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Physics education research for 21st century learning

Lei Bao[1*] and Kathleen Koenig[2]

Abstract

Education goals have evolved to emphasize student acquisition of the knowledge and attributes necessary to successfully contribute to the workforce and global economy of the twenty-first Century. The new education standards emphasize higher end skills including reasoning, creativity, and open problem solving. Although there is substantial research evidence and consensus around identifying essential twenty-first Century skills, there is a lack of research that focuses on how the related subskills interact and develop over time. This paper provides a brief review of physics education research as a means for providing a context towards future work in promoting deep learning and fostering abilities in high-end reasoning. Through a synthesis of the literature around twenty-first Century skills and physics education, a set of concretely defined education and research goals are suggested for future research, along with how these may impact the next generation physics courses and how physics should be taught in the future.

Keywords: Physics education research, Twenty-first century learning, STEM education, Scientific reasoning, Deep learning

Introduction

Education is the primary service offered by society to prepare its future generation workforce. The goals of education should therefore meet the demands of the changing world. The concept of learner-centered, active learning has broad, growing support in the research literature as an empirically validated teaching practice that best promotes learning for modern day students (Freeman et al., 2014). It stems out of the constructivist view of learning, which emphasizes that it is the learner who needs to actively construct knowledge and the teacher should assume the role of a facilitator rather than the source of knowledge. As implied by the constructivist view, learner-centered education usually emphasizes active-engagement and inquiry style teaching-learning methods, in which the learners can effectively construct their understanding under the guidance of instruction. The learner-centered education also requires educators and researchers to focus their efforts on the learners' needs, not only to deliver effective teaching-learning approaches, but also to continuously align instructional practices to the education goals of the times. The goals of introductory college courses in science, technology, engineering, and mathematics (STEM) disciplines have constantly evolved from some notion of weed-out courses that emphasize content drilling, to the current constructivist active-engagement type of learning that promotes interest in STEM careers and fosters high-end cognitive abilities.

Following the conceptually defined framework of twenty-first Century teaching and learning, this paper aims to provide contextualized operational definitions of the goals for twenty-first Century learning in physics (and STEM in general) as well as the rationale for the importance of these outcomes for current students. Aligning to the twenty-first Century learning goals, research in physics education is briefly reviewed to provide a context towards future work in promoting deep learning and fostering abilities in high-end reasoning in parallel. Through a synthesis of the literature around twenty-first Century skills and physics education, a set of concretely defined education and research goals are suggested for future research. These goals include: domain-specific research in physics learning; fostering scientific reasoning abilities that are transferable across the STEM disciplines; and dissemination of research-validated curriculum and approaches to teaching and learning. Although this review has a focus on physics education research (PER), it is beneficial to expand the perspective to view physics education in the broader context of STEM learning. Therefore, much of the discussion will

* Correspondence: bao.15@osu.edu
[1]The Ohio State University, Columbus, OH 43210, USA
Full list of author information is available at the end of the article

blend PER with STEM education as a continuum body of work on teaching and learning.

Education goals for twenty-first century learning

Education goals have evolved to emphasize student acquisition of essential "21st Century skills", which define the knowledge and attributes necessary to successfully contribute to the workforce and global economy of the 21st Century (National Research Council, 2011, 2012a). In general, these standards seek to transition from emphasizing content-based drilling and memorization towards fostering higher-end skills including reasoning, creativity, and open problem solving (United States Chamber of Commerce, 2017). Initiatives on advancing twenty-first Century education focus on skills that converge on three broad clusters: cognitive, interpersonal, and intrapersonal, all of which include a rich set of sub-dimensions.

Within the cognitive domain, multiple competencies have been proposed, including deep learning, non-routine problem solving, systems thinking, critical thinking, computational and information literacy, reasoning and argumentation, and innovation (National Research Council, 2012b; National Science and Technology Council, 2018). Interpersonal skills are those necessary for relating to others, including the ability to work creatively and collaboratively as well as communicate clearly. Intrapersonal skills, on the other hand, reside within the individual and include metacognitive thinking, adaptability, and self-management. These involve the ability to adjust one's strategy or approach along with the ability to work towards important goals without significant distraction, both essential for sustained success in long-term problem solving and career development.

Although many descriptions exist for what qualifies as twenty-first Century skills, student abilities in scientific reasoning and critical thinking are the most commonly noted and widely studied. They are highly connected with the other cognitive skills of problem solving, decision making, and creative thinking (Bailin, 1996; Facione, 1990; Fisher, 2001; Lipman, 2003; Marzano et al., 1988), and have been important educational goals since the 1980s (Binkley et al., 2010; NCET, 1987). As a result, they play a foundational role in defining, assessing, and developing twenty-first Century skills.

