Learning how to do science education: Four waves of reform

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In the modern era of the past half-century, we have seen four waves of science education reform activity. Our view is that these waves are building toward cumulative improvement of science education as a learning enterprise. Each wave has been: (1) distinguished by a different focus of design, (2) led by different primary proponents, and (3) contributed to new learning about what additional emphases will be necessary to achieve desirable outcomes for science education – and a consequent new wave of activity and design. Consideration of these four waves will help contextualize the contributions represented in this volume.

The first wave occurred in the 1950s and 1960s in response to a sense that our schools were not providing the challenging education in science needed to maintain America's edge as a center of scientific research in the post-WWII period. This era of science reform was spawned in significant measure by the creation of the National Science Foundation (NSF) in 1950 and its dramatically accelerated funding following the Soviet Union's 1957 launch of the first man-made space satellite, Sputnik. Scientists in major research universities were leading proponents of new science curricula in this wave, which aimed to introduce students to advances in recent scientific findings and to expose them to uses of the scientific method. Teachers' needs to learn this new content, and a

focus on all students, not only the elite, were relatively neglected factors, as implementations of these curricula evidenced.

The second wave in the 1970s and 1980s was characterized by cognitive science studies of learners' reasoning in the context of science education. These studies led to careful accounts of differences in expert and novice patterns of thinking and reasoning. While studies were designed to investigate novice and expert reasoning differences, science educators began to consider new ways to diagnose student's developmental level of understanding in order to foster learning trajectories from novice to expert (e.g., confronting misconceptions, and providing bridging analogies). Technologies were developed to enable broader access to learning with simulations and dynamic visualizations of complex scientific concepts and systems. Issues of curriculum standards, teacher development, assessment design, and educational leadership were less central to this wave than in the reform wave to follow.

The third wave in the late 1980s and 1990s involved the creation of national and state standards, to specify what students should know and be able to do at particular grade levels in specific subject domains (e.g., the National Science Education Standards). New learning assessments were also developed in accord with this emphasis on standards, and the needs were recognized to index curricula to specific standards, and to align standards, curricula, and assessments. Relatively neglected were the realities of teacher customizations of curriculum implementation to serve local needs, the need for fostering coherence of learners' scientific understanding, and the importance of embedded assessments to guide teacher support for improving student learning.

The fourth wave involves the emergence of a systemic approach to designing learning environments for advancing coherent understanding of science subject matter by learners. Science educators and researchers have recognized the need for planful coordination of curriculum design, activities, and tools to support different teaching methods that can foster students' expertise in linking and connecting disparate ideas concerning science, embedded learning assessments that can guide instructional practices, and teacher professional development supports that can foster continued learning about how to improve teaching practice.

It is important to observe that in any one of these waves of science education reform, there were voices anticipating the emergence of subsequent waves. Our aim is to highlight the dominant central tendencies of American science education reforms during these periods.

The Curriculum Reform Movement

Starting in the 1950s there was an outcry against the low standards in America's schools, alleged to be brought on by the progressive movement in education, which had fostered 'life adjustment' education for greater functional relevance to the everyday activities of students. The implication of such life adjustment for science education was a focus on application rather than mastery of structured subject matter (DeBoer, 1991; National Society for the Study of Education, 1947). At about the same time, as the Soviet Union in 1957 launched the 23-inch wide, 184-pound Sputnik 1 space satellite aboard the world's first intercontinental ballistic missile—which some described as a "technological Pearl Harbor" (Halberstam, 1993)—there was the fear that Soviet scientific prowess had surpassed the United States, and the Cold War worry that the

satellite represented a precursor capability to nuclear attack. Only a month later the USSR launched the far larger 1,120 pound Sputnik 2, spawning fears that missiles were shortly to follow. In response to these Sputniks, within a year the United States government had formed NASA, the Defense Advanced Research Projects Agency (DARPA), dramatically enhanced NSF research funding, and reformulated science, technology, engineering and mathematics education policy with the National Defense Education Act (Stine, 2007). This momentum accelerated the efforts—already underway in 1956—of a group of scientists funded by the National Science Foundation (as well as the Ford Foundation and the Alfred P. Sloan Foundation) to develop a new curriculum for high school physics that would focus on science as the product of theory and human inquiry through experimentation (Physical Science Study Committee, or PSSC: see Finlay, 1962).

