Chapter 24: Science Education and the Learning Sciences: A coevolutionary connection

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The world's nations are facing unprecedented social, economic, and environmental challenges, and education has a vital role to play in the development of knowledge, skills, and attitudes that allow individuals to contribute to and realize an inclusive and sustainable future. As stated in a 2018 OECD report, *The Future of Education and Skills: Education 2030*, "Learning to form clear and purposeful goals, work with others with differing perspectives, find untapped opportunities, and identify multiple solutions to big problems will be essential in the coming years. ..In an era characterized by a new explosion of scientific knowledge and a growing array of complex social problems, it is appropriate that curricula should continue to evolve, perhaps in radical ways" (OECD, 2018; p. 4).

Education researchers have been studying how to most effectively teach and learn science for almost a century. For example, in the United States with the support of prominent scientists and funding from the National Science Foundation, a series of large-budget, science curricula emerged in the 1950s and the 1960s. These programs emphasized hands-on learning and often included science textbooks and simple kits for hands-on activities (e.g., Science Curriculum Improvement Study, SCIS; Karplus and

Their, 1967; Biological Sciences Curriculum Study, BSCS; 1960). This research into how students learn science, and how to teach science most effectively, was often grounded in the scholarship of education and psychology. For example, the American science curriculum designers of the 1950s and 1960s drew from the work of Piaget and Dewey in the design of their curricular materials.

While science education was established as a research area before the origins of the learning sciences in the 1990s, many learning scientists ground their work in science education and science learning has always been a central concern of the learning sciences. Many chapters in this handbook focus their discussions on science-based contexts and examples, including diSessa (this volume) on conceptual change, Krajcik and Shin (this volume) on project-based learning, Abrahamson & Lindgren (this volume) on embodied learning, and Schneider and Radu (this volume) on augmented reality and learning.

There are several explanations for this synergy and flow of ideas between the learning sciences and science education. Reasons include the recognition of the importance of critical thinking, problem-solving, and the study of ill-structured problems in learning across many domains, including topics from economics, psychology, medicine, agriculture, and political science (e.g., NRC, 2019).

In biology, scientists use the idea of *coevolution* to describe the process of synchronistic changes in two different species over time, resulting in a frequently mutually beneficial relationship between the two species. Over historical time, many species of insects and flowering plants have coevolved relative to each other and supported the mutually beneficial existence of the two organisms over thousands of years. Species such as the acacia tree and acacia ants illustrate the concept of coevolution. The acacia tree makes a substance on its leaves that is food for the ants; in return, when predators threaten the tree, the ants release a chemical (pheromone) and organize into a large group to overcome the predator and defend the tree from being eaten.

In this chapter, we argue that the learning sciences and science education have coevolved, a co-evolution that began with the emergence of the learning sciences in the 1990s and that continues today. Our chapter begins with a discussion of four areas of educational scholarship in which the learning sciences and science education have worked in mutually beneficial ways to shape each other's scholarship, resulting in advantageous outcomes for both fields. In selecting our four areas of educational scholarship, we selected themes that illustrate large-scale changes influenced by both learning sciences and science education research, as well as themes that have emerged across multiple countries and continents. This chapter presents each of the four areas of scholarship, followed by a brief overview of recent research in the learning sciences and science education. In each area of scholarship, key ideas are represented through context-rich examples to illustrate particular aspects of the learning sciences/science education coevolution. We conclude with suggested research questions that warrant additional study.

Science Knowledge Is Situated and Learned Socially

One of the most important advancements in the learning sciences, which has greatly resonated in science education research, has been the shift away from viewing learning as an individual cognitive process to the idea that knowledge and knowing are situated in social and cultural contexts. This perspective is referred to as the *sociocultural approach* or the *situated approach* (see Engeström, this volume; Holland & Lave, 2009; Lave & Wenger, 1991; Pellegrino, 2020; Rogoff et al., 2007). Learning, in this perspective, is viewed as active participation in authentic activities that take place within communities' practices. By participating in such activities, initially in a peripheral manner but increasingly with more centralized roles, novices gradually develop not only an understanding of the big ideas or rich conceptual products of the learning experience, but also appropriate the unique ways of thinking and doing in which experts in the community come to know – a process known as *enculturation* into the community (see also Collins & Kapur, this volume; Hod & Sagy, 2019; Hod, Bielaczyc, & Ben-Zvi, 2018).