The literature for critical thinking is extensive (Bangert-Drowns & Bankert, 1990; Facione, 1990; Glaser, 1941). Various definitions exist with common underlying principles. Broadly defined, critical thinking is the application of the cognitive skills and strategies that aim for and support evidence-based decision making. It is the thinking involved in solving problems, formulating inferences, calculating likelihoods, and making decisions (Halpern, 1999). It is the "reasonable reflective thinking focused on deciding what to believe or do" (Ennis, 1993). Critical thinking is recognized as a way to understand and evaluate subject matter; producing reliable knowledge and improving thinking itself (Paul, 1990; Siegel, 1988).

The notion of scientific reasoning is often used to label the set of skills that support critical thinking, problem solving, and creativity in STEM. Broadly defined, scientific reasoning includes the thinking and reasoning skills involved in inquiry, experimentation, evidence evaluation, inference and argument that support the formation and modification of concepts and theories about the natural world; such as the ability to systematically explore a problem, formulate and test hypotheses, manipulate and isolate variables, and observe and evaluate consequences (Bao et al., 2009; Zimmerman, 2000). Critical thinking and scientific reasoning share many features, where both emphasize evidence-based decision making in multivariable causal conditions. Critical thinking can be promoted through the development of scientific reasoning, which includes student ability to reach a reliable conclusion after identifying a question, formulating hypotheses, gathering relevant data, and logically testing and evaluating the hypothesis. In this way, scientific reasoning can be viewed as a scientific domain instantiation of critical thinking in the context of STEM learning.

In STEM learning, cognitive aspects of the twenty-first Century skills aim to develop reasoning skills, critical thinking skills, and deep understanding, all of which allow students to develop well connected expert-like knowledge structures and engage in meaningful scientific inquiry and problem solving. Within physics education, a core component of STEM education, the learning of conceptual understanding and problem solving remains a current emphasis. However, the fast-changing work environment and technology-driven world require a new set of core knowledge, skills, and habits of mind to solve complex interdisciplinary problems, gather and evaluate evidence, and make sense of information from a variety of sources (Tanenbaum, 2016). The education goals in physics are transitioning towards ability fostering as well as extension and integration with other STEM disciplines. Although curriculum that supports these goals is limited, there are a number of attempts, particularly in developing active learning classrooms and inquiry-based laboratory activities, which have demonstrated success. Some of these are described later in this paper as they provide a foundation for future work in physics education.

Interpersonal skills, such as communication and collaboration, are also essential for twenty-first Century problem-solving tasks, which are often open-ended, complex, and team-based. As the world becomes more connected in a multitude of dimensions, tackling significant problems involving complex systems often goes beyond the individual and requires working with others who are increasingly from culturally diverse backgrounds. Due to the rise of communication technologies, being able to articulate thoughts and ideas in a variety of formats and contexts is crucial, as well as the ability to effectively listen or observe to decipher meaning. Interpersonal skills can be promoted by integrating group-learning experiences into the classroom setting, while providing students with the opportunity to engage in open-ended tasks with a team of peer learners who may propose more than one plausible solution. These experiences should be designed such that students must work collaboratively and responsibly in teams to develop creative solutions, which are later disseminated through informative presentations and clearly written scientific reports. Although educational settings in general have moved to providing students with more and more opportunities for collaborative learning, a lack of effective assessments for these important skills has been a limiting factor for producing informative research and widespread implementation. See Liu (2010) for an overview of measurement instruments reported in the research literature.

Intrapersonal skills are based on the individual and include the ability to manage one's behavior and emotions to achieve goals. These are especially important for adapting in the fast-evolving collaborative modern work environment and for learning new tasks to solve increasingly challenging interdisciplinary problems, both of which require intellectual openness, work ethic, initiative, and metacognition, to name a few. These skills can be promoted using instruction which, for example, includes metacognitive learning strategies, provides opportunities to make choices and set goals for learning, and explicitly connects to everyday life events. However, like interpersonal skills, the availability of relevant assessments challenges advancement in this area. In this review, the vast amount of studies on interpersonal and intrapersonal skills will not be discussed in order to keep the main focus on the cognitive side of skills and reasoning.

The purpose behind discussing twenty-first Century skills is that this set of skills provides important guidance for establishing essential education goals for modern society and learners. However, although there is substantial research evidence and consensus around identifying necessary twenty-first Century skills, there is a lack of research that focuses on how the related subskills interact and develop over time (Reimers & Chung, 2016), with much of the existing research residing in academic literature that is focused on psychology rather than education systems (National Research Council, 2012a). Therefore, a major and challenging task for discipline-based education researchers and educators is to operationally define discipline-specific goals that align with the twenty-first Century skills for each of the STEM fields. In the following sections, this paper will provide a limited vision of the research endeavors in physics education that can translate the past and current success into sustained impact for twenty-first Century teaching and learning.

