# Preparing Students with 21st Century Skills: Integrating Scientific Knowledge, Skills, and Epistemic Beliefs in Middle School Science Curricula

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**Abstract** In the 21st century, every citizen needs to acquire adequate scientific knowledge and skills to be competitive in the job market, and be scientific literate in everyday contexts. The recent push for STEAM education calls for integrating science, technology, engineering, art, and mathematic components together to prepare students for 21th century challenges. To address these concerns, in this chapter we discuss how to prepare students with critical skills to succeed in the 21st century. Our discussion of reconceptualizing science curriculum in middle school level is based on three major perspectives. To prepare students to face the challenges in the 21st century, educators need to help students (1) acquire sufficient core scientific knowledge, (2) gain skills needed to engage in scientific practice, and (3) develop sophisticated epistemic beliefs to understand the nature of scientific knowledge and the methods of making it. We discuss the importance of each perspective in science education in light of the current literature, and address some remaining issues for future directions.

**Keywords** Science curriculum · 21st century skills · Argumentation · Epistemology · Middle school

## Introduction

### *Overarching Goal of Science Education in the 21st Century*

In the 21st century, as modern society has been reshaped by technological advancement, scientific innovation, and globalization, workforce development demands

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have shifted (NSTA, 2011). In science education, rather than being expected to know a list of science topics, American high school graduates are expected to "(1) appreciate the beauty and wonder of science, (2) have adequate knowledge to engage in public discussion on socio-scientific issues, (3) become careful consumers of scientific and technology information in their daily lives, (4) be capable of and continue to learn science outside of school, and (5) acquire adequate skills of science to enter the career of their choice" (NRC, 2012, p. 1). Core to strong performance in science is the integration of technology, engineering, arts, and mathematics into science education, as these complementary disciplines provide tools and processes by which people can investigate natural phenomena and design solutions to scientific problems (Bequette & Bequette, 2012; NGSS Lead States, 2013; Platz, 2007).

## *Challenges for Students in the 21st Century*

Compared to non-STEM careers, STEM-related employment will increase greatly in the next few decades (Ashby, 2006; BLS, 2013). However, too few American middle school students are proficient in mathematics and science, which makes it difficult for them to enter STEM fields (PCAST, 2010). Fewer than one in five twelfth graders are proficient in mathematics and interested in STEM subjects (BHEF, 2010). Besides mathematics, students need to have sufficient scientific knowledge and critical skills to engage scientific practices (NSTA, 2011). Although not every student will choose to work in STEM fields, as citizens in the 21st century, they all need to be well prepared to address authentic scientific problems.

In the 21st century, the continuing expansion of human knowledge demands that everyone gain the skills to acquire, select, evaluate, and use information appropriately and effectively (AASL, 2007). In a society where the Internet is the defining technology for literacy and learning (Leu et al., 2011), students need to be able to read, write, learn, and communicate using the Internet and other information technology (Drew, 2013).

Modern society also requires that people be able to solve increasingly complex problems in everyday and professional contexts (Jonassen, 2011). Every student needs to be able to use modern technology and tools such as computers and information and communications technology (ICT) as an aid to construct and communicate new information to solve problems (Kim & Lee, 2013).

With the development of modern society, a growing number of socio-scientific issues have been presented in society. Every individual, as a citizen, needs to be equipped with decision making skills and scientific literate to make well-informed decisions and take active roles in society (Saunders & Rennie, 2013; Walker & Zeidler, 2007).

## *Potential Solutions*

To help students meet 21st century challenges, there is an urgent need to reconceptualize and reform current science curriculum at K-12 level. In this chapter, we focus on core scientific knowledge, critical skills for scientific practices, and sophisticated epistemic beliefs as three major perspectives to reconceptualize science education in middle school level. To prepare students to face 21st century challenges, educators need to help students (1) acquire sufficient core scientific knowledge, (2) gain skills needed to engage in scientific practice, and (3) develop sophisticated epistemic beliefs to understand the nature of scientific knowledge and the methods of constructing it. We discuss each perspective in the following sections.

## How to Teach Scientific Knowledge in the 21st Century

In an age of knowledge explosion, the purpose of K-12 science education is not to teach students all the scientific knowledge they need in their everyday and professional contexts, but rather to focus on a limited number of disciplinary core ideas and crosscutting concepts (NRC, 2007, 2012; NGSS Lead States, 2013). These core ideas and crosscutting concepts are fundamental to the development of science understanding so that students can continually build on and connect with many related scientific concepts (NRC, 2007). Helping students gain core scientific knowledge and improve their information literacy will enable students to continue to learn scientific knowledge in and out of school (Kereluik, Mishra, Fahnoe, & Terry, 2013).