Related efforts followed for high school biology (BSCS: Glass, 1962), chemistry (the Chemical Bond Approach/CBA: Strong, 1962; CHEM Study: Merrill & Ridgway, 1969), earth science, and later the social sciences. Jerome Bruner summarizes these views and their grounding in cognitive psychology in the famous 1960 book *The Process of Education,* which was his synthesis from a ten-day long Woods Hole Conference of scientists and educators convened by the National Academy of Sciences. The curricula these scientists were developing had two goals: 1) to update the content of the materials taught to focus on the latest scientific developments, with a central emphasis on "structure" in terms of fundamental principles and their inter-relationships, and 2) to teach scientific inquiry rather than a large array of facts. Students were engaged in hands-

on activities designed to teach scientific measurement, hypothesis testing, and data analysis.

These curricula brought together the best ideas of scientists as to how to prepare young people for future careers in science and other occupations that require systematic thinking and reasoning. In subsequent years, NSF funded introductory physical science courses, as well as elementary school science curricula pursuing the same goals as the high school courses: Science – A Process Approach (SAPA), Elementary Science Study (ESS), and Science Curriculum Improvement Study (SCIS).

How extensively were these curricula used? The new curricula met with initial enthusiasm and were taken up throughout the country by a variety of school districts. By the 1976-1977 school year, 49% of the surveyed school districts were using one of the versions of the BSCS biology materials, 20% were using either CHEM Study or CBA chemistry materials, and 23% were using either PSSC or Harvard Project Physics materials (DeBoer, 1991, pp. 166-167). But Holt textbooks were still dominant in the three high school science subjects. And while the biology curriculum met with initial success, there developed a backlash to its emphasis on teaching evolution. The strongest backlash to the new curricula came with *Man: A Course of Study*, which was developed to teach social studies to middle school students (Dow, 1991). The course featured comparisons of animal behavior to human behavior and included videos of Eskimos and the moral decisions they face due to the harsh conditions of living in the arctic. These topics raised two concerns among conservative Americans: 1) Comparisons of humans with animals seemed to imply that humans were simply animals, which they thought would encourage kids to behave like animals. 2) The Eskimo videos appeared to support

moral relativism, which violated beliefs in absolute moral standards of behavior. The backlash against the curricula put re-authorization of the National Science Foundation at risk, and led to the end of all curriculum development by the National Science Foundation in the early 1980's.

In addition to these salient backlashes, there were many reasons why the curricula were not taken up more widely throughout American schools. Educational faculty were marginally involved in most of the curriculum development efforts, so unrealistic assumptions were made about the contexts of curriculum implementation. The materials were more sophisticated than most students were accustomed to, and so their use was concentrated among the strongest science students, who might go on to careers in science. Because the curricula involve scientific inquiry, they required materials that were difficult to manage and that teachers were often unfamiliar with. Hence the courses were more difficult to teach, which discouraged many teachers from taking them on. Further, the National Science Foundation did not invest heavily enough in professional development to support teachers to make the transition to this new approach to science teaching, so that often teachers who did adopt the curricula continued to teach in their traditional manner. The approach was in fact so novel, with its emphasis on scientific inquiry, that it is not clear that most teachers had the background to master the understanding required to teach the material effectively. And finally, as Hurd (1970) highlighted in reviewing these unprecedented science curriculum reform efforts, the everyday life relevancies of science and the motivations for learning science relating to them were under-emphasized. This was an issue not only for the learners, but for the

parents, community leaders, teachers, school administrators and other stakeholders whose support for these reforms was needed.

When the curriculum reform movement faded, the scientists who had been leaders in the attempt to improve K-12 science and mathematics education went back to their laboratories and largely gave up on improving science education. Their movement was followed by a new effort in the cognitive sciences to study the nature of scientific understanding and to develop new tools for fostering student learning.

The Cognitive Science Movement

In the 1970s there developed a new approach to studying understanding and learning, in part inspired by the development of the digital computer and the attempts to develop artificially intelligent programs that could mimic human thinking and learning (Greeno, 1980). The digital computer provided a kind of lens through which to study how scientific experts do their work and how novices differ from the experts in their approach to problems. Cognitive scientists believed that much of expert knowledge was tacit, and hence missing from what is taught to students. By studying the contrasting ways that novices and experts think about scientific problems, they believed they could tease out the underlying tacit knowledge that experts use to solve problems. Then they planned to design learning environments that would embed the critical knowledge that learners needed to move through the stages toward expertise (Bruer, 1994; McGilly, 1994).