Theories of situated learning have co-evolved with and shaped knowledge and research in science education in several ways. For example, when scientific knowledge is considered to be situated, research on how science is learned is conducted in very different ways. In cognitive-focused studies, researchers isolate factors to explain the cognitive processes of the individual. In contrast, in sociocultural research studies, researchers holistically explore the messy naturalistic settings in which learning occurs (classroom, museum, home) to explain how all sorts of social and cultural factors play together in a learning process (see also Barab, this volume; Kali, 2016). In this way, classroom occurrences that may have been considered as *noise,* obscuring the researched phenomenon in cognitive-focused research (e.g., unintended side conversations between students) are considered *data* in sociocultural research, enriching our understanding of the phenomenon. Nathan and Sawyer (this volume) refer to these contrasting research approaches as *elemental* (studies of individual learning) and *systemic* (studies of social systems and practices). Increasingly, the theoretical notion of "situatedness" has served as a rationale for designing innovative learning environments and educational interventions in various disciplinary areas. These interventions, in turn, enable further exploration of the ways people learn.

In designing science learning environments, the situated perspective has led to the development of rich, contextual learning experiences that, in some cases, are very different from a traditional "instructionist" pedagogy (See Sawyer, Chapter 1, this volume), where teachers provide scientific facts and procedures to students through lecture or demonstration. Specifically, the rich, contextual learning experiences available when learning occurs in and around socio-scientific issues (SSIs)-- such as the public controversies surrounding genetically modified food (Walker & Zeidler, 2007) or global warming (Khishfe & Lederman, 2006)-- are excellent examples of the situated learning of science (Lindahl, Folkeson, Zeidler, 2019; Sadler, 2009; Zeidler, Herman, & Sadler, 2019). Learning science within and through SSIs also expands the dialogue on both who should learn science and the purpose of learning; two ideas expanded upon later in this chapter.

In his comprehensive review, Sadler (2009) illustrates how SSIs can serve as ideal contexts for science education as framed by situated learning theory. By engaging students in the exploration of ill-structured problems that involve complex undetermined solutions (Kuhn, 2010; Zohar & Nemet, 2002), require negotiation of scientific ideas, and tend to be controversial in nature (Bricker & Bell, 2008), teaching with SSIs, according to Sadler, can transform the culture of school science into a culture of communities of practice. In other words, the activities that students engage in when learning about SSIs resemble those that active citizens carry out in a modern world, and thus provide students with an opportunity to engage in authentic problem-solving within a community. In response to the onset of the Coronavirus pandemic in 2020, many schools attempted to engage students in project-based learning activities (Krajcik & Shin, this volume) designed to address the open-ended and ill-structured nature of the knowledge that was known then around the issue of the pandemic. As with most SSIs, these attempts highlighted the important role that science education has for supporting students in coping with the complex nature of such problems (Pietrocola, Rodrigues, Berocot, & Schnorr, 2020), as well as to develop habits of mind that would enable them to identify misinformation that often characterizes media coverage of SSIs (Sharon & Baram-Tsabari, 2020). Studies of science reform curricula based on SSIs have demonstrated the importance of teacher professional development to assist students in developing such learning with rich, ill-structured SSI contexts (Sadler, 2020).

Sadler’s review and other research studies also demonstrate that SSI activities, when properly designed (e.g., by supporting students in developing scientific skills during their exploration of the SSI), can increase student interest and motivation to learn science, serve as productive contexts for learning science content, foster students’ higher-order thinking skills, and, encourage them to become “involved in their communities in new ways as they explore and contribute to solutions for local problems” (Sadler, 2009, p. 33; OECD, 2018). More recent research also indicates that emphasis on student discussion and argumentation around SSIs encourages the development of openmindedness, and vigilance toward bias and traits such as empathy, caring and societal responsibility (Zeidler, 2019).