### *Integration of Core Scientific Knowledge*

#### Crosscutting Concepts and Disciplinary Core Ideas

The National Research Council proposed that K-12 science education should be centered on three major dimensions: scientific and engineering practices, crosscutting concepts, and disciplinary core ideas (NRC, 2012). This framework forms the foundation of K-12 science curriculum by outlining what to teach (crosscutting concepts and disciplinary core ideas) and how to teach (through scientific and engineering practices). Crosscutting concepts are concepts that bridge and unify various fields in science and engineering as they present a common way of knowing in science (Duschl, 2012). Learning these crosscutting concepts can enable students to connect knowledge from various disciplines to form a coherent understanding of scientific methods. For instance, by learning the first two crosscutting concepts—*patterns* and *cause and effect*—students can understand that scientists observe and explore patterns and use scientific methods to investigate cause and effect relationships to explain and interpret patterns (NRC, 2012).

There are several core ideas (e.g., Newton's laws of motion and the theory of biological evolution) in the physics, life sciences, earth and space sciences, and engineering, technology and application of science (NRC, 2012). The disciplinary core ideas are foundational and central concepts and theories that help students build conceptual understanding in natural sciences. In engineering, there are certain core ideas that are different from those of science. Besides core ideas in the field of natural sciences, students should also learn core ideas of engineering, technology, and art design processes, such as delimiting engineering problems, and optimizing design solutions, and balancing aesthetic and utility concerns.

### Integration of Core Scientific Knowledge Through Scientific and Engineering Practice

In the past few decades, teaching science through a process of inquiry has long been advocated in several policy documents (e.g., AAAS, 1990; NRC, 1996). However, research has consistently shown that simply engaging in scientific inquiry is insufficient to help students acquire disciplinary core ideas and understanding of the nature of science (Khishfe & Abd-El-Khalick, 2002; Sandoval, 2005; Schwarz & White, 2005). Many school scientific inquiry tasks do not incorporate the epistemic aspect of real science and engineering practices (Chinn & Malhotra, 2002; Prins, Bulte, & Pilot, 2011). Moreover, a narrow focus on the performance of inquiry skills may cause the understanding of the nature of science and disciplinary core ideas in science education to be deemphasized (Abd-El-Khalick et al., 2004).

To be clear, we do not mean that students should not engage in scientific inquiry; as one form of scientific practice, scientific inquiry certainly involves most scientific practices. In the framework for K-12 science education (NRC, 2012), eight science and engineering practices (such as developing and using models, using mathematics and computational thinking, constructing explanations) were emphasized. However, it is not likely that inquiry-based learning tasks can cover all of these practices. Therefore, teachers can use crosscutting concepts and disciplinary core ideas as the foundational content onto which particular scientific or engineering practices can build. As such, certain scientific and engineering practices can focus on a few particular types of practices to emphasize relevant core scientific knowledge. In this way, by engaging in science practice, students can perceive how core scientific knowledge is constructed and developed, which will help them to develop understandings of the nature of science as well as relevant inquiry skills (Abd-El-Khalick et al., 2004; Ford, 2008). Engaging in engineering practice can also help students understand how engineers apply various knowledge, modern tools, scientific methods to solve practical problems (Sneider, 2012). By integrating core scientific knowledge with scientific and engineering practices, students will have opportunities to deepen their understanding of core ideas in each disciplinary and apply crosscutting concepts across disciplines (NRC, 2012). In addition, science and engineering practices are often applied in design process for inventing and innovating artifacts and products to address functional, aesthetic, environmental, and economic concerns. As one way to connect science, engineering, and art practices, teaching design process holds potential to integrate STEM education and art education in K-12 curriculum (Vande Zande, 2010).

### *Integration of Core Scientific Knowledge Through Addressing Socio-Scientific Issues*

In the past few decades, a growing number of complex, controversial, and problematic issues such as global warming, alternative fuels, and genetically modified food have been presented in our society. Such issues are often referred to as socio-scientific issues—issues "based on scientific concepts or problems, controversial in nature, discussed in public outlets and frequently subject to political and social influences" (Sadler & Zeidler, 2005, p. 113). All citizens need to be equipped with decision making skills and scientific literacy to make well-informed decisions and take active roles in society (Saunders & Rennie, 2013; Walker & Zeidler, 2007).