In carrying out this research agenda, cognitive scientists identified a large number of alternative conceptions about scientific phenomena that are common among novices and which systematically depart from expert knowledge (Smith, diSessa, & Roschelle, 1993/1994). For example they identified a number of novice ideas about force and

motion (e.g., diSessa, 1986; McCloskey, Caramazza, & Green, 1980), about the earth, sun and moon system (e.g., Sadler, 1987; Vosniadou & Brewer, 1992), about electricity (e.g., Collins & Gentner, 1987), and about biology (e.g., Carey, 1985; Stewart, 1983). Researchers in this tradition have developed techniques for helping students overcome their misconceptions, through approaches such as bridging analogies (Clement, 1993) and identifying different facets of understanding requiring integration (Minstrell, 1991). There was also research directed at identifying and improving the strategies that students use to learn mathematics (Schoenfeld, 1985) and science (Chi, et al., 1989). The goal was to construct learning environments that directly addressed the understandings and misunderstandings that learners brought to learning about science.

A third focus of this work was to design computer-based learning environments that would enhance students' ability to learn science. Over the years cognitive scientists have developed a variety of computer-based environments that teach scientific inquiry and conceptual understanding, such as ThinkerTools (White, 1984), GenScope/Biologica (Hickey et al., 2003), Galapagos Finches (Reiser et al., 2001), and WISE (Hsi & Linn, 2000). Another goal has been the development of systems for creating scientific models, such as Boxer (diSessa, 2002), Model-It (Jackson, Stratford, Krajcik, & Soloway, 1994), and object-based parallel modeling languages such as StarLogo (Colella, Klopfer & Resnick, 2001), NetLogo (Resnick & Wilensky, 1998), AgentSheets (Repenning & Sumner, 1995) and World-Maker (Ogborn, 1999). Yet other efforts have provided capacities for students to collect, graph and analyze scientific data from the environments using sensors and probes (Soloway et al., 1999; Tinker & Krajcik, 2001), and established scientific data visualization and "collaboratory" project-based inquiry environments for

students (Edelson et al., 1999; Pea et al., 1997). The development of computer-based systems to foster science learning is still an active research area in the cognitive sciences.

Even as the cognitive science movement had vital influences over thought leaders in science education reforms, its practical impact on any significant proportion of the nearly 50 million American K-12 students was minimal. Many of the insights about how to promote individual conceptual change in specific topics in science derived from small-scale studies in local teaching experiments, and were not incorporated in curricula that were broadly accessible or implemented. The research-based technologies for engaging learners and teachers in scientific model building, inquiry activities collecting real-world data with sensors and probes, and scientific data visualization and analysis, among other approaches, have been more indicative of leading-edge schools and teachers than they are mainstream. While part of the issue in the diffusion of these innovations is simply one of funding for technology appropriation on suitable scale (e.g., Office of Technology Assessment, 1988; PCAST, 1997; Pea, Wulf, Elliot & Darling, 2003), the scope of cognitive science studies was not inclusive enough to incorporate the issues of alignment with curriculum standards, needed teacher support and professional development activities, assessments for educational accountability, and other facets of the educational system that came to be recognized as essential to promoting learners' scientific understanding in educational settings.

The Standards Movement

Following on the heels of *A Nation at Risk: The Imperative for Educational Reform* (National Commission on Excellence in Education, 1983), a new movement to improve science education began to develop national content standards as to what knowledge and

skills students should learn in K-12 education. As DeBoer (2000) makes clear, the timing was propitious, for the science education community was debating “whether science education was primarily about science content or primarily about science-based social issues”, following NSTA’s (1982) urging that the goal of science education was "to develop scientifically literate individuals who understand how science, technology, and society influence one another and who are able to use this knowledge in their everyday decision-making."