Proposed education and research goals

Physics education research (PER) is often considered an early pioneer in discipline-based education research (National Research Council, 2012c), with well-established, broad, and influential outcomes (e.g., Hake, 1998; Hsu, Brewe, Foster, & Harper, 2004; McDermott & Redish, 1999; Meltzer & Thornton, 2012). Through the integration of twenty-first Century skills with the PER literature, a set of broadly defined education and research goals is proposed for future PER work:

1. Discipline-specific deep learning: Cognitive and education research involving physics learning has established a rich literature on student learning behaviors along with a number of frameworks. Some of the popular frameworks include conceptual understanding and concept change, problem solving, knowledge structure, deep learning, and knowledge integration. Aligned with twenty-first Century skills, future research in physics learning should aim to integrate the multiple areas of existing work, such that they help students develop well integrated knowledge structures in order to achieve deep leaning in physics.
2. Fostering scientific reasoning for transfer across STEM disciplines: The broad literature in physics learning and scientific reasoning can provide a solid foundation to further develop effective physics education approaches, such as active engagement instruction and inquiry labs, specifically targeting scientific inquiry abilities and reasoning skills. Since scientific reasoning is a more domain-general cognitive ability, success in physics can also more readily inform research and education practices in other STEM fields.
3. Research, development, assessment, and dissemination of effective education approaches: Developing and maintaining a supportive infrastructure of education research and implementation has always been a challenge, not only in physics but in all STEM areas. The twenty-first Century education requires researchers and instructors across STEM to work together as an extended community in order to construct a sustainable integrated STEM education environment. Through this new infrastructure, effective team-based inquiry learning and meaningful assessment can be delivered to help students develop a comprehensive skills set including deep

understanding and scientific reasoning, as well as communication and other non-cognitive abilities.

The suggested research will generate understanding and resources to support education practices that meet the requirements of the Next Generation Science Standards (NGSS), which explicitly emphasize three areas of learning including disciplinary core ideas, crosscutting concepts, and practices (National Research Council, 2012b). The first goal for promoting deep learning of disciplinary knowledge corresponds well to the NGSS emphasis on disciplinary core ideas, which play a central role in helping students develop well integrated knowledge structures to achieve deep understanding. The second goal on fostering transferable scientific reasoning skills supports the NGSS emphasis on crosscutting concepts and practices. Scientific reasoning skills are crosscutting cognitive abilities that are essential to the development of domain-general concepts and modeling strategies. In addition, the development of scientific reasoning requires inquiry-based learning and practices. Therefore, research on scientific reasoning can produce a valuable knowledge base on education means that are effective for developing crosscutting concepts and promoting meaningful practices in STEM. The third research goal addresses the challenge in the assessment of high-end skills and the dissemination of effective educational approaches, which supports all NGSS initiatives to ensure sustainable development and lasting impact. The following sections will discuss the research literature that provides the foundation for these three research goals and identify the specific challenges that will need to be addressed in future work.

Promoting deep learning in physics education

Physics education for the twenty-first Century aims to foster high-end reasoning skills and promote deep conceptual understanding. However, many traditional education systems place strong emphasis on only problem solving with the expectation that students obtain deep conceptual understanding through repetitive problem-solving practices, which often doesn't occur (Alonso, 1992). This focus on problem solving has been shown to have limitations as a number of studies have revealed disconnections between learning conceptual understanding and problem-solving skills (Chiu, 2001; Chiu, Guo, & Treagust, 2007; Hoellwarth, Moelter, & Knight, 2005; Kim & Pak, 2002; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987; Stamovlasis, Tsaparlis, Kamilatos, Papaoikonomou, & Zarotiadou, 2005). In fact, drilling in problem solving may actually promote memorization of context-specific solutions with minimal generalization rather than transitioning students from novices to experts.

Towards conceptual understanding and learning, many models and definitions have been established to study and describe student conceptual knowledge states and development. For example, students coming into a physics classroom often hold deeply rooted, stable understandings that differ from expert conceptions. These are commonly referred to as misconceptions or alternative conceptions (Clement, 1982; Duit & Treagust, 2003; Dykstra Jr, Boyle, & Monarch, 1992; Halloun & Hestenes, 1985a, 1985b). Such students' conceptions are context dependent and exist as disconnected knowledge fragments, which are strongly situated within specific contexts (Bao & Redish, 2001, 2006; Minstrell, 1992).