In recent years, researchers have encouraged the incorporation of socio-scientific issues (SSI) in science curricula (Sadler & Donnelly, 2006; Saunders & Rennie, 2013). Socio-scientific issues, by definition, have political and social implications for everyone in society (Sadler & Zeidler, 2005). By integrating SSIs with a focus on scientific content knowledge in science instruction, students may perceive the importance and value of scientific knowledge and see how scientific practices issues are related to their daily lives, which in turn may motivate students' interests in science (Dawson & Venville, 2010; Dolan, Nichols, & Zeidler, 2009). More importantly, SSIs can provide meaningful contexts for science instruction, which can potentially support students' learning of content knowledge (Sadler, Barab, & Scott, 2007). By engaging in learning with SSIs, students can significantly improve their understanding of relevant content knowledge (Applebaum, Barker, & Pinzino, 2006; Barab, Sadler, Heiselt, Hickey, & Zuiker, 2010) As SSIs often involve interdisciplinary knowledge, they can provide contexts for students to see how crosscutting concepts apply across different fields. Moreover, SSIs are often found in areas of science in which there are disagreements among experts and few simple and clear solutions (Kolstø et al., 2006). By addressing SSIs, students' understanding of the nature of science can be promoted (Eastwood et al., 2012; Khishfe & Lederman, 2006).

## Development of Skills to Engage in Scientific Practice in the 21st Century

### *21st Century Skills*

To ensure that students are well prepared to face 21st century challenges, researchers and educators have started to identify the essential skills needed in 21st century. Proposed by National Research Council (2010), there are five skills that are essential for every student to acquire in a fast-paced, rapidly changed world: adaptability, complex communication/social skills, non-routine problem solving, self-management/self-development, and systems thinking. According to the Partnership for 21st century skills (P21, 2009), 21st century skills consist of:

- Learning and innovation skills, which include (1) creativity and innovation, (2) critical thinking and problem solving, (3) communication and (4) collaboration.
- Information, media and technology literacy skills, which include (1) information literacy, (2) media literacy, and (3) information and communication technology literacy.
- Life and career skills, which include: (1) adaptability and, flexibility (2) initiative and self-direction, (3) cross-cultural and social skills, (4) accountability and productivity, and (5) responsibility and leadership.

The two definitions of 21st century skills proposed by both P21 and NRC together reflect the requirements and expectations for students as workers and citizens in the 21st century. Science education cannot and should not take full responsibility to develop all 21st century skills, but science education can offer a rich context for developing many 21st century skills (Bybee, 2010). Twenty-first century skills also provide new perspectives to frame essential skills in science that have long been valued, and new skills that are required for future generations (P21, 2009). Based on the 21st century skills proposed by NRC (2010) and P21 (2009), we identified a few essential skills that are critical for students to succeed in science education in middle school level.

## *Essential Skills to be Developed in Science Education*

### Effectively Acquiring and Evaluating Information

The continuing expansion of human knowledge demands that every student be able to acquire, evaluate, use, and integrate information appropriately and effectively (AASL, 2007). Especially with the increasing use of the Internet in and out of school, students need to be information literate to be able to read, write, learn, and communicate using the Internet and other information technology (Drew, 2013). In the context of science education, information literacy involves evaluating the credibility, validity, and reliability of information to interpret data, critically integrating information from multiple sources, and constructing scientific arguments to effectively engage in science learning (P21, 2009). During problem solving, students often need to search for or connect to relevant knowledge, propose solutions, and evaluate potential solutions against certain criteria (Jonassen, 2003). To be effectively engaged in scientific practices and complex problem solving, especially in online learning environments, students need to have sufficient skills to identify information needs, locate information sources, evaluate, and synthesize information from a variety of sources (Brand-Gruwel, Wopereis, & Walraven, 2009).

In the 21st century, computers and the Internet have been widely used in K-12 schools. In fall 2008, the ratio of students to instructional computers with Internet access was 3.1–1 in the U.S. public school (Gray, Thomas, & Lewis, 2010).

Although provided with easy access to an abundance of online resources, students often do not have sufficient skills to critically acquire, use and evaluate online information (Kuiper, Volman, & Terwel, 2009). Much web-based information combines varied text structures and formats, which poses unique challenges for young students to read and comprehend. Moreover, since online information is easy to create and distribute, determining the credibility of online information can be difficult (Baildon & Damico, 2011). In the context of science education, middle school students often struggle to use the Internet effectively to acquire relevant information during their scientific practices (Raes, Schellens, & De Wever, 2010). First, middle school students tend to use the Internet to search for quick answers rather than take time to understand and make sense of the online information (Kim, Hannafin, & Bryan, 2007). Second, middle school students' online learning is often disoriented and inefficient as students do not have sufficient searching skills and they are easily distracted by irrelevant online information (Zhang & Quintana, 2012). Third, online inquiry requires strong self-regulation ability and metacognitive awareness to monitor learning process (Brand-Gruwel et al., 2009); however, middle school students often lack such skills to plan or monitor their online learning process (Kuiper et al., 2009).