Situated learning of science around SSIs can also lead to student impact within local communities. In one example from two successive projects funded by the US Agency for International Development (USAID), the Egyptian Science, Technology, Engineering and Mathematics (STEM) Schools Project (ESSP) has partnered with the Ministry of Education in Egypt to establish cutting-edge public high-schools in Egypt. The three-year curriculum in these Egyptian STEM schools is focused on solving Egypt's eleven Grand Challenges, such as the lack of water. Each semester as a part of their coursework, student teams take on one of the Grand Challenges and develop innovative prototype solutions that serve as 60% of their semester grade. In addition, many of the prototype solutions lead to ideas that could be implemented within local communities. For example, a team of high school girls developed a more efficient water purification system that reduced energy consumption by 24% by lowering the boiling point of water (https://www.youtube.com/watch?v=R5TD925gI6M). Starting with one Egyptian STEM-focused high school in 2011, there are now 19 advanced schools across Egypt using the Grand Challenges curriculum. Based on the success of the first ESSP project and a follow-on project, STEM Teacher Preparation and School Strengthening Activity (STESSA), there are plans to increase to 27 schools in the next five years, with one school in each Egyptian Governorate. In addition, five new teacher preparation programs will be established at five Egyptian universities.

Promising Research Questions in this Area

The shift away from viewing science learning as an individual cognitive process to the idea that knowledge and knowing in science are situated in social and cultural contexts presents rich new research questions for fruitful study. These include the following:

- What are the implications of blurring the boundaries between “school culture”, which typically develops around instructionist pedagogy (See Sawyer, Chapter 1, this volume), and an ill-structured, problem-based, situated “science culture” for student learning?
- How do teachers and instructional materials foster, support, and nurture students’ motivation and agency within and around SSI learning environments?
- As teaching using SSI is very different from more traditional teaching approaches, how are teaching practices different from instructionism and how can teachers address these challenges?
- How should teacher training and professional programs support teachers in developing the skills required to teach situated science?

What Science Knowledge, Skills, Attitudes, and Values Should Be Learned?

For many years, national policy and standards documents from a variety of nations and government organizations provided descriptions of the nature and amount of scientific knowledge that should be the focus of teaching and learning for primary and secondary students (e.g., NRC, 2012, in the United States; OECD, 2018). Fortunately, there is substantial agreement about the types of science knowledge that best prepare citizens for their future. For example, there is significant agreement that scientific knowledge and the solving of ill-structured problems has never been more critical. In Egypt, a policy document called Sustainable Development Strategy: Egypt Vision 2030 emphasizes STEM education as an essential priority to improve Egyptian citizens' quality of life (Egyptian Ministry of Planning and Economic Development, 2016). This priority served as a foundation for the Egyptian Ministry of Education-USAID STEM secondary school curriculum development team, mentioned earlier, that designed a three-year high school curriculum integrated with Egypt’s Grand Challenges.

How do we describe the science knowledge emphasized in these emerging, problem-based curricula? Educational research and policy documents state that these programs emphasize learning three types of scientific knowledge taught concurrently. The first type of science knowledge is called *science and engineering practices* (NRC, 2019), also called ways of knowing (Barzilai & Zohar, 2016), or scientific processes (NRC, 1996). These terms refer to the knowledge and skills obtained and practiced by scientists when they do scientific work, including asking questions, constructing scientific arguments, analyzing data, and using models to make predictions (NRC, 2019). The second type of science knowledge is called *disciplinary core ideas* (NRC, 2019), also called content knowledge or the body of scientific knowledge. This type of knowledge refers to scientific information that comprises many facts, definitions, and formulas such as “energy can be moved from place to place by moving objects or through sound, light, or electric currents” (Achieve, 2013, PS3.A). The third type of knowledge mentioned in some documents is called the *crosscutting concepts* (NRC, 2012). *Crosscutting concepts* are big thematic ideas, such as systems, energy, or patterns, that cut across individual scientific disciplines.

Interestingly, while all three types of science knowledge are often declared critical, a wide range of research studies reveal that most classroom resource materials, such as textbooks, emphasize only the second type of science knowledge: *disciplinary core ideas*. There is less emphasis on the first type of knowledge: *science and engineering practices* (e.g., NRC, 2019, OECD, 2018), and even fewer examples of programs emphasizing *crosscutting concepts*.