In modeling students' knowledge structures, DiSessa's proposed phenomenological primitives (p-prim) describe a learner's implicit thinking, cued from specific contexts, as an underpinning cognitive construct for a learner's expressed conception (DiSessa, 1993; Smith III, DiSessa, & Roschelle, 1994). Facets, on the other hand, map between the implicit p-prim and concrete statements of beliefs and are developed as discrete and independent units of thought, knowledge, or strategies used by individuals to address specific situations (Minstrell, 1992). Ontological categories, defined by Chi, describe student reasoning in the most general sense. Chi believed that these are distinct, stable, and constraining, and that a core reason behind novices' difficulties in physics is that they think of physics within the category of matter instead of processes (Chi, 1992; Chi & Slotta, 1993; Chi, Slotta, & De Leeuw, 1994; Slotta, Chi, & Joram, 1995). More details on conceptual learning and problem solving are well summarized in the literature (Hsu et al., 2004; McDermott & Redish, 1999), from which a common theme emerges from the models and definitions. That is, learning is context dependent and students with poor conceptual understanding typically have locally connected knowledge structures with isolated conceptual constructs that are unable to establish similarities and contrasts between contexts.

Additionally, this idea of fragmentation is demonstrated through many studies on student problem solving in physics and other fields. It has been shown that a student's knowledge organization is a key aspect for distinguishing experts from novices (Bagno, Eylon, & Ganiel, 2000; Chi, Feltovich, & Glaser, 1981; De Jong & Ferguson-Hesler, 1986; Eylon & Reif, 1984; Ferguson-Hesler & De Jong, 1990; Heller & Reif, 1984; Larkin, McDermott, Simon, & Simon, 1980; Smith, 1992; Veldhuis, 1990; Wexler, 1982). Expert's knowledge is organized around core principles of physics, which are applied to guide problem solving and develop connections between different domains as well as new, unfamiliar situations (Brown, 1989; Perkins & Salomon, 1989; Salomon & Perkins, 1989). Novices, on the other hand, lack a well-organized knowledge structure and often solve problems by relying on surface features that are directly mapped to certain problem-solving outcomes through memorization (Chi, Bassok, Lewis, Reimann, &

Glaser, 1989; Hardiman, Dufresne, & Mestre, 1989; Schoenfeld & Herrmann, 1982).

This lack of organization creates many difficulties in the comprehension of basic concepts and in solving complex problems. This leads to the common complaint that students' knowledge of physics is reduced to formulas and vague labels of the concepts, which are unable to substantively contribute to meaningful reasoning processes. A novice's fragmented knowledge structure severely limits the learner's conceptual understanding. In essence, these students are able to memorize how to approach a problem given specific information but lack the understanding of the underlying concept of the approach, limiting their ability to apply this approach to a novel situation. In order to achieve expert-like understanding, a student's knowledge structure must integrate all of the fragmented ideas around the core principle to form a coherent and fully connected conceptual framework.

Towards a more general theoretical consideration, students' alternative conceptions and fragmentation in knowledge structures can be viewed through both the "naïve theory" framework (e.g., Posner, Strike, Hewson, & Gertzog, 1982; Vosniadou, Vamvakoussi, & Skopeliti, 2008) and the "knowledge in pieces" (DiSessa, 1993) perspective. The "naïve theory" framework considers students entering the classroom with stable and coherent ideas (naïve theories) about the natural world that differ from those presented by experts. In the "knowledge in pieces" perspective, student knowledge is constructed in real-time and incorporates context features with the p-prims to form the observed conceptual expressions. Although there exists an ongoing debate between these two views (Kalman & Lattery, 2018), it is more productive to focus on their instructional implications for promoting meaningful conceptual change in students' knowledge structures.

In the process of learning, students may enter the classroom with a range of initial states depending on the population and content. For topics with well-established empirical experiences, students often have developed their own ideas and understanding, while on topics without prior exposure, students may create their initial understanding in real-time based on related prior knowledge and given contextual features (Bao & Redish, 2006). These initial states of understanding, regardless of their origin, are usually different from those of experts. Therefore, the main function of teaching and learning is to guide students to modify their initial understanding towards the experts' views. Although students' initial understanding may exist as a body of coherent ideas within limited contexts, as students start to change their knowledge structures throughout the learning process, they may evolve into a wide range of transitional states with varying levels of knowledge integration and coherence. The discussion in this brief review on students' knowledge structures regarding fragmentation and integration are primarily focused on the transitional stages emerged through learning.

The corresponding instructional goal is then to help students more effectively develop an integrated knowledge structure so as to achieve a deep conceptual understanding. From an educator's perspective, Bloom's taxonomy of education objectives establishes a hierarchy of six levels of cognitive skills based on their specificity and complexity: Remember (lowest and most specific), Understand, Apply, Analyze, Evaluate, and Create (highest and most general and complex) (Anderson et al., 2001; Bloom, Engelhart, Furst, Hill, & Krathwohl, 1956). This hierarchy of skills exemplifies the transition of a learner's cognitive development from a fragmented and contextually situated knowledge structure (novice with low level cognitive skills) to a well-integrated and globally networked expert-like structure (with high level cognitive skills).