## Constructing Scientific Arguments

Engaging in argumentation is a critical scientific process, as scientists often construct evidence-based arguments to interpret results and make conclusions (Bricker & Bell, 2008; Ford, 2012; Osborne, Erduran, & Simon, 2004). Therefore, argumentation skill, defined as the skill to support claims with evidence and premises through critical thinking and social interaction (Golanics & Nussbaum, 2007; Perelman & Olbrechts-Tyteca, 1958), is an essential skill in science learning. For instance, to engage in problem solving or scientific discussion, students need to gain sufficient argumentation ability to weigh the risks and benefits of alternative solutions, pose questions, evaluate evidence and counter evidence to make well informed decisions and engage in debate and discussion about problem solutions (Dawson & Venville, 2010). Central to argumentation is design of an argument and consideration of an audience, and such design can be informed by design processes and client interaction processes in engineering (Dym, Agogino, Eris, Frey, & Leifer, 2005) and the arts (Swanson, 1994). Unfortunately, engaging in argumentation is challenging for middle school students (Yoon, 2011). Middle school students often find it difficult to identify and gather relevant evidence (Pedersen & Liu, 2002), and struggle to back up claims with evidence (Glassner, Weinstock, & Neuman, 2005). Students' difficulties might be due to two reasons: middle school students' often lack sufficient cognitive ability (Kuhn & Udell, 2007) to engage in argumentation, and they often do not have sophisticated epistemological understanding of the meaning of justification and how to use evidence to justify something (Mason & Boscolo, 2004). Effective integration of engineering and art design processes into science curricula may also enhance middle school students' argumentation abilities (Dym et al., 2005; Swanson, 1994).

### Using Modern Tools to Solve Problems Collaboratively

As Popper (1999)noted, all life is problem solving. As problems people face in their daily and professional contexts become increasingly complex, people use various modern tools to solve problems instead of their bare hands (Jonassen, 2003). Therefore, students not only need to be able to search for and use online information, but also need to use information and communications technology (ICT) as an aid to construct, communicate new information to solve problems (Kim & Lee, 2013). ICT innovations provide students with new tools for doing science including gathering, interpreting and analyzing data and communicating results (P21, 2009). As such, ICT literacy (the ability to use "digital technology, communications tools, and/or networks to access, manage, integrate, evaluate and create information" (International ICT Literacy Panel, 2002, p. 2) is an essential ability for students to solve real-world problems (Casner-Lotto, Barrington, Barrington, & Barrington, 2006; EU Communities, 2007). Moreover, to solve problems in a computer-based learning environment, students need to cope with technological complexity so that the joint cognitive system (human and computer) can perform its intended functions (Angeli, 2013; Hollnagel & Woods, 2005).

In the 21st century, most scientific investigations are conducted by groups of researchers rather than individuals, which requires researchers to effectively communicate and collaborate with their team members to solve problems (Hung, 2013). Only if research is appropriately presented and described, it can be understood, confirmed, and advanced by other researchers. In the context of science education, students also need to be able to communicate effectively about science through written and oral communication (Anderman, Sinatra, & Gray, 2012). Communication and collaboration skills, defined by the abilities to understand and respond appropriately to both verbal and nonverbal information (such as mathematical and graphical representation of ideas and observation) from others, are critical for students to succeed in the 21st century (NRC, 2010; P21, 2009). In K-12 science education, students often conduct group projects or assignments, so adequate communication and collaboration skills are essential for them to build shared understandings various communication needs.

## *Technologies to Support Students*

### Technology to Support Online Inquiry

To help students overcome these difficulties, computer-based scaffolds have been used in K-12 classroom in recent years. Scaffolding is interactive support provided by a more capable person or technological tools to enable students perform a task that they cannot do without help (Belland, 2014; Puntambekar & Hubscher, 2002; Wood, Bruner, & Ross, 1976). For example, Zhang and Quintana (2012) designed a computer-based scaffold called the *Digital IdeaKeeper* to help students search for, analyze, and synthesize online information and regulate their inquiry process. First, *IdeaKeeper* provides an integrated learning environment for students to conduct online inquiry. By embedding the Google search engine and other tools in it, *IdeaKeeper* keeps online inquiry activities in one space to make it more efficient. Second, it helps students plan their online inquiry by articulating the driving questions and sub-questions as the objects of online inquiry. Students can monitor their progress by referring to the driving questions, which in turn help them to manage their inquiry process. Third, by outlining four activity spaces (planning, searching, analyzing, and synthesizing), *IdeaKeeper* makes the structure of online inquiry more explicit to students to foster deep engagement with learning content. It contains several prompts for students to evaluate the trustworthiness and usefulness of online information. Last, *IdeaKeeper* can automatically record URLs, search term and results, and browsing history for students; therefore, students can focus on more meaningful learning tasks such as note taking, sense making, and synthesizing. The affordances of *IdeaKeeper* enable students to engage in more efficient and deep learning during online inquiry through two mechanisms of computer-based scaffolds, structuring and problematizing (Reiser, 2004). It provides needed structures for students to engage in online inquiry by making the learning objects and process more explicit, and also problematizes the meaningful learning tasks by guiding students to critically evaluate and synthesize online information.