Instructional materials that emphasize *disciplinary core ideas* in isolation are prevalent even though research shows that learning of *disciplinary core ideas* is most effective when students learn them concurrently with the other two science knowledge types (NRC, 2019). Programs emphasizing *disciplinary core ideas* in isolation are also standard in situations where the learning approach is labeled "traditional," such as learning through textbooks or "cookbook-style" laboratories. Classroom lab experiments are referred to pejoratively as "cookbook" when students are explicitly told what actions to take and in what sequence, which is similar to following directions from a cookbook to prepare a recipe. The term is always pejorative because the research is very clear: This is ineffective pedagogy. Unfortunately, the pedagogical practice of teaching isolated *disciplinary core ideas* is deeply embedded in schools due to decades of a pedagogy and assessment cycle that places a great deal of emphasis on memorizing facts and definitions that are assessed with paper-and-pencil tests (Shepard, 2000).

As a result of the robust findings emerging from learning sciences and science education research, however, this "instructionist" focus (see Sawyer, Chapter 1, this volume) has been increasingly criticized as out of sync with today's knowledge and innovation age. A large body of recent research suggests that instructional materials that emphasize learning all three types of science knowledge in concert lead to substantial learning outcomes (NRC, 2019). These research studies demonstrate that learning all three types of science knowledge concurrently not only strengthens and deepens the understanding of the *disciplinary core ideas*, but it also supports critical thinking and problem solving within scientific knowledge domains (e.g., NRC, 2019; Songer, Kelcey, & Gotwals, 2009). As a result, many countries now emphasize the importance of developing the three kinds of knowledge in concert through instructional materials that emphasize 21st-century learning skills, such as critical thinking and problem solving (Partnership for 21st Century Skills, 2011), within science and other disciplines.

In many countries, this shift in knowledge and skills is also evident in education policy documents. For instance, in the United States, the current national science standards are presented as performance expectations, e.g., learning goals that systematically blend one *disciplinary core idea* with a *science and engineering practice* and a *crosscutting concept*. This work draws from foundational theories of learning and a conceptual framework document developed by learning scientists, scientists, and science educators (NRC, 2019).

Table 24.1 presents comparative science standards from the United States that illustrate this shift in the type of scientific knowledge emphasized in K-12 science classrooms. The left column shows a life science standard from the U.S. science standards of the 1990s (NRC, 1996). The right column presents a similar life science standard from the U.S. science standards of 2013 (Achieve, 2013). Notice that while both standards include *science and engineering practices* and *disciplinary core ideas*, the more recent standards emphasize the importance of combining the types of scientific knowledge into one standard. Table 24.2 lists a middle school standard that illustrates how all three kinds of scientific knowledge combined in one performance expectation.

Table 24.1: *Contrasting versions of U.S. national science standards (1996 and 2013)*

	The U.S. National Science Education Standards (1996) (Separate presentation of *science and engineering practices* and *disciplinary core ideas*, with no mention of *crosscutting concepts*)	The U.S. Next Generation Science Standards (2013) (One presentation that blends *science and engineering practices*, *disciplinary core ideas*, and *crosscutting concepts*)
Disciplinary Core Idea	"Content Standard 5–8: The number of organisms an ecosystem can support depends on the resources available and abiotic factors, such as quantity of light and water, range of temperatures, and soil composition…Lack of resources and other factors, such as predation and climate, limit the growth of populations in specific niches in the ecosystem."	"Middle School, Life Science 2–1: Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations."
Science and Engineering Practice	"Inquiry Standard: "Develop descriptions, explanations, predictions and models using evidence."	

Table 24.2: Next Generation Science Standard Performance Expectation for middle school students, grades 6-8 in the United States. Note that the Performance Expectation, MS-LS2-4, asks students to demonstrate an understanding that includes each of the three dimensions of science knowledge: *Science and Engineering Practices*, *Disciplinary Core Ideas*, and *Crosscutting Concepts*. (Achieve, 2014).

<table>
<tr><td colspan="3">KS-LS2-4 Ecosystems: Interactions, Energy, Dynamics</td></tr>
<tr><td colspan="3">Students who demonstrate understanding can:

MS-LS2-4. Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations. [Clarification Statement: Emphasis is on recognizing patterns in data and making warranted inferences about changes in populations, and on evaluating empirical evidence supporting arguments about changes to ecosystems.]</td></tr>
<tr><td colspan="3"><i>The performance expectation above was developed using the following elements from the NRC document, A Framework for K-12 Science Education.</i></td></tr>
<tr><td>Science and Engineering Practices</td><td>Disciplinary Core Ideas</td><td>Crosscutting Concepts</td></tr>
<tr><td><i>Engaging in Argument from Evidence</i></td><td><i>LS2.C: Ecosystem Dynamics, Functioning, and Resilience</i></td><td><i>Stability and Change</i></td></tr>
<tr><td>* Engaging in argument from evidence in 6-8 builds on K-5 experiences and progresses to constructing a convincing argument that supports or refutes claims for either explanations or solutions about the natural and designed world(s).