As a student's learning progresses from lower to higher cognitive levels, the student's knowledge structure becomes more integrated and is easier to transfer across contexts (less context specific). For example, beginning stage students may only be able to memorize and perform limited applications of the features of certain contexts and their conditional variations, with which the students were specifically taught. This leads to the establishment of a locally connected knowledge construct. When a student's learning progresses from the level of Remember to Understand, the student begins to develop connections among some of the fragmented pieces to form a more fully connected network linking a larger set of contexts, thus advancing into a higher level of understanding. These connections and the ability to transfer between different situations form the basis of deep conceptual understanding. This growth of connections leads to a more complete and integrated cognitive structure, which can be mapped to a higher level on Bloom's taxonomy. This occurs when students are able to relate a larger number of different contextual and conditional aspects of a concept for analyzing and evaluating to a wider variety of problem situations.

Promoting the growth of connections would appear to aid in student learning. Exactly which teaching methods best facilitate this are dependent on the concepts and skills being learned and should be determined through research. However, it has been well recognized that traditional instruction often fails to help students obtain expert-like conceptual understanding, with many misconceptions still existing after instruction, indicating weak integration within a student's knowledge structure (McKeachie, 1986).

Recognizing the failures of traditional teaching, various research-informed teaching methods have been developed to enhance student conceptual learning along with diagnostic tests, which aim to measure the existence of misconceptions. Most advances in teaching methods focus on the inclusion of inquiry-based interactive-engagement elements in lecture, recitations, and labs. In physics education, these methods were popularized after Hake's landmark study demonstrated the effectiveness of interactive-engagement over traditional lectures (Hake, 1998). Some of these methods include the use of peer instruction (Mazur, 1997), personal response systems (e.g., Reay, Bao, Li, Warnakulasooriya, & Baugh, 2005), studio-style instruction (Beichner et al., 2007), and inquiry-based learning (Etkina & Van Heuvelen, 2001; Laws, 2004; McDermott, 1996; Thornton & Sokoloff, 1998). The key approach of these methods aims to improve student learning by carefully targeting deficits in student knowledge and actively encouraging students to explore and discuss. Rather than rote memorization, these approaches help promote generalization and deeper conceptual understanding by building connections between knowledge elements.

Based on the literature, including Bloom's taxonomy and the new education standards that emphasize twenty-first Century skills, a common focus on teaching and learning can be identified. This focus emphasizes helping students develop connections among fragmented segments of their knowledge pieces and is aligned with the knowledge integration perspective, which focuses on helping students develop and refine their knowledge structure toward a more coherently organized and extensively connected network of ideas (Lee, Liu, & Linn, 2011; Linn, 2005; Nordine, Krajcik, & Fortus, 2011; Shen, Liu, & Chang, 2017). For meaningful learning to occur, new concepts must be integrated into a learner's existing knowledge structure by linking the new knowledge to already understood concepts.

Forming an integrated knowledge structure is therefore essential to achieving deep learning, not only in physics but also in all STEM fields. However, defining what connections must occur at different stages of learning, as well as understanding the instructional methods necessary for effectively developing such connections within each STEM disciplinary context, are necessary for current and future research. Together these will provide the much needed foundational knowledge base to guide the development of the next generation of curriculum and classroom environment designed around twenty-first Century learning.

Developing scientific reasoning with inquiry labs

Scientific reasoning is part of the widely emphasized cognitive strand of twenty-first Century skills. Through development of scientific reasoning skills, students' critical thinking, open-ended problem-solving abilities, and decision-making skills can be improved. In this way, targeting scientific reasoning as a curricular objective is aligned with the goals emphasized in twenty-first Century education. Also, there is a growing body of research on the importance of student development of scientific reasoning, which have been found to positively correlate with course achievement (Cavallo, Rozman, Blickenstaff, & Walker, 2003; Johnson & Lawson, 1998), improvement on concept tests (Coletta & Phillips, 2005; She & Liao, 2010), engagement in higher levels of problem solving (Cracolice, Deming, & Ehlert, 2008; Fabby & Koenig, 2013); and success on transfer (Ates & Cataloglu, 2007; Jensen & Lawson, 2011).