## Tools to Construct Scientific Arguments

The technology-based argument construction tools can potentially help middle school students overcome the challenges of constructing arguments and build more coherent and cohesive arguments (Linn, 2003). For instance, a context-specific computer-based scaffold called *ExplanationConstructor* is designed to help students construct and evaluate scientific explanations for natural phenomena (Sandoval & Reiser, 2004). *ExplanationConstructor* is an electronic journal to record students' investigations. It embeds several prompts for students to set up investigation goals, construct scientific explanation, and use evidence to support causal claims. *ExplanationConstructor* provides domain-specific prompts for students to guide students use evidence to construct and evaluate their scientific explanations. It makes epistemic criteria more explicit to help students evaluate evidence, which in turn can help them understand what counts as explanations and evidence. The guides in *ExplanationConstructor* make the scientific way of knowing more explicit for students by helping them understand how to construct coherent scientific explanation and framing students' inquiry process in epistemically important ways (Sandoval & Reiser, 2004).

The key feature of domain-general scaffolds is to support students' development of more generic concepts and skills that can be applied across domains (Davis, 2003). For instance, as an example of domain-general computer-based scaffolds, the *Connection Log* (Belland, Glazewski, & Richardson, 2010) provides domain-general scaffolds for students to construct evidence-based arguments. To support students' development of argumentation skills in a domain-generic way, the *Connection Log* divides construction of arguments into five common stages: define the problem, determine needed information, find and organize needed information, develop claim, link evidence to claim (Belland, Glazewski, & Richardson, 2008). Within each stage, students follow the prompts to engage in different components of argumentation such as search for evidence, link evidence to claims, and back claims with evidence.

Designers who wish to promote generic skills that can be applied across domains may choose to develop domain-general scaffolds (McNeill, Lizotte, Krajcik, & Marx, 2006). However, meta-analysis indicates no significant difference between domain-general and domain specific scaffolds on cognitive outcomes (Belland, Walker, Olsen, & Leary, 2015). Thus, designers can make the additional considerations of whether target students need the additional content knowledge support that might be provided with context-specific scaffolds, or whether developing a scaffold that can be used more widely with units of varying content is desired.

## Technology to Support Collaborative Learning

Collaborative learning, defined as two or more individuals working together to complete certain learning tasks, has been documented to be an effective way to support learning (Chiu & Khoo, 2003; Fawcett & Garton, 2005). In collaborative learning, students need to interact with their peers, to acquire deep understandings of the content knowledge, and establish and maintain share understandings of the learning tasks (Janssen & Bodemer, 2013). To help students effectively engage in collaborative learning, computer-supported collaborative learning (CSCL) environments have been developed to help students share ideas and construct knowledge and scientific explanations (Noroozi, Weinberger, Biemans, Mulder, & Chizari, 2012). For instance, Linn, Davis and Bell (2004) developed an online learning environment called Web-based Inquiry Science Environment (WISE) to support students to engage in collaborative learning in scientific inquiry. Within the WISE platform, Clark, D'Angelo and Menekse (2009) developed an online discussion tool called *personally-seeded scripts* that demonstrated effective to help ninth grade students engage in online argumentative discussion. In the *personally-seeded scripts*, students need to articulate and select their initial scientific explanations of certain concepts, such as heat and thermal equilibrium, from a set of pre-scripted phrases. To help students engage in a more meaningful argumentative discussion from different perspectives, students who select different explanations will be assigned into a discussion group. Then, students with different perspectives can elaborate their scientific explanations in their own words and engage in asynchronous online discussion to co-construct, revise, and evaluate their scientific explanations (Clark et al., 2009). The *personally-seeded scripts* enable students with different perspectives to work together to increase diversity of perspective in the discussion, which adopts a critical pedagogical strategy to engage students in argumentation (Osborne et al., 2004). In addition, in the *personally-seeded scripts*, rather than simply dividing up the labor to accomplish learning tasks efficiently, students collaborate together in a more meaningful way by providing their unique insights and knowledge to construct their shared understandings of scientific concepts.

