" (Rudolph, 2002, p. 83). Jerrold Zacharias—physicist at MIT and member of the United States Office of Defense Mobilization's Science Advisory Committee—perfectly fit the description of an ideal candidate. With funding from the NSF, Zacharias created a group that began the process of improving curriculum and instruction in science education; whereas the group's ideas about education were radical at the time, the ideas have become integrated fully in all modern science education pedagogies.

Physical Science Study Committee

The Physical Science Study Committee (PSSC) was formed in the fall of 1956 by Zacharias, who quickly added other members of the scientific elite: Massachusetts Institute of Technology (MIT) president James Killian, Polaroid founder Edwin Land, Educational Testing Service president Henry Chauncey, and other prominent physicists from elite higher education institutions (Rudolph, 2006). Zacharias—and other members of the PSSC—had previous experience with large-scale scientific research and development projects; these projects were successful because scientists used a broad-based, analytical approach to solve complex problems (Rudolph, 2002). The PSSC approached curriculum development with the same methodology, integrating emerging technologies into goal-directed systems to create high-quality curriculum and instructional methods.

Up to and during the 1950s, most high school physics courses were delivered by textbooks. In the most popular science textbook, there were no descriptions of experiments or graphs showing the results of experiments that would justify any of the book's many assertive statements. In addition, the textbook did not have an accompanying laboratory program; for students in a course with this textbook, science was equated with vocabulary (Haber-Schaim, 2006). Zacharias had a different perspective about the teaching of physics; his ideas led to a unique course. Physics was not to be presented as a body of unchanging facts that students must memorize; rather, physics is best understood as living discipline with which students engage. Although one goal of the PSSC course was that students would learn physics content, the other goal of the PSSC course emphasized the process of reasoning from empirical evidence. "The question Zacharias hoped to get students to ask themselves at all times was 'how do you know?' What was your 'basis for belief' in any assertion about how the world works?" (Rudolph, 2002, p. 122). These questions formed the most important lesson for any student leaving a physics course designed by the PSSC: Students should understand that knowledge of the world is based on evidence.

To have students understand that evidence drives knowledge about physics (or any other subject), Zacharias envisioned the physics course using any set of materials that were useful for learning by the students; these materials included films, slides, textbooks, ancillary reading, and laboratory apparatus (Haber-Schaim, 2006). The laboratory activities—coupled with other materials—would "enable students to develop a deeper understanding of the dialectical march from experiment to theory and back again" (Rudolph, 2002, p. 130). While revolutionary at the time, the idea of placing the process of science on equal status as science content has been broadly accepted and implemented at all levels by the science education community. The *Next Generation Science Standards* (NGSS Lead States, 2013) and many state science standards—including South Carolina's (South Carolina Department of Education, 2014)—contain statements that students from kindergarten to upper-level secondary courses should act like a scientist, using laboratory materials to determine evidence and construct arguments from the evidence. One of the lasting effects of the PSSC is the mainstream implementation of the scientific process into science courses; this legacy has been carried by other instructional approaches.

Another important aspect in the curricular and instructional methods of the PSSC are foundational principles. Science was to be presented as a human endeavor, allowing students to understand that anyone can do science (Haber-Schaim, 2006). The selection of topics was crucial for students to understand this idea; the PSSC chose a set of five essential ideas about science:

- The unity of physical science.
- The observation of regularities leading to the formulation of laws.
- The prediction of phenomena from laws.
- The limitations of laws.
- The importance of models in the development of physics. (Haber-Schaim, 2006)

These foundational ideas are still used today, most recently in the *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Academy of Sciences, 2012). This framework establishes three dimensions for science education: Scientific and engineering practices; crosscutting concepts; and, disciplinary core ideas. These dimensions incorporate many of five essential ideas about science developed by the PSSC and place the science process and content on an equal status; information and organization of this framework echoes the ideas of Zacharias and work by the PSSC.

Influence of Robert Karplus

In the 1960s and 1970s, science education continued to evolve. Robert Karplus—a theoretical physicist and head of the Science Curriculum Improvement Study (SCIS) at the University of California, Berkeley—was one of the leaders during this era. Karplus and colleague Herb Thier utilized psychological research from the work of Jean Piaget and Jerome Bruner to create a practical program for students in grades K-6 (Kratochvil & Crawford, 1971). The curricular ideas for the program were constructed from a set of three guidelines:

1. The experiential and conceptual aspects of teaching should be distinguished from one another.
2. The curriculum construction should use major theories of intellectual development and learning, even if the theories provide conflicting interpretations.
3. The curriculum should have learning cycles with three phases: Exploration, invention, and discovery. (Karplus, 1969)

These guidelines provided students with experiences that differed from those they have outside of science courses; the experiences were unique, unusual, and engaging, affording students the opportunity for discovery (Bybee, 2010).