Unfortunately, research has shown that college students are lacking in scientific reasoning. Lawson (1992) found that ~ 50% of intro biology students are not capable of applying scientific reasoning in learning, including the ability to develop hypotheses, control variables, and design experiments; all necessary for meaningful scientific inquiry. Research has also found that traditional courses do not significantly develop these abilities, with pre-to-post-test gains of 1%–2%, while inquiry-based courses have gains around 7% (Koenig, Schen, & Bao, 2012; Koenig, Schen, Edwards, & Bao, 2012). Others found that undergraduates have difficulty developing evidence-based decisions and differentiating between and linking evidence with claims (Kuhn, 1992; Shaw, 1996; Zeineddin & Abd-El-Khalick, 2010). A large scale international study suggested that learning of physics content knowledge with traditional teaching practices does not improve students' scientific reasoning skills (Bao et al., 2009).

Aligned to twenty-first Century learning, it is important to implement curriculum that is specifically designed for developing scientific reasoning abilities within current education settings. Although traditional lectures may continue for decades due to infrastructure constraints, a unique opportunity can be found in the lab curriculum, which may be more readily transformed to include hands-on minds-on group learning activities that are ideal for developing students' abilities in scientific inquiry and reasoning.

For well over a century, the laboratory has held a distinctive role in student learning (Meltzer & Otero, 2015). However, many existing labs, which haven't changed much since the late 1980s, have received criticism for their outdated cookbook style that lacks effectiveness in developing high-end skills. In addition, labs have been primarily used as a means for verifying the physical principles presented in lecture, and unfortunately, Hofstein and Lunetta (1982) found in an early review of the literature that research was unable to demonstrate the impact of the lab on student content learning.

About this same time, a shift towards a constructivist view of learning gained popularity and influenced lab curriculum development towards engaging students in the process of constructing knowledge through science inquiry. Curricula, such as Physics by Inquiry (McDermott, 1996), Real-Time Physics (Sokoloff, Thornton, & Laws, 2011), and Workshop Physics (Laws, 2004), were developed with a primary focus on engaging students in cognitive conflict to address misconceptions. Although these approaches have been shown to be highly successful in improving deep learning of physics concepts (McDermott & Redish, 1999), the emphasis on conceptual learning does not sufficiently impact the domain general scientific reasoning skills necessitated in the goals of twenty-first Century learning.

Reform in science education, both in terms of targeted content and skills, along with the emergence of knowledge regarding human cognition and learning (Bransford, Brown, & Cocking, 2000), have generated renewed interest in the potential of inquiry-based lab settings for skill development. In these types of hands-on minds-on learning, students apply the methods and procedures of science inquiry to investigate phenomena and construct scientific claims, solve problems, and communicate outcomes, which holds promise for developing both conceptual understanding and scientific reasoning skills in parallel (Trowbridge, Bybee, & Powell, 2000). In addition, the availability of technology to enhance inquiry-based learning has seen exponential growth, along with the emergence of more appropriate research methodologies to support research on student learning.

Although inquiry-based labs hold promise for developing students' high-end reasoning, analytic, and scientific inquiry abilities, these educational endeavors have not become widespread, with many existing physics laboratory courses still viewed merely as a place to illustrate the physical principles from the lecture course (Meltzer & Otero, 2015). Developing scientific ideas from practical experiences, however, is a complex process. Students need sufficient time and opportunity for interaction and reflection on complex, investigative tasks. Blended learning, which merges lecture and lab (such as studio style courses), addresses this issue to some extent, but has experienced limited adoption, likely due to the demanding infrastructure resources, including dedicated technology-intensive classroom space, equipment and maintenance costs, and fully committed trained staff.

Therefore, there is an immediate need to transform the existing standalone lab courses, within the constraints of the existing education infrastructure, into more inquiry-based designs, with one of its primary goals dedicated to developing scientific reasoning skills. These labs should center on constructing knowledge, along with hands-on minds-on practical skills and scientific reasoning, to support modeling a problem, designing and implementing experiments, analyzing and interpreting data, drawing and evaluating conclusions, and effective communication. In particular, training on scientific reasoning needs to be explicitly addressed in the lab curriculum, which should contain components specifically targeting a set of operationally-defined scientific reasoning skills, such as ability to control variables or engage in multivariate causal reasoning. Although effective inquiry may also implicitly develop some aspects of scientific reasoning skills, such development is far less efficient and varies with context when the primary focus is on conceptual learning.

Several recent efforts to enhance the standalone lab course have shown promise in supporting education goals that better align with twenty-first Century learning. For example, the Investigative Science Learning Environment (ISLE) labs involve a series of tasks designed to help students develop the "habits of mind" of scientists and engineers (Etkina et al., 2006). The curriculum targets reasoning as well as the lab learning outcomes published by the American Association of Physics Teachers (Kozminski et al., 2014). Operationally, ISLE methods focus on scaffolding students' developing conceptual understanding using inquiry learning without a heavy emphasis on cognitive conflict, making it more appropriate and effective for entry level students and K-12 teachers.