With the development of information and communication technology, the collaborative learning can also be supported in mobile learning environments. In a recent study, Laru, Järvelä and Clariana (2012) developed a mobile message application called *Flyer to* help middle school students engage in collaborative learning in a context of outdoor field trip. During field trips, students are presented with relevant scientific problems composed by scientists on the storyboard messages in the *Flyer*. Each student can use *Flyer* to develop scientific claims to answer the questions by using the embedded template that requires students to fill out their claims, evidence, and warrant. Students can send out and receive "flyers" of their scientific claims to each other, and engage in small group discussion to compare their knowledge claims with their group members (Laru et al., 2012). With the embedded procedural and metacognitive scaffolds in the *Flyer*, students can engage in scientific inquiry in authentic settings, which in turn can promote their science learning (Anderson, Thomas, & Nashon, 2009).

## Prompting Sophisticated Epistemic Beliefs

It has long been a goal of science education that students develop an understanding of the nature of science (Abd-El-Khalick, 2012). Middle school students who are proficient in science should understand the nature and development of scientific knowledge (NRC, 2007). In fact, students do not automatically develop sophisticated understandings of science by experiencing inquiry tasks in school (Abd-El-Khalick et al., 2004). Research on epistemic beliefs in the context of science education can help educators understand how and why students understand the nature of science in certain ways and how to promote their understandings of the nature of science (Sandoval, 2005; Wu & Wu, 2010).

### *Middle School Students' Epistemic Beliefs*

In the current literature, researchers adopt different ways to conceptualize individuals' epistemic beliefs. According to the developmental approach, individuals' epistemic beliefs develop from a naïve position to a more sophisticated position through a stage-like, developmental sequence (Greene, Azevedo, & Torney-Purta, 2008; Hofer & Pintrich, 1997). Among developmental frameworks of epistemic beliefs, the sequenced levels in these models can be commonly labeled as: (1) absolutism/objectivism in which individuals believe that knowledge is either right or wrong and can be known with certainty, (2) multiplism/subjectivism, in which individuals believe knowledge consists of subjective, uncertain opinions which can be equally right (Buehl & Alexander, 2001), and (3) evaluativism/objectivism-subjectivism, which views knowledge as evolving and needing to be critically judged based on criteria such as critical thinking and evidence (Kuhn, Cheney, & Weinstock, 2000). Although some research suggested that students' epistemological beliefs do not develop much prior to high school age due to inadequate cognitive and metacognitive ability to monitor and control their thinking process (Kitchener, 2002), more recent studies showed that early adolescents can hold relatively sophisticated beliefs (Muis, Bendixen, & Haerle, 2006). For instance, some middle school students can hold evaluativist epistemic beliefs and these relatively sophisticated epistemic beliefs influenced the process and strategies they use during internet-based learning (Barzilai & Zohar, 2012).

As a multidimensional approach, Hofer and Pintrich (1997) proposed that epistemic beliefs include four independent dimensions: (1) the certainty of knowledge, (2) the simplicity of knowledge, (3) the source of knowledge, and (4) the justification of knowledge (Hofer, 2000). Research based on the multidimensional approach (e.g., Mason, Boldrin, & Ariasi, 2009) indicated that middle school students can express reflections about the nature of knowledge and the knowing process on the four factors of epistemic beliefs proposed by Hofer and Pintrich (1997). In other words, in each dimension, certain (not all) middle school students can hold relatively sophisticated epistemic beliefs. Generally speaking, the current literature showed that middle school students to some extend can perceive their active role in knowledge construction and hold suboptimal understanding of the complex, uncertain, changing nature of the scientific knowledge (Ricco, Schuyten Pierce, & Medinilla, 2009).