The new standard-setting effort, which worked to reconcile the poles of this debate by integrating them, was led by scientists, science educators, curriculum developers, and assessment experts (Bybee,1997; Collins,1998). The first effort along these lines was *Project 2061: Science for All Americans,* taken up by the American Association for the Advancement of Science (Rutherford & Ahlgren, 1990). Founded in 1985, Project 2061 is a long-term AAAS initiative to help all Americans become literate in science, mathematics, and technology. Their work has attempted to specify the important themes in science and the habits of mind critical to science, as well as specifying the critical ideas and skills important to science.

Following the lead of the AAAS, and spurred by the dual events in 1989 of the National Governors’ Association calling for “clear national performance goals" as a way to raise standards in education, and the release by the National Council of Teachers of Mathematics (NCTM, 1989) of its *Curriculum and Evaluation Standards for School Mathematics*, the National Research Council began in 1992 to work to develop a set of National Science Education Standards for K-12 science education (National Research Council,1996). These standards outline what students need to know, understand, and be

able to do to be scientifically literate at different grade levels. They also develop professional development standards that present a vision for the development of professional knowledge and skill among teachers, as well as specifications for assessments to measure student understanding. Finally they propose standards for evaluating the quality of science education programs and the support systems to improve science education.

In conjunction with these developments, there has been an effort to develop new assessments to measure how well science education in America is meeting the new standards. The *Benchmarks for Science Literacy* (AAAS, 1993) and *The National Science Education Standards* (National Research Council, 1996) served as guiding frameworks for each state to develop their science frameworks and their state assessments for science learning. The affiliated science of assessment in this new policy environment is well reviewed in the National Academies of Science volume: *Knowing What Students Know* (Pellegrino, Chudowsky & Glaser, 2001).

The challenges to meeting the formidable standards outlined in these policy documents from AAAS and NRC are evident in reports from the field. As a recent National Research Council report (2007) argues: "Despite recurrent efforts to improve science education through curriculum reform and standards-based reform, there is still a long way to go. In hindsight, several factors may help to explain the limited impact of these substantial reform efforts. They include the complex political and technical aspects of implementation, insufficient teacher preparation and professional development, discontinuous streams of reform, mismatches between the goals of the initiatives and assessments, and insufficient and inequitable material resources devoted to education and

reform (Berliner, 2005; Kozol, 2005; Spillane, 2001). These factors are inevitably part of the education reform problem and constrain how theories of teaching and learning are enacted in school settings."

The policy tensions of enactment of explicit science standards are also a recurrent issue for any science education reform efforts. Kirst and Bird (1997; also see Massell, 1994) articulate four primary areas of political tension that help explain the difficulties of establishing supportive coalitions for science content standards in and out of schools: (1) the tension between leadership and political consensus; (2) the tension between flexible and specific standards; (3) the tension between up-to-date dynamic standards and reasonable expectations for change in the system; and (4) the tension between professional leadership and public understanding of what the new standards will entail.

The Systemic Approach to Coherence in Science Learning

The contributions of this volume reflect the growing recognition that a systemic approach to designing and assessing science learning environments in schools is essential to the prospects of continuous improvement in science learning outcomes for all students. We see their efforts as representing the importance of the positive developments in each of the three prior waves of science educational reform. The chapters acknowledge the importance of "structure" – the fundamental principles of science subject matter and their interrelationships, and the contributions of well-designed curricula in promoting student understanding of such structure (first wave). Beyond the contributions of the scientists' understandings of content structure, however, they reflect the insights and achievements of the cognitive science and learning science communities in articulating how the development of science expertise is promoted through specific types of learning activities

(second wave). Their emphasis on the aim of "coherence" in learner understanding of science content is importantly *generative* in nature, asserting that coherent understanding of science will be evidenced in students' efforts to productively connect science classroom ideas to their observations of the everyday world and to continued science learning throughout their lives.