Likewise, Koenig, Wood, Bortner, and Bao (2019) have developed a lab curriculum that is intentionally designed around the twenty-first Century learning goals for developing cognitive, interpersonal, and intrapersonal abilities. In terms of the cognitive domain, the lab learning outcomes center on critical thinking and scientific reasoning but do so through operationally defined sub-skills, all of which are transferrable across STEM. These selected sub-skills are found in the research literature, and include the ability to control variables and engage in data analytics and causal reasoning. For each targeted sub-skill, a series of pre-lab and in-class activities provide students with repeated, deliberate practice within multiple hypothetical science-based scenarios followed by real inquiry-based lab contexts. This explicit instructional strategy has been shown to be essential for the development of scientific reasoning (Chen & Klahr, 1999). In addition, the Karplus Learning Cycle (Karplus, 1964) provides the foundation for the structure of the lab activities and involves cycles of exploration, concept introduction, and concept application. The curricular framework is such that as the course progresses, the students engage in increasingly complex tasks, which allow students the opportunity to learn gradually through a progression from simple to complex skills.

As part of this same curriculum, students' interpersonal skills are developed, in part, through teamwork, as students work in groups of 3 or 4 to address open-ended research questions, such as, *What impacts the period of a pendulum?* In addition, due to time constraints, students learn early on about the importance of working together in an efficient manor towards a common goal, with one set of written lab records per team submitted after each lab. Checkpoints built into all in-class activities involve Socratic dialogue between the instructor and students and promote oral communication. This use of directed questioning guides students in articulating their reasoning behind decisions and claims made, while supporting the development of scientific reasoning and conceptual understanding in parallel (Hake, 1992). Students' intrapersonal skills, as well as communication skills, are promoted through the submission of individual lab reports. These reports require students to reflect upon their learning over each of four multi-week experiments and synthesize their ideas into evidence-based arguments, which support a claim. Due to the length of several weeks over which students collect data for each of these reports, the ability to organize the data and manage their time becomes essential.

Despite the growing emphasis on research and development of curriculum that targets twenty-first Century learning, converting a traditionally taught lab course into a meaningful inquiry-based learning environment is challenging in current reform efforts. Typically, the biggest challenge is a lack of resources; including faculty time to create or adapt inquiry-based materials for the local setting, training faculty and graduate student instructors who are likely unfamiliar with this approach, and the potential cost of new equipment. Koenig et al. (2019) addressed these potential implementation barriers by designing curriculum with these challenges in mind. That is, the curriculum was designed as a flexible set of modules that target specific sub-skills, with each module consisting of pre-lab (hypothetical) and in-lab (real) activities. Each module was designed around a curricular framework such that an adopting institution can use the materials as written, or can incorporate their existing equipment and experiments into the framework with minimal effort. Other non-traditional approaches have also been experimented with, such as the work by Sobhanzadeh, Kalman, and Thompson (2017), which targets typical misconceptions by using conceptual questions to engage students in making a prediction, designing and conducting a related experiment, and determining whether or not the results support the hypothesis.

Another challenge for inquiry labs is the assessment of skills-based learning outcomes. For assessment of scientific reasoning, a new instrument on inquiry in scientific thinking analytics and reasoning (iSTAR) has been developed, which can be easily implemented across large numbers of students as both a pre- and post-test to assess gains. iSTAR assesses reasoning skills necessary in the systematical conduct of scientific inquiry, which includes the ability to explore a problem, formulate and test hypotheses, manipulate and isolate variables, and observe and evaluate the consequences (see www.istarassessment.org). The new instrument expands upon the commonly used classroom test of scientific reasoning (Lawson, 1978, 2000), which has been identified with a number of validity weaknesses and a ceiling effect for college students (Bao, Xiao, Koenig, & Han, 2018).

Many education innovations need supporting infrastructures that can ensure adoption and lasting impact. However, making large-scale changes to current education settings can be risky, if not impossible. New education approaches, therefore, need to be designed to adapt to current environmental constraints. Since higher-end skills are a primary focus of twenty-first Century learning, which are most effectively developed in inquiry-based group settings, transforming current lecture and lab courses into this new format is critical. Although this transformation presents great challenges, promising solutions have already emerged from various research efforts. Perhaps the biggest challenge is for STEM educators and researchers to form an alliance to work together to re-engineer many details of the current education infrastructure in order to overcome the multitude of implementation obstacles.

Conclusion

This paper attempts to identify a few central ideas to provide a broad picture for future research and development in physics education, or STEM education in general, to promote twenty-first Century learning. Through a synthesis of the existing literature within the authors' limited scope, a number of views surface.