* Construct an oral and written argument supported by empirical evidence and scientific reasoning to support or refute an explanation or a model for a phenomenon or a solution to a problem.</td><td>* Ecosystems are dynamic in nature; their characteristics can vary over time. Disruptions to any physical or biological component of an ecosystem can lead to shifts in all its populations.</td><td>* Small changes in one part of a system might cause large changes in another part.</td></tr>
</table>

The shift in the desired learning outcome from *disciplinary core ideas* in isolation to learning all three types of knowledge at the same time requires a fundamental change in science pedagogy. Classroom activities must shift to a conscious emphasis on using *science and engineering practices* such as arguments, data analysis, and models about the topic to foster deep, conceptual understandings of the *disciplinary core ideas* and the *crosscutting concepts*. This pedagogical shift may seem like a minor change to classroom practice but requires dramatic shifts in classroom activities. For example, classroom activities must discourage memorization of inert, disciplinary science facts and instead encourage deep conceptual development of science content through engagement with and through *science and engineering practices*, such as gathering and analyzing data about the biodiversity of a local stream to understand concepts associated with ecology. There is substantive research evidence that this pedagogical change has resulted in better learning outcomes: quasi-experimental research has demonstrated that students who engage in curricular programs that emphasize learning *disciplinary core ideas* while engaging in *science and engineering practices* and *crosscutting concepts* demonstrated enhanced learning outcomes when compared to students involved in a curricular program that emphasized only the disciplinary core ideas in isolation (e.g., NRC, 2019; Songer et al., 2009).

Promising Research Questions in this Area

Shifting science learning goals away from isolated *disciplinary core ideas* and towards learning *disciplinary core ideas* in conjunction with *science and engineering practices* and *crosscutting concepts* provides opportunities for new research studies, such as the following:

- What kinds of instructional materials support learning of *disciplinary core ideas*, *science and engineering practices*, and *crosscutting concepts* in concert?
- How does learning all three kinds of scientific knowledge in concert change learners' attitudes about science?
- What forms of assessment, both formative and summative, are needed to provide valuable information on students' struggles and successes as they develop understandings of *disciplinary core ideas*, *science and engineering practices*, and *crosscutting concepts*?

Science Pedagogy: What Do Teaching and Learning Look Like?