## *Critical Epistemic Beliefs to Engage in Scientific Practices*

The epistemic beliefs frameworks mentioned above often were developed or verified by interviews, questionnaire, and assessments which focus on students' self-reported beliefs about the professional science or formal scientific practices (Wu & Wu, 2010). To be distinguished from this type of epistemic beliefs, Sandoval (2005) proposed a term 'practical epistemologies', which refers to four critical practical epistemological notions that are essential for students to effectively engage in scientific inquiry and evaluate scientific claims. The first practical epistemology is that *scientific knowledge is constructed*, which means students need to understand that scientific knowledge is socially constructed, so people do not simply accept knowledge because it is true. Rather, the authority of knowledge is evaluated based on whether it provides value (such as provide an explanation to a phenomenon) for certain social, historical communities (Sandoval, 2005). The second notion of Sandoval's practical epistemologies is *diversity of scientific methods,* which posits that there is no universal scientific method. In reality, scientists adopt a broad range of methods as they explore different kinds of phenomena in various domains (Windschitl, 2004). By understanding the diversity of scientific methods, students are expected to be able to evaluate the appropriateness of the scientific method of a particular practice (Sandoval, 2005). The third notion of Sandoval's practical epistemologies is *forms of scientific knowledge*, which varied in their explanatory or predictive power and in their ways to interpret and describe the nature world (Sandoval, 2005). Scientific inquiry involves different types of practices for different purposes such as proposing hypotheses, verifying explanation, applying theories to interpret certain patterns. By perceiving the difference between various types of knowledge, students can deepen their understanding of the purposes of scientific practices, which in turn can support their inquiry practices. The last practical epistemology is *scientific knowledge varies in certainty* (Sandoval, 2005). This notion is similar to the dimension of uncertain, tentative nature of science presented in the frameworks of epistemic beliefs discussed earlier. The tentativeness of knowledge does not mean that no knowledge is worth believe, rather, it reflect an evaluativism point of view: knowledge varied in its tentativeness and need to be critically evaluated based on certain criteria such as reasoning or evidence-based argumentation (Kuhn et al., 2000). To sum up, these four notions of practical epistemologies complement the conceptualization of formal epistemic beliefs. Practical epistemologies represent several important epistemological goals for students to engage in scientific practices: understand the nature of scientific knowledge, the process of constructing scientific knowledge, and the criteria of evaluating scientific knowledge during their own inquiry practices.

## *Promoting Sophisticated Epistemic Beliefs*

Promoting students' understanding of the nature of science and inquiry is not an easy task. Since epistemic beliefs are innate characteristics of students, one cannot simply teach students to hold sophisticated beliefs. Although few studies in the current literature examined in what way students' epistemic beliefs can be promoted (Ferguson & Bråten, 2013; Knight & Mattick, 2006), the current literature can still shed some light on the strategies to promote students' epistemic beliefs.

### Challenging Students' Current Beliefs—Prompt Epistemic Doubt

Cognitive disequilibrium is a driving force for individuals to progress through stages of cognitive development (Piaget, 1985). Likewise, the development of epistemic beliefs may be driven by cognitive disequilibrium (Hofer & Pintrich, 1997). Bendixen and Rule (2004) proposed a mechanism of change of epistemic beliefs in which epistemic doubt is the driving force of epistemic beliefs development. As an impetus for epistemic change, epistemic doubt involves weighing evidence and discerning the truthfulness of conflicting beliefs (Bendixen & Rule, 2004). Advancing epistemic beliefs also require epistemic volition that can protect one's concentration on solving epistemic doubt and avoid distractions (Bendixen &

Rule, 2004). By using resolution strategies such as reflection and social interaction (e.g., engaging in argumentation with other individuals), epistemic beliefs can be advanced, or at least changed. Epistemic beliefs develop in a dynamic process influenced by many contextual and social factors; as such, one's epistemic beliefs can develop in fits and starts, and can thus become more primitive before it becomes more sophisticated (Bendixen & Rule, 2004). The components of this mechanism of epistemic change (epistemic doubt and resolution strategies) have been identified while college students read multiple documents containing conflicting scientific evidence (Ferguson, Bråten, & Strømsø, 2012). Middle school students can reflect on and develop their epistemic beliefs by reading conflicting online sources (Barzilai & Zohar, 2012). As such, one strategy to prompt epistemic beliefs is to enable students to challenge their current naïve epistemic beliefs. For example, engaging in online inquiry may help students be exposed to multiple sources of knowledge during their knowledge construction process. Therefore, students may perceive the uncertain, subjective nature of scientific knowledge, which can in turn promote a reassessment of their current epistemic beliefs such as scientific knowledge is certain and unchanging.

### Prompting Students to Set High Level Epistemic Aims and Epistemic Values

Epistemic aims are goals of finding, understanding, and explaining things, and forming beliefs, which refers to what type of epistemic achievement (e.g., true beliefs, minimally justified beliefs) an individual pursues (Chinn, Buckland, & Samarapungavan, 2011). Epistemic values refer to the value system people have toward different types of epistemic achievement (Alfano, 2012; Chinn et al., 2011). For example, one may hold the epistemic value that the pursuit of truth is the ultimate goal. Such an epistemic value would lead one to strive to find truth through consultation of multiple, high quality sources (Alfano, 2012; Chinn et al., 2011), an approach that tends to reliably lead to truth (Goldman, 1993). An individual whose epistemic aim is to acquire minimally justified beliefs might accept a knowledge claim even if its justification is weak (Chinn et al., 2011). Individuals who value theoretical knowledge over practical knowledge (such as how to conduct an experiment) will more likely set sophisticated epistemic aims to acquire theoretical knowledge than practical knowledge.