One of the lasting legacies by Karplus and others at the SCIS is the idea of a learning cycle (Karplus, 1969). The learning cycle provides a framework for the organization of curriculum, instruction, and assessment; this framework allows course designers to sequence activities to maximize student achievement. The SCIS learning cycle consisted of three phases: Exploration, invention, and discovery. During the exploration phase, the learner is allowed to impose their ideas and preconceptions on the subject matter to be investigated (Karplus, 1969). This will often lead to conflict between the results of the experiment and preconceptions; from this conflict, the teacher learns information about the students' understanding. In the invention phase, conceptual information is provided to the students to reconcile the differences between experimental results and preconceptions. Finally, the discovery phase allows students to resolve any lingering differences by establishing a new feedback pattern for actions and observations (Karplus, 1969). Repetition and practice occur at the conceptual level, leading to a deeper and more complete understanding of the phenomena. The idea of a learning cycle has become embedded in science education, having substantial research support and widespread application through textbooks on science teaching and learning.

Modeling Instruction

Modeling Instruction began in the early 1980s from a partnership between Malcolm Wells, a high school physics and chemistry teacher, and David Hestenes, a theoretical physicist and physics education researcher at Arizona State University. Wells began his teaching career with a powerful boost from PSSC and Harvard Project Physics teacher workshops in the heyday of Sputnik space-race fever; these workshops positively influenced his view towards teaching (Wells, Hestenes, & Swackhamer, 1995). Wells became a "hands-on" teacher, always eager to build his own apparatuses that provided simple demonstrations of deep physics. The high school in which Wells taught was near Arizona State University (ASU); Wells participated in many science and education courses at ASU throughout his high school teaching career. Eventually, Wells decided to complete his doctoral degree in physics education at ASU. Wells joined the Hestenes group for his research, so Hestenes became Wells' advisor. Wells wanted to perform research that would greatly contribute to the field of physics education; Wells and Hestenes discussed possibilities for several years. During the time of these discussions, Hestenes also was advising Ibrahim Halloun, a graduate student performing work on a *Mechanics Diagnostic* test. This test measures the difference between scientifically accepted Newtonian concepts and the students' personal beliefs about the physical world (Wells et al., 1995). Wells administered the *Mechanics Diagnostic* test with his students, expecting the students to score highly on the assessment. However, Wells was shocked by how poorly students had performed; confronted by the dismal scores of his students on the *Diagnostic*, Wells soon concluded that the fault was in his teaching and set about doing better (Wells et al., 1995). The decision by Wells to improve his teaching practice launched his doctoral research, ultimately leading to the creation of Modeling Instruction.

Wells had already abandoned the traditional lecture-demonstration method in favor a student-centered inquiry approach based on the learning cycle popularized by Robert Karplus

(Wells et al., 1995) when he administered the *Mechanics Diagnostic* test. Wells deeply understood all aspects of the learning cycle from a university course in methods of science teaching; however, faced with the poor scores, Wells determined something essential was missing from the learning cycle. After reviewing work by Hestenes proposing a theory of physics instruction with modeling as the central theme, Wells mastered the details and implemented the theory (Wells et al., 1995). Wells created a version of Modeling Instruction that was laboratory-based and adapted to scientific inquiry. It emphasized the use of models to describe and explain physical phenomena rather than solve problems, aiming to teach modeling skills as the essential foundation for scientific inquiry. To accomplish this in a systematic fashion, Wells developed the Modeling Cycle (Wells et al., 1995). By the end of Wells' doctoral work, the modeling method could be described as cooperative inquiry with modeling structure and emphasis (Wells et al., 1995). After further refinement over several years, the Modeling Cycle was designed to have two stages: Model development and model deployment (Wells et al., 1995). As a rough comparison with Karplus' work, model development encompassed the exploration and invention stages of the learning cycle whereas model deployment corresponded to the discovery stage (Wells et al., 1995).

After the completion of the doctoral work and further refinement of Modeling Instruction, Wells, Hestenes, and others created summer workshops for teachers interested in this methodology. From 1989 to 2005, these workshops were funded by grants from the NSF; after 2005, a non-profit known as the American Modeling Teachers Association (AMTA) was formed to continue offering summer workshops and further develop curriculum and instructional materials. Resources for Modeling Instruction (AMTA, 2017b) have been created for physics, chemistry, biology, physical science and middle school science, with future work directed towards elementary school science. Hestenes (1987, 2006, 2010, 2015, & 2016) has continued to develop the theoretical foundations of Modeling Instruction, utilizing information and methods from philosophy and cognitive psychology.

Table 2.1

Comparison of Pedagogical Ideas throughout the History of Science Education

Timeframe	Person / Organization	Pedagogical Ideas
Mid-1800s to 1900	Charles Eliot / Committee of Ten	Laboratories included in science courses; List of laboratories became the first set of national science standards
1900 to the end of World War II	School Boards throughout the United States	Era of scientific management whereby school boards sought to create standardized and efficient school systems
1950s to 1960s	Jerrold Zacharias / PSSC	Focus on scientific content and process of science; Big question for students to answer: "How do you know?"
1960s to 1970s	Robert Karplus / SCIS	Learning Cycle: Exploration, invention, discovery
1980s to current	Malcolm Wells, David Hestenes / AMTA	Modeling Theory of Cognition; Modeling Cycle: Model construction, model refinement, model application

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