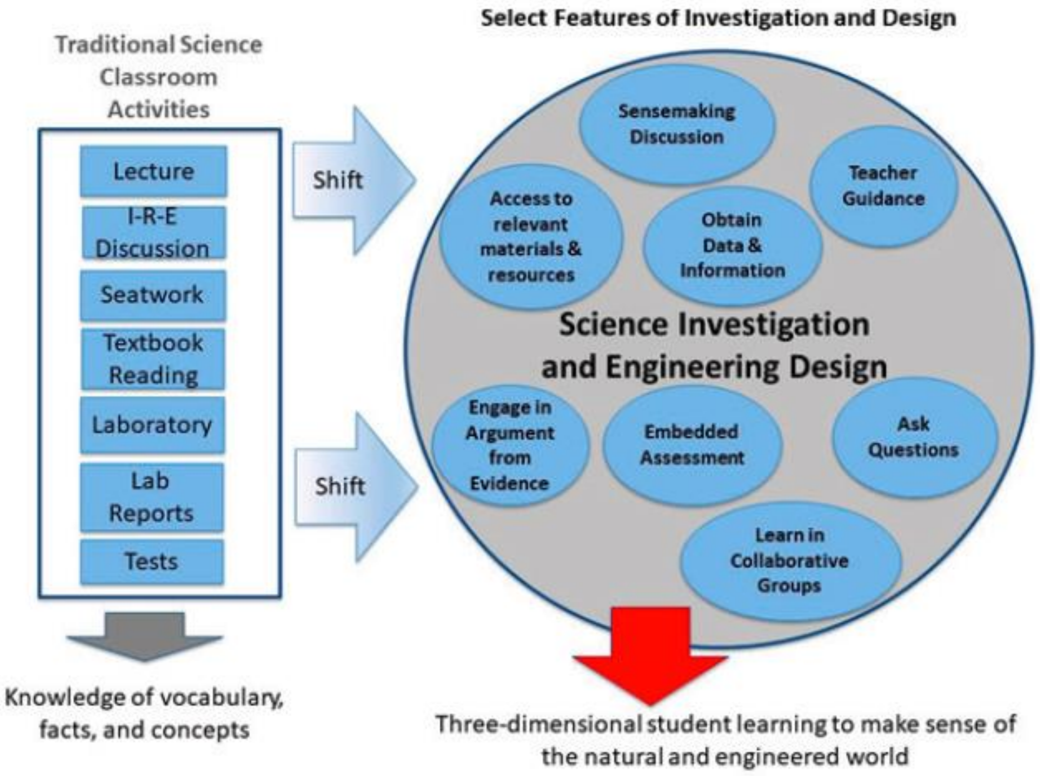
Related to this shift from teaching isolated *disciplinary core ideas* and science facts to teaching all three kinds of science knowledge in a blended fashion, a second shift is in the pedagogical practices that support learning. This section explores the shifts that have occurred in teacher moves and instructional materials that support the blended science knowledge and complex reasoning in science.

For most of the 20th century, many of the instructional models for science classrooms emphasized some combination of science lectures and highly specified "cookbook" laboratories. But these pedagogies would only work if the best way to learn science was to listen to lectures, memorize lecture or textbook-based science facts, or repeat steps of a science experiment exactly the same way as others had before. Now, after several decades of science education research, we know that this is false, and that these pedagogies are ineffective. A shift from science knowledge as declarative facts toward science knowledge as *disciplinary core ideas* learned through the *science and engineering practices* and *crosscutting concepts* requires new teacher behaviors, new instructional models, and new instructional supports. We characterize this shift as a shift from instructionist approaches to guided instruction, including pedagogies that build on prior knowledge, emphasize scaffolds and fading (see Reiser & Tabak, this volume), and emphasize metacognitive reflection (see Winne & Azevedo, this volume).

As with the shift from teaching simplistic disciplinary core ideas to teaching all three types of scientific knowledge, the shift in pedagogies to support blended science knowledge has deep roots in learning sciences and science education research. Research studies and learning theories from the learning sciences remind us that the learning of science and other topics is anchored in constructivism (e.g., Inhelder & Piaget, 1958), and this learning takes into account an organized developmental progression of activities that include higher-order thinking even at younger ages (e.g., Metz, 2000). Research studies by important early learning scientists like Ann Brown (e.g., Brown, Ellery, & Campione, 1998) provided evidence in the 1980s and 1990s that the development of deep conceptual understandings of science takes time, guidance such as catalysts and mediation, and repeated exposures (Brown et al., 1998; NRC, 2019). Learners develop deep understandings of disciplinary content as a result of organized "recyclings": structured sequences of activities that embrace rich conceptual ideas through repeated interactions at increasingly abstract levels (e.g., the Karplus spiral curriculum, 1977; Songer, 2006). A central component of repeated interaction is the idea of organized, learner-focused guidance, often in the form of cognitive scaffolds (Reiser & Tabak, this volume; Palinscar, 1998; Quintana et al., 2004).

As mentioned previously, research studies have demonstrated that teaching *disciplinary core ideas* concurrently with *science and engineering practices and crosscutting concepts* can be done well when the activities center on activities organized around a series of science investigations or engineering design projects and local phenomena (NRC, 2019). These situated learning contexts provide opportunities for students to ask their own questions and engage with science content in a variety of ways. Teaching and learning that is centered around investigations and phenomena is very different from the passive memorization of fixed information associated with instructionism. Student work consists of asking questions, generating and evaluating models and solutions to illustrate their reasoning, collecting and analyzing their own data, and continuously revising their ideas and thinking (NRC, 2019).