Education is a service to prepare (not to select) the future workforce and should be designed as learner-centered, with the education goals and teaching-learning methods tailored to the needs and characteristics of the learners themselves. Given space constraints, the reader is referred to the meta-analysis conducted by Freeman et al. (2014), which provides strong support for learner-centered instruction. The changing world of the twenty-first Century informs the establishment of new education goals, which should be used to guide research and development of teaching and learning for present day students. Aligned to twenty-first Century learning, the new science standards have set the goals for STEM education to transition towards promoting deep learning of disciplinary knowledge, thereby building upon decades of research in PER, while fostering a wide range of general high-end cognitive and non-cognitive abilities that are transferable across all disciplines.

Following these education goals, more research is needed to operationally define and assess the desired high-end reasoning abilities. Building on a clear definition with effective assessments, a large number of empirical studies are needed to investigate how high-end abilities can be developed in parallel with deep learning of concepts, such that what is learned can be generalized to impact the development of curriculum and teaching methods which promote skills-based learning across all STEM fields. Specifically for PER, future research should emphasize knowledge integration to promote deep conceptual understanding in physics along with inquiry learning to foster scientific reasoning. Integration of physics learning in contexts that connect to other STEM disciplines is also an area for more research. Cross-cutting, interdisciplinary connections are becoming important features of the future generation physics curriculum and defines how physics should be taught collaboratively with other STEM courses.

This paper proposed meaningful areas for future research that are aligned with clearly defined education goals for twenty-first Century learning. Based on the existing literature, a number of challenges are noted for future directions of research, including the need for:

- clear and operational definitions of goals to guide research and practice
- concrete operational definitions of high-end abilities for which students are expected to develop
- effective assessment methods and instruments to measure high-end abilities and other components of twenty-first Century learning
- a knowledge base of the curriculum and teaching and learning environments that effectively support the development of advanced skills
- integration of knowledge and ability development regarding within-discipline and cross-discipline learning in STEM
- effective means to disseminate successful education practices

The list is by no means exhaustive, but these themes emerge above others. In addition, the high-end abilities discussed in this paper focus primarily on scientific reasoning, which is highly connected to other skills, such as critical thinking, systems thinking, multivariable modeling, computational thinking, design thinking, etc. These abilities are expected to develop in STEM learning, although some may be emphasized more within certain disciplines than others. Due to the limited scope of this paper, not all of these abilities were discussed in detail but should be considered an integral part of STEM learning.

Finally, a metacognitive position on education research is worth reflection. One important understanding is that the fundamental learning mechanism hasn't changed, although the context in which learning occurs has evolved rapidly as a manifestation of the fast-forwarding technology world. Since learning is a process at the interface between a learner's mind and the environment, the main focus of educators should always be on the learner's interaction with the environment, not just the environment. In recent education developments, many new learning platforms have emerged at an exponential rate, such as the massive open online courses (MOOCs), STEM creative labs, and other online learning resources, to name a few. As attractive as these may be, it is risky to indiscriminately follow trends in education technology and commercially-incentivized initiatives before such interventions are shown to be effective by research. Trends come and go but educators foster students who have only a limited time to experience education. Therefore, delivering effective education is a high-stakes task and needs to be carefully and ethically planned and implemented. When game-changing opportunities emerge, one needs to not only consider the winners (and what they can win), but also the impact on all that is involved.

Based on a century of education research, consensus has settled on a fundamental mechanism of teaching and learning, which suggests that knowledge is developed within a learner through constructive processes and that team-based guided scientific inquiry is an effective method for promoting deep learning of content knowledge as well as developing high-end cognitive abilities, such as scientific reasoning. Emerging technology and methods should serve to facilitate (not to replace) such learning by providing more effective education settings and conveniently accessible resources. This is an important relationship that should survive many generations of technological and societal changes in the future to come. From a physicist's point of view, a fundamental relation like this can be considered the "mechanics" of teaching and learning. Therefore, educators and researchers should hold on to these few fundamental principles without being distracted by the surfacing ripples of the world's motion forward.

Abbreviations

AAPT: American Association of Physics Teachers; ISLE: Investigative Science Learning Environment; iSTAR: Inquiry in Scientific Thinking Analytics and Reasoning; MOOC: Massive open online course; NGSS: New Generation Science Standards; PER: Physics education research; STEM: Science Technology Engineering and Math

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Authors' contributions

LB developed the concept, wrote a significant portion of the review and position, and synthesized the paper. KK wrote and edited a significant portion of the paper. Both authors read and approved the final manuscript.

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Author details
[1]The Ohio State University, Columbus, OH 43210, USA. [2]University of Cincinnati, Cincinnati, OH 45221, USA.

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