In addition to the integrative focus on science content structure and coherence of its generative understanding by learners, the projects reported in this volume are attentive to both the achievements and shortfalls to date of the standards movement (third wave). In the fourth wave we are calling "the systemic approach", we see the emergence of a system-based approach to designing learning environments that are accountable to advancing coherent understanding of science subject matter by all learners. By coherent understanding of science the authors refer to a kind of *productive agency in scientific literacy* - "to both having a sense of the connectedness of science ideas and having the inclination to link ideas together and apply them to the situation at hand. Coherent understanding includes deliberate efforts to explain observations of phenomena, make decisions about matters involving science and technology, and seek ways to resolve conundrums." (Chapter 1, ms p. 2)

What are the hallmarks of a systemic approach? Most centrally, it is system-based in its full recognition of the inter-coordinated nature of content *standards*, high quality *curriculum* current to the science, learning *activities* that foster the development of coherent scientific understanding and literacies, formative *assessments* that can guide instructional support, *teacher development practices* that enhance how practitioners serve the aims of science learning, the roles of *educational leaders* in creating and sustaining

science reforms, and the *outcome measures* that provide accountability to improvements in science learning towards the content standards. Secondly, it recognizes the school system and affiliated stakeholder groups as a *learning organization*, in which cycles of adaptation are providing new learning about how to achieve coherent science understanding among learners. For example, these cycles may be about curriculum adaptation, in which teachers modify curricula to serve diagnosed needs among their specific learners; they may be about teacher professional development adaptation, in which educational leaders modify programs of supporting how their teachers learn to promote coherent understanding for all learners; they may be about assessment adaptation, in that test items developed may better serve their multiple purposes in subsequent iterations once their mettle is tested and revisions developed. The chapters provide ample evidence of how the efforts of the Technology Enhanced Learning in Science (TELS) Center and the Center for Curriculum Materials in Science (CCMS) to promote coherence can serve as a model learning organization along such dimensions as these.

The Future

In retrospect, we can see the beginnings of each new wave of science educational reform in small trends within prior waves. For example, concerns with the issue of development of coherent domain understanding pressed in the contributions of this volume are expressed in Bruner's (1960) *Process of Education*, while considerations of the systemic nature of the science educational reform process are expressed in the standards movement wave. Looking to prospects, what can we sense of a fifth wave?

In the deliberations at the workshop in June 2007 at which chapter authors came together to share perspectives and recommendations on each others' work, and in the science educational reform literature more broadly, we see several themes surfacing that may become candidate seeds for the growth of one or more new waves of reform. How these will play out only time will tell.

First, we can imagine an emerging wave in which there is a more concentrated effort in addressing the growing issues of better accommodating learner diversity in cultural and language backgrounds, and of systematically bridging informal and formal learning (e.g., Banks et al., 2007; Bransford et al., 2006). To foster coherence in science learning for all Americans, dealing productively with the diversity of informal learning resources available in families, peer networks, communities and neighborhoods, and among science learning participants from diverse language, cultural and socio-economic backgrounds has to become central. The chapter by Tate et al. (this volume) foregrounds these issues, and we applaud their effort to synthesize design principles for curriculum design and teacher education to make needed progress on encompassing diversity.

We can also see the glimmerings of an expanding science education which better reflects the reshaping of scientific practices that integrally utilize new technologies (e.g., remote instruments such as space telescopes; gene databases; data analysis using scientific visualization; complex multi-scale modeling using grid computing) and new socio-technical practices for organizing scientific inquiry (e.g., distributed collaboratories). For an extensive list of how cyber-infrastructure is changing the way scientific discovery and communication take place, and its implications for education, see the NSF Cyberinfrastructure for 21st Century Discovery report (NSF, 2007). The chapter

by Krajcik et al. (this volume) serves to illustrate how TELS and CCMS are appropriately employing uses of technology in instruction that can help transform the science classroom into an environment in which learners actively construct knowledge: "Learning technologies allow students to extend what they can do in the classroom, using the computer to access real data on the World-Wide Web, expand interaction and collaboration with others via networks, use electronic probes to gather data, employ graphing and visualization tools to analyze data, create models of complex systems, and produce multimedia artifacts" (ms, p. 6). While the challenges of making these uses of technologies to support science learning pervasive for all learners in all classrooms are formidable, it is hard to see how science education can adequately reflect changes in scientific practices and affiliated habits of mind without greater technology integration into educational activities.

In closing, we observe that the tensions of science education reform described by Kirst and Bird (1997) will not go away under any waves of reform, but are intrinsic to the value-laden nature of the educational enterprise and its complex relationships to the reproduction and continued invention of society. But we can come to recognize these tensions and do all we can to create innovative systems of design, implementation, assessment and critical appraisal that better meet the needs of society for a scientifically literate citizenry. In our view, these four waves of science education reform and the original synthetic contributions of the present volume represent significant progress toward this objective.

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