Recognizing the need for activities to engage all students and build productively on individuals’ prior knowledge, new research studies have provided us with much more effective tools and pedagogical moves to capture and work with students’ prior ideas (Penuel & Reiser, 2018; also see DiSessa, this volume; Reiser & Tabak, this volume; Scardamalia & Bereiter, this volume; Andriessen & Baker, this volume). Figure 24.1 illustrates how research-based pedagogies differ from instructionist classroom practices. For example, the goals of traditional science classrooms are indicated at the left of Figure 24.1 as *Knowledge of vocabulary, facts and concepts*. In contrast, the goals of instruction centered on science investigation and engineering design are indicated at the right of Figure 24.1 as *Three dimensional student learning to make sense of the natural and engineered world.* Similarly, the kinds of activities students engage in shift from lectures and lab reports to sensemaking discussions and engaging in argument from evidence.



Select features of science investigation and engineering design and how they differ from activities in traditional science classrooms.
NOTE: The boxes in the list on the left contain examples of approaches used in traditional science classrooms. The small circles on the right represent examples of features of learning via investigation and design. The examples are not exhaustive, and many other approaches are possible within investigation and design.

Figure 24.1. Select features of science investigation and engineering design and how they differ from science activities in traditional science classrooms (from NRC, 2019; p. 83).

Promising Research Questions in this Area

The pedagogical shift from lectures and cookbook labs to collaborative and participatory activities centered on science investigations, engineering design, and local phenomena present rich new research questions for fruitful study. These include the following:

- What do pedagogical moves that support blended science learning, such as sense-making discussions, look like in different classroom settings?

- Once classroom activities are not as prescribed as a lecture or a cookbook-style laboratory, how do teachers and students learn to continuously adapt and adjust classroom activities to support blended science learning?
- How do teachers or students select local phenomena to be studied? What makes a phenomenon fruitful for learning *disciplinary core ideas* through *science and engineering practices* and *crosscutting concepts*?

Who Should Learn Science?

One of the major advances in science education over the past seventy years has been the shift in target audience for who should learn science. In the 1950s, when science education was first perceived as a national priority, many national school systems focused on students who would become “future scientists,” with the goal of ensuring scientific and technological advance in the economy and the military. In the United States, the National Science Foundation (NSF) was founded in 1950, and one of its first goals was to identify the most promising young scientists and fund their graduate training. Today, most countries consider science knowledge and problem-solving to be important literacies for *all* students and citizens. This shift from science for a few, to science for everyone, can be described as taking place in four waves of reforms (Pea & Collins, 2008). The first, which occurred in the United States from the 1950s to the 1960s, and which was followed by similar reforms in other countries, was driven by a sense that schools were not providing the appropriate education that would maintain America’s leadership in science and technology. To a large extent, this concern stemmed from the Soviet Union’s October 1957 launch of the first man-made space satellite – *Sputnik*. This wave of reform was characterized by the development of new science curricula that introduced students with what was then the latest scientific advancements and emphasized the scientific method in ways that, to a large extent, correspond with current perspectives on science education. However, these were targeted toward college-bound high schoolers who were most likely to become scientists, while most students continued to learn science taught with traditional pedagogies.

The next three waves of reform, according to Pea and Collins, were the *cognitive science* reform wave (the 1970s–1980s), the *standards* reform wave (1980s–1990s), and the *systematic approach* reform wave (2000s to 2010s). Focusing on the diversity aspect in these reforms, a gradual increase is evident in terms of addressing the needs of *all* learners. In the cognitive science reform, the study of learners' reasoning enabled science curriculum developers to better diagnose students' developmental level and to design supports for coping with various misconceptions, using strategies such as bridging analogies (see diSessa, this volume). In the standards reform, learning assessments were revised to better align with standards that defined, as mentioned previously, not only what all students *should know*, but also what they *should be able to do* at particular grade levels. Finally, in the fourth wave of reform, systematic means were developed so that all students would be able to reach these standards. Pea and Collins (2008) describe these means as follows: "planful coordination of curriculum design, activities, and tools to support (a) different teaching methods that will foster students' expertise in linking and connecting disparate ideas concerning science, (b) embedded learning assessments to guide instructional practices, and (c) teacher professional development to foster continued learning about how to improve teaching practice" (p. 4). When they published their 2008 chapter, they claimed that then-current curricular efforts represented this systematic approach, and that this approach would enable quality science education for all (see also the book *Designing Coherent Science Education* by Kali, Linn, & Roseman, 2008, where Pea and Collins's chapter is introduced).