As one component of epistemic cognition, individual's epistemic beliefs and epistemic aims and value are interrelated. Helping students to set up sophisticated epistemic aims will motivate them to perceive the complex nature of scientific knowledge and enable them to conduct personal justification of scientific knowledge. In the context of science education, teachers can help students set up high level epistemic aims during knowledge acquisition and perceive values of scientific knowledge, which in turn will help students develop their epistemic beliefs.

### Establishing a Positive Epistemic Climate

To help students develop sophisticated epistemic beliefs, educators need to establish an environment or climate in which such sophisticated epistemic beliefs are encouraged. The epistemic climate—"how the nature of knowledge and knowing is portrayed and perceived" (Muis & Duffy, 2013, p. 124) —is critical to students' development of epistemic beliefs. Research showed that epistemic climate can be established through teaching and modeling of critical thinking, evaluation of problem solving approach, and making connections to students' prior knowledge, which in turn can help graduate students reflect on and challenge their current epistemic beliefs, and promote their epistemic beliefs and use of critical thinking strategies (Muis & Duffy, 2013). In the context of middle school, the epistemic climate is even more important as students are at critical age to form their beliefs system.

Another important aspect to establishing a positive epistemic climate is the cultivation of students' epistemic virtues. Individual's dispositions such as truth-seeking, systematicity, and maturity correlated with their epistemic beliefs (Valanides & Angeli, 2008). In Chinn et al.'s framework (2011), epistemic virtues such as intellectual carefulness, intellectual courage, and open-mindedness, are dispositions that can effectively help people achieve epistemic aims. To establish an epistemic climate that supports the development of epistemic beliefs, teachers need to cultivate epistemic virtues such as intellectual carefulness and intellectual courage to encourage students to set up higher epistemic aims and pursue them. By using strategies such as rewarding students who display epistemic virtues, establish or preset role models, teacher can set up a learning culture that value epistemic virtues.

## Remaining Issues

### *Are Middle School Students Ready to Develop Sophisticated Epistemic Beliefs?*

As discussed earlier, a few studies showed that some middle school students can perceive the complex, uncertain nature of scientific knowledge and acknowledge their active role in knowledge construction (Ricco et al., 2009). However, applying these beliefs during their scientific practices requires epistemic monitoring and judgment (Hofer, 2004). For example, during online searching, metacognitive thinking processes might guide students to spontaneously monitor and judge online information during their searching. However, such metacognitive processes might be too advanced for middle school students to acquire (Mason & Boldrin, 2008). Even first-year college students hold strong beliefs that scientific knowledge comes from external authorities and recognized expertise rather than themselves (Hofer, 2000).

Students often hold strong beliefs that justification needs to be provided by authorities until they reach college age (Greene et al., 2008). The fact that many middle school students tend to rely external authority as the source of knowledge and justification may simply be because they do not have the abilities or resources to conduct personal justification. Students may consider textbooks as credible sources of knowledge because they believe that knowledge claims in textbooks are supported by a large body of empirical evidence (Chinn et al., 2011). In certain contexts of science learning, such as doing a simple calculation, relying on authorities might be an effective way for learning as this type of knowledge is considered fixed and certain (Muis & Duffy, 2013). As a result, students' epistemic beliefs should be considered and evaluated within certain learning contexts. Future research is needed to address the influence of contextual factors on students' epistemic beliefs, and explore how to design instructions to promote students' epistemic beliefs in various learning contexts.

### *How can One Help Students Transfer Learned Knowledge and Skills in the Future?*

The purpose of science education is to prepare students with adequate knowledge and skills, and the ability to apply such in future. Although computer-based scaffolds can provide substantial supports for students to engage in scientific practices in various ways, in the current literature few studies examine transfer of scaffolded skills. It remains unknown whether students can apply the knowledge and skills they learn after receiving scaffolding. The notion of scaffolding is to provide temporary support for students and help them eventually accomplish tasks on their own (Puntambekar & Hubscher, 2002). Hence, it is necessary to uncover what students have learned in a computer-based scaffolding learning environment, as well as whether and how they can transfer learned knowledge and skills in future. As studies consistently showed that students fail to transfer learned knowledge and skills, researchers started to reconceptualize transfer from an abstract, highly conceptual process to a perceptual processes (Day & Goldstone, 2012). For instance, in a recent conceptual framework of transfer of learning, Nokes-Malach and Mestre (2013) conceptualized transfer of learning as a sense-making and satisficing process in which individuals keep constructing representations of context and generating and making sense of solutions so that different types of transfer mechanisms can be triggered when individual is dealing with complex cognitive tasks. Therefore, one instructional implication is to engage students in complex, integrated learning tasks so that application of multiple mechanisms might be promoted (Nokes-Malach & Mestre, 2013). However, future research is needed to explore how to design instructions with specific aims to promote students' transfer of learning.

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