We agree with the four-wave historical account of Pea and Collins (2008). But we think it must be updated, because since that publication appeared, we have witnessed the emergence of a fifth wave of reform - the *connecting schools with the networked society* wave. Tabak, Ben-Zvi, and Kali (2019) describe learning in today's networked society as a process of shared meaning-making in which people co-create knowledge in technology-enhanced learning environments and communities. Within this realm, many incidental opportunities for learning science occur, for instance, among people who open up groups in social networking platforms to study and co-create campaigns regarding local environmental struggles. Kali (in press) observed that "several pedagogical approaches have been developed which seek to adopt promising trajectories of spontaneous learning within the networked society, and bring them to school, without 'schoolifying' them—that is, without trivializing them to align with standardized academic requirements". Examples that are particularly relevant to science education are the makers' movement (see Halverson & Sheridan, this volume; Blikstein 2013), serious games (see Steinkuehler & Squire, this volume; Barab & Dede, 2007) and citizen science (Hecker, Haklay, Bowser, Makuch, Vogel & Bonn, 2018; NAS, 2018; Sagy et al., 2019). We elaborate on the latter, which we view as an especially promising trajectory in the *connecting schools with the networked society*, wave five reform, and the extended view of who should learn and participate in science.

Citizen science is a genre of research that brings together participants from the general public and scientists around projects involving various fields of science. This genre has become more widely accepted in the past decade, with the prevalence of mobile technologies that enable volunteers around the world to actively participate in various aspects of scientific research (Kali, in press). It covers a large variety of disciplinary areas and includes research projects initiated by the public, by community organizations, or by professional scientists. This richness is expressed, for instance, in the Zooniverse website (2020), the world's largest citizen science web-portal, accommodating about one-hundred citizen-science projects in areas categorized into arts, biology, climate, history, language, literature, medicine, nature, physics, social science, and space. Zooniverse projects have already yielded dozens of scientific publications, some of which are co-authored with citizen participants.

The proliferation of citizen science projects in the past decade has resulted in growing awareness of their potential to enhance school practice. As stated in the website of the Taking Citizen Science to School center (TCSS, 2020), school participation in citizen science seeks to enable students from various socio-economic backgrounds not only to learn science by engaging in issues that are relevant to their communities, but also to take an active part in advancing knowledge and decision-making regarding these issues in collaboration with scientists or other experts (also see Scardamalia & Bereiter, this volume). Research on school participation in citizen science has already shown promising findings with regard to student learning (Atias et al., 2020; Ballard, Dixon, & Harris, 2017; Golumbic, Fishbain, Baram-Tsabari, 2019; Harris, Dixon, Bird & Ballard, 2019); teacher learning (Kali, Sagy, Benichou, Atias, & Levin-Peled, 2019) and promoting school wide reform in science education embracing innovative pedagogies (Hod Sagy, Kali, & TCSS, 2018).

Promising Research Questions in this Area

The shift from science education for a select few to science education as a core component of science literacy and critical thinking for everyone presents rich new research questions for fruitful study. These include the following:

- How can *connecting schools with the networked society* curricula be designed so that diversity and cultural differences within classrooms become assets (e.g., by presenting multiple perspectives on socio-scientific issues) rather than impediments for science education?
- How can commonly used technologies such as smartphones be used as part of such curricula?
- How can out-of-school collaborations (e.g., between schools and scientists or other experts) be instigated, sustained and scaled to enable *all* learners to engage in science education programs that connect schools with the networked society?

Conclusions

The fields of the learning sciences and science education are deeply intertwined. While the exact mechanism and directionality of change is not always easy to articulate, we have described shifts and movement in both disciplines that have benefited both fields. In particular, we see evidence of mutual shaping when the contexts and kinds of science learned become immersed within various situated contexts, including local phenomena, global challenges, and citizen science projects. Mutual shaping is also evident in who is empowered and championed to learn science. The shift from isolated learners to communities collectively engaged in *connecting schools with the networked society* demonstrates new possibilities for learning and recognizing the value and impact of our knowledge in solving environmental, economic, and societal problems.

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